Improving the Photometric Calibration of the Enigmatic Star KIC 8462852

Adam J. Lahey
Douglas M. Dimick
Andrew C. Layden
Bowling Green State University, Department of Physics and Astronomy, 104 Overman Hall, Bowling Green, OH 43403; address email correspondence to laydena@bgsu.edu

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Abstract The star KIC 8462852 undergoes dimming events whose origin remains unexplained. Observers from the AAVSO have obtained an impressive amount of data on this challenging, low-amplitude, irregular variable star. We present new, all-sky observations of KIC 8462852 and its surrounding comparison stars in order to refine their photometric calibration, obtaining $V = 11.892$ and $I_C = 11.210$ mag for KIC 8462852 itself. However, our calibration is not definitive and we recommend additional observations that should enable a more precise and accurate recalibration of the AAVSO photometry. We also present our photometric time-series for KIC 8462852 that spans 1.6 years in which we find hints for dimming below its canonical brightness in the days around 2017 May 18.

1. Introduction

The *Kepler* space telescope monitored over 150,000 stars for over four years searching for transiting exoplanets (Borucki *et al.* 2010). Most of the thousands of detections involved the periodic dimming of a host star by $\lesssim 1\%$ as an exoplanet passed between the star and Earth, but one series of dimming events that stood out involved the host star KIC 8462852 (TYC 3162-665-1, 2MASS J20061546+4427248, colloquially referred to as "Boyajian's Star" or "Tabby's Star," and hereafter abbreviated "KIC"). This star was observed to dim, apparently aperiodically, with two main events (denoted D800 and D1500) that reduced the star's flux by $\gtrsim 15\%$ (Boyajian *et al.* 2016). These authors showed that these extraordinary events were astrophysical in origin, not observational, and they considered a variety of explanations for the dimming.

As part of their analysis, Boyajian *et al.* (2016) obtained a variety of observations of KIC, including optical photometry using a 0.9-m Schmidt telescope yielding un-dimmed magnitudes of $V = 11.705 \pm 0.017$ mag, $I_C = 11.051 \pm 0.098$ mag, and $B–V = 0.557$ mag. Other data indicated that KIC is a normal F3-type dwarf star with no apparent infrared excess to indicate the presence of a dust disk.

Searches of the photographic record suggested a gradual dimming of KIC over the last century (Schaefer 2016), though others have questioned this result (Hipke *et al.* 2016, 2017). Additionally, a careful analysis of the *Kepler* data indicated a more pronounced dimming over the four-year duration of the *Kepler* mission, with an accelerated dimming in its last year (Montet and Simon 2016). More recent observations using both space- and ground-based equipment appear to confirm this dimming (Meng *et al.* 2017). Thus, evidence of brightness changes exists on timescales of a century, of years, and of days in this otherwise apparently normal F-type star.

These observational studies have spawned a number of explanations for the brightness variations of KIC, beginning with a series of possibilities entertained by Boyajian *et al.* (2016). They found the most plausible explanation to be obscuration by a swarm of dusty fragments on a comet-like orbit, relaxing dynamically after the break-up of their parent body. Other researchers have hypothesized different explanations for the dimming, including (i) Sun-centered rings of obscuring material in the outer Solar System (Katz 2017) or compact dust clouds in the interstellar medium (Wright and Sigurdsson 2016), (ii) a ringed planet and associated clouds of Trojan objects in orbit around KIC (Ballesteros *et al.* 2017), (iii) the outer layers of KIC cooling and dimming as they dissipate energy from an earlier planetary in-spiral event (Metzger *et al.* 2017), and (iv) transits by a swarm of megastructures near KIC fabricated by an intelligent civilization (Wright *et al.* 2016). Clearly, KIC is a rare and remarkable object worthy of long-term photometric monitoring to detect new dimming events, which may in turn constrain hypotheses of their origin.

In 2015 October, an appeal for observations of KIC by AAVSO observers was placed via *AAVSO Alert Notice 532* (AAVSO 2015a). The AAVSO Variable Star Plotter (AAVSO 2015b; finder chart, X15551E accessed 2015 Oct 27.) provided a finder chart for KIC along with four comparison stars and their APASS magnitudes, which are shown in Table 1, along with the AAVSO Photometric All-Sky Survey (APASS) photometry of KIC itself (Henden and Munari 2014). Specifically, columns 2–3 show the equatorial coordinates of each star, columns 4–5 show the Johnson V-band magnitude and its uncertainty, and columns 6–7 show the Johnson $B–V$ color and its uncertainty. Columns 8–9 show the APASS Sloan i-band magnitude and its uncertainty after conversion to the Cousins I_C system using the transformations for Population I stars in Table 4 of Jordi *et al.* (2006) (see the Appendix for details). These values were from APASS Data Release 9 (Henden *et al.* 2015). Each star in the table was observed five times, though perhaps not in every filter given the zero values in the uncertainty columns for some of the i-band entries, a sign that may indicate only a single visit to the field in that filter (as described in the APASS documentation).

