Young Stellar Clusters in the Vela D Molecular Cloud

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It is now well established by means of direct and indirect observations that most, if not all, stars are formed in groups rather than in isolation (Clarke, Bonnell & Hillenbrand 2000). An important result that strongly constrains theories of massive star and stellar cluster formation is that the stellar density of young stellar clusters seems to depend on the mass of the most massive star in the cluster. Low-mass stars are usually found to form in loose groups with typical densities of a few stars per cubic parsec (Gomez et al. 1993), while high-mass stars are found within dense stellar clusters of up to 10^4 stars per cubic parsec (e.g. the Orion Nebula Cluster, Hillenbrand & Hartmann 1998). To explain this different behaviour, it has been proposed that massive stars may form with a process that is drastically different from the standard accretion picture, e.g. by coalescence of lower mass seeds in a dense cluster environment. The transition between these two modes of formation should occur in the intermediate-mass regime, namely $2 \lesssim M/M_{\odot} \lesssim 15$.

In order to probe this transition, Testi et al. (1999) recently completed an extensive near infrared (NIR) survey for young clusters around optically visible intermediate-mass stars (Herbig Ae/Be stars) in the northern hemisphere. The main result of this survey is that there is a strong correlation between the spectral type of the Herbig Ae/Be stars and the membership number of the stellar groups around them. Furthermore, there is compelling evidence that the most massive stars in their sample are surrounded by *denser,* not simply more populous clusters. These findings are in qualitative agreement with models that suggest a causal relationship between the birth of a massive star and the presence of rich stellar clusters. The observed correlation and scatter, however, could also be explained in terms of random assembling clusters with membership size distribution of the form $g(N) \sim N^{-1.7}$ picking stars from a standard IMP (Bonnell & Clarke 1999). In this view, since massive stars are rare objects compared to low-mass stars, they will be observed only as members of large ensembles of stars (clusters), while the detection of an isolated high-mass star would have a relatively low probability. As discussed in Testi et al. (2001), there are two observational strategies to provide additional constraints on which of the two models is the most appropriate: to expand the sample of optically revealed young O and B stars to increase the statistics, and to search for clusters in complete samples of luminous embedded sources in giant molecular clouds. The young high-mass isolated objects predicted by the random model should be detected in such surveys. However, to properly compare with the models, it is essential to carry out observations around the target luminous objects

