Mon. Not. R. Astron. Soc. **300,** L39–L42 (1998)

Confirmation of the oblique pulsator model for the rapidly oscillating Ap star HR 3831

I. K. Baldry,[1] D. W. Kurtz[2] and T. R. Bedding[1]
[1]*Chatterton Astronomy Department, School of Physics, University of Sydney, NSW 2006, Australia*
[2]*Department of Astronomy, University of Cape Town, Rondebosch 7700, South Africa*

Accepted 1998 September 9. Received 1998 June 22

ABSTRACT

We have detected pulsational radial velocity variations in the rapidly oscillating Ap star HR 3831 which are amplitude- and phase-modulated in the same manner as the photometric variations. In particular, the radial velocities show the same 180° phase reversal at magnetic quadrature as the photometric variations. This confirms the oblique pulsator model, and rules out the spotted pulsator model for these stars.

Key words: stars: chemically peculiar – stars: individual: HR 3831 – stars: oscillations – stars: variables: other.

1 INTRODUCTION

The rapidly oscillating Ap stars are cool, magnetic Ap stars which pulsate in high-overtone p modes of low degree. Frequency analyses of the light variations of many of these stars reveal frequency multiplets – usually triplets – with precisely equal frequency separations of the components, and with the separations equal to, or very nearly equal to, the rotation frequency. Therefore the first explanation of these triplets that comes to mind is that a set of rotationally perturbed m modes are excited. In the reference frame of the star these frequencies are split by (Ledoux 1951)

$$\nu_m = \nu_0 + mC_{n,\ell}\Omega, \tag{1}$$

where $C_{n,\ell}$ is a constant that depends on the structure of the star. For an external observer the rotation frequency adds to that to give

$$\nu_m = \nu_0 - m(1 - C_{n,\ell})\Omega. \tag{2}$$

For A-star models and pulsation modes appropriate to the roAp stars, Takata & Shibahashi (1995) found $C_{n,\ell} \simeq 0.003$–0.01. However, Kurtz (1982) showed that $C_{n,\ell}$ is substantially less than this in two roAp stars. Later in the best-observed roAp star, HR 3831, Kurtz et al. (1992) were able to show that $C_{n,\ell} \leq 2 \times 10^{-5}$ at the 3σ confidence level. This is two orders of magnitude less than the theoretically predicted values. This, coupled with the coincidence of the magnetic extrema and the times of pulsation maxima in some roAp stars (which argues that the frequency splitting is precisely the rotational frequency), makes the hypothesis of rotationally perturbed m modes extremely unlikely.

Because of this, Kurtz (1982) proposed the oblique pulsator model to explain these frequency patterns. In this model the pulsation modes are low-degree, axisymmetric modes (typically $\ell = 1,\ m = 0$) with their axis of symmetry aligned with the obliquely rotating magnetic axis of the star. This model has enjoyed considerable success in explaining the observations of the roAp stars (see particularly Shibahashi & Takata 1993 and Takata & Shibahashi 1994, 1995).

The oblique pulsator model supposes that the pulsation modes are locked to the obliquely rotating magnetic field. The likelihood of this was considered questionable by Dolez & Gough (1982) and by Mathys (1985), the latter of whom developed the spotted pulsator model as an alternative. It is well-known that the Ap stars show light variations as a function of rotation because of an inhomogeneous distribution of elements on their surfaces. To first order there are ‘spots’ associated with the magnetic poles which give rise to rotational light variations. This ‘mean light’ rotational variability of itself cannot explain the frequency triplets observed in the roAp stars – its amplitude of a few tens of millimagnitudes is far too small. In the spotted pulsator model, Mathys supposed that the pulsation modes are symmetric about the rotation axis of the star, but that the ratio of the flux and radius amplitudes, and the phase lag between them, is variable because of the spots. Since the spots are close to the obliquely rotating magnetic poles, this model also explains the frequency spacing equality with the rotational frequency.

Mathys pointed out a direct test to distinguish the oblique pulsator model and the spotted pulsator model: the measurement of the pulsational radial velocity variations. The oblique pulsator model requires the radial velocities to be amplitude- and phase-modulated in the same way as the light variations. The spotted pulsator model requires a single non-modulated radial velocity amplitude.

