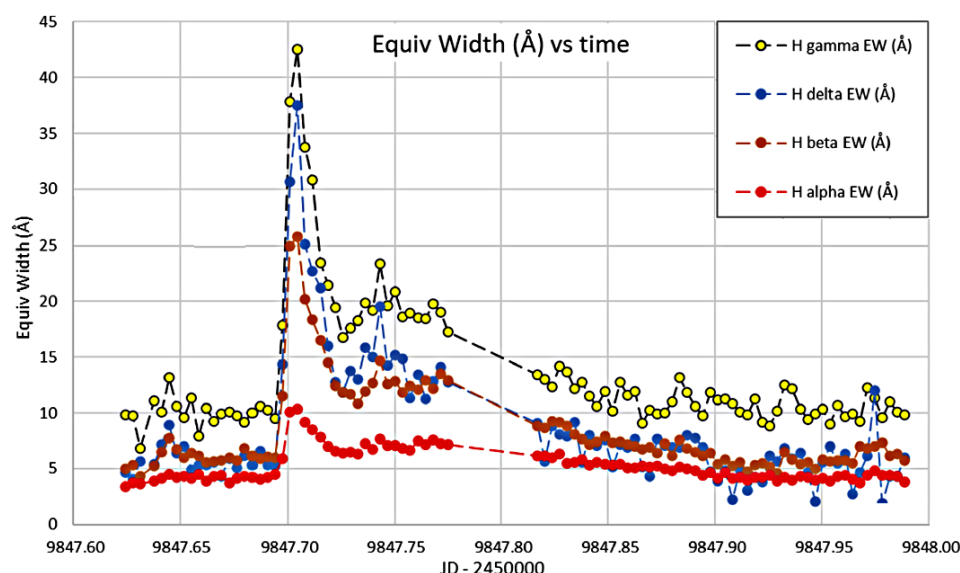


The Journal of the American Association of Variable Star Observers

Spectrophotometry of a Flare on EQ Pegasi A



Strength of the Balmer H-alpha, H-beta, H-gamma, and H-delta lines during the flare, showing their gradual decays. The hump during the decline phase is seen on all of them.

Also in this issue...

- Digital Photometry, Period Analysis, Light Curve Deconvolution, and Evolutionary Status of the High Amplitude δ Scuti Variable Star KO Piscium
- How a Precessional Oscillation Ceases: the Dissolution of the Circumstellar Disk of Pleione
- Empirical Transformation Formulae from APASS DR9 to the Johnson–Kron–Cousins $B V R_c I_c$ Photometric System

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The Journal of the American Association of Variable Star Observers

Volume 54, Number 1, 2026

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Nancy D. Morrison

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Editorial

Data Exploration

Nancy D. Morrison

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It's time for me to don my university professor hat and speak to students. At some level, we are all students.

During the past year or so, a few submitted papers have contained paragraphs that purport to describe a graph but bear no relation (or even the opposite relation) to the actual appearance of the graph. They appear intended to describe an expected outcome of the investigation, not the graph. But the data, not the authors' expectations, should drive the results of research. Every analysis should begin with a visual exploration of a graph of the data.

A more subtle form of this problem arises when authors follow the usual approach of fitting a function to a scatterplot of data but allow their expectations to govern their choice what function to fit. Instead, it is important to allow the data speak for themselves and let the shape of the distribution of data points to drive the choice of fitted function, with the proviso that the simplest function that will fit the data should generally be chosen.

Let the data guide initial decisions. Does the fitted function pass through the middle of the cloud of data points? Is the fit being unduly influenced by a few outliers near the extremes of the range of data? Do the data really require all the wiggles in the fitted function?

Here is a data set giving the heights and weights (along with other characteristics) of a sample of children under 12 (Verzani 2005). One expects that height and weight increase together over time, and the existence of the often-used body mass index (equal to mass divided by height squared) suggests a quadratic component, but I am aware of no other expectations about these data.

Figure 1 shows a least-squares straight line fitted naively to all the data. Inspection of the cloud of data points suggests the presence of three classes of children: (1) that represented by most of the points, which trace out a roughly linear trend lying mostly below the fitted line; (2) that represented by the diffuse cloud of points extending far above the line; and (3) the single outlier at the extreme lower left. If I were a medical student interpreting the plot, I might be tempted to suppose that (3) represents an infant, (2) represents overweight or obese children, and (1) represents normal growth. In addition, (2) might suggest a growth spurt at around age 12. The artificial limit at age 12 makes this part of the graph difficult to interpret.

By definition, a least-squares fit satisfies the condition that the sum of the squares of the differences between the data points and their corresponding y values on the fitted function

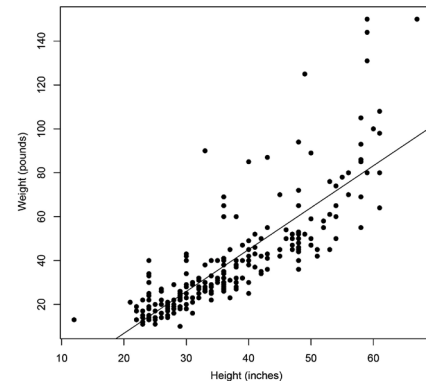


Figure 1. Height plotted against weight for the sample of children in the kids.weight data set, fitted with a least-squares straight line.

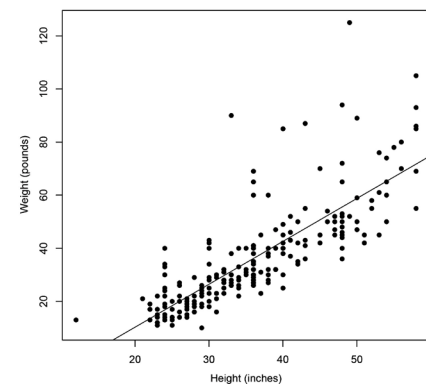


Figure 2. Height plotted against weight for the subset of children in the kids.weight data set with heights less than 59 inches, fitted with a least-squares straight line.

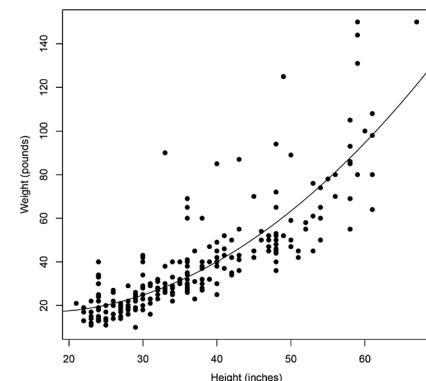


Figure 3. Height plotted against weight for the sample of children, infant outlier omitted, in the kids.weight data set, fitted with a least-squares quadratic function.

is a minimum. In order to satisfy this condition, this particular fit is pulled toward the dispersed points above the line and away from the hypothetically normal cloud of points. A way of addressing this problem is to remove the most strongly outlying points from the data set. In this case, this approach would not be the best because it would involve removing a lot of outliers, and it can be difficult to know exactly which outliers to remove. Outliers are a matter of debate in astronomical data science. Some people object to removing any outliers, as long as they represent valid data.

In an effort to fit group (1) alone, I used the data for heights of 58 inches or less to make a linear fit, which is shown in Figure 2. It does a better job of going through the hypothetically “normal” points around a height of 50 inches, but it is still affected by the high-lying outliers. I tried removing the infant outlier, but that made no difference in this case. Usually, outliers near the end of the range of the data are of concern, but this data set includes enough other points to outweigh the effect of that one.

On the other hand, given the existence of the body mass index, a quadratic (parabolic) fit may make sense. Figure 3 shows a least-squares quadratic fit to all the data except the infant outlier. This fit represents neither the hypothetically “normal” points nor the trend of the high-weight points well. I tried a higher-order function—a cubic—with slightly improved results at the high end of the range of the data, but unreasonable results at the low end. Further efforts to improve the fit might

result in overinterpretation of the data, given the artificial limit at age 12.

If I were forced to choose one of these three fits, I would choose the one in Figure 2, because it is the simplest model. Probably, though, we should conclude that a simple fitted function does not give a good description of this data set. Verzani (2005) suggests further analysis based on additional dimensions of the data (age and gender), but that would be beyond the scope of this essay.

Unlike most astronomical data, this data set does not include measurement errors. Consideration of measurement error is another stage of data exploration and is likewise beyond the scope of this essay. For now, enjoy a visual journey through your data!

Acknowledgement

For graphics and analysis, this article used R version 4.6.0, which is freely available from

<https://cran.r-project.org/mirrors.html>
for Windows, macOS, and Linux. The R commands used are given in the Appendix.

References

Verzani, J. 2005, *Using R for Introductory Statistics*, Chapman & Hall/CRC, Boca Raton, FL, 85 .

Appendix: R commands used in this essay

```

# Comments begin with #
# This is not complete code.
# If you want to run this, you may need to define new variables.
#
# Download and make available the data set
# Lots of other needed packages ('dependencies') will also be downloaded.
# If you have limited disk space, use caution.
where <- "http://www.math.csi.cuny.edu/UsingR"
install.packages("UsingR")
library(UsingR)
data(package="UsingR")
attach(kid.weights)

# Make Figure 1
plot(height,weight,pch=16,xlab="Height (inches)",ylab="Weight (pounds)")
lm(weight~height)
# Output from 'lm' follows.
Call:
lm(formula = weight ~ height)

Coefficients:
(Intercept) height
-31.342 1.909

# Overplot the straight line
abline(-31.342,1.909)

# Make Figure 2

# Fit only the smaller heights
plot(height[which(height<59)],weight[which(height<59)],pch=16,
      xlab="Height (inches),ylab="Weight (pounds)")
lm(weight[which(height<59)]~height[which(height<59)])

Call:
lm(formula = weight[which(height < 59)] ~ height[which(height < 59)])

Coefficients:
(Intercept) height[which(height < 59)]
-22.017 1.616

abline(-22.017,1.616)

# Fit with a quadratic, without the infant (index 54)
# The infant distorts the quadratic fit.
plot(height[-54],weight[-54],pch=16,xlab="Height (inches)",ylab="Weight (pounds)")
coeff2 <- lm(weight[-54]~height[-54]+I(height[-54]^2))
c2 <- coef(coeff2)
c2
(Intercept) height[-54] I(height[-54]^2)
27.14221910 -1.28160965 0.04009977
quad2 <- function(x) {c2[1] + c2[2] * x + c2[3] * x^2}
# Overplot the quadratic fit.
x <-seq(10,70,by=1)
lines(x,quad2(x))

# Clean up
detach(kid.weights)

```

Analysis of 33 Binary Systems Initially Discovered with the ROTSE-I Telescope

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Abstract We present results of an ongoing search for variable stars first identified using high cadence data from the ROTSE-I telescope. To date, this search has identified over 100 previously undiscovered binary systems, which were initially submitted to and approved by the International Variable Star Index. In this preliminary analysis, these stars were analyzed and classified using a range of approaches. The high cadence data were supplemented by data from the ROTSE-I-based NSVS, as well as the CRTS, SuperWASP, and ASAS surveys. This paper describes this work and further details an updated analysis of 33 binary systems. This refined sample consists of 4 β Per, 6 β Lyr, 20 W UMa, and 3 ELL variables. Of the variables analyzed, period values range from 0.24801 to 3.11608 d. Measured amplitudes range from 0.064 to 0.553 magnitude of variation in the ROTSE passband. A full list of final, standardized periods and amplitudes are provided with their differences from the preliminary results for comparison.

1. Introduction

Binary stars are exceedingly common. Duquenooy and Mayor (1991) found that around 58% of G-dwarf field stars have a binary companion, after correcting for sample incompleteness. With the advent of large-scale all-sky surveys, some aimed at detecting variable stars but many more with cadences well suited for their discovery as ancillary targets, many binary systems have been observed. Early surveys such as the Robotic Optical Transient Search Experiment (ROTSE-I; Akerlof *et al.* 2000), the Northern Sky Variability Survey (NSVS, based on ROTSE-I data) (Woźniak *et al.* 2004), the Optical Gravitational Lensing Experiment (OGLE; Udalski *et al.* 1992), and the All-Sky Automated Survey (ASAS; Pojmański 1997) helped to pioneer the field for modern surveys like the All-Sky Automated Survey for Supernovae (ASAS-SN). ASAS-SN data alone should contain approximately 1 million variable sources (Kochanek *et al.* 2017), of which eclipsing binaries are the most abundant type (Cuevas-Otahola *et al.* 2019). Other large surveys such as the Wide Angle Search for Planets (WASP; Butters *et al.* 2010) and the Catalina Sky Survey (CSS; Drake *et al.* 2014) are also valuable sources of variable star observations. Many of these observations have been compiled into the AAVSO International Variable Star Index (VSX; Watson *et al.* 2006), one of the most complete public catalogs of known variable stars (Drake *et al.* 2014).

The ubiquitous nature of eclipsing binary systems contributes to their utility as standard candles, specifically for W Ursae Majoris (W UMa) systems. The period-color relation for W UMa variables was noted by Eggen (1967). Lucy (1968) formulated a theoretical model of a W UMa system in which both components interact via a common equipotential. With these results, Rucinski (1994) used the proportionality between luminosity and effective temperature to derive calibrations for W UMa absolute magnitudes (M_V) in terms of B–V and V–I_c color, as well as orbital period. Using W UMa variables as standard candles, they developed a preliminary calibration which was refined in subsequent studies (Rucinski 1996; Rucinski and Duerbeck 1997; Rucinski 2004) so M_V can be calibrated to an uncertainty of ± 0.25 mag. Additionally, tight contact binaries, such as W UMa systems, experience orbital period changes caused by mass symmetrization (Sargisyan *et al.* 2019), marking them as potential progenitors for some classes of cataclysmic optical transients.

Recent photometric investigations found this period change to be on the order of -2×10^{-7} day/year for V1197 Her (Zhou and Soonthornthum 2019), -4×10^{-7} day/year for AV Puppis (Han *et al.* 2019), and 1×10^{-7} day/year for V2790 Ori (Kriwattanawong and Kriwattanawong 2019). One such system, TY Pup, which experiences a period change on the order of 5×10^{-8} day/year (Sarotsakulchai *et al.* 2018), has been identified as a progenitor candidate of luminous red novae (LRNe). LRNe are a form of intermediate-luminosity optical transient, with luminosities brighter than that of a typical nova but dimmer than a supernova (Berger *et al.* 2009). LRNe typically peak at $M_V = -13$ to -15 absolute mag, with possible progenitors being unstable massive stars, an envelope ejection from a close binary system, or a merger of a binary system (Pastorello *et al.* 2019; Kamiński *et al.* 2018).

1.1. Binary system parameters

In general, binary systems can provide valuable tools for constraining properties of stellar evolution. Direct derivations of stellar mass are only possible for stars in binary systems. Photometric light curves of eclipsing binary systems alone can provide measurements of the orbital inclination, relative stellar radii, eccentricities, and effective surface temperatures of a system (eg. Burki *et al.* 2005). When these light curves are combined with spectroscopy the mass, radius, surface gravity, effective surface temperature, mean density, and luminosity of each component can be constrained (Binnendijk 1970; Southworth *et al.* 2011). With the known luminosity of a binary, the distance to the system can be found. This combined with the large proportion of binary systems makes eclipsing binaries an important part of the cosmic distance ladder. These parameters can be combined into large statistical studies constraining the mass ratio, orbital period, separation, and multiplicity distributions of binary populations (Duquenooy and Mayor 1991; Fischer and Marcy 1992; Patience *et al.* 2002; Connelley *et al.* 2008; Duchêne and Kraus 2013; Moe and Di Stefano 2017; Duchêne *et al.* 2018). Binary mass ratio, orbital period, separation, and multiplicity distributions are used to verify theoretical models and simulations, either those specifically pertaining to binary system formation (Lucy 1968; Kroupa 1995; Reggiani and Meyer 2011; Marks *et al.* 2011; Cuevas-Otahola *et al.* 2019) or general models of stellar evolution (Goodwin *et al.* 2007; Lomax *et al.* 2015; Bate 2019). In particular, Sadavoy and Stahler (2017) found that in the model of stellar evolution best emulating observations from the Perseus Molecular Cloud, all stars first form as wide binaries.

1.2. Paper overview

The population of eclipsing variable stars includes systems with periods as short as hours. High cadence observations are particularly well suited to detect these systems because this observing strategy provides direct, in-night demonstration of light curve shape, period and classification, even before phasing has been performed. This paper presents an effort to utilize dedicated, high cadence data taken with the ROTSE-I telescope (Akerlof *et al.* 1999) for eclipsing variable detection. The high cadence data were used to search for untriggered orphan gamma ray burst (GRB) optical afterglows (Kehoe *et al.* 2002). The Variable Stars Project (VSP) was developed for student researchers to utilize these data to measure rapidly varying periodic variables that are a vital step in the cosmic distance ladder. In this paper, we focus on binary systems, which are the most frequently encountered in the high cadence ROTSE-I data sample. Section 2 describes ROTSE telescope characteristics and the resulting data collection process. Section 3 covers the process of phasing nightly light curve data to derive period and amplitude values for each binary system. Section 4 presents the results of the analysis process for each binary sub-type along with their associated light curves.

2. Data Collection

2.1. Detector and operation

ROTSE-I was a telescope located in Los Alamos, New Mexico, with a patrolling range from the north pole to a declination of -38° . ROTSE-I employed a co-mounted two-by-two array of telephoto lenses fixed on a rapid-slewing mount. Each telescope had a 8.2° field of view yielding a total 256 deg^2 field. The ROTSE-I telescope was operated without photometric filter to maximize signal-to-noise for the gamma ray burst program. The peak sensitivity is covered by the Cousins R-band. Photometric calibration routines were undertaken to produce color-corrected magnitudes, such that ROTSE observations are placed on a V-band equivalent scale. While in operation, if there were not any existing GRB trigger or follow up observations, sky patrol exposures were taken throughout the night such that pairs of 80-second exposures were taken for each field. In the later half of 1999 through 2000, an alternative schedule of observations was used intermittently to support the search for untriggered gamma-ray bursts, see Figure 1 in Kehoe *et al.* (2002). Data were taken using either the stare or switch pointing modes. Stare mode consists of a dedicated night of repeated images of a single field with no repointings to other locations during the night. In switch mode, five 80-s exposures are taken at one pointing, followed by five exposures at a second location and a restart at the first field. A more detailed description of the ROTSE-I detector can be found in Akerlof *et al.* (1999).

Detection of variable star candidates and light curve phasing were conducted using ROTSE-I untriggered GRB optical burst search data. Here, light curve phasing refers to the process by which unevenly sampled time-series observations are passed through an algorithm which allows for detection and characterization of a variable star's periodicity. Table 1 in Kehoe *et al.* (2002) contains the dates, coordinates of fields, total area, and observing protocol for each set of observations. These data achieved limiting magnitudes of 15.0 to 16.1 with a mean limiting magnitude of 15.7, as measured in m_{ROTSE} . The sky patrol data provide a rich sample for variable measurements (Akerlof *et al.* 2000), and contain the subset of data used for NSVS (Woźniak *et al.* 2004). Also obtained using the ROTSE-I telescope, NSVS observations consist of two consecutive 80-second exposures for each field (Woźniak *et al.* 2004).

ROTSE-I data were reduced using standard ROTSE pipelines—starting with dark and flat corrections (Kehoe *et al.* 2001). Source extraction was performed using Source Extractor (Bertin and Arnouts 1996). Astrometric and photometric calibration were achieved by comparison to the USNO 1.0 Catalog (Monet 1996) as with Kehoe *et al.* (2001). Observations containing data from individual objects were matched by position over a series of exposures, usually a single night. Flat corrections also helped account for vignetting, which occurs in images which exhibit a radial falloff of intensity from the center of the image. Relative photometry was performed using the median magnitude of template sources in good observations, as described by Kehoe *et al.* (2002).

2.2. Source selection

A candidate variable star is selected via statistical cuts to the light curve. The variation in magnitude, $\Delta m = m_{\text{max}} - m_{\text{min}}$, was selected to be ≥ 0.1 where m_{max} and m_{min} are the maximum and minimum observed magnitudes. The significance of the variation, σ_{max} as defined in Equation 1, was selected to be ≥ 3 , where the two extrema measurements are omitted. $\epsilon_{\text{max'}}$ and $\epsilon_{\text{min'}}$ are the uncertainties in these maximum and minimum observed magnitudes.

$$\sigma_{\text{max}} = \frac{m_{\text{max'}} - m_{\text{min'}}}{\sqrt{\epsilon_{\text{max'}}^2 + \epsilon_{\text{min'}}^2}} \quad (1)$$

The χ^2 of the observations to a constant magnitude value, as defined in Equation 2 was selected to be ≥ 2 .

$$\chi^2 = \sum_{k=1}^n \frac{(m_k - \bar{m}_k)^2}{\sigma_k^2} \quad (2)$$

where n is the number of measurements, m_k is the k th observed magnitude, σ_k is the uncertainty in the k th observed magnitude, and $\bar{m}_k$ is the average magnitude taken over the entire light curve for that night. This process helped account for saturation, which occurs when an imaging pixel becomes over-exposed and leaks electrons from incident photons onto adjacent pixels. This leads to effects that can be visually discerned such as blooming. Saturation was taken into account in this candidate selection process such that we remove observations from the calculation of Δm , $\sigma_{\text{max'}}$, and χ^2 .

A light curve for each variable star candidate on each night was extracted for all the nights it was observed. Further selection of candidates entailed a visual inspection that fully exploited the high degree of redundancy in the stare-and-switch scheduled data. This includes the redundancy from many closely spaced observations per night, as well as multiple closely spaced nights. We developed a method enforcing basic soundness of the light curve properties upon visual inspection. We require of the observations: confirmation, consistency, and continuity of the observed variability. Confirmation requires that an observation is verified by measurements adjacent in time, within the window of the readout time plus the following exposure. The requirement of visual and statistical consistency between consecutive observations was used to visually filter outlier observations potentially caused by hot pixels, cloud cover, cosmic rays, or other effects. Continuity weighed the validity of the temporal variation in magnitude of a potential variable, discarding those nightly light curves that exhibit magnitude changes between consecutive observations that are well beyond the statistical errors on the pair of measurements. Such behavior can happen, for instance, with stars undergoing erratic blending and de-blending with a nearby star. Rapid variation on the scale of 1 to 2 minutes is not expected to dominate the pulsating or eclipsing systems that are the subject of this study. Candidates were retained only if they satisfied these criteria on two or more nights. Surviving objects had all nights' observations assembled into light curves which were then phased. Light curves showing a strong pattern of variability like in Figure 1 were flagged as likely variable stars. Coordinates of candidates passing visual

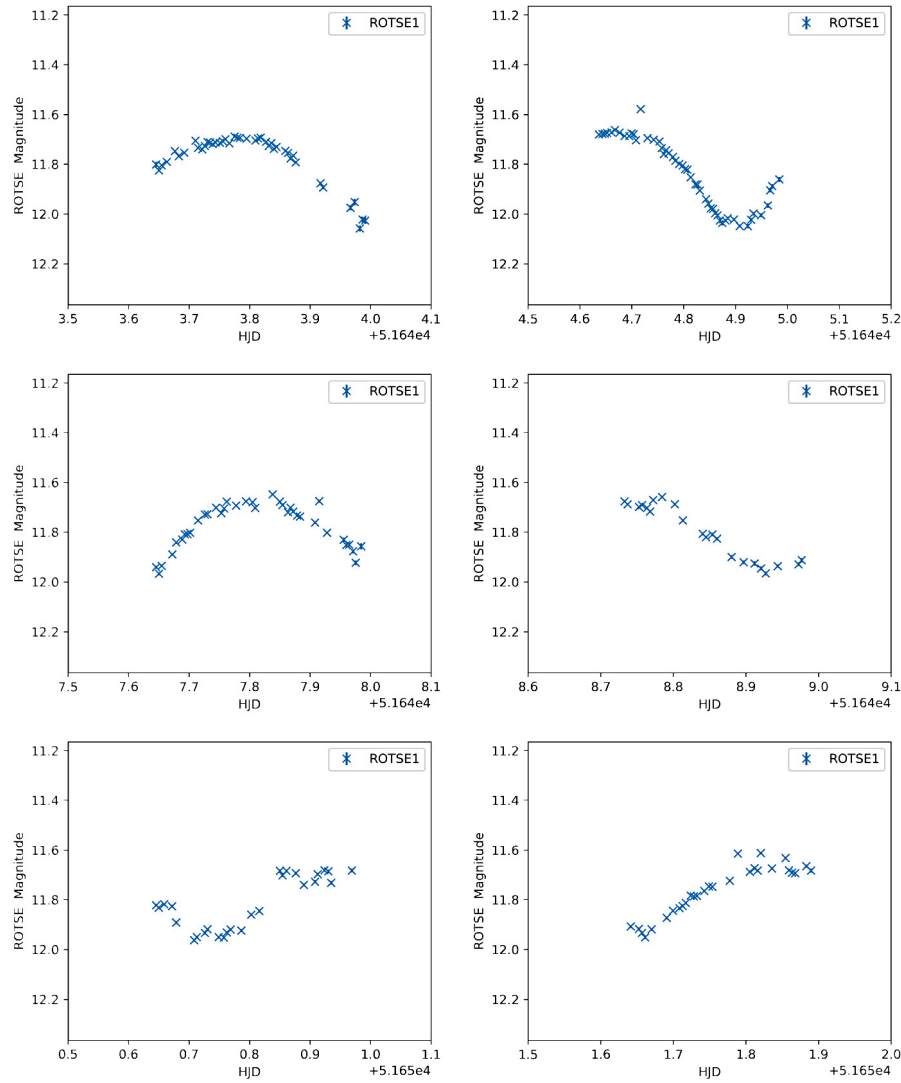


Figure 1. Each plot shows one night of data from ROTSE1 J112205.64+464333.4. The light curves clearly display variability.

inspection were searched in the VSX (Watson *et al.* 2006). Undiscovered variables were prioritized for further analysis and are the focus of this paper.

Additional challenges in variable star analysis included blending, where light sources from adjacent stars overlap with the coordinates under inspection and contaminate measurements that influence the resulting light curve (Melchior *et al.* 2021). Steps were taken to document the temporal variability of blended star systems, with the V-band data from surrounding systems used to quantify the impact that nearby stars have on the variable system under consideration. After accounting for the impact of surrounding systems, the true magnitude of variation for the variable star can be calculated. Supporting documentation was then submitted to the VSX to denote status of the variable and list the coordinates of all systems near the blended star.

3. Data analysis

3.1. Preliminary phasing and classification

Each variable system listed in this paper was analyzed twice.

The initial analysis was conducted by several coauthors over a decade, with the earliest VSP entries in the VSX dating back to 2013. Several earlier published candidates are also included in Fagg *et al.* (2009). This section describes our preliminary analysis which covers the process for obtaining results that have been published in VSX. The VSX results have been used by the broader scientific community, and so we describe this process for their benefit, although we recommend that our new results from the process outlined in section 3.2 should be used henceforth.

In the preliminary analysis, nightly light curve data for each variable were concatenated to provide a multi-day light curve. A least-squares cubic spline fit algorithm, (single_phase, Akerlof *et al.* 1994) was used to identify the most probable period and amplitude of the variable. Depending on the quality of the data and structure of the light curve, we may obtain an integer multiple or fraction of the true period. In this event, other phasing programs such as PERIOD04, a program designed for time string analysis (Lenz and Breger 2005), were used to refine the period value. The robustness of the final results is demonstrated by the fact that very different approaches were

taken between preliminary and final analysis, with both methods in agreement. If phasing was unsuccessful using the ROTSE-I data alone, we initially employed the following prescription to augment with further data. Supplementing with NSVS data were prioritized because NSVS was fundamentally compatible with the high cadence data as they came from the same instrument. If NSVS data were not available, or phasing was still unsuccessful, we next used CRTS data to augment ROTSE datasets. In order to combine ROTSE data with external catalogs, a photometric offset was applied. If using CRTS, we took the nearest data to the VSX coordinates of the object, calculated the median magnitudes of the CRTS data and ROTSE-I data corresponding to the object, and shifted the CRTS median magnitude to match the ROTSE-I median magnitude which accounted for the difference between CRTS “V” and ROTSE m_{ROTSE} . If CRTS data were not available, as was the case in later years, or the fit was still incomplete or ambiguous, we would incorporate SuperWASP data. Later, we began to include ASAS(-SN) data, with the aforementioned photometric adjustment so that we could integrate the samples. Ultimately, many of the variables had several different data samples, on different photometric footing, contributing at different levels to the final light curve. In addition, ROTSE epochs were on the Modified Julian Date (MJD) system while other surveys, such as SuperWASP and ASAS, were on the Heliocentric Julian Date (HJD) system. If data on the HJD system were used in phasing for a candidate, ROTSE MJD epochs were converted to the HJD system for phasing and plotting. This was done by converting MJD to Julian Date (JD) before the final calculation of HJD via Equation 3:

$$\text{HJD} = \text{JD} - \frac{r}{c} \cdot [\sin \delta \cdot \sin \delta_{\odot} + \cos \delta \cdot \cos \delta_{\odot} \cdot \cos(\alpha - \alpha_{\odot})] \quad (3)$$

where JD is the ROTSE Julian Date, r is the distance between the sun and the observer, c is the speed of light, α and δ are the right ascension and declination values for the variable star, with subscript $\odot$ referring to the right ascension and declination of the Sun. The various surveys also have different levels of instrument sensitivity, which upon combination with ROTSE-I data produced light curves of varying quality. We therefore term the analysis in section 3.1 as the “preliminary analysis” of these objects, with following efforts in section 3.2 establishing a standardized process for combining ROTSE-I data with specific external catalogs.

The light curve shape, period, and amplitude were utilized to determine the variability type, in accordance with the variable star type designations in VSX (Otero *et al.* 2015). A candidate was submitted to VSX with the ROTSE candidate name, variability type, magnitude range, period, epoch, rise/eclipse duration, supporting papers, supporting names from other telescopes, and a final phased light curve. All 33 stars in this paper completed this process, and this version of analysis concludes the “preliminary analysis” of these objects. The tables listed in section 4 include the information necessary to extract the preliminary measurements already provided in VSX.

3.2. Final standardized analysis

The heterogeneous nature of these preliminary results,

provided with different sets of data in different magnitude systems and different understanding of observation uncertainties, makes generalization from the full population of found variable stars difficult. The presence of obvious instrumental artifacts in the phased samples is also a potential source of bias in the measurements. This is particularly a problem because we seek the most precise understanding of these systems and their periods. As a result, all ROTSE-I eclipsing binaries were systematically reanalyzed and the details are described in this section. The parameters of the systems listed in section 4 are from the improved secondary analysis. The results quoted in section 4 should supersede the previous parameters in VSX from our preliminary analysis.

The standardized phasing process was similar to that of section 3.1, with some improvements based on lessons learned in the preliminary analysis. An internally developed calibration process was applied to remove any instrumental or atmospheric impacts on magnitudes. It accomplished this by identifying systematic shifts in magnitude correlated between nearby non-variables for a given observation. These discrepancies in magnitude between successive observations are nonphysical and due to differences in observing conditions between exposures. The algorithm calculates corrections to variable star light curves by finding the negative of the deviation in magnitude from the mean within each corresponding observation of light curves from nearby reference stars. A filtering algorithm was applied which removed any observation that had not been confirmed, or found to be consistent with another consecutive observation. Pairs of consecutive observations were then averaged into one point on the light curve. Unpaired, but otherwise confirmed and consistent, observations were retained unmodified. These two algorithms improved overall data quality by reducing outliers in the ROTSE-I data.

After the data were filtered and calibrated, each system’s period was obtained using `single_phase`. If this period was comparable to the preliminary period, within 0.001 day (d), and a phased light curve that exhibited one or two distinct minima, not more, with consistent maxima—the variable was considered to be successfully re-phased. If re-phasing with ROTSE-I data alone did not reproduce the preliminary period, external surveys were added to resolve the discrepancy. `single_phase` was applied to the photometrically shifted external catalog after combining with ROTSE-I data. If this period, an integer multiple of this period, or a simple fraction of this period was comparable to the VSX period and the light curve passed visual inspection, the variable was considered to be successfully re-phased.

Previous use of the aforementioned catalogs showed that some datasets displayed large amounts of scatter, or had outsized photometric errors compared to the high cadence ROTSE-I data. As part of the final standardized data analysis, a numerical comparison was performed on each of the NSVS, ASAS-SN, SuperWASP, and CRTS catalogs. This analysis measured which catalogs best complemented the ROTSE-I data. This catalog was then used as the default external dataset for the entirety of the standardized analysis.

Carefully choosing a supporting dataset allowed for a standardized, reproducible approach that enabled a high-precision reporting of variable star periods. This was performed

via a curve fitting approach to the ROTSE data, which then was used to measure the quality of agreement between the ROTSE data and external catalogs. Polynomial fitting was used because it gave the most flexible and consistently accurate fits across the variety of variable star light curves under consideration. This approach fits coefficients, a_n that minimize the squared difference between the dataset and the fitting function on a given order n as shown by Equation 4.

$$f(x) = a_n x_n + a_{n-1} x^{n-1} + \dots + a_2 x^2 + a_1 x^1 + a_0. \quad (4)$$

After performing a polynomial fit on the ROTSE-I data, comparisons are then made between the external catalogs and the ROTSE-I fit through use of the root mean square, shown in Equation 5.

$$\text{RMS} = \sqrt{\frac{\sum (m_{\text{fit}} - m_{\text{cat}})^2}{N}}. \quad (5)$$

Here N is the number of data points in the catalog being compared, and m_{fit} and m_{cat} denoting the magnitude values of the fit line and magnitude values from an external catalog's dataset, respectively. The RMS of each external catalog to the ROTSE-I fit line was then compared overall among all variables being analyzed. This process showed that ASAS-SN consistently had the smallest RMS when measured against the ROTSE-I data, thus it was chosen as the main supporting dataset for final variable star analysis.

Before use, ASAS-SN data were filtered for V-band observations and then shifted so that its mean magnitude value matched that of ROTSE-I. To provide a meaningful combination of the two data sets, a maximum of three times the amount of ROTSE-I data points was established as the limit for ASAS-SN data; this allowed for full coverage of maxima and minima of each variable system's light curve.

4. Results

Four classifications of binary system were identified in our results: β Lyr, β Per, W UMa, and ELL systems. The period and amplitude measurements of the standardized analysis, with indications of differences from the preliminary analyses, are given in Tables 1 through 4. All phased light curves are shown for the standardized results, displaying the ROTSE-I high cadence measurements and ASAS-SN measurements where utilized. In general, changes in period were small, around one second or less. Some deviations were larger, with seven stars showing differences over 10 seconds, and one with a period changed by 5.8 minutes (ROTSE1 J165428.16+422437.2). The amplitudes and magnitude ranges are now all on a common m_{ROTSE} photometric scale. We also examined final phased light curves for evidence of changed classification. In this sample, all prior classifications remain unchanged.

This work rephased 33 different ROTSE-I variables, which are plotted in their respective sections below. These 33 were chosen from a list of 71 variables needing reanalysis, with the remaining 38 intended for a following research effort. Parameters in the following tables are P_{fin} , the updated period

from phasing ROTSE-I with ASAS-SN data, ΔP , the difference in period between final and preliminary analysis via $P_{\text{fin}} - P_{\text{prelim}}$, ΔAmp , the difference in amplitude between the final analysis (Amp) and the preliminary value, Max, the system's maximum magnitude, while Min_1 and Min_2 refer to the primary and secondary minimum magnitudes, respectively. Prelim ΔM provides the magnitude range and effective band from the preliminary analysis. The effective band is listed in units used by the official VSX submission and thus may differ from the R1 passband used in this dataset.

4.1. β Per Variables

β Per (also known as EA or Algol-type) systems are detached eclipsing binaries consisting of separated spherical or only slightly ellipsoidal stars, resulting in clear start and stop of eclipses and normally flat maxima. A secondary minimum may not be evident, and periods range from 0.2 d up to a year or more. The VSP project has identified and submitted to VSX the previously undiscovered EA variable stars that are listed in Table 1 with light curve plots shown in Figure 2. We observe periods from about 0.5 d and up. Though our analysis would tend to have low efficiency for periods significantly longer than one day, we do see one Algol to have a period as high as 3.12 d, the highest in this overall sample. The systems show a range in amplitude of 0.16 to 0.35 mag measured in m_{ROTSE} . One of these systems shows no clear secondary minimum. In two cases, there is some evidence potentially indicating ellipsoidal components—ROTSE1 J000534.65+344449.0 and ROTSE1 J001118.58+232757.4. These also exhibit the largest secondary minima and the shortest periods. The standardized analysis revealed that light curve data corresponding to ROTSE-I J111719.74+394303.0 display a lack of temporal variability in other catalogs to include ASAS-SN, SuperWASP, and CRTS. As such, we do not currently believe it to be a variable.

4.2. β Lyr Variables

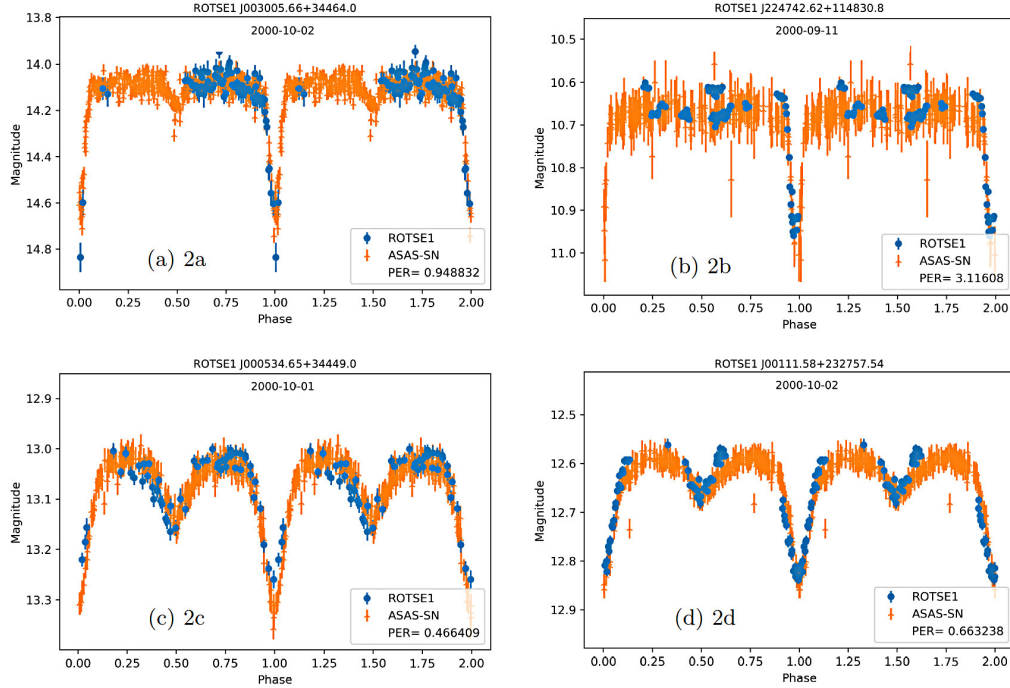
β Lyr (EB) stars are contact eclipsing binaries whose light curves are characterized by a continuous change of the system's magnitude between eclipses, making it impossible to determine the exact start or end of eclipses. The secondary minimum is always observed, but is distinctly smaller than the primary minimum. Periods are generally greater than 0.5 d and amplitudes can be up to 2 magnitudes. The VSP project has identified and submitted to VSX the previously undiscovered β Lyr variable stars that are listed in Table 2 and light curve plots shown in Figure 3. The β Lyr variables analyzed range in period from 0.46d to 1.0d, with amplitudes ranging from 0.1 to 0.55 mag. All of these have varying maxima with no clear indication of start or end of eclipse, suggesting these systems have two ellipsoidal components. This group includes systems resembling the ellipsoidal Algols above, and those that look very much like W UMa contact binaries.

4.3. W UMa Variables

W UMa (EW) variable stars are contact eclipsing binaries whose light curves are characterized by a continuous change of the system's magnitude between eclipses, making it impossible to determine the exact start or end of eclipses. W UMa binaries

Table 1. Final phased parameters for β Per variables, including differences with respect to the preliminary measurements.

Designation	P_{fin}	ΔP	Amp	ΔAmp	Max	Min1	Min2	Prelim ΔM
ROTSE1 J003005.66+344643.0	0.948832	0	0.352	-0.248	14.034	14.386	14.158	14.0–14.6 R1
ROTSE1 J000534.65+344449.0	0.466409	0.000002	0.268	-0.013	13.010	13.264	13.138	13.934 (0.596) r
ROTSE1 J001118.58+232757.4	0.663238	-0.000004	0.22	-0.03	12.555	12.779	12.633	12.53–12.78 R1
ROTSE1 J224742.62+114830.8	3.11608	0.000084	0.163	-0.157	10.570	10.939	10.689	10.65–10.97 V

Figure 2. Phased light curves for four β Per variables using ROTSE-I and ASAS-SN data. Shown are a) ROTSE1 J003005.66+344643.0, b) ROTSE1 J224742.62+114830.8, c) ROTSE1 J000534.65+344449.0, and d) ROTSE1 J001118.58+232757.4.

are in closer contact than β Lyr and belong to later spectral types. They generally have periods less than 1 d and are comprised of two ellipsoidal components. Both minima are almost equal. Amplitudes are generally less than 0.8 magnitude. Some W UMa systems can look similar to β Lyr systems. The VSP project has identified and submitted to VSX the previously undiscovered W UMa variable stars that are listed in Table 3, with light curve plots shown in Figures 4 through 6. We observe periods from 0.25 d to approximately 0.45 d, with one as long as 0.92 d. For the most part, these periods are shorter than the β Lyr periods discussed above. Several of these variables were analyzed with ROTSE-I high cadence data alone, yielding slightly larger shifts in measured period from our preliminary analysis than the stars including ASAS-SN data. In three cases the shifts are ~ 0.5 –1 min. This is likely due to the short lever arm of the high cadence data, which can cause reduced sensitivity to periods. We hope to revisit this issue with data from the ROTSE-III telescopes in a later publication. The W UMa variables in this analysis range in amplitude from 0.06 to 0.55 magnitude. Most systems exhibit very similar minima, but two show substantial differences in primary and secondary minima and almost resemble β Lyr's: ROTSE1 J163708.48+524129.0 and ROTSE1 J233733.14+260416.6. There were no breaks in the light curves and both components in all systems are likely ellipsoidal. Note

that ROTSE1 J122729.50+474420.0 is a suspected W UMa/RS system according to preliminary analysis. The final standardized analysis leaves this classification unchanged.

4.4. Rotating ellipsoidal variables

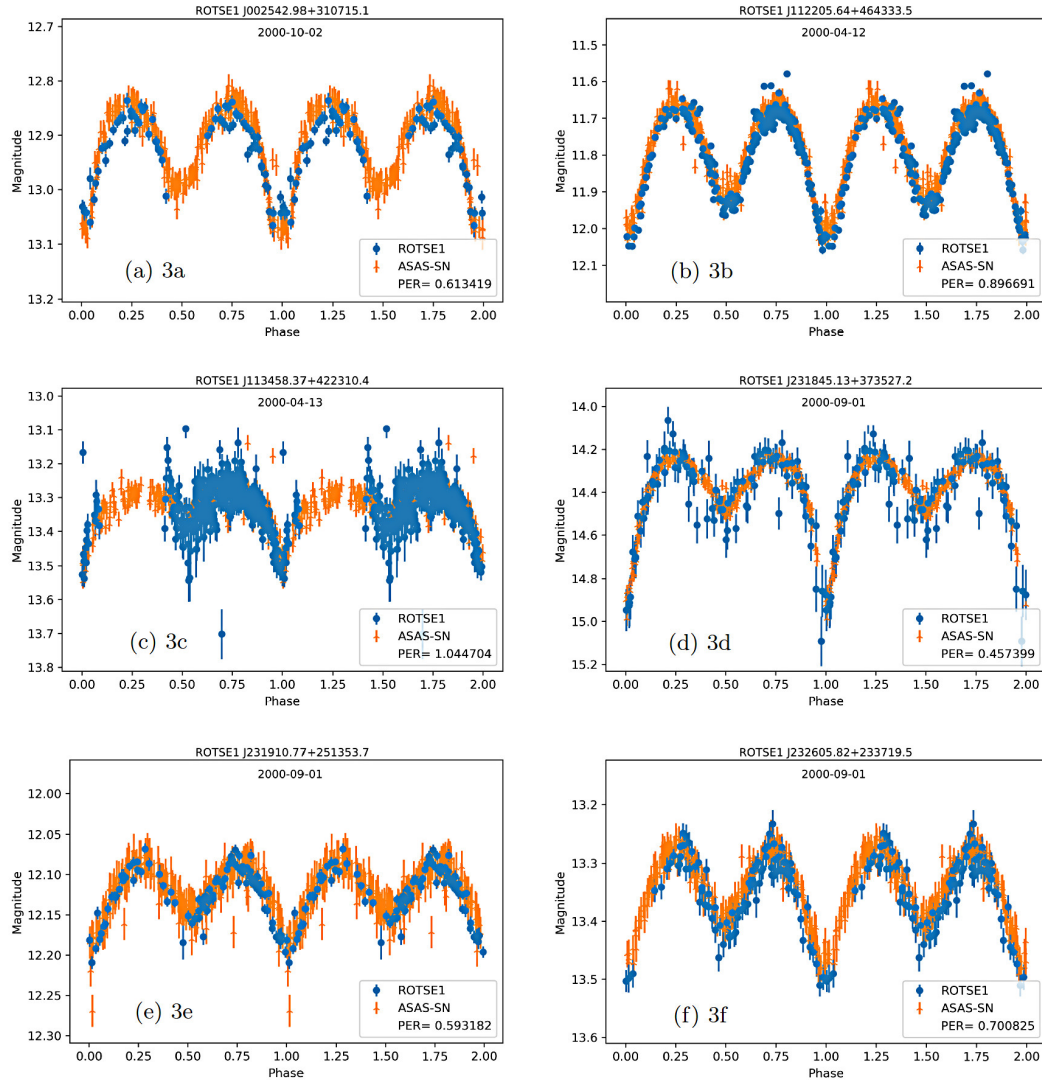
Rotating Ellipsoidal (ELL) variable stars are noneclipsing contact binaries that change in brightness due to the ellipsoidal shape of the component stars. ELL light curves are characterized by a continuous change of the system's magnitude. These variables tend to have very small amplitudes < 0.1 mag and can look like W UMa systems in some cases. The VSP project has identified and submitted to VSX several previously undiscovered ELL variable stars, listed in Table 4 and plotted in Figure 7. The final standardized analysis of these systems demonstrated period values ranging between 0.32 and 0.62 d, with amplitudes of approximately 0.1 mag. In all cases, secondary minima resemble the primary minima.

5. Conclusion

This study presents a standardized analysis of 33 short period binary variable stars discovered with ROTSE-I high cadence data and documented in VSX. The preliminary analysis that led to discovery was also described and differences of the

Table 2. Final phased parameters for β Lyr variables, including differences with respect to the preliminary measurements.

Designation	P_{fin}	ΔP	Amp	ΔAmp	Max	Min1	Min2	Prelim ΔM
ROTSE1 J002542.98+310715.1	0.613419	0.000015	0.236	-0.024	12.838	13.074	13.001	12.86-13.12 R1
ROTSE1 J112205.64+464333.5	0.896691	0.000005	0.344	-0.026	11.679	12.036	11.947	11.68-12.05 R1
ROTSE1 J113458.37+422310.4	1.044704	0	0.166	-0.034	13.281	13.345	13.302	13.24-13.44 V
ROTSE1 J231845.13+373527.2	0.457399	-0.000004	0.549	-0.196	14.245	14.798	14.473	14.504 (0.745) g
ROTSE1 J231910.77+251353.7	0.593182	0.000026	0.099	-0.021	12.087	12.187	12.152	11.77-11.89 CV
ROTSE1 J232605.82+233719.5	0.700825	-0.000001	0.191	-0.039	13.279	13.500	13.423	12.94-13.17 V

Figure 3. Phased light curves for six β Lyr variables using ROTSE-I and ASAS-SN data. Shown are a) ROTSE1 J002542.98+310715.1, b) ROTSE1 J112205.64+464333.5, c) ROTSE1 J113458.37+422310.4, d) ROTSE1 J231845.13+373527.2, e) ROTSE1 J231910.77+251353.7, and f) ROTSE1 J232605.82+233719.5.

two results are provided. We developed algorithms to make the photometry more robust against instrumental effects, including filtering of low quality observations and a relative photometry calibration. A curve fitting process was introduced to compare the contribution of external catalogs to the phased ROTSE data, with ASAS-SN demonstrating lowest average RMS to the ROTSE data. 34 previously characterized variables were analyzed with the new pipeline, resulting in updated periods and amplitudes for 33 of these sources. One system was determined

to be nonvariable. All variables in this study have updated magnitude ranges and amplitudes as a result of the analysis, here presented with standardized photometry. Further efforts will involve extending the analysis to an additional sample of 38 unresolved variables, and the addition of binary system parameter calculations through use of a Wilson-Devinney code (Kallrath 2022) such as PHysics Of Eclipsing BinariEs (PHOEBE; Conroy *et al.* 2020).

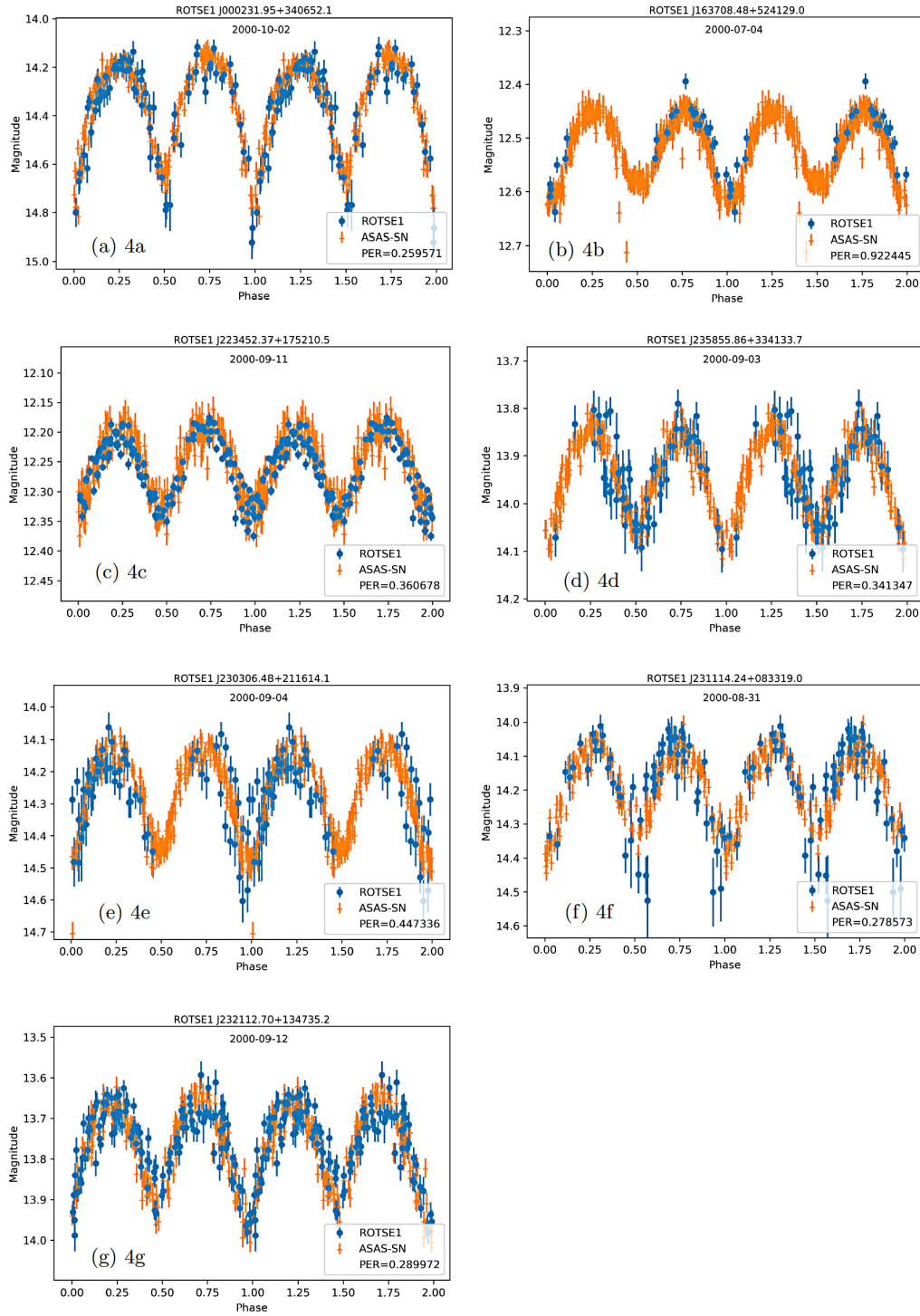


Figure 4. Phased light curves for seven W UMa variables using ROTSE-1 and ASAS-SN data. Shown are a) ROTSE1 J000231.95+340652.1, b) ROTSE1 J163708.48+524129.0, c) ROTSE1 J223452.37+175210.5, d) ROTSE1 J235855.86+334133.7, e) ROTSE1 J230306.48+211614.1, f) ROTSE1 J231114.24+083319.0, and g) ROTSE1 J232112.70+134735.2.

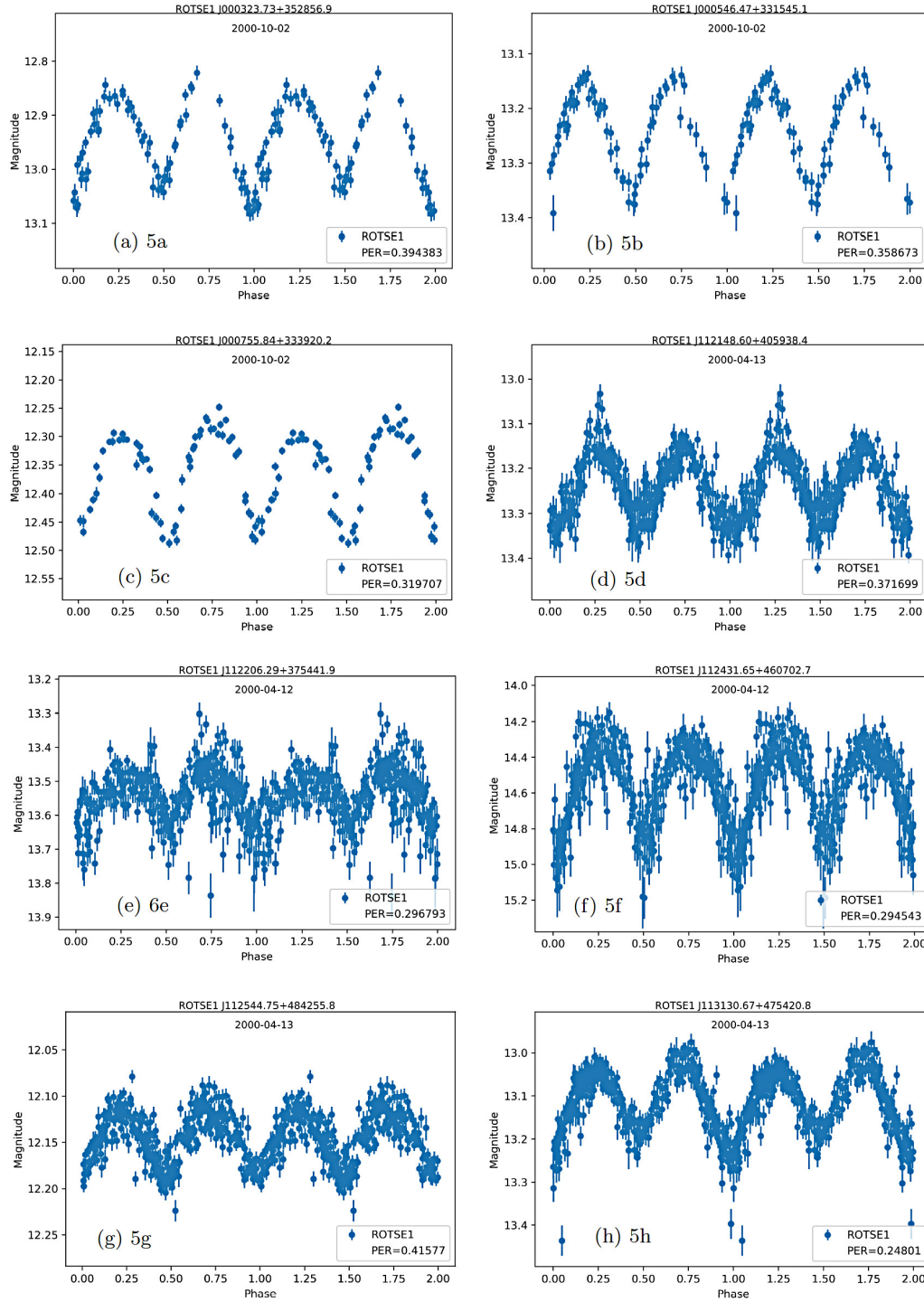


Figure 5. Phased light curves for eight W UMa variables using ROTSE-I data. Shown are a) J000323.73+352856.9, b) ROTSE1 J000546.47+331545.1, c) ROTSE1 J000755.84+333920.2, d) ROTSE1 J112148.60+405938.4, e) ROTSE1 J112206.29+375441.9, f) ROTSE1 J112431.65+460702.7, g) ROTSE1 J112544.75+484255.8, and h) ROTSE1 J113130.67+475420.8.

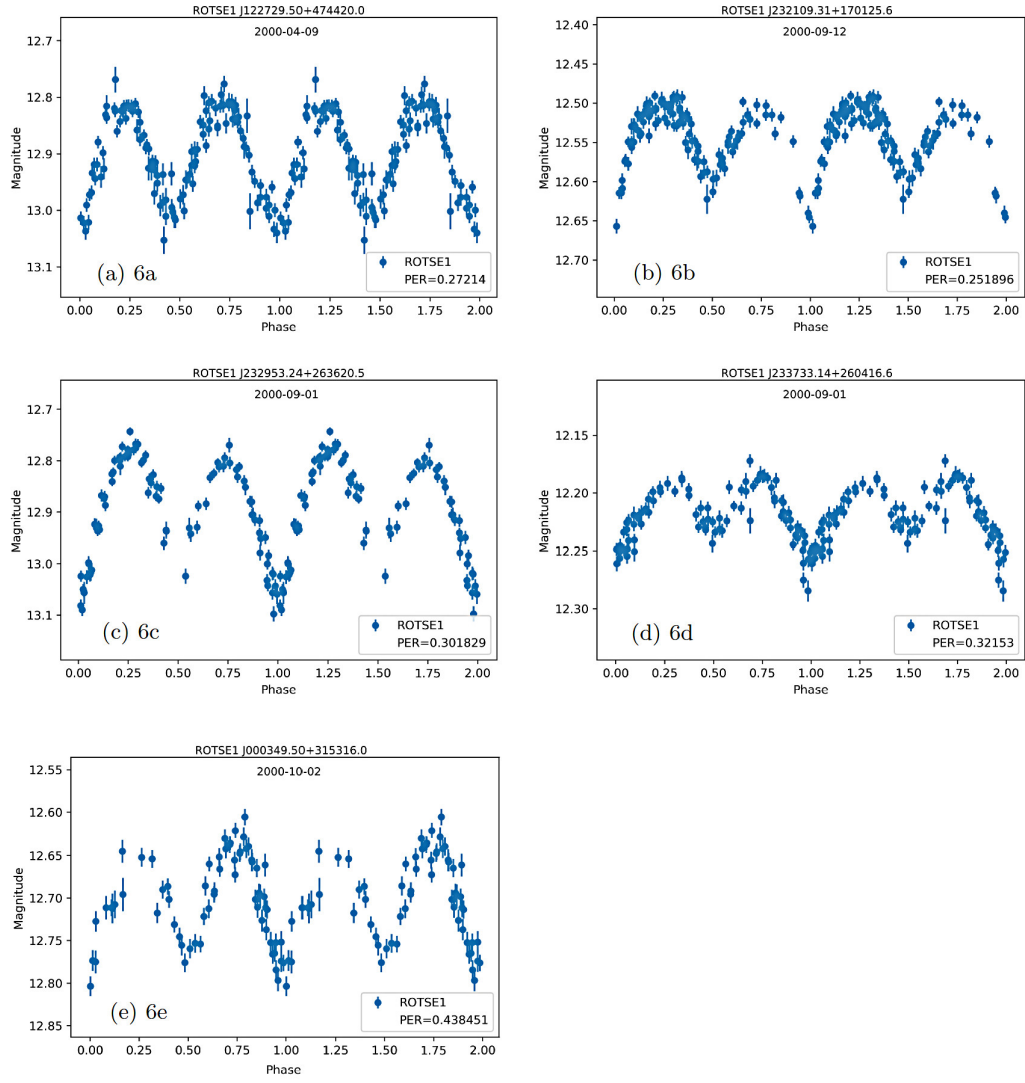


Figure 6. Phased light curves for five W UMa variables using ROTSE-I data. Shown are a) ROTSE1 J122729.50+474420.0, b) ROTSE1 J232109.31+170125.6, c) ROTSE1 J232953.24+263620.5, d) ROTSE1 J233733.14+260416.6, and e) ROTSE1 J000349.50+315316.0.

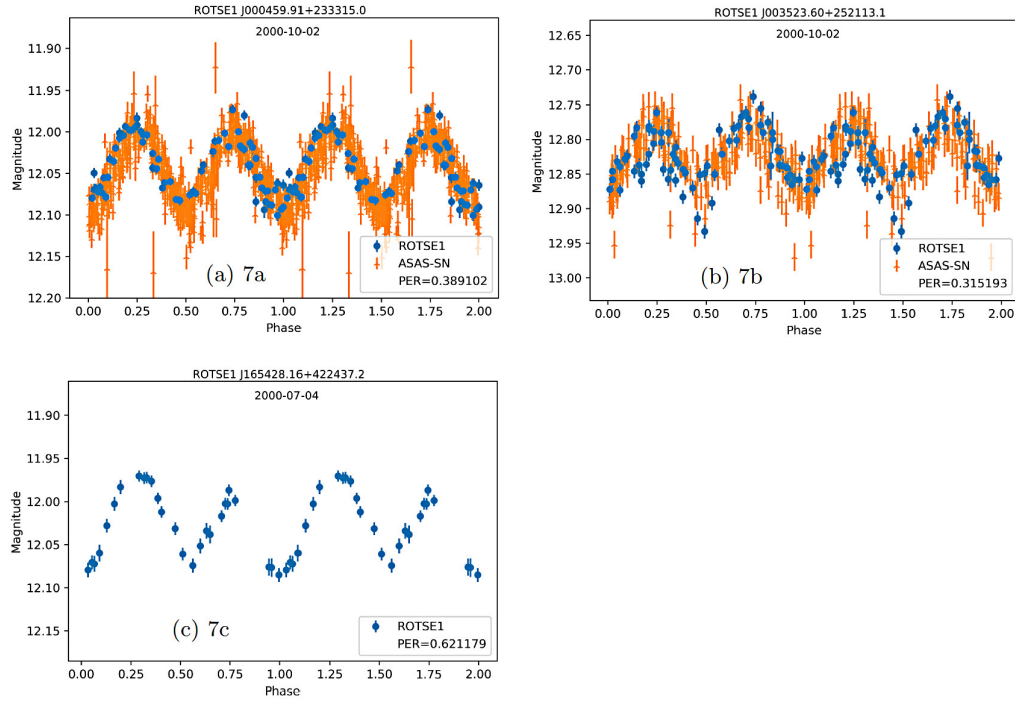


Figure 7. Phased lightcurves for three ELL variables using ROTSE-I and ASAS-SN data. Shown are a) ROTSE1 J000459.91+233315.0, b) ROTSE1 J003523.60+252113.1, and c) ROTSE1 J165428.16+422437.2.

Table 3. Final Phased Parameters for W UMa variables, including differences with respect to the preliminary measurements.

Designation	P_{fin}	ΔP	Amp	ΔAmp	Max	$Min1$	$Min2$	Prelim ΔM
ROTSE1 J000231.95+340652.1	0.259571	0.000003	0.512	-0.188	14.164	14.677	14.627	14.3–15.0 R1
ROTSE1 J000323.73+352856.9*	0.394383	0.000083	0.238	-0.105	12.816	13.054	13.026	13.068 (0.343) r
ROTSE1 J000349.50+315316.0*	0.438451	0.000371	0.144	-0.006	12.187	12.251	12.230	12.63–12.78 R1
ROTSE1 J000546.47+331545.1*	0.358673	-0.000149	0.214	-0.016	13.150	13.364	13.356	13.15–13.38 R1
ROTSE1 J000755.84+333920.2*	0.319707	0.000103	0.212	0.022	12.274	12.486	12.469	12.42–12.61 R1
ROTSE1 J112148.60+405938.4*	0.371699	0	0.185	0.015	13.142	13.326	13.314	13.16–13.33 R1
ROTSE1 J112206.29+375441.9*	0.296793	0.000014	0.175	0.025	13.460	13.635	13.606	13.46–13.61 R1
ROTSE1 J112431.65+460702.7*	0.294543	-0.000157	0.553	-0.047	14.347	14.900	14.804	14.3–14.9 R1
ROTSE1 J112544.75+484255.8*	0.41577	-0.000322	0.067	-0.003	12.118	12.185	12.183	12.11–12.18 R1
ROTSE1 J113130.67+475420.8*	0.24801	0.00001	0.206	-0.094	13.015	13.221	13.186	13.0–13.3 R1
ROTSE1 J122729.50+474420.0*	0.27214	-0.000698	0.207	0.007	12.809	13.016	12.995	12.83–13.03 R1
ROTSE1 J163708.48+524129.0	0.922445	0	0.180	-0.01	12.445	12.626	12.590	12.46–12.65 V
ROTSE1 J223452.37+175210.5	0.360678	-0.000014	0.143	-0.007	12.187	12.336	12.333	12.13–12.28 V
ROTSE1 J230306.48+211614.1	0.447336	0	0.355	-0.078	14.137	14.419	14.402	14.169 (0.433) r
ROTSE1 J231114.24+083319.0	0.278573	-0.000038	0.293	0.003	14.070	14.368	14.323	14.04–14.33 R1
ROTSE1 J232112.70+134735.2	0.289972	0	0.283	0.003	13.677	13.929	13.872	13.62–13.90 CV
ROTSE1 J232109.31+170125.6*	0.251896	0.000002	0.130	0	12.503	12.634	12.595	12.50–12.63 V
ROTSE1 J232953.24+263620.5*	0.301829	-0.000071	0.273	-0.01	12.777	13.050	12.994	13.111 (0.283) g
ROTSE1 J233733.14+260416.6*	0.32153	-0.000067	0.064	0.004	12.187	12.251	12.230	12.06–12.12 V
ROTSE1 J235855.86+334133.7	0.341347	0	0.232	-0.024	13.842	14.074	14.044	13.706 (0.256) r

Note: Variables with “*” mark systems that were analyzed with ROTSE-I data alone.

Table 4. Final Phased Parameters for ELL variables, including differences with respect to the preliminary measurements.

Designation	P_{fin}	ΔP	Amp	ΔAmp	Max	$Min1$	$Min2$	Prelim ΔM
ROTSE1 J000459.91+233315.0	0.389102	0.000008	0.093	-0.007	12.000	12.093	12.093	11.97–12.07 R1
ROTSE1 J003523.60+252113.1	0.315193	0.000360	0.093	-0.007	12.779	12.872	12.860	12.83–12.93 CV
ROTSE1 J165428.16+422437.2*	0.621179	-0.004010	0.118	0.008	11.966	12.084	12.065	11.97–12.08 R1

Note: Variables with “*” mark systems that were analyzed with ROTSE-I data alone.

6. Data availability

The data for the variable stars referenced in this paper are available via Zenodo (<https://doi.org/10.5281/zenodo.19828971>). All data follow a three-column format of date, magnitude, and error.

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Photometric Distance to the RR Lyrae Star W Canum Venaticorum using Period-Luminosity-Metallicity Relationships

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Abstract Photometric observations and analysis of W Canum Venaticorum are undertaken to verify the period-luminosity-metallicity equations derived by Catelan and Cáceres and also Garofalo. Imaging using B, V, i, and z bands was taken over the course of two weeks. The photometry files were processed through Astrosource to calculate the period and apparent magnitudes. The metallicity value used for the calculations was -1.0982 found in GAIA DR3. Using the above relationships, the distance for RR Lyrae star W Canum Venaticorum was determined to be 929 ± 20 parsecs using Catelan and Cáceres equations and 876 ± 10 parsecs using the Garofalo equation. The distance using Catelan and Cáceres equations is comparable to the parallax distance calculated by GAIA DR3 data of 918 ± 15 parsecs, whereas the distance calculated using the Garofalo equation is significantly lower.

1. Introduction

Stars of the RR Lyrae class are among the most important tracers of old stellar populations. They are generally found to be low-mass, metal-poor, Population II objects that have evolved past the main sequence, undergone the helium flash, and now reside on the horizontal branch where core helium fusion dominates their energy production. However, many of these stars can also be found in the thick disk of the galaxy (known as field stars) and can have a higher metal content. The horizontal branch cuts across the instability strip, a region in which pulsational driving becomes effective. RR Lyrae stars fall squarely within this zone, and their envelopes become unstable to radial oscillations triggered by the κ -mechanism in partially ionized helium layers. These pulsations lead to changes in brightness that repeat with remarkable regularity, with characteristic periods of about 0.2–1 day and light-curve amplitudes of several tenths of a magnitude (Cacciari and Clementini 2003).

Their variability is intrinsic rather than geometric, arising from cyclical expansion and contraction of the stellar envelope. The predictability of these oscillations makes RR Lyrae stars a well-defined subclass of variable stars. Furthermore, their nearly constant absolute magnitude, with an average value around $M_V \approx +0.6$ for halo metallicities, allows them to serve as reliable standard candles (Muraveva *et al.* 2018). Distances derived from RR Lyrae measurements provide crucial constraints on the ages of globular clusters, the structure of the Galactic halo, and the calibration of the cosmic distance scale.

This paper examines light curves for the RR Lyrae star W Canum Venaticorum (W CVn) using Bessel B and V filters, and SDSS/PanSTARRS i and z filters. Both the period and apparent magnitude will be determined, and the distance to W CVn will be calculated using period-luminosity-metallicity

relations developed by Cáceres and Catelan (Catelan *et al.* 2004; Cáceres and Catelan 2008) and Garofalo *et al.* (2022). Similar studies have been conducted for other RR Lyrae stars as seen in some recent publications such as Dow *et al.* (2023) and Baltich *et al.* (2024).

2. Observations

Images of W CVn (R.A. 211.6125° , Dec. $+37.8281^\circ$ (J2000)) were collected through a worldwide network of telescopes called the Las Cumbres Observatory (LCO) (Brown *et al.* 2013). The images were taken with 0.4-meter telescopes with QHY600 CMOS cameras attached. We collected images through B, V, i, and z filters. For each passband, images were taken between February 28, 2024, and March 7, 2024. Table 1 lists the exposure times for each filter. After obtaining the images, *ASTROIMAGEJ* was used to evaluate the quality of each image (Collins *et al.* 2017). A total of about 57 images were obtained from each filter after the poor quality images were thrown out.

All images were processed through a data pipeline created by Our Solar Siblings (OSS Pipeline) (Fitzgerald 2018). The photometric data were then calculated using the Source Extractor Kron (SEK) (Bertin and Arnouts 1996). The photometry files were then analyzed in a PYTHON program

Table 1. Exposure time used per filter from each cadence.

Band	Exposure Time (s)
B	40
V	25
i	60
z	200

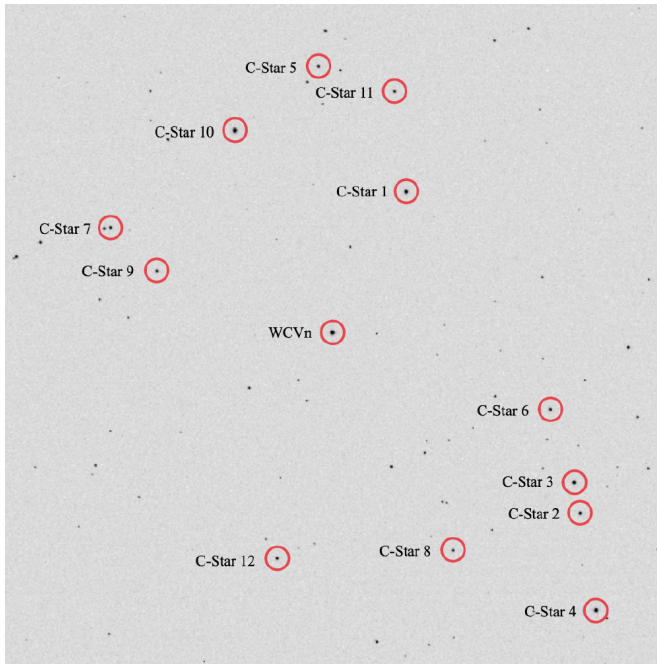


Figure 1. Comparison stars used in ASTROSOURCE analysis. The image is 30 by 30 arcminutes, north is up, east is left. See Table 2 for more information.

called ASTROSOURCE (Fitzgerald *et al.* 2021). ASTROSOURCE used catalogs from APASS (Henden *et al.* 2016) and PanSTARRS (Magnier *et al.* 2020; Flewelling *et al.* 2020) to calibrate with nearby stars (Figure 1). ASTROSOURCE chose comparison stars based on similarity in magnitude with minimal variation to W CVn (Table 2). ASTROSOURCE returned period estimates for W CVn using the phase dispersion minimization (PDM) method (Stellingwerf 1978) and the distance method (DM) (Dworetzky 1983). The program also returned mid-magnitude estimates, amplitude, and accompanying errors.

In order to account for interstellar dust, observations in the B filter were made to adjust measurements made in other filters by using the interstellar reddening $E(B-V)$. A value of 0.0045 was chosen for interstellar reddening based on the value found on the Galactic Dust Reddening and Extinction web page found at the NASA/IPAC Infrared Science Archive (Schlegel *et al.* 1998; Schlafly and Finkbeiner 2011). The extinction for each filter was calculated using the extinction law equations found in Cardelli *et al.* (1989). The extinction values we used are listed in Table 4.

3. Methodology

RR Lyrae stars are related to the metallicity through a luminosity-metallicity relationship in the optical passbands. In the near and mid-infrared passbands, this relation is through a period-luminosity-metallicity (PLZ) relationship, where the following is the relation for the magnitude in the V-band (Catelan *et al.* 2004):

$$M_V = 2.288 + 0.882 \log Z + 0.108 (\log Z)^2 \quad (1)$$

Cáceres and Catelan (2008) derived the following PLZ equations for the magnitude in the i and z bands:

$$M_i = 0.908 - 1.035 \log P + 0.220 \log Z \quad (2)$$

$$M_z = 0.839 - 1.295 \log P + 0.211 \log Z \quad (3)$$

Equations 4 and 5 relate the metallicity, also written as $[\text{Fe}/\text{H}]$, to $\log Z$.

$$\log Z = [\text{Fe}/\text{H}] - 1.765 \quad (4)$$

$$[\text{Fe}/\text{H}] = [\text{Fe}/\text{H}] + \log(0.638f + 0.362) \quad (5)$$

The assumption $f \approx 10^{0.3}$ was also utilized (Catelan *et al.* 2004). In addition, we used Garofalo's equation that estimates the absolute magnitude in the V band (Garofalo *et al.* 2022):

$$M_V = (0.33^{+0.2}_{-0.2}) [\text{Fe}/\text{H}] + (1.133^{+0.3}_{-0.3}) \quad (6)$$

Finally, the distance modulus equation was used to determine the distance to W CVn:

$$d = 10^{(m - M - A + 5) / 5} \quad (7)$$

where m is our measured apparent mid-magnitude in each filter, M is the absolute magnitude as calculated using the Cáceres and Catelan equations (using the period and metallicity), and A is the extinction at a specific wavelength and is based on an interstellar reddening of $E(B-V) = 0.0045$ as discussed previously. A metallicity value of -1.0982 was used in the above equations and was taken from GAIA DR3 data.

4. Results

Figures 2, 3, 4, and 5 show the phased light curves of W CVn detailing the changes in apparent magnitude. The curves showcase the sharp slope and small bump that is the typical light curve shape for RRab stars. A different zero-point offset date is used for each filter depending on when the first good quality image in that filter was started. For this reason the phased light curves all peak at different moments on the phased diagrams, but this does not affect the period calculated for each filter.

Table 5 shows the average magnitudes, calculated by ASTROSOURCE by comparing the highest and lowest values for the apparent magnitudes observed. Table 5 also lists the amplitude of the light curves. Values for W CVn's period, as calculated by Astrosources, are located in Table 3, with the respective methods and errors listed for each band. These period values align closely with the published period value on the AAVSO International Variable Star Index (VSX) website (Watson *et al.* 2006, 2014) of 0.5517588 days, increasing confidence in the method of period analysis.

Using Equations 1 through 5, three absolute magnitude values were calculated and one value from Equation 6 (which is specific for the V-band data). The resultant values from these

Table 2. Comparison stars used in each filter with apparent magnitudes and errors calculated by Astrosource.

