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# HD 12098 – A new northern hemisphere roAp star

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**Abstract.** We present the analysis of 65 hours of high speed photometric observations of HD 12098 taken from State Observatory, Naini Tal and Gurushikhar Observatory, Mt. Abu on sixteen nights spanning from November 1999 to November 2000. HD 12098 is the first rapidly oscillating Ap star discovered from the "Naini Tal-Cape survey for northern hemisphere roAp stars". It is the 32nd in the complete list. HD 12098 exhibits one predominant mode of oscillation at $\nu_1 = 2.1738$ mHz. The second-most significant frequency in our data is at $\nu_2 = 2.1641$ mHz with a 1 cycle/day alias ambiguity. We argue that $\nu_2$ is a rotational sidelobe of $\nu_1$, rather than an independent pulsation mode. Evidence for the presence of two other frequencies at 2.1807 and 2.3056 mHz is also presented.

**Key words.** stars: chemically peculiar – stars: oscillations – stars: individual: HD 12098

## 1. Introduction

Many cool Ap stars exhibit anomalously strong Sr, Cr and Eu lines coupled with high magnetic fields frequently as strong as several kilogauss. A few of these chemically peculiar stars exhibit broadband light oscillations in the 4–16 min period range with amplitudes of few millimagnitude (mmag). This subset of Ap stars is termed as rapidly oscillating Ap (roAp) stars and the oscillations are attributed to low-order ($l < 3$), high overtone ($n \gg l$) non-radial pulsation modes (see Kurtz 1990; Martinez & Kurtz 1995 for reviews). Long term variations in amplitude of pulsations are observed in many roAp stars. This modulation can be explained in the light of the oblique pulsator model. In this model the pulsation and magnetic axes are oblique with respect to the rotation axis of the star. The modulation in the amplitude is then caused by the orientation effect due to the periodic variation in the angle between the pulsation axis and the line of sight. This effect seen in many roAp stars is therefore extremely useful in determining the rotation period of the star (Kurtz 1982).

In order to detect new roAp stars in the northern hemisphere, the *"Naini Tal-Cape Survey"* was initiated in 1997 (Ashoka et al. 2000; Martinez et al. 2001), because 28 of the previously known 31 roAp stars are in the southern hemisphere. HD 12098 is the first roAp star discovered from this survey. The co-ordinates of this star ($\alpha_{2000} = 02^{\rm h}00\overset{\rm m}{.}7$, $\delta_{2000} = 58^\circ\,31\overset{\prime}{.}6$ ) make it the northern-most known roAp star. HD 12098 is of spectral type F0 (Olsen 1980) and has an apparent magnitude $m_V = 7.974$. It has Strömgren color indices $(b - y) = 0.191$, $m_1 = 0.328, c_1 = 0.517, \beta = 2.796$ (Hauck & Mermilliod 1998). $\delta m_1 = -0.122$ and $\delta c_1 = -0.279$ are calculated using the calibrations of Crawford (1975). Recently Wade et al. (2001) have detected a variable longitudinal magnetic field of ≈2kG in HD 12098. They also predict a rotational period of the order of one week. HD 12098 was discovered in 1999 from Naini Tal as a roAp star having a period of 7.68 min with an evidence for multi-periodicity (Martinez et al. 2000) and amplitude modulation. We obtained about 65 hours of high speed photometric data as part of follow-up observations out of which around 45 hours are from Mt. Abu during October 2000. Analysis of these data indicates the presence of multi-periodic oscillations in the star. Among these, one frequency is most likely due to the rotational modulation of the predominant frequency. This supports the oblique pulsator model for this star as is the case with several other roAp stars. Probable evidence of the other rotational side-lobe and the presence of other modes of pulsation are presented here. Details of observations and data analysis are given in the next section while results,

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**Table 1.** Journal of high speed photometric observations of HD 12098. The second column is the BJD at the center of the run, third column is the total duration of observations. Last column lists the amplitude corresponding to the frequency 2.1738 mHz for the individual nights (ref. Sect. 2.3).

