Photometric and Spectroscopic Review of the Beat Cepheid AS Cassiopeiae

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Abstract Photometric and spectroscopic data of the galactic beat Cepheid star (DCEPB) AS Cas (ASASSN-V J002537.77+641347.9) were obtained from three AAVSOnet observatories of the American Association of Variable Star Observers (AAVSO) located in New Hampshire (BSM-NH2), New Mexico (BSM-NM2), and Hawaii (BSM-Hamren). The spectroscopic data and their analysis were performed at the Three Hills Observatory in Wigton, UK. A total of 9027 observations for light curve analysis were made with B, V, R, I Johnson-Cousins filters from July 22, 2020 to November 8, 2023. The photometric data were analyzed with the Date Compensated Discrete Fourier Transform (DCDFT) and CLEANest methods, yielding a fundamental period (P0) of 3.02465 days ± 0.00034 and a first-overtone period (P1) of 2.15547 days ± 0.00033. The epoch used for the curve analysis was JD 2459654.736. This set of new observations is the largest compared to those previously made. Our results confirm the double- mode nature of AS Cas and, therefore, its classification as a DCEPB star. A series of low-resolution spectra were recorded over a range of phases, allowing the change in spectral class to be tracked (G0I–F6I corresponding to a T_{eff} range of 5590–6420 K). An interstellar reddening E(B–V) of 0.9 mag has been estimated from the shape of the spectrum continuum.

1. Introduction

Variable stars of the δ Cepheid (DCEP) type are post-main sequence, yellow supergiant stars with masses greater than three solar masses. Their light curves feature a very distinctive shark-fin profile: they peak very rapidly towards their maximum brightness and afterwards dim slowly until they reach their minimum. This cycle repeats itself in a regular manner with the period correlating closely with the mean luminosity of the star: the more luminous the star, the longer its cycle (period) (Leavitt and Pickering 1912). This means that once the period of this type of star has been figured out, its mean luminosity and absolute magnitude can be inferred. Once the absolute magnitude is known, the distance to the star can be derived using the inverse square law after correcting for interstellar absorption. DCEP stars have therefore proved to be very useful standard candles since the third decade of the 20th century, when Edwin P. Hubble inferred, observing precisely DCEP stars, that Andromeda and similar "spiral nebulae" were indeed other galaxies beyond our own Milky Way (Hubble 1929). Since then they have been extensively used to measure astronomical distances.

AS Cas is a type DCEPB star. The difference between a DCEP and a beat Cepheid is that the first has only one pulsation mode, while the latter features two pulsation modes: a fundamental period (P0) and a first-overtone period (P1). This makes AS Cas an anomalous star of the DCEP class, and, as Berdnikov (1992) points out: "It is impossible to understand a particular class of objects without studying its anomalous members."

The main goal of this research is to refine—through the analysis of the light curve of a larger set of new observations—the P0 and P1 of this star, as well as to gain more knowledge of its nature by performing a spectroscopic analysis of it.

This document is structured in the following way: section 2 is an overview of the observational history of AS Cas; section 3 describes the method followed to gather our observations; section 4 details the reduction methods applied to the data; section 5 features the light curves and spectroscopic analysis; section 6 contains the results of this research, and section 7 the final discussion.

2. Observational history

AS Cas was systematically observed before by Henden (1980) and Berdnikov *et al.* (1992). Henden made a total of 23 observations with the Johnson V filter, and estimated a P0 of 3.021(15) days with an amplitude of 0.59 and a P1 of 2.290(9) days with an amplitude of 0.13, to obtain a P1/P0 = 0.76 ratio. Berdnikov *et al.* made a total of 54 observations with a Johnson V filter. Berdnikov (1992) shortly after derived a P0 of 3.024675 days and a P1 of 2.155557 days, to get a P1/P0 ratio of 0.71. The maximum brightness observed by Berdnikov *et al.* and his team was 11.67 V and minimum was 12.69 V, with an amplitude of 0.59 for P0 and of 0.13 for P1. The *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2017) contains the data obtained by Berdnikov *et al.* (1992).

The All Sky Automated Survey for Supernovae—Sky Patrol database (ASAS-SN SP; Shappee *et al.* 2014; Kochanek *et al.* 2017) reports 590 observations with the Johnson V filter made from December 17, 2014, to November 27, 2018. The maximum observed brightness was 11.638 V, and minimum was 13.034 V. This survey reports only a P0 of 3.02125 days.

After these three sets of observations, no further Johnson V observations have been published until the ones performed for this research.

