THE RICH p-MODE PULSATION SPECTRUM OF HD 60435

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I. INTRODUCTION

Twelve cool Ap stars are known at present to undergo rapid light oscillations at low amplitude ($\Delta B < 0\overset{m}{.}012$) and with periods of minutes. These rapidly oscillating Ap (roAp) stars also exhibit amplitude modulation with timescales of days, which correspond to the magnetic/ rotation periods (when those have been measured). In at least one case (HR 3831), 180° phase shifts in the dominant oscillation are seen twice per modulation cycle.

The oscillations are presumed to be high-overtone p-mode pulsations of low degree. The roAp stars appear to fall within the δ Scuti instability strip, which would provide a natural driving mechanism for such pulsations. The excitation of overtones much higher than are detected in the δ Scutis may be a consequence of the strong magnetic fields of the peculiar A stars.

The observed modulation and phase shifts of the oscillations can be explained by the oblique pulsator model (Kurtz 1982), in which nonradial pulsations of an roAp star are forced to align with that star's magnetic field axis, as opposed to its rotation axis.

HD 60435 possesses the most complicated oscillation spectrum yet observed among the roAp stars. Kurtz (1984) first detected periods near 12 and 6 minutes in this star. A coordinated observing campaign by Matthews, Kurtz, and Wehlau (1986) revealed additional periods near 15 and 4 minutes. The 6- and 4-min oscillations may be in 3:2:1 resonance with their 12-min counterpart; however, there was no apparent explanation of the occurrence of oscillations at the selected periods of 12 and 15 minutes. In fact, this is a riddle common to all of the roAp stars: Why should only a few modes be excited from the dense spectrum of frequencies possible for such stars (as found in the models of Shibahashi and Saio (1985) and Gabriel et al. (1985) and echoed in the Sun's five-minutes oscillations)?

The observations reported here demonstrate that HD 60435 actually oscillates in many modes, though not simultaneously, across a relatively broad frequency range. In light of this, the mode selection problem for the roAp stars may not be as severe as previously thought.

J. Christensen-Dalsgaard and S. Frandsen (eds.), Advances in Helio- and Asteroseismology, 261–264.

II. THE LATEST OBSERVATIONS AND FREQUENCY ANALYSIS

Rapid B photometry of HD 60435 was carried out during 30 nights from 8 January to 16 February 1985 (plus five nights in November 1984 and one in March 1985). Observations were collected using the 0.6-m University of Toronto telescope at the Las Campanas Observatory (LCO), Chile; the 0.9-m telescope of the Cerro Tololo Inter-American Observatory (CTIO); and the 0.5 m telescope of the South African Astronomical Observatory (SAAO). Contiguous data from one of the Chilean sites and SAAO were obtained on nine nights.

The measurements consisted of continuous 20-second integrations through a Johnson B filter, with occasional (aperiodic) interruptions for sky readings and guiding. No comparison star was employed for the rapid photometry. The sensitivity of the observations to rapid variability was dependent on the stability of the sky transparency on each night.

A sample light curve of HD 60435, in which the "12-min" oscillations (frequency ≃ 1.4 mHz) of the star are prominent, is shown in Fig. 1. (See also the amplitude spectrum in the seventh panel of Fig. 2.)

The photometric data were searched for rapid oscillations using a modification (Matthews and Wehlau 1985) of Deeming's (1975) Fourier periodogram for unequally spaced time series.

Figure 2 is a selection of ten amplitude spectra generated in this way from individual nights of observations. The dashed lines represent amplitudes above which peaks are considered significant at the 99% level. The peaks seen at frequencies less than about 0.5 mHz are residuals of sky variations. These particular spectra were chosen to illustrate some of the noteworthy features of the oscillations of HD 60435:

