Light Curve Analysis of 185 YSOs: New Periods Discovered for 9 Stars

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Abstract Using AAVSO's VStar software, all 185 YSOs listed in the AAVSO's Target Tool were analyzed using the Date Compensated Discrete Fourier Transform (DCDFT) algorithm, searching for periodicity. Light curves created from the AID (AAVSO International Database) data and ASAS-SN data were used for this analysis. Of the 185 YSO candidates analyzed, new semiregular periods were discovered for nine stars. The remaining 176 YSO candidates analyzed did not show significant semiregular periodicity, were unable to be analyzed due to the lack of enough usable data, or already had periods listed in VSX or ASAS-SN.

1. Introduction

The AAVSO Target Tool lists 185 YSO (Young Stellar Objects) candidates. YSOs are stars in their earliest stages of development. As these stars age, there are many physical processes both internally and externally that impact their variability. Regular observation and analysis of YSOs is key in better understanding stellar evolution from protostar to main sequence. YSOs are highly variable, and their variability is often irregular.

Using the most recent data from AID (Kafka 2021) and ASAS-SN (Shappee *et al.* 2014; Kochanek *et al.* 2017) on these 185 YSO candidates, periods have been discovered for nine stars.

2. Light curve analysis using DC DFT algorithm

2.1. Methods

From the list of 185 YSO candidates in AAVSO's Target Tool (https://www.aavso.org/aavso-target-tool), a DC DFT algorithm (Ferraz-Mello 1981) in the AAVSO's software VStar (Benn 2012) was used to look for periodicity in the light curves of any YSO candidates as long as the star had at least 100 Johnson V-band observations in the AID.

If a YSO candidate met these two criteria, its AAVSO light curve data set was downloaded into VStar, where a DC DFT algorithm was used to look for any periodicity in the Johnson V-band. The Johnson V-band was chosen because most stars in the AID have primarily Visual and Johnson V-band data, with other light bands being sporadic and therefore not useful in this analysis.

Each star was then run through the ASAS-SN database (Shappee *et al.* 2014; Kochanek *et al.* 2017). The ASAS-SN data were downloaded into VStar and combined with the AID data. DC DFT was used for various bands / means to search for any regular periodicity.

2.2. Results

Most of the YSO candidates analyzed were listed as irregular variables of various types (UXOR, IS, INS, CTTS, etc.) and as expected, a DC DFT analysis of their data was unable to find any significant periodicity (i.e. confirming their classification as irregular variables). Of the 185 YSO candidates:

- 73 stars did not have enough data to provide a useful analysis (i.e. they had less than 100 Johnson V-band observations in the AID).
- 95 of the stars showed no significant periodicity.
- Due to the AID and ASAS-SN data spacing, low periods (less than 30 days) are difficult to detect with these data sets and a DCDFT analysis alone.
    - 17 of those 95 stars had previously recorded periods in VSX (Watson *et al.* 2006–2014). Those periods in VSX ranged from 2.09 d to 18.58 d.
    - 13 of those 95 stars had previously recorded periods in ASAS-SN. Those periods ranged from 0.5d to 27.0d.
- 8 stars showed periods consistent with those already reported in ASAS-SN or other literature. Periods ranged from 62 d to 1297 d.
- 9 stars showed new periods (Table 1).

The list of the 176 YSO candidates without new periods are not listed here; however, they are available upon request or by using the AAVSO Target Tool.

2.3. Notes and discussion

The nine stars showing new periods were queued in SIMBAD to look for previous literature references and in VIZIER for data and references to their spectral type, variation type, and Gaia data (Table 2).

CT Vul DC DFT analysis in VStar created a periodogram which indicated a power of 100.33 for the frequency 0.002588, which correlated to a period of 386 days (Figure 1). The period model of 386 days shown in red within the light curve from VStar (Figure 2) shows that the model period is a close fit to the actual observations. While CT Vul appears to follow the 386-day period regularly, there are fluctuations in the range of these semi-regular variations. At JD 2456750, JD 2458250, and JD 2458750 (Figure 2), CT Vul moves to various faint magnitudes, reaching as low as magnitude 16.7 in the V-band at JD 2458250, while at other faint sections, the star appears to remain brighter than magnitude 15.

Schaefer (1986) and others have labeled CT Vul as a R CrB star. R CrB stars are a rare class of variable stars in which they remain at a fairly stable maximum brightness until occasionally their brightness abruptly drops by a large but variable amount for an indeterminate length of time before brightening back to the previous maximum. This variable drop in brightness is believed to be caused when a stream of matter is ejected out of the star, and some of the metals condense, obscuring the star. These ejections are related to semiregular pulsations that R CrB stars undergo (Trimble 1972). The light curve developed

Table 1. New semi-regular periodicity of YSO candidates.

Star	GCVS Type	Number of Data Points	Time Period of Data	Period (days)	Johnson V Range (mag)
CT Vul	IS	648	Mar. 2014–Aug. 2019	386	2.7
FY Lac	I	936	June 2013–Nov. 2020	279	1.1
MY Lup	TTS	11711	Mar. 2016–Sep. 2018	2.63	1.0
SV Cep	UXOR	2432	Sep. 2005–Nov. 2020	975	1.2
V0369 Per	IS	1084	Dec. 2011–Oct. 2020	212	1.8
V0561 Cyg	ISB	1547	July 2011–Nov. 2020	101	1.1
V1331 Cyg	INST	2244	June 2011–May 2021	449	1.1
V1515 Cyg	FUOR	2407	Sep. 2001–Nov. 2020	341	1.5
WW Vul	UXOR	6627	Sep. 2000–May 2021	69	2.0

Table 2. Gaia DR2 Data (Gaia Collaboration *et al.* 2018) on stars with new periods discovered.

Star	R.A. (J2000) h m s	Dec. (J2000) ° ' "	Distance (pc)	Effective Temo. (K)	Radius (solRad)	Luminosity (solLum)
CT Vul	19 47 32.57	+20 54 17.79	1121	5068	1.95	2.27
FY Lac	22 32 35.51	+45 31 46.27	1050	3306	102.14	1123.14
MY Lup	16 00 44.52	–41 55 30.93	156	4412	1.60	0.88
SV Cep	22 21 33.22	+73 40 27.10	344	6395	2.04	6.25
V0369 Per	02 51 17.20	+38 14 40.77	11494	3771	—	—
V0561 Cyg	20 25 58.22	+52 08 41.19	2458	3306	91.76	906.21
V1331 Cyg	21 01 09.21	+50 21 44.80	596	4403	4.97	8.36
V1515 Cyg	20 23 48.02	+42 12 25.78	1008	3595	9.59	13.85
WW Vul	19 25 58.75	+21 12 31.33	504	6634	2.69	12.62

here could be consistent with the behavior of an R CrB star. Though holding to a fairly consistent maximum brightness between 14.0 and 14.3 (V band), CT Vul dramatically drops in brightness to as low as magnitude 16.7 before returning to its maximum. This cyclic pulsation occurs approximately every 386 days.

