REPLACING COLOUR BLINDNESS WITH DEPTH PERCEPTION

Rapid spectroscopy and multicolour photometry of roAp stars

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Warning to the unsuspecting reader: The editors of this volume have (bravely) asked me to "preserve the spirit" of my oral presentation. It is difficult to translate the stirring grandeur of a multi-coloured flashing bowtie into mere words and diagrams. Failing to evoke that grandeur, I have instead settled for occasionally capturing the tackiness of my battery-operated talk in Kyoto.

1. Observing in monochrome

Until recently, most efforts to observe the rapidly oscillating Ap (roAp) stars have concentrated on rapid photometry through a single broad- or intermediate-band filter. This technique can efficiently sample the short pulsation periods of roAp stars (typically 5 – 12 min) even with a telescope of only modest aperture. It is the optimum search strategy for detection of new oscillators.

The single broadband approach is also attractive for global campaigns to resolve the fine structure of roAp eigenspectra. Such a campaign requires many telescopes spaced in longitude (to increase the duty cycle and suppress aliasing in the frequency analysis) monitoring a single bright star for several weeks (to achieve frequency resolution of order 1 μHz). In practice, only 1-m-class or smaller telescopes can be dedicated for so long to a single star (e.g., the WET network) so a broad bandpass is usually necessary to ensure adequate count rates to be sensitive to oscillation amplitudes of a few millimag. These types of monochrome observations have successfully yielded eigenspectra with the sensitivity and resolution essential to asteroseismology (e.g., Kurtz et al. 1989).

However, we've reached a threshold where such data must be supplemented by rapid spectroscopy and photometry at many bandpasses if we are to (a) identify the individual modes in roAp stars, and (b) fully exploit those modes to probe atmospheric structure and/or dynamics with depth.

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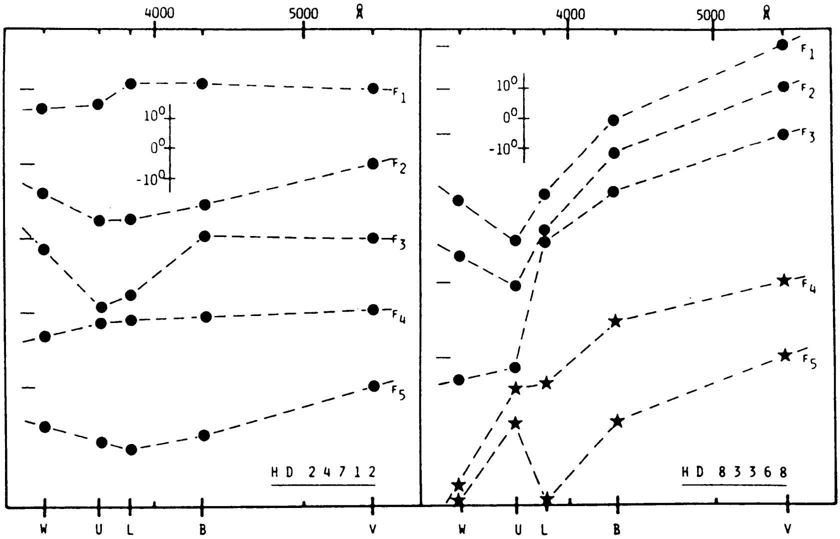

Figure 1. Phase shifts of the oscillations of two roAp stars in five bandpasses (relative to Walraven V), from Weiss (1986).

2. The early days of colour

The first three-colour Hollywood movie produced in the Technicolour process was "Becky Sharp", made in 1935. That's a piece of trivia about colour, but there was nothing trivial about the first rapid *five*-colour (Walraven) photometry of roAp stars by Weiss & Schneider (1984). Their results were the first indication that the pulsation amplitudes of roAp stars drop steeply with increasing wavelength, far more steeply than other known pulsators.

Weiss & Schneider (1984) were also the first to try and use multicolour data as a diagnostic of the physics of roAp stars. Inspired by the success of Balona & Stobie (1979) in identifying modes of δ Scuti stars and Cepheids from phase shifts between their light and colour curves, they tried to apply the same technique to α Cir. The results were ambiguous and inconsistent, even for different runs on the same star. Kurtz & Balona (1984) encountered similar problems in mode identification, based on their Johnson BV data of α Cir.

