The A-Star Puzzle
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Pre-Main-Sequence A-type stars

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Abstract. Young A-type stars in the pre–main-sequence (PMS) evolutionary phase are particularly interesting objects since they cover the mass range ($\sim$1.5-4 $M_\odot$) which is most sensitive to the internal conditions inherited from the protostellar phase. In particular, they undergo a process of thermal relaxation from which they emerge as fully radiative objects contracting towards the Main Sequence. A-type stars also show intense surface activity (including winds, accretion, pulsations) whose origin is still not completely understood, and infrared excesses related to the presence of circumstellar disks and envelopes. Disks display significant evolution in the dust properties, likely signalling the occurrence of protoplanetary growth. Finally, A-type stars are generally found in multiple systems and small aggregates with lower mass companions.

Keywords. Stars: evolution, stars: Pre–Main-Sequence, stars: oscillations (including pulsations), stars: variables: δ Scuti

1. Introduction

Young A-type stars do not resemble their mature siblings. As a class, they are known as Herbig Ae stars (Herbig 1960) because of the presence of optical emission lines in their spectra, their association with nebulosities, and conspicuous infrared excesses in the spectral energy distributions. Their early evolution is marked by the occurrence of a variety of phenomena that disappear in the course of time. When they emerge from the protostellar phase, their internal structure is highly unrelaxed and must undergo a global readjustment. Unlike low-mass protostars which are fully convective, intermediate mass protostars (in the mass range $\sim$1.5 to 4 $M_\odot$) have developed a radiatively stable core and an outer convective region where deuterium burns in a shell (Palla & Stahler 1990). As a result, stars in this mass range begin with a modest surface luminosity and undergo thermal relaxation in which the central regions contract while transferring heat to the expanding external regions. Then, in a short time, the star acquires its full luminosity and begins contracting towards the Main Sequence (Palla & Stahler 1993).

Another distinction of young A stars is their surface activity. Winds are relatively common at rates $\sim 10^{-8} - 10^{-7}$ $M_\odot$ yr^{-1}, but their origin is not understood (Corcoran & Ray 1997, Catala & Boehm 1994). Evidence for accretion at similar rates is also available from ultraviolet lines and redshifted Lyman α lines (Deleuil *et al.* 2004). Equally unexplained is the X-ray emission with luminosities intermediate between those in T Tauri and massive stars (Hamaguchi *et al.* 2001). Also, young A stars rotate more rapidly than lower mass objects, but still significantly below breakup and below the values observed in Main Sequence stars of the same spectral type (Boehm & Catala 1995). Thus, they should spin up considerably during (PMS) contraction, assuming conservation of angular momentum. Additionally, their outer layers are subject to a δ Scuti-like pulsational instability, albeit for a limited amount of time (Marconi & Palla 1998). Finally, and quite importantly,

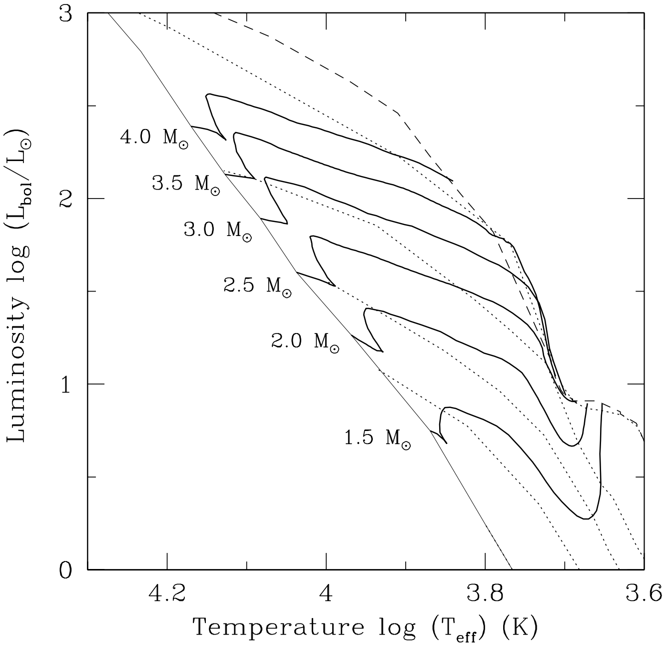

Figure 1. HR diagram of stars in the mass range 1.5–4 $M_\odot$. The evolutionary tracks start at the birthline (dashed line) and end on the ZAMS (thin solid line). Selected isochrones (dotted lines) are for 0.1, 1, 3, and 10 Myr (from top to bottom). (Adapted from Palla & Stahler 1999)

circumstellar disks are almost invariably found around them with characteristics that indicate significant evolution during the PMS phase.