Noting the differences between the photometry of Boyajian *et al.* 2016) and of APASS for KIC, and the relatively large uncertainties in the APASS magnitudes for the comparison stars, we became concerned about the quality of the calibrated photometry AAVSO observers are producing. Specifically, systematic offsets might occur between AAVSO work and the

Table 1. APASS Photometry.

Star	R.A. (J2000) h m s	Dec. (J2000) ° ′ ″	V_J	V_{err}	$(B-V)_J$	$(B-V)_{err}$	I_C[a]	I_{err}
KIC	20 06 15.457	+44 27 24.61	11.852	0.046	0.508	0.062	11.132	0.059
113[b]	20 06 48.087	+44 22 48.14	11.263	0.054	0.458	0.068	10.655	0.042
116[b]	20 07 09.068	+44 20 17.06	11.590	0.050	0.543	0.059	10.890	0.008[c]
124[b]	20 06 01.237	+44 29 32.20	12.427	0.029	0.804	0.048	11.429	0.046
128[b]	20 06 21.194	+44 30 51.28	12.789	0.050	0.481	0.067	12.025	0.029
C1	20 07 08.759	+44 24 23.07	10.291	0.067	0.260	0.146	10.036	0.146
C2	20 06 55.880	+44 26 43.35	10.655	0.064	1.328	0.073	9.426	0.021[c]
C3[d]	20 06 36.311	+44 27 03.17	12.415	0.036	0.932	0.050	11.252	0.031
C4	20 06 34.778	+44 27 34.35	12.349	0.045	1.484	0.057	10.880	0.027
C5	20 06 31.134	+44 35 19.35	10.079	0.055	1.231	0.069	8.859	0.008[c]
C6	20 06 23.647	+44 27 38.14	11.698	0.033	1.178	0.047	10.531	0.033
C7	20 06 08.977	+44 24 30.19	11.175	0.038	1.187	0.054	9.994	0.088
C8	20 06 07.757	+44 26 03.71	11.542	0.032	1.208	0.047	10.367	0.097
C9	20 06 00.392	+44 25 54.05	13.327	0.038	1.010	0.048	12.125	0.092
C10	20 06 01.708	+44 34 17.17	10.895	0.060	1.461	0.075	9.524	0.024[c]
C11	20 05 45.056	+44 21 15.85	12.316	0.038	1.469	0.050	10.847	0.083
C12	20 05 25.952	+44 20 35.42	10.877	0.050	1.236	0.062	9.591	0.049
C13	20 05 25.446	+44 31 21.14	11.242	0.039	1.224	0.052	9.977	0.089

a. The original APASS photometry in the Sloan i*-band was transformed to the Cousins* I_C *system using the relations of Jordi* et al. *(2006) shown in the Appendix.*

b. The AAVSO AUID numbers are 113 = 000-BLS-551, 116 = 000-BLS-553, 124 = 000-BLS-549, and 128 = 000-BLS-555.

c. This star had an entry of zero in the APASS i*-error column, suggesting only one* i*-band photometric measure is available for this star; its* I_C *magnitude should be treated with caution.*

d. In 2017 September, 000-BLS-549 was removed from the VSP list of comparison stars for KIC and replaced by this one, 000-BML-045, which also appears as "124" on new VSP finder charts.

Table 2. Photometric Nights.

Date	Filter	N_{std}	N_{fld}	c_0	c_1	c_2	RMS	N_{KIC}	Weight
2016/03/18	V	21	7	6.952	0.169	+0.002	0.053	3	1
2016/03/21	V	30	9	6.916	0.201	+0.031	0.051	5	2
2016/09/02	V	36	11	7.074	0.002	+0.026	0.066	4	1
2017/02/04	I_C	28	10	7.265	0.056	-0.034	0.037	8	1
2017/03/15	I_C	65	15	7.232	0.095	-0.063	0.050	23	2
2017/03/23	I_C	43	14	7.119	0.207	-0.017	0.044	18	1

Table 3. BGSU All-Sky Photometry.

