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The Naini Tal – Cape survey for pulsations in chemically peculiar A-type stars

I. Methods and preliminary results

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Abstract. A new survey for pulsating, chemically peculiar A- and F-type stars in the northern hemisphere has been initiated using the 1-m telescope at Uttar Pradesh State Observatory in Naini Tal. The survey is primarily structured to reveal high-overtone pulsations in chemically peculiar A–F stars, but it is also revealing low-overtone δ Scuti-type pulsations in stars with peculiar colours. This paper describes the scope and methods of the survey. Preliminary observations of 28 candidate stars are presented and the discovery of three new pulsators, HD 12098, HD 13038 and HD 13079, is announced. Null results for the remaining 25 stars are also discussed.

Key words. stars: chemically peculiar – stars: individual: HD 12098, HD 13038, HD 13079 – stars: oscillations – stars: variables: δ Scuti

1. Introduction

Pulsation is a common phenomenon among the A–F stars. About 30 per cent of the stars in this part of the Hertzprung-Russell (HR) diagram are δ Scuti stars which pulsate with amplitudes ranging from a few mmag to almost a magnitude. This is also the region of the HR diagram where one finds the magnetic chemically peculiar Ap/Fp stars and non-magnetic Am/Fm metallic-line stars.

With few exceptions, the δ Scuti stars are chemically normal. This is consistent with the view that the spectral peculiarities in the chemically peculiar stars are produced by chemical diffusion (e.g. Michaud 1980; Alecian 1986), and are confined to the surface. (Pulsation would disrupt the element separation established by the frail diffusion process, erasing the chemical anomalies.) There is a handful of chemically peculiar Am, marginal Am and luminous, cool evolved Am ("ρ Puppis") stars that exhibit low-overtone δ Scuti pulsation, but there are as yet no undisputed cases of such pulsation in Ap stars (Kreidl 1986). However, some Ap stars *do* exhibit high-overtone pulsation (see below). The presence of pulsations in CP stars places constraints on theories for the origin of the peculiarities. For a discussion of the issues of pulsation and metallicism in CP stars, see Kurtz (2000) and the references therein.

The *rapidly oscillating Ap stars* ("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 in the range 5.6–15.0 min. The photometric amplitudes of the variations in roAp stars range from about 0.6 mmag (an observational lower limit) to several mmag in Johnson B light. The pulsation axis is aligned with the magnetic axis, which is oblique to the rotation axis. This causes the pulsations to be seen from variable aspect as the star rotates, leading to modulation of the amplitude and phase as described by the *oblique pulsator model* (Kurtz 1990; Takata & Shibahashi 1995). For a discussion on the excitation of the pulsations in roAp stars, and what distinguishes them from δ Scuti and Am-type pulsators, refer to the papers by Gautschy et al. (1998) and Balmforth et al. (2001), and references therein. The multi-periodic p-mode oscillations in roAp stars are

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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.

At the start of this survey, there were 31 known roAp stars, 28 of which are southern objects. The disparity in the number of known roAp stars in the two hemispheres reflects the greater survey efforts at the South African Astronomical Observatory (SAAO) compared with other searches for roAp stars (Table 1). We are now applying the successful techniques developed in the Cape Survey (Martinez et al. 1991, 1994a,b) to a northern hemisphere search for roAp stars. As a by-product, this survey is also revealing low-overtone pulsations in A–F stars with peculiar colours. In this paper we report the discovery of three new variables, HD 12098, HD 13038 and HD 13079. HD 12098 is a new roAp star, and the other two stars have δ Scuti-type periods.

2. Candidate selection and observing strategy

The primary source of candidates for the Cape Survey was the *Michigan Spectral Catalogue* (Houk & Cowley 1975, et seq.), which was used to select all cool Ap stars; that is, stars with marked Sr, Cr or Eu line-strength anomalies. Since a comparable reference work is not available for northern hemisphere stars, we resorted to using A- and F-type stars in the HD catalogue for which Strömgren *uvby* and Hβ photometry is archived in the Simbad data base at the Centre de Données astronomiques de Strasbourg.

