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Pulsational frequencies in the δ Scuti stars V624 Tauri and HD 23194

Results of the STEPHI X campaign on the Pleiades cluster

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Abstract. The results of the tenth multi-site campaign of the STEPHI network are reported. The δ Scuti stars V624 Tau (HD 23156) and HD 23194, belonging to the Pleiades cluster, were observed photometrically for 34 days on three continents during 1999 November–December. An overall run of 343 hours of data was collected. Seven frequencies for V624 Tau and two frequencies for HD 23194 have been found above a 99% confidence level. These results greatly improve those found in previous studies with much less data. A preliminary comparison of observed and theoretical frequencies suggests that both stars may oscillate with radial and non-radial p modes of radial orders typical among δ Scuti stars.

Key words. stars: oscillations – stars: variables: δ Sct – stars: individual: HD 23156, HD 23194

1. Introduction

The STEPHI network (STEllar PHotometry International, see, for example, Michel et al. 2000) is an international collaboration aimed at improving our knowledge and description of the physical processes at work in the interior of δ Scuti stars, which are representative of normal A-type stars. STEPHI was born in 1986 and so far eleven campaigns have already been carried out, during which more than 14 δ Scuti stars have been observed. With this campaign, we complete a sample of six δ Scuti stars observed in the Pleiades cluster (V650 Tau, Belmonte & Michel 1991, Michel et al. 1991; V647 Tau, Liu et al. 1999; V534 Tau and HD 23628, Li et al. 2001; V624 Tau and HD 23194, this paper). With an age of ≈100 Myr, this cluster is a good object for performing studies of young main-sequence stars by means of asteroseismology.

The distance estimates reported to date for the Pleiades are rather controversial. The distance based on HIPPARCOS parallaxes is $116.3\pm^{3.3}_{3.2}$ pc, corresponding to a distance modulus of 5.33 ± 0.06 mag (Mermilliod et al. 1997). On the other hand, the distance estimates based on comparing the cluster's main sequence to that of nearby stars lead to distance values of ≈130 pc, which corresponds to a distance modulus of about 5.60 mag (e.g. 5.65±0.38 mag, Eggen 1986; 5.60±0.05 mag, Pinsonneault et al. 1998; 5.61 ± 0.03 mag, Stello & Nissen 2001). The metallicity of the cluster is typical of Population I stars, [Fe/H] = −0.03 (Boesgaard & Friel 1990).

The target star V624 Tau was identified as a short-period pulsating variable by Breger (1972). HD 23194 was selected as a supplementary target since it was considered a non-classified δ Scuti star (Koen et al. 1999). The comparison star HD 23246 was chosen because it has a similar colour to that of the target stars and is located close enough to permit the simultaneous monitoring of all the stars within the field of view of the photometer

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Table 1. Observational properties of the stars observed in the STEPHI 1999 campaign.

Star	HD	ST	V	$B-V$	$U-B$	$v \sin i$ ($\mathrm{km\,s^{-1}}$)	β
V624 Tau	23156	A7V	8.22	+0.25	+0.14	70	2.823
Supplementary	23194	A5V, Am	8.05	+0.20	+0.15	20	2.881
Comparison	23246	A8V	8.17	+0.27	+0.09	200	2.773

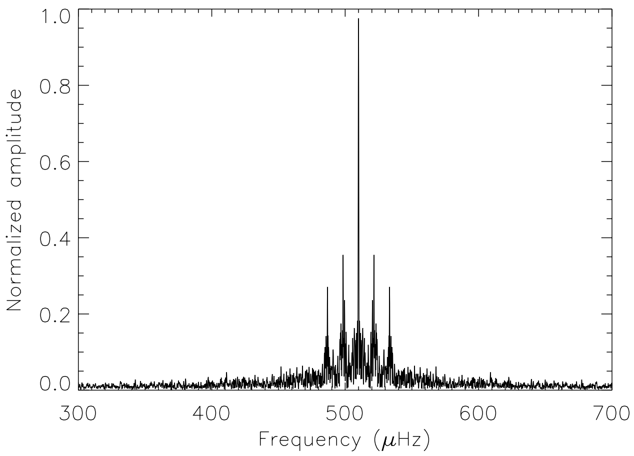

Fig. 1. Spectral window in amplitude corresponding to Series A: 1999 Nov. 27–Dec. 30. Side lobes are at 35% of the main lobe.

