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Rapid Pulsations in Ap Stars

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Abstract. The rapidly oscillating Ap (roAp) stars are upper main-sequence stars that pulsate in non-radial p modes of high overtone. We present an observer's overview of the roAp phenomenon and discuss significant developments since the last major observational reviews of Kurtz (1990a) and Matthews (1991).

1. Introduction

The Ap (for 'A peculiar') stars are magnetic, chemically peculiar main-sequence stars spanning a temperature range that starts just below the cool edge of the instability strip and extends well beyond the blue edge to hotter temperatures (Wolff 1983). The magnetic fields in these stars are predominantly global dipolar fields with typical effective field strengths of 1–2 kG. The Ap stars exhibit spectrum, magnetic, photometric and radial velocity variability, all with the same period in a given star. The oblique rotator model (Stibbs 1950, Wolff 1983) explains the variations by postulating that the spectral peculiarities originate in spots of anomalous abundance on the stellar surface and that the magnetic axis is inclined with respect to the rotation axis. In this model the variations are a consequence of seeing the spots and the magnetic geometry from variable aspect as the star rotates. The coolest Ap stars, those with anomalously strong lines of Sr, Cr, Eu and other rare earths, overlap the instability strip where it crosses the main sequence. Kurtz's (1982) discovery of rapid pulsations in a number of cool Ap stars has elicited much interest because of the potential for using the pulsations to probe these stars' magnetic structures, atmospheres and interiors. Much of the early work on these rapidly oscillating Ap (roAp) stars concentrated on characterizing the roAp phenomenon and searching for new members of the class. Table 1 lists the 27 roAp stars known as of this writing. The Cape roAp star survey, the most prolific source of new roAp stars, is described by Martinez elsewhere in these proceedings. This review begins with an overview of our current understanding of the phenomenology of roAp star light curves. This is followed by a discussion of the physics of the roAp phenomenon and the oblique pulsator model. In the second half of the review, we focus on recent observational developments. This review builds on recent reviews by Kurtz (1990a), Matthews (1991) and Shibahashi (1991). Kurtz and Matthews emphasize the observations while Shibahashi emphasizes theoretical developments.

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Table 1. The rapidly oscillating Ap stars.

HD *HR*	V	Spectral Type	Period[a] (min)	ΔB^b	$\Delta\nu^c$ (μHz)	P_{rot} (day)	B_{eff} (G)
6532	8.4	Ap SrCrEu	7.1	5	47	1.9448	
9289	9.4	Ap SrEu	10.5	3			
12932	10.2	Ap SrEuCr	11.6	4			
19918	9.3	Ap SrEuCr	14.5	2			
24712 *1217*	6.0	Ap SrEu(Cr)	6.2	10	68	12.4572	+400 to +1300
42659	6.8	Ap SrCrEu	9.7	0.8	52		
60435	8.9	Ap Sr(Eu)	12.0[d]	16		7.6793	< 1000
80316	7.8	Ap Sr(Eu)	7.4	2		2.1?	
83368 *3831*	6.2	Ap SrEuCr	11.6	10		2.851962	-700 to +700
84041	9.3	Ap SrEuCr	15.0	6	60	3.69	
86181	9.3	Ap Sr	6.2	5			
101065	8.0	Controversial	12.1	16	58	3.94?	-2200
119027	10.0	Ap SrEu(Cr)	8.7	2	52		
128898 *5463*	3.2	Ap SrEu(Cr)	6.8	5	50	4.46	-300
134214	7.5	Ap SrEu(Cr)	5.6	7			
137949	6.7	Ap SrEuCr	8.3	3	40		+1400 to +1800
150562	9.8	A/F(p Eu)	10.8	0.8			
161459	10.3	Ap EuSrCr	12.0	1.3			
166473	7.9	Ap SrEuCr	8.8	2	68		
176232 *7167*	5.9	F0p SrEu	11.6	0.6	51		
190290	9.9	Ap EuSr	7.3	2	58		
193756	9.2	Ap SrCrEu	13.0	0.9			
196470	9.7	Ap SrEu(Cr)	10.8	0.7			
201601 *8097*	4.7	F0p	12.4	3	58		-800 to +500
203932	8.8	Ap SrEu	5.9	2	66		
217522	7.5	Ap (Si)Cr	13.9	4	31		
218495	9.4	Ap EuSr	7.4	1			

[a] In the case of multi-periodic stars, the period listed is that with the highest amplitude.
[b] ΔB_{max}, the amplitudes listed are peak-to-peak amplitudes, in mmag.
[c] This column lists the asymptotic p-mode spacing inferred from measurements of the frequency spacing in the multi-periodic stars.
[d] This is a representative value for the most commonly detected periods in this star.

