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The next step in photometric ground-based asteroseismology: Probing stellar interiors from the Concordia Station

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Abstract. The low scintillation noise expected for night time observations at the Concordia station leads to the expectation of scintillation-limited photometric noise as much as 10 times lower than can be obtained from any other site in the world. This is of particular interest for bright high frequency pulsators - solar-like pulsators, roAp stars - where the noise is scintillation limited. For pulsating white dwarfs stars, sub-dwarf B pulsators, and many other stars of intense asteroseismic interest, photometric noise will also be less than for other observing sites. A single 2-m photometric telescope at Concordia will be able to produce higher precision asteroseismic data sets than the best yet obtained by the Whole Earth Telescope (WET) – data obtained by the vast effort of dozens of astronomers observing at sites all over the world. In just a few years of observations, the cost of such a telescope will be less than the cost of running WET for the same length of time. The 35-cm test telescope will immediately be capable of producing photometric data sets superior to any obtained heretofore on bright stars such as the roAp stars and solar-like oscillators. Examples using data on the roAp stars HR 3831 from one and two sites, and on the roAp star HR 1217 using WET indicate that the level of the highest noise peaks in the amplitude spectra of light curves obtained with the 35-cm test telescope should be as low as 6 μmag for a three-week run on a bright roAp star. With a 2-m telescope could come down to 1 μmag for the brightest stars.

Key words. asteroseismology photometry

1. Introduction

In his now-classic monograph, *The Internal Constitution of the Stars*, Sir Arthur Stanley Eddington (1926) began with this paragraph:

> At first sight it would seem that the deep interior of the sun and stars is less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?

Eddington's answer to this was that theory can show us the interior of stars, but now there is an observational answer: asteroseismology. With the resounding success of helioseismology in determining the interior structure and rotation of the sun, astronomers have been delighted with the recent discovery of solar-like oscillations in the stars β Hyi (Bedding et al. 2001), α Cen (Bouchy & Carrier 2001) and ξ Hya (Frandsen et al. 2002), amongst others. There is now the true possibility of seismology of a variety of solar-like stars using spectroscopic techniques, and there is the promise of seismology for these stars using photometric techniques from Concordia. However, prior to the recent discovery of solar-like oscillations, asteroseismic techniques have been applied to many other kinds of pulsating stars across the HR Diagram for more than two decades to study a wide variety of stellar interior and surface conditions.

Fig. 1 shows a pulsation HR Diagram highlighting some kinds of pulsating stars that that are of asteroseismic interest. I will not discuss here the many classes and the fascinating physics that can be extracted from each. Asteroseismology is such a booming field that there are international conferences on the subject more frequently than once per year. Two recent proceedings that provide introductions to the many kinds of stars of interest are: *Radial and nonradial pulsations as probes of stellar physics* (Aerts, Bedding & Christensen-Dalsgaard 2002) and *Asteroseismology across the HR diagram* (Thompson, Cunha & Monteiro 2003).

In this paper I will introduce asteroseismology and the Whole Earth Telescope (WET), then give an example from WET on the rapidly oscillating Ap star HR 1217. A 2-m photometric telescope at Concordia will supersede WET for many applications, will dominate ground-based asteroseismic studies and will complement and extend space-based studies with the soon-to-be-launched space asteroseismic missions MOST, COROT and EDDINGTON.

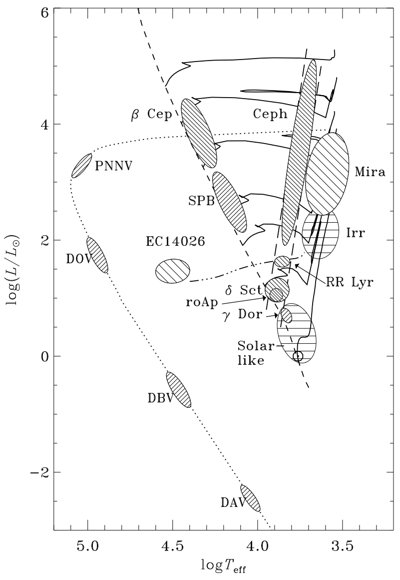

Fig. 1. A pulsation HR Diagram showing the positions of many classes of pulsating stars. Courtesy Jørgen Christensen-Dalsgaard.