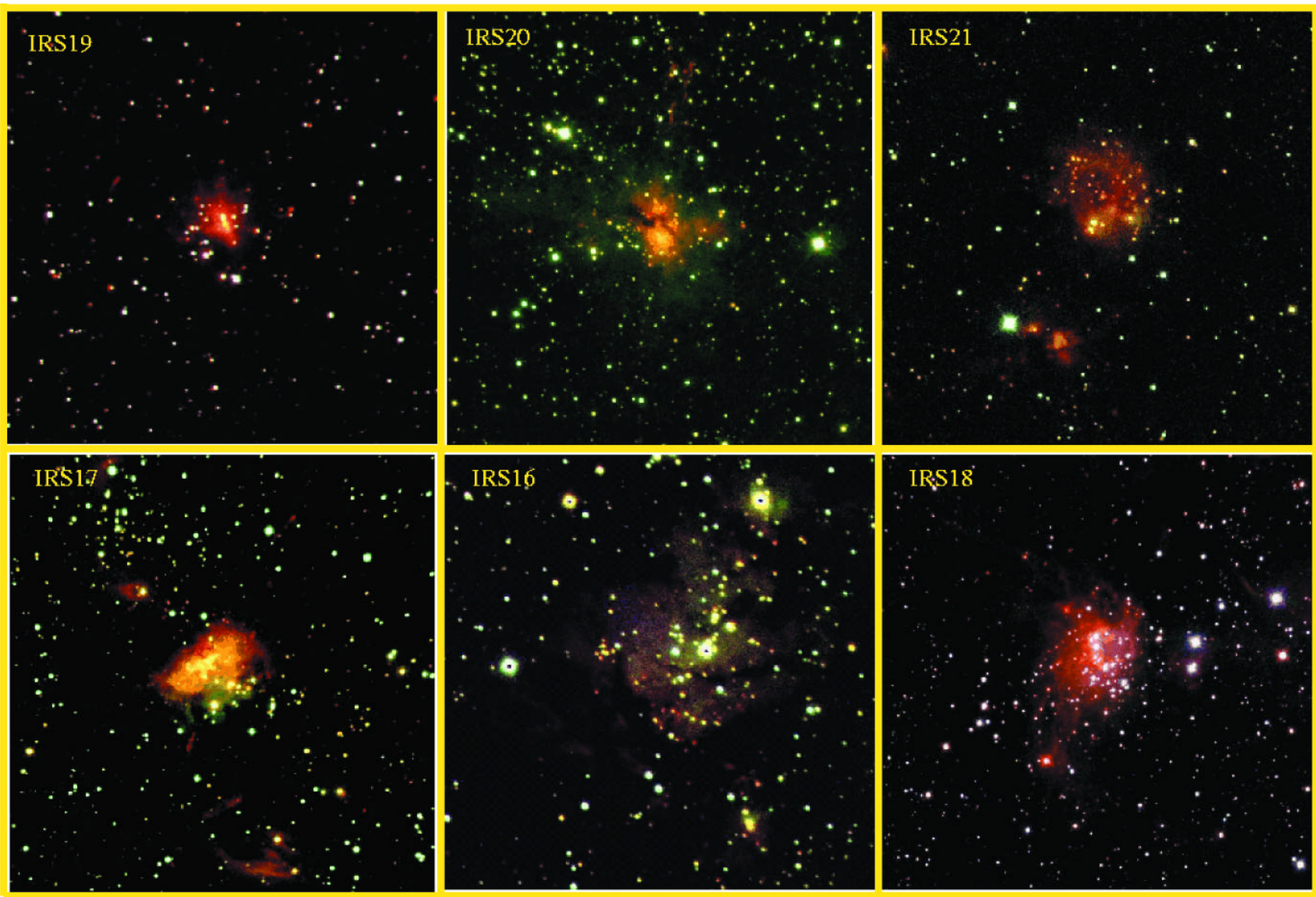

Figure 1: NTT/SOFI near infrared "true-colour" images (J blue, H green, K_s red) of the fields centred on the luminous IRAS sources in the Vela D molecular cloud. The sources are ordered by increasing far infrared (IRAS) luminosity from left to right and top to bottom.

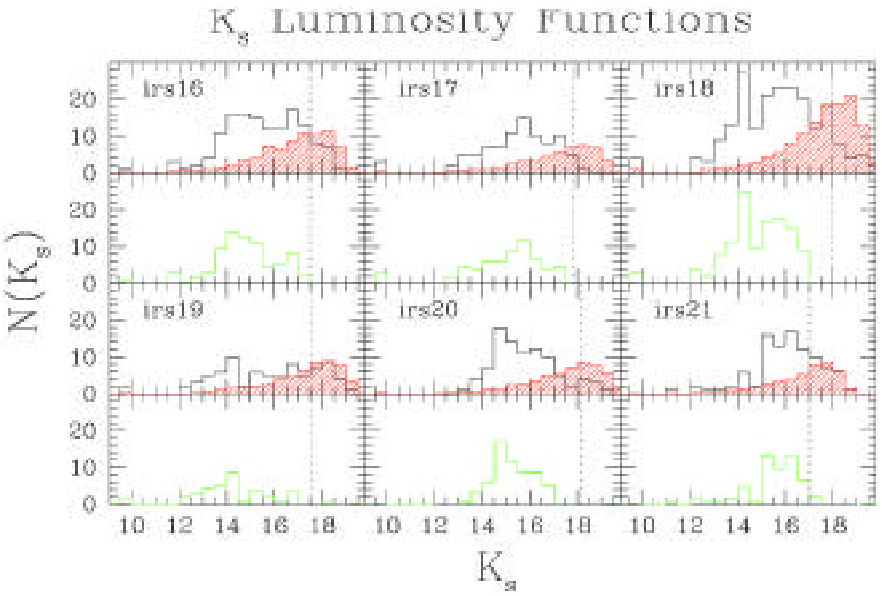

Figure 2: K_s luminosity functions for the observed sample. For each field in the top panel we show the observed K_sLF at the image centre (black histogram) and at the edges (red shaded histogram), normalised to the same area. The estimated K_sLF of each cluster, obtained by subtracting the "edge" from the "central" K_sLFs, are shown in the bottom panels as green histograms. The dotted vertical lines mark the K_s completeness magnitude.