2. The phenomenology of roAp star light curves

1. The pulsation periods of the roAp stars are in the range 5.6 to 15.0 min. The amplitudes are all ≤ 16 millimagnitudes (mmag) peak to peak in Johnson B light. Because of the shortness of these periods, roAp stars are detected and studied using non-differential high-speed photometry. Experience has shown that it is possible to distinguish between real variations in the star and variations caused by sky transparency. Nonetheless, stable, well maintained equipment and an excellent photometric site are required for roAp star photometry. The observational techniques and common pitfalls have been discussed in detail by Martinez (1993a).

2. The light curves of many roAp stars show complex changes in amplitude on time-scales of several hours. This is the signature of beating among several excited modes. In the Fourier frequency domain, the signal content of the oscillations manifests itself as a region of power containing a series of equally spaced peaks. This is reminiscent of the Fourier spectrum of the solar 5-min oscillations. There is a significant difference though; in the Sun, the envelope of excited frequencies contains all the modes expected, whereas in the roAp stars only a few modes are excited to observable amplitudes.

3. In about $\frac{1}{3}$ of the roAp stars the harmonics of the principal oscillation frequencies are seen in the Fourier spectra of the light curves. What this means is that the pulse shape in these stars is non-sinusoidal, implying that the oscillations are non-linear. These non-linearities are not understood; δ Scuti stars which oscillate with amplitudes of a few tenths of a magnitude do not show harmonics, yet roAp stars which oscillate with amplitudes of 1–2 mmag do.

4. In addition to short-term amplitude modulation caused by beating of independent pulsation frequencies, the oscillations also undergo amplitude modulation on time scales of several days, or longer. For those roAp stars with known magnetic periods, the period of the amplitude modulation is equal to the rotation period. The bottom panel in Fig. 1 illustrates this for HR 3831. The pulsation amplitude is maximum at magnetic extremum (i.e., when one of the magnetic poles is viewed directly) and minimum at quadrature. This amplitude modulation manifests itself in the Fourier spectrum of the oscillations as an equally spaced frequency multiplet centered on the pulsation frequency. The spacing of the frequencies in the multiplet is equal to the rotation frequency.

5. For HR 3831 Kurtz et al. (1992b) have shown that the period of the pulsation amplitude modulation is equal to the period of the mean-light photometric variation caused by oblique rotation. They use this to show that an interpretation of the pulsation amplitude modulation as rotationally perturbed m modes requires that the Ledoux (1951) rotational splitting constant $C_{n\ell} \leq 2 \times 10^{-5}$ at the 3σ confidence level, making that interpretation highly unlikely.

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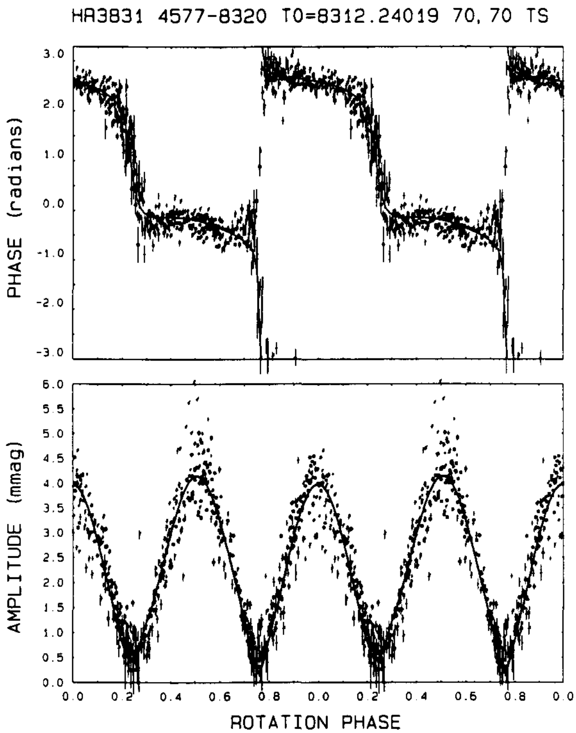

Figure 1. The observed phase and amplitude of the pulsations in HR 3831 as a function of rotation phase. Phase 0.0 is defined to be magnetic maximum.

