STAR FORMATION IN CLUSTERS: FROM ISO TO FIRST

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Abstract

FIRST will give a great contribution to the study of star formation. We think that at the beginning of the mission it will be crucial to carry out few selected key projects able to give important indications for all the following observations. We suggest: the survey of large areas of sky (in particular the galactic plane) and the systematic study of a few clusters and protoclusters close to the Sun in order to take the full advantage of the spatial resolution of FIRST.

Key words: stars:formation; stars:clusters

1. Introduction

The formation of isolated stars is a process now fairly well understood and several models have been suggested during the last two decades (e.g. Mouskovias & Ciolek 1999, Shu et al. 1987, Palla & Stahler 1999, Bernasconi & Mader 1996).

However, the observed large fraction of stars belonging to multiple systems and the observational evidence that most stars form in clusters (e.g. Nordh et al. 1996 for Chamaleon; Lada et al. 1991 for L1630; Wilking & Lada 1985 for Taurus) show that interactions among the forming objects play an important role during star formation. This has also been highlighted by Palla & Stahler (2000), who observationally found that star formation in clusters is constant for million years, then it undergoes to a steep acceleration. In particular the study of star formation in clusters is important for:

i) The study of the origin of the initial mass function, crucial to understand the evolution of the stellar populations in our and other galaxies. In fact, even if the mechanism that fixes the final mass of stars is not understood, it is well agreed that the explanation has to be found in protoclusters, which represent the first stages of cluster formation (Williams et al. 1995, André & Motte 2000). Millimeter surveys of protoclusters (e.g. Testi & Sargent 1998, Motte et al. 1998) are affected by large uncertainties in the determination of the masses, because the spectral energy distributions (SEDs) of the pre-stellar cores (e.g. L1544 in Fig.1) peak at 100 - 200 μm, in the FIRST spectral range, and observations around the peak are crucial for the determination of the dust temperature, which is necessary to estimate the dust masses.

ii) The formation of massive stars: the mass of the most massive object of a cluster seems to increase with the stellar density of the cluster (e.g. Zinnecker et al. 1993). As an example, in Taurus, a region of low mass star formation, the average distance between stars is 0.3 pc (Gomez et al. 1993), while the intermediate mass stars like Herbig AeBe are inside clusters with a separation ranging from 0.2 pc, for the less massive objects, to 0.06 pc for the most massive ones (Testi et al. 1999). Finally, in the high mass stars region of the Trapezium cluster a stellar density in excess of 2200 pc^{-3} has been found (Herbig & Terndrup 1986), with an average distance among stars of less than 15.000 AU. These small distances are of the order of the stellar envelopes, making highly probable the occurring of interactions among protostars during the star formation process.

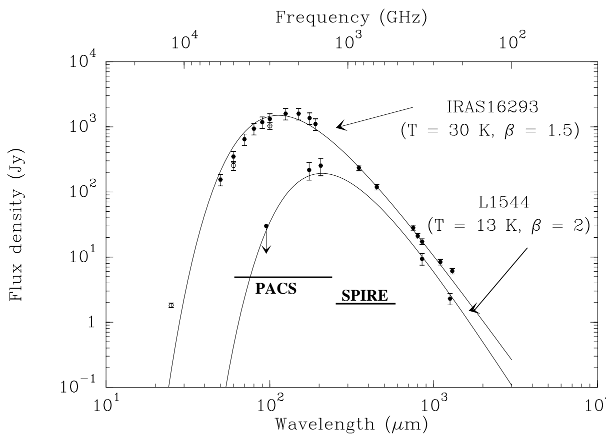

Figure 1. Spectral energy distribution of the pre-stellar core L1544 and the protostar IRAS 16293, together with simple gray body fits. PACS and SPIRE spectral windows are reported (adapted from André et al. 2000).

2. Star formation in clusters: the role of FIRST

It is known that protostars are luminous: in particular low mass stars are much more luminous during the protostellar phase than during the Main Sequence phase (e.g. Stahler 1988, D'Antona & Mazzitelli 1994). Therefore, if

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stars are born in clusters, the factor that limits the detections is more likely confusion (e.g. Franceschini et al. 1991) rather than sensitivity. Besides, because protostars are evolving very fast, we can easily have in the same beam objects in different evolutionary stages, with completely different physical characteristics that can not be easily discriminated (Saraceno et al. 2000). It follows that it is very important to have high spatial resolution in the FIR and submillimeter, where the SEDs of protostars peak (Fig.1).

