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Binarity and multiperiodicity in high-amplitude δ Scuti stars

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ABSTRACT

We have carried out a photometric and spectroscopic survey of bright high-amplitude δ Scuti (HADS) stars. The aim was to detect binarity and multiperiodicity (or both) in order to explore the possibility of combining binary star astrophysics with stellar oscillations. Here, we present the first results for 10, predominantly southern, HADS variables. We detected the orbital motion of RS Gru with a semi-amplitude of $\sim$6.5 km s^{-1} and 11.5 d period. The companion is inferred to be a low-mass dwarf star in a close orbit around RS Gru. We found multiperiodicity in RY Lep from both photometric and radial velocity data and detected orbital motion in the radial velocities with hints of a possible period of 500–700 d. The data also revealed that the amplitude of the secondary frequency is variable on the time-scale of a few years, whereas the dominant mode is stable. Radial velocities of AD CMi revealed cycle-to-cycle variations, which might be due to non-radial pulsations. We confirmed the multiperiodic nature of BQ Ind, while we obtained the first radial velocity curves of ZZ Mic and BE Lyn. The radial velocity curve and the O–C diagram of CY Aqr are consistent with the long-period binary hypothesis. We took new time series photometry on XX Cyg, DY Her and DY Peg, with which we updated their O–C diagrams.

Key words: methods: observational – techniques: photometric – techniques: radial velocities – binaries: general – binaries: spectroscopic – δ Scuti.

1 INTRODUCTION

δ Scuti stars are short-period pulsating variables of A–F spectral types, located at the intersection of the main sequence and the classical instability strip in the Hertzsprung–Russell diagram. Typical periods are of the order of a few hours with amplitudes less than 1 mag. A prominent group within the family comprises the high-amplitude δ Scuti (HADS) stars, which have *V*-band amplitudes larger than 0.3 mag. Population II members of the group are also known as SX Phoenicis stars, often found in globular clusters (for a review of δ Scuti stars see e.g. Rodríguez & Breger (2001)).

HADSs are the short-period counterparts of the classical Cepheids, excited by the κ-mechanism and pulsating in one or two radial modes, usually in the fundamental and first-overtone modes (McNamara 2000). The data in Rodríguez & Breger (2001) show that there is no rapidly rotating HADS ($v \sin i \leq 40$ km s^{-1}), suggesting an intimate relationship between the rotational state and the excitation of pulsations. In recent years, the number of HADS known with multimode oscillations has rapidly grown, hinting a new potential for the asteroseismic studies of these objects (e.g. Poretti 2003; Poretti et al. 2005). Several investigations suggested that some of the stars might have non-radial pulsation modes present (McNamara 2000; Poretti et al. 2005). However, an important parameter in modelling stellar oscillations is the mass of the star, which is usually constrained from evolutionary models. This will inevitably lead to great uncertainties in any kind of modelling attempts, so that independent mass estimates could be of paramount importance. Thus, binary δ Scutis may play a key role in understanding oscillations of these stars.

There has been a great interest recently in δ Scuti stars that reside in eclipsing binary systems (e.g. Kim et al. 2003; Mkrtichian et al. 2006; Soydugan et al. 2006; Christiansen et al. 2007; Pigulski & Michalska 2007). Currently, we know about 40 such δ Scutis, of

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which only one belongs to the HADS group (Christiansen et al. 2007). There are also a handful of non-eclipsing binary HADS (Rodríguez & Breger 2001), usually deduced from the apparent cyclic period changes but with a few exceptions, like the single-lined spectroscopic binary SZ Lyn. The low number of binary δ Scutis suggests a strong observational bias, because one needs accurate observations with a long time-span to detect multiplicity unambiguously (Rodríguez & Breger 2001).

In this paper, we present the results of our investigations into binarity and multiple periodicity in bright HADS variables. The sample was initially selected from the variable star catalogue of the *Hipparcos* satellite, which contains 21 'SX Phe' type stars (Perryman et al. 1997b). Of these, here we discuss nine stars (and RY Lep in addition), i.e. our present sample contains almost half of all known bright HADS. Using a wide range of telescopes and instruments, we have been monitoring the target stars over the last five years, extending the earlier studies by our group (Kiss & Szatmáry 1995; Kiss et al. 2002; Derekas et al. 2003; Szakáts, Szabó & Szatmáry 2008).

The paper is organized as follows. The observations and the data analysis are described in Section 2. The main discussion is in Section 3, in which the results for individual stars are presented. A brief summary is given in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The observed stars and their main observational properties are listed in Table 1. The full log of observations is given in Table A1 in the Appendix. All data presented in this paper are available for download from the CDS, Strasbourg.

Observations were carried out using seven different instruments at five observatories in Australia, Hungary and the USA on a total of 65 nights between 2003 October and 2008 July. In the following, we briefly describe the telescopes and the detectors used in this project, in an order of increasing mirror size.

(i) *Szeged Observatory, 0.4 m (Sz40).* *V*-band CCD photometry of XX Cyg was carried out with the 0.4-m Newtonian telescope at Szeged Observatory. The telescope has an 11 × 17 arcmin^2 field of view and the detector was an SBIG ST-7 CCD camera (765 × 510 pixel at 9 μm). We took observations for XX Cyg with exposure time of 45 s.

Table 1. The list of programme stars. The asterisks mark multiperiodic stars, for which this table contains the dominant period only. References for the parameters are the following: (a) Rodríguez et al. (1996); (b) Rodríguez & Breger (2001); (c) Perryman et al. (1997b); (d) Kholopov et al. (1985–1988); (e) Szakáts et al. (2008); (f) Blake et al. (2003); (g) Rodríguez et al. (1995b); (h) Fu & Sterken (2003) and (i) Derekas et al. (2003).

Star	Pop[a]	V_{max}	V_{min}	P (d)	Observations
RY Lep*	I	$8^{\mathrm{m}}.20$	$9^{\mathrm{m}}.10$	0.225 144 10[c]	*I*/sp.
AD CMi*	I	$9^{\mathrm{m}}.21$	$9^{\mathrm{m}}.51$	0.122 974 43[d]	sp.
BE Lyn	I	$8^{\mathrm{m}}.60$	$9^{\mathrm{m}}.00$	0.095 869 52[e]	sp.
DY Her	I	$10^{\mathrm{m}}.15$	$10^{\mathrm{m}}.66$	0.148 631 35[d]	*V*
XX Cyg	II	$11^{\mathrm{m}}.28$	$12^{\mathrm{m}}.13$	0.134 865 11[f]	*V*
BQ Ind*	II[b]	$9^{\mathrm{m}}.78$	$10^{\mathrm{m}}.05$	0.082 000 15[c]	*I*
ZZ Mic*	I	$9^{\mathrm{m}}.27$	$9^{\mathrm{m}}.69$	0.067 183 50[d]	*BV*/sp.
RS Gru	I	$7^{\mathrm{m}}.92$	$8^{\mathrm{m}}.51$	0.147 011 31[g]	*BVI*/sp.
CY Aqr	II	$10^{\mathrm{m}}.42$	$11^{\mathrm{m}}.16$	0.061 038 33[h]	*BVI*/sp.
DY Peg	II	$9^{\mathrm{m}}.95$	$10^{\mathrm{m}}.62$	0.072 926 30[i]	*V*

(ii) *Siding Spring Observatory, 0.5 m (APT50).* Time series CCD photometry was obtained for RY Lep, BQ Ind and CY Aqr with the Automated Patrol Telescope (APT) at Siding Spring Observatory, which is owned and operated by the University of New South Wales (UNSW). The telescope was originally a Baker–Nunn design converted into CCD imaging (Carter et al. 1992) and has a three-element correcting lens and an f/1 spherical primary mirror. The camera has an EEV CCD05-20 chip with 770 × 1150 (22.5 μm) pixel to image a 2 × 3 deg^2 field of view. We obtained *I*-band images with exposure times between 3 and 60 s, depending on the star and the weather conditions.

(iii) *Siding Spring Observatory, 24 in/0.6 m (SSO60).* Photoelectric photometry of ZZ Mic, RS Gru and CY Aqr was obtained with the 0.6 m f/18 Cassegrain reflector, on which a single-channel photometer was mounted. It had a computer-controlled eight-hole filter wheel, for which the dwell times on each filter can be varied. The detector was a thermoelectrically cooled Hamamatsu R647-4 photomultiplier tube with a 9-mm diameter bi-alkali (blue-sensitive) photocathode (Handler et al. 2000). We used *B*, *V* and *I* filters and the exposure time varied between 15 and 30 s, depending on the brightness of the observed star.

(iv) *Piszkéstető Station, 0.6 m (P60).* *V*-band CCD photometry was obtained on CY Aqr, XX Cyg, DY Her and DY Peg with the 60/90/180 cm Schmidt telescope mounted at the Piszkéstető Station of the Konkoly Observatory. The detector was a Photometrics AT200 CCD camera (1536 × 1024 9 μm pixels, FOV = 28 × 19 arcmin^2).

(v) *Fred Lawrence Whipple Observatory, 1.5 m (MH150).* High-resolution spectra were obtained on BE Lyn with the Tillinghast Reflection Echelle Spectrograph (TRES) and the 1.5-m telescope at the Fred Lawrence Whipple Observatory on Mt. Hopkins, Arizona. TRES is a high-throughput fibre-fed echelle. It is cross-dispersed, yielding a passband of 380–920 nm over the 51 spectral orders. It accommodates three optical fibre pairs (science + sky) of different diameters, to offer a match for seeing conditions. Simultaneous ThAr calibration is also available via a separate fibre. The available resolutions are 64, 35 and 31 K, depending on the fibre size selected (1.5, 2.3 or 3.2 arcsec, respectively). The observations were taken as part of the instrument commissioning, using the small fibre and 300 s integration times. The 4.6 × 2 k detector was binned 2 × 2 in order to improve the duty cycle (15 s readout time), providing a slightly undersampled full width at half-maximum (FWHM) of 2.0 pixel.