3. Observations

From July 22, 2020 to November 8, 2023, we performed a total of 9027 observations of AS Cas. These observations were carried out at three different observatories of the AAVSOnet

(Table 1) which used similar equipment (Table 2). Johnson B and V and Cousins R and I filters were used for the observations. The pixel size of the complementary metal-oxide-semiconductor (CMOS) cameras used was 2.4 μm, giving a resolution of 1.98"/px at 2 × 2 binning; this is equivalent to a field of view of 0.755° × 0.505°, i.e. a total of 1372.59^2 arcminutes. All the images were dark-, flat-, and bias-processed in each observatory shortly after each set of observations was made. Observations were made with different exposure times, depending on the filter used and specific conditions of each observatory (Table 3). A summary of the observations per filter and observatory can be found in Table 4, and all the data can be accessed from the AAVSO International Database (AID; Kloppenborg 2023).

A series of low-resolution spectra of AS Cas covering a range of phases were recorded using an ALPY600 long-slit grism spectrograph mounted on a 280-mm aperture Schmidt Cassegrain telescope at Three Hills Observatory in northwest England. The resolution was 1.2 nm and the exposure times varied between 1.5 and 2.5 hours in total, for a target signal-to-noise ratio (SNR) of 100 in the continuum at 550 nm, although significantly lower in the blue due to the reduced instrument sensitivity and intrinsic redness of the target (mean B–V = 1.4). All the spectra can be accessed from the BAA Spectroscopy Database (BAA 2022).

Table 1. AAVSOnet observatories.

Observatory	*Location*	*Longitude (°)*	*Latitude (°)*	*Altitude (m)*
BSM-NH2	New Hampshire	71.6 W	43.7 N	200
BSM-NM2	New Mexico	105.5 W	32.9 N	2182
BSM-Hamren	Hawaii	118.3 W	35.6 N	915

Table 2. Equipment.

Equipment	*Description*
Telescope	Takahashi E-180 f/2.8 Astrograph
Mount	Software Bisque Paramount ME
Camera	ZWO ASI183MM-Pro CMOS
Electronic Filter Wheel	ZWO EFW for 8 filters
Filters	Johnson B, Johnson V, Cousins R, Cousins I
Electronic Focuser	ZWO EAF

Table 3. Exposure times per filter.

Filter	*BSM-NH2 (seconds)*	*BSM-NM2 (seconds)*	*BSM-Hamren (seconds)*
Johnson B	60–120	60–120	60
Johnson V	30–90	30–60	30
Cousins R	20–90	20–40	20
Cousins I	20–90	20–40	20

Table 4. Summary of observations.

Filter	*Max. m*	*Min. m*	*Δm*	*Uncertainty*	*Median -U*	*Std. Err. Avg.*
B	12.724	14.051	1.327	0.020	0.017	0.010
V	11.562	12.619	1.057	0.016	0.013	0.007
R	10.77	11.664	0.894	0.018	0.014	0.008
I	10.034	10.904	0.87	0.025	0.019	0.006

4. Reduction methodology

Differential ensemble photometry (DEP) was performed for each of the B, V, R, I filters. The comparison and check stars used for the DEP can be found in Table 5, which includes the uncertainty observed for the check star for each of the filters used. Photometric analysis was done with the online program VPhot (AAVSO 2012). Obvious outliers were removed from the data set. Each reported observation is the result of a stack of three sub-exposures for each filter in order to improve the SNR. The 3009 observations reported to AID is the net amount obtained after removing the rejected observations and dividing the remaining observations by three, which correspond to the stacked sub-exposures of each set of observations per filter.

The spectra were reduced with ISIS software (Buil 2021) using a standard pipeline (bias, dark, flat correction, cosmic ray removal, geometric correction, sky background subtraction, spectrum binning optimized to maximize SNR, wavelength calibration using a Ne Ar lamp). The spectra were then calibrated in relative flux as measured at the top of Earth's atmosphere, using as a reference contemporaneous measurements of the low-extinction hot main sequence star HD 223274 (A0V) at matching air mass, compared with a standard reference spectrum for an A0V star from the Pickles Stellar Spectral Flux Library (Pickles 1998). Figure 1 shows typical as-measured spectra at high, low, and intermediate brightness. (The phases were calculated using the parameters in this paper.)

5. Analysis

Light curve analysis was done with the software VStar (Benn 2013) version 2.22.1 using the calibrated and stacked data obtained with the Johnson V filter. The algorithm employed to figure out the period of AS Cas was the Date Compensated Discrete Fourier Transform (DCDFT) (Foster 1995, 2010). We have chosen this method since it is better suited to the analysis of data which is not evenly time distributed (Figure 2). Additionally, the CLEANest method was also applied (Foster 2010) since it allows to detect and describe with higher degree of certainty multi-periodic signals. This is especially important when two or more periods are suspected to be present in a star's pulsation.

