

# The onset of cluster formation around Herbig Ae/Be stars

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**Abstract.** The large body of near infrared observations presented in Testi et al. (1997; 1998) are analysed with the aim of characterizing the young stellar clusters surrounding Herbig Ae/Be stars. The results confirm the tendency of early Be stars to be surrounded by dense clusters of lower mass “companions”, while Ae stars are never found to be associated with conspicuous groups. The transition between the different environments appears to occur smoothly from Ae to Be stars without a sharp threshold.

No correlation of the richness of the stellar groups detected is found with the galactic position or the age of the central Herbig Ae/Be star.

The stellar volume densities estimated for the groups surrounding pre-main-sequence stars of intermediate mass show the transition from the low density aggregates of T Tauri stars and the dense clusters around massive stars.

Only the most massive stars (10–20  $M_{\odot}$ ) are found to be associated with dense ( $\sim 10^3 \text{ pc}^{-3}$ ) stellar clusters. This is exactly the mass regime at which the conventional accretion scenario for isolated star formation faces theoretical problems. Thus our findings strongly supports the idea that the formation of high-mass stars is influenced by dynamical interaction in a young cluster environment.

**Key words:** stars: formation – stars: pre-main sequence – infrared: stars – open clusters and associations: general

## 1. Introduction

The tendency of stars to form in approximately coeval groups, rather than in isolation, is by now a well established observational fact (Lada et al. 1993; Zinnecker et al. 1993; Gomez et al. 1993; Hillenbrand 1995, 1997; Testi et al. 1997). A result which sets stringent constraints to the theory is the fact that the “richness” of the groups depends on the mass of the most massive star in the cluster: low-mass stars form in loose groups of a few objects per cubic parsec (Gomez et al. 1993), which in the following we will call “aggregates”, while high-mass stars are usually found to form in dense clusters with densities up

to  $10^4$  objects per cubic parsec in the case of the Trapezium cluster (see e.g. McCaughrean & Stauffer 1994; Hillenbrand & Hartmann 1998). The transition between these two modes of formation occurs in the mass interval  $2 \lesssim M/M_{\odot} \lesssim 15$ .

Herbig Ae/Be stars (Herbig 1960) are pre-main-sequence (PMS) stars of intermediate-mass located outside complex star forming regions. These stars are sufficiently old (age  $\sim 0.5$ –5 Myr) to be optically visible, but still young enough that any population of lower mass stars born in the same environment has not had time to move away from their birthplace. Thus, the fields around Herbig Ae/Be stars represent ideal targets to study the transition from aggregates to dense clusters and to empirically probe the onset of cluster formation.

Multiwavelength studies of the environments of several Herbig Ae/Be stars in the optical, near infrared and millimeter (LkH $\alpha$  101: Barsony et al. 1991, Aspin & Barsony 1994; BD+40 $^{\circ}$ 4124: Hillenbrand et al. 1995, Palla et al. 1995; MacH12: Plazy & Ménard 1997) have shown that the young clusters are still partially embedded in the parent molecular clouds and that near infrared observations, especially at K-band (2.2  $\mu\text{m}$ ), are best suited to detect the less massive companions to the Herbig Ae/Be star itself. Observations at near infrared wavelengths of a consistent number (16) of fields around Herbig Ae/Be stars have been presented by Li et al. (1994). Their study is focused at the detection of bright companions and/or diffuse emission which may affect large beam photometry of the Herbig stars, and, for this reason, it is limited to a small area around each star, much smaller than the extent of the known clusters (e.g. LkH $\alpha$  101, BD+40 $^{\circ}$ 4124).

The first statistical study aimed at investigating the properties of star formation around Herbig Ae/Be stars using K-band images has been carried out by Hillenbrand (1995). In spite of the relatively small number of observed fields (17), Hillenbrand has found evidence for a correlation between the mass of the Herbig Ae/Be star and the surface density of K-band stars detected around it. These initial results were confirmed by Testi et al. (1997; hereafter Paper I), who obtained J, H and K images of moderately large fields around 19 Herbig Ae/Be stars. Using various methods to define the richness of the star cluster, in addition to simple K-band star counts, in Paper I we have shown a clear dependence of the richness of the embedded clusters with the spectral type of the Herbig Ae/Be star. Moreover, our data

seemed to indicate that the clustered mode of star formation appears at a detectable level only for stars of spectral type B5–B7 or earlier. Whether the transition from isolated stars to clusters has a threshold or is a smooth function of stellar type (or, better, mass) is still unclear because of the small statistical significance of the samples studied so far.

In order to complete our systematic study of Herbig stars, we have observed in the near infrared a second sample of 26 fields selected from the compilations of Finkenzeller & Mundt (1984) and Thé et al. (1994). Among the observed stars, we included Z CMa whose spectral type is F5 and whose membership to the Herbig group has been disputed. However, we will not consider it in the analysis of the clustering properties. Together with the 19 stars analysed in Paper I, our final sample consists of 44 objects covering almost uniformly the whole spectral range from O9 to A7 stars.