| Date | Time (BJD) (2451000+) | Duration (hours) | Amp. (mmag) |
|---|---|---|---|
| 21 Nov. 1999[a] | 504.27369 | 2.51 | 0.689 |
| 20 Dec. 1999[a] | 533.15988 | 2.00 | 0.381 |
| 21 Dec. 1999[a] | 534.18171 | 1.24 | 1.461 |
| 22 Dec. 1999[a] | 535.17755 | 3.12 | 1.412 |
| 08 Oct. 2000[a] | 826.30268 | 1.10 | 0.370 |
| 11 Oct. 2000[a] | 829.27440 | 2.64 | 1.199 |
| 12 Oct. 2000[a] | 830.25841 | 1.58 | 0.834 |
| 15 Oct. 2000[a] | 833.28734 | 2.01 | 0.673 |
| 16 Oct. 2000[a] | 834.94355 | 1.42 | 0.800 |
| 18 Oct. 2000[b] | 836.39091 | 5.19 | 1.054 |
| 19 Oct. 2000[b] | 837.33851 | 7.75 | 0.567 |
| 20 Oct. 2000[b] | 838.32158 | 7.76 | 0.534 |
| 21 Oct. 2000[b] | 839.31472 | 7.06 | 0.657 |
| 22 Oct. 2000[b] | 840.29415 | 7.82 | 1.904 |
| 23 Oct. 2000[b] | 841.31576 | 8.85 | 1.196 |
| 07 Nov. 2000[a] | 856.21624 | 2.64 | 1.469 |
| Total duration | | 64.99 hrs | |

[a] Observed at Naini Tal.
[b] Observed at Mt. Abu.

discussion and conclusions are given in the remaining part of the paper.

## 2. Observations and data analysis

The details of observations, data reductions and pulsation analysis are given in the following subsections.

### 2.1. Data collection and reduction

The pulsations in the star HD 12098 were discovered on the night of 21/22 November 1999 during the roAp star survey observations at the 1.04 m Sampurnanand telescope of state observatory, Naini Tal, India. Follow up observations were carried out at Naini Tal and also at the 1.2 m telescope at Gurushikhar, Mt. Abu, India. The log of observations is given in Table 1.

On both the telescopes we used a three channel photometer (Ashoka et al. 2001). During the survey at Naini Tal, we often use only the main channel of the photometer, while the follow up observations at Mt. Abu are conducted using all the three channels, monitoring a field star and sky simultaneously. HD 12098 is a double star with a companion which is 2.6 mag fainter and at an angular separation of 6″ (Olsen 1980). During observations, both stars are kept well within the diaphragm of 30″. The data are acquired as continuous 10 s integrations in the Johnson *B*-filter using the Quilt-9 software (Nather et al. 1990) running on a PC. Altogether, data for HD 12098 are obtained on sixteen nights. Out of them, the nights from Naini Tal are with durations of observations ranging from 1.1 to 3.1 hours while the six nights' data from Mt. Abu are of relatively longer duration ranging from 7.06 to 8.85 hours except on one night where the duration is 5.19 hour. The data obtained at both the places are corrected for dead time, sky background and earth's atmospheric extinction trend.

The data sets are in time expressed as barycentric Julian day (BJD) versus fractional intensity with respect to the mean intensity of the star. Since the fractional intensity variations are very small these values are given as mmag. Figure 1 presents typical light curve of the star HD 12098 obtained on 21/22 Oct. 2000 and 22/23 Oct. 2000. The presence of the 7.6 min oscillation and the day to day variation in pulsation amplitude is clearly evident in the light curves.