Schneider (cf. Weiss 1986) also obtained phase-shift information for two other roAp stars, HR 1217 (HD 24712) and HR 3831 (HD 83368), shown in Figure 1. Although the theories of Balona & Stobie (1979) and Stamford & Watson (1981) do not appear to apply to the roAp pulsations, there must be diagnostic information in these phase differences. Currently, Thebe Medupe and Jan Christensen-Dalsgaard are trying to develop a theory to understand the pulsation phase vs. wavelength dependence in roAp stars.

An interesting sidelight to the early applications of multicolour data was Kurtz's (1991, private communication) experiment to use α Cir as its own photometric comparison. Exploiting the steep drop in roAp amplitude with wavelength first recognised by Weiss & Schneider, Kurtz observed α Cir simultaneously in B and I (with a beamsplitter) and obtained reasonable $B-I$ differential photometry even through up to 1.5 mag of extinction (but no bright moonlight). Although the technique has limited applications, it is a reminder that we must always be on the lookout for innovative ways to study stars, such as those described below.

3. Rapid multicolour photometry... but no quick solutions

The steep wavelength dependence of roAp amplitudes was considered a nuisance or a curiousity, until Matthews et al. (1990) suggested it might be a way to probe the atmosphere of one of these chemically peculiar stars. Matthews et al. (1996) used their simultaneous eight-colour optical and infrared rapid photometry of HR 3831 to derive limb darkening coefficients and a $T-\tau$ curve for that star's atmosphere.

Medupe (1997) and Medupe & Kurtz (1997) later demonstrated that limb darkening is not the dominant effect and argued that there is a significant gradient in pulsation amplitude with depth in the upper 2000 km of stars like α Cir. This implies the presence of a radial node very high in the stellar atmosphere. Matthews (1997) has countered that the pronounced abundance stratifications in the upper atmospheres of roAp stars make it dangerous to translate light amplitude vs. wavelength into temperature amplitude vs. depth.

4. Rapid spectroscopy... gradual understanding?

Some of the missing pieces of this puzzle might be found if we tear the puzzling flux distributions of roAp stars into even smaller pieces: going from broad multiband photometry to high-resolution spectroscopy.

The first efforts at rapid spectroscopy of roAp stars were aimed at detecting the radial velocity (RV) variations associated with the light oscillations. There were two general approaches: (1) Fabry-Perot readings of the intensities of the red and blue wings of a single stellar absorption line (e.g., Ando et al. 1988; Belmonte et al. 1989); and (2) cross-correlation of the positions of a large number of lines covering several tens of Ångstroms in high-resolution coudé spectra (e.g., Matthews et al. 1988).

The latter approach – intended to increase the S/N of the measurements by including many lines – yielded the first definitive detection of RV oscillations in an roAp star, HR 1217 (Matthews et al. 1988). The RV semi-amplitude was only $\sim$200 m/s at a time when simultaneous photometry showed a B semi-amplitude of about 3.4 millimag. This result was in stark contrast to

