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ATMOSPHERIC STRUCTURE OF THE PULSATING Ap [CP2] STAR HR 3831 FROM RAPID MULTICOLOUR PHOTOMETRY

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OPENING A NEW WINDOW ON Ap ATMOSPHERES

Rapidly oscillating Ap (roAp) stars are cool magnetic CP2 stars which vary with periods of a few minutes and amplitudes less than 0.01 mag and 1 km/s in light and velocity. Analysis of their *p*-mode eigenfrequency patterns and splittings gives information about evolutionary state, rotation rate, magnetic field geometry and internal field strength (see Kurtz 1990; Matthews 1991). We present here an example of how roAp pulsations can be used to obtain an estimate of the temperature structure of an Ap atmosphere.

The pulsation amplitudes of roAp stars decline more rapidly with increasing wavelength than other known pulsators. Matthews *et al.* (1990) explained this by the wavelength dependence of limb darkening and its weighting effect on the integrated amplitude of an $(\ell, m) = (1,0)$ mode. This dipole mode – which appears to dominate roAp stars; in particular, HR 3831 – has two special properties:

- It does not change the projected area of the stellar disk, so all light variations can be attributed to flux (temperature) variations; and
- No matter what the inclination of the mode (except $i = 90°$), limb darkening *increases* the net amplitude measured on the visible disk.

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FROM PULSATION AMPLITUDES TO ATMOSPHERIC STRUCTURE

Stronger limb darkening at shorter wavelengths enhances the amplitudes. By measuring amplitudes at various wavelengths, we can estimate the limb darkening coefficients and hence, the temperature structure of the atmosphere.

Using the CTIO 1.0- and 1.5-m telescopes simultaneously in November 1991, we obtained high-speed photometry of the roAp star HR 3831 in the optical (Strömgren *vby*, Cousins *RI*) and infrared (*JHK*). Figure 1 shows the Fourier amplitude spectra in the 8 bandpasses for the night of 25 Nov; the data cover ~18 pulsation cycles near phase 0.4 of the 2.85-d magnetic period of this star (Kurtz *et al.* 1990); i.e., just before magnetic and pulsation amplitude maximum. The prominent peak visible at shorter wavelengths occurs near 122 d^{-1} ($P = 11.8$ min): the dominant pulsation mode of HR 3831.

Models of the brightness oscillations of an $(\ell, m) = (1,0)$ mode for a given inclination i, mean temperature $T_{\rm eff}$ and temperature variation $\Delta T_{\rm puls}$ were produced for all eight bandpasses. These were then weighted by the limb-darkening relation:

$$\frac{I_\nu(\theta)}{I_\nu(0)} = 1 - \beta_\nu(1 - cos\theta).$$

where β_ν is a free parameter. The resulting amplitude ratios were compared to the observed ratios and the coefficients β_ν estimated by least-squares fitting.

The resulting values of β_ν were used to solve the expression:

$$\frac{I_\nu(\theta)}{I_\nu(0)} = \int_0^\infty \frac{S_\nu(\tau_\nu)}{I_\nu(0)} e^{-\tau_\nu sec\theta} sec\theta \, d\tau_\nu$$

where the source function was modelled by the expansion

$$S_\nu(\tau_\nu) = a_0 + a_1\tau_\nu + a_2\tau_\nu^2 + a_3\tau_\nu^3 + a_4\tau_\nu^4 + a_5\tau_\nu^5$$

and $I_\nu(0)$ was sampled over the expected range of luminosity for an F0 V star. The coefficients a_j were obtained by *LU* inversion of the 6×6 matrix.

Finally, the source function was equated with the Planck function

$$S_\nu(\tau_\nu) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kt} - 1}$$

to produce the temperature structure as a function of optical depth.

AN EMPIRICAL $T - \tau$ RELATION FOR HR 3831

Model fits were performed for a range of mean effective temperatures [$7500\ K \leq T_{\rm eff} \leq 8500\ K$] and inclinations of the pulsation pole [$30° \leq i \leq 80°$]. The observed amplitude ratios (and upper limits) of HR 3831 require a **steeper $T - \tau$ relation than for a solar atmosphere.** However, a monotonic $T - \tau$ curve cannot account for the data. The only solution is obtained by invoking a **temperature inversion near $\log\tau_{5000Å} \simeq$ -0.7**, as shown in Figure 2. If real, this inversion suggests a strong source of opacity near that optical depth. If an artifact of the fit, it may mean that limb darkening is not the sole mechanism weighting the observed pulsation amplitudes. Flux redistribution by spots is a possibility, especially if the spots are linked to the magnetic (and pulsational) geometry. Even so, significant redistribution out to 2.2μ is unlikely, so the steepness of the $T - \tau$ curve is a robust result.

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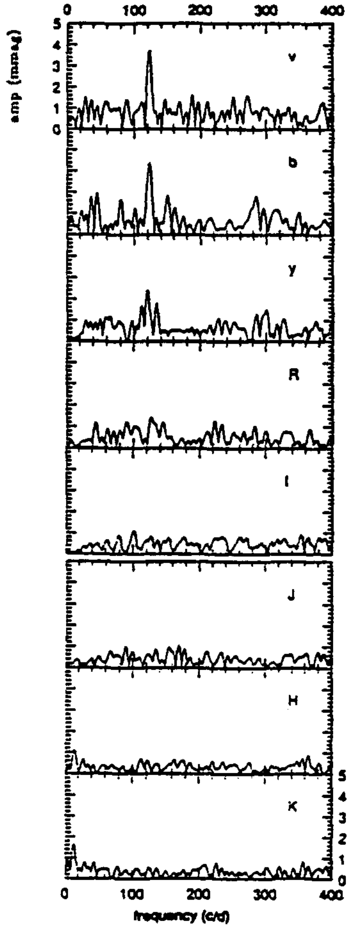
Figure 1. Fourier amplitude spectra of the pulsations of HR 3831.



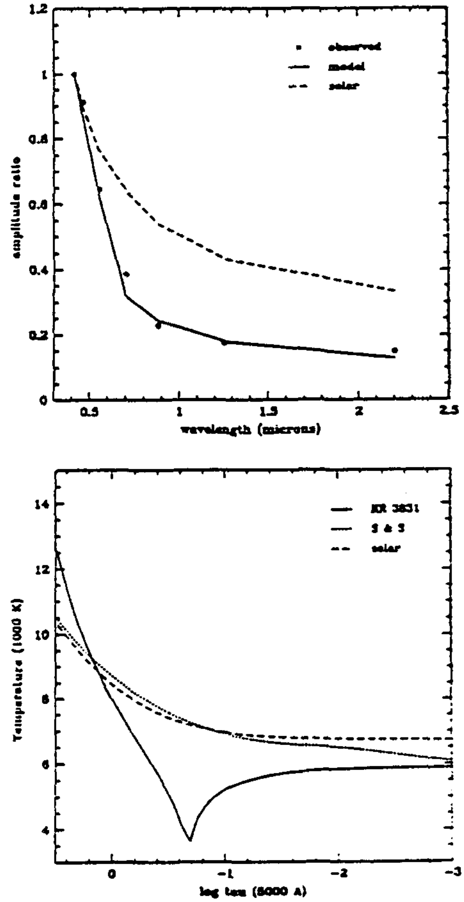


Figure 2. Is there a temperature inversion in the atmosphere of HR 3831? Above is the model fit to the observed amplitude ratios compared to that expected for a grey atmosphere. Below is the resulting $T-\tau$ relation, compared to the grey curve and a model by Shibahashi and Saio (1985) to account for roAp pulsation frequencies observed above the acoustic cutoff of a standard model.

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