Photometric Analysis of HD 213616: a Multi-modal δ Scuti Variable Star

Vance Petriew
P.O. Box 9 Station main, White City, SK S4L 5B1, Canada; vance.petriew@sasktel.net

Horace A. Smith
Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA; smith@pa.msu.edu

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Abstract We analyzed new photometry of HD 213616, showing that, instead of being a W Ursae Majoris eclipsing binary, it is a multimode δ Scuti star of relatively high amplitude. Three independent pulsation modes were identified in a Fourier analysis of the photometry, in addition to several combination pulsation frequencies.

1. Introduction

In a quest for brighter eclipsing binary targets from the online AAVSO's Variable Star Index (VSX; Watson *et al.* 2014), the star HD 213616 (R.A. 22^h 32^m 07.8^s, Dec. +39° 47' 56.2" (2000.0)) was randomly selected for an all-night time series run. After one night of photometry, it was clear that the current VSX classification of HD 213616 as an EW (W Ursae Majoris) eclipsing variable was incorrect. As we will show in the remainder of this paper, HD 213616 instead appears to be a δ Scuti (DSCT) type variable.

2. Data

To better capture this variable star's behavior, multiple nights of data were collected during the 2015 and 2016 observing seasons. Data were collected late into season one using an SBIG ST7-XME CCD camera coupled to a Celestron CPC-800 GPS telescope. The CCD camera is equipped with a single Johnson V filter which was employed for all observations. The effective focal length is 906 mm. The 9-μm pixels of the SBIG camera provide an image scale of 2.05 arcseconds per pixel.

In 2016, the same telescope and CCD camera were used to collect more data, bringing the total number of aperture photometry data points used in this analysis to 10,524. The date range of the observations is HJD 2457291 to HJD 2457635.

The reference star used for photometry was TYC 3205-1759-1 (R.A. 22^h 30^m 28.4^s, Dec. +39° 46' 09.5" (2000.0)). When the photometry was entered into the AAVSO International Database (AID; Kafka 2016), a V magnitude of 9.08 was adopted for the reference star. As of Data Release 9, the V magnitude for TYC 3205-1759-1 from the APASS catalogue (Henden and Munari 2014) is 9.087 ± 0.057. Note that the comparison star is quite red, with an APASS B–V value around 1.4. The check star used was TYC 3205-1808-1 (R.A. 22^h 30^m 11.1^s, Dec. +39° 36' 28.6" (2000.0)). Integration times for each frame were 30 seconds, which produced SNR values above 300 for both the variable and the reference star. The software MAXIM DL version 5.01 (Diffraction Limited 2012) was used to perform differential aperture photometry of the dataset. Typical aperture sizes are 7 to 9 pixels in size with a gap of 8 and an annulus of 10 pixels. All frames were bias, dark, and flat field corrected. Data were exported from MAXIM DL and into MICROSOFT EXCEL to calculate error bars for the data based on the formula

$$\text{Error} = [(\sigma(k-c))^2 + (1/\text{SNR})^2]^{0.5} \quad (1)$$

following the recommendation of Koppleman (2005), where σ(k−c) is the standard deviation for the comparison star minus check star magnitudes and SNR is the signal-to-noise ratio of the measurement.

The typical uncertainty of differential V magnitudes for a single observing session is 0.008 magnitude, with the largest uncertainty being around 0.014 magnitude. There may be slight offsets from night to night but these typically run in the range of 0.01 magnitude and were not accounted for in the dataset. The photometric data points were not extinction corrected. The distribution of the observations over time is shown in Figure 1. Figure 2 illustrates the variation of HD 213616 during four nights of observation. The photometry of HD 213616 has been entered into the AAVSO International Database.

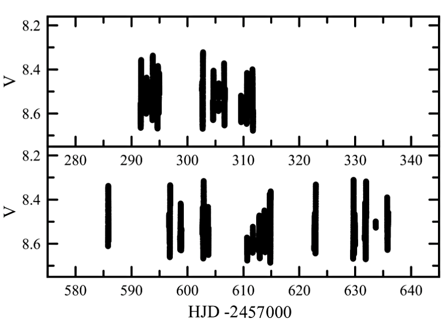

Figure 1. Light curve for HD 213616 from 2015 (top panel) and 2016 (bottom panel).

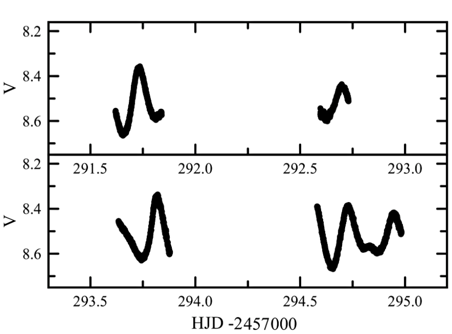

Figure 2. Light curve of HD 213616 from the first four nights of observation.