Figure 3 shows the DCDFT periodogram of the analyzed data, in which P0 and P1 can be identified. The periodogram's tallest peak corresponds to P0 at a period of 3.02465 days. P0 features two harmonics, one at P0 and a second at period 1.51233 days. Period aliases of P0 can be found at periods 3.05003 and 2.99972 days, and for the second harmonic at periods 1.49986, 1.48783, and 1.49399 days. These last three constitute the second-tallest peak of this periodogram. P1 lies at the peak of period 2.15553 days, showing here two period aliases at 2.16848 and 2.14290 days. The graph in Figure 4 shows the phased light curve of P0. The solid red line corresponds to the model obtained after applying the aforementioned algorithms. P1's periodogram, obtained from the residuals after subtracting the model from the original data, can be found in Figure 5.

Table 5. Comparison and Check stars.

Star	*Type*	*R.A. (J2000.0)* *h m s*	*Dec. (J2000.0)* *° ′ ″*	*B*	*V*	*R*	*I*
121	Comparison	00 27 06	+64 14 13	12.945	12.105	11.547	11.027
123	Check	00 25 37	+64 08 02	13.015 ± 0.008	12.319 ± 0.008	11.426 ± 0.008	11.388 ± 0.013

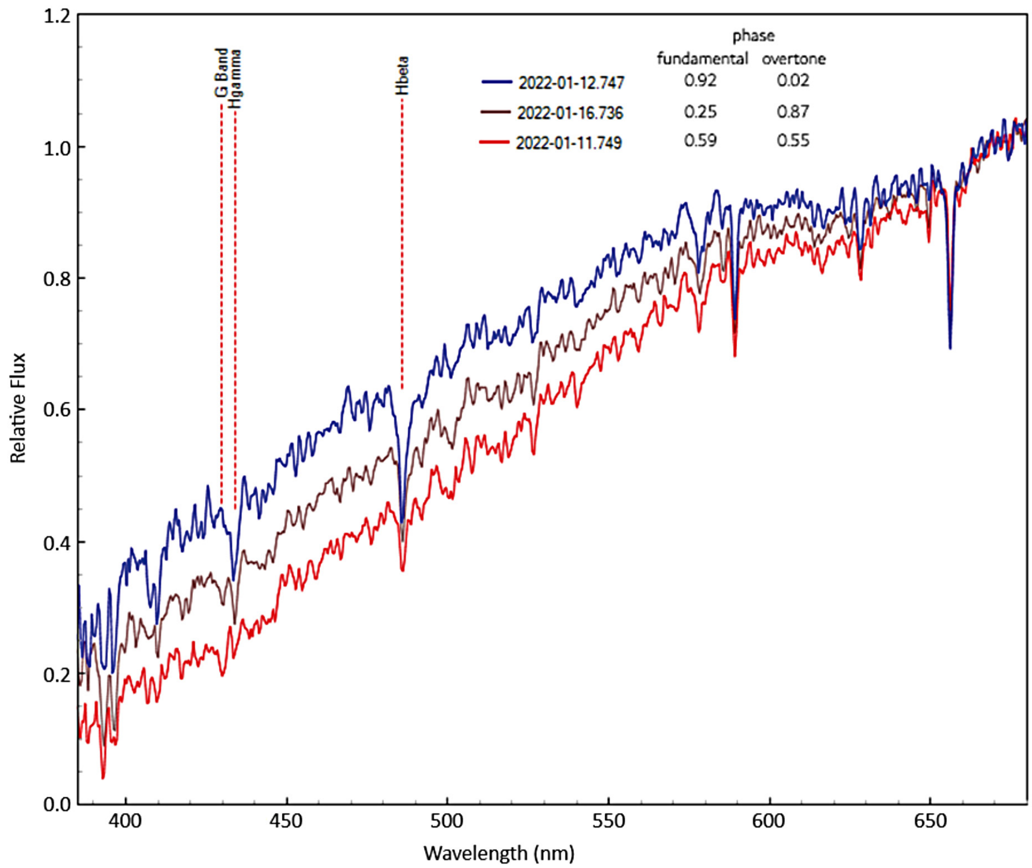

Figure 1. As-measured spectra at high (blue), low (red), and intermediate (brown) brightness (normalized at λ6800 Å).