($\approx 12' \times 16'$). There are no indications of photometric variability in this star. Table 1 shows the main observational parameters corresponding to the target and comparison stars as taken from the SIMBAD database operated by CDS (Centre de Données astronomique de Strasbourg).

Studies on metal abundances in the Pleiades cluster reveal that while V624 Tau is considered a normal A7 δ Scuti star, HD 23194 has been classified either as an SB marginal Am or as a normal A5 star. In particular, Gray & Garrison (1989) concluded that both stars have normal abundances. Similar results were reported by Burkhart & Coupry (1997). Hui-Bon-Hoa & Alecian (1998) found nearly atypical abundance patterns for V624 Tau with marginal over-abundances of all elements apart from Mg and Ni, which were found to be clearly enhanced. They also found an almost solar composition in HD 23194 with a clear overabundance of Mg and Ni. Abt & Levato (1978) suggested that HD 23194 be considered as an Am star on the basis of finding a marginal deficiency of Ca. Also, according to Renson's (1992) catalogue of Am/Ap stars, HD 23194 is a marginal Am star. Koen et al. (1999) suggested HD 23194 be considered as a marginal Am star.

In recent years, several Am stars have been discovered to be δ Scuti variables (Rodríguez et al. 2000; Kurtz 1998). However, it is still an open question whether the amplitude distribution of Am δ Scuti variables shows any special behaviour (for example, a preference of low-amplitude pulsation).

2. The observations

The observations in this campaign were carried out over the period 1999 November 27–December 30. As has been done in previous STEPHI campaigns, we observed from three sites well distributed in longitude around the Earth: San Pedro Mártir (SPM) in Baja California, Mexico; Xing Long Station (XL) in Beijing, China; and Observatorio del Teide (OT) in Tenerife, Spain. In this way, we are able to limit systematic gaps in the monitoring of the light curves of our target stars, avoiding the formation of strong aliasing through side lobes of the spectral window in the Fourier spectrum.

Table 2 gives the log of observations[1]. Bad weather conditions at the OT did not allow us to get more than two nights of data. However, a total amount of 343 hours of useful data were obtained during 34 nights of observations from the three sites. Taking overlapping between observatories into account (data marked with small cases in Table 2) this amount is reduced to 337.2 hours. Thus, the efficiency of the observations was 41.3% of the cycle. This coverage is typical of STEPHI campaigns (~40%). If we consider the dataset only from November 27 to December 17, the duty cycle increases to 64.5%. An analysis with all the data (hereafter Series A) and a complementary analysis with only these latter data (hereafter Series B) were carried out.

Four-channel photometers were used at each site. Three of the channels were employed to monitor the stars (targets and comparison), while the fourth channel was devoted to measuring the adjacent sky. Interferometric blue filters ($\lambda \approx 4200$ Å, $\Delta\lambda \approx 190$ Å) were implemented individually in each channel.

The data reduction is similar to that reported in previous STEPHI campaigns (for details see Álvarez et al. 1998). We produced three temporal series with magnitude differences: V624 Tau−comparison, HD 23194−comparison and V624 Tau−HD 23194. The latter curve allows us to detect possible frequency peaks not intrinsic to the target stars in the two first light series. In order to remove low-frequency trends that can affect the detection of the oscillation modes at higher frequencies, a least-squares fit to a parabola is applied and subtracted from every light each night. The mean of the residuals is subtracted for each night in each curve and the definitive

[1] The data of the STEPHI X campaign are available on request.

Table 2. Log of observations. Observing time is expressed in minutes.