Comparison Star	R.A.(°)	Dec.(°)	Bands	B Mag.	V Mag.	i Mag.	z Mag.
1	211.5476354	37.9319113	B,V,i,z	12.107 ± 0.003	11.275 ± 0.004	10.939 ± 0.013	10.692 ± 0.015
2	211.3852492	37.6955333	B,V,i	13.205 ± 0.003	12.170 ± 0.007	11.699 ± 0.015	N/A
3	211.3907793	37.7180782	B,V,i	12.559 ± 0.009	11.927 ± 0.008	11.796 ± 0.014	N/A
4	211.3706404	37.6242472	B,i	12.350 ± 0.007	N/A	10.915 ± 0.016	N/A
5	211.6300121	38.0235794	B,V	13.525 ± 0.009	12.857 ± 0.010	N/A	N/A
6	211.4129185	37.7717453	B,V,i	12.789 ± 0.010	12.212 ± 0.007	12.098 ± 0.015	N/A
7	211.823809	37.9049704	B,V	13.182 ± 0.011	12.561 ± 0.010	N/A	N/A
8	211.5038085	37.6682278	B	13.994 ± 0.010	N/A	N/A	N/A
9	211.7805695	37.8732447	V,z	N/A	12.653 ± 0.009	N/A	10.934 ± 0.012
10	211.7081054	37.9766018	V,i,z	N/A	10.842 ± 0.009	9.515 ± 0.015	9.51486125 ± 0.015
11	211.5588243	38.0049359	V	N/A	13.053 ± 0.009	N/A	N/A
12	211.6675248	37.6621346	i	N/A	N/A	12.770 ± 0.015	N/A

Table 3. Calculated periods for each band from Astrosource.

Band	DM (d)	DM Error (d)	PDM (d)	PDM Error (d)
B	0.55162	0.01350	0.55243	0.00990
V	0.55243	0.014625	0.55162	0.00954
i	0.55162	0.013455	0.55135	0.009585
z	0.55243	0.015705	0.55144	0.01116

Table 4. Extinction values used for each filter in the cadence.

Band	A
B	0.01810
V	0.01395
i	0.00953
z	0.00687

Table 5. Calculated middle apparent magnitudes for each band from ASTROSOURCE.

Band	Middle Mag.	Mag. Error	Amplitude
B	10.866	0.003	1.111
V	10.495	0.003	0.867
i	10.553	0.015	0.598
z	10.411	0.015	0.520

Table 6. Calculated absolute magnitudes for the V, i, and z bands using Equations (1–6).

Band	Absolute Magnitude	Error
V (Cáceres and Catelan)	0.709	0.032
i (Cáceres and Catelan)	0.592	0.022
z (Cáceres and Catelan)	0.614	0.021
V (Garofalo)	0.768	0.003

Note: Each filter is labeled with the source of the equation used.

Table 7. Photometric distances (in parsecs) using the Cáceres and Catelan equations and Garofalo equations.

Band	Distance (pc)	Error
V (Cáceres and Catelan)	900	36
i (Cáceres and Catelan)	978	37
z (Cáceres and Catelan)	908	31
Viz (Cáceres and Catelan)	929	20
V (Garofalo)	876	10

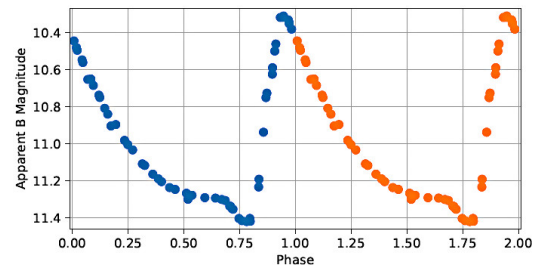


Figure 2. Phased lightcurve for the B band.

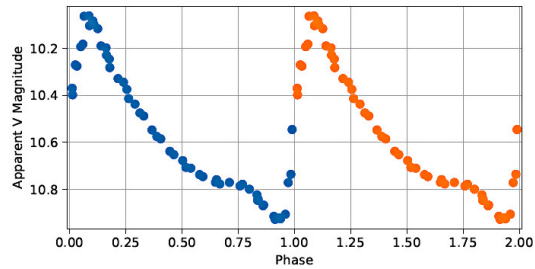


Figure 3. Phased lightcurve for the V band.

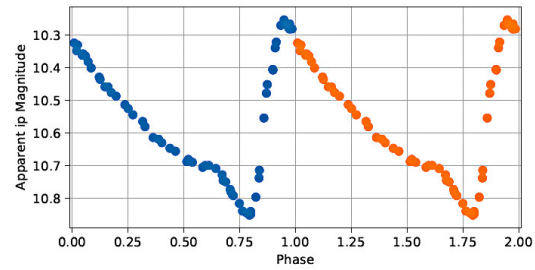


Figure 4. Phased lightcurve for the i band.

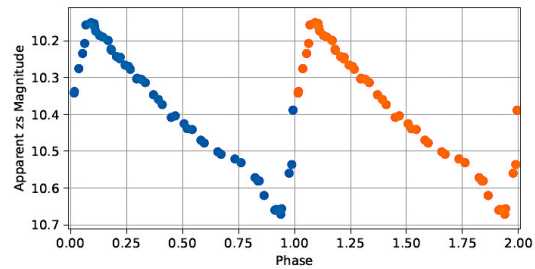


Figure 5. Phased lightcurve for the z band.

equations were used in Equation 7 to estimate the distance to W CVn. The first three estimates in Table 7 are values for the Cáceres and Catelan model and the last value is for the Garofalo model with their respective errors. GAIA's measurement for the parallax angle was 1.0886 ± 0.0185 mas (Gaia Collab. 2023), which is equivalent to a distance of 918 ± 15 parsecs. The values predicted using the Cáceres and Catelan model are within range of the measured value from GAIA, whereas the value calculated using the Garofalo model is significantly lower than the value measured by GAIA.

5. Conclusion

The goal of this project was to measure the distance to RR Lyrae star W Canum Venaticorum. This was done by measuring the photometric distance via analyzing exposures taken in the B, V, i, and z bands over a period of time. Using AstroImageJ we evaluated the quality of each image, and all photometry files were analyzed through Astrosource, returning estimates for period, mid-magnitude, and amplitude. These were later used to calculate the distance to W CVn. The average distance was determined to be 929 ± 20 parsecs using Cáceres and Catelan model and 876 ± 10 parsecs using the Garofalo model. The value for the distance obtained by using Cáceres and Catelan equations for RR Lyrae stars agrees with the parallax distance measured by GAIA DR3 of 918 ± 15 parsecs. More study and analysis are required to determine the reason for the discrepancy between the Cáceres and Catelan model and the Garofalo model. Some sources of uncertainty might be how the mid-magnitudes are calculated as discussed in Bono *et al.* (1995) and our choice of the GAIA DR3 metallicity whose value was not reported with reliability errors. Since the Garofalo equation depends solely on the metallicity, any error in this number can greatly affect the value calculated for the absolute magnitude in V.

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Digital Photometry, Period Analysis, Light Curve Deconvolution, and Evolutionary Status of the High Amplitude δ Scuti Variable Star KO Piscium

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Abstract We present precisely timed digitally derived photometric B, V, and R_c magnitude data for the High Amplitude δ Scuti (HADS) pulsating variable star KO Psc. The measurements were taken at the Desert Blooms Observatory (DBO) and the Stonecrest Observatory (SO) between October 25, 2021, and October 6, 2025. These data were combined with V and CV magnitudes from the AAVSO International Database (AID), measurements from the SuperWasp project, and stellar flux values from the Transiting Exoplanet Survey Satellite (TESS) resulting in a total of 430 times of maxima (ToMx), providing an updated linear ephemeris. V magnitudes and B–V color indices from the multi-color DBO and SO data yielded estimates of luminosity, effective temperature, and other stellar parameters. Discrete Fourier deconvolution of the data revealed a fundamental and five significant harmonics. Comparison with PARSEC stellar models gave some insight into the evolutionary status of KO Psc.

1. Introduction

KO Psc (GSC 1750-1237, ASAS 011024+2719.3; 12.3–12.7 V) is listed in the AAVSO Variable Star Index, VSX (VSX; Watson *et al.* 2014), as a High Amplitude δ Scuti (HADS) pulsating variable star. The star was initially listed in VSX in 2005, but the web page lists an earlier reference (Pojmański 2002). The Pojmański paper is a report on the All Sky Automated Survey (ASAS).

δ Scuti stars plot on a Hertzsprung-Russell diagram above the main sequence in an area called the instability strip. They fall between high-amplitude radial pulsators, like Cepheid variables, and non-radial pulsators (Breger 2000), with spectral types between A2 and F2 (Rodriguez and Breger 2001), with effective temperatures between 6300 and 8600 K (Uytterhoeven *et al.* 2011). Some δ Sct stars are radial pulsators with changes in stellar diameter, and some have non-radial shape changes. HADS stars form a sub-group of δ Sct pulsators with relatively high amplitudes (V-mag light curve amplitudes of 0.10–0.30 mag), and typically have pulsation periods of $0.05 < P < 0.25$ d. Masses range from about 1 to 2.5 $M_{\odot}$, depending on the metallicity. Luminosities generally fall between the main sequence and normal giants. These typical values can be referenced to McNamara (2000), and a much more complete discussion of δ Sct and HADS stars is given by Lv *et al.* (2022).

Our goal in this study was to provide multi-color (B, V, and R_c) digital photometry data for KO Psc, and to combine them with other information from the literature in a fairly detailed analysis. The magnitudes and B–V color index derived from these measurements provide a means of determining luminosity, L_* , effective temperature, T_{eff} , and other stellar parameters. We found additional data from the SuperWasp survey measurements (Butters *et al.* 2010), the *Information Bulletin on Variable Stars* (IBVS; Wils 2011, 2012), the AAVSO International Database (AID; Kafka 2021), and flux values from the TESS

satellite (Ricker *et al.* 2015; Antoci *et al.* 2019). These, along with our measurements, provided a total of 430 new times of maxima (ToMx), which were used for predicted time difference (PTD) analysis to produce an updated linear ephemeris. DFT processing of portions of the data set gives some perspective about the nature of the pulsations, and comparison of T_{eff} and luminosity with PARSEC stellar models gives indications of the evolutionary status of the star.

2. Observations, data reduction, photometric processing, and additional data sources

2.1. Observations

Between October 25 and November 19, 2021, precisely timed photometric observations of KO Psc were made with a QSI 683 ws-8 CCD camera at the secondary focus of a Meade 16 ACF scope operating at f/7.2 at the Desert Blooms Observatory (DBO) near Benson, Arizona (110.2575° W, 31.9409° N). This system provided a field of view (FOV) of 21' × 16' with an image scale of 0.76 arcsec/pixel (bin = 2 × 2). Additional measurements were made between November 12 and 17, 2021, with an SBIG ST10-XME CCD camera at the secondary focus of a 0.3-m f/8 Ritchey-Chretien telescope at the Stonecrest Observatory (SO) near Fort Davis, Texas (103.9767° W, 30.6167° N). This instrument gives a FOV of 21' × 14' and an image scale of 1.73 arcsec/pixel (bin = 3 × 3). Finally, between October 3 and 6, 2025, a ZWO ASI2600MM CMOS camera was used with the Meade 16 at DBO to gather additional data. This system yields a FOV of 31.7' × 20.5' with a resolution of 1.18 arcsec/pixel (bin 2 × 2). THE SKYX Pro v 10.5.0 (Software Bisque 2019) was used for image acquisition at both DBO and SO. Our computer clocks were synced to web based standard times at the beginning of each session, and THE SKYX program provided times for the center of each exposure. Both instruments at DBO used B, V, and R_c filters manufactured to match the

Johnson-Cousins Bessell specification, while at SO, only B and V filters were used. At DBO, exposures of 105 s were used for the B and R_c filters, and 90 s were used for the V filter with the QSI camera. Exposures of 120 s for B, and 105 s for V and R_c were used for the ASI2600MM camera. At SO, exposure times of 300 s were used for the B filter, and 120 s for the V filter.

2.2. Image reduction

IMAGESPLUS v6.5 (ImagesPlus 2020) was used for dark subtraction and flat correction of all images. The images were registered either in ImagesPlus or with AIP4WIN v2.4.0 (Berry and Burnell 2005).

2.3. Photometric processing

Photometric processing was performed with MPO Canopus v10.8.5.0 (Minor Planet Observer 2010) on all images to determine catalog-based magnitudes using the APASS star fields (Henden *et al.* 2009, 2010, 2011; Smith *et al.* 2011) that are built into the program. Magnitudes were generated using ensembles of five non-varying comparison stars. Canopus also provides uncertainties for each magnitude using the sum in quadrature of uncertainties based on SNR values for the target and all comparison stars. Table 1 lists identities, J2000 coordinates, APASS DR9 V-magnitudes, and color indices (B–V) for KO Psc and the comparison stars. All images were taken above 30° altitude and, considering the small FOV for each system, differential atmospheric extinction was ignored. The average uncertainty in the transformed target star magnitudes for all images with all filters from both DBO and SO was 0.05 or less, and in no case was the uncertainty greater than 0.1 mag. All photometric data acquired for and used in this study can be retrieved from the AAVSO International Database.

2.4. Additional data sources

We found a significant amount of additional data for KO Psc. SuperWasp survey measurements (Butters *et al.* 2010) provided 55 ToMx values between June 23, 2004, and November 29, 2006. The *Information Bulletin on Variable Stars* (IBVS) (Wils 2011, 2012) listed another six times between September 5, 2010, and November 11, 2011. The AAVSO International Database (AID; Kafka 2021) included CV and V band data that gave up another 15 maxima between October 26, 2016, and October 12, 2021. Finally, the Mikulski Archive

for Space Telescopes (STSci 2024) provided access to 10,788 time-series flux measurements from the TESS project (Ricker *et al.* 2015; Antoci *et al.* 2019) taken between September 30 and October 29, 2022. These measurements use a broad band of wavelengths from 600 to 1000 nm, approximately centered near the Cousins I_c band. This large data set provided an additional 285 ToMx times.

3. Results and discussion

3.1. Period analysis

A robust way of determining the period of a pulsating variable star using data of different types and from different sources is predicted-time difference (PTD) analysis. Precisely measured times of extrema, in this case 430 times of maximum brightness, ToMx, were compared to those predicted by a selected linear ephemeris, and the ephemeris parameters were adjusted to find the best fit. This process can provide a very accurate period as part of a new linear ephemeris. The ToMx times, however, must be in the same units, and we had to do some conversions. The Super WASP, IBVS, AID, and transformed SO and DBO data used for this study were all in Julian date (JD) while the TESS measurements were expressed in Barycentric Julian Date–Barycentric Dynamical Time (BJD_{TDB}). All of the JD times were converted to BJD_{TDB} to agree with the TESS values. Conversion to BJD_{TDB} was done using a web site¹ maintained by the Ohio State University (Eastman *et al.* 2010).

Polynomial approximations of degree 3 through 8 built into the MAVKA program (Andrych *et al.* 2020) were used to determine ToMx values and associated uncertainties from the SuperWasp data. The program automatically selects the algebraic polynomial that best fits the extrema. We used the PERANSO program (Paunzen and Vanmunster 2016) to determine the DBO, SO, and TESS ToMx times. PERANSO uses periodic orthogonal (Schwarzenberg-Czerny 1996) to fit observations and analysis of variance (ANOVA) to determine fit quality. A total of 430 ToMx times were used in the analysis. A table containing source, band-pass, ToMx, uncertainty, cycle number, and PTD values for KO Psc is available on the AAVSO ftp site at <ftp://ftp.aavso.org/public/datasets/4038-Gilchrist-kopsc.csv>.

Figure 1 is a plot of the PTD vs. cycle number. Both linear (red) and quadratic (green) trendlines are fitted to the data. Values

Table 1. Astrometric coordinates (J2000), V-mag and color indices (B–V) for KO Psc and five comparison stars (1–5) used during this study.

Star	Identifier	R.A. (J2000)			Dec. (J2000)			V mag.	B–V
		h	m	s	°	'	"	APASS ^a	APASS ^a
T	KO Psc	01	10	24.2	+27	19	15.2	12.537	0.257
C1	GSC 1750-0538	01	09	55.5	+27	23	03.0	12.869	0.508
C2	GSC 1750-1288	01	09	48.9	+27	22	07.9	13.810	0.608
C3	GSC 1750-0809	01	09	47.4	+27	20	31.5	13.664	0.605
C4	GSC 1750-1186	01	10	28.1	+27	17	37.0	12.835	0.861
C5	GSC 1750-0512	01	11	00.9	+27	28	40.5	13.244	0.485

^a V-mag and (B–V) for comparison stars derived from APASS DB9 described by (Henden *et al.* 2009, 2010, 2011 and Smith *et al.* 2011), as well as on the AAVSO web site (<http://www.aavso.org/apass>).

¹ OSU site: <https://astroutils.astronomy.osu.edu/time/hjd2bjd.html>

from the VSX web page defined the linear ephemeris (Equation 1) that was used as a starting point for the PTD analysis.

$$\text{Max (HJD)} = 2455824.4952 + 0.08697753 E. \quad (1)$$

A new linear ephemeris from the PTD analysis (Equation 2) gives the best fit period and uncertainties determined by linear regression.

$$\begin{aligned} \text{Max (BJD}_{\text{TDB}}) &= (2460954.94821 \pm 0.00007) \\ &+ (0.086977442 \pm 0.000000002) E. \quad (2) \end{aligned}$$

Note that the times in Equation 2 and the data that were used are in BJD_{TDB}, while they are in HJD in Equation 1. The similarity between the linear and non-linear fits in Figure 1 shows that the period of KO Psc has been quite stable since 2004.

3.2. Phased Light curve (LC) plots and effective temperature

The period from the PTD analysis in section 3.1, $P=0.086977442$ d, was used to produce folded (phased) light curves (LCs) for all the DBO and SO data used in this study. All of the LCs show the relatively rapid rise in brightness followed by a slower dimming, which is expected for HADS stars (McNamara 2000). Figure 2 is a plot of the folded LCs for the DBO and SO data. The phase was selected so that minimum brightness is at phase = 0.

The average and standard deviation (σ) for (B–V) over the full LC are (B–V) = 0.2604 and $\sigma = 0.0543$. In this case, σ represents the variability in B–V over the entire cycle, not the uncertainty in the overall average. We believe a more representative uncertainty is ± 0.0017 . The technique we used to determine the uncertainty is discussed in Gilchrist (2025). The APASS DB9 value for B–V is 0.257 ± 0.247 . We also determined B–V values using points near minimum brightness ($0.95 < \text{phase} < 1.05$) and near maximum brightness ($0.30 < \text{phase} < 0.36$). Here, the average and standard deviations were used. These results are listed in Table 2.

3.3. Stellar parameters

Before the effective temperature, T_{eff} , of a star can be determined from the B–V color index, corrections must be made for interstellar extinction. The GALextin website (Amôres *et al.* 2021) provides access to different models (Amôres and Lépine 2005, 2007; Schlegel *et al.* 1998; Schlafly and Finkbeiner 2011; Schlafly *et al.* 2014). A parallax of 0.7838 ± 0.0179 mas for KO Psc is listed in GAIA-DR3 (GAIA Collab. *et al.* 2021). This inverts into a distance

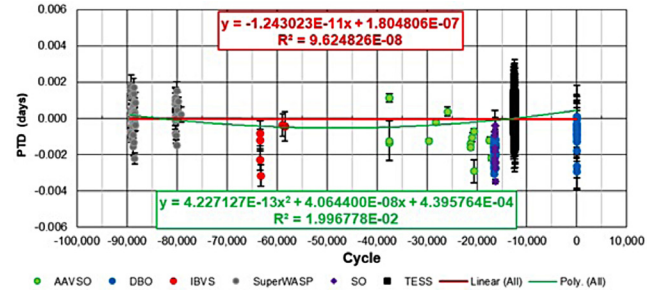


Figure 1. PTD vs cycle number for KO Psc. The dense clusters of gray points at the left are from SuperWASP, the red points near –60,000 cycles are from IBVS, the light green points scattered between –30,000 and –20,000 cycles are from the AAVSO data base, the purple points near –17,000 cycles are from SO, the dense cluster of black points near 13,000 cycles are from TESS, and the light blue points near 17,000 and zero cycles are from DBO. The red line and the equation at the top of the plot are the best linear fit to all of the data. The green line and the equation at bottom of the plot are the best quadratic fit. The non-linear term in the quadratic fit is quite small, indicating that there has been very little change since 2004.

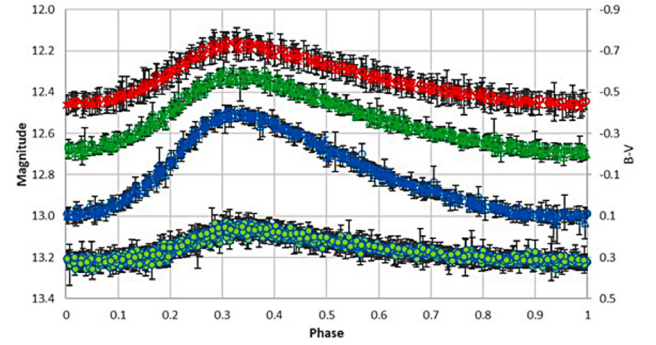


Figure 2. Phased plots of LCs from DBO and SO photometry. The RC data are at the top in red, the V magnitudes are further down in green, the B values are near the middle in blue. Finally, the B–V color index is plotted on a different scale near the bottom in blue-green.

of $d = 1276 \pm 29$ pc. Using this distance along with galactic coordinates of longitude = 128.098 and latitude = –35.361, Amôres and Lépine model A (Amôres and Lépine 2005) gives a reddening value of $A_V = 0.208 \pm 0.775$. The (B–V) color index correction $E(B-V) = (0.208 \pm 0.775)/3.1 = 0.067 \pm 0.25$.

Table 2 includes B–V color indices from the DBO and SO observations and from the APASS database. Values for (B–V)₀, corrected for interstellar extinction (Amôres and Lépine 2005), are also listed. The effective temperature (T_{eff}) values and their uncertainties were determined using Table 4 from Pecaut and Mamajek (2013). That table also shows that the effective temperature $T_{\text{eff}} = 7883$ K falls between spectral classes of A6 and A7.

Table 2. B–V for KO Psc along with corresponding (B–V)₀ and T_{eff}

Source	B–V mag.	B–V unc.	(B–V) ₀ mag.	(B–V) ₀ unc.	$\log T_{\text{eff}}$ ^{**}	$\log T_{\text{eff}}$ unc.	T_{eff} K	T_{eff} unc.
DBO and SO nr max	0.167	0.022	0.100	0.251	3.932	0.094	8543	1853
DBO and SO nr min	0.318	0.013	0.251	0.250	3.875	0.094	7498	1632
DBO and SO average	0.26	0.002	0.193	0.250	3.897	0.094	7883	1704
APASS DB9	0.257	0.244	0.190	0.349	3.898	0.131	7904	2387

^{*}(B–V)₀ = (B–V) – E(B–V) where E(B–V) = 0.067 ± 0.25 (Amôres and Lépine 2005). ^{**} T_{eff} = effective temperature (K) (Pecaut and Mamajek 2013).

The average V magnitude for KO Psc from the combined DBO and SO measurements is 12.537 mag, with a standard deviation of $\sigma = 0.122$ mag. As with B–V, σ is more an indication of the variability of the star rather than the uncertainty in the average value. Using the same technique, Gilchrist (2025), we determined an estimate of the uncertainty of ± 0.002 mag. Combining this with a distance of $d = 1276 \pm 29$ pc and a reddening of $A_V = 0.208 \pm 0.775$ in the distance modulus equation yields the absolute visual magnitude.

$$M_V = 5 - 5 \log(d) + (V - A_V) = 1.80 \pm 0.777 \text{ mag}. \quad (3)$$

A period-luminosity relationship given by McNamara (2011) has subsequently been refined by Ziaali *et al.* (2019) and Barac *et al.* (2022). Using the period from the PTD analysis $P = (0.086977442 \pm 0.000000002) \text{ d}$, the Barac equation yields:

$$M_V = (-3.01 \pm 0.07) \log(P) - (1.40 \pm 0.07) = 1.79 \pm 0.1 \text{ mag}. \quad (4)$$

These two values agree nicely. A weighted average of these is $M_V = 1.79 \pm 0.14$ mag.

Using tables from Pecaut and Mamajek (2013) with $T_{\text{eff}} = 7883 \pm 1704 \text{ K}$, we find a bolometric correction $BC_V = -0.0086 \pm 0.1907$ mag. This gives $M_{\text{bol}*} = 1.78 \pm 0.238$ for KO Psc. Using a bolometric magnitude for The Sun of $M_{\odot} = 4.75 \pm 0.02$, the luminosity can be found as:

$$L_* = L_{\odot} 10^{[(M_{\text{bol}\odot} - M_{\text{bol}*})/2.5]} = (15.39 \pm 3.39) L_{\odot}. \quad (5)$$

With this luminosity and a solar temperature of $T_{\odot} = 5772 \pm 0.8 \text{ K}$, the radius of KO Psc can be estimated by

$$R_* = \sqrt{(L_*(T_{\odot}/T_*)^4)} = (2.10 \pm 0.94) \quad (6)$$

An empirical period-radius relationship for HADS stars is given by Laney *et al.* (2003). Their equation gives

$$R_* = R_{\odot} 10^{[(1.106 \pm 0.012) + (0.725 \pm 0.01) \times \log P + (0.029 \pm 0.024)]} = (2.23 \pm 0.15) R_{\odot}. \quad (7)$$

The exponent in Equation 7 includes two constant terms. The equation is intended for both HADS and other pulsators, and the second term is to be used only for HADS stars. The two radius estimates do not quite agree but their calculated uncertainties do overlap. A weighted average of the two values yields $R_* = 2.23 \pm 0.21 R_{\odot}$. The uncertainties in all of these parameters were determined by propagating the uncertainties in the input values through the various equations either directly or using the Uncertainty Calculator (Shattuck 2025).

3.4. Fourier transform analysis

Discrete Fourier transform analysis (DFT) was performed separately on each color of the combined measurements from DBO and SO, and on the TESS data, using the PERIOD04 program (Lenz and Breger 2005). In each case, a fundamental mode frequency was determined (spectral window = 100 d^{-1}). After processing all of the original data, prewhitening was used to look for oscillations in the residuals by removing the most

significant signals from the previous steps. This process was repeated until the signal-to-noise ratio (SNR) fell below six. This cutoff is derived from a couple of recent papers (Baran *et al.* 2015; Baran and Koen 2021). Depending on data cadence and coverage, they reported that values as low as 4.6 to 5.7 in successive prewhitened DFT analysis could yield results with a False Alarm Probability threshold $FAP = 0.01\%$. For this study, we chose the slightly larger value of six.

Analysis of the TESS and all three colors of the DBO and SO data yielded fundamental frequencies near $F1 \approx 11.497 \text{ d}^{-1}$ and three harmonics near $F2 \approx 22.994 \text{ d}^{-1}$, $F3 \approx 34.492 \text{ d}^{-1}$, $F4 \approx 45.989 \text{ d}^{-1}$. The TESS measurements produced these same results, but yielded two additional harmonics, $F5 \approx 57.487 \text{ d}^{-1}$ and $F6 \approx 68.983 \text{ d}^{-1}$.

Table 3 lists the DFT frequencies, amplitudes, and phases for the TESS flux measurements and the DBO and SO B, V, and R_c magnitudes. The associated uncertainties for each value were determined using the Monte Carlo simulation built into the PERIOD04 program. In each case, 400 iterations were attempted for the simulations, but not all of these processed successfully. The number of successful processes ranged from 261 up to 400. We decided to list the results with three decimal places, but some of the predicted uncertainties are quite small, and these are presented in scientific notation. Small differences in the frequencies begin to show up in the second or third decimal place, and this is probably a better indication of the uncertainties. Spectral window and amplitude spectrum plots for the DFT analysis are presented in Figure 3. The TESS results are on

Table 3. Frequencies, amplitudes, and phases with associated uncertainties from DFT analysis of KO Psc DSO and SO magnitude measurements and TESS flux data.

Source	Freq. d^{-1}	Freq. Unc.*	Amp.	Amp. Unc.*	Phase	Phase Unc.*	SNR
DBO and SO B filter			Mag.				
F1	11.497	0.001	0.230	0.018	0.008	0.123	171
F2	22.996	0.007	0.064	0.004	0.569	0.984	57
F3	34.490	1.0E–05	0.021	0.001	0.303	0.843	23
F4	45.990	0.012	0.010	0.001	0.729	0.662	13
DBO and SO V filter			Mag.				
F1	11.498	1.1E–06	0.167	0.001	0.457	0.001	92
F2	22.995	3.9E–06	0.047	0.001	0.586	0.002	52
F3	34.491	1.1E–05	0.015	0.001	0.953	0.007	22
F4	45.986	0.008	0.006	0.001	0.370	0.209	8
DBO R_c filter			Mag.				
F1	11.497	9.0E–07	0.132	0.001	0.998	0.001	122
F2	22.992	3.1E–06	0.039	0.001	0.338	0.002	39
F3	34.488	9.8E–06	0.012	0.001	0.006	0.007	18
F4	45.984	0.002	0.006	0.001	0.243	0.049	10
TESS			Norm. Flux				
F1	11.497	7.9E–06	0.106	4.4E–05	0.508	6.2E–05	1463
F2	22.994	2.6E–05	0.032	4.3E–05	0.664	2.2E–04	530
F3	34.492	7.3E–05	0.010	4.6E–05	0.731	0.001	177
F4	45.989	2.0E–04	0.004	4.5E–05	0.735	0.002	83
F5	57.487	1.517	0.002	7.2E–04	0.783	0.201	32
F6	68.983	1.421	0.001	3.9E–04	0.785	0.238	17

* Uncertainties were estimated using the Monte Carlo simulation routine built into PERIOD04 (Lenz and Breger 2005).

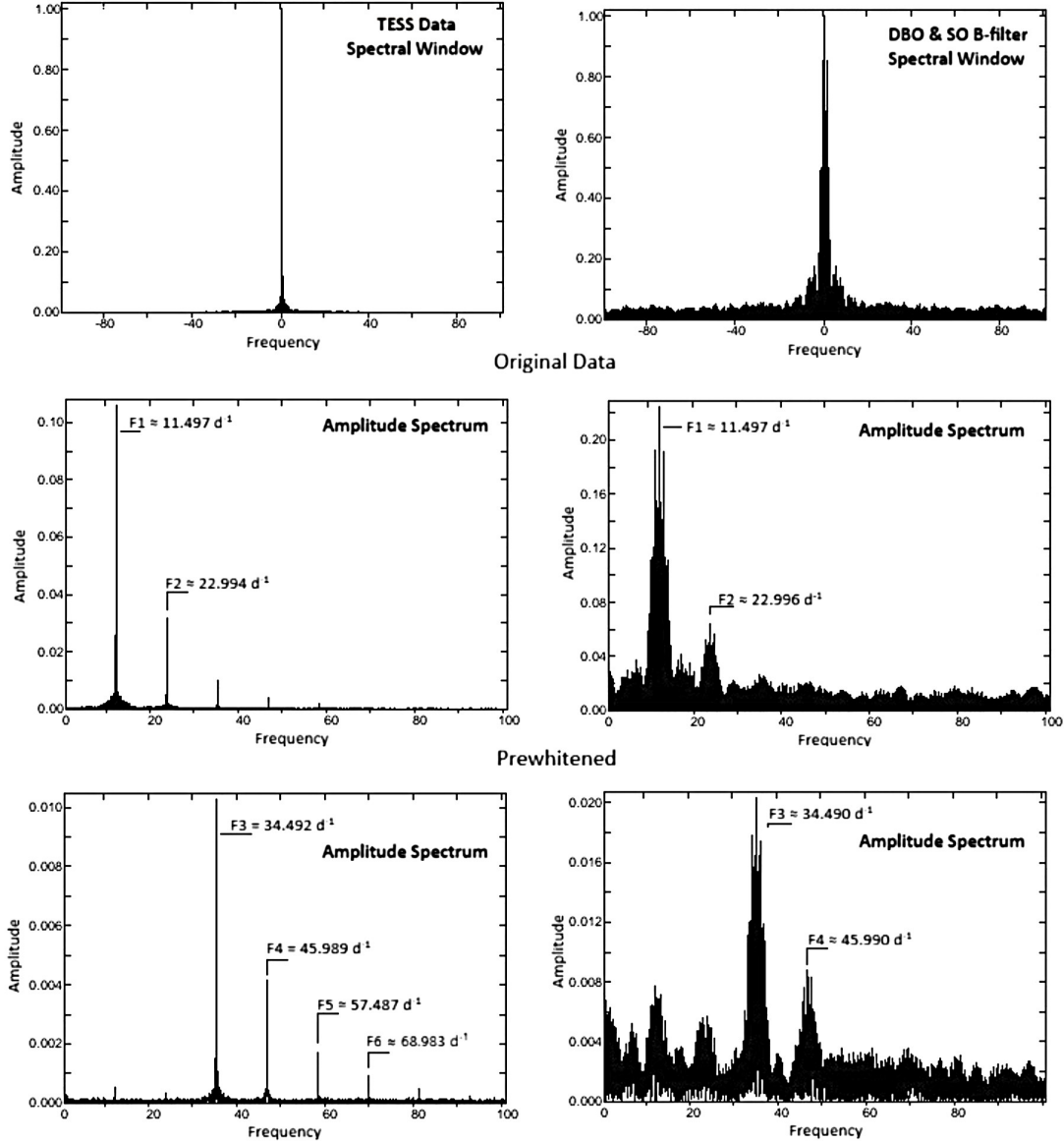


Figure 3. PERIOD04 DFT spectral window and amplitude spectrum plots for KO Psc. The TESS results are at the left, and the DBO&SO data are at the right. Spectral window plots are at the top, amplitude plots of the original data are in the middle, and plots after two steps of prewhitening are at the bottom.

the left and similar plots for the DBO and SO B-filter data on the right. Spectral window plots are at the top, amplitude plots of the original data are in the middle, and amplitude plots after two steps of prewhitening are at the bottom. Plots of results for the V and R_c filters are similar to those for the B filter. As expected, the spectral window shows a maximum amplitude near 1 at a frequency of zero. The amplitude plots of the original data clearly show the fundamental and some of the harmonics. Additional harmonics can be seen in the prewhitened data plots.

3.5. Evolutionary status

PARSEC theoretical stellar evolutionary models (Bressan *et al.* 2012) are available on the web². Different files are available for a variety of stellar masses and metallicities. The luminosity, L_* , and effective temperature, T_{eff} , of KO Psc from this study can be compared with the closest models to provide estimates

of the mass, radius, and age. No high-resolution spectra were available for KO Psc, and we do not know the metallicity. Considering its location, a distance of $d = 1276 \pm 29$ pc, a galactic longitude = 128.098, and latitude = -35.361 , our subject is most likely a galactic disk star rather than a halo object. We will assume that the metallicity is similar to the solar value. The Sun's metallicity, however, is somewhat uncertain, with recently reported numbers ranging between $Z = 0.01$ and $Z = 0.02$. A value of $Z_{\odot} = 0.0142$ was proposed by Asplund *et al.* (2009). Later, von Steiger and Zurbuchen (2016) questioned this result and suggested the value of $Z_{\odot} = 0.0196$ based on the analysis of the solar wind. Soon thereafter, Serenelli *et al.* (2016) showed that the derived composition disagrees with observables from the basic solar model. Obviously, the problem of a definitive value for $Z_{\odot}$ still remains an open question. We selected PARSEC models with metallicities of $Z = 0.01$ and $Z = 0.02$ to bracket the solar value.

² PARSEC models: http://stev.oapd.inaf.it/PARSEC/tracks_v12s.html

Figure 4 is a theoretical HR diagram showing the T_{eff} and luminosity of KO Psc along with the instability strip for p-mode pulsators (Xiong *et al.* 2016). Compared to other HADS stars, KO Psc is relatively hot, and it plots near the blue edge of the instability strip. In addition, several known HADS and SX Phe stars (Balona 2018), and several HADS stars from more recent papers (Alton and Stepień 2019; Alton 2019; Alton and Gilchrist 2022; Alton 2022; Gilchrist and Alton 2023; Gilchrist 2024a; Gilchrist 2024b; Gilchrist 2025; Gilchrist *et al.* 2025) are plotted. To complete the figure, selected PARSEC evolutionary tracks (Bressan *et al.* 2012) are plotted. Two groups of three models are presented. The blue curves are for metallicity $Z=0.01$, and the red curves are for $Z = 0.02$. In each case models for three different masses that pass close to the position of KO Psc are presented.

The closest approach of each model to the position of KO Psc was determined, and then a multi-step process combining interpolation and extrapolation was used to estimate the age, mass, and radius of KO Psc. The uncertainties were determined by propagating the uncertainties in effective temperature, T_{eff} and luminosity, L_* , through the interpolation/extrapolation process. The predicted values are listed in Table 4.

The PARSEC models suggest a mass between 1.699 and 1.861 $M_{\odot}$ and an age between 0.821 and 1.177 Gyr. The predicted stellar radius, between 2.104 and 2.111, compares with the 2.23 $R_{\odot}$ value measured in this study.

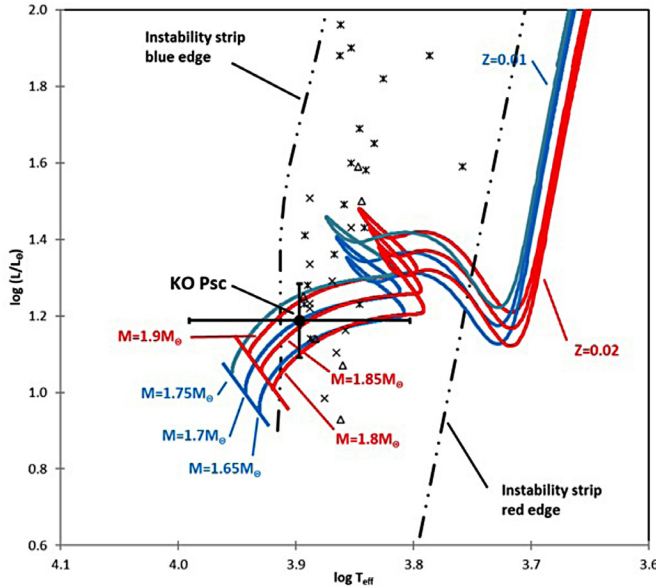


Figure 4. Evolutionary tracks from PARSEC models (Bressan *et al.* 2012) are shown as solid blue lines for $Z = 0.01$ with $M_* = 1.65$, $M_* = 1.70$, and $M_* = 1.75 M_{\odot}$, and red lines for $Z = 0.02$ with $M_* = 1.80$, $M_* = 1.85$, and $M_* = 1.90 M_{\odot}$. The edges of the instability strip for radial p-mode pulsators (Xiong *et al.* 2016) are plotted as dot-dash lines. The position of KO Psc is plotted with uncertainties. Additional points from Balona (2018) are plotted with asterisks for HADS and Δ symbols for SX Phe stars. X symbols show the positions of other HADS stars from more recent papers (Alton and Stepień 2019; Alton 2019; Alton and Gilchrist 2022; Alton 2022; Gilchrist and Alton 2023; Gilchrist 2024a, 2025; and Gilchrist *et al.* 2025).

Table 4. Stellar parameters for KO Psc predicted from evolutionary models (PARSEC^a), using T_{eff} and L_* at observations from DBO and SO.

Parameter	PARSEC ^b	PARSEC ^c	DBO and SO
Mass ($M_{\odot}$)	1.699 ± 0.040	1.861 ± 0.042	—
Radius ($R_{\odot}$)	2.104 ± 0.134	2.111 ± 0.035	2.23 ± 0.21
Age (Gyr)	1.177 ± 0.005	0.821 ± 0.045	—

^a Bressan *et al.*, 2012

^b Interpolation between $Z = 0.01$ with $M = 1.65$, 1.7, and 1.75 $M_{\odot}$.

^c Interpolation between $Z = 0.02$ with $M = 1.8$, 1.85, and 1.9 $M_{\odot}$.

4. Conclusions

The light curve we found for KO Psc has the typical shape, amplitude, and period expected for a HADS variable star. PTD analysis produced a period of $P = 0.086977442 \pm 0.000000002$ d, and showed that the period has been stable since 2004. With correction for interstellar reddening, our $(B-V)_0$ measurement gives a $T_{\text{eff}} = (7883 \pm 1704)$ K. The corrected V magnitude yields a luminosity $L_* = (15.39 \pm 3.39) L_{\odot}$. Also computed is the stellar radius, $R_* = (2.23 \pm 0.21) R_{\odot}$. DFT analysis of data from all sources produced a fundamental frequency of $F1 \approx 11.497 \text{ d}^{-1}$ and harmonics $F2 \approx 22.994 \text{ d}^{-1}$, $F3 \approx 34.492 \text{ d}^{-1}$, $F4 \approx 45.989 \text{ d}^{-1}$. The TESS data contain two additional statistically significant harmonics, $F5 \approx 57.487 \text{ d}^{-1}$ and $F6 \approx 68.983 \text{ d}^{-1}$. The temperature and luminosity fall near the blue edge within the instability strip for p-mode pulsators. Comparison with PARSEC stellar models produced estimates of the stellar mass (1.699 to 1.861 $M_{\odot}$), radius (2.104 to 2.111 $R_{\odot}$), and age (0.821 to 1.177 Gyr).

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The Mikulski Archive for Space Telescopes at mast.stsci.edu gave access to TESS measurements. The CDS-VizieR web site operated by the Centre de Données Astronomiques de Strasbourg, France (<https://vizier.cds.unistra.fr/viz-bin/VizieR>), provided access to several databases including GAIA DR2, GAIA DR3, and TESS. The Ohio State University site⁵ was used to convert times from HJD to BJD_{TDB} .

³ Gaia: <https://www.cosmos.esa.int/gaia>

⁴ DPAC: <https://www.cosmos.esa.int/web/gaia/dpac/consortium>

⁵ OSU site: <https://astroutils.astronomy.osu.edu/time/hjd2bjd.html>

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⁶ Shattuck (2025): <https://www.colby.edu/chemistry/PChem/scripts/error.html?ModPagespeed=off>

Observational Constraints on Periods and Magnitudes of Cepheid and Suspected Variables in Gemini

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Abstract This study investigates five variable stars: NSV 3558, NSV 16755, NSV 2775, ζ Gem, and W Gem. The latter two have been well-studied and are confirmed to be classical Cepheids, while the remaining three have only been identified as potential variables—hence the NSV (*New Catalogue of Suspected Variable Stars*) status. Observations were made using our university's Planewave CDK-700 telescope, capturing optical light in the Johnson B- and V-bands over 46 days. Images were reduced with standard techniques, including darks, flats, and biases. Photometric analysis involved measuring photon counts for each star, which were then converted to magnitudes using GD 71 as a reference star. We confirm periods for the known Cepheids to match their previously defined values, while eliminating NSV 2775 as a possible variable and constraining the periods of NSV 3558 and NSV 16755 to 23.0 and 23.68 days, respectively.

1. Introduction

The Hipparcos satellite was developed to create the first high precision catalogue of stellar positions and distances using precise parallax measurements. The Tycho-1 star catalogue resulted from the Tycho experiment on the Hipparcos satellite. In addition to precise position and distance measurements, it also contains photometric data in the B- and V-bands. The survey's efforts culminated in the Tycho catalogue in 1997, encompassing over one million stars Hoeg *et al.* (1997), later expanding into the Tycho-2 catalogue in 2000 with 2.5 million stars (Hoeg *et al.* 2000) through enhanced data reductions and integration of previous ground-based observations.

A byproduct of this cataloging of stars is that many were flagged for variability, where they joined a list of others from various surveys in the *General Catalogue of Variable Stars* 5.1 (GCVS; Samus *et al.* 2017). This is where our three candidates for suspected variable stars—NSV 3558, NSV 16755, and NSV 2775—were chosen. The primary criterion for selecting candidates was their magnitude range, as the telescope being used has an observational limiting magnitude of +16.

Additionally, two well-documented Cepheid variables were chosen for observation to serve as a baseline for verifying the reliability of subsequent measurements. ζ Geminorum (ζ Gem) is a classical Cepheid located around 500 parsecs away that varies between spectral types F7Ib and G3Ib (Kervella *et al.* 2001). It has been a focal point of astronomical research since its variability was confirmed in 1844 (Henroteau 1925), exhibiting regular radial pulsations with a period of 10.15 days (Mykhailo *et al.* 2023), and varying in brightness from a visual magnitude of 3.62 to 4.18 (Shobbrook 1992; Kiss 1998; Kervella *et al.* 2001). W Geminorum (W Gem), also a classical Cepheid, is much further away at around 1200 parsecs (Groenewegen 2013). Its spectral type varies between F5 and G1 (Samus *et al.* 2017). It is known to pulsate with a period of 7.91 days (Szabados 1991; Meyer 2023) and vary in brightness from a visual magnitude of 6.55 to 7.37 (Moffet and Barnes 1985; Kiss 1998). While less studied than ζ Gem, W Gem's classification as a Type I Cepheid is well documented in the

AAVSO's Variable Star Index (VSX; Watson *et al.* 2014) and the *General Catalogue of Variable Stars* (Samus *et al.* 2017). Right Ascension and Declination values for all five variable stars are included in Table 1.

2. Methods

2.1. Telescope

Data was collected using a CDK-700 PlaneWave telescope located at our university's observatory. The PlaneWave telescope has a 70-cm aperture and 454-cm focal length. A Diffraction Limited STXL-6303E camera was used in capturing the images.

Table 1. Observational details of target stars.

AAVSO UID	Star Name	R. A. (J2000)			Dec. (J2000)		
		h	m	s	°	'	"
000-BBM-966	NSV 3558	07	22	31.51	13	08	08.7
000-BCY-106	NSV 16755	06	01	11.81	22	32	37.4
N/A	NSV 2775	06	00	53.26	22	41	10.2
000-BBM-362	Zeta Gem	07	04	06.53	20	34	13.1
000-BCV-926	W Gem	06	34	57.45	15	19	49.7
N/A	GD 71	05	52	27.62	15	53	13.2

Table 2. Net exposure times.

Date of Observation	B (sec)	V (sec)
2025-Feb-03	150	150
2025-Feb-08	150	150
2025-Feb-16	150	150
2025-Feb-17	150	150
2025-Feb-20	150	150
2025-Feb-24	150	150
2025-Mar-04	150	150
2025-Mar-05	150	150
2025-Mar-10	150	150
2025-Mar-11	150	150
2025-Mar-16	150	150
2025-Mar-18	150	150
2025-Mar-21	150	150

The camera has a field of view of $21' \times 14'$. A pixel size of 9 microns results in an overall resolution of $0.41''/\text{pix}$.

2.2. Images and photometry

Data collection spanned 46 days, from 2025 February 3 to March 21, with observations conducted two to four times weekly, totaling approximately 20 nights. Images were collected in Johnson B- and V- band filters (Bessell 1990) and taken with an exposure time of 30 seconds each, with 5 frames per object per filter captured each night for a total exposure time of 150 seconds (Table 2). Data were processed using *ASTROIMAGEJ* (Collins *et al.* 2017), applying flat-field corrections for CCD sensitivity variations, dark frame subtraction for thermal noise, and bias frame correction for baseline noise. Aperture photometry was used to measure photon counts and background levels for each target, with the background subsequently subtracted from the counts.

On 2025 March 18, an anomalous observation night resulted in photon counts approximately half the typical range for all targets. We decided that this outlier should be excluded from period analysis, as it represented a systematic environmental or instrumental error rather than intrinsic stellar variability, which would have compromised the accuracy of our differential photometry and introduced false artifacts into the period modeling.

2.3. Magnitude calibration

The reference star chosen for magnitude conversion was GD 71; its right ascension and declination values are also included in Table 1. This star belongs to the Landolt catalogue for UVBRI photometric-standard stars, and hence serves as a reliable constant to calibrate the variable magnitudes (Landolt 1992). It was not in the same frame as the variables, but was chosen because it was the closest standard reference star to the other observed stars. This was important to ensure that they were undergoing the same atmospheric and observational conditions in order to establish a baseline for corrections. GD 71's known B and V magnitudes are 12.7 and 13.0, respectively, so these were the reference values used for calibration. Magnitudes for the target stars were subsequently derived via differential photometry using the formula:

$$m = m_{\text{ref}} - 2.5 \log_{10} \left(\frac{b}{b_{\text{ref}}} \right) \quad (1)$$

Table 3. Photometry results for NSV 3558.

<i>JD</i>	<i>B (mag)</i>	<i>V (mag)</i>
2460709.5	9.9258 ± 0.0605	9.9010 ± 0.0387
2460714.5	10.2756 ± 0.0203	10.2786 ± 0.0184
2460722.5	10.4121 ± 0.0105	10.3842 ± 0.0145
2460723.5	10.4361 ± 0.0167	10.5142 ± 0.0160
2460726.5	10.4051 ± 0.0138	10.3740 ± 0.0103
2460730.5	10.4028 ± 0.0138	10.3711 ± 0.0156
2460738.5	10.2225 ± 0.0083	10.2414 ± 0.0144
2460739.5	10.2126 ± 0.0205	10.2843 ± 0.0406
2460744.5	10.3403 ± 0.0105	10.3080 ± 0.0178
2460745.5	10.3280 ± 0.0184	10.3065 ± 0.0214
2460750.5	10.3438 ± 0.0145	10.3249 ± 0.0353
2460755.5	10.1423 ± 0.0171	9.4206 ± 0.0750

Table 4. Photometry results for NSV 16755.

<i>JD</i>	<i>B (mag)</i>	<i>V (mag)</i>
2460709.5	9.1058 ± 0.0631	8.9595 ± 0.0426
2460714.5	9.6529 ± 0.0260	9.6978 ± 0.0222
2460722.5	9.6788 ± 0.0115	9.7077 ± 0.0175
2460723.5	9.7079 ± 0.0109	9.7900 ± 0.0254
2460726.5	9.6864 ± 0.0068	9.7195 ± 0.0139
2460730.5	9.6993 ± 0.0091	9.7460 ± 0.0141
2460738.5	9.6001 ± 0.0087	9.6770 ± 0.0135
2460739.5	9.6096 ± 0.0272	9.7176 ± 0.0076
2460744.5	9.6614 ± 0.0076	9.6941 ± 0.0140
2460745.5	9.6529 ± 0.0153	9.6900 ± 0.0190
2460750.5	9.7120 ± 0.0286	9.7080 ± 0.0277
2460755.5	9.6544 ± 0.0166	8.9450 ± 0.0823

Table 5. Photometry results for NSV 2775.

<i>JD</i>	<i>B (mag)</i>	<i>V (mag)</i>
2460709.5	12.2821 ± 0.0969	12.0330 ± 0.0367
2460714.5	12.2009 ± 0.0270	11.9909 ± 0.0196
2460722.5	12.2108 ± 0.0149	12.0260 ± 0.0138
2460723.5	12.2079 ± 0.0177	12.0680 ± 0.0199
2460726.5	12.1976 ± 0.0139	12.0500 ± 0.0066
2460730.5	12.2198 ± 0.0080	12.0557 ± 0.0196
2460738.5	12.1277 ± 0.0088	11.9984 ± 0.0133
2460739.5	12.1352 ± 0.0188	12.0264 ± 0.0472
2460744.5	12.2056 ± 0.0081	12.0050 ± 0.0189
2460745.5	12.1903 ± 0.0239	12.0161 ± 0.0193
2460750.5	12.2276 ± 0.0232	12.0282 ± 0.0282
2460755.5	12.1896 ± 0.0113	11.2823 ± 0.0727

Table 6. Photometry results for W Gem.

<i>JD</i>	<i>B (mag)</i>	<i>V (mag)</i>
2460709.5	7.5229 ± 0.0517	6.9830 ± 0.0486
2460714.5	8.9337 ± 0.0226	8.3440 ± 0.0143
2460722.5	8.9881 ± 0.0133	8.2440 ± 0.0196
2460723.5	8.6251 ± 0.0138	8.1270 ± 0.0117
2460726.5	8.1622 ± 0.0096	7.6640 ± 0.0303
2460730.5	8.9880 ± 0.0078	8.3640 ± 0.0133
2460738.5	8.8497 ± 0.0194	8.1725 ± 0.0170
2460739.5	8.3288 ± 0.0172	7.8525 ± 0.0317
2460744.5	8.6580 ± 0.0078	8.0390 ± 0.0312
2460745.5	8.8772 ± 0.0126	8.1390 ± 0.0164
2460750.5	8.1182 ± 0.0163	7.6190 ± 0.0349
2460755.5	8.1622 ± 0.0204	6.9026 ± 0.0985

Table 7. Photometry results for Zeta Gem.

<i>JD</i>	<i>B (mag)</i>	<i>V (mag)</i>
2460709.5	5.4202 ± 0.0670	4.7544 ± 0.0339
2460714.5	5.3897 ± 0.0126	5.2350 ± 0.0479
2460722.5	5.5698 ± 0.0176	5.1760 ± 0.0161
2460723.5	5.4790 ± 0.0128	5.3480 ± 0.0204
2460726.5	5.7287 ± 0.0023	5.4950 ± 0.0119
2460730.5	5.9130 ± 0.0097	5.6013 ± 0.0127
2460738.5	5.8796 ± 0.0196	5.4225 ± 0.0121
2460739.5	5.9200 ± 0.0285	5.7370 ± 0.0965
2460744.5	5.3419 ± 0.0091	5.2396 ± 0.0182
2460745.5	5.4458 ± 0.0168	5.2634 ± 0.0226
2460750.5	5.9195 ± 0.0139	5.5089 ± 0.0253
2460755.5	5.3178 ± 0.0248	4.3700 ± 0.0788

where m_{ref} is the reference star's magnitude, and b and b_{ref} are the measured photon counts. This was applied separately for B- and V- bands. A night-by-night account of each star's magnitudes can be found in Tables 3 through 7.

2.4. Period fitting

The Date Compensated Discrete Fourier Transform (DC DFT) algorithm, originally described by Ferraz-Mello (1981), was employed to search for potential periods in the B and V magnitude data for each star. An initial run using the standard DC DFT algorithm produced spurious results: all targets displayed a dominant period of approximately 197 days, regardless of object type, inconsistent with the expected periods of known Cepheids (ζ Gem: 10.15 days; W Gem: 7.91 days) and unlikely for suspected variables given that it was identified for all of them.

To investigate this artifact, we tested duplicating all data points, which doubled the effective sample size. This produced more diverse periods, with those for ζ Gem and W Gem aligning more closely with their literature values. The ~ 197 -day period was identified as a low-frequency artifact, likely resulting from a systematic trend over the data sets of each object, which DC DFT misinterpreted as a partial sinusoidal cycle.

To derive reliable periods without artificial duplication, we re-analyzed the original datasets using the DC DFT with Period Range option. This method performs Fourier analysis with user-specified parameters, allowing for the exclusion of artificial peaks. A period range of 1 to 50 days and a resolution of 0.01 day were selected to ensure sensitivity to periods from short-term variations up to the multi-week timescales for the unknown targets. This approach successfully eliminated the 197-day alias and produced distinct, physically reasonable periods for each star.

For each target, the periods derived from the B-band data were compared with those from the V-band data. Periods were considered reliable if the results of the two filters agreed within the formal uncertainties. In cases of discrepancy, the light curves for each filter were inspected visually, and the period producing the cleanest, least-scattered curve in both bands was adopted. The final adopted periods are presented in Figure 1. Periodograms showing the most probable periods for each star are shown in Figures 2 through 6.

Visual inspection of the light curves reveals two outliers near phase 0.5 across some targets. These data points correspond to February 3 and March 21, the first and final day of our observation window. On these nights, measurements were systematically brighter than typical oscillations. These points were caused by transient atmospheric extinction found only in the reference star, particularly in the V band for March 21. They slightly broaden the formal uncertainties, however, retaining them preserves the maximum possible frequency resolution for the DC DFT algorithm, so the benefit of their presence outweighs their statistical burden.

3. Results

The photometric analysis of the five stars observed yielded the following results. Light curves and period estimates were

derived, along with the Date Compensated Discrete Fourier Transform (DC DFT) algorithm, as detailed in section 2.4. The analysis focused on constraining periods and verifying variability.

For the known Cepheid variable W Gem, the measured B-band period is 7.87 ± 0.06 days, with a V-band period of 7.68 ± 0.10 days. This compares favorably to the literature value of 7.91 days (Moffet and Barnes 1985; Kiss 1998; Szabados 1991; Meyer 2023). The light curve shows sinusoidal pulsations characteristic of a Classical Cepheid, with visual magnitudes ranging from 6.90 to 8.36, also slightly dimmer and wider in range than historical observations of 6.55 to 7.37 (Moffet and Barnes 1985; Kiss 1998).

For the known Cepheid variable ζ Gem, the measured period from the B-band data is 10.99 ± 0.05 days, with a corresponding V-band period of 11.25 ± 0.12 days. These values are relatively consistent with the published period of 10.15 days (Shobbrook 1992; Kiss 1998; Kervella *et al.* 2001; Mykhailo *et al.* 2023). The light curve exhibits regular sinusoidal variations, consistent with its classification as a Classical Cepheid. The observed visual magnitudes fluctuated between 4.22 and 5.53, a wider range and overall slightly dimmer than the recorded values of 3.61 to 4.18 (Shobbrook 1992; Kiss 1998; Kervella *et al.* 2001).

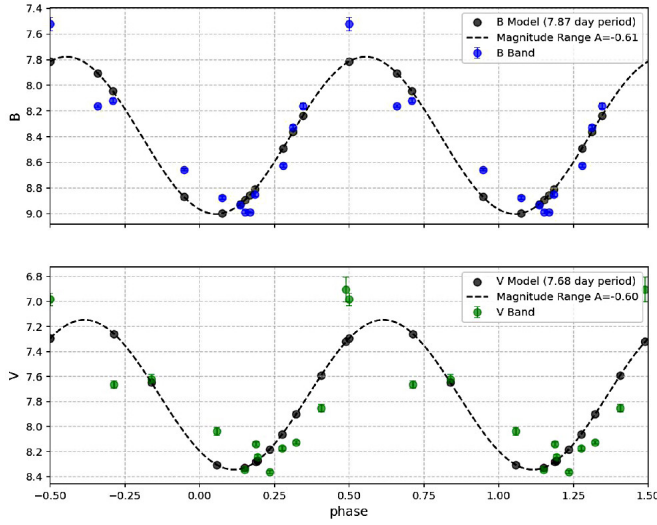
For the suspected variable NSV 3558, the visual magnitude range is recorded to be between 9.42 and 10.52. This is consistent with the established magnitudes of 9.55 (Hoeg *et al.* 2000) and 10.40 (Cannon and Pickering 1918–1924). The period analysis produces a B-band period of 24.96 ± 0.04 days and a V-band period of 23.0 ± 0.09 days. This star exhibited the strongest, most consistent periodicity out of each suspected variable studied, and has the highest chance of being identified as a genuine variable.

For NSV 16755, the light curve indicates weak periodicity amid outliers, with a visual magnitude range of 8.95 to 9.80. These values are consistent with the established magnitude values of 8.94 (Hoeg *et al.* 2000) and 9.10 (Cannon and Pickering 1918–1924). The dominant periods are 27.10 ± 0.05 days in the B-band and 23.68 ± 0.09 days in the V-band. This implies possible variability but requires further data to rule out constancy, as seen in some NSV reclassifications.

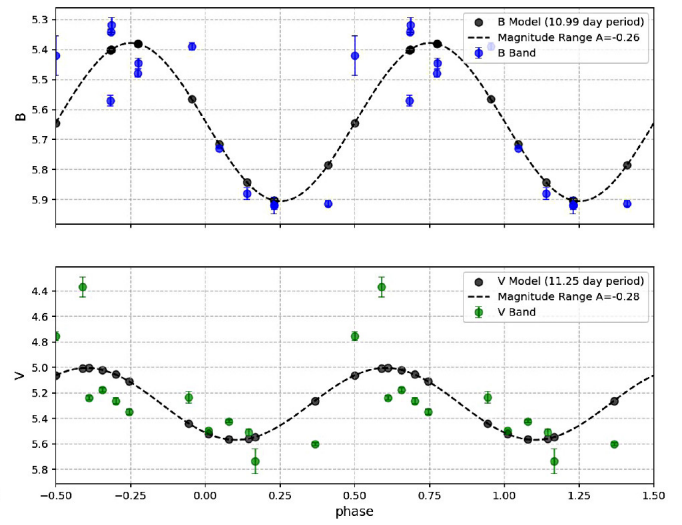
For NSV 2775, the visual magnitude range is found to be between 11.28 and 12.08. This is consistent with one recorded magnitude of 11.94 (Gaia Collab. 2023), but slightly brighter than the another of 12.28 (Hoeg *et al.* 2000). The B-band period is 20.46 ± 0.01 days, while the V-band period is 7.11 ± 0.07 days. The values are significantly divergent, and considering that the data appears to be non-varying in the V band, with the exception of one outlier, it is likely that the trend found reflects noise rather than intrinsic variability. Therefore, NSV 2775 is not believed to exhibit genuine variability.

A notable feature of the analysis for some suspected variables is the significant discrepancy in period estimates between B and V bands. NSV 16755 shows a difference of roughly 3.4 days, while NSV 2775 shows an extreme divergence of over 13 days. This is best explained by the interaction between the limitations of our dataset and the nature of the stars themselves. The observation window was limited to 46 days, only two theoretical pulsation cycles. Over such a short

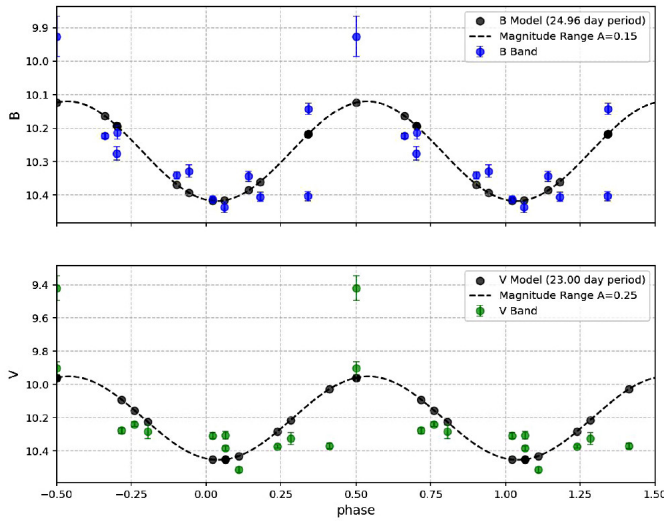
W Gem



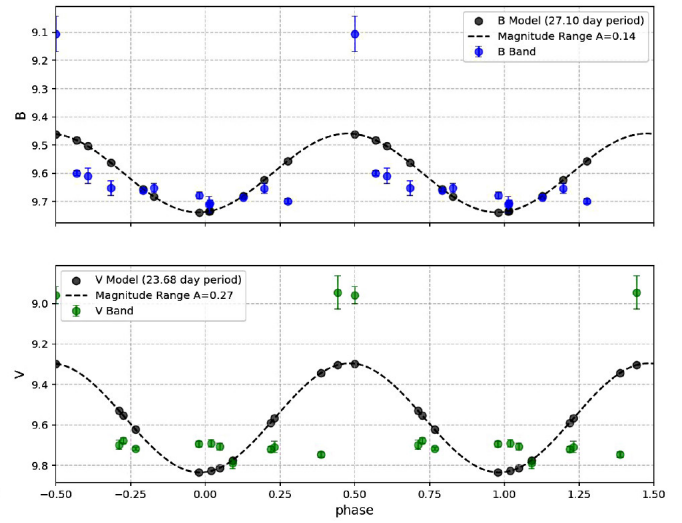
Zeta Gem



NSV 3558



NSV 16755



NSV 2775

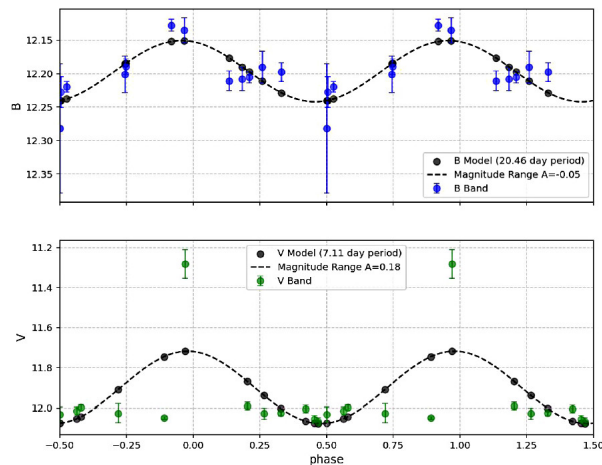


Figure 1. Phased light curves for the five target stars, folded according to their derived periods in the B band (top subplots) and V band (bottom subplots). Blue/green points represent the observed magnitudes, while black points/lines show the period models. Periods and magnitude ranges for each band are labeled in the subplots.

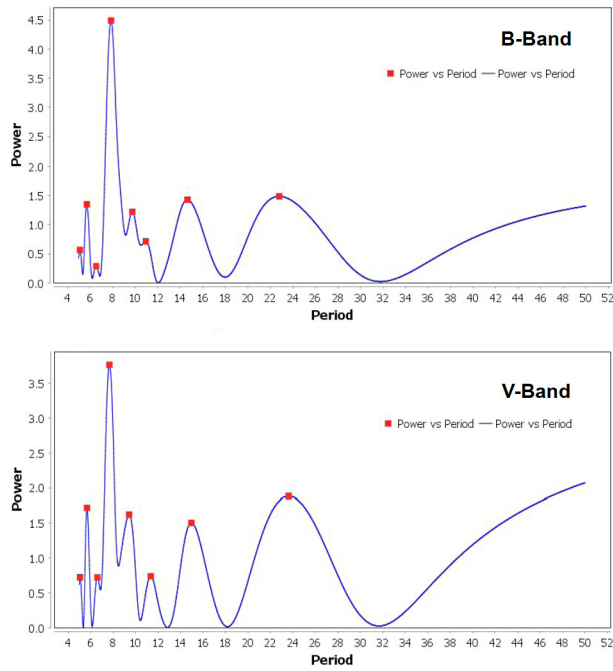


Figure 2. Periodogram for W Gem showing the likelihood of various periods in the B band (top subplots) and V band (bottom subplots).

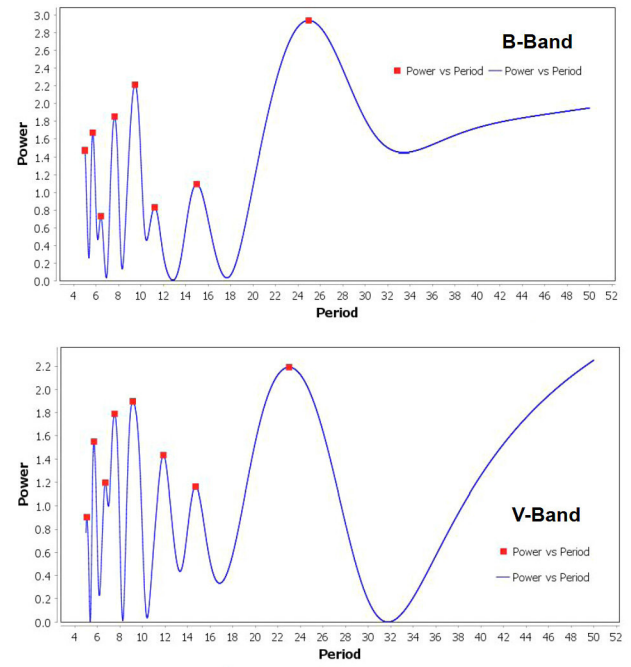


Figure 4. Periodogram for NSV 3558 showing the likelihood of various periods in the B band (top subplots) and V band (bottom subplots).

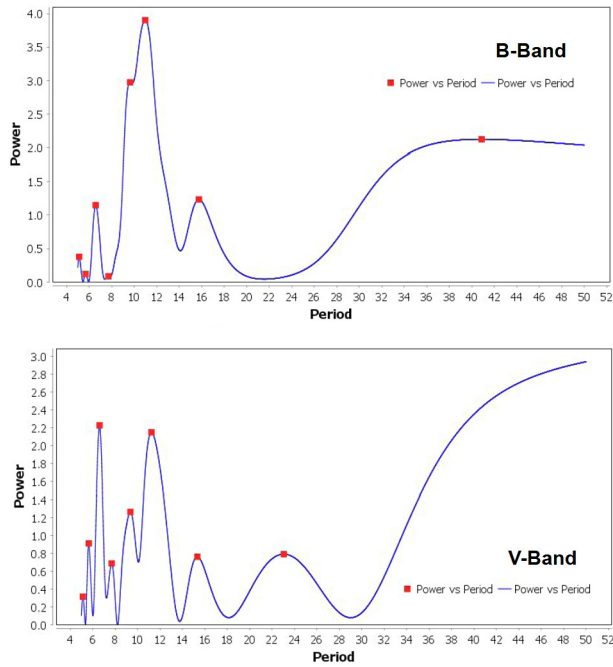


Figure 3. Periodogram for Zeta Gem showing the likelihood of various periods in the B band (top subplots) and V band (bottom subplots).

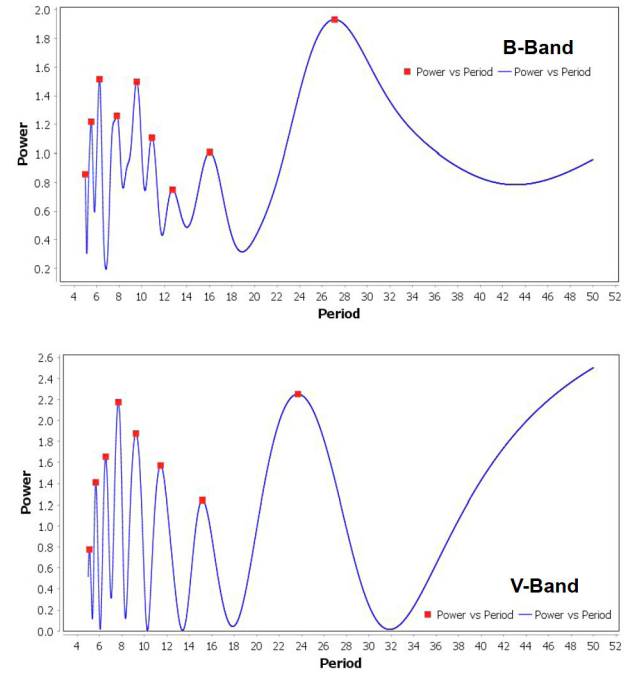


Figure 5. Periodogram for NSV 16755 showing the likelihood of various periods in the B band (top subplots) and V band (bottom subplots).

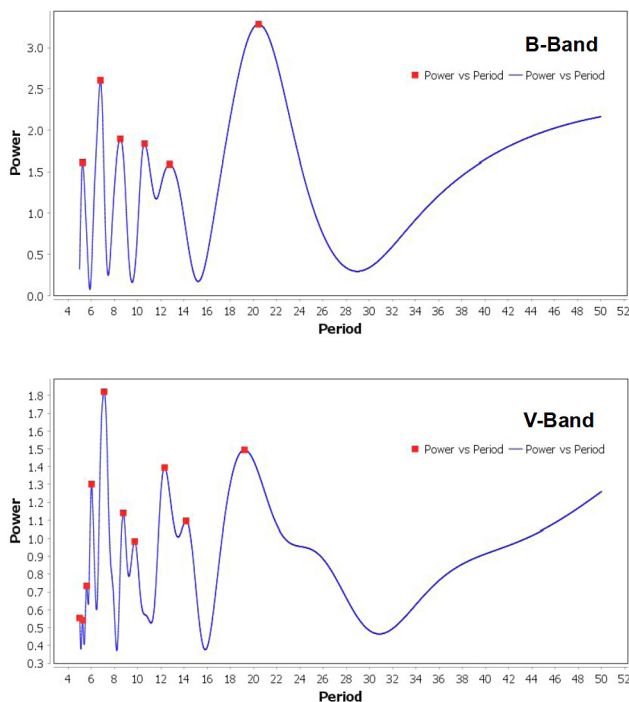


Figure 6. Periodogram for NSV 2775 showing the likelihood of various periods in the B band (top subplots) and V band (bottom subplots).

baseline, Fourier algorithms are highly susceptible to noise and single-night outliers (such as that seen on March 21st). When intrinsic variability is weak, or entirely absent, the output fails to converge across filters.

4. Conclusions

Observations of two known Cepheids, ζ Gem and W Gem, result in measured periods of 11.25 and 7.68 days, respectively, in close agreement with published values. For the NSV stars, evidence suggests that NSV 2775 is most likely not a variable star, while NSV 3558 and NSV 16755 have measured periods of around 23.0 and 23.68 days, respectively. All stars had magnitudes reasonably close to their previously published values.

However, the limited 46-day observation window and the March 18th anomaly constrained precision, potentially leaving the data trends susceptible to outliers. If the periods of NSV 3558 and NSV 16755 are as determined, then they were only observed for roughly two pulsation periods. These limitations underscore the need for longer baselines to distinguish true variability from noise. Future research should extend monitoring to

cover multiple cycles and mitigate anomalies through denser sampling. Such enhancements could enable reclassification of these NSV stars, expanding the database of available variables and advancing variable star astronomy.

5. Acknowledgements

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How a Precessional Oscillation Ceases: Observational Evidence for the Dissolution of the Circumstellar Disk of Pleione

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Abstract Observational evidence presented in this article confirms recent theoretical predictions that sustained tidal forcing leads to disk warping, splitting into inner and outer components, and eventual dissipation of the outer disk. The morphology of the line profiles indicates a recurrent, tidally induced tilt of the circumstellar disk by approximately 30° . This scenario is directly confirmed in the present article. In particular, the exponential decay and ultimate disappearance of the orbital modulation in the H α central absorption demonstrate the physical dissolution of the detached outer disk. These observations document, for the first time, the extinction of a tidally driven precessional oscillation in a Be-star disk.

1. Introduction

Pleione (28 Tau) is a classical Be star well known for recurrent transitions between Be and shell phases on timescales of several decades. Such behavior has long been attributed to changes in the geometry and orientation of its circumstellar disk. The system's binary nature introduces an additional dynamical agent: a companion star in an eccentric orbit with a period of 218 days. Recent theoretical and modeling efforts, such as by Marr *et al.* (2022) and Suffak *et al.* (2023), have significantly improved the interpretation of the variability of the Pleione disk parameters. Marr *et al.* (2022) demonstrated that the observed Be-shell transition between 2005 and 2019 can be reproduced without invoking changes in disk density, solely through variations in disk inclination caused by precession. Building on this, Suffak *et al.* (2023) showed that sustained tidal torques can destabilize a tilted disk, leading to its separation into inner and outer components, with the outer disk precessing independently and ultimately dissipating. The present study provides long-term observational evidence that directly traces this predicted evolutionary sequence.

2. Relevance of the central depression (CD)

The depth of the H α CA (often also “central depth” or “central absorption”) is defined as the difference between the local continuum level (equal to unity) and the minimum value

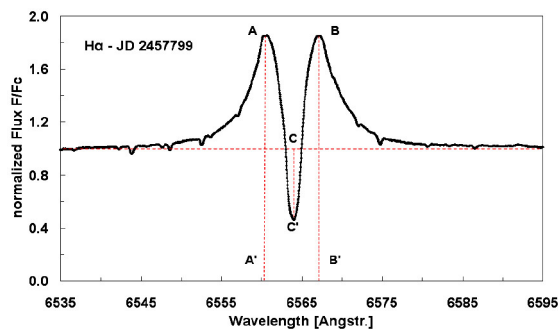


Figure 1. Measured quantities illustrated on an H α line profile: (AA') and (BB') emission peaks, depth of the central depression (CC'). The horizontal line marks the normalized continuum.

at the line minimum intensity (Figure 1). While the H α emission line samples the disk as a whole, the region probed by the shell lines, represented by the depth of the central depression CC', is restricted to the line of sight. The diagnostics they provide should not be ignored, as their properties reflect the structure and dynamics of the disk in the observer's direction.

2.1. Diagnostic value

The CD is a direct proxy for the optical depth of the disk along the line of sight and the inclination. A deep CD (near 0 or very small flux values in the core) indicates that dense disk material is obscuring the star's photosphere. This is characteristic of the “shell phase” (edge-on).

2.2. The inverse trend $1/CD$

An increase in this value (or a decrease in CD depth) means that absorption is weakening. This has been observed since JD 2456500 (around 2013). This suggests that the absorbing matter is moving away from the line of sight and could have two causes: 1. Geometrically: the disk precesses out of the line of sight (transition from edge-on to pole-on); 2. Physically: the disk dissipates, and its density decreases.

The Marr model predicts that both occur: The detached outer ring precesses and dissipates. The observed data impressively confirm this process. Importantly, comparable orbital modulation was absent during earlier strong shell phases in the 1970s and around 1980, indicating a fundamentally different disk geometry during those epochs.

3. Tidally induced disk tilting

The depth and temporal behavior of the shell absorption require a temporary increase in the effective inclination of the disk relative to the observer. The observed absorption strengths imply a tilt angle of approximately 30° relative to the stellar equatorial plane.

This result is fully consistent with the inclination ranges explored by Marr *et al.* (2022), who showed that changes between roughly 25° and 144° can reproduce the observed transitions between emission-dominated and shell-type H α profiles at constant disk density. In this framework, the periodic

strengthening of the shell absorption during periastron passages reflects transient increases in the projected disk column density due to tidal tilting.

4. Disk precession, splitting, and physical scenario

Marr *et al.* (2022) modeled the disk as a single, coherently precessing structure with a precession period of approximately 80 years. However, hydrodynamic simulations by Suffak *et al.* (2023) demonstrate that sustained tidal forcing of a sufficiently tilted disk leads to a dynamical instability.

In the scenario of the schematic model in Figure 2, the inner disk gradually settles back toward the star's equatorial plane, while mass feeding from the stellar interior continues to sustain the disk. At the same time, the outer disk undergoes slow precession over a period of about 15 years and progressively dissipates. This sequence forms part of a repeating cycle of roughly 34 years, which consistently explains both the short-term and long-term variability observed in Pleione.

The disk tearing, its precession, and its gradual dispersal are most clearly reflected in the time evolution of the central absorption depth (CD) in the H α line profile. Figure 3 illustrates the long-term behavior of the CD over a 27-year interval, together with its inverse representation ($1/CD$, shown as red points).