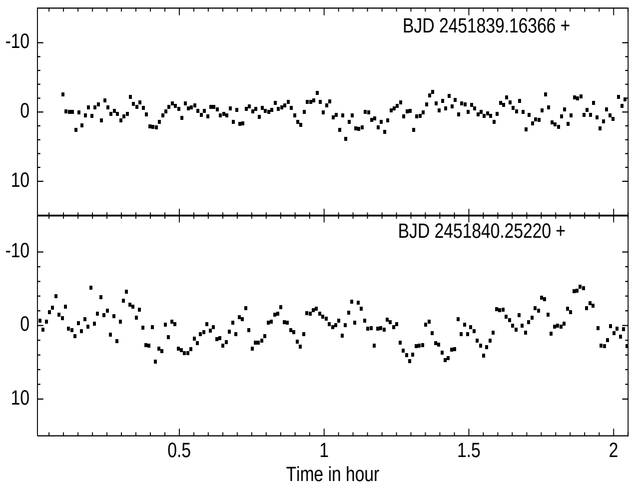


**Fig. 1.** A representative light curve of the star HD 12098 obtained on nights BJD 2451839 and 2451840. Each point represents the average of four 10 s integrations in the Johnson *B* filter.

### 2.2. Pulsation analysis

The presence of periodicity in the data-sets is searched for using the Discrete Fourier Transform (DFT) technique. All the individual runs exhibit a period around 7.7 min with varying amplitudes. The data sets collected at Mt. Abu, all of which are of considerable length also exhibit the presence of a frequency at 2.17 mHz in each of the runs, but with night to night variation in amplitudes ranging from 0.5 to 1.9 mmag. This clearly indicates the likelihood of the star being multi-periodic. In order to resolve closely spaced frequencies, all the runs from Mt. Abu are concatenated together and subjected to the DFT. Figure 2 shows the amplitude spectrum of this data set in the 0–5 mHz range. The dominant frequencies are around 2.2 mHz and there is no excess power well above the noise level in any other region of the frequency spectrum up to the Nyquist frequency (50 mHz). There

