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Properties of young cluster in star forming regions

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Abstract. Twenty-six high-luminosity IRAS sources believed to be in the early phases of high-mass star formation have been observed in the Near-IR (J, H, K_s) to characterise the clustering properties of their young stellar population and compare them with those of more evolved objects (e.g., Herbig Ae/Be stars) of comparable mass. Observations reveal that the greater part of these medium-high star forming regions are really associated with stellar clusters. Their characterisation with density profiles, colour-colour and colour-magnitude diagrams and K_s luminosity functions (KLFs) confirms that these clusters prevalently contain pre-main-sequence low mass objects. The KLFs comparison with the results of a model that produces synthetic cluster, starting from different assumptions for Initial Mass Function (IMF), source ages and Star Formation History (SFH), reveals that the young sources, within these clusters, aren't coeval but their formation takes place over a time period of millions years. We confirm the relation between the mass of the most massive star in the cluster and the cluster's richness indicator, found for clusters around Herbig Ae/Be stars. Finally the finding that the most massive object in these regions is younger than the other cluster members (Molinari et al. 2008) is a further indication that high mass stars are the latest to form.

Key words. Stars: formation – Stars: imaging – Stars: luminosity function, mass function – Stars: pre-main sequence – Infrared: stars

1. Introduction

The last few decades have been characterised by a large effort to improve our understanding of how stars form both from a theoretical and from an observational point of view.

Our scientific goal is to answer to some of the open issues on the star formation process. When an high mass protostar form, is it isolated or within a cluster? If the last scenario is true, are the cluster members coeval? Or is the star formation a process distributed over few to several million years? In this work we explore the properties of embedded clusters asso-

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Send offprint requests to: F. Faustini ciated with high mass protostellar candidates. Our sample was selected from a larger sample of candidate high-mass protostars selected and analysed, in the past decade, by Molinari et al. (1996, 2000, 2002).

2. NIR observations and data analysis

26 fields were imaged in J, H, and K_s bands during 3 nights at the Palomar 60-inch telescope (equipped with a 256×256 NICMOS-3 array, with a pixel scale of $0\farcs62$/pix and total FOV of $2\farcm6\times2\farcm6$) and in 3 nights at the ESO-NTT (using the 1024×1024 SOFI camera, with a pixel scale of $0\farcs29$/pix and a total FOV of $4\farcm9\times4\farcm9$). Extraction and photometry of point sources for all images was carried using the IRAF package. The identification of a cluster results from the analysis of stellar density in the field. A cluster is detected within $1'$ of the IRAS position for 23 out of the 26 observed fields (88% detection rate). We will first derive qualitative indications concerning the nature of the identified clusters using simple diagnostic tools like colour-colour and colour-magnitude diagrams. The diagnostic power of our observations is limited because we do not know which objects in the cluster area are real cluster members and we do not know the exact amount of dust extinction (originating within the hosting clump) and IR excess (originating in the immediate circumstellar environment) pertaining to each source. The [J-H] *vs* [H-K_s] diagram shows that a significant fraction of the sources has colours compatible with main-sequence stars with a variable amount of extinction reddening (computed adopting the Rieke & Lebofsky 1985 extinction curve), but many sources show colours typical of young pre-MS objects with an intrinsic IR excess arising from warm circumstellar dust distributed in disks (Lada & Adams 1992). This fraction of sources offers a straightforward indication of the youth of the cluster. This is confirmed from the analysis of colour-magnitude diagram where, compared to the main sequence, a significant fraction of the sources (after the corrections due to extinction) are on its right, where the evolutive tracks for Pre-MS sources (Palla & Sthaler 1999) can also be found, and could be therefore interpreted as very young pre-MS objects.

The observed KLF, for each cluster, is obtained simply counting all detected sources within the cluster area as identified from the cluster density profile. To account for the field star contamination in a statistically significant way we subtract from the KLF built on the cluster area, the KLF built in a region outside the cluster area but still in the same imaged field, after normalising for the different areas. Regions where the field stars KLF is built have a lower extinction respect to the cluster one, so the background contribution is likely to be overestimated.

3. Initial mass functions and star formation histories

Lacking the detailed knowledge on individual stars in the clusters, fundamental quantities like the IMF and SFH cannot be directly derived from, e.g., the KLF. We are then forced to obtain these using statistical simulations of clusters based on different input parameters and performing a statistical comparison between synthetic and observed KLFs.

3.1. SCG

We developed a model to create statistically significant cluster simulations obtained for different assumptions of IMF and SFH (source ages and their distribution), and compare the synthetic KLFs with the observed field-subtracted KLFs. We call this model Synthetic Cluster Generator (SCG).

A cluster is created by adding stars whose masses and ages are assigned via a Monte-Carlo extraction according to the chosen IMF and SFH; the pre-MS evolutive tracks of Palla & Sthaler (1999) are then used to convert them into J, H and K_s magnitudes. The 3D distribution of stars is obtained by randomly choosing for each star a set of x,y,z; this is needed to assign, using submm continuum images, the proper column of cold dust. To properly simulate the pre-MS stars, we also need to include the effect of an IR excess due to warm dust in the circumstellar envelopes and disks. We used the distribution of $[H-K_S]_{ex}$ colour excesses as measured for a sample of Pre-MS stars in Taurus, as used by Hillenbrand & Carpenter (2000). The K_s magnitude of the synthetic star was then compared with the limiting magnitude typical of the cluster being simulated to determine if the star could have been detected in our observations. This procedure is repeated until the number of synthetic detectable stars equals the number of revealed cluster members; at this point the cluster generation process is complete. To provide statistical significance, the model is run 200 times for any given set of input parameters, and the median KLF is later adopted for the comparison with the observed one. We tested three different assumptions for star formation histories in our cluster simulations: single burst-like event, constant star formation rate and a gaussian rate (hereafter SB, CR and GR). As for the IMFs, we allowed three different choices from Kroupa (1993), Scalo (1998) and Salpeter (1955), with the latter modified introducing a different slope for $M<1$ $M_{\odot}$that coincides with that of the Scalo (1998) IMF.