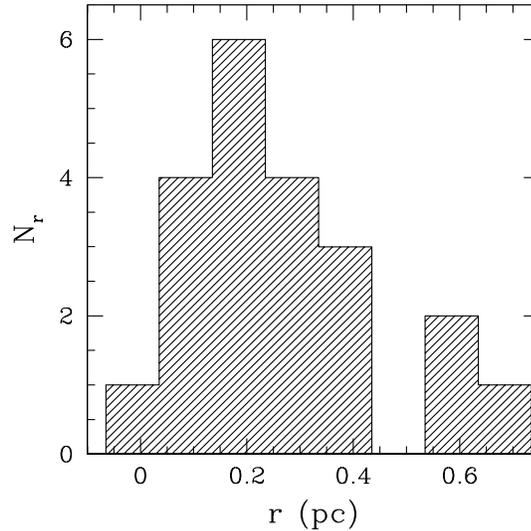
We have included in our sample 33 out of the 39 stars (85%) with declination greater than  $-11.5^\circ$  listed in Finkenzeller & Mundt (1984) and replaced the remaining six objects with 11 stars of similar spectral type taken from the updated catalog of Thé et al. (1994, Table I of members and candidate members). Thus, we are confident that the final sample gives a fairly complete representation of the whole class of Herbig Ae/Be stars and that the inferences discussed in this paper should have a solid physical and statistical meaning.

In a companion paper (Testi et al. 1998; hereafter Paper II), we have collected the observational material (images, colour-colour diagrams and stellar density profiles) of each of the combined sample of 44 fields. In this paper, we present the results of the analysis of this large body of observations aimed at the detection, characterization and comparison of the small star clusters around intermediate-mass PMS stars.

## 2. Results

### 2.1. Richness indicators

In our previous studies we have identified the most suitable indicators of the richness of embedded stellar cluster that greatly reduce the problem of background/foreground contamination. The two quantities of interest are the number of stars in the K-band image within 0.21 pc from the Herbig star with an absolute K magnitude  $M_K \leq 5.2$  ( $\mathcal{N}_K$ ), and the integral over distance of the source surface density profile subtracted by the average source density measured at the edge of each field, ( $I_C$ ). The choice of a radius of 0.2 pc for computing  $\mathcal{N}_K$  is suggested by the typical value of the cluster size determined in Paper II, as the distance from the Herbig star where the sources surface density profile reaches the background level. As illustrated in Fig. 1, the distribution of the radii of the stellar density enhancement shows a clear peak around  $r \sim 0.2$  pc. This result is in good agreement with that found in various young stellar clusters (Hillenbrand 1995; Carpenter et al. 1997). It is remarkable that stellar groups with a few to several hundred members share similar sizes, corresponding to the typical dimensions of dense cores in molecular clouds.



**Fig. 1.** Distribution of the cluster radii of 21 stellar groups detected by computing the source surface density profiles obtained in Paper II.

The values of  $\mathcal{N}_K$  and  $I_C$  computed for the 44 stars of our complete sample are given in Columns 3 and 4 of Table 1, together with the name and spectral type of the Herbig Ae/Be star at the center of each field. The uncertainty on  $I_C$  has been calculated by propagating the error in the determination of the background stellar density at large distances from the Herbig star. As in Paper I, we discuss the dependence of the richness indicators on the spectral type of the Herbig star rather than on its mass, even though the latter is the relevant physical parameter. The main reasons for this choice are the proximity of the Herbig star to the main sequence (and hence a close relation between spectral type and mass is “almost” well defined) and the much larger uncertainties in the mass estimates based on the location of the stars in the HR diagram and the use of evolutionary tracks. On the other hand, spectral types of young stars are usually determined with an uncertainty of one or two subclasses, with the exception of a few cases (see the discussion in Paper II). In particular, RNO 1B and MWC 300 do not have a reliable classification and in the literature they are generically referred to as Be stars. For plotting purposes, we have arbitrarily assigned a B5 classification to both of them. These stars have both values of  $I_C$  and  $\mathcal{N}_K$  typical of B stars, and the assigned spectral type of B5 does not affect our results.

The variation of  $\mathcal{N}_K$  and  $I_C$  as a function of the spectral type of the Herbig star is shown in Figs. 2 and 3, respectively. Both figures confirm the initial results found in Paper I and by Hillenbrand 1995 that higher mass stars tend to be surrounded by richer clusters. As expected, the evidence for clusters is more pronounced using  $I_C$  instead of  $\mathcal{N}_K$ , but the fact that the same trend is seen in both indicators gives strength to its real significance.

In addition to the evidence for a variation of  $I_C$  with spectral type, the results of Fig. 3 suggest the existence of three regimes for the distribution of stars around Herbig stars. In the first one, characterized by  $I_C \gtrsim 40$ , the Herbig stars are definitely asso-

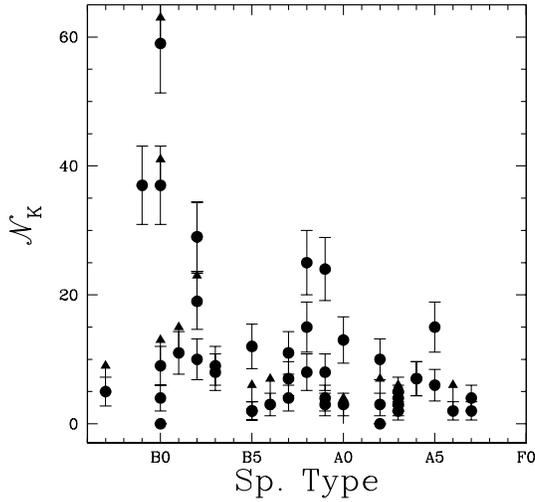
**Table 1.** Values of the *richness indicators*.