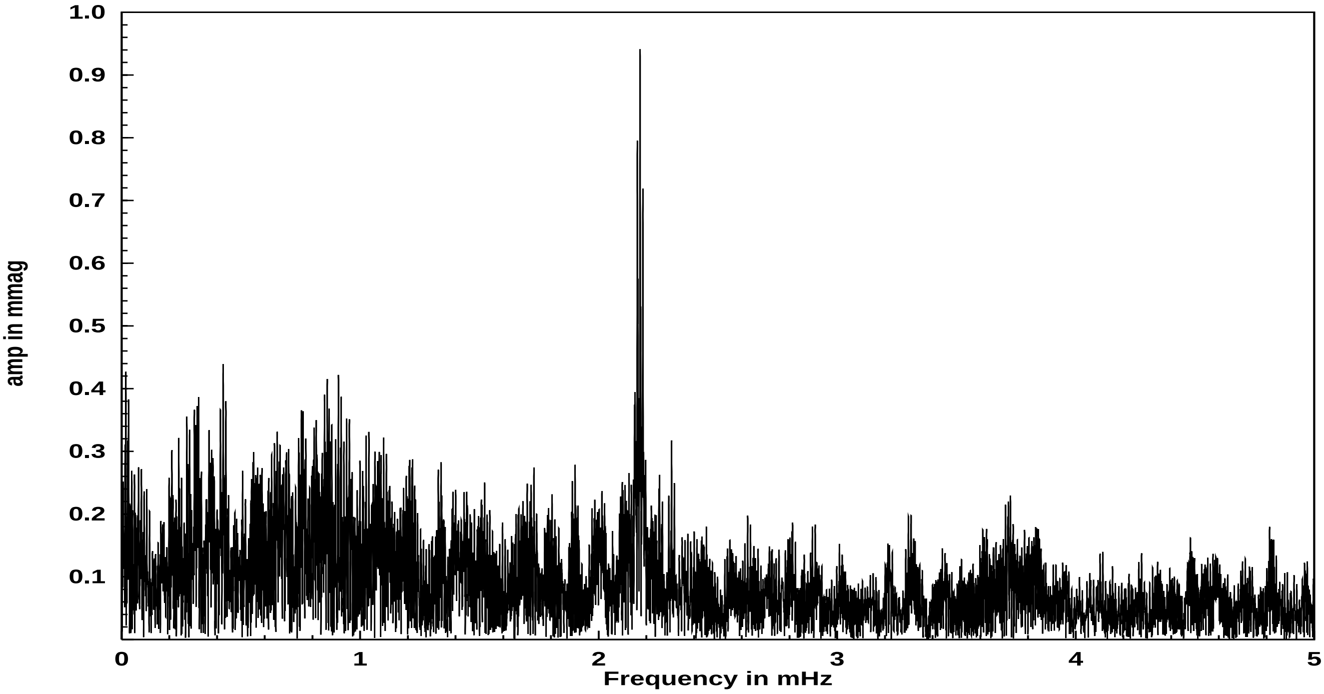


**Fig. 2.** The Fourier transform of the Mt. Abu data set obtained during BJD 2451836-841. It is evident that the dominant frequencies located around 2.2 mHz are well above the noise level.

