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Time–Resolved Photoelectric, Photometric and High–Resolution Spectroscopic Data Analysis of a Luminous Ap Star HD 103498

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Abstract. This paper presents combined results of the photometric and spectroscopic data analysis of a luminous Ap star HD 103498. The time series fast–photometric observations were carried out during 17 nights using the PMT based three–channel fast photometer mounted on the 1.04–m Sampurnanand telescope of the ARIES at Nainital. The fast photometric data sets of five nights obtained in 2007 show clear evidence of the 15–min periodic variability, however, the same periodicity was not found in the remaining data sets. The time–series spectroscopic observations using the 2.56–m telescope at La Palma taken near the same night as of the photometric epoch did not show any radial velocity variations either. The spectroscopic abundance analysis shows that HD 103498 is an evolved Ap star with large overabundances of Si, Cr, and Fe, and moderate overabundances of the rare–earth elements. The multi–band photometric observations using the SBIG ST–402 camera attached to the 60–cm telescope of the Maidanak observatory in Uzbekistan did not detect any such short period variability up to ~ 10 mmag, however, the eclipsing nature of the known binary component HR 4560 of period $1^{\rm d}\!.73$ is confirmed.

Key words: stars: chemically peculiar – stars: stars: oscillations – stars: variables: roAp: variable: δ Scuti

1 Introduction

The chemically peculiar star HD 103498 (65 UMa D, HR 4561) is a member of a hierarchical multiple system consisting of four objects. The schematic diagram of the multiple system ADS 8347 is shown in Fig. 1. According to Pourbaix et al. (2004), HD 103498 is a south–eastern component of the visual binary ADS 8347 (separation 63″) containing HR 4561 and HR 4560, the latter being a spectroscopic binary 65 UMa AC. HD 103498 was used as a comparison star for the differential photometry to study the low–amplitude δ Sct pulsations in HR 4594 and HR 8210 (Kurtz, 1979). The first magnetic field measurements of HD 103498 were reported by Glagolevskij et al. (1985) who discovered a moderate negative longitudinal magnetic field ($\langle B_z \rangle \sim -630$ G). Aurière et al. (2007) measured a much weaker

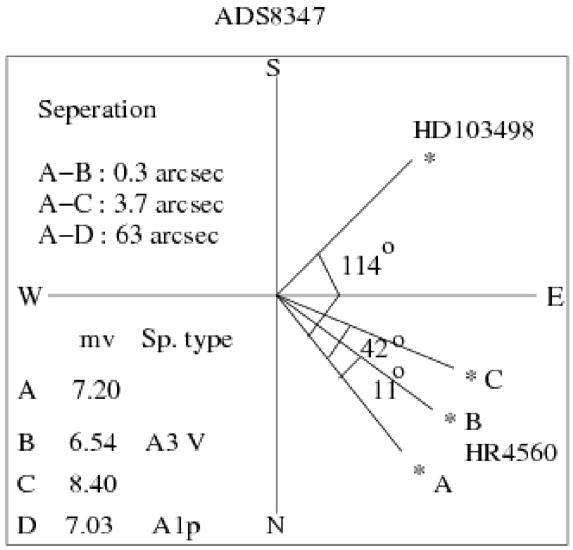

Figure 1: The schematic diagram of the multiple system ADS 8347. The system consists of two visual binaries HD 103498 and HR 4560, where the later is itself a spectroscopic binary.

longitudinal field $\langle B_z \rangle$, that varied between ± 200 G with a period of $15^{\mathrm{d}}.83$.

HD 103498 has Strömgren indices $b-y=0.003$, $m_1=0.196$, $c_1=1.010$ and $H_\beta=2.858$ (Hauck & Mermilliod, 1998). Abt & Morrell (1995) classified it as a CrSrEu–type peculiar star. An average effective temperature $T_{\mathrm{eff}} = 9370 \pm 140$ and $\log g = 3.90$ were obtained using the calibration of Strömgren (Moon & Dworetsky, 1985) and Geneva photometry (Kunzli et al., 1997) using the TEMPLOGG package (Kaiser, 2006). A reasonable fit of the Hα and Hβ line profiles resulted in effective temperature and gravity $T_{\mathrm{eff}} = 9500$ K and $\log g = 3.6$, respectively. Considering the weighted mean parallax value of the entire system, 4.02 ± 0.40 mas, the reddening parameter $E(B-V) = 0.007$ and interstellar absorption $A_v = 0.021$ mag (Huchra & Willner, 1973), the derived luminosity of HD 103498 is $\log(L/L_\odot) = 2.00 \pm 0.09$, that is very close to the value $\log(L/L_\odot) = 2.06$, determined by Aurière et al. (2007).

Tiwari et al. (2007) reported a 15–min periodic oscillation with a varying amplitude from night to night. The location of this star in the H–R diagram (see Fig. 8) towards a larger luminosity and higher temperature is contrary to any roAp star observed till now, making it an unusual pulsator. Therefore, to check the possible 15–min pulsations in HD 103498, we continued the photometric monitoring and obtained the high–resolution time series spectroscopic observations for the corresponding radial velocity (RV) variations.