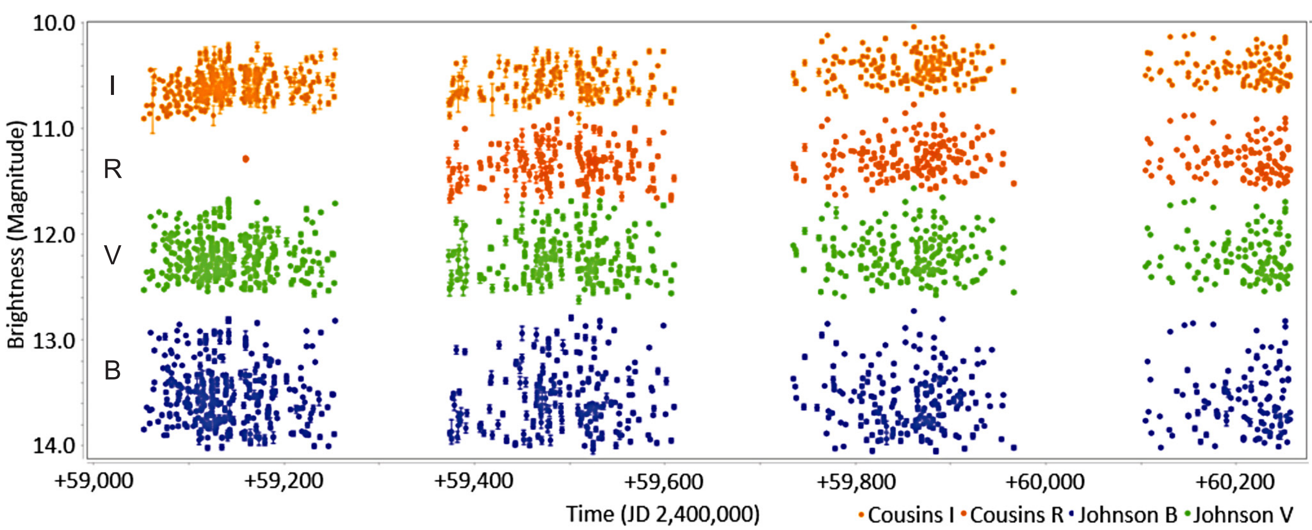

Figure 2. Light curves in Johnsons B (blue) and V (green) filters, and Cousins R (red) and I (orange) filters.

