Recently Refined Periods for the High Amplitude δ Scuti Stars V1338 Centauri, V1430 Scorpii, and V1307 Scorpii

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Abstract Digital Single Lens Reflex (DSLR) photometry of the high amplitude δ Scuti stars V1338 Centauri, V1430 Scorpii, and V1307 Scorpii was taken during the southern autumn and winter of 2015. Fourier analysis revealed pulsation frequencies corresponding to periods very close to those previously reported with significant contributions from harmonics. Only in the case of V1430 Scorpii was another independent frequency detected. The oscillation periods were refined by calculating linear ephemerides based on previously published epochs for each star, and the epochs determined by the author. These periods are: V1338 Centauri, 0.13093808 d; V1430 Scorpii, 0.08377709 d; and V1307 Scorpii, 0.11703066 d.

1. Introduction

The observation of δ Scuti stars by amateur astronomers can yield data not available from professional photometric surveys. Because of their short periods (a few hours), time series photometry by CCD or DSLR photometry can capture a light curve through an entire cycle at least, and sometimes a number of cycles, from a single night's observations. If observations are made for several nights over a period of weeks during one observing season for one star, sufficient data will be obtained for Fourier analysis and for the calculation of the epochs of several times of maximum light (TOM). From the latter, ephemerides can be calculated, and, particularly if historical TOMs are also available, periods can be determined with substantial accuracy.

V1338 Centauri (HD 123460) was first reported to be variable by Strohmeier *et al*. (1968) from photometry of photographic plates, although at that time the type of variability was not stated, nor was an ephemeris reported. The only other reference found is its entry in the *General Catalogue of Variable Stars* (GCVS; Samus *et al*. 2007–2013), where it is classified as a δ Scuti star, with a period of 0.1309382 day, at epoch JD 2453764.8191.

The star now designated as V1430 Sco (GSC 07369 00459) was first identified to be variable by Otero (2007), using the database of the Northern Sky Variability Survey (Wozniak *et al.* 2004) and the ASAS-3 database (Pojmański 2002). It was found to be a high amplitude δ Scuti star (HADS) with the epoch reported by Otero being JD 2453096.878 and the period 0.0837770 day.

The star now designated V1307 Sco (GSC 07892 01411) was recognized as a HADS by Wils *et al*. (2004), using the ASAS-3 database. Its variability was first identified by Strohmeier (1967) from photographic plates, but the type of variability was not stated, and the period was not known at that time. Wils *et al.* reported the epoch HJD 2452057.700 and the period 0.117031 day.

In view of the significant lapse of time since the last reported epochs of these stars (9, 11, and 14 years, respectively), DSLR photometry was taken between April and August 2015, with the aims of confirming and if possible refining their pulsation frequencies.

2. Data and analysis

2.1. Observations

Time series DSLR photometry of V1338 Cen, V1430 Sco, and V1307 Sco was taken between 24 April and 8 August 2015. RAW images were taken with a Canon EOS 500D camera through a Celestron C9.25 Schmidt-Cassegrain telescope on a Losmandy GM-8 German equatorial mount. Exposures of 120 seconds at ISO 800 were taken at intervals of 140 seconds. Dark frames were captured during meridian flips, and flat frames were obtained after dawn with the telescope aimed at the zenith and a white acrylic sheet used as a diffuser placed over the front of the telescope.

Comparison and check stars were chosen with V magnitudes and B–V color indices as close as possible to those of the variables. They are listed in Table 1. The V magnitudes and B–V color indices were obtained from the AAVSO Photometric All-Sky Survey (APASS; Henden *et al.* 2014).

The numbers of usable images for photometry obtained for the three stars were as follows: V1338 Cen, 979 images; V1430 Sco, 898 images; and V1307 Sco, 561 images. V1338 Cen and V1430 Sco were both observed during six nights, while V1307 Sco was observed during four nights. For both V1338 Cen and V1430 Sco, ten peaks of the light curves were obtained for the calculations of linear ephemerides, and four peaks were obtained for V1307 Sco.

