Small-Telescope Astronomy on Global Scales
ASP Conference Series, Vol. 246, 2001
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High-Speed Photometry of Bright roAp Stars With Small Telescopes

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Abstract. The rapidly oscillating Ap stars are magnetic peculiar A stars which pulsate in multiple p modes with periods in the range of about 6 to 16 minutes with their oscillation axes aligned with the oblique magnetic axes of the stars. Some of these stars have the richest frequency spectra of any non-degenerate stars other than the sun. This paper shows how photometric observations using small telescopes can be used to work on several astrophysically interesting problems posed by these stars. An example of high precision photometry is shown. The proof of oblique dipole pulsation, the distortion of pulsation modes (probably by the magnetic field), and the determination of asteroseismic luminosities are all discussed. The latter, especially when combined with new theoretical developments concerning magnetic field-pulsation interaction, suggests that Ap stars have lower effective temperatures and/or smaller radii than has been previously thought. It is pointed out that this may be related to the recently discovered extreme discrepancy in effective temperature determined from the wings and cores of the Hα line.

1. Introduction

Small telescopes have one great advantage over large telescopes: large amounts of time are available on them. This means that research projects which demand extended time coverage can in practice *only* be done with small telescopes. Small telescopes have a further advantage over large telescopes in that extended coverage campaigns – observing runs which need multisite longitude coverage to avoid temporal gaps in the data – are much more easily organised with small telescopes where the demands for time are more relaxed. Papers in this volume demonstrate both of these advantages in a variety of ways: for all-sky monitoring, for temporal coverage of variable objects, for supernova searches and gamma-ray-burst optical identification; for the search for extra-solar planets; for the study of near-earth objects and Kuiper-belt objects; for microlensing observations; and, more and more importantly, for education and public understanding of science.

Many of these new uses of small telescopes are revolutionary, such as the tens of thousands of variable stars discovered and studied in detail by the MACHO (Massive Compact Halo Object) survey. But one of the main, traditional uses of small telescopes is alive and well – the photometric study of pulsating variable stars. Here are some examples: There are now hundreds of Slowly Pulsating B (SPB) stars known (see Balona 2000; Dziembowski 1998; Aerts, Waelkens & de Cat 1998) and nearly as many of the recently discovered γ Dor stars (Kaye et al. 2000). Both of these classes are pulsating in g modes which are particularly useful for probing conditions in the stellar cores. Helioseismologists have long sought even a single g mode in the sun (unsuccessfully), so the prospect of the asteroseismic study of g modes in SPB and γ Dor stars is exciting and, with multiple pulsation periods in the range of 1–3 days typically, only small telescopes can provide the long-term photometric data needed to determine their frequency spectra. Similarly, asteroseismological studies of g modes in white dwarfs (Kawaler 1998) and p modes in δ Sct stars (Handler 2000; see also papers in the proceedings edited by Breger & Montgomery 2000) are the preserve of small-telescope astronomy.

My own research interest is primarily in rapidly oscillating Ap (roAp) stars which, like other examples just given, are stars which can be studied intensively photometrically with small telescopes. In the next section I will give some brief background material on these stars and why they are interesting, and give some examples of research on them that has been done with small telescopes.

2. roAp Stars With Small Telescopes

There are many types of peculiar stars on the upper main sequence. I have discussed the nomenclature for these stars in detail (Kurtz 2000) and recommend that paper for readers who wish to know more about the various classes and subclasses of peculiar stars, and the convoluted terminology associated with them. In this paper I will discuss the rapidly oscillating Ap (roAp) stars which are mid-A to early-F main sequence Ap SrCrEu stars which pulsate in high-overtone p modes with periods in the range 6–16 min and peak-to-peak amplitudes $\Delta B \leq 0.016$ mag – generally much less. They mostly lie within the δ Sct instability strip, but a few of them are cooler. Although they largely overlap with the δ Sct stars, it now seems probable that the driving mechanism for their pulsation is H I ionisation (Dziembowski & Goode 1996; Cunha et al. 2001), rather than He II ionisation as in the δ Sct stars.

The roAp are oblique pulsators: they pulsate in non-radial p modes with their pulsation axes aligned to their magnetic axes which are themselves inclined to the rotation axes of the stars. This is a unique characteristic not known in any other pulsator, and it allows us to see the non-radial mode from a varying viewing angle. That provides more information about the mode type – its degree ℓ and order m – than can be obtained for other types of pulsating stars. For much more detail about the roAp stars and their interpretation, see the extensive recent review by Kurtz & Martinez (2000), or earlier reviews and discussions by Weiss (1986), Shibahashi (1987, 1990), Kurtz (1990), Matthews (1991), Martinez, Kurtz & Kaufmann (1991), Martinez (1993), and Martinez & Kurtz (1994a,b; 1995).