6. Kurtz et al. (1992b) showed for HR 3831 that the time of magnetic extremum coincides with the time of pulsation-amplitude maximum but differs from the mean-light extremum at the 5σ confidence level. In HR 1217, a similar result obtains at the 3σ level (Kurtz et al. 1989). These findings indicate a deviation from cylindrical symmetry for the magnetic field geometry and abundance distributions in those two stars.

7. The phase behaviour of the rapid oscillations has been studied in detail for two roAp stars, namely HD 6532 and HR 3831. Between quadratures, the phase is approximately constant. At quadratures, the phase undergoes a π-radian jump. This variation is shown for HR 3831 in Figure 1.

8. The oscillation spectra of the roAp stars are not stationary. In some multi-periodic stars the distribution of amplitudes among the different frequencies changes on a time-scale shorter than the rotation period. In other stars a given frequency pattern is constant for a few rotation cycles. The topic of mode changes and lifetimes forms the subject of Section 5.

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9. *It was recently discovered that the frequency of the oscillation in the singly-periodic star HR 3831 varies on a time-scale of several hundred days in a fashion not yet well characterized. Similar, though less extensive results have been obtained for a few other roAp stars and it appears that such frequency variations may be the norm, rather than the exception. This topic is discussed fully in Section 6.*

3. The physics of the roAp phenomenon

The shortness of the pulsation periods in the roAp stars implies that they pulsate in high-order p modes similar to those of the well-studied solar 5-minute oscillations. The very fact that we observe the oscillations photometrically implies that low-order modes are excited. The asymptotic theory of low-degree, high-overtone ($n \gg \ell$) p-mode pulsation (Tassoul 1980) predicts that the eigenfrequencies of the modes are given by

$$\nu_{n\ell} \simeq \Delta\nu(n + \ell/2 + \epsilon) + \delta\nu, \tag{1}$$

where ϵ is a constant dependent on the equilibrium structure of the star and $\delta\nu$ is a second-order term. To first order, the eigenfrequencies have a uniform spacing $\Delta\nu$ given by

$$\Delta\nu = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1}, \tag{2}$$

where $c(r)$ is the sound speed. This spacing $\Delta\nu$ is the reciprocal of the time it takes for a sound wave to cross the star. For the Sun $\Delta\nu = 135\,\mu$Hz, which translates to a sound crossing time of 2.06 hr. The roAp stars have $\Delta\nu$ values between 30 and 70 μHz, corresponding to sound crossing times of 9.3–4.0 hr, consistent with their larger radii. When $\Delta\nu$ is expressed in terms of structural parameters by $\Delta\nu \propto \sqrt{(}GM/R^3)$, one may readily show, using the mass-luminosity relation, that the loci of constant $\Delta\nu$ are essentially lines of constant R in a theoretical H-R diagram. These loci have been calculated by a variety of people modelling p-mode oscillations in A-type stars, *viz.* Gabriel et al. (1985), Shibahashi & Saio (1985) and Heller & Kawaler (1988).

One of the properties of eq. (1) is that, to first order, it is degenerate for modes with the same value of $(n + \ell/2)$. Thus, consecutive overtones $(n, n+1)$ of modes with exclusively even or odd ℓ are spaced by $\Delta\nu$, whereas alternating even and odd ℓ modes are spaced by $\frac{1}{2}\Delta\nu$. The problem is to decide whether the observed spacing in a given star corresponds to $\Delta\nu$ or $\frac{1}{2}\Delta\nu$. The various A-star models mentioned above all indicate that $\Delta\nu$ = 50–80 μHz for a slightly evolved 2$M_\odot$ star. In several roAp stars a frequency spacing of $\sim$ 25–30 μHz is observed. In such cases, the theoretical overtone spacing, and the fact that Ap stars are not highly evolved objects, are used to argue that alternating even and odd ℓ modes are present. However, such conclusions are only secure if an independent luminosity estimate is available for the star. Matthews (1989) has noted that the ratio $\frac{\Delta\nu}{<\nu>}$ falls around the preferred values 0.040 and 0.025 for the roAp stars. This result, if confirmed, could be used to remove the ambiguity in determining $\Delta\nu$. Another way suggested to determine $\Delta\nu$ is to measure the

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rate of frequency change due to evolution (Heller & Kawaler 1988). A more evolved star has a smaller value of $\Delta\nu$ and a higher rate of frequency change. In practice this is probably not possible for reasons discussed in Section 6.

