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LETTER

*Letter to the Editor*

# Hipparcos data on Herbig Ae/Be stars: an evolutionary scenario ⋆

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**Abstract.** Fundamental astrophysical parameters (distance, temperature, luminosity, mass, age) of a sample of 10 Herbig Ae/Be candidates and 3 non-emission line A and B stars in star forming regions were computed combining Hipparcos parallaxes with data from literature. All genuine Herbig stars in our sample are located between the birthline and the zero-age main sequence (ZAMS) in the Hertzsprung-Russell diagram (HRD), in accordance with what is expected for pre-main sequence stars. The region in the HRD close to the birthline is relatively devoid of stars when compared to the region closer to the ZAMS, in agreement with the expected evolutionary time scales. The Herbig Ae/Be stars not associated with star forming regions were found to be located close to the ZAMS. Additionally we discuss a possible evolutionary scenario for the circumstellar environment of Herbig stars.

**Key words:** Circumstellar matter – Stars: Distances – HR diagram – Stars: Pre-main sequence – Stars: Variables

## 1. Introduction

In a historical paper Herbig (1960) was the first to realize that the "Be and Ae stars associated with nebulosity" are in fact stars of intermediate mass still in their pre-main sequence (PMS) phase of evolution: stars which have lost most of their envelope of infalling gas and dust, but are not yet fusing hydrogen into helium and whose energy is mainly supplied by gravitational contraction. Criteria for membership of this class of stars, now more commonly known as Herbig Ae/Be (HAeBe) stars, are (Thé et al. 1994): (1) spectral type earlier than F8; (2) presence of emission lines; (3) presence of IR-excess in the spectral energy distribution; (4) location in or near a probable star formation region.

Later, stars were found which are not near any plausible star formation region, but show all other characteristics of HAeBe stars. Whether these so-called isolated Herbig Ae/Be stars are young stellar objects remains controversial. Moreover, the membership criteria outlined above do not uniquely select intermediate-mass pre-main sequence stars, but will also select evolved massive stars (Davies et al. 1990) which are still located in the region where they formed. Therefore one has to be careful in identifying Herbig stars with pre-main sequence objects (Herbig 1992).

In this *letter* we will derive astrophysical parameters of a sample of 10 Herbig Ae/Be candidates as well as 3 non emission-line A and B-type stars in star formation regions for which the Hipparcos mission resulted in $3\sigma$ detections of the parallax. An attempt will be made to construct an evolutionary scenario for the circumstellar environment of HaeBe stars. In a forthcoming paper (van den Ancker et al. 1997b; Paper II) we will study the photometric behaviour of the Herbig Ae/Be stellar group using the photometric data on all Herbig stars provided by Hipparcos.

## 2. Data Analysis

Accurate absolute astrometry as well as photometry was obtained by Hipparcos on a sample of 38 A- and B-type stars in nearby star forming regions. This sample is a subset of a list of objects (Thé et al. 1982) which was accepted in 1982 by the Hipparcos consortium and which was released to the P.I. prior to the publication of the Hipparcos Catalogue (ESA 1997), in which a full description of the data products will be given. Table 1 lists the stars for which a $3\sigma$ detection of the parallax was achieved. A full analysis of the complete sample will be given in Paper II.

The first two columns in Table 1 give the Hipparcos number and the name of each star. The third column lists the trigono-

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⋆ Based on data from the Hipparcos astrometry satellite.