2.1. High-Precision, High-Speed Photometry of roAp Stars

Some of the highest precision photometric observations ever made have been on the roAp stars. The technique used to observe these stars is high-speed photometry which uses continuous integrations without interruptions for comparison star observations. This is not possible for observing lower-frequency variable stars because of variations in the transparency of the Earth's atmosphere, but at the frequencies of the pulsations of the roAp stars (equivalent to periods in the 6 to 16-min range) the source of noise is predominantly atmospheric scintillation which has a flat frequency spectrum in this range (when the observations are made under excellent photometric conditions). The roAp stars are also bright, so photon statistical noise is less than the scintillation noise.

Fig. 1 shows an example of the very high precision that is possible using small telescopes. This is a continuous 12.5-hr light curve of the roAp star HR 3831 using the Cerro Tololo Interamerican Observatory (CTIO) 0.6-m telescope and the South African Astronomical Observatory (SAAO) 0.75-m telescope. It is typical of the quality of data obtainable from good photometric sites using very small telescopes. Low-frequency sky transparency variations have been filtered from the data; this is why I use the term *high precision* to describe the data, not *high accuracy*. Although the relative variations shown are precisely known, the absolute brightness of the star is poorly known because of the lack of the use of comparison and standard stars.

The light curve shown in Fig. 1 was part of a 17-day, two-site campaign on HR 3831 by Kurtz, Kanaan & Martinez (1993 - KKM) from CTIO and SAAO. Their data set could only be obtained on small telescopes, given the length of the campaign. A low-resolution Fourier Transform of their data is shown in Fig. 2. There the fundamental frequencies (there actually 7 of them - see KKM) and their harmonics can be seen. The level of the *highest* noise peaks is less than 0.1 mmag and the formal error on the amplitudes of the pulsation modes is formally 9 μmag (KKM). This high precision has been used to show that the pulsation mode of HR 3831 cannot be described as a single normal mode, and that, in turn, has been the impetus for many theoretical investigations of the way in which the magnetic field and the pulsation modes interact in roAp stars (Shibahashi 1986, 1987, 1990; Shibahashi & Takata 1993; Takata & Shibahashi 1995; Dziembowski & Goode 1996; Cunha & Gough 2000; Bigot et al. 2000).

2.2. A Distorted Dipole Mode

HR 3831 pulsates in a single mode which is a distorted oblique dipole mode – probably distorted by the magnetic field, although that is not yet understood. Fig. 3 shows the way the pulsation amplitude and phase vary with the 2.851976-d rotation period of the star (Kurtz et al. 1997). Each point in Fig. 3 represents, typically, one hour of observation covering about 5 pulsation cycles. Kurtz et al. (1997) had a long-term monitoring program for HR 3831 where they observed it as often as possible throughout its observing season for years with the SAAO 0.5-m telescope. Thus the astrophysical information gleaned from Fig. 3 was obtained from observations with a very small telescope indeed.

From a broad-band linear polarisation study of the magnetic field in HR 3831 we know that the rotational inclination, i, is near 90° (Bagnulo, private communication; see Landolfi et al. 1997 for a discussion of the technique for constraining