Star	V	SEM_V	N_V	I_C	SEM_I	N_I	$V-I_C$
KIC	11.892	0.006	12	11.210	0.010	49	0.683
113	11.284	0.007	12	10.701	0.010	49	0.584
116	11.616	0.005	10	10.927	0.009	46	0.689
124[a]	12.461	0.009	12	11.492	0.011	49	0.969
128[b]	12.859	0.015	12	12.060	0.014	49	0.800
C1	10.314	0.008	6	10.015	0.014	48	0.299
C2	10.681	0.009	12	9.465	0.038	10	1.216
C3	12.444	0.010	12	11.317	0.015	49	1.127
C4[b]	12.404	0.012	12	10.897	0.016	49	1.507
C5	10.131	0.012	3	9.008	0.033	8	1.122
C6	11.731	0.008	12	10.551	0.014	49	1.180
C7	11.208	0.006	12	10.022	0.016	45	1.186
C8	11.574	0.012	12	10.346	0.014	49	1.228
C9[c]	13.285	0.029	12	12.152	0.015	49	1.133
C10	10.916	0.008	11	9.584	0.037	9	1.332
C11	12.342	0.010	12	10.882	0.014	46	1.460
C12	10.915	0.006	6	—	—	0	—
C13	11.288	0.009	6	—	—	0	—

a. A very low-amplitude rotational variable, KIC~8462696 is not a reliable comparison star.

b. Gary (2017) found a linear trend in brightness over four months, making this a questionable comparison star.

c. We suspect our V*-band photometry for star C9 is in error, and we recommend* $V = 13.35 \pm 0.02$ *and* $V-I_C = 1.20 \pm 0.03$ *mag for this star.*

Note: Comparison stars C5 and C10 were saturated on many of our images, while C12 and C13 were outside the field of view on all of our I*-band images.*

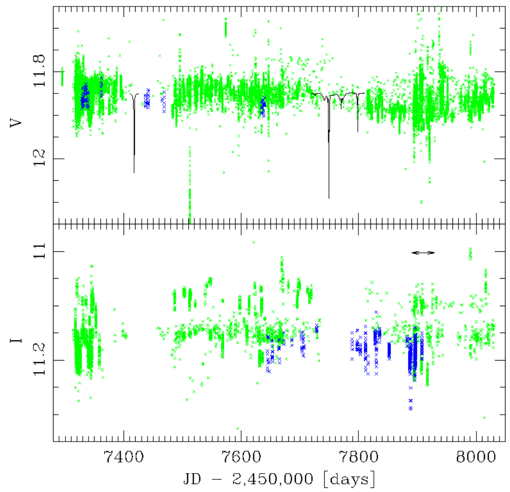

Figure 1. The time-series photometry of KIC 8462852 in the *V* (top panel) and I_C (bottom panel) from the AAVSO International Database, from inception to 2017 Oct 1, is shown as small green crosses. The larger blue crosses show our photometry (see section 2.2). The black curves in the top panel indicate the depth and duration of the first two major dimming events, observed by *Kepler* and presented in Figure 1 of Boyajian *et al.* (2016), at arbitrary times as described in section 1 (D800 is to the left, D1500 is to the right). The arrows in the bottom panel mark the 2017 May dimming episode noted in *AAVSO Alert Notice 579*.

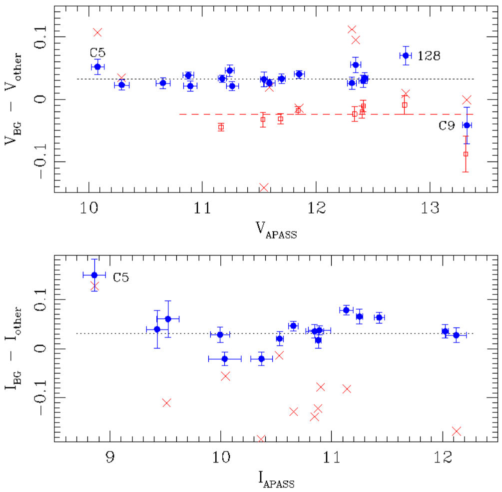

Figure 2. The magnitude difference between our comparison star magnitudes from Table 3 and the APASS photometry from Table 1 (circles), the Pan-STARRS photometry from Chambers *et al.* (2016) (crosses), and photometry from Gary (2017) (squares) is plotted as a function of APASS magnitude for the *V* (top) and I_C (bottom) passbands. The equations of Jordi *et al.* (2006) were used to transform the original APASS and Pan-STARRS photometry to VIC as described in section 2.1, where the labeled outlier points are also discussed. The dashed lines mark the median value for each data set.

