

Detection of δ Scuti-like pulsation in H254, a pre-main sequence F-type star in IC 348^{*}

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Abstract. We present time series observations of intermediate mass PMS stars belonging to the young star cluster IC 348. The new data reveal that a young member of the cluster, H254, undergoes periodic light variations with δ Scuti-like characteristics. This occurrence provides an unambiguous evidence confirming the prediction that intermediate-mass pre-main sequence (PMS) stars should experience this transient instability during their approach to the main-sequence.

On the basis of the measured frequency $f = 7.406 \text{ d}^{-1}$, we are able to constrain the intrinsic stellar parameters of H254 by means of linear, non adiabatic, radial pulsation models. The range of the resulting luminosity and effective temperature permitted by the models is narrower than the observational values. In particular, the pulsation analysis allows to derive an independent estimate of the distance to IC 348 of about 320 pc. Further observations could either confirm the monophasic nature of H254 or reveal the presence of other frequencies.

Key words. stars: variables: δ Scuti – stars: oscillations – stars: fundamental parameters – stars: pre-main sequence

1. Introduction

IC 348 is a young (≤ 10 Myr), nearby ($d \approx 300$ pc) cluster within the Perseus complex. The cluster belongs to the Per OB2 association, and is located near the tip of the Perseus ridge which contains other star-forming regions, such as NGC 1333 (Blaauw 1952; Herbig 1998). A number of T Tauri stars were discovered in IC 348 by Herbig (1954) who suggested that these stars could be as young as the OB association. The age of IC 348 has been debated in the literature due to the discrepancy between the kinematic age (1–1.4 Myr, Herbig 1998 and references therein) and that obtained from evolutionary considerations (3–20 Myr, Strom et al. 1974; Trullols & Jordi 1997). According to Herbig (1998), the mean age of IC 348 inferred from its faint members is much smaller than previous evolutionary estimates, but the age spread of individual stars encompass most of evaluations in the literature. In fact, reconstruction of the history of the cluster indicates that star formation increased dramatically about 3×10^6 years ago, with an e -folding time of the accelerating phase of just 1×10^6 yr (Palla & Stahler 2001). Current estimates of the distance to IC 348 range from 240–260 pc (Trullols & Jordi 1997; Černis 1993) to

316 pc (Herbig 1998). However, there are indications in favor of the larger distance (see discussion in Herbig 1998).

Recently, about 50 new variable stars have been discovered in IC 348 by Herbst et al. (2000) who studied their long term behavior over a period of several months. All these variable stars are classical or weak-lined T Tauri stars, while none of the early-type members showed any variability. Unfortunately, this extensive work does not provide information on the possible existence of δ Scuti-like oscillations with time scales of the order of hours or less in the cluster members.

During the last few years a growing interest has developed in the study of the pulsational properties of young stars of intermediate mass (e.g., Marconi et al. 2001, 2002; Kurtz & Catala 2001 and references therein). After the initial identification of pre-main-sequence (PMS) δ Scuti candidates in the open cluster NGC 2264 (Breger 1972), several studies have reported results on the search for this kind of variability in known Herbig Ae stars (Kurtz & Marang 1995; Donati et al. 1997; Kurtz & Muller 1999, 2001; Marconi et al. 2000, 2001; Pigulski et al. 2000; Pinheiro et al. 2002).

These investigations were stimulated by the theoretical study of Marconi & Palla (1998) that established the location of the instability strip for PMS objects on the basis of nonlinear convective hydrodynamical models. As shown in our previous

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^{*} Based on observations collected at the Loiano Observatory, Italy and the San Pedro Martir Observatory, México.

investigations (Marconi et al. 2000, 2001, 2002), the comparison between observed periodicities and the predictions of linear non-adiabatic models provides useful constraints on the occurrence of radial pulsations, as well as on the intrinsic stellar parameters. Moreover, the morphology of the PMS and post-MS tracks together with the comparison of the predicted instability strip helps to constrain the evolutionary state and the modal stability.

However, apart from Breger's candidates in NGC 2264 for which only few hours of observations are available, the other identified PMS δ Scuti are isolated Herbig Ae stars. Obviously, the theoretical analysis outlined above is expected to give the best results for stars in clusters where the uncertainties in distance, age and reddening are less and the same for all the members. For this reason, we have selected IC 348 whose small distance, young age, and relatively large population offer a good opportunity to investigate the short time scale pulsation of some of its members.