FY Lac DC DFT analysis in VStar shows semiregular periodicity at 279 days (Figure 3). FY Lac is listed in Gaia DR2 (Gaia Collaboration 2018) collection of Long Period Variable candidates (LPVc). It is an M6 star (Lee *et al.* 1947). FY Lac is likely a semiregular pulsating red giant. The title of long period variable would also fit this star, as it does not show the regularity or large brightness variations of a Cepheid or a Mira variable but it does show semiregular variability.

MY Lup Due to an abundance of AID data for this star, a highly frequent period of 2.63 days was discovered (Figure 4). MY Lup is a K0 star (Alcalá *et al.* 2017), categorized as a T Tau star in VSX and most literature. T Tau stars are quick-rotating young stars on their way to the main sequence. The cause of this short-period variation shown here in this analysis is difficult to pinpoint. Some T Tau stars are known to contain large sunspots, which could diminish the brightness of MY Lup during each short rotation. T Tau stars are also known to have powerful stellar winds and/or mass ejections of materials through jets at their poles. T Tau variation is often attributed to unevenly distributed dust and debris in the disk surrounding the star. More research is needed to find the cause of this 2.63-day cyclic drop of ~1 magnitude.

SV Cep DC DFT analysis in VStar shows semiregular periodicity at 975 days (Figure 5). It is listed as a Herbig Ae/Be star in Simbad and in most literature. SV Cep is $2.5\,M_{\odot}$, which puts it on the smaller end of Herbig Ae/Be stars (typically $2–8M_{\odot}$). This star is known to have a circumstellar disk, and this disk is extremely well studied. Many have theorized that SV Cep's disk is not homogenized, but rather contains populations of dust varying in size, density, and material make-up. Using infrared observations during different periods of SV Cep's brightness variation, Friedemann *et al.* (1992) were able to determine that at least three different grain populations exist within SV Cep's circumstellar disk. Since SV Cep is listed in VSX as a UXOR or UX Ori star, the long-period semiregular variation seen in this analysis would be consistent with variability in other UXOR stars (most of which are Herbig Ae/Be stars). VSX defines a UXOR as a star with "irregular variations on time-scales of days around a mean brightness level that changes on a much longer time-scale (typically years), sometimes in a quasi-cyclic fashion...." The variation over 975 days could account for the quasi-cyclic mean brightness levels that change, while the star's brightness varies greatly on a shorter time scale (Figure 6).

V369 Per DC DFT analysis shows a semiregular period of 212 days for V369 Per (Figure 7). The data cover 2,655 days between July 7, 2013, and October 14, 2020. This star is not particularly well studied, but is among the large catalogue of LPVc from Gaia DR2 (Gaia Collaboration 2018). Gaia DR2 also classifies V369 Per as a Mira variable with a period estimate of ~282 days. Skiff (2009) classifies this star as a M5 star, and with its distance (11,494 pc) and low proper motion in Gaia DR2, it is likely a pulsating semiregular red giant. Combined with the light curve and model of a 212-day period (Figure 7), this analysis appears to confirm the Gaia DR2 classification of V369 Per as a Mira variable.

V561 Cyg DC DFT analysis shows a semiregular period of 101 days for V561 Cyg (Figure 9). It appears in Gaia DR2 (Gaia Collaboration 2018) as a Mira and is listed with a spectrum of G-K (Samus *et al.* 2007–2017). It is an extremely luminous star, recorded at 906 times as luminous as the sun. This fact, combined with the Mira-like variation, low proper motion, and distance, makes this star a likely candidate for a pulsating giant (G or K giant). An analysis of the 101-day period model overlaid on the light curve in VSTAR (Figure 10) does show some Mira-like variation. A lack of frequent enough measurement makes this evidence suggestive at best, and more data at a higher cadence are needed to confirm this period and V561 Cyg's potential classification as a Mira variable.

V1331 Cyg DC DFT analysis shows a semiregular period of 449 days for V1331 Cyg (Figure 11). There is some variation in classification of this star's spectral type, but F0/F4-G5 (Gramajo *et al.* 2014) seems to be the most commonly referenced spectral type. It is also listed as a T Tau star in the pre-FUOR stage (FU Ori star—when a star experiences a large change in brightness and spectral type), though this is highly debated in a number of papers. Quanz *et al.* (2007) suggest that V1331 Cyg does not meet the behavioral requirements to be labeled as a pre-FUOR or FUOR star. A FUOR eruption in the past may have shaped some of the disc and dust around V1331 Cyg, including the large outer ring that surrounds V1331 Cyg. It is unclear what internal or external processes may be causing this semiregular variation at ~449 days.

V1515 Cyg DC DFT analysis shows a semiregular period of 341 days for V1515 Cyg (Figure 12). This star has a spectrum G0/G2Ib (Skiff 2009), and is labeled as a FUOR. It is listed among Gaia DR2's LPVc as a Mira variable (Gaia Collaboration 2018). The light curve from VSTAR (Figure 13) also shows an overall decrease in brightness, even while lesser cycles of brightening and darkening occurred around every 341 days. In October 2004, the mean of the Johnson V measurements at maximum was 12.7, and by July of 2020, the mean at maximum was 13.9. This is consistent with a star post-FUOR episode or ejection, as many stars darken by one or two magnitudes in the months and years after a FUOR ejection or episode. A portion of the light curve from JD 2456020 to 2459177 includes enough data and a high enough cadance to compare the 341-day period model to the actual measurements. Though there are some semiregular variations similar to a Mira variable, more data and closer intervals are needed to confirm or deny Gaia DR2's categorization as a Mira. Since the star otherwise shows signs of being a T Tau star and an FUOR (designations of pre-main sequence stars), it would be unlikely that this star was a Mira (designation of a star in the late stages of stellar evolution).