To optimize our chances of discovering new roAp stars we search for oscillations mainly in the subset of stars with Strömgren photometric indices similar to those determined for roAp stars in the Cape Survey:

$0.08 \le b - y \le 0.29$
$0.20 \le m_1 \le 0.32$
$\delta m_1 \ge 0.01$
$0.49 \le c_1 \le 0.85$
$\delta c_1 \le 0.04$
$2.70 \le \beta \le 2.83.$

The Hβ index indicates a temperature range from around A3 to F2. The m_1 and c_1 indices indicate enhanced metallicity and increased line blanketing, respectively. These are characteristics which are associated with Am and Ap stars. Indices in the ranges given above are not an unambiguous indicator of roAp pulsation, although they serve to narrow down the field of candidates to the most promising subset. However, we caution that roAp star surveys should explore the extent of the roAp phenomenon, and should not be confined to these observed limits determined from the known roAp stars.

The most efficient way to search for new roAp stars is through the technique of high-speed photometry. The extremely low oscillation amplitudes (often <1 mmag) demand high photometric precision. With care, such precision can be routinely attained at a good site such as Naini Tal.

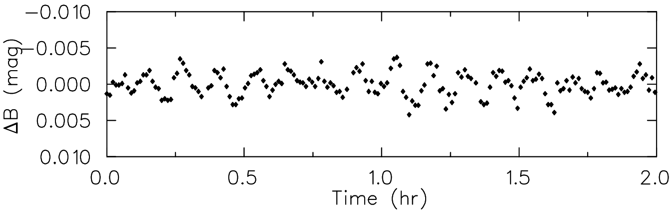

Fig. 1. The Johnson B light curve of HD 12098 on night JD 2451535

The observing strategy is simple. We acquire time-series photometry of candidate stars for 1–2 hr, which suffices to reveal roAp pulsations on a good night. However, a single null result is insufficient to exclude a candidate for two reasons. Firstly, because the roAp stars are oblique non-radial pulsators, the amplitude of the pulsations is modulated with rotation. For a dipole pulsation, when the star is magnetic (pulsation) pole-on, the observed pulsation amplitude is at a maximum. When the star is in quadrature, the amplitude is zero. The second reason why one may obtain a null result for pulsation is that the star is multi-periodic and one happens to observe it during the 1–2 hr when destructive interference of the modes renders them undetectable. Thus, all candidate stars are observed for 1–2 hr per night on several occasions. The candidate stars are all bright, so the noise is dominated by scintillation, rather than photon statistics. Since the noise scales as the $-2/3$ power of telescope aperture (Young 1967; Dravins et al. 1998), it pays to use telescopes in the 1-m class, or larger if possible.

The observing strategy outlined above clearly requires considerable amounts of telescope time. Fortunately the candidate stars are almost all brighter than 10th magnitude (in B), so the searches may be conducted near the full moon periods, when telescopes are often undersubscribed.