**Table 1.** Astrophysical parameters of programme stars.

| Name | | $\pi$ | $f_{\rm rej}$ | $d$ | Association | | | $d_{\rm lit}$ | Ref. | Sp. Type | Ref. | $A_V$ | $\log T_{\rm eff}$ | $\log L_\star/L_\odot$ | $M$ | Age |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HIP | Other | [mas] | [%] | [pc] | D.C. | R.N. | S.A. | [pc] | | | | [$^{\rm m}$] | | | [M$_\odot$] | [Myr] |
| 22910 | AB Aur | 6.9±1.0 | 0 | $144^{+23}_{-17}$ | L1519,(L1517) | | Tau R2 | 140 | (1) | A0Ve | (11) | 0.50 | 4.00 | $1.72^{+0.13}_{-0.11}$ | 2.4±0.2 | 2.5±1.0 |
| 34116 | HD 53367 | 4.1±1.4 | 8 | $250^{+120}_{-60}$ | L1657 | S292 | CMa R1 | 1150 | (2) | B0IVe | (12) | 2.23 | 4.50 | $4.04^{+0.34}_{-0.26}$ | 13±3 | ¿ 0.05 |
| 54413 | HD 97048 | 5.7±0.8 | 0 | $180^{+30}_{-20}$ | DC297.2-15.6 | S135 | CED 111 | 160 | (3) | B9–A0ep+sh | (3) | 1.24 | 4.00 | $1.61^{+0.13}_{-0.10}$ | 2.5±0.2 | ¿ 2 |
| 54557 | HD 97300 | 5.3±1.0 | 1 | $190^{+40}_{-30}$ | | | CED 112 | 160 | (3) | B9V | (13) | 1.33 | 4.02 | $1.54^{+0.17}_{-0.15}$ | 2.5±0.3 | ¿ 3 |
| 56379 | HD 100546 | 9.7±0.6 | 0 | $103^{+7}_{-6}$ | (DC296.2-7.9) | | | 170 | (4) | B9Vne | (14) | 0.28 | 4.02 | $1.51^{+0.06}_{-0.05}$ | 2.4±0.1 | ¿ 10 |
| 58520 | HD 104237 | 8.6±0.5 | 0 | $116^{+8}_{-7}$ | | | Cha III | 84 | (4) | A0Vpe | (4) | 0.71 | 3.98 | $1.77^{+0.06}_{-0.06}$ | 2.5±0.1 | 2.0±0.5 |
| 79080 | HR 5999 | 4.8±0.9 | 0 | $210^{+50}_{-30}$ | DC339.7+9.2 | S14 | Lupus 3 | 140 | (5) | A5–7III/IVe+sh | (12) | 0.37 | 3.88 | $1.89^{+0.17}_{-0.15}$ | 3.1±0.5 | 0.6±0.4 |
| 80462 | HD 147889 | 7.4±1.2 | 0 | $140^{+30}_{-20}$ | L1687 | IC 4603 | Sco R1 | 160 | (6) | B2V | (15) | 3.32 | 4.34 | $3.32^{+0.16}_{-0.13}$ | 7.5±1.0 | ¿ 0.1 |
| 81624 | HD 150193 | 6.7±1.7 | 3 | $150^{+50}_{-30}$ | L1729 | | Sco R1 | 160 | (6) | A1Ve | (16) | 1.61 | 3.97 | $1.47^{+0.25}_{-0.19}$ | 2.3±0.2 | ¿ 2 |
| 87819 | HD 163296 | 8.2±1.0 | 0 | $122^{+17}_{-13}$ | | | | 150 | (7) | A1Ve | (16) | 0.25 | 3.97 | $1.48^{+0.12}_{-0.10}$ | 2.3±0.1 | ¿ 2.5 |
| 93425 | HD 176386 | 7.4±1.2 | 0 | $140^{+30}_{-20}$ | DC359.8-17.9 | NGC 6727 | | 130 | (8) | B9IV | (17) | 0.62 | 4.03 | $1.69^{+0.14}_{-0.13}$ | 2.7±0.2 | ¿ 2 |
| 100289 | BD+40 4124 | 9.3±2.2 | 18 | $110^{+30}_{-20}$ | L888/L895 | NGC 6910 | Cyg R1 | 980 | (9) | B2Ve | (18) | 3.16 | 4.34 | $2.04^{+0.23}_{-0.19}$ | | |
| 103763 | HD 200775 | 2.3±0.6 | 0 | $430^{+160}_{-90}$ | L1174 | NGC 7023 | Cep R2 | 440 | (10) | B2.5IVe | (19) | 1.92 | 4.31 | $3.89^{+0.26}_{-0.21}$ | 10±2 | 0.02±0.01 |