Once they reach the Main Sequence, A-type stars continue to show interesting properties, but most of the excitement is gone. The major changes take place in a very short time, from ~17 Myr for a 1.5 $M_\odot$ star to ~1 Myr for a 3.5 $M_\odot$ object. Now we shall provide an overview of the main properties and the many puzzles that characterize the brief, but intense early life of A stars.

2. Evolutionary properties

As stated above, the initial phases of PMS evolution are marked by the persistence of the conditions inherited from protostellar accretion. Intermediate mass stars are the most affected by the prior history and their evolution departs significantly from the standard results established in the works of Hayashi, Iben and collaborators in the 1960s. A more modern description of PMS evolution in the Hertzprung-Russell (HR) diagram from the birthline to the ZAMS is shown in Figure 1 (Palla & Stahler 1999). The birthline is the locus where stars first appear in the HR diagram after the main accretion phase and the results displayed here have been obtained assuming a protostellar mass accretion rate of $\dot{M}_{\rm acc} = 10^{-5}\ M_\odot\,{\rm yr}^{-1}$, typical of the observed values in dense molecular cores undergoing dynamical collapse (e.g., Lee *et al.* 2004). Although quantitatively the initial conditions change with $\dot{M}_{\rm acc}$, the qualitative behavior of protostars is not changed substantially (see a discussion in Palla 2002).

The main feature of the new tracks of Figure 1 is the complete absence of a fully convective phase. Starting at about 1.5 $M_\odot$, PMS stars have almost fully depleted their initial deuterium reservoir and, due to their small radius (~4 $R_\odot$), do not have any

Table 1. Evolution of intermediate-mass PMS stars

Property	1.5 $M_\odot$	2.0 $M_\odot$	2.5 $M_\odot$	3.0 $M_\odot$	3.5 $M_\odot$	4.0 $M_\odot$
$R_{\rm init}$ ($R_\odot$)	5.0	4.4	4.1	4.0	4.2	7.8
$R_{\rm ZAMS}$ ($R_\odot$)	1.7	1.8	2.1	2.3	2.5	2.7
$\Delta M_{con}^{\rm init}$ ($M_\odot$)	1.5	2.0	1.8	1.1	0.7	...
$\Delta M_{con}^{\rm ZAMS}$ ($M_\odot$)	0.2	0.3	0.5	0.6	0.7	0.9
$t_{\rm rad}$ (Myr)	9.4	3.4	1.3	0.4	0.07	...
$t_{\rm ZAMS}$ (Myr)	17	8.4	3.9	2.0	1.3	0.8

energy sources (nuclear or cooling from the surface) to maintain convection. Thus, their evolution starts near the bottom of the Hayashi phase and quickly joins the radiative tracks of homologous contraction.

Stars in the range 2.5–3.5 $M_\odot$ begin their evolution at low luminosity and move up to join the radiative track. In fact, the tracks loop behind the birthline and then recross it before pursuing the horizontal paths. These stars undergo a nonhomologous contraction and a thermal relaxation during which the radius, luminosity, and effective temperature all increase, while the outer convection disappears. Note also the crowding of the tracks that all start from about the same position before moving up vertically. Thus, assigning a correct mass to stars in this part of the HR diagram is tricky.

Finally, stars of mass $\gtrsim$4 $M_\odot$ appear immediately on the radiative track and begin to contract homologously under their own gravity. As the star contracts, the average interior luminosity rises as $R_*^{-1/2}$, as is evident from the slope of the tracks.

Some important properties of the evolution, both at the beginning and the end of the PMS phase, are given in Table 1. The first two rows list the stellar radii on the birthline and on the ZAMS. Note the similarity of the values of $R_{\rm init}$ that explains the crowding of the tracks in Figure 1. The table also lists $\Delta M_{\rm con}$, the mass in the convection zone. For the ZAMS models, this convection is located in the center and is due to the strongly temperature-sensitive CN burning. Finally, $t_{\rm rad}$ is the time (in units of 10^6 yr) when the star becomes fully radiative, measured relative to the star's appearance on the birthline. Note the dramatic reduction of $t_{\rm rad}$ for stars more massive than $\sim$3 $M_\odot$. The last entry, $t_{\rm ZAMS}$, gives the total duration of the PMS phase.

