Fragmentation in Molecular Clouds and the Origin of the Stellar Initial Mass Function

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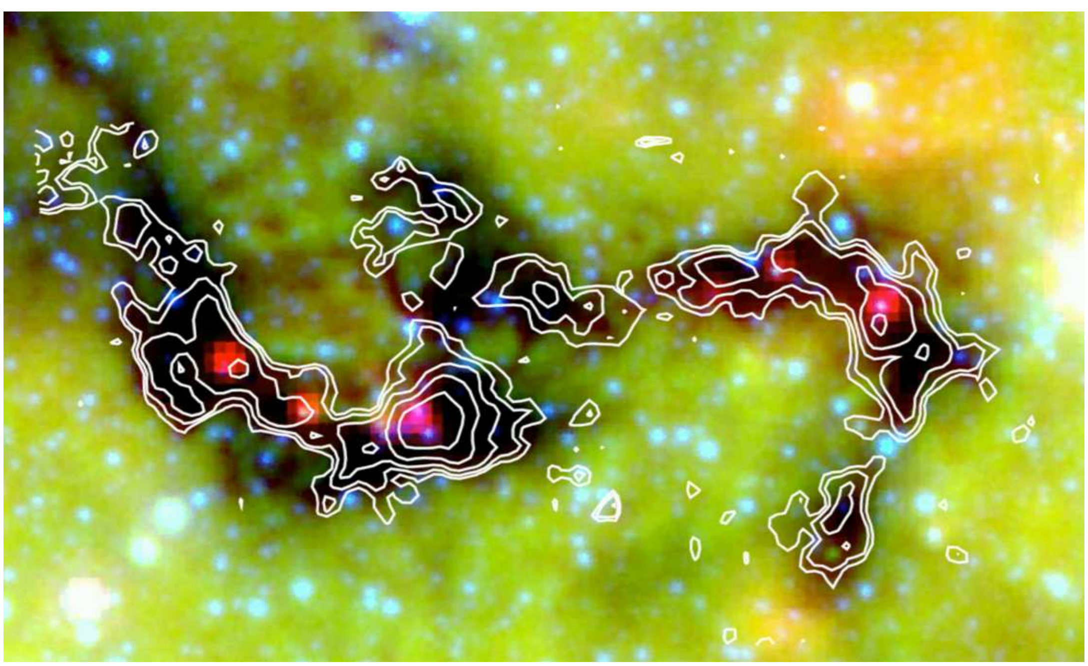

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Executive Summary

The stellar Initial Mass Function (IMF) is remarkably consistent over a host of environments in the Galactic neighborhood. The physical processes responsible for producing a seemingly invariant IMF have long been the subject of theoretical investigation. Recently, a potential link has been made between the mass distribution of clumps in nearby molecular clouds and the stellar IMF. To make a definitive determination if the stellar IMF is imprinted in the cloud structure, future observations need to show 1) that the mass function of clumps in molecular clouds is similar to the stellar/substellar IMF down to $\sim$0.01 $M_\odot$, and 2) that the clump mass function is invariant to environment as is the stellar IMF. Such surveys can be conducted with the next generation of large format bolometer cameras and heterodyne arrays on 25-100 m class single aperture telescopes (CCAT, GBT, LMT) and with high resolution interferometric observations (ALMA, CARMA, EVLA, SMA) of targeted regions.

1. Introduction

The distribution of stellar masses that form in a local volume of space, also known as the stellar Initial Mass Function (IMF), shows remarkable consistency in environments ranging from globular clusters, to starburst clusters, and to sparse star-forming regions (Kroupa 2002; Chabrier 2003). The physical processes that lead to a seemingly invariant IMF in the local universe have long been the subject of theoretical conjecture. Gravitational or turbulent fragmentation, feedback from stellar winds and outflows, competitive accretion, ejection of protostellar cores, and stellar mergers have all been proposed to explain various aspects of the IMF shape (see review by Larson 2003).