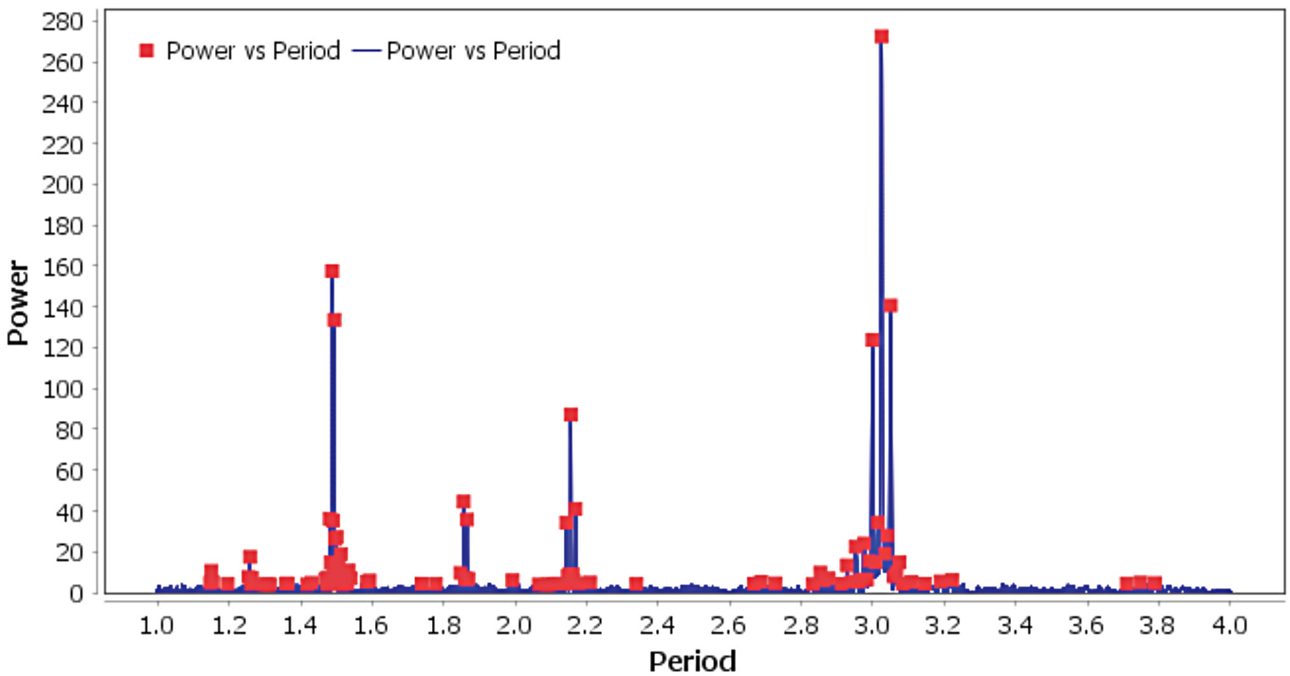

Figure 3. AS Cas periodogram of original data: Johnson V filter.

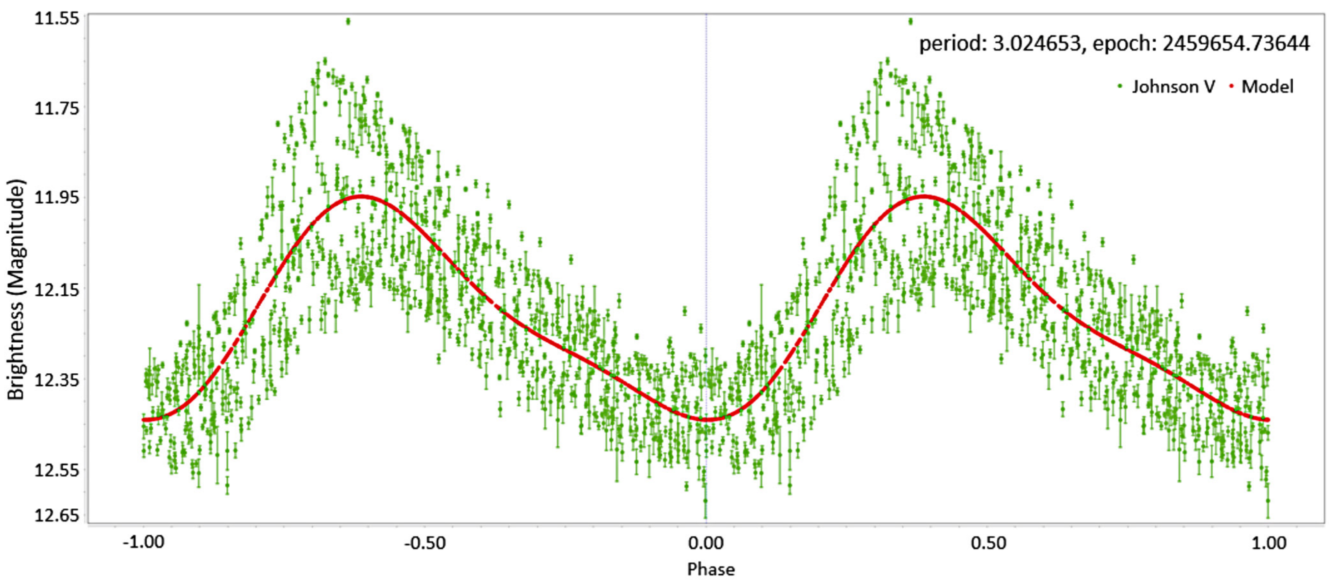

Figure 4. Phase plot of AS Cas for P0 in Johnson V filter. Green dots represent the stacked and calibrated observations, while the red curve shows the fit of the applied model considering P0 DCDFT periodogram and the CLEANest method.