Star	Type	Age (Myr)	$\mathcal{N}_K$	$I_C$	$\mathcal{N}_K^0$	$\mathcal{N}_K^2$	$I_C^0$	$I_C^2$	$\text{Log}(\rho_{\mathcal{N}_K})$	$\text{Log}(\rho_{I_C})$
V645 Cyg	O7	–	>5	29.5 ± 2	>5	>5	> 29.5 ± 2	> 29.5 ± 2	2.1	2.9
MWC 297	O9	–	37	20.4 ± 1	24	23	14.3 ± 1	13.3 ± 1	3.0	2.8
MWC 137	B0	–	>59	76.0 ± 9	57	55	70.1 ± 5	64.4 ± 4	3.2	3.4
R Mon	B0	–	0	–12.8 ± 3	0	0	–5.1 ± 3	–5.1 ± 3	0.0	0.0
BHJ 71	B0	–	4	4.0 ± 3	1	1	–0.4 ± 1	–0.3 ± 1	2.0	2.1
MWC 1080	B0	–	>9	31.0 ± 3	>9	>9	> 31.0 ± 3	> 31.0 ± 3	2.4	3.0
AS 310	B0	–	>37	70.0 ± 17	>34	>34	> 70.2 ± 17	> 70.2 ± 17	3.0	3.3
RNO 6	B1	–	>11	11.0 ± 1	>11	>11	> 11.0 ± 1	> 11.0 ± 1	2.5	2.5
HD 52721	B2	–	10	20.5 ± 4	5	5	11.1 ± 8	11.1 ± 8	2.4	2.8
BD+65°1637	B2	–	29	75.0 ± 5	24	28	58.4 ± 4	63.4 ± 4	2.9	3.3
HD 216629	B2	–	29	34.0 ± 6	23	22	27.0 ± 6	25.3 ± 7	2.9	3.0
BD+40°4124	B2	–	19	11.0 ± 3	16	16	12.6 ± 2	12.9 ± 2	2.7	2.5
HD 37490	B3	–	9	9.9 ± 3	6	6	3.4 ± 1	3.8 ± 1	2.4	2.5
HD 200775	B3	–	8	1.9 ± 1	7	7	1.0 ± 1	1.0 ± 1	2.3	1.8
MWC 300	Be	–	>2	21.0 ± 8	>2	>2	> 21.9 ± 8	> 21.9 ± 8	1.7	2.8
RNO 1B	Be	–	12	9.7 ± 1	12	12	8.9 ± 1	9.0 ± 8	2.5	2.5
HD 259431	B5	0.05	2	0.9 ± 2	0	0	–1.7 ± 3	–0.2 ± 2	1.7	1.4
XY Per	B6	2.0	3	11.3 ± 3	2	5	–0.5 ± 1	–0.1 ± 1	1.9	2.5
LkH $\alpha$ 25	B7	0.2	11	14.5 ± 5	8	5	10.3 ± 3	9.0 ± 3	2.5	2.6
HD 250550	B7	0.5	4	2.2 ± 2	2	2	0.8 ± 1	0.8 ± 1	2.0	1.8
LkH $\alpha$ 215	B7	0.1	7	3.9 ± 1	6	4	5.4 ± 1	3.6 ± 1	2.3	2.1
LkH $\alpha$ 257	B8	2.0	15	5.5 ± 6	14	16	8.3 ± 3	9.5 ± 4	2.6	2.2
BD+61°154	B8	0.1	8	–1.4 ± 3	4	4	2.0 ± 1	2.4 ± 1	2.3	0.0
VY Mon	B8	0.05	25	23.2 ± 5	18	16	14.9 ± 2	12.9 ± 2	2.8	2.8
VV Ser	B9	1.0	24	16.9 ± 5	20	23	3.1 ± 2	3.0 ± 2	2.8	2.7
V380 Ori	B9	1.0	3	–2.0 ± 2	3	3	–1.5 ± 3	–1.5 ± 3	1.9	0.0
V1012 Ori	B9	–	4	1.9 ± 2	4	4	1.0 ± 1	1.0 ± 1	2.0	1.8
LkH $\alpha$ 218	B9	1.0	8	2.0 ± 5	5	7	1.7 ± 1	2.0 ± 1	2.3	1.8
AB Aur	A0	1.5	>3	3.0 ± 6	>1	>3	–1.0 ± 2	–2.3 ± 2	1.9	2.0
VX Cas	A0	1.0	13	4.5 ± 4	34	35	3.9 ± 4	4.4 ± 4	2.5	2.1
HD 245185	A2	7.0	10	4.5 ± 5	19	19	5.0 ± 1	5.0 ± 1	2.4	2.1
MWC 480	A2	7.0	>3	5.0 ± 6	>9	>9	–2.4 ± 2	–2.4 ± 2	1.9	2.2
UX Ori	A2	1.0	0	–0.3 ± 1	0	0	–0.1 ± 1	–0.1 ± 1	0.0	0.0
T Ori	A3	1.0	5	1.0 ± 2	4	7	0.4 ± 1	1.9 ± 2	2.1	1.5
IP Per	A3	7.0	3	5.3 ± 4	6	6	–0.7 ± 3	–0.7 ± 3	1.9	2.2
LkH $\alpha$ 208	A3	1.0	4	2.2 ± 5	3	2	1.2 ± 1	2.0 ± 1	2.0	1.8
MWC 758	A3	6.0	>2	3.4 ± 1	>3	>3	–0.3 ± 1	–0.3 ± 1	1.7	2.0
RR Tau	A4	0.1	7	0.8 ± 6	2	2	–0.4 ± 4	–3.2 ± 3	2.3	1.4
HK Ori	A4	7.5	7	2.2 ± 1	11	11	2.2 ± 1	2.2 ± 1	2.3	1.8
Mac H12	A5	–	15	5.1 ± 1	21	21	5.9 ± 1	6.6 ± 1	2.6	2.2
LkH $\alpha$ 198	A5	10.0	6	–10.6 ± 11	14	14	–9.4 ± 10	–8.4 ± 9	2.2	0.0
Elias 1	A6	–	>2	2.0 ± 3	>2	>2	1.0 ± 1	1.0 ± 1	1.7	1.8
BF Ori	A7	3.0	4	1.1 ± 1	3	3	1.1 ± 1	1.1 ± 1	2.0	1.5
LkH $\alpha$ 233	A7	4.0	2	1.0 ± 1	4	5	0.6 ± 1	1.5 ± 1	1.7	1.5