2. Asteroseismology

The pulsating stars highlighted in Fig. 1 are driven to oscillate in normal modes – either pressure modes (p-modes) where the restoring for to the perturbation from equilibrium is pressure and the motions are mostly radial, or gravity modes (g-modes) where the restoring force is gravity and the motions are mostly horizontal. The p-modes are acoustic modes, sound waves, with frequencies that are primarily sensitive to the conditions in the envelope of the star. The g-modes are primarily sensitive to conditions in the stellar core. For a thorough introduction to helioseismology and asteroseismology, see Christensen-Dalsgaard (2002), or consult the standard texts on stellar pulsation by Unno et al. (1989) and Cox (1980). For an introduction at a popular level, see Leibacher et al. (1985) and Gough et al. (1996).

The greatest observational successes in asteroseismology to date have been multisite WET campaigns on white dwarf stars pulsating in g-modes. The best-observed star is the pre-white dwarf star PG 1159-035 which has been observed during four WET campaigns with duty cycles of up to 65% for 12-day and 17-day runs in 1989 and 1993. During the 1989 campaign 264 hr of nearly continuous time-series photometry was obtained. The power spectrum of the data set was completely resolved into 125 individual frequencies, 101 of which were identified with specific low-degree $\ell = 1, 2$ g-modes. Existing linear theory for white dwarfs determine, or strongly constrain, many of the fundamental physical parameters of star: Its mass is found to be $0.586 \pm 0.003 \mathrm{M}_\odot$, its rotation period is 1.38 day, its magnetic field less than 6000 G, its pulsation and rotation axes are aligned, and its outer layers are compositionally stratified (Winget et al. 1991). Clearly, asteroseismology is apowerful tool for the study of stellar structure.

It is campaigns such as these that asteroseismology at Concordia will be improving upon. Given the current knowledge of the weather patterns at Dome C, it should easily be possible to attain the duty cycles obtained by the WET campaigns on PG 1159, and it will definitely be possible to get much longer runs at Concordia. WET campaigns are limited to 2–3 weeks by the logistics of organising 50 astronomers and getting time at about a dozen observatories. As I show below, it will also be more cost-effective to do the science at Concordia.

Asteroseismology of white dwarf stars will require a 2-m photometric telescope because of the faintness of these stars. But there are bright stars that can be observed asteroseismically with the planned 35-cm test telescope. Those are the bright solar-like oscillators (discussed by Grec, these proceedings) and the rapidly oscillating Ap (roAp) stars.

3. Photometric capabilities of small telescopes

The roAp stars have been observed photometrically since their discovery (Kurtz 1982) over 20 years ago. Frequency analyses of their light curves have yielded rich asteroseismic information on the degrees of the pulsation modes, distortion of the modes from normal modes, magnetic geometries, and luminosities. The latter, in particular, are derived asteroseismically and have been shown to agree well with Hipparcos luminosities (Matthews, Kurtz & Martinez 1999). New theoretical work on the interaction of pulsation with both rotation and the magnetic field by Bigot & Dziembowski (2002) has presented an entirely new look at the oblique pulsator model of these stars; they find that the pulsation axis is inclined to both the magnetic and rotation axes, and the pulsation modes are complex combinations of spherical harmonics that result in modes that, in many cases, can be travelling waves looking similar to (but are not exactly) sectoral m-modes. This unique geometry of the pulsation modes in roAp stars allows us to examine their non-radial pulsation modes from varying aspect as can be done with no other type of star.

Many of the roAp stars are bright, hence are prime candidates for photometric observations with the Concordia 35-cm test telescope, then later at even-higher precision with a 2-m photometric telescope. HR 3831 is one of the best-studied of the roAp stars, and it can be used to show how asteroseismic photometric studies will be improved at Concordia. It is an Ap SrCrEu star with $\mathrm{T}_{\mathrm{eff}} = 8000\,\mathrm{K}$ and $R = 2.9 \pm 0.1\,\mathrm{R}_\odot$. Its effective magnetic field strength varies about a mean of zero with an amplitude of $737 \pm 68\,\mathrm{G}$ (Mathys 1991). Its quadratic magnetic field strength is strong with an average intensity of 11 KG (Mathys 1995). HR 3831 has a single, distorted dipole pulsation mode for which both pulsation poles come into view as the mode is viewed with varying