In the remainder of this paper we present a Fourier analysis of the new photometry that supports the DSCT classification for this star. We also discuss the earlier observations of HD 213616 that suggested that the star was instead an EW variable.

3. Analysis

We Fourier-analyzed the photometric observations using the PERIOD04 routine (Lenz and Breger 2005). Scans were performed for the frequency range 0–50 cycles / day for the 2015 and 2016 datasets individually (frequency resolution $\Delta\nu = 10^{-4}$ d^{-1}) and for the entire 2015–2016 dataset (frequency resolution $\Delta\nu = 10^{-5}$ d^{-1}). Because the observations were obtained from a single site, we also inspected the spectral windows of the observations to gain insight into possible aliasing problems. We adopted an iterative approach to find significant frequencies, using PERIOD04 to identify the strongest frequency, cleaning the data to remove that frequency, rescanning, identifying the next strongest frequency, and repeating until we detected all the frequencies with amplitudes greater than about 4 times the typical noise in the spectrum. Results are shown in Table 1 for the frequencies detected and their amplitudes and phases. The numbers in parentheses are an estimate of the uncertainty in each quantity. PERIOD04 offers two ways of estimating uncertainties of derived parameters, a least squares error calculation and a monte carlo simulation. If one of these approaches gave a significantly larger uncertainty than the other, we adopted the larger uncertainty in Table 1. We also examined the effects that small changes in the PERIOD04 scanning parameters had upon the derived frequencies, amplitudes, and phases. In a few instances this suggested that the actual uncertainties should be slightly larger than the formal uncertainties returned by the PERIOD04 routine. If so, we chose the larger, more conservative, estimate of error.

In all of the analyses, three frequencies, f1, f2, and f3, were dominant. The frequency near 10.67 c / d could be interpreted as 2f1, a harmonic of the f1 frequency. Four other frequencies could be interpreted as combinations of the first three frequencies. In addition, for the entire 2015–2016 dataset, some power (amplitude 0.007 magnitude) was found at a frequency of 0.03905 d^{-1}, corresponding to a period of 25.61 days. We are not certain of the reality of this frequency, since it is not seen in the separate analyses of the 2015 and 2016 observations, and because the corresponding period is within a factor of 1 or 2 of the total time spans covered by the 2015 and 2016 observations, taking each year separately.

Including just the f1, f2, f3, and 2f1 components in an analysis reduces the root mean square scatter in the 2015–2016 magnitudes from 0.083 mag. to a residual scatter of 0.017 mag. Including all of the components in the analysis further reduces the residuals to 0.011 magnitude, close to the expected observational uncertainty. For the 2015 observations alone, the corresponding numbers are 0.079 mag., 0.014 mag., and 0.010 mag. For the 2016 observations only, the corresponding numbers are 0.085 mag., 0.017 mag., and 0.011 mag.

To illustrate the appearance of the Fourier spectrum, in Figure 3 we show a portion of the spectrum for the 2015–2016 observations. In Figure 4, we show the spectrum after the data have been prewhitened to remove the significant frequencies.

Table 1. Fourier analysis.

Frequency (c/d)	*V (amplitude)*	*Phase*	*Identification*
2015–2016			
5.33800(1)	0.0946(1)	0.374(1)	f1
6.68087(1)	0.0289(1)	0.200(1)	f2
8.02710(1)	0.0429(1)	0.402(1)	f3
10.67595(2)	0.0111(2)	0.922(2)	2f1
1.34308(2)	0.0095(2)	0.442(2)	f2-f1
2.68890(2)	0.0093(2)	0.119(3)	f3-f1
12.01582(3)	0.0061(2)	0.272(3)	f1+f2
13.36507(3)	0.0077(2)	0.906(3)	f1+f3
2015			
5.3381(1)	0.0948(3)	0.641(1)	f1
6.6798(2)	0.0282(2)	0.509(1)	f2
8.0275(1)	0.0415(2)	0.189(1)	f3
10.6711(4)	0.0118(2)	0.837(3)	2f1
1.3463(10)	0.0060(2)	0.950(6)	f2-f1
2.6890(6)	0.0093(2)	0.366(4)	f3-f1
12.0179(14)	0.0039(2)	0.391(8)	f1+f2
13.3670(6)	0.0070(3)	0.307(5)	f1+f3
2016			
5.3380(1)	0.0942(1)	0.374(1)	f1
6.6809(1)	0.0294(1)	0.472(1)	f2
8.0268(1)	0.0437(1)	0.688(1)	f3
10.6770(2)	0.0116(1)	0.422(3)	2f1
1.3446(2)	0.0125(1)	0.890(3)	f2-f1
2.6885(2)	0.0091(1)	0.157(4)	f3-f1
12.0168(3)	0.0069(1)	0.116(5)	f1+f2
13.3657(3)	0.0078(1)	0.606(3)	f1+f3

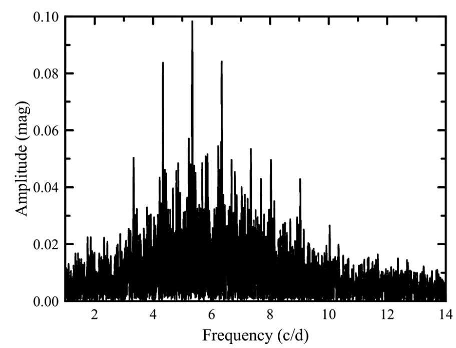

Figure 3. A portion of the Fourier spectrum for the 2015–2016 observations before any frequency has been cleaned.