Direct evidence to indicate which of these mechanisms, if any, play a dominant role in governing the IMF shape remains elusive. One intriguing observational development is emerging evidence that the mass function of dense "clumps" in molecular clouds is similar in shape to the stellar IMF (Ward-Thompson et al. 2007). Since many of the clumps have sizes and masses needed to form individual stars, the inference is that the clump mass function directly translates into the stellar IMF. In this contribution, we describe how observations over the next decade will establish if the clump mass function in nearby molecular clouds follows the stellar IMF to the substellar regime, and if the clump mass function is similar over a wide range of environments in the Galaxy. If this is indeed the case, it will provide compelling evidence that the stellar IMF is imprinted in the fragmentation structure of molecular clouds. Otherwise, alternative mechanisms or a combination of processes may need to be invoked to explain the origin of the IMF.

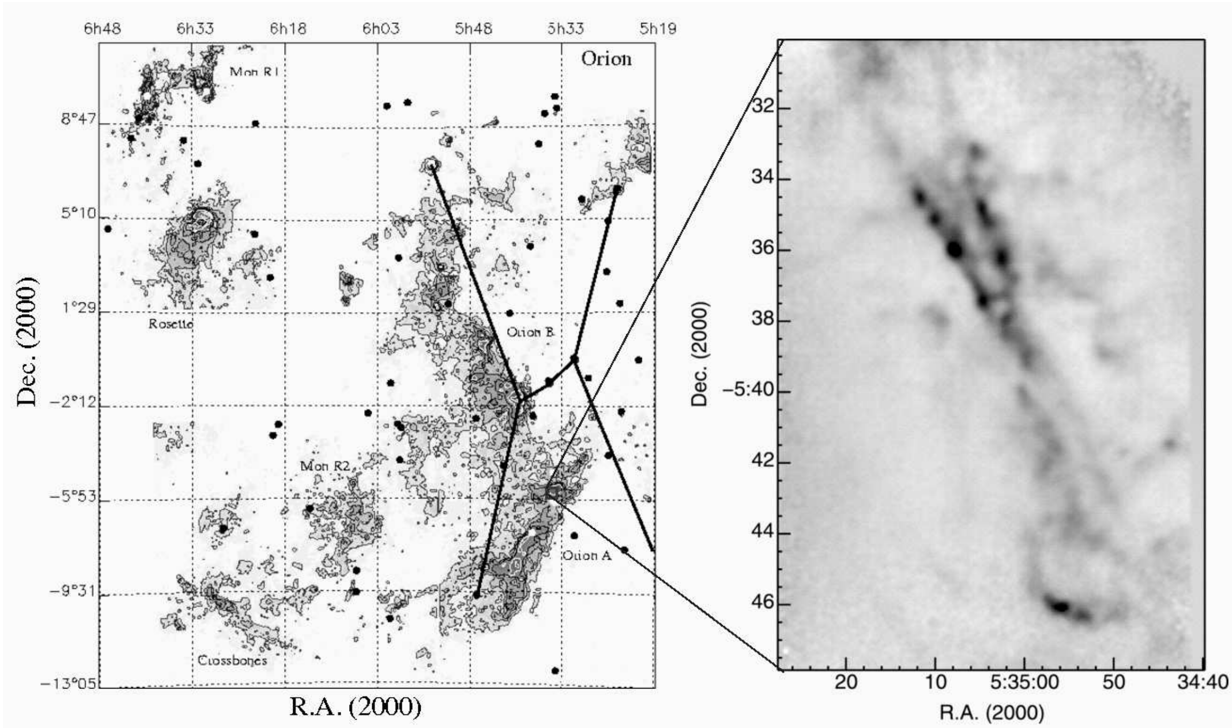

Fig. 1.— *Left:* Extinction map of the Orion and Monoceros region (Cambrésy 1999). *Right:* SCUBA 850 μm continuum map of a portion of the Orion A molecular cloud (Johnstone & Bally 2006). These observations and others like it have been used to infer the mass spectrum of clumps in star forming regions.