3. Circumstellar disks around A stars

Once the main phase of accretion is completed, the stellar core emerges as an optically visible star along the birthline. The circumstellar matter around the star, partly distributed in a disk and the rest in an extended envelope, still emits copiously at infrared and millimeter wavelengths. The spectral energy distributions of Herbig Ae stars resemble those observed in classical T Tauri stars (CTTSs), thus suggesting that the dust responsible for the thermal emission has similar properties and geometrical distribution (e.g., Hillenbrand *et al.* 1992). However, there are important differences. Unlike CTTSs, a significant fraction of the luminosity is emitted at short wavelengths with a prominent peak at 2–3 μm (Meeus *et al.* 2001). These properties cannot be explained in terms of standard disk models where the dust is heated by viscosity and stellar radiation, and is distributed in optically thick and geometrically thin or flared disks. Thus, some basic modifications of the disk structure are required. For example, Dullemond *et al.* (2001) have suggested that the innermost regions where the dust sublimates (few tenths of AU)

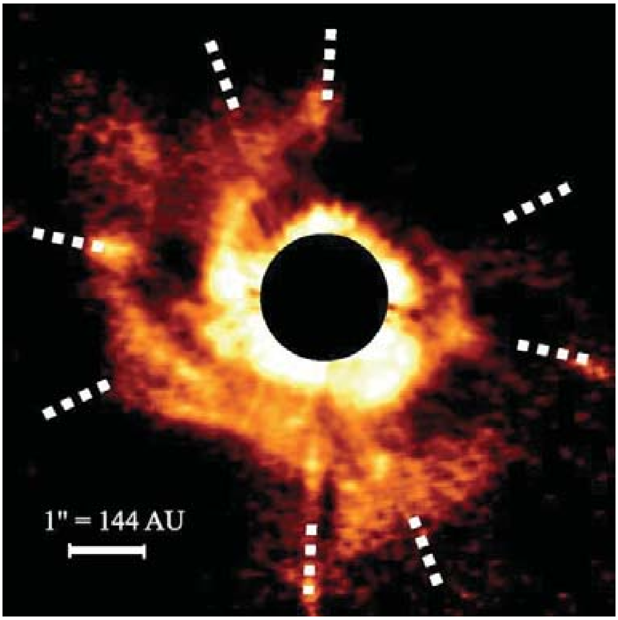

Figure 2. Disk around AB Aur. H-band image at resolution 0.1 arcsec obtained with a coronagraphic imager on Subaru (Fukagawa *et al.* 2004).

are distributed in an optically thick puffed-up rim that shadows the optically thin dust at larger distances (which remains cool), thus explaining the strong NIR emission.

The predictions of these models and the geometrical shape of the disks can now be directly probed by means of near- and mid-IR interferometry and adaptive optics on large telescopes that can resolve regions ~0.1 to a few AU in size at the typical distances of 0.3–1 kpc. The initial results indicate that indeed the data are best reproduced by flared passive disks with puffed-up inner rims (Eisner *et al.* 2004, Leinert *et al.* 2004). A particularly striking example is the circumstellar disk around AB Aurigae shown in Figure 2. This A0 star is one of the closest (d=144 pc) and best studied Herbig Ae objects, with mass $\sim 2.5\ M_\odot$ and age ~4 Myr. Millimeter observations of ^{13}CO gas have revealed the presence of a rotating disk ~450 AU in radius and an estimated mass $\sim 0.02\ M_\odot$ (Mannings & Sargent 1998). The disk is immersed in an extended envelope (>1000 AU) visible in scattered light. The image in Figure 2 shows that the extended emission has a double spiral structure almost the same size of the CO disk and is possibly associated with the latter rather than the envelope (Fukagawa *et al.* 2004).

That disks are common around Ae stars is directly seen at millimeter wavelengths where spatially resolved images reveal disk features at scales of few hundred AU in CO emission (Dutrey 2004). Interestingly, while Keplerian disks are found between 75 and 100% of Ae stars, the percentage drops dramatically for the more massive Herbig Be stars. This is shown in the upper panel of Figure 3 that covers two orders of magnitude in stellar mass (from CTTSs to B0 type stars). A likely explanation of this trend is related to the rapid dispersal of the disks around more massive and luminous stars which are subject to strong UV radiation fields and more powerful outflows. Finally, the lower panel of Figure 3 reveals that although the disk mass increases with stellar mass, the ratio of the disk-to-star mass remains basically constant in the range 0.2–3 $M_\odot$, implying that all PMS stars have low-mass disks.