(vi) *Siding Spring Observatory, 2.3 m (SSO230).* Spectroscopic observations were carried out for RY Lep, AD CMi, ZZ Mic, RS Gru and CY Aqr with the 2.3 m Australian National University (ANU) telescope at the Siding Spring Observatory, Australia. All spectra were taken with the Double Beam Spectrograph using the 1200 mm^{-1} gratings in both the arms of the spectrograph. The projected slit width was 2 arcsec on the sky, which was about the median seeing during our observations. The spectra covered the wavelength ranges 4200–5200 Å in the blue arm and 5700–6700 Å in the red arm. The dispersion was 0.55 Å pixel^{-1}, leading to a nominal resolution of about 1 Å. The exposure time varied between 50 and 180 s depending on the observed star and the weather conditions.

(vii) *Anglo-Australian Observatory, 3.9 m (Anglo-Australian Telescope).* We used the 3.9 m Anglo-Australian Telescope (AAT) equipped with the University College of London Echelle Spectograph (UCLES) for 4.2 h of high-resolution spectroscopy of RS Gru. The observations were taken during service time. Our echelle spectra include 56 orders with a central wavelength of 6183 Å and a resolving power $\lambda/\Delta\lambda \approx 40\,000$. The exposure time was 300 s.

Table 2. New times of maximum (HJD 2400000).

Star	$\mathrm{HJD_{max}}$	Filter	Star	$\mathrm{HJD_{max}}$	Filter
RS Gru	52920.0196	*V*	CY Aqr	53334.9453	*I*
RS Gru	52921.9311	*V*	CY Aqr	53336.9592	*I*
RS Gru	52922.0772	*V*	CY Aqr	53337.9357	*I*
RS Gru	52923.9905	*V*	CY Aqr	54307.5293	*V*
RS Gru	52925.0188	*V*	CY Aqr	54308.5073	*V*
CY Aqr	52920.9223	*V*	XX Cyg	54307.4294	*V*
CY Aqr	52920.9827	*V*	XX Cyg	54309.4515	*V*
CY Aqr	52921.0439	*V*	XX Cyg	54677.3633	*V*
CY Aqr	52923.0587	*V*	DY Her	54304.4772	*V*
CY Aqr	52926.9643	*V*	DY Peg	54305.4731	*V*
CY Aqr	52927.0258	*V*			

All data were reduced with standard tools and procedures. Photoelectric photometry taken with the SSO60 instrument was transformed to the standard system using the coefficients from Berdnikov & Turner (2004). Uncertainties in the Fourier amplitudes were calculated following the considerations of Kjeldsen (2003). The *BV* standard magnitudes of comparison stars were taken from Kharchenko (2001), while *I* standard magnitudes were taken from the DENIS catalogue (The DENIS consortium 2005). The CCD observations were reduced in IRAF[1], including bias removal and flat-field correction utilizing sky-flat images taken during the evening or morning twilight. Differential magnitudes were calculated with aperture photometry using two comparison stars of similar brightnesses.

Thanks to the dense sampling of the light curves, new times of maximum light for monoperiodic stars were easy to determine from the individual cycles. This was done by fitting fifth-order polynomials to the light curves around the maxima. We estimate the typical uncertainty to be about ±0.0003 d. The new times of maximum light are listed in Table 2.

For the multiperiodic stars, we performed standard Fourier analysis with pre-whitening using Period04 (Lenz & Breger 2005). Least-squares fitting of the parameters was also included and the signal-to-noise ratio (S/N) of each frequency was calculated following Breger et al. (1993).

All spectra were reduced with standard tasks in IRAF. Reduction consisted of bias and flat-field corrections, aperture extraction, wavelength calibration and continuum normalization. We checked the consistency of wavelength calibrations via the constant positions of strong telluric features, which verified the stability of the system. Radial velocities were determined with the task *fxcor*, applying the cross-correlation method using a well-matching theoretical template spectrum from the extensive spectral library of Munari et al. (2005). For consistency, the velocities presented in this paper were all determined from a 50 Å region centred on the Hα line. The high-resolution spectra for BE Lyn and RS Gru allowed us to compare hydrogen and metallic line velocities, which will be discussed in a subsequent paper. We made barycentric corrections to every radial velocity value. Depending on the S/N of the spectra, the estimated uncertainty of the radial velocities ranged from 1 to 5 km s^{-1}. Radial velocities from the AAT and MH150 Echelle spectra have much better accuracy, $\leq$100 m s^{-1}.

3 RESULTS

3.1 RS Gruis

RS Gru (HD 206379; HIP 107231) is a monoperiodic HADS with a pulsation period of 0.147 d and a mean magnitude of ∼7.9 mag. Its light variation was first detected by Hoffmeister (1956) and studied later by Eggen (1956) and Oosterhoff & Walraven (1966). Kinman (1961) took photometric and spectroscopic observations and measured a mean velocity of 81 km s^{-1} with a velocity amplitude of ∼45 km s^{-1}. McNamara & Feltz (1976) obtained *uvbyβ* photometry and spectrographic data and determined physical parameters. van Citters (1976) acquired photoelectric radial velocity curves on two nights, while further photometric observations were taken by Dean et al. (1977). New radial velocity measurements taken by Balona & Martin (1978a) showed unambiguously the variation of the centre-of-mass velocity, indicating the binary nature of RS Gru but the orbital period was not determined for nearly three decades. Further investigations were done by Breger (1980), Andreasen (1983), McNamara (1985), Antonello et al. (1986), Garrido, Garcia-Lobo & Rodríguez (1990), Claret, Rodríguez & Garcia (1990) and Rodríguez et al. (1990b). Period decrease was found by Rodríguez et al. (1995a,b) and physical parameters were also calculated by Rodríguez et al. (1995b). Joner & Laney (2004) took high-quality spectroscopic measurements and determined the radius and the absolute magnitude for RS Gru. They again showed unambiguously that RS Gru is a spectroscopic binary with an orbital period of approximately two weeks but no exact period was given.

We obtained standard *BVI* photoelectric photometry using SSO60 on four nights in 2003 and one night in 2004. For differential magnitudes, we used two comparison stars: comp = HD 207193 ($V = 6.79$ mag, $B - V = 0.35$ mag) and check = HD 207615 ($V = 8.53$ mag, $B - V = 0.08$ mag). The full log of observations is given in Table A1 and the light and colour variation are plotted in Fig. 1.

To measure the orbital period of the system, we obtained medium-resolution spectroscopy on 16 nights between 2003 and 2005 using the SSO230 instrument. In addition, we observed the star with the

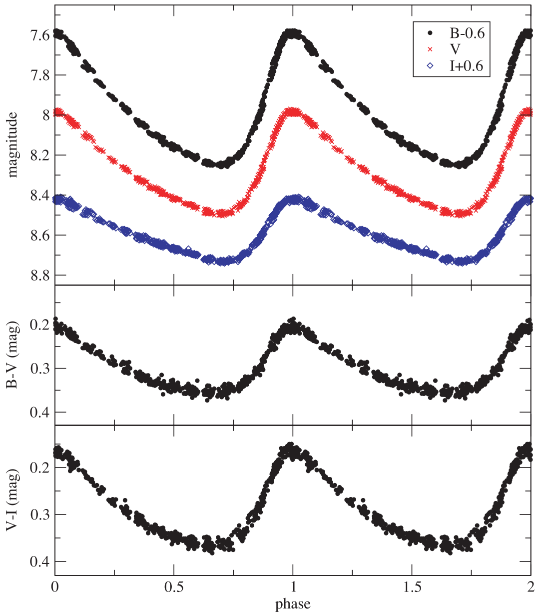

Figure 1. Standard light and colour variations of RS Gru (E_0 = 2452 920.0196; $P = 0.14\,701\,131$ d).

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[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.

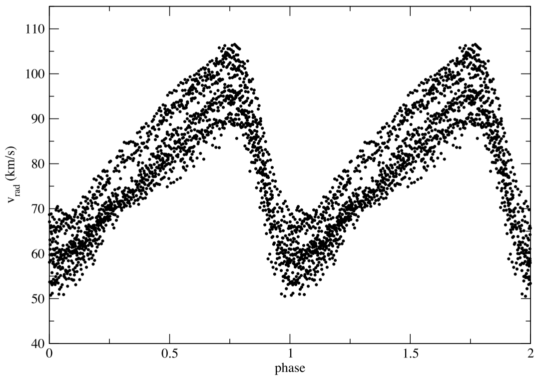

Figure 2. Radial velocities of RS Gru, phased with the pulsation period.

Table 3. Centre of mass velocities of RS Gru.

HJD 2400000 (d)	v_γ (km s^{-1})	HJD 2400000 (d)	v_γ (km s^{-1})
52922.0214	73.5±0.2	53524.2197	88.2±0.3
53274.1377	82.8±0.2	53600.0627	73.2±0.2
53275.1222	84.4±0.2	53601.0413	78.2±0.2
53276.0892	78.3±0.2	53604.0516	86.0±0.8
53520.2614	73.1±0.2	53605.1980	84.8±0.3
53521.2482	76.3±0.2	53606.2073	86.5±0.1
53522.2248	77.5±0.2	53937.2552	84.6±0.05
53523.2573	82.5±0.2		

AAT on 1 night in 2006. The whole phased data set is shown in Fig. 2, where the continuously changing shift in the systemic velocity is evident.