standard system defined by Landolt (1992). More importantly, because different AAVSO observers may choose to use a different comparison star among the four available, systematic offsets might occur between the results of different AAVSO observers. Individually, such offsets might be interpreted as low-level dimming events, while collectively, the scatter they inject into the time-series might hinder detection of such dips.

Figure 1 shows the time-series *V* and I_C photometry of KIC downloaded from the AAVSO International Database (Kafka 2017; accessed 2017 Oct 3). In this data set, there are 30,497 measurements in *V*, 4158 in I_C, 7357 in *B*, 2666 in *R*, and including visual observations and measurements in other filter passbands the entire data set comprises an impressive 44,678 entries. Notice that in the lower panel, an "upper tier" of data exists with I_C brighter than 11.12 mag. The AAVSO Light Curve Generator (AAVSO 2017) was employed to recognize that comparison star 124 (AUID 000-BLS-549) was used in calibrating the vast majority of these points, whereas the vast majority of points in the lower tier used either comparison star 113 (000-BLS-551) or an ensemble of comparison stars (also see section 2). This underscores the importance of reliable comparison stars in obtaining a tight time series for KIC.

To further demonstrate the challenge for ground-based observers attempting to detect dimming events like those seen in KIC by the high-precision space-based *Kepler* photometry system, we have taken the large dips D800 and D1500 from Figure 1 of Boyajian *et al.* (2016), converted them from normalized flux into magnitudes, and placed them at arbitrary locations along the time axis of Figure 1 (for convenience of display; the actual dips occurred near Julian dates 2455626 and 2456353 days, respectively). Given the size of the dips in comparison with the photometric scatter, it is clear that every effort—including using precise and accurate comparison star magnitudes—must be made to minimize errors in the final time series of KIC and thereby improve the likelihood of detecting future dimming events, particularly smaller ones at the level of a few hundredths of a magnitude.

The median magnitudes of the AAVSO data shown in Figure 1 are 11.845 mag in *V* and 11.169 mag in I_C, after omitting data taken before the 2017 May dimming event (Boyajian *et al.* 2017) and all I_C data in the "upper tier." Their standard deviations are 0.033 and 0.025 mag in *V* and I_C, respectively. However, the median error the observers associated with their magnitude for KIC was about 0.007 mag for both filters. This represents an "internal" error estimate largely based on the signal and noise in an image, while the standard deviation is an "external" estimate of the typical uncertainty in a single observation that also includes photometric calibration effects. For both *V* and I_C, the relatively large standard deviations suggest that the calibration of the ~1%-level differential photometry obtained by AAVSO observers may be degraded in the calibration process by the standard photometry of the comparison stars, though part may be due to uncertainties in color-term corrections applied by individual observers. This led us to attempt higher quality all-sky photometry of KIC and its comparison stars, along with newly-proposed comparison stars that might be helpful for telescopes with larger apertures and/or smaller fields-of-view (these stars are listed as objects C1–C13 in the lower portion of Table 1).

2. Observations

We obtained images of KIC using the 0.5-m Cassegrain reflector at Bowling Green State University (BGSU) in Bowling Green, Ohio (latitude 41° 22' 42" N, longitude 83° 39' 33" W, elevation 225 m), using an Apogee Ap6e CCD camera having 1024 × 1024 pixels, each 24 µm in size, yielding a 21 × 21 arcmin field of view at a scale of 1.2 arcsec pixel^{-1}. We used custom colored glass filters ANDV4121 and ANDV4123 from the Andover Corporation to replicate the V and I_C passbands, respectively. Due to a malfunction of our filter wheel, we took all of the images on a given night, including flat field images of the clear twilight sky, in either V or I_C, meaning that contemporaneous photometry in the two passbands is not available. Images were processed using the flat field images along with bias and dark frames.

We elected to focus on the V and I_C passbands because of their common usage among AAVSO observers, their wide spectral separation, and the location of their peak throughputs in the redder half of the spectrum where many CCDs (including our own) have their highest quantum efficiency. Unlike the original *Kepler* observations, the use of two or more filters may help to distinguish between sources of dimming events caused by dust obscuration and grey transit events (Meng *et al.* 2017).