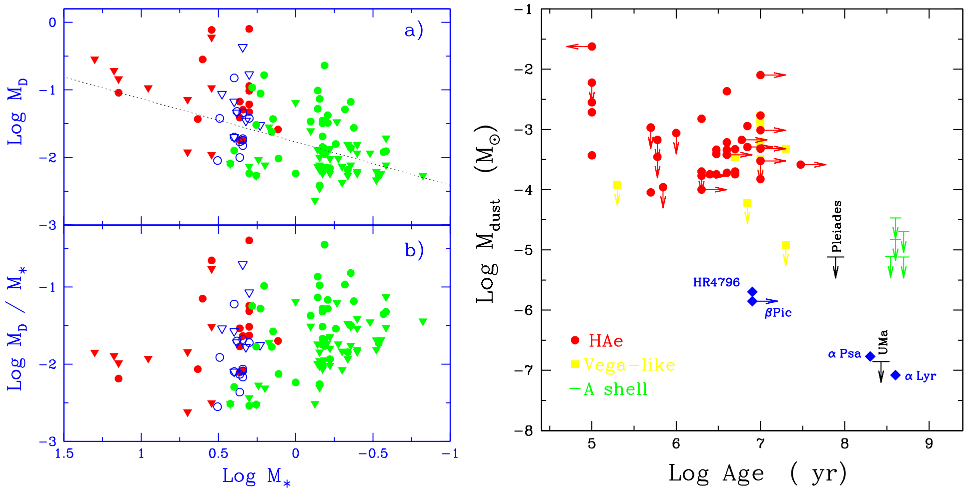

Figure 3. Left: Properties of disks around low- and intermediate-mass stars. *Upper panel*: disk mass as a function of the stellar mass as inferred from mm-interferometric observations. Filled and empty circles are detections, while triangles are upper limits. *Lower panel*: ratio of the disk-to-star mass *vs.* stellar mass (Natta 2004). Right: Evolution of the disk mass with time for A-type stars (Natta *et al.* 2000).

As a last property of disks, let us point out that A-type stars provide the strongest evidence for disk evolution during the PMS phase and on the MS. The time evolution of the disk mass is displayed in the right panel of Figure 3 covering more than 4 decades in stellar ages. For ages less than ∼10 Myr, the disk mass is about constant. Then, in objects on the ZAMS, such as HR 4796 and β Pic, the disks are significantly reduced in mass and almost completely devoid of gas (so-called *debris disks*). At this stage, there is also evidence for grain growth in which dust gradually agglomerates into larger, more crystalline structures that should favor planetesimal condensation. The dust grains are subject to the Poyting-Robertson drag from stellar photons which causes them to spiral inward. Others must be resupplied, presumably through the mutual collisions of larger orbiting bodies. In fully evolved stars (α Lyr and α PsA, $\gtrsim$200 Myr) the dust becomes undetectable in scattered light and visible only in the far-IR and its actual luminosity has declined to only $\sim 10^{-5}\ L_*$.

4. Interaction with the environment

Most Herbig Ae stars are found close to or embedded within their natal gas clouds. Studies of the distribution of the ^{13}CO emission reveal the pattern shown in Figure 4 where the youngest stars are still immersed in dense cores (top) while the older ones are found in cavities created during PMS evolution (Fuente *et al.* 2002). The physical process responsible for the removal of the dense gas is likely to be related to the activity of bipolar outflows during the protostellar phase. Bipolar outflows sweep out matter along the poles and creat a biconical cavity. Material in the envelope accretes onto a circumstellar disk that feeds the growing star. In this way, the cloud evolves toward a more centrally peaked morphology while a significant fraction of the core material is dispersed. Assuming a typical accretion rate of $10^{-5}\ M_\odot\,\mathrm{yr}^{-1}$, an A-type star (2-4 $M_\odot$) will be formed in a few×0.1 Myr. By this time, about 90% of the dense core is dispersed. From a few×0.1 Myr to $\simeq$1 Myr, the star begins the PMS contraction and only a small amount of circumstellar matter is removed because (a) the outflow activity fades rapidly