The extensive study of Luhman et al. (1998) provides a detailed census of the stellar members of the cluster. From the comparison between the stellar parameters and the topology of the instability strip calculated by Marconi & Palla (1998), we have selected three PMS δ Scuti candidates: H83, H254, and H261 (following Herbig's 1998 notation). Their properties are listed in Table 1. In this paper, we present the results of an extensive observational search that resulted in the detection of variability in one star, H254. The paper is organized as follows: in Sect. 2 observations and data analysis are discussed, whereas the frequency analysis for the identified PMS δ Scuti candidate is presented in Sect. 3. In Sect. 4 we compare the resulting periodicity with the predictions of PMS evolutionary and pulsation models. Some final remarks close the paper.

2. Observations and data reduction

Observations were carried out with two different telescopes: the 1.54 m Loiano Observatory Telescope (Bologna, Italy), and the 1.5 m telescope in San Pedro Martir (México, SPM hereafter). Observations in Loiano were obtained using both a focal reducer instrument (BFOSC, Bologna Faint Object Spectroscopic Camera, see www.bo.astro.it/loiano/observe.htm) and a three channel photometer (TTCP, see www.na.astro.it/~silvotti/TTCP.html and Ališauskas et al. 2000). Observations in SPM were carried out using the six channel spectrophotometer (see 132.248.3.38/Instruments/danes/photomdan.html) which can simultaneously operate the *wby* filters. The observation log is reported in Table 2.

Observations with BFOSC were obtained in the period 8–12 Sep. 2001 during an observing run dedicated to test a new set of Strömgren filters acquired by the Capodimonte Astronomical Observatory. The night of Sep. 9 was lost due to bad weather. The BFOSC instrument is equipped with an EEV CCD 1300×1340 pixel², the pixel scale is 0.58 arcsec pix⁻¹ for a total field of view of $12.6' \times 13.0'$. The observations were carried out with the Strömgren *by* filters and the typical exposure times were 40–80 s, enough to reach a very high *S/N* (~ 1000) for our candidates. In this way, we were able to obtain around

60 phase points per night. The seeing was bad (~ 3 – 4 arcsec) during the night of Sep. 8, whereas it was around 2 arcsec or less during the other nights.

The pre-reduction was performed in the usual way by subtracting a bias frame from all the scientific frames and dividing them by a flat field (dome flat field) obtained during each night separately. Since the field of IC 348 is not crowded and the target stars are very bright, we decided to perform aperture photometry. To this aim, we used the DAOPHOT II program (Stetson 1987) with a fixed circular aperture of 40 pixels (~ 23 arcsec), whereas the sky was evaluated in an annulus of 15 pixels around the aperture (starting 2 pixels beyond the central circular aperture). On each frame we have found and measured about 210 stars. In order to have compatible (instrumental) photometry in each frame (for a given filter), we chose a reference image taken with the best seeing and corrected the instrumental magnitudes of each frame by using all the stars in common with the reference frame. We note that we did not observe standard stars since we are only interested in the time series analysis of stars in IC 348 and for this task absolute photometry is not necessary.

Finally, the procedure described above allowed us to investigate the short term variability of each candidate in IC 348.

2.1. Periodic light variability of H254

A plot of HJD vs. magnitude reveals that H261 and H83 are constant at a level of a few thousandths of magnitude on a timescale of a day, whereas they show a slight night-by-night variation of the mean light level of the order of 0.01 mag. On the contrary, H254 is found to vary both in *b* and *y* on a timescale of ~ 3 hr with an amplitude of about 0.02 mag. The light curves obtained in 4 nights of observations are shown in the upper panel of Fig. 1. In addition to fast variability, there are some indications of the presence of a slow variation (see the difference in minimum light between first and second night and the small variations of the nightly means) not correlated with the δ Scuti-like pulsation we are seeking.

This encouraging result led us to plan new observations of H254. In particular, we aimed at using the fast three channel photometer available at the Loiano telescope (the TTCP photometer), which has the advantage of allowing differential photometry by observing simultaneously the variable and comparison star and the sky. Such a procedure guarantees very precise photometry even in the case of thin cirrus over the sky. Moreover, data reduction is much easier and faster than with CCD observations.