2 Observations and Data Reduction

HD 103498 was observed in both photometric and spectroscopic modes using the PMT based photometer, CCD camera and high–resolution spectrograph mounted on the 1.04–m telescope of the ARIES, the Maidanak observatory 0.60–m telescope in Uzbekistan and the 2.56–m Nordic Optical Telescope telescope in La Palma, respectively. Table 1 lists the log of these observations carried out during the last four years. The observations and adopted data reduction techniques are described in the following subsections.

Table 1: Observational log for HD 103498. Photoelectric observations were taken using the 1.04–m telescope of the ARIES (S. No. 1 − 17), the CCD photometric observations were taken using the Maidanak observatory 0.60–m telescope in Uzbekistan (S. No. 18 − 23), and high–resolution spectroscopic observations were taken using the 2.56–m Nordic Optical Telescope telescope in La Palma (S. No. 24). The phase ϕ corresponds to $t_0 =$ HJD 2450000.

Set No.	Time (HJD) (2450000 +)	Δt (hr)	f (mHz)	A (mmag)	ϕ ($\pm$0.2)
1.	4101.46794	1.44	–	–	0.10
2.	4165.20987	2.74	1.06 ± 0.10	0.95	0.12
3.	4166.19829	1.85	1.10 ± 0.13	0.49	0.19
4.	4196.15852	3.10	1.18 ± 0.12	1.69	0.08
5.	4197.12757	1.82	1.09 ± 0.17	1.71	0.14
6.	4198.10264	6.33	1.13 ± 0.03	0.81	0.21
7.	4455.45086	1.03	–	–	0.46
8.	4459.46167	1.35	–	–	0.71
9.	4584.14787	1.22	–	–	0.59
10.	4585.11297	2.10	–	–	0.65
11.	4831.34313	3.24	–	–	0.21
12.	4842.32422	1.83	–	–	0.90
13.	4869.29544	2.11	–	–	0.60
14.	4870.28783	1.71	–	–	0.66
15.	4898.18485	1.95	–	–	0.43
16.	4899.28240	1.97	–	–	0.50
17.	4959.12810	3.53	–	–	0.28
18.	5000.23865	1.54	–	–	0.85
19.	5001.26123	0.72	–	–	0.91
20.	5002.24278	1.27	–	–	0.99
21.	5004.19488	2.40	–	–	0.10
22.	5005.20180	1.36	–	–	0.17
23.	5008.20252	1.05	–	–	0.36
24.	4865.62400	3.40	–	–	0.37

2.1 High–Speed Photometry

High–speed photometric observations of HD 103498 were carried out in two channel modes (one for HD 103498 and the other for sky) using a three–channel fast photometer attached to the 1.04–m Sampurnanand telescope of the ARIES. The time–series photoelectric photometry was obtained through the Johnson B–filter with integrations of 10 sec each. An aperture of $30''$ was used to minimize flux variations, caused by the seeing fluctuations and guiding. The location of the star at the center of the aperture was checked using manual guiding in a non–periodic time–interval. The data reduction processes involve: (a) visual inspection of the light curve to identify and remove the bad data points; (b) correction for coincident counting losses; (c) subtraction of the interpolated sky background and (d) correction for the mean atmospheric extinction. After applying these corrections, the times of the mid–points of each data point were converted into the heliocentric Julian dates (HJD) up to an accuracy of a second. The reduced data comprised of a time–series of the HJD and ΔB magnitudes with respect to the mean values of the run. The time–series data was subjected to the frequency analysis using the Deeming's Discrete Fourier Transform (DFT) for the unequally–

spaced data (Deeming, 1975). The frequency analysis produces an amplitude spectrum that provides the frequencies, amplitude and phase acting as input parameters for the further analysis.

A number of photometric light curves of HD 103498 are shown in Fig. 2, and the corresponding amplitude spectra are shown in Fig. 3. The long term sky–transparency variations from the time–series data were removed by subtracting a sinusoidal function of frequency f_1, amplitude A_1 and phase ϕ_1 of the form $A_1 \cos(2\pi f_1 t+\phi_1)$ — a technique known as "prewhitening". The process was repeated till the sky transparency peaks reduced to the level of the scintillation noise. The amplitude spectra (Fig. 3) clearly show that the star light is constant towards the end of year 2006. A peak appeared at the frequency of 1.06 mHz on March 05, 2007 which faded away during the following night. After a month–long interval the amplitude peaked again and subsequently dropped on April 07, 2007. On the same night having the longest observing run, we found a double–peaked profile. Further observations did not show any prominent peaks at this frequency. The frequency spectra also show the amplitude modulations which is generally observed in the roAp stars which might be due to one or several effects: (a) changing the aspects as the star rotates, (b) beating between the unresolved pulsation modes; and (c) real amplitude variations of the mode of pulsations.