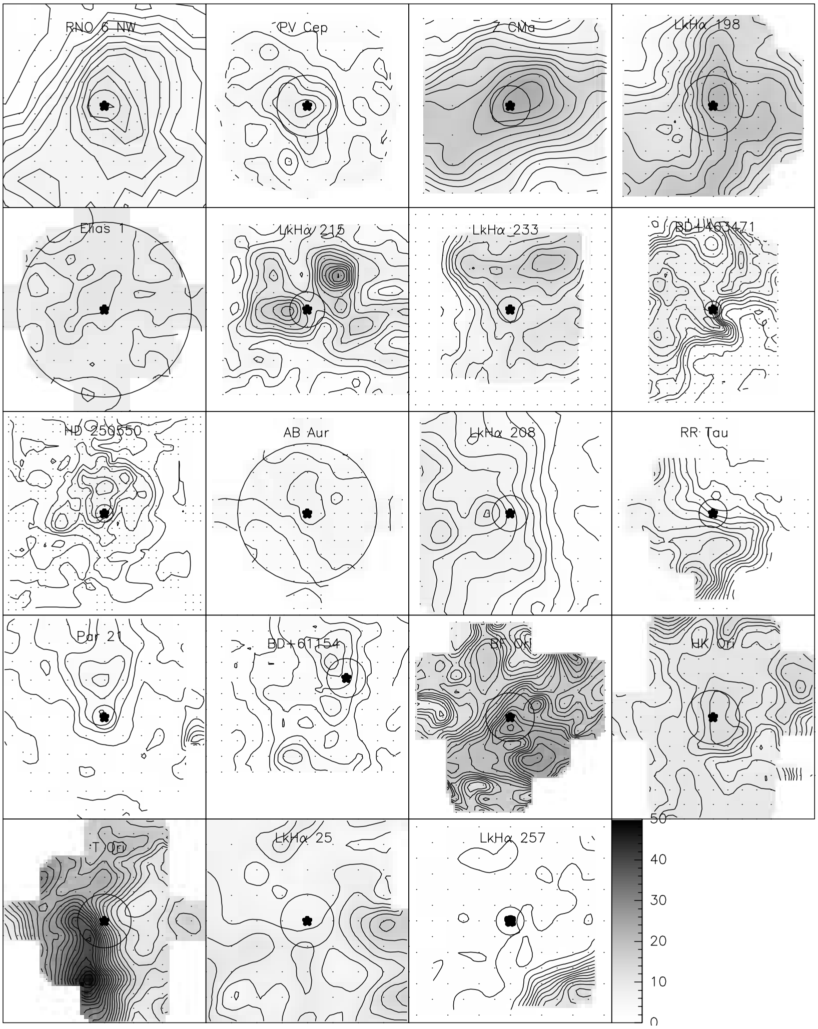

Figure 4. The birth sites of Ae stars seen in ^{13}CO emission. The size of the box varies from source to source. In each panel, a circle of 0.08 pc in radius is drawn around the central star (Fuente *et al.* 2002).

in time, and (b) the stellar surface is still too cold to generate UV photons that can photodissociate the surrounding gas. Finally, from $\gtrsim$1 Myr to ~10 Myr the star reaches the ZAMS and completes the creation of the cavity thanks to the UV radiation, albeit at a slow rate due to the low effective temperatures. This evolutionary sequence highlights once more the transitional character of A-type stars. The late-type A stars behave like T Tauri stars and their associated weak winds, whereas the early-type A stars begin to show the phenomenology (both radiative and mechanical) associated with the more luminous Be-type objects.

In addition to the properties of the gas, it is interesting to consider the issue of stellar companionship. It is well known that most stars are found in binary or multiple systems. Herbig Ae stars are no exception. The binary frequency of A0-A9 stars with a semi-major axis less than 2000 AU (corresponding to log P=5-7 days) is 42%, or 50-60% when corrected for incompleteness (Bouvier & Corporon 2001). For comparison, the binary