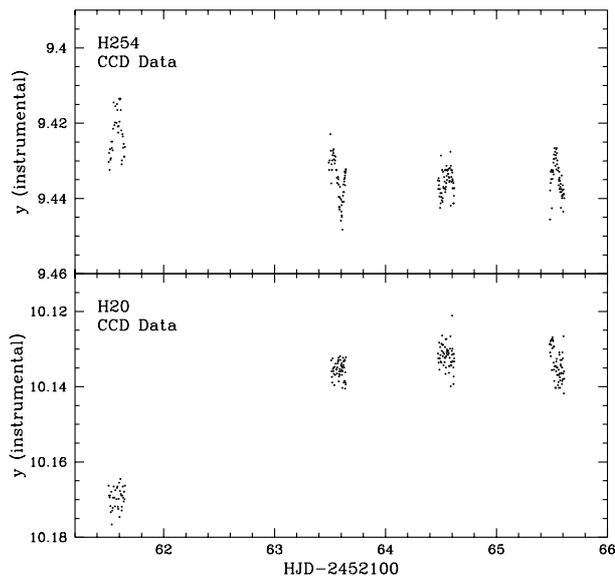
In order to find a suitable comparison star near H254 for differential photometry with the three channel photometer, we used the available CCD observations. The comparison star had to satisfy the following requirements: 1) to be constant at least on the time scale of one day; 2) to be close enough to H254 ($7' < r < 10'$, due to the characteristics of the TTCP); 3) to have a brightness and color not too different from those of H254. These constraints are reasonably satisfied only by the star H20 at a distance of $\sim 7.4'$ from H254 and of spectral type

Table 1. Properties of the stars H83, H254 and H261 belonging to IC348. Values for T_{eff} and L_{bol} are taken from Luhman et al. (1998). For the errors in T_{eff} and L_{bol} see discussion in Sect. 4.

Star	α (J2000)	δ (J2000)	ST	V (mag)	T_{eff} (K)	L_{bol} (L_{\odot})
H83	3 44 19.12	+32 09 30.8	F0	11.9	7200 ± 170	6.6 ± 2.3
H254	3 44 31.21	+32 06 22.1	F0	10.6	7200 ± 170	31.4 ± 10.1
H261	3 44 24.67	+32 10 14.4	F2	11.6	6890 ± 160	15.0 ± 4.8

F8 (F0 for H254). In order to verify the stability of H20¹ on timescales of less than about one day, we show its magnitude vs HJD in the bottom panel of Fig. 1. H20 is constant over periods of several hours, whereas it appears to have night-to-night variations of the mean light level of about 0.03 mag. This behavior is not surprising, considering that PMS stars can show variability due to the interaction with circumstellar material. However, since we are interested in short term variability only, we can use H20 as a good comparison star.

Observations of H254 with the TTCP were obtained during December 2001 (1 night) and January 2002 (6 nights) only in the BV Johnson filters with exposure times of 10 s in both filters.

**Fig. 1.** Instrumental CCD light curve of H20 and H254.

Observations in SPM were made simultaneously with the Jan. 2002 run at Loiano. This fact guaranteed an almost continuous coverage of H254 for about 11–12 hours on average. The instrument used in SPM was a 6 channel spectrophotometer which allows to observe in the Strömgren $uvwby$ filters simultaneously. Since the instrument behaves as a single channel photometer, variable and comparison were observed in the sequence V, S, C, S... (V = variable, S = sky, C = comparison). Data obtained during Jan. 8 and 13, 2002 were rejected due to the poor sky conditions. On the contrary, photometric condi-

¹ H20 is not included in the field of Herbst et al. (2000) who investigated the variability in IC 348 on a time scale of the order of one day.

Table 2. Journal of the observations: $uvwby$ are in the Strömgren system, BV are in the Johnson system.

Period	Teles.	Instr.	Filt.	Star
8,10–12/9/01	Loiano	BFOSC	by	H83,H254,H261
6/12/01	Loiano	TTCP	BV	H254
8–13/1/02	Loiano	TTCP	BV	H254
8–13/1/02	SPM	6 ch. sp.	$uvwby$	H254

tions occurred during the remaining nights, allowing a calibration of H20 in terms of the standard Strömgren indexes $V, b - y, m1, c1$. We derived the following values: $V = 11.348 \pm 0.020$, $b - y = 0.477 \pm 0.007$, $m1 = 0.197 \pm 0.034$, $c1 = 0.489 \pm 0.061$ (average of 385 data points). We note that the reddening free quantities [$m1$] and [$c1$] (Strömgren 1966) for H20 are consistent with its spectral type.