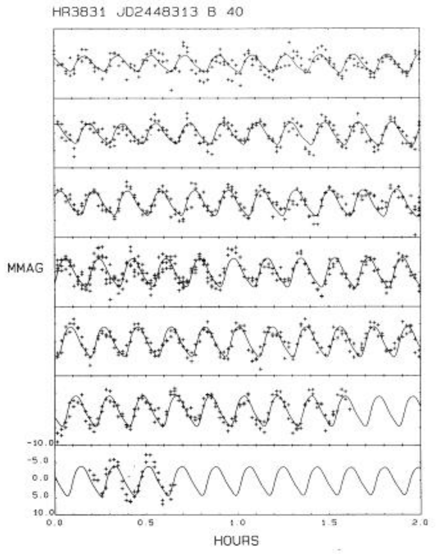

Fig. 2. A light curve for HR 3831 taken with the SAAO 1.0-m and CTIO 0.6-m telescopes on JD2448313. The panels read like lines of print; this is a continuous 12.6-hr light curve. The quality of these data is typical for the size of telescopes used and the photometric quality of the observing sites. At the beginning of the fourth panel there is an overlap in time between the two sites which can be seen as a doubling of the data point density. From Kurtz, Kanaan & Martinez (1993).

aspect over the rotation period of the star, $P_{\rm rot} = 2.851976$ day.

Fig. 2 shows a light curve for HR 3831 obtained over a 12.6-hr time span with the 1.0-m telescope of the South African Astronomical Observatory (SAAO) and the 0.6-m telescope of the Cerro Tololo Inter-American Observatory (CTIO) in Chile. This light curve is indicative of the quality of photometry that can be obtained from some of the world's best observing sites for bright stars. Indications from day-time observations and tests are that Concordia is superior photometrically to SAAO and CTIO, so it is worth examining the sources of noise to see what can be expected from Dome C.

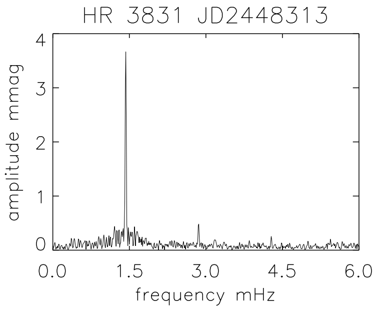

Fig. 3. The amplitude spectrum of the light curve shown in Fig. 2

The best way to do this is to look at the Fourier Transform of the light curves. Fig. 3 shows this for the light curve seen in Fig. 2. The principal pulsation frequency and its first and second harmonics can easily be seen against a background of noise with highest peaks in the amplitude spectrum of about 0.1 mmag which is 1 part in 10^4 in intensity. This is about the lowest noise level reached for good photometric nights at good sites with small telescopes for this length of observing run.

The noise in Fig. 3 is scintillation limited. This is an extremely important point. For bright stars with periods of the order of minutes, such as the solar-like oscillators and roAp stars that will be the first targets from Concordia, scintillation limits the noise. Fossat (these proceedings) argues that the extremely low level of high altitude wind at Dome C leads to the expectation that the scintillation noise should be about a factor of 10 lower than other sites - sites heretofore considered to be the best photometric sites in the world. If the night-time scintillation noise is, in fact, a factor of 10 lower than at other observing sites, then the 35-cm test telescope will obtain noise levels over a 12-hr run on HR 3831, and other stars of the same brightness, of 0.02 mmag, or 20 parts in 10^6, for the highest peaks in the amplitude spectrum. Scintillation noise varies roughly inversely with the telescope aperture, hence the above 0.02 mmag was arrived at by doubling the noise from Fig. 3, because of the smaller aperture of the 35-cm test telescope, and then dividing this by 10. It is important to note that the usual measure of noise, the standard deviation of the amplitude, is about a factor of 2 to 3 lower than the height of the highest peaks in the amplitude spectrum, depending on the data set. I have conservatively used the level of the highest peaks in the amplitude spectra because they can easily be seen and judged, and because decisions about signals that are real, or at least worth following up, are made on the basis of a peak standing out above the noise in the amplitude spectrum.

For the search for solar-like oscillations (Grec, these proceedings), it will be necessary to have a 4σ detection in the amplitude spectrum, and to repeat that detection in two independent light curves, for the result to be believable. The reason why 3σ I not good enough is that the chance of a 3σ peak is 1 in 200 and the amplitude spectrum for a long observing run on a star will have thousands of independent frequencies searched, virtually guaranteeing some 3σ peaks. Hence the need for a more stringent criterion than 3σ. In practice this means that the detected peak will be about twice the height of the highest noise peaks. The sun varies by 3 μmag when observed as a star, so it will be necessary to reduce the highest noise peaks to about 1–2 μmag to detect a solar-like oscillator with the same amplitude as the sun. Of course, some such stars may have larger amplitudes; indeed, a survey with a dedicated telescope at Dome C will fulfil a long-needed demand, and it is worth noting that such a survey *cannot* be done with the upcoming space missions. They will be dedicted to the intense study of known pulsators - quite possibly stars found from Concordia.