2.1. Photometric observations

On six very clear nights, we obtained images of the KIC field over an interval of 1–2 hours, interleaved with images of standard stars from Landolt (1992) or Clem and Landolt (2016) selected to span a wide range in color and airmass. The seeing on these images varied from 3–6 arcsec FWHM with a median of 4 arcsec. Aperture photometry, using a large aperture of 19 arcsec diameter to capture all the light in each star, was performed on the processed images. The resulting instrumental magnitudes (v) of each standard star at airmass (X) on a specific night were employed in a least-squares regression of the form

$$v - V = c_0 + c_1 X + c_2 (B–V), \tag{1}$$

where V and $(B–V)$ are the standard magnitude and color from Landolt's lists. An analogous equation using i instrumental magnitudes, I_C standard magnitudes, and $(V–I_C)$ standard colors was employed for our long wavelength data. The details of these regressions are summarized in Table 2, in which the columns are (1) date of observation, (2) the filter employed, (3) the number of Landolt standard stars used that night, (4) the number of independent Landolt fields observed, (5)–(7) the coefficient values from Equation 1, (8) the root-mean-squared scatter of the observed magnitudes around the best-fit line for the Landolt standards, (9) the number of independent visits to the KIC field that night, and (10) the weight given to observations from that night (see below). Equatorial standards from Landolt (1992) were used during the first four nights, while standards at declination ~50° from Clem and Landolt (2016), much closer on the sky to the KIC field, were used during the last two nights.

Next, we solved Equation 1 for the standard magnitude (V or I_C) and used the coefficients c_0–c_2 from the fits along with a star's color ($B–V$ or $V–I_C$) from APASS found in Table 1 and our instrumental magnitude (v or i) for each star (comparison star or KIC) on each image taken during each photometric night (This non-standard procedure of assuming known, constant colors was necessitated by our malfunctioning filter wheel. We do not expect the colors of the comparison stars to vary from their values in Table 1, and the color of KIC might only vary if we happened to observe it during a dip. The somewhat large uncertainties on the APASS colors shown in Table 1 are reduced by the small color-term coefficients c_2 in Table 2, so we expect the resulting random errors in our photometry to be less than 0.003 mag in most cases, e.g., $c_2 \times (B–V)_{\mathrm{err}} = +0.031 \times 0.1$ mag. Our calibration of the field is thus not strictly independent, and small systematic offsets will be present if the APASS colors have systematic errors.)

We calculated the weighted mean of the N_{KIC} measurements for each star along with its standard error of the mean (SEM). Considering factors in Table 2 and beyond, particularly the values of the c_1 and c_2 coefficients in relation to their historical norms at our observatory, we judged the nights of 2016 March 21 in V and 2017 March 15 in I_C to be significantly better than the other nights, and gave them double weight in determining our final VI_C magnitudes of the comparison stars near KIC, which we list in Table 3. Had we adopted uniform weights, our mean magnitudes would be ~0.002 mag fainter in V and ~0.005 mag fainter in I_C than the values shown in this table. The SEM values in Table 3 describe the random uncertainties in the star-to-star magnitude ranking; uncertainty in the zero-points of our photometry may shift all the magnitudes systematically by an unknown amount. We computed the nightly mean magnitude of each star and calculated their standard deviation as an estimate of the overall uncertainty in our photometric zero-point, finding ~0.02 mag for a typical star. A particular star may have been overexposed or off the CCD field of view on some images, so the number of measurements in Table 3, N_V or N_I, may be less than the number of images available in that filter, N_{KIC}. The right-most column of Table 3 shows our estimate of each star's $V–I_C$ color, obtained by subtracting the non-contemporaneous V and I_C magnitudes in the table. While most of our new stars are redder than KIC itself, some observers who have determined their color-term coefficient c_2 with care may elect to use them because of their brightness or proximity to KIC.

Figure 2 shows the magnitude differences between our values and those found in APASS. In the case of the I-band, we used the I_C magnitudes from Table 1 which were converted from the original APASS Sloan i magnitudes as described in the Appendix. In the V-band panel, we see a flat relationship with a median offset of 0.032 mag and a standard deviation of 0.022 mag. In the I-band panel, the median offset is 0.031 mag with a larger standard deviation of 0.040 mag. The offsets in both V and I_C indicate that our magnitudes are systematically fainter than the APASS ones by about 1.5-times the estimated uncertainty in our photometric zero-point.

