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Recent results on Pre-main sequence δ Scuti stars.

V. Ripepi[1], M. Marconi[1], F. Palla[2], S. Bernabei[3,4], A. Ruoppo[1,5], F. Cusano[1,5], and J.M. Alcalá[1]

[1] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Napoli, Via Moiariello 16, I-80131 Napoli, Italy e-mail: `ripepi@na.astro.it, marconi@na.astro.it, jmea@na.astro.it`
[2] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy e-mail: `palla@arcetri.astro.it`
[3] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Bologna, Via Ranzani 1, 40127 Bologna, Italy
[4] Departimento de Astrofísica, Universidad de La Laguna, Avda. Astrofisico F. Sánchez sn, 30071 La Laguna, Spain e-mail: `stefano.bernabei@bo.astro.it`
[5] Dipartimento di Scienze Fisiche, Università Federico II, Complesso Monte S. Angelo, 80126, Napoli, Italy e-mail: `ruoppo@na.astro.it, fcusano@na.astro.it`

Abstract. Intermediate mass Pre-main sequence stars ($1.5\ M_\odot < M < 5M_\odot$) cross the instability strip on their way to the main sequence. They are therefore expected to be pulsating in a similar way as the δ Scuti stars. In this contribution we present the status of the observational studies of pulsations in these stars with special emphasis on recent results from our group. The prospects for future investigations of these objects from the ground and from space are discussed.

Key words. Stars: variables – Stars: Pre-Main-Sequence – Stars: δ Scuti

1. Introduction

Intermediate mass Pre-Main-Sequence (PMS) stars (M>1.5 $M_\odot$), often referred to as Herbig Ae/Be stars (Herbig 1960), are known to show photometric and spectroscopic variability on very different time-scales. Variable extinction due to circumstellar dust causes variations on week timescales, whereas clumped accretion or chromospheric activity is responsible for hours to days variability (see e.g. Catala 2003). The fact that Herbig Ae/Be stars cross the pulsation instability strip of the more evolved δ Scuti stars during their contraction toward the Main Sequence, suggests that the variability on time scales of minutes to hours is due to pulsation (see Baade & Stahl 1989; Kurtz & Marang 1995).

Indeed the possible presence of pulsators among Herbig Ae/Be stars is particularly attractive since the precise observables which can be measured, i.e. the pulsation frequencies can, in principle, allow us to test evolutionary models by constraining the internal structure using asteroseismological techniques.

Send offprint requests to: V. Ripepi

The first detection of pulsation among Herbig Ae/Be stars date back to 1972 with the discovery of the two candidates V588 and V589 Mon in the young open cluster NGC 2264 (Breger 1972). This initial finding was confirmed by subsequent observations of δ Scuti-like pulsations in the Herbig Ae stars HR5999 (Kurtz & Marang 1995) and HD104237 (Donati et al. 1997).

These papers stimulated the first theoretical investigation of the PMS instability strip based on non-linear convective hydrodynamical models (Marconi & Palla 1998) who calculated the topology of the PMS instability strip for the first three radial modes. These authors also found that the interior structure of PMS stars crossing the instability strip is significantly different from that of more evolved Main Sequence stars (with the same mass and temperature), even though the envelopes structures are similar. This property was subsequently confirmed by Suran et al. (2001) who made a comparative study of the seismology of a 1.8 $M_{\odot}$ PMS and post-MS star. Suran et al. (2001) pointed out that the unstable frequency range is approximately the same for PMS and post-MS stars, but that some non-radial modes are very sensitive to the deep internal structure of the star. In particular, it is possible to discriminate between the PMS and post-MS stage, using differences in the oscillation frequency distribution in the low frequency range (i.e. g modes).
An other important aspect of PMS δ Scuti studies is represented by the possibility to search for mode frequency changes due to evolution of the stellar inner structure (Breger & Pamyatnykh 1998). In fact, PMS evolutionary time scales are short enough to give relative variations of pulsation periods of the order of $\dot{P}/P$=10^{-6}, corresponding to about 0.4 h in 10 years for the epoch of maxima in the case of the star HR 5999 (Catala 2003).