We now turn to a discussion of the second-order term, $\delta\nu$. We have already noted that Tassoul's relation is degenerate for modes (n, ℓ) and $(n \pm 1, \ell \mp 2)$. The term $\delta\nu$ lifts this degeneracy by introducing a slight frequency separation $\delta\nu \ll \Delta\nu$ between such modes. Physically, what happens is that modes (n, ℓ) and $(n \pm 1, \ell \mp 2)$ have very similar mode structures outside the core but slightly dissimilar mode structures in the centre. This difference in central mode structures is a measure of the sound speed gradient in the stellar core. Since this gradient changes as nuclear burning changes the molecular weight distribution in the core, the small frequency separation contains information about the star's evolutionary state. Christensen-Dalsgaard (1988) has created a theoretical asteroseismological H-R diagram by plotting $\Delta\nu$ against $\delta\nu$ for a grid of models. By using these two observable quantities to plot stars in such a diagram, it should be possible to obtain asteroseismological mass and age estimates. Much observational work in recent years has been aimed at providing stars to calibrate such a diagram. At present, the Sun is the only star which can be plotted on this diagram with certainty.

4. The Oblique Pulsator Model

Much of the phenomenology of roAp star light curves can be understood in terms of the oblique pulsator model (Kurtz 1982, 1990a). This model postulates that a roAp star pulsates non-radially and that the pulsation axis coincides with the magnetic axis, which is itself inclined with respect to the rotation axis. This very simple model can explain the observed amplitude modulation of the rapid oscillations and the oscillation phase flips at magnetic crossover (Fig. 1) as natural consequences of viewing the pulsations from varying aspect as the star rotates. The oblique pulsator model predicts that a frequency of mode ℓ is split by rotation into a multiplet of $(2\ell + 1)$ frequencies. The multiplet is centered on the pulsation frequency in the rest frame of the star, and the multiplet frequency spacing is the rotation frequency, Ω_{rot}. The amplitudes of the side-band components are determined by the relative strength of the Coriolis force ($\propto \Omega_{\rm rot}$) to the Lorentz force ($\propto B^2$). In the limiting case where magnetic effects dominate, the pulsation axis is locked to the magnetic axis and the resulting frequency multiplet is symmetric. As rotation effects increase, the pattern of side-lobes becomes increasingly asymmetrical.

When it was first proposed, this model seemed to offer a substantially adequate explanation for the observation of an equally spaced asymmetric frequency triplet in the roAp star HR 3831. However, in the last few years it has become apparent that the situation is a good deal more complicated than was previously thought. Kurtz et al. (1993) have discovered that the fine structure in HR 3831 originally thought to be a triplet is in fact part of a septuplet. Indeed, they showed that it is possible to express the oscillations as a sum of axisymmetric spherical harmonics of degree $\ell = 0$, 1, 2 and 3 using the spherical harmonic decomposition technique developed by Kurtz (1992a). The solid lines in Fig. 1 show the fits they obtained. Although the observations were well reproduced by this procedure, there was no physical justification for using it. To explain the septuplet in HR 3831, Shibahashi & Takata (1993) refined the treatment of the effects of the Lorentz and Coriolis forces on non-radial oscillations in a rotating magnetic oblique pulsator. Using their refined model, they showed that the effect of the magnetic field on an axisymmetric dipole mode is to distort the dipole oscillation pattern in such a way that axisymmetric octupole components arise; this leads to an asymmetric equally spaced frequency septuplet instead of a triplet. This distortion of the basic dipole pattern led Shibahashi & Takata to christen their model the 'distorted oblique pulsator model.' [1]

