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The p-mode spectra of the roAp stars

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Abstract. This paper discusses the general properties of the p-mode spectra of roAp stars and provides a table of these properties for the 28 currently known roAp stars.

Key words: stars: pulsations, stars: chemically peculiar, asteroseismology

1. Introduction

The rapidly oscillating Ap (roAp) stars are cool, magnetic, chemically peculiar A-F IV-V stars which exhibit low-degree, high-overtone, non-radial p-mode pulsations with periods in the range 5.6–15.0 min. The photometric amplitudes of the variations in roAp stars range from about 0.07 mmag (an observational lower limit) to several mmag in Johnson B light. The pulsations in the roAp stars are similar in nature to those seen in integrated sunlight but with several important differences: (i) the pulsation amplitudes in the roAp stars are three to four orders of magnitude larger than in the Sun, (ii) the pulsations in roAp stars occur in the presence of global magnetic fields of several hundred to several thousand gauss, and (iii) the manner in which the pulsation energy is distributed among the possible modes differs between the Sun and the roAp stars (in the Sun all possible modes within a given frequency range are seen whereas in some roAp stars certain modes seem to be missing — this has implications for the mode selection mechanism in these stars). Nevertheless, the pulsations in the roAp stars open a valuable window on astrophysical processes in chemically peculiar stars of the upper main sequence.

The pulsation axis in a roAp star is aligned with the magnetic axis, which is oblique to the rotation axis. Because they are aligned with the magnetic axis, the non-radial modes are seen from variable aspect as the star rotates. These ideas are embodied in the *oblique pulsator model* (Kurtz 1990) which provides a generally accurate description of the oscillation phenomena of roAp stars. The model predicts the splitting of a pulsation mode of degree ℓ into $(2\ell + 1)$ frequency components equally separated by the rotation frequency. From the multiplet amplitudes one can infer ℓ and establish constraints on the inclination of the rotation axis and the obliquity of the magnetic (pulsation) axis.

The naive oblique pulsator model just described ignores Coriolis and magnetic effects. It predicts frequency multiplets with amplitude symmetry about the central frequency whereas in fact marked amplitude asymmetries are observed. Dziembowski & Goode (1985) and Kurtz & Shibahashi (1986) augmented the oblique pulsator model by incorporating magnetic and Coriolis perturbations and thereby explained the asymmetries in the rotation sidelobes. In the augmented model the degree of asymmetry provides a measure of the integrated global interior magnetic field strength - a value inaccessible to conventional surface magnetic measurement techniques.

The oblique pulsator model makes specific predictions about changes in the pulsation amplitude and phase of the oscillations as the star rotates. For a dipole pulsation mode the two hemispheres of the star pulsate in anti-phase. A π-radian pulsation phase reversal is expected at magnetic quadrature as one pulsation pole disappears and the other comes into view. Those roAp stars that pulsate in a single, high amplitude dipole mode permit close scrutiny of these predictions and reveal that the situation is somewhat more complicated. Studies of the pulsation amplitude and phase in the stars HR 3831 and HD 6532 show that the pulsation modes in these stars are distorted dipoles (Kurtz et al. 1993 and 1996, respectively). Refinements of the oblique pulsator model by Shibahashi & Takata (1993) and Takata & Shibahashi (1995) taking into account, respectively, higher-order terms and the quadrupole component of the magnetic field provide substantial (though not complete) understanding of the distorted dipole modes in these stars.

Most of the roAp stars pulsate in more than just a single dipole mode and it is these multi-mode pulsators that have generated the widespread interest in applying the techniques of helioseismology to roAp stars. Some stars, like HR 1217 (HD 24712), have p-mode spectra reminiscent of the solar p-mode spectrum. The frequency spacings in these stars permit asteroseismological luminosity determinations. Since the normal calibrations of temperature and luminosity cannot be applied reliably to chemically peculiar stars these asteroseismological luminosities are the most reliable luminosity estimates that we have. They indicate that the roAp stars are H-core burning Population-I stars that lie in the instability strip 1-2 mag above the main sequence. We can check the asteroseismological luminosities against parallax luminosities for two roAp stars, α Cir and γ Equ. For γ Equ (HD 201601) the two luminosity estimates agree within 0.1 mag. For α Cir (HD 128898) the parallax and asteroseimological luminosities differ by 0.4 mag.