Instrumental magnitudes in B and V were calculated after performing aperture photomery on the images from the blue and green channels of the DSLR sensor using the sofware AIP4WIN (Berry and Burnell 2011). Transformed magnitudes in B and V were calculated using transformation coefficients determined from standard stars in the E regions (Menzies *et al.* 1989).

Table 1. The δ Scuti stars and their respective comparison and check stars reported in the present paper.

Variable Star	*Comparison Star*	*Comp. V*	*Comp. B–V*	*Check Star*	*Check V*	*Check B–V*
V1338 Cen	HD 123547	10.417	0.432	HD 123503	10.288	0.554
V1430 Sco	HD 154588	9.905	0.488	HD 319439	9.974	0.463
V1307 Sco	HD 324056	10.129	0.479	HD 324055	10.590	0.483

The time in JD of each magnitude calculation was taken to be the mid point of each DSLR exposure. The heliocentric correction for each night's data was calculated for the mid point in time of the observing run for the night, and the correction applied to all data points for that night.

The time series instrumental magnitude differences between the comparison and check stars for the green channel have standard deviations as follows. For a single night, the standard deviations ranged from 0.006 to 0.009 mag. for V1338 Cen, from 0.005 to 0.008 mag. for V1430 Sco, and from 0.007 to 0.010 mag. for V1307 Sco. The standard deviations of these instrumental magnitude differences for the data from all nights analysed together are 0.008 mag. for V1338 Cen, 0.007 mag. for V1430 Sco, and 0.009 mag. for V1307 Sco.

2.2. Time series analysis

Fourier analysis of the light curves was undertaken with the software PERIOD04 (Lenz and Breger 2004), for which the following settings were used. Frequencies were sought between zero and 50 d^{-1}, using a high step rate (1/20T, where T is the length of the data in days). After each frequency was calculated, the Improve All function was activated, which applies a non-linear least-squares fitting algorithm. After several frequencies were identified, signal/noise ratios for the second and subsequent frequencies were calculated using a box size of $2d^{-1}$. Thus, the range of frequencies across which signal/noise ratios were calculated was (f_n – box size / 2) to (f_n + box size / 2) = (f_n – 1) to (f_n + 1), f_n being the frequency of interest. Frequencies with signal/noise ratios greater than 10 were regarded as being significant. Least squares uncertainties were calculated for each frequency (and for the corresponding semiamplitudes and phases), with the uncertainties for frequency and phase uncorrelated.

The time of each peak in the light curve (TOM) was taken as the time in HJD of the peak value of a 10th order polynomial expression fitted to each peak and its ascending and descending limbs, using the software PERANSO (Vanmunster 2013). A 10th order expression (rather than a lower order) was selected, because the resulting calculated light curve fitted best by eye the sharp peaks of the actual light curves of V1338 Cen and V1307 Sco. With lower order polynomial expressions, the peaks of the fitted curves were shifted in comparison with the actual data. Linear ephemerides were calculated as the least squares linear fit for TOM versus epoch, from the literature and from the new data reported herein.

3. Results

Table 2 lists the frequencies (d^{-1}) together with their errors (least squares uncertainties) and signal/noise ratios (SNRs) for the three target stars. Apart from the dominant frequency (f1) for each of the stars, most of the other frequencies (and in the case of V1307 Sco, all of the other frequencies) are Fourier harmonics, integer multiples of f1. However, in the case of V1430 Sco, f4 at 18.4335 d^{-1} is not a Fourier harmonic. It has a semiamplitude of 0.008 mag. in V, substantially less than the semiamplitude of f1 at 0.15 mag. In the case of V1338 Cen, f5 at 1.020 d^{-1} is not a Fourier harmonic, and is considered to be spurious, for reasons noted in the Discussion. It has a semiamplitude of 0.021 mag., again significantly lower than the semiamplitude of 0.21 mag. for f1.

