PROBING THE INTERIORS OF ROAP STARS

Stellar Tubas That Sound Like Piccolos

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1. The overture: harmonies of the main sequence band

Chemically peculiar magnetic (Ap) stars in the Instability Strip shouldn't really pulsate (since the helium in their very stable atmospheres appears to have gravitationally settled below the He II ionisation zone). And if they did pulsate, they should have periods of a few hours like the δ Scuti variables, since the Ap stars have comparable mean densities and their atmospheric peculiarities wouldn't strongly affect the global eigenfunctions of low-degree p-modes.

As it turns out, some Ap stars *do* pulsate, but not in their fundamental or low-order resonances like δ Scuti stars. The rapidly oscillating Ap (roAp) stars (Kurtz 1990; Martinez & Kurtz 1995; Martinez 1996, this Symposium) vibrate in very high overtones of $n \sim 25-40$, like the solar oscillations seen in integrated light and velocity. Unlike the Sun, however, the roAp stars have coherent oscillations with amplitudes of millimagnitudes whose phases remain constant or drift only slowly over many years. In the symphony of stellar pulsators, the roAp stars are low-pitched tubas that are masquerading as high-pitched piccolos (while the Sun is a bassoon which sits idly on the floor, quietly resonating with the random vibrations of passing traffic).

Why are the high overtones so strongly driven in roAp stars? A very good question, which won't be answered here.[1] Regardless of the answer, we can still apply asymptotic pulsation theory (e.g., Tassoul 1990) and other techniques to these high-overtone p-modes to learn more about Ap stars.

Why should anyone want to learn more about Ap stars? Another good question, which will be answered (I hope) in this paper.

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[1] Or anywhere else with certainty at this time, although Wojciech Dziembowski (private communication) is convinced hydrogen ionisation must be the key.

J. Provost and F.-X. Schmider (eds.), Sounding Solar and Stellar Interiors, 387-394.

2. Using roAp stars as astrophysical laboratories

The strong magnetic fields and pronounced vertical and horizontal abundance gradients in Ap stars make them excellent testbeds for the theories of stellar magnetism (dynamos vs. fossil fields) and radiative diffusion. The oscillations of the roAp stars can serve as a diagnostic of these properties, as well as the global structures and ages of stars in this region of the H-R Diagram.

Since the high-overtone p-modes of roAp stars have most of their amplitude highly concentrated in the outer layers of the star, they should be very sensitive to atmospheric properties. However, there is also useful information about the interior, thanks to the second-order term δ_{02} in the frequency spacing which is highly sensitive to the sound-speed gradient in the core. A few examples of both types of diagnostics – featuring advances presented at this Symposium – are discussed briefly below.

3. In the atmosphere

The pulsation amplitude of an roAp star drops with increasing wavelength much more rapidly than expected for a pulsating blackbody (which is a reasonable approximation for classical pulsators like Cepheids and δ Scuti stars). This must be telling us something about what's going on in the atmosphere of an Ap star. *What* it tells us is still a matter of debate.

3.1. MULTICOLOUR PHOTOMETRY OF ROAP STARS: PROBING MODE DYNAMICS OR ATMOSPHERIC STRUCTURE?

Matthews *et al.* (1990, 1996) argued that this steep wavelength dependence could be explained by the weighting effect of limb darkening on the dominant $(\ell, m) = (1,0)$ dipole mode of an roAp star, which always enhances the net amplitude integrated over the stellar disk. They used this to infer that the atmospheric $T - \tau$ gradient of the roAp star HR 3831 is much steeper than that for the Sun. This agrees with Shibahashi & Saio's (1985) mechanism to explain why some Ap stars oscillate in frequencies well above the acoustic cutoff for a grey atmosphere. It also agrees with the steeper atmospheric gradient employed by Muthsam & Stepień (1992) to model the line profiles of Ap spectra.