The brightest comparison star, C5, is an outlier in both panels of Figure 2, probably because the star was saturated in our images and those of APASS when the seeing was good. The original comparison star 128 and the new star C9 are outliers in V, perhaps because of their lower fluxes, though both are near the median value in I_C at the faint end of that distribution. If we reject these outliers, we obtain a standard deviation of 0.010 mag in V indicating a close correspondence between our magnitudes and those of APASS, though a systematic offset of 0.032 mag remains. Rejecting from the I_C data stars C2 and C10 (both of which are very bright in I_C and may suffer from saturation according to the APASS documentation) along with C5, we find a standard deviation of 0.029 mag and a median offset of 0.026 mag. Thus the star-to-star scatter between our magnitudes and those of APASS remains relatively large in I_C, and substantial zero-point shifts exist between these data sets in both V and I_C.

We require a third-party set of precision photometry to clarify whether the APASS or our photometry better represents the standard system. The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) project aims to provide high-precision digital photometry in the Sloan *grizy* bandpasses over most of the sky (Chambers *et al.* 2016). We accessed photometry from their recent Data Release 1 (accessed 2017 Oct 11) via the Mikulski Archive for Space Telescopes (Space Telesc. Sci. Inst. 2017) and found close positional matches for many of the stars in Table 1. However, after we transformed these magnitudes to VI_C using the relations in Jordi *et al.* 2006), we found large, random differences with respect to our data and the APASS data (see the crosses in Figure 2), making the Pan-STARRS data unhelpful in answering our question. This is not surprising since most of these stars are brighter than the Pan-STARRS saturation limit of 12–14 mag.

Recently, a post to the AAVSO Forum on the campaign for KIC by Dave Lane (2017) and Brad Walter's reply (Walter 2017) alerted the community to the variability of two of the comparison stars commonly used by AAVSO observers: star 124 (AUID 000-BLS-549) and star 128 (000-BLS-555), based on information in a webpage published by Gary (2017). In a reply post, Brad Walters confirmed that star 124 is identified in the SIMBAD database as a rotational variable with an optical magnitude range <0.01 mag and a period near 17 days (Reinhold *et al.* 2013), while star 128 is not a recognized variable star. Interestingly, star 124 is not an outlier in our Figure 2; the low-amplitude of its variations and that fact that we, and APASS, observed it multiple times at random phases suggests that any deviation from its mean value has been averaged out to below the scatter in this diagram. We also note that the low-amplitude, short-period variability of star 124 cannot by itself explain the 0.06-mag separation of the two “tiers” seen in the *I*-band panel of Figure 1. Since Lane's posting, it appears that the original star 124 (AUID 000-BLS-549) was removed from the VSP and replaced with a new comparison star (000-BML-045, our C3) with a similar magnitude. Unfortunately, this star also receives the label “124” on new VSP charts; users are encouraged to refer to these stars by their AUID number to avoid confusion.

In his unrefereed webpage, Gary (2017) presented all-sky *BV* photometry of 25 potential comparison stars within ~5 arcmin of KIC which he monitored over four months. He was able to detect the photometric variability of star 124 (his #24), and he saw a linear decline of $\Delta V \approx 0.005$ mag in the brightness of star 128 (his #20; he saw similar linear behavior in several other stars in the field). Eight of Gary's comparison stars are in common with our data shown in Table 3; the photometric comparison is shown by the squares in Figure 2. As was the case for the APASS comparison, the star C9 is ~0.07 mag below the other stars, suggesting that the photometric error is in our *V*-band data, and that $V = 13.35 \pm 0.02$ mag (the average of the APASS and Gary values) is a better estimate for this star. Ignoring C9, we see a tight relationship with a standard deviation of 0.013 mag and a median offset of –0.024 mag (–0.031 mag if the questionable stars 124 and 128 are also rejected). This systematic offset, in which Gary's magnitudes are fainter than ours, is in the opposite sense of the comparison with APASS.

While we acknowledge that Gary's description of his all-sky photometry is lacking specifics and has not been subject to scientific review, the fact that Gary's and the APASS photometry sets bracket our own encourages us to think that our *V*-band photometry has the most reliable zero-point calibration and thus may represent the best current estimates for the actual magnitudes of these stars. Unfortunately, third-party photometry in the *I*-band does not yet exist and so we remain uncertain about whether the APASS data or ours are to be preferred. In order to fully resolve the photometric zero-point of the comparison stars at the 0.01-mag level, we recommend new observations of comparison stars in the KIC field, including stars out to ±10 arcmin from KIC to include the commonly-used stars 116 and 113, along with other comparison stars on our list.

