The first high-amplitude delta Scuti star in an eclipsing binary system

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ABSTRACT
We report the discovery of the first high-amplitude δ Scuti star in an eclipsing binary, which we have designated UNSW-V-500. The system is an Algol-type semi-detached eclipsing binary of maximum brightness $V = 12.52$ mag. A best-fitting solution to the binary light curve and two radial velocity curves is derived using the Wilson-Devinney code. We identify a late A spectral type primary component of mass $1.49 \pm 0.02 M_\odot$ and a late K spectral type secondary of mass $0.33 \pm 0.02 M_\odot$, with an inclination of $86.5 \pm 1.0^\circ$, and a period of $5.3504751 \pm 0.0000006$ d. A Fourier analysis of the residuals from this solution is performed using PERIOD04 to investigate the δ Scuti pulsations. We detect a single pulsation frequency of $f_1 = 13.621 \pm 0.015$ cd$^{-1}$, and it appears this is the first overtone radial mode frequency. This system provides the first opportunity to measure the dynamical mass for a star of this variable type; previously, masses have been derived from stellar evolution and pulsation models.

Key words: variables: δ Scuti – binaries: eclipsing.

1 INTRODUCTION
The serendipitous arrangement of a pulsating star in an eclipsing binary system represents a unique laboratory for astrophysical measurements. The binarity constrains the physical and geometrical parameters of the system, and can also assist in mode identification in the pulsations. Since the pulsating star and non-pulsating companion can reasonably be assumed to have formed from the same parent cloud, we can utilise information from the non-pulsating companion in identifying stellar evolution models for pulsating stars. We present here the first known example of a high-amplitude δ Scuti (HADS) star in an eclipsing binary system, designated UNSW-V-500.

δ Scuti stars are the main-sequence analogues of Cepheid variables. They are late A to early F spectral type, and pulsate with periods of between 1–6 hours. They are typically on or slightly above the main-sequence. Low-amplitude δ Scuti stars typically pulsate in many higher, non-radial modes simultaneously with amplitudes of less than 0.05 mag. High-amplitude δ Scuti pulsate primarily in the radial modes and have higher amplitudes, with the conventional cut-off given as $A_V \geq 0.30$ mag. Fig. 1 shows the δ Scuti region of the HR diagram; high-amplitude δ Scuti stars are constrained to a narrower range in $T_{\text{eff}}$ of width $\sim 300$ K within this region. The subset of low metallicity Population II HADS stars are designated as SX Phe stars. Prior to the discovery of UNSW-V-500, all bright field HADS stars were identified as pulsating in the fundamental radial mode. A significant fraction ($\sim 40$ per cent) are double-mode pulsators, additionally pulsating in the radial first overtone mode (McNamara 2000a). However, SX Phe stars have been identified in globular clusters as pulsating in the first overtone rather than the fundamental mode (McNamara 2000a; Nemec et al. 1994).

Soydugan et al. (2006) present a list of 25 confirmed eclipsing binary systems with pulsating components in the δ Scuti region of the instability strip. All of these have low pulsation amplitudes, ranging from $A_V = 0.007–0.02$ mag and up to $A_B = 0.06$ mag. Three systems that have been studied in detail are Y Cam (Kim et al. 2002), AS Eri (Mkrtichian et al. 2004) and AB Cas (Rodríguez et al. 2004). Parameters of these systems are

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low spatial resolution of 0.4 arcsec per pixel. We have used a customised aperture photometry data reduction pipeline to construct our target light curves. The results of the project include the discovery of a new eclipsing system of K7 dwarf components [Young et al. 2006].