Periodic variability of 15–min variability detection in the photoelectric photometry of HD 103498 is unlikely to be spurious, since during two observing nights two non-variables and two known δ Scuti stars were also observed just before and after HD 103498. We also calculated the confidence level of the signal according to Scargle's (1982) criteria. A 98% confidence level is shown in Fig. 3 by the horizontal dotted lines. During four nights the confidence level of the peak is $> 99\%$, except April 07, 2007 (HJD 2454166), where the level was 97.23% (Joshi et al., 2010). Therefore, the variability observed in HD 103498 has almost no chance of being an artifact.

2.2 High–Resolution Time–Series Spectroscopy

To check the photoelectric pulsational variability in HD 103498, high–resolution time–resolved spectroscopy of HD 103498 was performed using the Fibre–fed Echelle Spectrograph at the 2.56–m Nordic Optical Telescope. A spectral resolution of $R=47000$ was achieved in the wavelength range of 3635 – 7270 Å. A total of 71 stellar spectra were collected on the night of February 2, 2009 (HJD 2454865) for a duration of 3.4 hr, with exposure time of 120 sec. A a sampling rate of 168 sec was achieved with the read out time of 48 sec, that is sufficient to resolve the 15–min pulsation period suspected in HD 103498. Two ThAr reference spectra were obtained at the beginning and end of the stellar time series. The identification of lines was based on the theoretical spectrum calculated for the entire observed spectral region, using the line extraction from VALD (Kupka et al., 1999 and references therein) and DREAM (Biémont et al., 1999) databases. We used the REDUCE package of Piskunov & Valenti (2002) to perform the standard steps of the echelle spectra reduction (construction of the master flat field and bias frames, order location, flat–fielding and wavelength calibration) followed by the optimal extraction of the stellar spectra. The typical signal–to–noise ratio of the individual observations is 80 – 100 around λ 5000 Å. To make a proper selection of unblended and minimally blended lines for the abundance calculations, we synthesized the whole observed spectral region of 3965 – 7270 Å with the help of the SYNTH3 code (Kochukhov, 2007). The best fit to the observed unblended line profiles was achieved for $v_{\rm e} \sin i = 12$ km/s that is close to $v_{\rm e} \sin i = 13$ km/s derived by Aurière et al. (2007). Microturbulent velocity of $\xi_{\rm t} = 1.0 \pm 0.2$ km/s was obtained as an averaged value between the values derived from numerous lines of Cr I, Cr II, Fe I, and Fe II.

2.2.1 Cross–Correlation Radial Velocity Analysis

In the large spectral regime, the cross–correlation analysis technique is an optimal approach for the spectroscopic search of pulsations. The RV curves obtained with this method were analysed using the standard DFT technique. Fig. 4 shows the amplitude spectra for 7 consecutive echelle