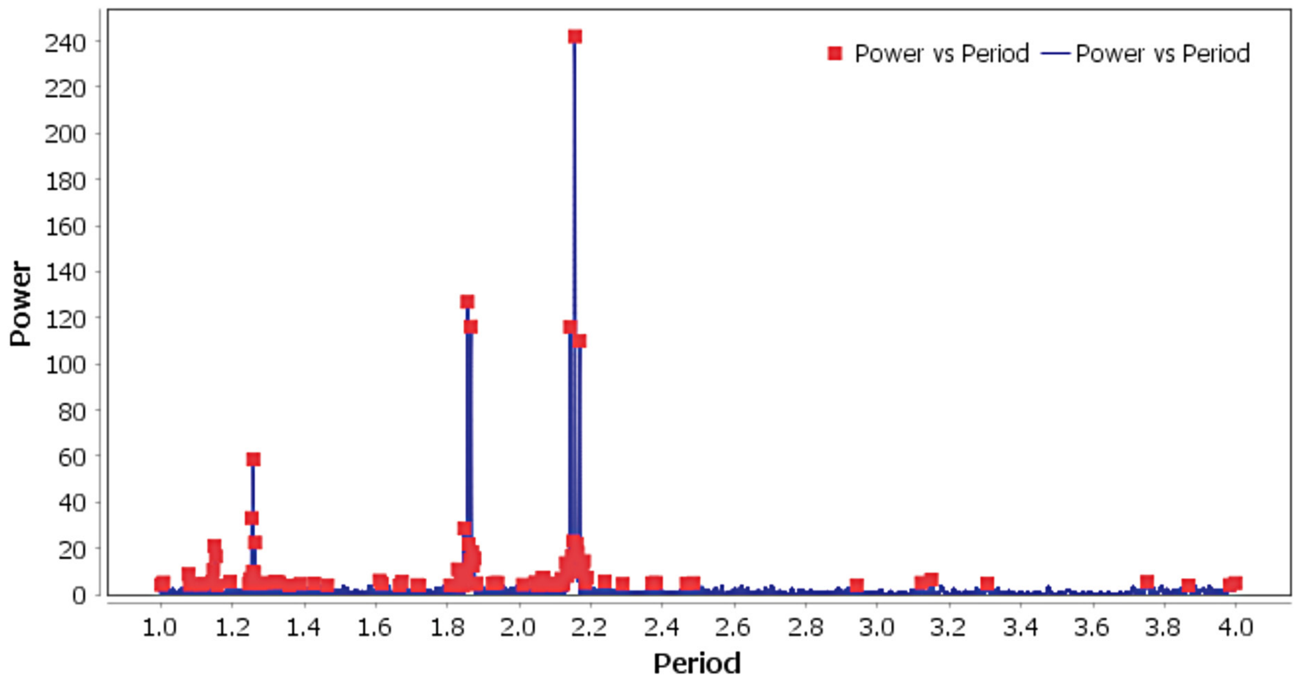

Figure 5. Periodogram of the residuals of AS Cas original data (Johnson V filter). P1 stands out clearly.

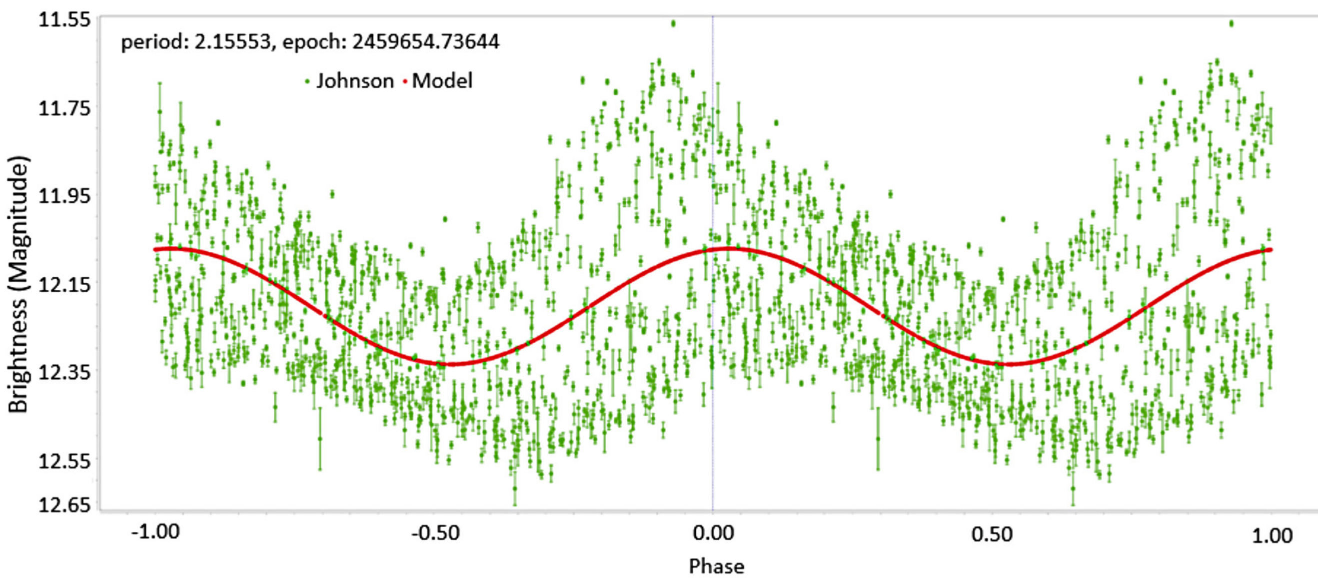

Figure 6. Phase plot P1 Johnson V filter for AS Cas.