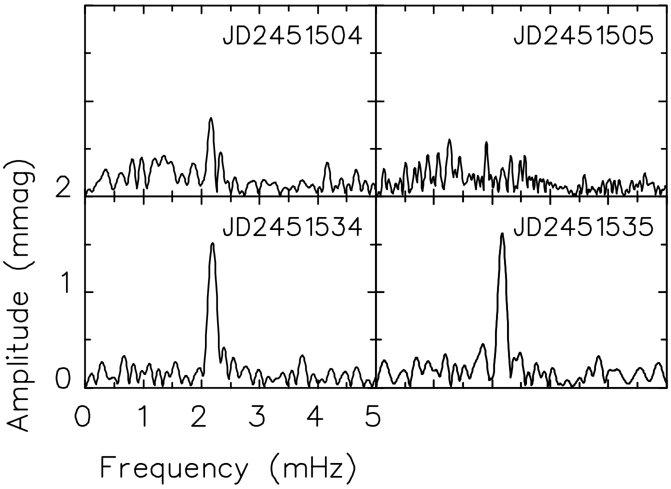

Fig. 2. Amplitude spectra of the light curves of HD 12098

Table 1. Searches for high-overtone pulsation in normal and peculiar A stars

Reference	Sample size
Kurtz (1982)	5 Ap SrCrEu field stars
Matthews & Wehlau (1985)	4 northern field Ap stars
Matthews et al. (1988)	4 Ap stars in NGC 2516
Heller & Kramer (1988)	4 northern field Ap stars
Schutt (1991)	36 northern normal A0–A5 stars
Nelson & Kreidl (1993)	120 northern Ap stars in range B8–F4
Belmonte (1989)	8 northern Fp/Ap stars
Hildebrandt (1992)	4 normal and peculiar A stars
Martinez et al. (1991, 1994a,b)	300 southern Ap SrCrEu stars
Dorokhova et al. (1998)	unspecified number of mostly northern Ap stars
Handler et al. (1999)	17 northern Ap stars

3. Observations and preliminary results

High-speed photometric observations of 28 candidate stars were acquired during the months of November–January in 1997–2000. The data were obtained using a high-speed photometer attached to the 104-cm Sampurnanand reflector of the Uttar Pradesh State Observatory at Nainital. The data were acquired as a time series of continuous 10–s integrations with occasional interruptions for sky background measurements. As we were searching for variations in the 5–15-min range, no comparison stars were used. A photometric aperture of 30 arcsec or larger was used to minimize errors from seeing fluctuations and guiding. A journal of the observations is given in Table 2, which lists, for each star, the heliocentric Julian date of the start of the observations, the duration in hours, the standard deviation σ (in millimagnitudes) of one observation with respect to the mean for the night, and a remark concerning variability. All observations were acquired in Johnson B light, unless otherwise specified in the "Remark" column.

The standard reduction procedure used in this survey is as follows: the observations are corrected for coincidence counting losses, sky background, and mean atmospheric extinction ($\kappa_{\rm B} = 0.26$ for Naini Tal). The discrete Fourier transform (Deeming 1975; Kurtz 1985) of the reduced light curve is then computed to search for coherent oscillations. There is always some degree of contamination of single-channel high-speed photometry by sky transparency variations. These variations are usually removed by prewhitening the peaks at low frequencies (i.e. <0.5 mHz) until the low-frequency noise drops to the level of the scintillation noise. This is a correction which must be applied with caution, as it does not discriminate between sky transparency variations and real variations in the star. It is therefore important to inspect the light curves for evidence of long-term ($P > 0.5$ hr) stellar oscillations before prewhitening them. Section 3.1.3 is a case in point of the potential rewards of doing so.

3.1. New variable stars

3.1.1. HD 12098–A new roAp star

HD 12098 is classified as an F0 star in the HD catalogue, but it has Strömgren indices indicative of strong metallicity found in the Am and Ap stars, viz. $b - y = 0.191$, $m_1 = 0.328$, $c_1 = 0.517$ and $\beta = 2.796$ (Hauck & Mermilliod 1998).

On the basis of these peculiar colours we decided to search for rapid oscillations in HD 12098 on night 21/22 November 1999, JD 2451504. We were rewarded with the discovery of 7-minute oscillations. These oscillations were observed again on nights JD 2451505, 51534 and 51535. Figure 1 shows the light curve obtained on night JD 2451535.

The discovery of rapid oscillations in HD 12098 is consistent with the high metallicism indicated by the peculiar colours, and implies an Ap (rather than Am) nature for this star.

Figure 2 shows the amplitude spectra of our light curves of this star. The signal is clearly modulated in amplitude. On the nights when a signal is present, the amplitude spectrum peaks strongly at ∼2.18 mHz ($P =$ 7.6 min). The amplitude modulation evident in Fig. 2 may be caused by beating among several frequencies and/or oblique, non-radial pulsations being seen from variable aspect as the star rotates.