Identification of UNSW-V-500 as demonstrating both eclipsing and pulsating variations was made during routine cataloguing of the variable light curves detected in the transit search, to be published separately. The photometry aperture used in the reduction process, which is nearly 1 arcmin in diameter, can usually be expected to contain more than one star due to crowding effects in the target fields (typically chosen to have a Galactic latitude of 10°–20°). Higher resolution images from the Digitized Sky Survey catalogue showed that in the case of UNSW-V-500 the photometry aperture contained one bright central star and 6 additional stars at least 3.5 magnitudes fainter. Due to the large amplitudes of the δ Scuti pulsations (diluted to ∼0.1 mag in the original photometry aperture) the system was identified with the bright central star, α 21000 = 13h 10m 18.7s, δ 21000 = −45° 9′ 13″. A catalogue search revealed that this system had been previously observed and identified in the All Sky Automated Survey Catalog of Variable Stars III [Pojmanski 2004] as an eclipsing binary system, designated ASCAS131018-4509.2. From their data they measured an initial epoch of $T_0 = JD2451892.6$ and a period of $P = 5.350479$ d. However, their precision was insufficient for detection of the δ Scuti pulsation.

In the original run of 29 nights one secondary minimum and two partial secondary eclipses were observed, but only two primary eclipse images available. In order to improve coverage of this part of the light curve, UNSW-V-500 was observed again in the same configuration as described previously on two nights in February 2007 and March 2007 at the predicted times of primary eclipse. These two nights and the 22 best nights of the 2006 data are shown in Fig. 2, phased at a period of 5.3504751 d. The primary eclipse data conclusively confirmed that the light curve was not the result of a δ Scuti star blended with a background eclipsing binary: the flat-bottomed eclipses show no sign of the pulsations that are evident in the remainder of the light curve. Therefore, the δ Scuti star must be fully eclipsed by the secondary component of the binary during primary eclipse. The inset in Fig. 2 shows the flat primary eclipse in more detail.

In order to confirm the identification of the bright central star in the original photometry aperture as the eclipsing binary, higher spatial resolution observations were obtained with the 40-inch telescope at Siding Spring Observatory. The WFI CCD mosaic was used, with an image scale of 0.38 arcsec per pixel. Observations were taken on a single night in January 2007, in the Johnson V filter. These data were reduced using a modified version of our aperture photometry pipeline. The identification of the pulsating star was confirmed and the data are shown in Fig. 3 as solid circles. For comparison, the light curve of a nearby star of similar magnitude, GSC0824700373, is shown as open squares. The lower limit on the amplitude of the δ Scuti pulsation, diluted in these data by light from the secondary, is $A_V = 0.21 ± 0.02$ mag. Combined with a primary eclipse depth in the $I$ band of ∼60

![Figure 1. A HR diagram showing the positions of δ Scuti stars in eclipsing binaries. The solid triangles are data from Table 4 of Soydugan et al. (2006). The open circles are from McNamara (2000). UNSW-V-500 is shown as an open square. The observational red and blue edges of the classical instability strip are shown, as well as the theoretical zero-age main sequence.](image-url)
The first high-amplitude delta Scuti star in an eclipsing binary system

Table 1. A sample of δ Scuti stars in eclipsing binary systems. $A_V$ is the amplitude of the δ Scuti pulsations.

| Name   | $V$ mag | $A_V$ mag | Spectral Type | $P_{\text{puls}}$ (d) | $P_{\text{orb}}$ (d) | Inclination $^\circ$  
|--------|---------|-----------|---------------|-------------------|-------------------|-------------------|
| Y Cam  | 10.56   | 0.04      | A7V           | 0.063             | 3.3055            | 86               |
| AB Cas | 10.16   | 0.05      | A3V           | 0.058             | 1.3669            | 87.5             |
| AS Eri | 8.31    | 0.0068    | A3V           | 0.016             | 2.6642            | –                |
| UNSW-V-500 | 12.52 $^a$ | ~0.35±0.5 | A7V     | 0.0734±0.0001     | 5.3504751±0.000006 | 86.5±1.0         

$^a$ $V_{\text{max}}$ from the ASAS catalogue.