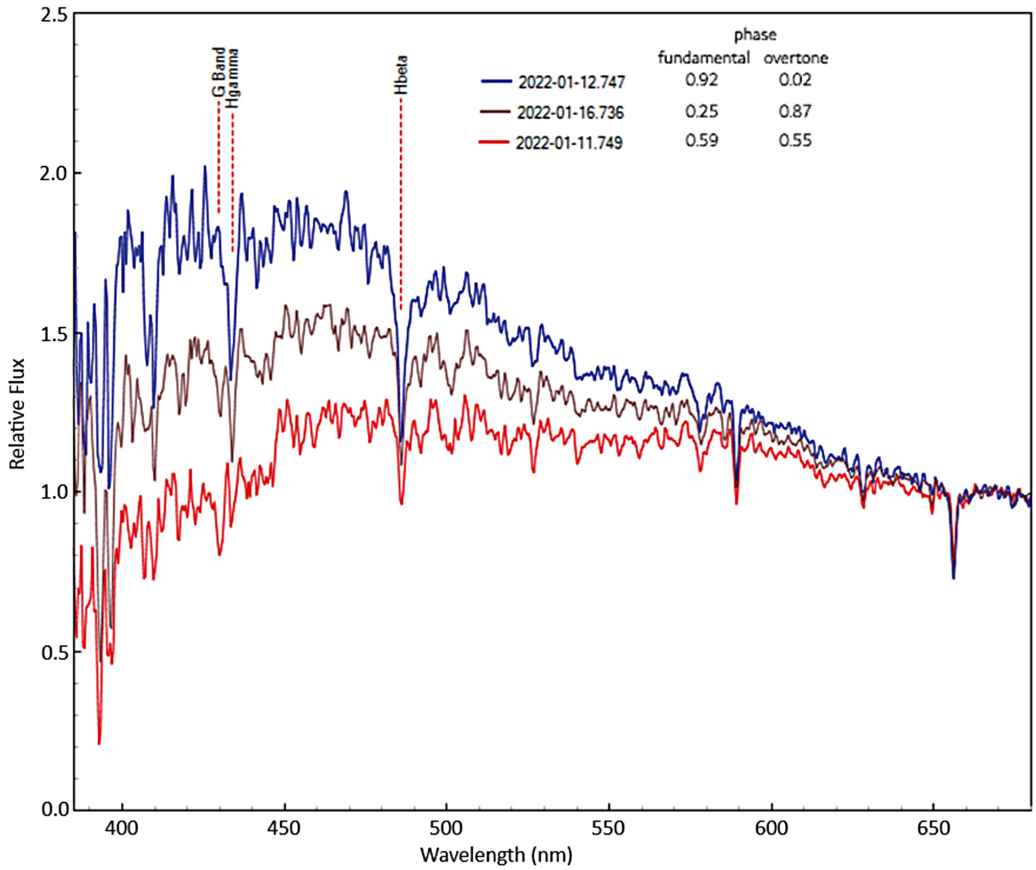

Figure 7. Spectra in Figure 1 de-reddened by E(B–V) = 0.9.