complete down to at least 0.1–0.2 $M_\odot$ over a field of view large enough to cover the expected cluster size. The NTT/SOFI combination, with the provided field of view and sensitivity is an ideal asset to collect the required data and settle this fundamental issue. Moreover, due to the reduced extinction compared to the optical, the near infrared bands (especially K_s) are the most effective for this type of studies, in fact the young clusters are expected to be at least partially embedded within their parent molecular cloud core. In this paper we report on the results of a study of a complete sample of luminous IRAS sources in the Vela-D giant molecular cloud.

1. The Vela-D Luminous IRAS Sources

Low-resolution observations in the CO(1–0) mm-line of the region of the galactic plane defined by 255° $\leq l \leq$ 275°, –5° $\leq b <$ +5° carried out by Murphy & May (1991) uncovered the existence of an emission ridge in the range $0 \leq \upsilon_{LSR} \leq 15$ km s^{-1} which was promptly dubbed "Vela Molecular Ridge" (VMR). These authors found the molecular gas complex to be made out of four main molecular clouds that they indicated as A, B, C and D, ~ 10^5 $M_\odot$ each. Liseau et al. (1992) studied the association of luminous IRAS sources with the VMR and selected among them a complete sample of protostellar objects based on IRAS colours, their spectral slopes from the near- to the far-infrared and the velocity of the parental molecular gas. They also discussed the distance of the VMR, concluding that clouds ACD are likely to be located ~ 700 ± 200 pc from the Sun. On this basis, they found no O-type stars recently having been formed in the VMR, although birth of intermediate-mass stars is in progress. Massi et al. (1999, 2000) examined in detail NIR images of the subsample of IRAS protostellar sources (12) belonging to the D cloud, concluding that most of their bolometric luminosity arises from single young stellar objects (or close pairs of young stellar objects) of intermediate mass embedded in young stellar clusters. We selected the most luminous ($L_{bol} > 10^3$ $L_\odot$) IRAS sources in the subsample of Massi et al. (1999, 2000), namely IRS 17, 18, 19, 20 and 21 (following the classification of Liseau et al. 1992), adding IRS 16, a source not included by Liseau et al. (1992) in their final list of protostellar objects associated with the VMR possibly because of its failure in fulfilling some of the rather conservative selection criteria chosen, although lying toward an HII region.

Our observations were designed to reach at K_s band a completeness magnitude high enough to be sensitive to all stars more massive than 0.1 $M_\odot$ in all the clusters. From the observations of Massi et al. (2000), the age of all known young clusters in our sample is less than 1 Myr and the visual extinction much less than 30 mag, as derived from the brightest members of the clusters. Using the methods described in Testi et al. (1998) and the PMS evolutionary tracks from Palla & Stahler (1999), these constraints translate in a required K_s completeness magnitude of ~ 17, this figure having been used to design the observing strategy and integration times. The expected cluster sizes were estimated from the Testi et al. (1999) and Massi et al. (2000) surveys, which found an average cluster radius of 0.2 pc, corresponding to ~ 1 arcmin at the distance of the Vela D cloud.

The clusters were observed with SOFI at the NTT through the J, H and K_s broad-band filters and with the large-field objective offering an instantaneous field coverage of ~ 5 arcmin with