WW Vul DC DFT analysis in VSTAR shows semiregular periodicity at 69 days for WW Vul (Figure 14). WW Vul is a well-studied star with a spectrum of A2IVe (Mora *et al.* 2001) and is labeled as a UXOR. As defined for SV Cep above, these stars show variation on a short time-scale, while displaying an overall shift in brightness over longer time-scales, sometimes in a cyclic or quasi-cyclic manner. The AID data and ASAS-SN data are too sporadic to compare the model period at 69 days to the light curve in order to determine what kind of variation might be happening. Consistent with UXOR stars, the variation appears cyclic overall, with lots of micro-variations on short time scales. The amount of darkening and brightening also varies within each cycle. In some cycles, WW Vul darkens by as much as 1.75 magnitude in the Johnson V-band, while in other cycles, a variation of 0.5 magnitude is observed. There also appears to be a large brightening event culminating at a maximum magnitude (V-band) of 9.99 at JD 2456549. More data and high frequency intervals are needed to continue to learn about WW Vul and seek to explain the internal and/or external causes of its semiregular variations.

3. Conclusions

Nine variable stars have been shown to have new semiregular periods. Continued monitoring of these nine variable stars is necessary to confirm these newly discovered periods and to understand the physical processes that cause this semiregular periodicity in these stellar systems. Understanding the various processes at work in stellar systems as they evolve from protostar to the main sequence and beyond is essential in understanding the evolution of our own solar system, and all stellar systems.

As shown in Table 1, CT Vul shows a period of 386 days and the findings here appear to confirm the theory of Schaefer (1986) that CT Vul is an R CrB-type star. FY Lac shows semiregular variability at around 279 days. Gaia DR2 (Gaia Collaboration 2018) lists this star at a LPVc and the findings here of periodicity at 279 days confirms that categorization. MY Lup showed a very short period of 2.63 days. It is listed as a T Tau-type star, but it is difficult to pinpoint the exact internal or external causes of this strong and frequent periodicity. SV Cep shows a period of 975 days. It is listed as a Herbig Ae/Be star and an UXOR, and the light curve and periodicity appear to confirm its categorization as an UXOR. V369 Per shows a periodicity of 212 days. The light curve shows Mira-like variation at this periodicity, and confirms its previous categorization by Gaia DR2 as a Mira-type star. V561 Cyg shows a period of 101 days. It is listed in Gaia DR2 as a Mira-type star (Gaia Collaboration 2018). Due to AID and ASAS-SN data for this star being sporadic, there is not enough of a complete light curve here to confirm this categorization, though some Mira-like motion can be seen in the light curve. More research and smaller-interval data measurements are needed. V1331 Cyg shows a period of 449 days. Some literature list this star as an FUOR, though other papers indicate there may not be enough evidence to accurately list it as an FUOR. The light curve with data from AID and ASAS-SN does not give conclusive evidence as to this categorization, and therefore more research is needed to confirm or disprove its categorization as an FUOR and to explain this 449-day periodicity. V1515 Cyg shows a period of 341 days. It is listed as an FUOR in Simbad, though Gaia DR2 lists it as a Mira-type star. The light curve generated from AID and ASAS-SN data shows some signs that the star may be in a post-FUOR period as the overall brightness decreased steadily over time, even while the semi-cyclic variations appeared every 341 days. More data are needed to accurately categorize this star properly and to explain the periodicity discovered here. WW Vul shows a period of 69 days. It is categorized as an

UXOR, and the light curve overall appears consistent with this designation (cyclic overall, with micro-variations on shorter time scales of days to weeks). Further and more frequent observations are needed to better understand the type of variability WW Vul is experiencing, and the cause(s) of that variation.

Of the 176 remaining YSOc from the AAVSO Target Tool list, 73 stars did not have enough data to provide a useful analysis, and 95 of the stars showed no significant periodicity (though due to the AID and ASAS-SN data spacing, low periods (less than 30 days) are difficult to detect with these data sets and a DCDFT analysis alone). 17 of those 95 stars had previously recorded periods in VSX; those periods in VSX ranged from 2.09 to 18.58 days. 13 of those 95 stars had previously recorded periods in ASAS-SN; those periods ranged from 0.5 to 27.0 days. Eight of those 95 stars showed periods consistent with those already reported in ASAS-SN or other literature; those periods ranged from 62 to 1,297 days.

4. Acknowledgements

I want to acknowledge the variable star observations from the AAVSO International Database contributed by observers around the world and used in this research. There are too many observers to list by name, but without their observations, this type of data analysis would not be possible. Thanks to the developers of the VStar data analysis and visualization software package, which allowed for the analysis of AID data using the DC DFT algorithm. This research paper has also made use of the SIMBAD and Vizier databases. The International Variable Star Index (VSX) database, operated at AAVSO, Cambridge, Massachusetts, was also very helpful in completing this research. Special thanks also to the developers of the DC DFT algorithm, which allowed this analysis to take place.

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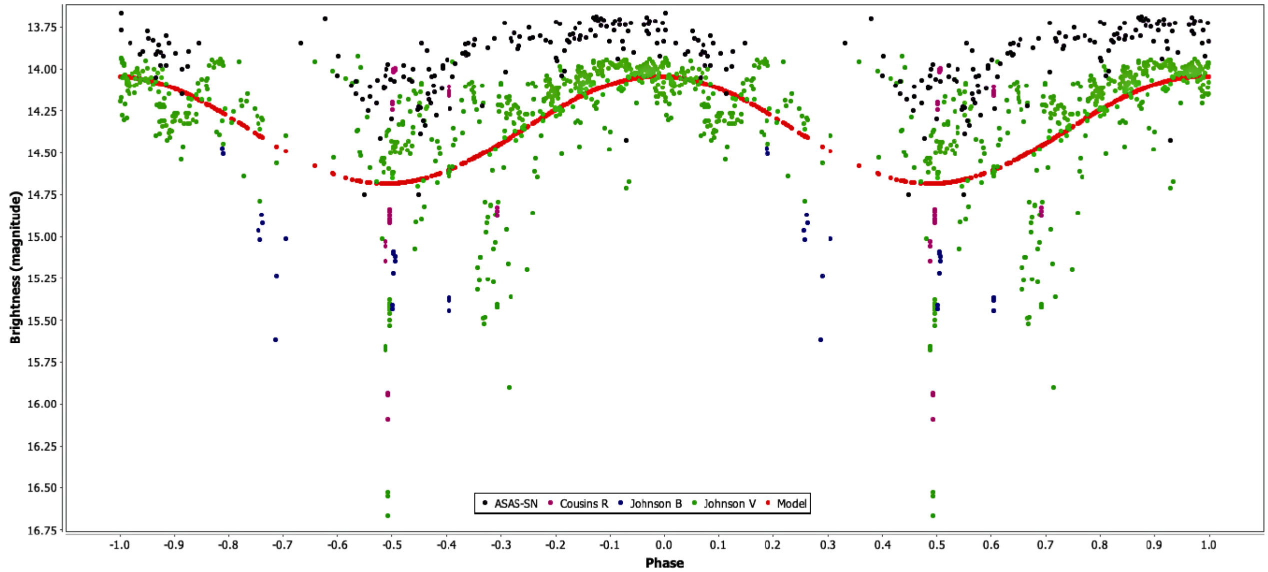

Figure 1. Phase plot for CT Vul (period 386 d, epoch 2456891) including AID and ASAS-SN data.