Figure 2. The phased light curve of 24 nights of data taken with the Automated Patrol Telescope in the $I$ band. The upper curve is the original data, with the scatter outside the primary eclipse due to the δ Scuti pulsation. The lower curve is the same data with the δ Scuti pulsation reconstructed from the frequency analysis and removed. In both cases, the solid line is the fit to the original curve using the Wilson-Devinney code. Panel (a) shows the primary eclipse in more detail — there is no evidence of δ Scuti variations in this region.

2.2 Spectroscopy

Several medium resolution spectra ($R \sim 6000$) were obtained over two nights in February 2007 with the Double-Beam Spectrograph on the 2.3-m telescope at Siding Spring Observatory. The wavelength range covered was 3900–4400 Å in the blue arm and 8000–8900 Å in the red. The spectra were reduced using standard IRAF$^1$ spectroscopy routines. The observations were alternated with arc spectra of FeAr in the blue and NeAr in the red. The flux calibration of the system was performed using the standard stars HR4469 and HR4963. The spectra were rebinned to a resolution of 10 Å using the IRAF routine REBIN and compared with UVILIB template spectra (Pickles 1998). Visual inspection resulted in the classification of the spectra as an A7V star. The phase coverage was insufficient to measure the dynamical mass.

To obtain sufficient phase coverage, we obtained additional spectra with the same instrument on five nights in May 2007. The gratings and grating angle were changed to give a wavelength coverage of 3600–4700 Å in the blue arm and 6000–7000 Å in the red. The same procedure of alternating observations with arc spectra for wavelength calibration was followed, however to improve the stability of the calibration between arc spectra we used the night sky lines present in each spectrum in the red half of the data for additional calibration. The data were then continuum normalised. The red data clearly show spectral features of both the primary and secondary components, and also a significant component of $H_{\alpha}$ emission. Given the semi-detached nature of UNSW-V-500 (see Sec. 3) this may indicate the existence of a gas stream between the two components (see for instance the set of well observed Algol-type eclipsing binaries in Richards & Allbright (1999); Vesper et al. (2001)).
The blue data are entirely dominated by the spectrum of the primary component. Therefore the blue data were used to identify the spectral type of the primary, by using the preliminary identification from the earlier data and the ATLAS9 synthetic stellar template library (Munari et al. 2005), rebinned as previously. We performed a least-squares fit and identified the $T_{\text{eff}} = 7500K$, log $g = 4.0$, [Fe/H] = $-0.5$ template as the best fit. From the residuals to this fit, we attempted to match the spectrum of the secondary component. A preliminary light curve analysis had indicated a secondary component with a temperature of $\sim 4200K$; hence the least-squares fit to the residuals was restricted to the ATLAS9 models with $T_{\text{eff}} = 4250K$ and [Fe/H] = $-0.5$, since we can assume the binary system will have a common origin and thus metallicity. The best fit was achieved with the log $g = 3.0$ template. We note again that the pulsating primary component is essentially fully eclipsed by the secondary star at primary eclipse. Therefore, a high resolution spectrum during the time of primary eclipse would necessarily be a spectrum of the secondary star, and would be useful for constraining the stellar spectral type and physical parameters derived via light curve-fitting in Section 3.

2.3 Radial velocity analysis

In order to extract the radial velocities of the two binary components, we used the program TODCOR (Zucker & Mazeh 1994), which performs a two-dimensional correlation between two supplied template spectra and an object spectrum of a binary system. Using the two ATLAS9 templates identified previously, radial velocities were extracted for the majority of the spectra we had obtained. The correlation was limited to the wavelength region 6200–6530 Å to avoid the Hα emission noted previously. The flux ratio of the secondary to the primary template spectra was left as a free parameter for TODCOR, and was found to vary from 0.2–0.4 with phase.

The radial velocities are shown in Fig. 4, with the primary component shown as circles and the secondary component as squares. The lines are the best-fitting sine curves, with velocity amplitudes of $K_1 = 27.0 \pm 1.8$ km s$^{-1}$ and $K_2 = 121.2 \pm 1.4$ km s$^{-1}$, indicating a mass ratio of $0.22 \pm 0.02$, and a systemic velocity of $43.6 \pm 0.9$ km s$^{-1}$.