We performed a period analysis of the radial velocities, which revealed the main pulsation frequency at $f_1 = 6.802$ c d^{-1}, its integer harmonics $(2f_1, 3f_1)$ and a low-frequency component at about ∼0.11 c d^{-1}, corresponding to a period of 9 d. However, we did not accept this as the orbital period because the high-amplitude pulsation and random sampling may interplay and thus render the results unreliable. Therefore, we determined the orbital period as follows. First, we selected the best-defined single-night radial velocity curve to fit a smooth trigonometric polynomial to the phased radial velocity (RV) data. Then, we used the fixed polynomial to determine individual γ-velocities for each night by fitting the zero-point only. This way we could determine the centre-of-mass velocity on 15 nights (listed in Table 3). The Fourier spectrum of the data (Fig. 3) shows a broad hump of peaks around 0.1 c d^{-1} with the highest peak at 0.087 c d^{-1}, which we identify as the most likely orbital frequency. The phased γ-velocities (Fig. 4) show a reasonably convincing sine-wave, for which the best-fitting curve (solid line in Fig. 4) indicates a velocity amplitude of $K = 6.5$ km s^{-1}.

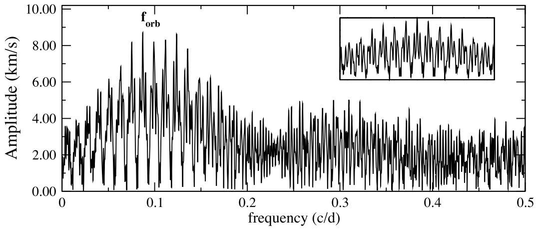

Figure 3. Fourier spectrum of the γ-velocities of RS Gru. Inset shows the spectral window.

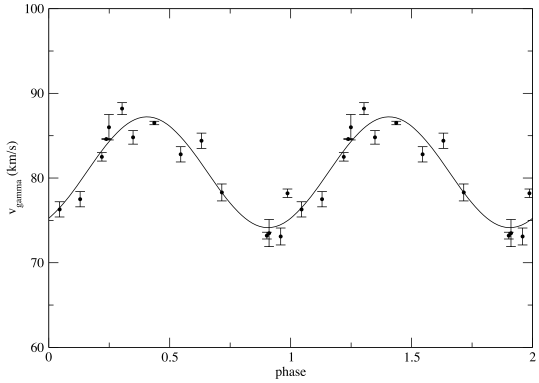

Figure 4. γ-velocity variation of RS Gru phased with $P_{\rm orb} = 11.5$ d.

Table 4. Estimated mass (M_2) for the companion of RS Gru.

	$M_1 = 1.5\,{\rm M}_\odot$	$M_1 = 2\,{\rm M}_\odot$	$M_1 = 2.5\,{\rm M}_\odot$
Inclination (°)	M_2 (M$_\odot$)	M_2 (M$_\odot$)	M_2 (M$_\odot$)
90	0.09	0.11	0.13
70	0.10	0.12	0.14
50	0.12	0.15	0.17
30	0.20	0.24	0.27
10	0.66	0.78	0.89

From these, we can estimate the mass of the companion from the mass function (Hilditch 2001): $f(M) = (1.0361 \times 10^{-7})(1 - e^2)^{3/2}\, K^3\, P = M_2^3 \sin^3 i/(M_1 + M_2)^2 = 3.3 \times 10^{-4}\,{\rm M}_\odot$. Assuming that the δ Scuti mass is about 1.5–2.5 M$_\odot$, the calculated minimum mass for the companion at different inclinations is shown in Table 4. The derived masses show that the companion of the RS Gru is most likely a low-mass star. We can also estimate the semimajor axis of the system, which is about ∼0.1 au ($a = 0.11$ au at $M_2 = 0.09\,{\rm M}_\odot$ and $a = 0.13$ au at $M_2 = 0.89\,{\rm M}_\odot$).

There is an interesting possibility to determine the pulsation constant, which is most useful for pulsating stars in eclipsing binaries, where the radius of the stars can be determined accurately (Jørgensen & Grønbech 1978). Combining Kepler's third law and the pulsation constant formula:

$$\frac{a^3}{P_{\rm orb}^2} = \frac{G}{4\pi^2}(M_1 + M_2) \quad \text{and} \quad Q = P_{\rm pul}\left(\frac{M_1}{R_1^3}\right)^{1/2} \tag{1}$$

results in (using the same units)

$$Q = 0.1159\frac{P_{\rm pul}}{P_{\rm orb}}\left(\frac{R_1}{a}\right)^{-3/2}\left(1 + \frac{M_2}{M_1}\right)^{-1/2}. \tag{2}$$

Adopting $R_1 = 2.9 \pm 0.1\,{\rm R}_\odot$ (Balona & Martin 1978a), $P_{\rm pul} = 0.147$ d, $P_{\rm orb} = 11.5$ d, $a = 0.12 \pm 0.01$ au, $M_1 = 2.0 \pm 0.1\,{\rm M}_\odot$ (Rodríguez et al. 1995b) and $M_2 = 0.2 \pm 0.02\,{\rm M}_\odot$, the resulting $Q = 0.037 \pm 0.013$ d is consistent with pulsations in the radial fundamental mode. The dominant sources of error are the radius, the unknown inclination and the orbital semimajor axis, which pose a significant limitation at this stage. It is nevertheless reassuring that the given orbital period and size yield a consistent picture of RS Gru being a fundamental mode pulsator.

3.2 RY Leporis

The light variation of RY Lep (HD 38882; HIP 27400; $V = 8.2$ mag; $I = 8.3$ mag) was discovered by Strohmeier (1964) and the star was thought to be an eclipsing binary with an unknown period for more than two decades. The SIMBAD data base still lists it as an eclipsing binary. Diethelm (1985) obtained five nights of observations which revealed the real HADS nature of this star. He determined the pulsation period as 0.2254 d and also noted small cycle-to-cycle variations, but the data were not sufficient to draw a firm conclusion. Rodríguez et al. (1995b) determined physical parameters based on one night of $uvby\beta$ observations, covering one pulsation cycle. Laney, Joner & Schwendiman (2002) found aperiodic or possibly multiperiodic variations and detected binary motion in the radial velocities with a period more than 500 d. Finally, Rodríguez et al. (2004) have shown unambiguously the multiperiodic nature of RY Lep ($f_1 = 4.4416$ c d^{-1}, $f_2 = 6.60$ c d^{-1}) and its binarity was also suggested from an analysis of the O–C diagram (details have not yet been published).

To study RY Lep photometrically, we obtained I-band CCD images on 20 nights between 2004 October and 2005 January using the APT50 instrument. We obtained more than 5000 data points with 10 s exposures. The full log of observations is given in Table A1. For the aperture photometry, we used two comparison stars: comp = GSC 05926−01037 ($V = 9.98$ mag, $I = 9.34$ mag, $B - V = 1.2$ mag) and check = HD 39036 ($V = 8.21$ mag, $I = 8.72$ mag, $B - V = 1.06$ mag). The full light curve is shown in Fig. 5.

We performed standard Fourier analysis of the data. Fig. 6 shows the results of the frequency search. We identified the two main pulsational frequencies at $f_1 = 4.4415$ c d^{-1} and $f_2 = 6.5987$ c d^{-1}. A further 14 statistically significant peaks were found in the data, which are mainly the various linear combinations of the two pulsation modes, and thereupon validating the pulsational nature of f_2. The results of the period analysis are summarized in Table 5.

The resulting frequencies (f_1, f_2) are in a very good agreement with those by Rodríguez et al. (2004). We have two low-amplitude peaks that seem to be significant and may be related to pulsations (f_{14} and f_{15}), similarly to V743 Cen, AI Vel and VW Ari, where 3, 4 and 7 frequencies were detected, respectively (McAlary & Wehlau 1979; Walraven, Walraven & Balona 1992; Liu et al. 1996). Three low-frequency components that are presumably artefacts (f_7, f_{10} and f_{12}). The frequency ratio of f_1 and f_2 is 0.6731 which is not compatible with the usual scenario of fundamental and first-overtone radial modes (FU/1O ≈ 0.77). Rodríguez et al. (2004) identified f_1 with the fundamental mode and f_2 with a non-radial p_2 mode. The frequency ratio could also indicate first- and third-overtone radial modes, for which theoretical models predict 1O/3O ≈ 0.68 (Santolamazza et al. 2001), but the physical parameters of the star, such as temperature, luminosity and evolutionary mass, are not compatible with that possibility (Rodríguez et al. 1995b, 2004).

Looking at the pulsational amplitudes of RY Lep, one can note some interesting features. In our data, the amplitude ratio of the f_2 and f_1 frequencies is about 0.5. Contrary to this, observations by Rodríguez et al. (2004) implied a significantly lower amplitude ratio of about 0.1. If we use a transformation factor $F \approx 1.7$ between the I- and the V-band amplitudes (see fig. 2 of Balona & Evers (1999)), numbers in Table 5 imply $\Delta V(f_1) = 164.6$ mmag and $\Delta V(f_2) = 79.2$ mmag. In comparison, the data in Rodríguez et al. (2004), obtained between 1998 and 2002, revealed $\Delta V(f_1) = 164.8$ mmag and $\Delta V(f_2) = 11.1$ mmag (Rodríguez, personal communication). We conclude that f_1 seems to be very stable in amplitude, whereas f_2 shows strong amplitude variations, with recent data implying an eight-times larger amplitude.