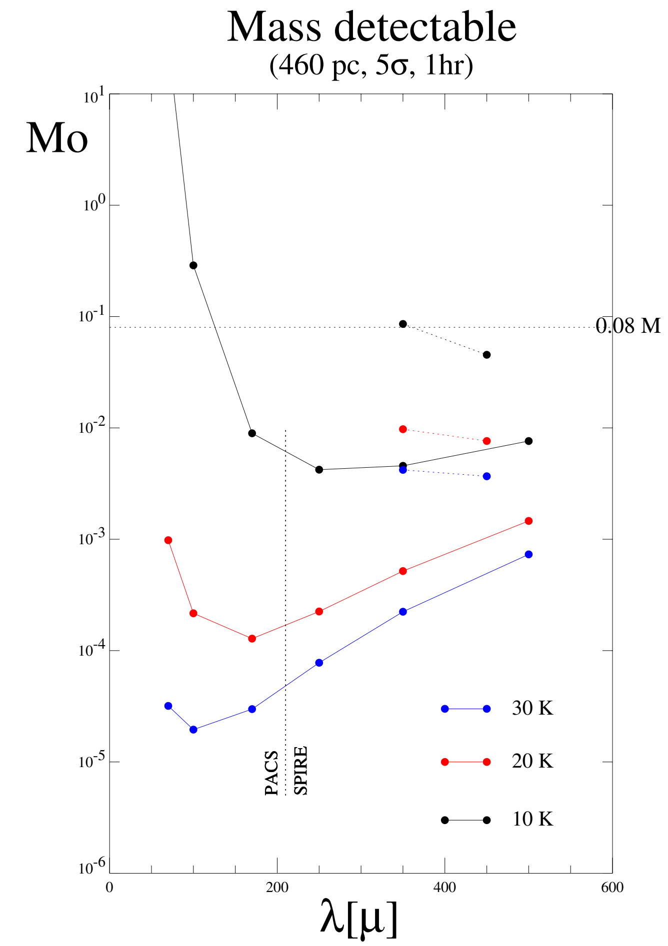

Figure 2. Minimum detectable mass, for different dust temperatures. The solid lines represent the PACS and SPIRE detection limits, while the dashed lines on the right give the limits for the JCMT (15m) with the SCUBA camera. The horizontal dashed line corresponds to the mass limit for Hydrogen ignition.

The two imaging instruments of FIRST, PACS and SPIRE, have both broad-band and line imaging capabilities. PACS works in the range where the SEDs of protostars peak and, having a pixel resolution as small as 5 arcsec, it is the best instrument for the study of known clusters, while SPIRE, having a lower spatial resolution but a larger field of view (a factor ∼ 5 larger than PACS) is the best instrument to survey large areas of sky. These fundamental capabilities of the two instruments suggest two kinds of key projects for the study of star formation with FIRST.

1) The survey of large areas of sky, as discussed by P. André and by S. Molinari at this conference, using the fast mapping capability of SPIRE. Molinari et al. show that all the galactic plane can be surveyed with SPIRE in 70 days at a limiting sensitivity of 100 mJy. This survey could be complete down to $\sim 0.1\ M_\odot$ for $D \leq 500$ pc and to $\sim 10\ M_\odot$ for $D \leq 5$ kpc. The galactic plane survey should be one of the highest priority projects of FIRST and should be published in the first year to make possible the follow-up observations similar to those discussed in the next point.

2) the study of known condensations using PACS and SPIRE, to measure the SED of individual members of clusters and protoclusters and using the spectrometers of both instruments to study the ISM of clusters. Most of the time of these programmes will be used by PACS, whose photometric capabilities are necessary both to measure the SEDs around the peaks and to minimize source confusion using its high spatial resolution.

Since the proposal 1) is discussed by other authors in these proceedings, in the following sections we will discuss the programs introduced in 2).

3. Pointed observations of known clusters.

The mean separation of ≤ 0.4 pc found by Herbig & Terndrup (1986) in the Trapezium cluster is of the order of the size of the stellar envelopes and of the disks observed by HST in the same region. Therefore we tentatively assume that this dimension is of the order of the limit given by source confusion. This separation corresponds to a resolution of ∼ 18 arcsec at the distance of Orion and ∼ 60 arcsec at the distance of Taurus, well above the FIRST spatial resolution. Therefore we think that *all the known clusters and protoclusters within 500 pc have to be studied by FIRST at high priority* because, within this distance, we will not be much limited by source confusion. Within this distance we should easily detect all accreting objects to the limit of H burning (e.g. Fig.9 of Stahler 1988), and all the pre-stellar condensations to the limit of the Jupiter mass ($\sim 10^{-3} M_\odot$). This is shown in Fig.2, where the minimum mass detectable by FIRST is plotted for an object at the distance of Orion. The minimum mass is computed for dust temperatures of 10, 20 and 30 K, as: $M_{dust} = S_\nu\ D^2/k\ B_\nu(T)$ (Hildebrand 1983) where S_ν is the minimum detectable flux, D the distance of the cloud, k the dust emissivity and $B_\nu(T)$ the Planck function at the temperature T. The figure shows that all the spatially resolved proto-brown dwarfs should be detected by FIRST. Moreover the FIR colors will be able to discriminate among the different evolutionary stages of protostars (Pezzuto et al. 1999, Saraceno et al. 1999a).

