NON-RADIAL OSCILLATIONS IN δ SCUTI STARS AND RAPIDLY OSCILLATING AP STARS

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Abstract. The present state of our knowledge of non-radial oscillations in δ Scuti stars and Rapidly Oscillating Ap stars is discussed primarily from an observational point of view. For the δ Scuti stars the need for complete frequency solutions for multi-periodic non-radial oscillating stars is emphasized in order for stellar seismology of these stars to be possible. An introduction to the Rapidly Oscillating Ap stars is given along with reference to a more complete recent review of those stars.

The δ Scuti stars.

It is clear from a large number of observational studies of δ Scuti stars that many of them pulsate in non-radial modes. However, many things about the nature of pulsations in δ Scuti stars are not clear. Some δ Scuti stars pulsate in a single stable radial mode; some pulsate in more than one stable radial mode; some pulsate in both radial and non-radial modes; some are claimed to switch modes or pulsate in modes with lifetimes short on the time-scale of the observations. See Breger's (1979) review of the δ Scuti stars for a discussion of these points.

It is perhaps indicative of the state of research on these objects over the past five years that little has been learned about the nature of the non-radial oscillations in δ Scuti stars since Breger's review article. While the study of non-radial oscillations in the sun and other stars has become an exciting new field with many investigators working both theoretically and observationally on a variety of non-radially oscillating stars, the δ Scuti stars seem to have been somewhat neglected. In order to use non-radial oscillations as physical probes of the interiors of δ Scuti stars, *i.e.* in order to do δ Scuti star seismology, complete

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frequency solutions for multi-periodic, non-radial oscillating δ Scuti stars are needed. These frequency solutions are not being produced, but, in my opinion, they could be.

The most complete frequency analysis for a non-radial oscillating δ Scuti star is probably that of Balona & Stobie (1980) on 1 Mon. They present a convincing case that this star pulsates with three stable pulsation modes which give rise to six frequencies. They find that the three principal frequencies of oscillation are nearly, but not quite equally split. From this and from the phase shift between the light and colour curves, $\Delta\phi(V,B-V)$, it appears that the frequency of highest amplitude is due to pulsation in a radial mode and the two frequencies unequally split from it are due to pulsation in $\ell=1$, $m=+1$ and -1 modes. If correct, this implies an extremely close frequency spacing between the dominant radial mode and the unresolved central $\ell=1$, $m=0$ mode. An analysis of the line profile variations in 1 Mon (Smith 1982) is consistent with this interpretation.

The slight inequality of the frequency spacing in 1 Mon might, of course, be attributed to second order effects in the rotational splitting relation (Ledoux 1951). In that case, however, there is a problem with the interpretation of phase shift $\Delta\phi(V,B-V)$ and line profile variation both of which point towards radial pulsation.

Returning to the point that frequency solutions for non-radial oscillating δ Scuti stars could be produced: It seems likely to me that many δ Scuti stars pulsate multi-periodically in non-radial modes. The reasons that there are so few frequency solutions for such stars are probably due to their low amplitude, short data sets, and daily aliasing problems. To solve these problems, coordinated, intensive campaigns of observations of multi-periodic δ Scuti stars from several observatories are required. An example of a research project which I suspect would be successful is further observations of θ Tuc from at least two, and preferably three observatories well spaced in longitude over a period of about two weeks. There was a time when θ Tuc was considered to be an example of a δ Scuti star which changed modes on a time scale as short as 24 hours (Stobie & Shobbrook 1976). New observations of θ Tuc (Kurtz 1980) showed, however, that the frequency of highest amplitude in this star was stable over a period of at least 7 years which implies that the other frequencies present might well be stable also. Frequency analyses of the θ Tuc data sets showed that some of the oscillation frequencies in this star are separated by nearly integral multiples of 1 d^{-1} which exacerbates the difficulty of getting a definitive frequency solution. The only way around this problem is to obtain contemporaneous observations from two or more observatories. In the case of θ Tuc this should be relatively easy to do since the star is bright and can be easily and accurately observed with small telescopes. Many other δ Scuti stars which are in the northern hemisphere could be similarly studied.