2. Observations of PMS δ Scuti variables

Since the seminal work by Marconi & Palla (1998) our group started a systematic photometric monitoring program of intermediate mass PMS stars with spectral types from A to F2-3 with the aims to: 1) identify the largest number of pulsating objects in order to observationally determine the boundaries of the instability strip for PMS δ Scuti pulsation; 2) study in detail through multisite campaigns selected objects showing multiperiodicity (see Marconi et al. 2001; Ripepi et al. 2002; Pinheiro et al. 2003; Ripepi et al. 2003; Bernabei et al. 2004). The multiperiodic pulsators are potential candidates for future asteroseismological analysis.

Similar observational programs have been carried out by various groups. As a results the current number of known or suspected candidates amounts to about 34 stars (see the updated list at http://ams.astro.univie.ac.at/pms_corot.php, and the reviews by Zwintz et al. 2004; Marconi & Palla 2004; Marconi et al. 2004). In particular over 34 candidates, 29 have been studied photometrically, but most of them have insufficient data due both to the short duration of the observations and/or to the poor duty cycle. Therefore most of the periodograms are affected by aliasing problems and are not useful for asteroseismology.

Only 5 stars have been observed by means of multisite campaigns: V588 and V589 Mon (12 and 19 frequencies respectively, Zwintz et al. 2004), V351 Ori (5 frequencies, Ripepi et al. 2003), IP Per (9 frequencies, Ripepi et al. 2005), and HD 34282 (9 frequencies, Amado et al. 2005).

Concerning spectroscopic studies, radial velocities and line profile analysis (the latter being sensible to high degree modes, very useful for asteroseismology) have been carried out only for few stars: V351 Ori (5 frequencies, Balona et al. 2002), β Pic (19 frequencies, Koen et al. 2003), HD 104237 (5 frequencies, Boehm et al. 2004), and the binary star RS Cha (Alecian et al. 2005). This last object is very interesting because it is an eclipsing double-lined spectroscopic binary. Preliminary results based on high resolution spectroscopy (Alecian et al. 2005) seem to show that both components are pulsating. This star therefore will offer the unique opportunity to obtain stringent constraints on pulsating models.

3. Theoretical interpretation

The comparison between observed frequencies and those predicted by linear non-adiabatic pulsation analysis allows us to evaluate the position in the HR diagram and the mass for both field and cluster pulsator (see Fig. 1). No object is predicted to be located to the right of the red boundary of the theoretical instability strip by Marconi & Palla (1998). Some objects are predicted to pulsate in higher overtones than the second one and then to be located to the left of the 2^{nd} overtone blue edge. However it can be seen in Fig. 1) that the majority of the pulsators are located within the observed instability strip for evolved δ Scuti stars (Breger & Pamyatnykh 1998).

Most of the well observed candidates PMS δ Scuti stars show frequencies which cannot be reproduced by radial analysis only. Clearly non-radial modes are present in this class of stars. A thorough interpretation of observed frequencies at the light of non-radial pulsation theory is still lacking for PMS δ Scuti stars.

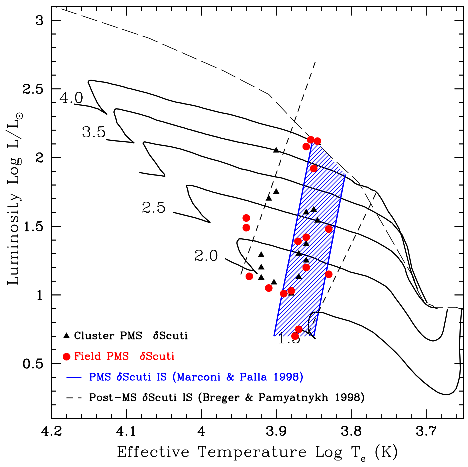

Fig. 1. The position of PMS δ Scuti stars in the HR diagram as predicted on the basis of the comparison between the observed periodicities and linear nonadiabatic radial pulsation models. The shaded region is the theoretical instability strip for the first three radial modes (Marconi & Palla 1998), that is the region between the second overtone blue edge and the fundamental red edge. The dashed lines represent the instability strip of more evolved δ Scuti stars (Breger & Pamyatnykh 1998).