Day	Date 1999	HJD 2450000+	SPM	XL	OT
1	Nov. 27	1510	-	181	-
2	Nov. 28	1511	-	475	-
3	Nov. 29	1512	-	524	-
4	Nov. 30	1513	-	466	-
5	Dec. 01	1514	148[a]	605[a]	-
6	Dec. 02	1515	556	-	-
7	Dec. 03	1516	443	-	-
8	Dec. 04	1517	318	512	-
9	Dec. 05	1518	531	520	-
10	Dec. 06	1519	451[a]	594[a]	-
11	Dec. 07	1520	527	576	-
12	Dec. 08	1521	518	356	-
13	Dec. 09	1522	532[a]	577[a]	-
14	Dec. 10	1523	432	-	-
15	Dec. 11	1524	-	-	496[c]
16	Dec. 12	1525	311[ac]	564[ab]	500[bc]
17	Dec. 13	1526	486[c]	-	-
18	Dec. 14	1527	517	547	-
19	Dec. 15	1528	414	521	-
20	Dec. 16	1529	496[a]	586[a]	-
21	Dec. 17	1530	500	353	-
22	Dec. 18	1531	-	549	-
23	Dec. 19	1532	-	513	-
24	Dec. 20	1533	-	553	-
25	Dec. 21	1534	-	-	-
26	Dec. 22	1535	-	-	-
27	Dec. 23	1536	-	551	-
28	Dec. 24	1537	-	440	-
29	Dec. 25	1538	-	330	-
30	Dec. 26	1539	-	-	-
31	Dec. 27	1540	-	-	-
32	Dec. 28	1541	-	461	-
33	Dec. 29	1542	-	525	-
34	Dec. 30	1543	-	524	-
Total	observing	time	SPM	XL	OT
Nov. 27	Dec. 30	20 579	7180	12 403	996
Nov. 27	Dec. 17	16 133	7180	7957	996

[a] Overlap between SPM and XL observations.
[b] Overlap between XL and OT observations.
[c] Overlap between OT and SPM observations.
Total observing time: 383 h.
Overlap during the observations: 5.8 h.

time series derived. Overlap between sites is handled by taking the mean of the common data.

A total of 5.8 hours of overlapped data were obtained during the whole campaign, with the longest interval being 90 min (see Table 2). These data can be used to analyse the quality of the measurements. To this end, we have compared the light curves (target-comparison) at two observatories obtained in overlapped segments, computing the dispersion in their differences. We have found that the value of the dispersion strongly depends on the integration time. If this time is as short as 1 min, the dispersion is about 5 mmag but for an integration time of 10 min, σ is about 1 mmag. The latter is more representative of the typical periods of delta scuti stars, while the former includes high frequency noise.

3. Spectral analysis

The amplitude spectrum of the time series considered in the previous section was obtained by using an iterative sine wave fit (ISWF; Ponman 1981). In particular we fit the light curve to a sinusoidal function, $A\cos(2\pi\nu t - \varphi)$, for a given set of frequencies, ν, in the range of interest.

The window function of the observations is shown in Fig. 1. A one-day alias of 35% of the main lobe amplitude is presented. The resolution as measured from the FWHM of the main lobe in the spectral window is $\Delta\nu = 0.51$ μHz. When considering the series B (from Nov. 27 to Dec. 17) the side lobes are at 28% of the main lobe and the resolutions is $\Delta\nu = 0.70$ μHz.

In the following we shall mainly show the results concerning the whole dataset. Series B does confirm the frequencies detected with Series A and can be used to discuss a possible one-day alias.

The amplitude spectra of the differential light curves V624 Tau−comparison and HD 23194−comparison are plotted in Figs. 2 and 3 respectively. We considered a pre-whitening method such that in each step the frequency peak with the largest amplitude is subtracted from the time series. In order to decide which of the detected peaks in the amplitude spectrum can be regarded as intrinsic to the stars we follow Álvarez et al. (1998), where it was shown that 3.7 times the mean amplitude level in the spectrum, calculated in boxes of 100 μHz, can represent very well the 99% confidence level given by statistical tests, such as those proposed by Fisher (1929), Nowroozi (1967), Koen (1990) or Scargle (1982). Similar criteria was used in early STEPHI articles (Michel et al. 1992; Belmonte et al. 1994). This confidence level is computed for each step in the pre-whitening process. Applying the method until the whole spectrum is below this level, the frequency peaks which are, with a probability of 99%, due to the star's pulsation are obtained (see Figs. 2 and 3).

