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LETTER

Letter to the Editor

Pulsation in two Herbig Ae stars: HD 35929 and V351 Ori*

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Abstract. New photometric observations of seven intermediate mass pre-main sequence δ Scuti candidates are presented. The periods and pulsation modes are derived for two of these stars, namely HD 35929 and V351 Ori. The comparison between observations and nonlinear pulsational models allows us to provide some initial constraints on their mass and evolutionary state. As an illustration we discuss the use of periods to identify the mode of pulsation in these two stars and to have an independent estimate of their distances.

Key words: stars: distances – stars: evolution – stars: fundamental parameters – stars: Hertzsprung–Russel (HR) and C-M diagrams – stars: pre-main sequence – stars: variables: δ Sct

1. Introduction

Young pre–main-sequence (PMS) stars of mass greater than $\sim$1.5 $M_\odot$ cross the region of pulsational instability during their contraction toward the main-sequence. The location of the instability strip in the H-R diagram has been recently identified by means of nonlinear models for the first three radial modes (Marconi & Palla 1998). The time spent by intermediate-mass stars within the boundaries of the strip represents a small fraction of the Kelvin-Helmoltz time scale, varying between $\sim$10% for a star of 1.5 $M_\odot$ and $\sim$5% for a 4 $M_\odot$ star. Despite the brevity of this phase, however, a number of known Herbig Ae stars have the appropriate combination of luminosity and effective temperature to become pulsationally unstable. In our previous study, we suggested to look for δ Scuti-type photometric variations with periods of minutes to several hours and amplitudes less than few tenths of magnitudes in a sample of Herbig Ae stars whose position in the H-R diagram coincides with the instability strip.

The identification of a few PMS objects pulsating as δ Scuti stars (Breger 1972), the prototype being the star HR 5999 (Kurtz & Marang 1995), has provided some support to the connection between variability and stellar pulsation. Of particular interest is the Ae star HD 104237 that shows both short- and long-term velocity changes of spectral lines (Donati et al. 1997). These variations indicate that the star is undergoing radial pulsations with a period of approximately 40 minutes and an amplitude of about 1 km s^{-1} (see also Böhm et al. 2000, in preparation). Interestingly, HD 104237 is the first intermediate mass PMS star with a measured magnetic field (Donati et al. 1997). A few new PMS candidate pulsators have been recently identified by Pigulski et al. (2000).

Stimulated by these initial results, we have started a photometric investigation of a sample of seven Herbig Ae stars with spectral types in the range A5 to F5, located within or near the boundaries of the instability strip. For some of them, large time scale variations have been observed during the long term monitoring program of variable stars conducted at ESO (LTPV project: Sterken et al. 1995 and references therein). However, no information is available on their variability on time scales shorter than 2 or 3 days.

The main goal of our study is to detect and characterize the pulsation properties of young stars. This way, we can improve our knowledge of their internal structure and obtain unique constraints on the theoretical predictions of the models. Ultimately, the analysis of the pulsation characteristics can yield an indirect estimate of the stellar mass. This represents a powerful method for stars that are not part of the restricted group of spectroscopic binary systems. In this Letter, we report the discovery of two additional Herbig Ae stars which show evidence for variability of the δ Scuti-type.

2. Selection of the sample, observations and data reduction

The selection of the stars was based on their spectral type. As an initial choice, we have adopted values published in the literature. To have an independent check on the effective temperature of the selected stars, we have used the Strömgren photometry provided by the ESO catalogues of the LTPV project. Then, we have placed the stars in the dereddened color-color [m1]–[c1] diagram (see Strömgren 1966), and compared their position with the theoretical colors from model atmospheres (Kurucz 1992). As a result, we derived a sample of seven stars with spectral