The oscillation spectra of many roAp stars are non-stationary in the sense that the distribution of pulsation amplitudes among the different modes is time dependent. As a rule, roAp stars in which only a few (say, 1–3) modes are excited have more stable amplitude spectra than stars in which many different modes are excited. Examples of 'mode-stable' stars are HD 101065 and HR 3831 (HD 83368) which have had the same mode structure for over 16 yr. The best example of a star with highly variable mode structure is HD 60435 which has been observed to pulsate predominantly in so many different modes that it is not possible to talk about a 'principal pulsation frequency' for that star in the same way as is done for the other roAp stars. Other roAp stars exhibiting similar behaviour are HD 201601 (γ Equ), HD 84041 and HD 119027.

The amplitude spectra of the roAp stars also reveal non-linearities in the pulsations. About one third of the roAp stars exhibit a non-sinusoidal pulse shape indicating that the pulsations are non-linear. These non-linearities are not understood; δ Scuti stars oscillate with amplitudes of a few tenths of a magnitude and show no evidence of these harmonics while roAp stars which oscillate with amplitudes of 1–2 mmag do.

Almost all roAp stars which have been studied over several years show long-term frequency variability. The best-studied case is HR 3831 which varies cyclically with a peak-to-peak amplitude of 0.12 μHz on a time-scale of 1.6 yr. Other work indicates similar frequency variations in HD 12932, α Cir (HD 128898), HD 134214, HD 137949, HD 101065 and HR 1217. Not *all* roAp stars show frequency variability though. HD 6532, for which we have 10 yr of data spanning 1984–1994, shows as yet no signs of frequency variability.

The frequency variations in the roAp stars are reminiscent of similar variations in the solar oscillation frequencies during the solar cycle (e.g. Bachman & Brown 1993). This has led to the speculation that the frequency variations in roAp stars are caused by intrinsic magnetic cycles in those stars. Unfortunately this idea cannot be tested by direct magnetic measurements since the conjectured magnetic variations are orders of magnitude less than can be detected by conventional methods. We should mention here that the frequency variations described above are orders of magnitude larger than those expected from model predictions of frequency change due to evolution (e.g. Heller & Kawaler 1988) and thus exclude the possibility of measuring frequency changes to determine the evolutionary stages of these stars.

Table 1 summarizes the properties of the p-mode spectra of the 28 roAp stars known as of this writing. Readers interested in a more detailed introduction to the roAp phenomenon are referred to the recent, readily available reviews by Kurtz (1990), Matthews (1991), and Shibahashi (1991). Kurtz and Matthews highlight observational developments while Shibahashi discusses theoretical developments.

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References

Bachman K.T., Brown T.M., 1993, ApJ, 411, L45.
Dziembowski W., Goode P., 1985, ApJ, 296, L27.
Heller C.H., Kawaler S.D., 1988, ApJ, 329, L43.
Kurtz D.W., 1990, Annual Reviews Astron. Astrophys., 28, 607.
Kurtz D.W., Shibahashi H., 1986, MNRAS, 223, 557.
Kurtz D.W. et al., 1993, MNRAS, 260, 343.
Kurtz D.W. et al., 1996, MNRAS, in press.
Matthews J.M., 1991, PASP, 103, 5.
Shibahashi H., 1991, in *Challenges to theories of the structure of moderate-mass stars,* eds D.O. Gough, J. Toomre, Springer, Berlin, p. 393.
Shibahashi H. & Takata M., 1993, PASJ, 45, 617.
Takata M. & Shibahashi H., 1995, PASJ, 47, 219.

Table 1: Properties of the p-mode spectra of the roAp stars

HD *HR*	V	ΔB [a] mmag	ν [b] μHz	N_ν [c]	$\Delta\nu$ [d] μHz	P_{rot} d
6532	8.4	5	2402	1		1.944973
9289	9.4	3.5	1585	>3?	20 or 30	?
12932	10.2	4	1436	1		?
19918	9.3	2.8	1510	2	30 ± 1 d^{-1}	?
24712 *1217*	6.0	8	2688	6	34	12.4572
42659	6.8	0.8	1736?	> 1?		?
60435	8.9	8	1043–1433	> 10?	25.8	7.6793
80316	7.8	1.5	2252	1		inconclusive
83368 *3831*	6.2	8	1428	1		2.851982
84041	9.3	2	1113	4?	31	3.69
86181	9.3	4.6	2688	> 1?		?
101065	8.0	13	1373	3	58	?
119027	10.0	2	1914	5	26	?
128898 *5463*	3.2	5	2442	5	25	4.4790
134214	7.5	7	2950	1		?
137949	6.7	3	2015	> 1?	40?	?
150562	9.8	1.5	1559 or 1547	> 1?		?
161459	10.3	2.4	1390	> 1?		?
166473	7.9	1.4	1881 or 1892	3?	36?	?
176232 *7167*	5.9	1.2	1436	3	50	?
185256	9.9	3	1630	> 1?		?
190290	9.9	2.3	2270	2	40	?
193756	9.2	1.7	1284	1		?
196470	9.7	1.4	1544	> 1?		?
201601 *8097*	4.7	2	1365	4	30	> 70 yr
203932	8.8	1.6	2805	4?	33	?
217522	7.5	2.6	1200	3	15	?
218495	9.4	2.3	2240	1		?