From Fig. 2 it can be seen that V624 Tau shows a wide spread of high signal-to-noise peaks between 400 μHz and 530 μHz; also, a high S/N peak at ≈250 μHz is present. In contrast HD 23194 has two main peaks at ≈533 μHz and 575 μHz (see Fig. 3).

The noise in the spectra has a typical $1/f$ pattern truncated at lower frequencies as a consequence of the parabola fit. The mean noise level for HD 23194 is a bit higher than that derived for V624 Tau. Namely, in HD 23194 the mean noise at 200 μHz is 500 μmag and 350 μmag at 700 μHz while this level reaches 350 μmag and 250 μmag respectively in V624 Tau. A high concentration of low-frequency noise can also be seen with an amplitude of 1 mmag around 100 μHz for HD 23194.

In order to confirm the results obtained with the ISWF technique, we have re-computed the amplitude spectra

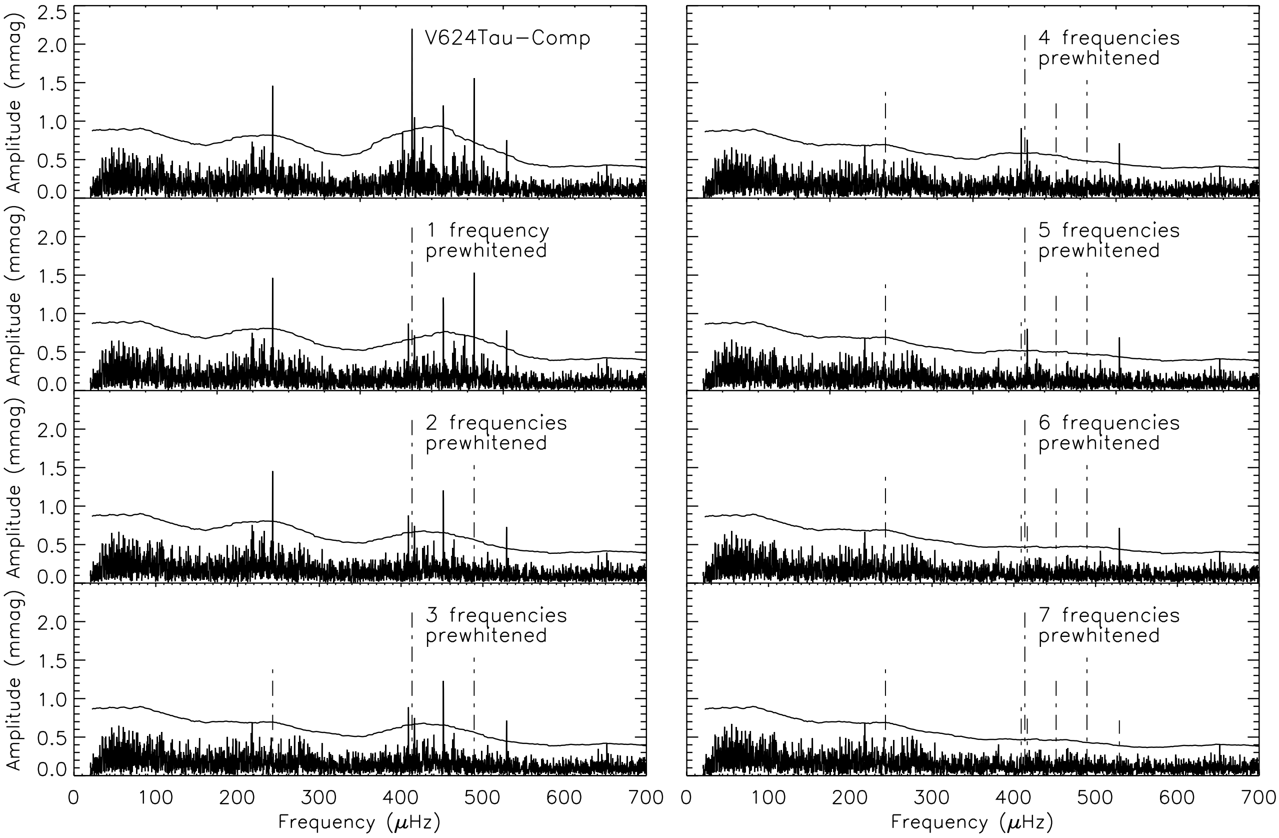

Fig. 2. Pre-whitening process in V624 Tau. In each panel, from the top to the bottom, one peak above the confidence level (continuous line) is selected and removed from the time series and a new spectrum is obtained. In each spectrum, the prewhitened frequencies are shown with dot-dashed lines. The confidence levels are computed as indicated in the text.

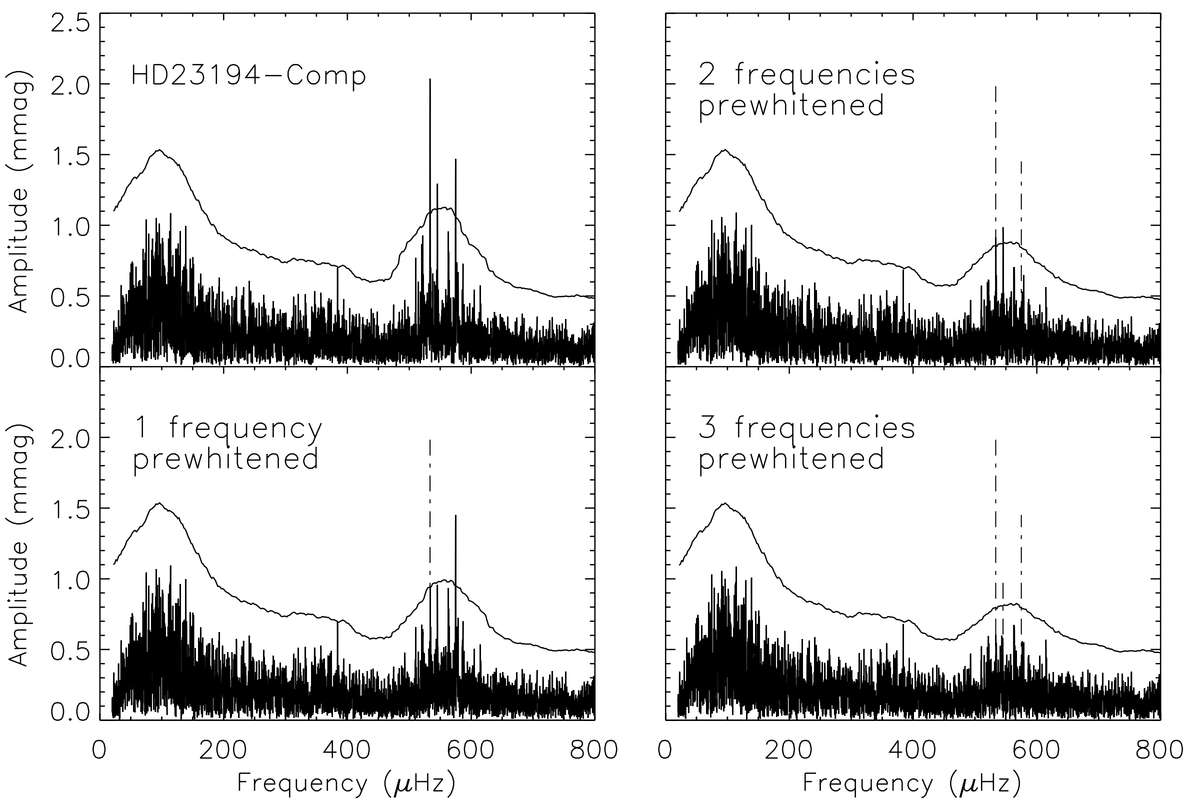

Fig. 3. Same as Fig. 2 but for HD 23194.