For the purposes of this paper, frequencies discovered by Fourier analysis were not reported if the signal/noise ratio fell below 10, with the exception of the special case of the frequency of 1.020 d^{-1} for V1338 Cen, mentioned above, with a signal/noise ratio of 9.4. Further frequencies discovered but not reported here had signal/noise ratios that ranged from 2.4 to 6.1. It is possible that frequencies with signal/noise ratios between 4 and 10 could be real. However, a conservative approach has been taken by the author in restricting included frequencies to those with a higher probability of validity, to avoid reporting what may be false frequencies.

Figure 1 illustrates phased light curves for V1338 Cen, V1430 Sco, and V1307 Sco which were created in PERIOD04 using the dominant (f1) frequencies listed for each of these stars in Table 2. For V1338 Cen and V1430 Sco there are subtle shoulders in the descending limbs of the phase plots.

The fits of the data using the reported frequencies leave residual root mean squares for the V magnitude of the variable stars of 0.015 mag. for V1338 Cen, 0.008 mag. for V1430 Sco, and 0.024 mag. for V1307 Sco.

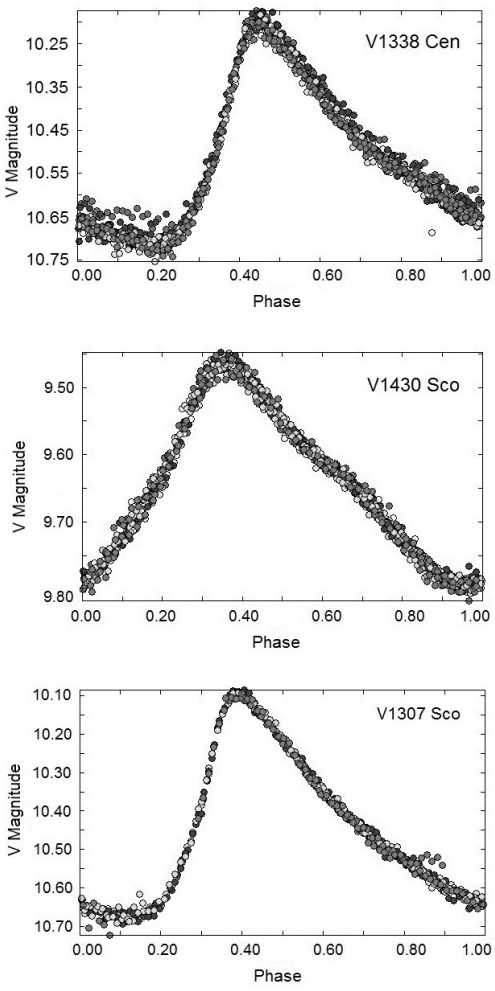

Figure 1. Phased light curves for V1338 Cen, V1430 Sco, and V1307 Sco. A subtle shoulder can be seen in the descending limbs of the curves for V1338 Cen and V1430 Sco.

Table 2. Frequencies of pulsation (d^{-1}), errors of the frequencies, and their signal/noise ratios (SNR) from PERIOD04 Fourier analysis. The error values are least squares uncertainties, with the uncertainties for frequency and phase uncorrelated.

	V1338 Cen			*V1430 Sco*			*V1307 Sco*		
	Frequency	*Error*	*SNR*	*Frequency*	*Error*	*SNR*	*Frequency*	*Error*	*SNR*
f1	7.6372	0.0001	—	11.93629	0.00004	—	8.54475	0.00007	—
f2	15.2739	0.0002	93.8	23.8727	0.0002	60.3	17.0890	0.0002	83.9
f3	22.9112	0.0006	55.0	35.8105	0.0006	26.7	25.6337	0.0004	28.8
f4	30.546	0.001	23.4	18.4335	0.0008	11.7	34.1781	0.0008	16.3
f5	1.020	0.001	9.4	47.7455	0.001	16.4	42.7180	0.002	15.4
f6	38.187	0.002	16.5	—	—	—	—	—	—

Table 3. Times of maximum light (TOM) in heliocentric Julian days (HJD) representing the peaks of the light curves of the target variable stars and the errors of the estimates. The TOMs are the calculated peak values of 10th order polynomial expressions fitted to each light curve segment comprising the ascending limb, peak and descending limb of the curve. The values listed are those output by PERANSO, and are not truncated to the last significant digit.