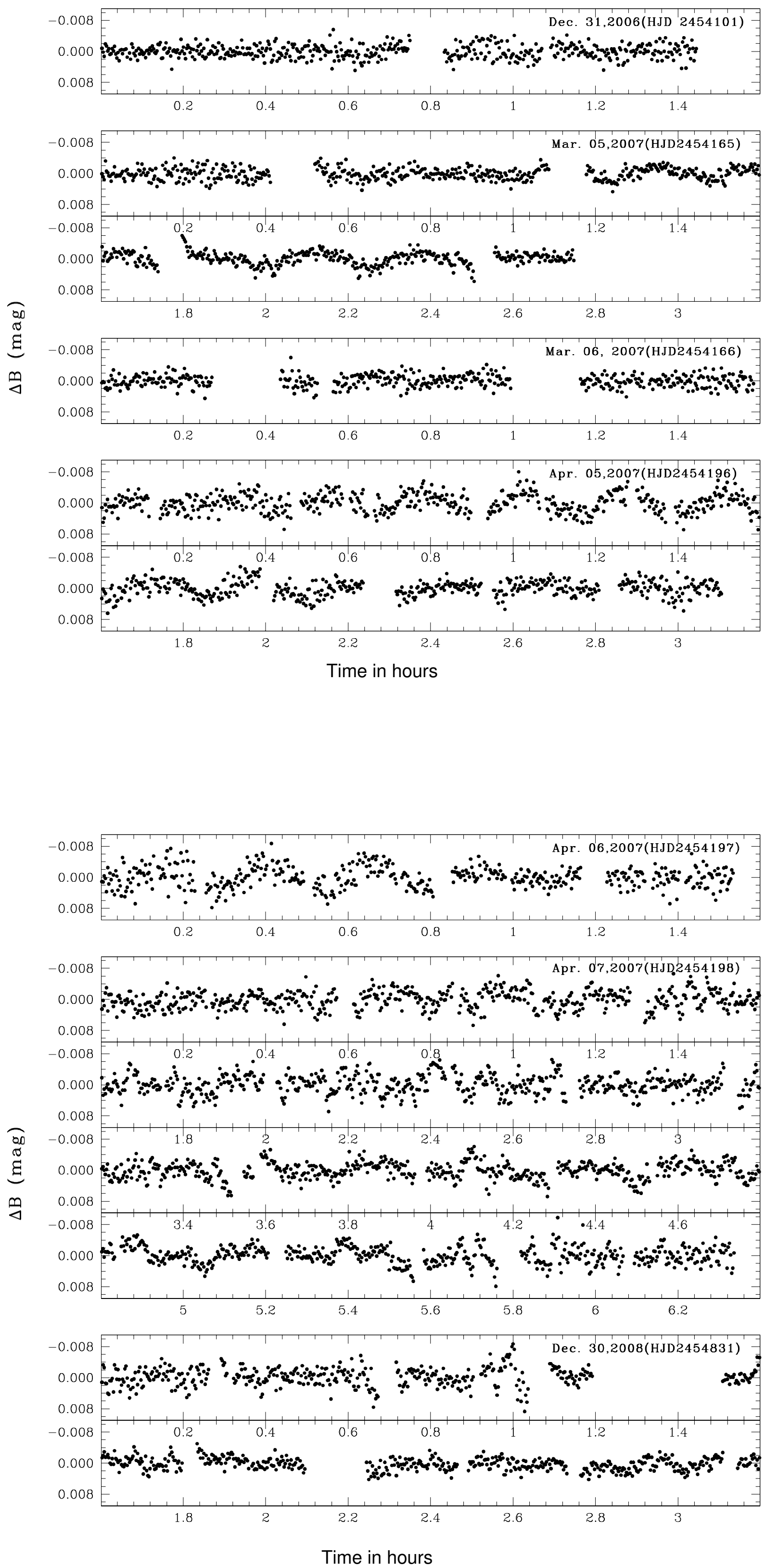

Figure 2: Sample photoelectric light curves of HD 103498 obtained in different nights between 2006 to 2008. The HJD (2450000 +) of the each observation is marked in each panel.

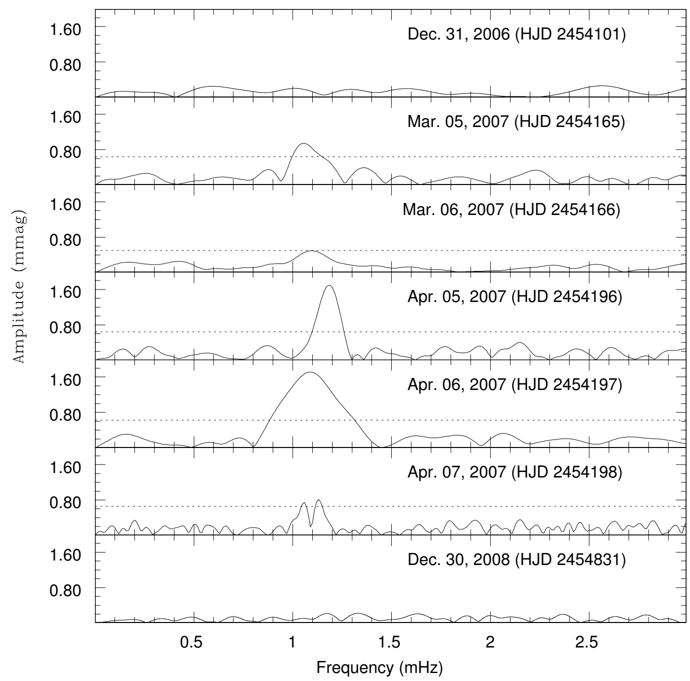

Figure 3: The amplitude spectra of the light curves shown in Fig. 1. The horizontal dotted line corresponds to the 98% confidence level, calculated according to the criteria of Scargle (1982).