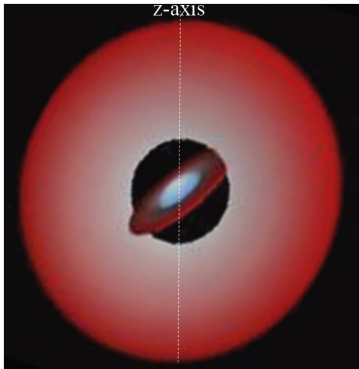


Figure 2. A schematic view of a dissipating circumstellar disk system. The star is located at the center (blue) and is surrounded by two distinct disk components: an inner disk (dark red) and an outer disk (orange), separated by a gap. The z-axis indicates the star's rotation axis (with kind permission of R. Hirata (2008)).

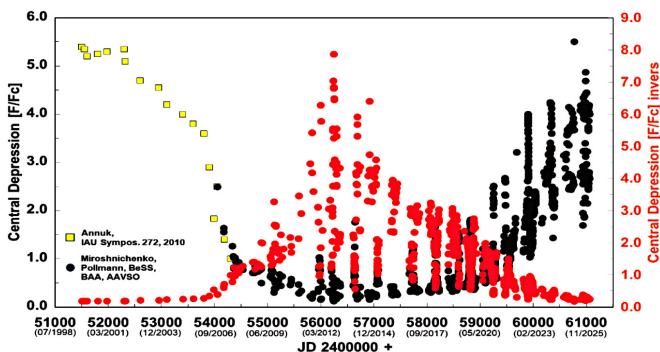


Figure 3. Long-term evolution of the H α central absorption depth (CD) and its inverse ($1/CD$, red points). The gradual increase of $1/CD$ reflects the progressive weakening of the shell absorption. See text for data sources.

5. Observational evidence for disk dissipation

The long-term evolution of the H α central absorption provides the total amount of material along the line of sight through the outer part of the disk, i.e. the summed amount of gas from the edge of the optically dense inner region to the outer regions of the disk.

Figure 3 shows the time frame of the changes in the CD and its reciprocal $1/CD$, with the latter particularly illustrating the circumstances. Spectra/CD data are from Annuk (2011), Miroshnichenko (2025), and the spectroscopy databases of the BeSS, BAA, and AAVSO (Obs. de Meudon. 2025; British Astron. Assoc. 2025; Kloppenborg 2025).

Beginning around JD 2456500, the inverse CD follows an exponential decay (Figure 3), indicative of a systematic reduction in absorbing material. After subtraction of this exponential trend, the residuals in Figure 5 reveal a clear 218-day modulation until approximately JD 2461000.

6. Physical interpretation of the decay timescale τ

The exponential fit to the long-term evolution of the inverse central absorption introduces a characteristic decay timescale τ . Although formally obtained as a fit parameter, τ has a clear physical meaning in the context of the disk-splitting scenario. The central absorption depth in H α is proportional to the projected column density of circumstellar material along the line of sight. Consequently, the inverse quantity $1/CD$ provides a sensitive measure of the amount of absorbing material in the detached outer disk and is consistent with the radiative transfer predictions of the hydrodynamic tearing disk model in Suffak *et al.* (2024). An exponential increase of $1/CD$ therefore implies an exponential decrease of the effective absorbing column density.

In this framework, the decay timescale τ represents the characteristic dissipation timescale of the outer disk component after its dynamical detachment from the inner disk. Specifically, τ corresponds to the time over which the absorbing column density of the outer disk is reduced to approximately $1/e$ of its initial value.

A dissipation time (τ) of 6.7 years (2446 days, Figure 4) for the outer ring fits well with a cool, detached ring whose viscosity is possibly lower than that of the hot inner disk. The fitted exponential decay strongly suggests that dissipation is dominated by viscous diffusion (as theoretically expected) and not by chaotic instabilities or stellar winds (“blowing off”). Observations of other Be stars, such as 66 Ophiuchi, show dissipation times ranging from years to decades (Marr 2022).

This behavior cannot be explained by geometric effects such as disk precession or inclination changes alone, as explored by Marr *et al.* (2022). Instead, the observed exponential decay requires a genuine physical loss of disk material, consistent with the gradual dispersal of a disk that is no longer replenished by mass injection from the star.

The value of τ therefore provides a direct observational constraint on the dissipation efficiency of a tidally detached Be-star disk. Together with the observed duration over which the orbital modulation persists, τ offers an empirical benchmark

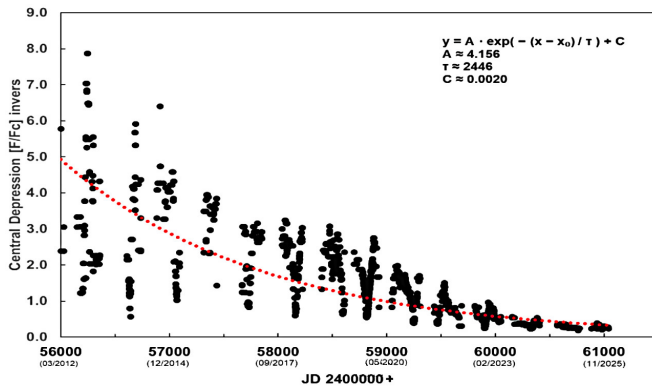


Figure 4. Exponential fit to the inverse CD long-term trend. The parameters A (initial amplitude), τ (decay timescale), and C (constant background) were determined by least-squares minimization. Beyond JD ≈ 2461000 , the orbital modulation disappears entirely.

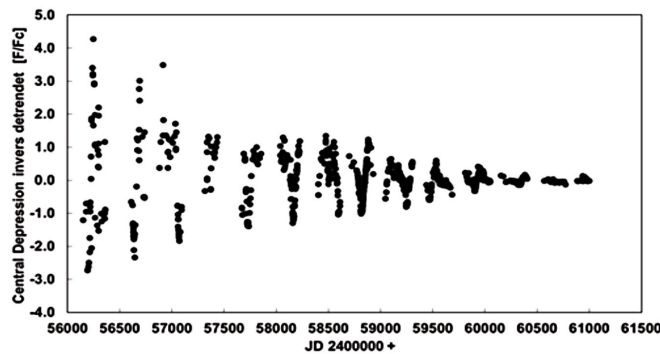


Figure 5. Residuals after subtraction of the exponential trend from $1/CD$. The absence of the 218-day signal demonstrates that the outer disk component subject to tidal forcing has fully dissipated.

for future hydrodynamic and viscous disk simulations, such as those presented by Suffak *et al.* (2023).

The $H\alpha$ -V/R ratio of Pleione also exhibits periodic modulation with a characteristic timescale of 218 days. This value agrees with the variability of the central absorption component (CD) and is consistent with the results reported by Pollmann and Leonardi in *IBVS* No. 6199 (2015). The period estimate is based on spectroscopic time-series observations of the $H\alpha$ line profile obtained over several observation intervals. The reproducibility of the 218-day period supports the interpretation that the V/R variability and the modulation of the central absorption CD are determined by the same underlying dynamic process in the circumstellar disk.

7. Novel observational contributions beyond Marr *et al.* (2022) and Suffak *et al.* (2023)

While the studies of Marr (2022), Marr *et al.* (2022), and Suffak *et al.* (2023) provide a consistent theoretical framework, they are necessarily limited by model assumptions and temporal coverage. The present work extends these studies in several fundamental ways.

The exponential decay of the inverse central absorption provides the first direct observational tracer of outer-disk dissipation in Pleione. Disk precession alone cannot produce such a decay; it requires a genuine reduction of disk mass.

The data demonstrate the extinction of the tidally driven orbital modulation. The disappearance of the 218-day signal once the exponential decay has progressed confirms a key but previously untested prediction of the disk-splitting scenario: tidal signatures vanish when the outer disk is gone.

The long-term dataset allows an observational separation of geometric variability and physical disk loss. Early variations are consistent with inclination effects at constant density, while the later behavior unequivocally indicates real dissipation.

Finally, the continuous temporal coverage across a critical evolutionary phase uniquely documents the transition from a tidally modulated, precessing disk to a state where the outer disk has completely vanished. This provides quantitative constraints on dissipation timescales that are not accessible from modeling alone.

8. Conclusions

Long-term $H\alpha$ monitoring of Pleione provides direct observational confirmation of recent theoretical predictions for tidally distorted Be-star disks. The observations show that:

1. A ~ 34 -year cycle, in which the inner disk returns to the equatorial plane and the outer disk precesses and dissipates, explains the Pleione CD variability.
2. The exponential decay of the $H\alpha$ central absorption traces the physical dissipation of this disk.
3. The disappearance of the orbital modulation marks the extinction of a tidally driven precessional oscillation.

These results establish a clear empirical link between disk precession, disk splitting, and disk dissipation in Pleione. They further demonstrate the exceptional scientific value of sustained spectroscopic monitoring and highlight the important role of coordinated amateur–professional collaboration.

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Ephemeris Refinement for Qatar-4 b, HAT-P-18 b, and CoRoT-1 b with Small Telescope and TESS Observations

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Abstract We present updated transit timing measurements for three hot Jupiters (Qatar-4 b, HAT-P-18 b, and CoRoT-1 b) by leveraging data collected from the MicroObservatory Telescope Network, a network of small, robotic ground-based telescopes, and the NASA Transiting Exoplanet Survey Satellite (TESS). By combining these data with archival published results, we present the most precise orbital solutions to date for all three systems, allowing for precise transit time predictions for future missions. We report an updated mid-transit time for Qatar-4 b of $2458919.5838 \pm 0.000089 \text{ BJD}_{\text{TDB}}$ and an updated orbital period of $1.80536560 \pm 0.00000021$ days. For HAT-P-18 b, we find a mid-transit time of $2459743.85340 \pm 0.000022 \text{ BJD}_{\text{TDB}}$ and an updated orbital period of $5.50802957 \pm 0.00000012$ days. For CoRoT-1 b, we report a mid-transit time of $2456268.99083 \pm 0.000099 \text{ BJD}_{\text{TDB}}$ and an updated orbital period of $1.50896846 \pm 0.000000071$ days. Our results demonstrate improvements over recently published ephemerides, with reductions of 36.4%, 4.35%, and 17.5% in mid-transit time uncertainties and 65.0%, 77.4%, and 16.9% in orbital period uncertainties for Qatar-4 b, HAT-P-18 b, and CoRoT-1 b, respectively. The results of this study improve the precision of future transit predictions and demonstrate the value of coordinated small-telescope monitoring (and citizen science initiatives) when updating the orbital parameters of hot Jupiters.

1. Introduction

The rapid pace of exoplanet discovery has offered both unprecedented opportunities and logistical challenges for the astronomical community. There have been over 6,000 confirmed exoplanets discovered with over 7,000 candidates still to be validated. As time progresses, ephemeris predictions degrade as observational uncertainties compound with each orbit, leading to increasingly imprecise transit time predictions (Fowler *et al.* 2021; Zellem *et al.* 2020). Hot Jupiters, while being one of the most extensively studied classes of exoplanets, are also particularly vulnerable to their mid-transit time uncertainties degrading more rapidly than long-period planets due to their proximity to their host star(s) (Zellem *et al.* 2020).

Consequently, regular follow-up observations are necessary to maintain precise mid-transit times. This effort is crucial in enabling precise future transit time predictions for subsequent studies using telescopes such as the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST), or the upcoming Atmospheric Remote-sensing Infrared Exoplanet Large-survey (Ariel) mission. The efficient scheduling of these large space-based telescopes is necessary to limit wasted time and maximize science returns.

The sheer volume of targets requiring follow-up observations make using solely space- or large, ground-based telescopes impractical due to their strict temporal and financial constraints. For example, thousands of planet candidates and confirmed exoplanets have been identified by TESS that will require

follow-up observations to maintain accurate transit ephemerides (Guerrero *et al.* 2021). Leveraging data collected by citizen science initiatives such as Exoplanet Watch (NASA 2026) can address the challenges of accessing large ground- and space-based telescope observations to maintain mid-transit times. Exoplanet Watch engages citizen scientists in collecting and analyzing data with small, ground-based telescopes such as the 6-inch robotic telescopes from the MicroObservatory Robotic Telescope Network (Sadler *et al.* 2001). The approach of integrating large volumes of citizen science observations with publicly available space-based telescope observations and published results from previous studies using high-precision instruments help to build a broader observational baseline (e.g., Noguer *et al.* 2024). Studies have shown that using these expanded data sets improves mid-transit time precision compared to using smaller datasets from high-precision telescopes alone (Hewitt *et al.* 2023a, 2024; Mizrahi *et al.* 2021; Pearson *et al.* 2022; Torres *et al.* 2025). Additionally, the NASA Transiting Exoplanet Survey Satellite (TESS; Ricker *et al.* 2015) continuously generates high-quality light curves for known exoplanets during its all-sky survey, including systems that present observational challenges from Earth's surface. Leveraging these space-based observations in combination with more readily accessible ground-based data allows for routine ephemeris refinement of many hot Jupiters (e.g., Ivshina and Winn 2022; Kokori *et al.* 2023; Noguer *et al.* 2024; Sgro *et al.* 2024).

In this study, we refined the mid-transit times and orbital periods of Qatar-4 b, HAT-P-18 b, and CoRoT-1 b by combining small, ground-based robotic telescope observations with new TESS data and previously published results, demonstrating that coordinated citizen-science monitoring can meaningfully improve ephemerides beyond studies relying primarily on space-based or professional observatory data alone. The work done in this study represents a culmination of the efforts completed across three semesters of an online Course-based Undergraduate Research Experience (CURE) as part of the online Astronomy and Planetary Science degree program at Arizona State University. The course was developed as a way to give online students the opportunity to engage in authentic research. Details of the course structure and impacts on student affective outcomes are discussed in Hewitt *et al.* (2023b).

2. Ground-based observatories

Our data were primarily acquired using the MicroObservatory Robotic Telescope Network developed and operated by the Harvard Smithsonian Center for Astrophysics. The MicroObservatory Robotic Telescope Network is designed to allow students, educators, and other users to capture and analyze images of celestial objects from anywhere with an internet connection, without needing their own telescope (Sadler *et al.* 2001). These telescopes are positioned at observatories linked with the Harvard College Observatory in Massachusetts and the Whipple Observatory in Arizona. The observations used in this study were collected with the “*Cecilia*” and “*Ben*” telescopes located at the Fred Lawrence Whipple Observatory on Mt. Hopkins, at an elevation of approximately 2590 meters.

Like all the MicroObservatory telescopes, *Cecilia* and *Ben* are identical, entirely self-contained systems designed to prevent weather-related damage and ensure nightly observations for extended periods with minimal maintenance. *Cecilia* and *Ben* are both custom-designed Maksutov-Newtonian telescopes, featuring a primary mirror with a diameter of 6 inches and a focal length of 560 mm. The telescope is paired with a specialized Kodak KAF1400 CCD imaging sensor, which has pixels measuring 6.9 microns on each side, resulting in an imaging field of view measuring 0.94×0.72 degrees. A 2×2 pixel binning technique was applied, producing an effective resolution of 5.0 arc-seconds per pixel (Sadler *et al.* 2001). Imaging was performed utilizing a clear (visible) filter with exposure durations of 60 seconds.

Five additional CoRoT-1 b observations were obtained using a privately operated Planewave CDK24 telescope hosted at Sierra Remote Observatories (California, USA). The 24-inch (0.61 m) f/6.5 system was paired with an SBIG Aluma AC4040 CMOS camera (4096×4096 pixels; $9 \mu\text{m}$ pixel size; typical read noise $4.5 e^-$) and operated with thermoelectric cooling. Exposure times ranged from 0.01 to 3600 s.

3. Data

3.1. Ground-based data

For the photometric evaluation of all ground-based data in this study, including observations from both MicroObservatory and the private observatory, we used the EXoplanet Transit Interpretation Code (EXOTIC; Zellem *et al.* 2020), a PYTHON 3 pipeline developed and maintained by Exoplanet Watch. EXOTIC processes raw photometric images in FITS format by tracking the positions of target and comparison stars across all frames and performing aperture photometry to produce time-series light curves. Model parameters are estimated using a Bayesian fitting routine. We allowed the following parameters to vary in the fitting process: mid-transit time, planet-to-star radius ratio, orbital inclination, transit duration, and airmass correction terms. A full description of the EXOTIC fitting procedure is outlined in Zellem *et al.* (2020). This software can be operated both on local machines and cloud platforms, such as Google Colaboratory (Colab). Our team opted to use the Google Colab platform to run EXOTIC, leveraging its collaborative features for ease of sharing data and data products between researchers.

We employed a two-stage quality control process following the standardized methodology described in Hewitt *et al.* (2024, 2023a). First, we performed an initial reduction of all observations to identify potentially significant ($> 3\sigma$) light curves. We defined statistical significance by the ratio of the measured transit depth to its associated uncertainty. All images were then re-examined by subsets of the authors to ensure consistent quality standards across all reductions. Images were evaluated based on several criteria: cloud coverage, visual noise, atmospheric haze, streaking from tracking errors, and adverse weather conditions. Images were excluded from the final dataset if any of these factors compromised our ability to reliably identify the target star or surrounding comparison stars.

For each target, we identified suitable comparison stars for EXOTIC's photometric fitting procedure. All comparison

stars for Qatar-4 b and HAT-P-18 b were selected from the American Association of Variable Star Observers (AAVSO) recommendations and verified to be non-variable. For CoRoT-1 b, with no AAVSO-recommended comparison stars available in the field of view, we selected comparison stars located near CoRoT-1 b to ensure they were affected similarly by systematic effects, such as variations in air mass. Figure 1 presents the comparison star positions within the field of view for each target as generated by the AAVSO Variable Star Plotter (VSP; Craig *et al.* 2023).

In this study, we reduced 14 statistically significant light curves of CoRoT-1 b obtained using data from the MicroObservatory Robotic Telescope Network and the Planewave CDK24 telescope. We also reduced 17 statistically significant light curves of Qatar-4 b and 10 of HAT-P-18 b, all obtained using the MicroObservatory. Representative light curves from MicroObservatory observations for each target are shown in Figure 2, while the full set of light curves reduced using MicroObservatory and the Planewave CDK24 is presented in Appendix A. A summary of the mid-transit times and transit depths for all significant ground-based observations is presented in Table 1.

3.2. Transiting Exoplanet Survey Satellite (TESS) data

Qatar-4b, HAT-P-18b, and CoRoT-1b were observed by TESS in Sectors 84 (2024 October 1–October 26), 79 (2024 May 21–June 02), and 87 (2024 December 18–2025 January 14), respectively, at 2-minute cadences. These observations occurred after the most recently published ephemeris updates that utilized TESS data for each system (Ivshina and Winn 2022; Kokori *et al.* 2023). The calibrated time-series data analyzed in this work were retrieved from the Mikulski Archive for Space Telescopes (MAST; STScI 2024) and processed following the light-curve extraction and cleaning procedure described by Noguer *et al.* (2024). This method incorporates an updated aperture selection scheme based on Pearson (2019), which mitigates pointing-induced systematics. Data obtained within 30 minutes of TESS momentum dump events were excluded due to elevated systematic noise. Additionally, we removed 3σ outliers using a rolling median filter with a 32-minute window. Quality-flagged data points were also excluded. Long-term stellar variability was detrended using the PYTHON package WOTAN (Hippke *et al.* 2019), with detrending parameters chosen to preserve the planetary transit signals. Example light curves for each target are presented in Figure 3 with the full set of TESS data presented in Appendix B. The resulting mid-transit times and transit depths are presented in Table 2.

4. Analysis

In order to derive updated mid-transit times, we created Observed–Calculated (O–C) plots for each of our targets. In addition to the mid-transit times reduced in this study (Tables 1 and 2), we also included those derived in previous studies. For Qatar-4b, we included mid-transit times from Kokori *et al.* (2022, 2023) and Ivshina and Winn (2022) fits of Wang *et al.* (2021), Mallonn *et al.* (2019), and Alsubai *et al.* (2017). The O–C plot for HAT-P-18b included published mid-transit times

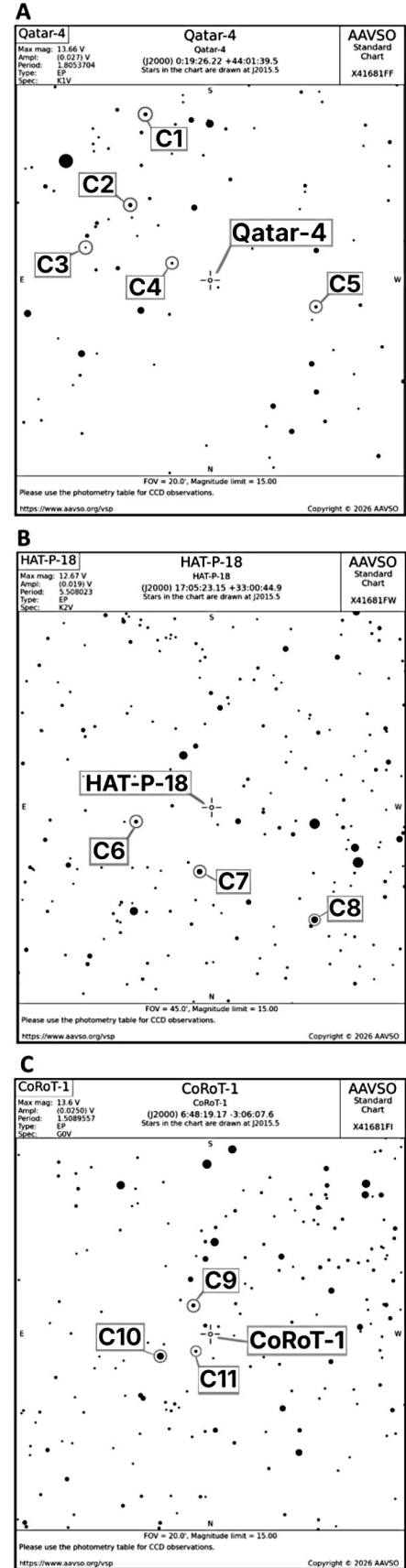


Figure 1. AAVSO VSP star charts for Qatar-4b (A), HAT-P-18b (B), and CoRoT-1b (C). The field of views are 20', 45', and 20', respectively. The comparison stars used in this study are labeled C-1 through C-11.

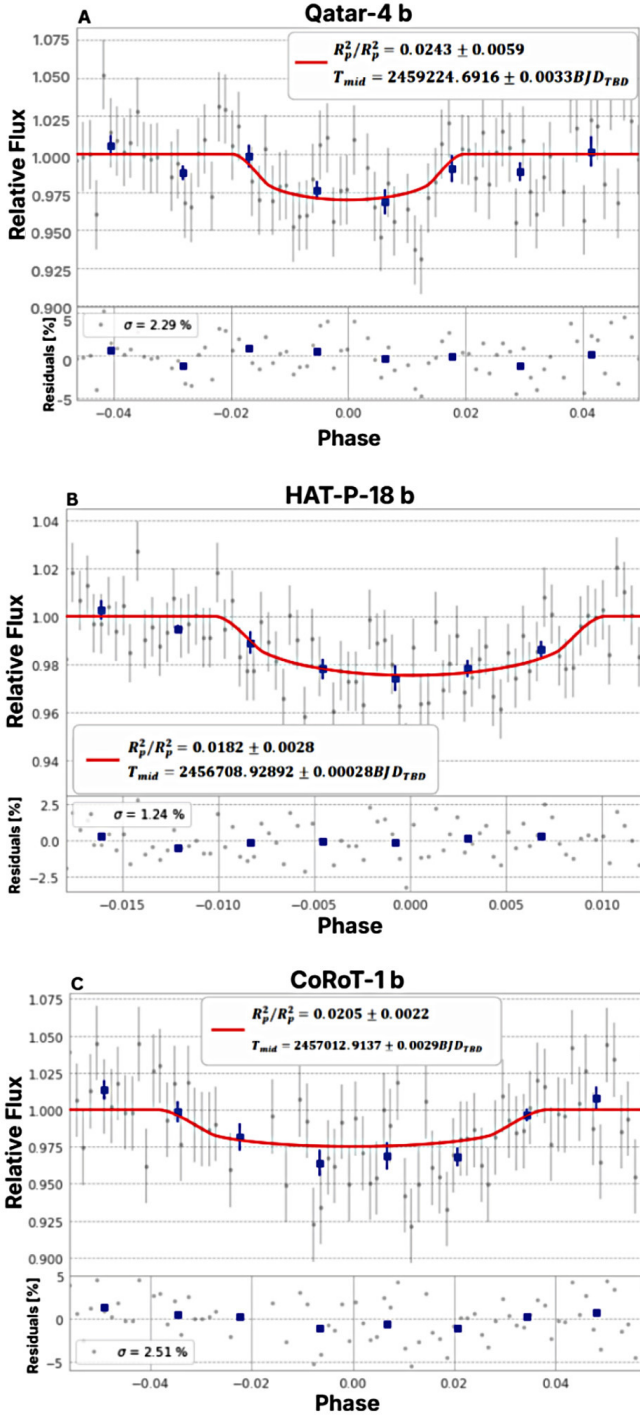


Figure 2. Example light curves reduced using MicroObservatory data for each target. Qatar-4 b (A) was observed on 2021-01-10, HAT-P-18 b (B) was observed on 2014-02-09, and CoRoT-1 b (C) was observed on 2014-12-20. The gray data points represent data collected from each image of the data set. The blue data points represent an average from a set of binned data points and were used to fit the light curve.

Table 1. Mid-transit times and transit depths for the statistically significant detections ($> 3\sigma$) reduced in this study using ground-based data.

Target	Date	Mid-Transit Time (BJD_{TDB})	R_p^2/R_s^2
Qatar-4 b	2017-02-02	2457787.6189 ± 0.0024	0.0339 ± 0.0037
	2019-05-25	2458628.922 ± 0.0013	0.0338 ± 0.0065
	2020-10-08	2459130.8131 ± 0.0032	0.0410 ± 0.0110
	2020-10-25	2459148.8591 ± 0.0039	0.0274 ± 0.0048
	2020-11-04	2459157.89920 ± 0.0038	0.0338 ± 0.0076
	2020-11-15	2459168.7229 ± 0.0035	0.0280 ± 0.0058
	2020-11-24	2459177.7586 ± 0.0050	$0.0340 \pm .010$
	2020-12-23	2459206.6441 ± 0.0038	0.0337 ± 0.0066
	2021-01-10	2459224.6916 ± 0.0033	0.0243 ± 0.0059
	2021-10-05	2459493.7006 ± 0.0031	0.0338 ± 0.0042
	2021-11-12	2459531.6115 ± 0.0045	0.0337 ± 0.0041
	2021-12-01	2459549.6673 ± 0.0033	0.0249 ± 0.0052
	2021-12-28	2459576.7434 ± 0.0043	0.0338 ± 0.0033
	2022-02-03	2459614.636 ± 0.0023	0.0337 ± 0.0042
	2022-11-27	2459910.7301 ± 0.0043	0.0185 ± 0.0034
	2023-08-12	2460168.914 ± 0.011	0.0340 ± 0.019
	2023-11-04	2460253.729 ± 0.0046	0.0214 ± 0.0064
HAT-P-18 b	2014-02-09	$2456708.92892 \pm 0.00028$	0.0182 ± 0.0028
	2015-09-15	$2457281.76205 \pm 0.00071$	0.019 ± 0.0027
	2017-06-16	2457920.6976 ± 0.0024	0.0187 ± 0.0041
	2018-06-19	2458289.728 ± 0.0011	0.0224 ± 0.0018
	2019-06-23	2458658.7762 ± 0.0026	0.0204 ± 0.0061
	2020-07-07	2459038.8276 ± 0.0037	0.0121 ± 0.0031
	2020-07-30	2459060.8626 ± 0.0031	0.0219 ± 0.0046
	2021-05-06	2459341.767 ± 0.0038	0.0220 ± 0.0030
	2021-06-08	2459374.8207 ± 0.0026	0.0259 ± 0.0051
	2022-07-05	2459765.8753 ± 0.0030	0.0232 ± 0.0052
CoRoT-1 b	2013-01-04	2456297.6641 ± 0.0023	0.0205 ± 0.0022
	2013-03-31	2456383.676 ± 0.0021	0.0204 ± 0.0026
	2013-04-03	2456386.6926 ± 0.0024	0.0205 ± 0.0040
	2014-12-20	2457012.9137 ± 0.0029	0.0205 ± 0.0022
	2017-01-08	2457762.8687 ± 0.0037	0.0205 ± 0.0031
	2017-02-24	2457809.6417 ± 0.0033	0.0205 ± 0.0052
	2019-03-28	2458571.6797 ± 0.0045	0.0202 ± 0.0043
	2021-02-16	2459262.7837 ± 0.0052	0.0205 ± 0.0041
	2022-03-26	2459665.6746 ± 0.0055	0.0205 ± 0.0044
	2024-11-21*	2460635.9566 ± 0.0024	0.0205 ± 0.00095
	2025-01-13*	2460688.7483 ± 0.0015	0.0205 ± 0.00037
	2025-01-16*	2460691.7671 ± 0.0018	0.0139 ± 0.0015
	2025-01-19*	2460694.7945 ± 0.0012	0.0161 ± 0.0017
	2025-01-22*	2460697.8098 ± 0.0012	0.0174 ± 0.0012

*Data collected from the Planewave CDK24 telescope.

from Hartman *et al.* (2011), Kirk *et al.* (2017), Fu *et al.* (2022), Patel and Espinoza (2022), Kokori *et al.* (2022, 2023), Ivshina and Winn (2022), and Ivshina and Winn (2022) fits of Seeliger *et al.* (2015). Finally, for CoRoT-1 b, we included mid-transit times from Barge *et al.* (2008), Pont *et al.* (2010), Ivshina and Winn (2022), and Ivshina and Winn (2022) fits of Bean (2009), Gillon *et al.* (2009), Sada *et al.* (2012), and Turner *et al.* (2016). For consistency, we included only the studies that derived their published mid-transit times using measured light curves. All the previously published mid-transit times used in the creation of the O–C plots for this study can be found in Appendix C.

We used a PYTHON code provided by Exoplanet Watch titled the “Exoplanet Ephemeris Fitting Tutorial,” to generate O–C plots for the three targets and to calculate updated ephemerides. The code uses nested sampling to fit a linear ephemeris model to the observed transit times, yielding updated estimates of the orbital period and mid-transit time (Pearson

Table 2. Derived parameters from the Transiting Exoplanet Survey Satellite (TESS) transit data individual fits for Qatar-4 b, HAT-P-18 b and CoRoT-1 b.

Target	Date	Mid-Transit Time (BJD_{TDB})	R_p^2/R_s^2	Sector
Qatar-4 b	2024-10-02	2460585.9333 ± 0.0010	0.01689 ± 0.00095	84
	2024-10-04	2460587.7411 ± 0.0010	0.01573 ± 0.00091	84
	2024-10-06	$2460589.54486 \pm 0.00089$	0.01703 ± 0.00088	84
	2024-10-07	2460591.3509 ± 0.0010	0.01582 ± 0.00083	84
	2024-10-09	$2460593.15577 \pm 0.00098$	0.01759 ± 0.00087	84
	2024-10-11	$2460594.96256 \pm 0.00088$	0.01704 ± 0.00084	84
	2024-10-15	$2460598.57367 \pm 0.00087$	0.01885 ± 0.00090	84
	2024-10-16	2460600.37972 ± 0.0010	0.0165 ± 0.00087	84
	2024-10-18	$2460602.18287 \pm 0.00095$	0.01605 ± 0.00089	84
	2024-10-22	$2460605.79407 \pm 0.00095$	0.01924 ± 0.00091	84
	2024-10-24	$2460607.59953 \pm 0.00097$	0.01688 ± 0.00093	84
	2024-10-25	$2460609.40469 \pm 0.00088$	0.01717 ± 0.00088	84
	2024-05-23	2460454.3893 ± 0.00059	0.0183 ± 0.00048	79
	2024-06-03	2460465.4050 ± 0.00062	0.01841 ± 0.00046	79
	2024-06-09	$2460470.91268 \pm 0.00055$	0.01853 ± 0.00045	79
CoRoT-1 b	2024-12-23	2460667.6339 ± 0.0036	0.00940 ± 0.0015	87
	2024-12-24	2460669.1430 ± 0.0040	0.0098 ± 0.0017	87
	2024-12-26	2460670.6531 ± 0.0037	0.0091 ± 0.0015	87
	2024-12-27	2460672.1637 ± 0.0039	0.0089 ± 0.0015	87
	2024-12-29	2460673.6695 ± 0.0046	0.0094 ± 0.0014	87
	2024-12-30	2460675.1828 ± 0.0038	0.0086 ± 0.0015	87
	2025-01-05	2460681.2137 ± 0.0055	0.0083 ± 0.0015	87
	2025-01-07	2460682.7252 ± 0.0045	0.0081 ± 0.0016	87
	2025-01-08	2460684.2342 ± 0.0039	0.0085 ± 0.0015	87
	2025-01-10	2460685.7430 ± 0.0041	0.0081 ± 0.0015	87
	2025-01-11	2460687.2498 ± 0.0045	0.0092 ± 0.0016	87
	2025-01-13	2460688.7568 ± 0.0056	0.0073 ± 0.0016	87

Table 3. The updated mid-transit times and periods for Qatar-4 b, HAT-P-18 b, and CoRoT-1 b.

Target	Mid-Transit Time (BJD_{TDB})	Period (days)
Qatar-4 b	$2458919.5838 \pm 0.000089$	$1.80536560 \pm 0.00000021$
HAT-P-18 b	$2459743.85340 \pm 0.000022$	$5.50802957 \pm 0.00000012$
CoRoT-1 b	$2456268.99083 \pm 0.000099$	$1.50896846 \pm 0.000000071$

et al. 2022). For each target, the most recently published values of the mid-transit time and orbital period were used as priors in the ephemeris fitting. For Qatar-4b, we adopted the priors of $T_0 = 2458919.58363 \pm 0.00015$ BJD_{TDB} and $P = 1.80536403 \pm 0.00000054$ days (Kokori *et al.* 2023). For HAT-P-18 b, the priors were $T_0 = 2459743.853395 \pm 0.000023$ BJD_{TDB} (Fu *et al.* 2022) and $P = 5.5080232 \pm 0.0000056$ days (Patel and Espinoza 2022). For CoRoT-1 b, we used priors of $T_0 = 2456268.99119 \pm 0.00012$ BJD_{TDB} and $P = 1.508968772 \pm 0.000000083$ days (Ivshina and Winn 2022). The O–C plots and posterior distributions are presented in Figures 4 and 5, respectively.

5. Results

In this study, we present updated mid-transit times and periods for three planets: Qatar-4b, HAT-P-18 b, and CoRoT-1 b, derived by integrating data collected from small, ground-based, robotic telescopes, new TESS data, and archival published results. The results are summarized in Table 3.

We compared our updated mid-transit time uncertainties and orbital period uncertainties to those most recently published in prior studies. Our measurements reduce Qatar-4 b’s mid-transit time uncertainty by 36.4% and its orbital period uncertainty by 65.0% relative to the most recently published values (Kokori *et al.* 2023). HAT-P-18 b’s mid-transit time uncertainty was reduced slightly by 4.35% when compared to Fu *et al.* (2022), a study that utilized an observation collected using JWST Near Infrared Imager and Slitless Spectrograph single object slitless spectroscopy (NIRISS/SOSS) to characterize the planet’s atmosphere and present an updated ephemeris. The orbital period uncertainty was reduced by 77.4% compared to the most recently published value (Kokori *et al.* 2023). Finally, CoRoT-1 b’s mid-transit uncertainty was reduced by 17.5% and its orbital period uncertainty by 16.9% relative to those presented in Ivshina and Winn (2022).

In addition to the direct comparisons, we also forward-propagated the mid-transit time uncertainties reported in this study along with previously published mid-transit time uncertainties to a potential start date of the *Ariel* science missions (adopting 2031 January 1), in order to investigate the potential impact our study has on future observations of Qatar-4 b, HAT-P-18 b, and CoRoT-1 b. We calculated the planets’ mid-transit time uncertainties for the future date using Equation 1 which is analytically derived in Zellem *et al.* (2020):

$$\Delta T_{\text{mid}} = (n_{\text{orbit}}^2 \cdot \Delta P^2 + 2n_{\text{orbit}} \cdot \Delta P \Delta T_0 + T_0^2)^{1/2} \quad (1)$$

where n_{orbit} is the number of orbits that will occur before the future date, P is the orbital period of the planet, and T_0 is the

Table 4. Mid-transit times and orbital periods from this work and the most recent previous studies, along with the resulting mid-transit time uncertainties forward propagated to an estimated Ariel mission start date of 2031 January 1 (2462867.50 BJD_{TDB}).

Target	Source	Mid-Transit Time (BJD _{TDB})	Period (days)	Propagated Mid-Transit Time Uncertainty (BJD _{TDB})
Qatar-4 b	This Work	2458919.5838 ± 0.000089	1.80536560 ± 0.00000021	0.00047
	Kokori <i>et al.</i> (2023)	2458919.58363 ± 0.00015	1.80536403 ± 0.00000054	0.0012
HAT-P-18 b	This Work	2459743.85340 ± 0.000022	5.50802957 ± 0.00000012	0.000072
	Fu <i>et al.</i> (2022)*	2459743.853395 ± 0.000023	5.50802941 ± 0.00000053	0.00030
CoRoT-1 b	This Work	2456268.99083 ± 0.000099	1.50896846 ± 0.00000071	0.00033
	Ivshina and Winn (2022)	2456268.99119 ± 0.00012	1.508968772 ± 0.000000083	0.00038

*For HAT-P-18 b, the orbital period was adopted from Kokori *et al.* (2023), as Fu *et al.* (2022) did not report a period.

established mid-transit time. The second term in Equation 1 was dropped since none of the previous studies reported their covariance term. Dropping the covariance term will lead to a slight underestimation of the resulting uncertainty in the mid-transit time. However, because our updated period uncertainties are substantially smaller than previous values, the effect on comparative forward-propagated uncertainties is minimal. We applied this forward propagation both to the mid-transit time uncertainties derived in this study and to the most recently published ephemerides for each target. The values used in the calculations as well as the final results are presented in Table 4.

The results of the forward propagation demonstrate how the updated mid-transit times presented in this study yield lower uncertainties in the propagated mid-transit times with the incorporation of more data. Our results for Qatar-4b yield a 61% smaller uncertainty in the propagated mid-transit time. Similar improvements are found for HAT-P-18b and CoRoT-1b, with reductions of 76% and 13%, respectively.

6. Conclusion

In this study, we presented updated mid-transit times and orbital periods for three hot Jupiters: Qatar-4b, HAT-P-18b, and CoRoT-1b, by integrating data collected from small, ground-based observatories and personal telescopes, unreduced TESS data, and previously published results. We reported an updated mid-transit time of $2458919.5838 \pm 0.000089$ BJD_{TDB} and orbital period of $1.80536560 \pm 0.00000021$ days for Qatar-4b, a mid-transit time of $2459743.85340 \pm 0.000022$ BJD_{TDB} and orbital period of $5.50802957 \pm 0.00000012$ days for HAT-P-18b, and a midtransit time of $2456268.99083 \pm 0.000099$ BJD_{TDB} and orbital period of $1.50896846 \pm 0.00000071$ days for CoRoT-1b. For all three targets, the updated ephemerides demonstrate improved precision compared to previous published values. These improvements demonstrate the continued value of long-term, ground-based monitoring and the importance of integrating multiple data sources in maintaining accurate exoplanet ephemerides.

To assess the long-term impact of these updated ephemerides, we forward-propagated the mid-transit time uncertainties found in this study to a potential start date of the *Ariel* science operations (2031 January 1). The updated ephemerides presented in this study yield smaller propagated mid-transit time uncertainties compared to those derived from previously published ephemerides, underscoring the importance

of regular ephemeris refinement. These improvements are particularly relevant for hot Jupiters, whose short orbital periods cause uncertainties to accumulate rapidly and can otherwise compromise the efficiency of time-critical observations with space-based facilities.

The results of this study highlight the continued value of coordinated, long-term ground-based monitoring programs and demonstrate that ephemeris refinement can be achieved by combining ground-based telescope data, space-based survey data, and previously published results. Citizen science initiatives, such as Exoplanet Watch, play a critical role in maintaining accurate exoplanet ephemerides, helping to minimize the temporal and financial constraints of using large ground-based and space-based observatories.

7. Acknowledgements

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This work is supported by the National Science Foundation (NSF) under grant #IUSE 2121225.

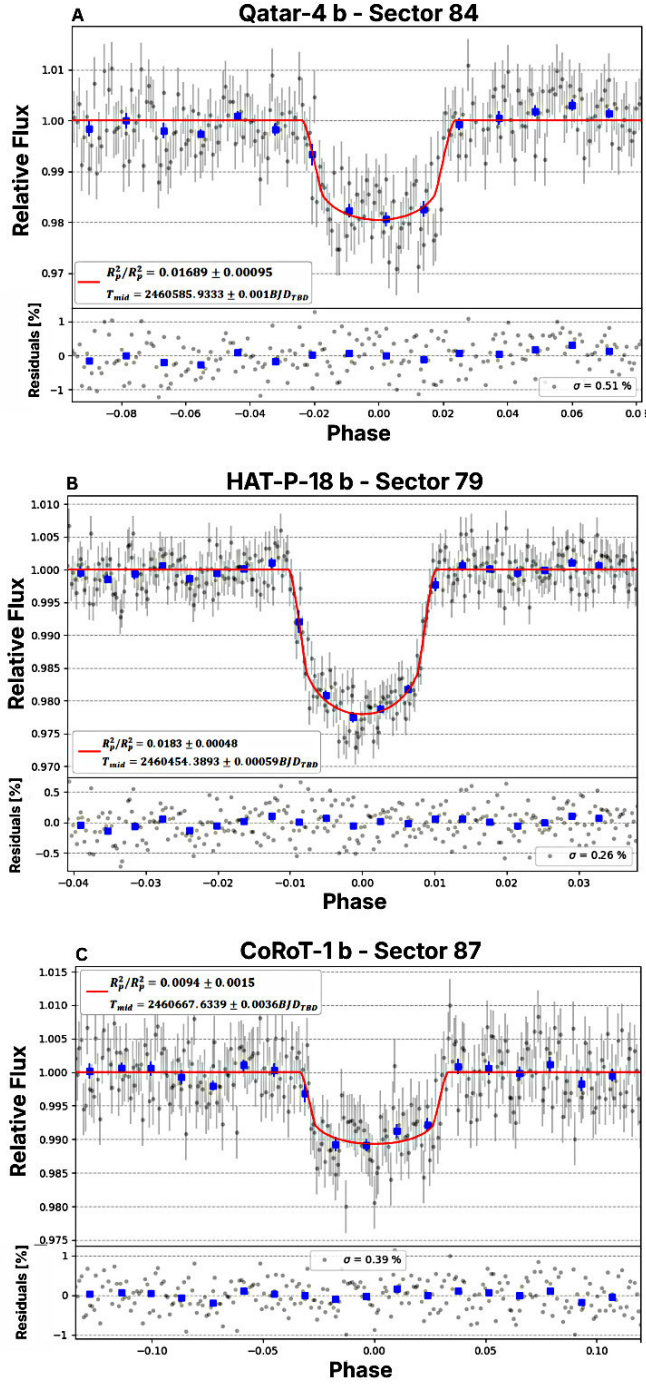


Figure 3. Example light curves reduced using TESS data for each target. Qatar-4 b (A) was observed on 2024-10-02, HAT-P-18 b (B) was observed on 2024-05-23, and CoRoT-1 b (C) was observed on 2024-12-23.

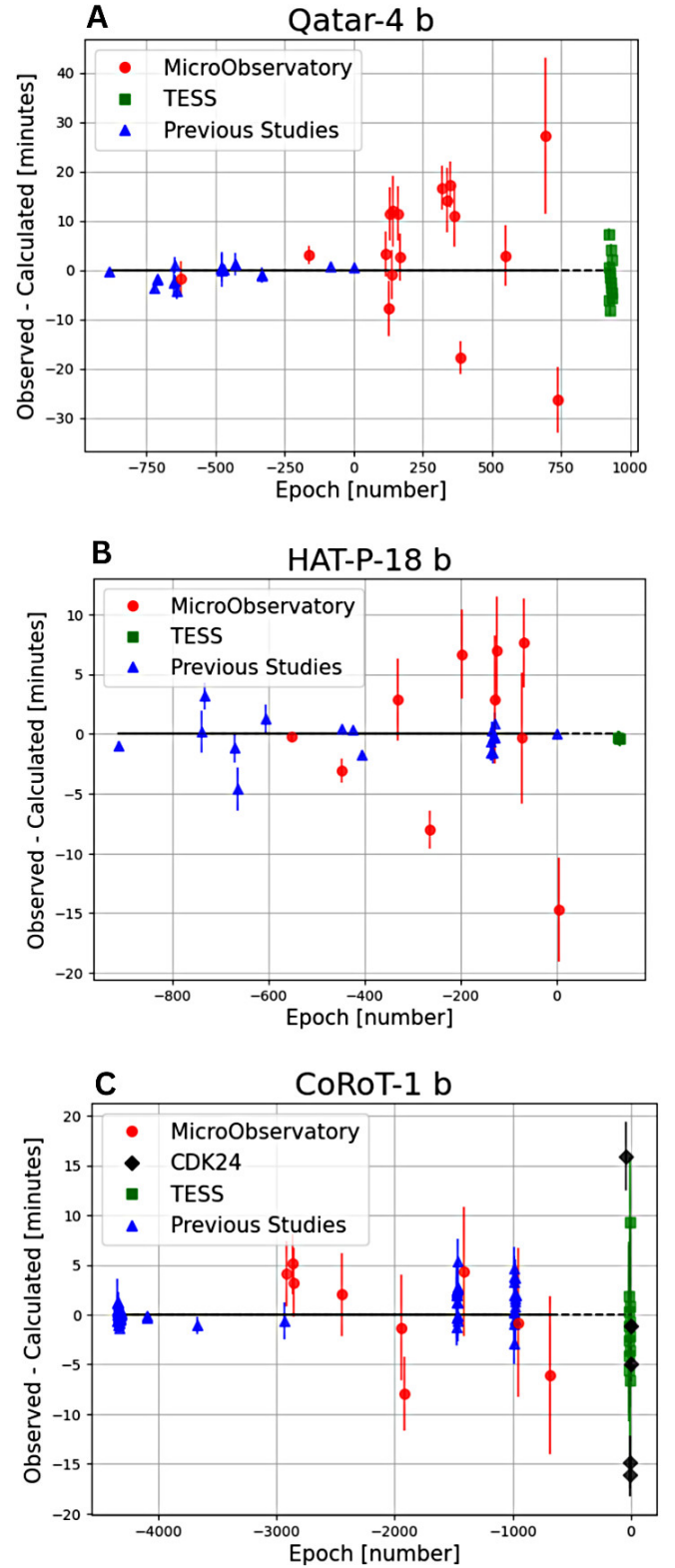


Figure 4. O-C plots for Qatar-4 b (A), HAT-P-18 b (B), and CoRoT-1 b (C) using ground-based and TESS data as well as previously published values. The priors used for (A) were $T_0 = 2458919.58363 \pm 0.00015 \text{ BJD}_{\text{TDB}}$ and $P = 1.80536403 \pm 0.00000054 \text{ days}$, the priors used for (B) were $T_0 = 2459743.853395 \pm 0.000023 \text{ BJD}_{\text{TDB}}$ and $P = 5.5080232 \pm 0.0000056 \text{ days}$, and the priors used for (C) $T_0 = 2456268.99119 \pm 0.00012 \text{ BJD}_{\text{TDB}}$ and $P = 1.508968772 \pm 0.000000083 \text{ days}$.

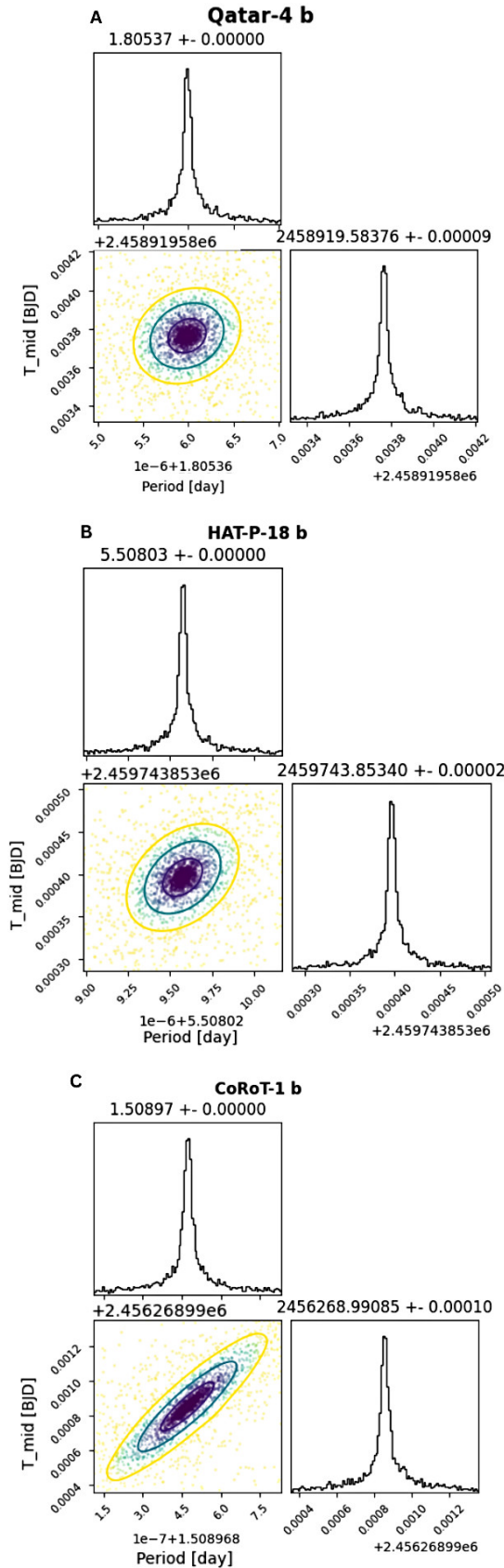


Figure 5. The posterior plot distributions for our newly calculated mid-transit times and orbital periods for Qatar-4 b (A), HAT-P-18 b (B), and CoRoT-1 b (C).

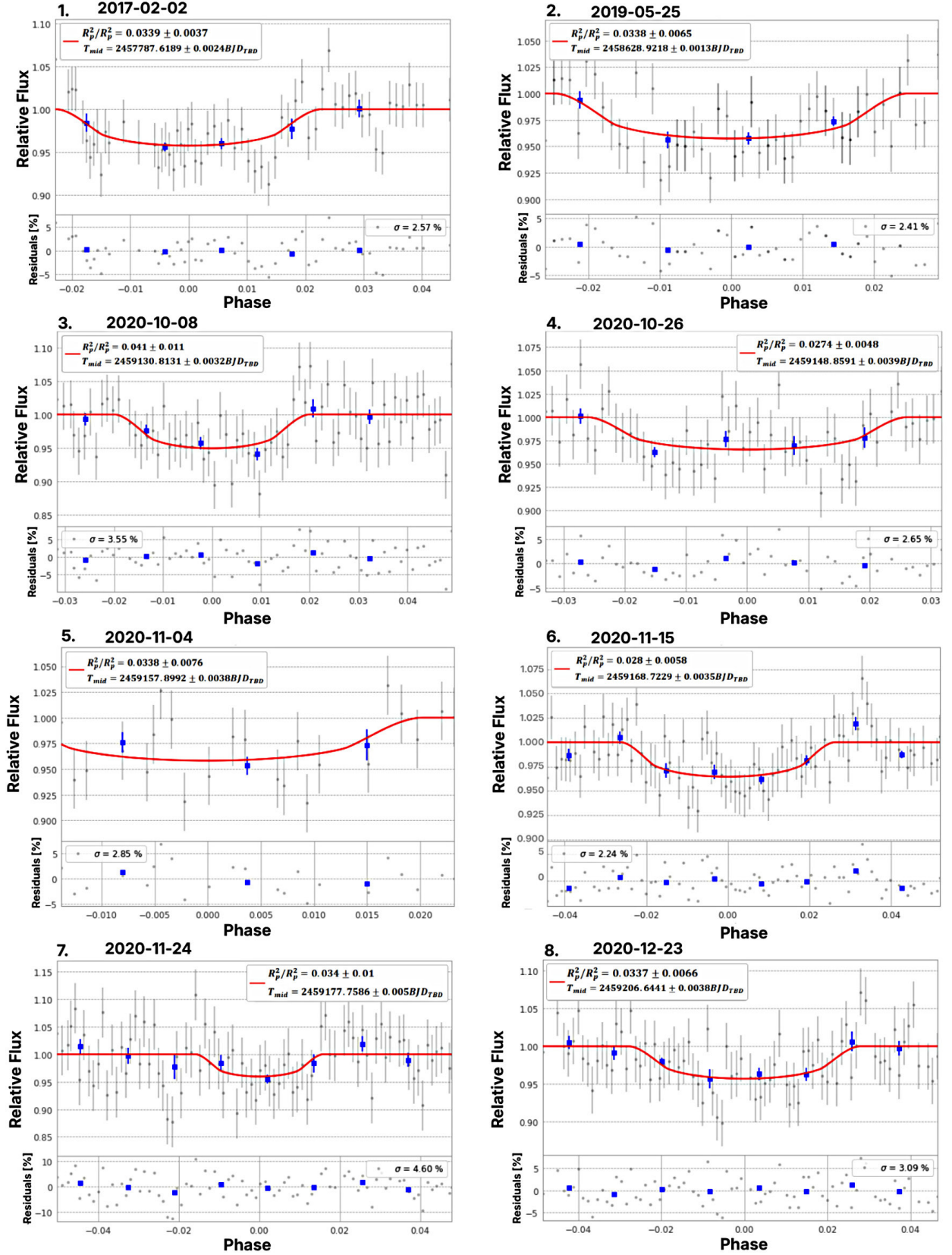
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¹ NASA (2026): <https://science.nasa.gov/citizen-science/exoplanet-watch/exoplanet-watch-overview>

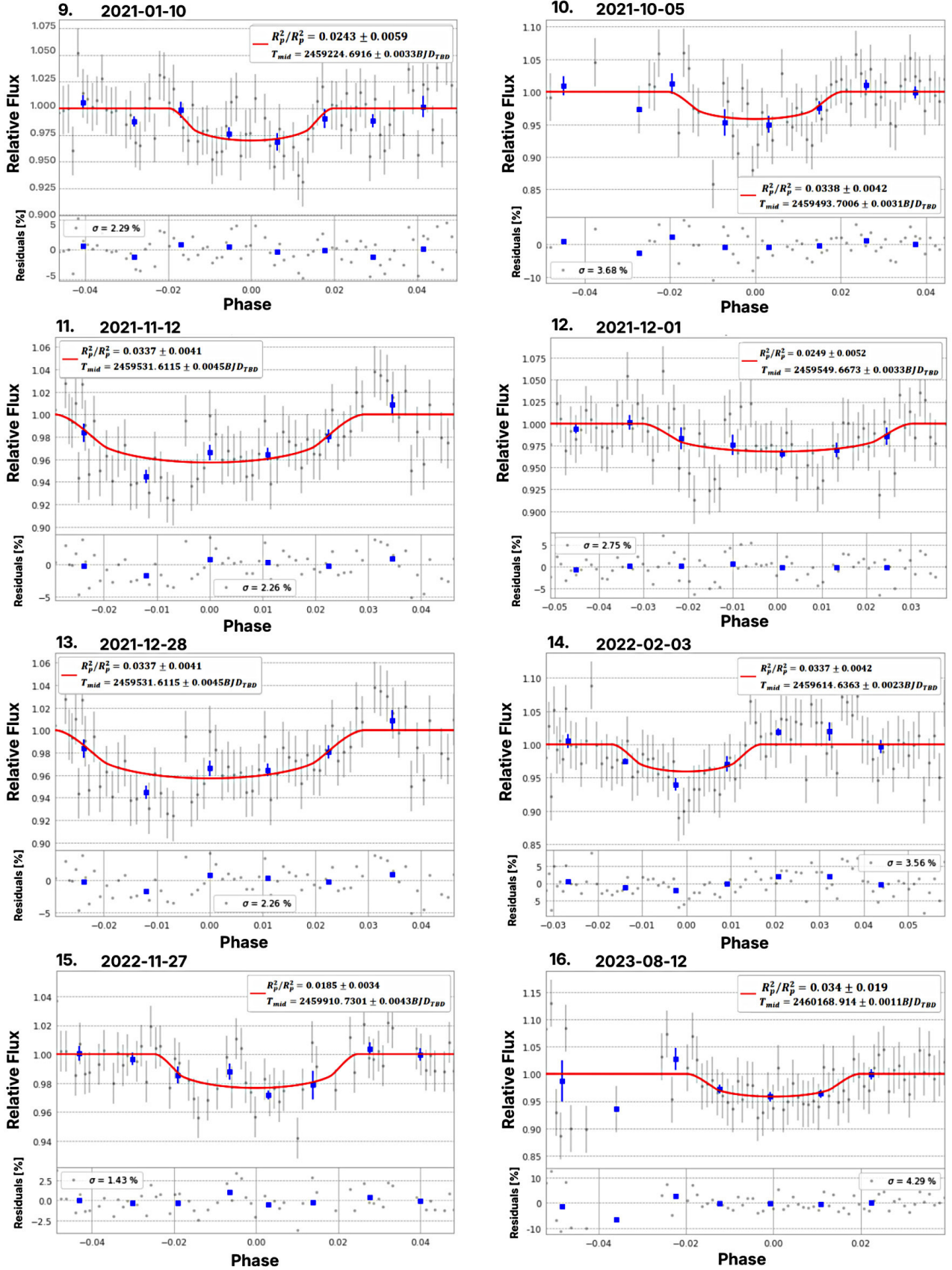
Appendix A: Significant detections of Qatar-4b, HAT-P-18b, and CoRoT-1b, reduced using ground-based data

Qatar-4 b



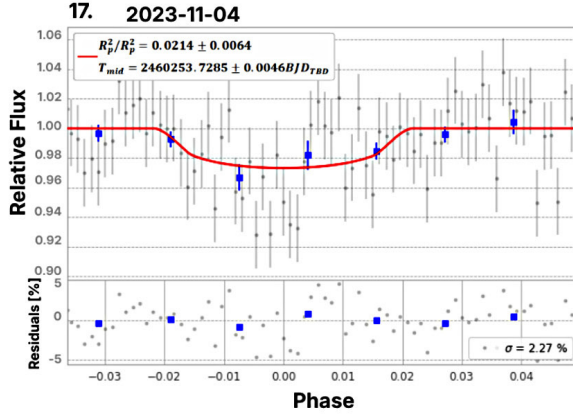
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Appendix A: Significant detections of Qatar-4b, HAT-P-18b, and CoRoT-1b, reduced using ground-based data, cont.

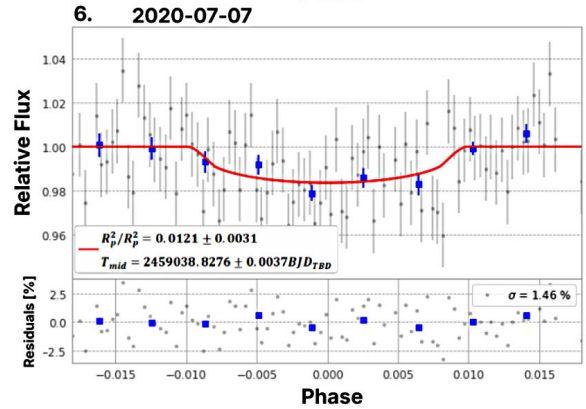
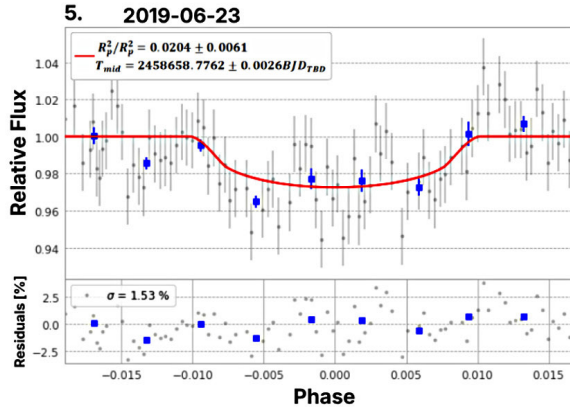
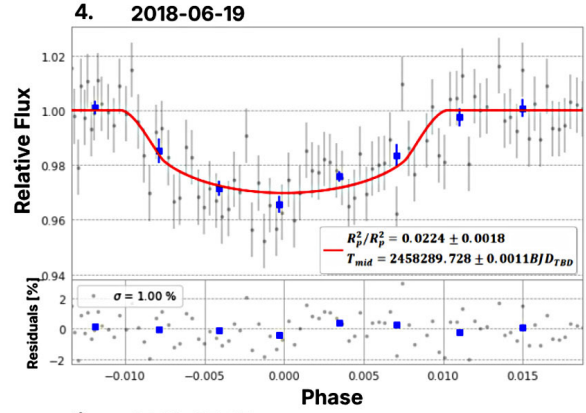
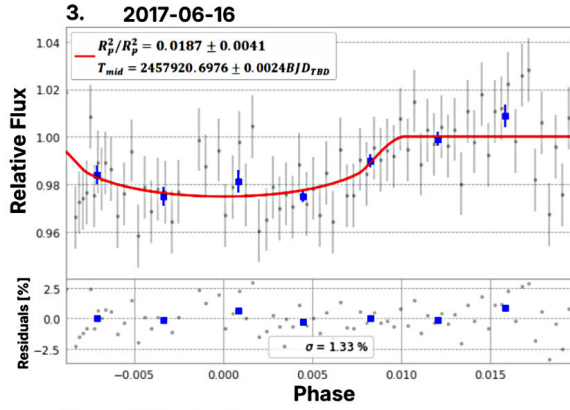
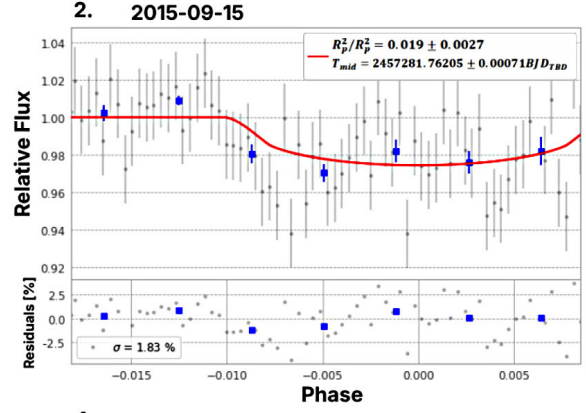
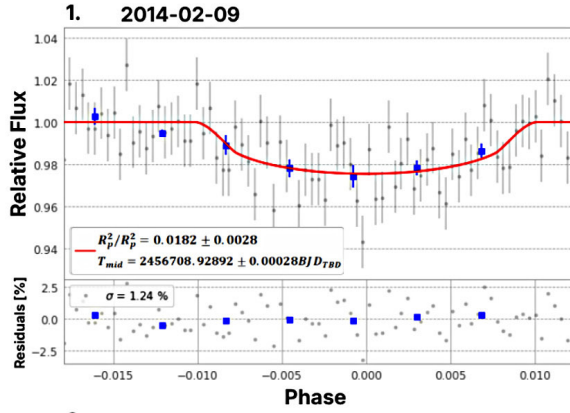


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Appendix A: Significant detections of Qatar-4 b, HAT-P-18 b, and CoRoT-1 b, reduced using ground-based data, cont.

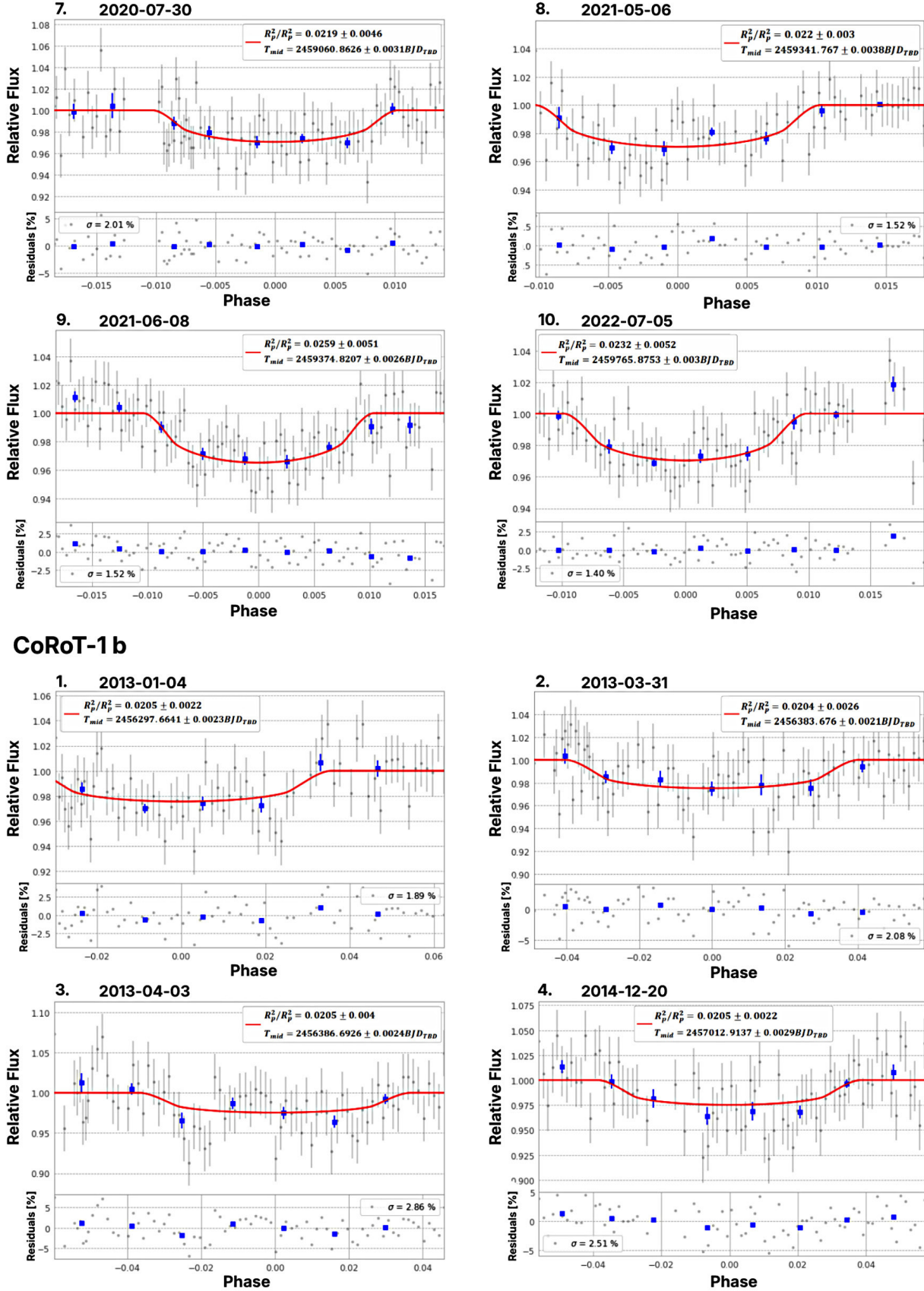


HAT-P-18 b



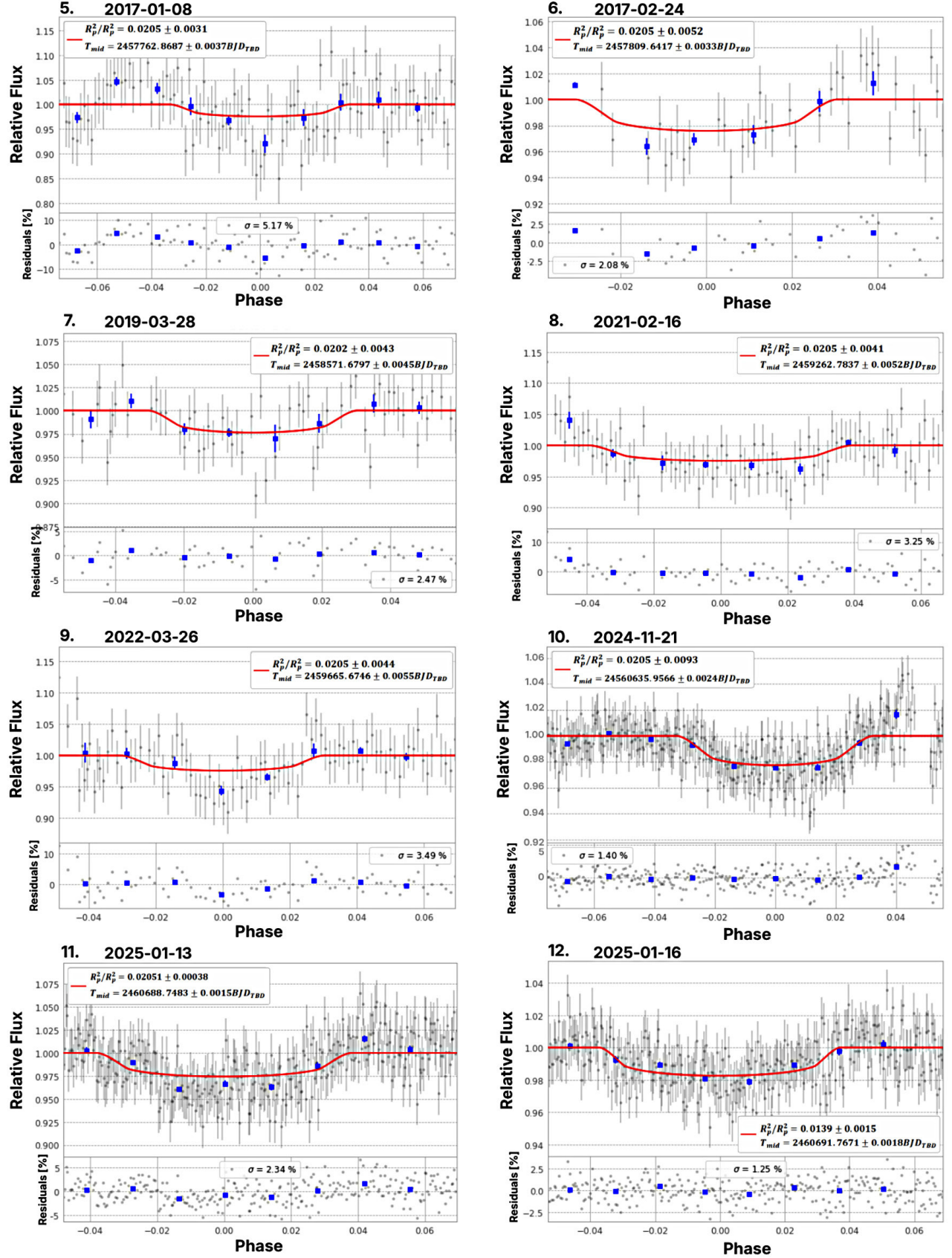
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Appendix A: Significant detections of Qatar-4b, HAT-P-18b, and CoRoT-1 b, reduced using ground-based data, cont.



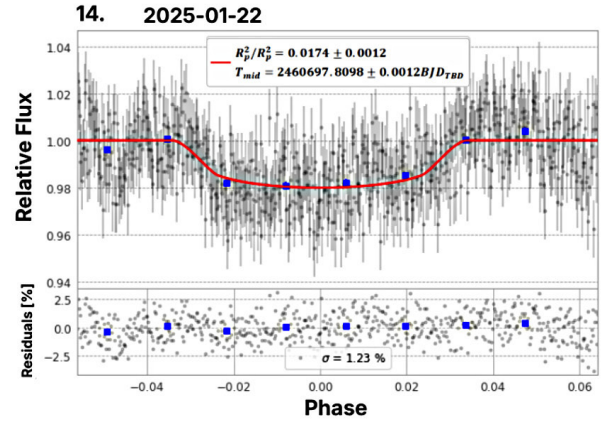
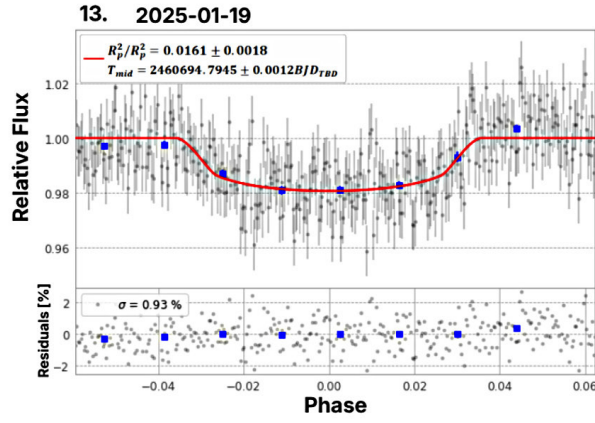
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Appendix A: Significant detections of Qatar-4 b, HAT-P-18 b, and CoRoT-1 b, reduced using ground-based data, cont.



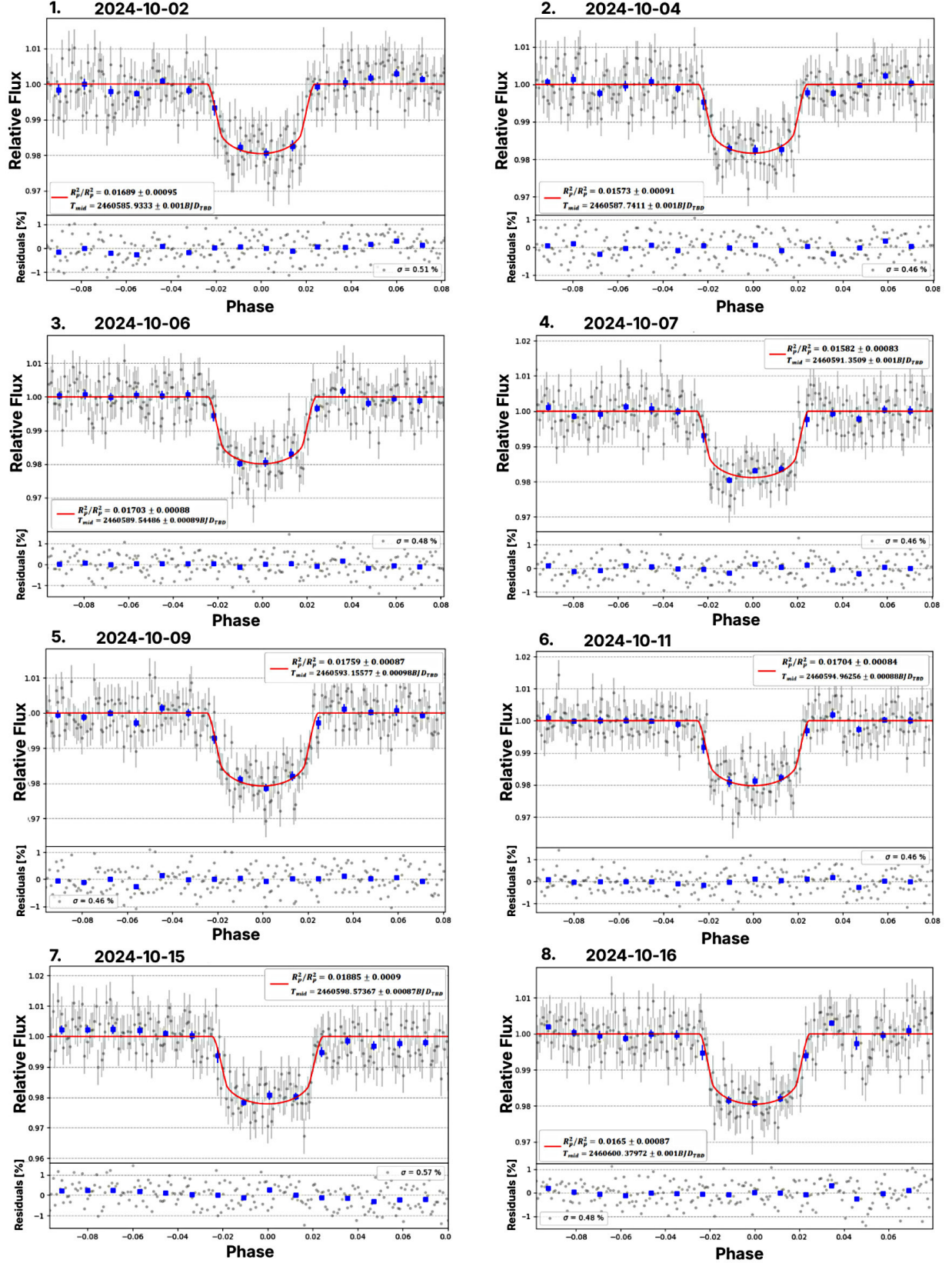
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Appendix A: Significant detections of Qatar-4 b, HAT-P-18 b, and CoRoT-1 b, reduced using ground-based data, cont.