The large scatter in the primary component data of $\sim 20$ km s$^{-1}$ is due to the $\delta$ Scuti radial velocity pulsations, and is similar to the radial velocity amplitude of other HADS stars we have measured with the same instrument (Derekas et al. 2006). The frequency spectrum of these data were analysed in the same manner described in Sec. 3 and two peaks corresponding to the orbital and pulsational periods (5.36 d and 0.073 d) were identified, a second confirmation that this is not a blended system.

3 BINARY SYSTEM

In order to fit the orbital parameters of UNSW-V-500, we applied the Wilson-Devinney code (Wilson & Devinney 1971; Wilson 1979, 1990) to the APT light curve and the two radial velocity curves simultaneously. This system is an Algol-type semi-detached eclipsing binary system, with the secondary star filling its Roche lobe, and consequently the code was operated in mode 5. The effective temperature of the primary was fixed at $T_1 = 7500K$ from the template fit. The gravity brightening coefficients were set to 1.00 for the radiative primary component and 0.32 for the convective secondary component. The albedos were set to the standard theoretical value of 1.00. The bolometric and bandpass-specific limb darkening coefficients were adopted from values for the closest models in van Hamme (1993). The third light $i_3$ was assumed to be non-zero due to the crowded photometry aperture, and was allowed to vary as a free parameter. It was given an initial value of $i_3 = 0.2$ from an estimate of the maximum total contribution to the normalised flux at phase 0.25. The eccentricity was assumed to be $\sim 0$ due to the secondary eclipse occurring at a phase of 0.5. To confirm this, the eccentricity was allowed to vary and did not result in any significant improvement in the fit, so was fixed at 0 for the subsequent fitting. The semi-major axis was fixed at 15.69 $R_\odot$ from the total mass and period of the system, and the systemic velocity was fixed at 43.6 km s$^{-1}$. The mass ratio was fixed at 0.22 from the radial velocity data. The free parameters were thus the third light $i_3$, the inclination $i$, the effective temperature of the secondary $T_2$, the potential (as defined by Kopal (1954)) of the primary $T_1$ and the luminosity of the primary $L_1$. The values of these parameters used in the final solution are shown in Table 2, as are the derived quantities for the two components of mass, radius, log $g$ and $M_{\text{bol}}$.

The solid line in Fig. 2 shows the best-fitting solution. The high inclination ($i = 86.5 \pm 1.0^\circ$) is indicated by the flat bottom of the primary eclipse. In fact this is the first eclipsing binary system containing a pulsating component to demonstrate a flat-bottomed eclipse, with the possible exception of the recent discovery of the pulsating component of HD 99612 (Pigulski & Michalska 2005).
The first high-amplitude delta Scuti star in an eclipsing binary system

Figure 5. The residuals in the original data after the subtraction of the best-fitting binary solution, between phases 0.1 and 0.9.

Table 2. The parameters for the binary system solution. Starred quantities indicate the free parameters in the Wilson-Devinney code. Quoted errors for the starred quantities and the calculated quantities \(L_2\) and \(\Omega_2\) are standard deviations produced by the Wilson-Devinney code. * These are the bandpass luminosities in the \(I\)-band. ** This is the corrected value of the third light for reference phase 0.25.

| Parameter | Value |
|-----------|-------|
| \(e^*\)   | 0.0000 |
| \(q^*\)   | 0.22±0.02 |
| \(T_1\) (K) | 7500 |
| \(T_2^*\) (K) | 3850±20 |
| \(L_1^* (L_\odot)^a\) | 6.96±0.03 |
| \(L_2 (L_\odot)^a\) | 3.89±0.03 |
| \(\Omega_1^*\) | 6.9±0.1 |
| \(\Omega_2^*\) | 2.3±0.1 |
| \(i^* (^\circ)\) | 86.5±1.0 |
| \(l_{3,b}^*\) | 0.096±0.005 |
| \(M_1 (M_\odot)\) | 1.49±0.02 |
| \(M_2 (M_\odot)\) | 0.33±0.02 |
| \(R_1 (R_\odot)\) | 2.35±0.02 |
| \(R_2 (R_\odot)\) | 4.04±0.01 |
| \(M_{bol,1}\) | 1.80±0.02 |
| \(M_{bol,2}\) | 3.53±0.02 |
| \(\log g_1\) | 3.87±0.01 |
| \(\log g_2\) | 2.74±0.01 |