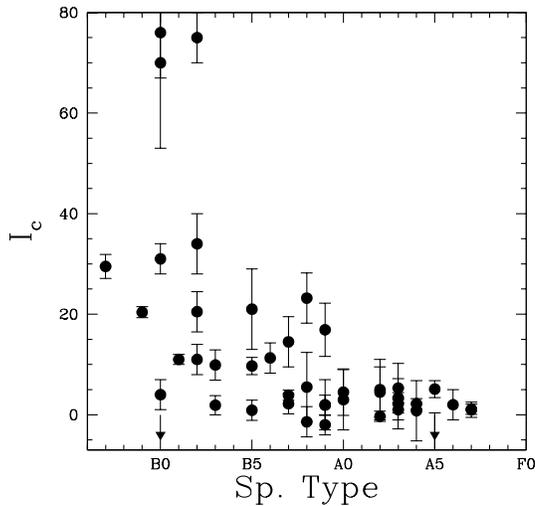
ciated with rich clusters; in the intermediate regime with  $10 \lesssim I_C \lesssim 40$  a small cluster may be present; in the third case where  $I_C \lesssim 10$  only small aggregates or background stars in the field are found, a situation similar to that observed in low-mass star forming regions. Three stars of our sample (MWC 137, AS 310 and BD+65°1637) belong to the first group. The sizes of the clusters derived for these stars in Paper II are on the large side of the distribution ( $\sim 0.4$  pc), however, at least in two cases (AS 310 and BD+65°1637) the Herbig star is not at the center of the cluster, and this results in an overestimate of the clus-

ter radius, determined from the radial density profile. Among stars of early spectral types, we find a large spread of values of  $I_C$ . In some cases, the low  $I_C$  are dubious. For example, V645 Cyg and MWC 1080 have relatively low values of  $I_C$  typical of the intermediate regime. However, both stars are embedded in bright nebulosities which may affect the star count resulting in a severe underestimate of the actual stellar density. In other cases, however, the low values of  $I_C$  may be real.

The presence of groups or small clusters is secure around most of the stars belonging to the intermediate regime. A clear



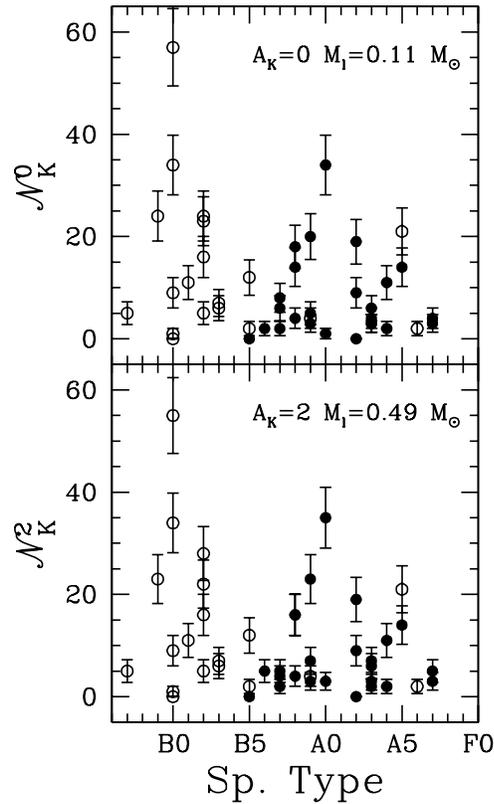
**Fig. 2.**  $\mathcal{N}_K$  as a function of the spectral type of the Herbig Ae/Be star. The two stars with an uncertain spectral type Be have been plotted as B5.



**Fig. 3.**  $I_C$  versus spectral type for the whole sample. As in Fig. 2, the two stars with an uncertain spectral type Be have been plotted as B5.

central density peak is observed in the density profiles of almost all stars of this group, as shown in Paper II. Typically, the Herbig star is located at the center of the stellar group, which generally has a round shape. A possible exception is the VY Mon field, where the stellar aggregate has an elongated structure with an aspect ratio of approximately 4:1 (the Herbig star is at the center). HD 52721 is not associated with molecular gas (Fuente et al. 1998), it is a rather old star, and the large cluster radius is probably the result of dynamical relaxation.