The first spectroscopic measurement of RY Lep was presented by Popper (1966), where the spectral type was determined as F0. Recently, Laney et al. (2002) found clear evidence for binary motion using radial velocity measurements but the data did not allow them

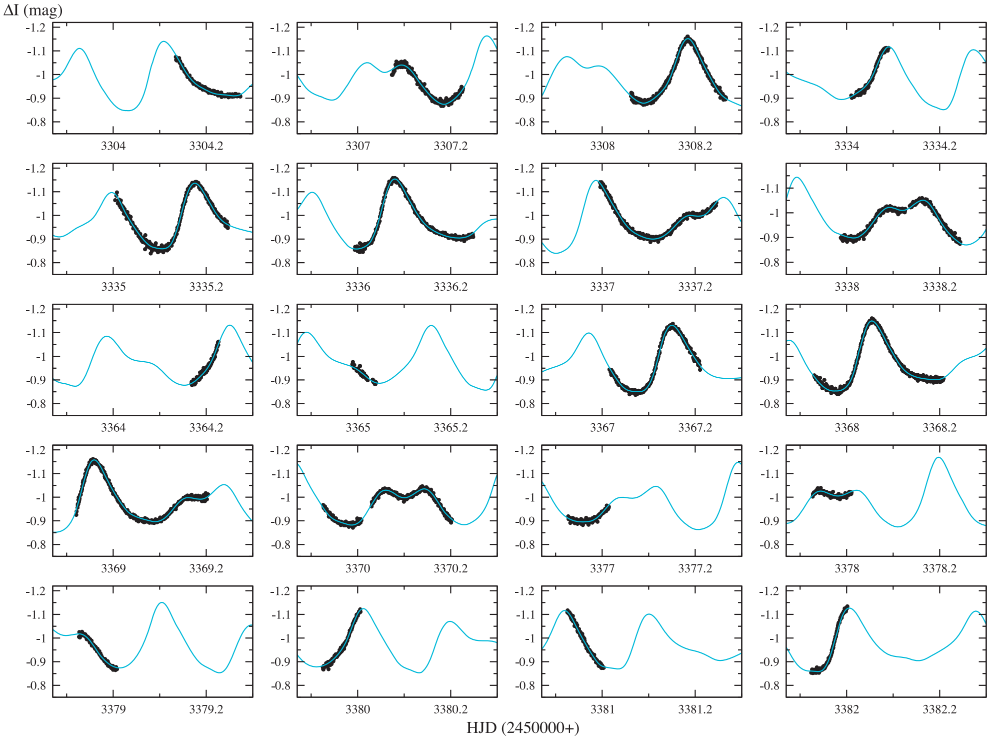

Figure 5. Individual light curves of RY Lep (small dots) with the light-curve fit (continuous line).

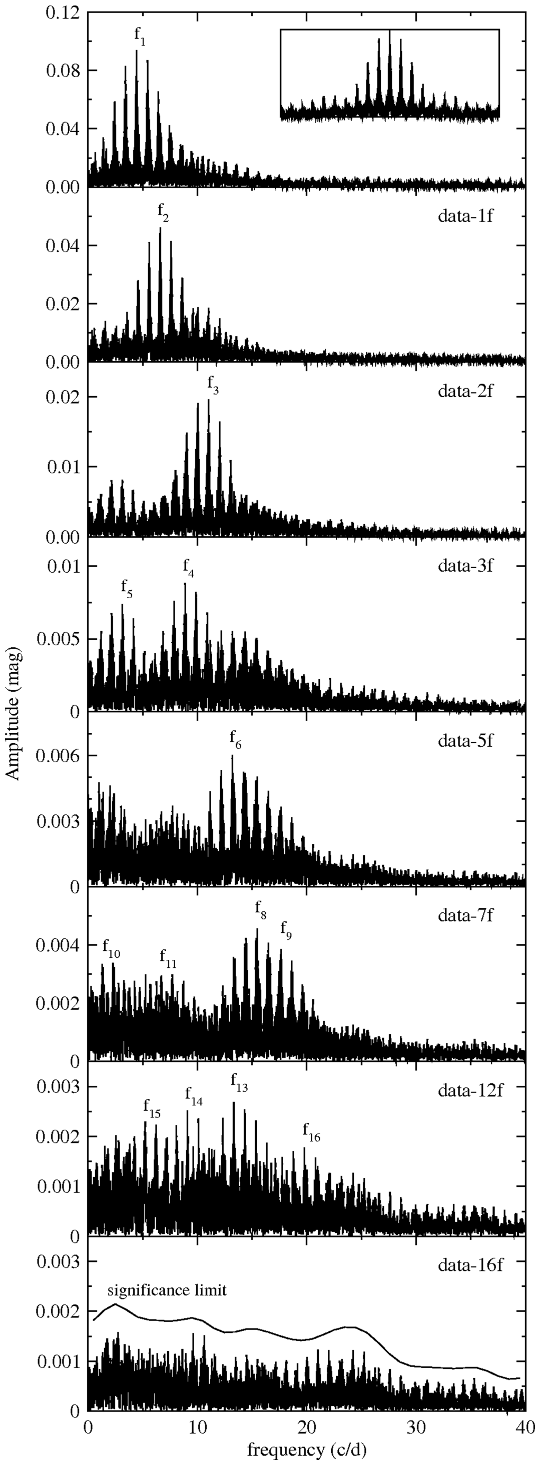

Figure 6. Amplitude spectra of 20 nights of *I*-band data for RY Lep. The insert shows the window function. From top to bottom panel, every panel shows an amplitude spectrum pre-whitened with all frequencies marked in the panels above. 16 frequencies can be identified with S/N larger than 4.

to determine the orbital period which appeared to be longer than 500 d.

We obtained radial velocity measurements on four nights in 2004 and two nights in 2005. The RV curves of the seasonal data sets (2004 February, 2004 October and 2005 December) phased with the main period (f_1) are presented in Fig. 7 with three different symbols.

Table 5. The result of the period analysis for RY Lep. f_1 and f_2 are the two pulsation modes, the remaining peaks are predominantly to be the harmonics or linear combinations of these two frequencies. '?' denotes frequencies with no unambiguous identification.

Number	Frequency (d^{-1})	Amplitude (mmag)	S/N	Frequency identification
		±0.4		
f_1	4.4415	96.8	204	
f_2	6.5987	46.6	103	
f_3	11.0402	19.3	42	$f_1 + f_2$
f_4	8.8830	10.5	24	$2f_1$
f_5	3.1600	10.2	20	$f_2 - f_1 + 1.0$
f_6	13.1978	5.3	14	$2f_2$
f_7	0.0046	5.0	12	?
f_8	15.4833	4.0	10	$2f_1 + f_2$
f_9	17.6382	3.7	10	$f_1 + 2f_2$
f_{10}	1.3962	5.6	12	?
f_{11}	6.7237	3.6	8	$3f_1 - f_2$
f_{12}	0.2379	3.4	8	?
f_{13}	13.3228	3.2	8	$3f_1$
f_{14}	9.0885	2.9	8	?
f_{15}	5.2661	3.5	8	?
f_{16}	19.7970	1.9	5	$3f_2$

The pulsation amplitude of RY Lep is about 30 km s^{-1} and its multiperiodic nature causes cycle-to-cycle variations in the RV curves. The 2004 February and 2005 December data sets have basically the same γ-velocity values but the 2004 October data set has a higher value by about 25–30 km s^{-1}. This leads to the conclusion that the orbital motion is clearly detected in the almost 700 d long data set, which is in a agreement with Laney et al. (2002) but still does not allow us to determine the orbital period. To estimate the approximate nature of the companion, we assumed that the orbital period is about 730 d (Laney, Joner & Rodríguez 2003) and took the full range of 25 km s^{-1} in v_γ as an estimate of the $2\mathrm{K}_1$ velocity amplitude. Repeating the same calculations as for RS Gru, the companion's mass is about $1.1 \pm 0.15\,\mathrm{M}_\odot$ and the orbital semimajor axis is 2.3 au, i.e. the companion is comparable to RY Lep in mass. The lack of notable spectral lines from the secondary may suggest a white dwarf but a firm conclusion would require spectra with broader coverage.

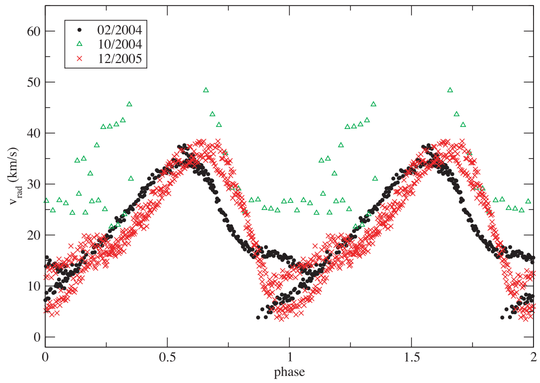

Figure 7. The RV curve of RY Lep phased with $P = 0.225$ d. The data of six nights in 2004 and 2005 clearly show ~25 km s^{-1} of γ-velocity shift between the two sets of observations. Note that the 2004 October data set is binned.