However, Medupe & Kurtz (1996, this Symposium; see also Kurtz & Medupe 1996) have argued analytically and through numerical simulations that limb darkening cannot enhance the amplitudes enough at short wavelengths (near 4500 Å) to account for the observations. Instead, they propose that the drop in photometric amplitude with wavelength is due to an actual drop in the local temperature amplitude ΔT of the mode with height in

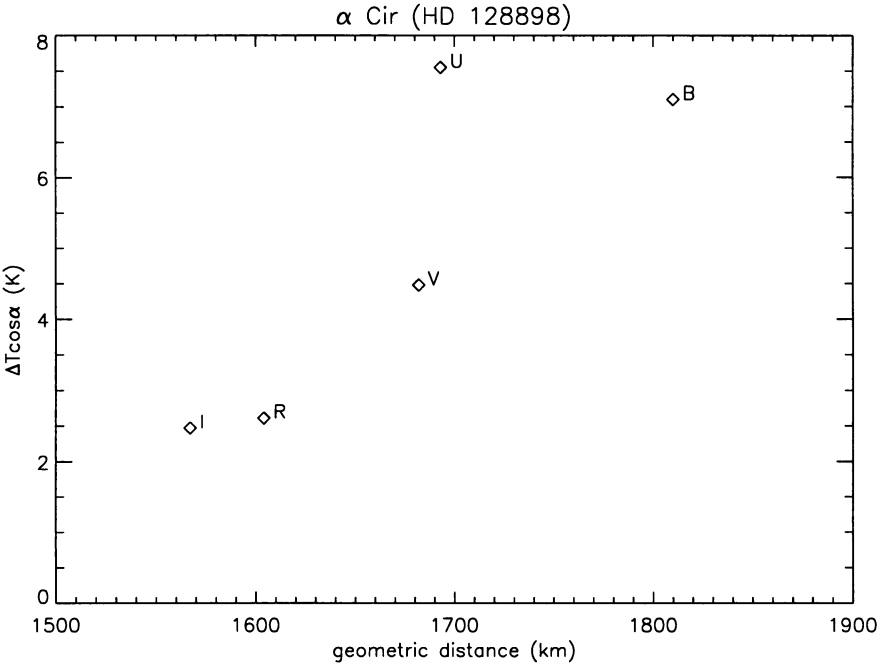

Figure 1. ***Sampling the vertical wavelength of a high-order p-mode?*** The predicted temperature amplitude of the dominant dipole mode of α Cir as a function of atmospheric depth, based on its observed photometric amplitudes in five bandpasses. (From Medupe & Kurtz 1996, this Symposium.)

the atmosphere, where the continuum at longer wavelengths is produced at greater heights. Figure 1 shows the variation in $\Delta T cos\alpha$ (containing the unknown inclination α of the dipole mode) as a function of depth which can account for Medupe & Kurtz's multicolour photometry of the roAp star α Circini. Since the wavelength range of their *UBVRI* filter set spans a range in geometrical depth in the Ap atmosphere of about 300 km, this implies that the radial node separation Δr_{node} in the upper layers is surprisingly small: of order 10^{-3} $R_{\star}$.

Medupe & Kurtz (1996, this Symposium) present a convincing case that limb darkening alone is insufficient to cause the observed amplitude decrease with wavelength in roAp stars. However, this may still prove to be a diagnostic of atmospheric structure. The steep μ gradients in abundance expected in the highly stratified upper atmosphere of an Ap star may cause mode trapping which would produce extremely small values of Δr_{node} implied by Figure 1. Medupe & Kurtz did not include compositional gradients in their models of $\Delta T cos\alpha$. Perhaps changes in flux with depth due to local changes in the metal opacity can weight the photometric amplitudes without dramatic changes in the temperature amplitude.