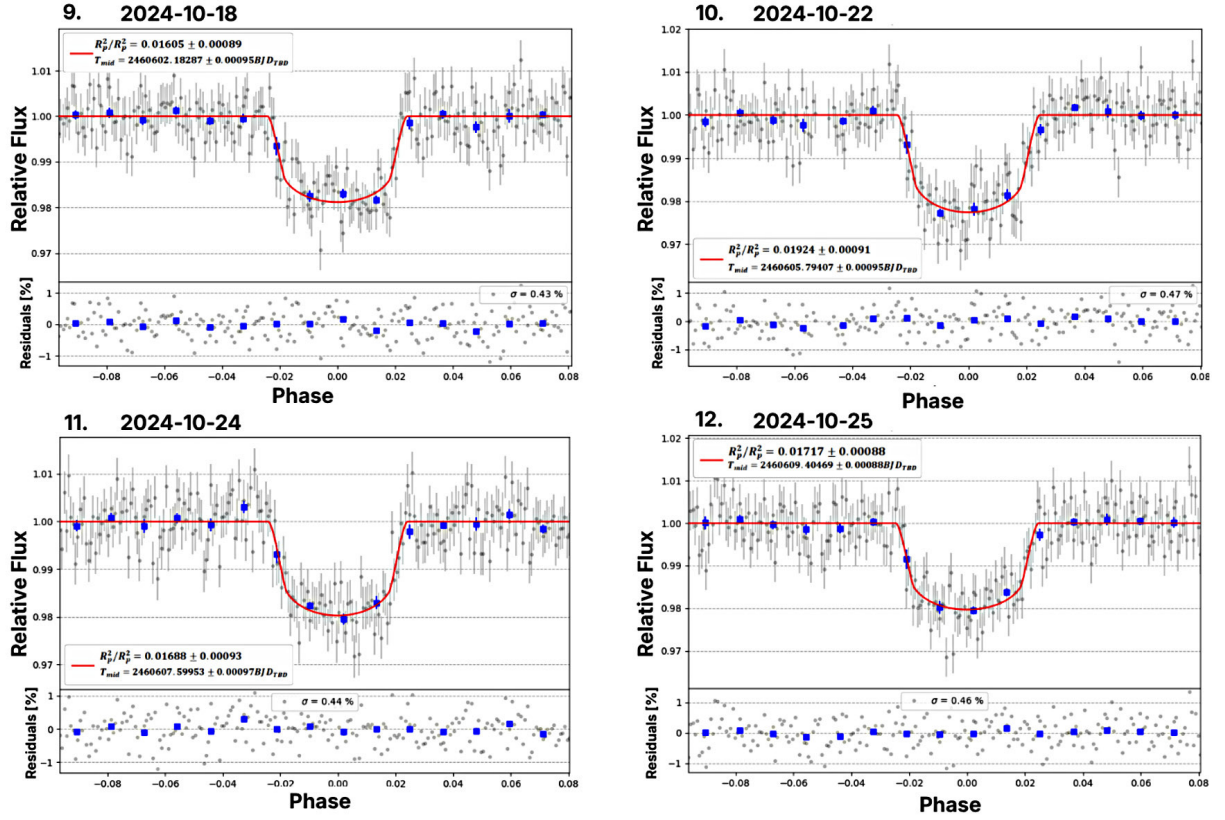
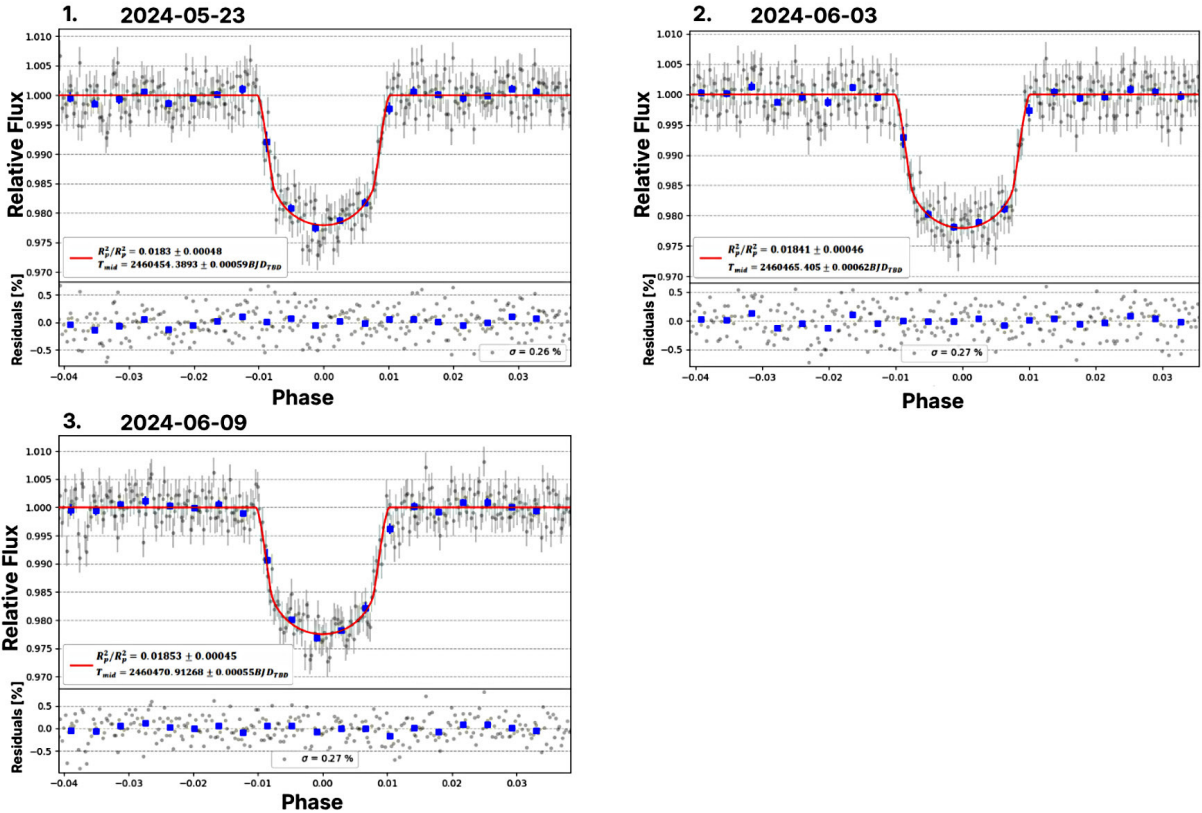
Appendix B: Significant detections of Qatar-4b, HAT-P-18b, and CoRoT-1 b, reduced using TESS data

Qatar-4 b



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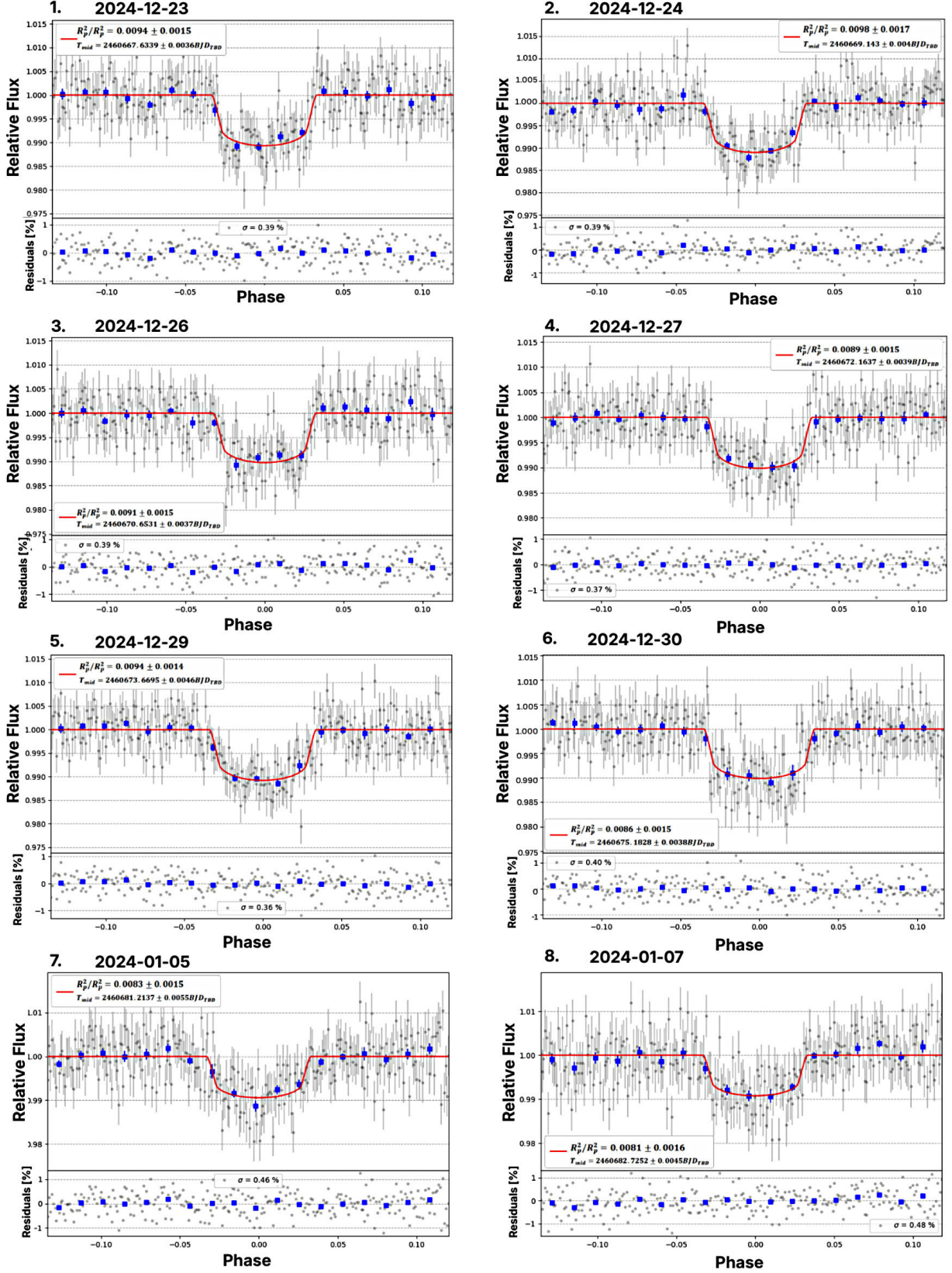
Appendix B: Significant detections of Qatar-4b, HAT-P-18b, and CoRoT-1 b, reduced using TESS data, cont.

**HAT-P-18 b**

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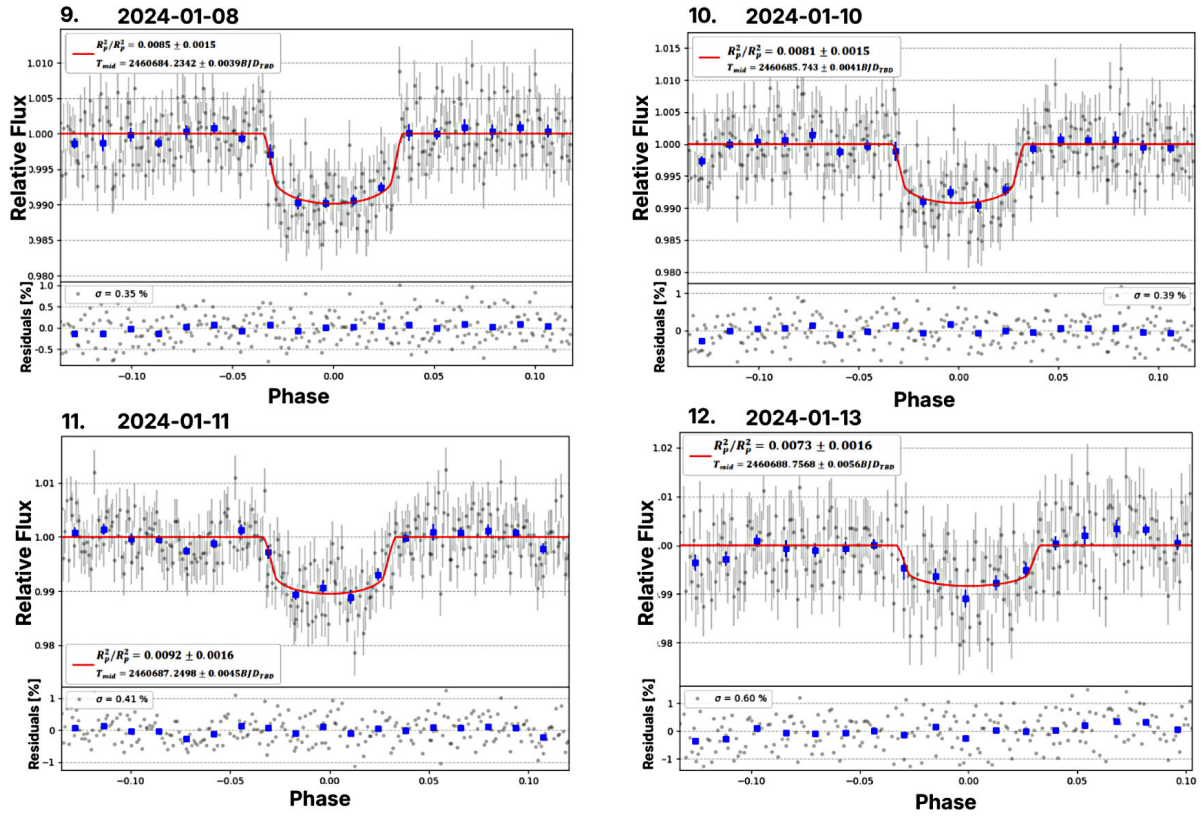
Appendix B: Significant detections of Qatar-4 b, HAT-P-18 b, and CoRoT-1 b, reduced using TESS data, cont.

CoRoT-1 b



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Appendix B: Significant detections of Qatar-4b, HAT-P-18b, and CoRoT-1 b, reduced using TESS data, cont.



Appendix C: Prior solutions included in the O–C plots for Qatar-4 b, HAT-P-18 b, and CoRoT-1 b (Figure 4)

Table C1. Prior solutions included in the O–C plots for Qatar-4 b, HAT-P-18 b, and CoRoT-1 b (Figure 4).

<i>Target</i>	<i>Mid-Transit Time (BJD_{TDB})</i>	<i>Reference</i>
Qatar-4 b	2457323.64130 ± 0.0004895	Ivshina and Winn (2022) fit of Wang <i>et al.</i> (2021)
	2457617.91334 ± 0.0005241	Ivshina and Winn (2022) fit of Wang <i>et al.</i> (2021)
	2457637.77349 ± 0.0005464	Ivshina and Winn (2022) fit of Wang <i>et al.</i> (2021)
	2457637.77361 ± 0.00046	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019) and Alsubai <i>et al.</i> (2017)
	2457744.28950 ± 0.00164	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2457753.31672 ± 0.00074	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2457753.31884 ± 0.00115	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2457762.34209 ± 0.00125	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458049.39801 ± 0.00058	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458058.42459 ± 0.00235	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458058.42511 ± 0.00203	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458071.06228 ± 0.0007135	Ivshina and Winn (2022) fit of Wang <i>et al.</i> (2021)
	2458143.27752 ± 0.00082	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458143.27761 ± 0.00159	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458316.59098 ± 0.000516	Ivshina and Winn (2022) fit of Wang <i>et al.</i> (2021)
	2458316.59101 ± 0.00103	Ivshina and Winn (2022) fit of Mallonn <i>et al.</i> (2019)
	2458767.93317 ± 0.00014	Kokori <i>et al.</i> (2022)
	2458919.58363 ± 0.00015	Kokori <i>et al.</i> (2023)
HAT-P-18 b	2454715.02174 ± 0.00020	Hartman <i>et al.</i> (2011)
	2457408.449133 ± 0.000081	Kokori <i>et al.</i> (2023)
	2459743.853395 ± 0.000023	Fu <i>et al.</i> (2022)
	2459033.31735 ^{+0.00021} _{-0.00022}	Patel and Espinoza (2022)
	2457276.25646 ± 0.00010	Kokori <i>et al.</i> (2022)
	2457507.59219566 ^{+0.00019400} _{-0.00018100}	Kirk <i>et al.</i> (2017)
	2455673.41967 ± 0.00124	Ivshina and Winn (2022) fit of Seeliger <i>et al.</i> (2015)
	2455706.46993 ± 0.0008	Ivshina and Winn (2022) fit of Seeliger <i>et al.</i> (2015)
	2456053.47276 ± 0.00084	Ivshina and Winn (2022) fit of Seeliger <i>et al.</i> (2015)
	2456086.51856 ± 0.00125	Ivshina and Winn (2022) fit of Seeliger <i>et al.</i> (2015)
	2456411.49638 ± 0.00084	Ivshina and Winn (2022) fit of Seeliger <i>et al.</i> (2015)
	2458989.25287 ± 0.0006096	Ivshina and Winn (2022)
	2458994.76030 ± 0.0004839	Ivshina and Winn (2022)
	2459005.77761 ± 0.0005205	Ivshina and Winn (2022)
	2459011.28525 ± 0.0007245	Ivshina and Winn (2022)
	2459016.79238 ± 0.0006163	Ivshina and Winn (2022)
	2459027.80945 ± 0.0006292	Ivshina and Winn (2022)
	2459033.31820 ± 0.0006397	Ivshina and Winn (2022)
CoRoT-1 b	2454138.32761 ± 0.00047	Ivshina and Winn (2022) fit of Bean, (2009)
	2454139.83712 ± 0.00059	Ivshina and Winn (2022) fit of Bean, (2009)
	2454141.34485 ± 0.00062	Ivshina and Winn (2022) fit of Bean, (2009)
	2454142.85425 ± 0.00039	Ivshina and Winn (2022) fit of Bean, (2009)
	2454144.36411 ± 0.00163	Ivshina and Winn (2022) fit of Bean, (2009)
	2454145.87255 ± 0.00042	Ivshina and Winn (2022) fit of Bean, (2009)
	2454147.38076 ± 0.00048	Ivshina and Winn (2022) fit of Bean, (2009)
	2454148.88942 ± 0.00038	Ivshina and Winn (2022) fit of Bean, (2009)
	2454150.39899 ± 0.00026	Ivshina and Winn (2022) fit of Bean, (2009)
	2454151.90798 ± 0.00045	Ivshina and Winn (2022) fit of Bean, (2009)
	2454153.41661 ± 0.00041	Ivshina and Winn (2022) fit of Bean, (2009)
	2454154.92615 ± 0.00035	Ivshina and Winn (2022) fit of Bean, (2009)
	2454156.43527 ± 0.00026	Ivshina and Winn (2022) fit of Bean, (2009)
	2454157.94481 ± 0.00073	Ivshina and Winn (2022) fit of Bean, (2009)
	2454159.4532 ± 0.0001	Barge <i>et al.</i> (2008)
	2454159.45331 ± 0.0005	Ivshina and Winn (2022) fit of Bean, (2009)
	2454160.96252 ± 0.00029	Ivshina and Winn (2022) fit of Bean, (2009)
	2454162.47066 ± 0.00045	Ivshina and Winn (2022) fit of Bean, (2009)
	2454163.97926 ± 0.00044	Ivshina and Winn (2022) fit of Bean, (2009)
	2454165.48852 ± 0.00047	Ivshina and Winn (2022) fit of Bean, (2009)
	2454166.99747 ± 0.00054	Ivshina and Winn (2022) fit of Bean, (2009)
	2454168.50619 ± 0.00028	Ivshina and Winn (2022) fit of Bean, (2009)
	2454170.01596 ± 0.00020	Ivshina and Winn (2022) fit of Bean, (2009)

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Table C1. Prior solutions included in the O–C plots for Qatar-4 b, HAT-P-18 b, and CoRoT-1 b (Figure 4), cont.

Target	Mid-Transit Time (BJD_{TDB})	Reference
CoRoT-1 b	2454171.52372 $\pm$ 0.00028	Ivshina and Winn (2022) fit of Bean, (2009)
	2454173.03365 $\pm$ 0.00026	Ivshina and Winn (2022) fit of Bean, (2009)
	2454174.54240 $\pm$ 0.00033	Ivshina and Winn (2022) fit of Bean, (2009)
	2454176.05183 $\pm$ 0.00026	Ivshina and Winn (2022) fit of Bean, (2009)
	2454177.56026 $\pm$ 0.00023	Ivshina and Winn (2022) fit of Bean, (2009)
	2454179.06932 $\pm$ 0.00029	Ivshina and Winn (2022) fit of Bean, (2009)
	2454180.57844 $\pm$ 0.00025	Ivshina and Winn (2022) fit of Bean, (2009)
	2454183.59609 $\pm$ 0.00024	Ivshina and Winn (2022) fit of Bean, (2009)
	2454185.10512 $\pm$ 0.00031	Ivshina and Winn (2022) fit of Bean, (2009)
	2454186.61471 $\pm$ 0.00031	Ivshina and Winn (2022) fit of Bean, (2009)
	2454188.12338 $\pm$ 0.0005	Ivshina and Winn (2022) fit of Bean, (2009)
	2454189.63227 $\pm$ 0.00038	Ivshina and Winn (2022) fit of Bean, (2009)
	2454191.14143 $\pm$ 0.00026	Ivshina and Winn (2022) fit of Bean, (2009)
	2454524.6231 $\pm$ 0.0002	Pont <i>et al.</i> (2010)
	2454524.62324 $\pm$ 0.00013	Ivshina and Winn (2022) fit of Gillon <i>et al.</i> (2009)
	2455162.91621 $\pm$ 0.00059	Ivshina and Winn (2022) fit of Sada <i>et al.</i> (2012)
	2456268.99040 $\pm$ 0.0013	Ivshina and Winn (2022) fit of Turner <i>et al.</i> (2016)
	2458469.06821 $\pm$ 0.0012333	Ivshina and Winn (2022)
	2458470.57717 $\pm$ 0.0013167	Ivshina and Winn (2022)
	2458472.08565 $\pm$ 0.0014233	Ivshina and Winn (2022)
	2458473.59354 $\pm$ 0.0014722	Ivshina and Winn (2022)
	2458475.10442 $\pm$ 0.0014377	Ivshina and Winn (2022)
	2458476.61084 $\pm$ 0.0013014	Ivshina and Winn (2022)
	2458479.63123 $\pm$ 0.0019923	Ivshina and Winn (2022)
	2458481.13813 $\pm$ 0.0013734	Ivshina and Winn (2022)
	2458482.64751 $\pm$ 0.0014385	Ivshina and Winn (2022)
	2458484.16026 $\pm$ 0.001535	Ivshina and Winn (2022)
	2458485.66746 $\pm$ 0.0014853	Ivshina and Winn (2022)
	2458487.17535 $\pm$ 0.001727	Ivshina and Winn (2022)
	2458488.68526 $\pm$ 0.0014447	Ivshina and Winn (2022)
	2459202.42349 $\pm$ 0.001405	Ivshina and Winn (2022)
	2459203.93381 $\pm$ 0.0013578	Ivshina and Winn (2022)
	2459205.44363 $\pm$ 0.0010803	Ivshina and Winn (2022)
	2459206.95508 $\pm$ 0.0014073	Ivshina and Winn (2022)
	2459208.46275 $\pm$ 0.0011239	Ivshina and Winn (2022)
	2459209.97053 $\pm$ 0.0014639	Ivshina and Winn (2022)
	2459211.48163 $\pm$ 0.0013722	Ivshina and Winn (2022)
	2459212.99149 $\pm$ 0.0015417	Ivshina and Winn (2022)
	2459216.00736 $\pm$ 0.0010382	Ivshina and Winn (2022)
	2459217.51579 $\pm$ 0.0014488	Ivshina and Winn (2022)
	2459219.02554 $\pm$ 0.0012323	Ivshina and Winn (2022)
	2459220.53278 $\pm$ 0.0018204	Ivshina and Winn (2022)
	2459222.04305 $\pm$ 0.0013553	Ivshina and Winn (2022)
	2459223.55080 $\pm$ 0.0016507	Ivshina and Winn (2022)
	2459225.06259 $\pm$ 0.0013206	Ivshina and Winn (2022)
	2459226.57034 $\pm$ 0.0013817	Ivshina and Winn (2022)

A Photometric Study of the Near-Contact Binary CE Pegasi

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Abstract Presented are multi-band photometry for the eclipsing binary CE Pegasi observed on 17 nights in August and September 2025. A photometric light curve solution was derived from the Wilson-Devinny program using observations from five passbands (B, V, g', r', and i'). The results indicate that CE Peg is a semidetached near-contact binary with a mass ratio of $q = 0.315$ and an orbital inclination of 83° . The cooler K6 secondary star fills its Roche lobe and the F0 primary nearly so with a filling factor of 96.8%. The period analysis using 35 minima timings, spanning 30 years, found an unchanging orbital period of 0.6420292 d.

1. Introduction

The variability of CE Peg (2MASS J21404695+2509153, HV 6156, NSVS 8776019, GSC 02193-01640) was discovered by Shapley and Hughes (1940) while searching for variable stars at high galactic latitudes. They classified this star as an eclipsing binary with an orbital period of 0.6420 day and a visual magnitude range of 13.2–14.2. Several more recent low cadence surveys have also identified its eclipsing binary light variations: The All-Sky Automated Survey, the Northern Sky Variability Survey, and the All-Sky Automated Survey for Supernovae (ASAS; Pojmański 2002; NSVS, Woźniak *et al.* 2004; ASAS-SN, Jayasinghe *et al.* 2018). Using the NSVS database Hoffman *et al.* (2008) classified CE Peg as a β Lyrae eclipsing binary. The light curves of β Lyrae stars display unequal primary and secondary minima and are continuously changing in brightness between eclipses due to ellipsoidal variations. Their evolutionary states range from two detached main sequence stars in tight orbits, to semidetached binaries with mass transfer, to near-contact binaries (NCB) with a highly evolved secondary and less evolved primary. Detailed photometric analysis and period studies of β Lyrae systems can provide valuable insight into understanding the physical characteristics of these binaries.

In this paper high cadence multi-band photometric observations of CE Peg are presented in section 2. An orbital period analysis and updated ephemerides are presented in section 3. Photometric solutions using the 2015 version of the Wilson-Devinny (WD) program are presented in section 4. Discussion of the results is presented in section 5 and conclusions in section 6.

2. Photometric observations

Photometric observations were acquired in August and September 2025 using the Waffelow Creek Observatory's 0.36-m Ritchey-Chrétien telescope (<https://obs.ejmj.net>; see the Table 1 Observation Log). The telescope was equipped with a Johnson-Sloan multicolor QHY268M camera that gives a $29' \times 19'$ field-of-view. VOYAGER software was used for automated image acquisition and DONUTS for improved photometric precision (Voyager 2024; McCormac 2013). DONUTS is an autoguiding algorithm that fixes the stars on the same sensor pixels for each image acquired throughout

the observing campaign. Observations were taken in five passbands, Johnson B and V, and Sloan g', r', and i'. The light images were calibrated using bias, dark, and flat frames. MIRA software was used for image calibration and differential aperture photometry (Mirametries 2024). The Figure 1 chart shows the locations of the comparison and check stars and Table 2 lists their coordinates, and standard magnitudes from the AAVSO Photometric All-Sky Survey database (APASS; Henden *et al.* 2015). The instrumental magnitudes of each observation were converted to standard magnitudes and the Heliocentric Julian Date (HJD) to orbital phase (ϕ). Figure 2 shows the observed light curves with orbital phase plotted from -0.6 to 0.6 with negative phase defined as $(\phi-1)$. The light curve properties for each passband are listed in Table 3. The check star magnitudes were plotted each night with no significant variability detected (see bottom panel of Figure 2). The check star standard deviations ranged from 3 to 5 mmag. The flatness of the secondary minimum indicates a total eclipse with an approximate duration of 34 minutes. All the observations can be accessed through the AAVSO International Database (Kafka 2017).

3. Period analysis and ephemerides

A literature search located 31 minima timings for this star with an additional 4 timings determined from the new observations using the Kwee and van Woerden (1956) method. An initial linear ephemeris was formed from the earliest primary minima timing available and the orbital period taken from the AAVSO Variable Star Index (VSX; Watson *et al.* 2014):

$$\text{HJD Min I} = 2450030.372 (3) + 0.64202 \text{ E.} \quad (1)$$

The timings and their errors (if available) are collected in Table 4. Included in this table are the cycle numbers and the difference between the observed and the predicted minima times (O–C) calculated from Equation 1. An updated linear ephemeris was computed by least-squares:

$$\text{HJD Min I} = 2460923.6816 (2) + 0.6420291(9) \text{ E.} \quad (2)$$

This ephemeris was used to phase the observations. Figure 3 shows the residuals from Equation 1 (top panel) and the best-fit linear line of Equation 2. The residuals from the Equation 2 fit

are shown in the bottom panel of Figure 3. The residuals give little indication of a secular or a cyclic period change in the 30 years covered by the minima timings.

4. Light curve analysis

4.1. Color, temperature, spectral type, absolute magnitude, and luminosity

The photometric observations for each color were binned in both phase and magnitude using a phase width of 0.01. The observations falling into each bin were averaged in both phase and magnitude. The resulting 100 normal points for each color were used for light curve modeling. The binned Johnson B and V magnitudes were linearly interpolated to form (B–V) color indices. The mean observed color over the full phase range is $(B-V) = 0.564 \pm 0.006$. The color excess, obtained from dust maps based on Pan-STARRS1 and 2MASS photometry and Gaia parallaxes, was used to correct for interstellar reddening (Green *et al.* 2018). The color excess is $E(B-V) = 0.040 \pm 0.006$. To correct for extinction in the V passband, the extinction-to-reddening ratio of $A_V/E(B-V)$ gives a value of $A_V = 0.123 \pm 0.018$.

The LAMOST Low-Resolution Spectroscopic Survey (DR11) obtained a spectrum of CE Peg on November 13, 2020 (Figure 4). The LAMOST pipeline found an effective temperature and spectral type, $T_{\text{eff}} = 7063 \pm 100$ K and F0. This is in good agreement with a value derived from Gaia DR3 data, $T_{\text{eff}} = 7079 \pm 97$ K (2024 SHBoost Catalog: Khalatyan *et al.* 2024). The LAMOST value was assigned to the primary star for light curve modeling.

The absolute visual magnitude, $M_V = 2.51 \pm 0.01$, was determined from the mean-apparent magnitude corrected for extinction, $m_V = 12.77 \pm 0.02$, and the Gaia DR3 distance for this star, $d = 1107 \pm 14$ pc (Gaia Collaboration *et al.* 2023). Combining the computed absolute magnitude with the Sun's absolute magnitude gives a visual luminosity of $L_{V\odot} = 8.0 \pm 0.2$.

4.2. Synthetic light curve modeling

The light curves of CE Peg are best described as β Lyrae type. The continuous light variation indicates that the component stars are tidally distorted and the large difference in minima depths suggests a significant temperature difference between the component stars. These light curve properties suggest a semidetached or detached Roche configuration with the stars nearly in contact.

For modeling, the 100 normal points for each light curve were converted to flux with an average of 6 observations per normal point (see section 4.1). BINARY MAKER 3.0 software was used to make the preliminary fits to each light curve (BM3; Bradstreet and Steelman 2002). The stellar and orbital parameters from each BM3 fit were averaged. These parameters were used as the starting inputs for the computation of simultaneous five-color light curve solutions using the WD program (Wilson and Devinney 1971; van Hamme and Wilson 1998). The following WD settings were used for solution iterations:

- Each normal point was assigned a weight equal to the number of observations forming that point

- Radiative treatment—Kurucz model stellar atmospheres
- Effective temperature of primary star fixed at $T_1 = 7063$ K
- Logarithmic limb-darkening coefficients calculated using the method of van Hamme (1993)
- The WD program was set to Mode-2 for detached binaries
- Standard radiative parameters were assigned to the primary star and convective parameters for the secondary star:
 - gravity brightening: $g_1 = 1.0$, $g_2 = 0.32$ (von Zeipel 1924; Lucy 1968)
 - bolometric albedo: $A_1 = 1.0$, $A_2 = 0.5$ (Ruciński 1969)
- Adjustable parameters: inclination (i), mass ratio ($q = M_2 / M_1$), potentials (Ω_1 , Ω_2), temperature of the secondary star (T_2), band-specific luminosity for each wavelength (L), and third light (L_3).

The parameter subscripts 1 and 2 refer to the hotter and cooler component stars, respectively.

For the first WD solution attempt, convective parameters were assigned to both stars. The solution iterations did converge, but the resulting synthetic light curves fit the observed secondary eclipse poorly and both stars exceeded their critical lobes. The primary star's effective temperature is in the region where energy transport in the outer envelope of main sequence stars transitions from convective to radiative. A second attempt using standard radiative parameters for the primary star resulted in a much-improved fit. The solution parameters are shown in column 2 of Table 5. This solution indicates CE Peg is semidetached with the secondary star filling its Roche lobe.

The observed light curves are reasonably symmetric with Max I and Max II nearly the same brightness (see Table 3). The fit between the observed and synthetic light curves was very good except for a small deficit of light between secondary minimum and Max II (see Figure 5). This asymmetry is apparent in each color. This may indicate the presence of a cool spot(s) on the facing hemisphere of the secondary star. Cool spots are not unexpected, given this star's rapid rotation and convective envelope. The BM3 program was used to model this small asymmetry by placing a cool spot on the secondary star. The spot parameters, latitude, longitude, spot size, and temperature factor were adjusted until a good fit was obtained. The best-fit parameters were then incorporated into a new WD model. The final WD solution parameters are shown in column 3 of Table 5. The comparison of the parameter values between the two solutions shows they are essentially the same, except for a 63% reduction in residuals for the spotted model. The top panel of Figure 6 displays the spotted model fits overlaid onto the observed light curves and the middle panel the residuals. The bottom panel shows the WD model color curves overlaid onto the observed (B–V) curves. A graphical presentation of the CE Peg system is shown in Figure 7 (Bradstreet and Steelman 2002). The third-light corrections (L_3) were negligibly small or negative throughout the solution process. The solution mass ratio, $q = 0.3154$, should be well determined, given the total secondary eclipse (Wilson 1978; Terrell and Wilson 2005).

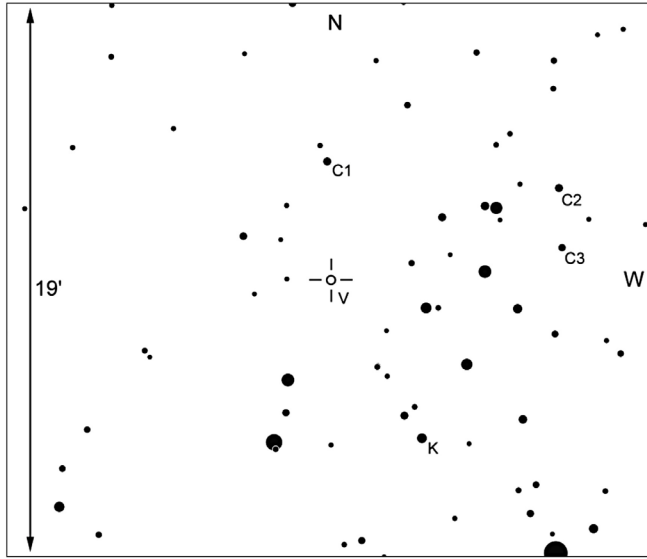


Figure 1. Finder chart for CE Peg (V), comparison (C), and check (K) stars. This chart was generated by the AAVSO Variable Star Plotter (Craig *et al.* 2023).

Table 1. Observation log.

Filter	Dates (2025)	No. Nights	No. Images
B	Aug 24, 25; Sep 2, 3, 4, 10	6	571
V	Aug 24, 25; Sep 2, 3, 4, 10	6	573
g'	Aug 15, 16, 17, 19	4	505
r'	Aug 15, 16, 17, 19	4	511
i'	Sep 11, 12, 15, 16, 23, 25, 26	7	900

Table 2. Standard comparison and check star magnitudes.

System	R.A. (2000) h	Dec. (2000) °	B	V	g'	r'	i'
CE Peg	21.67971	+25.15422	--	--	--	--	--
GSC 02193-01747 (C)	21.67987	+25.22196	13.302	12.639	12.944	12.514	12.403
GSC 02193-00681 (C)	21.67005	+25.20674	13.438	12.686	13.054	12.540	12.393
GSC 02193-01692 (C)	21.66993	+25.17271	13.722	12.981	13.317	12.819	12.679
GSC 02193-01763 (K)	21.67586	+25.06409	12.664	11.996	12.311	11.862	11.747
Mean magnitudes of the K-star observations			12.686 ± 0.004	11.991 ± 0.003	12.314 ± 0.005	11.855 ± 0.004	11.727 ± 0.004

Table 3. Average light curve properties.

	Min I Mag.	Min II Mag.	Δ Mag. Min II – Min I	Max I Mag.	Max II Mag.	Δ Mag. Max II – Max I	Mag. Range Max I – Min I
B	13.933 ±0.006	13.489 ±0.006	-0.444 ±0.009	13.291 ±0.004	13.297 ±0.006	0.006 ±0.007	0.639 ±0.008
V	13.350 ±0.004	12.928 ±0.006	-0.422 ±0.007	12.730 ±0.007	12.740 ±0.006	0.009 ±0.009	0.611 ±0.008
g'	13.621 ±0.004	13.178 ±0.002	-0.442 ±0.005	12.989 ±0.005	12.994 ±0.007	-0.005 ±0.009	0.627 ±0.008
r'	13.270 ±0.005	12.861 ±0.005	-0.410 ±0.011	12.660 ±0.003	12.673 ±0.002	0.013 ±0.011	0.597 ±0.011
i'	13.208 ±0.005	12.822 ±0.006	-0.386 ±0.007	12.616 ±0.003	12.623 ±0.003	0.007 ±0.004	0.586 ±0.005

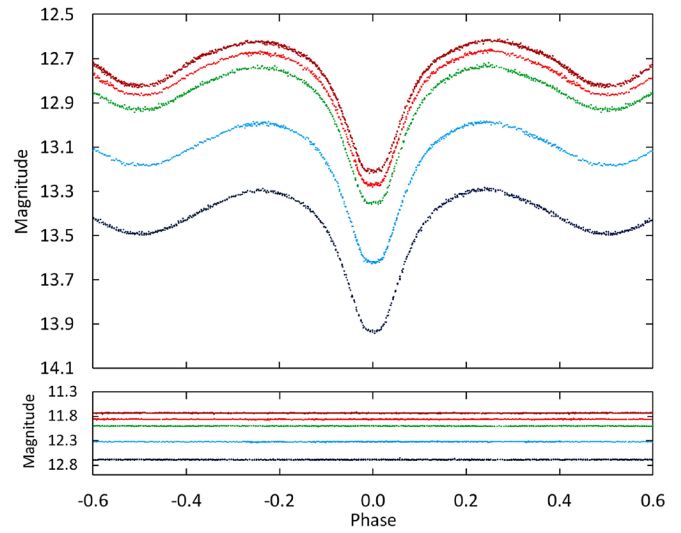


Figure 2. The folded CCD light curves in standard magnitudes. From top to bottom the passbands are i', r', V, g', and B. In the same order, the bottom curves are the check-star magnitudes. Error bars were omitted from the plotted points for clarity.

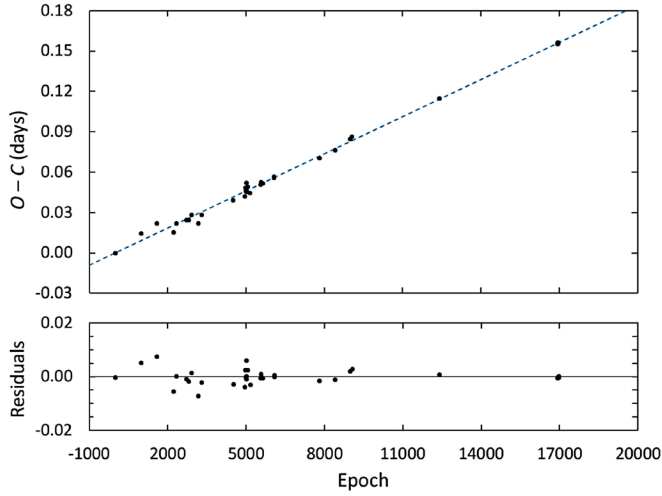


Figure 3. The top panel shows the O–C residuals calculated from the linear ephemeris of Equation 1 (filled circles). The dashed line is the linear best-fit from Equation 2. The bottom panel shows the residuals from the linear fit.

Table 4. Times of minima and O–C residuals.

Type	Epoch HJD 2400000+	Error	Cycle No.	(O–C)	Reference
ccd	50030.3720	0.0031	0.0	0.00000	1
ccd	50660.5290	0.0056	981.5	0.01437	1
ccd	51043.5017	0.0005	1578.0	0.02214	2
ccd	51465.3019	0.0030	2235.0	0.01520	3
ccd	51535.2888	0.0063	2344.0	0.02192	3
ccd	51780.5428	0.0029	2726.0	0.02428	4
ccd	51838.3247	0.0030	2816.0	0.02437	4
ccd	51899.3205	0.0030	2911.0	0.02824	4
ccd	52062.3874	0.0067	3165.0	0.02210	5
ccd	52144.5722	0.0013	3293.0	0.02834	6
ccd	52929.4523	—	4515.5	0.03899	7
ccd	53216.4383	0.0022	4962.5	0.04205	8
ccd	53222.5437	0.0023	4972.0	0.04826	8
ccd	53233.4556	0.0013	4989.0	0.04582	8
ccd	53242.4442	0.0011	5003.0	0.04614	8
ccd	53250.4697	0.0022	5015.5	0.04639	8
ccd	53251.4318	0.0027	5017.0	0.04546	8
ccd	53257.5378	0.0007	5026.5	0.05227	8
ccd	53284.4996	0.0007	5068.5	0.04923	8
ccd	53341.3138	0.0008	5157.0	0.04466	9
ccd	53599.4120	—	5559.0	0.05082	10
ccd	53613.5379	0.0007	5581.0	0.05228	11
ccd	53613.5381	0.0006	5581.0	0.05248	12
ccd	53651.4164	0.0006	5640.0	0.05160	11
ccd	53936.4777	0.0006	6084.0	0.05602	13
ccd	53936.4783	0.0003	6084.0	0.05662	14
ccd	55048.4709	0.0003	7816.0	0.07058	15
ccd	55428.5524	0.0022	8408.0	0.07624	16
ccd	55806.3898	0.0026	8996.5	0.08487	17
ccd	55849.7277	0.0004	9064.0	0.08642	18
ccd	57993.4609	0.0023	12403.0	0.11484	19
ccd	60903.7781	0.0001	16936.0	0.15536	20
ccd	60912.7670	0.0002	16950.0	0.15598	20
ccd	60921.7555	0.0002	16964.0	0.15620	20
ccd	60923.6811	0.0002	16967.0	0.15577	20

References: (1) Šafář and Zejda (2000a); (2) Šafář and Zejda (2000b); (3) Šafář and Zejda (2002); (4) Luboš (2007); (5) Zejda (2004); (6) Diethelm (2001); (7) Hübscher (2005); (8) Hübscher et al. (2005); (9) Diethelm (2005); (10) Le Borgne and Klotz (2006); (11) Hübscher et al. (2006); (12) Zejda (2006); (13) Hübscher and Walter (2007); (14) Hübscher (2007); (15) Hübscher et al. (2010); (16) Hübscher (2011); (17) Hübscher and Lehmann (2012); (18) Diethelm (2012); (19) Pagel (2021); (20) this paper.

Table 5. Results derived from WD light curve modeling.

Parameter	No Spot	Spot
i (°)	83.1 ± 0.2	83.1 ± 0.2
T_1 (K)	17063	17063
T_2 (K)	4346 ± 14	4346 ± 10
Ω_1	2.569 ± 0.002	2.569 ± 0.001
Ω_2	2.500 ± 0.007	2.500 ± 0.005
q (M_2/M_1)	0.3154 ± 0.0008	0.3154 ± 0.0006
$L_1/(L_1+L_2)$ (B)	0.987 ± 0.011	0.987 ± 0.008
$L_1/(L_1+L_2)$ (V)	0.972 ± 0.011	0.972 ± 0.008
$L_1/(L_1+L_2)$ (g')	0.982 ± 0.011	0.982 ± 0.008
$L_1/(L_1+L_2)$ (r')	0.960 ± 0.012	0.960 ± 0.008
$L_1/(L_1+L_2)$ (i')	0.944 ± 0.012	0.944 ± 0.009
r_1 side	0.4686 ± 0.0004	0.4706 ± 0.0004
r_2 side	0.2765 ± 0.0013	0.2873 ± 0.0013
filling factor ₁	96.8%	96.8%
filling factor ₂	99.7%	99.7%

Cool spot	Star 2
colatitude (°)	—
longitude (°)	—
spot radius (°)	—
temp. factor	—

Residuals	0.00060	0.00038
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Note: The errors in the stellar parameters result from the least-squares fit to the model. The actual uncertainties are considerably larger. The subscripts 1 and 2 refer to the star being eclipsed at primary and secondary minimum respectively. ¹ Parameters not adjusted.

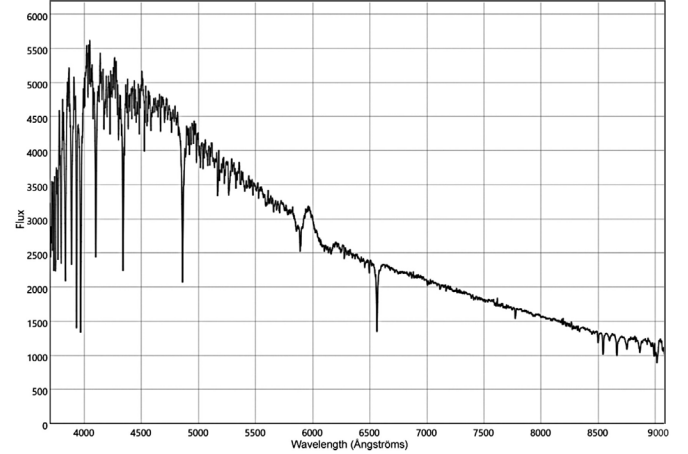


Figure 4. LAMOST low resolution spectrum of CE Peg.

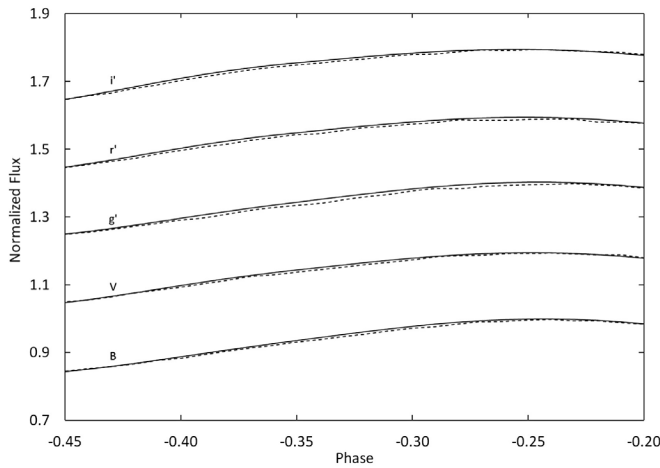


Figure 5. Enlarged view of observed light curves (dashed line) and the WD spotless model light curves (solid line). The deficit of light between orbital phase -0.45 and -0.25 indicates a possible cool spot on the secondary star.

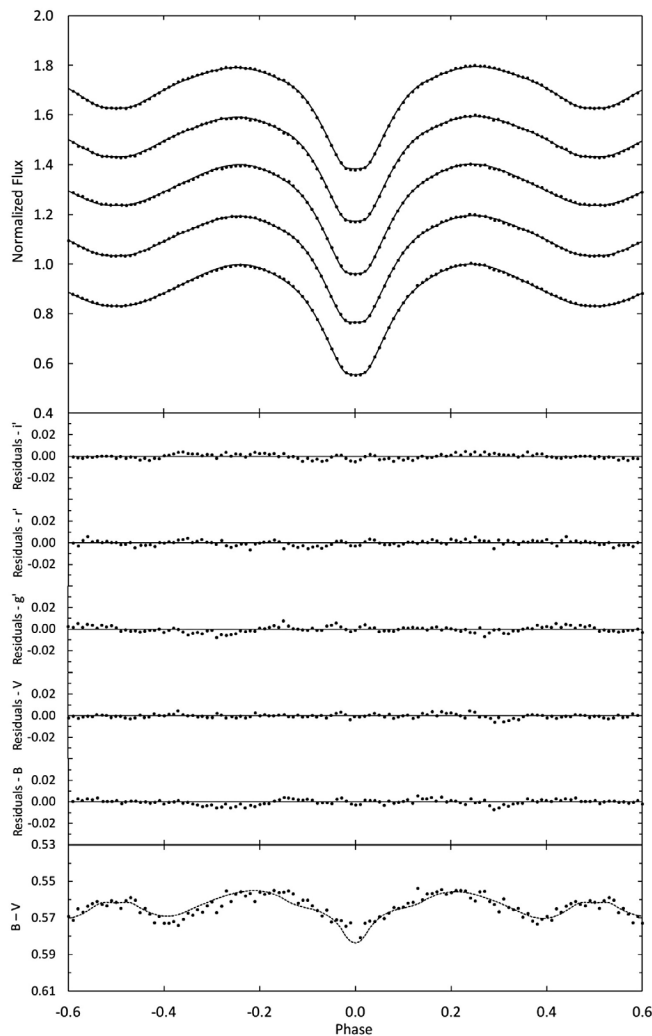


Figure 6. The top panel shows a comparison between the WD best-fit model (solid curves) and the observed normalized flux curves. From top to bottom, the passbands are i' , r' , g' , V , and B with each light curve offset by 0.2. The residuals are shown in the middle panel. The bottom panel displays the $(B-V)$ color curves. The observed colors are the filled circles, and the dashed line is the color variations calculated from the WD model. Error bars are omitted from the plotted points for clarity.

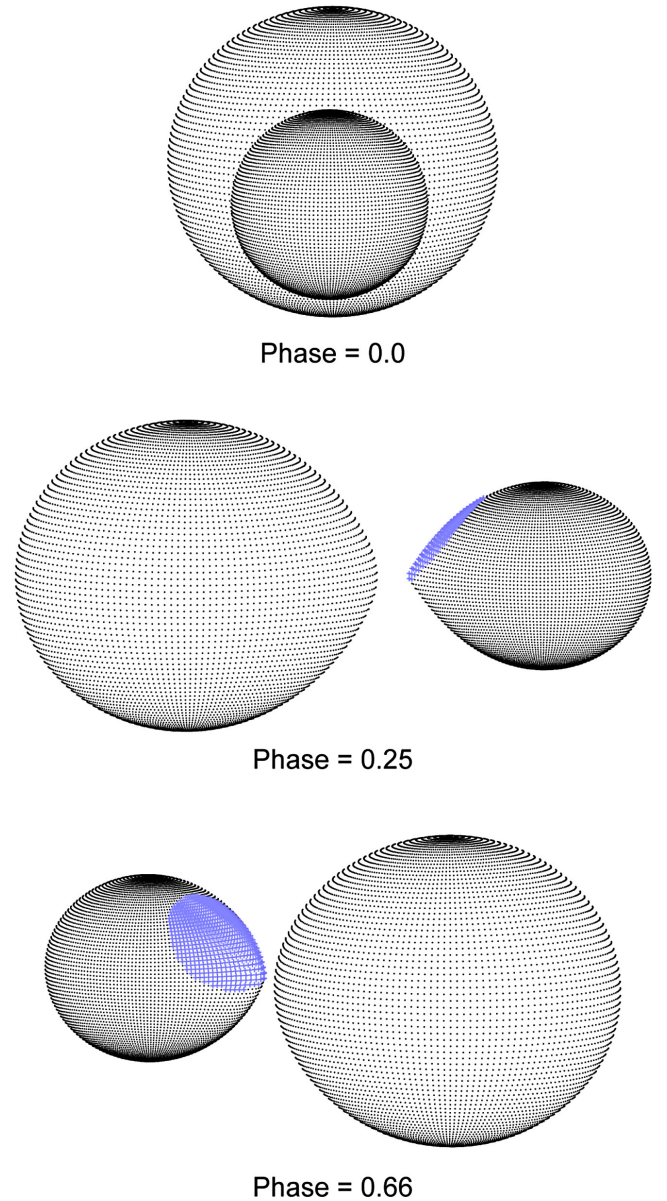


Figure 7. Roche lobe surfaces for the best-fit WD model.

As an additional check, a q -search was performed by completing several WD solutions using a set of fixed mass ratios that ranged from 0.29 to 0.35. The results show a well-defined minimum near 0.32, which is in good agreement with the solution mass ratio (see Figure 8).

5. Discussion

CE Peg has the characteristics of a near-contact binary (NCB) which include strong tidal interactions, facing surfaces that are less than 0.1 radii apart, and orbital periods that are less than one day (Shaw 1990). The WD light curve solution gives a semidetached SD2 Roche configuration due to the cooler, less massive secondary star filling its critical surface (Shaw 1994; Yakut and Eggleton 2005). The hot primary star almost fills its Roche lobe with a filling-factor of 96.8% (see Figure 9). Other properties of SD2 type binaries include symmetrical light curves

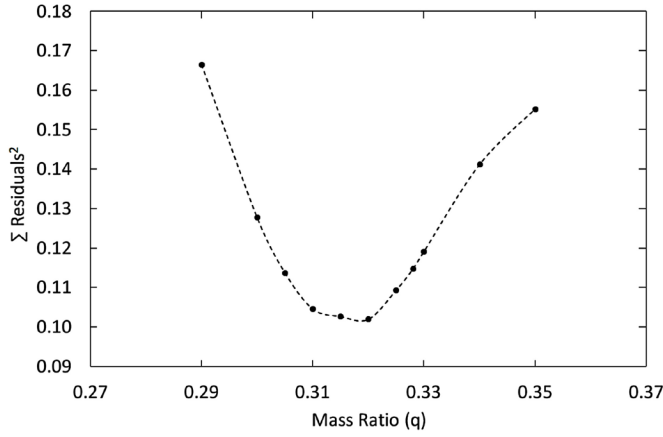


Figure 8. The q-search results show the relation between the sum of the residuals squared and the mass ratio.

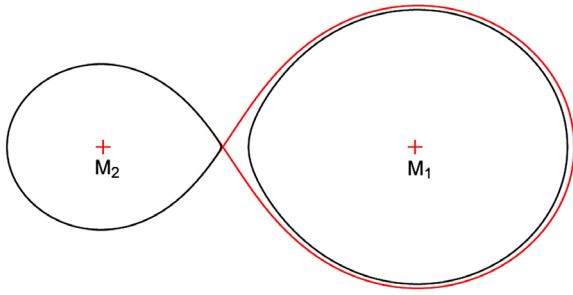


Figure 9. Roche configuration in the orbital plane. The red line denotes the critical lobe and the black lines the potential surfaces of the two stars for the WD solution. The mass center of each star is labeled.

(no O’Connell effect) and orbital periods that are increasing due to conservative mass transfer from the less massive to the more massive star. The observed light curves are symmetrical with Max I equal to Max II, but the period study (section 3) showed an orbital period that is constant. This inconsistency may be the result of a combination of angular momentum loss from magnetic braking, which works to shorten the orbital period, and the rate of mass transfer, which would lengthen the period. These two mechanisms may be strongly competitive in semidetached systems (Nanouris *et al.* 2011, 2015; Erdem and Öztürk, 2014).

The absolute stellar parameters of the component stars can be estimated using the WD solution mass ratio and an approximate mass of the primary star. For short period Algol and NCB binaries, the primary component is likely to be an unevolved main sequence star (Shaw 1994; Yakut and Eggleton 2005; Stepień and Kiraga 2013). The mass of the primary star was interpolated from the online table of Pecaut and Mamajek (2013) using its effective temperature. The secondary star mass was calculated by combining the primary star mass and the mass ratio. The distance between the mass centers of the component stars was found using Newton’s form of Kepler’s Third Law (Equation 3),

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)} \quad (3)$$

The bolometric magnitudes, radii, and surface gravities of each star were taken from the output of the WD Light Curve

Table 6. Provisional absolute parameters.

Parameter	Symbol	Value
Stellar masses	$M_1 (M_\odot)$	1.52 ± 0.06
	$M_2 (M_\odot)$	0.48 ± 0.02
Semimajor axis	$a (R_\odot)$	3.95 ± 0.06
Mean stellar radii	$R_1 (R_\odot)$	1.84 ± 0.03
	$R_2 (R_\odot)$	1.12 ± 0.02
Bolometric magnitude	$M_{\text{bol},1}$	2.54 ± 0.06
	$M_{\text{bol},2}$	5.72 ± 0.15
Stellar luminosity	$L_1 (L_\odot)$	7.57 ± 0.42
	$L_2 (L_\odot)$	0.40 ± 0.06
Surface gravity	$\log g_1 (\text{cgs})$	4.09 ± 0.03
	$\log g_2 (\text{cgs})$	4.02 ± 0.03

Note: The calculated values in this table are provisional. Radial velocity observations are necessary for direct determination of M_1 , M_2 , and a .

program. Shaw (1994) found the radii of SD2 secondary stars are 2 to 3 times larger compared to main sequence stars of the same mass. The radius of CE Peg’s secondary star is oversized by a factor of 2.3. The stellar luminosities were calculated by combining the bolometric magnitudes of the stars and the sun. The provisional stellar parameter values have been collected in Table 6.

The visual luminosities of the component stars, $L_{1V} = 8.1 \pm 0.5$ and $L_{2V} = 0.22 \pm 0.03$, were computed using the bolometric corrections taken from the online tables of Pecaut and Mamajek (2013). Summing gives a system luminosity of $L_V = 8.3 \pm 0.5 L_\odot$, which is in good agreement with the value determined from observed quantities, $L_V = 8.0 \pm 0.2 L_\odot$ (see section 4.1). The distance to this binary, $d = 1128 \pm 35$ pc, was derived from the system visual luminosity and the extinction corrected apparent magnitude. This value is consistent with the distance from Gaia astrometry, $d = 1107 \pm 14$ pc.

6. Conclusions

The new high cadence multiband observations of CE Pegasi revealed β Lyrae type light curves. The hotter primary star occults the smaller star, causing a brief total eclipse at secondary minimum. The photometric solution was derived based on the B, V, g’, r’, and i’ observations. CE Peg is a near-contact SD2-type binary with the secondary star filling its Roche lobe and the primary star nearly filling its lobe (98.6%). The system has a mass ratio of $q = 0.315$ and an orbital inclination of 83.1° . The spectral types of the main sequence primary and the oversized secondary stars are F0 and K6, respectively. The small light curve asymmetries were addressed by modeling a single cool spot on the facing hemisphere of the secondary star. The ephemeris was updated using new minima timings from the observations. The period analysis gave little indication of a secular period change over the past 30 years.

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Measuring Zenith Sky Brightness and Color Changes during the April 8, 2024 Total Solar Eclipse Using Filtered Sky Quality Meters

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Abstract Zenith sky brightness measurements were obtained on the line of totality during the April 8, 2024, total solar eclipse. Observations were made at two sites: Wickliffe, Kentucky, and Oxford, Ohio. A set of four Sky Quality Meters (SQMs) fitted with clear (L), red (R), green (G), and blue (B) filters collected data at each site. During totality, sky brightness dropped to 13.27 ± 0.1 mag/arcsec² at Wickliffe, Kentucky, and 12.99 ± 0.1 mag/arcsec² at Oxford, Ohio. These values are consistent with past eclipse observations and are brighter than nautical twilight. Over the course of the partial eclipse the spectral content prior to totality, as measured by the R–B and G–B indices, remained constant. During totality, the spectral content shifted towards B, consistent with the light arriving at zenith from outside the umbra after multiple scattering events. The spectral content of zenith sky brightness post-totality decreased at a constant rate due to changes in solar altitude. The use of color-filtered SQMs greatly simplifies the data collection process with regards to both photometric and spectrophotometric measurements.

1. Introduction

During a total solar eclipse, the disk of the Sun is covered by the disk of the Moon, and the sky darkens; however, this darkness does not rival that of the night sky due to the presence of sunlight scattered by the atmosphere from regions outside of totality. Photometric measurements of zenith sky brightness have been conducted for the past hundred years or so, while a handful of spectrophotometric measurements have been made only over the last sixty years or so (Sharp *et al.* 1966; Hall 1971; Shaw 1975; Silverman and Mullen 1975; Kirilov *et al.* 2001; Suzuki and Yamamoto 2013; Shaw *et al.* 2022). Previous total eclipse observations have established several photometric and spectrophotometric characteristics: (a) Zenith during totality is 10^{-3} times that of a normal daytime sky while a full moon at night is 10^{-6} times that of normal daytime brightness. (b) Sky brightness at zenith is a linear function of solar obscuration up to 99.8% coverage. (c) The spectral signature of the sky shifts towards the blue from about a minute before to about a minute after totality. (d) Local effects including atmospheric conditions and solar elevation angle become important near and during totality.

Theoretical models for sky brightness and color during total solar eclipses employ first- and second-order Rayleigh scattering processes (Gedzelman 1975; Shaw 1975). Both models qualitatively agree with observations of a reddened horizon and blue enrichment at zenith. Gedzelman (1975) confined his work to modeling sky conditions near the horizon. Shaw (1978) modeled the full sky; his work predicted a zenith spectral radiance in blue that was 20% lower than that observed during the 1973 total eclipse observed from Africa. More recently, Shaw *et al.* (2022) utilized the 1975 Shaw model with a calibrated all-sky image at totality during the 2017 eclipse. Their predicted and measured brightnesses agreed to within a factor of 2. Refinement of atmospheric

scattering models during total solar eclipses should be possible with additional data from spectrophotometric measurements and all-sky imaging during solar eclipses.

The total solar eclipse of April 8, 2024, stretched across North America. The line of totality ran from southern Canada through 13 U. S. states (Maine, New Hampshire, Vermont, New York, Pennsylvania, Ohio, Indiana, Illinois, Kentucky, Missouri, Arkansas, Oklahoma, and Texas) and across central Mexico. We present photometric measurements in the L, R, G, B bands at two different sites in America: Wickliffe, Kentucky, and Oxford, Ohio. At both sites, the skies had passing clouds for about an hour before and after totality; visibility was good at both sites and recorded to be approximately 10 miles, according to archival data from timeanddate.com (Time and Date AS. 1995–2026).

2. Instrumentation

Prior to 2016 sky brightness measurements were primarily obtained using photoelectric photometers and spectroscopes (Sharp *et al.* 1966; Hall 1971; Silverman and Mullen 1975).

During the 2017 total solar eclipse, Shaw *et al.* (2022) utilized a radiometrically calibrated all-sky camera to examine sky brightness and color in the R, G, B bands. Two groups (Pramudya and Arkanuddin 2016; Wijaya *et al.* 2016) used SQMs to measure sky brightness at zenith during the 2016 total solar eclipse.

There are several Unihedron SQM models and all designed to measure night sky brightness at zenith in magnitudes per arcsecond squared (mpsas). This study used the SQM-L-DL model which has data logging capabilities and is powered by six 1.5-V batteries. SQM-L models include a lens that narrows the acceptance angle of the device to a 20-degree cone around zenith. The SQM uncertainty for any individual measurement is ± 0.1 magnitude per square arcsecond (mpsas), as stated by

the manufacturer. Thus, comparing the difference between any two SQMs measurements results in an experimental uncertainty of ± 0.14 , using the addition of errors in quadrature. Full technical specifications and performance of the SQM-L models are available from Cinzano (2005).

We constructed two identical devices to measure zenith sky brightness. Each device consisted of four SQM-L-DL units in protective housing. Each individual SQM-L-DL was fitted with a single color filter: either an clear (L), red (R), green (G), or blue (B) filter. We used the 1.25-inch LRGB filter set from ZWO Astro (2026). Observations at each site were made starting about an hour before the eclipse began and continued for roughly an hour after totality.

Measurements for each device are corrected for extinction of light from the glass window on the weatherproof housing as well as detector response and transmission losses from its respective L, R, G, B filter. Each color filter has nominally uniform transmission of approximately 92% along its bandpass. Spoelstra (2014) used SQMs with color filters to monitor night sky brightness and we are using a device similar to his, so we employ his method to determine our correction factors. The reading from a spectral band depends on the SQM detector response and the filter transmission. The true light level measured by our device is given in Equation 1:

$$m_{\text{corrected}} = m_{\text{reading}} - 2.5 \log (1/R_{\text{band}}), \quad (1)$$

Here R_{band} is the average response in the spectral band. It is calculated by taking the sum of the detector response at each wavelength λ multiplied by the filter transmission T_{λ} in each wavelength interval Δ_{λ} and dividing by the number of wavelength intervals. This is given in Equation 2 by

$$R_{\text{band}} = (\text{Sum} (R_{\text{detector} \times T_{\lambda}}) / n_{\Delta_{\lambda}}. \quad (2)$$

The correction factors for each filter are listed in Table 1.

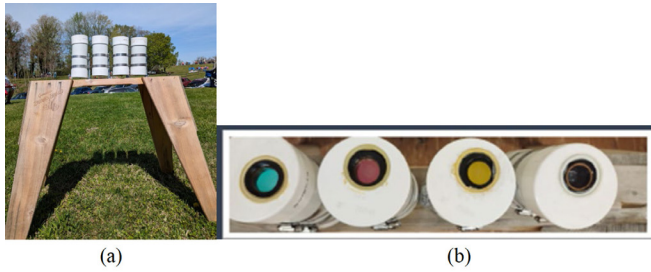


Figure 1. (a) Bank of SQM-L-DL devices in weatherproof housing and mounted on a sawhorse viewed from the side. (b) A view from the top with filters visible, from left to right: Red (R), Green (G), Blue (B), and clear or luminous (L).

Table 1. Corrections for SQM response and RGB filter transmission.

Filter Color	Wavelength Band (nm)	Color Wavelength (nm)	Correction Factors R_{band} (%)	$-2.5 \log (1/R_{\text{band}})$ (mag/arcsec ²)
Red	600–680	640	93	−0.08
Green	500–550	525	77	−0.29
Blue	411–470	440	59	−0.58

3. Results and discussion

3.1. Zenith sky brightness

Measurements were made at two sites along the line of totality: the details for each site are found in Table 2. The SQM-L-DL with the clear (L) filter is saturated until roughly 10 minutes prior to totality at either site, as see in Figure 2; the device is known to have a saturation threshold of 5.9 mpsas. The vertical dotted lines from left to right indicate the predicted times of C2 (start of totality), C3 (end of totality), and C4 (end of partial eclipse). Note that there is a slight discrepancy between predicted and measured times, probably because the SQM clocks were not synchronized with local atomic time.

Table 2. Sites and eclipse characteristics (timeanddate.com).

	Oxford, Ohio	Wickliffe, Kentucky
Latitude and Longitude	39.51° N, 84.75° W	37.05° N, 88.94° W
Time Zone	EDT	CDT
Length of Eclipse	2 ^h 30 ^m	2 ^h 36 ^m
Length of Totality	3 ^m 53 ^s	2 ^m 46 ^s
C1 Local Time	13:57:39	12:42:00
C1 Solar Altitude	55.8°	60.2°
C2 Local Time	15:12:13	13:59:18
C2 Solar Altitude	49.6°	57.5°
Maximum Local Time	15:14:10	14:00:41
Maximum Solar Altitude	49.4°	57.4°
C3 Local Time	15:16:06	14:02:04
C3 Solar Altitude	49.1°	57.1°
C4 Local Time	16:27:52	15:17:52
C4 Solar Altitude	38.8°	149.6°

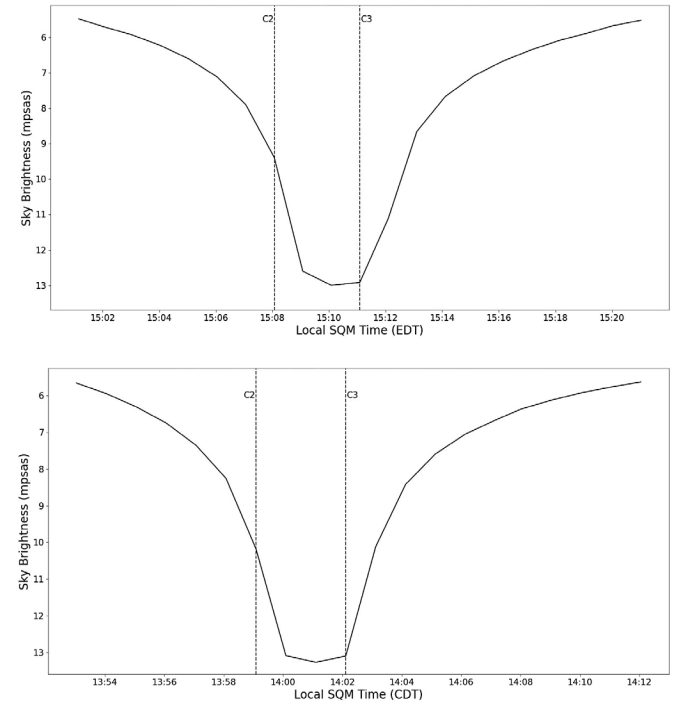


Figure 2. Zenith sky brightness as measured by an SQM with a clear (L-band) filter. Times are in local daylight savings: EDT for Oxford, Ohio, (top) and CDT for Wickliffe, Kentucky, (bottom). Predicted times of C2 and C3 are indicated by the vertical dashed lines: the discrepancy is likely due to SQM clocks not being synchronized to local atomic time.

The darkest measurement of zenith sky brightness for each site occurs during maximum eclipse or mid-totality. At Oxford, Ohio, this was 12.99 ± 0.1 mpsas and 13.27 ± 0.1 mpsas for the Wickliffe, Kentucky, site. These values are consistent with SQM measurements for the March 9, 2016, eclipse: 12.88 mpsas (Wijaya, *et al.* 2016) and 12.47 mpsas (Pramudya and Arkanuddin 2016). Zenith sky brightness at maximum eclipse is slightly brighter than zenith sky brightness of nautical twilight, which is between 13.68 and 13.94 mpsas (Schmude 2024).

3.2. Planetary visibility and zenith brightness

Venus and Jupiter were clearly visible to the naked eye during totality: see Figure 3, which was produced using Stellarium online software (Stellarium Web 2026). When looking southward, Jupiter (magnitude -1.89) appeared roughly 30 degrees to the upper left of the eclipsed Sun and Venus (magnitude -3.78) was located about 15 degrees to lower right of the eclipsed Sun. Mars (magnitude 1.17) and Saturn (magnitude 1.14) were difficult to spot with the naked eye.

Planetary visibility during the eclipse can be determined using the relationship derived by Fisher (2006) which relates sky brightness to naked eye limiting magnitude (NELM). The relationship between NELM and sky brightness B (in mpsas) is given in Equation 3 by

$$\text{NELM} = 7.93 - 5 * \log(10^{((4.316 - B/5) + 1)}) \quad (3)$$

At Oxford, Ohio, where $B = 12.99$, the NELM was -0.70 , while at Wickliffe, Kentucky, with $B = 13.27$, the NELM was -0.43 . At both sites, Saturn and Mars were well below the threshold of naked eye visibility while both Venus and Jupiter were much brighter than the naked eye threshold.

3.3. Zenith sky color

Measurements of sky brightness in the red (R), green (G), and blue (B) were obtained at each site (see Figure 4). During totality, red light is attenuated to a greater extent than blue or green. This is consistent with Rayleigh scattering: most of the light making it to zenith during totality represents light from outside the umbral shadow that has been scattered multiple times.

Spectral changes are revealed by taking the color index $B-R$ for our data (Sharp *et al.* 1966; Silverman and Mullen 1975). A larger negative number for these differences translates to an excess of blue. As seen in Figure 5, both sites show a nearly constant color ratio between R and B until totality, consistent with previous studies (Hall 1971; Sharp *et al.* 1966). It is clear from these plots that during totality, the ratio of blue light increases relative to red light as would be expected if multiply-scattered photons reach zenith from outside the umbral shadow. After totality, the relative intensities of red and blue decrease with decreasing solar altitude.

4. Concluding remarks

We have several recommendations for future SQM observations of total solar eclipses. First, the SQM data

collection rate should be reduced to a 10-second interval to improve resolution during totality. Second, the green-filtered SQM can be eliminated as it offers little additional information: the L, R, B filters are sufficient to measure sky brightness and spectral content. Finally, it is desirable to synchronize SQMs with local atomic time if accurate timing of C2 and C3 are desired. There is currently a dearth of such measurements made during total solar eclipses. Such measurements would be useful to inform scattering models (Shaw *et al.* 2022;

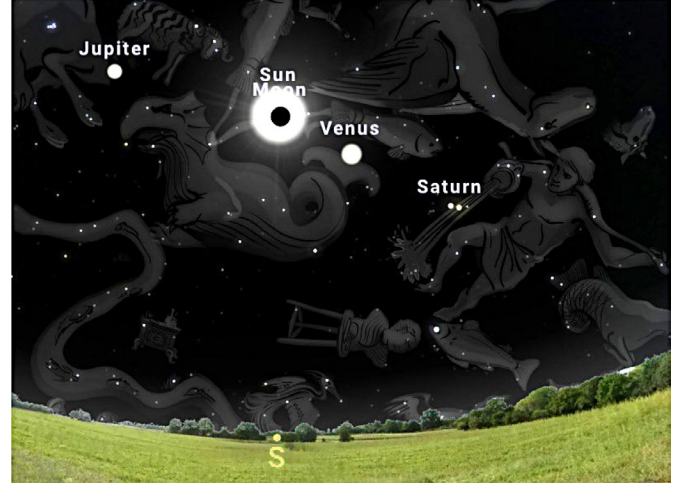


Figure 3. Planets near the eclipsed sun. Only Jupiter and Venus were easily visible to the naked eye. This image is a view directly south at totality. Saturn is the yellow dot and Mars is the smaller, red object immediately to its right. This was produced using Stellarium online software (<https://stellarium-web.org>).

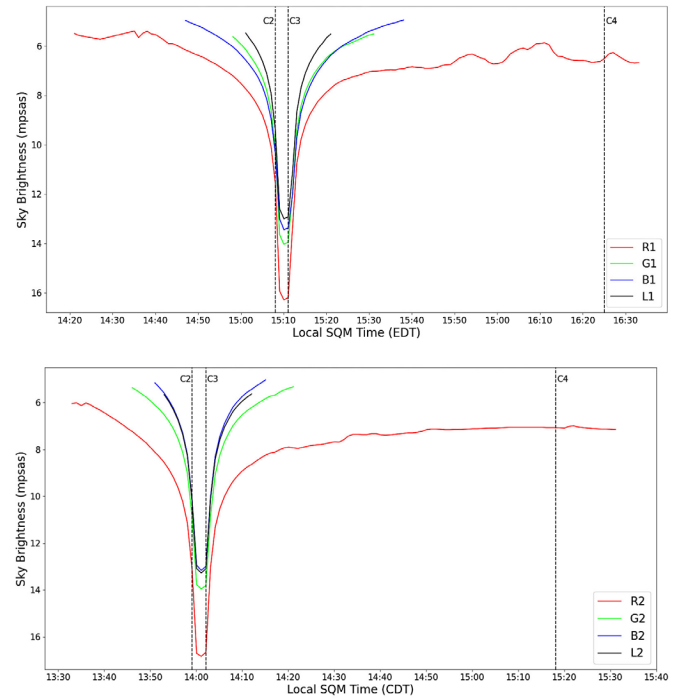


Figure 4. Zenith brightness at Oxford, Ohio, (top) and Wickliffe, Kentucky, (bottom), measured by SQMs with red, green, and blue filters. Note that the red light shows greater extinction during totality than both blue and green. Note that green and blue are quite close in magnitude and the relative intensities are flipped at both sites. This discrepancy is probably due to a combination of experimental uncertainty and local and geometric effects (Silverman and Mullen 1975).

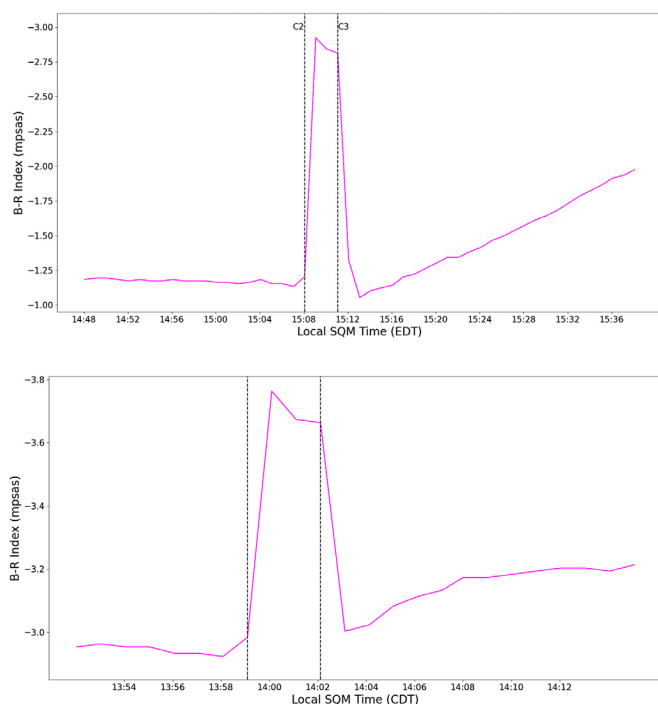


Figure 5. Spectral content around totality measured by color index B–R. Prior to totality, the spectral content is constant. After totality, the ratio decreases linearly with decreasing solar altitude. During totality the deficit of red light compared to both blue and green is what would be expected if light arriving at zenith is primarily from multiply scattered photons from outside the umbral shadow.

Shaw 1975). As mentioned by Hall (1971) comparison of results from different measurements is complicated by instrumental factors including calibration and type of instrument used. The use of SQMs and filters with known properties could provide a standardized measurement system that would simplify comparison of future eclipse observations at different locations and dates. The use of SQMs greatly reduces the complexity of setup and data reduction and researchers currently in possession of SQMs can contribute to such studies.

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Characterizing Photonic Ring Resonator Filters for OH Suppressed Near-infrared Astronomy

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Abstract Supernova cosmology relies on accurate measurement of the absolute magnitudes of Type Ia supernovae. Observation in the visible incurs significant systematic uncertainties in these measurements due to their high degree of interstellar dust extinction. Observing in the near-infrared (750–2500 nm) mitigates this issue by decreasing attenuation, decreasing dispersion, and increasing supernova observation distances. However, ground-based observations in the near-infrared suffer from sky background caused by atmospheric OH emission lines. Advancements in photonic ring resonator filter devices make it feasible to suppress these lines. In this paper, we evaluate the performance of a prototype photonic ring resonator device developed for use in the lower H-band (1480–1620 nm). Specifically, we characterize the progression of suppressed wavelengths into the upper H-band (1620–1800 nm) enabling the suppression of emission lines over a broader wavelength range.