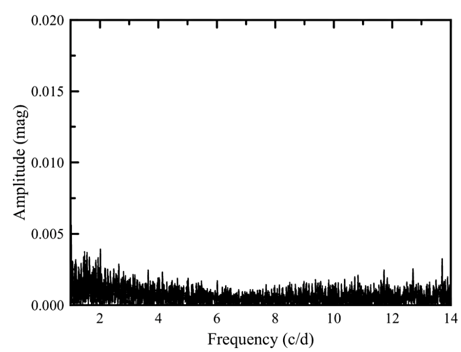

Figure 4. The residual Fourier spectrum for the 2015-2016 observations after the frequencies of Table 1 have been cleaned. Note that the amplitude scale is different from that of Figure 3.

Although the frequencies and amplitudes for the components in Table 1 are similar for the 2015–2016, 2015, and 2016 data, they are not identical, and, in fact, they sometimes differ by more than the adopted error bars. However, given the problems inherent when observations are from a single location, we hesitate to conclude that the year-to-year differences are real. New observations, particularly from multiple longitudes, would help in evaluating the stability of the frequency components observed in HD 213616.

4. Discussion

As noted above, the Variable Star Index (VSX) lists HD 213616 as a probable W Ursae Majoris eclipsing variable. The VSX lists a frequency of 2.6690 c/d, which is half the frequency of the f1 component found in this analysis. That result is based upon data from the WASP survey (Butters *et al.* 2010) that was obtained between HJD 2453154 and 2454669. There are 4,721 photometric points for HD 213616 listed in the SuperWASP public archive (http://www.superwasp.org/), although a few of these show large deviations from the others and are likely erroneous. HD 213616 is also identified as variable in the Chandra Variable Guide Star Catalog (Nichols *et al.* 2010), but with less than a day of observation those data are not sufficient for a period determination.

A period search analysis of the SuperWASP data using the PERIODOGRAM software available on the NASA Exoplanet Archive (2016) website (http://exoplanetarchive.ipac.caltech.edu/) with a resolution of 0.0001 does, however, reveal the three dominant frequencies of Table 1, as well as aliases that differ by one or more cycles per day from those frequencies. In the analysis of the SuperWASP data the frequencies recovered that appear to correspond to f1, f2, and f3 are: 5.3380 c/d, 6.6811 c/d, and 8.0272 c/d. Although the SuperWASP data cover a longer time interval than the data in Table 1, there are fewer observations per day, raising the susceptibility to aliases with a different number of cycles per day.

The existence of three independent frequencies plus combination terms in the light curve of HD 213616 indicates that it is not a W UMa binary. Instead, it strongly indicates that HD 213616 is a high amplitude δ Scuti pulsator (HADS). HADS variables generally have one or more frequencies greater than 5 c/d and amplitudes greater than 0.3 magnitude. The magnitude range in Figure 1 and our derived periods would thus place HD 213616 within the HADS class. The F5 spectral type of HD 213616 in the SIMBAD database would be consistent with a δ Scuti identification, although it would be near the cool limit for such stars (Catelan and Smith 2015). Many HADS stars have one or two main periods which are often interpreted as being the radial fundamental and first overtone modes (Templeton 2000; Balona 2016). In double-mode HADS stars, the ratio of the periods is usually in the range 0.76–0.78 (Furgoni 2016). In the case of HD 213616, however, we have three apparently independent frequencies, suggesting the existence of three modes. Nor do the period ratios of any combination of f1, f2, and f3 fall within the 0.76 to 0.78 range.

HADS stars with three modes are not unknown. For example, KIC 6382916 was found to have modes with frequencies of 4.9107, 6.4314, and 8.0350 c/d, reminiscent of the three possible modes in HD 213616 (Ulusoy *et al.* 2013). However, for KIC 6382916, the amplitudes of the first two modes were comparable, while the third had a much smaller amplitude. The f1 frequency for HD 213616 has the largest amplitude but the amplitudes of f2 and f3 are not very different from one another and only 2 or 3 times smaller than the amplitude of f1. If the two smallest frequencies for HD 213616 are interpreted as being the fundamental and first overtone radial modes, the period ratio of 0.799 would be within the range of period ratios observed for the two largest amplitude modes within δ Scuti stars observed by the Kepler mission that have five or more combination frequencies (Balona 2016). However, it is by no means certain that we can interpret f1 and f2 as fundamental and first overtone radial modes. HD 213616 might thus repay further study.

5. Acknowledgements

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