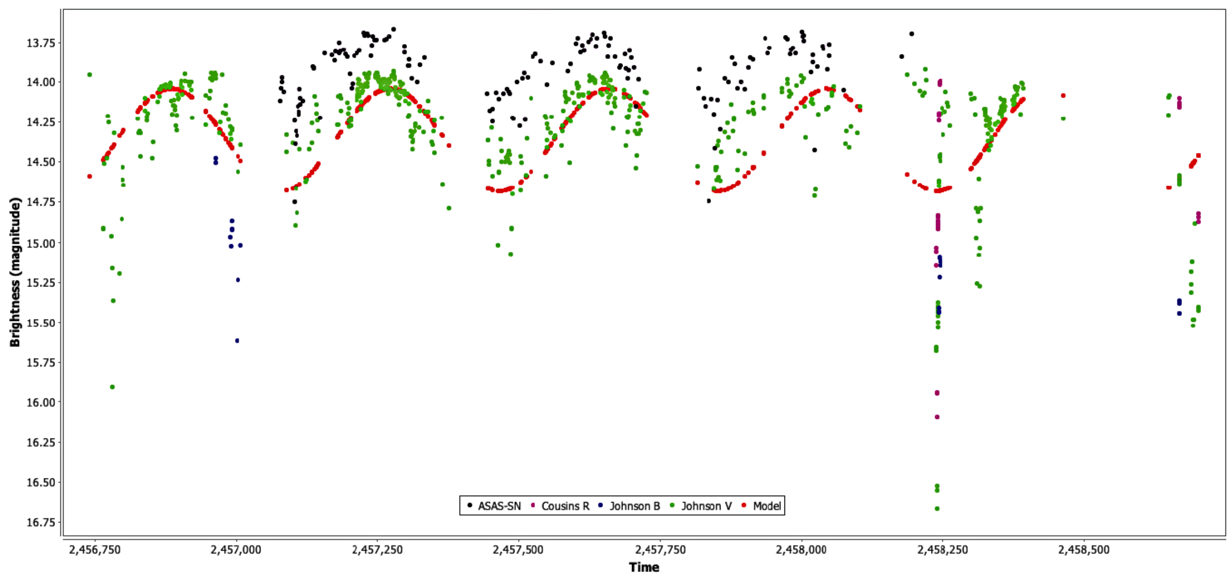

Figure 2. Light curve for CT Vul including AID and ASAS-SN data.

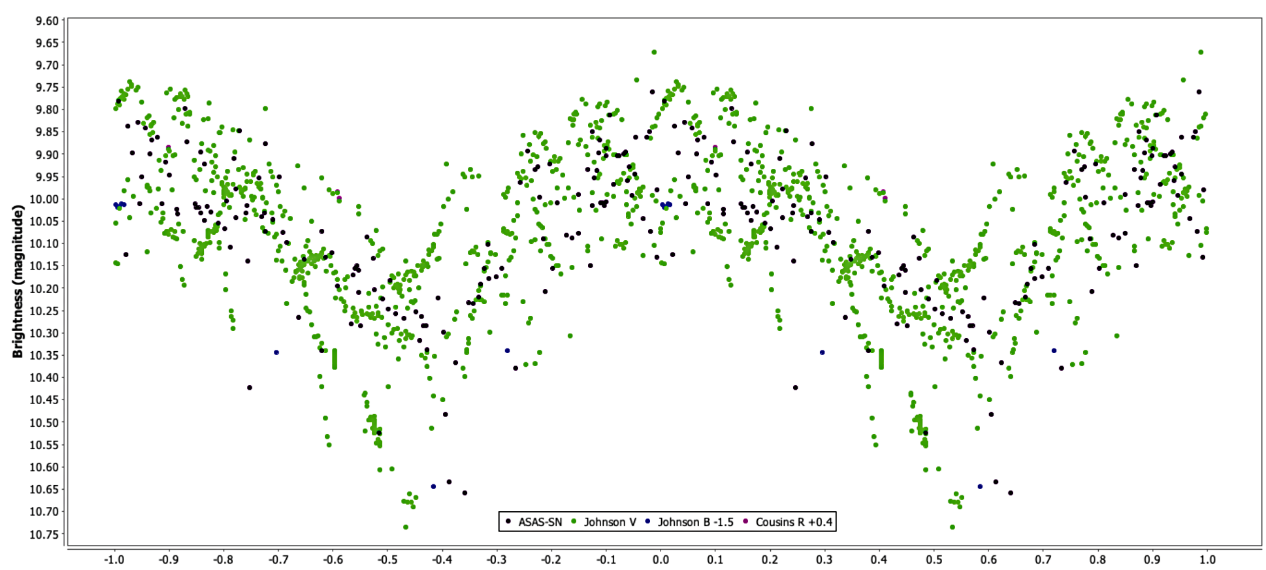

Figure 3. Phase plot for FY Lac (period 279 d, epoch 2456608) including AID and ASAS-SN data.