Can the 1–2 μmag level be reached from Concordia? Can it be done with the 35-cm telescope? I argued above that a 12-hr run will give a highest-peak noise level of 20 μmag with a 35-cm telescope. To reduce that by a factor of 10, a 100-day run will be needed. This is within the realm of possibility, but is daunting. In practice, with the 35-cm telescope, it will be necessary to find solar-like stars that have larger amplitudes than the sun, making detection easier, and to study known bright pulsators of astrophysical interest that have much larger amplitudes such as the roAp stars. Later, when larger photometric telescopes are available, the noise level will drop and the length of run needed for detection will be reduced accordingly. A 2-m telescope will immediately give noise levels about a factor of 6 lower than the 35-cm test telescope, leading to the expectation of highest peaks in the noise in the amplitude spectra of about 4 μmag. For ground-based asteroseismology precision such as that is currently just a dream - a dream that can be fulfilled at Concordia.

There is another major noise source to contend with. That is low frequency sky transparency noise. It comes devastatingly as cloud, but also occurs in perfectly clear skies from changes in humidity and changes in the amount of particulate matter in the air. Both of these should be exceedingly low at Dome C, and are thus not a concern. What is a concern is cirrus clouds. Those can be seen towards the horizon in many day-time pictures of the Concordia station. It is not yet known how much they will influence night-time observations.

Fig. 4 shows the amplitude spectrum for a light curve of HR 3831 with no filtering of the low frequency variations caused by sky transparency variations, and with them filtered out. These data were obtained under photometric conditions at SAAO. The low-frequency noise seen in the unfiltered data is normal and common at all observing sites. The important point here is that it drops rapidly with increasing frequency down to the scintillation noise limit; periods shorter than about 15 – 20 min (frequencies higher than about 1 mHz) are unaffected. With a careful selection of star fields, it should be possible at Dome C to study stars with comparison stars in the same field and further reduce the low-frequency noise with the comparison star

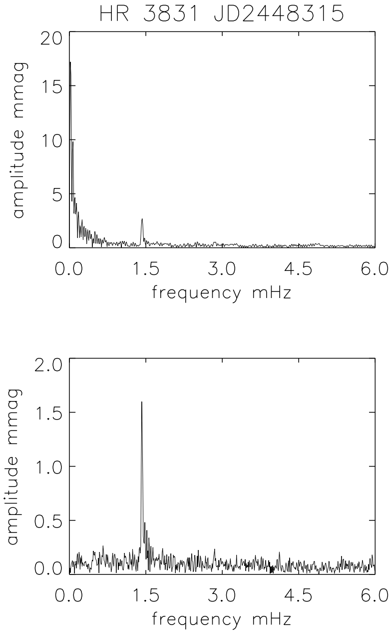

Fig. 4. Amplitude spectra of an 8-hr light curve of HR 3831 obtained from SAAO on JD2448315 under photometric conditions. The upper panel shows the amplitude spectrum for the data after they have been corrected for mean extinction. Low frequency sky transparency variations are common at this amplitude under good photometric conditions. They drop rapidly to the scintillation noise limit and do not interfere with observations at frequencies typical of solar-like oscillators and roAp stars. The lower panel shows the amplitude spectrum after the low frequency noise has been filtered.

data, but only in the absence of cirrus. *Any* cirrus, even that too thin to see by eye, will increase the low frequency noise and swamp any signal of interest at the level of a solar-like oscillator or a roAp star such at HR 3831. We can be optimistic that the frequency of cirrus cloud cover at Dome C will be less than that at other good photometric sites from what is already known from day-time studies, but the exact fraction of truly photometric weather will not be known until the first winter-over and night time observations with the 35-cm test telescope.

Thus far I have only shown what can be done in a short observing run of 8 - 12 hr. Next I will show what can be accomplished with a large multi-site effort and look at the prospects for asteroseismology from Concordia in light of that.