3.2. RADIAL VELOCITY OSCILLATIONS: PROBING MODE DYNAMICS OR HORIZONTAL STRUCTURE?

Medupe & Kurtz may have found support for their interpretation from an unexpected quarter: precise radial velocity (RV) measurements of α Cir obtained by Viskum, Baldry *et al.* (1996, this Symposium; cf. Frandsen 1996, these Proceedings). Using 6400 moderate resolution spectra containing telluric lines near 6900 Å as a velocity fiducial, they convincingly detected RV oscillations at the star's known photometric period of $\sim$ 6.8 minutes and its first harmonic. Moreover, by separately analysing the RV variations of several spectral 'windows' of metal lines, they find a wide range of oscillation phases, with two groups differing in phase by about π radians (see Figure 2). Viskum, Baldry *et al.* argue that these two groups of lines are formed at locations in the atmosphere on either side of a radial node in the p-mode pulsational eigenfunction. Like Medupe & Kurtz's result, this suggests a very small nodal separation in the upper atmosphere.

I suggest an alternative interpretation: that Figure 2 shows ions which may be grouped on either side of the *horizontal* node on the surface of α Cir, as opposed to either side of a radial node within the atmosphere. The dominant dipole mode of the star means it is divided into two hemispheres which are pulsating in anti-phase, divided by a node along the pulsational equator (which is also presumed to be the magnetic equator in roAp stars). The distribution of elements on the surface of an Ap star can be highly inhomogeneous (e.g., Rice & Wehlau 1991) due to the effects of diffusion regulated by the magnetic field geometry. Different ions can be grouped around the magnetic poles, for instance. This situation is illustrated schematically in Figure 3.

Ions concentrated in opposite magnetic hemispheres would exhibit RV variations π radians out of phase with one another, as observed by Viskum, Baldry *et al.* In this scenario, the groups of lines in Figure 2 whose RV amplitudes are comparable to the noise would be located at the equatorial node (see Figure 3).

Frandsen (private communication) has pointed out that spectroscopy of α Cir does not seem to reveal strong starspots and Kurtz (private communication; cf. Kurtz et al. 1994) cautions that the equatorial node of α Cir may be located relatively close to the star's limb. Both suggest that these factors argue against the surface inhomogeneity scenario. However, the fact that the inclination and obliquity of α Cir may cause one hemisphere of the dipole to dominate the visible disk at all rotational phases would also reduce any rotational modulation due to polar spots or rings. Spectroscopically, lines due to ions raised high in the stellar atmosphere could have a