3.3 AD Canis Minoris

One of the best studied HADS is AD CMi (HD 64191; HIP 38473; $V = 9.38$ mag), whose light variation was discovered by Hoffmeister (1934) and classified as an eclipsing binary by Zessewitch (1950). The first detailed study of the star was done by Abhyankar (1959) who took photometric and spectroscopic observations but the data were not sufficient to determine the radius using the Wesselink method. Further observations were obtained by Anderson & McNamara (1960), Epstein & Abraham de Epstein (1973), Dean et al. (1977) and Balona & Stobie (1983). Breger (1975) used *uvby*β photometry to determine radius, mass and variations of physical parameters during the pulsation cycle, while McNamara (1985) found that the rotational velocity is smaller than 20 km s^{-1}. Fourier decomposition of the light curve (Antonello et al. 1986) showed a surprisingly high ϕ_{21} value, suggestive of overtone pulsation. However, the star seems to pulsate in fundamental mode as other monoperiodic HADS stars do (Kilambi & Rahman 1993). There has been no explanation for this phenomenon. Kim (1990) and Kim & Joner (1994) determined the radius of AD CMi, using the visual surface brightness method, and found a very good agreement with angular diameters from theoretical and empirical relationships. Kilambi & Rahman (1993) analysed eight nights of *UBVR* photometry and calculated physical parameters that agree well with Breger (1975) and suggested that the star is lying on the cool-edge of the instability strip of the Population I stars. Jiang (1987) reported a continuous period increase at the star, which was confirmed by Rodríguez, Rolland & Lopez de Coca (1988) and Rodríguez, Rolland & Lopez de Coca (1990a). The stability of light curve was studied by Rodríguez (1999) who found no significant long-term changes in amplitude. The first suggestion for binarity for AD CMi was presented by Fu & Jiang (1996), who found a possible orbital period of 30 yr from the O–C diagram. Most recently, Hurta, Pócs & Szeidl (2007) and Khokhuntod et al. (2007) have studied the period variations of AD CMi using published and new data. They deduced the presence of light-time effect due to binarity and a slow period increase due to evolutionary effect. In addition, Khokhuntod et al. (2007) detected an extra low-frequency component in the photometric data, which provides a possible explanation for the large scatter of the O–C diagram.

We performed spectroscopic measurements on three nights in 2004 February (see Table A1). The phased RV data (Fig. 8) have a mean amplitude of ~25 km s^{-1}, while showing significant cycle-to-cycle variation. The mean velocity is about 40 km s^{-1}. Two radial velocity measurements are available in the literature (Abhyankar 1959; Balona & Stobie 1983). They determined γ-velocities at 34.5 and 38.8 km s^{-1}, respectively. Hurta et al. (2007) interpreted the current O–C diagram as a combination of a continuous period increase and light-time effect. The amplitude of the orbital motion is expected to be about 1.1 km s^{-1} (Hurta et al. 2007). Considering this orbital amplitude, our data are in a good agreement with Balona & Stobie (1983). The Abhyankar (1959) data, six points in total, are of lower quality and have poor phase coverage, so that the larger difference is still compatible with our result.

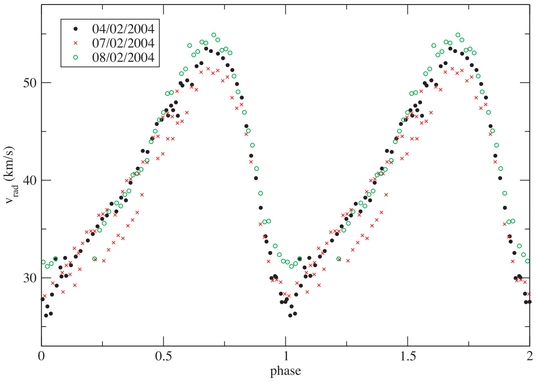

Figure 8. RV curve of AD CMi phased with the pulsation period ($E_0 = 2449\,401.1320$ d; $P = 0.122\,974\,43$ d).

Petersen & Høg (1998) were the first to note that AD CMi may be peculiar in terms of luminosity because the *Hipparcos* parallax indicated that the star, among five others, was situated approximately 3 mag below the standard period-luminosity relation. They even suggested the possible existence of an 'AD CMi group'. We have checked the new reduction of the *Hipparcos* data (van Leeuwen 2007). The updated parallax $\pi = 6.20 \pm 1.47$ mas differs by about 1σ from the original value at $\pi_{\rm old} = 8.40 \pm 1.73$ mas. While the new value pushes the absolute magnitude of AD CMi about 1 mag brighter, there is still a significant shift left unexplained. Studies of HADS/SX Phe variables in clusters and nearby galaxies (e.g. Poretti et al. 2006) do not indicate this large spread in absolute magnitude, so that we suspect that there might be a yet-to-identify source of systematic error in some of the *Hipparcos* HADSs.

Our data also show cycle-to-cycle variations in the shape of RV curve that are within a range of 2–3 km s^{-1} as shown in the phase diagram in Fig. 8. This might be due to the presence of an additional pulsation mode but our data are not extensive enough to resolve multiple modes. If this secondary mode is the same one reported by Khokhuntod et al. (2007), its amplitude must change in time, because the very low amplitude in the Khokhuntod et al. (2007) data is hardly compatible with the 2–3 km s^{-1} cycle-to-cycle RV change we find in the spectroscopic measurements. It is interesting to add that the Abhyankar (1959) data showed a larger peak-to-peak amplitude of about 35 km s^{-1}, which may also be due to cycle-to-cycle variations caused by a second excited mode.

3.4 BQ Indi

BQ Ind (HD 198830; HIP 103290) was discovered to be a variable by the *Hipparcos* satellite and has a mean magnitude $V = 9.8$ mag, $I = 9.7$ mag and a period of 0.081 9877 d (Perryman et al. 1997a). The multiperiodic nature of the star first discovered by Sterken, Fu & Brogt (2003), who determined two frequencies ($f_1 = 12.1951$ c d^{-1}, $f_2 = 15.7686$ c d^{-1}), corresponding to the fundamental and first-overtone modes. Since then, no further observations have been reported in the literature.

We performed CCD photometry on BQ Ind on six consecutive nights in 2004 with APT50. More than 700 data points were obtained with 30–40 s exposure time in I band; a log of observations is given in Table A1. For the aperture photometry, we used two comparison stars: comp = GSC 08800−00069 ($V = 10.6$ mag, $I = 9.51$ mag, $B - V = 1.28$ mag) and check = PPM 774 605 ($V = 10.5$ mag, $I = 9.34$ mag, $B - V = 1.38$ mag). The full light curve is shown in Fig. 9.

The amplitude spectrum is shown in Fig. 10. The primary peak was found at $f_1 = 12.1961$ d^{-1} and the next pre-whitening step yielded the secondary frequency at $f_2 = 15.7593$ d^{-1}. After subtracting the two main frequencies, we ended up at their linear combination and then the integer harmonics ($2f_1$, $3f_1$) of the primary frequency. Their parameters are summarized in Table 6.

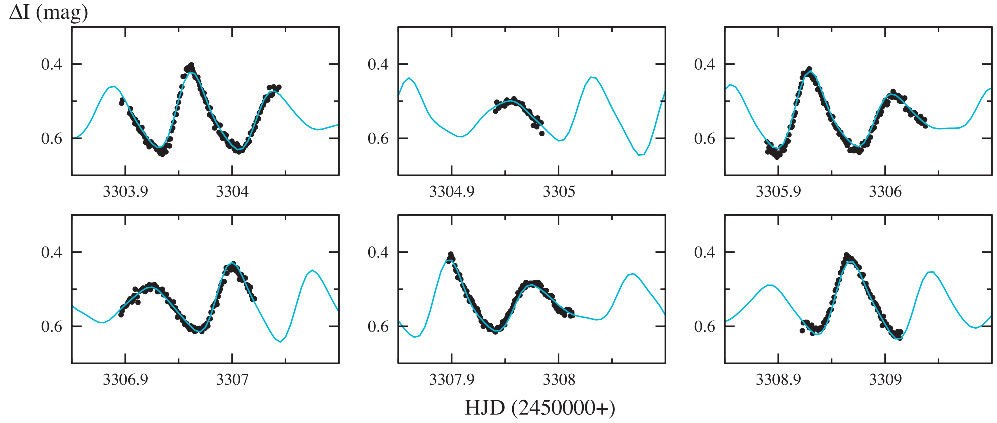

Figure 9. Individual light curves of BQ Ind (small dots) with the five-component fit.

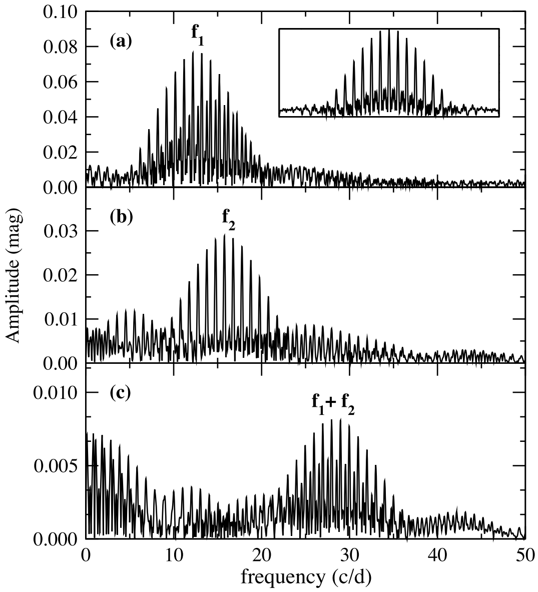

Figure 10. Fourier analysis of BQ Ind. Panel a: amplitude spectrum of the complete data set. The insert shows the window function. Panel b: after removal of the main period and its harmonics, the secondary period is clearly seen. Panel c: after removal of the secondary period, the next peak is the linear combination of the two frequencies.

Table 6. The result of the period analysis for BQ Ind.

Number	Frequency (d^{-1})	Amplitude (mmag)	S/N	Mode combination
		±1.1		
f_1	12.1961	71.1	54	
f_2	15.7593	30.2	29	
f_3	27.9580	9.0	6	f_1+f_2
f_4	24.3903	10.4	7	$2f_1$
f_5	36.5671	2.9	5	$3f_1$

The resulting two frequencies (f_1, f_2) confirm the double-mode nature of BQ Ind, and are in a very good agreement (within 1 per cent) with the frequencies determined by Sterken et al. (2003), with no further frequencies in the residuals. The period ratio is $f_1/f_2 = 0.7739$, which suggests fundamental (f_1) and first-overtone (f_2) mode pulsation.