1. Introduction

Astronomical sources are detectable when a source’s incident flux is higher than its background flux. Currently, long exposure sky-subtraction techniques can be employed to detect faint sources (Morganson *et al.* 2018; Blanton *et al.* 2011). One significant source of background flux in the near-infrared (NIR, 750–2500 nm) arises from molecular emission in the atmosphere, called sky background. In the H-band (λ_{eff} , the throughput-weighted average wavelength of a filter throughput function, is ~ 1650 nm for the H-band), re-emission of light through atmospheric OH radicals creates an abundance of emission lines that impede NIR measurements. Rousselot *et al.* (2000) provides a computed spectrum demonstrating OH emission’s impacts on the observed H-band. These OH emission lines increase photon noise in observed spectra and, accordingly, decrease measurements’ signal-to-noise ratio (SNR). As a result, ground-based observations in the NIR require impractically long exposure times that would harm measurements’ sensitivity to time domain signals. Additionally, standard sky-subtraction techniques are challenging in the NIR because their backgrounds experience both long and short temporal variability. Long term temporal variability arises from OH molecules only exciting during the day. Excited OH molecules slowly de-excite

overnight, causing the background emission spectra to gradually weaken. Conversely short term temporal variability, typically on the scale of minutes, results from random atmospheric pressure changes. Both types of variability in emission spectra make sky subtraction methods difficult to implement (Ellis and Bland-Hawthorn 2008).

This complication is problematic for the measurement of dark energy with Type Ia supernovae (SNe Ia), which depends on accurate measurement of their absolute magnitudes for use as standardizable candles (Avelino *et al.* 2019; Barone-Nugent *et al.* 2012). Observing SNe Ia in the visible leads to large systematic uncertainties due to variability from interstellar dust extinction (Brout *et al.* 2022). NIR observation mitigates this issue by minimizing the impacts of attenuation and scatter from interstellar dust. As demonstrated by Wood-Vasey *et al.* (2008), Phillips (2012), Avelino *et al.* (2019), and Peterson *et al.* (2024) the RMS scatter of SNe Ia distances measured from photometric surveys is significantly reduced when light curve fits incorporate information from the Y ($\lambda_{\text{eff}} \sim 1000$ nm), J ($\lambda_{\text{eff}} \sim 1250$ nm), H ($\lambda_{\text{eff}} \sim 1650$ nm), and K ($\lambda_{\text{eff}} \sim 2200$ nm) bands, spanning the NIR. The most recent of these studies (Peterson *et al.* 2024) showed a reduction in SNe Ia Hubble Diagram distance modulus residual RSD (robust median absolute standard deviation) by up to 0.047 mag when considering YJH-

band data as compared to only considering visible (Sloan *gri* band or ATLAS *co*-band) data for the same set of SNe Ia, with the H to *gri* band comparison showing the largest difference. Peterson *et al.* (2024) also finds a small reduction in the size of the so-called “mass-step,” a step discontinuity in estimated SNe Ia luminosities with respect to their host masses, with the H-band once again showing the smallest and least statistically significant mass step. These benefits of observing in the NIR would improve systematic uncertainties of The Vera Rubin Observatory Legacy Survey of Space and Time (LSST). While LSST does not fully extend into the infrared, this paper seeks to pursue research and development of ring resonator filters for use in such a follow-up instrument. To best utilize the NIR’s advantages, the sky background impacts of atmospheric OH emission lines must be mitigated. Space-based observations provide one possible solution for the elimination of sky background from OH emission lines. However, this is not a widely accessible solution due to cost and design challenges.

Since each emission line’s wavelength is known, it is possible to suppress these emission lines in a measured spectrum—a method termed sky background suppression. This method lowers the sky background flux, achieving ground-based observations with better SNRs. However, background suppression requires high precision; even a misalignment of a fraction of a nanometer can impede the suppression of emission lines. PRR filters for OH suppression have dips with full widths at half max (FWHM) of 0.2 nm for adequate OH suppression (Liu *et al.* 2021; Kuehn *et al.* 2020). High precision astronomical spectrographs require 4 to 6 samples per FWHM for accurate reconstruction of a symmetric line shape (Robertson 2017; Chance *et al.* 2005). We employ ten samples across the linewidth such that there is sufficient information about each dip’s shape to ensure total suppression regardless of symmetry. Accordingly, a resolution of 20 pm is used to ensure complete suppression.

Two filtering methods are currently under investigation for background suppression: photonic ring resonators (PRRs) and fiber Bragg gratings (FBGs). FBGs utilize refractive index modulation to reflect back narrow bands of a specified wavelength, while allowing the remaining light to transmit through the fiber (Werneck *et al.* 2017). However, the aperiodic FBGs needed for OH suppression are expensive and do not have the ability to tune for primary sources of maladjustment, e.g. by using athermal tuning (Yoffe *et al.* 1995). In the event of small manufacturing errors, the lack of tunability would prevent accurate placement of dips that could harm the quality of background suppression. PRRs, conversely, eliminate specific wavelengths (called suppressed wavelengths) through their circular waveguides as described in section 2. Combining several PRRs in series suppresses multiple wavelengths (Heebner *et al.* 2007). In PRRs the suppressed wavelength is set during fabrication, but can be adjusted after fabrication by heating or cooling the PRR. Additionally, PRRs are modular, easily scaled, and can be as much as ten times smaller than FBGs. As a result, series of PRRs are more easily implemented in compact packages than FBGs.

For these reasons, we studied PRRs’ utility in suppressing NIR sky background. Previous work in the field has focused

on measuring the performance of PRR devices in the lower H-band (1480–1620 nm) (Liu *et al.* 2021; Kuehn *et al.* 2020; Kuehn *et al.* 2024). In this paper, we expand the study of PRR performance in background suppression into the upper H-band (1620–1800 nm). To achieve this, we construct an experimental setup to determine the performance of a PRR device for a subsection of the upper H-band (1620–1665 nm) and then characterize its performance. With the collected data, we extrapolate on a constructed fit to quantify the evolution of different performance metrics, particularly the suppressed wavelengths, from the lower H-band into the upper H-band.

2. PRR Theory and fabrication

A photonic ring resonator consists of a circular waveguide and a source fiber that are evanescently coupled to suppress individual wavelengths. Evanescent coupling allows some energy—in the form of an evanescent wave—to transmit with an exponential decay between closely spaced waveguides, particularly in conditions at or near total internal reflection (TIR) (Hecht 2002). Figure 1 showcases the basic structure of a PRR.

As a result of evanescent coupling, the entire spectrum of input light cross-couples into the ring. Within the ring, each wavelength undergoes repeated TIR. For the case of negligible attenuation from coupling, wavelengths that do not meet the resonance condition (Equation 1) are destructively interfered,

$$\phi = 2\pi m, \quad (1)$$

where ϕ is the input signal’s phase at a given wavelength and m is a positive integer called the order. The wavelength at which the resonance condition is met for $m = 1$ is termed the first order resonant wavelength (λ_{res}). Subsequent resonance conditions occur at integer multiples of the ring’s circumference. These higher order resonant wavelengths ($\lambda_{\text{res},m}$) couple into the loop, becoming the single-pass transmission shown in Figure 1. Here, they form a series of standing waves created from the original injected signal (Bogaerts *et al.* 2012). Upon re-coupling with the waveguide, the π phase shift from the single pass transmission in the loop induces destructive interference at the resonant wavelengths in the input signal (see Equation 3.15 in Heebner *et al.* (2007)). Thus, the PRR’s output signal contains dips at each resonant wavelength in the output spectrum; the wavelengths at which those dips occur are also called suppressed

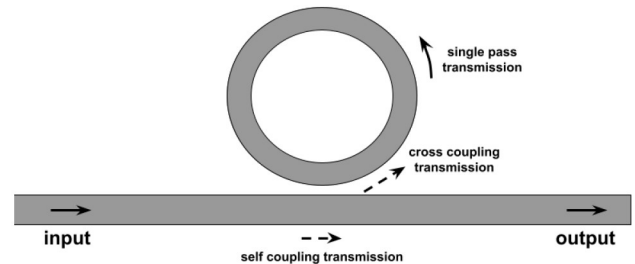


Figure 1. Diagram provides an abstract representation of the evanescent coupling between the ring resonator and the source fiber. Solid arrows indicate signals, while dashed arrows indicate coupling coefficients.

wavelengths ($\lambda_{\text{sup},m}$). The spacing between consecutive modes of resonant frequencies is referred to as the free spectral range (FSR_λ). For a single ring resonator, the resonant wavelength of the mode and the free spectral range are determined by the PRR's circumference (L), the group refractive index (n_g), the order (m), and the free space wavelength (λ_0) of the ring resonator (Heebner *et al.* 2007).

$$\lambda_{\text{res},m} = m \lambda_{\text{res}} = m L n_g \quad (2)$$

$$\text{FSR}_\lambda = \frac{\lambda_0^2}{L n_g} \quad (3)$$

The order is necessarily a positive integer. The group refractive index quantifies the phase delay in the waveguide per unit of length; it is dependent upon the material of transmission (Heebner *et al.* 2007).

3. Apparatus and data

A single PRR, however, can only suppress one OH emission line at a time. The simultaneous suppression of multiple emission lines requires the coupling of multiple PRRs. Previous work by our collaboration produced a device of five in-series PRRs such that five lines in the lower H-band could be suppressed. These five PRRs were embedded within a silicon wafer that was fiber-coupled with astronomical instrumentation

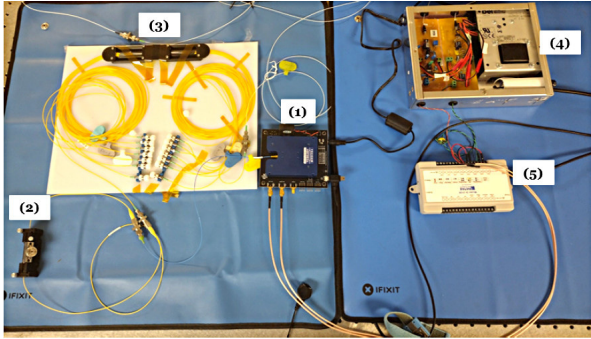


Figure 2. (1) tunable laser with wavelength range of 1620 to 1665 nm, (2) adjustable polarization controller, (3) photonic ring resonator device ANT-07, (4) InGaAs detector, (5) digitizer. All components are connected via fiber coupling.

(Liu *et al.* 2021; Kuehn *et al.* 2020). This silicon wafer was designed at Argonne National Lab, fabricated by Applied Nanotools, Inc, and termed ANT-07.

The collaboration then constructed a setup to test ANT-07 in the lower H-band. We constructed a similar experimental setup to test ANT-07 in the upper H-band (see Figure 2). In both setups, a tunable laser was fiber-optically coupled to an in-line fiber optic polarization controller and, later, ANT-07. The output from ANT-07 was recorded by an InGaAs detector (designed by Dave Underwood at Argonne National Lab) which was subsequently fed into a digitizer. In the lower H-band setup, the tunable laser was a TLK-1550R from ThorLabs with a range of 1480 to 1620 nm. In the upper H-band, we used the FP4209 InstaTune Fast Random-Access Tunable Laser from Freedom Photonics with a range of 1620 to 1665 nm.

Additionally, the upper H-band experimental setup included a protractor to measure the angle of the in-line polarization controller, which we varied incrementally to determine the angle at which the dips were strongest. We collected data using this setup for several relative polarization angles, including -120° , -90° , -45° , 0° , 45° , and 90° . These increments are selected due to the coarse precision of our measurements. It is crucial to note that the angle of the in-line polarizer does not directly describe the polarization of the transmitted signal. Rather, it allows for the selection of specific angles that maximize the output spectrum's SNR. Figure 3 contains some representative measurements.

Based off these spectra and an analysis of their SNRs, the in-line polarizer angle was set to -120° for all subsequent upper H-band measurements. This selection minimized the polarization-related effects on spectra, which can obscure true dip locations (as seen in Figures 3a and 3b). Additionally, the dips are quite broad at the sixth order of suppression (Figure 3c). Section 4 will discuss the causes and consequences of this broadening with reference to the lower H-band spectra (Figure 4) and the upper H-band spectra (Figure 5).

4. Analysis and results

The lower H-band spectrum contains the first four orders of dips produced by suppression in ANT-07 ($m=1, 2, 3, 4$). Henceforth, the first four orders will be referred to as the lower

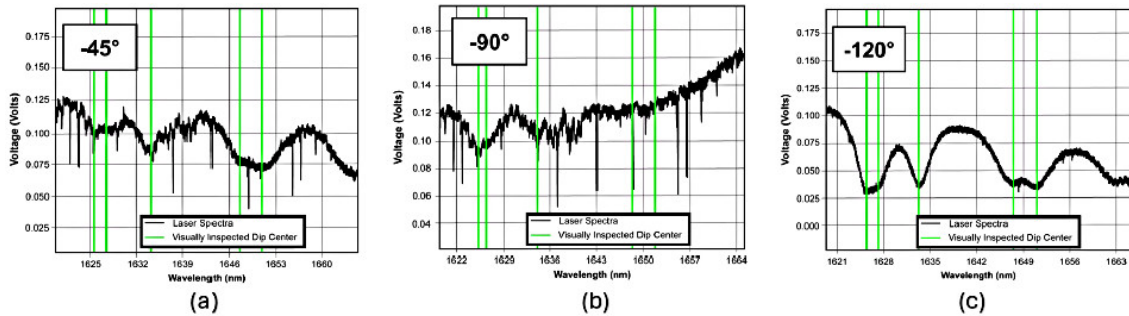


Figure 3. Unflattened spectra of ANT-07 in the upper H-band. All dips are in their sixth order. The relative polarization angles are (a) -45° , (b) -90° , (c) -120° . Spectrum (c) was selected for subsequent upper H-band analysis. Green lines indicate the visually inspected dip locations from (c), as later determined in Table 3 and shown in Figure 5. Spectra (a) and (b) have these dip locations overlaid, demonstrating how polarization artifacts can obscure the true dip locations. Please note that angles are approximate due to setup limitations.

H-band. The lower H-band spectrum produced by ANT-07 was flattened to account for broad features of the continuum. The spectrum was flattened by fitting a polynomial to segments of the continuum, and then flattening each individual segment relative to its local full illumination. This piecewise approach minimized the impacts of increasing attenuation with order. The flattened lower H-band spectrum is presented in Figure 4.

The performance metrics used to characterize the dips created from each of ANT-07's PRRs are: suppressed wavelength ($\lambda_{\text{sup},m}$), full width at half maximum (FWHM), and depth. To extract the performance metrics from the spectrum, we created a script that found the lowest points of the spectrum and took them to be at the minima of intended dips. An inverse Lorentzian distribution was then fitted to these dips to identify their minima (Fang et al. 2020). The minima of these Lorentzian fits were taken to be the suppressed wavelengths. The FWHM and depths for each dip were also extracted and recorded from the fit. The red curves in Figure 4 indicate the inverse Lorentzian distributions that were predicted by the dip-fitting script, while the experimentally measured spectrum is in blue. Metrics predicted by this script were termed dip-fitted (DF) performance metrics. In addition to these DF metrics for ANT-07, we also recorded the FWHM and depth as determined by visual inspection. These visually-inspected (VI) metrics were recorded due to concerns about the accuracy of measurements made by the dip-fitting script, which is still the subject of ongoing development.

Figure 4 indicates that, as a dip's order increases, its FWHM also increases such that consecutive dips begin to blend together and become unresolvable. This is expected, as FWHM of a dip is proportional to the suppressed wavelength squared (Ellis et al. 2023). The dips also become more shallow with increasing wavelength, likely a result of increased attenuation due to detuning (Heebner et al. 2007).

As seen in Figure 4, only the third dip avoids blending with its neighboring dips. The third dip's lack of blending at higher orders allows for the most accurate extraction of performance metrics, both DF and VI. Accordingly, the performance metrics

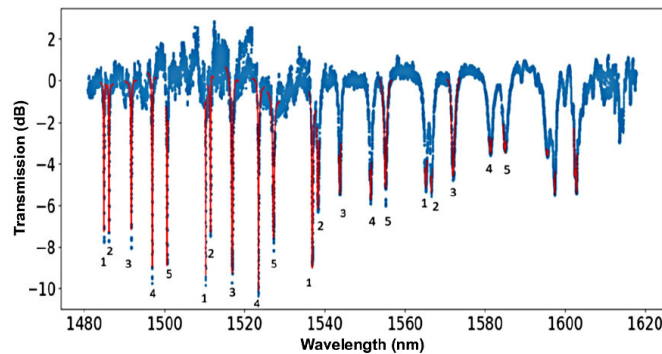


Figure 4. Flattened spectrum taken of ANT-07 in the range of 1480 to 1620 nm. Each number below the dips indicates the ring resonator by which the dip was created. The blue curves are the spectrum that was transmitted to the InGaAs detector by ANT-07, while the red curves are dips that were constructed by a dip-fitting script. The order locations are approximately: first order (1480–1505 nm), second order (1510–1525 nm), third order (1537–1555 nm), and fourth order (1565–1590 nm). The fifth order is indiscernible.

Table 1. DF and VI performance metrics of the third dip created by the third PRR in ANT-07 for the first four orders contained in the lower H-band.

m	DF $\lambda_{\text{sup},m}$ (nm)	DF depth (dB)	VI depth (dB)	DF FWHM (nm)	VI FWHM (nm)
1	1491.696	7.121	8.0	0.1735	0.14
2	1516.921	9.555	9.3	0.3450	0.30
3	1543.763	2.140	5.4	0.3919	0.45
4	1572.098	4.662	4.7	0.9552	0.85

Note: Refer to Table A1 in the Appendix for the tabulated performance metrics of the first, second, fourth, and fifth dips.

of the third dip are separated from those of the other dips. The values of both the DF and VI performance metrics for ANT-07's third dip in the lower H-band are tabulated in Table 1. The performance metrics for the first, second, fourth, and fifth dips are tabulated in Table A1 of Appendix A.

The performance metrics considered going forward are the DF suppressed wavelength, VI depth, and VI FWHM. The VI depth and FWHM are selected in lieu of their DF counterparts because the DF script struggled to extract these metrics. Only the third dip has DF depths and FWHMs that are somewhat consistent with their VI counterparts (Table 1). For all other dips, the DF depth and DF FWHM are inconsistent with their VI counterparts as early as the third order (Table A1). This inconsistency indicates that the dip-fitting script failed to accurately extract depth and FWHM metrics, likely as a result of worsened blending with increasing order. Accordingly, polynomial fits for extrapolation must be constructed from the DF suppressed wavelength, VI depth, and VI FWHM of each dip in the lower H-band (Tables 1 and A1). Particular emphasis is placed on the results from the third dip, as it is least impacted by blending.

From each dip's selected metrics in the lower H-band (Tables 1 and A1), polynomial fits are constructed using least-squares minimization to predict performance metrics at the sixth order ($m=6$) for all five dips. Henceforth, the sixth order is referred to as the upper H-band. For the DF suppressed wavelength ($\lambda_{\text{sup},m}$) we attempt linear, quadratic-linear, quadratic-only, and cubic-quadratic-linear fits. For the extrapolation of the VI FWHM and VI depth, only linear fits are considered. A χ -squared test is conducted to determine each model's goodness of fit for predicting the performance metrics of all five dips through the lower H-band. The χ -squared test statistic is given by Equation 4.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{2\sigma_i^2}, \quad (4)$$

where O_i is the observed metric, E_i is the fitted metric, and σ_i is the uncertainty on the observed metric. For the prediction of the DF suppressed wavelength, σ is taken to be 10 pm based on the projected resolution of the laser and the granularity of the spectrum. For the prediction of the VI depth and the VI FWHM, σ is taken to be 0.25 dB based on the ability to visually estimate the continuum level to then subtract the dip depth. All measurement uncertainties are assumed to be constant and not varying with order. The quadratic-only fit yielded a χ -squared value (χ^2) on the order of 10^6 , indicating the fit

Table 2. χ^2 values from computing the χ -squared test statistic on the polynomial models constructed from each dip's performance metrics in the lower H-band (Tables 1 and A1).

Dip #	χ^2 of VI depth lin. fit	χ^2 of VI FWHM lin. fit	χ^2 of DF $\lambda_{sup,m}$ lin. fit	χ^2 of DF $\lambda_{sup,m}$ quad-lin. fit
1	50.0	0.4	10,616	14.0
2	2.0	0.4	10,817	7.5
3	40.0	0.2	12,092	3.8
4	40.0	0.04	14,184	37.0
5	2.0	0.1	13,705	24.0

Note: All polynomial models were constructed by the least-squares minimization method.

was highly inaccurate. The cubic-quadratic-linear fit yielded χ^2 's on the order 10^{-20} , indicating that the fit was highly over-constrained. Accordingly, these polynomial fits were excluded from analyses. The remaining χ^2 's (Table 2) indicate that the linear fit for the VI depth is possibly inaccurate and the linear fit for DF suppressed wavelength is almost certainly inaccurate.

We then extrapolate to predict the DF suppressed wavelength, VI depth, and VI FWHM for all dips at $m=6$ in the upper H-band (Tables 3 and 4). Note that the first, second, fourth, and fifth dips in the upper H-band spectrum (see Figure 5) are broader and more difficult to resolve than they were for lower orders. As a result, there are insufficient regions of the spectrum at full illumination to construct segmented polynomial fits for the flattening of the spectrum. The unflattened spectrum

Table 3. Model-predicted suppressed wavelengths ($\lambda_{sup,m}$) of all dips at the sixth order compared with their experimental VI counterparts.

Dip #	Pred. $\lambda_{sup,m}$ lin. fit (nm)	Pred. $\lambda_{sup,m}$ quad-lin. fit (nm)	VI $\lambda_{sup,m}$ experimental (nm)
1	1617.96	1625.96	1625.50
2	1619.50	1627.59	1627.50
3	1624.93	1633.48	1634.00
4	1636.82	1646.07	1648.00
5	1640.56	1649.66	1651.25

Note: The linear and quadratic-linear fits used for extrapolation were constructed from the DF suppressed wavelengths in Tables 1 and A1.

Table 4. Model-predicted depths and FWHMs of all dips at the sixth order.

Dip #	Pred. Depth lin. fit (dB)	Pred. FWHM lin. fit (nm)
1	4.54	1.07
2	3.83	1.31
3	2.02	1.23
4	-0.72	1.40
5	-0.39	1.67

Note: The linear fits used for extrapolation were constructed from the VI depths and VI FWHMs presented in Tables 1 and A1. Experimental VI depths and VI FWHMs were only successfully extracted for the third dip. Those values were 1 dB and 2.5 nm, respectively.

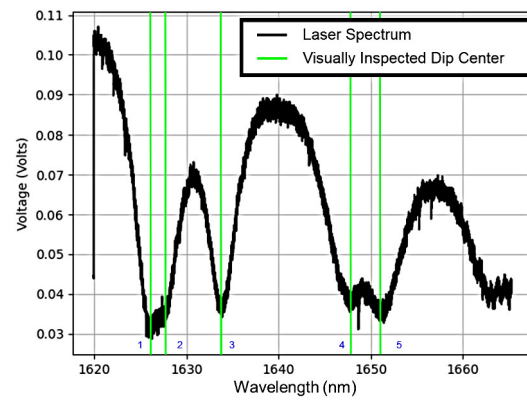


Figure 5. Sixth order unflattened spectrum of ANT-07 taken in the range of 1620 nm to 1665 nm. Flattening was not achievable in the upper H-band due to dip broadening. Green lines indicate visually inspected dip centers ($\lambda_{sup,m}$) from Table 3 and are numbered according to their ring resonator in blue. Please note that, because the dip-fitter was not used to extract metrics, there is no inverse-Lorentzian fitted to the curves as had been done in Figure 4.

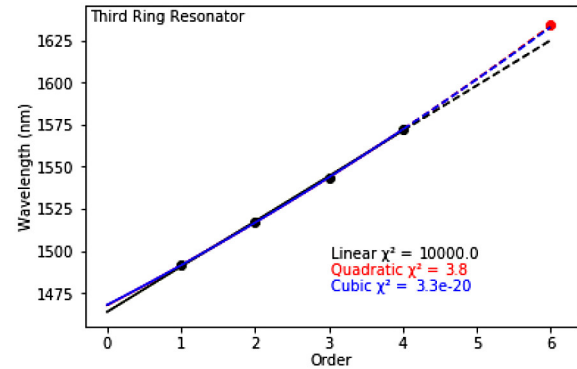


Figure 6. The fits and extrapolations for the third dip with increasing order. Dashed lines indicate extrapolations for $m > 4$. Black is the linear fit, red is the quadratic-linear model, and blue is the cubic-quadratic-linear model. Note that the quadratic and cubic fits overlap with one another. χ^2 's are tabulated in the bottom right. The red point at $m=6$ is the measured suppressed wavelength for ANT-07's third dip, while black points are the measured suppressed wavelengths from the lower H-band.

is instead processed. Like the dips at $m=5$ in Figure 4, the DF script was not suited for this spectrum and did not yield meaningful results.

Thus, we determined performance metrics by visual inspection for the sixth order. While the suppressed wavelength could be measured by visual inspection for all dips at the sixth order, the high degree of blending made it difficult to visually extract their depths and FWHMs. For this reason, VI depth and VI FWHM were measured for only the third dip due to its lack of blending. The third dip's VI depth and FWHM were measured as 1 dB and 2.5 nm, respectively. The predicted and experimental suppressed wavelengths for the sixth order are tabulated in Table 3. Table 4 only contains the model-predicted depths and FWHMs. The predicted metrics for the third dip are compared with the experimental VI measurements in Figures 6 and 7.

5. Discussion

Based on these analyses, the best model for the prediction of suppressed wavelength with respect to order appears to be

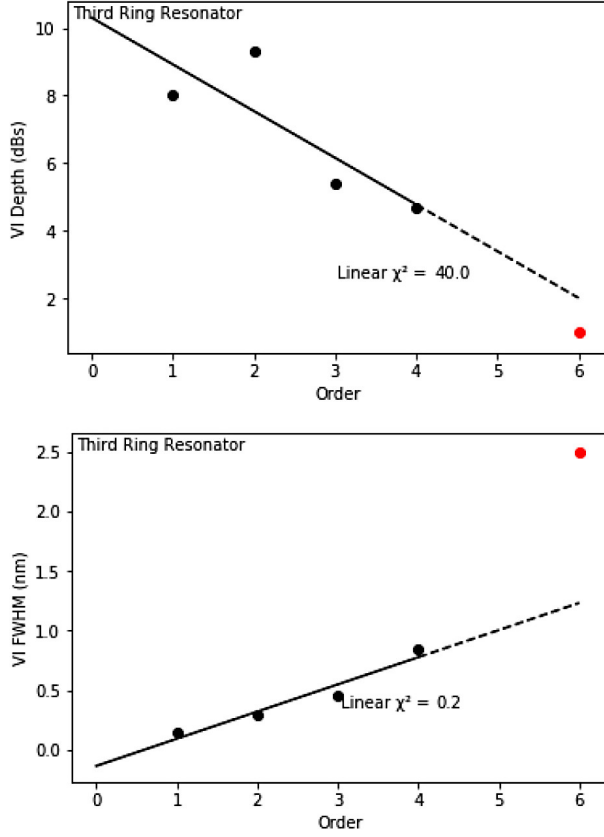


Figure 7. Plots showing the linear fits and extrapolations for VI depth (top) and FWHM (bottom) of the third PRR's dips with order. Dashed lines indicate extrapolations for $m > 4$. The red points at the 6th order are the experimental VI measurements for depth and FWHM, respectively.

a linear-quadratic fit. This is indicated by Table 2, for which the linear χ^2 is far too large and the linear-quadratic-cubic χ^2 is near zero. This is further corroborated by the experimental measurement of the suppressed wavelength for the third dip at the sixth order, seen in Figure 6. We suspect that the relationship between order and suppressed wavelength follows a quadratic curve as a result of the quadratic term that arises in the FSR_λ according to Equation 3. However, it should be noted that this equation for FSR assumes that the dispersion of light (n_g) is constant across all wavelengths. In practice, this is not true due to the material properties of the resonator (Ellis *et al.* 2023). Based on work by a PhD student in the collaboration (Liu 2024), the group refractive index progresses in an approximately linear fashion with respect to the input wavelength of light for ANT-07. Accordingly, we shed the assumption that the group refractive index was constant by adding a linear wavelength-dependent dispersion term:

$$n_g(\lambda) = n_0 + n_1\lambda \quad (5)$$

where n_1 is the linear wavelength dependent dispersion term, and n_0 is the base index of refraction. In this equation, λ can be any wavelength of light injected into the ring resonator. However, only the resonant wavelengths ($\lambda_{\text{res},m}$) are of practical interest. Equation 3 can then be substituted into Equation 5, and its Taylor series expansion yields:

$$\text{FSR}_\lambda = \frac{\lambda_0^2}{L n_0} \left(1 - 1 \left(\frac{n_1}{n_0} \lambda \right) + \left(\frac{n_1}{n_0} \lambda \right)^2 \right) \quad (6)$$

Because n_1/n_0 is not negligible, the result is that the FSR has linear, quadratic, and cubic terms that contribute to the location of the suppressed wavelength. There is a loss of accuracy between the fourth and fifth dips in our quadratic suppressed wavelength predictions, possibly indicating a need for a cubic term in the model. However, the χ^2 from our attempted cubic fit indicates a high degree of over-fitting. The use of a cubic term for suppressed wavelength prediction requires further exploration.

The trends of the third dip for the VI depth and VI FWHM are much less certain. The χ^2 's for depth vary quite drastically; goodness of fit varies from decent to poor. There is some evidence for a linear fit in the case of the third dip, as the measurement from the upper H-band spectrum seems to suggest a somewhat linear nature (see Figure 7 (top)). For FWHM, the χ^2 's are sufficiently small, but the measured FWHM from $m=6$ does not corroborate this finding (see Figure 7 (bottom)). At present, it is clear that linear fitting alone cannot accurately predict the depth and FWHM for ANT-07 in the upper H-band.

6. Further work

Currently, there is still much ongoing and future work before these PRR filters can be integrated into a telescope. Some immediate items include adjustments to the dip-fitting script and updates to the current experimental setup.

Precision estimations of FWHM and depth will be necessary to achieve total line suppression in telescopes. Currently, the dip-fitting script's predictions of FWHM and depth do not align with VI measurements. The collaboration is presently working to improve the dip-fitting script by comparing the performances of different fitted distributions, such as the Voigt, as well as studying the impacts of spectrum flattening on the dip-fitter's extracted metrics. After improving the dip-fitters extraction of FWHM and depth, we will need to better characterize the relationships that FWHM and depth have with order.

There is also a need to improve the precision and reproducibility of polarization measurements. The current polarization tracking method does not yield a precise measure of polarization, but rather a discrete benchmark. Ongoing work in the group attempts to more finely sample the spectrum across angles of the in-line polarizer so that the dips' SNR can be maximized.

It is important to note that these ring resonator filters are still in an early stage of development and have not yet been integrated or tested on a telescope. Several long-term tasks remain before integration will be feasible. These include:

- (1) Narrowing ring resonators' dip depths to improve OH line suppression.
- (2) Construction of a thermal controller to tune multiple dips' suppressed wavelengths on a chip.
- (3) Design and construction of compact packaging for implementation in a telescope's optical path.

Upon successfully integrating these chips in a telescope, our group expects to either license the design to other observatories and individual astronomers, or to construct these systems for the astronomical community.

7. Conclusions

In this paper, we characterized three performance metrics for a prototype photonic ring-resonator (PRR) filter device intended for the suppression of atmospheric OH emission lines. The PRR's output spectrum in the lower H-band ($m=1, 2, 3, 4$) was used to predict three performance metrics in the upper H-band ($m=6$): suppressed wavelength, depth, and full width at half maximum (FWHM).

To make these predictions, polynomial models were fitted from the lower H-band data and then used to extrapolate to the upper H-band. These models were evaluated from both a χ -squared analysis and a comparison with experimentally determined performance metrics in the upper H-band. From this comparison, we find evidence that suppressed wavelengths progress with order according to a quadratic function. This relationship is consistent with the theoretical dependence of a PRR's free spectral range with increasing wavelength (and, therefore, order). This finding is a significant first step towards the prediction of a PRR's dip location and shape such that OH emission lines can be more accurately suppressed over a broader wavelength range. In contrast, no significant trends were identified for the progression of depth and FWHM with order.

Crucially, this paper demonstrates that PRR filters have the potential to be viable for sky background suppression in the near-infrared. We successfully demonstrated that our current PRR filter performs as expected from the theory shown in section 5. Additionally, we successfully quantified the coefficients in Equation 3 and demonstrated the capabilities of our upper H-band testbed for PRR filters with a relatively straightforward analysis. Further, this work illuminates the challenges associated with utilizing higher order dips in a PRR filter for the suppression of sky background.

8. Acknowledgements

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Appendix A: Performance metrics for the first, second, fourth, and fifth dips

Table A1. The performance metrics of the first, second, fourth, and fifth dips created by ANT-07 for the first four orders contained in the lower H-band.

<i>Dip</i>	<i>Order</i>	<i>DF $\lambda_{sup,m}$ (nm)</i>	<i>DF depth (dB)</i>	<i>VI depth (dB)</i>	<i>DF FWHM (nm)</i>	<i>VI FWHM (nm)</i>
1	1	1484.971	7.089	7.7	0.1282	0.12
1	2	1510.302	8.419	9.8	0.1651	0.15
1	3	1536.974	7.976	8.2	0.3236	0.35
1	4	1565.218	1.068	5.2	0.4651	0.75
2	1	1486.181	7.101	7.7	0.1230	0.11
2	2	1511.555	7.247	7.5	0.1439	0.14
2	3	1538.313	3.631	6.2	0.7279	0.51
2	4	1566.629	0.958	5.4	0.3259	0.85
4	1	1496.912	9.199	9.6	0.1692	0.14
4	2	1523.454	9.970	10.2	0.2703	0.30
4	3	1551.485	1.586	5.7	0.2066	0.45
4	4	1581.392	0.752	3.5	0.6833	0.85
5	1	1500.613	7.267	8.8	0.1130	0.14
5	2	1527.174	6.778	7.6	0.4370	0.40
5	3	1555.234	5.215	5.2	0.6946	0.65
5	4	1585 ^a	—	3.3	—	1.10

^aFor the fourth order of the fifth dip, the fitter failed to find the dip. The VI-suppressed wavelength has been included in lieu of the DF-suppressed wavelength.
Note: DF indicates the values that were determined by the dip-fitter, while VI indicates the values that were determined by visual inspection.

Photometric Capabilities and Scientific Applications of the Meshtitsa Private Observatory

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Abstract This paper presents the Meshtitsa Observatory—a small-aperture technical platform for high-precision photometric astronomical observations. Located near Pernik, Bulgaria, it is a privately operated roll-off-roof facility equipped with a 0.25-m telescope, CMOS camera, and photometric filters. All operations are remotely managed using a Debian-based INDIGO server infrastructure. The observatory has successfully captured light curves of cataclysmic stars, stellar flares, and transit events of hot Jupiter-type exoplanets with sufficient photometric precision for scientific analysis. These results demonstrate the viability of small-aperture observatories.

1. Introduction

Within professional optical astronomy, telescopes are commonly sorted by aperture into *small* ($D \leq 2$ m), *medium* (2–5 m), and *large* (6–12 m) categories (NRC 2015). In the non-professional realm, the threshold shifts downward; the NASA’s Exoplanet Watch program, for example, designates any instrument with $D \leq 1$ m as “small” and shows that telescopes as modest as 0.15–0.25 m routinely supply transit ephemerides and high-cadence light curves of variable targets (Zellem *et al.* 2020). Because they are affordable, easily automated, and rapidly re-tasked, small telescopes remain indispensable for tracking swiftly evolving phenomena, ranging from near-Earth asteroids and cataclysmic variable stars to shallow exoplanet transits, and they often provide the first layer of discovery and follow-up, leaving larger telescopes free for deep imaging and high-resolution spectroscopy.

Cataclysmic variables (CVs) are a group of stars that show sudden and unpredictable changes in brightness. Nowadays, it is well known that their high-amplitude outbursts are due to an increased accretion rate onto the disk formed around the more massive companion of a close binary system, comprised of a white dwarf and a late-type main-sequence star. Their erratic behavior has attracted both professional and non-professional astronomers. Even small telescopes make them visible, and hundreds more can be monitored using modern CCD/CMOS cameras. The field is especially open to community contributions, as professionals cannot monitor all known objects.

The study of distant planets has also become a field of activity for both professional and citizen scientists. Several indirect methods for exoplanet research and discovery have been utilized, most notably the transit method, which is available for small-aperture ground-based observations—a telescope with an aperture of 0.25 m can achieve accurate enough results to obtain a good model fit, e.g. Fowler *et al.* (2021).

Stellar flares are high-energy events on stellar surfaces, triggered by the reconnection of magnetic field lines. They are believed to occur in the upper atmosphere of all main-

sequence stars that possess a convective layer and are driven by similar physical processes. In the Sun, flares arise in regions of enhanced magnetic activity, whereas in M-dwarf stars, these events seem to occur across the whole stellar surface (Benz and Güdel 2010).

In this study, we present results from observations of CV stars—a newly discovered dwarf-nova superhumps during superoutburst, exoplanet transit, and stellar flares of an M-dwarf star conducted at the Meshtitsa Observatory, indicating sufficient photometric precision of small astronomical telescopes, operated entirely remotely and in an automated manner. The Meshtitsa Observatory is a private, donation-funded astronomical facility featuring a typical roll-off-roof design, optimized for remote management. Located in the village of Meshtitsa, near Pernik, Bulgaria, the site sits at an altitude of 690–695 m at coordinates: 42.67°N, 23.00°E.

The observatory operates under Bortle class 4 skies, providing favorable conditions for astronomical observations. With an average of ≈ 200 clear nights per year, the facility is dedicated to continuous time-domain monitoring using a small-aperture telescope.

2. System configuration

2.1. Telescope

The observatory is equipped with a Sky-Watcher Telescope N 250/1200 PDS Explorer BD OTA², shown in Figure 1. The telescope is fitted with a Baader MPCC Mark III coma corrector. The optical parameters of the system are shown in Table 1.

Table 1. Sky-Watcher Telescope N 250/1200 PDS Explorer parameters.

Parameter	Value
Optical design	Parabolic Newtonian reflector
Aperture (mm)	250
Focal length (mm)	1200
Aperture ratio (f/)	4.8
Tube length (mm)	1120
Tube weight (kg)	14.5

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Although operating near the limits of its load capacity, the German equatorial mount EQ6-R Pro³ provides reliable object tracking. Automatic guiding is achieved using a TS Optics Guidescope AC 80/600⁴ with an ASI290MC guiding camera⁵. The guiding process is controlled by the INDIGO software framework, which supports a variety of guiding algorithms to ensure stable tracking and high-quality guiding performance during long exposure sequences. The system is optimized to deliver an average RMSE guiding error below 0.5".

The entire system is managed by the INDIGO platform and the Ain INDIGO Imager running on a Linux operating system, which is also being used at professional observatories⁶. The INDIGO software enables full remote control and an automated workflow, including pointing, highly detailed task scheduling for exact times, roof opening and closing, and sky-condition monitoring in cooperation with a CLOUDWATCHER⁷ device (cloud cover monitoring, precipitation, and alarms when unfavorable weather conditions arise). With this integrated software-and-hardware setup, the observatory operates completely autonomously, eliminating the need for constant supervision during observations.

2.2. Filters

The telescope at the Meshtitsa Observatory is equipped with a photometric Baader UBVRI Bessel Filter Set 36mm⁸ (Figure 2).

Following best practices and the recommendations outlined in the *AAVSO Guide to CCD/CMOS Photometry*, Chapter 6 (AAVSO 2022), tests were conducted to improve photometric accuracy by imaging standard fields to measure transformation coefficients for each filter. The coefficients shown in Table 2 are derived using the AAVSO Transform Generator (AAVSO 2014).

2.3. Camera

The ASI 533 MM Pro⁹ camera is a high-performance monochrome imaging device well-suited for both artistic astrophotography and scientific research (see Figure 3). It features a Sony IMX533 back-illuminated CMOS sensor. One of its major advantages is the complete absence of amp glow, which results in exceptionally clean raw images and simplifies the calibration process.

The ASI 533 MM Pro also has a dual-stage TEC cooling system that can reduce the sensor temperature by up to 35°C below ambient, effectively minimizing thermal noise during long exposures. The camera parameters are summarized in Table 3.

The sensor quantum efficiency curve (QE), shown in Figure 4 peaks above 90% in the blue-green part of the spectrum (approximately 450–500 nm), making it highly efficient for most photometric work in the B, V, and R bands. ASI 533 MM Pro has limited sensitivity in the U band, with quantum efficiency dropping significantly around 350–400 nm. Although U-band photometry can be performed with this camera, it requires considerably longer exposures than in the B- or V-band.

A linearity test was conducted under stable observational conditions. The ASI533MM Pro camera was operated at a constant sensor temperature of 0°C, using a steady, uniformly

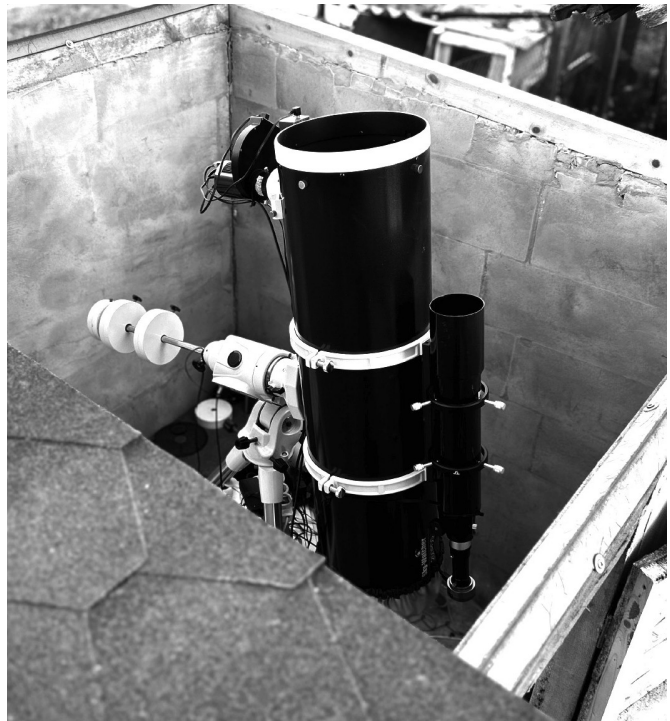


Figure 1. The telescope at the Meshtitsa Observatory, a 0.25m Sky-Watcher Newtonian reflector (f/4.8, focal length 1200mm) mounted on an EQ6-R Pro German equatorial mount.

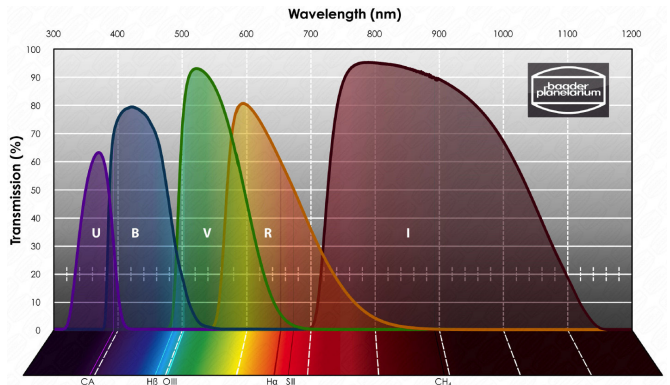


Figure 2. Spectral profile of Baader Bessel-UBVRI Filters. Image source: Baader Planetarium (2026).

Table 2. Standard-system transformation coefficients derived for the Meshtitsa telescope.

Coefficient	Value	Error
T_{bv}	1.095	0.009
$T_{b_{bv}}$	0.080	0.012
T_{br}	1.144	0.013
$T_{b_{br}}$	0.050	0.006
$T_{v_{bv}}$	-0.008	0.015
T_{vr}	1.255	0.033
$T_{v_{vr}}$	-0.012	0.025
$T_{r_{vr}}$	-0.221	0.030



Figure 3. Camera ASI533 MM Pro CMOS, filter wheel, and automatic focuser mounted on the 0.25-m telescope.

Table 3. ASI 533 MM Pro camera parameters.¹

Parameter	Value
Sensor	CMOS Chip (Sony IMX533)
Light spectrum	U (limited sensitivity) + Visible + NIR
Total pixels	9 MP
Resolution W x H	3 008 × 3 008 px
Pixel size	3.76 μ m
Bit depth	14
Full well capacity	50 000
Max. cooling difference below ambient temperature	35° C
Weight	410 g

¹ Source: <https://www.zwoastro.com/product/asi533-pro-series/>

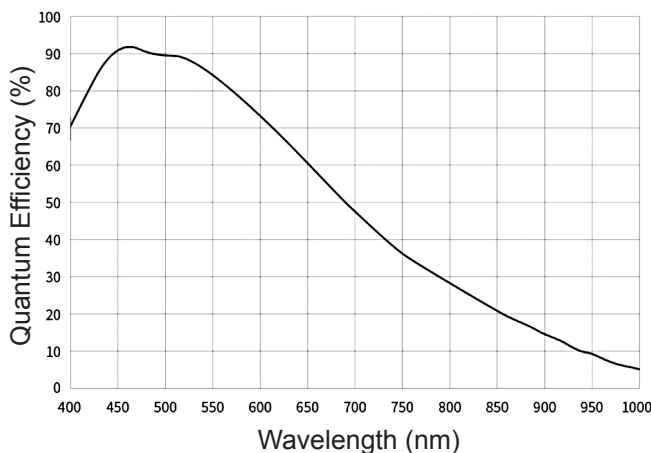


Figure 4. Quantum Efficiency of ASI533MM Pro CMOS camera according to the manufacturer's website. Image source: Suzhou ZWO Co., Ltd. (2026).

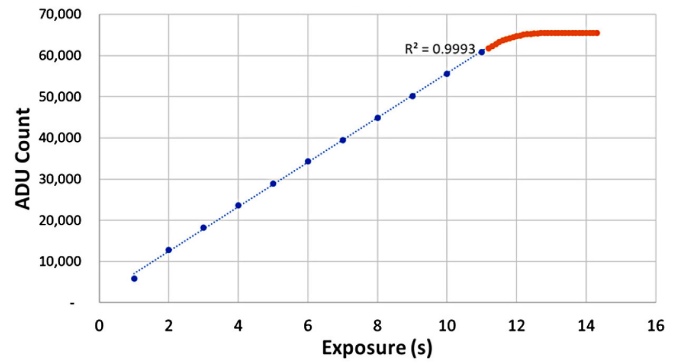


Figure 5. Linearity test (Gain 0, Offset 10) for the ASI533MM camera in Meshtitsa Observatory showing relation between ADU counts and exposure time.

illuminated surface as the light source. A broadband L (luminance) filter was placed in the optical path. Exposure times were varied from 1.0 to 15.0 seconds in steps of 1.0 second, and the camera settings were fixed at Gain = 0 and Offset = 10 to maximize dynamic range. For each exposure, the mean ADU value for the frame was measured.

The resulting data, shown in Figure 5, demonstrate a well-defined linear response up to approximately 60,000 ADU. Beyond this level, the response begins to flatten as the detector approaches its saturation regime. Although the sensor uses a 14-bit analog-to-digital converter (ADC), its output is internally mapped to a 16-bit format, allowing for digital values up to 65,535. The maximum recorded value in fully saturated pixels is 65,532 ADU. For optimal photometric results, exposures should be adjusted to keep the peak signal below ~60,000 ADU, thereby avoiding non-linear compression near the ADC ceiling.

2.4. Optical performance

The Meshtitsa Observatory is located near Pernik, Bulgaria, at an altitude of 695 m. The typical seeing conditions are characterized by FWHM between 2.0" and 2.5". Under a clear, moonless night, and with the telescope pointed at an altitude of at least 60° above the horizon, the current optical system achieves a limiting magnitude of ≈ 17.5 in the V band with a 30-second exposure at a signal-to-noise ratio of ≈ 7 , which was estimated by the astrometric software ASTAP¹⁰. Long-term measurements performed over several months with a Lunatico Astronomia CloudWatcher¹¹ indicate that the maximum sky darkness at the site reaches 19.7 mag/arcsec².

For a system with 3.76 μ m pixel size and 1200 mm focal length, a scale of 0.64" per pixel is close to oversampling for typical seeing conditions at a given location. At 2×2 binning, the resulting pixel scale is approximately 1.3" per pixel, which better matches the atmospheric resolution limit. At a focal length of 1200 mm, combined with the sensor size of 11.31×11.31 mm, the system provides a field of view of approximately $0.5^\circ \times 0.5^\circ$.

As an example, Figure 6 shows a V425 Cas stellar field from a 300-second calibrated science image.

The image generated by the ASTAP aberration inspector (Figure 7) displays star cutouts sampled from a 3×3 grid, demonstrating how the PSF varies across the field.

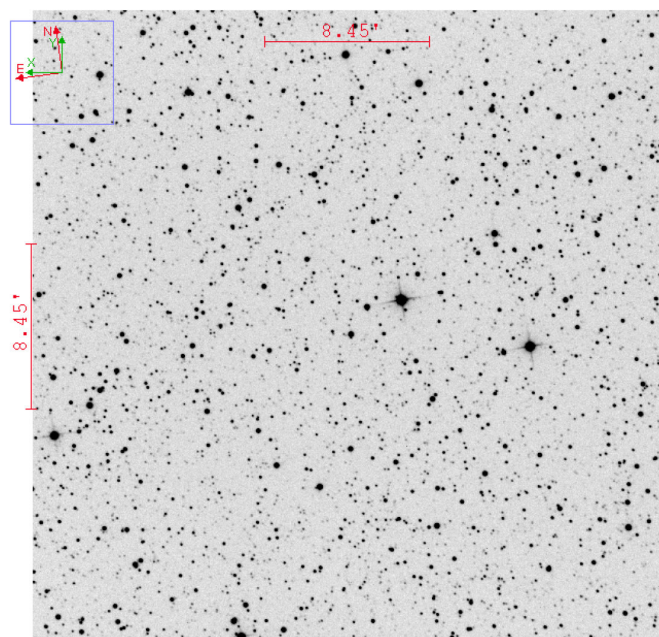


Figure 6. Single calibrated frame of a V425 Cas stellar field obtained with the V filter (300 s exposure, 2×2 binning, gain 0, offset 10).

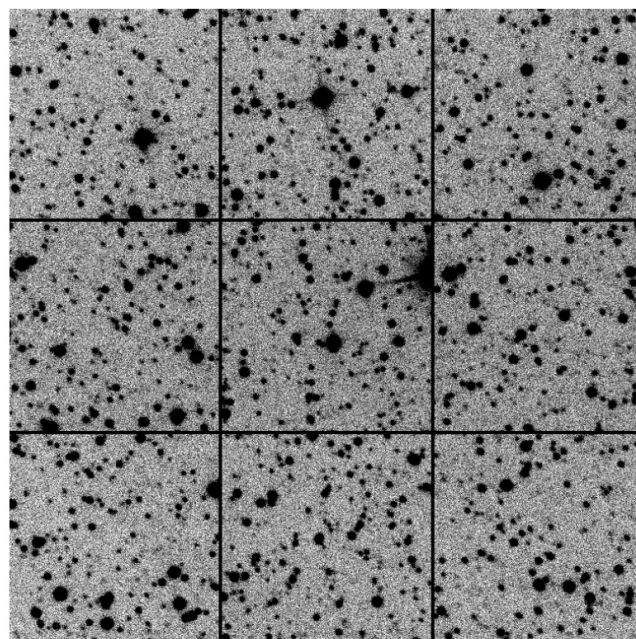


Figure 7. ASTAP aberration inspector for the V425 Cas field: a 3×3 grid of stellar cutouts sampling the corners, edges, and center of the frame, used to assess spatial variations of the PSF and field-dependent optical aberrations.

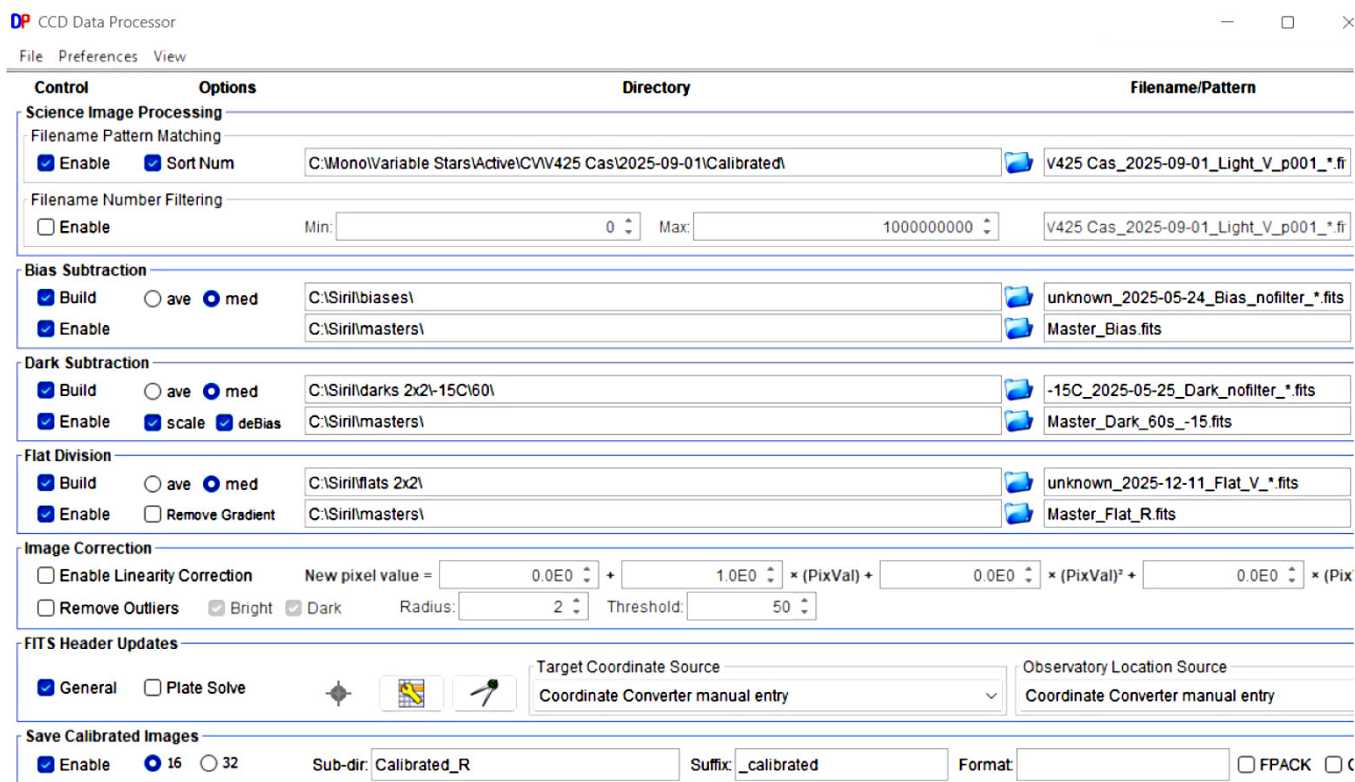


Figure 8. ASTROIMAGEJ Data Processor interface for building master calibration frames and calibration of science images.

2.5. Calibration strategy

The calibration of the science images followed standard CCD reduction procedures, including the acquisition of bias, dark, and flat-field frames, and was performed using *ASTROIMAGEJ* (Collins *et al.* 2017), as illustrated in Figure 8.

Bias frames were obtained with the telescope aperture closed, using an exposure time of 0 s. A total of 99 bias frames were acquired and later combined using the median method.

Dark frames were also taken with the telescope aperture closed, matching both the exposure time and the CCD temperature used during the scientific observations. Typically, the camera operated at -20°C , a temperature at which, according to the manufacturer's specifications, the thermal noise of the detector is negligible. If environmental conditions did not allow operation at this temperature, the camera was set to at least -15°C . For each of these operating temperatures, dedicated dark frames were obtained using the same exposure and temperature as those in the observations.

The enabled calibration options in the *ASTROIMAGEJ* CCD Data Processor are summarized in Table 4.

Flat fields (see Figure 9) were obtained immediately after sunset. The exposure time was adjusted so that the mean pixel value in each frame was maintained at $\sim 30,000\text{ADU}$, well within the linear response range of the camera. At least seven flat-field frames were taken for each filter, and all calibration frames were stacked using median combining to remove cosmic rays and residual artifacts. *ASTROIMAGEJ* generates a normalized master flat by scaling individual frames to a common intensity level. This master flat is then applied to science images by division.

Table 4. AstroImageJ (AIJ) CCD Data Processor calibration options.

Step	Enabled Options
Bias subtraction	Build master bias; apply bias subtraction; combine method: median
Dark subtraction	Build master dark; apply dark subtraction; deBias; dark scaling; combine method: median
Flat division	Build master flat; apply flat-field correction; combine method: median



Figure 9. A master flat field obtained in the V filter, created from the median combination of multiple twilight flats.

3. Results

Data from the Meshtitsa Observatory are available through the AAVSO (Kloppenborg 2025) and are already being used in astronomical research. Exoplanet transit observations have likewise been incorporated into NASA's Exoplanet Watch¹² database. The following section presents several new results that demonstrate the capabilities of small telescopes such as the one at the Meshtitsa Observatory.

3.1. Superhumps of dwarf nova GOTO065054+593624

The dwarf nova GOTO065054+593624 (GOTO0650) was discovered on 4 October 2024 (Killestein *et al.* 2024), by the GOTO all-sky survey¹³ and quickly identified by volunteers from the Kilonova Seekers¹⁴. Their rapid classification allowed immediate follow-up, revealing a WZ Sge type cataclysmic star with an 8.5-magnitude outburst (Killestein *et al.* 2025). The Meshtitsa Observatory joined the follow-up campaign and conducted observations over 26 nights, spanning 98 hours, across a two-month period, making it one of the sites that detected the first superhumps of the star during its outburst.

Among all observations, superhumps were identified in a total of six instances. The observations listed in Table 5, were processed using *ASTROIMAGEJ*. The periodogram at Figure 10 reveals the first detected superhumps for the GOTO0650, visible as periodic brightness modulation with an amplitude of 0.06 (M). Using the Generalized Lomb–Scargle (Zechmeister and Kürster 2009), the superhump period was determined to be $\approx 91 \pm 1\text{ min}$.

The superhump period is crucial for determining the mass ratio of the system's components (Kato and Osaki 2013). This is done through the *superhump period excess*,

$$\epsilon = \frac{P_{\text{sh}}}{P_{\text{orb}}} - 1 \quad (1)$$

where P_{sh} is the measured superhump period and P_{orb} is the orbital period of the binary.

Typical superhump period excesses in WZ Sge systems range from 0.8% to 1.5%. Assuming GOTO0650 follows this trend, the orbital period can be tentatively constrained to lie in the 88–90 minute range, e.g. Killestein *et al.* (2025). However, applying this relation requires an independent measurement of the orbital period P_{orb} , typically obtained through radial velocity studies.

3.2. Transit of exoplanet TOI-2109b on 22 March 2024

TOI-2109b is an ultrahot Jupiter-like exoplanet discovered in 2021 by NASA's Transiting Exoplanet Survey Satellite (TESS)¹⁵. The planet orbits an F-type star located about 855 light years away. TOI-2109b possesses a mass of approximately 5.02 Jupiter masses and a radius about 1.35 Jupiter radii. Observations of newly discovered exoplanets are particularly valuable, as their ephemerides are still being refined.

A transit of TOI-2109b was observed from Meshtitsa Observatory on 22 March 2024. The observation was conducted using a photometric V filter with an exposure time of 60 seconds per frame. Over approximately 4 hours, a total of 215 frames were captured. Both the photometric measurements and the

Table 5. Photometric observations of GOTO0650 with superhump period determination.

<i>Obs. Start UTC</i>	<i>Obs. End UTC</i>	<i>Dur. (h)</i>	<i>Mean Mag. V</i>	<i>Mean Err. V</i>	<i>Ampl. Mag. V</i>	<i>Period</i>
10/20/2024 19:45	10/21/2024 2:39	6.9	14.220	0.011	0.055	0.06332
10/22/2024 19:18	10/23/2024 2:54	7.6	14.275	0.016	0.034	0.06293
10/23/2024 19:48	10/24/2024 2:42	6.9	14.352	0.013	0.032	0.06382
10/25/2024 19:38	10/26/2024 2:56	7.3	14.534	0.015	0.030	0.06327
10/26/2024 19:28	10/27/2024 2:22	6.9	14.639	0.015	0.025	0.06196
10/27/2024 19:49	10/28/2024 2:25	6.6	14.744	0.015	0.022	0.06334

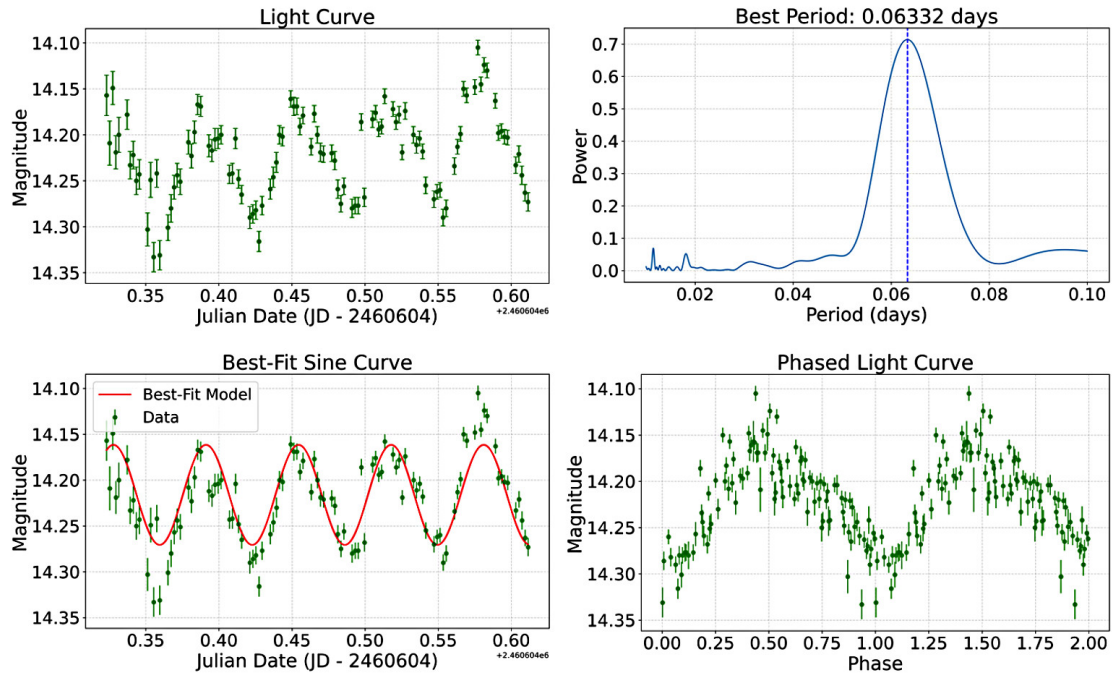


Figure 10. Periodogram and V-band light curve from the first observing night on Oct 20, 2024 on which superhumps of GOTO0650 were detected. The period derived with the Generalized Lomb–Scargle algorithm was used to compute the best-fitting sinusoid over the original photometric data.

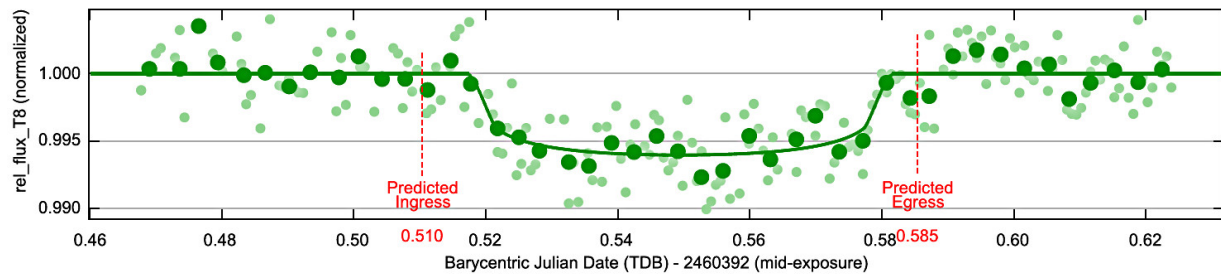


Figure 11. Relative flux light curve of TOI-2109b based on 215 V-band exposures taken on 22 March 2024. The data points represent the differential photometry of the target star using nearby comparison stars. The smooth model curve shows the best-fit transit profile calculated within ASTROIMAGEJ, based on the observed flux decrease during the planetary transit. The characteristic U-shape reflects the partial occultation of the stellar disk by the orbiting planet.

Table 6. Flares of AD Leo captured between 16 January and 2 May 2025 in B band (Johnson B filter) with a 30-seconds cadence.

Flare No.	Flare Start JD	Flare End JD	Dur. (min)	Peak JD	Peak Mag.	δ Mag.	Energy in B (erg)
1	2460695.39903	2460695.42996	45	2460695.40336	10.32	0.51	1.90e+32
2	2460710.32434	2460710.33953	22	2460710.32990	10.66	0.18	2.48e+31
3	2460712.39542	2460712.42106	37	2460712.40529	10.69	0.15	1.60e+31
4	2460721.37398	2460721.38063	10	2460721.37651	10.78	0.06	1.74e+30
5	2460727.39928	2460727.41245	19	2460727.40507	10.04	0.81	7.00e+31
6	2460727.41513	2460727.42673	17	2460727.41738	10.69	0.16	1.45e+31
7	2460729.45763	2460729.46819	15	2460729.46021	10.74	0.11	3.47e+31
8	2460729.51584	2460729.52411	12	2460729.51942	10.77	0.08	3.38e+30
9	2460732.31972	2460732.38421	93	2460732.32789	10.11	0.74	1.06e+33
10	2460732.38772	2460732.39952	17	2460732.39038	10.10	0.75	3.02e+32
11	2460739.31536	2460739.33539	29	2460739.32174	10.46	0.39	2.28e+32
12	2460739.33812	2460739.38395	66	2460739.34096	10.04	0.81	2.46e+32
13	2460739.46924	2460739.48108	17	2460739.47281	10.58	0.27	3.21e+31
14	2460756.27626	2460756.30324	39	2460756.27891	10.33	0.51	1.90e+32
15	2460773.27872	2460773.28845	14	2460773.28205	10.75	0.09	2.63e+31
16	2460773.31697	2460773.32446	11	2460773.31929	10.77	0.08	1.47e+31

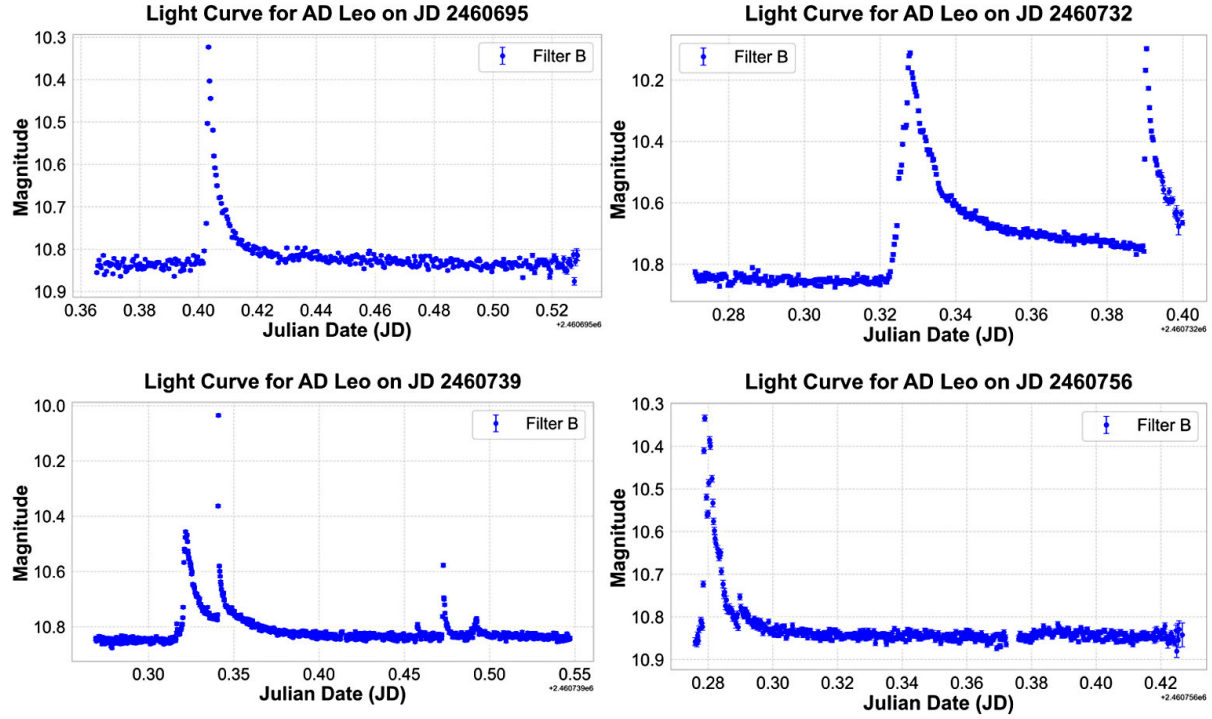


Figure 12. Light curves of several of the most characteristic AD Leo flares obtained at Meshtitsa Observatory in the B filter with a 30-second cadence.

transit model fit, shown in Figure 11, were derived using AIJ's built-in differential photometry and fitting tools.

The transit light curve of TOI-2109b obtained on 22 March 2024 was modeled using the fitting tools in ASTROIMAGEJ. The best-fit parameters are consistent with the published ephemerides, e.g. Wong *et al.* (2021).

The fitted planet-to-star radius ratio is $(R_p/R_*)^2 = 0.00511$, corresponding to a transit depth of 6.0 ppt. The total transit duration was measured as $t_{14} = 0.0646 \text{ d } (01^{\text{h}} 33^{\text{m}} 01^{\text{s}})$. Assuming the stellar radius $R_* = 1.698 R_\odot$, this corresponds to a planetary radius of $R_p = 1.18 R_{\text{Jup}}$. The fit yields a transit geometry with an inclination of $i \approx 71^\circ$.

The quality of the fit is reflected by the statistical indicators: the RMS of the residuals is 0.00207 in normalized flux (~ 2.1 ppt), and the reduced chi-square is $\chi^2/\text{dof} = 1.07$.

3.3. Flares of AD Leo captured between 16 January and 2 May 2025

AD Leo is a dM3.5e star, only about 5 pc from the Sun. Statistical analyses indicate that it produces energetic flares at a moderate rate and ranks among the most thoroughly studied flare stars in the solar neighborhood, e.g. Pettersen and Coleman (1981).

Table 6 lists 16 B-band flares of AD Leo observed with a 30-s cadence between 16 January and 2 May 2025. Energies were calculated by applying the standard time integration of the luminosity, widely formalized by flare-energy studies, e.g. Hunt-Walker *et al.* (2012). The software used in energy calculation is a custom in-house PYTHON-based program developed specifically for this project. At present, it is not publicly released.

Representative AD Leo light curves in Figure 12 display the classic fast-rise-exponential-decay (FRED) flare profiles.

4. Conclusions

In this study, selected first results from observations conducted with the remote Meshtitsa Observatory were presented:

- V-band monitoring during the outburst of the dwarf nova GOTO065054 revealed the onset of superhumps and yielded a period of 91 ± 1 min.
- A transit observation of TOI-2109b revealed a duration of 0.0646 d with a depth of 6.0 ppt, aligning with predicted values, and yielded key statistics on which the planetary radius estimate rests.
- Several high-cadence B-band flares on AD Leo were presented.

These results show that observations from small, non-professional observatories achieve sufficient precision for use in professional studies. Their capacity for frequent, targeted monitoring makes them an indispensable part of global astronomical networks, especially for tracking dynamic or unpredictable objects that larger surveys may miss. Beyond the individual results, this work affirms the strategic role of citizen-science observatories in modern time-domain astronomy. Currently, Meshtitsa Observatory continues to conduct regular observations and participate in international campaigns.

5. Acknowledgements

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Notes

¹ <https://orcid.org/0009-0002-1484-7029>

² Sky-Watcher Telescope N 250/1200: <https://skywatcher.com/product/bkp-250-ds/>

³ Sky-Watcher Telescope EQ6-R Pro: <https://skywatcher.com/product/eq6r-pro/>

⁴ TS Optics Guidscope AC 80/600: <https://www.teleskop-express.de/en/telescopes-4/achromatic-refractor-54/ts-opticsguiding-scope-80-600-mm-with-adjustable-tube-rings-8797/>

⁵ ZWO Astro ASI290MC camera: <https://www.zwoastro.com/product-category/cameras/>

⁶ INDIGO platform: <https://www.indigo-astronomy.org/>

⁷ CLOUDWATCHER: <https://lunaticoastro.com/aag-cloud-watcher/>

⁸ Baader UBVRI Bessel filter set: <https://www.baader-planetarium.com/en/baader-ubvri-bessel-filter-setphotometric.html/>

⁹ ZWO Astro ASI 533 MM Pro: <https://www.zwoastro.com/product/asi533-pro-series/>

¹⁰ ASTAP astrometric software: <https://www.hnsky.org/astap.htm/>

¹¹ Lunatico Astronomia CLOUDWATCHER: <https://www.lunaticoastro.com>

¹² NASA Exoplanet Watch: <https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/overview/>

¹³ GOTO all sky survey: <https://goto-observatory.org/>

¹⁴ Kilonova Seekers: <https://www.zooniverse.org/projects/tkillestein/kilonova-seekers/>

¹⁵ NASA Transiting Exoplanet Survey: <https://tess.mit.edu/>

¹⁶ Scorpion Shipping Ltd.: <https://scorpion-shipping.net/>

¹⁷ Institute for Advanced Physical Studies: <https://iaps.institute/>

Empirical Transformation Formulae from APASS DR9 to the Johnson–Kron–Cousins $BVR_C I_C$ Photometric System

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Abstract We present new empirical polynomial transformation equations from the AAVSO Photometric All-Sky Survey Data Release 9 (APASS DR9) Sloan gri photometry to the Johnson–Kron–Cousins (JKC) $BVR_C I_C$ system, derived via Orthogonal Distance Regression (ODR) on 41,311 APASS DR9 stars and validated independently on $N = 287$ standards drawn from four catalogues. Model selection between candidate polynomial orders uses the Akaike Information Criterion (AIC). Compared with the most widely used linear transformations from the literature, the new formulae reduce the validation root-mean-square (RMS) scatter by +7% in V (0.030 mag), +36% in B (0.053 mag), +26% in R_C (0.043 mag), and +30% in I_C (0.073 mag); throughout this paper, percentages express the relative reduction of the RMS in magnitudes (i.e. +7% means $\text{RMS}_{\text{new}} = 0.93 \times \text{RMS}_{\text{old}}$). Residual chromatic slopes versus $(g-r)_0$ are consistent with zero for V, R_C , and I_C , and significantly reduced for B; no significant reddening-dependent slope is found in B, R_C , or I_C , and the V slope is at the millimagnitude level. The second-order reddening bias between reddening-corrected and observed-magnitude inputs is bounded analytically below 0.001 mag for V and B at $E(B-V) = 0.20$ mag. The transformations are valid for $-0.28 \leq (g-r) \leq +1.10$ (spectral types OB to late K). The I_C formula is provisional, pending a larger validation sample. A public PYTHON implementation, APASS2JOHNSON v5.0, is provided with automatic APASS retrieval, Schlegel-Finkbeiner-Davis (SFD) reddening corrections, and full error propagation.

1. Introduction

The AAVSO Photometric All-Sky Survey Data Release 9 (APASS; Henden *et al.* 2016) provides Sloan gri photometry for ~ 62 million stars in the range $7 < V < 17$ with $> 99\%$ sky coverage. This makes APASS the natural photometric reference for CCD (Charge-Coupled Device) images obtained through Johnson–Kron–Cousins (JKC) $BVR_C I_C$ filters, which remain the dominant standard system for variable star monitoring, minor-body photometry, and stellar population studies.

Previous gri $\rightarrow BVR_C I_C$ transformations—linear relations from Lupton (2005) and polynomials from Jordi *et al.* (2006), both calibrated on ~ 100 –300 stars—exhibit highly significant chromatic residuals in all bands (regression-slope significance $p < 0.001$ vs. $(g-r)_0$ for both sets; see section 5 and Table 3). This work re-derives these transformations using a calibration sample 100 – $400 \times$ larger ($N = 41,311$ APASS DR9 stars cross-matched to Landolt fields) and validates independently on $N = 287$ standards from four catalogues, achieving $\text{RMS}_V = 0.030$ mag (+7%, i.e. 0.002 mag), $\text{RMS}_B = 0.053$ mag (+36%, i.e. 0.030 mag), $\text{RMS}_{R_C} = 0.043$ mag (+26%, i.e. 0.015 mag) over Lupton (2005). The I_C transformation is improved but remains provisional (section 5.3).

Section 2 describes the data and method. Section 3 presents the formulae, including section 3.3 on reddening bias analysis. Section 4 describes the validation sample. Section 5 presents results. Section 6 discusses limitations. Section 7 describes the software. Section 8 provides conclusions. Appendix A gives auxiliary algebraic derivations.

2. Calibration data and method

2.1. Calibration sample

The calibration sample consists of 41,311 APASS DR9 stars

selected from sky regions covered by Landolt (1992, 2009) standard fields at Galactic latitudes $|b| > 15^\circ$, retaining stars with $\sigma_g \leq 0.08$ mag, $\sigma_r \leq 0.08$ mag, $-0.28 \leq (g-r) \leq +1.10$, and no APASS variability flags, plus iterative $3.5 \cdot \text{MAD}$ (median absolute deviation) outlier rejection during the ODR fitting procedure. The resulting 41,311-star sample covers $V \approx 10$ –17 and the full OB-to-M spectral type range. It should be emphasized that the V and B magnitudes used here are not direct measurements of Landolt standards: they are APASS DR9 photometric values, calibrated onto the Landolt (1992) photometric system through the APASS pipeline, which uses primary Landolt equatorial standards together with Sloan Digital Sky Survey (SDSS) standards in nightly all-sky solutions (Henden *et al.* 2016; Munari *et al.* 2014). The internal precision of APASS DR9 photometry is ≈ 0.012 – 0.013 mag in B and V at the bright end, with typical calibration errors of 0.02 mag (Henden *et al.* 2016). The complete input photometric data from which this calibration sample are selected (51,347 APASS DR9 entries from the queried sky regions, before quality cuts) is available as an electronic table in the Zenodo dataset accompanying this paper (see Data Availability statement in the Appendix); a sample extract is shown in Appendix Table A1. Per-star $E(B-V)$ values were retrieved from the Schlafly and Finkbeiner (2011) SFD reddening maps via the NASA/IPAC IRSA service, applying the Cardelli *et al.* (1989) extinction law with $R_V = 3.1$.