The first observational test of this was that of Matthews et al. (1988), who measured radial velocity variations in the roAp star HR 1217. They found that the radial velocity was amplitude-modulated between their two nights of observations in a manner consistent with the oblique pulsator model. However, HR 1217 is multi-periodic with at least six independent pulsation modes, and the amplitude is rotationally modulated with a period of

12.461 d – a time-scale long compared with the two consecutive nights of observation of Matthews et al. This left some doubt about whether the amplitude modulation of the radial velocities was rotational – in support of the oblique pulsator model – or whether it might just have been a consequence of unresolved beating among the six pulsation modes.

Recently, high-precision radial velocity measurements in the roAp star α Cir (Baldry et al. 1998, 1999) have vertically resolved the principal pulsation mode in that star – these observations look right through a radial node in the atmosphere. With this breakthrough and the demonstration that radial velocity measurements of roAp stars can be made with good signal-to-noise ratios, we decided to make a similar observation of HR 3831 to distinguish definitively between the oblique pulsator model and spotted pulsator model.

HR 3831 is the best-studied of the roAp stars. It is an Ap SrCrEu star with $T_{\rm eff} = 8000 \pm 200$ K and $R = 2.9 \pm 0.1\,{\rm R}_{\odot}$. Its effective magnetic field strength varies about a mean of zero with an amplitude of 737 ± 68 G (Mathys 1991). Its quadratic magnetic field strength is strong with an average intensity of 11 kG (Mathys 1995). HR 3831 has a single distorted dipole pulsation mode, with a frequency of 1428 μHz, for which both pulsation poles come into view as the mode is viewed with varying aspect over the rotation period of the star, $P_{\rm rot} = 2.851976$ d (Kurtz et al. 1997). The photometric pulsational amplitude modulation, which occurs with the rotation, generates a frequency septuplet with components which are split by exactly the rotation frequency. A series of papers discusses that septuplet observationally and empirically (Kurtz, Kanaan & Martinez 1993), and theoretically (Shibahashi & Takata 1993; Takata & Shibahashi 1994, 1995; Dziembowski & Goode 1996).

We have obtained spectra of HR 3831, which show radial velocity variations that are amplitude- and phase-modulated in the same way as the photometric variability. In this paper we compare these radial velocities with contemporaneous photometry, and with a precise model of the photometric amplitude and phase variations from detailed previous photometric work. Our results are in agreement with the oblique pulsator model and clearly rule out the spotted pulsator model.

2 OBSERVATIONS

2.1 Spectroscopy

We have obtained intermediate-resolution spectra of HR 3831 using the coudé spectrograph (dispersion of 0.49 Å pixel^{-1}) on the 74-inch (1.88-m) telescope at Mt Stromlo, Australia. We have a total of 1400 spectra from a one-week period in 1997 March (JD 245 0517 to 245 0525), with each spectrum having a minimum of 60 000 photons Å^{-1}. The average number of photons Å^{-1} in each spectrum was 270 000. The exposure time was 100 s, with an overhead between exposures of 20 s.

The CCD images were reduced to spectra using the same procedures as were used on the Stromlo data by Baldry et al. (1998). On each spectrum two measurements were made, a cross-correlation shift of the Hα line and an intensity ratio between the core and wings of the line ($R_{\rm cw}$). The Hα velocity was measured using a region from 6552 to 6574 Å, with a telluric band from 6865 to 6931 Å used as a fiducial reference. See Baldry et al. (1998) for details of the cross-correlation technique used. The $R_{\rm cw}$ measurement is the intensity in a filter with FWHM$\sim$6 Å (centred on Hα) divided by a filter with FWHM$\sim$45 Å. Such an observable was used by Baldry et al. (1999) to produce a high signal-to-noise ratio amplitude spectrum, in order to detect pulsation modes in α Cir.

2.2 Photometry

A group at the South African Astronomical Observatory (SAAO) and the University of Cape Town (UCT) has been obtaining high-speed photometric observations of HR 3831 through a Johnson *B* filter since late 1980. For the last five years they have been obtaining 1 h of high-speed photometric observations on each night when one of them is observing, during the entire season when HR 3831 is observable, November to June. Each of those 1-h observing sessions covers about five pulsation cycles, from which they can determine the pulsation phase with sufficient precision to follow the frequency variability of HR 3831 over time. See Kurtz et al. (1997) for a discussion of the data reduction and long-term results for the frequency variability of HR 3831.