It is likely that theoreticians will spend little time considering stellar seismology of δ Scuti stars until frequency solutions for multi-periodic, non-radially oscillating δ Scuti stars are produced by observers. I therefore urge δ Scuti star observers to concentrate their efforts on collaborative contemporaneous observations of multi-periodic δ Scuti stars from more than one observatory in order to derive complete frequency solutions for these stars. This is needed much more than the discovery of new δ Scuti stars (we know they are very common) or incomplete frequency solutions for many stars.

The Rapidly Oscillating Ap stars

I have recently given an extensive review of the Rapidly Oscillating Ap stars (Kurtz 1985). In the interest of brevity and to avoid unnecessary repetition, therefore, I reproduce the introduction to that review and tables of the Rapidly Oscillating Ap stars below and refer the reader to the rest of that paper for further information.

The Rapidly Oscillating Ap stars are cool magnetic Ap stars which oscillate with periods between 4 and 15 min with peak-to-peak light variations of $B \leq 0.016$ mag. There are, as of this writing, eleven of these stars known. In tables 1-3 they are listed along with some of their observational characteristics and references to literature on them.

The short periods present in the light variations of these stars strongly suggest that their variations are due to high overtone *p*-mode oscillations. Kurtz (1982) has shown that the amplitude of the oscillations in some of them is modulated with the rotation period of the star with the times of maximum pulsation amplitude coinciding with the times of maximum extrema of the measured effective magnetic field strength. He has shown that the frequency pattern of these oscillations can be simply described by assuming that the oscillations are non-radial *p*-modes of low degree (ℓ small) with the axis of oscillation aligned with the magnetic axis of the star (the *oblique pulsator model*).

A problem with this model is that for oscillations about a magnetic axis which is inclined to the rotation axis of the star, advection is expected to cause the pulsation pattern to precess with respect to the magnetic axis. This is the same effect that lifts the degeneracy of the *m*-modes in a rotating star. This drift of the time of maximum pulsation amplitude with respect to the time of extremum of the magnetic field strength is not observed, however. In HR 1217 the times of pulsation amplitude maximum and effective magnetic field maximum have remained in phase with each other over 3 years of observations and in HR 3831 they have remained in phase over 4 years of observations. From calculations of $C_{n,\ell}$ (Shibahashi & Saio 1985a) we would expect to have already seen a drift in these phases in HR 1217 and HR 3831 if it were going to occur.

Dolez & Gough (1982) addressed this problem and suggested that the growth time for the oscillations in the Rapidly Oscillating Ap stars is short compared to the expected precession time of the pulsation axis for an oblique pulsator. Thus they suggest that only oscillations which are currently aligned with the magnetic field are excited to observable amplitudes. Shibahashi & Saio (1985a,b) agree with Dolez & Gough on this point. From calculations of the effect of the magnetic field on the oscillations, Dziembowski & Goode (1985a,b) suggest that the oscillations are dominated by the magnetic field rather than by rotation. Hence they expect that the pulsation axis will not drift with respect to the magnetic axis.

Mathys (1984, 1985) has proposed an alternative to the oblique pulsator model, the *spotted pulsator model*. He suggests that the oscillations in the Rapidly Oscillating Ap stars are aligned with the rotation axis of the star and that the amplitude modulation of the oscillations is due to surface inhomogeneities and a variable ratio of surface flux to radius variations with cylindrical symmetry about the magnetic axis of the star. This explains the observed frequency splitting seen in these stars and allows arbitrary amplitudes for the observed frequencies. It also avoids the problems discussed in the last paragraph. It does, however, have several free parameters which are unknown and currently unmeasurable and hence it is neither applicable nor testable.