To refine our determination of the pulsation frequency in HD 12098, and to search for further frequencies causing amplitude modulation, we computed the discrete Fourier transform of the combined data for nights JD 2451534–35. This yielded a highly aliased window pattern of amplitude 1.6 mmag centered on $\nu = 2.174$ mHz with a ± 1 day^{-1} alias ambiguity. Removal of this frequency (and its aliases) yields no further peaks above a noise level of 0.3 mmag. This means that the amplitude modulation evident in Fig. 2 (whether it is due to beating of multiple modes, or rotation, or both) occurs on a time-scale commensurate with multiples of the 1 d^{-1} alias spacing.

Table 2. Journal of high-speed photometric observations. All observations are in Johnson B light, unless otherwise specified in the "Remark" column

Star	HJD start (day)	T (hr)	σ (mmag)	Remark
HD 12098	2451504.22153	2.51	1.2	roAp
HD 12098	2451505.07198	4.62	1.4	
HD 12098	2451534.15344	2.10	1.4	
HD 12098	2451535.14934	2.24	1.6	
HD 12690	2451150.08614	1.17	1.2	
HD 12881	2451144.17125	2.06	1.6	
HD 12881	2451150.14453	2.00	1.2	
HD 12881	2451151.17069	0.99	1.3	
HD 13038	2451146.13401	3.76	1.7	δ Sct
HD 13038	2451147.09267	4.63	2.4	
HD 13038	2451151.23969	3.22	1.7	
HD 13038	2451152.11802	6.68	2.5	
HD 13079	2450765.15417	2.02	18.6	δ Sct
HD 13079	2450768.06686	2.51	10.5	
HD 13929	2451148.10069	2.07	0.9	
HD 15023	2450768.18615	1.97	2.8	
HD 15023	2451148.19572	0.99	0.8	
HD 16956	2451145.14098	0.98	0.9	
HD 17431	2450767.11658	5.05	4.8	
HD 17431	2451145.21201	0.96	0.8	
HD 18460	2451149.19313	1.68	0.8	
HD 24015	2451148.25156	0.97	0.9	
HD 26894	2450768.27854	2.05	2.0	
HD 26894	2451145.27537	1.07	0.8	
HD 30110	2451150.28150	4.38	0.9	
HD 32404	2451148.30012	3.75	1.2	
HD 32404	2451149.27629	4.02	1.0	
HD 34202	2450767.34786	3.75	2.5	
HD 34202	2451145.33379	1.02	0.7	
HD 35325	2451144.28025	1.00	0.8	
HD 37154	2451144.33552	2.37	1.0	
HD 38143	2451147.35051	1.18	0.9	
HD 39066	2451145.38759	2.47	1.3	
HD 39066	2451146.30475	1.11	0.9	
HD 39066	2451147.29634	0.98	1.2	
HD 39550	2451146.35997	0.87	1.1	
HD 65339	2451144.44781	1.24	0.8	U filter
HD 65339	2451151.45620	1.02	1.0	U filter
HD 71866	2451146.42424	1.25	0.6	
HD 75698	2451151.39089	1.04	0.8	U filter
HD 88850	2451146.45776	0.96	1.2	
HD 92400	2451147.40789	1.02	1.2	
HD 92572	2451147.45929	0.97	1.2	
HD 92572	2451152.40955	1.23	1.3	
HD 94763	2451149.45510	0.94	1.2	
HD 99831	2451150.46928	0.71	1.0	

An exploratory study of the rapid oscillations in HD 12098 spanning two weeks should reveal the frequencies responsible for the amplitude modulation. At 2.2-mHz, the oscillations in HD 12098 are well resolved from the sky transparency variations at good photometric sites, so the prospects for detailed studies of the oscillations are quite good.