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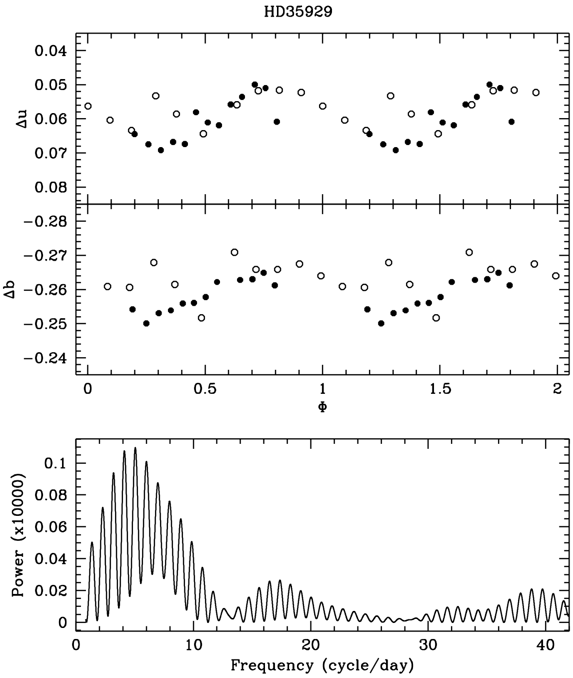

Fig. 1. Upper panels: differential (variable−comparison star) light curves of HD 35929 in the u- and b-filters. Filled and open circles refer to the first and second night of observation respectively. **Lower panel**: frequency spectrum of HD 35929.

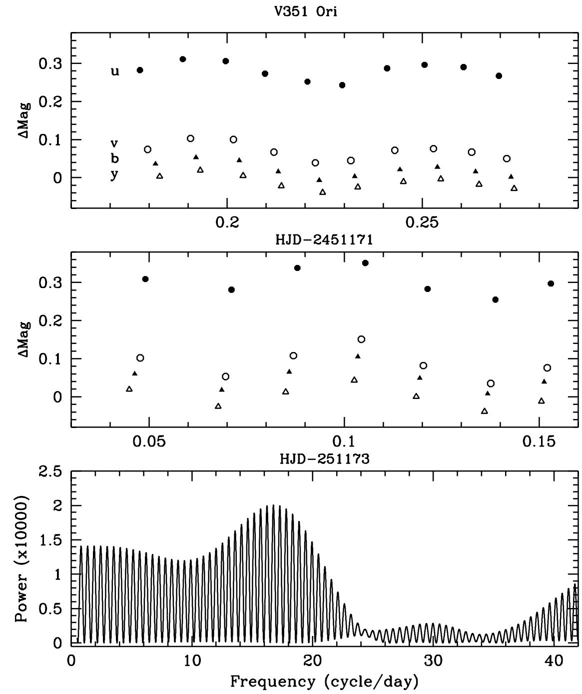

Fig. 2. Upper panels: differential (variable−comparison star) light curves of V351 Ori in the labeled filters for the nights of Dec. 23 (**top panel**) and Dec. 25 (**middle panel**). **Lower panel**: frequency spectrum of V351 Ori in the first and second night of observation (solid and dotted lines, respectively). The peak frequency (in days^{-1}) for each night is also indicated.

types between F5 and A5: V346 Ori, V351 Ori, BF Ori, BN Ori, NX Pup, HD 35929, and AK Sco.

The photometric observations were performed in two runs with different telescopes at ESO, La Silla. In the first period (Dec. 23–29, 1998), we used the 0.5k×0.5k CCD (Tektronix TK512CB) attached to the 0.9m DUTCH telescope. Five of the seven nights were photometric. In the second period (June 30 to July 4, 1999) we used the 2k×2k CCD (LORAL/LESSER) attached to the 1.5 m. DANISH telescope. Unfortunately, weather conditions were excellent for accurate photometric observations only during one night. Due to their brightness, all of the sources are suitable for observations in the Strömgren $uvby$-system. Two comparisons stars were used for each candidate variable; whenever possible, we observed the same comparison stars as in the LTPV program. Data reduction and analysis to derive instrumental aperture magnitudes were performed following the standard procedures under the MIDAS environment. The typical intrinsic instrumental photometric error in each Strömgren filter is of the order of a few thousands of a magnitude.