4. The case of IP Per

IP Per is a Herbig Ae star with: V=10.34 mag, spectral type A7V, $\log L/L_{\odot} \sim 1.0 \pm 0.05$ dex, $T_{\rm eff}\sim 8000\pm 200$ K (Miroshnichenko et al. 2001). By using this physical parameters in the HR diagram, IP Per falls in the instability strip for δ Scuti pulsation by Marconi & Palla (1998). In order to study in detail this star, we carried out a multisite campaign involving nine telescopes around the world (for details see Ripepi et al. 2004, 2005). As a result we were able to detect nine frequencies of pulsation as shown in Fig. 2 where we report the Fourier Frequency analysis for the visual dataset.

The observed periodicities can be used to constrain the intrinsic stellar properties of IP Per and in particular its mass and position in the HR diagram, through comparison with stellar pulsation models. Using a linear non-adiabatic pulsation code (see Marconi & Palla 1998; Marconi et al. 2004) we could not reproduce all the observed frequencies. In fact, we can recover at most 5 of the 9 observed frequencies for $M = 1.77 \pm 0.01 M_{\odot}$, $\log L/L_{\odot} = 0.992 \pm 0.003$, $\log T_{\rm eff} = 3.887 \pm 0.002$. This solution corresponds to a radial pulsation model which simultaneously oscillates in the first ($f1$), second ($f5$), third ($f2$), fifth ($f4$) and sixth ($f9$) overtones. Its position in the HR diagram is shown in Fig. 3 together with the predicted instability strip by Marconi & Palla (1998) and the PMS evolutionary tracks computed for the labelled stellar masses with the FRANEC stellar evolution code (Chieffi & Straniero 1989; Castellani et al. 1999). The $1.77 M_{\odot}$ PMS track is represented by the dotted line. Note that the predicted position in the HR diagram is consistent with the empirical determination based on the spectroscopic measurements (Miroshnichenko et al. 2001) represented by the filled circle in the figure.

Non-radial pulsation is clearly also present in this star. A preliminary interpretation of the observed frequencies through the

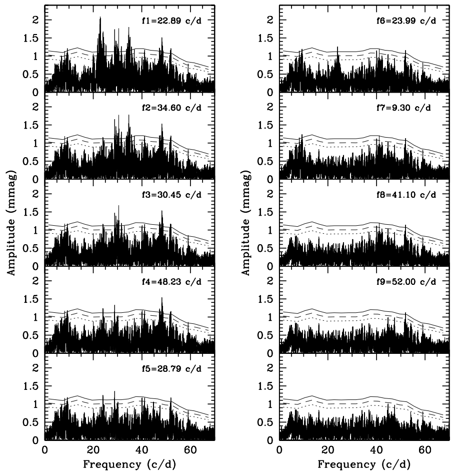

Fig. 2. Frequency analysis for the V dataset. The solid, dashed and dotted lines show respectively the 99.9%, 99% and 90% significant levels determined in a standard way (Kuschnig et al. 1997).

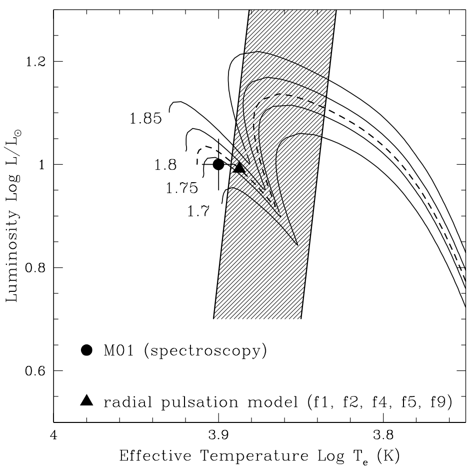

Fig. 3. Position in the HR diagram of the best-fit radial pulsation model for IP Per. The shaded region is the predicted instability strip by Marconi & Palla (1998). Solid lines are the PMS evolutionary tracks computed for the labelled stellar masses with the FRANEC stellar evolution code (Chieffi & Straniero 1989; Castellani et al. 1999). The dashed lines represent the $1.77 M_\odot$ PMS track with solar composition. The empirical determination based on the spectroscopic measurements (Miroshnichenko et al. 2001) is shown with a filled circle.

