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Facilities at ARIES for the Nainital–Cape Survey

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Abstract. A collaborative programme searching for mmag pulsations in chemically peculiar stars in the northern hemisphere was initiated in 1997 between Nainital, India, and Cape Town, South Africa. It was therefore named as the **Nainital–Cape Survey** programme. The detection limits imposed by the observing conditions (including atmospheric noise and telescope size) at both Manora Peak and Devasthal sites are described. The scintillation noise on the best photometric nights is ≈ 0.1 to 0.2 mmag for these sites. Both places allow one to detect few mmag variation in bright stars ($B \leq 12$ mag), and are therefore particularly well-suited for carrying out the proposed survey work. The main characteristics of the three-channel photometer developed at ARIES for carrying out the observations are also presented. This excellent instrument has been used extensively since 1999 at the f/13 Cassegrain focus of ARIES' 104 cm telescope. In particular, it allowed the survey to result in the discovery of δ Scuti like pulsations in four Am stars, in one rapidly oscillating Ap star, and in a number of probable variables so far. The future prospects are then presented, which regard the acquisition of a high speed time series CCD photometer, a project to build a 3-metre class telescope at Devasthal, and collaborative observations with Indian and foreign astronomical sites.

Key words. Stars: chemically peculiar stars—oscillations—δ Scuti—asteroseismology.

1. Introduction

About 30 per cent of the stars in the classical instability strip of the HR diagram are δ Scuti stars which pulsate with long periods (tens of minutes or more) and amplitudes ranging from a few millimagnitude (mmag) to almost one magnitude. In contrast, some pulsating stars are rapidly oscillating Ap (roAp) stars. These roAp stars are cool, magnetic, chemically peculiar A-F IV-V stars which exhibit low-degree, high-overtone, non-radial p-mode pulsations with periods ranging from 5 to 21 minutes. The multi-periodic p-mode oscillations in roAp stars are of considerable significance because they allow the use of asteroseismology as a tool in the study of the chemically peculiar stars of the upper main sequence.

In 1997, out of the 31 roAp stars then known in the sky, only 3 were located in the northern hemisphere's sky. This large difference between the numbers of known roAp stars in the two hemispheres was attributed by Martinez *et al.* (2001) to the fact that greater survey efforts had been made at the South African Astronomical Observatory (SAAO), in comparison to other astronomical sites. This conjecture gave birth to the idea of a collaborative survey programme between both hemispheres. The aim of such a programme was to apply the proved and successful observational and data reduction techniques used in the Cape Survey by Martinez *et al.* (1991, 1994a, b) to a northern hemisphere observational site. The major requirements for such a site were that the sky conditions should be as good as at SAAO; the site should benefit from experienced astronomers in the area; and an important number of observing nights should be allocated to this programme on a one-meter class telescope. Since ARIES, Nainital fulfills all these criteria, it was decided in 1997 to initiate the so-called Nainital–Cape Survey programme. Further details regarding the survey programme and the procedures for observations and data reductions have been described by Joshi (2004) and references therein.

This paper analyzes the sites' characteristics, and exposes the current and future facilities dedicated by ARIES to this programme. The main characteristics and detection limits of the Nainital (Manora Peak) and the future Devasthal sites are analyzed in the next section. The three channel fast photometer, the future plans for the survey work, and the main conclusions derived from the results obtained so far are described in sections 3, 4 and 5 respectively.

2. Manora Peak and Devasthal as observational sites

The characteristic features of the atmospheric noise at both Manora Peak and Devasthal sites along with the detection limits imposed by them for a meter class optical telescope are given in the following sub-sections.

2.1 *Sky transparency and scintillation*

The presence of extremely low oscillation amplitudes (often < 1 mmag) in the survey work demand high photometric precision. There are two main sources of atmospheric noise that an observer has to contend with under photometric conditions. First, there are sky transparency variations that occur on a time-scale of 20 min or longer. The other source of atmospheric noise is scintillation. The latter sets, in practice, the lower limit of detectability of oscillation amplitudes in the survey stars – rather than photon statistics because all the candidate stars are bright, see section 2.2. Since the scintillation noise scales as $-2/3$ power of the telescope aperture, and as 3/2 power of the air-mass (Young 1967), it is beneficial to use telescopes in the 1 m class or larger at relatively low air-mass.