3.1.2. HD 13038

The star HD 13038, which is classified as A3 in the Henry Draper catalogue, has Strömgren colours $b - y = 0.105, m_1 = 0.220, c_1 = 0.848$ and $\beta = 2.856$ (Hauck & Mermilliod 1998). The β index is consistent with an early A type, and the metallicity ($\delta m_1 = -0.014$) and luminosity ($\delta c_1 = -0.034$) indices are indicative of strong line blanketing in the Am and Ap stars.

HD 13038 oscillates with a period of 28.7 min. Figure 3 shows the light curve for this star on night JD 2451147. The light curve shows beating, which is indicative of the presence of at least one other frequency. Indeed, the amplitude spectrum of this light curve shows a prominent peak at 0.58 mHz, flanked by a lower-amplitude peak at 0.46 mHz (Fig. 3). Inspection of the Fourier transforms of the other available light curves confirms the presence of these two frequencies. Furthermore, they suggest that these two frequencies are intrinsically modulated in amplitude.

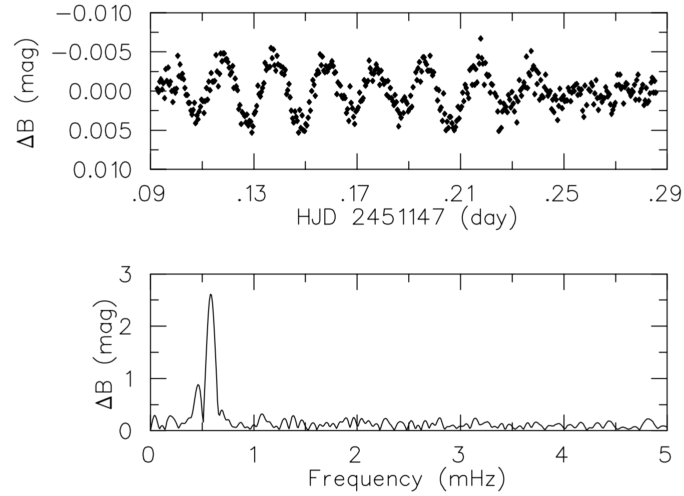

Fig. 3. Light curve and amplitude spectrum of the light curve of HD 13038 on night JD 2451147

The nature of HD 13038 is unclear. It has a pulsation period which is about twice as long as that of any roAp star, but is also unusually short for a δ Scuti star. [Two other δ Sct stars are known or suspected to have such short periods. These are the A4V primary of the eclipsing binary RZ Cas, which pulsates with a period of 22.4 min (Ohshima et al. 1998), and the A4V primary of the eclipsing binary AS Eri, which (probably) pulsates with a period of 24.4 min (Gamarova et al. 2000).] Spectroscopic observations will confirm the suspected Ap/Am nature of HD 13038. If it turns out to be an Ap star, this will break the dichotomy between the chemically normal δ Scuti stars, which pulsate in low overtones, and the chemically peculiar roAp stars, which pulsate in high overtones (Kurtz 2000).

3.1.3. HD 13079

HD 13079 (HIC 10023, CCDM 02090+3936) is a double star. The Hipparcos Hp magnitudes for the two components are 8.989 ± 0.007 and 11.311 ± 0.057. The separation and position angle are $\rho = 6.173 \pm 0.017''$ and $\theta = 254.4°$, respectively. The Strömgren photometric indices for the combined light of the two stars are: $b - y = 0.203, m_1 = 0.211, c_1 = 0.672, \delta m_1 = -0.023, \delta c_1 = -0.028$ and $\beta = 2.759$ (Hauck & Mermilliod 1998). The dereddened indices are $[\delta m_1] = -0.060$ and $[\delta c_1] = -0.069$. These indices are typical of the strongly line-blanketed spectra of cool Ap and Am stars. Spectroscopy reveals essentially solar abundances for the iron peak elements, which excludes HD 13079 being an Ap star. However, calcium is underabundant, suggesting that it is an Am star (F. Leone, private communication).