3.5 ZZ Microscopii

The short-period variability of ZZ Mic (HD 199757; HIP 103684) was discovered by Churms & Evans (1961). Its average V magnitude is 9.43 mag and the pulsation period is 0.0654 d. The first detailed analysis of this star was done by Leung (1968), who found cycle-to-cycle variation in ultraviolet light and also detected a period decrease. Later the photoelectric observations and data analysis (Chambliss 1971; Rodríguez 1999) did not confirm any change in the light-curve shape. Percy (1976) reanalysed Leung's observations and deduced two periods: 0.0654 and 0.0513 d, suggesting fundamental and first-overtone pulsations (Balona & Martin 1978b). Previously, Bessell (1969) analysed spectrophotometric and spectroscopic observations and determined the pulsation constant, masses and absolute magnitudes, concluding the first-overtone pulsating nature of ZZ Mic. The first radius determination of the star was carried out by Balona & Martin (1978b). The last analysis of the star was done by Rodríguez (1999), who studied the stability of the light curve and did not find any significant long-term amplitude change.

We took three nights of photoelectric observations in 2004 using B, V filters on SSO60. For the calculations of differential magnitudes, we used the following two comparison stars: comp = HD 199639 (V = 7.28 mag, $B - V$ = 0.16 mag) and check = HD 200320 (V = 8.96 mag, $B - V$ = 0.51 mag). The phase diagrams are shown in Fig. 11.

Since the discovery of ZZ Mic, it has been controversial in terms of changing the light-curve shape and being multiperiodic. In order to study the question, we performed a period analysis of our admittedly meagre V-band data. The pre-whitening steps are plotted in Fig. 12, while the resulting parameters are listed in Table 7. The Fourier spectrum is dominated by the main pulsational period (f_1 = 14.896 c d^{-1}) and its harmonic. With a much lower amplitude (A_3 = 14 mmag compared to A_1 = 147.3 mmag), we detected a secondary period at f_3 = 19.15 c d^{-1} which is in a reasonably good agreement with that of Percy (1976) (f_1 = 15.3 c d^{-1}, f_2 = 19.5 c d^{-1}). The S/N of this frequency is 8, which is quite low compared to f_1 and $2f_1$ but still above the significance limit.

Because of the limited data we have, we tried to detect the secondary frequency in other publicly available data. We analysed the data from the All Sky Automated Survey (ASAS) project

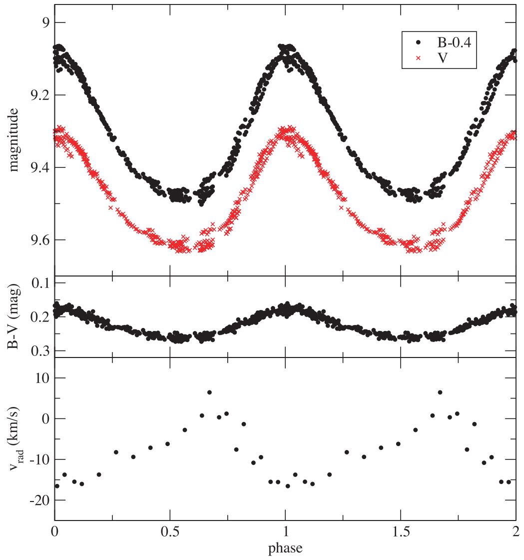

Figure 11. Standard light, colour and radial velocity variations of ZZ Mic ($E_0 = 2453\,305.9819$ d; $P = 0.067\,1835$ d).

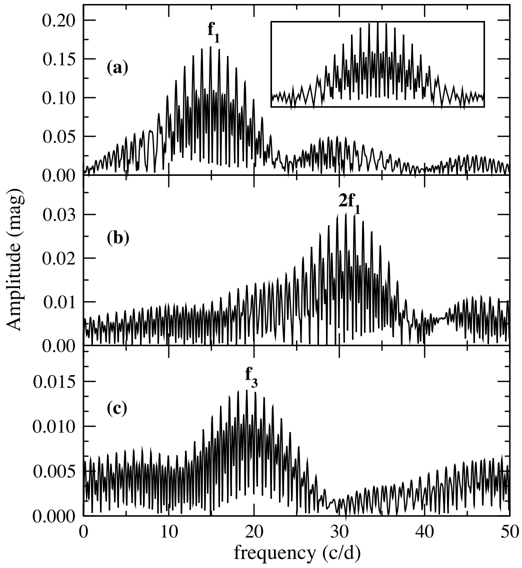

Figure 12. Fourier spectra of ZZ Mic with the pre-whitening steps. The insert shows the spectral window.

Table 7. The result of the period analysis for the ZZ Mic.

Number	Frequency (d^{-1})	Amplitude (mmag)	S/N	Mode combination
		±1.4		
f_1	14.896	147.3	85	
f_2	30.77	29.7	42	$2f_1$
f_3	19.15	14	8	

(Pojmański 2002). The Fourier spectrum of this data (Fig. 13) clearly shows the main pulsational period at f_1 =14.885 c d^{-1} but the noise level in the data set (∼23 mmag) is too high compared to the amplitude of the secondary frequency (∼14 mmag), which prevents any detection in the ASAS data.

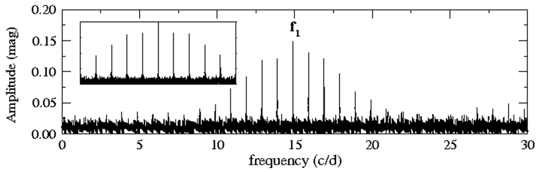

Figure 13. The Fourier spectrum of ZZ Mic using the ASAS data. The insert shows the spectral window.

If we accept f_3 as an independent mode, the ratio of the two modes is $f_1/f_3 = 0.778$. This suggests that f_1 is the fundamental mode and f_3 is the first-overtone mode. The fundamental mode identification for f_1 is strongly supported by the $ubvy\beta$ photometry of Rodríguez, Lopez-González & Lopez de Coca (2000). Moreover, f_1 must be a radial mode which was suggested from the phase shifts in *BV* photometry by Rodríguez et al. (1996).

Moreover, a period ratio of 0.778 seems to be too large for a normal Pop I HADS (Poretti et al. 2005; Petersen & Christensen-Dalsgaard 1996) which suggests that ZZ Mic is a Pop II star. However, the value of f_3 is not too reliable, so the period ratio might be slightly different. Studies on metal abundances and space motions (Breger 1980) suggest that ZZ Mic is a normal Pop I HADS, which is also supported by Rodríguez et al. (2000).

We obtained spectra simultaneously with *BV* light curves on one night using SSO230. The resulted RV curve is shown in the bottom panel of Fig. 11, which is the first radial velocity curve obtained of ZZ Mic. The full amplitude of the RV curve is 22 km s^{-1}.

3.6 CY Aquarii

CY Aqr (HIP 111719; $V = 10.7$ mag, $I = 10.3$ mag) is one of the shortest period HADS in the galactic field, with a pulsation period of 0.061 038 d, and has been subject to many investigations. It was discovered by Hoffmeister (1935). A number of early studies on the star are listed by Hardie & Tolbert (1961), who estimated physical parameters and found that the shape of the light curve varies. The period stability was studied by Ashbrook (1954), who found no change in period but noted a phase jump that seemed to be attributed to the star. Further studies were made by Zissell (1968), Nather & Warner (1972) and Bohusz & Udalski (1980). Changes in light-curve shape and the possibility of another period were also investigated in several papers, e.g. Elst (1972), Fitch (1973) and Figer (1978), but both phenomena were discounted later by Geyer & Hoffmann (1975), Percy (1975), Purgathofer & Schnell (1984) and Hintz & Joner (1997). Finally, Coates et al. (1994) set a definite upper limit of 1.5 mmag in *V* for the amplitude of any long-lived secondary period.

Kämper (1985) made a thorough period study and his results indicated the presence of random fluctuations in pulsation frequency that cannot be explained by considering only evolution. Other period change studies were performed by Rolland et al. (1986), Mahdy, Soliman & Hamdy (1988) and Powell, Joner & McNamara (1995). McNamara, Powell & Joner (1996) determined physical properties. Fu, Jiang & Liu (1994) suggested that the period changes due to the presence of an unseen companion with an orbital period of around 50 yr. Zhou, Fu & Jiang (1999) and Fu & Sterken (2003) studied the O–C diagram to characterize the long-term period evolution. They found a long-term cyclic component, and both suggested a possible binarity for CY Aqr with an orbital period of ∼62.4 and ∼52.5 yr, respectively.

We obtained three nights of standard *BVI* photoelectric, five nights of *I* band and five nights of CCD *V*-band photometry with

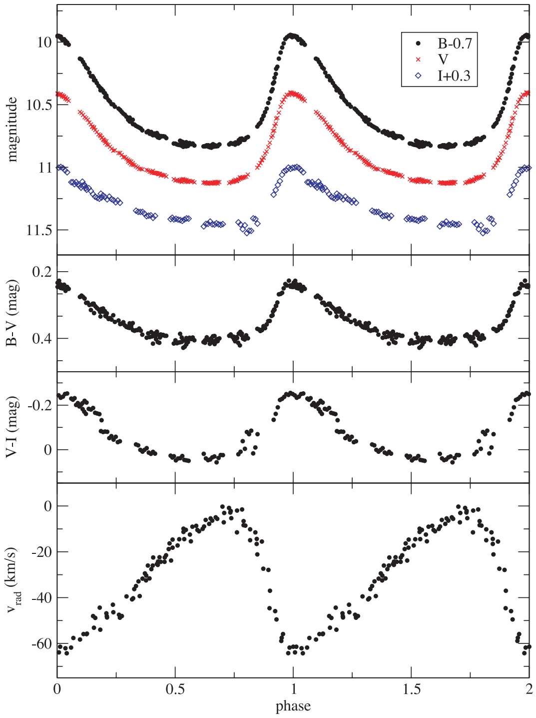

Figure 14. Standard light, colour and radial velocity variations of CY Aqr ($E_0 = 2452\,920.9223$ d; $P = 0.061\,038\,328$ d).