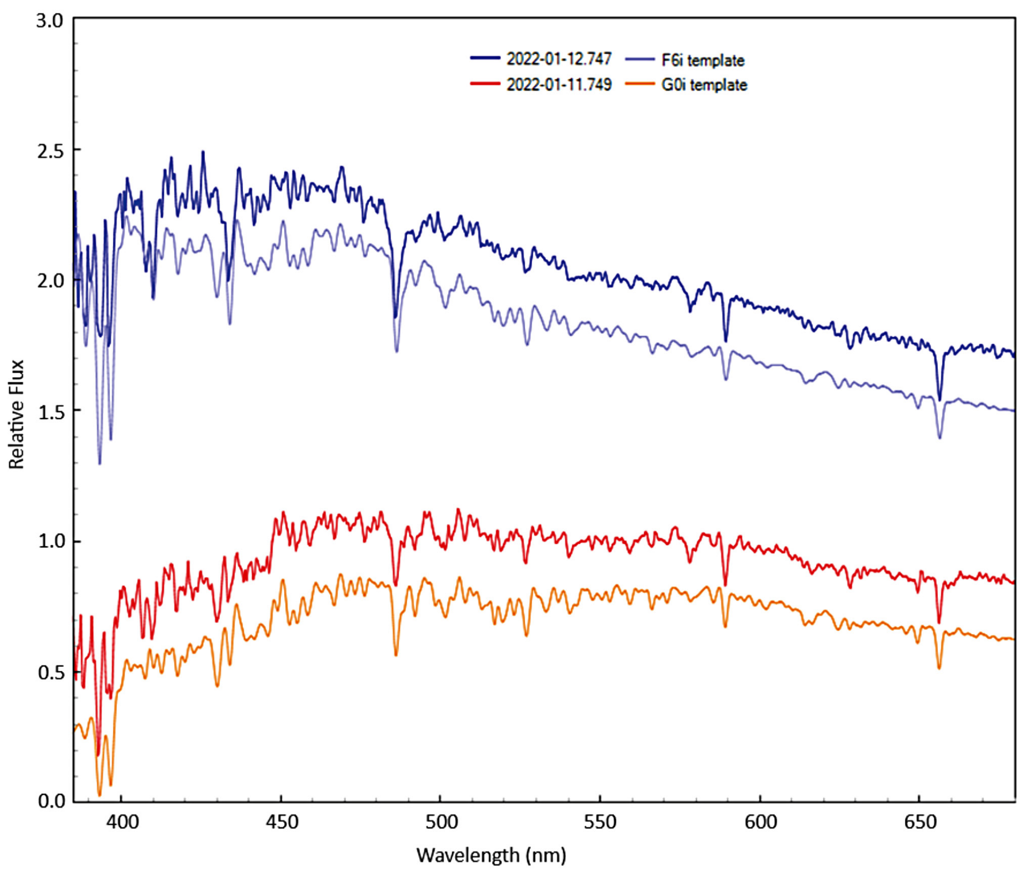

Figure 8. De-reddened spectra at high and low brightness compared with the corresponding template from the Pickles library (spectra displaced in y for clarity).

The tallest peak corresponds to P1 at a period of 2.15547 days. Aliases of P1 are the side lobes at periods 2.14277 and 2.16839 days. Two harmonics have been found for this period, the first at 2.15547 days and the second at 1.07774 days, thus confirming the double mode nature of AS Cas. Figure 6 is the phased light curve of P1, and again, the solid red line represents its corresponding model. The epoch used for this analysis was JD 2459654.736.

For the spectral classification, the as-measured spectra match that of a yellow supergiant, strongly reddened by interstellar dust. (The total galactic interstellar extinction in the direction of AS Cas from the NASA/IPAC Extragalactic Database (NASA/IPAC 2024) defines an upper limit for E (B–V) of 1.6.) A spectral classification can be estimated by comparing the features in the spectrum with template spectra of supergiant stars at similar resolution from the Pickles Stellar Spectral Flux Library (Pickles 1998). The strength of the Balmer lines (Allen 2020) and the Fraunhofer G band are particularly useful indicators here. This gives a spectral classification ranging from G0I to F6I from minimum to maximum brightness which corresponds to effective temperatures (T_{eff}) ranging from 5590 to 6420 K (Gray and Corbally 2009, p. 568).

Given these classifications, the interstellar extinction (IS) can be estimated by de-reddening the as-measured spectra, fitting the continuum shape to match the corresponding templates. This then gives an estimated reddening of E (B–V) = 0.9 ± 0.05. Figure 7 shows the spectra in Figure 1 de-reddened by this amount. Figure 8 shows the spectra at high and low brightness together with the corresponding template spectra.

6. Results

The 865 Johnson V observations of AS Cas obtained in this study yielded maximum and minimum magnitudes of 11.562 V and 12.619 V with an uncertainty ± 0.016 V. The estimated P0 of AS Cas was 3.02465 ± 0.00034 days, and the P1 2.15547 ± 0.00033 days. These results are within the range of those previously found. Due to the number of observations acquired, the reduction method, and analysis employed, we conclude that our results reflect with a higher degree of precision P0 and P1 of AS Cas.

We also find that AS Cas is a star with a spectral range of F6I to G0I. This range confirms its beat Cepheid nature. We estimated a T_{eff} with a range from 5590 to 6240 K.

7. Discussion

We have not observed significant differences of P0 and P1 of AS Cas when compared to previous observations. Although we conclude that the nature and evolutionary stage of AS Cas have remained constant from the first systematic observations made to those of this research, we encourage other colleagues to follow up with further observations in case this star shows period or amplitude changes in the future.

The spectroscopic results are compatible with published values for T_{eff} = 6385 K ± 118 at maximum based on modelling of a high-resolution spectrum taken near maximum light (Luck 2018) and E (B–V) = 0.83 ± 0.08 (Groenewegen 2020).

8. Acknowledgements

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[1]http://www.lulu.com/shop/grant-foster/analyzing-light-curves-a-practical-guide/paperback/product-11037112.html