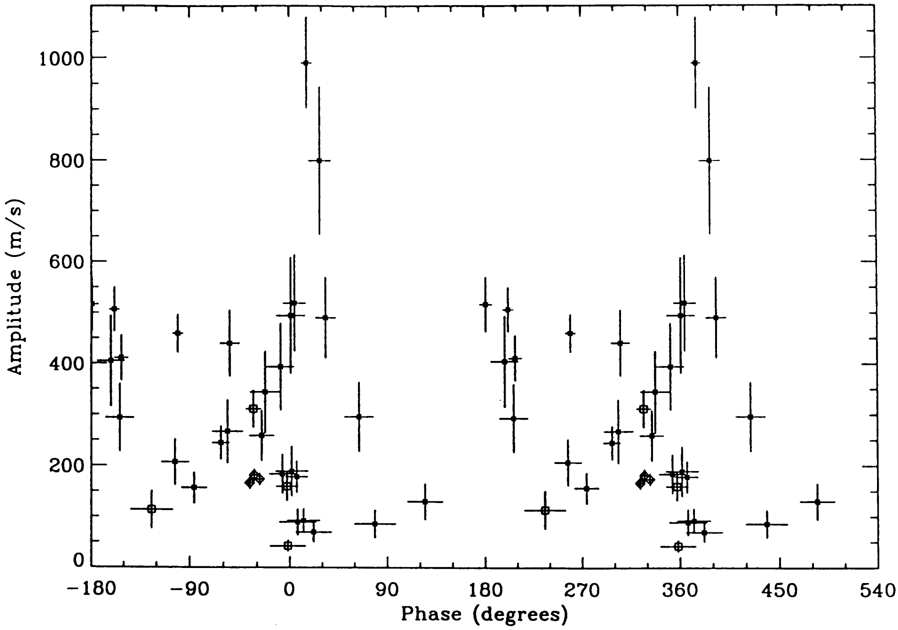

Figure 2. Amplitudes and phases of the principal pulsation mode in α Cir for different wavelength bands, from Baldry et al. (1998).

one Fabry-Perot result, which suffered poorer S/N but seemed to suggest RV amplitudes exceeding 1 km/s in the Ba II λ4930 line in HR 1217 (Ando et al. 1988). Meanwhile, Belmonte et al. (1989), using the λ5317.4 line, claimed a similar RV amplitude for HR 1217 as that reported by Matthews et al., but at a time when the light amplitude was only 1.2 millimag. However, the Matthews et al. estimate of the light-to-RV amplitude ratio proved remarkably consistent with a wide variety of other pulsators – from the Sun to Cepheids – as well as models (Kjeldsen & Bedding 1995).

In retrospect, it is possible that all these apparently contradictary measurements were correct. Recent findings suggest that comparing the multi- and single-line RV measurements was like comparing apples and oranges.

By examining the RV behaviour of many different metal lines in the roAp star α Cir, Baldry et al. (1998) took a bite out of one of those apples (presumably from the Tree of Knowledge) and cast us out of our Garden of mixed fruits (and into my Pit of mixed metaphors!). They found that lines in different wavelength bands showed different RV amplitudes *and phases* (see Figure 2). Independently, Kanaan & Hatzes (1998) found pronounced differences in the RV amplitudes (but *not* phases) of different lines in γ Equ, while Matthews & Scott (1996) noted evidence for line profile variations in certain lines in the same star (Figure 3; see also later in this section).