SSO60, APT50 and P60 between 2003 and 2007. The integration time was 15 s with SSO60 and 50 s with the APT50. The full log of observations is given in Table A1. Differential magnitudes were calculated using the following comparison stars: comp = GSC 00567−02242 ($V = 9.8$ mag, $I = 8.96$ mag, $B - V = 1.38$ mag) and check = GSC 00567−01242 ($V = 10.6$ mag, $I = 9.62$ mag, $B - V = 1.14$ mag). The resulting light and colour curves are plotted in the top three panels of Fig. 14. We determined new times of maximum that are listed in Table 2. The O–C diagram (not shown) is in a very good agreement with light-time solution determined by Fu & Sterken (2003).

We obtained spectroscopic observations on two nights in 2003 and 2004. The mean radial velocity is -38 km s^{-1}. This value is in a good agreement with previous data by Struve (1949) and Fernley et al. (1987), who measured -32 and -40 km s^{-1}, respectively. The predicted amplitude of mean velocity change due to the binarity is $\sim$1.4 km s^{-1} (Zhou et al. 1999) which is comparable to the accuracy of our observation. Furthermore, due to the high eccentricity and long period of the binary system, the mean velocity changed only slightly in the last 10 yr, which is far beyond our detection limit. In conclusion, our radial velocity observations do not contradict the current understanding of the nature of CY Aqr.

3.7 BE Lyncis

We obtained high-resolution spectroscopy of BE Lyn on three nights with MH150 in order to detect possible binarity or additional pulsational frequencies. The period change of this star inspired a series of studies by our group (Kiss & Szatmáry 1995; Derekas et al. 2003; Szakáts et al. 2008) and, while the initial orbital elements of the suspected binary system were ruled out and hence leaving the binarity unconfirmed, the lack of spectroscopic data in the literature has kept this star in our focus.

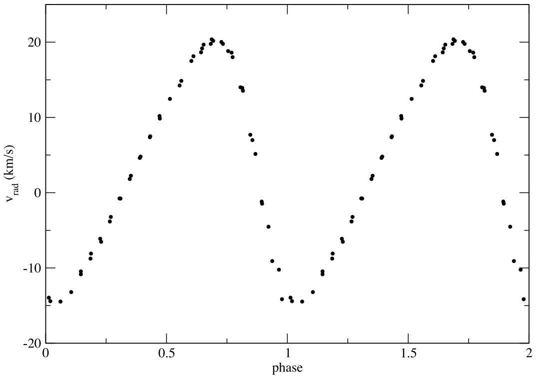

Figure 15. Phased RV curve of BE Lyn (HJD = 244 9749.4651 d, P = 0.09 586 952 d).

To our knowledge, our radial velocity measurements are the first obtained for BE Lyn. The phased RV curve is shown in Fig. 15, where we see characteristic shape and velocity amplitude for fundamental mode pulsation. The centre-of-mass velocity is measured at 3.4 km s^{-1}, while the amplitude of the variation is $\sim$34 km s^{-1}. There is no sign of γ-velocity change during the three nights of observation and we also could not detect any non-radial mode pulsation in the RV curve. Further study of the data in terms of velocity gradient within the stellar atmosphere is in progress.

3.8 Period updates for XX Cygni, DY Pegasi and DY Herculis

We performed times-series photometry on XX Cyg, DY Peg and DY Her. Previous studies of these stars are listed in Derekas et al. (2003). Since then, only DY Peg was studied by Hintz et al. (2004), who explained the period change of the star with two period breaks rather than continuously decreasing rate, as was previously thought.

We obtained three nights of V-band CCD photometry on XX Cyg with P60 and Sz40 and one-one night on DY Her and DY Peg with P60 during 2007 and 2008. The journal of observations is given in Table A1. We determined new times of maximum that are listed in Table 2. The updated O–C diagrams contain these and recently published data collected from the literature (Agerer & Hübscher 2003; Hübscher 2005; Hübscher, Paschke & Walter 2005; Bíró et al. 2006; Hübscher, Paschke & Walter 2006; Klingenberg, Dvorak & Robertson 2006; Hübscher 2007; Hübscher & Walter 2007).

We calculated the O–C diagram of XX Cyg using the following ephemeris: $\mathrm{HJD_{max}} = 245\,1757.3984 + 0.134\,86513 \times E$ (Derekas et al. 2003), and the resulting diagram is shown in the top panel of Fig. 16. The parabolic fit form of the O–C diagram is $\mathrm{HJD_{max}} = 0.0003 + 3.49 \times 10^{-8}E + 2.93 \times 10^{-13}E^2$ with an rms of 0.001 52 d. The second-order coefficient corresponds to a relative rate of period change $\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}t} = 1.17 \times 10^{-8}\mathrm{yr}^{-1}$, which is only slightly different from the value of 1.13×10^{-8} yr^{-1} given by Blake et al. (2003). Therefore, we can conclude that the period of XX Cyg has been increasing at a same rate of the last few years. The residuals have no signs of any other change.

The O–C diagram of DY Her was calculated with the following ephemeris: $\mathrm{HJD_{max}} = 243\,3439.4871 + 0.148\,6309 \times E$ (Derekas et al. 2003). The diagram is shown in the middle panel of Fig. 16. The O–C diagram was fitted with a parabolic form of $\mathrm{HJD_{max}} = -0.001(3) + 3.98 \times 10^{-7}E - 8.98 \times 10^{-13}E^2$ with an rms of 0.0013 d, which gives $\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}t} = -2.96 \times 10^{-8}\,\mathrm{yr}^{-1}$. There is 6 per cent difference in the rate of period change previously given by Derekas et al. (2003). The residuals do not show any other period

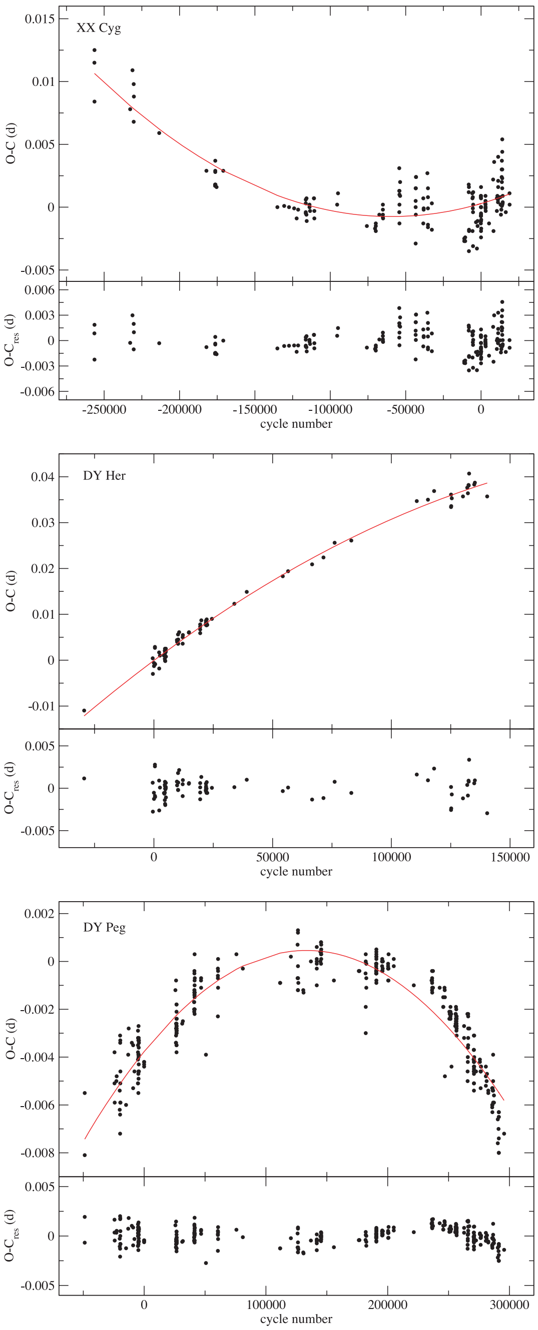

Figure 16. O–C diagram of DY Peg, DY Her and XX Cyg.

change, so we can conclude that the present results in period change are very well agreed with the previous studies of DY Her and the star is showing continuous slow period decrease.

Finally, we also updated the O–C diagram of DY Peg using the following ephemeris: $\mathrm{HJD_{max}} = 243\,2751.9655 + 0.072\,926\,302 \times E$ (Mahdy 1987) and shown the final O–C diagram in the bottom panel of Fig. 16. We performed a parabolic fit of the diagram that resulted in the following form: $\mathrm{HJD_{max}} = -0.003(8) + 6.34 \times 10^{-8}E - 2.38 \times 10^{-13}E^2$ with an rms of 0.0008 d. From this, we derived $\frac{1}{P}\frac{\mathrm{d}P}{\mathrm{d}t} = -3.27 \times 10^{-8}\,\mathrm{yr}^{-1}$ which is in a good agreement with Mahdy (1987), Peña, González & Hobart (1987) and Derekas et al. (2003). The residuals of the O–C diagram show some signs of cyclic change over 100 000 cycles but this data are insufficient to draw a firm conclusion.

4 CONCLUSIONS

We have carried out multicolour photometry and medium- and high-resolution spectroscopy of 10 bright HADS stars over 5 yr. Our aim was to detect binarity and/or multiperiodicity in HADS variables in order to deepen our knowledge of interaction between oscillations and binarity.