Finally, the large majority ( $\sim 65\%$ ) of the Herbig stars of the sample have very low values of  $I_C$  showing no enhancements above the background stellar density. All the fields around stars with spectral type later than B9 belong to this group. However, although most of these stars have spectral types later than B7-B8, there are extreme cases of early-type stars that deserve some discussion. First, the negative value of  $I_C$  found for R Mon (B0)

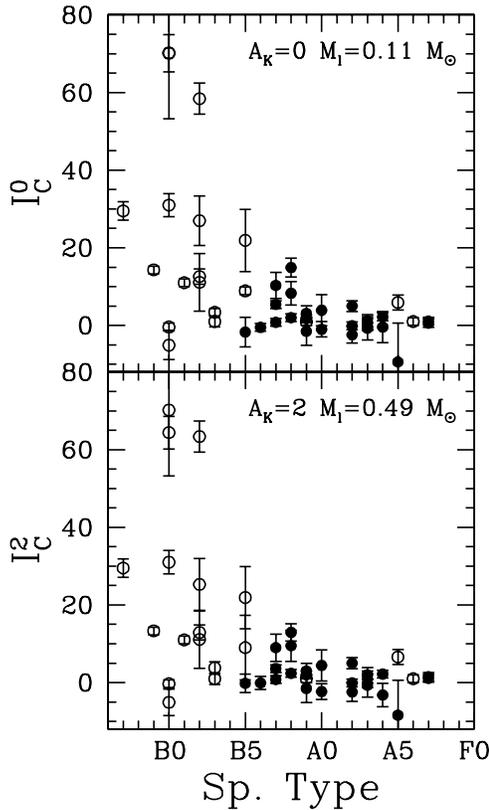


**Fig. 4.**  $\mathcal{N}_K^0$  and  $\mathcal{N}_K^2$  as a function of the spectral type of the Herbig Ae/Be star. Open circles denote fields for which we could not compute the age using the Herbig Ae/Be star parameters (see Paper II and Sect. 2.2 of the main text). As in Fig. 2, the two stars with an uncertain spectral type Be have been plotted as B5.

is probably due to localized extinction around the star, which is probably on the observer side of a molecular clump. Also, the stars BHJ 71 (B0), HD 200775 (B3) and HD 259431 (B5) have anomalously low values of  $I_C$ . The first one is a poorly studied star, and we have not been able to find any information on the molecular gas in the literature (see Paper II). HD 200775 is in many respect very similar to BD 65°1637: same spectral type, same molecular gas morphology and similar evolutionary status (Fuente et al. 1998). The absence of a cluster of young stars around HD 200775, as opposed to the rich cluster around BD 65°1637, may be the result of dynamical dissipation (see below) or reflect a difference in the environment. HD 259431 appears to be isolated in spite of the large amount of molecular material around it (Hillenbrand 1995). Among late-type stars, LkH $\alpha$  198 stands out for its negative value of  $I_C$  due to the bright nebulosity and localized extinction. Interesting cases with an indication of an extended population of embedded sources but not spatially concentrated around the Herbig star are VX Cas (A0), HD 245185 (A2) and Mac H12 (A5).

## 2.2. Mass sensitivity correction

Since young stars change their bolometric luminosity and effective temperature during PMS evolution, the mass of the smallest



**Fig. 5.**  $I_C^0$  and  $I_C^2$  versus spectral type for the whole sample. Open circles as in Fig. 4. As in Fig. 2, the two stars with an uncertain spectral type Be have been plotted as B5.

star detectable ( $M_l$ ) in our K-band images is a function of age ( $t_c$ ), of the absolute completeness K-magnitude ( $M_K^c$ ) and of the extinction along the line of sight ( $A_K$ ).

In Paper II, using the PMS evolutionary tracks for intermediate mass stars of Palla & Stahler (1993) and the compilation of stellar parameters from the literature, we have computed in an homogeneous way the ages of most of the stars later than B5. Then, using the PMS evolutionary tracks for low mass stars of D’Antona & Mazzitelli (1994), we have translated  $M_K^c$  into  $M_l$  for two values of the extinction ( $A_K = 0$  and 2) assuming that all the stars in each group are coeval with the Herbig Ae/Be star.

There are some stars (mostly early Be types) for which it is not possible to derive ages from PMS tracks. For these stars, we have estimated the age in the following way. From the results of Paper II we see that the Herbig Ae systems tend to be 1 to 10 Myr old (the mean value is  $\sim 4.6$  Myr), while Be systems tend to be younger than 1 Myr (with a mean age of  $\sim 0.7$  Myr). Thus we decided to adopt as age  $t_c = 0.5$  Myr for the 17 Be systems and  $t_c = 5$  Myr for the 2 Ae systems without an age determination in Paper II.

If  $A_K \sim 0$  mag, all the fields with a good age estimate from Paper II are complete to less than  $0.1 M_\odot$ , with the only exception of the two fields around HK Ori and LkH $\alpha$ 198. In this case,  $\mathcal{N}_K$  and  $I_c$  sample the totality of the stellar population in practi-

cally all fields. If  $A_K \sim 2$  mag, the minimum mass is generally larger, ranging from  $< 0.1$  to  $0.49 M_\odot$  in HK Ori. For each field we have computed the absolute magnitude corresponding to these masses and the corresponding extinctions at K-band, then we have calculated the two *richness indicators* discussed in Sect. 2 considering, in each field, only the stars with magnitude lower than the computed one. In this way, under the assumption that the mean extinction is approximately the same in all fields (and for all stars in each field), we have calculated mass limited *richness indicators*. The values of  $\mathcal{N}_K$  and  $I_C$  for  $A_K = 0$  and 2 ( $\mathcal{N}_K^0, \mathcal{N}_K^2, I_C^0$  and  $I_C^2$ ) are reported in Table 1, Columns 6–9. Since some of the fields without an estimate of the age of the Herbig Ae/Be star have mass sensitivities lower than our limits (which are based on HK Ori), some of the values reported are lower limits (indicated by  $>$ ).