4. WET XCOV20 – the roAp star HR 1217

The Whole Earth Telescope (WET) conducted an extended coverage campaign, XCOV20, for three-weeks on the $V = 6$ roAp star HR 1217 in November-December 2001. HR 1217 is a prototypical rapidly oscillating Ap star that has presented a test to the theory of nonradial stellar pulsation. Observations in 1986 (Kurtz et al. 1989) showed a clear pattern of five modes with alternating frequency spacings of 33.3 μHz and 34.6 μHz, with a sixth mode at a problematic spacing of 50.0 μHz (which equals $1.5 \times 33.3\,\mu$Hz) to the high-frequency side. Asymptotic pulsation theory allowed for a frequency spacing of 34 μHz, but HIPPARCOS observations ruled out such a spacing. Thus, there seemed to be a frequency spacing of $\frac{3}{4}\Delta\nu_0$, where $\Delta\nu_0$ is the asymptotic frequency spacing for a high overtone p-mode pulsator such, and such a spacing was theoretically not expected. New theoretical calculations of magnetoacoustic modes in Ap stars by Cunha (2001) predicted that there should be a previously undetected mode 34 μHz higher than the main group, with a smaller spacing between it and the highest one. An outstanding result from XCOV20 was the discovery (Kurtz et al. 2001) of a newly detected frequency in the pulsation spectrum of this star, at the frequency predicted by Cunha (2001).

Fig. 5 shows an amplitude spectrum for the WET XCOV20 data with the low frequency sky transparency variations filtered. The scintillation-limited highest noise peaks are only about 50 μmag. Telescopes used in this campaign had apertures as small as 80 cm, and those smaller

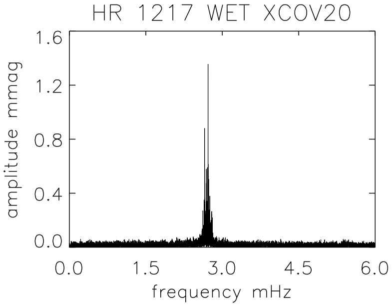

Fig. 5. An amplitude spectrum of 204 hr of observations of the roAp star HR 1217 during WET XCOV20. A duty cycle of 30% was achieved over a time span of three weeks. The scintillation-limited photometric noise has highest peaks of about 50 μmag. The y-axis is in units of mma = milli-modulation amplitude. This is parts per thousand in intensity and is nearly equal to mmag.

telescopes contribute more to the noise. The duty cycle obtained was 30%. We can estimate from this how well the 35-cm test telescope will do at Concordia: The noise will be 2 times higher because the telescope is smaller than the smallest WET telescopes; it will be 10 times smaller because of the low scintillation noise at Concordia; and it will be 1.6 times smaller because of the 80% duty cycle that can be expected. This gives an expectation of a noise level for the highest peaks of only 6 μmag for a three-week run with a 35-cm telescope. For a three-week run with a 2-m telescope at Concordia that we can expect the noise to be go down another factor of 6 to 1 μmag for the highest peaks.

That is a stunning result. Not only will it be possible to do better science in asteroseismic studies from Concordia, but it will be far less expensive and involve far less time-consuming effort on the parts of dozens of astronomers. For the most recent grant to run WET, it was estimated that the cost of telescope time, travel and astronomers' salaries amounts to US$55,000 per week. The best WET runs have obtained 60% duty cycles. Concordia will be able to do that, or better, for 20 weeks per year (given that bright stars can be observed into the twilight) with substantially better signal-to-noise. This is a bargain. A single 2-m asteroseismic telescope at Concordia can do superior science that should be valued at least at US$1,000,000 per year, and relieve about 4 person-years of observing effort per year. It is easy to see that in only a few observing seasons such a telescope will pay for itself.

5. Conclusions

The promise for photometric asteroseismology studies from the Concordia station is that they will have substantially better signal-to-noise than has been previously obtained from the best sites in the world, so many new discoveries will be made, and they will cost less in money and in the effort of astronomers than present multi-site campaigns. For there to be wide interest from asteroseismologists, a 2-m telescope is needed to be able to study white dwarf stars, sub-dwarf B stars and other faint stars. It is necessary first to test the night time conditions to be certain that the fraction of photometric weather and the low level of scintillation are as expected. The 35-cm test telescope planned for the first winter-over will test these conditions, and will be capable of studying roAp stars better than has previously been possible. It may even reach noise levels low enough for the photometric detection of solar-like oscillations for stars with amplitudes a few time higher than that of the sun. Then there are all the longer period pulsators in Fig. 1 that cannot be studied from the upcoming space missions… The propects for asteroseismology from Concordia are very bright indeed.

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