V1338 Cen		*V1430 Sco*		*V1307 Sco*	
TOM (HJD)	*Error*	*TOM (HJD)*	*Error*	*TOM (HJD)*	*Error*
2457136.997304	0.00080	2457179.002685	0.00103	2457222.028308	0.00053
2457137.128584	0.00069	2457179.170143	0.00090	2457240.052092	0.00067
2457137.258664	0.00084	2457192.993306	0.00076	2457242.041585	0.00072
2457138.044563	0.00075	2457193.160451	0.00072	2457242.977812	0.00065
2457138.175116	0.00082	2457193.999546	0.00066	—	—
2457146.032744	0.00095	2457194.166354	0.00065	—	—
2457146.164086	0.00093	2457206.983177	0.00080	—	—
2457146.949575	0.00100	2457207.905622	0.00074	—	—
2457152.973603	0.00102	2457207.990158	0.00067	—	—
2457154.020365	0.00095	2457209.915224	0.00065	—	—
2457154.150639	0.00086	—	—	—	—

The TOMs for all of the peaks of the light curves for the three variable stars are listed in Table 3, together with the errors of the estimates as calculated by PERANSO. Least squares linear fits for TOMs versus epoch revealed the following ephemerides, where the numbers in brackets represent the error of the last decimal place, and zero epoch is the first peak in the light curve determined by the author from his 2015 observations.

V1338 Cen:

$$T_{max}\ (HJD) = 2457136.9978\ (2) + 0.13093808\ (3)\ E \quad (1)$$

V1430 Sco:

$$T_{max}\ (HJD) = 2457179.0027\ (2) + 0.08377709\ (1)\ E \quad (2)$$

V1307 Sco:

$$T_{max}\ (HJD) = 2457222.0291\ (3) + 0.11703066\ (1)\ E \quad (3)$$

The periods from the above equations are almost identical to those previously published by other authors, namely, 0.1309382 day for V1338 Cen (Samus *et al.* 2007–2013), 0.0837770 day for V1430 Sco (Otero 2007), and 0.117031 day for V1307 Sco (Wils *et al.* 2004).

4. Discussion

Fourier analysis detected harmonics up to 5f1 for V1338 Cen and V1037 Sco, and up to 4f1 for V1430 Sco. They are representations of the extent to which the light curves are skewed from pure sinusoids.

In addition to the Fourier harmonics, special combinations of small instrumental effects and $1 d^{-1}$ aliasing could produce the peak observed at 1.020 d^{-1} in the data for V1338 Cen. Indeed, a single cycle seems systematically shifted in Figure 1 and the six observing nights were clustered into three pairs of consecutive nights (24 and 25 April, 3 and 4 May, and 10 and 11 May). Because of these factors, this peak is not considered to have a stellar origin.

In the case of V1430 Sco, the additional frequency f4 18.4335 d^{-1}, neither a Fourier harmonic nor a combination of other discovered frequencies, has a signal/noise ratio of 11.7 as calculated by PERIOD04, indicating clearly that it should be regarded as a valid pulsation frequency. This frequency has not previously been reported for this star. Its low semiamplitude of 0.008 mag. in comparison with the amplitude of 0.15 mag. for f1 is assumed to be the reason that it was not previously published. The frequency ratio f1/f4 is 0.644, indicating that this is not a fundamental to first overtone ratio, which should lie within the range 0.74 to 0.78 for δ Scuti stars pulsating in the radial mode (Breger 1979). It may therefore represent a non-radial mode, but a detailed consideration of both this possibility and subtle aliasing effects is beyond the resources of the author.

The calculation of linear ephemerides from the previously published TOMs together with the TOMs determined by the author has revealed periods that are essentially identical to those reported by others. The spans of time across which the new ephemerides were calculated, 9 years for V1338 Cen, 11 years for V1430 Sco, and 14 years for V1307 Sco, has allowed the periods of these stars to be reported herein with enhanced

accuracy: 0.13093808 day for V1338 Cen, 0.08377709 day for V1430 Sco, and 0.11703066 day for V1307 Sco.

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