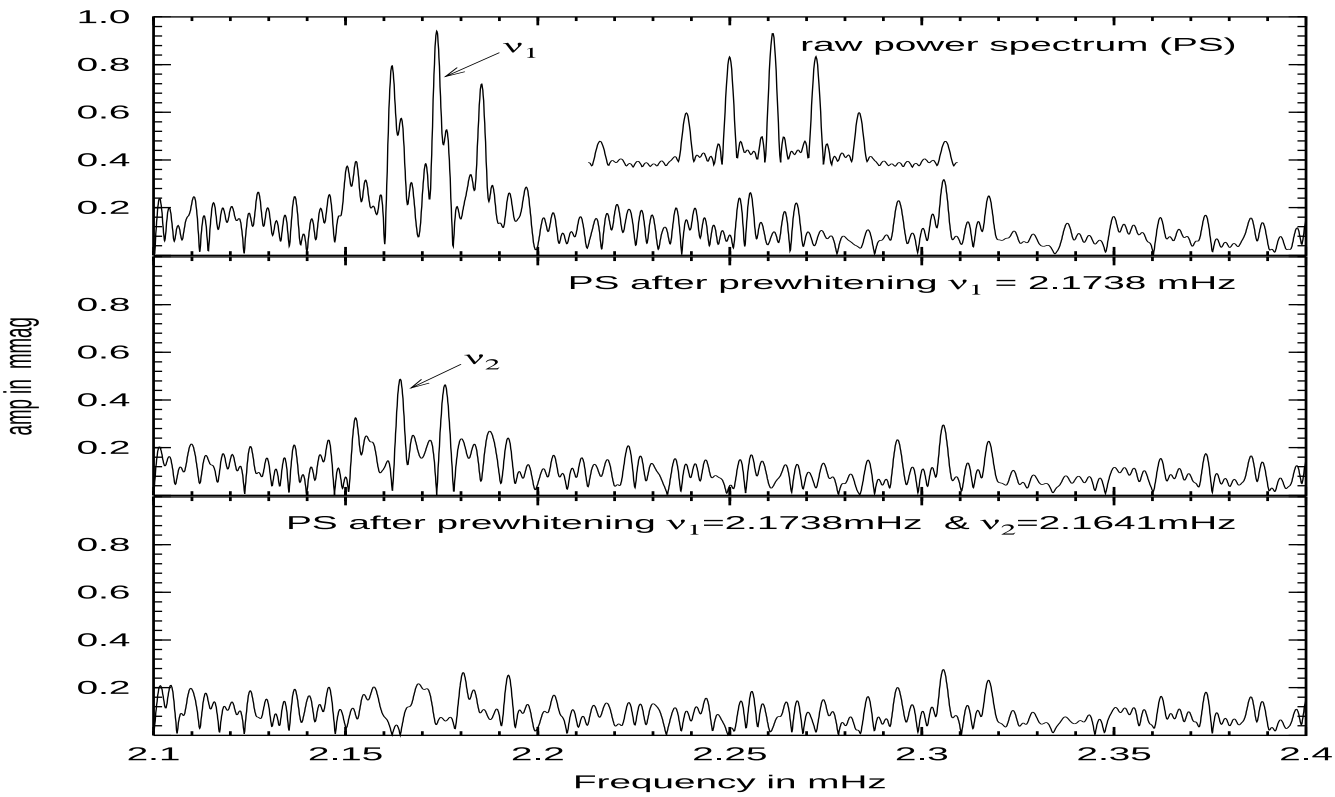


**Fig. 3.** A close-up view of the FT of the data set BJD 2451836-841. The second panel is the amplitude spectrum of the data after subtracting the frequency $\nu_1 = 2.1738$ mHz from the time domain. The third panel is amplitude spectrum after subtracting the frequencies $\nu_1 = 2.1738$ and $\nu_2 = 2.1641$ mHz from the time domain. The inset of panel I is the spectral window for the data-set calculated by sampling a noise-free sinusoidal with the frequency and amplitude of the highest peak in Fig. 2.

**Table 2.** The dominant frequencies and amplitudes obtained for the Mt. Abu data. First two columns are the results of the Fourier transforms (FT) and the last two columns are obtained by non-linear least square fit to the data.

| FT | | NLSQ | |
|---|---|---|---|
| Frequency (mHz) | Amplitude (mmag) | Frequency (mHz) | Amplitude (mmag) |
| 2.17372 | 0.941 | $2.17385 \pm 0.00006$ | $0.918 \pm 0.036$ |
| 2.16421 | 0.487 | $2.16414 \pm 0.00010$ | $0.511 \pm 0.036$ |
| 2.18060 | 0.263 | $2.18069 \pm 0.00016$ | $0.276 \pm 0.036$ |
| 2.30559 | 0.276 | $2.30559 \pm 0.00014$ | $0.279 \pm 0.035$ |

appear to be four frequencies present around 2.2 mHz which are given in Cols. 1 and 2 of Table 2.

The top panel of Fig. 3 shows an expanded view of the amplitude spectrum around 2.2 mHz. The highest peak in this spectrum is at $\nu_1 = 2.1737$ mHz with its 1 day alias pattern (the spectral window of the data set is shown in the inset). There is also an indication of a second period at a slightly lower frequency which is evident as double peak in $\nu_1$ and its left side alias. In order to see whether it is an independent frequency or not, we prewhitened the main frequency $\nu_1$ from the time domain and performed an FT again. The resultant amplitude spectrum of the residual data is shown in the second panel of Fig. 3. This clearly establishes the presence of a second frequency. The peak with highest amplitude in this pattern corresponds to a frequency $\nu_2 = 2.1641$ mHz. However, the amplitude of its alias at 2.1759 mHz is comparable. In FTs noise can alter the amplitudes of the peaks. Hence we cannot unambiguously identify which of the above two is the real frequency, although the existence of a second frequency is evident. Our identification of $\nu_2 = 2.1641$ mHz is thus subject to a 1/day alias ambiguity. We again prewhitened this frequency $\nu_2$ from the data set and the amplitude spectrum of the residual data is shown in the bottom panel of Fig. 3. There is an indication of two different frequency groups in this final spectrum, one around $\nu_3 = 2.181$ mHz and the other at $\nu_4 = 2.306$ mHz. Both of these frequencies are only marginally above the noise level and are identified only by the typical window pattern they exhibit. It may be noted however that while the spacing between $\nu_1$ and $\nu_2$ is about 9.5 $\mu$Hz, the spacing between the central frequency $\nu_1$ and $\nu_3$ is around 7 $\mu$Hz. If 2.1759 mHz is identified with $\nu_2$ then the spacing between $\nu_1$ and $\nu_2$ is as small as 2.1 $\mu$Hz.

The Mt. Abu data set is subjected to a non-linear least square fit in order to determine the errors on the frequencies and amplitudes of the four frequencies determined from the FT. The results of this analysis are given in Cols. 3 and 4 of Table 2.