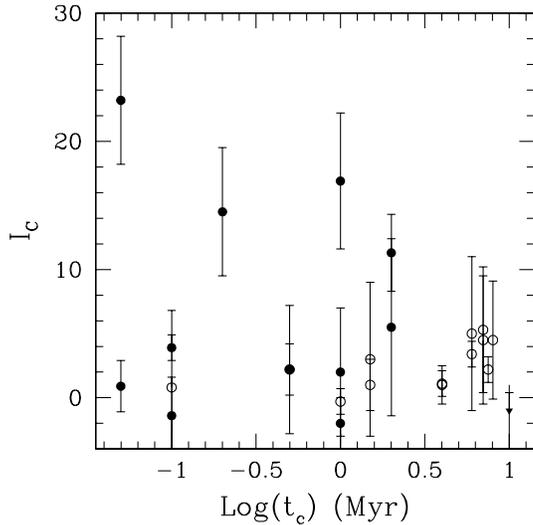
In Figs. 4 and 5 we show the behaviour of the “mass sensitivity corrected” indicators. Fig. 4 clearly shows that trend detected in Fig. 2 is completely cancelled by the bias introduced by the contamination from field stars. In fact, since the late type stars are older than early type the absolute magnitude corresponding to the same mass limit is higher for the Ae systems than for the Be systems, and since this discrepancy is not compensated by the difference in distance, we are effectively counting more field objects in Ae fields than in Be fields. On the contrary, Fig. 5 clearly shows the same trend as Fig. 3 supporting our conclusion of a dependence of  $I_C$  on the spectral type of the Herbig Ae/Be star. Therefore in the following we will use  $I_C$  which has a higher signal to noise ratio than  $I_C^0$  and  $I_C^2$ .

### 3. Discussion

In Paper I we suggested the presence of a threshold for the appearance of clusters around Herbig stars of spectral type earlier than  $\sim B7$ . The results discussed in the previous section confirm the property that Be systems are associated with more conspicuous groups than the Ae systems. Although the identification of a critical spectral type (or mass) is no longer evident in the complete sample, it is worth noting that no stars later than B9 show large groups, i.e. their  $I_C$  is  $\lesssim 10$ .

This general result raises some important issues: (1) is this difference between Be and Ae system related to a different location in the galaxy? (2) since Ae systems are generally older than Be systems, could the disappearance of the cluster be an evolutionary effect? (3) what is the typical environment in which intermediate mass stars form? (4) does the standard accretion scenario for the formation of Herbig stars need to be replaced by formation in clusters?

The first question is easy to answer. We do not find evidence for a dependence of the clustering properties with the galactic position of the target star, shown in Paper II. We must caution, however, that most of the observed stars lie in the outer regions of the Galaxy, due to the selection effect introduced by our observing sites in the northern hemisphere. Although we do not expect an opposite result toward the inner Galaxy, we must await the results of a similar study on a southern sample before generalizing our conclusion.



**Fig. 6.**  $I_C$  versus age. Only the fields with age determination from Paper II are presented. The arrow represents the field around LkH $\alpha$  198 ( $I_C = -10.6$ ). filled circles: Be systems; open circles: Ae systems.

### 3.1. Age effect

Following the age estimates given in Paper II, our sample of Herbig Ae/Be stars covers the range of ages from  $\sim 0.05$  to 10 Myr. As noted above, Ae stars tend to be older than Be stars. Thus, it is possible that the variation of the *richness indicators* from Be to Ae systems is caused by some evolutionary effect. It is possible that a stellar group composed by few tens or hundreds of objects could be dispersed on a timescale of a few million years and become undetectable (i.e. confused with the field stars) in older systems.

In order to explore this possibility more quantitatively, we show in Fig. 6 the run of  $I_C$  as a function of the age for the 25 fields with an age determination of the Herbig star (see Table 2 of paper II). The lack of stars with high values of  $I_C$  for ages greater than 2 Myr is related to the fact that our sample does not contain Be stars of that age. However, it is worth noting that for Be systems (filled circles in Fig. 6) younger than 2 Myr we find high and low values of  $I_C$  at any age.

From the figure we see that it does not seem to exist a correlation between the age of the Herbig star and the presence of a cluster. The correlation is only with the spectral type (or mass). Stars earlier than B7 have clusters or not independently of their age; stars later than B7 do not have clusters and are on average older than the rest. If we say for convenience that a cluster is detected for  $I_C \gtrsim 10$ , the oldest star surrounded by a cluster is XY Per with an age of 2 Myr. Since stars of age greater than  $\sim 4$  Myr do not have clusters, there are two possibilities to account for such property: these stars did form in relative isolation or the attending cluster has by now disappeared. The former explanation is obvious and does not require any further comment.

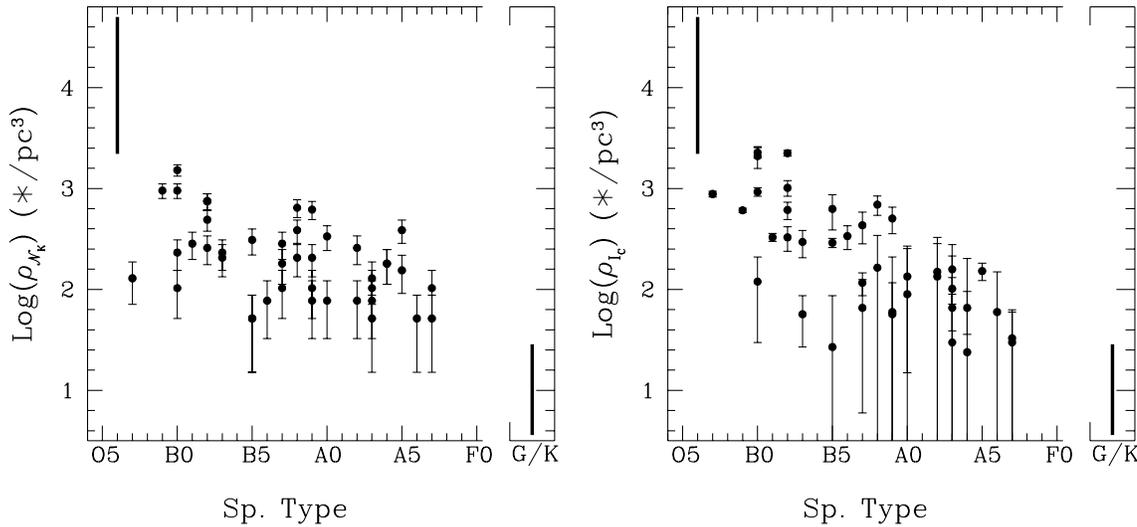
The second alternative is theoretically more interesting and we have performed several N-body simulations to verify under which conditions the dynamical evolution of a small cluster