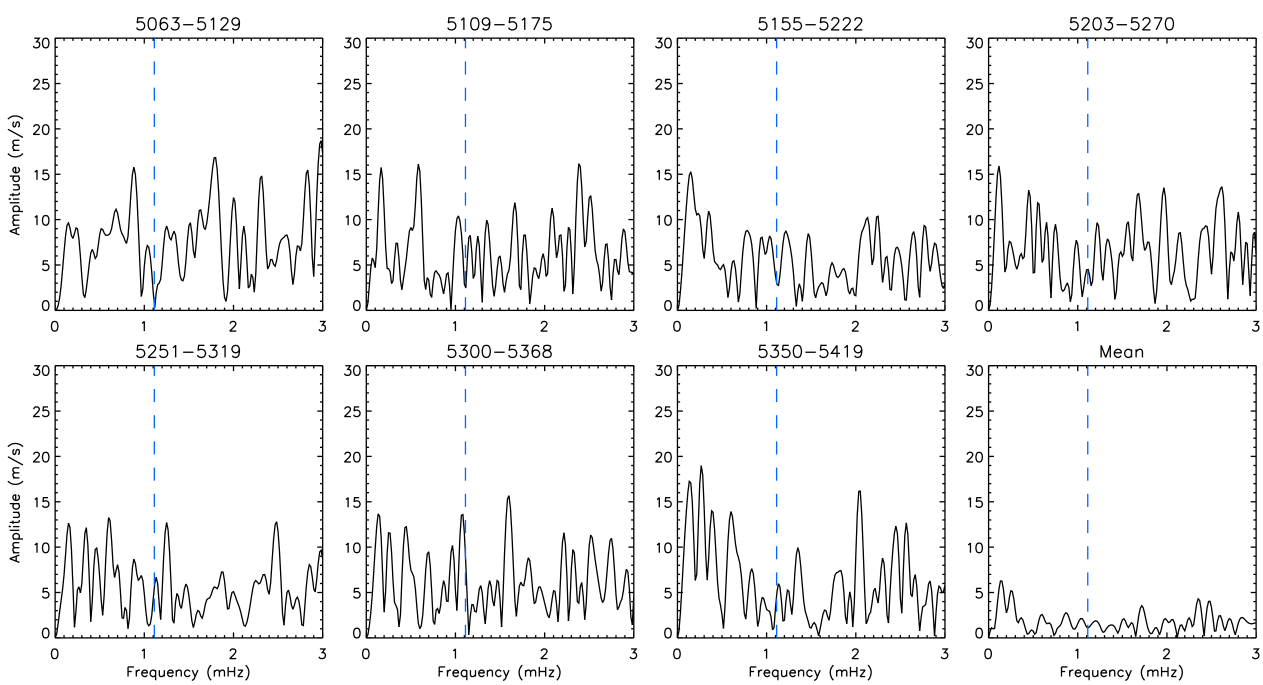

Figure 4: Amplitude spectra of the cross–correlation RV measurements for 7 representative echelle orders of the FIES spectra of HD 103498. The lower right panel shows the amplitude spectrum for velocity obtained by combining RV curves of 16 best orders. The vertical dashed line in each panel corresponds to the mean frequency, identified in the photometric observations.

orders in the spectral region, characterized by a high S/N and a large line density. The frequency spectra did not show any significant periodicity up to the velocity amplitude of 15 to 20 m/s. We also analysed a mean RV curve, obtained by combining the measurements for 16 echelle orders, for which the best RV precision was achieved. The corresponding FT spectrum is shown in the lower right panel of Fig. 4. It reveals no oscillations stronger than $\approx$5 m/s. The upper limit for the pulsations in the vicinity of the photometric frequency of HD 103498 is only 2.8 m/s. In most of roAp stars the lines of the REE in the first and second ionization stages usually show the highest RV amplitudes ($\sim$ 2.5 km/s). In HD 103498 these lines are either practically absent (REE II) or rather weak (REE III), while the lines of Fe–peak elements are numerous and strong. Therefore, a pulsational signal from the REE lines may be lost in the cross–correlation analysis. We made the center–of–gravity RV measurements of the individual lines of Pr III $\lambda\lambda$ 5300, 6867 Å and Nd III $\lambda\lambda$ 4914, 4927, 5050, 5102, 5294, 6327 Å and analysed the resulting mean RV curve for the two REE species. The corresponding FT spectrum did not show any evidence of the RV pulsation signal in the vicinity of the photometric frequency.

2.2.2 Abundance Analysis

The spectroscopic data of HD 103498 was also used to study its evolutionary status and chemical peculiarities. The abundance analysis of the star was based primarily on the averaged spectrum of our time–series spectroscopy in the spectral region of 3900 – 7270 Å. Model atmosphere was calculated with the ATLAS9 code (Kurucz, 1993) using the metallicity $[M/H] = +0.5$. To make a proper selection of unblended and minimally blended lines for the abundance calculations we synthesized the whole observed spectral region of 3965 – 7270 Å. Our analysis shows that HD 103498 is evolved from the Zero Age Main Sequence and its atmospheric abundances are similar to two other evolved Ap stars HD 133792 and HD 204411: large overabundances of Si, Cr, and Fe and moderate overabundances of the rare earth elements.

2.3 Time–Series CCD Photometry

To confirm the 15–min periodic variability detected in the photoelectric observations, time–series CCD photometry of HD 103498 was performed using the SBIG ST–402 camera mounted on the Maidanak observatory 60–cm telescope in Uzbekistan. The CCD photometric observations of HD 103498 were carried out in a total of 6 nights between June 17 – 25, 2009 (HJD 2455000 – 2455008). The observational run in different bands was made in the sequence of the B, I and V. The CCD chip consisting of 765×510 pixels with the read out noise of 1.5 e^- and gain of 13.8 e^-/ADU. Each pixel has a dimension of 9×9 μm subtending an area of 0.26×0.26 arcsec on the sky, thereby covering a total field of view 3.31×2.21 arcmin of the CCD chip. The pre–processing steps of the image analysis viz. bias subtraction, flat–fielding and cosmic ray removal were done using the Image Reduction and Analysis Facility (IRAF)[1] software. The instrumental magnitudes of the stars in the image frames were determined by the aperture photometry, using the DAOPHOT (Stetson, 1987). The magnitude of the HD 103498 was measured relative to the nearby visual binary HR 4560, located 63 arcsec away from HD 103498. Due to the limited field of view, we could not find any other comparison stars of similar magnitude and color, hence the differential photometry was performed relative to only one comparison star. For each night, the selection of the optimum aperture radius was done on the basis of minimal scatter found in the light curves.