We have selected a subset of these SAAO/UCT data which are centred on the times of our radial velocity observations. These photometric data were obtained on 26 nights spanning the dates JD 245 0402 to 245 0618. They comprise a total of 34 h of observation. There is a very small amount of frequency variability over this time-span, but it is not significant for the purposes of our analysis in this paper. It will be discussed in detail in a future publication by the SAAO/UCT group.

3 ANALYSIS AND RESULTS

The frequency pattern of HR 3831 is extremely well-known – the fundamental frequencies form a septuplet split by exactly the rotation frequency (Kurtz et al. 1997). For the relatively short data sets that we have in this paper, and for their signal-to-noise ratios, only the central frequency triplet is detectable. We have, therefore, fitted the central frequency triplet from Kurtz et al. (1997) to our photometric data, our radial velocity data and our $R_{\rm cw}$ data, with the results shown in Table 1.

It is clear from this table that the radial velocities are amplitude- and phase-modulated in the same manner as the photometric variations, confirming the oblique pulsator model. Within this model, the parameter $(A_{+1} + A_{-1})/A_0 = \tan i \tan \beta$ [see Takata & Shibahashi (1995) or. for a simpler derivation, Kurtz (1982)]. The analysis of 16 yr of data gives a value of 8.7 ± 0.2 for this parameter; the values in Table 1 for the photometric data, radial velocity data and $R_{\rm cw}$ data are all in agreement with this value, and with each other.

An easier way to view the data and to make the point that the radial velocities really are amplitude- and phase-modulated is to plot them against rotational phase. Kurtz et al. (1997) did this for the entire 16-yr photometric data set for HR 3831 – see their fig. 1. We have done the same using the same rotational ephemeris for the photometric, radial velocity and $R_{\rm cw}$ data. The results are shown in Figs 1 and 2. In Fig. 2 it is obvious that the radial velocities are amplitude-modulated and undergo the same 180° phase reversal at quadrature as the photometric observations in Fig. 1 – the clear signature of oblique dipole pulsation.

It is also clear in Fig. 2 and in Table 1 that the pulsation phase of the radial velocities is not the same as the pulsation phase for the photometry. Phase lags between the radial velocity and light curves are understood for some pulsating stars such as Cepheids, but are not well-studied or understood in others, such as δ Scuti stars and roAp stars. For the latter this long-standing problem is now beginning to be understood. A close examination of the radial

Table 1. Pulsational amplitudes and phases of the frequency triplet.

Frequency (μHz)	*B* amplitude (mmag)	*B* phase (radians)	RV amplitude (ms^{-1})	RV phase (radians)	R_{cw} amplitude (ppm)	R_{cw} phase (radians)
1423.951	1.91 ± 0.05	2.68 ± 0.03	435 ± 23	3.16 ± 0.05	1113 ± 43	1.05 ± 0.04
1428.009	0.52 ± 0.05	0.52 ± 0.10	120 ± 23	0.69 ± 0.19	154 ± 43	−0.05 ± 0.28
1432.067	1.66 ± 0.05	2.71 ± 0.03	294 ± 23	2.85 ± 0.09	917 ± 43	0.90 ± 0.05
	$\sigma = 1.81$		$\sigma = 575$		$\sigma = 1098$	
$\frac{A_{+1} + A_{-1}}{A_0}$	6.9 ± 0.7		6.1 ± 1.2		13.2 ± 3.7	

