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The first high-amplitude δ 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 $86\overset{\circ}{.}5 \pm 1\overset{\circ}{.}0$, and a period of $5.350\,4751 \pm 0.000\,0006$ 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 that 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: binaries: eclipsing – δ Scuti.

1 INTRODUCTION

The fortuitous 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 utilize 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 and 6 h. 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. HADS stars pulsate primarily in the radial modes and have higher amplitudes, with the conventional cut-off given as $A_V \geqslant 0.30$ mag. Fig. 1 shows the δ Scuti region of the Hertzsprung–Russell (HR) diagram; HADS stars are constrained to a narrower range in $T_{\rm eff}$ of width ∼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 either pulsating in the fundamental radial mode, in both the fundamental and the first overtone radial modes simultaneously (∼40 per cent, McNamara 2000a), or rarely in both the first and the second overtone radial modes simultaneously [VZ Cnc (Petersen & Høg 1998) and possibly V798 Cygni (Musazzi et al. 1998)]. However, SX Phe stars have been identified in globular clusters as pulsating in the first overtone rather than the fundamental radial mode (Nemec, Nemec & Lutz 1994; McNamara 2000b).

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 to $A_B = 0.06$ mag. Three systems that have been studied in detail are Y Cam (Kim et al. 2002a), AS Eri (Mkrtichian et al. 2004) and AB Cas (Rodríguez et al. 2004). Parameters of these systems are shown in Table 1, with the parameters of UNSW-V-500 shown for comparison.

We note that although 35 δ Scuti stars in eclipsing binary systems have been identified (25 in Soydugan et al. 2006; nine recently in Pigulski & Michalska 2007; and the subject of this paper), UNSW-V-500 is the first HADS star. This is a curious statistic, since surveys might be expected to be observationally biased towards finding HADS stars in these systems. A census of the Rodríguez, López-González & López de Coca (2000) catalogue shows that the detected fraction of HADS stars is ∼25 per cent of the total δ Scuti population. One assumes that this fraction is influenced by the same

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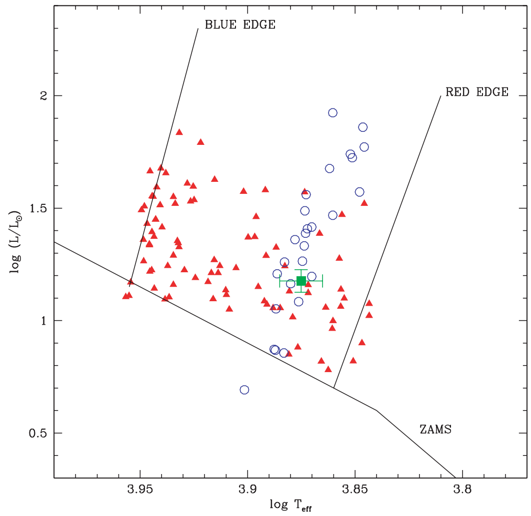

Figure 1. An HR diagram showing the positions of δ Scuti stars in eclipsing binaries. The solid triangles are data from table 4 of Soydugan et al. (2006). The open circles are HADS stars from table 2 of McNamara (2000b); the star considerably below the main sequence is the SX Phe-type variable BL Cam. UNSW-V-500 is shown as a solid square. The observational red and blue edges of the classical instability strip are shown, as well as the theoretical zero-age main-sequence.

observational selection bias affecting the detection of HADS stars in eclipsing binary systems; we are seeing a detection rate nearly an order of magnitude below this. However, it is difficult to draw conclusions from the small numbers of binary systems that have been found.

