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Star Formation in Clusters: Subclustering, Cloud Fragmentation and the Origin of the Stellar IMF

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Abstract. We review recent high spatial resolution millimeter continuum and spectral line observations of (proto-)cluster regions. These observations reveal that the mass distribution of prestellar cores is consistent with the initial mass function for field stars suggesting that the IMF is connected to the molecular clouds structure or the cloud fragmentation processes, rather than the details of the star formation mechanism. We discuss the evidence for at-birth subclustering independently obtained for two separate protoclusters. The presence of subclustering within coherent subclumps suggests that the fragmentation process is hierarchical and that young stellar clusters are assembled by independent substructures. The local (proto-)stellar density and star formation efficiency within the subclusters are much higher than the average values for the entire star forming cloud. Unfortunately, current observations are sparse and limited to the nearest star forming regions, for spatial resolution and sensitivity considerations, the future millimeter wave arrays, especially ALMA, will allow to expand considerably the sample of observed regions.

1. Introduction

There is now a fairly robust theory of how isolated, low-mass stars form (e.g. Shu et al. 1987; 1993). One notable omission, is the failure to predict the resulting stellar masses. Stars in the field are known to be distributed according to a well defined mass function (e.g. Salpeter 1955; Kroupa et al. 1993), and a complete theory of star formation should explain this mass distribution, the Initial Mass Function (IMF). Since it now seems very likely that most stars form in clusters rather than in isolation (Clarke et al. 2000), the way in which the IMF originates must be closely related to the way stars form in clusters. Indeed, young embedded clusters appear to be populated by stars with a mass distribution very close to that observed in the solar neighbourhood (Hillenbrand 1997).

The different theories of the IMF have been recently reviewed by several authors (e.g. Elmegreen 2001), two different phylosophies are generally considered: i) the observed distribution of stellar masses may result naturally from the protostellar accretion process, such as due to feedback effects (e.g. Fatuzzo & Adams 1996) or competitive accretion (Bonnell et al. 1997), alternatively, ii) it may be related to the molecular clouds structure and fragmentation processes (Elmegreen 2000; Myers 2000; Padoan & Nordlund 2001). If the fragmentation
hypothesis is correct, the mass distribution of prestellar condensations in cluster-forming molecular cores should follow the IMF of the stars in young embedded clusters and in the field. Millimeter wavelength interferometry offers both a high spatial resolution and high sensitivity that are critical to shedding light on this problem. At 3 mm the thermal emission from dust in the condensations is probably optically thin, allowing a reasonable estimate of clump masses, and thus an insight into the clump mass spectrum. High resolution imaging of extended areas of the sky at millimeter wavelengths can be performed by means of the multi-field interferometric imaging technique (see Testi & Sargent 2000 for its implementation at the OVRO array). In addition, an interferometer provides simultaneous observations of molecular line and broad band continuum emission. Any contamination of the continuum flux by molecular line radiation can therefore be eliminated. Finally, thanks to the interferometric filtering capability, smooth, extended emission from the molecular cloud in which cores are embedded is resolved out.

Using the Owens Valley Radio Observatory millimeter wave array, we have begun a program of high resolution, millimeter-wave mapping of molecular cloud cores with a view to establishing whether the prestellar clump mass function and the IMF are in general similar. Here we review our results for the Serpens star-forming core (Testi & Sargent 1998, Testi et al. 2000). The results of other surveys towards other regions as well as the promise of the next generation of millimeter arrays (ALMA) are also discussed.

2. The Serpens core

At a distance of 310 pc (de Lara et al. 1991), and with an angular extent of few arcmin (Loren et al. 1979), the Serpens molecular core is an ideal target to search for compact prestellar and protostellar condensations. Inside the 500-1500 \( M_\odot \) core is a young stellar cluster of approximate mass 15-40 \( M_\odot \) (Giovannetti et al. 1998), while far-infrared and submillimeter observations reveal the presence of a new generation of embedded objects (Casali et al. 1993; Hurt & Barsony 1996).

At low spatial resolution (\( \sim 50'' \)) the Serpens core appears as a massive rotating molecular clump which is fragmented in two main sub-clumps with size-scales of \( \sim 0.2 \) pc, each with a remarkable internal velocity coherence (Testi et al. 2000; Olmi et al. 2001). Our millimeter interferometric observations in the 99 GHz continuum and CS(2–1) line cover the inner regions of the clump and encompass all the sub-clumps structures seen at low spatial resolution. The details of the observations are given elsewhere and will not be reviewed here (see Testi & Sargent 1998; 2000).

The 3 mm continuum high resolution mosaic (Fig 1) further resolve the structure of the clump in a large number (\( \sim 30 \)) of cores. The mass of each of the dust condensations in Figure 1 can be calculated, assuming reasonable values for the parameters of the emitting dust (see Testi & Sargent 1998 for details). Using existing near- and far-infrared observations (Givannetti et al. 1998; Hurt & Barsony 1996), the few condensations associated with already formed stars were eliminated from our list of candidate prestellar and protostellar candidates. Figure 2 displays the cumulative mass spectrum for the remaining 26 continuum sources above a the \( \sim 4.5\sigma \) peak threshold of 4 mJy/beam. This mass
Figure 1. The 3 mm continuum hybrid mosaic of the Serpens core (Testi & Sargent 1998). The rms in the map is $\sim 0.9$ mJy/beam, and the synthesised beam, indicated by a black ellipse in the lower right corner, is $5.5'' \times 4.3''$ FWHM. Submillimeter and far-infrared sources from Casali et al. (1993) and Hurt & Barsony (1996) are indicated.