Before combining the three photometric datasets, one has to take into account that they were obtained in two different photometric systems. Johnson V and Strömgren y are easier and safer to combine than Johnson B and Strömgren b , because they differ only by a constant and a slight color term in $b - y$ (see e.g. Terranegra et al. 1994). The former is removed when one uses differential photometry and the latter can be neglected since H20 and H254 are both F-type stars. On this basis, $\delta y \approx \delta V$ and in the following we shall always refer to the data in the V band. The last step before proceeding to the frequency analysis was to rebin the Loiano photometry obtained with TTCP (averaging HJD and photometry every 5 data points) in order to have similar sampling and, in turn, a similar weight for each dataset in the fitting procedure.

The final dataset is shown in Fig. 2. We note that in this figure the data between nights 2452161–2452165 consist of differential photometry ($\delta V = V_{\text{H254}} - V_{\text{H20}}$) obtained from CCD observations. A comparison between these data and the ones shown in the bottom panel of Fig. 1 reveals that using H20 as comparison star leads to more precise photometry.

3. Frequency analysis of H254

The frequency analysis was performed using the Period98 package (available at www.astro.univie.ac.at/~dsn/), based on the Fourier transform method. For a better interpretation of the results, we have first calculated the spectral window for the whole data set. The result is shown in Fig. 3: any good frequency should display the same alias pattern as that shown in the figure.