2.2. Regression method

Transformation coefficients were determined via Orthogonal Distance Regression (ODR; Boggs and Rogers 1990), implemented via `scipy.odr` (Virtanen *et al.* 2020). Unlike Ordinary Least Squares (OLS), which assumes that uncertainties affect only the dependent variable, ODR minimizes the sum of orthogonal (perpendicular) distances from each data point

to the fitted curve, allowing for measurement errors on both the independent and dependent variables. This is appropriate here because the APASS color indices used as predictors carry photometric uncertainties comparable to those of the JKC magnitudes used as response variables; ignoring these errors with OLS would bias the slope coefficients toward zero (regression dilution). Model selection between candidate polynomial orders was performed using the Akaike Information Criterion (AIC; Akaike 1974), which balances goodness of fit against model complexity by penalising additional free parameters: $AIC = 2k - 2 \ln(L)$, where k is the number of parameters and L the maximum likelihood. The model with the lowest AIC is preferred, providing protection against overfitting. A degree-2 polynomial in $(g-r)$ is optimal for V , B , and R_c ; a 4-parameter model with $(r-i)$, $(r-i)^2$, and $(g-r)$ as covariate was selected for I_c . Iterative $3.5 \cdot \text{MAD}$ outlier rejection was applied during the fit. Bootstrap uncertainty estimates ($N = 1000$ resamplings) for the validation statistics were implemented with the assistance of an AI language model (Claude, Anthropic; see Acknowledgements for full disclosure).

3. Transformation formulae

3.1. Version A—reddening-corrected input magnitudes

Version A accepts reddening-corrected magnitudes g_0 , r_0 , i_0 and returns dereddened JKC magnitudes:

$$V_0 = g_0 - 0.01137 - 0.55868(g-r)_0 + 0.00563(g-r)_0^2 \quad (1)$$

$$B_0 = g_0 + 0.16841 + 0.44387(g-r)_0 + 0.02810(g-r)_0^2 \quad (2)$$

$$R_{c,0} = r_0 - 0.1462 - 0.0763(g-r)_0 - 0.0426(g-r)_0^2 \quad (3)$$

$$I_{c,0} = i_0 - 0.3235 + 0.4591(r-i)_0 - 0.2421(r-i)_0^2 - 0.3115(g-r)_0 \quad (4)$$

Table 1 reports all coefficients with 95% bootstrap confidence intervals ($N = 1000$ resamplings of the calibration sample).

Table 1. Transformation coefficients with 95% bootstrap confidence intervals.

Band	C_0	C_1	C_2	C_3 [($g-r$) covariate]
V	-0.01137 ± 0.0012	-0.55868 ± 0.0021	$+0.00563 \pm 0.0009$	—
B	$+0.16841 \pm 0.0028$	$+0.44387 \pm 0.0034$	$+0.02810 \pm 0.0015$	—
R_c	-0.1462 ± 0.0021	-0.0763 ± 0.0018	-0.0426 ± 0.0012	—
I_c	-0.3235 ± 0.0087	$+0.4591 \pm 0.0092$	-0.2421 ± 0.0078	-0.3115 ± 0.0065

Note. For V , B , R_c : $\text{Band} = \text{ref} + C_0 + C_1(g-r) + C_2(g-r)^2$, where $\text{ref} = g$ (for V , B) or $\text{ref} = r$ (for R_c). For I_c : $I_c = i + C_0 + C_1(r-i) + C_2(r-i)^2 + C_3(g-r)$. All four formulae are valid for $-0.28 \leq (g-r) \leq +1.10$. Uncertainties are 95% confidence intervals (CI) from $N = 1000$ bootstrap resamplings.

Table 2. Pure second-order bias term $|A_2 \Delta R^2 E(B-V)^2|$.

$E(B-V)$ (mag)	$ AV_2 $ (mag)	$ AB_2 $ (mag)	$ AR_{c,2} $ (mag)	$ AI_{c,2} $ (mag)	Context
0.05	<0.00002	<0.0001	<0.0001	<0.0003	High $ b $
0.10	<0.0001	<0.0003	<0.0004	<0.001	$\sim 1/30$ RMS
0.20	<0.0003	<0.001	<0.002	<0.004	$\sim 1/10$ RMS
0.30	<0.0005	<0.003	<0.004	<0.009	Use Version A
0.50	<0.002	<0.007	<0.010	<0.025	Do not use Version B

Notes. Computed with $\Delta R_{gr} = 0.940$, $\Delta R_{ri} = 0.640$ ($R_V = 3.1$; Cardelli et al. 1989). The color-dependent cross-term $2A_2(g-r)_0 \Delta R_{gr} E$ contributes ≤ 0.003 mag for V across the full color range at $E(B-V) = 0.20$ mag.

3.2. Version B—observed magnitudes (CCD operational use)

Version B accepts raw APASS DR9 observed magnitudes g , r , i directly, without prior reddening correction. By construction, Version B uses the same polynomial coefficients as Version A.

It is important to clarify the meaning of this statement. Only one ODR regression is performed in this work, on the dereddened calibration data (Version A); the coefficients of Version B are not the result of an independent fit on observed (reddened) magnitudes, but are deliberately set equal to those of Version A. The two transformations are therefore not mathematically equivalent: Version A returns dereddened JKC magnitudes, whereas Version B returns observed (reddened) JKC magnitudes, and they differ by a residual extinction term $V_B - V_A \approx R_{\text{eff}} \cdot E(B-V)$ (section 3.3, Appendix A). The choice to use the same coefficients in Version B is justified empirically and analytically: (i) analytically, the second-order reddening bias that this choice introduces is bounded: < 0.001 mag for V and B at $E(B-V) = 0.20$ mag, and < 0.010 mag for R_c at $E(B-V) = 0.50$ mag, well below typical APASS photometric uncertainties (section 3.3, Table 2, Appendix A2); (ii) empirically, the validation against 287 independent standard stars (section 5) confirms that a single set of polynomial coefficients reproduces both dereddened and observed photometry to within these analytical bounds across the full operational range of the formulae. The full algebraic derivation, which makes explicit how these residual terms arise and why they remain bounded, is given in Appendix A.

$$V = g - 0.01137 - 0.55868(g-r) + 0.00563(g-r)^2 \quad (5)$$

$$B = g + 0.16841 + 0.44387(g-r) + 0.02810(g-r)^2 \quad (6)$$

$$R_c = r - 0.1462 - 0.0763(g-r) - 0.0426(g-r)^2 \quad (7)$$

$$I_c = i - 0.3235 + 0.4591(r-i) - 0.2421(r-i)^2 - 0.3115(g-r) \quad (8)$$

Valid for $-0.28 \leq (g-r) \leq +1.10$. For $E(B-V) > 0.20$ mag, Version A with per-star SFD corrections is recommended (see section 3.3).

Figure 1 compares the transformation offsets for all four bands.

3.3. Second-order reddening bias analysis

Since Versions A and B share identical polynomial coefficients, the bias from using observed rather than dereddened magnitudes can be expressed analytically. For V (full derivation in Appendix A):

$$\Delta V \equiv V_B - V_A = [R_g + A_{1V} \Delta R_{gr} + 2A_{2V} (g-r)_0 \Delta R_{gr}] E(B-V) - A_{2V} \Delta R_{gr}^2 E(B-V)^2 \quad (9)$$

where $\Delta R_{gr} \equiv R_g - R_r = 3.640 - 2.700 = 0.940$. Here R_g and R_r are the total-to-selective extinction ratios for the SDSS g and r bands. The SDSS photometric system postdates Cardelli *et al.* (1989) and its bands do not appear in that paper. The values $R_g = 3.640$ and $R_r = 2.700$ are obtained by convolving the Cardelli *et al.* (1989) extinction law (with the O'Donnell 1994 update for the optical) with the SDSS g and r filter transmission profiles, as computed by the NASA/IPAC IRSA Dust Extinction Calculator (Schlafly and Finkbeiner 2011). The first (linear) term dominates at all practical reddening values. Its physical meaning: Version B returns an observed rather than dereddened magnitude, $V_B \approx V_A + R_V^{\text{eff}} E(B-V)$, where the effective extinction coefficient is:

$$R_V^{\text{eff}} = R_g + A_{1V} \Delta R_{gr} = +3.115 \text{ mag/mag} \quad (10)$$

$$R_B^{\text{eff}} = R_g + A_{1B} \Delta R_{gr} = +4.057 \text{ mag/mag} \quad (11)$$

$$R_{R_C}^{\text{eff}} = R_r + A_{1R_C} \Delta R_{gr} = +2.628 \text{ mag/mag} \quad (12)$$

$$R_{I_C}^{\text{eff}} = R_i + A_{1I_C} \Delta R_{ri} + A_{3I_C} \Delta R_{gr} = +2.061 \text{ mag/mag} \quad (13)$$

where $\Delta R_{ri} \equiv R_r - R_i = 2.700 - 2.060 = 0.640$.

For V and B, R_{eff} closely matches the nominal JKC extinction coefficients ($R_V = 3.100$, $R_B = 4.061$), confirming the physical consistency of these two transformations. For R_C and I_C , the effective coefficients differ more substantially from their JKC nominal values ($R_{R_C} = 2.320$, $R_{I_C} = 1.490$) because these transformations mix two SDSS bands with different extinction properties, so R_{eff} is not a direct analogue of a single-band extinction coefficient.

The second (quadratic) term, $A_2 \Delta R^2 E(B-V)^2$, is the pure second-order bias, quantified in Table 2. The bias is < 0.001 mag for V and B at $E(B-V) = 0.20$ mag, robust to $R_V \in [2.5, 3.5]$. Figure 2 demonstrates empirically that these theoretical biases do not appear in the validation residuals because both the Landolt and APASS magnitudes are observed quantities: line-of-sight extinction cancels in $\Delta(\text{band}) = \text{band}(\text{Landolt}) - \text{band}(\text{predicted})$.

3.3.1. Sensitivity to R_V variations

Sight lines toward star-forming regions or dense clouds may show $R_V \in [2.5, 3.5]$. Using Cardelli *et al.* (1989) extinction ratios scaled proportionally to R_V ($\Delta R_{gr}(R_V) = 0.940 \times R_V / 3.1$, $\Delta R_{ri}(R_V) = 0.640 \times R_V / 3.1$), the variation of the pure second-order term

between $R_V = 2.5$ ($\Delta R_{gr} = 0.758$) and $R_V = 3.5$ ($\Delta R_{gr} = 1.061$) for $E(B-V) = 0.20$ mag is:

$$|\Delta(\Delta V_2)| < 0.0002 \text{ mag}, \quad |\Delta(\Delta B_2)| < 0.001 \text{ mag},$$

$$|\Delta(\Delta R_{C,2})| < 0.001 \text{ mag}, \quad |\Delta(\Delta I_{C,2})| < 0.003 \text{ mag}.$$

All values are below typical APASS photometric uncertainties ($\sigma \approx 0.02$ mag), confirming robustness across the full Galactic R_V range.

3.3.2. Empirical demonstration

The dominant first-order bias $V_B - V_A$ does not manifest in the validation residuals because both Landolt and APASS magnitudes are observed quantities: the same line-of-sight extinction cancels in $\Delta(\text{band}) = \text{band}(\text{Landolt}) - \text{band}(\text{predicted})$. Both axes in Figures 2–3 are therefore in the observed photometric system, and the residuals remain consistent with zero across all $E(B-V)$ bins for B, R_C , and I_C (regression-slope significance $p = 0.843, 0.137$, and 0.558 , respectively, vs. $E(B-V)$; none significant). For V, a weak slope ($p = 0.020$, slope $= -0.005$ mag/mag) is present, consistent with the expected second-order extinction residual of ≤ 0.001 mag at $E(B-V) = 0.20$ mag and of negligible practical impact.

4. Validation sample

The $N = 287$ validation sample was assembled from four independent catalogues, none used in calibration:

1. Landolt (1992): 61 stars ($N_{\text{obs}} \geq 15$, $11 \leq V \leq 16.5$, $\sigma_V \leq 0.010$ mag, $E(B-V) \leq 0.50$ mag, $-0.28 \leq (g-r) \leq +1.10$, $3.0 \cdot \text{MAD}$ residual clipping).
2. Landolt (2013): 45 stars at $\delta \approx +50^\circ$ ($N_{\text{obs}} \geq 5$, $11 \leq V \leq 16.5$).
3. Clem and Landolt (2013): 119 stars with stratified $(B-V)$ color sampling and directly measured R_C and I_C .
4. Stetson collection (Pancino *et al.* 2022): 62 stars ($\sigma_V \leq 0.005$ mag, $\sigma_{gr} \leq 0.03$ mag, $3.5 \cdot \text{MAD}$ residual clipping applied to each band independently).

The combined sample spans spectral types OBA ($N = 51$), AF ($N = 85$), G ($N = 71$), K ($N = 60$), M ($N = 20$); $V = 11.0$ – 15.9 mag; $E(B-V) = 0.006$ – 0.47 mag; median $(g-r)_0 = 0.43$ mag. Throughout this paper, spectral types are not derived from individual spectroscopic classifications, but assigned by binning stars in dereddened color $(g-r)_0$ according to the standard ranges OBA: $(g-r)_0 < -0.10$; AF: $-0.10 \leq (g-r)_0 < +0.40$; G: $+0.40 \leq (g-r)_0 < +0.70$; K: $+0.70 \leq (g-r)_0 < +1.10$; M: $(g-r)_0 \geq +1.10$. These bins broadly correspond to the conventional spectral classes for main-sequence stars. Figure 4 summarizes its properties.

5. Results and comparison with previous work

5.1. Comparison formulae

The formulae compared in this work are:

Lupton (2005): linear transformations from the SDSS DR12 algorithm pages, derived by matching DR4 photometry to Stetson published photometry. The Lupton (2005) page reports internal fit residuals ($\sigma \approx 0.005$ – 0.011 mag) on his calibration

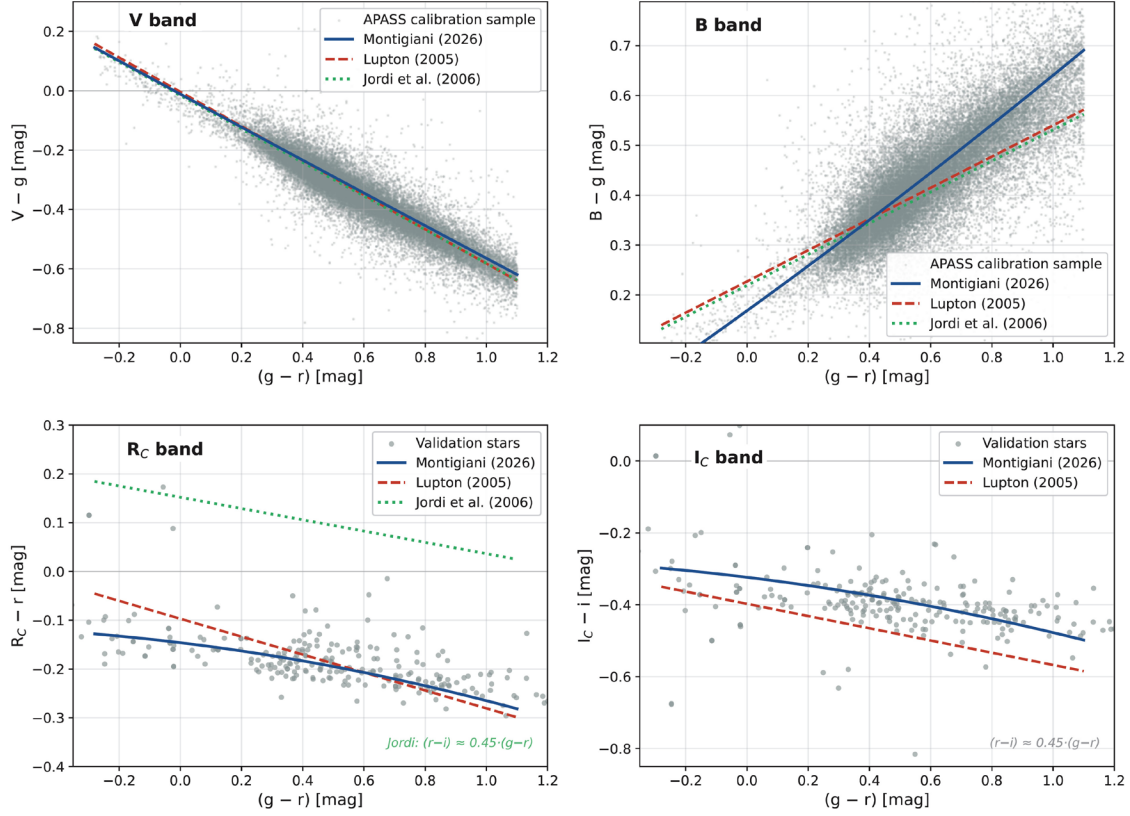


Figure 1. Transformation offsets (Band – reference SDSS band) as a function of $(g-r)$ for all four bands. Montigiani (2026): solid blue; Lupton (2005): dashed red; Jordi *et al.* (2006): dotted green. For the R_c and I_c panels, the Jordi curve is plotted using the approximation $(r-i) \approx 0.45 \cdot (g-r)$; no Jordi curve is shown for I_c because the formula requires the $(i-z)$ color index, unavailable in APASS DR9. Structural improvements are most significant for B (+36% RMS reduction over Lupton 2005).

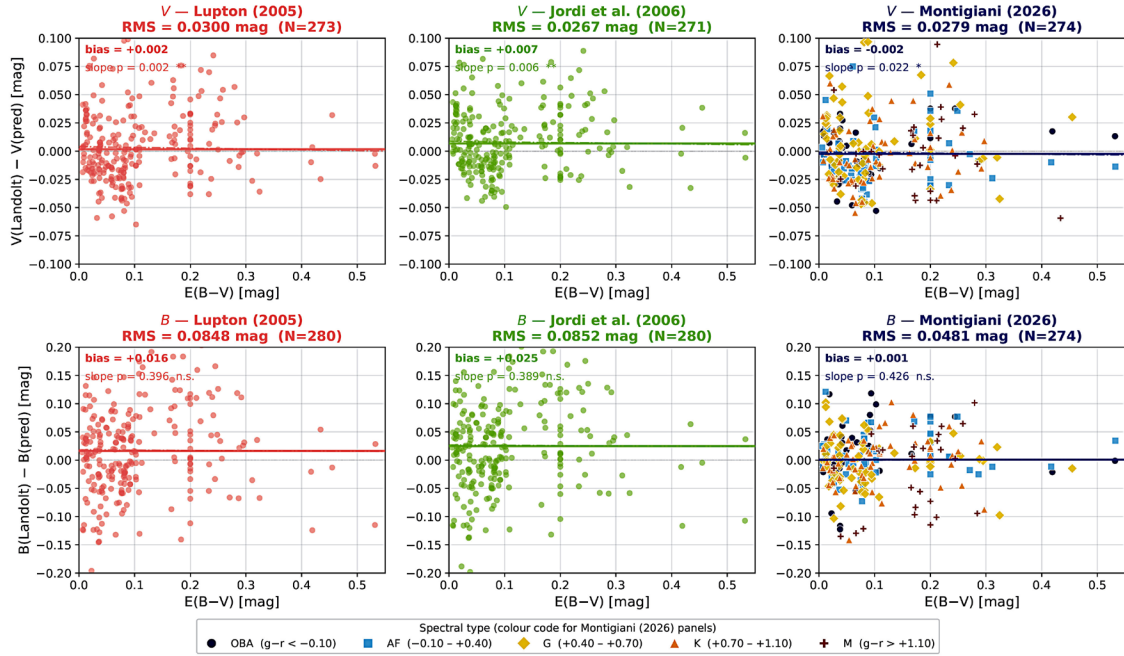


Figure 2. Residuals ΔV (top row) and ΔB (bottom row) versus $E(B-V)$ for the three formulae ($N = 287$ validation stars). Points are color-coded by spectral type in the Montigiani (2026) panels (right column): OBA, dark blue; AF, light blue; G, gold; K, orange; M, red. Solid lines: mean residual; dash-dotted lines: linear regression of residuals against $E(B-V)$ with significance code (***: $p < 0.001$; **: $p < 0.01$; *: $p < 0.05$; n.s.: not significant). The effective number of stars N reported in each panel varies because a $3.5 \cdot \text{MAD}$ sigma-clipping is applied independently for each (band, formula) combination to remove residual outliers (undetected variability, photometric blends, catalogue errors); the starting sample has 286 stars with complete photometry. Both Landolt and APASS magnitudes are observed quantities, so line-of-sight extinction cancels in $\Delta(\text{band}) = \text{band}(\text{Landolt}) - \text{band}(\text{predicted})$ and the residuals remain flat with $E(B-V)$ (consistent with the analytical bound of section 3.3, $< 0.001 \text{ mag}$ for V and B at $E(B-V) = 0.20 \text{ mag}$).

sample; these are substantially smaller than the RMS values quoted in Table 3, which are prediction errors on our independent 287-star validation sample—a conceptually different and generally larger quantity. The formulae used here are:

$$V = g - 0.5784(g-r) - 0.0038$$

$$B = g + 0.3130(g-r) + 0.2271$$

$$R_c = r - 0.1837(g-r) - 0.0971$$

$$I_c = i - 0.3780(r-i) - 0.3974$$

Jordi *et al.* (2006): polynomial transformations from Table 3 of Jordi *et al.* (2006), derived from Stetson standard-star fields compared with SDSS DR4. The formulae applied here are:

$$V = g - 0.565(g-r) - 0.016 \text{ (Population I)}$$

$$B = g + 0.312(g-r) + 0.219$$

$$R_c = r - 0.257(r-i) + 0.152 \text{ (Population I, } ugriz \rightarrow BVR_c I_c \text{, SDSS DR12 algorithm page)}$$

The I_c Jordi formula requires the $(i-z)$ color index, which is not available in APASS DR9; therefore no Jordi I_c comparison is presented.

Important note on the Jordi R_c comparison. The Population I formula $R_c - r = -0.257(r-i) + 0.152$ produces a large systematic offset (bias ≈ -0.30 mag on our validation sample) that dominates the scatter. This systematic offset arises because the Jordi Pop I formula was calibrated on a specific stellar population and may not be appropriate for a general-field sample spanning all spectral types. An alternative formula from the same SDSS DR12 page (general formula: $R_c - r = -0.153(r-i) - 0.117$) yields bias ≈ -0.046 mag and RMS = 0.040 mag on our sample, which is comparable to Montigiani (2026) (RMS = 0.043 mag). For this reason, the R_c comparison in Table 3 and Figure 6

shows the Jordi Pop I values as reported for completeness, but the improvement percentage quoted in section 5.4 refers to the comparison with Lupton (2005), which provides the fairest like-for-like benchmark.

5.2. Global validation statistics

Table 3 presents the full validation statistics. Throughout this section, the symbol p denotes the significance p -value of a linear regression of the residuals against the independent variable (chromatic, against $(g-r)_0$; or reddening, against $E(B-V)$); a small p ($p < 0.05$) indicates a statistically significant systematic trend. Where a regression slope itself is reported, it is given in mag/mag and labelled explicitly. Two slope-significance tests are reported: slope vs. $(g-r)_0$ characterizes chromatic systematics (Figures 5–6); slope vs. $E(B-V)$ characterizes reddening-dependent systematics (Figures 2–3). Bootstrap RMS uncertainties ($N = 1000$) provide 95% CI. Per-band, per-formula $3.5 \cdot \text{MAD}$ sigma-clipping is applied to remove residual outliers (undetected variables, photometric blends, catalogue errors); this is why the effective N reported in each panel of Figures 2, 3, 5, and 6 varies between 268 and 280 stars, starting from a sample of 286 with complete photometry in V , B , R_c , and I_c .

5.3. V and B bands

For V , Montigiani (2026) achieves RMS = 0.030 ± 0.002 mag (95% CI: 0.026–0.033) with bias ≈ 0 and no significant residual trend vs. $(g-r)_0$ ($p = 0.483$). A weak slope vs. $E(B-V)$ is present ($p = 0.020$, slope = -0.005 mag/mag). This small effect (≈ 0.001 mag at $E(B-V) = 0.20$ mag) is consistent with the expected second-order extinction residual from Version B usage and does not affect practical photometric precision. Lupton (2005) has comparable RMS (0.032 mag) but a highly significant chromatic slope ($p < 0.001$). The RMS improvement over Lupton is +7%.

Table 3. Validation statistics on $N = 287$ stars.

Band	Formula	Bias (mag)	RMS (mag)	95% CI (mag)	$p [(g-r)_0]$	$p [E(B-V)]$
V	Montigiani (2026)	−0.002	0.030	[0.026,0.033]	0.483 n.s.	0.020 *
V	Lupton (2005)	+0.003	0.032	—	<0.001 ***	—
V	Jordi <i>et al.</i> (2006)	+0.009	0.030	—	0.014 *	—
B	Montigiani (2026)	+0.001	0.053	[0.045,0.061]	<0.001 ***	0.843 n.s.
B	Lupton (2005)	+0.014	0.083	—	<0.001 ***	—
B	Jordi <i>et al.</i> (2006)	+0.023	0.084	—	<0.001 ***	—
R_c	Montigiani (2026)	+0.016	0.043	[0.037,0.048]	0.273 n.s.	0.137 n.s.
R_c	Lupton (2005)	−0.002	0.058	—	<0.001 ***	—
R_c	Jordi <i>et al.</i> (2006)*	−0.299	0.041	—	<0.001 ***	—
I_c	Montigiani (2026)	+0.025	0.073	[0.059,0.086]	0.767 n.s.	0.558 n.s.
I_c	Lupton (2005)	+0.059	0.105	—	<0.001 ***	—
I_c	Jordi <i>et al.</i> (2006)	n/a	n/a	—	n/a (no $i-z$)	n/a

*Jordi R_c uses the Population I formula ($R_{c-r} = -0.257(r-i) + 0.152$), which produces a large systematic bias (−0.30 mag) on the full validation sample. The RMS (0.041 mag) is dominated by this systematic offset and does not represent random scatter around a well-calibrated zero-point. See section 5.1 for details.

Notes: Bias = mean (Landolt − predicted): the mean signed offset between catalogue and predicted magnitudes; a value near zero indicates no systematic over- or under-prediction. In the photometric literature, this quantity is also referred to as the zero-point offset between the two systems; the two terms are used interchangeably and we adopt “bias” throughout this paper for consistency with the statistical convention. RMS = root-mean-square scatter of residuals around the mean: smaller values indicate better agreement with the standard catalogue. 95% CI = 95% confidence interval on the RMS, derived from nonparametric bootstrap resampling ($N = 1000$ resamplings of the validation sample with replacement); it quantifies the statistical uncertainty on the RMS estimate due to the finite sample size. $p [(g-r)_0]$: p -value of the linear regression of residuals vs. dereddened color $(g-r)_0$ (Figures 5–6); a small p -value ($p < 0.05$) indicates a statistically significant color-dependent (chromatic) systematic residual. $p [E(B-V)]$: p -value of the linear regression of residuals vs. color excess $E(B-V)$ (Figures 2–3); a small p -value indicates a reddening-dependent systematic. Significance codes: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s. = $p > 0.05$ (not significant).

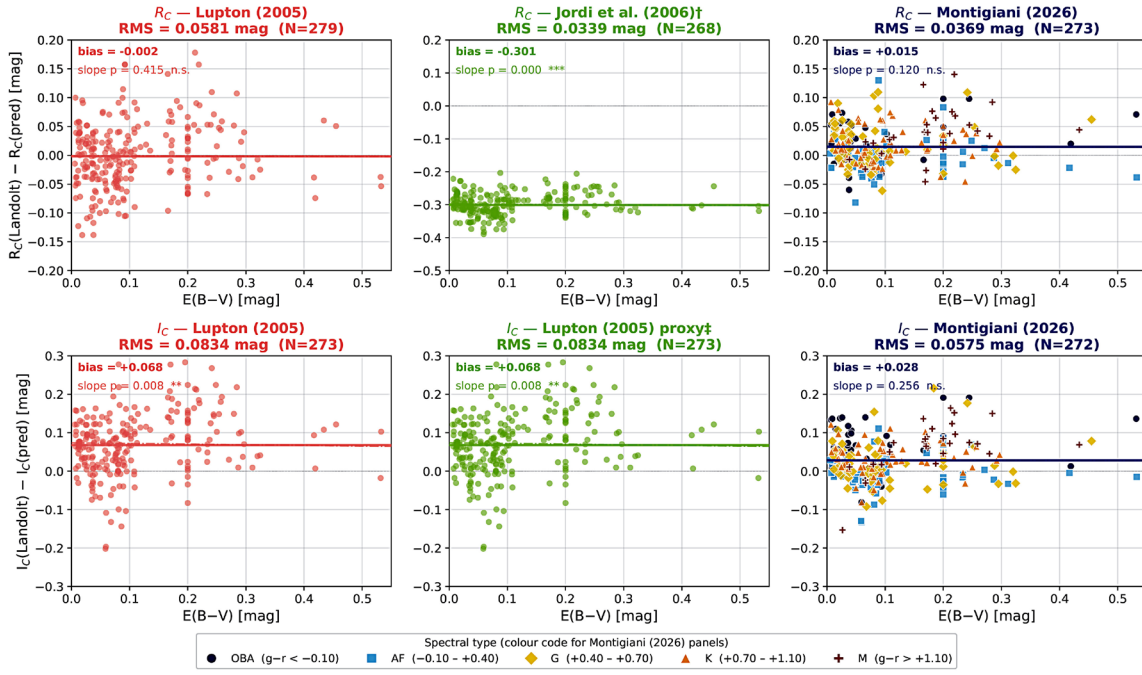


Figure 3. Residuals ΔR_C (top row) and ΔI_C (bottom row) versus $E(B-V)$ for the three formulae ($N = 287$ validation stars). Same conventions as Figure 2. The Jordi R_C Pop I formula shows a constant systematic offset of -0.30 mag, independent of $E(B-V)$ (see section 5.4 for discussion). The Jordi I_C formula requires $(i-z)$, unavailable in APASS DR9; the Lupton (2005) formula is shown as proxy (panel marker ‡). The marker † on the Jordi panel title denotes the Pop I formula $R_C - r = -0.257(r-i) + 0.152$, whose -0.30 -mag systematic bias is included in the residuals shown. As for V and B , the residuals are flat with respect to $E(B-V)$ for both Lupton and Montigiani, confirming that the analytical reddening biases derived in section 3.3 do not appear in the validation residuals because both APASS and Landolt magnitudes are observed (reddened) quantities. As in Figure 2, the effective N reported in each panel varies because of independent $3.5 \cdot \text{MAD}$ sigma-clipping per (band, formula) combination (starting sample: 286 stars).

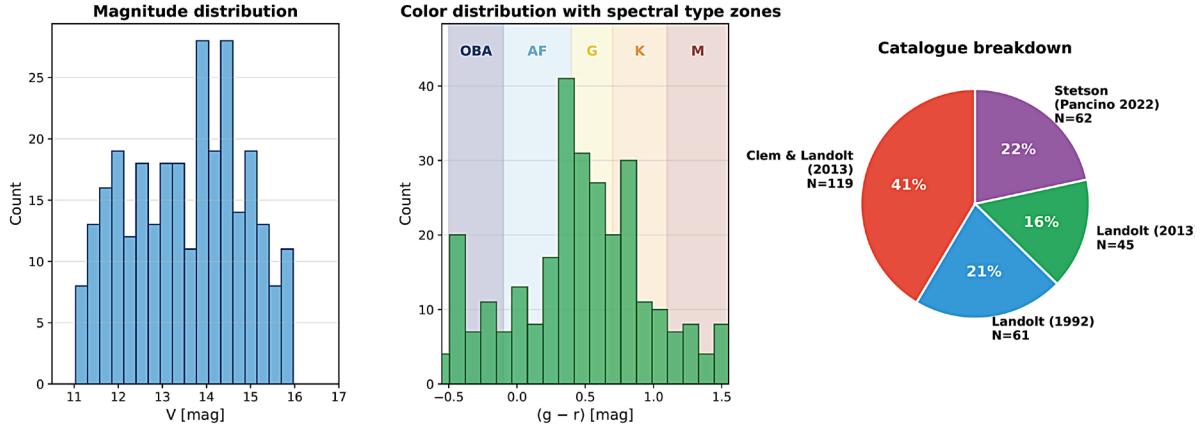


Figure 4. Properties of the $N = 287$ validation sample. Left: V magnitude distribution. Center: $(g-r)$ color distribution with spectral type zones indicated. Right: breakdown by source catalogue.

For B , the improvement is more substantial: $\text{RMS} = 0.053 \pm 0.004$ mag vs. 0.083 mag for Lupton ($+36\%$), with no slope vs. $E(B-V)$ ($p = 0.843$). The 95% CI $[0.045, 0.061]$ does not overlap with the Lupton value of 0.083 mag. A chromatic slope vs. $(g-r)_0$ persists for B ($p < 0.001$, slope $= +0.025$ mag/mag), a factor of five smaller than the Lupton slope ($+0.138$ mag/mag), and not a concern for practical applications. See Figure 5.

5.4. R_C and I_C bands

For R_C , Montigiani (2026) achieves $\text{RMS} = 0.043 \pm 0.004$ mag (95% CI: 0.037 – 0.048) with no significant slope vs. $(g-r)_0$ ($p = 0.273$) and no significant slope vs. $E(B-V)$

($p = 0.137$). This result is an improvement over the version presented in earlier drafts of this manuscript, where a weak $E(B-V)$ slope appeared due to a non-representative subset of the Stetson/Pancino sub-sample used during development. With the final validated $N = 287$ sample, no reddening-dependent systematic is detected. The improvement over Lupton (2005) is $+26\%$.

The Jordi (2006) Population I formula for R_C ($R_C - r = -0.257(r-i) + 0.152$) yields $\text{RMS} = 0.041$ mag on our sample, but with a very large systematic bias of -0.30 mag. This bias arises because the Pop I formula was derived on a narrow stellar population and does not generalize to the full

spectral type range of the validation sample. Unlike a constant zero-point offset, which could in principle be corrected by a single additive term, the -0.30 mag systematic in the Jordi Pop I formula is not constant: as visible in Figure 6 (center top panel), the residuals show a significant color-dependent trend across the full $(g-r)_0$ range (regression-slope significance $p < 0.001$), indicating that the offset varies with spectral type. A single correction term would remove the mean offset but leave a substantial chromatic residual, reducing but not eliminating the systematic. Montigiani (2026) therefore remains the recommended choice.

For I_c , the 4-parameter model achieves $RMS = 0.073 \pm 0.007$ mag (95% CI: 0.059–0.086) with no significant slope vs. $(g-r)_0$ ($p = 0.767$) and no significant slope vs. $E(B-V)$ ($p = 0.558$). The improvement over Lupton (2005) is +30%. The I_c transformation must still be considered provisional because the overall scatter ($\sigma \approx 0.073$ mag) remains large, and the validation sample contains only $N = 20$ M-type stars (7%), limiting the reliability of the formula at the reddest colors. See Figure 6.

5.5. Overall RMS comparison

Figure 7 summarizes the RMS comparison across all bands. The improvements of Montigiani (2026) over Lupton (2005) are: V +7%, B +36%, R_c +26%, I_c +30%. These improvements reflect the much larger calibration sample ($N = 41,311$ vs. ~ 300) and the use of polynomial rather than linear models where warranted.

6. Limitations

1. Version B reddening bias. The effective extinction coefficients are $R_V^{\text{eff}} \approx 3.115$ and $R_B^{\text{eff}} \approx 4.057$. The second-order bias $A_2 \Delta R^2 E(B-V)^2$ is < 0.001 mag for V and B at $E(B-V) = 0.20$ mag, robust to $R_V \in [2.5, 3.5]$. For $E(B-V) > 0.20$ mag, Version A with per-star SFD corrections is strongly recommended.

2. Spectral coverage. The validation sample contains $N = 20$ M-type (7%) and $N = 51$ OBA (18%) stars. Do not apply beyond $-0.28 \leq (g-r) \leq +1.10$, or for Be, Am, Ap, or eclipsing binary stars.

3. I_c formula—provisional. The I_c transformation shows the largest scatter ($\sigma \approx 0.073$ mag). For I_c photometry requiring $\sigma < 0.05$ mag, local calibration with Landolt standards is recommended.

4. Validation sample size. The validation sample ($N = 287$) is limited by the availability of well-calibrated JKC standards with APASS DR9 counterparts outside crowded stellar fields. The Stetson/Pancino catalogue (Pancino *et al.* 2022) is composed predominantly of globular cluster fields for which APASS DR9 photometry is unavailable owing to source blending. Future work will extend the validation to the Cousins (1981) and Graham (1982) E-region standards, which are located in uncrowded fields and partially overlap with APASS DR9 coverage.

5. APASS DR9 systematics. Spatially correlated zero-point errors at the ~ 0.02 mag level (Henden *et al.* 2016) contribute an accuracy floor not removed by the transformations.

7. Software

The PYTHON 3 package `APASS2JOHNSON.py` v5.0 implements these formulae with: (i) automatic APASS DR9 retrieval via VizieR/CDS; (ii) per-star $E(B-V)$ from SFD via NASA/IPAC IRSA (analytic fallback); (iii) Version A and Version B with identical coefficients; (iv) quadrature error propagation (photometric + calibration + extinction); (v) color-coded $E(B-V)$ warnings at 0.20 and 0.50 mag. The implementation makes use of NUMPY (Harris *et al.* 2020) and MATPLOTLIB (Hunter 2007) for numerical computations and visualisation.

The software is publicly available at:

GitHub: <https://github.com/Goldrake71/apass2johnson>

Zenodo DOI: <https://doi.org/10.5281/zenodo.19153252>

The repository includes full documentation, automated regression tests, and example files. The submission-tagged version is v5.0.

8. Conclusions

New empirical polynomial transformation formulae convert APASS gri magnitudes to the Johnson–Kron–Cousins BVR $_c$ I_c system. Main results:

1. V: $RMS = 0.030 \pm 0.002$ mag (95% CI: 0.026–0.033), +7% over Lupton (2005). No significant chromatic systematic (regression-slope significance $p = 0.483$ vs. $(g-r)_0$). A very weak reddening trend is detected ($p = 0.020$), but the actual regression slope is only -0.005 mag/mag, consistent with the expected second-order extinction residual and with negligible practical impact (≤ 0.001 mag at $E(B-V) = 0.20$ mag).

2. B: $RMS = 0.053 \pm 0.004$ mag (0.045–0.061), +36% over Lupton—the largest improvement of this work. No reddening trend (regression-slope significance $p = 0.843$, vs. $E(B-V)$). A residual chromatic trend persists ($p < 0.001$ vs. $(g-r)_0$), but the actual regression slope is $+0.025$ mag/mag, a factor of five smaller than Lupton’s slope of $+0.138$ mag/mag. The 95% C_1 does not overlap with the Lupton (2005) RMS value.

3. R_c : $RMS = 0.043 \pm 0.004$ mag (0.037–0.048), +26% over Lupton. No significant chromatic systematic (regression-slope significance $p = 0.273$ vs. $(g-r)_0$). No significant reddening systematic ($p = 0.137$ vs. $E(B-V)$). The formula is well-behaved across the full color and reddening range of the validation sample.

4. I_c : $RMS = 0.073 \pm 0.007$ mag (0.059–0.086), +30% over Lupton. No significant chromatic or reddening systematics (regression-slope significance $p = 0.767$ and $p = 0.558$, respectively, both well above the 0.05 threshold). This formula is provisional: the scatter ($\sigma \approx 0.073$ mag) remains large and the M-star coverage is limited ($N = 20$). For I_c photometry requiring $\sigma < 0.05$ mag, local calibration with standard stars is recommended.

5. Section 3.3 demonstrates analytically that the second-order reddening bias from using identical coefficients for Versions A and B is < 0.001 mag for V and B at $E(B-V) = 0.20$ mag, and < 0.010 mag for R_c at $E(B-V) = 0.50$ mag, robust to $R_V \in [2.5, 3.5]$.

6. Bootstrap resampling ($N = 1000$) confirms result stability. The 95% C_1 values for V, B, and R_c do not overlap with the corresponding Lupton (2005) RMS values.

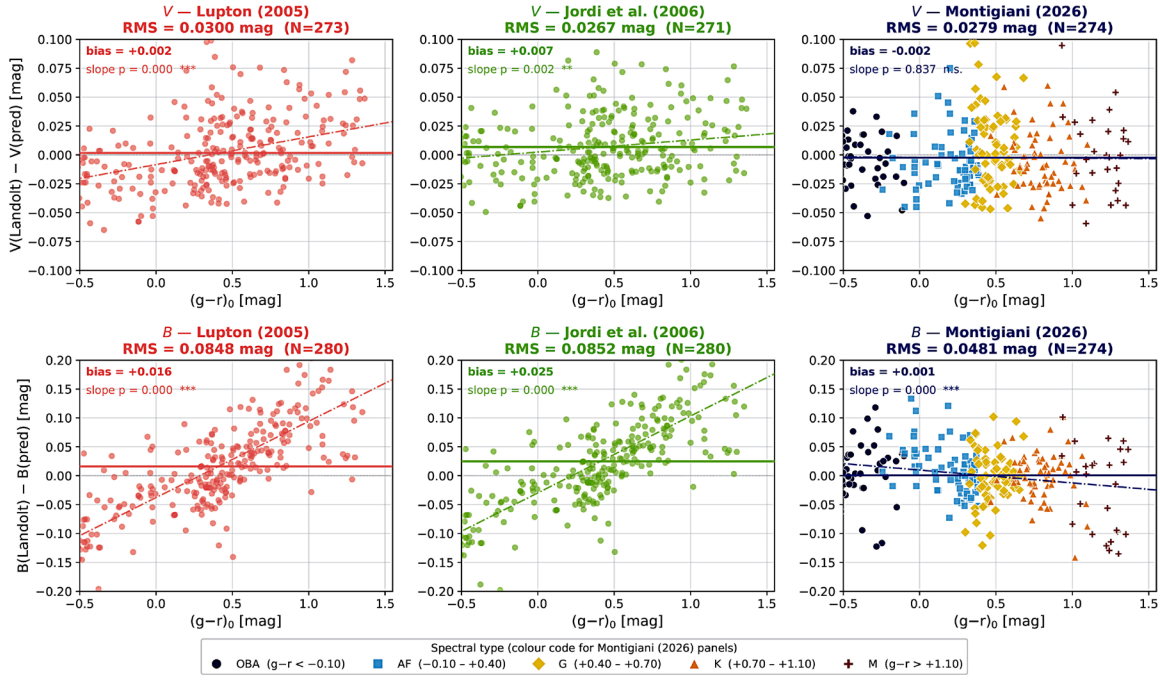


Figure 5. Residuals ΔV (top row) and ΔB (bottom row) vs. $(g-r)_0$ for the three formulae ($N = 287$ validation stars). For Montigiani (2026), the chromatic slope is consistent with zero for V ($p = 0.483$ n.s.) and significantly reduced for B compared to Lupton (2005) and Jordi *et al.* (2006) (see Table 3, $p[(g-r)_0]$ column). Color coding by spectral type applies to the Montigiani (2026) panels only: OBA, dark blue; AF, light blue; G, gold; K, orange; M, red. As in Figure 2, the effective N reported in each panel varies because a $3.5 \cdot \text{MAD}$ sigma-clipping is applied independently for each (band, formula) combination to remove residual outliers; the starting sample has 286 stars.

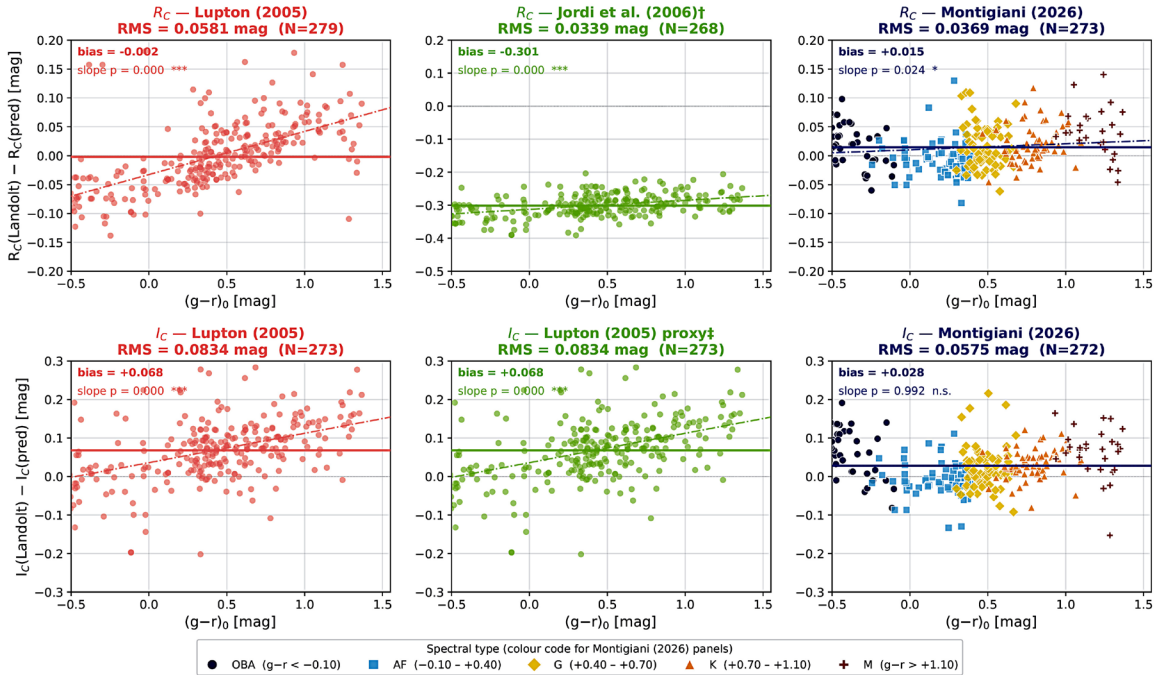


Figure 6. Residuals ΔR_c (top row) and ΔI_c (bottom row) vs. $(g-r)_0$ for the three formulae ($N = 287$ validation stars). Montigiani (2026) shows no significant chromatic slope in $(g-r)_0$ for either band ($p = 0.273$ and $p = 0.767$, respectively; see Table 3). The Jordi *et al.* (2006) R_c panel (center top) uses the Population I formula ($R_{c-r} = -0.257(r-i) + 0.152$), which produces a large systematic bias of -0.30 mag across the full color range (see section 5.1 for discussion). For I_c , no Jordi formula is available without the $(i-z)$ color index; the Lupton (2005) formula is shown as proxy (§). Color coding by spectral type applies to the Montigiani (2026) panels only: OBA dark blue, AF, light blue; G, gold; K, orange; M, red. As in Figure 2, the effective N reported in each panel varies because a $3.5 \cdot \text{MAD}$ sigma-clipping is applied independently for each (band, formula) combination to remove residual outliers; the starting sample has 286 stars.

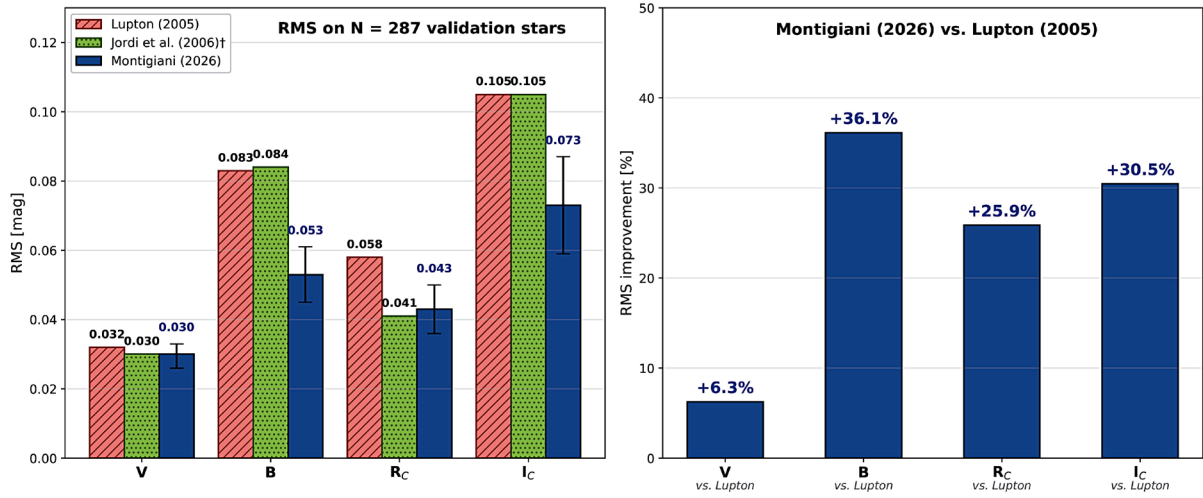


Figure 7. Left: bar chart of the validation RMS on $N = 287$ stars for each formula and band. All bars have the same fixed width; only the bar heights are meaningful, representing the RMS values in mag. The bar areas have no physical meaning and should not be compared. Right: Percentage improvement of Montigiani (2026) over the best previous formula. Error bars show 95% bootstrap confidence intervals for Montigiani (2026). The marker [†] on the Jordi (2006) legend label denotes the Population I formula for R_C , whose RMS includes a -0.30 mag systematic offset (see section 5.4); for I_C , the Jordi formula requires $(i-z)$, unavailable in APASS DR9, and the Lupton (2005) value is shown as proxy.

7. Software APASS2JOHNSON v5.0 is publicly available on GitHub with Zenodo DOI.

9. Acknowledgements

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¹Lupton (2005): <https://www.sdss.org/dr12/algorithms/sdssubvritransform>

Appendix A: Auxiliary algebraic derivations

A1. Rationale for the use of identical coefficients in Versions A and B

This section clarifies the logical and mathematical status of the statement, made in section 3.2, that Version B uses the same polynomial coefficients as Version A. Strictly, the two functional forms are not mathematically equivalent: a separate ODR fit on observed (reddened) magnitudes would in general yield slightly different coefficients than the fit on dereddened magnitudes used in this work. The use of identical coefficients in Version B is therefore a modelling choice—adopted by construction—and not an algebraic consequence of the calibration procedure. The validity of this choice rests on showing that the residual error introduced is bounded and quantifiable; we make this explicit below for the V band, the derivation for B and R_c being formally identical (with the appropriate numerical coefficients) and the case of I_c involving an additional $(g-r)$ covariate that contributes only a first-order extinction term.

Let (g, r, V) denote the observed APASS and Landolt magnitudes for a calibration star, and let $E \equiv E(B-V)$ be its reddening. Define dereddened quantities $g_0 = g - R_g E$, $r_0 = r - R_r E$, $V_0 = V - R_V E$, with extinction coefficients $R_g = 3.640$, $R_r = 2.700$, $R_V = 3.100$ (section 3.3). The color indices satisfy $(g-r)_0 = (g-r) - \Delta R_{gr} E$, with $\Delta R_{gr} \equiv R_g - R_r = 0.940$.

Version A is calibrated by ODR on the dereddened sample, yielding the predictor

$$V_a(g_0, r_0) = g_0 + c_0 + c_1(g-r)_0 + c_2(g-r)_0^2, \quad (A1)$$

where (c_0, c_1, c_2) are the fitted coefficients of Table 1. By construction, Version B reuses the same coefficients but accepts observed (reddened) magnitudes:

$$V_b(g, r) = g + c_0 + c_1(g-r) + c_2(g-r)^2. \quad (A2)$$

Substituting $g = g_0 + R_g E$ and $(g-r) = (g-r)_0 + \Delta R_{gr} E$ in Equation A2, expanding the quadratic, and subtracting Equation A1 gives, exactly,

$$V_b - V_a = (R_g + c_1 \Delta R_{gr}) E + 2c_2 \Delta R_{gr} (g-r)_0 E + c_2 (\Delta R_{gr})^2 E^2. \quad (A3)$$

Equation A3 is the algebraic core of the construction. Three observations follow.

(1) The dominant linear-in- E coefficient in Equation A3 is $R_V^{\text{eff}} \equiv R_g + c_1 \Delta R_{gr} = 3.640 + (-0.55868)(0.940) = 3.115$. This is numerically very close to the nominal Cardelli value $R_V = 3.100$, confirming that the linear term in Equation A3 reproduces the physical reddening of the Landolt V band that is expected to appear when one feeds reddened APASS magnitudes into the Version B formula. In this sense Version B does not introduce a spurious offset: the dominant E -term is the correct, physically expected JKC extinction, recovered self-consistently from the Version A coefficients and the SDSS extinction ratios.

(2) The departure of Equation A3 from a clean linear-in- E reddening law is contained in the cross-term $2C_2 \Delta R_{gr} (g-r)_0 E$ and the second-order term $c_2 (\Delta R_{gr})^2 E^2$. With $c_2 = 5.63 \times 10^{-3}$ for

V (Table 1) and $\Delta R_{gr} = 0.940$, the second-order term reaches at most 2.0×10^{-4} mag at $E = 0.20$ and 1.2×10^{-3} mag at $E = 0.50$. The cross-term, evaluated at the worst-case color $|(g-r)_0| = 1.10$ of the calibration range, is at most 2.3×10^{-3} mag at $E = 0.20$ and 5.8×10^{-3} mag at $E = 0.50$. Both contributions remain well below the typical APASS DR9 photometric uncertainty (0.02–0.03 mag).

(3) Equation A3 also clarifies what an independent ODR fit on observed (reddened) magnitudes would do. Such a fit would solve for coefficients (c'_0, c'_1, c'_2) that minimize the residuals between Landolt V (observed) and the Version-B functional form evaluated on observed g, r . The systematic E -dependent terms in Equation A3 would then be partially absorbed into (c'_0, c'_1, c'_2) , shifting them away from (c_0, c_1, c_2) by amounts of order $\langle E \rangle$ and $\langle E^2 \rangle$ weighted by the calibration sample. Two independent fits—one on dereddened, one on observed magnitudes—are therefore not, in general, expected to yield identical coefficients. The choice in this work is to perform a single, well-posed fit (Version A, on dereddened data, where the regression model is closer to a pure color transformation) and to inherit those coefficients for Version B. The systematic error introduced by this inheritance is precisely Equation A3 and is bounded as quantified in observation (2).

The same construction applies to B and R_c with the appropriate Table 1 coefficients and the corresponding extinction ratios; numerical evaluation gives $R_B^{\text{eff}} \approx 4.057$ (cf. nominal $R_B = 4.061$), confirming the same physical consistency. For I_c , an additional first-order term arises from the $(g-r)$ covariate, contributing $c_3 \Delta R_{gr} E$ to the linear term; the structure of the second-order corrections is otherwise identical.

In summary, the assertion that “Version B uses the same coefficients as Version A” is to be read in this constructive sense: a single ODR regression is performed (Version A); Version B applies the same coefficients to observed magnitudes, with the residual systematic given exactly by Equation A3; the linear part of Equation A3 reproduces the expected JKC extinction R_V to within a few thousandths of a magnitude per unit E , while the higher-order remainder is bounded at the millimagnitude level over the operational range and is verified empirically by the validation of section 5.

A2. Full expansion of $V_b - V_a$

With dereddened magnitudes $g_0 = g - R_g E$, $r_0 = r - R_r E$:

$$V_A = (g - R_g E) + A_{0V} + A_{1V} [(g-r) - \Delta R_{gr} E] + A_{2V} [(g-r) - \Delta R_{gr} E]^2 \quad (A4)$$

$$V_B = g + A_{0V} + A_{1V} (g-r) + A_{2V} (g-r)^2 \quad (A5)$$

Setting $(g-r)_0 \equiv (g-r) - \Delta R_{gr} E$ and $(g-r)_{\text{obs}} \equiv (g-r)$:

$$\begin{aligned} \Delta V &= V_B - V_A = R_g E + A_{1V} \Delta R_{gr} E + A_{2V} [(g-r)_{\text{obs}}^2 - (g-r)_0^2] \\ &= R_g E + A_{1V} \Delta R_{gr} E + A_{2V} [(g-r)_{\text{obs}} + (g-r)_0] \Delta R_{gr} E \end{aligned} \quad (A6)$$

Separating into first-order and second-order terms:

$$\Delta V_1 = [R_g + A_{1V} \Delta R_{gr} + 2A_{2V} (g-r)_0 \Delta R_{gr}] \cdot E(B-V) \quad (A7)$$

$$\Delta V_2 = -A_{2V} \Delta R_{gr}^2 \cdot E(B-V)^2 \quad (A8)$$

The derivation for B and R_C is formally identical with the respective coefficients. For I_C , the primary color index is $(r-i)$ with $\Delta R_{ri} = 0.640$, and the $(g-r)$ covariate adds $A_{3I_C} \Delta R_{gr} E$ to the first-order term.

A3. Effective extinction coefficient R_{eff}

$$R_V^{eff}((g-r)_0) = R_g + A_{1V} \Delta R_{gr} + 2A_{2V}(g-r)_0 \Delta R_{gr} \quad (A9)$$

The color dependence of R_V^{eff} is

$$dR_V^{eff}/d(g-r)_0 = 2A_{2V} \Delta R_{gr} \approx +0.011 \text{ (mag/mag) / mag.}$$

Over the full valid color range $(\Delta(g-r)_0 = 1.38 \text{ mag})$, the total variation is $+0.011 \times 1.38 \approx +0.015 \text{ mag/mag}$ —negligible relative to the uncertainty on R_V itself.

A4. Data availability

The complete input photometric data used to derive the transformation formulae presented in this paper—comprising 51,347 APASS DR9 entries from the queried sky regions, of which 41,311 entered the final calibration sample after the quality cuts described in section 2.1 and iterative outlier rejection during the ODR fit—are available as an electronic machine-readable table at:

Zenodo DOI: <https://doi.org/10.5281/zenodo.19153252>

The dataset includes a comprehensive README describing the contents, column definitions, data provenance, and reproducibility instructions. The companion software pipeline is available at: <https://github.com/Goldrake71/apass2johnson> (also archived on Zenodo at doi:10.5281/zenodo.19153252).

The independent 287-star validation sample used in section 4 is described in the accompanying README of the Zenodo dataset.

Table A1. Sample extract from the APASS DR9 Calibration Input.

$R.A. (J2000)$ $^{\circ}$	$Dec. (J2000)$ $^{\circ}$	V	σV	B	σB	g	σg	r	σr	i	σi	$nobs$
32.206	-75.543	16.242	0.000	16.854	0.000	16.579	0.036	16.062	0.036	15.769	0.000	3
48.537	-22.715	13.050	0.020	13.671	0.023	13.320	0.017	12.916	0.011	12.756	0.012	4
120.971	+18.228	15.783	0.035	16.458	0.090	16.102	0.017	15.584	0.022	15.371	0.006	6
135.689	+01.245	14.376	0.012	15.222	0.000	14.808	0.063	14.116	0.027	13.935	0.032	3
168.660	-24.404	14.899	0.015	15.617	0.076	15.234	0.014	14.638	0.014	14.446	0.063	6
169.438	-24.322	14.822	0.053	15.508	0.039	15.107	0.022	14.651	0.028	14.551	0.078	6
186.619	+50.744	14.343	0.051	14.842	0.045	14.435	0.055	14.131	0.062	13.967	0.088	4
209.852	-32.719	15.050	0.012	16.136	0.014	15.621	0.041	14.664	0.031	14.368	0.044	4
331.007	-26.698	14.839	0.042	15.844	0.025	15.304	0.016	14.496	0.006	14.213	0.006	2
343.009	+41.663	15.286	0.000	16.556	0.056	15.855	0.063	14.767	0.062	14.374	0.011	2

Notes: Listed here are 10 representative stars selected to span the color and uncertainty distributions of the input dataset; the full table of 51,347 entries is available on Zenodo (see text for access information). Magnitudes are in the APASS DR9 native system (B, V on the Landolt 1992 system; g, r, i on the Sloan AB system). Uncertainties of “0.000” indicate APASS magnitudes derived from a single observation in that filter, for which the formal error propagation yields zero; rows where σg or σr equals 0.000 are excluded from the calibration sample by the $\sigma \leq 0.08 \text{ mag}$ cut on the predictor bands described in section 2.1. The “nobs” column reports the number of separate observing nights for each star. The complete 51,347-row table, including all 37 columns of the original APASS DR9 query (positions, photometry, color indices, and quality flags), is available as an electronic table in the companion Zenodo dataset (see Data Availability statement).

Spectrophotometry of a Flare on EQ Pegasi A

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Abstract Time-series B-band and TESS photometry is combined with time-series spectroscopy to characterize the brightness profile and the development of spectral features of a large flare on EQ Peg A. At its peak, the flare increased the star’s brightness by 1.2 magnitudes in B-band, and it released $\approx 3.2 \times 10^{32}$ erg in B-band. Photometrically, the flare showed a typical “fast rise, exponential decay” shape, with FWHM ≈ 1.7 minutes. Time-series spectroscopy shows that the Balmer emission lines remain strong for a much longer time (FWHM ≈ 11 to 15 min, depending on the line), taking about 3.5 hours to return to their pre-flare strength. The continuum slope of the flare spectrum indicates a peak temperature of $T_{\text{Flare}} = 14,000 \text{ K} \pm 2000 \text{ K}$ (averaged over a 5-minute exposure). The photometric color index (B-TESS) indicates a peak color temperature of $T_{(\text{B-TESS})} \approx 11,800 \text{ K}$.

1. Introduction

Stellar flares occur randomly and relatively rarely. The concept for this project is that amateur astronomers can devote much more time to observing flare stars than can realistically be done by professional astronomers. Despite our modest equipment, we can probably make useful contributions to characterizing the photometry and spectroscopy of flares and adding to the collection of data about them. EQ Peg A was on our observing plan during TESS Sector 56, during which the target was within the TESS field of view.

EQ Peg (= GJ 896 = HIP 116132 = AAVSO UID 000-BCW-694, R.A. $23^{\text{h}} 31^{\text{m}} 52^{\text{s}}$, Dec. $+19^{\circ} 56' 14''$ (J2000)) is a well-known red dwarf flare-star. It has a large proper motion (nearly ≈ 0.6 a-s/yr), so its actual place in the sky will be noticeably different from your star chart. EQ Peg A and B comprise the visual binary star WIR 1AB whose orbit has a semi-major axis of ≈ 5.5 a-s and orbit period of $P \approx 229$ y (Hartkopf *et al.* 2001). An exoplanet (designated as GJ896 Ab) has been reported in orbit around the A star (Curiel *et al.* 2022). At the time of the observations reported here, EQ Peg B ($\approx 12^{\text{th}}$ magnitude according to SIMBAD) was separated by about 5.4 a-s.

EQ Peg was one of the targets of an ongoing project by a group of amateur astronomers (the “Red Dwarf Group”) to characterize stellar flares with simultaneous spectroscopy and photometry. Both EQ Peg A and B have been reported as flare stars (Owen *et al.* 1972); the flare reported here occurred on the brighter component (EQ Peg A).

2. Observations

Here I present the optical (B-band) photometry, TESS space-based near-IR photometry, and optical band low-resolution spectroscopy of the flare. The optical data are freely available from the AAVSO’s databases: photometry on the AID (Kloppenborg 2026a) and the spectroscopy on AVSpec (Kloppenborg 2026b). Near-infrared photometry from TESS can be freely downloaded via the lightcurve package (Lightcurve Collaboration 2018).

2.1. B-band photometry

Time-series photometry was done using a Hyperion CDK 12.5" f/8 Telescope and SBIG STL6303e camera with Johnson B-band filter. A continuous series of images were taken with 30 s exposure (and about 16 s image download time), with 2×2 binning yielding an image scale of 1.46 a-s/pix (binned). Aperture photometry used AAVSO’s VPhot package, with star/gap/sky radii of 4/8/16 pix ($= 5.8/11.7/23.4$ a-s). The comparison star used was TYC1723-69-1 (AAVSO ID = 000-BNZ-811) with assigned $B_{\text{mag}} = 11.796$ ($B-V = 0.972$). The faint component of the visual double was touching the edge of the star aperture, so there is probably some contamination from it in the photometry. No adjustment was made for this.

EQ Peg A’s light curve in Figure 1 shows the dramatic brightening (delta-mag 1.2 in B-band, briefly tripling the star’s luminosity) and characteristic flare profile of “Fast Rise, Exponential Decay.” The event is quite brief—it is nearly over in just 15 minutes, and the FWHM is much shorter than that.

The B-band photometry cadence barely resolves the rapid rise and fall of the event. Tovar Mendoza *et al.* (2022) developed a parametric model flare profile, based on a statistical analysis of a large sample of photometrically observed stellar flares, and a Python code that finds the model parameters (time of peak flux, FWHM, and peak amplitude) that fit a data set.

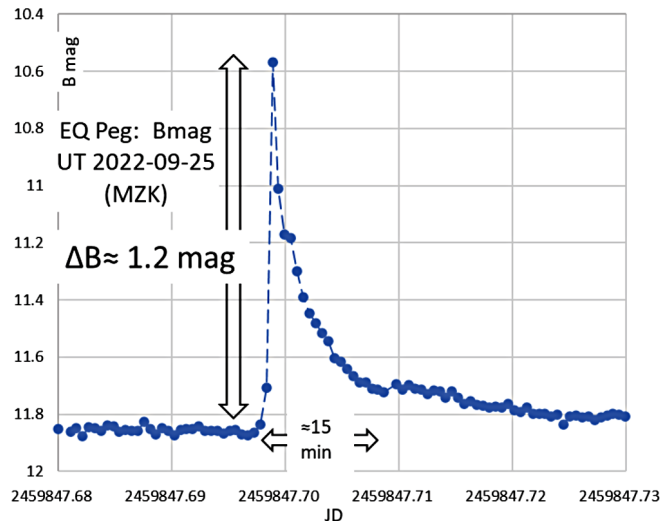


Figure 1. B-band photometry of the flare on EQ Peg.

The Tovar Mendoza model fits the B-band photometry of this flare quite well, as shown in Figure 2. The model fit result for the FWHM of this flare is just 1.65 minutes.

2.2. TESS space-based near-infrared photometry

The Transit Exoplanetary Survey Satellite (TESS; Ricker *et al.* 2015) photometry cameras have a very broad spectral response in the red/near-IR (spanning about 5800 Å to 10,000 Å). The TESS pixels are very large (≈ 21 a-s), so the companion star EQ Peg B is almost certainly included in the TESS flux. The AAVSO VSX (Watson *et al.* 2006) lists the “A” component as V=10.38 and spectral type M4Ve, and the “B” component as V=12.58 and spectral type M6Ve, implying a contamination amounting 12% of the total flux in V-band. However, the spectral types indicate the “B” component will be relatively brighter in the red/near-IR TESS band, leading to a possible contamination that could be as much as 23% of the total flux (based on spectral profiles for the two types from Pickles 1998). No adjustment for this was attempted in our analysis.

The TESS data for Sector 56 were downloaded using the lightcurve tool. The results reported here use the PDCSAP flux (which has common instrumental systematics removed). TESS PDCSAP flux ($e^- s^{-1}$) was converted to TESS magnitudes (“ T_{mag} ” hereafter) using the information in Vanderspek *et al.* (2018), which gives (Equation 1):

$$T_{\text{mag}} = -2.5 \log(S) + ZP, \quad (1)$$

where S is the TESS signal flux in $e^- s^{-1}$ and the zero-point is $ZP = 20.44$.

In the TESS band, the star is quite bright, and the delta-magnitude of the flare is much smaller than it is in the B-band. The flare created less than a tenth of a magnitude increase in the TESS band brightness, as shown in Figure 3.

The app of Eastman *et al.* (2010) was used to convert the time scales of the ground-based photometry and TESS photometry to BJD. The flare brightness peaks in the two bands are: B photometry peak data point = JD (UTC) 2459847.69885 = BJD 2459847.70501; TESS 20s cadence peak data point = BJD 2459847.705153.

The difference between the two is ≈ 12 sec, which is essentially simultaneous considering the 20-s cadence of TESS and 46-s cadence of the B-band photometry.

The full TESS Sector 56 light curve of EQ Peg A is shown in Figure 4. The exquisite precision of TESS photometry shows that the star’s brightness fluctuates by about 3% (full range) in a regular cycle. The most likely cause of the brightness cycle is rotational modulation, driven by a pattern of star-spots. Quite a few flares are obvious in this plot; our flare is indicated by the red box.

Norton *et al.* (2007) determined EQ Peg A’s rotation period to be 1.066 d from SuperWasp photometry; Morin *et al.* (2008) reported a rotation period of 1.061 d from Zeeman-Doppler imaging. A PDM analysis of the TESS Sector 56 PDCSAP flux using PERANSO software (Paunzen and Vanmunster 2016) gives a modulation period of $P = 1.06767$ d—consistent with Norton *et al.* (2007) but slightly different than Morin *et al.* (2008). Figure 5 shows the TESS light curve phased to rotation period $P = 1.06767$ d. The red arrow points to our flare. A qualitative

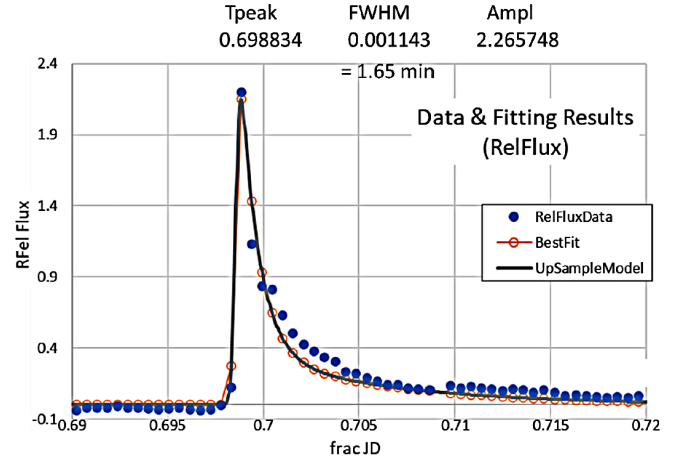


Figure 2. Best fit of Mendoza *et al.* (2022) model flare parameters to the B-band photometry of the flare on EQ Peg A.

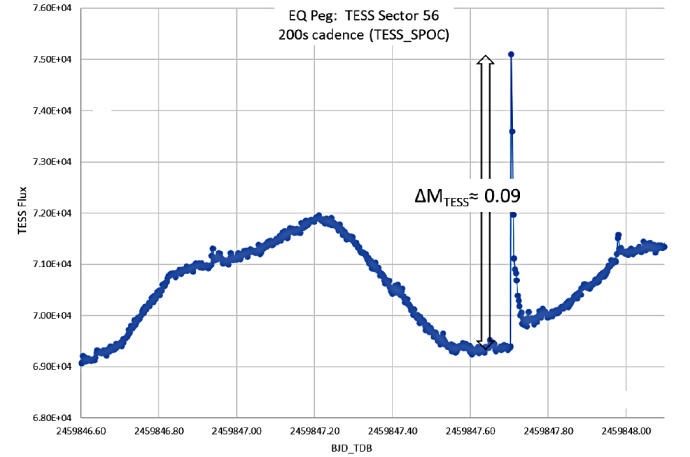


Figure 3. TESS light curve of EQ Peg at the time of our observations of the flare.

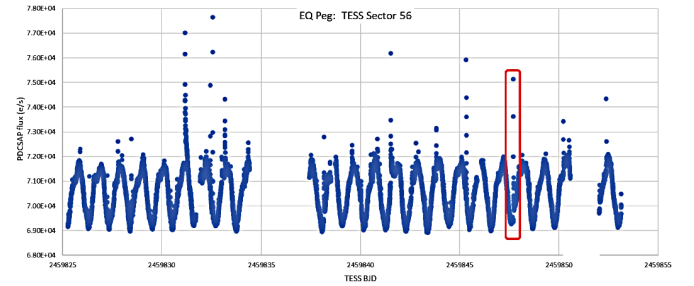


Figure 4. TESS Sector 56 light curve of EQ Peg, showing cyclic modulation punctuated by flare events. The red box indicates the flare that is the subject of this paper.

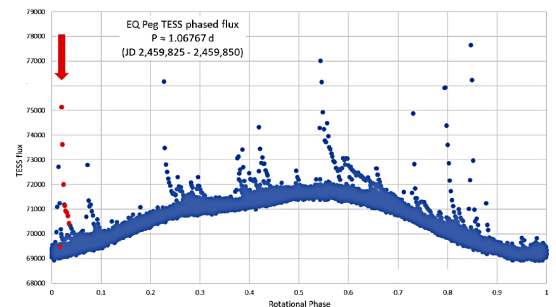


Figure 5. TESS Sector 56 light curve of EQ Peg, phased to stellar rotation period $P = 1.06767$ d. The red arrow points to the flare that is the subject of this paper.

look at this compilation of 22 observed rotations does not seem to show any obvious preference for flares to occur (or not occur) at particular rotational phases. This is consistent with the results of other studies, such as Hawley *et al.* (2014) and Zhang *et al.* (2025). Pratt *et al.* (2026) reported evidence for a small statistical preference for flares to be bunched (“sympathetic flares”), but did not see a correlation between flares and stellar rotational phase.

2.3. Optical low-resolution time-series spectroscopy

Time-series spectroscopy used a Shelyak ALPY spectrograph ($R \approx 500$) with an ATIK 314L+ camera, on a 16-inch RC telescope. The spectra cover the spectral range $\lambda \approx 3750 \text{ \AA}$ to $7250 \text{ \AA}$. The instrument uses a $23 \mu\text{m}$ slit ($= 1.45 \text{ a-s width}$), with the along-slit direction oriented East-West (i.e. perpendicular to the parallactic angle). The companion star EQ Peg B was clearly outside of the slit, as shown in the guider image in Figure 6, and there is no evidence of contamination by it in the spectrum images. Wavelength calibration is provided by a Ne-Ar lamp. Lamp images were taken at the start of the all-night run, and again after meridian-flip. There is a slight calibration-shift (most likely due to instrument flexure and temperature change), amounting to $1.5 \text{ \AA}$ over the night. The custom code that calculates emission line Equivalent Width accounts for this by shifting the observed wavelength of each line to its laboratory wavelength as part of the computations. Spectra of a Reference Star (HD 220933) were taken at large air mass (at the start of the observing run, elevation angle $= 38 \text{ deg}$, $AM \approx 1.6$) and low air mass (after meridian flip, elevation angle $= 72 \text{ deg}$, $AM = 1.05$), and used to establish the Instrument+Atmosphere response function (spanning the full spectral range). Experience shows that this will create accurate and repeatable relative flux spectra over the full spectral range. However, this step is not by itself sufficient for flux-calibration of the spectra. For that, B-band photometry is used, as discussed in section 3.2.

Spectra were processing using the ISIS code by Christian Buil (2026), which handles dark subtractions, flat correction, sky subtraction, wavelength calibration, and correction for instrument response and atmospheric extinction, yielding an exo-atmospheric relative-intensity spectrum. An all-night (8.7 hr) observing run collected 93 spectra at a cadence of about one spectrum every 5.1 minutes (300-s exposure and about 10 s download time for each spectrum). This cadence under-samples the impulsive rise and rapid fall of the photometric flare, but provides a useful view of the evolution of spectral features from pre-flare quiescence to flare peak, and through the long fade back to quiescence. Since the sensitivity of the camera is relatively poor in the blue region and the target star is very red, the signal to noise ratio in the (pseudo) continuum is strongly wavelength dependent; it ranges from $SNR \approx 8$ at Ca II (K) ($3933 \text{ \AA}$) to $SNR \approx 20$ at H gamma ($4340 \text{ \AA}$) to $SNR \approx 120$ at H alpha ($6563 \text{ \AA}$).

Figure 7 shows the Relative Intensity spectrum of the star before the flare began: a normal M4 dwarf spectrum, aside from the fact that it shows emission in the Balmer and Ca II (K) lines, hence its spectral type “M4Ve.”

Figure 8 shows the Relative Intensity spectra at three points in time: the quiescent state before the flare began, the spectrum

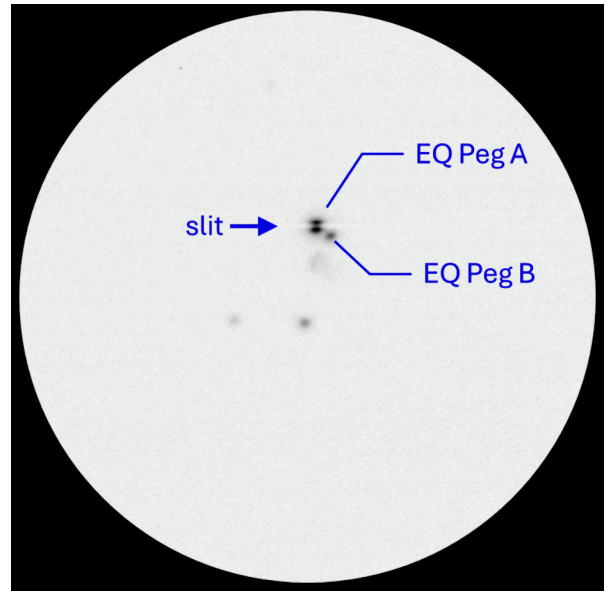


Figure 6. Guider image showing EQ Peg A on the spectrograph slit, and the companion EQ Peg B off of the slit. North is down and East to the right.