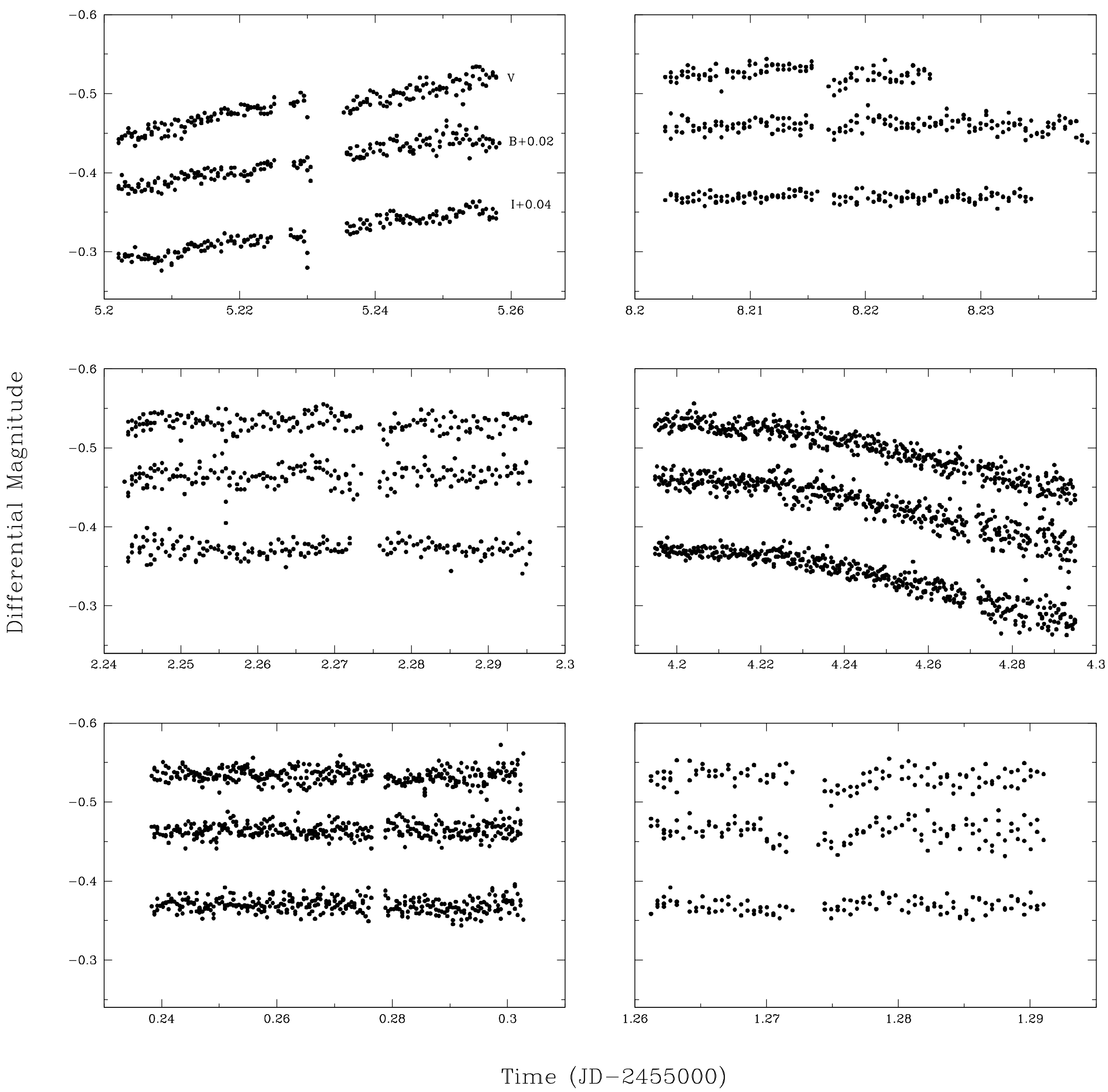

Figure 5: The time−magnitude diagrams of HD 103498 observed during 6 nights. For the purpose of clarity, I and B differential magnitudes are shifted by +0.04 and +0.02 mag, respectively.

2.3.1 Differential Light Curves

Fig. 5 shows the differential light curves of HD 103498, obtained in the Johnson B, V and I bands in 6 nights spanning between 17 to 25 June, 2009. To see a clear variation among different filters in Fig. 5, a unit of 0.02 and 0.04 mag is added in B and I filters, respectively. From the 4 nights, where the stars have not shown any systematic light variations, we derived a mean error (σ) of 11, 10 and 9 mmag in the B, V and I filters respectively. This is very high, compared to the amplitude of variability, reported in the photoelectric data ($\Delta B_{max} = 1.71$ mmag) by Tiwari et al. (2007). It