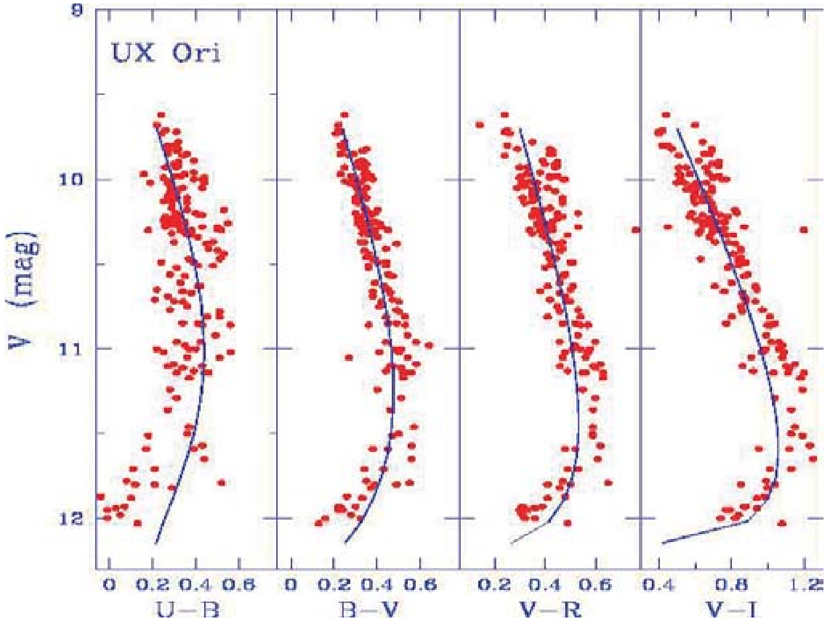

Figure 5. Color-magnitude diagrams of UX Ori showing the blueing effect at minimum (Rostopchina *et al.* 1999).

frequency of field G dwarfs in the same period interval is only 20%. Thus, binary Herbig Ae stars exceed binary G-type stars by a factor of 2 and show an higher percentage than binary T Tauri stars. This difference certainly has some bearing on the formation process. In particular, it is possible that Herbig Ae stars form in more crowded environments than lower mass stars and that dynamical interactions lead to capture of neighboring stars. Indeed, models of the evolution of small clusters predict an increase of the binary frequency with the mass of the primary. Interestingly, Ae stars tend to be found in aggregates with density $\lesssim 10^2$ stars pc^{-3} (Testi *et al.* 1999), higher than the isolated regime of T Tauri stars ($\lesssim 10$ stars pc^{-3}), but lower than the clusters associated with massive stars ($\gtrsim 10^3$ stars pc^{-3}).

5. Variability

Young A-type stars show evidence of a dusty environment, intense stellar activity and strong stellar winds. As a result they are photometrically, spectroscopically and polarimetrically variable on very different time scales and wavelength domains (e.g., Herbst & Shevchenko 1999). The typical long-term variability due to obscuration by circumstellar dust is called *UX Ori* variability from the name of the prototype object (see Figure 5). The periodicity has a time scale on the order of ∼1 yr and can be as large as 3 magnitudes in the V band. After a few days at minimum, the star resumes its normal brightness in several weeks. During the approach to minimum, the color becomes bluer and the polarization increases dramatically. Both effects suggest that the origin of the dimming is due to scattering by circumstellar dust distributed in optically thick clouds that partially occult the star (e.g., Grinin *et al.* 1991). The other type of variability takes place on shorter time scales (typically, few hours) and involves much smaller variations (few thousandths to few hundredths mag). Since the variability is associated with the κ mechanism, its study allows to peer into the the intrinsic properties (and through asteroseismology also the internal structure) of A-type stars, as we will describe next.

Table 2. Pulsation properties of known or suspected PMS δ Scuti stars.