can evolve so rapidly to dissipate the majority of its members in a time scale less than  $\sim 4$  Myr. We have considered models containing  $N = 100, 150$  and 200 stars starting from different initial conditions (virialized and non virialized clusters) and with varying frequency distributions of stellar masses (Salpeter, Scalo, Kroupa and uniform mass). The half-mass radius was varied between 0.4 and 0.7 pc and the typical velocity dispersion was  $2 \text{ km s}^{-1}$ . Thus, the clusters are initially richer and larger than those actually observed around Herbig stars characterized by  $I_C \sim 30\text{--}40$  and a radius of  $\sim 0.2$  pc. We have also varied the upper limit of the most massive object from  $20 M_\odot$ , corresponding to a O9 star, to  $2 M_\odot$ , corresponding to an A5 star. It is well known that the dynamical evolution of cluster models is very dependent on the choice of the IMF, especially in what concerns the effects of mass segregation at early times (e.g. de la Fuente Marcos 1995, 1997). We have not considered the presence of primordial binaries in the initial population.

For most runs, we have found that it is very difficult to loose a significant fraction of stars in the initial few crossing times, as required by the age constraints of the Herbig stars. The only cases where the stellar population decreases to less than half the initial value in about ten crossing times are those characterized by the lowest number of stars ( $N = 100$  in our models) distributed in mass according to a Salpeter IMF. The first point is a critical one, since the evaporation time increases very rapidly with the number of stars. Even models with  $N = 150$  do not evolve sufficiently rapidly. As for the IMF, the result is acceptable even though we know that a single power-law approximation must break down at subsolar values. More important, however, is the sensitivity of the evolution to the upper limit of the mass distribution. Only if the most massive star exceeds  $5 M_\odot$ , the evolution is fast enough that the system loses many members in several crossing times. Otherwise, it is impossible to modify the cluster composition in a few million years. Now, since a  $5 M_\odot$  corresponds to a B6 ZAMS star, it is clear that Herbig stars of later types which were formed in relatively small clusters would have retained the original population of companions at the observed age. *Therefore, we conclude that the fact that we do not see evidence for the presence of clusters around stars of type later than about B7-B8 is an imprint of the stellar formation mode rather than the consequence of the dynamical evolution of a presently dispersed cluster. On the other hand, the absence of clusters around some of the early type B stars could result from the dynamical evolution, especially in case of a relatively small initial population.*

### 3.2. The transition from loose to dense groups

The values of  $\mathcal{N}_K$  and  $I_C$  can be transformed into star (or effective star) volume densities using the average cluster radius of 0.2 pc and assuming spherical clusters. The logarithm of the stellar densities in sources per cubic parsec are reported in the last two columns of Table 1. This estimates of the stellar densities are affected by large uncertainties (as high as 30%, Hillenbrand 1995), due to the unknown depth of the clusters along the line of sight and the neglect of concentration effects, but it is a use-



**Fig. 7.** Stellar volume densities derived from  $N_K$  (left) and from  $I_C$  (right) versus spectral type of the central star. Stars with  $I_C < 0$  have been excluded. The heavy vertical line at O6 represents the range of stellar densities found in the Trapezium cluster, whereas that at G/K (not to scale) represents the densities of stellar groups in Taurus-Auriga.

ful approximation to be used for comparing the various regions. The resulting distributions shown in Fig. 7 confirm the apparent trend discussed in Sect. 2 and put on a firmer ground the suggestion of Hillenbrand (1995) of a physical relationship between cluster density and the maximum mass of the Herbig star. For comparison, we also show in Fig. 7 the stellar density range of the T Tauri aggregates found in Taurus-Auriga by Gomez et al. (1993) (shown as the solid line at G/K, not to scale), and the same quantity for the Trapezium cluster (McCaughrean & Stauffer 1994; Hillenbrand 1997). The conclusion is evident: *intermediate mass stars mark the transition from low density aggregates of  $\lesssim 10$  stars per cubic parsec of T Tauri stars to dense clusters of  $\gtrsim 10^3$  stars per cubic parsec associated with early-type stars.*