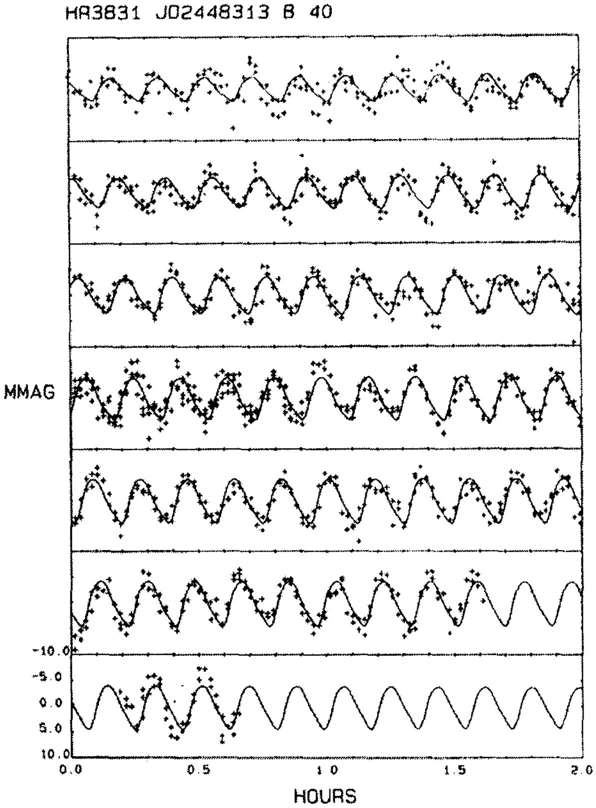

Figure 1. A light curve of HR 3831 taken on JD2448313 with the CTIO 0.6-m and SAAO 0.75-m telescopes. Each panel is two hours long; the entire light curve spans about 12.5 hr. Notice in the fourth panel that the data from the two observatories overlap and agree well. Each data point represents 40-s integration, an average over four of the original 10-s integrations used at the telescope. This is a typical procedure: using 10-s integrations means that less data is lost when bad points are discarded, but averaging to 40-s integrations filters some of the very high frequency noise to give a better presentation. It also reduces computing time when analysing the data. Low frequency noise caused by sky transparency variations has been filtered so there is no long-term variation in the light curve, but this has no effect on the time scale of the variations seen here. It does help with the visual comparison of the frequency solution (solid line) to the actual data points. These data are typical of the kind of data that can be obtained on roAp stars with small telescopes under good conditions and with well-functioning photometers. (from KKM 1993)

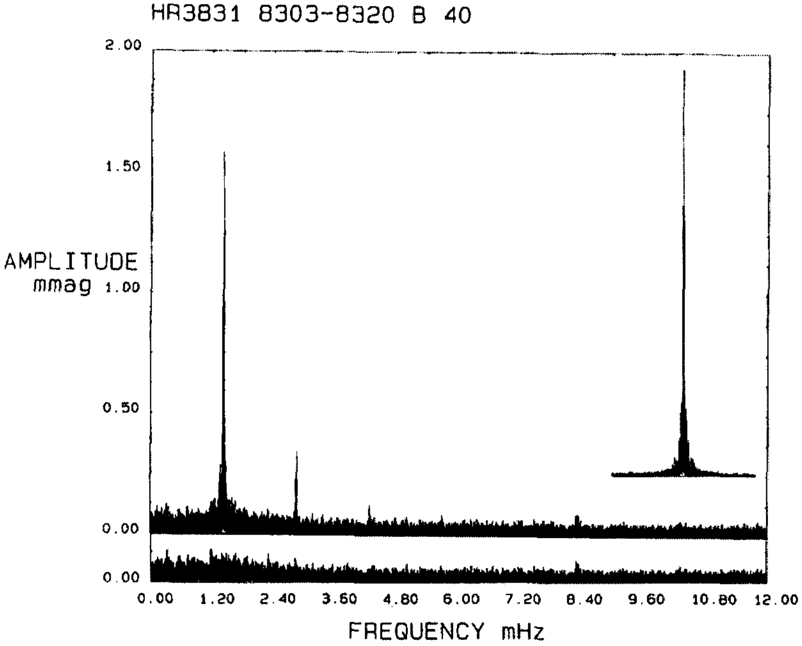

Figure 2. This amplitude spectrum shows that an excellent signal-to-noise ratio can be obtained for pulsation amplitudes less than a mmag with small telescopes at the frequencies of pulsation of the roAp stars. The noise level of the highest noise peaks in this figure are about 0.1 mmag and decrease with increasing frequency. This high precision, which is obtainable with small telescopes for bright rapidly oscillating stars (not just roAp stars), means that there are many astrophysically interesting observations to be done with small telescopes and photoelectric photometers. (from KKM 1993)

the magnetic field geometry), and its magnetic obliquity, β, is small – Bagnulo estimates $\beta \sim 8^\circ$, whereas I argue for a value nearer 30-40° from consideration of the pulsation amplitude spectrum. This disagreement is yet to be resolved. Whatever the value of β, with i near to 90° we see both magnetic poles as the star goes through its rotation cycle. This means we see both pulsation poles, too, since the magnetic and pulsation poles are aligned. With that in mind, Fig. 3 clearly demonstrates that the pulsation mode is a dipole mode. Rotation phase 0.0 is defined to be the time of pulsation maximum. At that time the pulsation semi-amplitude is about 4 mmag, as can be seen in the bottom half of Fig. 3. As HR 3831 rotates, the amplitude of the pulsation drops until the star is seen in quadrature where the amplitude is either zero, or very close to it. This is also the phase of magnetic crossover, and it occurs at rotation phase 0.25 because $i \approx 90^\circ$. As the opposite magnetic and pulsation pole comes into view, the amplitude again increases, and the pulsation phase reverses by 180°,