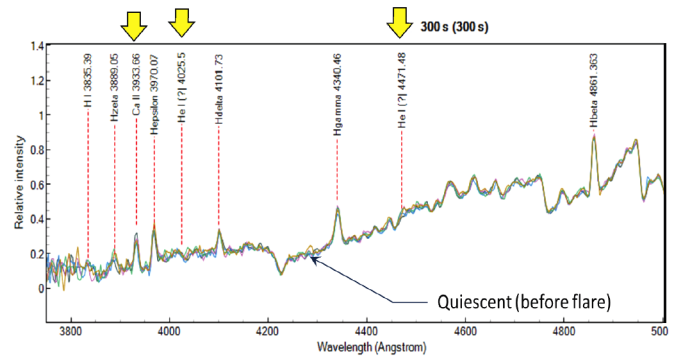


Figure 7. Spectra of EQ Peg during the “quiescent” state before the flare. This is an overlay of six spectra taken before the onset of the flare, showing the constancy of the quiescent spectrum over about 30 minutes before the flare (each spectrum exposure was 300 s).

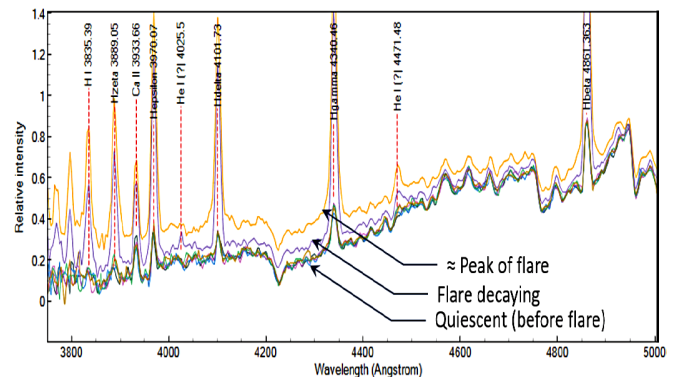


Figure 8. Changes in the spectrum near the peak of the flare, and during the photometric decay phase after the peak.

that captured the peak of the flare, and a spectrum taken during the decay phase.

The sequence clearly shows the strong increase in the Balmer emission lines and the Ca II (K) line, plus the appearance of He I emission lines during the flare.

The Equivalent Width (EW) of a spectral line is a useful measure of the line's strength. Figure 9 shows the change in the strength of the H-alpha line during the flare, and compares it to the changing B-band brightness. The emission line peaks simultaneously with the B-band brightness, but stays elevated long after the B-band brightness has returned to its quiescent level. The H-alpha EW shows a hump interrupting its gradual decay from maximum strength (at about JD = 2459847.74). That hump is visible in the detailed photometric light curve. There is a similar, but very tiny, hump on the TESS light curve at the same time.

The long gradual decay isn't peculiar to the H-alpha line. All of the Hydrogen Balmer emission lines peak simultaneously and fall very gradually, as shown in Figure 10.

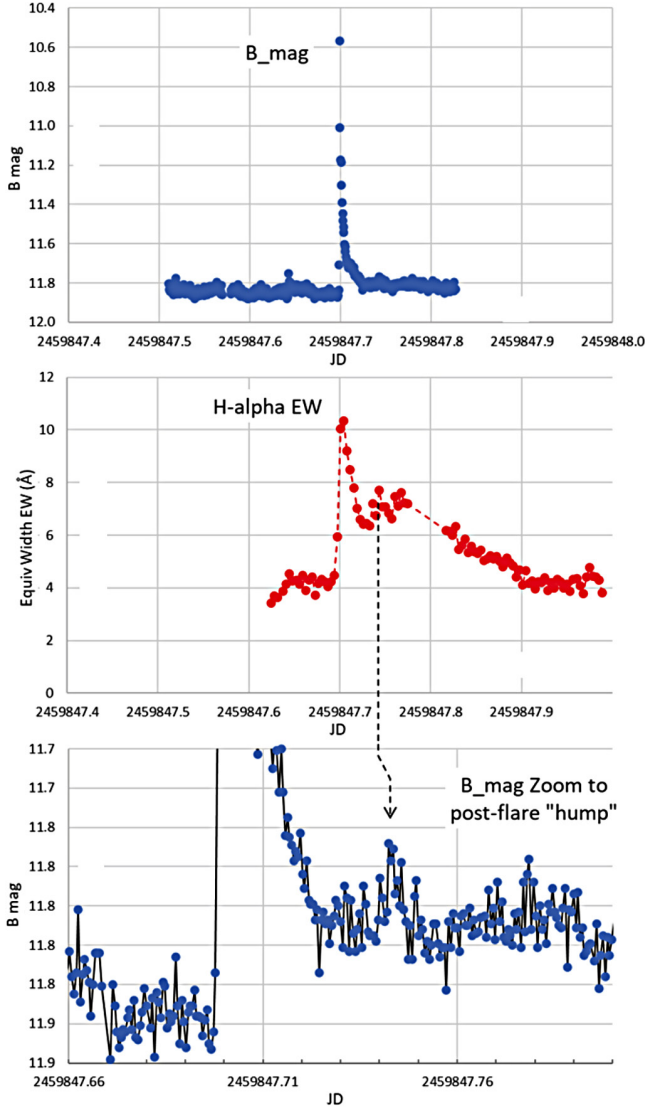


Figure 9. Comparison of H-alpha emission strength (Equivalent Width, Å) during the flare (middle graph) to the B-band brightness change (top graph). The hump that interrupts the decay of the H-alpha EW at 0.74 (dotted line) corresponds to a very small brightness hump in the photometry detail (bottom plot). The gap in H-alpha data is due to time lost during meridian flip.

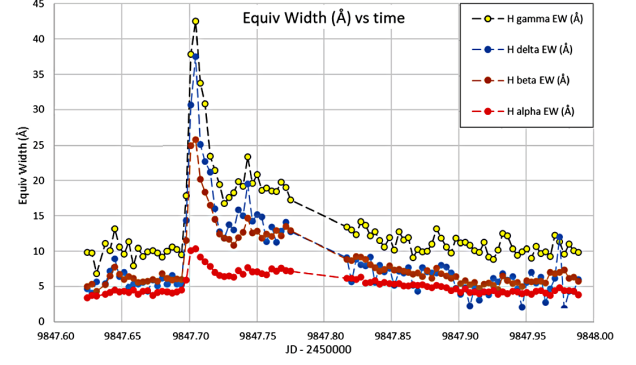


Figure 10. Strength of the Balmer H-alpha, H-beta, H-gamma, and H-delta lines during the flare, showing their gradual decays. The hump during the decline phase is seen on all of them. The gap in data (centered at about JD 2459847.80) is caused by meridian flip and reacquisition of the target.

3. Analysis

3.1. Photometry analysis

3.1.1. B-band

The luminosity (power emitted) of the flare is determined by a simplistic model, in which the flare is treated as a point source whose flux is added to that of the quiescent star. In this model, the observed luminosity is $L_{\text{obs}}(t) = L_Q + L_{\text{Flare}}(t)$. Writing the observation in terms of B-band magnitudes, and solving for the flare luminosity in B-band gives (Equation 2):

$$L_{\text{Flare}}(t) = L_Q \left[10^{-\left[\frac{(B_{\text{obs}}(t) - B_{Q,\text{Tgt}})}{2.5} \right]} - 1 \right] (\text{erg s}^{-1}), \quad (2)$$

where $B_{\text{obs}}(t)$ is the observed B-magnitude at time t (i.e. star + flare), $B_{Q,\text{Tgt}}$ is the B-magnitude of the star during quiescence (no flare), L_Q is the quiescent luminosity of the star (erg s^{-1}) in the B-band, and $L_{\text{Flare}}(t)$ is the luminosity of the flare (alone) vs. time.

Treating the flare as a point source is justified by results such as Bicz *et al.* (2025) who analyzed a sample of flares from EV Lac and V374 Peg and found that the flare area was a very small fraction of the stellar surface (the maximum value they found for AFlare was less than 1% of the stellar surface, and their median value was 0.04%).

The quiescent luminosity of the star (L_Q) is found by determining the absolute magnitude of EQ Peg in B-band, in quiescence (Equation 3):

$$M_{Q,B,\text{Tgt}} = B_{Q,\text{Tgt}} + 5 \log(\pi) + 5, \quad (3)$$

where $\pi = 0.162$ a-s is the star's parallax (from SIMBAD), and comparing the target with the Sun's absolute magnitude and luminosity in B-band using the magnitude equation (Equation 4):

$$M_{Q,B,\text{Tgt}} - M_{B,\odot} = -2.5 \log \left(\frac{L_{Q,B,\text{Tgt}}}{L_{B,\odot}} \right) \quad (4)$$

to solve for the target's quiescent luminosity. The absolute magnitude ($M_{B,\text{Sun}}$) and luminosity ($L_{B,\text{Sun}}$) of the Sun in B-band

(and many other photometric bands) are given by Willmer (2018) : $M_{B,\odot} = 5.44$, and $L_{B,\odot} = 5.008 \text{ E}+32$.

For EQ Peg A, the average B-mag observed over the 30 minutes preceding the start of the flare was $B_{Q,Tgt} = 11.855$ ($\sigma=0.01$), so its quiescent Absolute Magnitude in B-band is $MB_{Q,Tgt} = 11.855 + 5 \log(0.162) + 5 = 12.903$.

The resulting quiescent luminosity of EQ Peg A is $L_{Q,EPeg,B} = 5.18 \times 10^{29} \text{ erg s}^{-1}$ in the B-band. Integrating over the duration of the flare (refer back to Figure 1) gives the total energy released as $E_B \approx 3.2 \times 10^{32} \text{ ergs}$ in B-band.

3.1.2. TESS band

A similar procedure is used to analyze the flare luminosity and energy released in the TESS band. The average quiescent magnitude over the 30 minutes preceding the flare in the TESS band is $T_Q = 8.34$. The TESS light curve was essentially constant ($\sigma=0.0006 \text{ mag}$) over this time interval.

Willmer (2018) does not cover the TESS band, so his method and equations were followed to compute the Sun's absolute magnitude and luminosity in the TESS band, using the flux-calibrated solar spectrum from CalSpec (Bohlin *et al.* 2014), and the TESS spectral response function from Vanderspek (2018). The results are $M_{TESS,\odot} = 4.227$ and $L_{TESS,\odot} = 1.148 \text{ E}+33$.

The resulting quiescent luminosity of EQ Peg A in the TESS band is $L_{TESS,EPegA} = 1.00 \text{ E}+31 \text{ erg s}^{-1}$.

The star is much brighter in the TESS band than it is in the B-band, so despite the small delta-magnitude, the energy released by the flare in the TESS band was $\approx 6.6 \times 10^{32} \text{ erg}$ —more than twice as much as in the B-band.

3.1.3. Flare color-index and color temperature

The preceding analyses yield flare luminosity (ergs^{-1}) vs. time in both B- and TESS-band, which can be combined to estimate the blackbody color temperature of the flare. A two-step procedure was used. In step 1, Planck functions for an array of blackbody temperatures were integrated over the B- and TESS-bands using Equation 5,

$$L_{\text{band}}(T) = \int B(\lambda, T) R_{\text{band}}(\lambda) d\lambda, \quad (5)$$

where $B(\lambda, T)$ is the Planck function vs wavelength at temperature T and $R_{\text{band}}(\lambda)$ is the normalized response curve of the photometric band (B- or TESS-band).

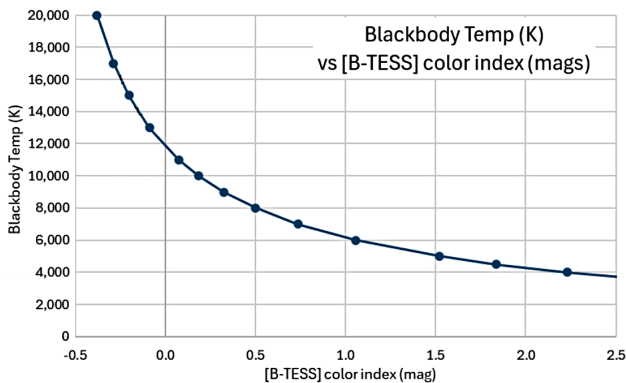


Figure 11. Blackbody (B-TESS) color index for Temperatures relevant to stellar flares.

For each blackbody temperature, the photometric color index was determined using Equation 6:

$$[B - T] = -2.5 \log \left(\frac{L_B(T)}{L_{TESS}(T)} \right). \quad (6)$$

This was done for a range of temperatures that is relevant to stellar flares. The result is the curve shown in Figure 11.

In step 2, the TESS 20-s cadence data was interpolated to the time of each B-band data point, and the flare luminosity in the B- and TESS-band at each time point was used to compute the observed color index (in magnitudes), which was used with the data from Figure 11 to estimate the flare color temperature. This approach is identical to that used by Howard *et al.* (2020), except that they worked in flux ratio instead of color index magnitudes. The results are shown in Figure 12. The flare temperature spikes to $T_{BB} \approx 11800 \text{ K}$, and then promptly falls to $T_{BB} \approx 8000 \text{ K}$, before beginning a long gradual cooling as the flare luminosity fades.

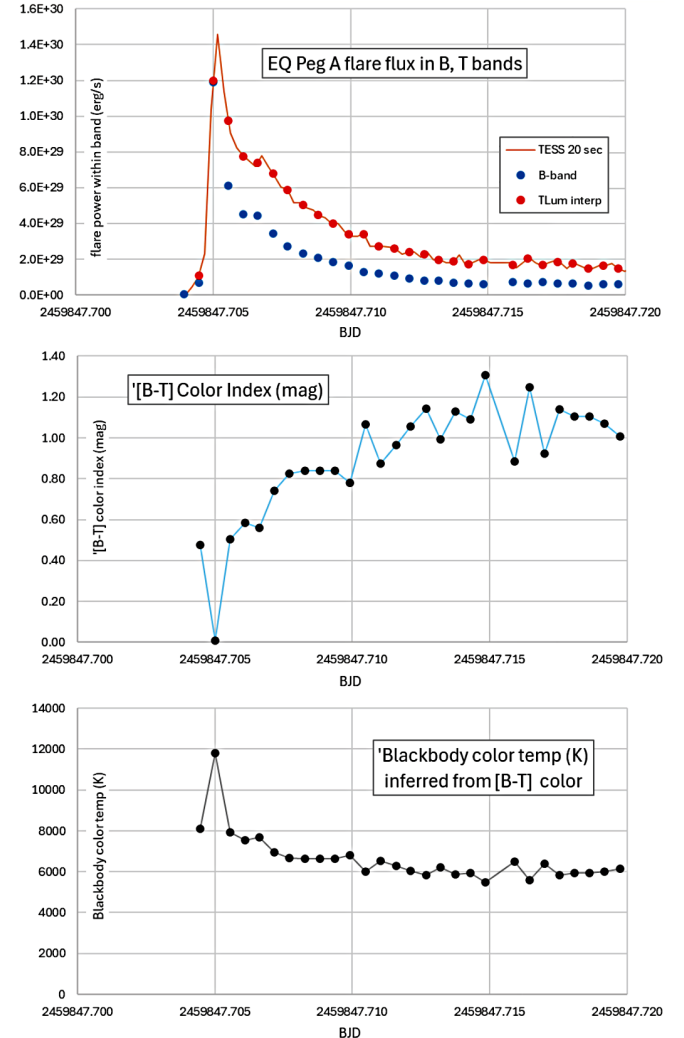


Figure 12. Determination of photometric blackbody temperature evolution of the flare. The top frame shows the flare power (luminosity, erg s^{-1}) in the B- and TESS- photometric bands. The middle frame shows the (B-TESS) color index (in magnitudes), and the bottom frame shows the inferred photometric blackbody temperature of the flare.

Howard *et al.* (2020) saw similar temperature evolution in their flares, although (not surprisingly) every flare has its own peak temperature and decay time-scale. Bicz *et al.* (2025) used a somewhat different method with B-band and TESS-band photometry to determine peak temperatures of a collection of flares on different stars. They found peak temperatures ranging from 5,700 K to 31,500 K—so the peak temperature reported for our flare is well within this range—and confirmed that the flare area is a very small fraction of the surface area of the star.

3.2. Flux-calibrating the spectra

A wonderful thing about having simultaneous photometry and spectroscopy is that the photometry can be used to flux-calibrate the spectra, using the method of Boyd (2023). The magnitude of a star is related to the integral of the star's spectral flux over a passband of interest. For example, if we focus on the B-band, and use Vega as the standard star ($B_{\text{Vega}} \approx 0.0$), then

$$B_{\text{star}} - B_{\text{Vega}} = -2.5 \log \frac{\int_0^\infty [F_{\text{star}}(\lambda)] * R_b(\lambda) d\lambda}{\int_0^\infty [F_{\text{Vega}}(\lambda)] * R_b(\lambda) d\lambda}. \quad (7)$$

Equation 7 is just another way of writing the definition of the magnitude system, where F_{star} and F_{Vega} are the flux-calibrated spectra of the target star and of Vega, and $R_b(\lambda)$ is the B-band response function.

The normal spectrum processing (e.g. using the ISIS software) yields only a relative flux spectrum $f_{\text{star}}(\lambda)$, normalized by the spectral processing pipeline. We then assume that the flux-calibrated spectrum of our target star is related to its relative flux spectrum by a factor K , such that Equation 8 holds:

$$F_{\text{star}}(\lambda) = K \cdot f_{\text{star}}(\lambda) \quad (8)$$

Since we have an independent photometric measurement of the B mag of the target from simultaneous photometry, we can solve Equation (8) for the K -factor that converts the relative flux spectrum of the target star into its fluxcalibrated spectrum, given by Equation 9:

$$K = \frac{10^{\left(\frac{ZP - B_{\text{star}}}{2.5}\right)}}{\int_0^\infty f_{\text{star}}(\lambda) * R_b(\lambda) d\lambda} \quad (9)$$

B_{star} is the observed B-mag of the star as a function of time, so K is also a function of time. The zero point comes from the flux-calibrated spectrum of Vega, using Equation 10:

$$ZP = B_{\text{Vega}} + 2.5 \log \left[\int_0^\infty F_{\text{Vega}}(\lambda) * R_b(\lambda) d\lambda \right]. \quad (10)$$

A custom PYTHON code was written to integrate the B-band photometry over the exposure duration of each spectrum, calculate the K -factor, and output the flux-calibrated spectrum corresponding to each relative-flux spectrum. In this way, the time-series of relative-flux spectra is translated into a time-series of flux-calibrated spectra of EQ Peg A, showing the evolution of star's spectral flux.

The time-series includes a set of spectra made during the quiescent state of the star, before the flare began. If we assume

that the flare is a flash of light coming from a tiny fraction of the star's surface, then what we observe during the flare event is quiescent star plus flare. This enables finding the flare-only spectrum by subtracting the quiescent "star only" spectrum from the "star plus flare" spectra. The flare-only spectra vs time, showing how the flare itself evolves, are determined using Equation 11:

$$F_{\text{Flare}}(\lambda, t) = F_{\text{star}}(\lambda, t) - F_{\text{quiescent}}(\lambda) \quad (11)$$

In practice, the quiescent spectrum was created from 6 spectra taken during the period prior to the flare, when the star's photometric B-band brightness was essentially constant. These were flux-calibrated, then averaged to yield $F_{\text{quiescent}}(\lambda)$.

The practical implementation of this approach is shown in Figure 13.

Considering the orientation of the slit (perpendicular to the parallactic angle, hence risking slit-function variations due to differential atmospheric dispersion, particularly in the blue end of the spectra), and the possibility of atmospheric changes over the duration of the flare, it is reasonable to be concerned about the reliability of such a treatment of the time-series spectra. Happily, the flare occurred when the target was very high in the sky, minimizing atmospheric effects. At the start of the flare, the elevation angle was 59° (airmass ≈ 1.17) and when the flare continuum (outside of the emission lines) returned to near-zero the elevation angle was 62° (air mass ≈ 1.09). Examination of the raw signal levels in the spectra images showed good consistency before and after the flare (no significant change in atmospheric conditions), and the flux-calibrated spectra during quiescence before the flare (see Figure 15 below) and 2 h after the flare show continuum levels that are essentially identical. So there seems to be no adverse atmospheric or slit function effects, and there was no attempt to compensate for such issues.

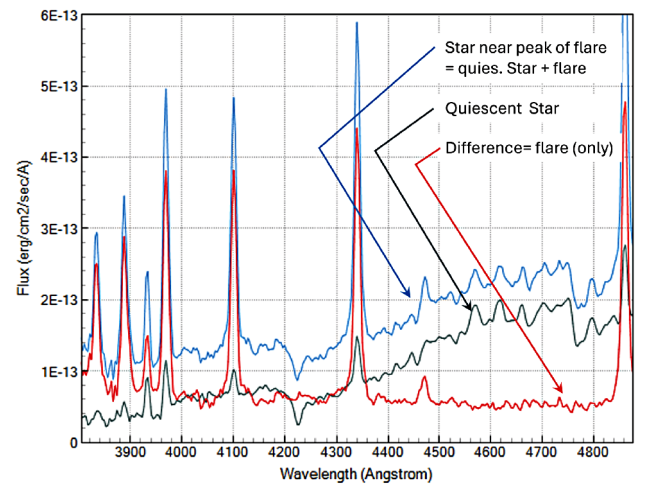


Figure 13. Example of the method of calculating the flare spectrum. All spectra are in flux-units ($\text{erg s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$). The black line is the average quiescent spectrum of the star. The blue line is the spectrum of the star near the peak of the flare. The red line is the difference between the two – the spectrum of the flare itself.

3.3. Evolution of the flare spectrum

This discussion will concentrate on five spectra identified in Table 1: one showing the quiescent state, three that show measurable views of the flare continuum, and one that shows the sustained emission lines after the continuum has returned to nearly the quiescent level.

The times and weighted-average B-magnitudes of these spectra are shown in Figure 14, with symbols that reasonably illustrate the duration of the spectrum exposures compared to the B-band photometry points.

The next several Figures illustrate the flare evolution, comparing the flare spectral flux in the blue portion of the spectral range (top), a detail of the H-gamma line (2nd), the B-band photometry (3rd) and the H-alpha line equivalent width (bottom).

Figure 15 shows the Quiescent state (JD-MID = 0.6941)—the B-mag and the H-alpha Equivalent Width are at their quiescent levels, and the flare spectrum is a flat line at zero flux (aside from measurement noise).

Figure 16 shows spectrum taken during the rise to peak brightness of the flare: B-mag has started its rapid rise, H-alpha and all the Balmer lines have started their rapid rise, the flare continuum level has jumped up, and enhanced emission lines have appeared.

Figure 17 is the very next spectrum—5 minutes after Figure 16—spanning the rapid rise and the peak of the flare's B-band brightness. The flare spectrum continuum is only slightly elevated from the preceding spectrum, but the emission lines are much strengthened.

Table 1. Identification of flux-calibrated spectra.

<i>JD-MID</i>	<i>B mag</i>	<i>Comments</i>
-2459847		
.6941	11.857	Quiescent, before start of flare
.6976	11.460	Start of photometric rise
.7011	11.287	Peak of flare
.7046	11.595	Emission lines strong, continuum fading
.7081	11.704	Emission lines elevated, but continuum too noisy to estimate blackbody temperature

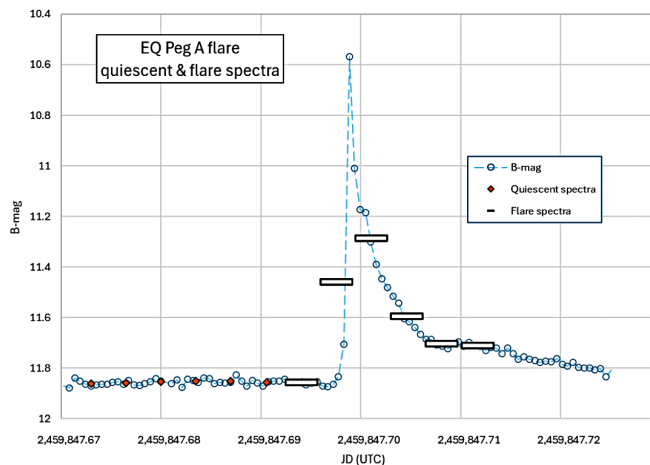


Figure 14. Spectra times and weighted-average magnitudes of flare spectra discussed in sections 3.1 and 3.2. Note the time-axis: this is a small portion of the overall photometry shown in Figures 15 through 19.

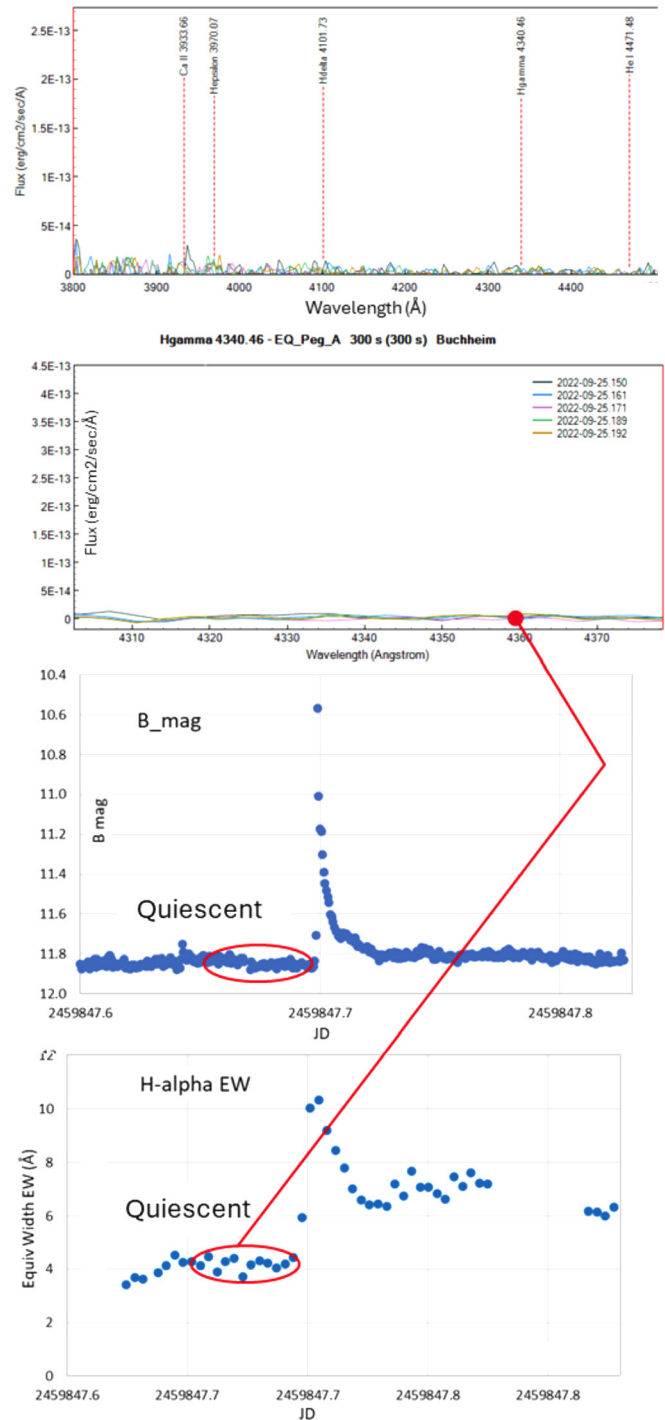


Figure 15. Flare spectrum in the quiescent state (pre-flare) at JD-MID = 0.6941.

Figure 18 spans most of the rapid fall in brightness. The flare continuum has dropped almost to its quiescent level, but the emission lines are still very strong. Note that the wings of the emission lines were significantly broadened during the flare, but they are now shrinking back to their normal width.

In Figure 19, when the photometric flare is just about over, the continuum is indistinguishable from the quiescent level, but emission lines are still elevated.

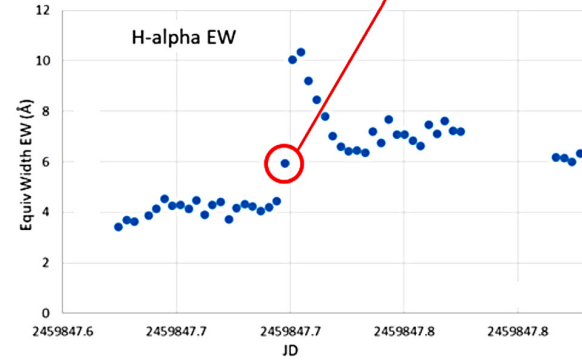
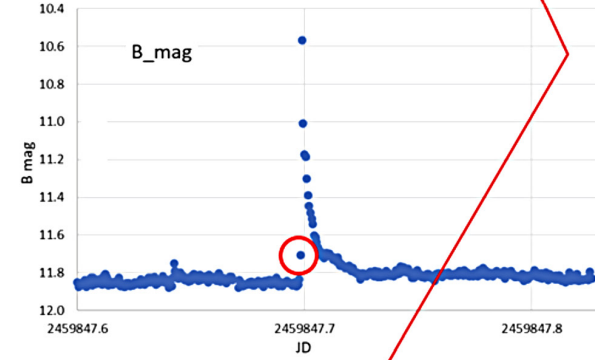
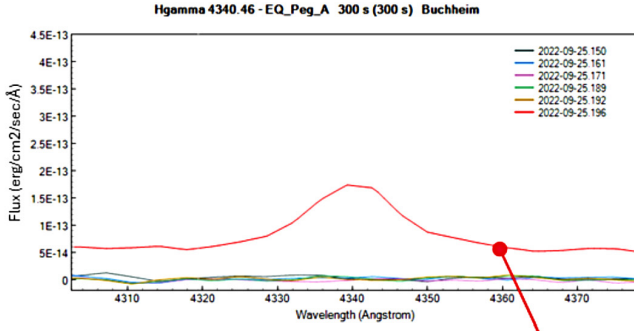
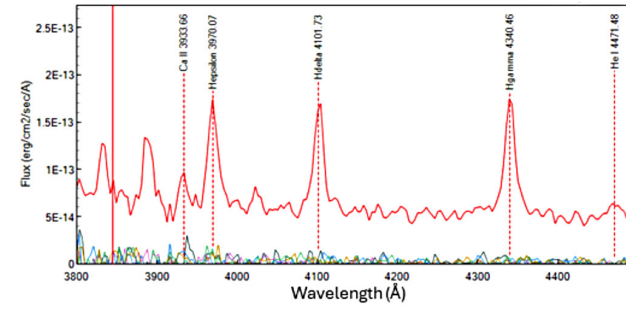


Figure 16. Flare spectrum at the very beginning of the flare, at JD-MID = 0.6976.

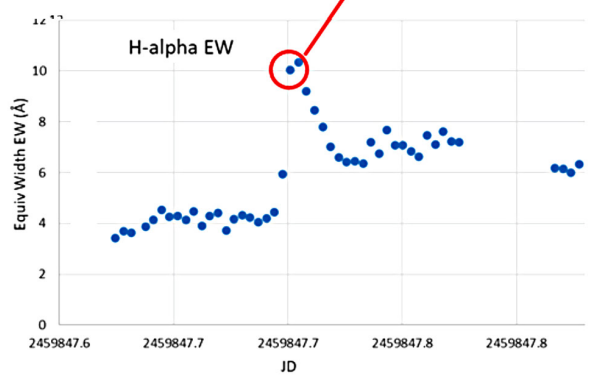
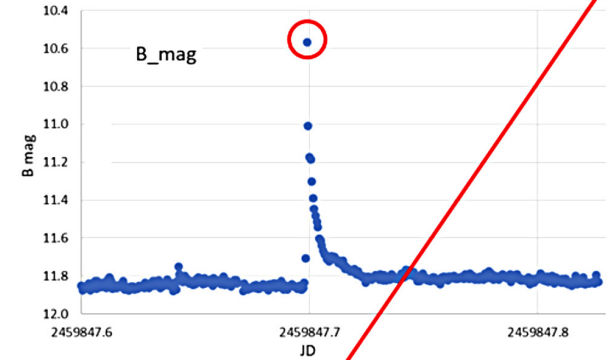
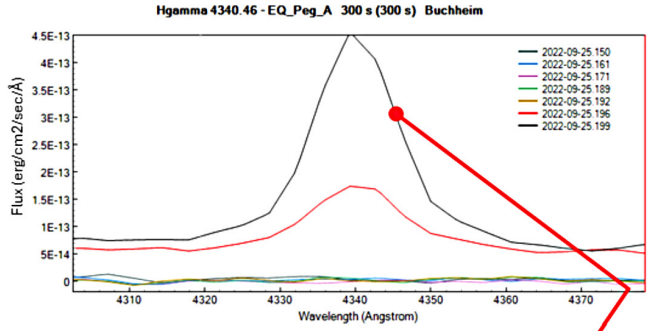
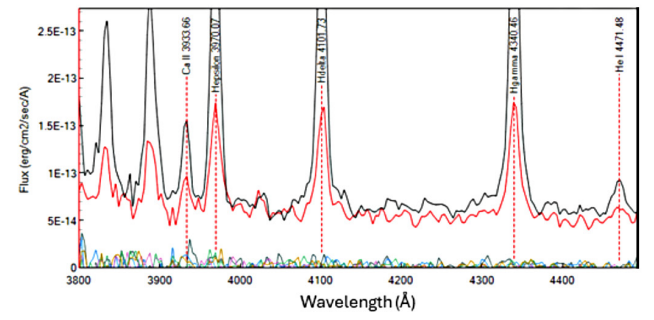


Figure 17. Flare spectrum at the peak of the flare at JD-MID = 0.7011.

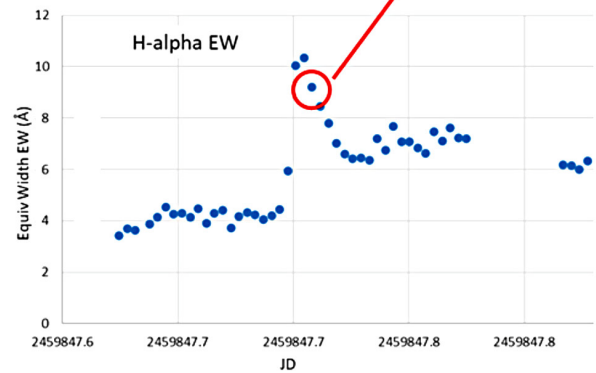
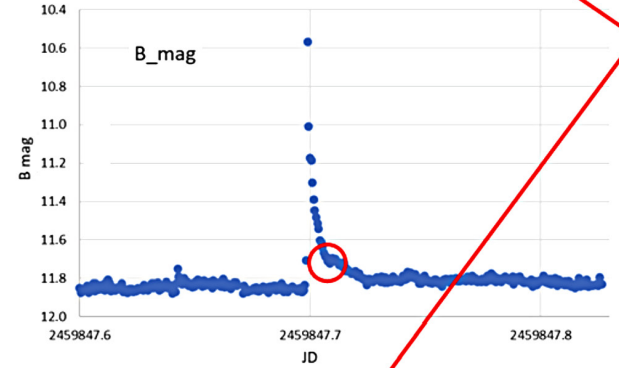
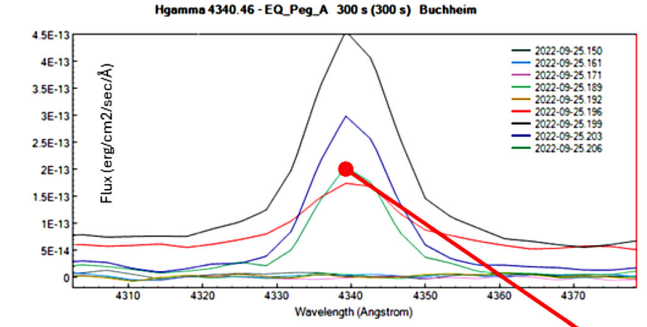
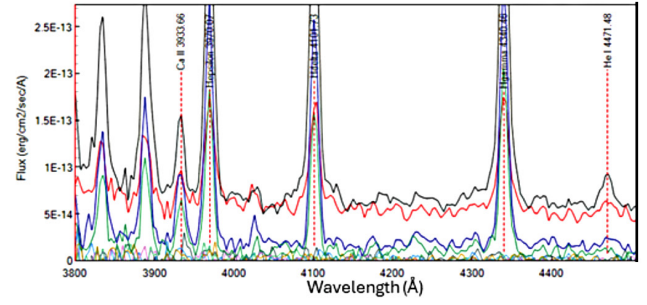
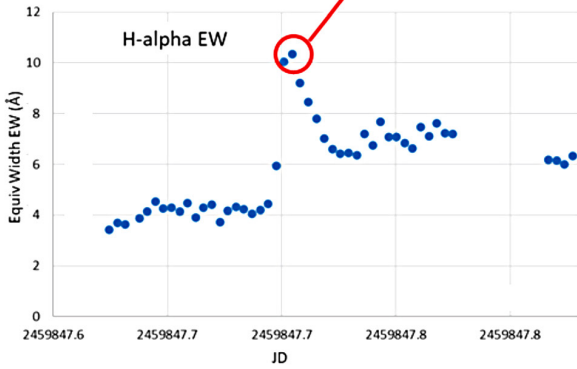
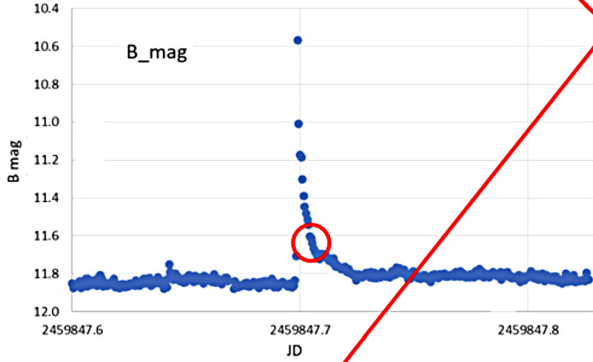
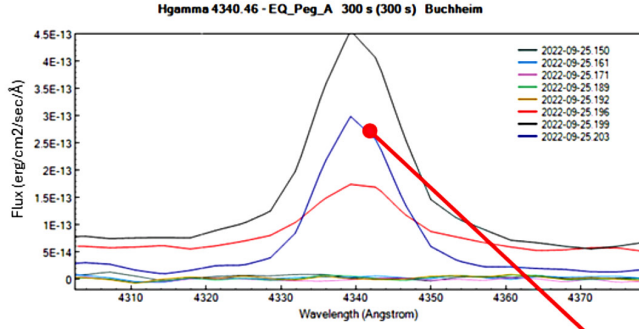
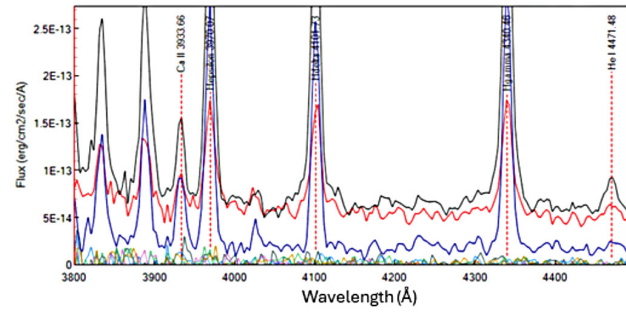


Figure 18. Flare spectrum during photometric decline at JD-MID = 0.7046. Note that the B-band brightness is nearing quiescence, but the H-alpha EW is still near its peak.

Figure 19. Flare spectrum at the end of the B-band flare at JD-MID = 0.7081.

3.4. Balmer line “time decrement”

The line flux vs. time of the bright emission lines is easily calculated from the flare-only spectra. The results are shown in Figure 20, for the Balmer lines and Ca II (K). There is a trend in the decay times ($t_{1/2}$ = the time to decay to 50% of the peak flux). As shown in Figure 21, the longer the wavelength, the longer it takes for the line to decay. This effect has been previously reported by Kowalski *et al.* (2013), who called it the Hydrogen Balmer “Time Decrement.”

3.5. Flare continuum temperature

Kowalski *et al.* (2013) described an approach to fitting the continuum of the flare spectra to a Planck (blackbody) curve, yielding an estimate of the flare continuum temperature. They identified narrow regions that are relatively free of both absorption and emission features. Three of their continuum regions are within the spectral range of our spectra of EQ Peg A, and are defined in Table 2.

Considering the low resolution and modest SNR of the spectra, a sort of “estimation by eye” was applied, which will be illustrated using the example of the spectrum at the peak of the flare, JD-MID = 0.7011. A family of blackbody curves of plausible temperatures are first scaled so that they all match the flare spectrum and the “C4500” continuum. Figure 22 shows this in overview.

The detail of blackbody curves vs flare spectrum at C4500 is shown in Figure 23.

The same blackbody curves as they pass through continuum region C4170 are shown in Figure 24.

At C4170, the coolest Planck curves (6000, 7000 K) seem too low, and the hottest (12000, 14000, 16000 K) seem to be high, but probably shouldn’t be ruled out at this point. The mid-range curves (8000, 10000 K) seem like fair fits to the continuum region, highlighted in grey.

A similar detail of the flare spectrum and blackbody curves at continuum region C6010 is shown in Figure 25.

Here, 7000 K and 8000 K blackbody curves seem to bracket the continuum region nearly perfectly. 6000 K is probably too high, and the curves for 10000 K through 16000 K are definitely too low. Considering this, and the picture at C4170, a fair estimate is that $T_{\text{Flare}} \approx 8000 \text{ K} \pm 2000 \text{ K}$ at this point in time.

A similar procedure was followed for the other flare spectra that showed a clear enough continuum for measurement. The resulting continuum temperatures are listed in Table 3.

These continuum temperatures are a bit higher than photometric color-temperatures at similar times shown in Figure 12, but qualitatively the trend is the same, and it is heartening that such similar temperatures are found from two different methods and two different wavelength regions. It seems that the initial burst of energy is the hottest, and the flare continuum continuously cools after this, while the emission lines remain elevated long after the continuum returns to its quiescent level. This result is similar to that seen in a flare on EV Lac by Ichihara *et al.* (2025).

3.6. Other emission lines

While the Balmer lines are most prominent in the flare spectrum, there are other weaker emission lines in the flare

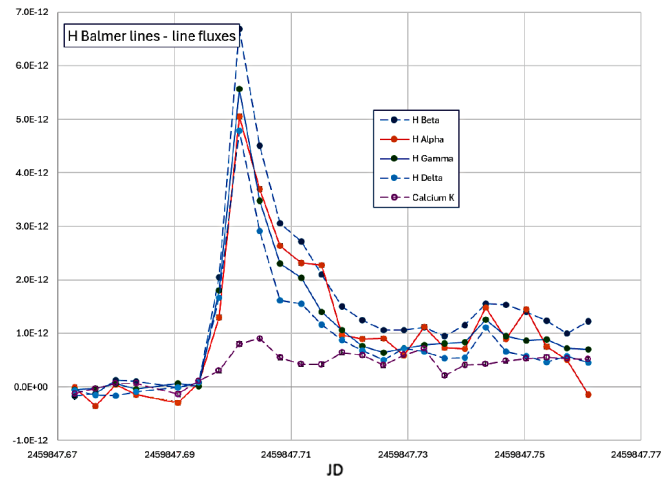


Figure 20. Balmer lines and Ca II (K) line flux vs time (flare-only).

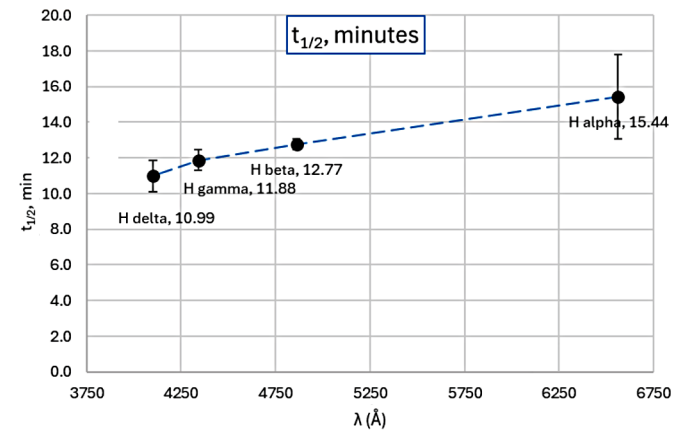


Figure 21. Balmer time decrement.

Table 2. Continuum regions used for fitting flare spectra to blackbody model (Planck function).

Continuum Measure	Spectral Range (Å)
C4170	4155–4185
C4500	4490–4520
C6010	5990–6030

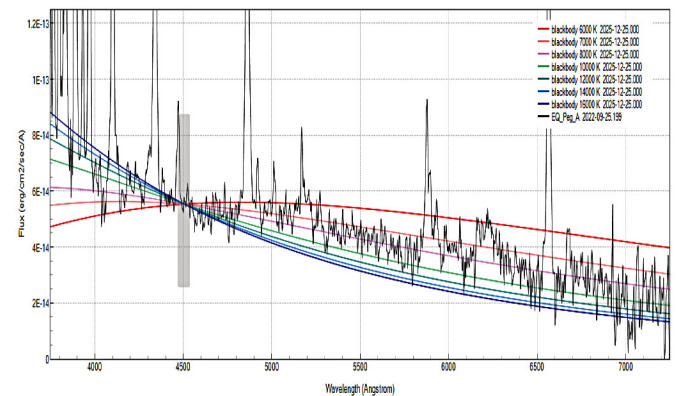


Figure 22. Overview of flare spectrum compared to blackbody spectra, scaled to match the flare at continuum spectral range “C4500” (highlight by grey rectangle).

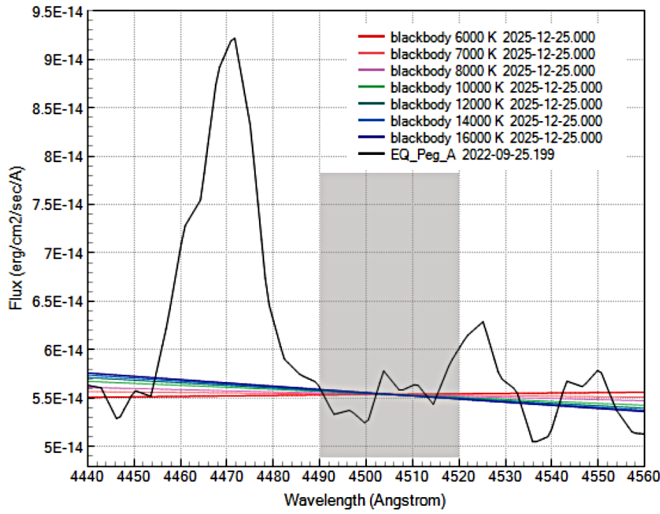


Figure 23. Blackbody curves passing through Continuum region C4500.

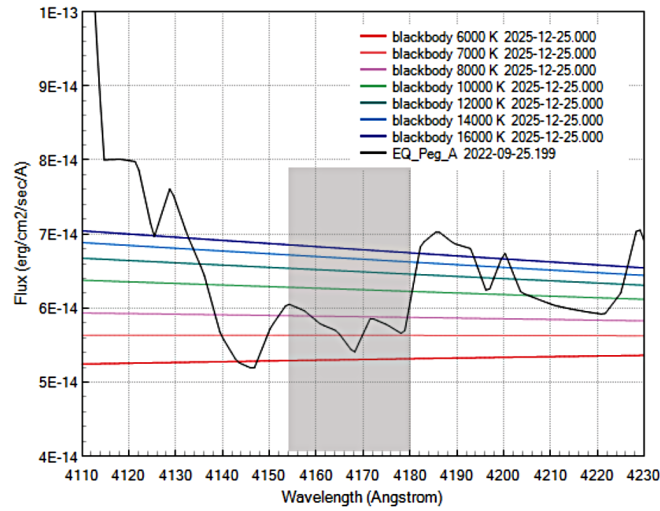


Figure 24. Blackbody curves passing through continuum region C4170.

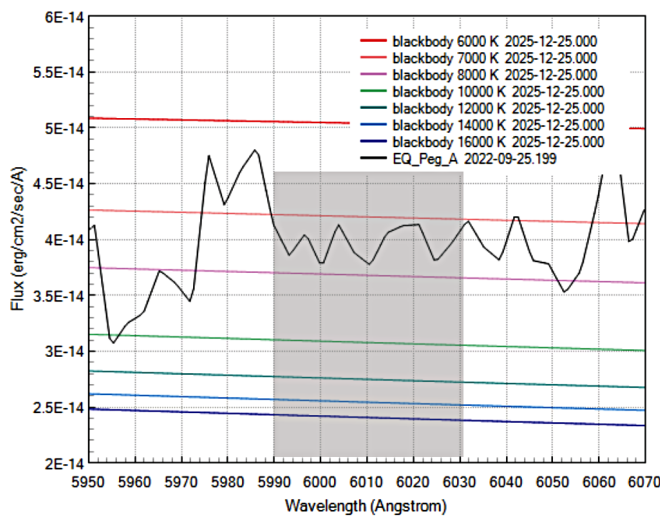


Figure 25. Blackbody curves passing through continuum region C6010.

Table 3. Evolution of flare spectrum continuum temperatures.

$JD-MID$ -2459847	B mag	T_{Flare} continuum temp (K)
.6976	11.460	$T_{Flare} = 14,000 \pm 2000$
.7011	11.287	$T_{Flare} = 8000 \pm 2000$
.7046	11.595	$T_{Flare} = 7000 \pm 2000$

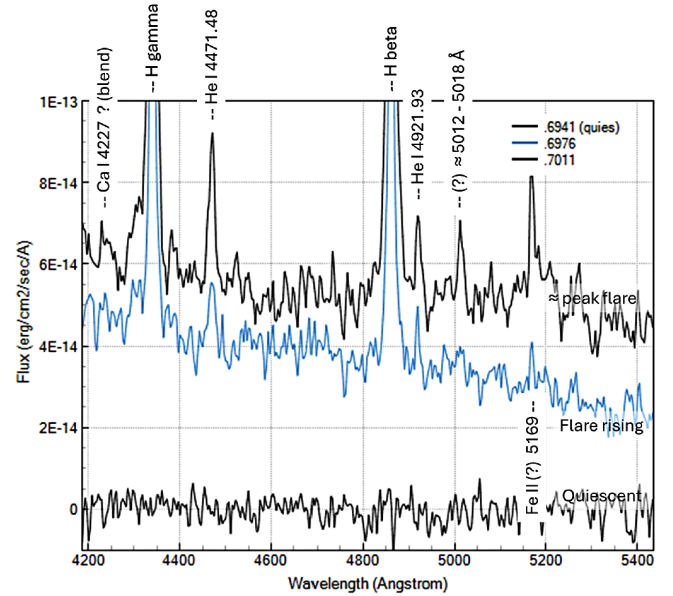
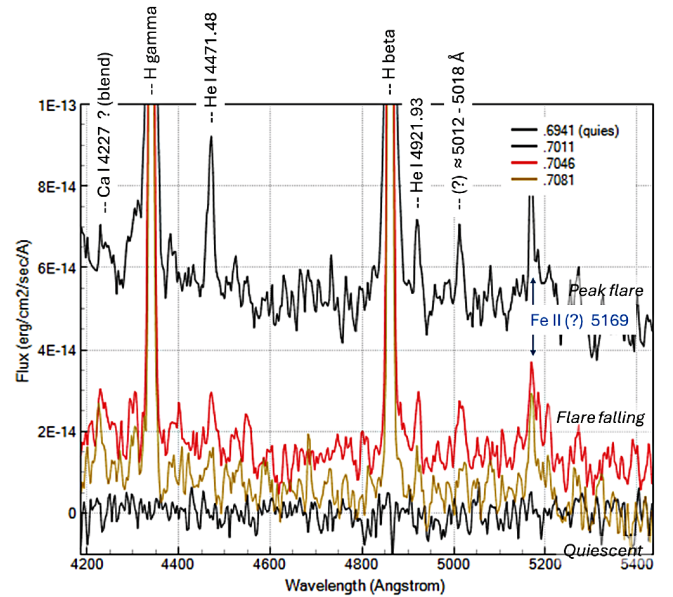
Figure 26. Detail of emission lines near H beta, at the start of the flare. Spectra are identified by their fractional JD: $t = (JD - 2459847)$. The quiescent spectrum ($t = .6941$) taken just before the start of the flare is shown for comparison. The next spectrum is $t = .6976$, showing the rise of the flare, with the peak flare at $t = .7011$ at the top.

Figure 27. Continuum and emission lines changing as the flare fades from its peak.

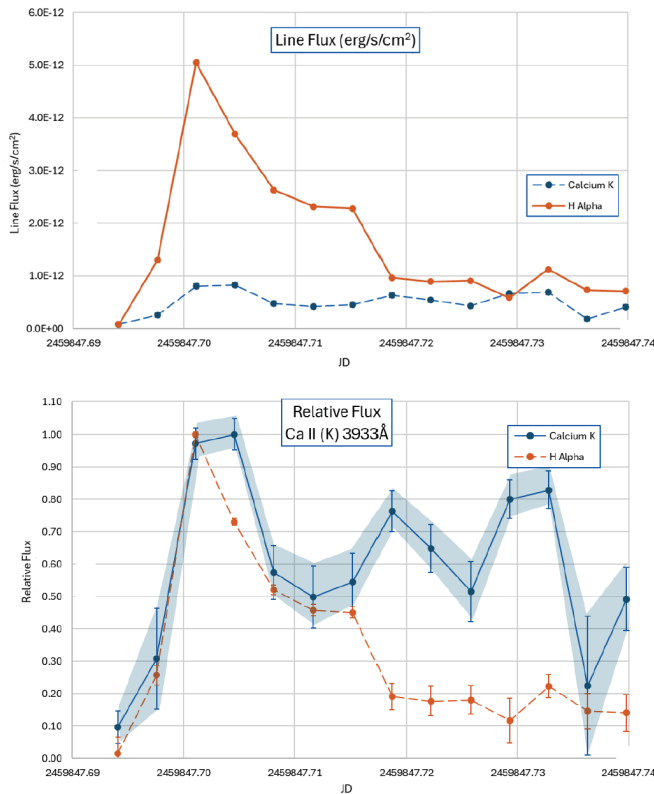


Figure 28. Line flux of the Ca II (K) emission line during the flare, with H alpha shown for comparison. The top graph shows the line strength in flux units. The bottom graph shows the same data, but with the flux normalized to the peak flux in each line. The signal level of Ca II (K) is low, and the spectrograph has low sensitivity to far-blue light (hence relatively poor signal to noise ratio), but the sustained strength of Ca II (K) seems to be real.

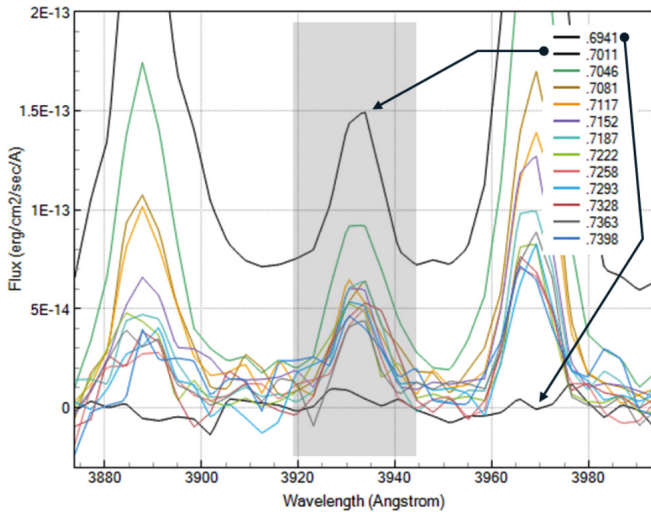


Figure 29. Detail of the time-series spectra in the Ca II (K) region (highlighted in gray), used for Figure 28. Spectrum “.6941” was taken just before the flare began, and provides a good view of the quiescent spectrum. Spectrum $t = .7011$ is the peak of the flare. The other curves show the spectra as the flare fades. The low SNR causing the wide scatter in the continuum region (left and right of line region) leads to “noise” in the line flux calculation; nevertheless, the sustained emission appears to be real.

spectrum. The first two spectra at the start of the flare are shown in Figure 26, illustrating the rise of several emission lines. The He I 4471 and He I 4922 lines appear promptly at the start of the flare. Abdul-Aziz *et al.* (1995) suspected Ca I (4227 Å) emission during a flare on EV Lac. The Ca I 4227 line might be seen (as a blend) in the spectrum at JD-MID .7011 (peak of the flare), but it is weak or absent in the preceding spectrum at the very beginning of the flare, so its appearance—if real—is delayed compared to the Balmer and He I lines. Kowalski *et al.* (2013) saw a feature at ≈ 5018 Å which they suspected might be a blend of He I, Fe II or Mg Ib; the spectra here show a similar blended feature at the same location. A sharp bright line at 5169 Å is apparent in these spectra; Abdul-Aziz (1995) suggested that this might be Fe II (5169) or a blend with Mg I (5167, 5173).

Figure 27 is similar to Figure 26, except that it shows the spectra taken as the flare fades from peak. It highlights the possible strengthening of the Ca II 4227 (?) line, while the Fe II (?) 5169 feature stays strong as the flare fades.

The Ca II (K) line in flare spectra often displays a different time evolution than the H I and He I lines (e.g. Kowalski 2013; Buchheim 2022). In this flare, as shown in Figure 28, it sustained a strong emission far longer than the H alpha (and the other H I and He I lines) did. There is also a hint that it may have peaked later than the H-alpha line, by about 5 minutes.

The signal level is low, so the noise level and scatter in the Ca II (K) line flux data is large. Nevertheless, the trend of sustained Ca II(K) emission for longer than it is seen in the H I lines seems to be real. Figure 29 shows the evolution of the Ca II (K) spectral region for 55 minutes after the peak of the flare.

4. Conclusions

For targets like this, amateur observers have an asset that professional researchers don't: we can invest a great deal of observing time in hopes of seeing—and measuring—short-lived, rare events like stellar flares.

Simultaneous spectroscopy and photometry increases the information that can be derived from amateur and small-telescope observations. This applies not just to stellar flares, but also to many types of stellar variability and transients. The two techniques (photometry and spectroscopy) need not be done by a single observer. Teamwork between photometrist and spectroscopist is effective, even if they are geographically separated, as was the case for this project. The spectra were made in Arizona, and the B-band photometry was done in Massachusetts, but serendipitously two observers provided overlapping data on this flare.

The data show many flare features that have been reported by professional projects, which is heartening confirmation of the fidelity of the small-telescope results. Even in situations like this, where we may not be breaking new ground, achieving replication of prior—relatively rare—observations and conclusions is a contribution to science.

5. Acknowledgements

I acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research.

This research has made use of the SIMBAD database, CDS, Strasbourg Astronomical Observatory, France (Wenger *et al.* 2000).

This research has made use of the VizieR catalogue access tool, CDS, Strasbourg Astronomical Observatory, France (Ochsenbein *et al.* 2000)).

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This research made use of Lightkurve, a PYTHON package for Kepler and TESS data analysis (Lightkurve Collaboration 2018).

This research made use of the program ISIS (Integrated Spectrographic Innovative Software; Buil 2026).

This research made use of Peranso (Vanmunster 2025), a light curve and period analysis software.

A hearty “thank you, and well-done!” to Ken Menzies and the other members of the Red Dwarf Group for their devotion to providing high-quality data in support of variable star investigations.

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¹ Vanderspek *et al.* (2018): https://archive.stsci.edu/files/live/sites/mast/files/home/missions-and-data/active-missions/tess/_documents/TESS_Instrument_Handbook_v0.1.pdf

Recent Maxima of 91 Short Period Pulsating Stars

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Abstract This paper contains times of maxima for 91 short period pulsating stars (primarily RR Lyrae and δ Scuti stars). These times of maxima represent the CCD observations received by the AAVSO Short Period Pulsators Section in 2025.

1. Recent observations

Table 1 contains times of maxima of 91 short period pulsating stars (primarily RR Lyrae and δ Scuti stars) calculated from CCD observations made by participants in the AAVSO's Short Period Pulsator (SPP) Section. This list will be web-archived and made available through the AAVSO ftp site at: <ftp://ftp.aavso.org/public/datasets/gsamj541spp91.txt>.

The error estimate is included. RR Lyr stars in this list, along with data from earlier AAVSO publications, are included in the GEOS database at: <http://rr-lyr.irap.omp.eu/dbrr/>. This database does not include δ Scuti stars.

These observations were reduced by the writer using the PERANSO program (Vanmunster 2004–2021). Column F indicates the filter used.

The linear elements in the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al.* 1985) were used to compute the O–C values for most stars. For a few exceptions where the GCVS elements are missing or are in significant error, light elements from another source are used: GP And, V799 Aur, V377 Boo, V876 Cep, V488 Gem, and V481 Lac (AAVSO VSX; Watson *et al.* 2014); VY CrB (Antipin 1996); RZ Cap (Samolyk 2010); V521 And, V2416 Cyg (Samolyk 2018);

GO Hya (GEOS 2021); AH Leo (Schmidt *et al.* 1995); and AA LMi (Samolyk 2023).

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Table 1. Recent times of maxima of stars in the AAVSO Short Period Pulsator program.

Star	JD (max) Hel. 2400000 +	Cycle	O–C (day)	F	Observer	Error (day)	Star	JD (max) Hel. 2400000 +	Cycle	O–C (day)	F	Observer	Error (day)
SW And	60688.3121	96220	–0.6085	V	T. Arranz	0.0008	AC And	60919.8298	17461	0.7152	V	G. Samolyk	0.0023
SW And	60707.3309	96263	–0.6077	V	T. Arranz	0.0008	AC And	60932.5251	17479	0.6081	V	T. Arranz	0.0014
SW And	60711.3122	96272	–0.6069	V	T. Arranz	0.0007	AC And	60944.5875	17496	0.5795	V	T. Arranz	0.0008
SW And	60923.5961	96752	–0.6171	V	T. Arranz	0.0006	AC And	61024.4159	17608	0.7490	V	T. Arranz	0.0018
SW And	60927.5762	96761	–0.6175	V	T. Arranz	0.0006	AT And	60920.5674	30113	–0.0070	V	T. Arranz	0.0017
SW And	60931.5574	96770	–0.6169	V	T. Arranz	0.0006	AT And	60926.7359	30123	–0.0076	V	G. Samolyk	0.0015
SW And	60934.6527	96777	–0.6175	V	T. Arranz	0.0007	AT And	60936.6088	30139	–0.0054	V	T. Arranz	0.0015
SW And	60935.5376	96779	–0.6172	V	T. Arranz	0.0006	AT And	60952.6472	30165	–0.0067	V	T. Arranz	0.0015
SW And	60954.5547	96822	–0.6181	V	T. Arranz	0.0006	AT And	61006.3190	30252	–0.0065	V	T. Arranz	0.0016
SW And	60962.5153	96840	–0.6185	V	T. Arranz	0.0007	DM And	60958.4163	40040	0.2097	V	T. Arranz	0.0014
SW And	60982.4162	96885	–0.6202	V	T. Arranz	0.0006	DY And	60943.5750	41240	–0.1989	V	T. Arranz	0.0009
SW And	61005.4143	96937	–0.6206	V	T. Arranz	0.0009	DY And	60947.7948	41247	–0.2007	V	K. Menzies	0.0014
XX And	60691.3911	29891	0.3189	V	T. Arranz	0.0011	DY And	60952.6196	41255	–0.2006	V	K. Menzies	0.0013
XX And	60712.3522	29920	0.3203	V	T. Arranz	0.0008	DY And	60952.6203	41255	–0.1999	V	T. Arranz	0.0011
XX And	60935.6841	30229	0.3233	V	G. Samolyk	0.0016	DY And	61024.3876	41374	–0.2000	V	T. Arranz	0.0019
XX And	60964.5977	30269	0.3270	V	T. Arranz	0.0014	GP And	60944.5914	41062	0.0018	V	G. Samolyk	0.0007
XX And	61001.4567	30320	0.3259	V	T. Arranz	0.0011	GP And	60944.6699	41063	0.0017	V	G. Samolyk	0.0004
AC And	60666.3564	17105	0.4432	V	T. Arranz	0.0019	GP And	60944.7488	41064	0.0019	V	G. Samolyk	0.0004
AC And	60912.5680	17451	0.5658	V	T. Arranz	0.0008	GP And	60944.8273	41065	0.0017	V	G. Samolyk	0.0003
AC And	60914.6859	17454	0.5499	V	G. Samolyk	0.0009	V521 And	58327.8081	39096	0.0214	V	G. Samolyk	0.0035

Table continued on following pages

Table 1. Recent times of maxima of stars in the AAVSO Short Period Pulsator program, cont.

<i>Star</i>	<i>JD (max)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O–C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Error</i> <i>(day)</i>	<i>Star</i>	<i>JD (max)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O–C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Error</i> <i>(day)</i>
V521 And	58734.8006	43127	0.0412	V	K. Menzies	0.0032	ST Boo	60894.3827	67031	0.1297	V	T. Arranz	0.0006
V521 And	60933.7953	64907	0.1106	V	G. Samolyk	0.0021	SW Boo	60751.8734	35403	0.6781	V	G. Samolyk	0.0011
V521 And	60956.7022	65134	0.0993	V	G. Samolyk	0.002	SW Boo	60761.6321	35422	0.6797	V	T. Arranz	0.0007
SW Aqr	60908.7920	77969	0.0053	V	G. Samolyk	0.0009	SW Boo	60789.3648	35476	0.6819	V	T. Arranz	0.0009
SW Aqr	60935.4315	78027	0.0052	V	T. Arranz	0.0007	SW Boo	60790.3906	35478	0.6807	V	T. Arranz	0.0008
TZ Aqr	60909.6208	40898	0.0163	V	T. Arranz	0.0015	SW Boo	60792.4459	35482	0.6819	V	T. Arranz	0.0008
TZ Aqr	60917.6179	40912	0.0167	V	T. Arranz	0.0014	SW Boo	60793.4726	35484	0.6815	V	T. Arranz	0.0009
YZ Aqr	60916.7690	46296	0.1008	V	G. Samolyk	0.0014	SW Boo	60795.5256	35488	0.6804	V	T. Arranz	0.0011
AA Aqr	60887.6121	65922	–0.2261	V	T. Arranz	0.0007	SW Boo	60812.4806	35521	0.6890	V	T. Arranz	0.0008
BO Aqr	60920.7864	27808	0.2652	V	G. Samolyk	0.0013	SZ Boo	60764.5394	63357	0.0143	V	T. Arranz	0.0010
BR Aqr	60682.2750	47826	–0.2651	V	T. Arranz	0.0008	SZ Boo	60765.5857	63359	0.0150	V	T. Arranz	0.0011
BR Aqr	60948.7483	48379	–0.2707	V	G. Samolyk	0.0011	TV Boo	60765.5898	115677	0.1457	V	T. Arranz	0.0018
CY Aqr	60973.5340	436858	0.0207	V	G. Samolyk	0.0003	TV Boo	60766.5163	115680	0.1345	V	T. Arranz	0.0015
CY Aqr	60973.5952	436859	0.0209	V	G. Samolyk	0.0004	TV Boo	60772.4713	115699	0.1509	V	T. Arranz	0.0025
CY Aqr	60973.6564	436860	0.0211	V	G. Samolyk	0.0003	TV Boo	60775.5967	115709	0.1507	V	T. Arranz	0.0013
CY Aqr	60973.7173	436861	0.0209	V	G. Samolyk	0.0006	TV Boo	60788.3827	115750	0.1218	V	T. Arranz	0.0009
DN Aqr	60973.6511	51358	0.0332	V	G. Samolyk	0.0018	TV Boo	60792.4731	115763	0.1489	V	T. Arranz	0.0016
RV Ari	60702.5600	275803	–0.0070	V	G. Samolyk	0.0009	TV Boo	60793.4088	115766	0.1469	V	T. Arranz	0.0013
RV Ari	60702.6622	275804	0.0021	V	G. Samolyk	0.0005	TV Boo	60795.5899	115773	0.1401	V	T. Arranz	0.0014
RV Ari	61031.4876	279335	–0.0084	V	G. Samolyk	0.0004	TV Boo	60797.4520	115779	0.1269	V	T. Arranz	0.0011
RV Ari	61031.5838	279336	–0.0054	V	G. Samolyk	0.0007	TV Boo	60812.4833	115827	0.1553	V	T. Arranz	0.0013
TZ Aur	60684.7880	104123	0.0197	V	G. Samolyk	0.0007	TV Boo	60813.4158	115830	0.1501	V	T. Arranz	0.0014
TZ Aur	60693.4044	104145	0.0192	V	T. Arranz	0.0007	TV Boo	60816.5169	115840	0.1256	V	T. Arranz	0.0011
TZ Aur	60707.5051	104181	0.0196	V	T. Arranz	0.0007	TV Boo	60818.3910	115846	0.1244	V	T. Arranz	0.0009
TZ Aur	60729.4382	104237	0.0190	V	T. Arranz	0.0007	TV Boo	60820.6090	115853	0.1545	V	T. Arranz	0.0012
TZ Aur	60733.3540	104247	0.0180	V	T. Arranz	0.0008	TV Boo	60823.4213	115862	0.1537	V	T. Arranz	0.0015
TZ Aur	60751.3727	104293	0.0197	V	T. Arranz	0.0009	TV Boo	60826.5193	115872	0.1261	V	T. Arranz	0.0009
TZ Aur	60953.8688	104810	0.0200	V	G. Samolyk	0.0008	TV Boo	60833.4205	115894	0.1510	V	T. Arranz	0.001
TZ Aur	60998.5199	104924	0.0202	V	T. Arranz	0.0006	TV Boo	60842.4917	115923	0.1580	V	T. Arranz	0.0009
BH Aur	60751.6980	39466	0.0160	V	G. Samolyk	0.0013	TV Boo	60847.4595	115939	0.1249	V	T. Arranz	0.0009
BH Aur	60760.3624	39485	0.0146	V	T. Arranz	0.0008	TW Boo	60793.7323	63694	–0.1417	V	G. Samolyk	0.0009
BH Aur	60945.5369	39891	0.0167	V	T. Arranz	0.0008	TW Boo	60822.4745	63748	–0.1423	V	T. Arranz	0.0008
BH Aur	60955.5699	39913	0.0157	V	T. Arranz	0.0008	UU Boo	60773.6385	54033	0.4431	V	T. Arranz	0.0007
BH Aur	61007.5649	40027	0.0165	V	T. Arranz	0.0008	UU Boo	60774.5525	54035	0.4433	V	T. Arranz	0.0007
BH Aur	61008.4781	40029	0.0175	V	T. Arranz	0.0009	UU Boo	60863.6559	54230	0.4472	V	K. Menzies	0.0008
BH Aur	61023.5280	40062	0.0164	V	T. Arranz	0.0009	UY Boo	60773.8984	29097	0.8148	V	G. Samolyk	0.0015
V799 Aur	60708.4955	85511	0.0095	V	T. Arranz	0.0005	UY Boo	60821.4149	29170	0.8202	V	T. Arranz	0.0009
V799 Aur	60708.5712	85512	0.0092	V	T. Arranz	0.0005	V377 Boo	60835.6149	19704	–0.0005	V	T. Arranz	0.0005
V799 Aur	60942.5730	88587	0.0104	V	T. Arranz	0.0005	UY Cam	60742.7067	94283	–0.0852	V	G. Samolyk	0.0016
V799 Aur	60942.6493	88588	0.0105	V	T. Arranz	0.0005	RW Cnc	60755.6130	38741	0.2625	V	G. Samolyk	0.0013
V799 Aur	61031.4549	89755	0.0101	V	T. Arranz	0.0004	RW Cnc	60764.3523	38757	0.2467	V	T. Arranz	0.0008
RS Boo	60746.8455	50290	–0.0208	V	K. Menzies	0.0007	RW Cnc	60765.4457	38759	0.2457	V	T. Arranz	0.0010
RS Boo	60764.5813	50337	–0.0199	V	T. Arranz	0.0005	RW Cnc	60776.4008	38779	0.2568	V	T. Arranz	0.0015
RS Boo	60766.4680	50342	–0.0199	V	T. Arranz	0.0007	RW Cnc	60788.4368	38801	0.2544	V	T. Arranz	0.0010
RS Boo	60775.5205	50366	–0.0236	V	T. Arranz	0.0006	RW Cnc	60793.3540	38810	0.2468	V	T. Arranz	0.0006
RS Boo	60790.6146	50406	–0.0230	V	T. Arranz	0.0007	RW Cnc	60796.6356	38816	0.2452	V	K. Menzies	0.0011
RS Boo	60797.4084	50424	–0.0213	V	T. Arranz	0.0006	TT Cnc	60695.7896	36829	0.1446	V	G. Samolyk	0.0011
RS Boo	60820.4273	50485	–0.0201	V	T. Arranz	0.0005	TT Cnc	60729.5859	36889	0.1340	V	T. Arranz	0.0015
RS Boo	60840.4227	50538	–0.0237	V	T. Arranz	0.0006	TT Cnc	60763.4116	36949	0.1527	V	T. Arranz	0.0011
RS Boo	60843.4421	50546	–0.0230	V	T. Arranz	0.0007	TT Cnc	60772.4244	36965	0.1503	V	T. Arranz	0.0011
RS Boo	60863.4417	50599	–0.0223	V	T. Arranz	0.0005	TT Cnc	60776.3698	36972	0.1516	V	T. Arranz	0.0009
RS Boo	60877.4049	50636	–0.0207	V	T. Arranz	0.0005	TT Cnc	60790.4430	36997	0.1385	V	T. Arranz	0.0008
ST Boo	60788.6024	66861	0.1388	V	T. Arranz	0.0009	KV Cnc	60761.4352	15936	0.0700	V	T. Arranz	0.0010
ST Boo	60793.5849	66869	0.1430	V	T. Arranz	0.0010	KV Cnc	60763.4360	15940	0.0628	V	T. Arranz	0.0009
ST Boo	60806.6532	66890	0.1431	V	K. Menzies	0.0008	KV Cnc	60764.4324	15942	0.0552	V	T. Arranz	0.0012
ST Boo	60813.4993	66901	0.1440	V	T. Arranz	0.0007	SS CVn	60839.4596	44339	–0.3880	V	T. Arranz	0.0007
ST Boo	60818.4794	66909	0.1458	V	T. Arranz	0.0011	RV Cap	60883.8714	60304	–0.1454	V	G. Samolyk	0.0011
ST Boo	60821.5904	66914	0.1454	V	T. Arranz	0.0007	RV Cap	60901.7833	60344	–0.1432	V	G. Samolyk	0.0008
ST Boo	60823.4569	66917	0.1450	V	T. Arranz	0.0009	RZ Cap	60857.8304	23623	0.0097	V	G. Samolyk	0.0014
ST Boo	60826.5702	66922	0.1468	V	T. Arranz	0.0010	VW Cap	60884.8170	112884	0.2912	V	G. Samolyk	0.0011
ST Boo	60833.4146	66933	0.1460	V	T. Arranz	0.0008	YZ Cap	60918.7043	62858	0.0472	V	G. Samolyk	0.0025
ST Boo	60866.3905	66986	0.1405	V	T. Arranz	0.0008	V876 Cep	60964.3454	56176	–0.0416	V	T. Arranz	0.0018
ST Boo	60874.4784	66999	0.1387	V	T. Arranz	0.0009	V876 Cep	60964.4965	56177	–0.0391	V	T. Arranz	0.0014
ST Boo	60879.4533	67007	0.1352	V	T. Arranz	0.0008	RR Cet	60977.7319	50262	0.0275	V	G. Samolyk	0.0009
ST Boo	60884.4312	67015	0.1348	V	T. Arranz	0.0008	RR Cet	61031.3762	50359	0.0281	V	T. Arranz	0.0014

Table continued on following pages

Table 1. Recent times of maxima of stars in the AAVSO Short Period Pulsator program, cont.