2 OBSERVATIONS

2.1 Photometry

UNSW-V-500 was initially observed over 29 nights from 2006 February to 2006 April. The photometric *I*-band observations were performed with the 0.5-m Automated Patrol Telescope at the Siding Spring Observatory, Australia. The observations formed part of an extrasolar planet transit search being undertaken by the University of New South Wales. The CCD has 770 × 1150 pixels and images a 2 × 3-deg^2 field with a relatively low spatial resolution of 9.4 arcsec pixel^{-1}. We have used a customized aperture photometry data-reduction pipeline to construct our target light curves. A full explanation of the transit search and the data-reduction process can be found in Hidas et al. (2005). The results of the project include the discovery of a new eclipsing system of K7 dwarf components (Young et al. 2006).

An 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 six additional stars at least 3.5 mag fainter. Due to the large amplitude of the δ Scuti pulsations (diluted to ∼0.1 mag in the original photometry aperture), the system was identified with the bright central star, $\alpha_{J2000} = 13^h10'18''.7$, $\delta_{J2000} = -45°9'13''$. 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 & Maciejewski 2004) as an eclipsing binary system, designated ASAS 131018−4509.2. From their data, they measured an initial epoch of T_0 = JD 245 1892.6 and a period of P = 5.350 479 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 eclipses egress. In order to improve the 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 2007 February and 2007 March at the predicted times of the primary eclipse. These two nights and the 22 best nights of the 2006 data are shown in Fig. 2, phased at a period of 5.350 4751 ± 0.000 0006 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 the Siding Spring Observatory. The WFI CCD mosaic was used, with an image-scale of 0.38 arcsec pixel^{-1}. Observations were taken on a single night in 2007 January, 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 the solid circles. For comparison, the light curve of a nearby star of similar magnitude, GSC0824700373, is shown as the open squares. The lower limit on the amplitude of the δ Scuti pulsation, diluted in these data by light from the secondary, is $A_V = 0.21 \pm 0.02$ mag. Combined with a primary eclipse depth in the *I* band of ∼60 per cent, the final lower limit is $A_V = 0.35 \pm 0.05$ mag, confirming this star as an HADS star.

2.2 Spectroscopy

Several medium-resolution spectra ($A \sim 6000$) were obtained over two nights in 2007 February with the Double-Beam Spectrograph

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_{puls} (d)	P_{orb} (d)	Inclination (°)
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	5.350 4751 ± 0.000 0006	86.5 ± 1.0

[a] V_{max} from the ASAS catalogue.

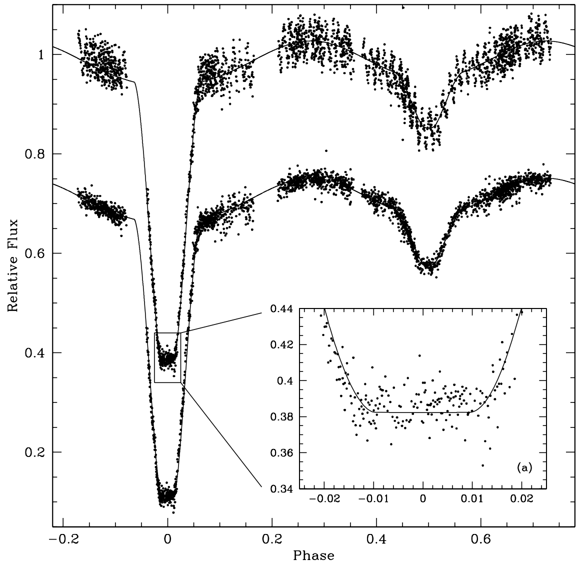

Figure 2. The phased light curve of 24 nights of data taken with the Automated Patrol Telescope in the *I* band. The upper curve is the original data, with the scatter outside the primary eclipse due to the δ Scuti pulsation. The lower curve is the same data with the δ Scuti pulsation reconstructed from 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.