Only two studies of protoclusters in the millimeter continuum have been published so far. One is the Serpens core, mapped with the OVRO interferometer at 3mm with

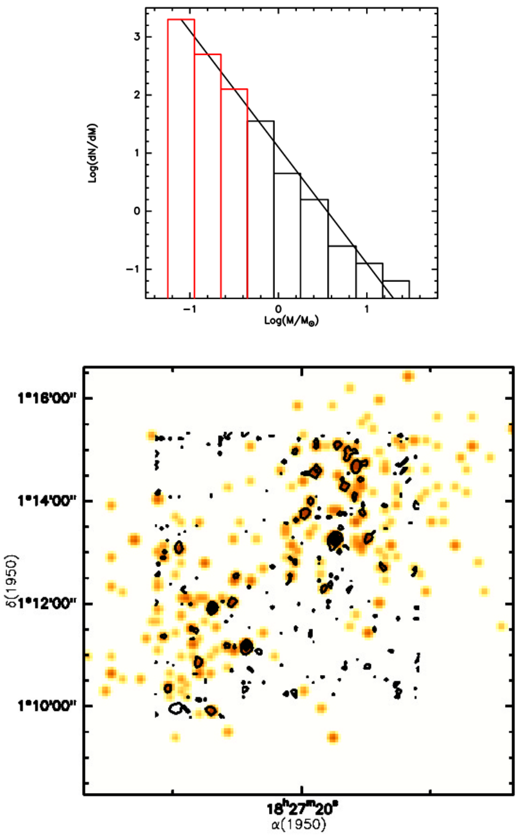

Figure 3. Bottom panel: in black the 5 × 5 arcmin map of the Serpens cloud core observed at 3mm with the OVRO interferometer (Testi & Sargent 1998),the resolution is 5.5" × 4.3" and the limiting sensitivity 3 mJy. In color the simulation of FIRST observation at a limiting sensitivity of 50 mJy ; Top panel: the derive mass spectrum, bleak from observation, in color the assumed one for the simulation.

a resolution of 5.5" $\times$ 4.3" (Testi & Sargent 1998) at a limiting sensitivity of 3 mJy; the other one is the ρ Ophiuchi core, mapped with the IRAM 30m telescope at 1.3mm with a resolution of 11" and a limiting sensitivity of $\sim$ 8 mJy (Motte et al. 1998).

Fig. 3 (lower panel) shows in black the millimeter map of the Serpens protocluster (Testi & Sargent 1998) with the 26 condensations detected: in the upper panel the derived mass function is reported in black. On the observed millimeter map we superimposed, in color, a simulation of what FIRST will be able to detect at 100 μm, at a 5 σ sensitivity of 50 mJy, (roughly the flux of 0.08 $M_\odot$). The number of possible detections of FIRST has been estimated assuming a linear extrapolation of the observed mass function (in color, Fig.3, upper panel) down to 0.08 $M_\odot$; the number of objects in each mass bin has been estimated and the mm flux has been computed assuming for the dust T = 20 K, emissivity k=0.005 cm^2/g at 1.3 mm and a β = 1.5. These simulated objects, assumed point-like, were smeared with a 100 μm diffraction pattern (2d gaussian) and distributed normally around the location where most objects were detected in the observations at 3.4 mm.

Table 1. Example of clusters and protoclusters within 500 pc to be measured with FIRST in high priority.

Possible targets	Area	PACS	SPIRE
		5σ 50mJy [hours]	
ρ-Oph main cloud	1° x 1°	50	10
Perseus NGC1333 (& sourrounding cores)	1° x 2°	100	20
Orion Complex (L1641, L1630, BN-KL, ΛOri)	1° x 5°	250	50
Chamaleon I	0.5° x 2°	50	10
Serpens protocluster	0.5 ° x 0.5 °	12	2
Lupus 1-2-3	1° x 2°	40	8
	Total	502	100

Given the field of view of SPIRE and PACS the entire Serpens core will be mapped with few exposures: the time needed to survey this area at a 5 σ sensitivity of 50 mJy in the three bands of PACS is of the order of two hours, while only 0.4 hours are needed for SPIRE. This very simple simulation shows that FIRST multi-band imaging observations will detect many more sources than those of the ground based millimeter observations, allowing precise definition of temperatures and masses of the individual cluster members, producing large samples of high statistical significance.