### 2.3. Search for long term period

The pulsation amplitudes of HD 12098 exhibit considerable variation from night to night. This is also indicative of long term periods. In order to search for periodic modulation of the pulsation amplitude on a time scale of days, we determine a nightly amplitude of the frequency $\nu_1$ by performing a linear least square (llsq) fit to each of the light curves acquired during 1999–2000. The amplitudes thus determined are listed in the fourth column of Table 1.

The resulting data-set of time vs. amplitude (Col. 2 vs. Col. 4 of Table 1) was then subjected to a discrete Fourier transform, non-linear least squares (nlsq) fit and a periodogram analysis using the folding technique. All these methods yielded around five peaks, with the highest corresponding to a period of 1.22 day (0.82 cycles per day). This period though not completely convincing provided best fit (with a variance 17% lower than the next best period) for the llsq fitted amplitudes from Table 1 as shown in Fig. 4.

## 3. Results and discussion

The pulsation frequencies determined above are discussed below in terms of pulsation models.

### 3.1. Frequency splitting and rotational period

From the analysis of Mt. Abu data, we have determined the presence of at least two dominant frequencies ($\nu_1 = 2.1738$ and $\nu_2 = 2.1641$ mHz) in our data set along with two other frequencies ($\nu_3 = 2.1807$ and $\nu_4 = 2.3056$ mHz). Several roAp stars are multi-periodic and exhibit many modes (viz., Kurtz 1990). Hence the first hypothesis to test is whether or not these are individual modes. The temperature of this star as estimated from both Strömgren indices and the spectral type, is 7820 ± 30 K (Moon & Dworetski 1985). From the evolutionary models the characteristic spacing ($\Delta\nu$) between alternate "$l$" and "$n$" modes for Ap stars has been given by Heller & Kawaler (1988) and Shibahashi & Saio (1985) as a function of temperature. If the two dominant frequencies in HD 12098 whose temperature is 7820 K, have to be independent modes with a frequency spacing of only 9.5 $\mu$Hz or less, the theoretical models would then imply a highly evolved star with a luminosity in excess of $2\,L_\odot$ and mass $> 2.5\,M_\odot$. None of the observational parameters show that HD 12098 is much more evolved than the other roAp stars. Moreover the typical spacing of alternate modes in other roAp stars ranges from 20 $\mu$Hz to 80 $\mu$Hz (Kurtz, 1990). We therefore conclude that the two dominant frequencies under discussion are unlikely to be independent modes.

An alternative explanation may be that, it is the "$m$" splitting due to rotation in $l = 1$ state (Ledoux 1951) which gives rise to $(2l+1)$ modes spaced in frequencies as