Table 3. Frequency peaks detected above a 99% confidence level in our target stars. ν_{P98} refers to frequencies calculated with the program PERIOD98. The origin of φ is at HJD 2451525.8. S/N is the signal-to-noise ratio after the prewhitening process. ν_a, ν_{aa}, ν_b and ν_{bb} are not considered as mode frequencies, see text for details.

Star		ν (μHz)	ν_{P98} (μHz)	A (mmag)	φ (rad)	S/N
V624 Tau	ν_{1a}	242.93	242.94	1.5	+2.7	8.2
	ν_{2a}	409.03	409.02	0.9	−2.1	7.2
	ν_{3a}	413.48	413.37	2.2	−0.7	17.5
	ν_{4a}	416.41	416.40	0.8	−2.0	6.3
	ν_{5a}	451.73	451.73	1.2	−0.7	9.7
	ν_{6a}	489.35	489.35	1.5	+2.3	13.0
	ν_{7a}	529.11	529.10	0.7	+2.6	6.8
	ν_a	*217.82*	*217.83*	*0.7*	*+2.2*	*3.7*
	ν_{aa}	*651.69*	–	*0.4*	*+2.0*	*3.6*
HD 23194	ν_{1b}	533.59	533.62	2.0	−2.3	9.4
	ν_{2b}	574.94	574.95	1.5	+2.1	6.7
	ν_b	*384.09*	–	*0.7*	*−1.1*	*3.6*
	ν_{bb}	*545.46*	*545.46*	*1.0*	*−2.5*	*4.4*

with the program PERIOD98 (Sperl 1998), which considers Fourier as well as muliple least-squares algorithms. This computer package allows to fit all the frequencies simultaneously in the magnitude domain. As shown below, the results obtained with this package are very similar to those found with the ISWF method.

4. Results

4.1. Detected frequencies

The results of the STEPHI X multi-site campaign are summarized in Table 3, where the detected frequencies with their corresponding amplitudes and phases are given.

The frequencies obtained with PERIOD98 for the light curves star−comparison are given in the column ν_{P98}. On average, the absolute differences between these frequencies and those obtained with the ISWF method are of 0.02 μHz. On the other hand, a rough estimate of the frequency errors, including somehow the interference with the noise, can be obtained by comparing the frequency values in the series star−comparison and V624 Tau−HD 23194. On average, the absolute differences are of 0.05 μHz. A similar result is found when frequencies computed with PERIOD98 are considered.

Figure 2 shows the results of the successive prewhitening of each frequency peak. The peak at ν_{7a} = 529.1 μHz was found with a significance of only 95% ($S/N \sim 3.5$) in the curve V624 Tau−HD 23194; however, it has $S/N \sim 7$ in the curve V624 Tau−comparison, using both the temporal Series A and B; hence, we may state that this peak is indeed intrinsic. Moreover, analysing a shorter series, for instance from Dec. 7 to Dec. 17, this peak is always present in the curve V624 Tau−comparison with a confidence level above 99% and a similar phase. Interference from nearby peaks or a higher noise level could place its amplitude slightly below our confidence level in the V624 Tau−HD 23194 light curve.

There are two peaks in the amplitude spectrum of V624 Tau that were found at the limit of the detection level (see the final spectrum in Fig. 2). In particular, the peak at ν_a = 217.8 μHz present in the light curve V624 Tau−comparison with a signal-to-noise of just 3.7, was found in the curve V624 Tau−HD 23194 with a significance no greater than 70% ($S/N \sim 2.5$). This peak was also found in Series B but with a smaller significance ($S/N \sim 3$) and similar phase. Therefore, we will not consider it as a secure detection of a frequency mode. The higher low-frequency noise level in the V624 Tau−HD 23194 curve as compared to V624 Tau−comparison could have affected its amplitude. In the same way, the peak at ν_{aa} = 651.7 μHz was found with $S/N \sim 3.6$; nonetheless, in this case it is present in the V624 Tau−HD 23194 curve with a very small significance showing a lower credibility.