2.2. Differential observations

We obtained additional images of the KIC field on non-photometric nights. Together with the photometric images described above, we have 15 nights (102 images) in V and 29 nights (559 images) in I_C with which to study the time-series behavior of KIC. On each of these images, we measured the instrumental aperture magnitude of KIC and each comparison star (using an aperture of 6–9 arcsec diameter to reduce sky noise) and from them determined differentially the standard magnitude of KIC using the equation

$$V_v = V_c + v_v - v_c - c_2\,[(B-V)_v - (B-V)_c], \tag{2}$$

where the v and c subscripts refer to the variable (KIC) and comparison star, respectively, the capital and lower-case letters again designate standard and instrumental magnitudes, and the $B-V$ colors were taken from Table 1. We used an analogous equation along with $(V-I_C)$ colors from Table 1 for the long wavelength data.

The classical approach to differential photometry of variable stars, practiced by most AAVSO observers, is to select one comparison star for use in the calibration and apply Equation 2 to produce a time series. A check star is then used to confirm the behavior. For the vast majority of variable stars, which exhibit a large amplitude or cyclic variations or both, this procedure is quite satisfactory. In the case of KIC, where the variations are both small and irregular, we need to be particularly careful about the selection of comparison stars, and we can take advantage of averaging over multiple comparison stars to reduce errors. We selected the ten most reliable stars from Table 3 and combined their ten magnitude estimates for KIC from each image using a weighted mean to get a best magnitude for the corresponding time, and used their SEM as a measure of the uncertainty in that ensemble magnitude. We did this for both V and I_C to produce our best data set, and repeated it using the APASS comparison star magnitudes from Table 1 for the same ten comparison stars to get a second time series that better matches the photometric zero-point of the AAVSO data; this data set is shown in Figure 1.

Six nights of our I_C data set are in the time range of the 2017 May dimming events reported in *AAVSO Alert Notice*

Table 4. BGSU Nightly Photometry.

JD^a	*Date*	*Median* I_C	σ	*SEM*	N_{obs}	Δt
7882.90	May 9	11.189	0.005	0.002	10	0.015
7886.81	May 13	11.224	0.011	0.001	70	0.139
7888.82	May 15	11.215	0.030	0.004	49	0.130
7895.73	May 22	11.220	0.018	0.002	62	0.162
7896.72	May 23	11.207	0.014	0.001	90	0.077
7907.76	June 3	11.204	0.014	0.002	35	0.032
<7852	—	11.207	0.016	0.003	23	207

a. Julian Date after subtraction of 2450000 days. All dates in column 2 are in calendar year 2017.

Note: These data were calculated using BGSU magnitudes from Table 3 for the comparison stars; subtract 0.029 mag to get values equivalent to the APASS system from Table 1.

579 (AAVSO 2017b) and by Boyajian *et al.* (2017). In Table 4 we report the median magnitude from each of these six nights, their standard deviation (σ) and SEM, along with the number of images and the time span of the images that night (Δt, in days). We computed similar nightly median magnitudes for our I_C data previous to 2017 April 9, when KIC was in its undimmed state. The final line of Table 4 reports the median and its statistics for these nightly values, and thus serves as a standard for comparison with our May nights. Only May 13, 15, and 22 are below this value, by 0.017, 0.008, and 0.013 mag, respectively. However, none deviates from the undimmed state by much more than 0.016 mag, the 1-σ level, so none are significantly below the pre-dip median. Nevertheless, it is intriguing that these three nights bracket the ~0.02 mag dip observed on May 18–19 reported by Boyajian *et al.* (2017).

Some of our data points from individual images drop to fainter magnitudes, in particular the six points near $I_C = 11.3$ mag at JD = 2457888.7 days shown in Figure 1. However, they show random scatter rather than a sequential progression of magnitude with time. Also, the magnitudes brighten by ~0.1 mag within fifteen minutes, much faster than the slopes of the D800 and D1500 events from Boyajian *et al.* (2016). These points are more likely due to poorly-calibrated pixels falling in the star aperture on these images, which suffered from higher than usual dark counts.