Name	F1 (c d^{-1})	F2 (c d^{-1})	F3 (c d^{-1})	F4 (c d^{-1})	ΔV (mag)	V (mag)	Sp.type	Ref.
V588 Mon	7.1865 ±0.0006	?	?		0.04	9.7	A7	1
V589 Mon	7.4385 ±0.0006	?	?		0.04	10.3	F2	1
HR 5999	4.812±0.010				0.02	7.0	A7	2
HD 104237	33 ± 0.2				0.02	6.6	A7	3
HD 35929	5.10 ± 0.13				0.02	8.1	A5	4
V351 Ori	15.687 ±0.002	13.337 ±0.002	16.868 ±0.002	11.780 ±0.002	0.1	8.9	A7	5
BL 50	13.9175 ±0.0005	9.8878 ±0.0009			0.02	14.5	–	6
HP 57	12.72557 ±0.0002	15.52437 ±0.0003			0.03	14.6	–	6
HD 142666	21.43±3				0.01	8.8	A8	7
V346 Ori	35.3±2.3	22.6±2.7	45.5±2.5	18.3±2.5	0.015	10.1	A5	8
H254	7.406±0.008				0.02	10.6	F0	9
NGC 6383-4	14.376	19.436	13.766	8.295	0.014	12.61	A7	10
NGC 6383-T55	19.024				0.002	20.9	–	10
IP Per	22.887	34.599	30.449	48.227	0.004	10.35	A7	11
V375 Lac	5.20±0.14	2.40±0.14	9.90±0.14		0.004	13.56	A7	12
VV Ser	5.15±0.01	8.61±0.01	4.46±0.01		0.005	11.87	A2(?)	12
BN Ori	10-12.7				0.002	9.67	F2 (?)	12
BF Ori	5.7±0.3				0.006	10.41	A5 (?)	12
HD34282	79.5±0.06	71.3±0.06			0.011	9.873	A0-A3	13
IC 4996-37	31.87				0.005	15.302	A5	14
IC 4996-40	42.89				0.008	15.028	A4	14

Sources: (1) Breger (1972), Peña *et al.* (2002), (2) Kurtz & Marang (1995), Kurtz & Catala (2001), (3) Donati *et al.* (1997), Kurtz & Muller (1999), (4) Marconi *et al.* (2000), (5) Ripepi *et al.* (2003), (6) Pigulski *et al.* (2000), (7) Kurtz & Müller (2001), (8) Pinheiro *et al.* (2003), (9) Ripepi *et al.* (2002), (10) Zwintz *et al.* (2004), (11) Ripepi *et al.* (2004), (12) Bernabei *et al.* (2004), (13) Amado *et al.* (2004), (14) Zwintz (2004, private communication)

5.1. *The δ Scuti type pulsation*

During the contraction phase toward the Main Sequence, intermediate-mass stars cross the pulsation instability strip of more evolved variables, suggesting that, despite the relatively short time spent in the strip ($\sim 10^5$-10^6 years), at least part of the observed activity could be due to intrinsic variability.

The first observational evidence for such variability was due to Breger (1972) who detected δ Scuti-like pulsations in two Herbig stars of the young cluster NGC 2264, namely V588 Mon and V589 Mon. The issue was reconsidered more than 20 years later by Kurtz & Marang (1995) and Donati *et al.* (1997) who found δ Scuti-like variability in the Herbig stars HR 5999 and HD 104237. Since then there has been a renewed interest in the study of these young pulsators, both from the observational and the theoretical points of view. For the latter, using convective nonlinear models, Marconi & Palla (1998) computed the first theoretical instability strip for PMS δ Scuti stars (see Figure 6). They also identified a list of candidates with spectral types in the range of the predicted instability region. This theoretical investigation stimulated new observational programs

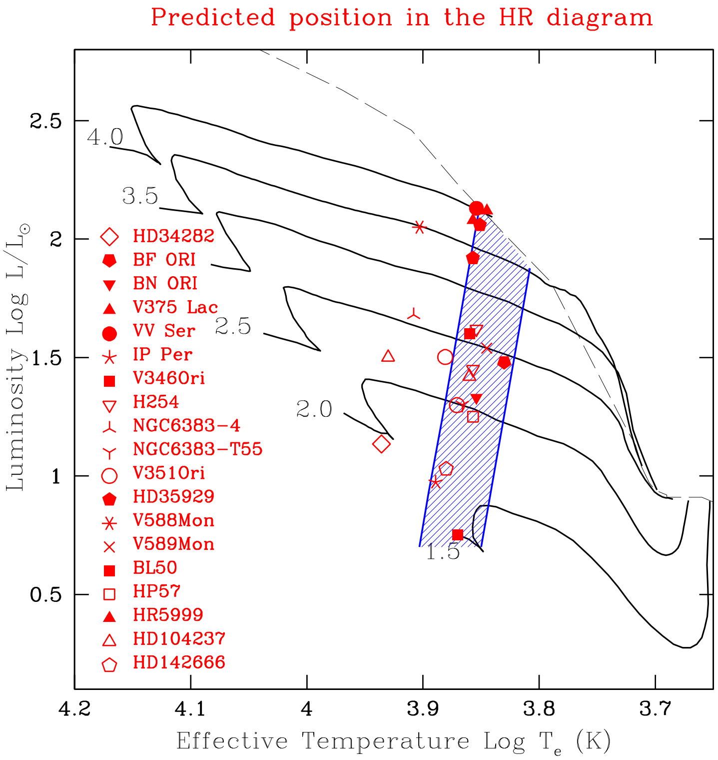

Figure 6. The position of PMS δ Scuti stars in the HR diagram as predicted on the basis of the comparison between the observed periodicities and linear nonadiabatic radial pulsation models. The dashed region is the theoretical instability strip for the first three radial modes (Marconi & Palla 1998), that is the region between the second overtone blue edge and the fundamental red edge.