$$\nu_m - \nu_o = (1 - C_{nl})m\Omega \quad (1)$$

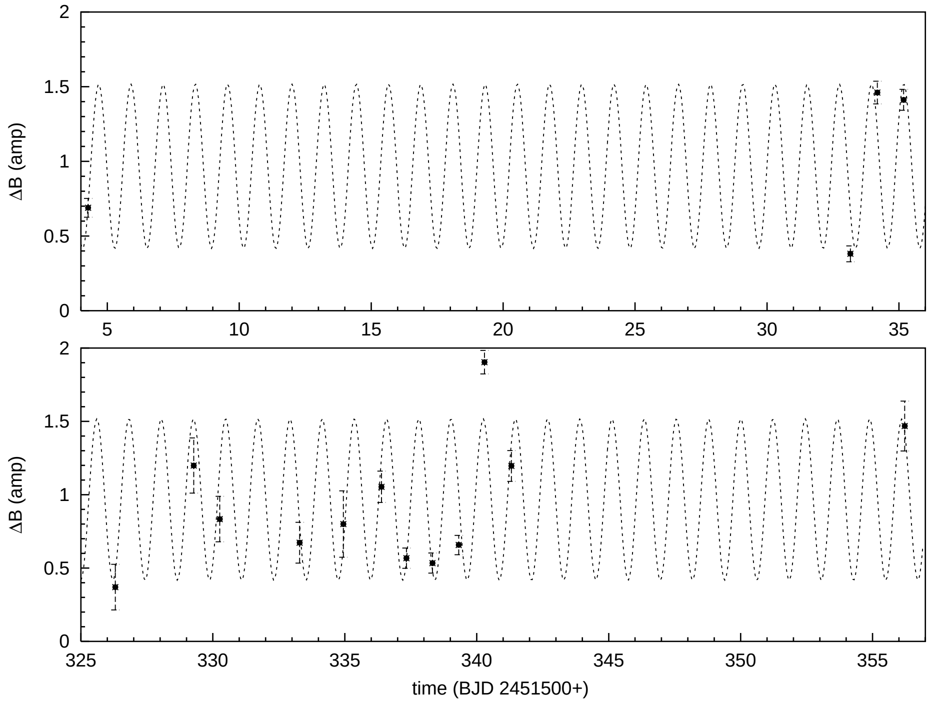


**Fig. 4.** Plot of pulsation amplitude of HD 12098 vs. BJD. *X*-axis is the BJD at the middle of the run and *Y*-axis is the pulsational amplitude in milli-magnitude. The points are the experimental results with the errors in the amplitude. The dashed curve is the sinusoidal corresponding to the period 1.22 day.

where $C_{nl}$ is a constant and $\Omega$ is the rotational frequency. For HD 12098, we have no a priori estimate of the rotational period. If we use the theoretical values of $C_{nl}$ in the range of 0.01 to 0.001 as given by Shibahashi & Saio (1985) in Eq. (1), a 9.5 $\mu$Hz frequency spacing implies a rotational period of around 1.21 to 1.22 day. In case the two frequencies are caused due to "m" splitting, then the weak 2.1807 mHz peak could be the third of the expected triplet. Whether this hypothesis is valid for HD 12098, requires an independent determination of its rotation period. Incidentally, such a measurement has often led to this theory being disproved in the case of other roAp stars (Kurtz 1990) favouring the oblique pulsator model instead.

The pulsation characteristics of roAp stars are well understood in terms of the oblique pulsator model (Kurtz 1982) and we apply it to HD 12098. The rotational period expected from the 9.5 $\mu$Hz frequency splitting of the two dominant frequency peaks is 1.22 day. In this case the third component of a conjectured $l = 1$ frequency triplet can be expected at 2.183 mHz. It may be noted that the unequal frequency spacing of the two observed side-lobes with respect to the main peak may be due to the presence of magnetic field.

Kurtz et al. (1990) and Shibahashi & Takata (1993) have described a generalized oblique pulsator model in which the effects of both the magnetic field and rotation are considered (see also Dziembowski & Goode 1985, 1986). The asymmetry in the amplitudes of the triplet can be used to estimate the effect of magnetic field vis-à-vis the rotational effect by the two parameters,

$$P_1 = \frac{A_{+1} + A_{-1}}{A_0} = \tan i \ \tan \beta \qquad (2)$$

where $A_{-1}, A_0, A_{+1}$ are amplitudes of the triplet corresponding to frequency in increasing order, $\beta$ is the angle between the rotation and magnetic axis (pulsation axis), $i$ is the inclination angle of the rotation axis to the observer; and

$$P_2 = \frac{A_{+1} - A_{-1}}{A_{+1} + A_{-1}} = \frac{C\Omega}{\omega_1^{(1)\mathrm{mag}} - \omega_0^{(1)\mathrm{mag}}} \qquad (3)$$

where $C$ is a constant, $\Omega$ is the rotation period and the perturbations due to the magnetic field depend on $|m|$ such that $\omega = \omega^{(0)} + \omega_{|m|}^{(1)\mathrm{mag}}$. From the values given in Table 2, we calculate $P_1 = 0.86$ and $P_2 = -0.29$.