5. Mode changes and mode lifetimes

Several roAp stars are observed to switch their principal pulsation frequency from time to time. Such frequency shifts are usually commensurate with some integer multiple of the p-mode spacing, $\Delta\nu$, and they are interpreted as shifts to a nearby overtone. An example of a star where such frequency shifts have been noted is HD 217522 (Kreidl et al. 1991). Observations in 1982 showed pulsation with a frequency $\nu_1 = 1215.29\,\mu$Hz whereas observations in 1989 showed that the principal pulsation frequency had shifted to $\nu_1 = 1199.9\,\mu$Hz, a shift of $15.4 \pm 0.1\,\mu$Hz. Moreover, the 1989 data showed a new frequency at $\nu_2 = 2017.4\,\mu$Hz at such a significance level that there was no chance it could have been missed in the 1982 observations. Such a frequency shift is orders of magnitude too high to arise from evolutionary changes in HD 217522. Kreidl et al. have interpreted the frequency shift as a mode change and have used the size of the shift to estimate the mass and luminosity of HD 217522.

In HD 217522, the mode change was not actually observed, but for the roAp star HD 60435 a transition from one pulsation mode to another was well observed. HD 60435 has the richest p-mode spectrum of the roAp stars. It pulsates with many frequencies having a basic spacing of $25.8\,\mu$Hz. This spacing is interpreted as $\Delta\nu/2$, the spacing of alternating even and odd ℓ modes. During a multi-site observing campaign from Chile and South Africa in 1985 (Matthews et al. 1987) this star was observed to undergo several mode transitions. In fact, so many mode changes were observed that one cannot meaningfully talk about a principal oscillation frequency for HD 60435. The lifetimes of some of the modes seem to be as short as a few days. A rotation period of 7.6793 ± 0.0006 days has been determined for HD 60435 by Kurtz et al. (1990b) from a study of its mean light variations. In many cases the modes have lifetimes shorter than one rotation cycle. These conclusions are secure. They were obtained from over 400 hr of contemporaneous multi-site data and there is no chance that they are artefacts produced by aliasing and frequency resolution problems.

There are other roAp stars with mode lifetimes on time-scales on days to weeks. Examples of such stars are HD 203932 (Martinez et al. 1990b), HR 1217

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[1] We do not review the Spotted Pulsator Model of Mathys (1985) here as it has not been developed further since last reviewed by Kurtz (1990a). We note that although the oblique pulsator model is more successful at explaining the phenomenology of roAp light curves, the physics invoked by the spotted pulsator model may yet prove to be necessary for a detailed, complete description of the oscillations.

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(Kurtz et al. 1989), HD 84041 (Martinez et al 1993b), HD 201601 (Libbrecht 1988) and HD 119027 (Martinez et al 1993c). These stars are not as well studied as HD 60435, but there is strong evidence that they pulsate in several modes and that their behaviour is qualitatively similar to that of HD 60435.

Kurtz (1990a) has pointed out that the pulsation mode lifetimes appear to be longer in those stars which pulsate in a few modes and shorter in stars with rich p-mode spectra. An example of a mode-stable star is HR 3831, which is singly periodic with harmonics. The principal dipole oscillation is amplitude-stable over more than 10 yr. There are slight frequency changes on time-scales of several hundred days which are discussed in Section 6. Another example of a well studied mode-stable star is HD 101065 which pulsates with one large amplitude mode and at least one other much smaller amplitude mode (Martinez & Kurtz 1990a). The large-amplitude mode seems to suffer some amplitude or phase instability on time-scales of 10 yr but is stable on shorter time-scales. HR 1217 pulsates with 6 modes (Kurtz et al. 1989) that are stable over one rotation cycle, but variable on a time-scale of 4 rotation cycles.

6. Frequency changes

From an asteroseismological standpoint, the richer the oscillation spectrum of the star, the more information it contains. However, there is one very important parameter which is best studied in singly periodic stars — it is the rate of frequency change. The way in which a frequency changes is an important clue to the cause of the change. A frequency change can be gradual or abrupt; it can be secular or periodic. Two of the most probable causes of gradual frequency change in a pulsating star are evolution and orbital motion. It is usually possible to identify orbital motion since the Doppler frequency shifts are periodic and sinusoidal (for circular orbits). Intrinsic frequency variations pose a tougher problem because the long-term secular frequency changes expected from evolution are confounded with comparatively short-term variations which are not yet understood.