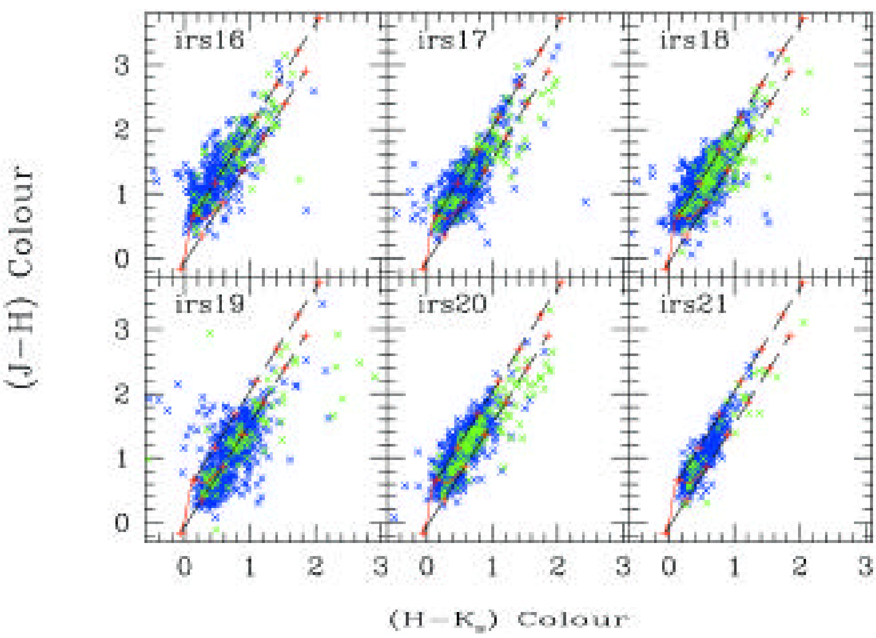

Figure 3: (J–H) vs. (H–K_s) colour-colour diagrams for the six observed regions. Sources within one arcminute from the field centres are shown in green, sources further away are shown in blue. The red line marks the location of main sequence, non reddened stars. The reddening vectors are shown as dashed lines with a red cross every 5 magnitudes. Sources in the inner regions show on average redder colours, some of them exhibit an infrared excess, typical of young stellar objects. Only very few sources are affected by extinction exceeding 25 mags in the visual.

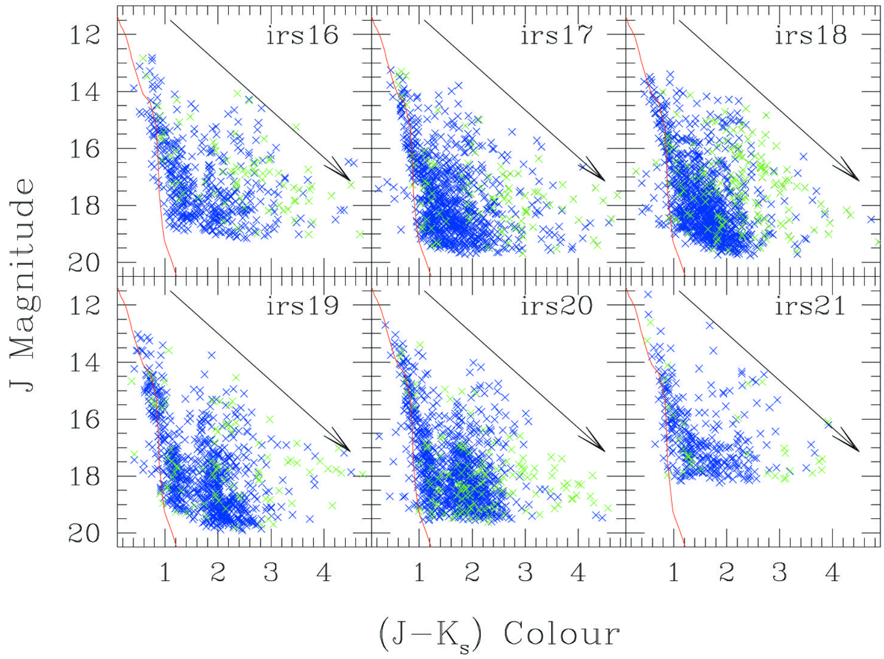

Figure 4: J vs. (H–K_s) colour-magnitude diagrams for the six observed regions. Sources within one arcminute from the field centres are shown in green, sources further away are shown in blue. The red line marks the location of main sequence, non reddened stars. The arrows show the direction of the reddening vectors and its length correspond to a visual extinction of 20 mag.

a pixel scale of 0.292 arcsec. We integrated for ~ 15 minutes per filter and cluster. Object and sky were alternatively observed to have a good sampling of the background variations. The images were reduced following the standard procedure and the "Special FlatField" technique. After combining the dithered frames, the final image quality is ~ 0.85 arcsec for all fields but IRS 16, which was observed under worse seeing conditions (1.1 arcsec).