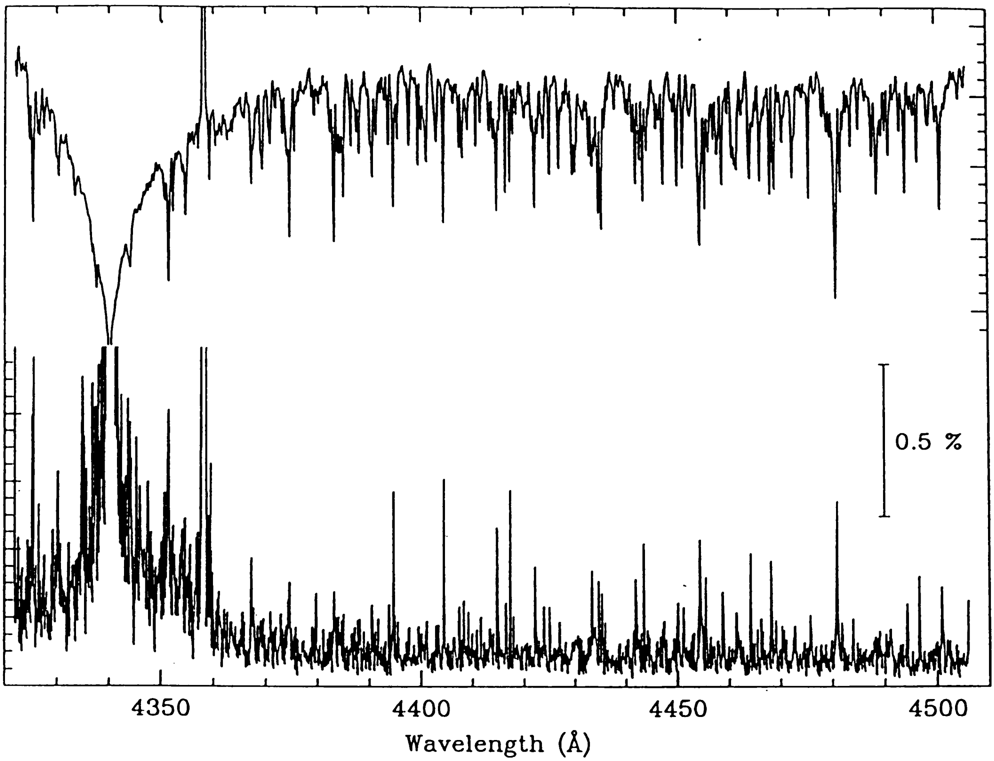

Figure 3. (top) Mean spectrum of γ Equ for 23 August 1988. (bottom) Mean absolute deviation of the individual rapid exposures from the mean. The bar indicates line profile variations with an amplitude of 0.5%. From Scott (1995).

What's going on? Both Baldry et al. (1998) and Kanaan & Hatzes (1998) find a general trend of lower amplitude with larger equivalent width (Figure 4). Is this a clue to the physical mechanism in play here? Baldry et al. interpret the range of amplitudes, and what they believe to be groups of lines varying in antiphase, as further evidence for a radial node high in the atmosphere of α Cir. Kanaan & Hatzes see no significant phase differences among the lines in *gamma* Equ, and believe the varying amplitudes are the result of suppression of oscillations by the magnetic field high in the atmosphere. I believe this to be unlikely, since the magnetic pressure should dominate over gas pressure even much deeper in the atmosphere.

The RV variations of roAp stars are clearly more complicated than we assumed only a decade ago. Individual lines can have amplitudes above 1 km/s while the net variation across a range of spectrum may be less than 10 m/s. That may account for the conflicting results of the cross-correlation