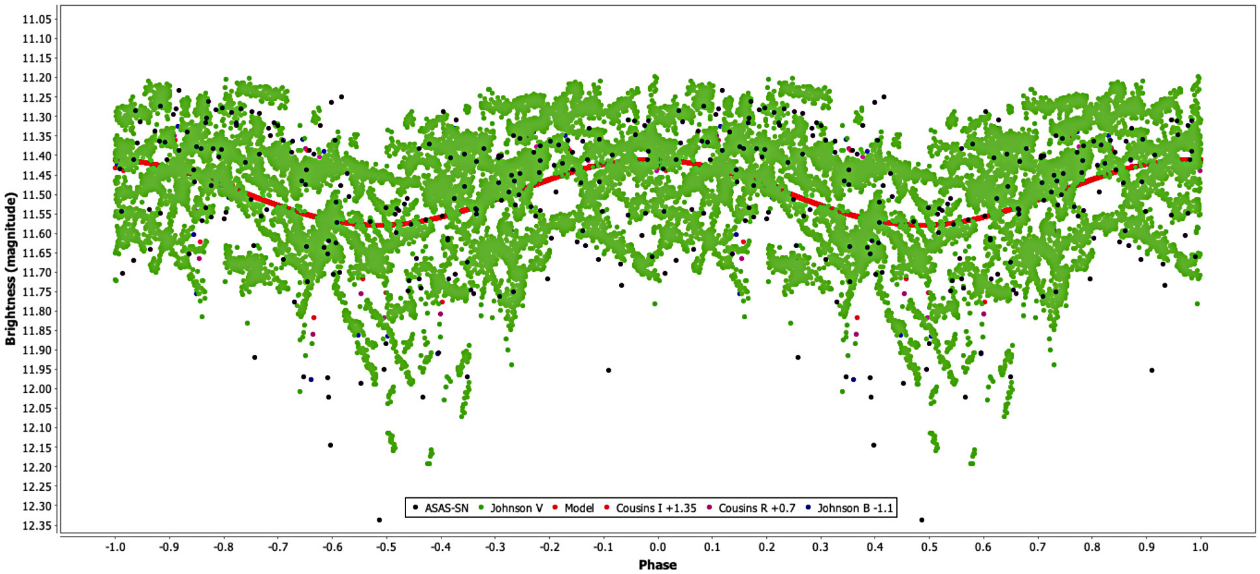

Figure 4. Phase plot for MY Lup (period 2.629 d, epoch 2457877.1) including AID and ASAS-SN data.

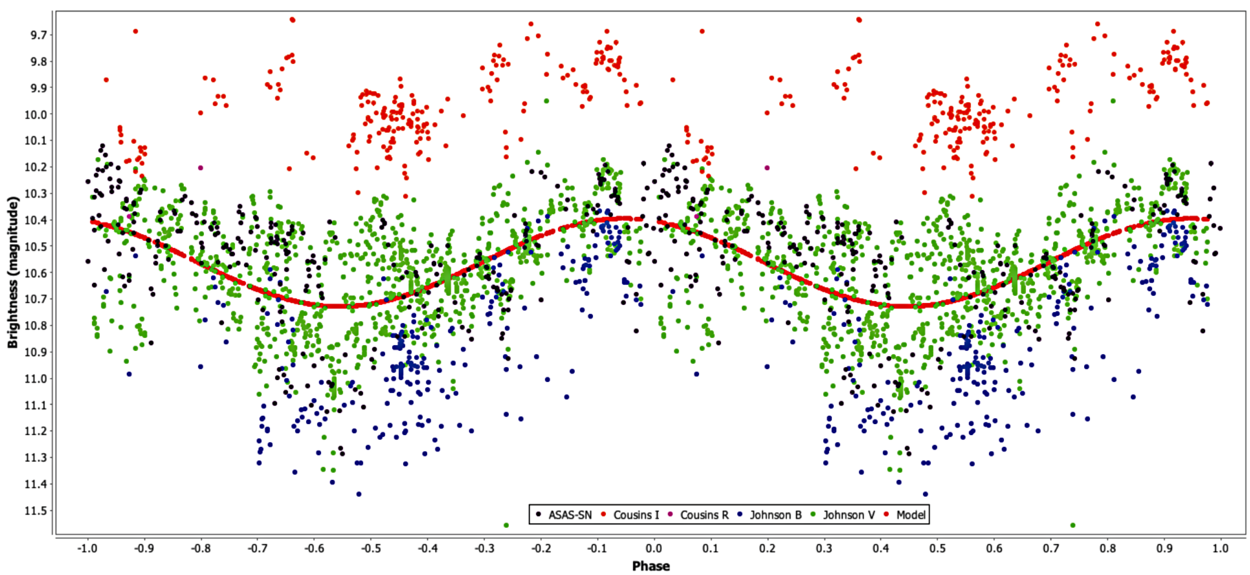

Figure 5. Phase plot for SV Cep (period 975 d, epoch 2455033) including AID and ASAS-SN data.

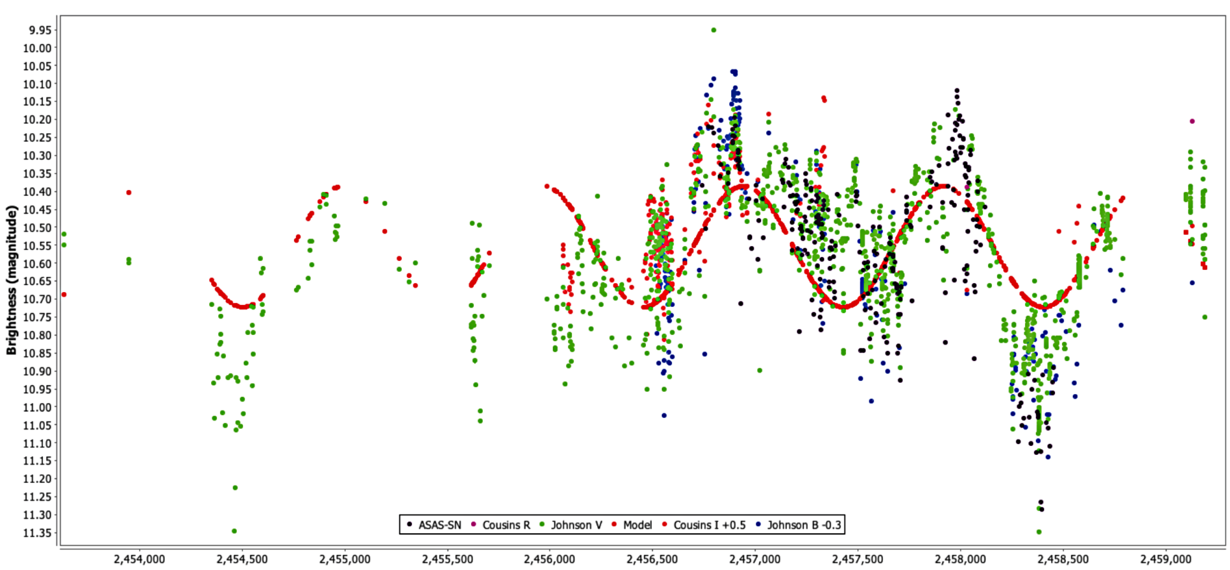

Figure 6. Light curve for SV Cep including AID and ASAS-SN data.