If $\nu_1$ and $\nu_2$ are interpreted as components of a rotational multiplet in HD 12098, this would correspond to a rotation period of 1.22 day. This would then make HD 12098 the fastest rotating known roAp star. Assuming a radius of $2\,R_\odot$ the equatorial velocity is calculated to be $\approx$80 km s$^{-1}$. For Ap stars the limit of $v \sin i$ is of the order of 10 km s$^{-1}$ (Wolff 1983). Hence for HD 12098, this would imply an $i \approx 10°$ and $\beta \approx 78°$. Based on the magnetic field studies, observations of pole reversal would indicate $\beta \geq 80°$. However, we remind the reader that $\nu_2$ is subject to a 1 cycle/day alias ambiguity. In the event that $\nu_2$ is identified with 2.1759 mHz instead of 2.1641 mHz, the spacing between $\nu_1$ and $\nu_2$ would be 2.1 $\mu$Hz. This would imply a rotational period of 5.51 day. Our present data cannot distinguish between these possibilities, and the issue will only be resolved by acquiring more data.

### 3.2. Other modes

The other frequency at the limit of detection in our complete data set is at 2.3056 mHz. This peak also exhibits the typical alias pattern and is comparable in amplitude to the 2.1807 mHz peak. It may be noted however that this frequency has been detected in some of our earlier data-sets. The runs in which this frequency is predominantly above the noise level corresponds to observations on BJD 2451504.27 and 533.16. Hence this may be either a short lived mode or a mode which is severely modulated. In addition we have also detected excess power around 4 mHz on several nights.

### 3.3. HD 12098 and other roAp stars

HD 12098 appears to exhibit a simple power spectrum at first glance. There are several roAp stars such as HD 196470 and HD 193756 (Martinez et al. 1991) which exhibit only a single frequency. However, HD 12098 appears to have few modes exhibiting effects of rotation in the star. Since the amplitude of the main pulsation does not exceed 2 mmag, it is one of the low amplitude roAp pulsator. Further observations may yield other low amplitude modes in the star, if there are any. If the rotation period of the star is 1.22 day or close to it, then it becomes the fastest rotating roAp star. HD 6532 which has a rotational period of 1.9455 day (Kurtz & Marang 1987) also has a similar amplitude spectrum with six frequency peaks (Kurtz & Cropper 1987). Another roAp star which is very similar is HD 80316 (Kurtz 1990). The rotation period of this star is not yet confirmed, but is probably around 2 days.

The estimated $\delta m_1 (= -0.122)$ for HD 12098 is at the extreme edge of the selection criteria which sets the limits for probable roAp stars for this index (Martinez & Kurtz 1995). However there are other roAp stars with even more negative $\delta m_1$ (e.g., HD 101065). In this respect it may be noted that HD 80316 has $\delta m_1 = -0.118$. The principal oscillation frequency of this star is 2.2516 mHz with an amplitude of 0.44 mmag. Hence HD 80316 can be considered very similar to HD 12098 in several observed properties including the frequency spectrum and the pulsation amplitude.

## 4. Conclusions

We have presented the photometric observations of a new roAp star HD 12098 discovered in the "Naini Tal-Cape survey for northern hemisphere roAp stars". The detailed analysis of the observations shows the presence of two predominant frequencies. The main frequency is at 2.1738 mHz corresponding to a period of 7.67 min with an amplitude of 0.918 mmag. The second frequency can be either 2.1641 or 2.1759 mHz. This is most likely the rotational side-lobe of the main frequency $\nu_1$.

Hence we propose that HD 12098 is an oblique pulsator which pulsates in the $l = 1$ mode with a main period of 7.67 min. The rotation period of this star is of the order of a few days, but with our data we are unable to discriminate between possible rotation periods of 1.2 d or 5.5 d. Independent determination of the rotational period using differential photometry, or additional multi-site high-speed observations are required to resolve this ambiguity and to improve our understanding of the pulsation spectrum of HD 12098.

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