1. There exists a series of frequencies across a range from about 0.7 to 1.5 mHz (i.e. periods between ∿20 and 12 min). The complete set is listed in the accompanying table. These frequencies comprise a pattern with a characteristic spacing of about 25.8 μHz, into which all but one (ν_k) can be placed. (See the second column of the table.)
2. Frequencies near 1.4 mHz are the most persistent and those oscillations reach the largest amplitudes, as noted in earlier runs.
3. A modulation timescale of ∿7-8 days for those oscillations is evident. JD 2446022, -082, -098, -105, and -112 are nights during which the "12-min" oscillations reached or approached maximum amplitude. This amplitude modulation is in phase with the long-term light variations of the star, in accord with the predictions of the oblique pulsator model.
4. On two of the nights listed above, JD 2446022 and -105, peaks (indicated by arrows in Fig. 2) occur near a frequency of 2.8 mHz (i.e. P ≃ 6 min). Although these peaks are just below the 99% confidence level, we believe they arise from a 2:1 resonance with the 1.4 mHz oscillations, experiencing the same modulation and rising above the noise only at peak amplitude.
5. Certain oscillations can grow to - or decay from - observable amplitude in less than a day (e.g. peak 'n' between JD 2446111 and -112 in Fig. 2). Mode lifetimes of only a few hours were predicted by Dolez and Gough (1982) for these stars based on their simple model; our observations lend support to their theoretical results.

III. MODE IDENTIFICATION

In a star undergoing p-mode pulsations, consecutive overtones of a given degree (such that $n \ll \ell \sim 1$) are expected to display roughly equal spacing in frequency, according to the relation: $\nu_{n,\ell} \sim \nu_o(n + \ell/2 + \varepsilon)$, where $\nu_{n,\ell}$ = frequency of a mode (n,ℓ), ν_o = the frequency spacing, and ε = a small constant dependent upon the stellar structure.

Shibahashi and Saio (1985) have calculated ν_o for several models of stars between 1.3 and 2.4 M_o. The value $\nu_o \sim 26$ μHz, suggested by our observations of HD 60435, is too small for a star near the main sequence in this mass range. However, twice that spacing is consistent with a moderately evolved A star. We have therefore argued that ν_o should be approximately 50-55 μHz for HD 60435, and that modes of both even and odd degree (whose adjacent overtones will be spaced by $\nu_o/2$) are present in its oscillation spectrum.

Using the equation above, we can also assign possible (n,ℓ) values to the observed frequencies, as shown in the third column of the table. Furthermore, detailed eigenfrequency calculations by Shibahashi and Saio and by Gabriel et al. (1985) independently show that the frequency spacings between modes should vary in a systematic fashion, providing yet another constraint on the mode identifications. For the observed frequencies in HD 60435, the predicted inequalities can be satisfied <u>only</u> by the selected modes (assuming $\ell \leq 2$) shown in the fourth column of the table.

Frequencies observed in HD 60435.

	ν (mHz) ± 0.0001	$\left(\frac{\nu - \nu_q}{25.8\ \mu Hz}\right)$	Possible mode[2] (w.r.t. ν_q)	Tentative identification	Dates detected (JD 2,446,000 +)
a	0.7090	29.00 = 29	$\{^{n-15}_{n-14}\},\ell\pm1$	(n-14,1)	077,097
b	0.7614	26.97 ≈ 27	$\{^{n-14}_{n-13}\},\ell\pm1$	(n-13,1)	097
c	0.8428	23.81 ≈ 24	n-12,ℓ	(n-12,2) (n-11,0)?	098
d	0.9397	20.06 ≈ 20	n-10,ℓ	(n-10,2)	082
e	0.9906	18.09 ≈ 18	n-9,ℓ	(n-9,2)	101
f	1.0433	16.04 ≈ 16	n-8,ℓ	(n-8,2)	078
g	1.0990	13.88 ≈ 14	n-7,ℓ	(n-7,2)	022,078
h	1.1482	11.98 ≈ 12	n-6,ℓ	(n-6,2)	077,079
i	1.1734	11.00 = 11	$\{^{n-6}_{n-5}\},\ell\pm1$	(n-5,1)	101
j	1.2250	9.00 = 9	$\{^{n-5}_{n-4}\},\ell\pm1$	(n-4,1)	022
k	1.2848	6.68[1]	...	...	105,112
l	1.3281	5.00 = 5	$\{^{n-3}_{n-2}\},\ell\pm1$	(n-2,1)	102,105
m	1.3525	4.06 ≈ 4	n-2,ℓ	(n-2,2)	019,021-022,079, 095-096,105,107
n	1.3810	2.95 ≈ 3	$\{^{n-2}_{n-1}\},\ell\pm1$	(n-1,1)	099,104,106,111-112
o	1.4073	1.93 ≈ 2	n-1,ℓ	(n-1,2)	074,105-106
p	1.4334	0.92 ≈ 1	$\{^{n-1}_{n}\},\ell\pm1$	(n,1)	075,082,097-098,104
q	1.4572	0	n,ℓ	(n,2)	Combined[3]