The oscillation periods in the Rapidly Oscillating Ap stars are so short that it seems likely that they are due to very high overtone *p*-mode pulsation. This raises the obvious questions why such high overtone pulsation modes should be preferentially excited and what mechanism selects only the few modes which are observed. Shibahashi (1983) has tried to answer these questions by suggesting that overstable magnetic convection is the driving mechanism in the Rapidly Oscillating Ap stars. Since this mechanism is most effective at the magnetic poles of the star, it gives a natural explanation of why the oscillations should be aligned with the magnetic axis. Shibahashi also calculates that the time scale for magnetic overstability in A stars is about 10 minutes; he therefore suggests that the observed modes are simply those with frequencies closest to the time-scale of the magnetic overstable convection which are resonantly excited. Cox (1984) has also discussed Shibahashi's idea. A difficulty with the idea of excitation of the Rapidly Oscillating Ap stars by magnetic overstability is that it introduces an additional pulsation mechanism where one is already known; all of the known Rapidly Oscillating Ap stars lie within the δ Scuti instability strip. There are also a few Ap stars which appear to be δ Scuti stars, a point discussed further in section 4. Dziembowski (1984) favours excitation of the oscillations in the Rapidly Oscillating Ap stars by the κ-mechanism; he suggests that the presence of the magnetic field may enhance the instability of some of the non-radial modes.

Definitive tests to distinguish between driving by the κ-mechanism or by magnetic overstability are difficult to devise. Finding a Rapidly Oscillating Ap star much hotter than the observed blue border of the δ Scuti instability strip would seem to be a good test, but that border is observationally not rigidly defined and theoretically may be dependent on the atmospheric structure and abundance distributions of the magnetic Ap stars which are not well known. In addition, it is clear that there are oscillating stars hotter than the blue border of the δ Scuti instability strip, such as the 53 Persei variables and the β Cephei variables, for which no pulsation mechanism is known. Finding a definitely non-magnetic rapidly oscillating star in the same part of the HR diagram as the Rapidly Oscillating Ap stars might disprove magnetic overstability- *if* it were certain that the star really was non-magnetic and if it were certain that yet another new class of variable stars had not been discovered.

The idea of the oblique pulsator model has given rise to several theoretical discussions. Cousens (1983) has independently developed the same idea which he calls the *Obliquely Oscillating Magnetic Rotator* and which he applies to a possible interpretation of the Blazhko effect in RR Lyrae stars. Aizenman *et al.* (1984) have calculated a formula for rotational mode splitting about an inclined axis which is discussed further by Pesnell (1985), but Shibahashi & Saio (1985b) dispute Aizenman *et al.*'s result. Dziembowski & Goode (1985a) also state that Aizenman *et al.*'s result is not applicable to any real system. Basically, Shibahashi & Saio's argument is that a spherical harmonic aligned along an axis inclined to the rotation axis can be rewritten as a linear summation of spherical harmonics about the rotation axis by a simple rotation of coordinates. They conclude that the Ledoux (1951) rotational splitting formula must still apply, which gives rise to the previously mentioned effect of the expected, but not observed, precession of the pulsation pattern with respect to the magnetic axis. Dziembowski & Goode claim that the oscillation modes in the Rapidly Oscillating Ap stars are not normal modes and hence a coordinate transformation of the axis of symmetry of a set

Table 1. Strömgren indices for the Rapidly Oscillating Ap stars

HD	HR	V	$b-y$	m_1	c_1	β	δc_1	refs
6532		8.45	0.084	0.237	0.846		−0.142	1,2
24712	1217	5.99	0.183	0.212	0.634	2.744	−0.034	1,2
60435		8.889	0.132	0.234	0.843		+0.035	3
83368	3831	6.174	0.146	0.203	0.796	2.827	−0.035	3,1
101065		8.004	0.448	0.368	−0.014	2.641	−0.386	4
128898	5643	3.198	0.152	0.195	0.760	2.831	−0.077	3,1
134214		7.479	0.211	0.288	0.597	2.766	−0.115	6,7
137949		6.674	0.188	0.321	0.584	2.833	−0.256	3,1
201601	8097	4.68	0.147	0.238	0.760	2.819	−0.058	1,2
203932		8.820	0.169	0.196	0.736	2.814	−0.072	3,5
217522		7.520	0.289	0.215	0.487	2.701	−0.046	3,5

references: (1) Hauck & Mermilliod 1980; (2) Blanco *et al.* 1970; (3) Vogt & Faundez 1979; (4) Kurtz & Wegner 1979; (5) Weiss (private communication); (6) Olsen & Perry 1984; (7) Olsen 1983.

Table 2. Magnetic field strengths and spectral types for the Rapidly Oscillating Ap stars.