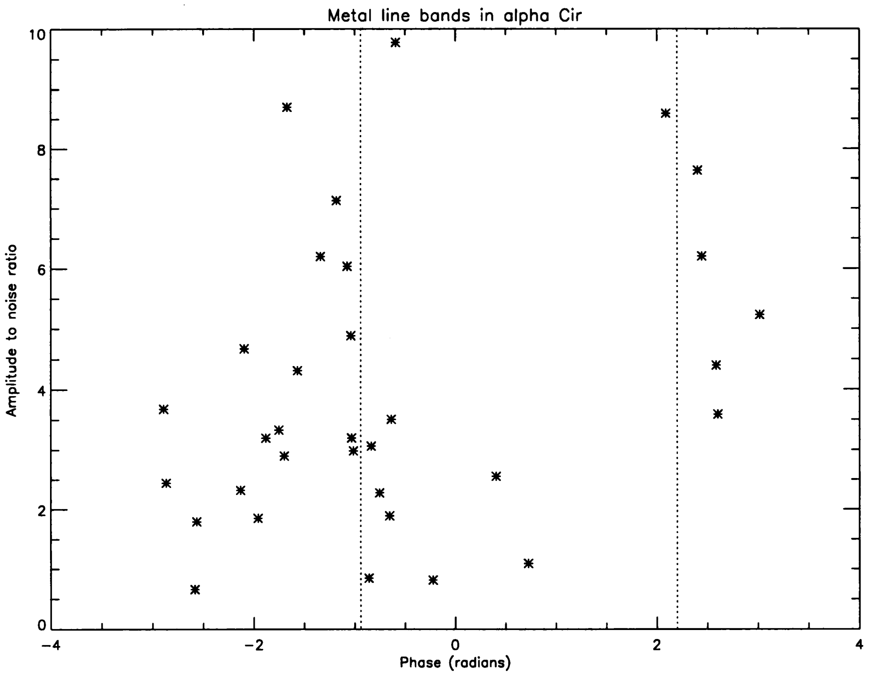

Figure 2. Déjà vu: Sampling the vertical wavelength of a high-order p-mode or mapping the surface of the dipole pattern? Radial velocity amplitudes (relative to the noise level) vs. oscillation phase for various windows of metal lines in the spectrum of α Cir. (Taken from Viskum, Baldry *et al.*, this Symposium.)

strong contribution from the limb, especially at wavelengths around 6500 Å where the limb darkening is relatively weak.

To settle the question, the ions corresponding to the different groups of 'anti-phase' lines must be identified and diffusion calculations performed to determine the depths and latitudes at which those ions would be most strongly concentrated.

3.3. MAPPING THE ATMOSPHERES OF AP STARS

Even if the Viskum, Baldry *et al.* (1996) results are not due to horizontal abundance inhomogeneities, this effect must be present in other roAp stars. Matthews & Scott (1995) and Scott & Matthews (1996, in preparation) have found evidence for line-profile variability with pulsational phase in the slowly-rotating roAp star γ Equulei. The projected rotational velocity $v\ sini$ of this star is so low that its surface cannot be mapped by Doppler Imaging methods (e.g., Rice & Wehlau 1991). High-resolution spectroscopy sampling both the rapid pulsation cycle of the star and its rotational cycle

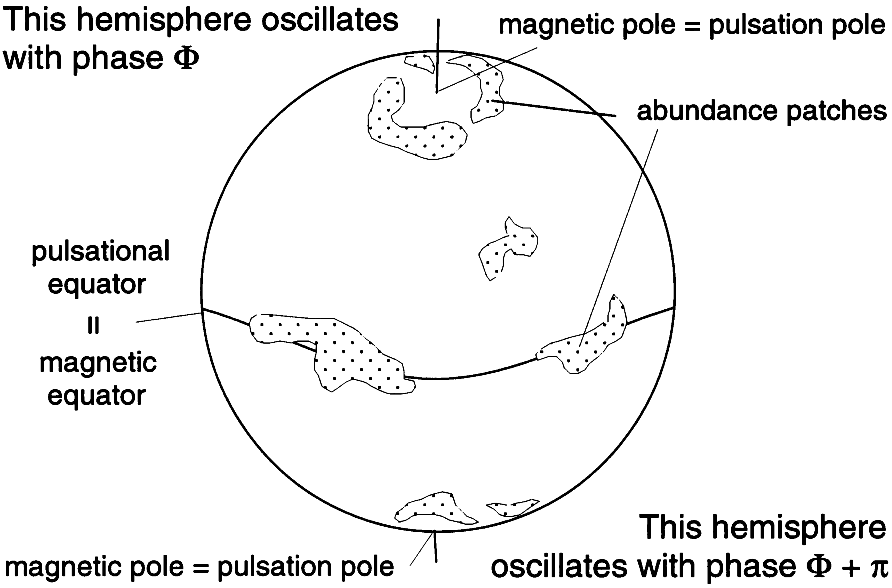

Figure 3. How to map the surface of an roAp star without Doppler Imaging. The $(\ell, m) = (1, 0)$ dipole mode of an roAp star has two hemispheres pulsating in anti-phase. Spectral lines produced by elements concentrated at different latitudes on the surface due to the combination of radiative diffusion and the magnetic field geometry would exhibit RV variations of different amplitudes and phases, as well as distinctive profile variations.

could constrain the latitudes and longitudes of various elements on the stellar surface (again, see Figure 3). I have new high-quality CFHT coudé spectra of the roAp stars 10 Aql and HD 42659 which should be ideal for this purpose (Matthews 1997, in preparation).