Figure 1 shows a schematic amplitude spectrum of atmospheric noise consisting of both the sky transparency variations and scintillation, obtainable with 8 hours of observations on a photometric night at Manora Peak, Nainital with the 104 cm Sampurnanand telescope. It can be seen that the sky transparency variations have larger amplitude at $\nu \leq 1.0$ mHz. Its level drops down to the level of the scintillation noise somewhere between 1 and 1.5 mHz. On good nights, these sky transparency peaks are well separated from the frequencies of interest ($\nu \geq 1.0$ mHz) indicating that the roAp

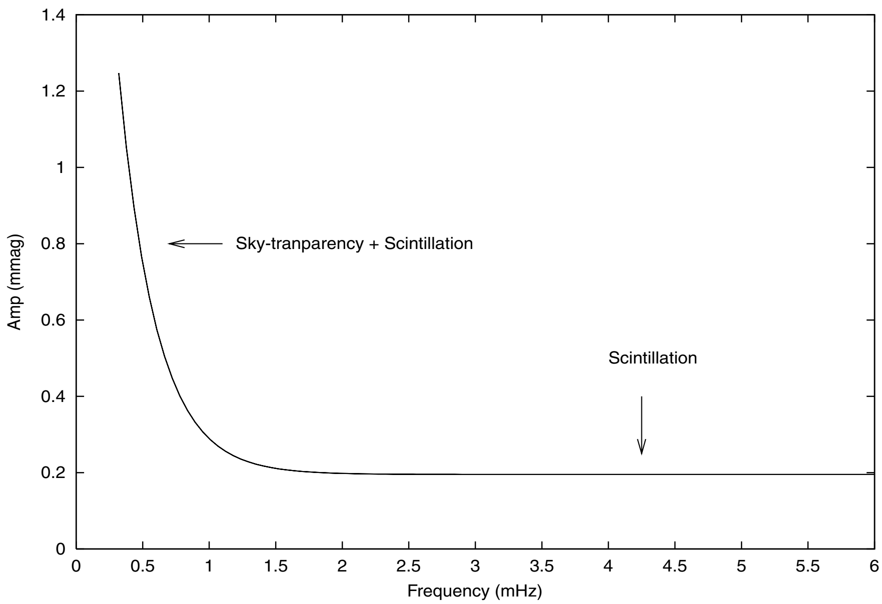

Figure 1. A schematic presentation of the sky-transparency and scintillation noise on a photometric night at Manora Peak, Nainital.

oscillations above the scintillation noise level can be detected without difficulty. On poor nights, the sky transparency noise can extend above 2.0 mHz making the detection of the roAp oscillations impossible. The level at which the sky transparency noise reaches the scintillation noise sets the lower frequency limit at which the oscillations can be detected and studied. Figure 1 indicates that the scintillation noise on a good photometric night is ~ 0.2 mmag. This is below the characteristic amplitude variations of most known roAp stars (a few mmag typically), and comparable to the scintillation level at the SAAO site.

Raw single-channel data of the variable star HD 98851 discovered at Nainital (Joshi 2004, 2005) are plotted in the upper panel of Fig. 2. One can notice gradual variations caused by changes in sky transparency, as well as oscillations due to the star. The application of a constant value of atmospheric extinction (0.26 mag/airmass) makes the star's oscillations clearly visible on a steady intensity level (Fig. 2, lower panel).

The results above show that Nainital is an excellent site to conduct the proposed survey work. Other characteristics of the site are reported by Kumar *et al.* (2000).

New optical observational facilities are currently being developed at another site, Devasthal, which is located about 50 km by road from Nainital towards the east. The results of an extended survey of the Devasthal site have been published by Sagar *et al.* (2000). Those indicate that the sky transparency at Devasthal is similar or better than that at Nainital, as it is located at a higher altitude, and situated further away from the light and other pollution sources. Consequently, Devasthal is a potentially excellent site for the present survey work as well.