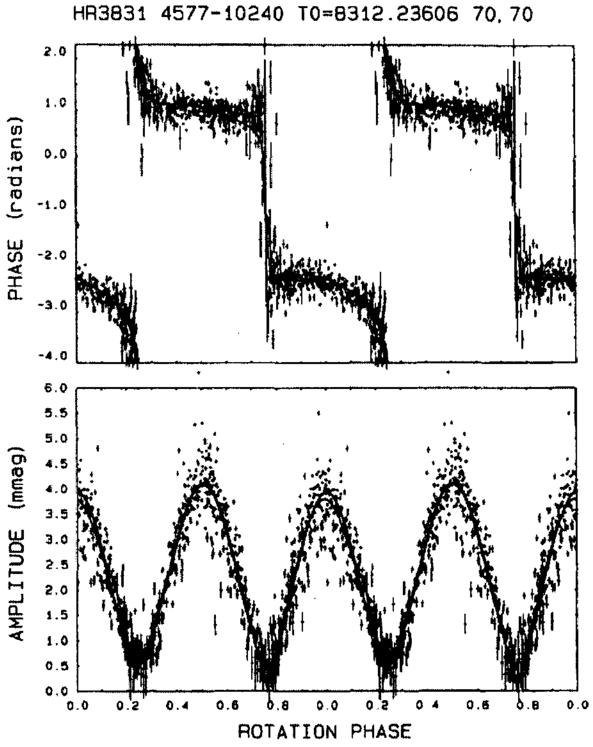

Figure 3. This diagram plots the pulsation amplitude (bottom) and phase (top) for HR 3831 over its 2.851976-d rotation period. Two full rotation cycles are shown. Each point represents typically one hr, or 5 pulsation cycles, of data. This diagram clearly demonstrates that HR 3831 pulsates in a distorted dipole mode. (from Kurtz et al. 1997)

as can be seen in the upper panel of Fig. 3. This form of amplitude modulation with the 180° phase reversal is a clear signature of a dipole pulsation mode.

From a study by Pekeris (1938) it was long thought that dipole pulsation modes were unphysical for pulsating stars because the geometric centre of the star undergoes an oscillation in space, apparently in disagreement with simple Newtonian physics. Christensen-Dalsgaard (1976) showed that the centre of mass of a stellar dipole oscillator is not displaced, hence such modes are possible for stars (although not for an incompressible sphere such as the Earth). We now know that the sun, some white dwarfs, and roAp stars do pulsate in dipole modes. Fig. 3 is the clearest demonstration of that, and it is largely the result of work with an 0.5-m telescope.

The mode in HR 3831 is not purely dipolar, however. It cannot be described by a single spherical harmonic; that is, it is not a normal mode. Kurtz (1992) demonstrated that the mode can be decomposed into a spherical harmonic series with $\ell = 0, 1, 2, 3$ components. Shibahashi & Takata (1993) and

Takata & Shibahashi (1995) used that as a basis to examine first the effects of the distortion of the pulsation eigenfunction by the magnetic field, and then the effects on the pulsation mode of a quadrupolar component to the magnetic field. Their results came much closer to matching the observations that previous theory had been able to, but complete agreement was not obtained. This possibly means that the magnetic field is not itself describable as a simple decentred dipole (which is what using a dipole plus quadrupole gives, to first order). Hence, again, these observations obtained with an 0.5-m telescope are initiating and constraining our understanding of both the magnetic field and pulsation geometry and the complex interaction between them. Many more detailed studies of other roAp stars are needed, and only with small telescopes will the large amounts of observing time needed be available.

2.3. Asteroseismic Luminosities

The pulsation modes of the roAp stars are high-overtone p modes that fit an asymptotic relation which describes the frequency separations as a function of the radial overtone, n, and the spherical harmonic degree, ℓ:

$$\nu_{n\ell} = \Delta\nu_0 \left(n + \tfrac{\ell}{2} + \varepsilon\right) + \delta\nu \qquad (1)$$

where

$$\Delta\nu_0 = \left(2\int_0^R \frac{\mathrm{d}r}{c\,(r)}\right)^{-1} \qquad (2)$$

(Tassoul 1980, 1990).