3. Conclusions

We obtained all-sky photometry of the enigmatic dimming star KIC 8462852 and its comparison stars in V and I_C using the 0.5-m telescope at BGSU. We obtained undimmed magnitudes of $V = 11.892$ and $I_C = 11.210$ mag for KIC, fainter than the APASS values by 0.04 and 0.08 mag, respectively, and $\gtrsim 0.15$ mag fainter than the V and I_C values from Boyajian *et al.* (2016). We estimated the uncertainty in our photometric zero-point to be ~0.02 mag, so these differences are significant. To aid our analysis and those of future studies, we provided photometry of thirteen additional comparison star candidates. Statistical analysis of these magnitudes with respect to their equivalents from APASS (Henden *et al.* 2015) and from unpublished work by Gary (2017) suggests that the star-to-star brightness differences in V are small, $\sigma \approx 0.01$ mag, so that differential photometry using these stars will be reliable. However, the star-to-star differences among the I_C magnitudes are larger, $\sigma \approx 0.03$ mag, suggesting that an observer's choice about which comparison star(s) to use in their differential photometry may significantly affect their resulting time-series data; this effect is probably responsible for some of the scatter seen in the current AAVSO *I*-band data shown in Figure 1. Furthermore, comparisons between the available data sets show that the overall photometric zero-points differ at the ~0.03 mag level. There is some evidence suggesting that our *V*-band photometric zero-point is the most reliable of the three, but it remains an open question whether the APASS data our ours provides the better photometric zero-point in I_C. We discuss shortcomings of the photometry for several of the current comparison stars of KIC 8462852 in section 2.1.

To address these problems, we recommend that new all-sky photometry be obtained from a clear, dark site using a low-noise CCD covering a field of view ≳20 arcmin. Multiple observations on at least three independent nights are desirable to reject outliers and average out random noise. Many visits to standard star fields from Clem and Landolt (2016) are needed to ensure a transformation to the standard system accurate to ≲ 0.01 mag. Obtaining such data in $BVRI_C$ will enable the recalibration, using an ensemble of comparison stars to reduce errors, of the full CCD-based AAVSO data set on KIC 8462852, currently over 44,000 measurements.

We also obtained time-series photometry of KIC 8462852 comprising 15 nights in V and 29 nights in I_C spanning 1.6 years. Three of these nights are near the 2017 May 18 dimming event reported by Boyajian *et al.* (2017), and while none indicates a dip deeper than 0.02 mag, each of the three measurements is up to 1-σ dimmer than the star's typical, pre-dip brightness. Together with data from other sources, including the recalibrated AAVSO data proposed above, these data may help to trace out the time history of the latest dimming event of this challenging, low-amplitude, irregular variable star.

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Appendix

To convert APASS photometry into the Cousins I_C equivalent, we utilized the equations in Table 4 of Jordi *et al.* (2006). Specifically, we solved their equation for bluer Population I stars,

$$r - R = 0.275\ (V{-}R) + 0.086, \tag{3}$$

for R and entered a star's APASS photometry in the Johnson V and Sloan r bands to get its magnitude on the Cousins R_C system. Then, we solved their equation (also for Population I stars)

$$i - I = 0.251\ (R{-}I) + 0.325, \tag{4}$$

for I and used the value of R_C output from the previous equation along with the star's APASS photometry in the Sloan i band to calculate its magnitude on the Cousins I_C system. We propagated the errors in the star's APASS photometry along with the errors in the coefficients for the equations above to obtain the uncertainty in the star's I_C magnitude, I_{err}. Both of these values are shown for each star in Table 1.

We assumed that the stars in the field of KIC are Population I stars because the Galactic latitude is low, $b = +6.64$ deg. If, however, a star belongs to Population II, its inferred I_C magnitude shown in Table 1 will be in error. To quantify the error, we calculated each star's I_C magnitude using the coefficients for the equations above appropriate for Population II stars (Jordi *et al.* 2006). The median difference between the Population I and II photometry is only +0.003 mag, and individual differences range from +0.037 mag for C1 to –0.009 mag for C11, where a positive deviation indicates that the Population II estimate is brighter. Given the relative frequencies of Population I and II stars in the Solar neighborhood, we think it unlikely that more than one or two stars are affected by this ambiguity; this could account for some of the outliers in Figure 2. However, a component of the overall scatter in this diagram is surely due to uncertainties in the transformation from APASS magnitudes in *Vri* to I_C magnitudes. For both these reasons, we advocate direct, high-quality I_C calibration of the comparison stars around KIC.