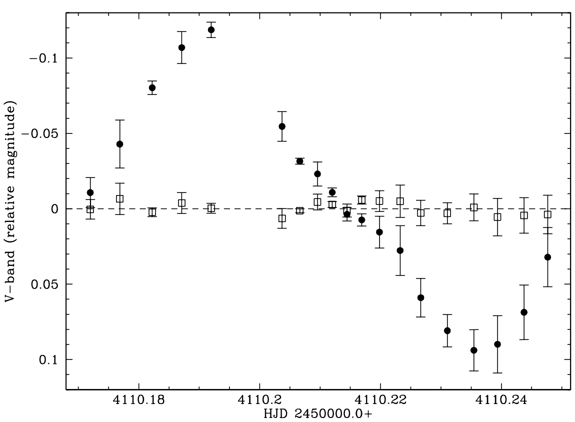

Figure 3. Light curves observed with the higher spatial resolution of the 40-inch telescope. The solid circles show the δ Scuti pulsation of our target, and the open squares show the light curve of the nearby star GSC0824700373 for comparison.

on the 2.3-m telescope at the 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 Fe–Ar in the blue and Ne–Ar 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). A 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 2007 May. The gratings and grating angle were set 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, we encountered significant shifts in the position of the arc spectra on the CCD between adjacent calibration frames. Therefore, 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-normalized. The red data clearly show spectral features of both the primary and the secondary components, and also a significant component of Hα emission. Given the semi-detached nature of UNSW-V-500 (see Section 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 & Albright 1999; Vesper, Honeycutt & Hunt 2001). The blue data show only single-lined spectral features, and 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 synthetic stellar template library released by Munari et al. (2005), rebinned as previously. We performed a least-squares fit and identified the $T_{\rm eff} = 7500$ K, $\log g = 4.0$, [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$4200 K; hence, the least-squares fit to the residuals was restricted to the stellar templates with $T_{\rm eff} = 4250$ K and [Fe/H] $= -0.5$, since we can assume that 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 stellar 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 H α 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 to 0.4 with phase.

The radial velocities are shown in Fig. 4, with the primary component shown as the circles and the secondary component as the 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 ± 0.02, and a systemic velocity of 43.6 ± 0.9 km s^{-1}.

The large scatter in the primary component data of $\sim$20 km s^{-1} is due to the δ Scuti radial velocity pulsations, and is similar to the radial velocity amplitude of other HADS stars we have measured

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

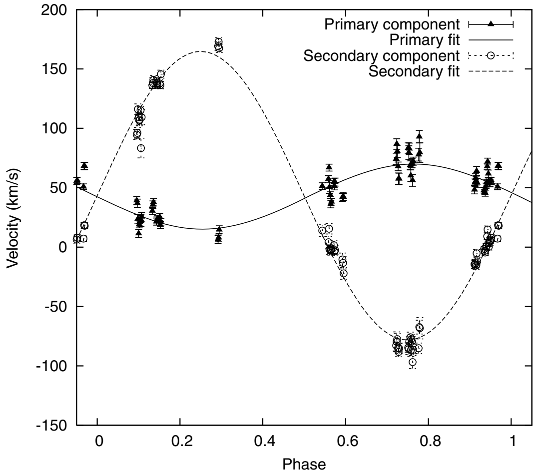

Figure 4. The radial velocities of the primary (solid triangles) and secondary (open circles) components. The lines are the best-fitting sine curves.

with the same instrument (Derekas et al. 2006). The frequency spectrum of these data was analysed in the same manner as described in Section 4 and two peaks corresponding to the orbital and pulsational periods (5.36 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 Automated Patrol Telescope (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 $T_1 =$ 7500 K 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 l_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 $l_3 = 0.2$ from an estimate of the maximum total contribution to the normalized flux at phase 0.25. The eccentricity was assumed to be ∼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 semimajor 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 l_3, the inclination i, the effective temperature of the secondary T_2, the potential as defined by Kopal (1954) of the primary Ω_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_{bol}.

The solid line in Fig. 2 shows the best-fitting solution. The high inclination ($i = 86\overset{\circ}{.}5 \pm 1\overset{\circ}{.}0$) 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

Table 2. The parameters for the binary system solution. The quantities marked with an asterisk indicate the free parameters in the Wilson–Devinney code. Quoted errors for the quantities marked with an asterisk and the calculated quantities (L_2 and Ω_2) are standard deviations produced by the Wilson–Devinney code.