In eq. 1 $\nu_{n\ell}$ is the frequency of a mode with radial overtone n and spherical degree ℓ, ε is a constant of order 1 depending on the stellar structure, and $\delta\nu$ is a second-order term which depends on the central condensation of the star. The "large spacing", $\Delta\nu_0$, is the inverse of the sound travel time across the star; for the roAp stars it can be used to determine an asteroseismic luminosity. This is done by comparing the observed value of $\Delta\nu_0$ with values computed from standard A-star models (e.g. see Heller & Kawaler 1987) for which lines of constant $\Delta\nu_0$ are similar to lines of constant radius. The more luminous the star, the lower the value of $\Delta\nu_0$, since higher luminosity means lower sound speed (because of lower density) and longer sound travel times (because of larger radii).

Matthews, Kurtz & Martinez (1999) compared parallaxes computed from asteroseismic luminosities for roAp stars with true parallaxes determined by HIPPARCOS. The agreement was excellent, as is shown in Fig. 4. The luminosities of the Ap stars are notoriously difficult to determine by spectroscopic and photometric means because of their extreme spectral peculiarities. The photometric techniques – particularly the use of the Strömgren δc_1 – fail spectacularly. For those roAp stars which are too far away to have HIPPARCOS luminosities, the asteroseismic luminosities are now the best available.

However, in Fig. 4 it can be seen that there is a systematic shift in the sense that the derived asteroseismic parallaxes are slightly smaller than the true HIPPARCOS parallaxes, meaning that the asteroseismic luminosities are overestimated. Matthews, Kurtz & Martinez (1999) suggested that this indicates

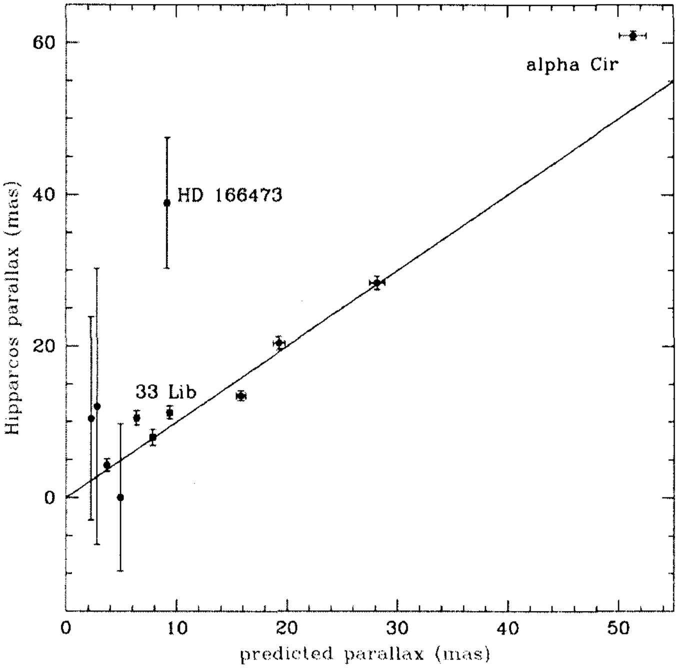

Figure 4. This diagram shows the asteroseismic parallaxes calculated from standard A-star models for 12 roAp stars compared to the HIPPARCOS parallaxes. The agreement is very good, demonstrating that for roAp stars that do not have HIPPARCOS parallaxes, the asteroseismic technique is the most reliable method to get their luminosities – a quantity difficult to determine spectroscopically or photometrically for the peculiar A stars. There is a small systematic shift in the sense that the asteroseismic parallaxes are too small. This suggests that the effective temperatures and/or the radii of Ap stars are systematically smaller than those determined using normal A-star models. (from Matthews, Kurtz & Martinez 1999)

that the roAp stars probably have lower effective temperatures or smaller radii than those of the standard A star models that were used to calculate the asteroseismic luminosities. New theoretical work by Cunha & Gough (2000) and Bigot et al. (2000) both indicate that one affect of the magnetic field on the large spacing, $\Delta\nu_0$, expected from eq. 1 is to increase the large spacing. This, in turn, increases the systematic shift in Fig. 4, suggesting even lower effective temperatures, or even smaller radii than previously thought. It is well-known that the atmospheres of the Ap stars are so peculiar that no atmospheric models are yet able to describe them completely. This is very well demonstrated by the "core-wing anomaly" in the Hα line recently discussed by Cowley et al. (2001). For many of the most peculiar of the Ap SrCrEu stars the wings of the Hα line match effective temperatures about 1000 K hotter than the very narrow Hα line cores.

New, more sophisticated models of Ap star atmospheres are needed to understand something so basic as the Hα line, amongst many other outstanding problems for these stars; those better models will also need solve the systematically high luminosity estimates from the asteroseismic $\Delta\nu_0$, thus providing an additional constraint on the models. Here is yet another example of astrophysical understanding resulting from observations which in practice can only be obtained with small telescopes.

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