References to Table 1: (1) Elias (1978); (2) Herbst et al. (1982); (3) Whittet et al. (1997); (4) Hu et al. (1989); (5) Hughes et al. (1993); (6) Whittet (1974); (7) Thé et al. (1985); (8) Marraco & Rydgren (1981); (9) Shevchenko et al. (1991); (10) Whitcomb et al. (1981); (11) Böhm & Catala (1993); (12) Finkenzeller (1985); (13) Rydgren (1980); (14) Houk et al. (1975); (15) Cohen (1973); (16) Houk et al. (1988); (17) Houk et al. (1982); (18) Hillenbrand et al. (1995); (19) Rogers et al. (1995).

metric parallax measured by Hipparcos and the $1\sigma$ uncertainty in this (both in milliarcseconds). The fourth column lists the percentage of measurements that had to be rejected to arrive at the solution for the parallax given in the third column. The next column in Table 1 gives the distance, with its $1\sigma$ uncertainty, computed from the parallax. Columns 6–8 contain names of the star forming region in which the star is located. In column 6 an association with a dark cloud from the catalogue of Lynds (1962), or its extension to the southern hemisphere (Hartley et al. 1986) is given. When the name of the dark cloud is in parentheses, this indicates that the star is located near the edge, so the association of the star with the cloud might be doubtful. The next column in Table 1 lists the reflection nebula with which the star is associated, whereas the 8$^{\rm th}$ column in Table 1 gives the name of a stellar aggregate with which the star is associated. A literature distance and a reference to the paper in which this was derived is provided in columns 9 and 10.

## 3. Astrophysical Parameters

In order to compute the total luminosity of the sample stars, photometric data, from the ultraviolet (ANS, TD1, IUE), through the optical (Walraven $WULBV$, Johnson/Cousins $UBVRI$) to the infrared ($JHKLMNQ$, IRAS), were collected from literature. Since many of the stars show strong variations in brightness, only optical and UV data obtained near maximum brightness were used. The stellar luminosity, extinction and effective temperature were computed following the method outlined in van den Ancker et al. (1997a). This method includes a correction for a possible anomalous extinction law towards the object. Since in HAeBes one often overestimates stellar temperatures from UV spectra due to the presence of heated layers in the immediate surroundings of the stars' photospheres (e.g. Blondel & Tjin A Djie 1994), and photometric methods to estimate stellar temperatures often yield erroneous results when the extinction law for the circumstellar material is anomalous, as is often the case for such stars (e.g. Thé et al. 1996), we only use spectral types from literature based on optical spectra (Table 1). The computed visual extinction at maximum brightness $A_V$, effective temperature $T_{\rm eff}$ and stellar luminosity $L_\star$ are listed in columns 13–15 of Table 1.

In Fig. 1, we plot the programme stars in the HR diagram. The error in $\log T_{\rm eff}$ is about 0.05 (or one subclass in spectral type), but individual data points may have larger errors. The error in luminosity is dominated by the error in the distance. Also shown in Fig. 1 are the pre-main sequence evolutionary tracks and the birthline (i.e. the line where a star first becomes optically visible on its evolution to the zero-age main sequence) computed by Palla & Stahler (1993). Using these evolutionary tracks and the isochrones given by the same authors, we can make an estimate of the masses and ages of our programme stars. These are listed in the last two columns of Table 1. Note that for HD 200775 the given age, based on it being a pre-main sequence star, is rather dubious. Given the short main sequence life time of a 10 M$_\odot$ star and the fact that the post-main sequence lifetime of such a star is much longer than its pre-main sequence contraction time, it seems more likely that HD 200775 is already evolving away from the ZAMS, in which case its age would be around 20 Myr.

## 4. Discussion and Conclusions

The observed distribution of stars fits well with what is expected for pre-main sequence stars: they are almost all located between (or at) the zero-age main sequence (ZAMS) and the birthline. There is a good correlation between the luminosity class (Table 1) and the position in the HRD: All giants are located to the right of the ZAMS. The clustering of stars around the evolutionary track of mass 2.5 M$_\odot$ in Fig. 1 is probably due to a selection effect: There are no Herbig Be stars in the nearest star forming