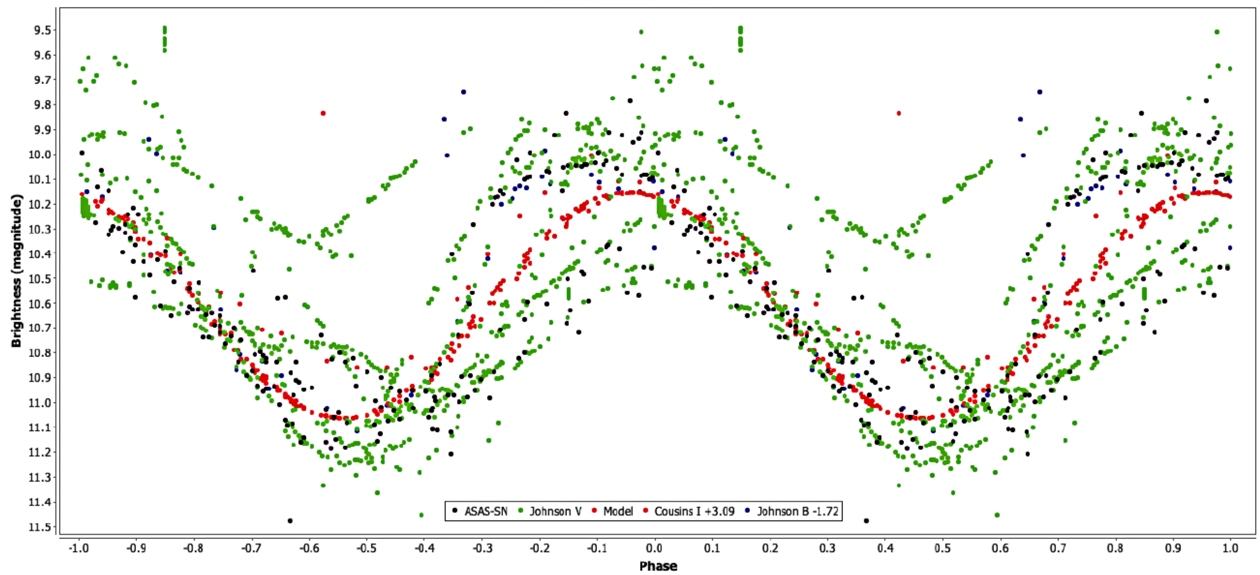

Figure 7. Phase plot for V369 Per (period 212 d, epoch 2456922) including AID and ASAS-SN data.

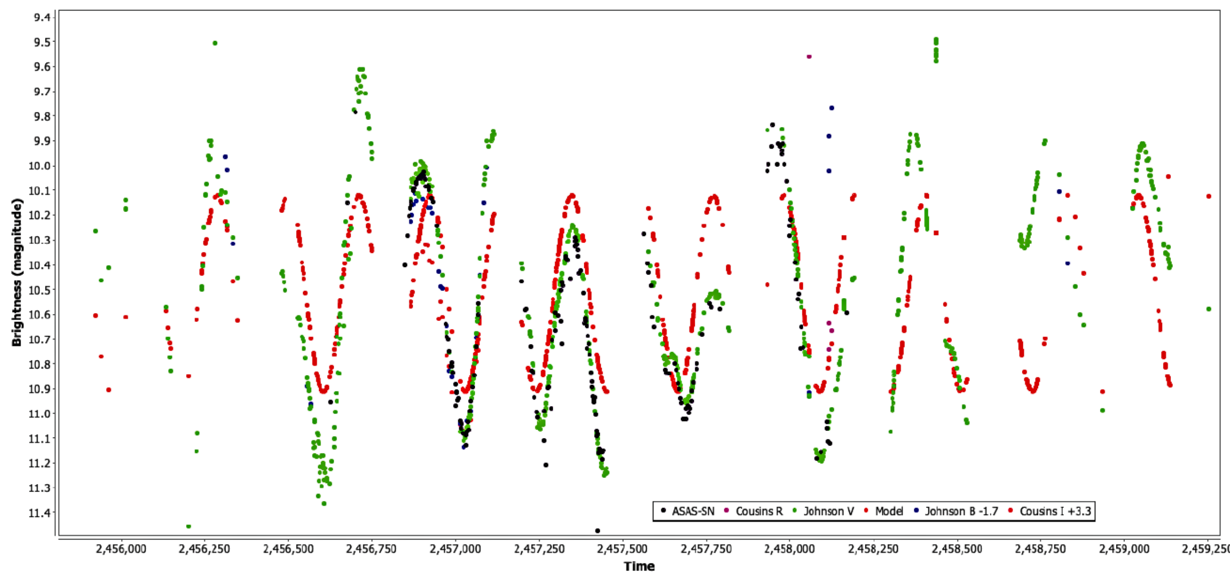

Figure 8. Light curve for V369 Per including AID and ASAS-SN data.

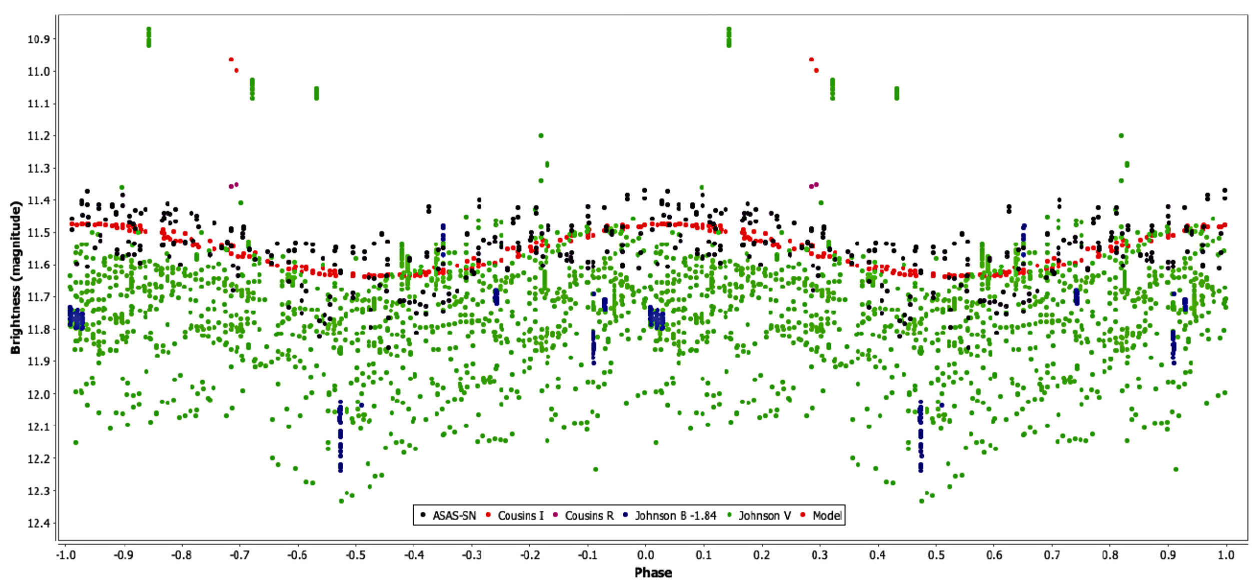

Figure 9. Phase plot for V561 Cyg (period 101 d, epoch 2457193) including AID and ASAS-SN data.