Figure 3 displays the pre-whitening process for HD 23194. The peak at ν_{bb} = 545.5 μHz was found above the 99% confidence level. Coinciding with a daily side lobe of ν_{1b} (the separation between both is of $\simeq$11.9 μHz), it has an amplitude (after removing ν_{1b} from the temporal series) of between 0.4 and 0.5 times that of ν_{1b} in Series A and of only 0.3 times in Series B, which has smaller side lobes. Therefore, it should be taken with caution and we did not include it in the definitive frequencies for this star. It can be seen in Fig. 3 that there is a peak at ν_b = 384.1 μHz with an amplitude at the border of the confidence level. However, it shows very low significance in the curve V624 Tau−HD 23194.

4.2. Discussion of the results

Breger (1972), after 4 hours of observations, reported for V624 Tau a main frequency at 482.2 μHz with an amplitude of 10 mmag that approximately agrees with our main detected frequency ν_{6a} = 489.4 μHz (with an amplitude of 1.53 mmag, see Table 3). Nevertheless, it is known that earlier observations having a limited temporal resolution and a poor spectral window allow the determination of only the "peak-to-peak" amplitude of the pulsational behaviour of the stars. Thus, we cannot expect a coincidence between the reported amplitudes for this mode. In support of this, it is instructive to see the plot of observational differential curves obtained in STEPHI VI campaign (Figs. 5 and 6 in Álvarez et al. 1998) where the "peak-to-peak" amplitude of the differential light curves is more than 20 mmag, while the amplitudes of the detected frequencies (Table 3 in Álvarez et al. 1998) are smaller than 2.4 mmag.

Koen et al. (1999), after 7.7 hours of observations, reported for HD 23194 a prominent sinusoidal variation at 567.3 μHz corresponding to a period of about 0.5 hours,

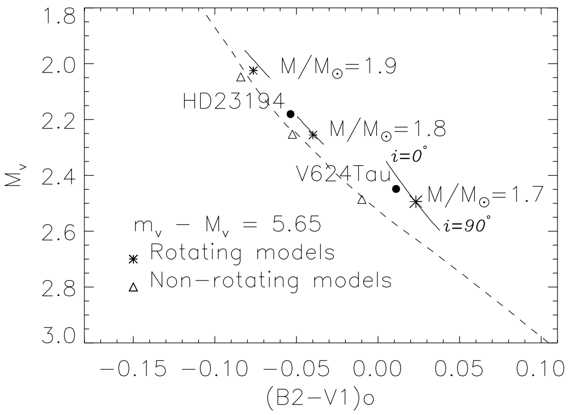

Fig. 4. Colour–magnitude diagram showing the location of the target stars (filled circles). Rotating and non-rotating models for an age of 105 Myr and $M/M_{\odot} = 1.7$, 1.8, 1.9 are shown with asterisks and triangles respectively. The dashed line is an isochrone for the same age. The solid lines are the colour–magnitudes for rotating models when the inclination angle of the star, i, runs from 90° to 0°.

with a B-band amplitude of the order of 4 mmag. This is well within the periods of the modes detected by us for this star (see Table 3), taking into account that their short run does not allow a precise comparison.

The two oscillation frequencies found in HD 23194 confirm that mild metallicism and pulsation can coexist in marginal Am stars. It is possible that the fact that the detected peaks are grouped into a narrow range at high frequencies is due to the Am character of this star, but obviously more work on the pulsational behaviour of Am stars is required.

4.3. Range of radial orders for the observed modes

With the information available, it is not possible to find a unique mode identification for the observed frequencies. However a comparison with stellar models gives some useful information. In order to find the range of radial orders for the observed frequencies, we consider rotating and non-rotating stellar models with input physics appropriate to the stars and cluster parameters. In particular a distance modulus of $M_V - m_V = 5.65$ (in agreement with the values of Meynet et al. 1993 and Stello & Nissen 2001), a metallicity of $Z = 0.02$ and an age of 105 Myr have been considered. The corresponding isochrone reasonably matches the colour–magnitude diagram of the Pleiades (see Fox Machado et al. 2001). The adiabatic oscillation eigenfrequencies of the theoretical models up to second order in the rotation rate are computed as in Fox Machado et al. (2001).