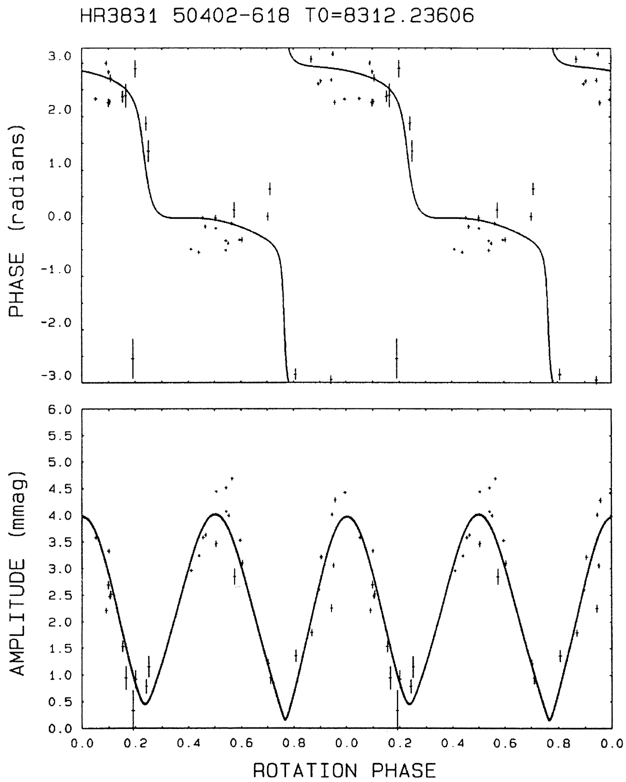

Figure 1. This diagram shows the pulsation phase and pulsation amplitude as a function of the rotation phase for the photometric observations of HR 3831. Each point plotted has been determined from a least-squares fit of the central frequency of the frequency septuplet (the true pulsation frequency of HR 3831) to one night of data. Those nightly data sets are usually about 1 h or 5 pulsation cycles long. The error bars are 1σ standard deviations from the least-squares fits. The solid-line fit is from a model decomposition of the frequency solution into a spherical harmonic series with $\ell = 0, 1, 2$ and 3 components (very similar to that described by Kurtz et al. 1993).

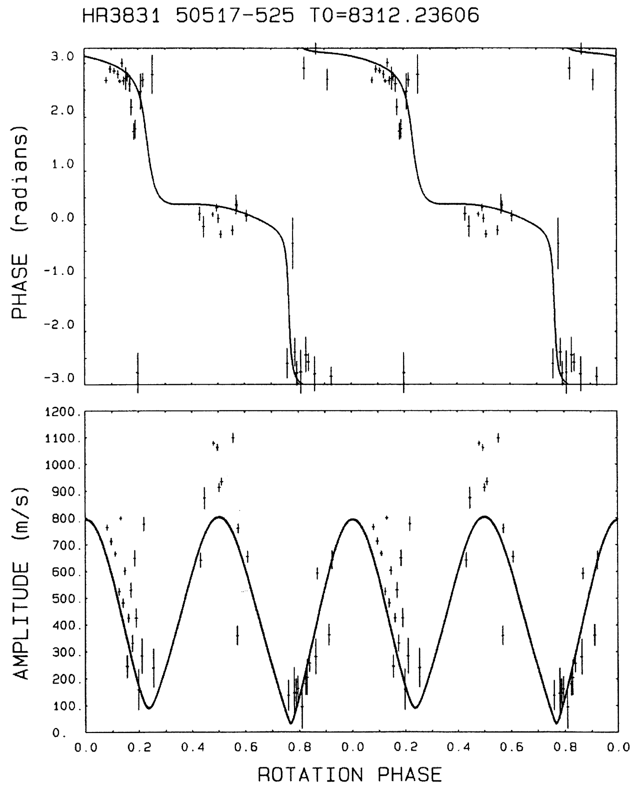

Figure 2. As Fig. 1, but for the radial velocity data. The fitted curve has been approximately scaled from the photometric solution as a guide. Note that the radial velocity rotational maximum occurs after the photometric maximum. Note also the small shift in pulsational phase on the *y*-axis of the upper diagram compared with Fig. 1.

velocities in the roAp star α Cir as a function of depth in the Hα line (Baldry et al. 1999) shows that the radial velocity phase is a function of depth in the atmosphere. It is also known that the photometric amplitude and phase are both functions of depth in the atmospheres of roAp stars (Medupe & Kurtz 1998). So the simple explanation for the pulsation phase difference between Figs 1 and 2 is that the radial velocities and photometric observations are sampling different depths in the atmosphere. This does not answer the much more interesting question of the physical cause of these phase shifts as a function of depth; that problem is currently under investigation by a number of groups.

It can also be seen in Fig. 2 that the rotational phase of the radial velocities seems to differ from the rotational phase of the photometric observations. We have examined this more carefully by fitting twice the rotational frequency, $2\Omega = 0.701\,268\,d^{-1}$ (Kurtz et al. 1997), to the radial velocity amplitude data and photometric amplitude data seen in Figs 1 and 2. The reason for fitting twice the rotation frequency is that the amplitudes are modulated twice per rotation, since both magnetic poles are seen over the rotation cycle. The results of those least-squares fits are shown in Table 2.

The phases of the fits in Table 2 would be zero if the rotational phases were the same as those determined from the photometric data of the model fit (Kurtz et al. 1993). For the photometric data this is true within 1σ. However, the radial velocity data differ by a bit more than 3σ from the model fit, confirming the impression given by examining Fig. 2. Given that this result is marginal, we do

Table 2. Rotational variation of the amplitude of the principal frequency.