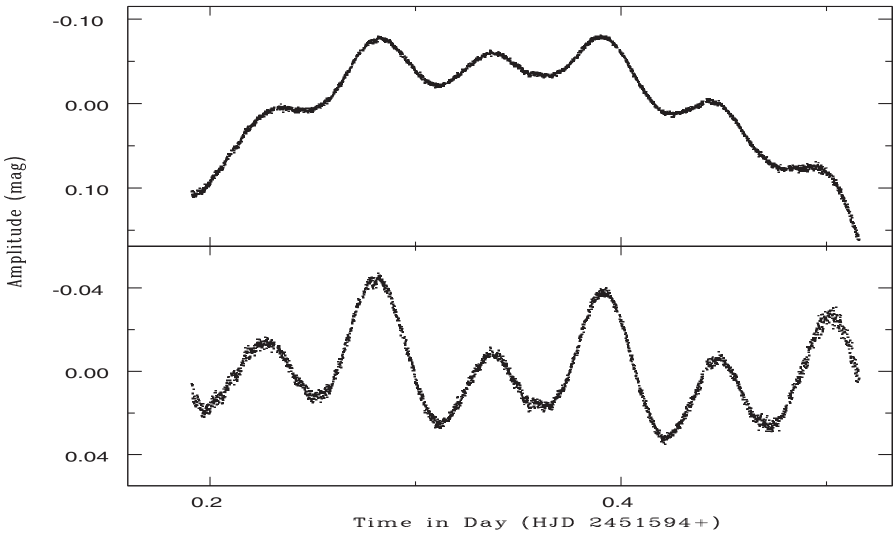

Figure 2. Light curve of HD 98851 obtained at Manora Peak. Upper panel: Raw data before extinction correction. Lower panel: Light curve after extinction correction.

2.2 *Detection limits imposed by both atmosphere and optics*

We present here an analysis of the detection limits determined by the scintillation noise, the photon noise and the background noise, to the detection of a variable signal. The study is made for both the Manora Peak and the Devasthal sites, and includes the effects of the optics (telescope + filters). The same telescope characteristics were assumed for both sites, though the one proposed to be placed at Devasthal will probably reveal superior optical performances to those assumed here.

Let us assume that a target star (magnitude m_λ, flux F_λ) pulsates with an amplitude of a few mmag (f). In differential photometry, the *signal* that we seek to detect is the *flux's variation* ΔF (corresponding to f) with respect to the average flux F_λ (corresponding to m_λ). This flux may be written as

$$\Delta F = F_\lambda(0)10^{-0.4m_\lambda}(1 - 10^{-0.4f}), \tag{1}$$

where $F_\lambda(0)$ is the flux at magnitude zero (in erg/cm^2/s/Å). Using an analysis similar to that of Mayya (1991), equation (6), the corresponding number of photons falling on the detector (just before amplification) during T seconds is

$$n_{\text{signal}} = \Delta F \Delta\lambda \; S \; \epsilon \; \eta \; 10^{\{-0.4\, x(\lambda) \sec Z\}} T \left(\frac{hc}{\lambda}\right)^{-1}, \tag{2}$$

where $\Delta\lambda$, S, ϵ, η, $x(\lambda)$, sec Z, h, and c are respectively the filter bandwidth (in Å), the telescope's aperture (cm^2), the reflectivity of primary and secondary mirrors (dimensionless, 0.85 in our case), the efficiency of the system (including transmission of all filters, photometers' Fabry lens and quantum efficiency, dimensionless, 0.23 in our case), the extinction in the considered band (mag), the airmass, Planck's constant (erg s) and speed of light (Å/s). The results below regard B band ($\lambda = 4380$ Å) because pulsations of roAp stars are generally monitored in this band. The values of all the atmospheric parameters for both sites can be found in Sagar *et al.* (2000) and Kumar *et al.* (2000).

The number of photons n_F corresponding to F, and the number of photons n_{sky} corresponding to the sky background can be derived in the same manner as in equation (2). (An aperture of 15 arcsec radius is used in the survey; this value was used to calculate the sky's background.)

The pulsation component oscillates around the average flux F. The average number of photons falling on the detector (just before amplification) is hence $n_F + n_{\text{sky}}$. Now, the joint effects of two phenomena will set the detection limit for a given site and telescope.