https://doi.org/10.1017/S0074180900158188 Published online by Cambridge University Press

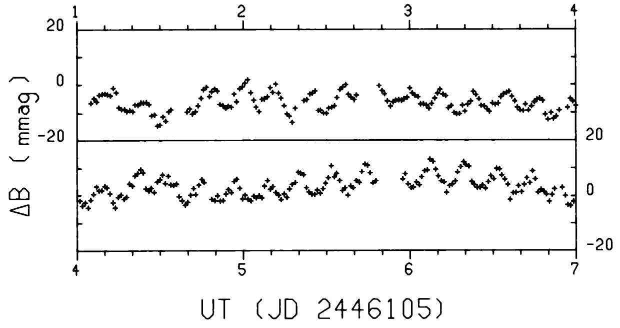
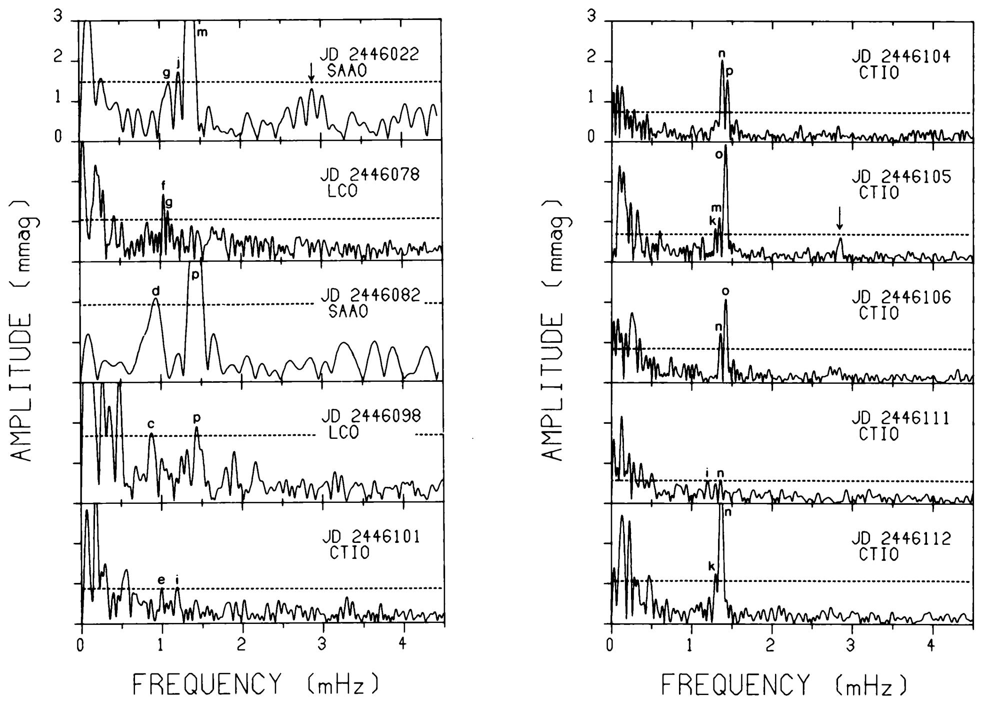


FIGURE 1.
A light curve of HD 60435 obtained using the CTIO 0.9-m telescope. Each point represents an average of three 20-second integrations through a Johnson B filter.

FIGURE 2. Selected amplitude spectra.



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