HD 13079 pulsates with a period of 73 min (Fig. 4). Inspection of the nightly amplitude spectra shows that all the signal power is contained in the range 0–1 mHz and also suggests that the amplitude of the oscillations is modulated.

The Hipparcos parallax of $\pi = 5.52 \pm 1.97$ mas indicates $M_V = 2.46^{+.66}_{-.96}$. At $(b - y) = 0.203$, this is about 0.5 mag above the main sequence, which places the star on the red edge of the instability strip (Breger 1979). The Hipparcos M_V is consistent with $M_V = 2.46 \pm 0.19$ derived from King's (1991) $P - L$ relation for δ Scuti stars pulsating in the fundamental mode.

3.2. Detection limits and null results

Although the discovery of pulsation is the object of this survey, the null results are also of interest in that they constrain the ubiquity of low-amplitude pulsation in a wide range on peculiar A-type stars on time-scales not probed by surveys using differential photometry. Figure 5 shows our null results in the Fourier domain with no prewhitening of low-frequency noise. Each panel contains the Fourier transform of an individual light curve. The HD number of the star is listed above the panel, and the Julian Date, the filter, the duration of the observations (in h) and the number of integrations are listed inside each panel. The reason why we show our null results in this form, rather than just as a list of star names, is because the noise is clearly not white noise, so one requires a careful definition of what is meant by constancy of a given candidate.

The detection limits for pulsations are different for the low-overtone and high-overtone oscillations. At frequencies above ∼1 mHz, the noise level (in the Fourier transform) is flat out to the Nyquist limit of 50 mHz for these data. This is scintillation noise, and it determines the detectibility of high-overtone roAp pulsations. As one moves toward lower frequencies, the noise levels show a general increase caused by sky transparency variations. For a good photometric site, this increase becomes significant around about 0.6 mHz, below which it becomes difficult to distinguish between low-overtone pulsations in the star and variations in sky transparency. Detectibility of the pulsations at these frequencies depends on the stability of detector response, the quality of the night (i.e. stability of sky transparency), the period of the oscillations, as well as their amplitude, and the duration of the light curve. For this reason it is important to inspect the light curves individually to determine the nature of the low-frequency "noise". It is in this step that the new variables HD 13038 and HD 13079 were discovered.

The prime objective of this survey is the detection of new roAp stars. There are several reasons why a roAp star