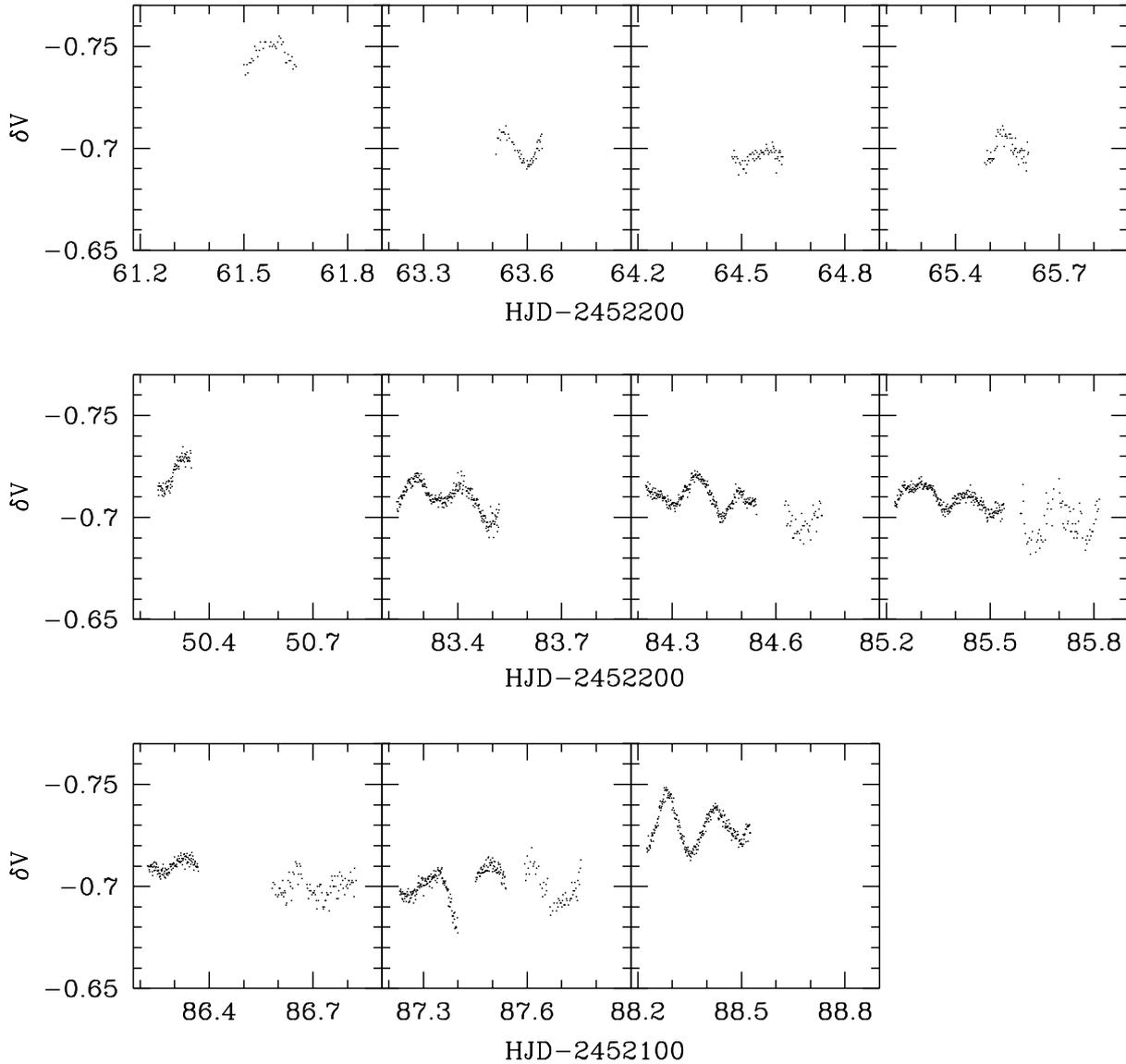


Fig. 2. Differential light curve for H254 ($\delta V = V_{\text{H254}} - V_{\text{H20}}$). CCD data are for HJD from 61 to 66, while the remaining data are those obtained with TTCP at Loiano and 6 chan. spect. at SPM.

As seen in Fig. 4, the Fourier analysis identifies four frequencies, whose properties are listed in Table 3. The low frequencies with $f_1 = 0.157$, $f_2 = 0.283$, and $f_3 = 0.931 \text{ d}^{-1}$ result from the long term behavior associated with a daily variation of H254 and, partially, with the similar variability in the comparison star, H20. After removal of f_1 , f_2 and f_3 , a fourth frequency is identified at $f_4 = 7.406 \text{ d}^{-1}$ (3.24 hr) which is typical of δ Scuti type pulsators. After the pre-whitening of f_4 , no other significant features are seen in the periodograms. In order to check the accuracy of our analysis, we show in Fig. 5 the light curve phased with the frequency $f_4 = 7.406 \text{ d}^{-1}$ after pre-whitening for the other frequencies. The figure reveals that almost all the data can be satisfactorily phased when using the quoted frequency.

We must caution that the presence of a one day alias makes our determination of the frequency still not definitive. In particular, the -1 day alias (i.e., a frequency $\sim 6.4 \text{ d}^{-1}$) shows an excess of power with respect to that expected on the basis of

Table 3. Frequencies, amplitudes and phases derived for the Fourier analysis of the data. The uncertainty on the frequencies is $\sim 0.008 \text{ d}^{-1}$.

	Frequency (d^{-1})	Amplitude (mmag)	Phase
f_1	0.157	12.5	0.001
f_2	0.283	9.0	0.758
f_3	0.931	6.5	0.065
f_4	7.406	5.4	0.028

the spectral window, suggesting that the true frequency could be the latter. This must be taken into account when interpreting the data in terms of the predictions of the pulsation models.

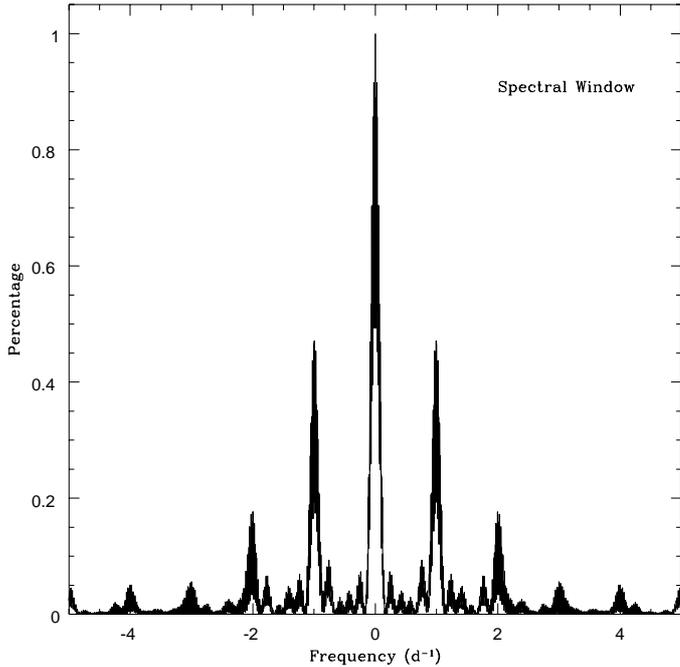


Fig. 3. Spectral window of our data set.