### 3.3. Implications for star formation

The conventional theory of protostellar infall successfully accounts for the formation and early stellar evolution of low- and intermediate-mass stars up to about  $10 M_\odot$ . The location of the stellar birthline and the distribution of the observed T Tauri and Herbig Ae/Be stars in the HR diagram are in excellent agreement with the theoretical predictions (Palla & Stahler 1990, 1993). Protostars more massive than about  $10 M_\odot$  burn hydrogen while still in the accretion phase and therefore join the main sequence, implying that stars of even higher mass have no contracting PMS phase. Observations of clusters such as NGC 6611 and the dense regions of the Trapezium cluster support this finding (e.g. Hillenbrand et al. 1993; Hillenbrand 1997). However, the accretion scenario of isolated protostars fails to explain the existence of massive stars. Radiation pressure by photons produced at the stellar and disk surfaces on the infalling gas begins to become significant at about the critical mass of  $10\text{--}15 M_\odot$  (e.g. Larson & Starrfield 1974; Yorke & Krugel 1977). This limit

can be increased by considering variations in the dust properties (abundances and sizes) or in the mass accretion rate (Wolfire & Cassinelli 1987). But in either case the required conditions are so extreme (dust depletion by at least one order of magnitude and accretion rates of at least  $10^{-3} M_\odot \text{ yr}^{-1}$ ) that they cannot reasonably apply in all circumstances. Any departure of the infall from spherical symmetry can also help to shift the critical mass to very massive objects (e.g. Nakano 1989; Jijina & Adams 1996).

The fact that, as we have seen, stars form in groups and clusters rather than in isolation may offer an alternate mechanism to circumvent the problem of the high luminosity of massive stars and the negative feedback on the accreting gas. Accretion processes in clusters has long been advocated to explain the shape of the initial mass function (Zinnecker 1982; Larson 1992; Price and Podsiadlowski 1995), and to account for the location of massive stars in the cluster centers (Bonnell et al. 1997). Very recently, Bonnell et al. (1998) have presented model calculations of the dynamical evolution of rich, young clusters that show that accretion-induced collisions of low- and intermediate-mass stars (formed in the standard accretion mode) can result in the formation of more massive objects in time scales less than  $10^6$  years. However, the process requires a critical stellar/protostellar density so that collisions and merging are frequent. For the formation of a star of mass of  $\sim 50 M_\odot$ , an initial density of  $\rho_* > 10^4 \text{ stars pc}^{-3}$  is required. This is the typical density observed in the central regions of large clusters such as the Orion Nebula cluster where stars so massive are indeed present, but it is hardly the case for the stars of our sample. As shown in Fig. 7, the highest stellar volume densities are limited to about  $2 \times 10^3 \text{ stars pc}^{-3}$ , almost an order of magnitude lower than the minimum value for the efficient collisional build-up of massive stars. These densities are found for stars of spectral type B0-B2, i.e. with ZAMS masses of about 20 to  $10 M_\odot$ .

Thus, these stars are at the borderline between the conditions of isolated and collisional accretion mechanisms. It would be extremely interesting to extend the Bonnell et al. (1998) models to less extreme conditions on the stellar density in order to explore the dynamical evolution of clusters resembling those observed around Herbig Be stars. Based on the observational evidence, we may conclude that *in most cases, the formation of Herbig stars can be understood in terms of the conventional accretion scenario, whereas for the most massive members of this group dynamical interactions in the cluster core and residual gas accretion can be of importance in determining the final mass, even though the observed stellar density is never extremely high.*

#### 4. Conclusions

Using the techniques described in Paper I, we have analyzed the near-infrared observations of the fields surrounding Herbig Ae/Be stars presented in Paper II with the goal of identifying and characterizing the presence of (partially) embedded clusters formed around the intermediate-mass stars. We have examined 44 fields around stars ranging in spectral types from A7 to O9. The main results of these studies can be summarized as follows.

We have confirmed and extended the correlation between the spectral type (or mass) of the Herbig stars and the number of nearby, lower mass objects, first noted by Hillenbrand (1995). Rich clusters with densities up to  $10^3 \text{ pc}^{-3}$  only appear around stars earlier than B5, corresponding to a mass of about  $6 M_{\odot}$ . Conversely, A-type stars are never accompanied by conspicuous groups and the typical density is less than  $50 \text{ pc}^{-3}$ . However, the transition between formation in loose groups and in clusters does not occur sharply around spectral type B7 as we suggested in Paper I. The appearance of denser stellar groups is quite smooth moving from Ae to Be systems, thus suggesting that intermediate-mass stars fill naturally the gap between the low-density, low-mass aggregates and the high-density, high-mass clusters.

Using a richness indicator,  $I_C$ , based on stellar surface density profiles, we have identified three regimes for the distribution of stars around Herbig Ae/Be stars: rich clusters characterized by values of  $I_C \gtrsim 40$ ; small clusters or aggregates with  $10 \lesssim I_C \lesssim 40$ , and small aggregates or background stars for lower values of  $I_C$ . Herbig stars with rich clusters are rare: only three stars of the sample definitely belong to the first group, whereas in other cases we have indication that the star counts may severely underestimate the actual stellar density. The typical cluster size is  $\sim 0.2 \text{ pc}$  irrespective of the richness of the clusters. This value is remarkably close to the dimension of dense cores in molecular clouds.

The majority of Herbig stars (65%) are found in the last regime, showing no enhancement above the background stellar density. All the stars with spectral types later than B9 belong to this regime and are generally older than Be stars. This result is not affected by different sensitivities to the lowest masses in different fields. From dynamical considerations, we conclude that the absence of clusters around late-Be and Ae stars is an imprint of stellar formation in relatively isolated cores (as in

the case of T Tauri stars), and not the result of rapid cluster evolution and dispersion.

The fact that the most massive Herbig stars have clusters strongly supports the notion that their formation has been influenced by dynamical interactions with lower mass stars and/or protostellar cores. It is no coincidence that the onset of clusters manifests at a mass of about  $8\text{--}10 M_{\odot}$  where the conventional accretion scenario for isolated protostars faces severe theoretical problems. Future studies of the formation and evolution of these stars should take into account the observational evidence for high stellar density environments.

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