Firstly, the arrival of the photons is random, and in the absence of atmosphere, their statistics would be Poissonian, with mean and variance $n_F + n_{\text{sky}}$. However, because of random fluctuations of the air's refractive index occurring in the upper atmosphere, any deterministic flux propagating through these turbulent layers becomes random. The rms of this scintillation effect corresponds to a number of photons n_{sc}, which can be estimated from Dravins *et al.* (1998), equation (10). We obtain

$$\begin{aligned} n_{sc} &= 0.09\ D^{-\frac{2}{3}}(\sec Z)^{1.75} e^{\frac{h}{h0}} (2T)^{-\frac{1}{2}} (n_{\text{sky}} + n_F) \\ &= \alpha(n_{\text{sky}+n_F}). \end{aligned} \tag{3}$$

In the above equation, D is the telescope aperture (in cm), h the altitude (1951 m for Manora Peak, 2420 m for Devasthal) and $h0 = 8000$ m. The integration time for the survey is $T = 10$ s.

Accounting now for the photon noise and the scintillation noise together, one sees that the photons falling on the amplifier follows a *doubly stochastic* process: the process is Poisson (because of random photon noise) with respect to a mean which is itself stochastic (because of scintillation). The study of these (so-called *mixed Poisson* processes) can be found mostly in the actuarial statistics literature (Grandel 1997); they have gained much attention recently in the field of astronomy, especially in extrasolar planet detection, see e.g., Canales & Cagigal (2001) and Aime & Soummer (2004). For such processes, the mean equals that of the Poisson process alone, and the variance is the sum of the variances of the two stochastic processes (photon noise and scintillation in our case). Consequently, using equation (3), the average number of photons falling on the amplifier is $n_{\text{sky}} + n_{n_F}$, and the associated variance is $n_{\text{sky}} + n_{n_F} + \alpha^2(n_{\text{sky}} + n_{n_F})^2$. Hence, the overall (rms) noise, expressed in photons and including the joint effects of sky background, scintillation and photon noises becomes

$$n_{\text{noise}} = \left(n_{\text{sky}} + n_{n_F} + \alpha^2(n_{\text{sky}} + n_{n_F})^2\right)^{\frac{1}{2}}. \tag{4}$$

This number can be evaluated for both Manora Peak and Devasthal sites. The signal-to-noise ratio (SNR) becomes

$$\frac{S}{N} = \frac{n_{\text{sig}}}{n_{\text{noise}}} = \frac{n_{\text{sig}}}{\left(n_{\text{sky}} + n_{n_F} + \alpha^2(n_{\text{sky}} + n_{n_F})^2\right)^{\frac{1}{2}}}, \tag{5}$$

where the expressions of the involved noises are detailed above. The SNR tells us whether a variation of f mmag in a m_λ magnitude star is possible to detect or not.

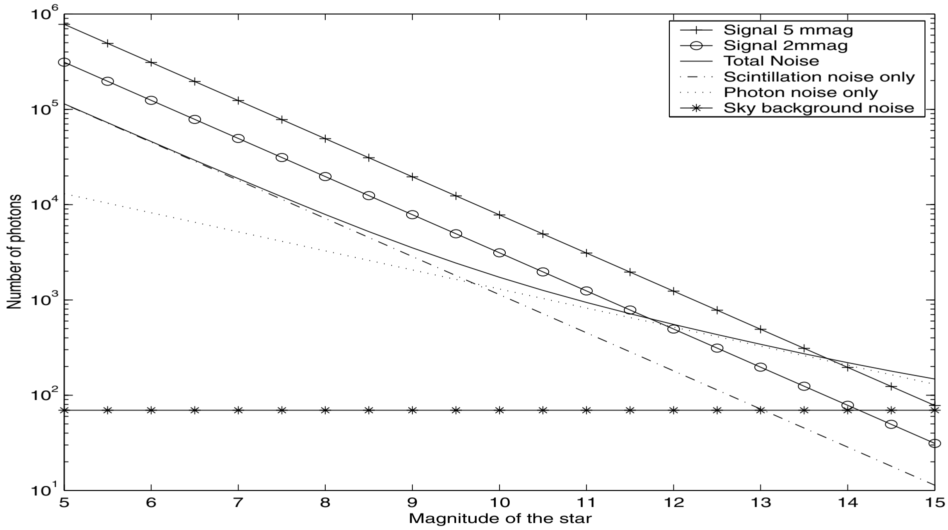

Figure 3. Signal and noise contributions at Devasthal for detecting a variation of 5 mmag and 2 mmag as a function of B mag for a star at the zenith.