<i>Star</i>	<i>JD (max) Hel. 2400000 +</i>	<i>Cycle</i>	<i>O–C (day)</i>	<i>F</i>	<i>Observer</i>	<i>Error (day)</i>	<i>Star</i>	<i>JD (max) Hel. 2400000 +</i>	<i>Cycle</i>	<i>O–C (day)</i>	<i>F</i>	<i>Observer</i>	<i>Error (day)</i>
RU Cet	60990.6175	36099	0.0848	V	G. Samolyk	0.0013	RW Dra	60849.4261	48478	0.3048	V	T. Arranz	0.0011
RV Cet	60708.3239	34640	0.2810	V	T. Arranz	0.0016	RW Dra	60853.4194	48487	0.3118	V	T. Arranz	0.0011
RV Cet	60975.7812	35069	0.2984	V	G. Samolyk	0.0025	RW Dra	60864.5261	48512	0.3456	V	T. Arranz	0.0009
RZ Cet	61002.6992	53066	−0.2623	V	G. Samolyk	0.0012	RW Dra	60868.5163	48521	0.3495	V	T. Arranz	0.0007
TY Cet	60956.8343	29442	0.0077	V	G. Samolyk	0.0023	RW Dra	60872.5016	48530	0.3486	V	T. Arranz	0.0006
UU Cet	60975.7016	32615	−0.2062	V	G. Samolyk	0.0022	RW Dra	60888.4037	48566	0.3057	V	T. Arranz	0.0009
VY CrB	60783.8274	41057	−0.2081	V	K. Menzies	0.0019	RW Dra	60895.4972	48582	0.3125	V	T. Arranz	0.0010
VY CrB	60822.6912	41141	−0.2327	V	K. Menzies	0.0014	RW Dra	60896.3853	48584	0.3148	V	T. Arranz	0.0008
XX Cyg	60836.6567	121464	0.0061	V	G. Samolyk	0.0007	RW Dra	60927.3902	48654	0.3155	V	T. Arranz	0.0006
XX Cyg	60836.7914	121465	0.0059	V	G. Samolyk	0.0006	XZ Dra	60854.7406	39720	−0.0942	V	G. Samolyk	0.0012
XX Cyg	60868.6194	121701	0.0058	V	T. Arranz	0.0004	XZ Dra	60881.4271	39776	−0.0916	V	T. Arranz	0.0009
XX Cyg	60877.6550	121768	0.0054	V	T. Arranz	0.0002	XZ Dra	60888.5739	39791	−0.0922	V	T. Arranz	0.0010
XX Cyg	60948.5937	122294	0.0051	V	G. Samolyk	0.0005	XZ Dra	60902.3991	39820	−0.0854	V	T. Arranz	0.0007
XZ Cyg	60859.8151	35866	−3.2871	V	G. Samolyk	0.0009	XZ Dra	60932.4107	39883	−0.0932	V	T. Arranz	0.0006
XZ Cyg	60861.6819	35870	−3.2871	V	G. Samolyk	0.0008	XZ Dra	60963.3810	39948	−0.0952	V	T. Arranz	0.0009
XZ Cyg	60863.5473	35874	−3.2885	V	T. Arranz	0.0005	RX Eri	60956.9289	66862	−0.0069	V	G. Samolyk	0.0011
XZ Cyg	60866.8122	35881	−3.2905	V	G. Samolyk	0.0008	SV Eri	60693.3072	35220	1.2890	V	T. Arranz	0.0021
XZ Cyg	60870.5417	35889	−3.2946	V	T. Arranz	0.0007	SV Eri	60968.8691	35606	1.3255	V	G. Samolyk	0.0018
XZ Cyg	60877.5372	35904	−3.2996	V	T. Arranz	0.0007	SS For	60957.7788	44989	−0.1624	V	G. Samolyk	0.0009
XZ Cyg	60880.8050	35911	−3.2987	V	G. Samolyk	0.0009	RR Gem	60691.5615	48665	−0.7638	V	T. Arranz	0.0008
XZ Cyg	60883.6102	35917	−3.2937	V	T. Arranz	0.0008	RR Gem	60693.5527	48670	−0.7592	V	T. Arranz	0.0006
XZ Cyg	60884.5430	35919	−3.2943	V	T. Arranz	0.0008	RR Gem	60696.7292	48678	−0.7612	V	G. Samolyk	0.0007
XZ Cyg	60885.4763	35921	−3.2944	V	T. Arranz	0.0009	RR Gem	60701.4992	48690	−0.7589	V	T. Arranz	0.0007
XZ Cyg	60889.6771	35930	−3.2939	V	G. Samolyk	0.0016	RR Gem	60707.4562	48705	−0.7616	V	T. Arranz	0.0006
XZ Cyg	60898.5502	35949	−3.2881	V	T. Arranz	0.0006	RR Gem	60721.3611	48740	−0.7625	V	T. Arranz	0.0006
XZ Cyg	60906.4828	35966	−3.2894	V	T. Arranz	0.0006	RR Gem	60727.3189	48755	−0.7644	V	T. Arranz	0.0007
XZ Cyg	60907.4150	35968	−3.2906	V	T. Arranz	0.0005	RR Gem	60730.5020	48763	−0.7598	V	T. Arranz	0.0008
XZ Cyg	60909.7459	35973	−3.2932	V	G. Samolyk	0.001	RR Gem	60732.4856	48768	−0.7627	V	T. Arranz	0.0005
XZ Cyg	60912.5410	35979	−3.2983	V	T. Arranz	0.0007	RR Gem	60761.4900	48841	−0.7620	V	T. Arranz	0.0006
XZ Cyg	60913.4743	35981	−3.2984	V	T. Arranz	0.0006	RR Gem	60773.4102	48871	−0.7611	V	T. Arranz	0.0006
XZ Cyg	60914.4066	35983	−3.2995	V	T. Arranz	0.0006	RR Gem	60775.3962	48876	−0.7617	V	T. Arranz	0.0008
XZ Cyg	60921.4013	35998	−3.3053	V	T. Arranz	0.0005	GQ Gem	60700.6948	53235	−0.2261	V	K. Menzies	0.0019
XZ Cyg	60935.3996	36028	−3.3080	V	T. Arranz	0.0008	V488 Gem	60732.4951	66379	−0.0488	V	T. Arranz	0.0005
DM Cyg	60874.5633	43567	0.1167	V	T. Arranz	0.0008	TW Her	60854.6722	98372	−0.0232	V	G. Samolyk	0.0006
DM Cyg	60882.5426	43586	0.1186	V	T. Arranz	0.0007	TW Her	60863.4669	98394	−0.0197	V	T. Arranz	0.0009
DM Cyg	60887.5781	43598	0.1158	V	T. Arranz	0.0006	TW Her	60873.4535	98419	−0.0231	V	T. Arranz	0.0005
DM Cyg	60892.6191	43610	0.1185	V	T. Arranz	0.0007	VX Her	60821.7603	85801	−0.1657	V	G. Samolyk	0.0006
DM Cyg	60895.5558	43617	0.1162	V	T. Arranz	0.0006	VX Her	60854.5464	85873	−0.1665	V	T. Arranz	0.0008
DM Cyg	60908.5710	43648	0.1157	V	T. Arranz	0.0007	VX Her	60855.4570	85875	−0.1666	V	T. Arranz	0.0007
DM Cyg	60913.6116	43660	0.1180	V	T. Arranz	0.0008	VX Her	60886.4212	85943	−0.1678	V	T. Arranz	0.0006
DM Cyg	60919.4881	43674	0.1165	V	T. Arranz	0.0008	VZ Her	60794.8006	54518	0.1067	V	K. Menzies	0.0009
DM Cyg	60922.4295	43681	0.1188	V	T. Arranz	0.0007	VZ Her	60840.5940	54622	0.1060	V	T. Arranz	0.0006
DM Cyg	60930.4047	43700	0.1167	V	T. Arranz	0.0008	VZ Her	60870.5380	54690	0.1077	V	T. Arranz	0.0007
DM Cyg	60943.4228	43731	0.1191	V	T. Arranz	0.0007	AR Her	60787.6889	41135	−1.2599	V	G. Samolyk	0.0013
DM Cyg	60951.3973	43750	0.1163	V	T. Arranz	0.0007	AR Her	60793.7794	41148	−1.2797	V	G. Samolyk	0.0009
DM Cyg	60959.3750	43769	0.1167	V	T. Arranz	0.0008	AR Her	60795.6603	41152	−1.2790	V	G. Samolyk	0.0008
DM Cyg	60975.3318	43807	0.1188	V	T. Arranz	0.0007	AR Her	60820.5707	41205	−1.2800	V	T. Arranz	0.001
DM Cyg	60983.3067	43826	0.1163	V	T. Arranz	0.0007	AR Her	60821.5185	41207	−1.2723	V	T. Arranz	0.0011
DM Cyg	61001.3621	43869	0.1178	V	T. Arranz	0.0005	AR Her	60845.4555	41258	−1.3067	V	T. Arranz	0.0015
V2416 Cyg	60836.6212	129255	0.0006	V	G. Samolyk	0.0015	AR Her	60849.7113	41267	−1.2812	V	G. Samolyk	0.001
V2416 Cyg	60836.6800	129256	0.0036	V	G. Samolyk	0.0016	AR Her	60852.5415	41273	−1.2711	V	T. Arranz	0.0013
V2416 Cyg	60836.7345	129257	0.0022	V	G. Samolyk	0.0016	AR Her	60853.4832	41275	−1.2695	V	T. Arranz	0.0009
V2416 Cyg	60836.7901	129258	0.0018	V	G. Samolyk	0.0017	AR Her	60854.4171	41277	−1.2757	V	T. Arranz	0.0013
V2416 Cyg	60836.8476	129259	0.0035	V	G. Samolyk	0.0016	AR Her	60868.4843	41307	−1.3093	V	T. Arranz	0.0011
V2416 Cyg	60867.5868	129809	0.0034	V	T. Arranz	0.0006	DL Her	60828.8017	38234	0.0739	V	G. Samolyk	0.0014
V2416 Cyg	60867.6425	129810	0.0032	V	T. Arranz	0.0007	DL Her	60852.4583	38274	0.0654	V	T. Arranz	0.0013
V2416 Cyg	60877.5878	129988	0.0001	V	T. Arranz	0.0012	DL Her	60859.5702	38286	0.0778	V	T. Arranz	0.0012
V2416 Cyg	60877.6426	129989	−0.0009	V	T. Arranz	0.0009	DL Her	60865.4833	38296	0.0746	V	T. Arranz	0.0009
V2416 Cyg	60948.5683	131258	0.0007	V	G. Samolyk	0.0012	DL Her	60881.4379	38323	0.0552	V	T. Arranz	0.0014
V2416 Cyg	60948.6261	131259	0.0027	V	G. Samolyk	0.0006	DL Her	60894.4751	38345	0.0766	V	T. Arranz	0.0006
RW Dra	60811.7822	48393	0.3088	V	G. Samolyk	0.0012	DL Her	60897.4315	38350	0.0749	V	T. Arranz	0.0009
RW Dra	60834.4015	48444	0.3394	V	T. Arranz	0.0008	DL Her	60911.6110	38374	0.0553	V	G. Samolyk	0.0015
RW Dra	60840.5828	48458	0.3198	V	T. Arranz	0.0007	DY Her	60807.6799	184135	−0.0408	V	G. Samolyk	0.0008
RW Dra	60844.5603	48467	0.3111	V	T. Arranz	0.0008	DY Her	60807.8294	184136	−0.0399	V	G. Samolyk	0.0008
RW Dra	60845.4452	48469	0.3101	V	T. Arranz	0.0008	DY Her	60828.6373	184276	−0.0404	V	G. Samolyk	0.0006

Table continued on next page

Table 1. Recent times of maxima of stars in the AAVSO Short Period Pulsator program, cont.

<i>Star</i>	<i>JD (max) Hel. 2400000 +</i>	<i>Cycle</i>	<i>O–C (day)</i>	<i>F</i>	<i>Observer</i>	<i>Error (day)</i>	<i>Star</i>	<i>JD (max) Hel. 2400000 +</i>	<i>Cycle</i>	<i>O–C (day)</i>	<i>F</i>	<i>Observer</i>	<i>Error (day)</i>
DY Her	60828.7851	184277	–0.0412	V	G. Samolyk	0.0007	MW Lyr	60878.4654	62429	–0.3555	V	T. Arranz	0.0013
DY Her	60835.6223	184323	–0.0411	V	T. Arranz	0.0007	MW Lyr	60880.4475	62434	–0.3626	V	T. Arranz	0.0016
DY Her	60838.5958	184343	–0.0402	V	T. Arranz	0.0006	MW Lyr	60882.4514	62439	–0.3480	V	T. Arranz	0.0015
DY Her	60858.6607	184478	–0.0405	V	G. Samolyk	0.0007	MW Lyr	60886.4410	62449	–0.3369	V	T. Arranz	0.0010
LS Her	60819.5339	142173	–0.0377	V	T. Arranz	0.0014	MW Lyr	60890.4108	62459	–0.3456	V	T. Arranz	0.0007
UU Hya	60710.8225	40529	0.0171	V	G. Samolyk	0.0011	MW Lyr	60892.3947	62464	–0.3509	V	T. Arranz	0.0009
DH Hya	60743.6656	60465	0.1454	V	G. Samolyk	0.0007	MW Lyr	60913.4598	62517	–0.3719	V	T. Arranz	0.0015
GO Hya	60752.7471	9791	0.0021	V	G. Samolyk	0.0021	ST Oph	60871.4200	72043	–0.0313	V	T. Arranz	0.0008
V481 Lac	60948.3253	33999	0.0583	V	T. Arranz	0.0007	ST Oph	60880.4274	72063	–0.0310	V	T. Arranz	0.0009
V481 Lac	60948.4928	34000	0.0518	V	T. Arranz	0.0010	AE Peg	60568.5809	42597	0.0579	V	T. Arranz	0.0009
V481 Lac	60948.6647	34001	0.0497	V	T. Arranz	0.0011	AE Peg	60569.5734	42599	0.0569	V	T. Arranz	0.0009
V481 Lac	60950.3664	34011	0.0114	V	T. Arranz	0.0022	AE Peg	60571.5617	42603	0.0584	V	T. Arranz	0.0011
V481 Lac	60950.5422	34012	0.0132	V	T. Arranz	0.0026	AV Peg	60909.6771	43853	0.2594	V	T. Arranz	0.0011
RR Leo	60746.7128	38575	0.2393	V	K. Menzies	0.0008	AV Peg	60911.6286	43858	0.2590	V	G. Samolyk	0.0006
RR Leo	60752.5948	38588	0.2401	V	G. Samolyk	0.0006	AV Peg	60911.6286	43858	0.2590	V	T. Arranz	0.0008
RR Leo	60816.3844	38729	0.2423	V	T. Arranz	0.0006	AV Peg	61010.3959	44111	0.2615	V	T. Arranz	0.0007
SS Leo	60743.8433	30275	–0.1333	V	G. Samolyk	0.0015	BH Peg	60918.5637	33625	–0.1059	V	T. Arranz	0.0034
ST Leo	60781.6546	68744	–0.0161	V	G. Samolyk	0.0010	BH Peg	60929.4767	33642	–0.0898	V	T. Arranz	0.0029
ST Leo	60819.4150	68823	–0.0165	V	T. Arranz	0.0007	BH Peg	61024.2722	33790	–0.1613	V	T. Arranz	0.0014
TV Leo	60802.6514	35314	0.1447	V	G. Samolyk	0.0013	DY Peg	60910.6063	225002	–0.0268	V	T. Arranz	0.0004
AA Leo	60781.7354	35388	–0.1475	V	G. Samolyk	0.0013	DY Peg	60910.6789	225003	–0.0272	V	T. Arranz	0.0005
AH Leo	60783.7227	26021	–0.4517	V	K. Menzies	0.0015	DY Peg	60918.4819	225110	–0.0272	V	T. Arranz	0.0004
AA LMi	60804.5948	34376	0.0185	V	G. Samolyk	0.0014	DY Peg	60918.5555	225111	–0.0266	V	T. Arranz	0.0003
AA LMi	60804.6428	34377	0.0123	V	G. Samolyk	0.0018	DY Peg	60918.6283	225112	–0.0267	V	T. Arranz	0.0004
AA LMi	60804.6976	34378	0.0128	V	G. Samolyk	0.0015	DY Peg	60952.6112	225578	–0.0275	V	G. Samolyk	0.0006
U Lep	60995.8125	33782	0.0376	V	G. Samolyk	0.0009	DY Peg	60952.6848	225579	–0.0268	V	G. Samolyk	0.0005
SZ Lyn	60690.5030	187216	0.0392	V	G. Samolyk	0.0009	DY Peg	60952.7568	225580	–0.0278	V	G. Samolyk	0.0005
SZ Lyn	60690.6236	187217	0.0392	V	G. Samolyk	0.0007	DY Peg	60952.8305	225581	–0.0269	V	G. Samolyk	0.0007
SZ Lyn	60690.7448	187218	0.0399	V	G. Samolyk	0.0006	DY Peg	60973.5420	225865	–0.0266	V	G. Samolyk	0.0005
SZ Lyn	60690.8648	187219	0.0394	V	G. Samolyk	0.0006	DY Peg	60973.6137	225866	–0.0278	V	G. Samolyk	0.0004
SZ Lyn	60708.4629	187365	0.0394	V	T. Arranz	0.0006	DY Peg	60973.6870	225867	–0.0274	V	G. Samolyk	0.0004
SZ Lyn	60708.5833	187366	0.0392	V	T. Arranz	0.0006	DY Peg	60973.7607	225868	–0.0266	V	G. Samolyk	0.0005
SZ Lyn	60716.5389	187432	0.0395	V	G. Samolyk	0.0006	RU Scl	60946.7886	60453	0.1403	V	G. Samolyk	0.0017
SZ Lyn	60716.6604	187433	0.0405	V	G. Samolyk	0.0007	RU Scl	60948.7594	60457	0.1378	V	G. Samolyk	0.0011
SZ Lyn	60733.4143	187572	0.0400	V	T. Arranz	0.0007	DF Ser	60802.7646	71030	0.1232	V	G. Samolyk	0.0011
SZ Lyn	60743.7811	187658	0.0408	V	G. Samolyk	0.0006	DF Ser	60822.4642	71075	0.1220	V	T. Arranz	0.0007
RR Lyr	60849.6597	31625	–0.9525	V	G. Samolyk	0.0011	RV UMa	60773.4538	33538	0.1465	V	T. Arranz	0.0008
RR Lyr	60866.6633	31655	–0.9549	V	G. Samolyk	0.0014	RV UMa	60774.3905	33540	0.1471	V	T. Arranz	0.0010
RR Lyr	60874.5981	31669	–0.9563	V	T. Arranz	0.0011	RV UMa	60789.3686	33572	0.1473	V	T. Arranz	0.0007
RZ Lyr	60862.6060	38493	–0.0699	V	T. Arranz	0.0011	RV UMa	60792.6434	33579	0.1457	V	G. Samolyk	0.0008
RZ Lyr	60866.6940	38501	–0.0718	V	G. Samolyk	0.001	RV UMa	60816.5131	33630	0.1443	V	T. Arranz	0.0009
RZ Lyr	60882.5493	38532	–0.0650	V	T. Arranz	0.0007	RV UMa	60824.4678	33647	0.1420	V	T. Arranz	0.0008
RZ Lyr	60883.5719	38534	–0.0649	V	T. Arranz	0.0006	RV UMa	60831.4900	33662	0.1433	V	T. Arranz	0.0012
RZ Lyr	60898.4002	38563	–0.0626	V	T. Arranz	0.0007	RV UMa	60832.4231	33664	0.1403	V	T. Arranz	0.0009
RZ Lyr	60911.6978	38589	–0.0573	V	G. Samolyk	0.001	RV UMa	60839.4492	33679	0.1455	V	T. Arranz	0.0012
RZ Lyr	60920.3889	38606	–0.0573	V	T. Arranz	0.0008	RV UMa	60847.4111	33696	0.1503	V	T. Arranz	0.0013
RZ Lyr	60921.4129	38608	–0.0558	V	T. Arranz	0.0007	AE UMa	61026.9414	295553	0.0047	V	G. Samolyk	0.0004
CX Lyr	60847.6389	45044	2.1188	V	K. Menzies	0.0019							

Recent Minima of 243 Eclipsing Binary Stars

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Abstract This paper continues the publication of times of minima for eclipsing binary stars. Times of minima for 243 eclipsing binary stars were determined from observations received by the American Association of Variable Star Observers (AAVSO) Eclipsing Binary Special Interest Group (formerly Section) from August 2025 through January 2026.

1. Recent observations

The accompanying list (Table 1) contains times of minima for 243 variable stars calculated from recent CCD observations made by participants in the AAVSO's eclipsing binary program. These observations were reduced by the observers or the writer using the method of Kwee and van Woerden (1956).

The linear elements in the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al.* 1985) were used to compute the O–C values for most stars. For a few exceptions where the GCVS elements are missing or are in significant error, light elements from another source are used: CD Cam (Baldwin and Samolyk 2007), AC CMi (Samolyk 2008), CW Cas (Samolyk 1992), DV Cep (Frank and Lichtenknecker 1987), DK Hya (Samolyk 1990), EF Ori (Baldwin and Samolyk 2005), GU Ori (Samolyk 1985).

The light elements used for QX And, EK Aqr, V409 Aql, V688 Aql, V719 Aql, V889 Aql, IU Cnc, V728 Her, MZ Lac, and ZZ Peg are from (Kreiner 2004).

The light elements used for V1713 Aql, V641 Aur, V1160 Cas, V1261 Cas, CW Cep, V700 Cep, V2181 Cyg, V2477 Cyg, PS Del, and VZ Psc are from (Paschke 2014).

The light elements used for V412 And, V562 Aur, V744 Cas, V1011 Cas, V870 Cep, V886 Cep, V919 Cep, V927 Cep, V3135 Cyg, V505 Lac, V546 Peg, and V2150 Tau are from (Watson *et al.* 2014).

The light elements used for MW And, V731 Cep, V348 Cyg, BB Per, V881 Per, and V495 Vul are from (Nelson 2014).

The standard error is included when available. Column F indicates the filter used. A “C” indicates a clear filter.

This list will be web-archived and made available through the AAVSO ftp site at:

<ftp://ftp.aavso.org/public/datasets/gsamj541eb243.txt>.

This list, along with the eclipsing binary data from earlier AAVSO publications, is also included in the

Lichtenknecker database administrated by the Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e. V. (BAV; Walter *et al.* 2015).

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¹ Walter *et al.* (2015), <https://www.bav-astro.eu/index.php/veroeffentlichungen/service-for-scientists/lkdb-engl>

Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program.

<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O-C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>	<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O-C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>
RT And	60919.8203	31447	-0.0151	V	G. Samolyk	0.0001	RX Ari	60990.6806	21942	0.0572	V	G. Samolyk	0.0003
RT And	60979.5685	31542	-0.0152	TG	J. A. Howell	0.0001	RX Ari	61021.5684	21972	0.0562	CV	J. A. Howell	0.0005
RT And	60996.5493	31569	-0.0155	V	G. Samolyk	0.0001	SS Ari	60933.8788	53956.5	-0.5099	V	G. Samolyk	0.0001
RT And	61057.5556	31666	-0.0154	TG	A. Smith	0.0001	RY Aur	60975.7325	8324	0.0148	V	G. Samolyk	0.0002
TW And	60957.6120	5321	-0.0789	V	G. Samolyk	0.0004	SX Aur	60992.6813	17214	0.0252	V	G. Samolyk	0.0003
TW And	61023.5752	5337	-0.0800	CV	J. A. Howell	0.0002	TT Aur	60985.7411	29821	-0.0057	V	G. Samolyk	0.0005
UU And	60933.7079	12974	0.1636	V	D. Lemay	0.0001	WW Aur	61023.7569	11120	0.0039	V	G. Samolyk	0.0002
UU And	60933.7081	12974	0.1638	V	G. Samolyk	0.0001	AP Aur	61002.7406	32595.5	2.1060	V	G. Samolyk	0.0003
UU And	60948.5717	12984	0.1644	V	T. Arranz	0.0001	EM Aur	61068.5449	16508	-1.1394	V	G. Samolyk	0.0004
WZ And	60933.7700	28838	0.1061	V	G. Samolyk	0.0001	EP Aur	60992.7131	58685	0.0266	V	G. Samolyk	0.0002
WZ And	60956.7267	28871	0.1061	V	G. Samolyk	0.0003	HP Aur	60947.8071	12785.5	0.0814	V	G. Samolyk	0.0002
WZ And	60963.6820	28881	0.1049	TG	J. A. Howell	0.0003	HP Aur	61024.6389	12839.5	0.0813	CV	J. A. Howell	0.0004
XZ And	60919.8179	27218	0.2338	V	G. Samolyk	0.0001	V562 Aur	60984.7691	17920	-0.0665	I	K. Menzies	0.0009
XZ And	60934.7483	27229	0.2341	V	D. Lemay	0.0001	V562 Aur	60984.7700	17920	-0.0656	V	K. Menzies	0.0005
XZ And	60964.6088	27251	0.2345	TG	J. A. Howell	0.0001	V562 Aur	61002.7466	17954	-0.0675	V	K. Menzies	0.0005
AB And	60913.8135	74736	-0.0575	V	G. Samolyk	0.0002	V641 Aur	60986.7715	19236.5	-0.0052	CV	K. Menzies	0.0002
AB And	60930.5736	74786.5	-0.0580	V	T. Arranz	0.0001	V641 Aur	61049.6286	19361	-0.0053	CV	K. Menzies	0.0001
AB And	60933.5602	74795.5	-0.0584	V	T. Arranz	0.0001	EF Boo	60887.4138	19945	0.0204	V	T. Arranz	0.0001
AB And	60937.3778	74807	-0.0575	V	L. Corp	0.0001	CD Cam	60944.7927	10707	-0.0269	V	G. Samolyk	0.0003
AD And	60948.7055	22253.5	-0.0543	V	G. Samolyk	0.0001	IU Cnc	61049.8127	20277	0.0548	V	K. Menzies	0.0003
AD And	60956.5948	22261.5	-0.0546	V	G. Samolyk	0.0002	RT CMa	61002.8334	26572	-0.8232	V	G. Samolyk	0.0002
AD And	60983.7196	22289	-0.0502	TG	J. A. Howell	0.0007	SX CMa	61020.7825	20271	0.0409	V	G. Samolyk	0.0004
AD And	60994.5661	22300	-0.0518	V	G. Samolyk	0.0005	TU CMa	61068.6954	30228	-0.0119	V	G. Samolyk	0.0001
BD And	60913.6470	56062	0.0183	V	G. Samolyk	0.0001	TZ CMa	60985.8919	17715	-0.2450	V	G. Samolyk	0.0003
BD And	60951.6045	56144	0.0178	V	G. Samolyk	0.0001	UU CMa	61013.8369	7577	-0.0259	V	G. Samolyk	0.0001
BD And	61007.6155	56265	0.0176	CV	J. A. Howell	0.0002	XZ CMi	60992.9409	32046	0.0100	V	G. Samolyk	0.0001
BX And	60933.8651	40001	-0.1363	V	G. Samolyk	0.0002	YY CMi	60996.9221	30140	0.0213	V	G. Samolyk	0.0005
BX And	60976.5730	40071	-0.1365	V	G. Samolyk	0.0002	AC CMi	60996.9456	10399	0.0088	V	G. Samolyk	0.0001
DS And	60951.6596	24551	0.0066	V	G. Samolyk	0.0002	AK CMi	60995.8917	31621	-0.0251	V	G. Samolyk	0.0001
LO And	60934.6353	22170	-0.0298	V	T. Arranz	0.0001	AM CMi	60995.9296	35078	0.2701	V	G. Samolyk	0.0002
LO And	60942.6251	22191	-0.0293	V	T. Arranz	0.0001	TY Cap	60918.3879	11328	0.0966	V	T. Arranz	0.0002
MW And	60933.7298	24570.5	-0.0140	CV	K. Menzies	0.0002	TY Cap	60922.6603	11331	0.0986	TG	J. A. Howell	0.0005
MW And	60933.8608	24571	-0.0149	CV	K. Menzies	0.0002	TY Cap	60932.6223	11338	0.0965	V	G. Samolyk	0.0003
QX And	60951.6308	20505	0.0199	V	G. Samolyk	0.0003	RZ Cas	60557.7536	14522	0.0704	V	G. Samolyk	0.0002
V412 And	60938.7926	4420.5	0.0011	V	K. Menzies	0.0001	RZ Cas	60900.7913	14809	0.0722	V	G. Samolyk	0.0002
RY Aqr	60934.6262	10226	-0.1780	TG	J. A. Howell	0.0001	RZ Cas	60948.6021	14849	0.0731	V	G. Samolyk	0.0004
CX Aqr	60934.7594	44032	0.0200	V	G. Samolyk	0.0001	TV Cas	60926.6457	9006	-0.0437	V	G. Samolyk	0.0002
CX Aqr	60965.3379	44087	0.0193	V	T. Arranz	0.0008	TV Cas	60948.3979	9018	-0.0426	V	T. Arranz	0.0001
CX Aqr	60987.5778	44127	0.0198	CV	J. A. Howell	0.0002	TW Cas	60953.7201	13264	0.0433	V	G. Samolyk	0.0001
CX Aqr	60992.5820	44136	0.0201	V	G. Samolyk	0.0001	ZZ Cas	60935.5951	22113	-0.0125	V	G. Samolyk	0.0003
CZ Aqr	60900.8215	20318	-0.0833	V	G. Samolyk	0.0001	ZZ Cas	60981.6060	22150	-0.0120	CV	J. A. Howell	0.0011
CZ Aqr	60971.5669	20400	-0.0837	TG	J. A. Howell	0.0002	AB Cas	60911.8179	13313	0.1643	V	G. Samolyk	0.0001
CZ Aqr	61023.3313	20460	-0.0845	V	T. Arranz	0.0001	AB Cas	60944.6233	13337	0.1647	V	G. Samolyk	0.0001
EK Aqr	60944.7449	27549.5	0.0730	V	G. Samolyk	0.0005	AB Cas	60970.5942	13356	0.1650	TG	J. A. Howell	0.0001
EK Aqr	60948.7249	27562.5	0.0681	V	G. Samolyk	0.0004	AB Cas	60996.5650	13375	0.1652	V	G. Samolyk	0.0001
XZ Aql	60901.7019	8881	0.1744	V	G. Samolyk	0.0001	CW Cas	60918.6666	60485.5	-0.1729	V	G. Samolyk	0.0002
XZ Aql	60912.3976	8886	0.1742	V	T. Arranz	0.0001	CW Cas	60918.8275	60486	-0.1715	V	G. Samolyk	0.0001
XZ Aql	60946.6244	8902	0.1741	V	G. Samolyk	0.0002	CW Cas	60934.6111	60535.5	-0.1716	V	G. Samolyk	0.0001
KO Aql	60936.4142	6651	0.1120	V	T. Arranz	0.0003	CW Cas	60934.7703	60536	-0.1719	V	G. Samolyk	0.0001
KP Aql	60951.5664	6104	-0.0202	V	G. Samolyk	0.0001	CW Cas	60959.6422	60614	-0.1714	V	T. Arranz	0.0001
OO Aql	60882.6130	43942	0.0914	TG	J. A. Howell	0.0002	IR Cas	60914.7966	27253	0.0234	V	G. Samolyk	0.0001
OO Aql	60887.4282	43951.5	0.0921	V	T. Arranz	0.0001	IR Cas	60953.5957	27310	0.0234	V	G. Samolyk	0.0001
OO Aql	60905.4184	43987	0.0913	V	T. Arranz	0.0001	IR Cas	60966.5287	27329	0.0234	V	T. Arranz	0.0001
OO Aql	60907.4456	43991	0.0914	V	T. Arranz	0.0001	IR Cas	60985.5884	27357	0.0239	V	G. Samolyk	0.0001
OO Aql	60911.7539	43999.5	0.0920	V	G. Samolyk	0.0003	IS Cas	60932.8312	17462	0.0787	V	G. Samolyk	0.0002
OO Aql	60923.4104	44022.5	0.0923	V	T. Arranz	0.0001	IS Cas	60958.6124	17476	0.0787	V	G. Samolyk	0.0001
OO Aql	60953.5640	44082	0.0920	V	G. Samolyk	0.0001	IS Cas	61008.3341	17503	0.0796	V	T. Arranz	0.0001
V343 Aql	60943.4233	17619	-0.0540	V	T. Arranz	0.0001	IT Cas	60909.7740	8250	0.0765	V	G. Samolyk	0.0001
V343 Aql	60952.6462	17624	-0.0541	V	G. Samolyk	0.0001	IT Cas	60960.4307	8263	0.0769	V	T. Arranz	0.0001
V343 Aql	60965.5579	17631	-0.0546	TG	J. A. Howell	0.0002	IV Cas	60900.8007	20076	-0.1742	V	G. Samolyk	0.0001
V346 Aql	60903.5541	17160	-0.0190	V	T. Arranz	0.0001	IV Cas	60926.7616	20102	-0.1749	V	G. Samolyk	0.0001
V346 Aql	60914.6176	17170	-0.0191	V	G. Samolyk	0.0001	IV Cas	60938.7433	20114	-0.1755	TG	J. A. Howell	0.0002
V346 Aql	60915.7239	17171	-0.0192	CV	J. A. Howell	0.0001	KR Cas	60976.4266	9367	-0.1744	V	T. Arranz	0.0001
V409 Aql	60892.4968	4095	-0.0148	V	T. Arranz	0.0002	MM Cas	60936.6190	22042	0.1403	V	G. Samolyk	0.0002
V688 Aql	60944.4293	2170.5	-0.0007	V	T. Arranz	0.0004	MM Cas	61008.4441	22104	0.1402	V	T. Arranz	0.0001
V719 Aql	60942.4243	1250	-0.0010	V	T. Arranz	0.0001	OR Cas	60906.6210	13403	-0.0406	V	D. Lemay	0.0001
V889 Aql	60906.4456	755	0.0426	V	T. Arranz	0.0001	OR Cas	60982.6091	13464	-0.0409	V	T. Arranz	0.0001
V926 Aql	60887.3973	1476	-0.2365	V	T. Arranz	0.0005	OR Cas	61002.5409	13480	-0.0405	CV	J. A. Howell	0.0006
V1713 Aql	60964.3391	15953	-0.0524	V	T. Arranz	0.0001	OR Cas	61007.5236	13484	-0.0406	V	T. Arranz	0.0001

Table continued on following pages

Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program, cont.

<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O-C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>	<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O-C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>
OX Cas	60911.8314	7890.5	0.0373	V	G. Samolyk	0.0002	TT Cet	61030.5542	58616	-0.1020	V	G. Samolyk	0.0002
PV Cas	60919.6812	11821	-0.0274	V	G. Samolyk	0.0001	TT Cet	61048.5344	58653	-0.1022	V	G. Samolyk	0.0001
PV Cas	60934.5807	11829.5	-0.0069	V	G. Samolyk	0.0002	TW Cet	60968.7465	58688	-0.0358	V	G. Samolyk	0.0001
PV Cas	60948.5837	11837.5	-0.0077	V	G. Samolyk	0.0001	TX Cet	60968.7571	24143	0.0166	V	G. Samolyk	0.0001
PV Cas	60954.6903	11841	-0.0277	V	D. Lemay	0.0001	TX Cet	60980.6103	24159	0.0164	TG	J. A. Howell	0.0004
PV Cas	61004.5976	11869.5	-0.0088	CV	J. A. Howell	0.0007	U CrB	60908.6870	12792	0.1558	V	G. Samolyk	0.0005
V364 Cas	60935.7643	17240	-0.0260	V	G. Samolyk	0.0002	TW CrB	60888.6368	39041	0.0674	TG	J. A. Howell	0.0002
V364 Cas	60956.5957	17253.5	-0.0260	V	G. Samolyk	0.0001	SW Cyg	60914.4955	4165	-0.4254	V	T. Arranz	0.0001
V364 Cas	61031.4354	17302	-0.0251	V	T. Arranz	0.0001	UW Cyg	60909.4692	4990	0.0390	V	T. Arranz	0.0001
V375 Cas	60936.6289	17846	0.3575	V	G. Samolyk	0.0002	WW Cyg	60888.5230	6182	0.1890	V	T. Arranz	0.0001
V375 Cas	60995.5696	17886	0.3628	V	G. Samolyk	0.0012	WW Cyg	60898.4760	6185	0.1887	V	T. Arranz	0.0001
V375 Cas	61007.3549	17894	0.3611	V	T. Arranz	0.0001	ZZ Cyg	60898.6043	25291	-0.0911	V	T. Arranz	0.0001
V380 Cas	60957.5958	26017	-0.0808	V	G. Samolyk	0.0002	ZZ Cyg	60910.5482	25310	-0.0909	V	T. Arranz	0.0001
V380 Cas	60984.7451	26037	-0.0770	CV	J. A. Howell	0.0006	ZZ Cyg	60937.5795	25353	-0.0901	TG	J. A. Howell	0.0001
V380 Cas	60995.6031	26045	-0.0772	TG	J. A. Howell	0.0007	ZZ Cyg	60947.6372	25369	-0.0903	V	G. Samolyk	0.0001
V523 Cas	60929.5875	84338.5	0.1625	V	T. Arranz	0.0001	AE Cyg	60930.5976	16864	-0.0040	V	G. Samolyk	0.0002
V523 Cas	60933.5608	84355.5	0.1630	V	T. Arranz	0.0001	AE Cyg	60994.5634	16930	-0.0046	V	G. Samolyk	0.0003
V523 Cas	60933.6778	84356	0.1632	V	T. Arranz	0.0001	BR Cyg	60873.6406	14509	0.0019	TG	J. A. Howell	0.0001
V523 Cas	60935.5467	84364	0.1626	V	T. Arranz	0.0001	BR Cyg	60909.6199	14536	0.0020	V	G. Samolyk	0.0001
V523 Cas	60935.6633	84364.5	0.1624	V	T. Arranz	0.0001	BR Cyg	60921.6133	14545	0.0023	V	T. Arranz	0.0001
V523 Cas	60954.5928	84445.5	0.1629	V	T. Arranz	0.0001	CG Cyg	60908.6193	34039	0.0887	V	T. Arranz	0.0001
V523 Cas	60958.5662	84462.5	0.1636	V	T. Arranz	0.0001	CG Cyg	60908.6196	34039	0.0890	V	G. Samolyk	0.0002
V523 Cas	60958.6830	84463	0.1635	V	T. Arranz	0.0001	CG Cyg	60910.5130	34042	0.0890	V	T. Arranz	0.0001
V523 Cas	60959.6169	84467	0.1627	V	T. Arranz	0.0001	CG Cyg	60920.6119	34058	0.0896	CV	J. A. Howell	0.0002
V744 Cas	61039.3833	2622	-0.2203	V	T. Arranz	0.0003	CG Cyg	60932.6032	34077	0.0892	V	G. Samolyk	0.0001
V1011 Cas	60958.8019	8152.5	-0.0154	V	K. Menzies	0.0002	CG Cyg	60956.5871	34115	0.0898	V	G. Samolyk	0.0001
V1060 Cas	61000.6279	4458	0.0008	V	K. Menzies	0.0006	CG Cyg	60992.5623	34172	0.0899	V	G. Samolyk	0.0001
V1261 Cas	61007.4919	22027.5	0.0278	V	T. Arranz	0.0003	DK Cyg	60926.6119	48709	0.1621	V	G. Samolyk	0.0001
U Cep	60908.7311	6565	0.2712	V	G. Samolyk	0.0005	DK Cyg	60945.4414	48749	0.1640	V	T. Arranz	0.0001
U Cep	60913.7182	6567	0.2722	V	G. Samolyk	0.0006	DK Cyg	60965.6816	48792	0.1645	TG	J. A. Howell	0.0003
U Cep	60918.7038	6569	0.2717	V	G. Samolyk	0.0001	DK Cyg	60966.3863	48793.5	0.1631	V	T. Arranz	0.0001
U Cep	60933.6629	6575	0.2725	V	G. Samolyk	0.0003	DL Cyg	60955.3772	3492	0.1602	V	T. Arranz	0.0008
WW Cep	60920.7169	23403	0.3811	V	G. Samolyk	0.0001	KR Cyg	60919.6431	37642	0.0298	V	G. Samolyk	0.0001
WW Cep	60943.7227	23418	0.3829	V	D. Lemay	0.0001	KV Cyg	60924.5056	11080	0.0675	V	T. Arranz	0.0004
WZ Cep	60913.8246	78749	-0.2731	V	G. Samolyk	0.0001	KV Cyg	60958.5717	11092	0.0657	V	G. Samolyk	0.0002
WZ Cep	60946.5934	78827.5	-0.2739	V	G. Samolyk	0.0001	MY Cyg	60890.6328	6752	0.0012	V	T. Arranz	0.0001
WZ Cep	60947.6353	78830	-0.2756	TG	J. A. Howell	0.0005	MY Cyg	60892.6469	6752.5	0.0127	V	G. Samolyk	0.0002
WZ Cep	61003.5717	78964	-0.2771	V	G. Samolyk	0.0002	MY Cyg	60894.6381	6753	0.0013	V	T. Arranz	0.0001
XX Cep	60913.6527	6877	0.0555	V	G. Samolyk	0.0002	V346 Cyg	60908.7135	9194	0.2288	V	G. Samolyk	0.0002
XX Cep	60941.7019	6889	0.0568	V	T. Arranz	0.0001	V346 Cyg	60911.4614	9195	0.2334	V	T. Arranz	0.0001
XX Cep	60967.4125	6900	0.0568	V	T. Arranz	0.0001	V346 Cyg	60933.4041	9203	0.2299	V	T. Arranz	0.0002
ZZ Cep	60920.7180	15404	-0.0202	V	G. Samolyk	0.0001	V348 Cyg	60947.5396	19561	0.1860	V	K. Menzies	0.0003
ZZ Cep	60963.5527	15424	-0.0215	TG	J. A. Howell	0.0004	V348 Cyg	60947.6821	19561.5	0.1863	V	K. Menzies	0.0001
ZZ Cep	61006.3896	15444	-0.0206	V	T. Arranz	0.0001	V387 Cyg	60916.6148	51407	0.0147	V	G. Samolyk	0.0001
CW Cep	60901.8238	9354	0.0032	V	G. Samolyk	0.0006	V387 Cyg	60957.6129	51471	0.0146	V	G. Samolyk	0.0001
CW Cep	60968.6773	9378.5	-0.0072	V	G. Samolyk	0.0004	V387 Cyg	60975.5495	51499	0.0145	V	G. Samolyk	0.0001
DK Cep	60954.4279	27755	0.0328	V	T. Arranz	0.0001	V388 Cyg	60914.6908	22073	-0.1746	V	G. Samolyk	0.0003
DL Cep	60999.6247	16592	0.0759	CV	J. A. Howell	0.0006	V388 Cyg	60915.5494	22074	-0.1751	V	T. Arranz	0.0002
DV Cep	60947.5737	12207	-0.0057	V	G. Samolyk	0.0001	V401 Cyg	60933.6051	29342	0.1172	V	G. Samolyk	0.0001
EE Cep	60993.1	13	3.2	B	G. Samolyk	0.4	V401 Cyg	60975.5600	29414	0.1161	V	G. Samolyk	0.0002
EE Cep	60993.2	13	3.3	R	G. Samolyk	0.2	V445 Cyg	60914.5387	10662	0.3422	V	T. Arranz	0.0001
EE Cep	60993.3	13	3.4	V	G. Samolyk	0.5	V456 Cyg	60897.6148	17938	0.0561	V	T. Arranz	0.0001
EE Cep	60993.3	13	3.4	I	G. Samolyk	0.3	V456 Cyg	60946.6297	17993	0.0554	V	G. Samolyk	0.0001
EG Cep	60911.6506	33633	-0.0137	V	G. Samolyk	0.0002	V466 Cyg	60908.4466	23092	0.0088	V	T. Arranz	0.0001
EG Cep	60936.7044	33679	-0.0125	TG	J. A. Howell	0.0002	V477 Cyg	60888.7543	7115.5	-0.5212	V	G. Samolyk	0.0005
GK Cep	61002.5770	23829	0.1855	B	G. Samolyk	0.0004	V548 Cyg	60907.6027	9113	0.0186	V	T. Arranz	0.0001
NW Cep	60964.4123	1198	-0.0065	V	T. Arranz	0.0001	V700 Cyg	60899.6212	99338.5	-0.0466	V	T. Arranz	0.0001
NW Cep	60975.4238	1202	-0.0069	V	T. Arranz	0.0001	V704 Cyg	60951.3804	40322	0.0447	V	T. Arranz	0.0002
V338 Cep	60958.3795	8004	0.0498	V	T. Arranz	0.0001	V753 Cyg	60903.4097	56908	0.0899	V	T. Arranz	0.0001
V731 Cep	60941.4481	832	-0.3116	V	T. Arranz	0.0001	V753 Cyg	60923.4084	56950	0.0887	V	T. Arranz	0.0001
V870 Cep	60957.5846	12290	0.0258	V	K. Menzies	0.0003	V995 Cyg	60891.5050	9712	0.7122	V	T. Arranz	0.0001
V870 Cep	60957.7371	12290.5	0.0277	V	K. Menzies	0.0003	V1034 Cyg	60891.5490	18377	0.0290	V	T. Arranz	0.0001
V886 Cep	60984.7346	2528	0.1852	V	K. Menzies	0.0008	V2181 Cyg	60903.5449	17694	-0.0179	V	T. Arranz	0.0006
V886 Cep	60984.7371	2528	0.1877	I	K. Menzies	0.0025	V2477 Cyg	60897.4143	30215.5	0.0049	V	T. Arranz	0.0002
V919 Cep	60983.4648	2013	-0.0117	V	T. Arranz	0.0002	V2477 Cyg	60897.5707	30216	0.0057	V	T. Arranz	0.0002
V927 Cep	60954.5246	1419	-0.0056	V	K. Menzies	0.0003	V3135 Cyg	60919.4656	1096.5	-0.1025	V	T. Arranz	0.0001
TT Cet	60953.7737	58458	-0.1014	V	G. Samolyk	0.0001	W Del	60904.4573	3657	0.0001	V	T. Arranz	0.0008
TT Cet	60991.6780	58536	-0.1017	TG	J. A. Howell	0.0002	TT Del	60911.4357	5461	-0.1642	V	T. Arranz	0.0002
TT Cet	61029.5821	58614	-0.1022	CV	J. A. Howell	0.0002	TT Del	60934.4036	5469	-0.1652	V	T. Arranz	0.0001

Table continued on next page

Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program, cont.

<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O-C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>	<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O-C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>
TY Del	60920.5550	15079	0.1076	V	T. Arranz	0.0001	RW Mon	61030.8927	14349	-0.0999	V	G. Samolyk	0.0001
TY Del	60933.6575	15090	0.1077	V	G. Samolyk	0.0001	BB Mon	61001.9031	46841	-0.0042	V	G. Samolyk	0.0002
TY Del	60939.6133	15095	0.1079	TG	J. A. Howell	0.0002	EP Mon	60992.9152	24479	0.0164	V	G. Samolyk	0.0002
YY Del	60902.4503	22624	0.0204	V	T. Arranz	0.0001	V501 Oph	60924.6236	31007	-0.0095	CV	J. A. Howell	0.0003
YY Del	60978.5872	22720	0.0204	V	G. Samolyk	0.0001	V501 Oph	60929.4635	31012	-0.0093	V	T. Arranz	0.0001
FZ Del	60918.7715	37786	-0.0288	V	G. Samolyk	0.0002	V501 Oph	60932.3674	31015	-0.0093	V	T. Arranz	0.0001
FZ Del	60934.4358	37806	-0.0288	V	T. Arranz	0.0001	V566 Oph	60888.3974	46509	0.3243	V	T. Arranz	0.0001
FZ Del	60944.6180	37819	-0.0283	TG	J. A. Howell	0.0001	V839 Oph	60891.3996	49982.5	0.3781	V	T. Arranz	0.0001
FZ Del	61002.5752	37893	-0.0289	V	G. Samolyk	0.0001	EF Ori	60996.8350	5339	0.0133	V	G. Samolyk	0.0003
PS Del	60901.5680	10575	-0.0169	V	T. Arranz	0.0003	ER Ori	60985.8692	45723.5	0.1837	V	G. Samolyk	0.0001
RZ Dra	60905.4720	30366	0.0827	V	T. Arranz	0.0002	FL Ori	60968.8831	10072	0.0392	V	G. Samolyk	0.0001
RZ Dra	60944.5845	30437	0.0831	V	G. Samolyk	0.0001	FR Ori	60995.8165	37517	0.0624	V	G. Samolyk	0.0002
UZ Dra	60901.6560	5927.5	0.0030	V	G. Samolyk	0.0001	FT Ori	61035.6552	6249	0.0290	CV	J. A. Howell	0.0003
UZ Dra	60932.6390	5937	0.0037	TG	J. A. Howell	0.0001	FZ Ori	60973.8706	42375	-0.0199	V	G. Samolyk	0.0003
UZ Dra	60942.4237	5940	0.0044	V	T. Arranz	0.0001	FZ Ori	61002.8692	42447.5	-0.0203	V	G. Samolyk	0.0003
S Equ	60921.5567	5333	0.1085	V	T. Arranz	0.0001	FZ Ori	61048.6667	42562	-0.0213	V	G. Samolyk	0.0002
TZ Eri	61003.7331	7133	0.4063	V	G. Samolyk	0.0001	GU Ori	60985.8236	38064	-0.0810	V	G. Samolyk	0.0002
YY Eri	60992.8146	60377.5	0.1776	V	G. Samolyk	0.0007	GU Ori	60996.8844	38087.5	-0.0812	V	G. Samolyk	0.0003
YY Eri	60996.8320	60390	0.1763	V	G. Samolyk	0.0001	U Peg	60932.7997	65161.5	-0.1893	V	G. Samolyk	0.0003
SX Gem	60992.9635	30699	-0.0635	V	G. Samolyk	0.0002	U Peg	60943.6708	65190.5	-0.1868	V	T. Arranz	0.0001
WW Gem	60995.7685	28285	0.0274	V	G. Samolyk	0.0004	U Peg	60985.6447	65302.5	-0.1885	CV	J. A. Howell	0.0005
AL Gem	61007.8546	24928	0.1218	V	G. Samolyk	0.0001	U Peg	60992.5765	65321	-0.1901	V	G. Samolyk	0.0002
SZ Her	60918.5918	23291	-0.0404	V	G. Samolyk	0.0001	TY Peg	60952.6694	6630	-0.5332	V	G. Samolyk	0.0001
SZ Her	60919.4100	23292	-0.0403	V	T. Arranz	0.0001	TY Peg	60983.5918	6640	-0.5330	TG	J. A. Howell	0.0003
UX Her	60885.6141	13696	0.2147	TG	J. A. Howell	0.0005	TY Peg	61008.3281	6648	-0.5345	V	T. Arranz	0.0001
UX Her	60896.4578	13703	0.2165	V	T. Arranz	0.0001	UX Peg	60996.7014	13318	0.0132	V	G. Samolyk	0.0005
V728 Her	60916.3863	17857.5	0.0511	V	T. Arranz	0.0001	ZZ Peg	61023.3319	12771	0.0032	V	T. Arranz	0.0003
V728 Her	60920.3915	17866	0.0503	V	T. Arranz	0.0001	AQ Peg	60892.7170	3545	0.5698	V	G. Samolyk	0.0008
V728 Her	60933.5874	17894	0.0499	TG	J. A. Howell	0.0004	AQ Peg	60992.5874	3563	0.5671	CV	J. A. Howell	0.0007
DK Hya	61048.8304	34881	-0.0035	V	G. Samolyk	0.0003	BB Peg	60913.7686	47439.5	-0.0437	V	G. Samolyk	0.0001
RT Lac	60967.3476	3172	-0.5853	V	T. Arranz	0.0002	BB Peg	60935.6386	47500	-0.0446	V	G. Samolyk	0.0002
RW Lac	60953.4478	4079	-0.0406	V	T. Arranz	0.0001	BB Peg	60943.5920	47522	-0.0442	TG	J. A. Howell	0.0004
SW Lac	60936.3566	48831	-0.1134	V	T. Arranz	0.0001	BB Peg	60962.3898	47574	-0.0445	V	T. Arranz	0.0001
SW Lac	60936.5173	48831.5	-0.1130	V	T. Arranz	0.0001	BG Peg	60934.8047	7889	-2.7214	V	G. Samolyk	0.0003
SW Lac	60936.6772	48832	-0.1135	V	T. Arranz	0.0001	BG Peg	60950.4241	7897	-2.7237	V	T. Arranz	0.0001
TW Lac	61007.3844	6422	0.5578	V	T. Arranz	0.0001	BX Peg	60961.4394	59789.5	-0.1571	V	T. Arranz	0.0001
TW Lac	61010.4221	6423	0.5581	V	T. Arranz	0.0001	BX Peg	60968.5906	59815	-0.1567	V	G. Samolyk	0.0001
VX Lac	60923.6110	14579	0.0941	CV	J. A. Howell	0.0001	DI Peg	60996.7181	22197	0.0326	V	G. Samolyk	0.0001
VX Lac	60926.8347	14582	0.0943	V	G. Samolyk	0.0001	DI Peg	61037.2914	22254	0.0323	V	T. Arranz	0.0001
VX Lac	60963.3673	14616	0.0941	V	T. Arranz	0.0001	EU Peg	60944.4324	37390	0.0549	V	T. Arranz	0.0001
AR Lac	60933.7748	9752	-0.0263	V	G. Samolyk	0.0002	GP Peg	60901.8415	20155	-0.0653	V	G. Samolyk	0.0004
AW Lac	60916.7966	30006	0.2235	V	G. Samolyk	0.0003	GP Peg	60990.6219	20246	-0.0661	CV	J. A. Howell	0.0003
AW Lac	60961.3665	30045	0.2223	V	T. Arranz	0.0002	GP Peg	61000.3787	20256	-0.0655	V	T. Arranz	0.0005
CM Lac	60941.4687	21135	-0.0043	V	T. Arranz	0.0001	KW Peg	60961.3814	15682	0.2800	V	T. Arranz	0.0002
CO Lac	60889.6931	21628.5	-0.0146	V	G. Samolyk	0.0003	V546 Peg	60999.5380	14881	-0.0773	V	K. Menzies	0.0002
CO Lac	60994.5634	21696.5	-0.0144	CV	J. A. Howell	0.0004	Z Per	60964.7753	5008	-0.4532	TG	J. A. Howell	0.0002
CO Lac	61039.2871	21725.5	-0.0147	V	T. Arranz	0.0001	Z Per	61013.6749	5024	-0.4545	V	G. Samolyk	0.0002
DG Lac	60947.7762	7450	-0.2891	V	G. Samolyk	0.0002	RT Per	60935.8313	32446	0.1302	V	G. Samolyk	0.0001
DG Lac	60956.6017	7454	-0.2897	TG	J. A. Howell	0.0005	RV Per	61055.6089	9632	0.0168	V	G. Samolyk	0.0004
DG Lac	60976.4608	7463	-0.2894	V	T. Arranz	0.0001	ST Per	60985.6372	7004	0.3309	V	G. Samolyk	0.0001
MZ Lac	60947.8312	2674	0.0000	V	G. Samolyk	0.0002	ST Per	60993.5831	7007	0.3319	TG	J. A. Howell	0.0002
MZ Lac	60960.4667	2678	0.0002	V	T. Arranz	0.0001	XZ Per	60909.7261	15111	-0.0945	V	D. Lemay	0.0001
MZ Lac	61001.5335	2691	0.0023	CV	J. A. Howell	0.0007	XZ Per	60962.7008	15157	-0.0950	TG	J. A. Howell	0.0002
V505 Lac	60941.3509	21332.5	-0.0207	V	T. Arranz	0.0001	XZ Per	61030.6460	15216	-0.0962	V	G. Samolyk	0.0001
Z Lep	60968.9362	33757	-0.2121	V	G. Samolyk	0.0002	BB Per	60954.8460	10599.5	0.2502	V	K. Menzies	0.0002
Z Lep	61003.7162	33792	-0.2121	CV	J. A. Howell	0.0002	BB Per	61049.5410	10794.5	0.2695	V	K. Menzies	0.0003
RR Lep	61001.8333	33454	-0.0570	V	G. Samolyk	0.0004	IT Per	61000.6438	20615	-0.0597	CV	J. A. Howell	0.0009
RV Lyr	60890.4541	4269	-0.3217	V	T. Arranz	0.0001	IT Per	61003.7129	20617	-0.0580	V	G. Samolyk	0.0002
RV Lyr	60908.4493	4274	-0.3218	V	T. Arranz	0.0001	IT Per	61020.5841	20628	-0.0578	CV	J. A. Howell	0.0009
UZ Lyr	60932.6145	9117	-0.0602	V	G. Samolyk	0.0002	IU Per	60973.6134	17925	0.0025	TG	J. A. Howell	0.0002
BV Lyr	60933.4373	15332	0.0436	V	T. Arranz	0.0001	IU Per	61003.6080	17960	0.0012	V	G. Samolyk	0.0002
EW Lyr	60916.4276	17661	0.3337	V	T. Arranz	0.0001	IU Per	61051.5989	18016	-0.0013	CV	J. A. Howell	0.0004
FL Lyr	60926.6316	10424	-0.0024	V	G. Samolyk	0.0001	KW Per	61041.6377	20013	0.0225	CV	J. A. Howell	0.0002
β Lyr	60858.22	917	3.68	B	G. Samolyk	0.11	V432 Per	60973.8377	78065.5	0.0763	V	G. Samolyk	0.0001
B Lyr	60858.24	917	3.70	V	G. Samolyk	0.15	V432 Per	60980.7363	78087	0.0623	CV	J. A. Howell	0.0004
B Lyr	60858.25	917	3.71	R	G. Samolyk	0.16	V881 Per	61016.6041	10425	-0.0252	V	K. Menzies	0.0005
B Lyr	60864.58	917.5	3.57	V	G. Samolyk	0.13	V881 Per	61022.6099	10440.5	-0.0237	CV	K. Menzies	0.0009
B Lyr	60864.60	917.5	3.59	B	G. Samolyk	0.21	V881 Per	61027.6459	10453.5	-0.0236	V	K. Menzies	0.0009
B Lyr	60864.62	917.5	3.61	R	G. Samolyk	0.19	B Per	61001.8390	5357	0.1764	V	G. Samolyk	0.0003

Table continued on next page

Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program, cont.

<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O–C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>	<i>Star</i>	<i>JD (min)</i> <i>Hel.</i> <i>2400000 +</i>	<i>Cycle</i>	<i>O–C</i> <i>(day)</i>	<i>F</i>	<i>Observer</i>	<i>Standard</i> <i>Error</i> <i>(day)</i>
Y Psc	60946.8196	4066	–0.0300	V	G. Samolyk	0.0005	RV Tri	60971.6810	19821	–0.0503	TG	J. A. Howell	0.0002
Y Psc	60950.5875	4067	–0.0279	TG	J. A. Howell	0.0001	RV Tri	61002.5810	19862	–0.0506	V	G. Samolyk	0.0001
Y Psc	61014.6013	4084	–0.0321	V	G. Samolyk	0.0003	VV UMa	61002.8984	22095	–0.0992	V	G. Samolyk	0.0002
RV Psc	61003.5610	66106	–0.0778	V	G. Samolyk	0.0002	W UMi	60934.6163	16020	–0.2515	V	G. Samolyk	0.0003
VZ Psc	60940.6118	65484.5	0.0027	V	T. Arranz	0.0002	W UMi	60985.6501	16050	–0.2524	V	G. Samolyk	0.0005
VZ Psc	60960.4671	65560.5	0.0023	V	L. Corp	0.0005	Z Vul	60890.5677	7309	–0.0226	V	T. Arranz	0.0001
UZ Pup	60995.9652	20610.5	–0.0137	V	G. Samolyk	0.0005	Z Vul	60927.3911	7324	–0.0232	V	T. Arranz	0.0001
U Sge	60892.5806	12945	0.0520	V	T. Arranz	0.0001	RR Vul	60945.4537	5130	–0.0743	V	T. Arranz	0.0001
U Sge	60946.6714	12961	0.0529	V	G. Samolyk	0.0002	AW Vul	60900.7337	18123	–0.0502	V	G. Samolyk	0.0001
V505 Sgr	60911.6281	13907	–0.1574	V	G. Samolyk	0.0003	AW Vul	60934.6042	18165	–0.0507	V	G. Samolyk	0.0001
RS Ser	60908.6622	43446	0.0177	V	G. Samolyk	0.0001	AW Vul	60934.6046	18165	–0.0503	V	T. Arranz	0.0001
RS Ser	60910.4566	43449	0.0177	V	T. Arranz	0.0001	AX Vul	60918.4123	7934	–0.0472	V	T. Arranz	0.0001
RW Tau	60992.7489	5529	–0.3471	V	G. Samolyk	0.0001	AY Vul	60901.4992	7551	–0.2636	V	T. Arranz	0.0001
RZ Tau	61001.8607	56114	0.1236	V	G. Samolyk	0.0001	AY Vul	60930.4471	7563	–0.2650	V	T. Arranz	0.0001
RZ Tau	61002.6923	56116	0.1238	CV	J. A. Howell	0.0003	BE Vul	60916.6347	13405	0.1039	V	G. Samolyk	0.0001
WY Tau	60992.8310	34053	0.0712	V	G. Samolyk	0.0003	BE Vul	60930.6038	13414	0.1046	V	G. Samolyk	0.0003
WY Tau	61022.6192	34096	0.0708	CV	J. A. Howell	0.0004	BE Vul	60955.4368	13430	0.1049	V	T. Arranz	0.0003
AC Tau	60994.7386	7516	0.2849	TG	J. A. Howell	0.0002	BO Vul	60896.5827	12800	0.0285	V	T. Arranz	0.0001
AQ Tau	61003.7208	25782	0.5099	V	G. Samolyk	0.0005	BO Vul	60968.5816	12837	0.0302	V	G. Samolyk	0.0001
CT Tau	60996.7687	23383	–0.0832	TG	J. A. Howell	0.0004	BS Vul	60903.4203	37044	–0.0448	V	T. Arranz	0.0001
CT Tau	60996.7714	23383	–0.0805	V	G. Samolyk	0.0003	BS Vul	60908.6546	37055	–0.0462	CV	J. A. Howell	0.0002
EQ Tau	60956.8325	60769.5	–0.0690	V	G. Samolyk	0.0001	BS Vul	60968.6275	37181	–0.0457	V	G. Samolyk	0.0001
EQ Tau	60973.7286	60819	–0.0696	TG	J. A. Howell	0.0001	BT Vul	60896.5967	22340	0.0087	V	T. Arranz	0.0001
HU Tau	61048.7485	9616	0.0487	V	G. Samolyk	0.0003	BU Vul	60888.6012	48076	0.0107	V	T. Arranz	0.0001
V1250 Tau	61037.5745	4104	0.0088	V	K. Menzies	0.0002	BU Vul	60913.6350	48120	0.0088	V	G. Samolyk	0.0001
V Tri	60707.3111	61915	–0.0048	V	T. Arranz	0.0001	BU Vul	60958.5852	48199	0.0086	V	G. Samolyk	0.0001
V Tri	60946.6601	62324	–0.0049	TG	J. A. Howell	0.0002	BU Vul	60995.5708	48264	0.0096	V	G. Samolyk	0.0005
V Tri	60947.8309	62326	–0.0046	V	G. Samolyk	0.0002	CD Vul	60908.7589	21368	–0.0093	V	G. Samolyk	0.0002
X Tri	60967.5879	19006	–0.1311	TG	J. A. Howell	0.0001	CD Vul	60915.5969	21378	–0.0087	CV	J. A. Howell	0.0002
X Tri	60992.8474	19032	–0.1315	V	G. Samolyk	0.0001	CD Vul	60915.5973	21378	–0.0083	V	T. Arranz	0.0001
RS Tri	60990.6828	12075	–0.0573	V	G. Samolyk	0.0001	V495 Vul	60912.4135	2717	0.0289	V	T. Arranz	0.0002
RV Tri	60952.8392	19796	–0.0504	V	G. Samolyk	0.0001	V495 Vul	60947.5818	2738.5	0.0418	V	G. Samolyk	0.0002

Recent Minima of 141 Eclipsing Binary Stars

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Abstract Previously unpublished 148 times of minima for 141 eclipsing binary stars are reported based on the author's CCD photometry conducted between May 2025 and April 2026.

1. Presenting the TOM and accompanying data

The accompanying list (Table 1) contains 148 times of minima (TOM) for 141 eclipsing binary (EB) stars derived from CCD observations made by the author using a 130-mm f/5 reflector or 70-mm f/5 refractor, V filter, and ZWO ASI533 MMPro imager (ZWO 2026). An observed TOM (and associated mean error) was the end result of applying the method of Kwee and van Woerden (1956) and making an heliocentric correction (BAA 2026). The raw data starting point for this is available in the AAVSO Database (Kloppenborg 2026), identified by observer code CK.

Using the linear elements (epoch and period) and associated cycle number—all presented in Table 1—a computed TOM was figured, and subtracted from the observed TOM to get the O–C values also displayed there. The elements used (for all of the EB stars except five) are from the Krakow Astronomica group's TIDAK database (Kreiner 2004).

These provide the historical “average ephemeris” presented in the lower left corners of the O–C diagrams found on the webpages for thousands of EB stars on this website. Note sometimes these have an epoch similar, if not identical to, that given in the *General Catalogue of Variable Stars* (GCVS; Kholopov *et al.* 1987). They are not to be confused with current best “prediction ephemeris” elements also found in the TIDAK database web pages. For four stars not included in the TIDAK database, the elements used are from the AAVSO VSX (Watson *et al.* 2014). Those stars are V400 Boo, CzeV707, V549 Dra, and V433 UMa. For one additional object, CI CrB, only the period is listed, as no epoch was listed in either TIDAK or VSX.

This list will be web-archived and made available through the AAVSO ftp site at:

<ftp://ftp.aavso.org/public/datasets/4063-Cook-541-eb141.txt>.

2. Acknowledgements

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Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program.

<i>Star</i>	<i>Heliocentric Min. JD 2400000+</i>	<i>Mean Error (d)</i>	<i>Cycle</i>	<i>O-C (d)</i>	<i>Epoch JD 2400000+</i>	<i>Period (d)</i>
V343 Aql	60952.6464	0.0003	17624	-0.0109	28443.4255	1.84460008
SS Ari	61025.6309	0.0055	40225.5	-0.2282	44694.7015	0.40599017
SX Aur	61107.6502	0.0002	35443	0.0806	18218.7357	1.21007911
TT Aur	61101.6898	0.0005	29908	0.0111	21242.2504	1.332734664
BF Aur	61056.7010	0.0004	12903	0.0352	40628.3709	1.58322056
EO Aur	61070.6375	0.0018	9809	-0.0003	21190.6936	4.0656483
IM Aur	61049.6253	0.0003	18217	-0.0389	38327.7981	1.24728913
TU Boo	61150.7566	0.0018	86604	-0.0378	33066.4436	0.324284684
TY Boo	60892.6929	0.0003	41873.5	-0.0533	47612.6035	0.317149096
TZ Boo	60868.6711	0.0004	57925.5	0.0578	43655.4984	0.29715954
XY Boo	60865.7593	0.0004	56434	-0.0565	39953.7505	0.370557913
AD Boo	60895.7188	0.0005	7826.5	0.0196	44704.1947	2.06880528
BW Boo	61157.7187	0.0042	6239.5	-0.1669	40362.754	3.3328202
GG Boo	60857.7006	0.0007	22479	-0.0014	51259.8643	0.42696907
GH Boo	60855.7323	0.0008	14549	-0.0045	51260.5214	0.6595103
GK Boo	61157.6523	0.0001	20608	-0.0071	51311.7396	0.47777173
GL Boo	60891.7627	0.0013	3004	-0.1457	51286.6905	3.197476
GM Boo	60864.7735	0.0016	24544	0.0788	52001.401	0.36111855
GP Boo	60868.7620	0.0007	11737	-0.0006	51258.8563	0.81877024
GR Boo	60863.7512	0.0004	23541	-0.0098	51996.587	0.376669386
HH Boo	60856.7189	0.0006	25395	-0.0042	52764.192	0.318666316
IK Boo	60864.7305	0.0010	24684	-0.0307	53382.6328	0.30311653
LM Boo	60895.7259	0.0003	14693	-0.0039	56077.5364	0.32792441
V400 Boo	60880.7614	0.0094	15109	0.0526	56448.816	0.293328
AL Cam	61156.7194	0.0004	26157	0.0121	26411.5337	1.32833175
TX Cnc	61146.6800	0.0007	69787	0.0246	34426.4633	0.382882085
BI CVn	60846.6724	0.0006	42898	-0.0317	44364.8374	0.38421061
DH CVn	60850.6852	0.0006	24070	-0.0505	52045.7923	0.36580571
EI CVn	60847.7224	0.0004	31267	-0.0384	52694.3807	0.260766305
EO CVn	60847.7115	0.0002	25689	0.0340	51628.2093	0.35888778
FN CVn	60856.7847	0.0006	15354	-0.0101	51479.871	0.61071537
HU CVn	60846.6234	0.0004	21471.5	0.0888	51244.5356	0.4471974
R CMa	61078.7218	0.0004	13810	0.0931	45391.2573	1.1359429
SX CMa	61198.7471	0.0007	20380.5	0.1116	28095.4011	1.62426017
TU CMa	61103.6619	0.0007	30259	0.0047	26977.4487	1.12780358
VW CMa	61123.7155	0.0012	46057	-0.1645	27924.2323	0.72083826
WW CMa	61120.6720	0.0005	3677	0.2042	51868.0474	2.516296
XZ CMi	61104.6568	0.0006	20884	0.0229	49016.7803	0.578809309
YY CMi	61110.7039	0.0003	30244	0.0107	28023.1532	1.09401997
AC CMi	61109.6823	0.0013	16916	0.0003	46439.8309	0.867217491
AK CMi	61105.6790	0.0001	20691	0.0068	49396.7062	0.565896575
AM CMi	61116.7160	0.0009	35196.5	0.0650	25244.5869	1.01919407
TV Cas	61013.6495	0.0005	9914	-0.1579	43043.6189	1.81260727
IV Cas	60967.7010	0.0002	20143	-0.0646	40854.6282	0.99851747
AH Cep	61010.6858	0.0008	14662	-0.0553	34989.4827	1.7747414
CQ Cep	60924.7896	0.0010	17345.5	-0.0866	32456.6654	1.64124475
CQ Cep	60925.6046	0.0016	17346	-0.0922	32456.6654	1.64124475
CX Cep	60928.7500	0.0027	7747	0.2555	44451.4234	2.126897
CX Cep	60977.6846	0.0024	7770	0.2715	44451.4234	2.126897
DK Cep	60935.6981	0.0005	27736	-0.0082	33590.5681	0.98590778
DL Cep	60968.6436	0.0006	16573	0.0106	33946.6117	1.6304846
DV Cep	60976.6229	0.0005	12232	0.0001	46763.3521	1.16197439
EK Cep	61017.7247	0.0003	4972	-0.0894	39002.8248	4.4277935
GK Cep	61015.6814	0.0009	23843	0.0109	38694.6992	0.936164546
GK Cep	61008.6627	0.0010	23835.5	0.0135	38694.6992	0.936164546
RZ Com	60852.6947	0.0004	76853	0.0574	34837.4179	0.338506231
SS Com	61054.7074	0.0010	87335.5	0.1140	25001.6274	0.41280998
RT CrB	60879.7464	0.0017	6372	0.0063	28273.303	5.1171433
RW CrB	60869.6942	0.0005	27695	0.0146	40751.7275	0.726410981
TW CrB	60872.7376	0.0003	39014	0.0141	37898.3562	0.588874951
YY CrB	60879.7176	0.0013	26354	-0.0071	50955.8775	0.37655943
AS CrB	60880.7161	0.0086	22254	0.0713	52409.4456	0.38065962
AV CrB	60863.7289	0.0005	27591	-0.0478	52360.4746	0.308191152
BR CrB	60882.8291	0.0003	12462.5	0.0086	51324.9641	0.7669293

Table continued on following pages

Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program, cont.

<i>Star</i>	<i>Heliocentric Min. JD 2400000+</i>	<i>Mean Error (d)</i>	<i>Cycle</i>	<i>O-C (d)</i>	<i>Epoch JD 2400000+</i>	<i>Period (d)</i>
CI CrB	60874.7849	0.0045	NA	NA	none found	0.350034
ZZ Cyg	60957.6944	0.0005	25385	-0.0523	45000.3406	0.628615563
MY Cyg	60926.6789	0.0004	4835	-0.0038	41561.6003	4.00518768
V387 Cyg	60973.6262	0.0003	51496	0.0048	27985.4555	0.640596666
V388 Cyg	60938.7438	0.0005	31843	-0.1061	33584.5796	0.85903559
V401 Cyg	60972.6475	0.0004	55145	0.0453	28838.3016	0.58272374
V444 Cyg	60956.7316	0.0010	4698.5	0.1741	41164.348	4.2124528
V444 Cyg	60954.6320	0.0009	4698	0.1807	41164.348	4.2124528
V444 Cyg	60975.6996	0.0008	4703	0.1861	41164.348	4.2124528
V1034 Cyg	60971.6585	0.0004	18459	0.0312	42938.4598	0.9769309
V2540 Cyg	60957.6984	0.0033	20152.5	-0.0302	52795.875	0.40500452
V2545 Cyg	60938.7179	0.0006	17042.5	0.0101	54646.4501	0.36920978
V2546 Cyg	60938.8085	0.0004	15382.5	0.0041	51358.749	0.622789236
TW Dra	60867.7736	0.0002	13238	0.5483	23712.042	2.8067067
V549 Dra	60867.7563	0.0010	8419.5	0.0036	57493.0243	0.4008229
YY Del	60943.6918	0.0002	44318	0.0465	25795.4395	0.793090974
CzeV707	60943.8360	0.0117	8015	0.0352	57245.8	0.461385
YY Eri	61055.6638	0.0004	60573	0.0119	41581.6229	0.321496855
SZ Her	60890.7764	0.0002	31663	0.0044	34987.3951	0.818096102
TT Her	60890.6880	0.0003	18491	-0.0163	44025.4578	0.912078659
CC Her	60894.7367	0.0002	20054	0.2363	26120.42	1.73402216
DI Her	60917.6977	0.0033	1771	-1.4171	42234.7673	10.550168
GL Her	60917.6993	0.0050	9659.5	0.0637	38266.3336	2.34497665
V450 Her	60884.7313	0.0002	8035	0.0064	46217.3458	1.8254361
V842 Her	60889.7506	0.0005	21653	0.0258	51816.3441	0.41903573
RX Hya	61114.6695	0.0012	7743	0.4153	43447.748	2.28161
WY Hya	61138.6708	0.0007	28725.5	0.0327	40570.979	0.716007
AV Hya	61133.7094	0.0028	35792	-0.0162	36673.4238	0.68340137
AW Lac	60931.6564	0.0004	14388	0.0728	44488.184	1.14285513
CM Lac	60944.6782	0.0001	21137	-0.0003	27026.3155	1.60469144
GX Lac	60918.7087	0.0008	2346	-0.0035	46009.3067	6.3552453
UV Leo	61144.6901	0.0002	46908.5	0.0194	32995.5518	0.600085676
UZ Leo	61142.7178	0.0011	34531.5	0.2117	39800.412	0.61804712
XY Leo	61112.6769	0.0003	56452	0.0211	45074.4819	0.284102846
XZ Leo	61112.6726	0.0011	32983.5	0.0989	45025.363	0.4877351
AG Leo	61158.6983	0.0070	10171.5	0.1432	26651.5918	3.3925147
EX Leo	61135.6751	0.0005	30924	0.0056	48499.9966	0.40860409
EX Leo	61137.7161	0.0005	30929	0.0036	48499.9966	0.40860409
RR Lep	61057.6752	0.0007	33515	-0.0253	30377.1679	0.9154269
AL Lep	61060.7132	0.0050	20488	-0.0092	51868.8851	0.44864493
GK Lib	60887.7065	0.0020	3503	-0.1516	53473.9278	2.1164517
FL Lyr	60854.7521	0.0001	10391	0.0024	38221.552	2.17815395
V571 Lyr	60950.7013	0.0003	7700	0.0391	51305.7046	1.2525919
BO Mon	61124.6837	0.0006	7917	0.1710	43507.6011	2.2252004
V839 Oph	60896.7161	0.0002	49995.5	0.1975	40448.4146	0.40899889
V2536 Oph	60896.7193	0.0022	4541	0.0161	51072.55	2.16343388
VV Ori	61079.7326	0.0012	12817	-0.0136	42041.6777	1.48537634
ER Ori	61054.6731	0.0004	42428	0.1122	43090.5353	0.423400246
FZ Ori	61115.6632	0.0004	42729.5	0.0656	44024.4629	0.39998443
beta Per	61027.6455	0.0009	7001	0.1600	40953.4657	2.8673075
UZ Pup	61132.6863	0.0009	20782.5	-0.0028	44613.6961	0.794851101
AV Pup	61111.7214	0.0010	68812	-0.1051	31178.131	0.43500691
V375 Sge	60951.7368	0.0013	3891	0.0033	52724.899	2.11432395
VZ Set	60934.6871	0.0008	14829	-0.0057	28368.2594	2.19613146
CW Set	60932.6863	0.0010	5021.5	-0.0241	51963.4195	1.78617762
DK Set	60942.7005	0.0007	26432	-0.0116	28755.344	1.217742438
EY Set	60941.6596	0.0009	28282	-0.0017	27953.9477	1.16638546
V Ser	60914.7730	0.0016	8970	0.0179	29936.4591	3.4535447
BI Ser	60874.7601	0.0005	27079	0.0114	28248.5484	1.20485248
CC Ser	60882.7047	0.0004	45349	0.0546	37481.0111	0.51603429
V577 Ser	60899.7508	0.0012	22681	-0.0028	53455.804	0.328202
RZ Tau	61059.6411	0.0010	56253	0.1554	37676.5928	0.415673705
EQ Tau	61097.6511	0.0007	61211	-0.0324	40203.4343	0.341347947
V781 Tau	61058.6641	0.0004	49821	-0.0091	43874.949	0.34490926

Table continued on next page

Table 1. Recent times of minima of stars in the AAVSO eclipsing binary program, cont.

<i>Star</i>	<i>Heliocentric Min. JD 2400000+</i>	<i>Mean Error (d)</i>	<i>Cycle</i>	<i>O–C (d)</i>	<i>Epoch JD 2400000+</i>	<i>Period (d)</i>
lambda Tau	61095.6620	0.0003	10015	0.0007	21506.859	3.9529508
X Tri	61031.7107	0.0008	39432	–0.0725	22722.3104	0.971532583
W UMa	61139.7575	0.0005	75595.5	–0.0956	35918.397	0.333637004
RW UMa	60816.7217	0.0006	2046	–0.1403	45823.3339	7.3282151
VV UMa	61139.6915	0.0006	31852	0.0064	39245.394	0.68737571
HR UMa	60812.7121	0.0015	8591	0.0041	54480.5834	0.7370649
OQ UMa	60861.6898	0.0005	33278	–0.0042	51432.173	0.283356
V433 UMa	60832.7670	0.0011	12350	0.0465	54500.715	0.512713
AK Vir	60858.7060	0.0004	15317	–0.0142	42576.398	1.1935968
FQ Vir	60843.6766	0.0002	11927	0.0130	51903.1506	0.74960283
HW Vir	60840.7146	0.0002	129457	–0.0003	45730.5578	0.116719506
V610 Vir	60844.6965	0.0021	21611	–0.0113	53499.6437	0.33987618
V626 Vir	60837.6999	0.0011	10186	0.0115	53871.595	0.683889
V632 Vir	60842.7629	0.0008	28028	0.0217	53912.622	0.247257
V637 Vir	60845.6864	0.0005	26926.5	–0.0002	53079.7795	0.28841131
BO Vul	60927.7176	0.0002	17279	–0.0840	27304.91	1.9458818
BS Vul	60948.6370	0.0001	37139	–0.0016	43271.5994	0.475969714
V495 Vul	60888.7225	0.0004	3814.5	0.0077	54651.5	1.635133
V495 Vul	60933.6708	0.0002	3842	–0.0102	54651.5	1.635133

NOTES