3. Results: δ Scuti candidates

The stars V346 Ori, V351 Ori, BF Ori, HD 35929, and AK Sco have been found to show photometric variability. For V351 Ori and HD 35929, we could derive reliable pulsational periods that fall in the expected range of δ Scuti type variability[1]. In Table 1 we report their main properties.

HD 35929 was observed during two nights (Dec. 28 and 29, 1998). The stars HD 37399 and HD 37210 were used for comparison. Unfortunately, HD 37210 turned out to be variable with a maximum amplitude in the u-filter of ∼0.03 mag and a rather monotonic variation. Therefore, the differential light curve of HD 35929 was derived using the data points relative to HD 37399 only. The instrumental phased light curves in Δu and Δb are shown in the two upper panels of Fig. 1. The frequency spectrum of HD 35929 obtained from the u-filter is shown in the lower panel of Fig. 1. The frequency spectrum peaks at 5.1 d^{-1}, i.e. 0.196d. We note that no significant differences in the calculated period are found using light curves in other filters.

V351 Ori was observed during the nights of Dec. 23 and 25, 1998. HD 38155 and HD 35298 were used as comparison stars. The latter turned out to be a variable star, with a maximum amplitude in u of ∼0.04 mag and a quasi-periodic behaviour. Thus, we use only HD 38155 for comparison. The differential magnitudes in each filter ($\Delta u, \Delta v, \Delta b, \Delta y$, computed as variable−comparison) are shown in the upper panels of Fig. 2. The light curve in the u-band, where the largest amplitude is observed, was used to determine the observed period of V351 Ori. The frequency spectrum of V351 Ori obtained from the u-filter is shown in the lower panel of Fig. 2. The main maximum in this spectrum corresponds to a period of 0.058 d. Again, no signif-

[1] As for V346 Ori and AK Sco, the variation seems δ Scuti-like, with u amplitudes of about 0.035 and 0.08 mag respectively but no period could be derived due to the poor phase coverage. As for BF Ori, its variation is clear ($\Delta u \sim 0.11$ mag), but seems rather monotonic

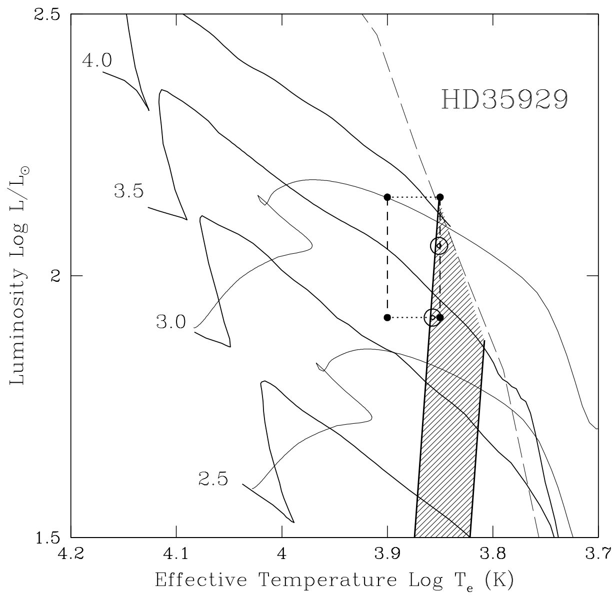

Fig. 3. The position of HD 35929 in the H-R diagram according to the estimates of spectral type and distance found in the literature (dotted box). The shaded region is the instability strip predicted by Marconi & Palla (1998). The PMS and post-MS evolutionary tracks are shown as thick and thin solid lines, respectively. The birth-line for the PMS evolutionary tracks is displayed by the dashed line.

icant differences in the derived periods occur when using light curves in other filters.

4. Evolutionary state of HD 35929 and V351 Ori

Although more systematic observations are needed to define the precise pulsational periods of HD 35929 and V351 Ori, the available data already provide some preliminary constraints on their position in the H-R diagram, stellar mass and evolutionary state. As remarked by the referee, the discussion presented in this section is useful as an *illustration* of how well-defined periods for these stars could indeed tightly constrain their evolutionary states.