HD	HR	H_e(G)	refs	Spectral Type	refs
6532				Ap SrCrEu	1
24712	1217	+300 to +1200	2	A5p	3
60435				Ap Sr(Eu)$_1$Fp SrEu	4,5
83368	3831	−700 to +700	6	Ap SrCrEu	7,5
101065		−2200	8	Controversial	9
128898	5643	−300(variable)	10,11,12	Ap SrEuCr,Ap SrEu	4,5
134214				F0, F0 SrEu	17
137949		+1400 to +1800	13	Fp SrCrEu	5
201601	8097	+500 to −800	14,15,16	F0p	3
203932				Ap SrEu$_2$	5,1
217522				Ap SiCr ,Fp SrEu	1,5

references: (1) Houk 1982; (2) Preston 1972; (3) Hoffleit 1982; (4) Houk & Cowley 1975; (5) Bidelman & MacConnell 1973; (6) Thompson 1983; (7) Houk 1978; (8) Wolff & Hagen 1976; (9) Kurtz & Wegner 1979; (10) Wood & Campusano 1975; (11) Borra & Landstreet 1975; (12) Borra & Landstreet 1980; (13) Wolff 1975; (14) Babcock 1958; (15) Bonsack & Pilachowski 1974; (16) Scholz 1979; (17) Henry Draper Catalogue.

Table 3. Frequencies derived for the Rapidly Oscillating Ap stars.

HD	HR	P(min)	f(mHz)	A(mmag)	refs
6532		6.956	2.39612	1.01	1
		6.938	2.40210	0.73	
		6.922	2.40761	0.55	
24712	1217	6.126	2.7208	2.13	2,3,4
		6.283	2.6528	2.07	
		6.202	2.6875	1.10	
		6.048	2.7556	0.90	
		6.361	2.6200	0.60	
		5.966	2.7936	0.44	
60435		15.141	1.10077	2	5
		12.784	1.30371	6	
		12.327	1.35210		
		12.070	1.38088		
		11.841	1.40749		
		11.625	1.43364		
		6.06	2.75	1.5	
		3.994	4.17307	2	
83368	3831	11.705	1.423950	2.14	4
		11.638	1.432069	1.75	
		11.671	1.428011	0.38	
		5.836	2.856019	0.45	
		5.852	2.847906	0.20	
		5.819	2.864139	0.18	
101065		12.140	1.372865	5.40	6,7,8,9
		12.674	1.315079	0.67	9
		6.070	2.7459	0.26	9
128898	5643	6.825	2.442041	1.91	10
		6.832	2.4395	0.38	
134214		5.650	2.9496	3.23	14
137949		8.272	2.0148	1.39	4
201601	8097	12.448	1.339	0.86	11
203932		5.942	2.804789	0.66	12
217522		13.716	1.21510	2	13

references: (1) Kurtz & Kreidl 1985; (2) Kurtz & Seeman 1983; (3) Kurtz, Schneider, & Weiss 1985; (4) Kurtz 1982; (5) Matthews, Kurtz, & Wehlau 1985; (6) Kurtz 1981; (7) Kurtz 1980; (8) Kurtz & Wegner 1979; (9) Kurtz unpublished; (10) Kurtz & Balona 1984; (11) Kurtz 1983a; (12) Kurtz 1984; (13) Kurtz 1983b; (14) Kreidl 1985.

of spherical harmonics does not provide a formally correct description of those modes.

Models for the Rapidly Oscillating Ap stars have been calculated by Gabriel *et al.* (1985) and by Shibahashi & Saio (1985a). Shibahashi & Saio find that the observed frequencies of some of the Rapidly Oscillating Ap stars are above the critical frequencies of their models. When the frequency of oscillation is greater than the critical frequency then the wavelength of the oscillation is short compared to the height of the surface boundary and the wave penetrates that surface boundary and is not trapped. Shibahashi & Saio calculate that to increase the critical frequency to a value above the highest observed frequencies in the Rapidly Oscillating Ap stars they must increase T_{eff}/T_{surf} to 1.5 times the value for standard A star models. This brings up the interesting possibility that the very coolest of the magnetic Ap stars, which appear to have spectral types around F0, may have effective temperatures significantly hotter than this spectral type implies.

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