Figure 4 shows the position of the target stars in a colour–magnitude diagram. The intrinsic colours in the Geneva photometric system were obtained as explained in Meynet & Hauck (1985). The filled circles correspond to the target stars. The dashed line represents an isochrone of 105 Myr. The triangles corresponds to non-rotating

Table 4. Possible range of radial orders for the observed frequencies.

Star Obs. frequency	$l = 0$	$l = 1$	$l = 2$
V624 Tau			
$\nu_1 = 242.9$	$n = 1, 2$	$n = 1$	$n = -1, 0$
$\nu_2 = 409.0$	$n = 4$	$n = 3, 4$	$n = 3$
$\nu_3 = 413.5$	$n = 4$	$n = 3, 4$	$n = 3$
$\nu_4 = 416.4$	$n = 4$	$n = 3, 4$	$n = 3$
$\nu_5 = 451.7$	$n = 5$	$n = 4$	$n = 3, 4$
$\nu_6 = 489.4$	$n = 5$	$n = 4, 5$	$n = 4$
$\nu_7 = 529.1$	$n = 6$	$n = 5$	$n = 4, 5$
HD 23194			
$\nu_1 = 533.6$	$n = 6$	$n = 5, 6$	$n = 5, 6$
$\nu_2 = 574.9$	$n = 6$	$n = 5, 6$	$n = 5, 6$

models at this age. The small and large asterisks corresponds to rotating models at the same age with appropriate initial rotational velocity, Ω_0, in order to be consistent with the projected rotational velocities of the target stars (the small asterisk are models with $\Omega_0 = 8.0 \times 10^{-5}$ s^{-1} and the large asterisk correspond to a model with $\Omega_0 = 1.2 \times 10^{-4}$ s^{-1}). The solid lines are the colour–magnitudes for the rotating models computed as in Pérez Hernández et al. (1999) when the inclination angle, i, of the star runs from 90° to 0°. From Fig. 4 we note that the position of V624 Tau approximately coincides with those of the theoretical model with $M = 1.7\ M_{\odot}$ while the location of HD 23194 is between that of the models with 1.8 $M_{\odot}$ and 1.9 $M_{\odot}$.

In Table 4 the possible range of radial orders for each degree associated with the observed frequencies is given. Here we have considered a full range of values for Ω_0 corresponding to the observed $v \sin i$ given in Table 1. It can be seen that the observed frequencies of both stars seems to correspond to p-modes. The oscillations in HD 23194 could correspond to relatively high overtones ($n = 5, 6$) with at least one non-radial mode. The observed frequencies in V624 Tau could include the fundamental mode ($n = 1$ for $l = 0$) as well as higher radial orders. Non-radial oscillations must also be present.

5. Conclusions

We have presented the results obtained in the STEPHI X multi-site campaign. Two stars of the Pleiades cluster were monitored for a period of 34 days during 1999 November–December. The three-continent run allowed us to reach a low noise level (∼450 μmag at 200 μHz) and a good spectral window (side lobes at 35% of the main lobe in amplitude). The efficiency of the observations was 41.3% of the cycle. With this campaign we completed a sample of six δ Scuti stars in the Pleiades, observed by the STEPHI network.

V624 Tau and HD 23194 have been found to be multiperiodic, non-radial pulsators with at least seven and two modes of oscillations respectively. We note that to date our campaign represents the most extensive work on V624 Tau and HD 23194 in terms of the time, data points and observatories involved. The spectral resolution reached and the signal-to-noise obtained increase the confidence and precision of our results.

Although a unique mode indentification has not been attempted, a preliminary comparison of observed and theoretic frequencies reveals that pulsations in V624 Tau are sparse, with radial orders from about the fundamental up to $n \sim 6$, while HD 23194 seems to oscillate with high overtone modes, with radial orders about $n \sim 5, 6$.

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