Heller & Kawaler (1988) have investigated evolutionary period changes theoretically for a series of A star models which they allowed to evolve off the main sequence. Their models yield values of $|d\ln\nu/dt| \sim 10^{-16}$–$10^{-17}\,\mathrm{s}^{-1}$. For a given T_{eff}, models with a smaller p-mode spacing have a higher luminosity and a higher $|d\nu/dt|$. By using the measured values of $d\nu/dt$ it should be possible to resolve ambiguities in the determination of $\Delta\nu$. In HR 1217, for example, there are two possible values of $\Delta\nu$, *viz.* $\Delta\nu = 34\,\mu$Hz and $68\,\mu$Hz (Kurtz et al. 1989). According to Heller & Kawaler's models, $d\nu/dt$ should be detectable with the 6 yr of observations available if $\Delta\nu = 34\,\mu$Hz, whereas it should not be detectable if $\Delta\nu = 68\,\mu$Hz. Unfortunately, Kurtz et al. (1989) find that alias ambiguities and the interaction of the many frequencies in HR 1217 preclude this. This illustrates the importance of the remark made in the opening paragraph of this section that $d\nu/dt$ is more readily determined in singly periodic stars. It also demonstrates the practical difficulty of using $d\nu/dt$ measurements to resolve ambiguities in the determination of $\Delta\nu$.

Several other roAp stars with less complicated oscillation spectra than HR 1217 have data sets long enough to permit a determination of $d\nu/dt$. In

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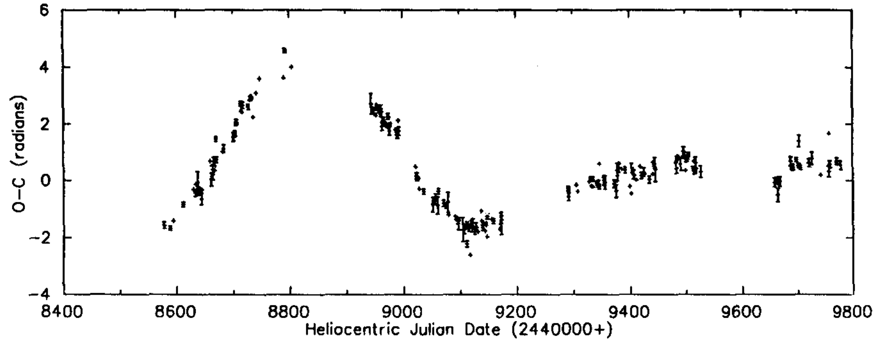

Figure 2. The long-term behaviour of the pulsation phase in HR 3831.

HD 101065, which oscillates with three frequencies, Martinez & Kurtz (1990a) find a rate of frequency change 10–100 times higher, and of the opposite sign, than expected for a hydrogen-core-burning A star. HD 137949 is another star that shows a period change several orders of magnitude larger than theoretical expectations for evolutionary effects (Kurtz, 1991).

Intrigued by these large frequency shifts, three years ago we started monitoring the pulsation frequency of HR 3831 on every possible night throughout its entire observing season (Fig. 2). These data show that the frequency of the principal pulsation mode varies cyclically by about 0.12 μHz on a time-scale of about two years. Note that by 'cyclic' we do not mean 'periodic' - the exact nature of the variations remains to be characterized. Similar, though less extensive, results have been obtained for α Cir (Kurtz et al. 1994b), HD 134214 (Kreidl et al. 1994) and HD 12932 (Martinez et al 1994). In fact, there are no roAp stars which have been monitored over several seasons for which a single, constant frequency fits the data. Frequency variability in these stars seems to be the norm. In a thorough analysis of 12 yr of HR 3831 data, Kurtz et al. (1994a) were able to exclude abrupt phase changes, a drift of the pulsation pole with respect to the magnetic pole, and orbital motion as the cause of the frequency variations. They also excluded evolutionary changes because $|d\nu/dt|$ is orders of magnitude higher than expected and its sign changes from season to season, contrary to all expectations of the way an evolutionary frequency change should behave.