distribution is well fitted by a power law $dN/dM \sim M^{-2.1}$, significantly steeper than the mass spectrum of larger-scale gaseous clumps in molecular clouds $dN/dM \sim M^{-1.7}$ (Williams et al. 2000), which is rejected by the Kolmogorov-Smirnov test at the 98% confidence level. Our power law exponent, $-2.1$, is close to the Salpeter (1955) IMF value, $-2.35$, and very similar to that suggested recently by Kroupa et al. (1993, see also his review in this volume) for solar and slightly subsolar stellar masses. The inferred masses and sizes of the cores suggest that these are self gravitating and are going to be the progenitors of individual stellar systems (single or multiple stars). Our result are supported by the findings by Motte et al. (1998), their IRAM-30m 1.3 mm continuum maps of $\rho$-Ophiuchi, another cluster forming core, show that the mass spectrum of the prestellar and protostellar clumps within the core appear consistent with the IMF. Taken together these observations provide compelling evidence for a “clump fragmentation” origin for the stellar IMF.

3. Hierarchical fragmentation and sub-clustering

In Figure 3 we show the OVRO CS(2–1) integrated intensity and first moment mosaics for the Serpens core. Most of the extended emission seen in the single dish maps (McMullin et al. 1994; 2000; Olmi et al. 2001) is missing, probably because the optically thick, extended, molecular line emission is resolved out by the interferometer. Most of the CS(2–1) emission we detect appears to be due
Figure 2. Cumulative mass spectrum of the protostellar and prestellar cores found in the 3 mm continuum mosaic shown in Figure 1. The dotted line is the best fitting power law $dN/dM \sim M^{-2.1}$, the dashed line shows the Salpeter IMF, and the dot-dashed line depicts the power law typical of gaseous clumps in molecular clouds, rejected by the Kolmogorov-Smirnov test at the 98% confidence level (Testi & Sargent 1998).

Figure 3. a) The OVRO CS(2–1) integrated intensity contour map at $5''.5 \times 4''.3$ resolution, superposed on the millimeter continuum mosaic. b) CS(2–1) first moment map, the direction of optical and near infrared outflows are marked (adapted from Testi et al. 2000).
to the known outflow sources. This interpretation is confirmed by the coincidence of the CS features with emission of molecular tracers enhanced in outflow regions. In Figure 3 we indicate these outflows along with their approximate orientations (Testi et al. 2000; Olmi et al. 2001; but see also Wolf-Chase et al. 1998; Hogerheijde et al. 1999).

We find that the millimeter continuum cores are mostly confined within the two subclumps detected in the large scale molecular line emission. Moreover, the direction of the flows from the protostars within a single subclump are well aligned (Figure 3). These findings together with the internal velocity coherence of the subclumps suggest a hierarchical picture for the fragmentation of the molecular cloud, in which coherent velocity structures (the sub-clumps) fragment to form the millimeter continuum cores, which are the progenitors of single stellar systems. Thus, within each of the sub-clumps an independent sub-cluster of protostars is being assembled. A similar behaviour is also observed in the ρ-Oph cluster, where Johnstone et al. (2001) noted a sub-clustering of the prestellar cores over the same scale length observed in Serpens, ∼ 0.2 pc. It is interesting to note that this scale-length is of the same order as the scale-length of the externally driven shear flow turbulence in non star-forming clouds, i.e. clouds without an internal perturbation (LaRosa et al. 1999). It is, however, premature at this point to argue if and how this process may affect star formation in molecular clouds.

The picture that comes out is that of a stellar cluster being assembled in denser subclusters that eventually will merge during the dynamical evolution of the (proto-)cluster on a timescale of a few million years (Testi et al. 2000; Clarke et al. 2000). An important consequence of this view is that even though the average (proto-)stellar density of the (proto-)cluster and the total star formation efficiency of the parent cloud are both rather low, the local density and star formation efficiency are expected to be much higher. In the case of the Serpens, while the average (proto-)stellar density and star formation efficiency are ∼ 400 ⋆/pc³ and ≤ 2 – 5%, both are a factor of ∼ 10 higher in the sub-clusters (Testi et al. 2000).

The conclusions, although consistently supported by independent observations of two different regions, are, however, preliminary, since the results of the surveys may be vitiated by small number statistics. Combined millimeter and infrared surveys of a larger number of cluster forming cores are necessary to ensure the required statistical significance. We note that in this respect the next generation millimeter arrays will be the ideal instruments to attain the required resolution and sensitivity. In fact, at the low resolution attainable with single dish instruments, it is not possible to resolve the parent cores of each individual star, and the mass distribution of the large scale gaseous clumps in molecular clouds is recovered (e.g. Tothill & White 2000). A tremendous advance is expected from the next generation millimeter array (ALMA). At the sensitivity, frequency coverage and spatial resolution of the ALMA baseline array, it will be possible to map at the same linear resolution and mass sensitivity than the Serpens OVRO mosaic the giant star forming regions (e.g. 30 Doradus) in the Large Magellanic Cloud, it will thus be possible to probe the initial conditions for star formation beyond our own galaxy.
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