Aarhus adiabatic non-radial pulsation code (http://astro.phys.au.dk/~jcd/adipack.n/), applied to the evolutionary structure of the 1.77 $M_\odot$ model reproducing $f1$, $f2$, $f4$, $f5$ and $f9$ with radial modes, seems to indicate that $f3$, $f6$ and $f8$ are associated with non-radial modes with $l = 2$.

5. Future prospects

The future of PMS δ Scuti studies relies mainly on space missions. Indeed, two asteroseismological satellites have the possibility to observe PMS stars: MOST and COROT. MOST (Microvariability and Oscillations of STars, http://www.astro.ubc.ca/MOST/) is equipped with a 15 cm telescope and a CCD camera. MOST already observed the two prototypes of the class: V588 and V589 Mon. The results will be available in the near future.

COROT (COnvection and ROTation of stars; http://corot.oamp.fr) will be launched in June 2006 and will observe a few fields for 5 months continuously and a few others for 10-20 days. In the context of Additional Programs there are a few proposals having also PMS δ Scuti stars as targets. Among these projects, we would describe more in detail the one (already approved by SC, P.I. V. Ripepi) concerning the observation (in the ESO-Planet field) of few selected stars in Dolidze 25, a distant, metallicity-deficient young open cluster which fall in the continuous viewing zone of COROT. In order to identify PMS objects in this cluster, we carried out a photometric (RI filters) and spectroscopic investigation of Dolidze 25 by using VIRMOS@VLT instrument. Photometry has been used to select targets for spectroscopy. In total we obtained ~900 spectra with medium resolution (2.5Å/pixel) and ~600 with higher resolution (0.6Å/pixel). The result of this investigation is reported in Fig. 4, where we present the CMD in the I vs (R-I) plane. The blue filled circles in the figure identify all the objects with R≤17.2 for which we have found Hα emission. As shown in the figure at least four of these ob-

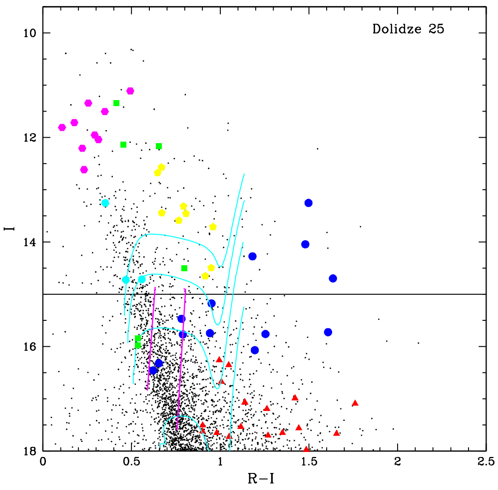

Fig. 4. CM-diagram in the I vs (R-I) plane for an area of about 25′x25′ centered on Dolidze 25 as obtained from VIMOS@VLT pre-imaging data (black dots). The various symbols (except the red triangles) show the young stars proposed to be observed with COROT. Note that at least four object fall within the observed instability strip for PMS δ Scuti pulsation (magenta solid line). Cyan lines show PMS tracks for Z=0.008 and masses of 1.5,2.5,3.5 and 4.5 $M_{\odot}$ (Degl'Innocenti & Marconi, private communication). As reference, the black solid line show roughly the level of V=16 mag

jects fall within or near the observed instability strip for PMS pulsation.

6. Conclusions

Asteroseismology applied to PMS δ Scuti stars would allow us to test the evolutionary status and the internal structure of these objects. However more theoretical work is needed in order to interpret present observations.

Observationally we are still in an early phase: the empirical instability strip is not well known and only for few stars the derived frequency spectrum is accurate enough to use asteroseismological techniques.

We expect great improvements in the study of PMS δ Scuti stars from space observations with the satellites MOST and COROT.

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