3.2. Comparison

The detailed comparison of the model KLFs functions to those observed was carried out only for those sources where the number of detected stars was sufficient (cluster richness indicator I_c $\geq$15) to allow a statistically significant comparison, and where submm information was available to allow meaningful estimates of extinction. The comparison of the observed KLFs, KLF_{Obs}, with the synthetic ones produced by SCG (KLF_{Syn}), for the full set of input parameters (IMF, SFH and age parameters) was carried out automatically. The KLFs are first compared bin by bin (the comparison being limited to those bins brighter than the completeness limit). A match is good for those bins where the number of sources coincides within the 1σ Poissonian error bar of the observed KLF. The total number of bins where a match is found is divided by the total number of bins useful for the comparison to get a KLF compatibility figure (in %). The higher is this percentage, the better is the overall match between KLF_{Obs} and KLF_{Syn}. We consider a further parameter that weights each matching bin by its relative richness, favouring the bins closer to the completeness limit and the KLF peak over those in the bright tail of the KLF.

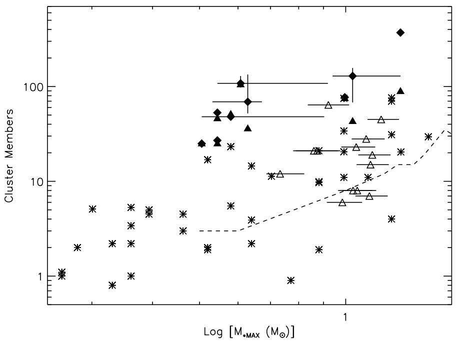

Fig. 1. Number of cluster members as a function of Mass of highest mass star. Asterisks are Herbig Ae/Be sample. Other points are our source sample: Full Diamonds are the $N_{\star}$ from our simulated clusters, Full Triangles are the same clusters with derived cluster I_c and, while Empty Triangles are those clusters which were not analysed with SCG; the full lines represent the total spread of the parameters from all SCG models that match the observed KLF.

4. Results

4.1. Comparison with Herbig Ae/Be

To characterise the clustering properties for objects in the early phase of evolution, we compare our results with those obtained for a sample of Herbig Ae/Be analysed by Testi et al. (1997, 1998). In these studies Testi et al. find that I_c is proportional to the spectral type (or mass) of the brightest cluster star. Figure 1 shows that the relationship between N_{star} and $M_{\star max}$ also holds for our clusters. This diagram can also be used as a diagnostic to discriminate between different classes of models for the origin of clusters. Testi et al. (2001) called *physical* the class of models which imply a physical relationship between the most massive star that forms and other environmental properties like the cluster richness or the mass of the gaseous clump where the stars originate from; examples are the "turbulent core" (McKee & Tan 2003), the "coalescence" (Bonnel et al. 1998), or the competitive accretion models (Bonnell & Bate 2006). In a second class of models, called *statistical*, the relationship between the most massive star in a cluster and its richness arises from the higher probability of finding the rare massive stars in rich clusters rather than in isolation (Bonnell & Clarke 1999). If clusters are populated by randomly picking stars from the field stars' initial mass function, then a significant fraction of high-mass stars are still associated with relatively poorly populated clusters. In other words massive stars can be found both in high-N clusters and, to a lesser extent, in low-N clusters. The dashed line in Fig. 1 delimits the region where 25% of the clusters randomly extracted from the IMF would follow in the statistical models in Testi et al. (2001). Indeed, if we consider our measurements of I_c for our entire sample (i.e. the full and empty triangles), a fair fraction of our targets (close to the expected 25%) are found below the dashed line. However, as noted above, the estimates based on I_c are very uncertain and most likely underestimate the number of members in our clusters. If we use the cluster membership as derived from our modelling, then all sources that we were able to model are well above the critical line.

4.2. Properties of our clusters

Perhaps the most important result of this work is that in virtually all clusters the observations are consistent with a star formation which goes on for quite some time; in most cases we cannot discriminate clearly between a constant or variable SFR but we can certainly exclude that the stars in clusters are coeval and originating from a SB of formation. Detailed studies toward the Orion Nebula Cluster show that stars have been forming for at least 10 t_{dyn}, or 20 t_{ff} (Palla & Sthaler 1999; Hillenbrand 1997), and our results would seem to generalise this on a larger sample of intermediate and high-mass star forming regions. Models of cluster formation via competitive accretion seemingly succeed in delivering an IMF close to the observed ones thanks to the spread of the accretion rates consequent to the competitive accretion mechanism, but the prediction that all stars are formed in about 5×10^5 yrs (Bonnel et al. 2004) for typical conditions in young clusters, corresponding to a dynamical time or so, is clearly in disagreement with our results. We instead favour scenarios (Tan & McKee 2002) where stars keep forming over several free-fall times thus providing the required age spread. The finding that the most massive object in the fields considered in this work are still being formed or have just finished a phase of intense accretion (Molinari et al. 2008) is a further indication that star formation is very likely to be a long-duration process in the life of a molecular cloud.

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