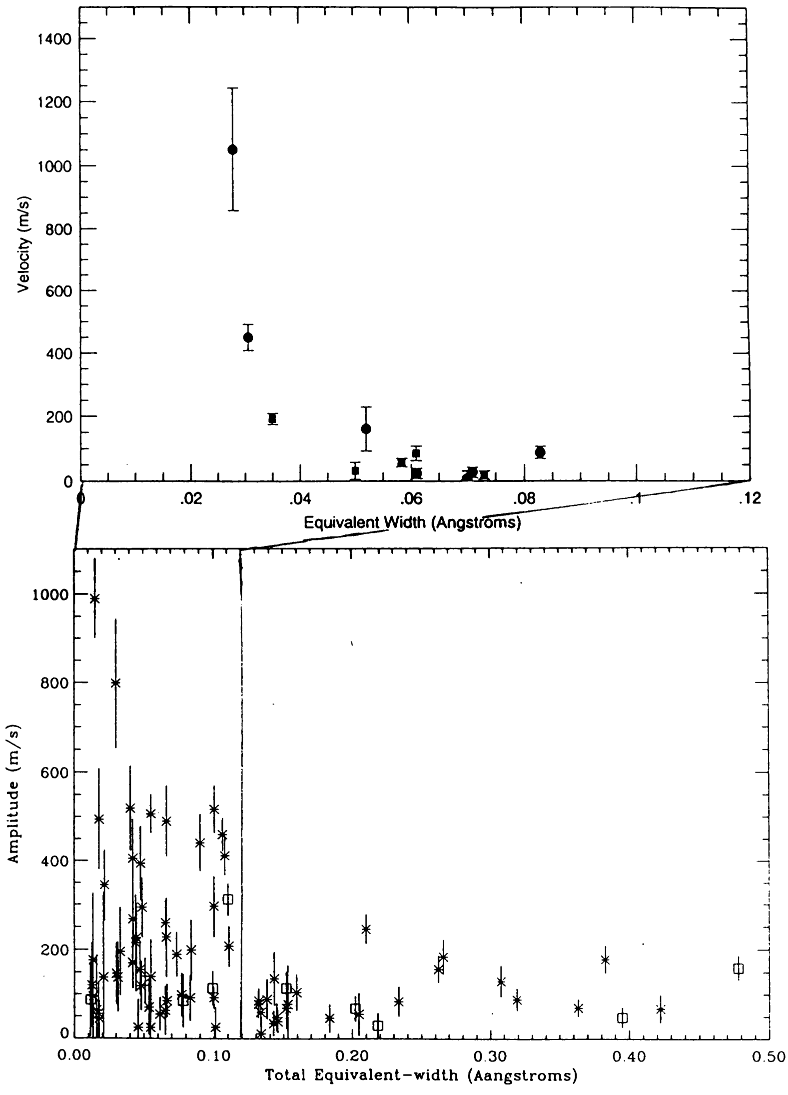

Figure 4. RV amplitude vs. equivalent width: (top) γ Equ (Kanaan & Hatzes 1998); (bottom) α Cir (Baldry et al. 1998). Note the differences in the horizontal and vertical scales.

and Fabry-Perot measurements of roAp stars in the past. It may be worth re-examining those data in light of the latest developments.

After the failure of mode identification by phase shifts in roAp stars, both Odell & Kreidl (1984) and Baade & Weiss (1987) anticipated the possibility of identifying the nonradial modes of roAp stars by the variations they induce in the spectral line profiles. This technique must overcome two hurdles: (1) the intrinsically low amplitudes of the pulsations, and (2) the inherently narrow lines of Ap stars, which tend to be slow rotators. Undaunted, Schneider &

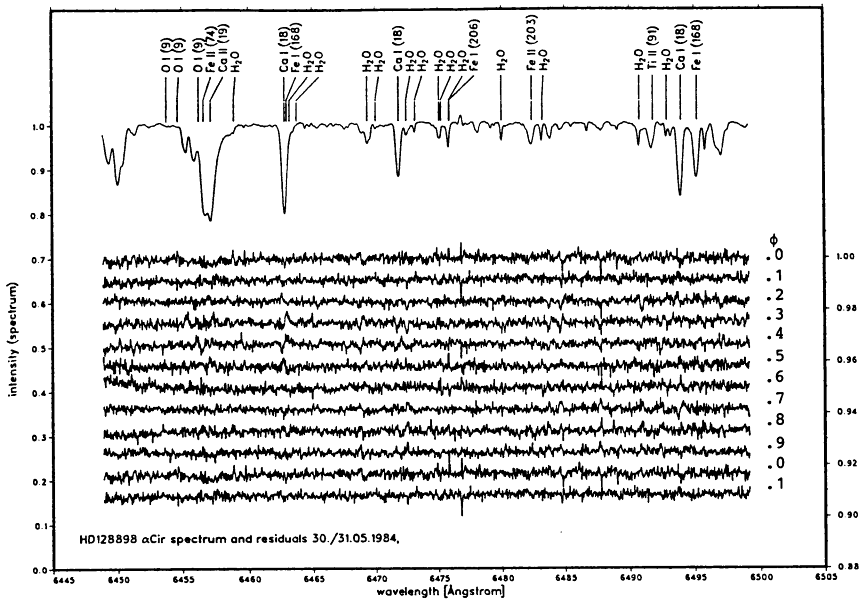

Figure 5. (top) The mean spectrum of α Cir between 6450Å and 6500Å, and (lower) the residuals ordered in pulsational phase. (From Schneider & Weiss 1989).

Weiss (1989) obtained over 300 short-exposure ESO coudé spectra of α Cir which they binned according to the known photometric period and searched for residual variations (see Figure 5) but found none larger than 0.5%.

Matthews & Scott (1996) adopted the same approach with higher-S/N coudé spectra of γ Equ from CFHT obtained in 1988. They see evidence for line profile variations in some lines at the level of nearly 1%. The variations appear consistent with high-overtone ($n \sim 80$) nonradial modes of degree $\ell = 2$ (see Figure 6), but better data are needed. Why only certain lines show profile changes is unclear, but it is likely related to the distribution of elements on the stellar surface and with depth. The amplitude of variability does not appear to correlate with factors like Landé g, excitation energy and $\log(gf)$.