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4 PULSATION

Once the binary solution has been subtracted, an analysis of the \(\delta\) Scuti pulsation can be performed. We have used data from phase 0.1 to 0.9 for this analysis, discarding those data around the primary eclipse where the HADS star is completely eclipsed. This reduces the total number of data points by 700, or \(\sim 25\) per cent. The residuals from the binary subtraction between phase 0.1 to 0.9 are shown in Fig. 5.

Fig. 6 shows the frequency analysis, as performed with the program PERIOD04 [Lenz & Breger 2003]. The spectral window is shown in panel (a). Panel (b) shows the initial periodogram. The dominant frequency is identified as \(f_1 = 13.621 \pm 0.015 \text{ cd}^{-1}\), i.e. a period of \(0.0734 \pm 0.0001 \text{ d}\), which is typical for \(\delta\) Scuti stars. The
four additional frequencies identified with a S/N > 4.0, as suggested by Breger et al. (1993), are shown in panel (c), after removal of $f_1$. These can be identified as low-power frequencies, probably due to artefacts of the binary subtraction ($f_2 = 0.187 \pm 0.033$ cd$^{-1}$ and $f_4 = 0.255 \pm 0.084$ cd$^{-1}$), or harmonics of $f_1$ ($f_3 = 2f_1 = 27.242 \pm 0.084$ cd$^{-1}$ and $f_5 = 3f_1 = 40.86 \pm 0.14$ cd$^{-1}$). The absence of any additional frequencies in the $\delta$ Scuti range supports the identification of a HADS star oscillating in a single radial mode to the limits of our detection.

As an additional check, these frequencies were removed from the original data. The resulting light curve is shown in Fig. 2, offset below the original data. The Wilson-Devinney code was re-run using this second light curve, with no significant change in the derived parameters.

Using the relation from Breger et al. (1993), we can calculate the pulsation constant $Q_{\text{obs}}$.

$$\log Q_{\text{obs}} = -6.456 + \log P + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_e$$ (1)

We find a $Q_{\text{obs}}$ of $0.025 \pm 0.001$. Petersen & Jørgensen (1972) derived theoretical pulsation constants of $Q_0 = 0.0333$ for the fundamental radial mode, $Q_1 = 0.0252$ for the first overtone radial mode, and $Q_2 = 0.0201$ for the second overtone radial mode. Inspection of the HADS stars catalogued in McNamara (2000b) reveals that of the 26 well studied field stars, all have observed pulsation constants in the range 0.0309-0.331, indicating they are pulsating in the fundamental mode. UNSW-V-500 appears to be the first identified to be pulsating primarily in the first overtone radial mode, joining a number of SX Phe stars in globular clusters to have been identified in this mode McNamara(2000b).

5 SUMMARY

We have presented here the detection of the first example of a high-amplitude $\delta$ Scuti star in an eclipsing binary system, and the probable first detection of a field HADS star pulsating in the single first overtone radial mode. Several HADS stars have been detected in binary systems previously (including SZ Lyn [Derekas et al. 2003] with a period of 1190 d; and RS Gru [Joner & Laney 2004] with a period of approximately 2 weeks), however these are much wider systems. This new fully eclipsing binary opens up many further opportunities for studies of HADS stars and pulsating stars in binary systems. Many of the poorly understood processes governing the effects of mass transfer, tidal interactions, rotation, convection and magnetism on $\delta$ Scuti pulsations may be explored with this system.

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