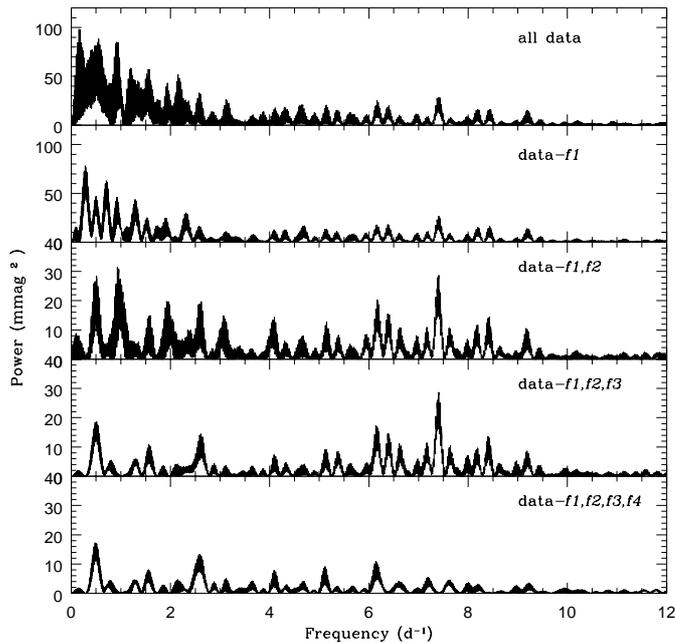


Fig. 4. Periodograms of V photometry for H254. The sequence from top to bottom shows the change of the periodogram pre-whitened by f_1 , f_2 , f_3 , and f_4 , respectively.

4. Theoretical constraints

Figure 6 shows the location in the HR diagram of the three PMS δ Scuti candidates in IC 348, along with several other cluster members of intermediate mass. The physical parameters are taken from Luhman et al. (1998) who assumed a distance to IC 348 of 316 pc (i.e. $DM = 7.5$ mag) as suggested by Herbig (1998). Unfortunately Luhman et al. do not provide the error estimate on effective temperature and luminosity. The values given in Table 1, and reported in Fig. 6, represent our estimates

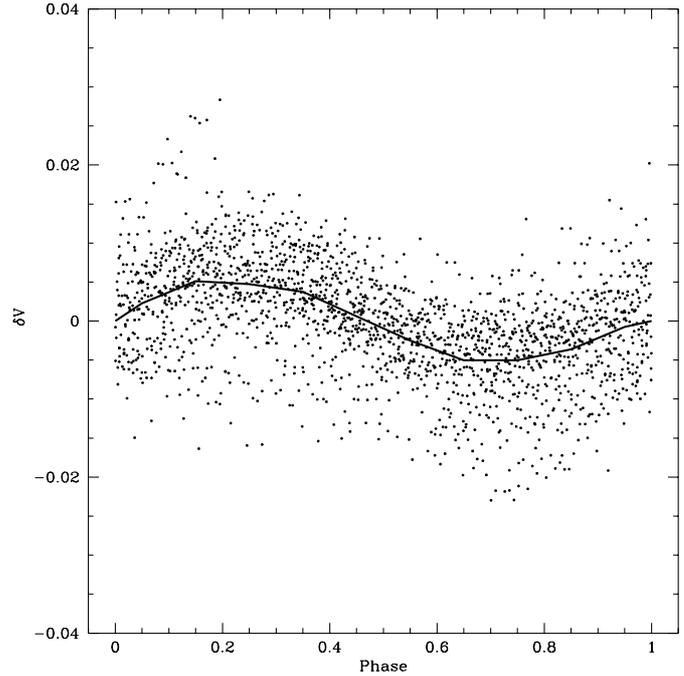


Fig. 5. Light curve of H254 obtained using the frequency $f_4 = 7.406$ d^{-1} and after removal of the frequencies f_1, f_2, f_3 . The solid line shows the same data after averaging magnitudes over a 10 phase bin.

obtained by propagating the errors due to the adopted calibrations between spectral type and T_{eff} and T_{eff} vs. bolometric correction. In particular, the error bar in the effective temperature comes from the uncertainty of ± 1 spectral class (using the calibrations of Schmidt-Kaler 1982, and Leggett et al. 1996), while the error on the luminosity comes mainly from the uncertainty in the bolometric correction when propagating the error in T_{eff} (using the relation between T_{eff} , intrinsic colors and bolometric corrections of Kenyon and Hartmann 1995).