Parameter	Value
e	0.0000
q^*	0.22 ± 0.02
T_1 (K)	7500
T_2* (K)	3850 ± 20
$L_1{}^{*a}$ ($L_\odot$)	6.96 ± 0.03
$L_2{}^a$ ($L_\odot$)	3.89 ± 0.03
Ω_1*	6.9 ± 0.1
Ω_2	2.3 ± 0.1
i* (°)	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
$M_{\mathrm{bol},1}$	1.80 ± 0.02
$M_{\mathrm{bol},2}$	3.53 ± 0.02
log g_1	3.87 ± 0.01
log g_2	2.74 ± 0.01

[a]These are the bandpass luminosites in the I band.
[b]This is the corrected value of the third light for reference phase 0.25.

eclipse, with the possible exception of the recent discovery of the pulsating component of HD 99612 (Pigulski & Michalska 2007). The normalized third light contribution is found to be 0.096 at the reference phase of 0.25.

We note that the log g values that have been derived in the Wilson–Devinney fit (3.87 ± 0.01 and 2.74 ± 0.01 for the primary and secondary components, respectively) confirm the estimated values from the synthetic template fitting (4.0 ± 0.5 and 3.0 ± 0.5) in Section 2.2.

From the T_{eff} and derived mass, we have identified the two components as a late-A spectral-type primary, confirming the A7V classification, and a late-K spectral-type secondary. Using the derived parameters, we attempted to fit the positions of the two components in the HR diagram with the Y^2 isochrones (Yi et al. 2001; Kim et al. 2002b) in order to find an age estimate for the system. However, we found that the isochrones and evolutionary tracks were unable to reproduce the current positions of the components; hence, we conclude that there has been significant mass transfer to the pulsating primary component from the secondary component. This component appears in a much more evolved state despite its lower mass, a well-recognized phenomenon known as the Algol paradox. We caution that standard evolution and pulsation models for HADS stars may not apply to UNSW-V-500 due to its binary evolution. However, we do note that it is well described by the ML3 mass–luminosity relation for HADS stars shown in fig. 1 of Petersen & Christensen-Dalsgaard (1996), which is based on models with a metal content of $Z = 0.02$.

4 PULSATION

Once the binary solution has been subtracted, an analysis of the δ Scuti pulsation can be performed. We have used data from phase