In Section 2, we review current measurements of the clump mass function, and then discuss in Section 3 the observations needed to make a definitive determination if fragmentation and the stellar mass function are intimately linked. In Section 4, we describe the instruments needed for future observations, including the next generation of bolometer cameras and heterodyne arrays on 25-100 m class single aperture telescopes (CCAT, LMT, GBT), and sensitive high-resolution interferometers (ALMA, CARMA, EVLA, SMA).

2. Current Observations of the Clump Mass Function

Current techniques to measure the clump mass function in molecular clouds include wide-field mapping of the dust continuum emission at wavelengths between 450 μm and 3 mm, molecular line surveys, and extinction mapping of background star light. Each of these techniques has unique advantages. Dust continuum surveys trace the densest regions in clouds, molecular line surveys probe the three dimensional cloud structure, and extinction surveys are insensitive to assumed dust temperatures and molecular abundances.

Dust continuum observations have been frequently used to measure the clump mass function due to the availability of bolometer cameras (e.g. AzTEC, BOLOCAM, LABOCA,

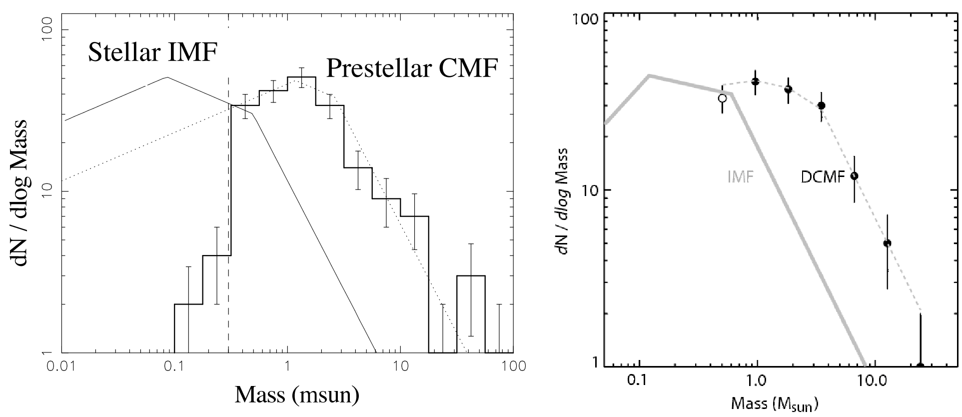

Fig. 2.— The observed clump mass function in the Orion B molecular cloud (left; Nutter & Ward-Thompson 2007) and the Pipe Nebula (right; Alves et al. 2007). The stellar IMF is indicated for comparison. In both clouds, the clump mass function flattens toward lower masses, which mimics the shape of the stellar IMF. These results suggest that the stellar IMF is imprinted in the cloud structure if ∼30% of the clump mass is formed into stars.

MAMBO, SCUBA) on 10-30 m class radio telescopes. As an example, Figure 1 presents the SCUBA 850 μm continuum image for a portion of the Orion molecular cloud (Johnstone & Bally 2006). Analysis of this region and several others have shown that the high mass end ($\gtrsim$1 $M_\odot$) of the clump mass spectrum can be represented by a power-law ($dN/dM \propto M^{-\alpha}$). The inferred values of α range between 2.1 and 2.5 (Motte, André, & Neri 1998; Testi & Sargent 1998; Johnstone et al. 2000, 2001; Reid & Wilson 2006; Enoch et al. 2008), and are similar to the slope of the Salpeter IMF ($\alpha = 2.35$).

More recently, continuum observations of the Orion B molecular cloud (Nutter & Ward-Thompson 2007) and extinction measurements toward the Pipe Nebula (Alves et al. 2007) have found that the clump mass function flattens toward lower clump masses (see Figure 2). The flattening of the clump mass function is similar to the stellar IMF, although the mass at which there is a break in the power-law is higher for clumps than for stars. These results have been interpreted to imply that the stellar IMF is derived from the clump mass function modulo a ∼30% efficiency in converting the clump mass into stars. If correct, these observations are evidence that the stellar IMF is imprinted in the molecular cloud structure.