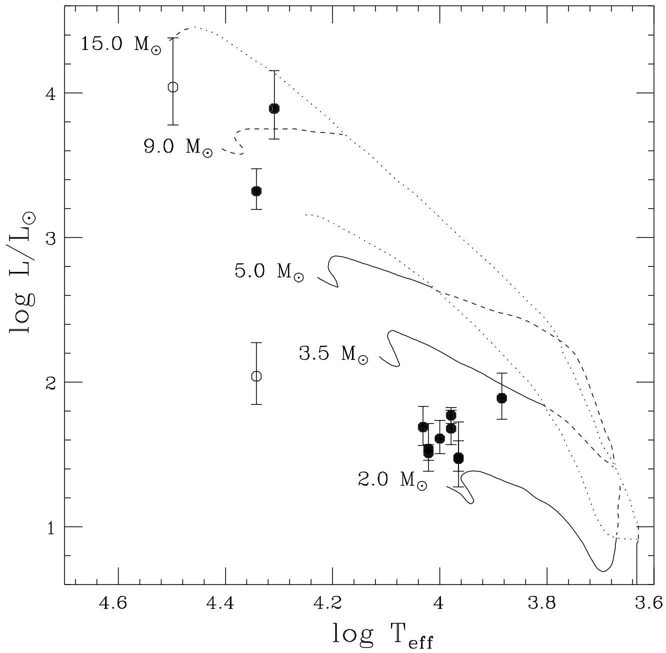


**Fig. 1.** Hertzsprung-Russell diagram of Herbig Ae/Be stars with parallaxes measured by Hipparcos. Open plot symbols indicate stars with $f_{\rm rej} > 3\%$. Also shown are the theoretical pre-main sequence evolutionary tracks (solid lines and dashed lines) and the birthlines for $10^{-4}$ (upper dotted line) and $10^{-5}$ $M_\odot$ $yr^{-1}$ (lower dotted line) by Palla & Stahler (1993).

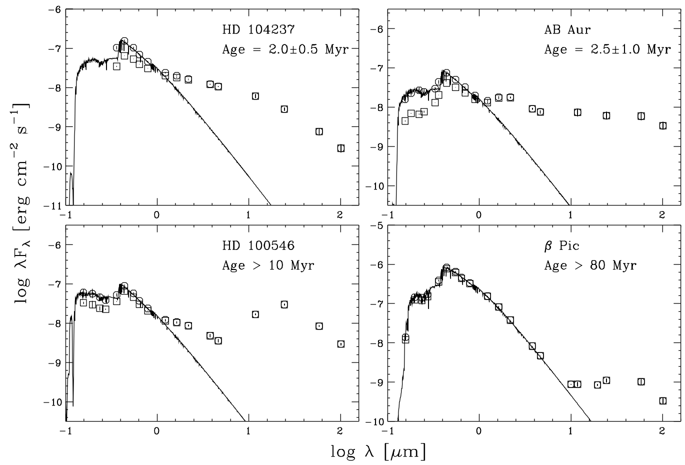


**Fig. 2.** Observed (squares) and extinction-corrected (circles) SEDs for (a) HD 104237, (b) AB Aur, (c) HD 100546, (d) $\beta$ Pic. Also shown are Kurucz (1991) models fitted to the extinction-corrected SEDs.

regions. Since the pre-main sequence evolution of B-type stars proceeds much faster than those of their A-type counterparts this could reflect a difference in age between nearby and more distant star forming regions.

Peculiar is the position of BD+40°4124 in Fig. 1, far below the ZAMS. Such a position seems impossible for a young stellar object. BD+40°4124 illuminates a reflection nebula, in which many other young stellar objects can be found (Hillenbrand et al. 1995), so the possibility of this being an extremely rare evolved object seen projected towards a star forming region can be excluded. Therefore one or more of our assumptions used for deriving this position in the HRD must be wrong. Different authors in literature agree well on the spectral type of BD+40°4124, B2–3e. Also, a spectral type which would place it near the zero-age main sequence is not compatible with the observed spectral energy distribution. However, the distance as measured by Hipparcos (110±30 pc) differs greatly from the literature value of the distance to the star forming region in which BD+40°4124 is located (1000 pc). Therefore we conclude that, although formally the Hipparcos data products give a $4\sigma$ detection for the parallax of BD+40°4124, this must be wrong. We note that for BD+40°4124 and HD 53367 the percentage of measurements that was rejected to arrive at the solution for the trigonometric parallax given in the Hipparcos Catalogue is very high, $f_{\rm rej} > 3\%$ (indicated by open circles in Fig. 1). Furthermore, BD+40°4124 was flagged as a variability induced mover in the Hipparcos Catalogue, most probably indicating problems with the astrometric solution. This case may reflect the difficulty of parallax determinations by Hipparcos in nebulous regions. For HD 53367 the discrepancy between the literature and Hipparcos distance that can be seen in Table 1 is statistically hardly significant.