Fig. 3 shows the location of HD 35929 in the H-R diagram. The dotted box accounts for the uncertainty in the spectral type (A5 to F0: Malfait et al. 1998, Miroshnichenko et al. 1997, van den Ancker et al. 1998) and distance (d =360 to 430 pc: van den Ancker et al. 1998). The instability strip for the first three radial modes, as predicted by Marconi & Palla (1998), is also shown together with the PMS evolutionary tracks computed by Palla & Stahler (1993) and the post-MS evolutionary tracks for 2.5 and 3.0 $M_\odot$ of Castellani et al. (1999). The two circles indicate the best combination of the stellar parameters (M, L, $T_{\rm eff}$) that yield a period equal to the observed one, $P = 0.196 \pm 0.005$ d. These values are listed in Table 2. The two solutions indicate a mass of 3.4 or 3.8 M$_\odot$, pulsating in the first overtone (FO) and second overtone (SO) respectively: in both cases, HD 35929 can be considered a PMS pulsator, as expected.

A combination of parameters for a post-MS stellar mass can also reproduce the pulsational period observed in HD 35929. In this case, the best choice would be a post-MS model of a 2.7 $M_\odot$ star with $L = 83\ L_\odot$ and $T_{\rm eff} = 6900$ K, pulsating in the SO mode. The location of this solution is quite close to the lower circle shown in Fig. 3. Although only few specific studies exist on HD 35929, some evidence supports the fact that HD 35929 is a young star associated with the Ori OB-1c association. For example, Malfait et al. (1998) have discussed the infrared excess observed toward this star, whereas Miroshnichenko et al. (1997) have suggested that the star might be in a transition phase between a PMS Herbig Ae star and a β Pictoris-type object. We also note that the pulsational character (period and H-R diagram location) of HD 35929 is similar in many respects to that of the well known Herbig Ae star HR 5999. From these considerations, we favor the conclusion that HD 35929 is a PMS star with a mass in the narrow range 3.4-3.8 $M_\odot$, pulsating in the FO or SO.

Finally we note that if the Strömgren indices [c1] and [m1] measured for this star are taken into account, together with published values for the $H\beta$ index, one derives an effective temperature $\log T_{\rm eff} = 3.84$ and a luminosity varying between 26 and 36 $L_\odot$. This means that according to the Strömgren photometry, HD35929 should be located on a $\sim 2.5 M_\odot$ evolutionary track and the period based on present data would be too long even for a pulsation in the fundamental mode. A possible explanation for this inconsistency could be that HD35929 is also a rapid rotator ($\sim$150 Km s^{-1}) so that the assumption of radial pulsation could be not completely correct. Future observations and numerical simulations are needed in order to properly address this problem.

Fig. 4 shows the location of V351 Ori in the H-R diagram. Here, the uncertainty on the luminosity is larger than for HD 35929, because of the distance ambiguity. The lower value corresponds to the minimum distance of 260 pc given in the Hipparcos catalogue (van den Ancker et al. 1998). The upper limit (inverted triangle) assumes that V351 Ori is located in the

Table 1. Herbig Ae stars with δ Scuti type variability

Star	V-mag	SpT[a]	d [pc][a]	P [d]
V351 Ori	8.9	A7IIIe	>210	0.058±0.001[b]
HD 35929	8.2	F0IIIe	>360	0.196±0.005

[a] van den Acker et al. (1998);
[b] main pulsation period

Table 2. Derived stellar parameters

Star	Mass ($M_\odot$)	L ($L_\odot$)	$T_{\rm eff}$ (K)	d (pc)	mode
HD 35929	3.4	83	7190	360	FO
	3.8	114	7100	420	SO
	2.7[a]	83	6900	360	SO
V351 Ori	1.85	17	7400	230	SO
	2.15	25	7480	280	TO