The cluster contains a non negligible population of stars with mass greater than $\sim 1.5 M_{\odot}$. However, only three objects fall within the boundaries of the theoretical instability strip calculated by Marconi & Palla (1998). Interestingly, their estimated ages cover a large range from ~ 1 Myr for H254 to ~ 10 Myr for H83, as can be deduced from the isochrones shown in the HR diagram. The three candidates lie within the instability region, with H261 and H83 located close to the red edge where pulsation amplitudes are expected to be very small. The theoretical uncertainty on the red boundary is of the order of ± 0.02 dex in $\log T_{\text{eff}}$ due to the sensitivity on the assumed mixing length parameter in the treatment of convection (see Stellingwerf 1982 for details on the treatment of convection in the pulsation code) which is more efficient toward the cooler part of the strip². This is consistent with the fact that a δ Scuti type variation has been found only in H254. Conversely, the lack of pulsation provides a strong empirical constraint to the red limit of the instability strip.

² Due to the lower efficiency of convection at higher effective temperatures, the uncertainty on the location of the blue boundary of the strip is about ± 0.005 dex.

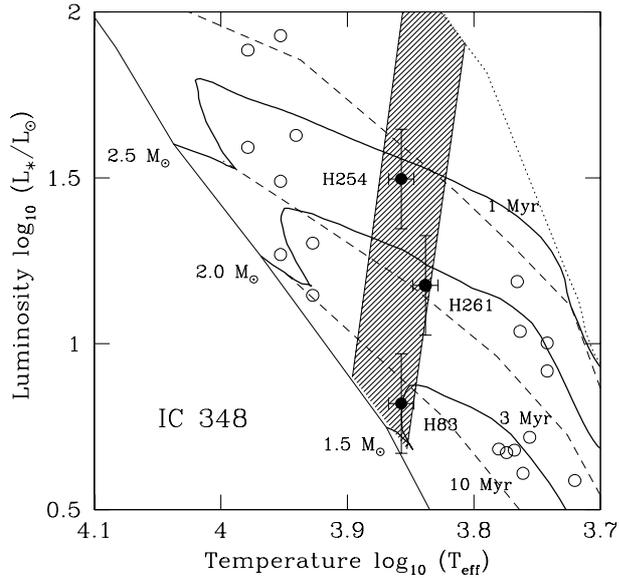


Fig. 6. Location of H83, H254 and H261 in the HR diagram. The filled circles represent the three δ Scuti candidates, while the empty circles represent the intermediate-mass cluster members. Stellar parameters are taken from Luhman et al. (1998). Also shown are the evolutionary tracks and isochrones by Palla & Stahler (1993), and the instability strip by Marconi & Palla (1998).

As shown in Fig. 6, H254 is located well inside the strip in a region where pulsation in the lowest modes is expected. In order to reproduce the observed periodicity of 7.406 d^{-1} , we have computed a sequence of linear non-adiabatic models with solar metallicity, varying the effective temperature and luminosity within the ranges given above. The stellar mass is evaluated from the evolutionary tracks. As a result, we find that H254 pulsates either in the fundamental mode or in the first overtone. Higher modes seem to be ruled out by the lack of consistency with the observed luminosity and effective temperature ranges and the observed periodicity. The values of mass, effective temperature and luminosity that characterize these models are listed in Table 4. In the table, we have also considered the frequency 6.406 d^{-1} that yields values of mass and luminosity in between those for the 7.406 d^{-1} . Note that in any case the range of stellar parameters permitted by the models is narrower than the observational values.