A fair number of stars in our sample cluster around the 2.5 $M_\odot$ track (Fig. 1). This allows us to construct an evolutionary sequence for their circumstellar environment. We select the objects HD 104237, AB Aur and HD 100546 for which reliable ages were estimated (Table 1), and plot their spectral energy distributions (SEDs) in Fig. 2. Included in Fig. 2 is the SED of $\beta$ Pic which is even older than HD 100546 (Crifo et al. 1997), but has a slightly lower mass. The younger stars in our sample have SEDs that tend to be more or less flat in the infrared, whereas for the more evolved ones the dust excess tends to have a double-peaked structure, with a broad dip in the energy distribution around 10 $\mu$m. Extrapolating such a behaviour, we would expect to end up with a higher-mass equivalent of a star like $\beta$ Pic. Interestingly, Waelkens et al. (1992) showed that the SEDs of Herbig stars can be classified as "flat" or "double-peaked" in the infrared and proposed an evolutionary scenario in which a broad dip around 10 $\mu$m develops with time. The ages derived from the Hipparcos data are consistent with such a scenario.

Spectroscopic evidence for evolution of the circumstellar dust component comes from observations with the Infrared Space Observatory ISO (Waelkens et al. 1996): HD 100546 shows a strong crystalline silicate component, similar to those seen in the ground-based 10 $\mu$m spectra of $\beta$ Pic (Knacke et al. 1993) and of comets (Hanner et al. 1994). A recent ISO spectrum of the comet Hale-Bopp also shows strong crystalline silicates (Crovisier et al. 1997). In contrast, the object HD 104237 shows little evidence for such a crystalline dust component (Malfait, private communication). The occurrence of crystalline dust is an indication for the degree of "processing" which the circumstellar material underwent after accretion from the molecular cloud, and is thus a measure of age. We find that for the small sample discussed here, the age derived from Hipparcos is consistent with the degree of processing seen in the ISO spectra.

We stress that the timescale for the evolution of the central star and the circumstellar material are probably not well coupled: studies of very young open clusters show that only a small percentage of the cluster stars, many of which are undoubtedly pre-main sequence in nature, show circumstellar gas and dust (e.g. van den Ancker et al. 1997a). Furthermore, it is known that some giants, with presumably lower stellar ages, do show a double-peaked infrared excess, making the construction of evolutionary sequences difficult. Provided that the initial configuration and spatial distribution of the circumstellar dust envelopes of the Herbig Ae/Be stars are similar, some unknown physical mechanism regulates the timescale at which the circumstellar matter is dispersed. So, while the *timescales* may be very different for individual stars, it is quite possible that the *sequence* is as proposed in Fig. 2.

It is tempting to speculate about the origins of the formation of a 10 $\mu$m dip. From the presence of 10 $\mu$m amorphous silicate emission in most Herbig Ae/Be stars, we know that the dust envelopes surrounding these stars must be optically thin, and that the presence of a broad dip around 10 $\mu$m must correspond to a physical gap in the radial distribution of dust around HAeBes. Such a gap can only be caused by perturbations by another body surrounding the central star. This could either be a low-mass star outside the dust shell, clearing the region between the inner and outer Lindblad resonances through long-range resonance effects (Lin & Papaloizou 1979), or a Jupiter-sized planet forming inside the dust envelope, clearing $2\sqrt{3}$ Roche lobe radii on either side of the planet (Artymowicz 1987). Since many of the HAeBes with faint companions detected in recent years by speckle interferometry as well as by Hipparcos (paper II) do not show a dip in their energy distributions, we consider the latter explanation more likely.

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