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

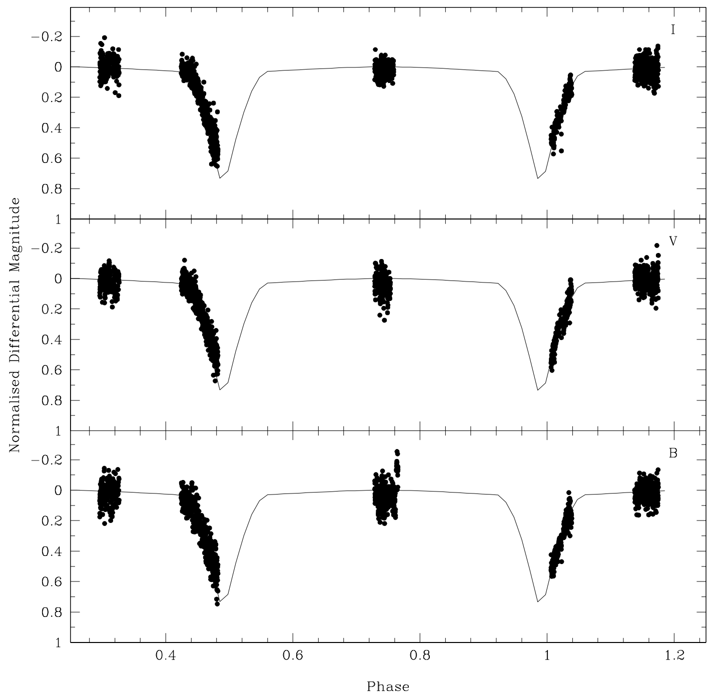

Figure 6: The phase light curves of the combined CCD photometric data. The eclipsing nature of HR 4560 is clearly visible. Each plot from top to bottom shows 3 light curves corresponding to I, B, and V respectively.

is not surprising that the quality of the photometric data in our observations has in fact peculated the low–amplitude pulsational variability, however some light variability is visible in the light curve shown in Fig. 5.

2.3.2 Eclipsing Nature of HR 4560

Due to a large scatter of about 10 mmag in our photometric observations, we could not see any short–term low–amplitude pulsational variability in the data. However, we have seen significant flux variations during the two nights out of total 6 nights of observations. In the night of 21 June, 2009, we have noticed a decrease in brightness of 0.134, 0.132 and 0.124 mag in the B, V and I filters, respectively, during 2.25 h observations, while a brightness increase of 0.093, 0.100 and 0.087 mag was noticed during the 1 h observations in the night of 22 June, 2009. Though due to the lack of sufficient amount of observations during these two nights, we could not determine the period and other physical parameters of the binary star, however, a primary and secondary eclipse was clearly visible during these two nights which fits perfectly well with the period of about $1^{\rm d}\!.73$, reported by Garica et al. (1986). When we fit the period and other parameters determined by Garica et al. (1986) in our data, as shown by the phase−magnitude diagram in the Fig. 6, we confirmed the eclipsing nature of the star HR 4560.

3 Discussions

In HD 103498, the presence of 15–min periodic oscillations in the photoelectric data of 5 nights, and non–detection of these oscillations in the follow–up spectroscopic and photometric observations of 18

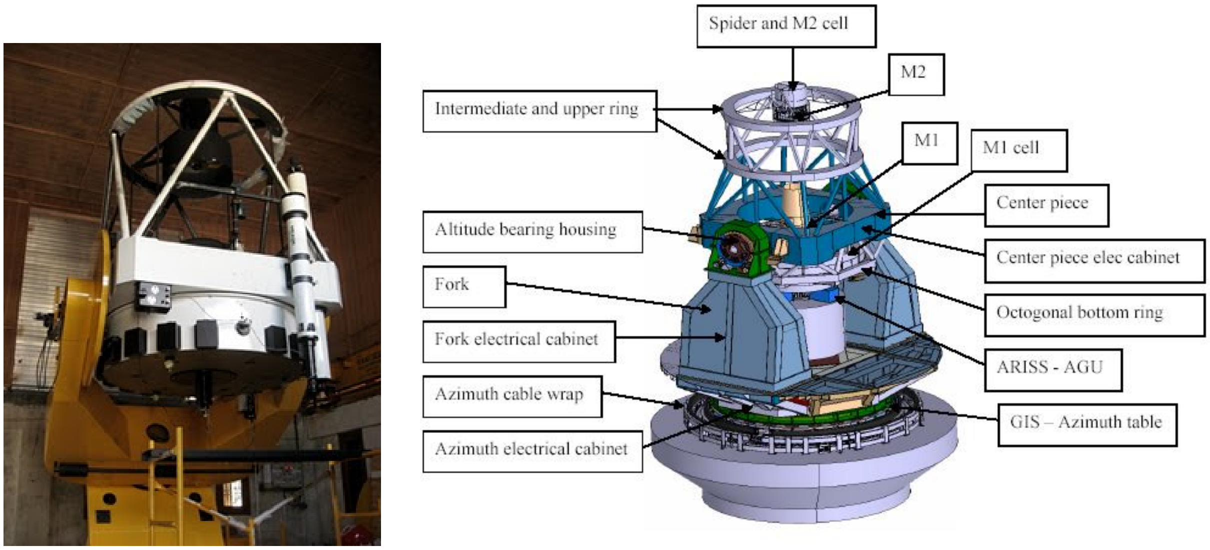

Figure 7: The left panel shows the photograph of 1.3–m telescope which has been successfully installed at the Devasthal site. The right panel shows a schematic diagram of the 3.6–m telescope to be installed by 2012.