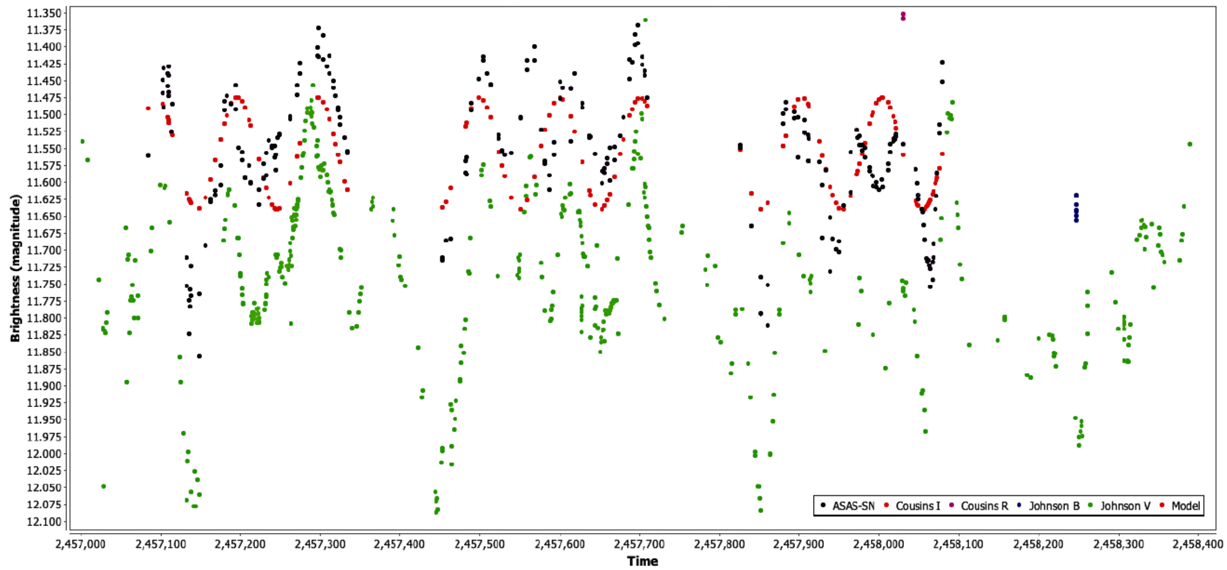

Figure 10. Light curve for V561 Cyg including AID and ASAS-SN data.

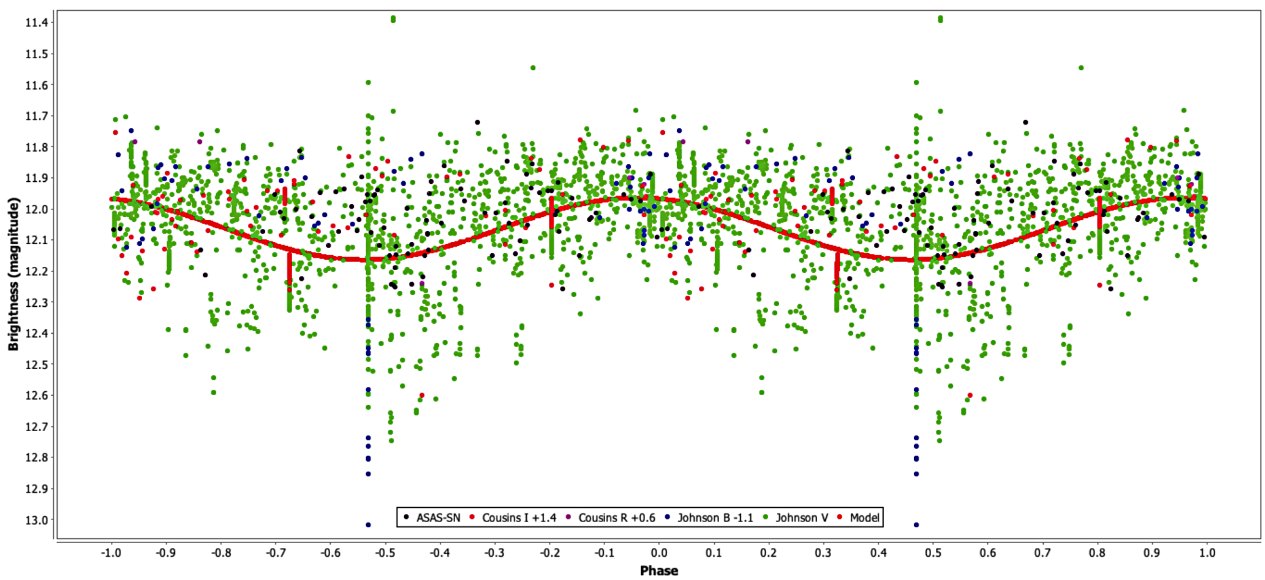

Figure 11. Phase plot for V1331 Cyg (period 449 d, epoch 2456878) including AID and ASAS-SN data.