The underlying astrophysics may elude us today, but we are clearly on the threshold of a new era of high-resolution spectral probes of roAp stars.

5. References

Ando, H. et al. (1988) *PASJ*, 40, 249.
Baade D. & Weiss, W.W. (1987) *A&ASuppl*, 67, 147.
Baldry, I.K. et al. (1998) *MNRAS*, in press.
Balona, L.A. & Stobie, R.S. (1979) *MNRAS*, 189, 649.
Belmonte, J.A. et al. (1989) *A&A*, 221, 41

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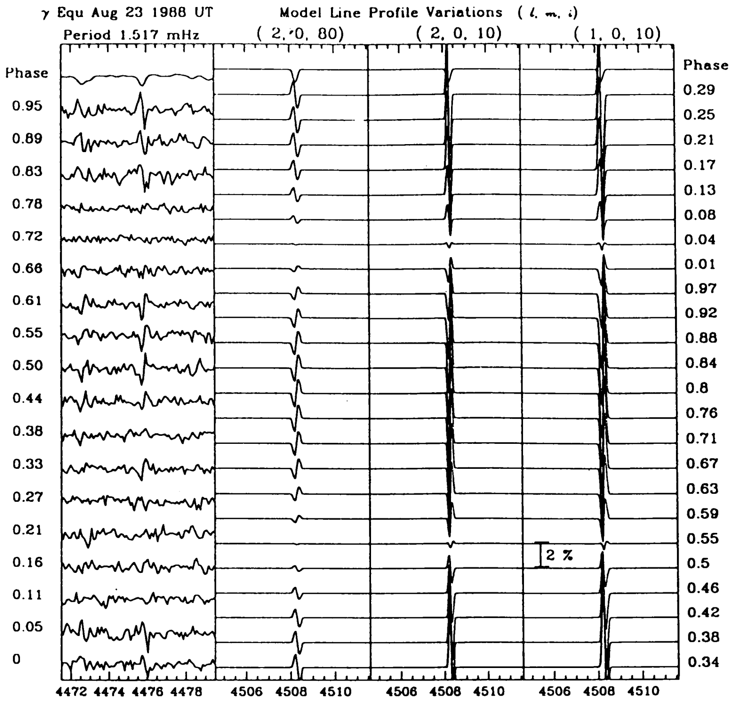

Figure 6. Line profile variations of the Fe I λ4476 line of γ Equ with pulsational phase (left), compared with synthetic residuals for various nonradial modes (right) whose amplitudes are consistent with the measured RV and light amplitudes of the star. The mean observed and model profiles are shown at top. Residuals are offset by 2% of the continuum level.

Kanaan A. & Hatzes, A. (1998) *ApJ*, accepted.
Kjeldsen, H. & Bedding, T.R. (1995) *A&A*, 293, 87.
Kurtz, D.W. & Balona, L.A. (1984) *MNRAS*, 210, 779.
Kurtz, D.W. et al. (1989) *MNRAS*, 240, 881.
Matthews, J.M. (1997) in IAU Symposium 181, pp. 387–394.
Matthews, J.M. & Scott, S. (1996) *ASPC*, 83, 58.
Matthews, J.M. et al. (1988) *ApJ*, 324, 1099.
Matthews, J.M. et al. (1990) *ApJ*, 365, L81.
Matthews, J.M. et al. (1996) *ApJ*, 459, 278.
Medupe, T. (1997) M.Sc. Thesis, University of Cape Town.
Medupe, T. & Kurtz (1997), in IAU Symposium 181, in press.
Odell, A. & Kriedl, T.J. (1984) in 25th Liege Astrophys. Coll., p. 148.
Scott, S. (1995) M.Sc. Thesis, University of British Columbia.
Schneider, H. & Weiss, W.W. (1989) *A&A*, 210, 147.
Stamford, P.A. & Watson, R.D. (1981) *Astrophys. Space Sci.*, 77, 131.
Weiss, W.W. (1986) in IAU Colloquium 90, pp. 219–231.
Weiss, W.W. & Schneider, H. (1984) *A&A*, 224, 101.