2. Results

In Figure 1 we show a subsection of the NTT/SOFI near infrared "true-colour" images of the fields surrounding the six IRAS sources that we surveyed. From the images it is immediately clear that we detected groups of very red sources in every field, and an increase of the stellar surface density toward the centre, where the luminous IRAS sources are located, is also evident. All clusters are embedded within a diffuse nebulosity, likely due to cluster members light scattered toward the line of sight by the dust in which the younger sources are still embedded. In a few cases, IRS 17 and IRS 20 are the most evident, we clearly detect in the K_s broad-band filter the line emission from collimated jets (see also Massi et al. 1997 for a narrow- band survey of the region) emerging from the inner regions of the clusters, confirming the youth of the objects.

More quantitatively the presence of an excess of (relatively) bright sources toward the map centres can be made clear by comparing K_s-band luminosity functions of the central regions with those of the image edges. In Figure 2, we show such comparison for all fields on our sample. In all cases, the presence of a cluster near the centre is clearly indicated by the excess of luminous sources with respect to the edge regions. In Figure 2 we also show the K_s completeness magnitudes for each field. As expected, our observations are deep enough to obtain a complete census of whole relevant young stellar population in all clusters. Additionally, we note that the derived cluster K_sLFs are all sharply declining above our completeness limits, suggesting that either the relative number of sub-stellar objects in the Vela D cluster is smaller than in other cluster forming regions (such as the Orion Nebula Cluster, Hillenbrand & Carpenter 2000), or that most of the sources within the clusters are affected by a visual extinction much lower than the A_V = 30 mag value that we have assumed to compute the sensitivity estimates. This latter explanation is in agreement with the near infrared colour-colour and colour-magnitude diagrams shown in Figures 3 and 4, where sources within 1 arcmin from the image centres are shown in green. On average, they show redder colours than sources further away from the centre and a fraction of them display a clear infrared excess, typical of young stellar objects. In the figures, the reddening vectors and the main sequence loci are also displayed, only very few sources are consistent with an extinction greater than 20 mag in the visual.

To obtain a quantitative estimate of the *richness* of the detected young stellar clusters, we followed the method described in Testi et al. (1999) and derived the *richness indicator* I_C for all six sources. I_C gives the "effective" number of cluster members, since it is defined as the integral of the radial K_s stellar surface density profile centred on the peak stellar surface density and corrected for the foreground/background stellar density as computed on the edge of the images. In Figure 5, we show I_C as a function of the maximum stellar mass in each cluster for the high-luminosity sources in the Vela D cloud compared with the results of Testi et al. (1999) toward Herbig Ae/Be systems and the low luminosity sources in the Vela D cloud (Massi et al. 2000). The mass sensitivity of our NTT survey is similar to the estimated mass sensitivity of the Herbig Ae/Be survey, while the

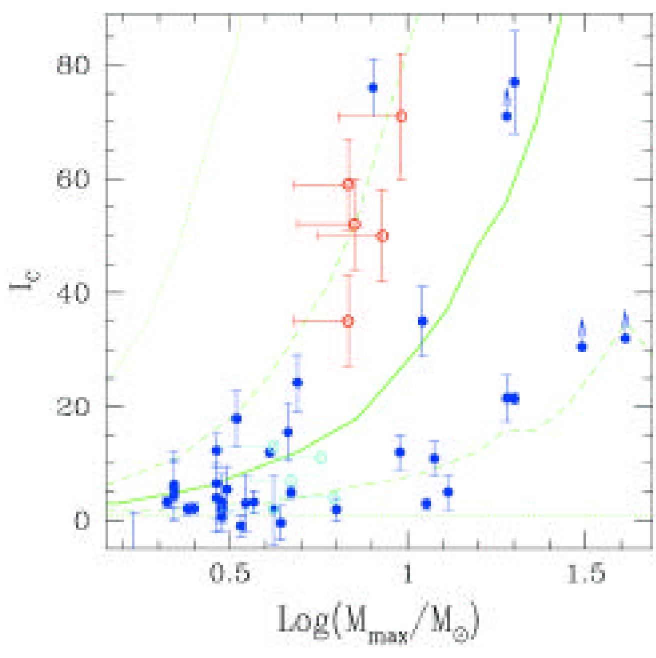

Figure 5: I_C versus maximum stellar mass for the luminous young clusters in the Vela D molecular cloud (red open circles), compared with the results toward low luminosity sources in the same cloud (cyan open circles) and the Herbig Ae/Be sample (blue filled circles). The prediction of the "random" model (see text) are shown in green: median results (solid line), 50% of the realisations (dashed lines), and 98% of the realisations (dotted lines).