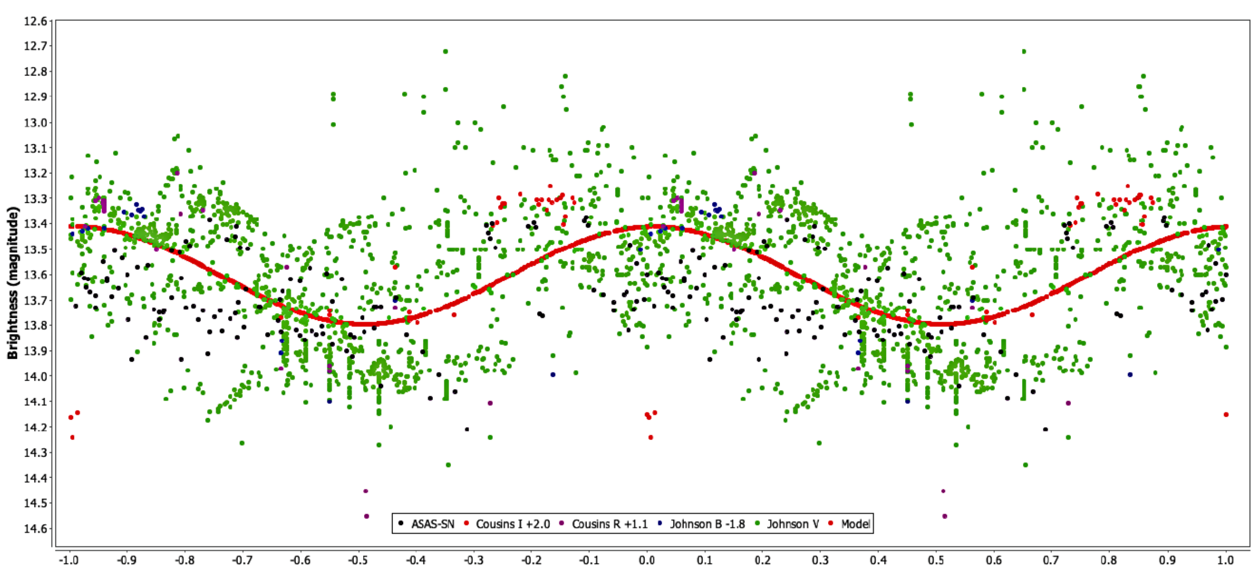

Figure 12. Phase plot for V1515 Cyg (period 341 d, epoch 2455468) including AID and ASAS-SN data.

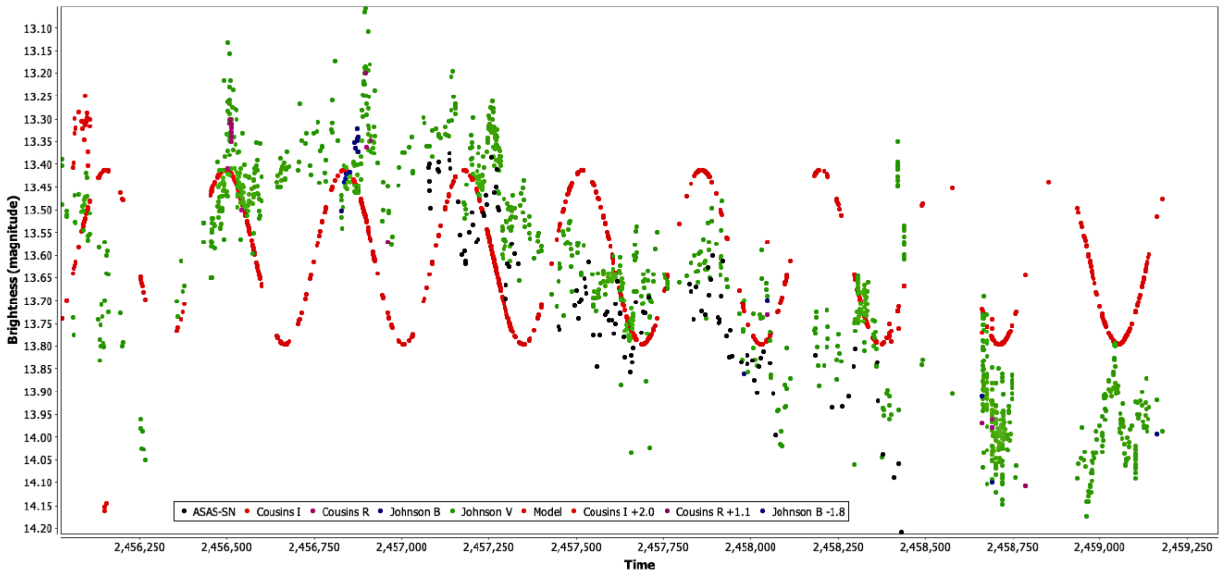

Figure 13. Light curve for V1515 Cyg including AID and ASAS-SN data.

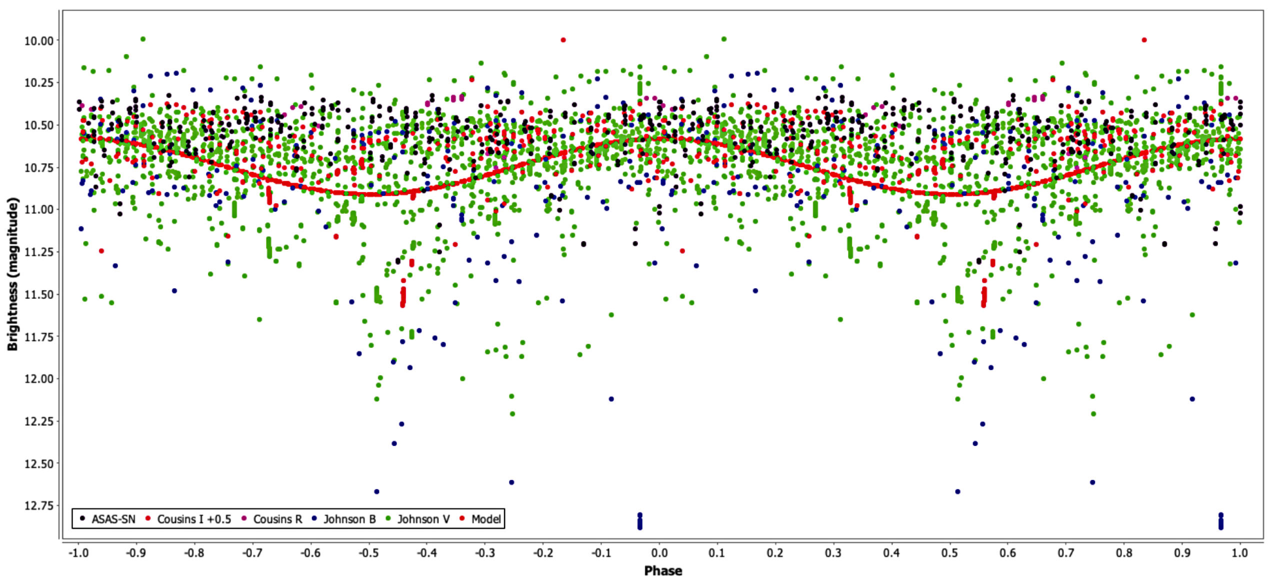

Figure 14. Phase plot for WW Vul (period 69 d, epoch 2452816) including AID and ASAS-SN data.