carried out by various groups with the result that the current number of known or suspected candidates amounts to about 20 stars.

A census of known or suspected PMS δ Scuti stars is reported in Table 2, whereas the position of these pulsators in the HR diagram, as resulting from the comparison between the observed and predicted pulsation frequencies, is shown in Figure 6. We notice the good agreement between the predicted instability strip and the location of observed pulsators. The only deviating objects are hotter than the theoretical second overtone blue edge and are indeed predicted to pulsate in higher overtones, whereas no pulsating object is found to the right of the theoretical red edge. The main limitations of this approach are: 1) the uncertainties still affecting many of the observed frequencies, due to poor data quality and/or the aliasing problem; 2) the difficulty of discriminating between PMS and post-MS evolutionary phases on the basis of radial models, in particular for pulsators that are predicted to be located close to the MS; and 3) that the likely presence of nonradial modes is not taken into account.

Concerning the first point, significant improvements can be obtained by means of multisite campaigns and will certainly be obtained with future satellite missions (e.g., EDDINGTON and COROT). As for the last two issues, it is clear that both radial and nonradial models should be computed to better understand the intrinsic properties of the rather unexplored class of young variable stars. To cope with this problem, we have started a project to apply the adiabatic nonradial code by Christensen-Dalsgaard (available on the web page http://astro.phys.au.dk/~jcd/adipack.n) to PMS evolutionary models. Preliminary results seem to suggest the coexistence of radial and nonradial frequencies at least in the young pulsators V351 Ori and IP Per.

6. Concluding remarks

Although PMS A-type stars cover a small mass interval ($\sim$1.5–4 $M_\odot$), they represent an interesting laboratory for the study of a variety of physical processes, many of which are still poorly understood. As a class, they share many of the characteristic properties of both the lower mass T Tauri stars and of the more massive Herbig Be objects, but depart from them in significant ways. Under the influence of protostellar evolution, A-type stars begin their PMS evolution as thermally unrelaxed structures that undergo a global readjustment from partially convective to fully radiative interiors in a short time scale. Circumstellar disks are much more frequent than in Herbig Be stars, and at least as common as in T Tauri stars. However, the more intense radiation field from the hotter stars makes standard viscous disk models insufficient to explain the observed infrared emission, requiring important modifications in the disk structure and geometry. Unlike Herbig Be stars, PMS A-type stars are generally found in relative isolation or in aggregates containing $\sim$10-100 lower mass members. Finally, their youth is marked by an intense surface activity, which includes winds, accretion, fast rotation, X-ray emission, variable obscuration from circumstellar dust and also intrinsic δ Scuti type pulsation. The latter, with its asteroseismological implications, can provide a unique tool to study their internal structure, to test evolutionary models, and to obtain independent estimates of the stellar mass, the fundamental parameter governing stellar evolution.

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Discussion

BUDOVIČOVÁ: Why do Be stars lack gaseous disks? It is one of their basic properties. Why is it different from Ae stars (having a gas disk)?

MARCONI: We are talking of PMS A-type and B-type stars. The lower frequency of disks around the latter may be due to a rapid distruction due to photoevaporation and/or winds. However, there are recent detections of circumstellar disks around Herbig Be stars (e.g., Fuente *et al.* 2003 ApJ 598, 39).

PISKUNOV: T Tauri stars come in two flavours: classical and weak-line. Do we see a similar phenomenon in pre-MS A stars?

MARCONI: No, the same distinction does not hold for Herbig Ae (or Be) stars. Although many young clusters contain a large population of intermediate mass PMS stars, only a small minority of these objects qualify as being genuine Herbig-type stars. As George Herbig suggested, this may indicate that either the Ae/Be phenomenon is a temporary one, or that some stars in that mass range do not show it at all. In this sense there might be two classes of A-type PMS stars.