Unfortunately, the uncertainties on luminosity and effective temperature still preclude a secure identification of the pulsation mode. Future higher quality observations of the short term photometric behavior will help to resolve the exact pulsation properties of H254. However, since we could not reproduce the observed period with any other combination of input parameters, our results clearly indicate that the pulsation period of 7.406 d^{-1} (or 6.406 d^{-1}) is incompatible with the possibility that H254 is of lower luminosity (hence mass) as in the case of a shorter distance, namely 240–260 pc (Trullós & Jordi 1997; Černis 1993) instead of 316 pc (Herbig 1998).

5. Conclusions

The present observations have revealed that the PMS F-type star H254, member of IC 348, undergoes periodic light variations with δ Scuti-like frequency. Since IC 348 has an

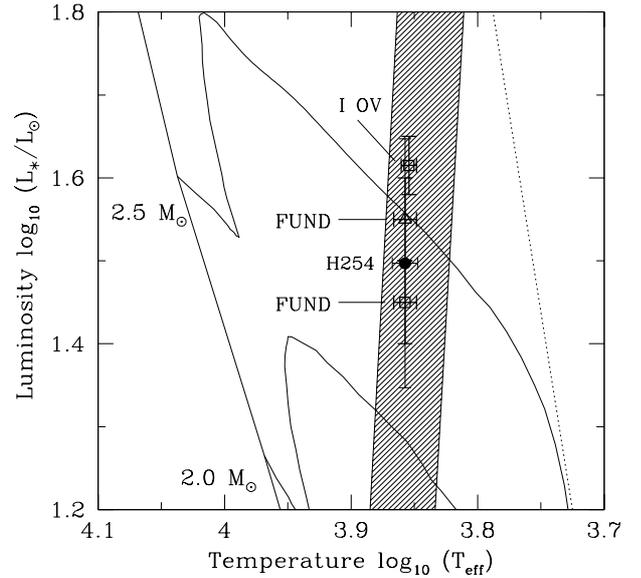


Fig. 7. Enlargement of the HR diagram for H254. The other symbols represent the best fit radial pulsation models with the values of the stellar parameters given in Table 4: squares are for the 7.406 d^{-1} period, while the triangle corresponds to the -1d alias.

Table 4. Best fit of radial pulsation models.

Period (d^{-1})	Mass (M_{\odot})	T_{eff} (K)	$\log L$ (L_{\odot})	Mode
7.406	2.6 ± 0.1	7150 ± 100	1.62 ± 0.04	I OV
7.406	2.3 ± 0.1	7200 ± 150	1.45 ± 0.05	FUND
6.406	2.50 ± 0.05	7200 ± 150	1.55 ± 0.05	FUND

estimated age of less than ~ 10 Myr and is still actively forming stars, the discovery of small amplitude pulsations in H254 confirms the prediction by Marconi & Palla (1998) that intermediate-mass PMS stars should experience this transient instability during their approach to the main-sequence. Other cases presented in the literature have some ambiguity regarding the actual evolutionary state, i.e. pre-main- vs. post-main-sequence (e.g., V351 Ori described in Marconi et al. 2001). Thus, IC 348 and NGC 2264 are the only two young clusters where δ Scuti-like pulsations in PMS stars have been detected so far. Similar searches should be conducted on other clusters to enlarge the sample of pulsating intermediate-mass stars. Good candidates can be found in, e.g., NGC 2362 (Moitinho et al. 2001) and the Upper Sco-Cen association (Preibisch & Zinnecker 1999) that contain a rather large population of stars of the appropriate spectral types.

In H254, we find only one mode of pulsation with $f_4 = 7.406 \text{ d}^{-1}$ (or 3.24 hr). Non-adiabatic linear models with the observed parameters of H254 show unstable modes of low order, namely the fundamental or the first overtone mode. The occurrence of just one mode of pulsations could be intrinsic or due to the detection threshold. Theoretical models of classical δ Scuti stars predict many unstable modes, in excess of what is actually observed (e.g. Bradley & Guzik 2000). On the other hand, monoperoiodic radially pulsating δ Scuti stars are known (20 CVn being the best example, Chadid et al. 2001), and H254

may represent the young counterpart of this (admittedly limited) class. Spectroscopic observations of this star should be carried out to confirm the photometric period found by us and to verify whether other modes are also present. Of course, the low amplitude of the modes may render the detection quite difficult. However, the identification of a young, monophasic pulsating star will be very useful to shed light on the physical mechanism that limits the amplitude of the pulsations. Thus, we encourage other groups interested in stellar pulsations to consider H254 for further study.

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