Massi et al. survey of low-luminosity sources in the Vela D cloud has a slightly lower sensitivity. The maximum stellar masses in the Vela clusters have been computed assuming that a fraction of the total luminosity ranging from 30% to 100% is emitted by the most massive object. The young IRAS sources in the Vela molecular cloud show the same trend as the Herbig Ae/Be stars: more massive stars are surrounded by rich clusters, while low-mass stars are found in relative isolation.

In the same plot, the result of the various surveys are compared with the predictions of a “random sampling model” (as described in Testi et al. 2001). Our results clearly deviate from the prediction of the model, since no massive object is found in isolation, and all lie above the median predictions of the model. These results suggest that there is a physical connection between clusters and high-mass stars. This does not necessarily *imply* that massive stars are formed by coalescence in (proto-)cluster environments, but suggests that the conditions to form a massive star are such that this process is associated with the formation of a cluster of (lower-mass) objects. The cluster could be either the catalyst of high-mass star formation or a by-product of it.

These conclusions should and will be made more firm by combining larger samples from various surveys toward different regions.

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Building Luminous Blue Compact Galaxies by Merging

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ABSTRACT

Observations of six luminous blue compact galaxies (LBCGs) and two star-forming companion galaxies were carried out with the CIGALE scanning Fabry-Perot interferometer attached to the ESO 3.6-m telescope, targeting the Hα emission line. The gaseous velocity field presents large-scale peculiarities, strong deviations to pure circular motions and sometimes, secondary dynamical components. In about half the cases, the observed rotational velocities are too small to allow for pure rotational support. If the gas and stars are dynamically coupled, a possible explanation is either that velocity dispersion dominates the gravitational support or the galaxies are not in dynamical equilibrium, because they are involved in mergers, explaining the peculiar kinematics. In two cases, we find evidence for the presence of dark matter within the extent of the Hα rotation curves and in two other cases we find marginal evidence. For most of the galaxies of the present sample, the observed peculiarities have probably as origin merging processes; in five cases, the merger hypothesis is the best way to explain the ignition of the starbursts. This is the most extensive study as yet of optical velocity fields of luminous blue compact galaxies.

1. Introduction

A Blue Compact Galaxy (BCG) is characterised by blue optical colours, $-21 < M_B < -12$, an HII-region-like emission-line spectrum, a compact appearance on photographic sky-survey plates, small to intermediate sizes, high star-formation rates per unit luminosity and low chemical abundances (e.g. Searle and Sergent, 1972). Moreover, most BCGs are rich in neutral hydrogen. There is no consensus on the process(es) that trigger the bursts of star formation. Three main scenarios have been proposed to explain it: (1) cyclic infall of cooled gas: Starbursts are terminated by SN winds, but when gas later accretes back, a new starburst may be ignited; (2) galaxy interactions and (3) collapse of protocloud if BCGs are genuinely young galaxies. Most arguments have been based on photometry alone. On the other hand, the dynamics of these systems are not well explored, still the creation of an energetic event like a sudden burst of star formation is likely to have dynamical causes and impacts, complicating the interpretation.

To improve our understanding of the dynamics and the triggering mechanisms behind the starburst activity, we have obtained Fabry-Perot data allowing us to achieve two-dimensional velocity fields with both high spatial and spectral (velocity) resolutions. BCGs are obviously the galaxies for which 2-D data are absolutely requested due to the non-axisymmetry of the velocity field around the centre of mass.

The selected BCGs are among the more luminous ones known in the nearby universe. The galaxies were observed at the Hα-emission line with the ESO 3.6-m telescope on La Silla. The exposure times ranged between 24 minutes and 160 minutes. In Östlin et al. (1999), we presented and described the data: Hα images, velocity fields, continuum maps and rotation curves. In