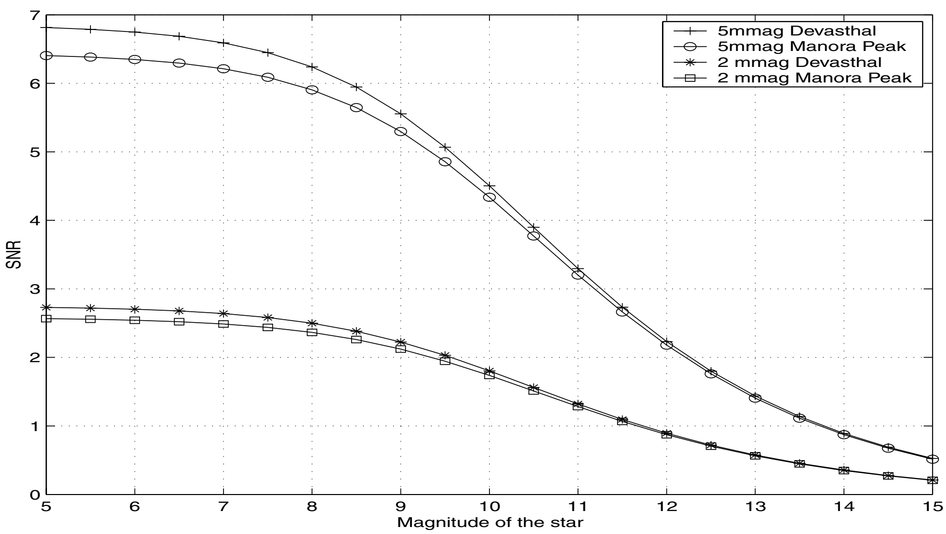

Figure 4. A comparison between the signal to noise ratios at Manora Peak and Devasthal for detecting 5 mmag and 2 mmag oscillations as a function of B mag for a star at the zenith.

Figure 3 illustrates the contributions of all the noise sources described above when trying to detect 5 mmag and 2 mmag variations as a function of B magnitude of a star at Devasthal. It can be seen that the sky background is negligible for all magnitudes of interest, and that the scintillation noise dominates the photon noise for bright stars.

Figure 4 compares the SNR (equation (5)) obtained at Devasthal and Manora Peak when trying to detect 5 and 2 mmag pulsations as a function of the B magnitude. Both sites allow the detection of 5 mmag pulsations for stars up to magnitude ≈ 14 in the blue, and 2 mmag up to magnitude ≈ 12. Also, one sees that Devasthal is even better than Manora Peak because of its more transparent sky and higher altitude.

The Devasthal site survey and the above results indicate remarkable photometric quality and stability of the sky conditions, which make the detection of a few mmag variations in bright stars ($B \leq 12.0$ mag) possible from Manora Peak, as well as from Devasthal for similar observing facilities.

3. ARIES' three-channel photometer

In order to carry out regular observations for the survey work at Manora Peak, Nainital, a new high speed three channel photometer was developed and fabricated (Ashoka *et al.* 2001; Gupta *et al.* 2001). Such photometers are essential for obtaining reliable and continuous time series data even under moderate sky conditions. The detector is a Hamamatsu R647-04 PMT made for photon counting applications at low light levels. The tube is blue sensitive with S–11 response. The photocathode has a size of 10 mm and is made of bialkali material. The tube has a gain of 2.2×10^6. The quantum efficiency is 30% around 400 nm. Further details of the instrumental parameters are given by Ashoka *et al.* (2001).