In Table 1 we give a tentative list of the most relevant clouds within 500 pc with a rough estimate of the area to be mapped and of the integration times needed, given the present sensitivities of PACS and SPIRE.

4. Imaging spectroscopy

The spectroscopic observations of the ISO satellite have shown the great power of FIR lines to trace the warm gas of the star forming regions (Saraceno et al. 1999b), where it is possible to find the signature of the interactions going on among the members of a clusters. The spectroscopic imaging capability of PACS and SPIRE will provide, for each spatially resolved element, a full spectrum at intermediate spectral resolution tracing the physical and chemical conditions of the gas and allowing the study of the processes going on (outflows, shocks, stellar winds, ionizing fields, etc.). Given the low extinction of the FIR lines, it will be possible to trace the innermost parts of the cluster, obscured in the near infrared.

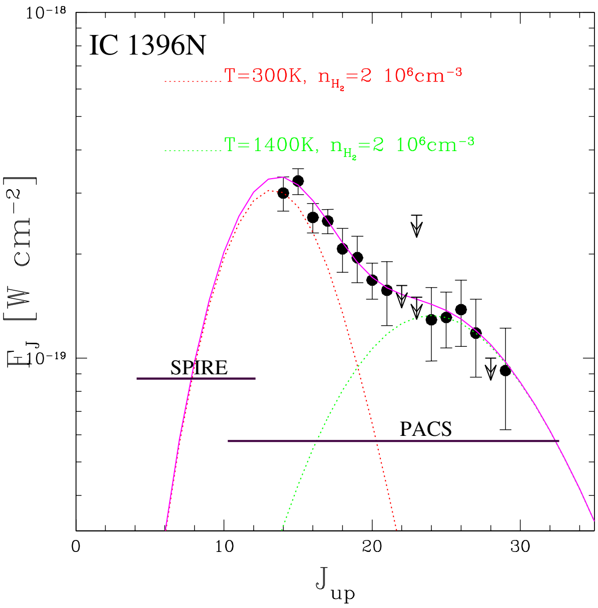

Figure 4. The CO lines detected by ISO-LWS toward the IC1396N source (Saraceno et al., in preparation) plotted as a function of the upper rotational quantum number (J_{up}). The model fit indicates the presence of two regions at different temperature in the beam. The SPIRE and PACS wavelength ranges are indicated.

One of the best tools to trace the gas inside the clusters is the CO molecule (Nisini et al. 1997, Saraceno et al. 1999b). CO is very abundant ($[CO]/[H_2]\sim10^{-4}$), has a relatively high dissociation energy (11.09 eV) and has transitions excited from the millimeter (in the cold gas of molecular clouds) to the near infrared (in the atmospheres of cool stars). In the FIR, the CO lines are generally optically thin and the line emission can be fitted to derive temperature and volume density. An example is given in Fig.4, where the ISO-LWS observations of IC1396N are reported with a model fit that clearly shows the presence in the beam of two gas components at different temperatures. FIRST will observe this source with a beam 100 times smaller, allowing to better discriminate the different emitting regions. Moreover, the SPIRE extended range in the submillimeter will allow to measure lines at lower values of the rotational quantum number (J_{up}) giving a definitely more accurate determination of temperature and density of the lower temperature gas component. The higher sensitivity of PACS, with respect to ISO-LWS, will allow to explore the high J_{up} part of the spectrum tracing the gas at temperatures as high as T$\simeq$ 2000 K. Finally the high spectral resolution of HIFI (R $\simeq 10^7$) will allow to dynamically discriminate the different emitting components.

Another important molecule used to trace the gas inside clusters is H_2O. The ISO results have shown that, in contrast with model predictions (e.g. Kaufman & Neufeld 1996), the gas cooling due to H_2O is significantly lower than the CO one (with very few exceptions). This seems to be due to a water vapour abundance definitively lower than the predicted one (Saraceno et al. 1999b, Nisini et al. 1999, van Dishoeck 1998a, van Dishoeck 1998b, Spinoglio et al. this conference): a result recently confirmed by the Submillimeter Wave Astronomy Satellite (SWAS) (see the papers of Melnick, Bergin, Snell, Neufeld, Matthew and collaborators in the special issue of the Astrophysical Journal dedicated to SWAS), which in addition did not detect any O_2 emission.

Both the ISO and SWAS results show that the current models do not explain the abundance of the oxygen bearing molecules, asking for a more detailed study of the oxygen chemistry. The high spatial and spectral resolution observations of H_2O, OH, O_2, O and CO that will be possible with FIRST will provide a much clearer picture of the oxygen chemistry.

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