4. In the interior

The principal mode spacing $\Delta\nu_0$ in the eigenfrequency spectrum of an roAp star can fix its radius $R_\star$ and luminosity $L_\star$ if the effective temperature T_{eff} is already known. This allows us to study the evolutionary traits of Ap stars. Soon we will be able to calibrate the results against luminosities of some roAp stars derived from Hipparcos parallaxes. The small separation δ_{02} in the eigenspectrum can also in principle yield the star's main sequence age (Christensen-Dalsgaard 1993) since δ_{02} is sensitive to the change in composition of the isothermal core brought about by H-burning. Audard & Provost (1993) have generated eigenspectra for $1 - 2M_\odot$ stars with convective cores which could be used for roAp stars (Matthews 1993).

Long-term frequency changes in some roAp stars (e.g., Kurtz et al. 1994) are reminiscent of changes seen in the Sun's eigenspectrum which correlate with the solar activity cycle. The latter have been interpreted as the effects of the solar dynamo. Could active dynamos be operating in Ap stars, despite their thin surface convection zones? Could a field generated in the star's convective core be strong enough to penetrate the surface and retain effective strengths of several kiloGauss? These are provocative questions whose impact may extend well beyond the regime of the Ap stars.

Rapid oscillations open another window on the internal magnetic properties of Ap stars through eigenfrequency perturbations. Dziembowski & Goode (1996) have modelled the effects of a curl-free dipole field on high-order p-modes and find perturbations $\Delta\nu_{mag} \sim 10 - 20\ \mu$Hz for modes and field intensities consistent with roAp stars. Unfortunately, these frequency shifts are comparable to the small separations δ_{02} (Audard & Provost 1993). Therefore, it is not a straightforward matter to derive the internal magnetic field strength and the main sequence age from the eigenfrequencies.

4.1. CAN WE UNTANGLE THE MAGNETIC FIELD LINES AND ISOCHRONES?

There may be a way out of the dilemma, if we can find an empirical link between the properties of the convective core of an Ap star and its magnetic field. Roxburgh (e.g., 1965) and Carlberg (1975) performed pioneering calculations on the influence of a magnetic field on the internal structure of a star. Das *et al.* (1984) demonstrated that a poloidal field will reduce the mass fraction of the convective core in their simple polytropic models. They found reductions in core size of order a few × 0.1 pressure scale heights (H_p). If we can calibrate the effect of a field on the convective core mass and radius, then the spacings of the roAp eigenfrequencies $\nu_{\ell,n}$ could be solved simultaneously for the:

- a) effect of the convective core on $\nu_{\ell,n}$
- b) field strength consistent with the convective core from a)
- c) magnetic perturbations on $\nu_{\ell,n}$ consistent with b)

One way to simulate a reduction in core size due to a magnetic field is to turn off core overshooting in the stellar model. Audard *et al.* (1995) have studied the seismic effects of core overshooting in models of $2M_\odot$ stars appropriate to the Ap mass range. The difference in eigenfrequencies between models with overshooting $\alpha \sim 0.2H_p$ (i.e., the non-magnetic case in my scenario) and no overshooting (i.e., a strong internal field) is of order 1 μHz. This is large enough compared to δ_{02} and $\Delta\nu_{mag}$ that the idea outlined here may indeed be feasible.

5. And the band plays on...

The papers on roAp stars presented at this Symposium reflect the rapid progress in the field, both observationally (e.g., spectacular detections of low-amplitude RV oscillations and precise multicolour photometry, each with time samplings of less than a minute) and theoretically (e.g., probes of the nodal structure of high-order p-modes, better treatments of the upper boundary of the acoustic cavity, and magnetic effects on the modes).

6. Acknowledgements

I am grateful to Thebe Medupe, Don Kurtz, Michael Viskum and Ivan Baldry for providing figures from their posters and for fruitful discussions. Thanks also to Nathalie Audard, Wojciech Dziembowski, Soren Frandsen, Alfred Gautschy, Peter Martinez and Hiromoto Shibahashi for insights.

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