The photometer is being used extensively for the survey work at Manora Peak since November 1999. We have mostly observed in B photometric passband as the tube response peaks in this passband. However, the photometer is capable of carrying out observations in U and V passbands also. While using three channels simultaneously, the sky contributions can be determined accurately even during variable moon-lit nights and dawn/dusk, because one channel of the photometer monitors the sky's contribution continuously. This also maximizes the utilization of the observing time on the telescope.

Regarding the sources of noises of the instrument, the high voltage (HV) supply has a capability of delivering 0.1 ma current, so that one unit itself can power three tubes. The low ripple (0.005% p-p) at maximum rating shows that the AC component is negligible, indicating that the HV is a perfect DC. The voltage is stable up to 0.01% for a change in 1V change in input, which is also negligible. This indicates that the voltage 1000v DC is very stable, and does not have any effect on the observed counts. Since the photocathode is blue sensitive, the tube does not need cooling. This is an end window tube with antimagnetic coating on the tube. This is the smallest (finger size) tube available for optical photometry. Because the tubes are small and uncooled, the whole photometer can be miniaturized. The dark counts at room temperature are ≈ 20 cps, which is again very low. Considering the overall performances on a 1 m size telescope in V band, one can observe a 16th magnitude star with a 10 s integration with instrumental SNR of 3.

Most of the time in a photometer however, the faintest star which we can observe depends on brightness of a star that one is able to see in the wide angle eyepiece, and on our ability to centre it in the diaphragm. Thus, the faintest stars may fail to be properly centred in the diaphragm, and one may thus lose a fraction of SNR – even though the corresponding flux could actually be detected by the instrument. In the case of CCD, we do not need to see and centre the star: we can centre the field and expose.

In conclusion, the global performances of the ARIES photometer are excellent for the purpose of this survey. Atmospheric scintillation, limited telescope aperture (and centering capabilities for fainter stars) are the major limiting factors for the discovery and the variability measurements of pulsating chemically peculiar variable stars. This photometer has contributed to a major extent to the discovery of the new variables reported in Girish *et al.* (2001) and Joshi (2004, 2005).

4. Future facilities

There is a plan in ARIES to build a high speed time-series CCD photometer following successful measurements obtained with such instruments recently by Nather & Mukadam (2004), and Nather *et al.* (2005). As discussed above, CCDs will allow us to probe fainter objects in comparison to photomultiplier tubes; this in addition to a higher quantum efficiency will allow more precise photometric measurements.

Besides, the excellent review presented by Kurtz (2005) in this workshop has clearly shown that the pulsation effects in chemically peculiar stars are more prominent in some spectral lines than in the continuum, as they originate higher in the atmosphere, where oscillation effects are more pronounced. We plan to carry out such high-resolution spectroscopic observations using the facilities available in India (Rao 2005) as well as abroad (Mkrtichian 2005). We have also planned to build a 3 m class optical telescope, where high resolution spectroscopic observations will be routinely obtained for these chemically peculiar stars.

Finally, in order to have dense and long temporal coverage, we are currently organizing simultaneous observations from many observational sites in India and abroad, as a collaborative effort (Dorokhova & Dorokhov 2005; Hojaev & Chen 2005).

5. Discussions and conclusions

We have obtained precise photometric observations for over 150 chemically peculiar stars during 1997 to 2004 on about 100 photometric nights using the 104 cm Sampurnanand telescope of Manora Peak, Nainital. The remarkable characteristics of Manora Peak's astronomical site together with the use of successful and proved data reduction techniques developed at SAAO lead us to discover (only) one roAp star, but several δ Scuti, and other types of variables. Although the survey work is indeed on-going, the results obtained so far confirm an overwhelmingly large numbers of roAp stars in the southern hemisphere's sky in comparison to its northern counterpart. The discovery of only one roAp star in the presented survey so far *can not* be attributed anymore either to poor sky conditions at the site, or to lesser survey efforts. This difference in both hemispheres is thus extremely intriguing. As current observation do (and may be upcoming observations will) tend to confirm it, the need of a theoretical explanation for that phenomenon becomes more and more important. However, it should be noted that the availability of Michigan spectral catalogue (Houk & Cowley 1975 and later volumes) for chemically peculiar stars was a major advantage to the search for roAp stars in the southern hemisphere.

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