To put our binary targets in a broader context, we have compiled a complete list of binary HADS variables, presented in Table 8. How do RS Gru and RY Lep, the two newly confirmed spectroscopic binaries, compare with other known systems? Looking at the eight stars in Table 8, we can see three distinct groups with markedly different orbital periods. RS Gru is one of the shortest-period binary and it is interesting to note that neither UNSW-V-500 nor RS Gru shows evidence of multimode pulsations. RY Lep is similar to SZ Lyn in both the orbital period and the reasonably large mass of the companion. These intermediate-period systems are also promising for detecting spectral features of the companion in the ultraviolet or infrared region, thus allowing a full dynamical mass determination. To be able to detect spectroscopically, the binary nature of the long-period systems will require very high precision spectroscopy, since the expected v_γ change is in the range of $1\ \mathrm{km\,s^{-1}}$.

To summarize, the main results of this paper are the follows.

(i) We monitored RS Gru spectroscopically on 17 nights in order to measure the orbital period. We derived the orbital period as 11.5 d.

(ii) We confirmed the multimode pulsation of RY Lep from CCD photometry, detecting and refining the frequencies of two independent modes. Spectroscopic measurements also show the multimode pulsation. We detected the orbital motion in the radial velocity curve, confirming the preliminary results of Laney et al. (2002) on the binary nature of RY Lep. Our 700-d long data set is in a good qualitative agreement with Laney et al. (2002). The limits on the orbital period and RV amplitude suggest a binary companion of about $1\ \mathrm{M_\odot}$, possibly a white dwarf star.

(iii) The radial velocity curve of AD CMi shows cycle-to-cycle variations that support the presence of a low-frequency mode pulsation reported by Khokhuntod et al. (2007). The centre-of-mass velocity is in a good agreement with the previous measurement by Balona & Stobie (1983) and does not contradict the binary hypothesis of the star, since the predicted γ-velocity change is around $1\ \mathrm{km\,s^{-1}}$.

(iv) We obtained the first spectroscopic measurements for BE Lyn. The RV curve has an amplitude of $\sim 34\ \mathrm{km\,s^{-1}}$ and the centre-of-mass velocity is $3.4\ \mathrm{km\,s^{-1}}$.

Table 8. Summary of the estimated masses of the companions in the known HADS binary systems. Sources for $P_{\rm orb}$ and masses are: (1) Christiansen et al. (2007), (2) Moffett et al. (1988), (3) Fu et al. (2008) (4) Fu & Jiang (1999), (5) Hurta et al. (2007) and (6) Fu, Sterken & Barrera (2004).

Star	$P_{\rm orb}$	$m_{\rm comp}(\mathrm{M_\odot})$	References
UNSW-V-500	5.35 d	∼0.3	1
RS Gru	11.5 d	0.1–0.2	This paper
RY Lep	730 d	∼1.1	This paper
SZ Lyn	3.2 yr	0.7–1.6	2
KZ Hya	26.8 yr	0.83–3.4	3
BS Aqr	31.7 yr	0.1–0.33	4
AD CMi	42.9 yr	0.15–1.0	5
CY Aqr	52.5 yr	0.1–0.76	6

(v) We confirmed the double-mode nature of BQ Ind, corresponding to the fundamental and first-overtone modes.

(vi) We detected a low-amplitude secondary period in the photometry of ZZ Mic but further observations are needed to confirm its validity. The RV curve has a full amplitude of 22 km s^{-1}.

(vii) We updated the O–C diagram for CY Aqr, corroborating binarity found by Zhou et al. (1999) and Fu & Sterken (2003). Our radial velocity data are in a good agreement with previous observations by Struve (1949) and Fernley et al. (1987) but have better accuracy.

(viii) We obtained new time series photometry on XX Cyg, DY Her and DY Peg and updated their O–C diagrams with new times of maximum. DY Her and DY Peg show continuous period decrease, while XX Cyg has continuous period increase.

Further analysis of the photometric and spectroscopic observations (e.g. determination of physical parameters) will be presented in a subsequent paper.

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APPENDIX A FULL LOG OF OBSERVATIONS

Table A1. Journal of observations.

Date	Filter	Instrument	Data points	Observation length	Date	Filter	Instrument	Data points	Observation length
RS Gru					AD CMi				
2003 October 07	*B*, *V*, *I*	SSO60	93	3.6 h	2004 February 04	Spectroscopic	SSO230	63	4.9 h
2003 October 09	*B*.*V*, *I*	SSO60	145	4.4 h	2004 February 07	Spectroscopic	SSO230	69	4.3 h
2003 October 11	*B*, *V*, *I*	SSO60	125	2.9 h	2004 February 08	Spectroscopic	SSO230	47	2.6 h
2003 October 12	*B*, *V*, *I*	SSO60	121	2.9 h	BQ Ind				
2004 October 02	*B*, *V*, *I*	SSO60	141	3.6 h	2004 October 25	*I*	APT60	153	3.5 h
2003 October 09	Spectroscopic	SSO230	151	3.9 h	2004 October 26	*I*	APT60	46	1.1 h
2004 September 25	Spectroscopic	SSO230	146	3.3 h	2004 October 27	*I*	APT60	156	3.6 h
2004 September 26	Spectroscopic	SSO230	170	3.4 h	2004 October 28	*I*	APT60	133	3.0 h
2004 September 27	Spectroscopic	SSO230	99	2.3 h	2004 October 29	*I*	APT60	120	2.8 h
2004 September 28	Spectroscopic	SSO230	14	0.3 h	2004 October 30	*I*	APT60	98	2.2 h
2005 May 28	Spectroscopic	SSO230	14	0.7 h	ZZ Mic				
2005 May 29	Spectroscopic	SSO230	179	3.8 h	2004 October 27	*B*, *V*	SSO60	148	2.7 h
2005 May 30	Spectroscopic	SSO230	203	4.1 h	2004 October 29	*B*, *V*	SSO60	105	1.7 h
2005 May 31	Spectroscopic	SSO230	161	4.2 h	2004 October 30	*B*, *V*	SSO60	124	2.1 h

Table A1 – *continued*

Date	Filter	Instrument	Data points	Observation length
2005 June 01	Spectroscopic	SSO230	86	3.4 h
2005 June 02	Spectroscopic	SSO230	57	1.4 h
2005 August 17	Spectroscopic	SSO230	116	2.9 h
2005 August 18	Spectroscopic	SSO230	125	3.2 h
2005 August 21	Spectroscopic	SSO230	8	1.1 h
2005 August 22	Spectroscopic	SSO230	37	3.5 h
2005 August 23	Spectroscopic	SSO230	98	3.4 h
2006 June 21	Spectroscopic	AAT	40	4.2 h
RY Lep				
2004 October 25	*I*	APT50	190	3.3 h
2004 October 28	*I*	APT50	246	3.7 h
2004 October 29	*I*	APT50	335	4.9 h
2004 November 24	*I*	APT50	105	1.9 h
2004 November 25	*I*	APT50	366	5.8 h
2004 November 26	*I*	APT50	345	6.1 h
2004 November 27	*I*	APT50	385	6.0 h
2004 November 28	*I*	APT50	380	6.2 h
2004 December 24	*I*	APT50	98	1.4 h
2004 December 25	*I*	APT50	60	1.2 h
2004 December 27	*I*	APT50	324	4.7 h
2004 December 28	*I*	APT50	464	6.7 h
2004 December 29	*I*	APT50	471	6.8 h
2004 December 30	*I*	APT50	419	6.6 h
2005 January 06	*I*	APT50	144	2.1 h
2005 January 07	*I*	APT50	140	2.0 h
2005 January 08	*I*	APT50	137	1.9 h
2005 January 09	*I*	APT50	135	1.9 h
2005 January 10	*I*	APT50	130	1.9 h
2005 January 11	*I*	APT50	128	1.9 h
2004 February 05	Spectroscopic	SSO230	178	4.5 h
2004 February 06	Spectroscopic	SSO230	134	3.9 h
2004 October 26	Spectroscopic	SSO230	28	1.3 h
2004 October 27	Spectroscopic	SSO230	75	3.9 h
2005 December 19	Spectroscopic	SSO230	233	5.5 h
2005 December 20	Spectroscopic	SSO230	203	5.5 h
2004 October 27	Spectroscopic	SSO230	41	2.4 h
CY Aqr				
2003 October 08	*V*, *I*	SSO60	193	4.0 h
2003 October 10	*V*, *I*	SSO60	85	1.7 h
2003 October 13	*B*, *V*	SSO60	175	2.9 h
2004 November 24	*I*	APT50	43	1.3 h
2004 November 25	*I*	APT50	47	1.3 h
2004 November 26	*I*	APT50	33	0.9 h
2004 November 27	*I*	APT50	45	1.3 h
2004 November 28	*I*	APT50	49	1.3 h
2007 July 25	*V*	P60	101	1.2 h
2007 July 26	*V*	P60	103	1.8 h
2003 October 08	Spectroscopic	SSO230	87	3.6 h
2004 July 04	Spectroscopic	SSO230	22	1.6 h
BE Lyn				
2007 October 25	Spectroscopic	MH150	10	1.0 h
2007 October 26	Spectroscopic	MH150	22	2.1 h
2007 October 27	Spectroscopic	MH150	20	2.0 h
XX Cyg				
2007 July 25	*V*	P60	117	3.2 h
2007 July 27	*V*	P60	201	3.6 h
2008 July 29	*V*	Sz40	85	3.3 h
DY Her				
2007 July 22	*V*	P60	131	2.2 h
DY Peg				
2007 July 23	*V*	P60	145	2.7 h

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