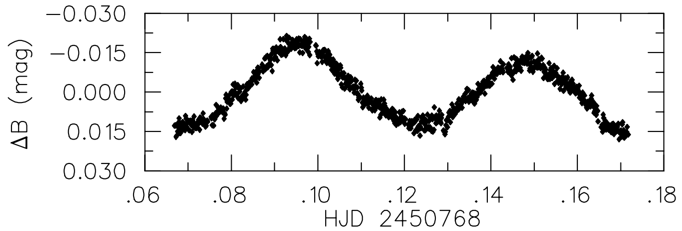

Fig. 4. The Johnson B light curve of HD 13079 on night JD 2450768

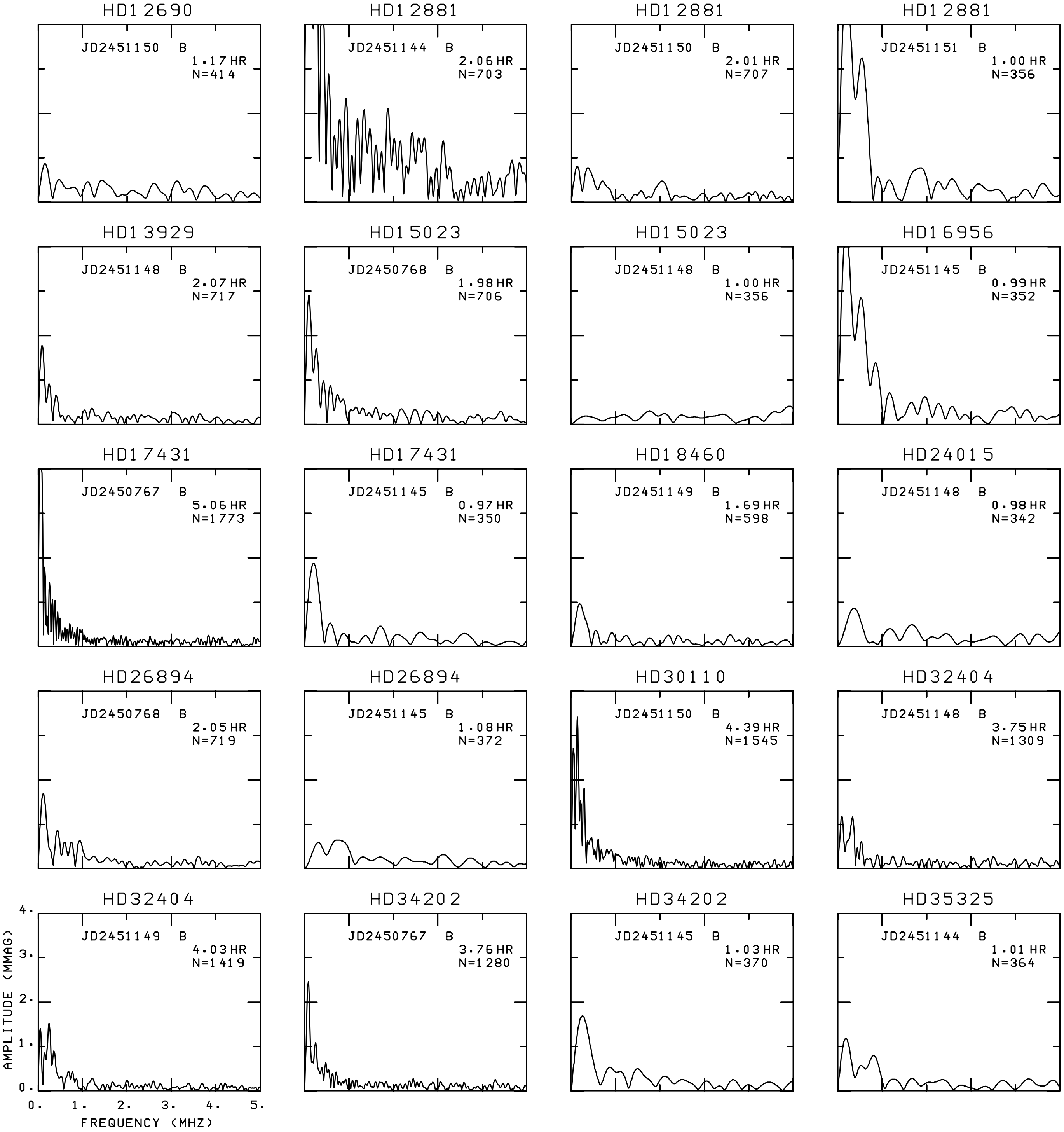

Fig. 5. Null results from the Naini Tal Cape Survey

might yield a null result when examined for pulsation (see Fig. 2), some intrinsic to the star and some due to atmospheric or instrumental causes. Rotational amplitude modulation in an oblique dipole pulsator makes it appear to be constant twice per rotation cycle [unless it is viewed rotation pole-on, or the magnetic (pulsation) and rotation axes coincide]. The duration of this type of constancy depends on the rotation period of the star, which is typically several days, but can be much longer (decades). Beating among different frequencies in a multi-periodic pulsator may also produce apparent constancy on the time-scale of a few hours. Alternatively, a star may appear to be constant in a 1–2 hr light curve simply because the noise and signal happen to be in anti-phase during that time. Pronounced sky transparency variations or high scintillation noise may also swamp a signal in short light curves.