3. Observational Goals

Despite the intriguing observational results to date, the results are far from conclusive. Two observational tests can establish a definitive link between the clump mass function and the stellar IMF. First, the clump mass function should continue to decline at masses smaller than the hydrogen burning limit, as does the stellar IMF (Chabrier 2003). Second, the clump mass function over all masses should be the same in low and high mass star forming regions.

Future observations should ideally have the following parameters to perform the required observational tests:

- *Sensitivity to clumps capable of forming a 0.01 $M_\odot$ brown dwarf*
  The IMF in nearby young clusters has been derived for masses as low as $\sim$0.01 $M_\odot$. Assuming a 30% "efficiency" in converting clump mass into stellar mass (Alves et al. 2007), observations of the clump mass function need to be complete for masses greater than 0.03 $M_\odot$. Thus, future observations must be an order of magnitude more sensitive than current surveys.

- *Angular resolution $< 5''$ to resolve 0.05 pc diameter clumps to 1 kpc*
  Observations of nearby molecular clouds are essential to measure the clump mass function to substellar masses. To measure the mass function in both low mass (e.g. Taurus, Ophiuchus, Chamaeleon I & II, Lupus) and high mass (e.g. Orion, Mon R2, Cepheus, North American Nebula) star forming regions, future observations must resolve clumps out to distances of $\sim$1 kpc. Since the diameter of dense clumps in nearby clouds are $\gtrsim$0.05 pc (Motte, André, & Neri 1998), observations must have an angular resolution of $< 5''$ to have > 2 resolution elements over the projected clump diameter.

- *Observations of the dust continuum and molecular lines*
  While extinction measurements are a powerful probe of cloud structure, the maps obtained from deep integrations on 8-m class infrared telescopes have achieved a resolution of $\gtrsim$10$''$ over limited area ($\sim$ 0.01 deg^2; Alves et al. 2001). Continuum and molecular lines observations, on the other hand, can readily achieve the required resolution over entire clouds. Dust emission probes dense regions where molecules may deplete onto grains. High spectral resolution observations of molecular lines measure the velocity field of the cores to determine the kinematic state (collapse, expansion, stability) of the clumps.

- *Surveys over tens of square degrees to image molecular clouds*
  To map the nearest molecular clouds, observations must encompass tens of square degrees on the sky (see, e.g., Figure 1). Wide field mapping is also essential to sample the clump mass function in the galactic center and the heart of the molecular ring, which will establish if the clump mass function has similar shape in the more extreme environments of the Galaxy.

- *Multi-wavelength observations to measure dust temperatures and emissivity*
  Dust temperatures can range from $\sim$10 K to $\gtrsim$100 K depending on the embedded stellar content. The power-law index (β) of the dust emissivity ($\kappa_\nu \propto \nu^\beta$) may also vary between 1 and 2 if the dust grains in the dense clumps have a range of sizes

and compositions. At minimum, observations at three wavelengths are required to disentangle these effects and measure accurate clump properties. Figure 3 shows the flux density for cold clumps at temperatures of 10 and 20 K. To derive accurate dust temperatures, one of the observed wavelengths must be at $\lambda < 350\,\mu$m to sample the Wien portion of the gray-body emission for $\beta = 2$ and $T_{\rm dust}$=10 K.

4. Recommendations

No single instrument or telescope can satisfy all of the goals outlined in Section 3, and observations on multiple platforms will be required. Our specific recommendations are:

- **Development of next-generation, large-format bolometer cameras**
  In the upcoming decade, ongoing development will lead to bolometer cameras with thousands of pixels and MKID (Microwave Kinetic Inductance Detector) cameras which image four or more bands simultaneously (Glenn et al. 2008). These next-generation instruments are essential to map dust emission over entire molecular clouds in multiple bands at high angular resolution.

- **Continued development of heterodyne focal plane arrays**
  Heterodyne arrays with upwards of 32 elements are already in operation on millimeter-wave telescopes. With continued community investment in developing technologies, these arrays have the potential to expand to hundreds of elements in the next decade. Combined with large single aperture telescopes (e.g. Cornell-Caltech Atacama Telescope, CCAT; Green Bank Telescope, GBT; Large Millimeter Telescope, LMT), these arrays will allow sensitive, high resolution imaging of the kinematic structure of dense clumps over entire molecular clouds.