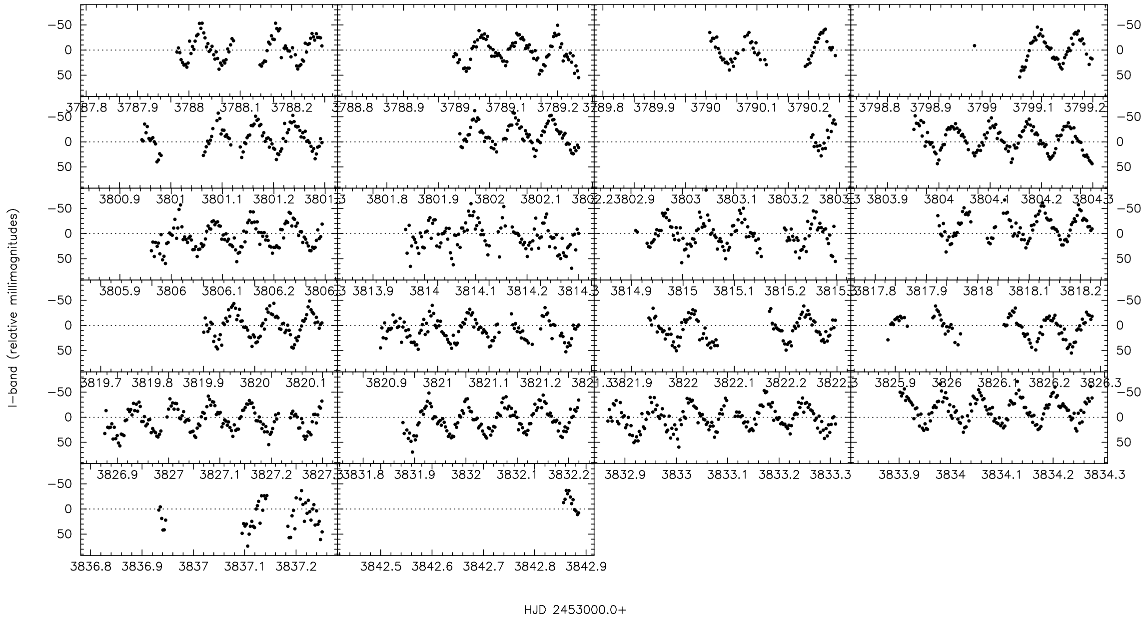

Figure 5. The residuals in the original data after the subtraction of the best-fitting binary solution, between phases 0.1 and 0.9.

0.1–0.9 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 ∼25 per cent. The residuals from the binary subtraction between phase 0.1 and 0.9 are shown in Fig. 5.

Fig. 6 shows the frequency analysis, as performed with the program PERIOD04 (Lenz & Breger 2005). The spectral window is shown in panel (a). Panel (b) shows the initial periodogram. The dominant frequency is identified as $f_1 = 13.621 \pm 0.015$ cd^{-1}, that is, a period of 0.0734 ± 0.0001 d, which is typical for δ Scuti stars. The four additional frequencies identified with an 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 δ Scuti range supports the identification of an HADS star oscillating in a single radial mode to the limits of our detection.

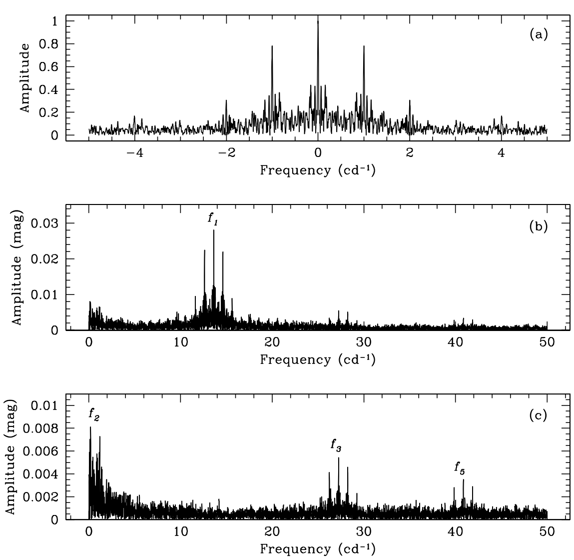

Figure 6. The frequency analysis of the pulsation. Panel (a) shows the spectral window. Panel (b) shows the strongest frequency f_1 at 13.621 cd^{-1}. Panel (c) shows the frequency spectrum with f_1 removed. On this scale, f_4 is coincident with f_2.

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 $Q_{\rm obs}$:

$$\log Q_{\rm obs} = -6.456 + \log P + 0.5 \log g + 0.1 M_{\rm bol} + \log T_{\rm e}. \quad (1)$$

We find a $Q_{\rm obs}$ of 0.025 ± 0.004. 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. An inspection of the HADS stars catalogued in McNamara (2000a) reveals that all of the 26 well-studied single- and double-mode field stars have observed pulsation constants in the range 0.0309–0.331, indicating that the dominant pulsation is in the fundamental radial mode. Several double-mode HADS stars have been independently identified by their period ratios to be pulsating in the first and second overtone radial modes (Musazzi et al. 1998; Petersen & Høg 1998). UNSW-V-500 appears to be the first single-mode field star identified 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 an HADS 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 δ Scuti pulsations may be explored with this system.

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