nights raise many questions about the definite presence of the pulsations. Possible reasons for non-detection of pulsational frequency in the photometric data of 2006, 2008 and 2009 may be due to the fact that real amplitude variations might be buried under the noise. The most dominant noise is the atmospheric noise, consisting of the scintillation noise and long–term sky transparency variations. The atmospheric noise is of a random nature and depends on the topology of the particular observing site, and can hence be minimized by installing bigger telescopes at a good observing site where the sky is photometric (Young, 1967). Towards the reduction of the atmospheric noise, the ARIES is now in the process of installing the 1.3–m and 3.6–m optical telescopes (Fig. 7) at a new astronomical site in Devasthal (longitude: $79^o40^{'}57''$ E, latitude: $29^o22'26''$ N, altitude: 2420 m).

The non–detection of pulsations in spectroscopic observations may be due to the fact that the observations were made at an unfavorable rotation phase, $\varphi \approx 0.25$ or 0.75, when the magnetic equator passes in front of the observer. Unfortunately, the magnetic ephemeris of HD 103498 is not known with enough accuracy to establish the precise rotational phase of our observations. The non-detection of the pulsational variability in the differential photometry is due to a large scatter in the time–series data.

Fig. 8 shows the position of HD 103498 on the H–R diagram, where an instability strip for the roAp stars is indicated (Cunha, 2002). For comparison the positions of the two evolved Ap stars, HD 133792 and HD 204411 are shown. The stellar evolutionary tracks for the mass range from 1.5 to 2.7 $M_{\odot}$ (Christensen–Dalsgaard, 1993) are also over–plotted. Pulsation calculations by Cunha (2002) and a more recent theoretical study by Théado et al. (2009) predict the excitation of pulsations in relatively hot and more evolved Ap stars. However, all of about 40 currently known roAp stars have temperatures in the $T_{\rm eff}$ interval from 6400 to 8100 K. The search for RV pulsations in evolved stars with $T_{\rm eff}$ larger than 8100 K was not successful (Freyhammer et al., 2008). If confirmed, the discovery of pulsations in HD 103498 with $T_{\rm eff} = 9500$ K may have a profound consequence on our understanding of the excitation of p–modes in magnetic Ap stars.

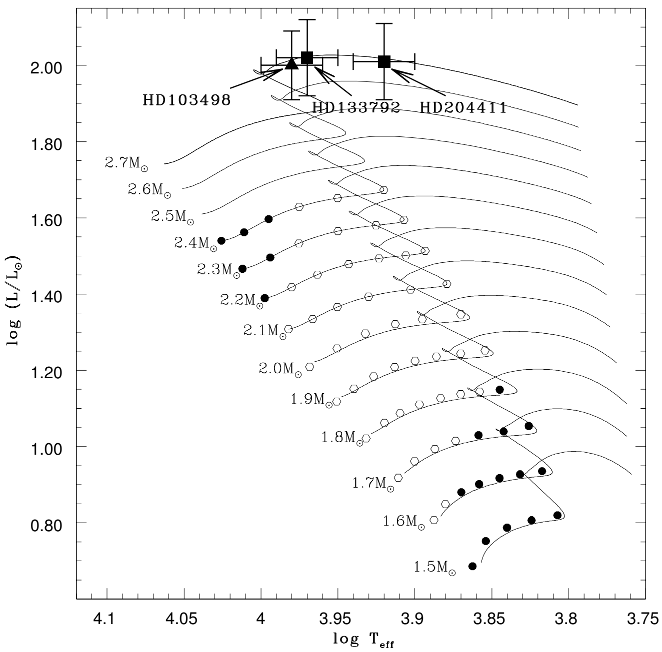

Figure 8: The HR diagram showing the position of HD 103498 (by symbol ▲) having $T_{\rm eff} = 9500 \pm 200$ K and $\log(L/L_\odot) = 2.0$. For comparison, positions of two evolved Ap stars HD 133792 and HD 204411 having $T_{\rm eff} = 9400 \pm 190$ K and $\log(L/L_\odot) = 2.02$; and $T_{\rm eff} = 8400 \pm 200$ K and $\log(L/L_\odot) = 2.01$, respectively, are also shown (by the ■ symbol). The filled circles show radiative envelope models in which no high–order acoustic oscillations were found, while the open circles show the models in which the latter were found.

4 Conclusions

The high–speed photometric observations of HD 103498 taken during five nights show clear evidence of pulsational variability of 15 min with an amplitude modulation. However, the same periodicity could not be confirmed in the follow–up photometric and spectroscopic observations. The abundance analysis of HD 103498 shows that Si, Cr, and Fe are overabundant, while the lines of the rare–earth elements, which are the best indicators of RV pulsations in roAp stars are rather weak. The cross–correlation RV analysis revealed no oscillations with the amplitudes above ≈ 5 m/s. The measurements of the center–of–gravity of eight individual REE lines also did not show any evidence of RV pulsation signal in the vicinity of the photometric frequency. The upcoming observational facilities at the Devasthal will certainly be helpful in the detection of a very low–amplitude pulsational variability in the CP stars.

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