[a] post-MS model

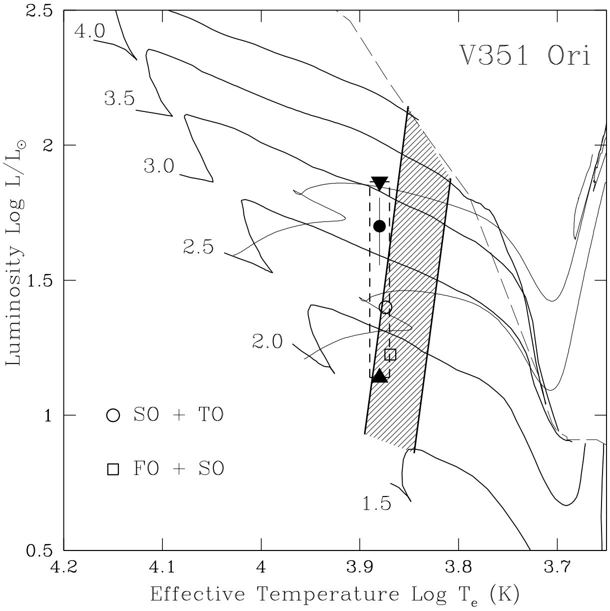

Fig. 4. Same as Fig. 3 but for V351 Ori. The filled triangles refer to the upper and lower limits of the distance. The open symbols are the best pulsation models reproducing an oscillation consistent with the observed period.

Orion molecular cloud at a distance of 460 pc. The dashed box corresponds to an uncertainty of ± 0.01 dex in $\log T_{\rm eff}$. Finally, the filled circle marks the position estimated by van den Ancker et al. (1996) with the associated error bar. As already pointed out, present data for V351 Ori suggest a pulsation period of 0.058 ± 0.002.

Using the constraints provided by this preliminary period and by the topology of the instability strip, we have computed linear nonadiabatic models to find the best set of stellar parameters that reproduce the pulsation of V351 Ori. The results are shown in Fig. 4 and the stellar parameters are given in Table 2. The solutions yield a stellar mass of 1.85 $M_\odot$ or 2.15 $M_\odot$, respectively, pulsating in the SO (open square in Fig. 4), or the third overtone (TO) mode (open circle in Fig. 4. For lower modes, the luminosity of the model would be lower than the estimated lower limit for V351 Ori, whereas higher modes are probably excluded by the closeness of the observational box to the second overtone blue boundary and we did not consider their occurrence. These solutions would tend to favor a distance of V351 Ori, smaller than that of the young stellar population of the Orion complex.

Recently, Koval'chuk & Pugach (1998) have argued on the basis of several peculiar photospheric properties that V351 Ori is in fact more evolved than previously thought and conclude that this star does not belong to the group of Herbig stars. From Fig. 4, we see that the the post-MS track of a 2 $M_\odot$ star intersects the corresponding PMS track at about the position of the best pulsational models. The degeneracy of the tracks does not allow to use the pulsational analysis to discriminate between the two evolutionary phases. However, this uncertainty would disappear if the distance of V351 Ori were the same as that of the Orion population stars. Then, the difference between the pre- and post-MS tracks would be large enough that the period analysis would rule out one of the two solutions. Future studies of V351 Ori should address this important aspect.

As in the case of HD35929, we used the measured Strömgren indices [c1] and [m1] to provide an independent evaluation of the location in the HR diagram of this star. The results, $\log T_{\rm eff} = 3.89$, $L \simeq 30 L_\odot$, now suggest a stellar mass of $\sim 2.25 M_\odot$ for this pulsator, in which case the observed periods would be consistent with an oscillation in the TO pulsation mode.

In conclusion, the present observations yield compelling evidence for the occurrence of δ Scuti-type pulsation in two Herbig Ae stars, HD 35929 and V351 Ori. The comparison with evolutionary and pulsational models provides independent, even if quite preliminary, constraints on the mass and evolutionary state of these stars.

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