[a] This is the typical peak-to-peak variation for a night when the star is "up" in amplitude.
[b] For multi-periodic stars the frequency of the mode with the highest amplitude is listed.
[c] This column lists the number of modes observed/suspected in a given star.
[d] This column lists the *observed* frequency spacing (i.e. no values multiplied by 2).

1996BASI...24..359M

Table 1: (continued)

HD *HR*	Harmonics	Mode changes	Frequency changes	Distorted dipole	Well studied	Reference
6532	√	×	×	√	√√√	Kurtz96
9289	×	?	?		√	Kurtz94b
12932	√	×	√		√√	Marti94e
19918	√	×	×		√√	Marti95
24712 *1217*	×	√	√		√√√	Kurtz89a
42659	×	?	?		×	Marti94c
60435	×	√	×		√√	Matth87
80316	×	×	?		×	Kurtz90b
83368 *3831*	√	×	√	√	√√√	Kurtz94
84041	×	√	?		√	Marti93
86181	×	?	?		×	Kurtz94c
101065	√	×	√		√√√	Marti90
119027	×	√	?		√	Marti93a
128898 *5463*	√	×	√		√√	Kurtz94a
134214	×	×	√		√√	Kreid94
137949	√	×	√		√	Kurtz91
150562	×	?	?		×	Marti94c
161459	√	?	?		×	Marti91
166473	√?	?	?		√	Kurtz87
176232 *7167*	×	?	?		√	Helle90
185256	×	?	?		×	Kurtz95
190290	×	?	?		×	Marti91
193756	×	?	?		×	Marti91
196470	×	?	?		×	Marti91
201601 *8097*	×	√	×		√√	Marti96
203932	×	√	×		√	Marti90a
217522	×	√	?		√√	Kreid91a
218495	√	?	?		×	Marti91

Helle90 = Heller & Kramer, 1990, MNRAS, 244, 372; **Kreid91a** = Kreidl et al., 1991, MNRAS, 250, 477; **Kreid94** = Kreidl et al., 1994, MNRAS, 270, 115; **Kurtz87** = Kurtz & Martinez, 1987, MNRAS, 226, 187; **Kurtz89a** = Kurtz et al., 1989, MNRAS, 240, 881; **Kurtz90b** = Kurtz, 1990, MNRAS, 242, 489; **Kurtz91** = Kurtz, 1991, MNRAS, 249, 468; **Kurtz94** = Kurtz et al., 1994, MNRAS, 268, 641; **Kurtz94a** = Kurtz et al., 1994, MNRAS, 270, 674; **Kurtz94b** = Kurtz et al., 1994, MNRAS, 271, 421; **Kurtz94c** = Kurtz & Martinez, 1994, IBVS, 4013; **Kurtz95** = Kurtz & Martinez, 1995, IBVS, 4209; **Kurtz96** = Kurtz et al., 1996, MNRAS, in press; **Marti90** = Martinez & Kurtz, 1990, MNRAS, 242, 636; **Marti90a** = Martinez et al., 1990, MNRAS, 246, 699; **Marti91** = Martinez et al., 1991, MNRAS, 250, 666; **Marti93** = Martinez et al., 1993, MNRAS, 263, 273; **Marti93a** = Martinez et al., 1993, MNRAS, 260, 9; **Marti94c** = Martinez & Kurtz, 1994, MNRAS, 271, 118; **Marti94e** = Martinez et al., 1994, MNRAS, 271, 305; **Marti95** = Martinez et al., 1995, MNRAS, in press; **Marti96** = Martinez et al., 1996, MNRAS, in press; **Matth87** = Matthews et al., 1987, ApJ, 313, 782;