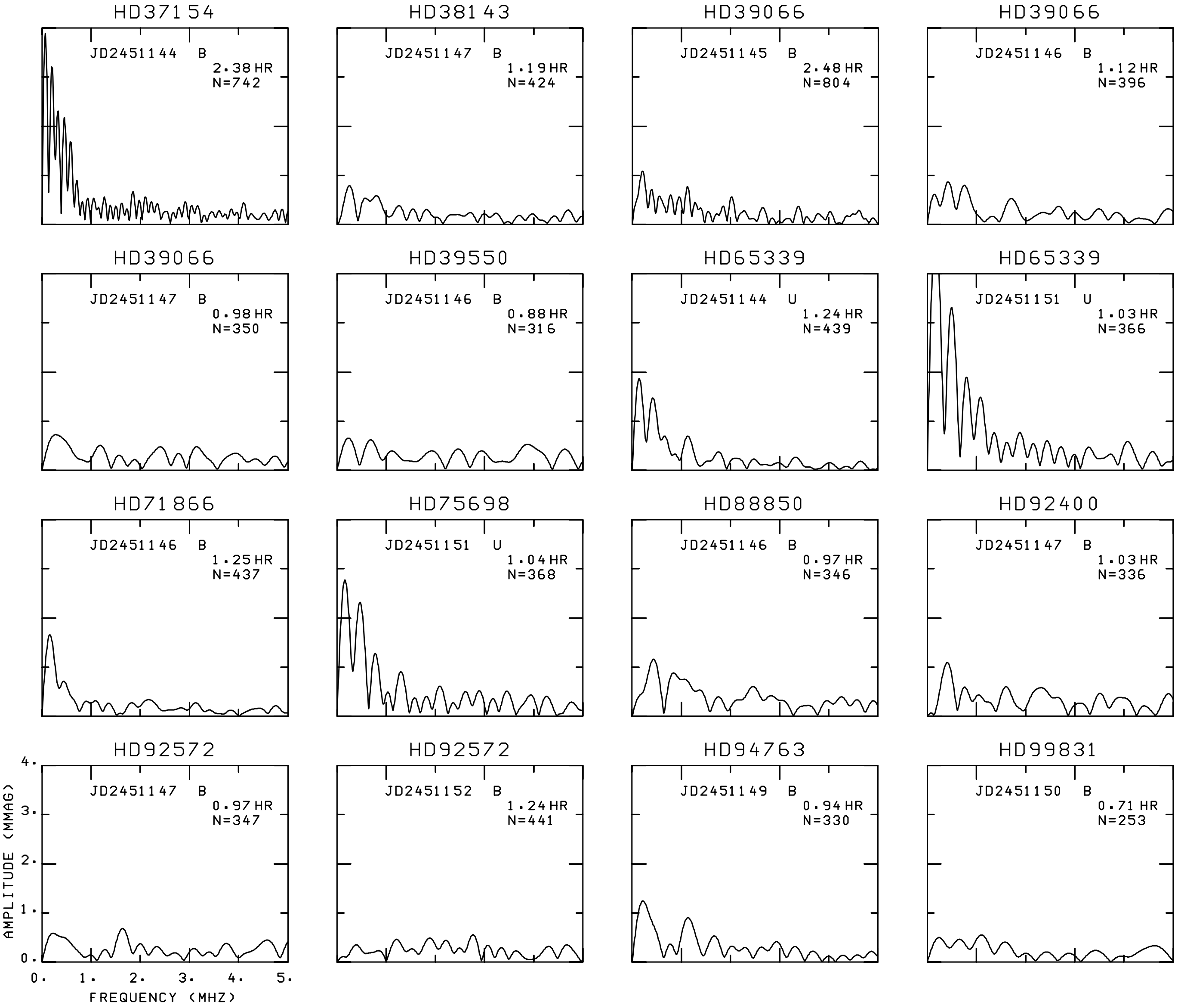

Fig. 5. continued

Thus, observers seeking new roAp stars should not be dissuaded from observing a star that is listed as a null result in this paper, especially if there is only one light curve.

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