So what is the cause of these frequency variations? For a possible answer to this question, we turn to helioseismology. One of the interesting recent results of helioseismology is that the frequencies of the solar p modes vary with the solar cycle (Elsworth et al. (1990), Libbrecht & Woodard (1990) and Bachmann & Brown (1993)). The range of that variation is about 0.5 μHz. This motivated Kurtz et al. (1994a) to suggest that the frequency variations in HR 3831 may be caused by variations in the stellar magnetic field, possibly in a stellar magnetic cycle. A direct observational test of this suggestion is not possible at present since inference from the Sun suggests that the these conjectured magnetic variations are orders of magnitude lower than can be detected with conventional magnetic measurements. Recently, Soon et al. (1993) suggested that the square of the ratio of the chromospheric oscillatory time-scale to the rotation period,

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$(P_{cyc}/P_{rot})^2$, is a measure of the theoretical dynamo number for cool, chromospherically active stars. Mindful of the danger of applying this suggestion to A stars, if we identify (P_{cyc}) with the cycle time of the frequency variation in HR 3831 we find $(P_{cyc}/P_{rot})^2 = 4.6$, which fits the extrapolation of Soon et al.'s relationship to higher temperature very well. Is this agreement purely a coincidence? Further monitoring of the principal pulsation frequency in HR 3831 and other roAp stars will allow us to test this.

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Discussion

Roxburgh: First I would like to take issue with your remark that Ap stars do not have convective regions. I would expect they have both convective core and a thin convective envelope. Next it is perfectly possible for a dynamo acting in one (or both) of these convective regions to drive a steady dynamo. It is not necessarily the case that dynamo driven fields have to be oscillating. Thus the magnetic field could be dynamo driven rather than fossil – or possibly have a dynamo component in addition to a fossil field. Since the Alfven travel time from centre to surface could be of the order of 1 year, this could produce surface variations which could be responsible for the observed variations in frequency.

Waelkens: Is there any possibility that your O-C variations are caused by orbiting planets?

Kurtz: No. The O-C diagrams do not repeat exactly from cycle to cycle as would be expected for a Doppler shift in frequency caused by orbital rotation.

Maeder: You mentioned these very interesting slow changes of the Ap stars frequencies. Would you please comment a bit more on their possible physical origin?

Kurtz: We have shown that the changes in the pulsation frequencies are intrinsic to the star, so this indicates a change in the sound speed or a change in the size of the acoustic cavity. We have guessed that these physical changes might be associated with a magnetic cycle, since the amplitude and time-scale of the frequency variations are similar to that seen in the Sun. The problem with the suggestion is that the magnetic fields in the Ap stars are thought to be fossil in origin, not dynamo driven, hence there is no theory to explain magnetic any magnetic cycles. So far as we know, there have been no other speculations about the physical origin of the frequency variations.

Shibahashi: You have concentrated in your talk mainly on the photometric observations. Some components with degree $\ell > 1$ may be substantially smeared out in the case of the luminosity variations integrated over the entire surface of the star. However, those components and the toroidal components, which might be induced by the magnetic fields, may contribute to the line profile variation. Could you say something about what has been done and what will be done in the spectroscopic observations to detect those components?

Kurtz: A few roAp stars have observed radial velocity variations: e.g., HR1217 was observed by Matthews, Wehlau, Walker & Young; γ Equ by Matthews (these proceedings). No one has yet detected line profile variations.

Jerzykiewicz: As you know, RRc variables show pulsation frequency variations similar to those of roAp stars. Would you care to comment on this?

Kurtz: No.

Smith: Regarding your plans to invert the $\Delta m_\lambda(t)$ to obtain $T(\tau)$ gradients in the atmosphere through limb darkening, it might also be productive to attempt this in the UV with Voyager. This effect works very well for NRP B stars (53 Per itself) in which differential increments in line blanketing provide some very sensitive tests of limb darkening-dependent parameters (including the nonradial modes themselves).

Kurtz: We have considered the feasibility of using the GHRS on HST to get the observations. For the A stars, though, there is little flux beyond the Balmer jump. We plan to work from the ground in the visible and infrared in the near future to see what we can learn.

Matthews: To apply the limb darkening analysis, we must assume the flux variations *un*weighted by limb darkening. In the UV, the spectral distribution is *so* distorted by line blanketing and the Balmer jump that one must assume a model atmosphere, which is dangerous (and circular) at this stage.

Goldreich: Solar p-mode frequency changes are associated with variations of order 200 G in rms magnetic field at the level of the photosphere. Would such variations be observable in Ap stars?

Kurtz: The errors in magnetic field measurements for Ap stars are generally 200 G or worse. Given a good reason, though, some improvement on this could be obtained for the brighter stars with an intensive observing effort.

Goldreich: Similar frequency variations could result from few percent variations of entropy in the photosphere. This might result from an interplay between convection and diffusive separation of elements.