Frequency (d^{-1})	B rotational amplitude (mmag)	B rotational phase (radians)	RV rotational amplitude (ms^{-1})	RV rotational phase (radians)	R_{cw} rotational amplitude (ppm)	R_{cw} rotational phase (radians)
0.701268	1.76 ± 0.12 $\sigma = 0.50$	-0.06 ± 0.07	382 ± 36 $\sigma = 168$	-0.41 ± 0.09	836 ± 77 $\sigma = 345$	-0.20 ± 0.08

not wish to over-interpret it. We do note, though, that the 'spots' on HR 3831 are not concentric with the magnetic and pulsational poles. Kurtz et al. (1992) showed that the light variations caused by the spots reach an extremum 0.062 ± 0.002 rotation periods after the pulsational and magnetic extrema. The radial velocities in Fig. 2 and Table 2 reach maximum 0.41 ± 0.09 rad ($= 0.065 \pm 0.014$ periods) after the photometric variations – the same as the lag for the mean light variations.

If this result is correct, it means that the radial velocity variations are centred on the spots, while the temperature variations – which produce the light variations – are centred on the magnetic field. Thus, while we have clearly ruled out the spotted pulsator model, it is clear that the spots do have an observable influence on the pulsations for observations of the precision that is now obtainable. This is probably because the relative H distribution causes our Hα observations to be centred on the spots, even though the broad-band photometry, which measures temperature variations for a dipole mode, shows the pulsation mode to be aligned with the magnetic field. New, more precise radial velocity measurements are needed to examine this interesting effect in more detail.

There have been many discussions of the meaning of the phase shift between the colour and light variations in the roAp stars (e.g. Matthews et al. 1988; Watson 1988) and the velocity-to-light amplitude, $2K/\Delta m_V$ (e.g. Matthews et al. 1988; Kjeldsen & Bedding 1995). It is now clear that these parameters for the roAp stars cannot be compared with those for other types of pulsating stars, such as the δ Scuti stars. This is because we see over a large fraction of a vertical wavelength of the pulsation modes in roAp stars, sometimes looking right through a radial node (Baldry et al. 1999). Since the radial velocity measurements and photometric measurements at various wavelengths are often sampling different depths, where amplitudes and phases differ, then phase lags, phase shifts and amplitude ratios will be highly variable.

ACKNOWLEDGMENTS

We thank the SAAO astronomers Fred Marang, Francois van Wyk and Greg Roberts for their kind permission to use their unpublished photometric observations of HR 3831. We are also grateful to MSSSO for their support. IKB and TRB thank the Australian Research Council for financial support.

REFERENCES

Baldry I. K., Bedding T. R., Viskum M., Kjeldsen H., Frandsen S., 1998, MNRAS, 295, 33
Baldry I. K., Viskum M., Bedding T. R., Kjeldsen H., Frandsen S., 1999, MNRAS, in press
Dolez N., Gough D. O., 1982, in Cox J. P., Hansen C. L., eds, Pulsations in Classical and Cataclysmic Variable Stars. JILA, Boulder p. 248
Dziembowski W., Goode P. R., 1996, ApJ, 458, 338
Kjeldsen H., Bedding T. R., 1995, A&A, 293, 87
Kurtz D. W., 1982, MNRAS, 200, 807
Kurtz D. W., Kanaan A., Martinez P., Tripe P., 1992, MNRAS, 255, 289
Kurtz D. W., Kanaan A., Martinez P., 1993, MNRAS, 260, 343
Kurtz D. W., van Wyk F., Roberts G., Marang F., Handler G., Medupe R., Kilkenny D., 1997, MNRAS, 287, 69
Ledoux P., 1951, ApJ, 114, 373
Mathys G., 1985, A&A, 151, 315
Mathys G., 1991, A&AS, 89, 121
Mathys G., 1995, A&A, 293, 746
Matthews J. M., Wehlau W. H., Walker G. A. H., Yang S., 1988, ApJ, 324, 1099
Medupe R., Kurtz D. W., 1998, MNRAS, 299, 371
Shibahashi H., Takata M., 1993, PASJ, 45, 617
Takata M., Shibahashi H., 1994, PASJ, 46, 301
Takata M., Shibahashi H., 1995, PASJ, 47, 219
Watson R. D., 1988, Ap&SS, 140, 255

This paper has been typeset from a TEX/LATEX file prepared by the author.