- **Support for 25-50 m class millimeter/submillimeter telescopes**
  Equipped with bolometer cameras containing ∼20,000 pixels, the next generation of millimeter (LMT) and submillimeter (CCAT) telescopes will map the clump mass function below the peak in the stellar mass function and down to substellar masses (see Figure 3) in nearby ($\lesssim$1 kpc) clouds. In the extreme conditions of the galactic center, the high angular resolution achieved with CCAT ($3.5''$ @ $350\,\mu$m) and the LMT ($6''$ @1.2mm) will resolve $1\,M_\odot$ clumps as small as 0.15 pc in size. The high resolution and sensitivity is essential to determine if the clump mass function has the same shape in a wide range of environments.

- **Support for millimeter-wave interferometry**
  The most massive dense cores in molecular clouds contain thousands of solar masses

within a parsec sized region. These massive cores are the progenitors of star clusters. Since clusters have peak stellar surface densities of > 5000 pc^{-2} (Gutermuth et al. 2005), sub-arcsecond resolution is needed to resolve individual clumps. In the foreseeable future, this resolution can be achieved at millimeter and submillimeter wavelengths only with interferometry, including ALMA, CARMA, the EVLA, and the SMA. Combining these interferometric observations with complementary single dish maps from CCAT, LMT, and GBT are necessary to recover all of the emission from the molecular clouds.

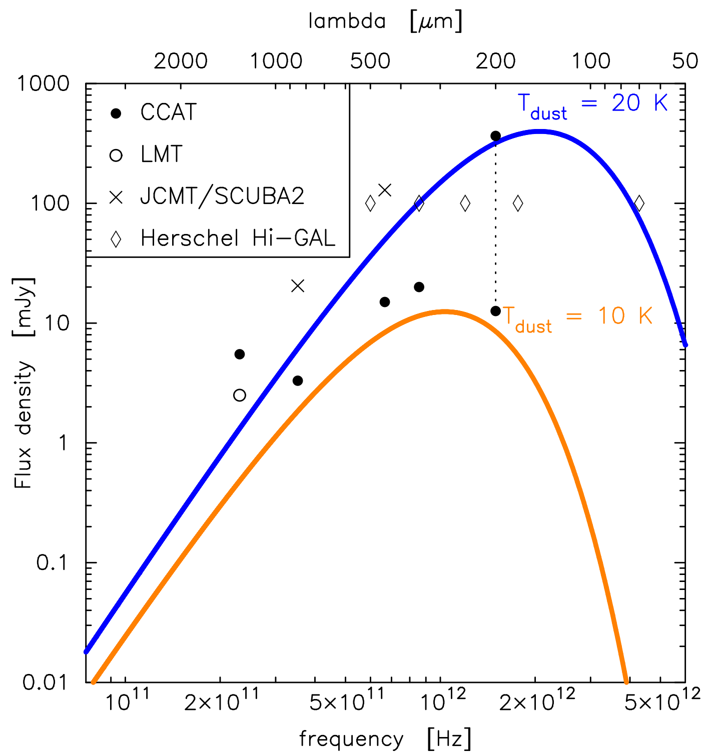

Fig. 3.— Flux density versus wavelength for a 0.03 $M_\odot$ clump at a distance of 1 kpc with a temperature of 10 K (orange curve) and 20 K (blue). Symbols indicate the 5σ point-source detection limits for future wide-field continuum surveys. CCAT and LMT sensitivities are calculated for imaging a 1 deg^2 region in 1 hour with 20k pixel background limited cameras. The upper point at 200 μm is the CCAT mapping sensitivity, and the lower point at 200 μm is the sensitivity of a 1 hour pointed observation. The relative low sensitivity at 200 μm is due to atmospheric transmission. Also shown are the 5σ detection limits for JCMT/SCUBA2 surveys of an equivalent area, and for the Herschel key project to map the galactic plane. This figure illustrates that continuum surveys with next-generation bolometer cameras on 25-50 m class submillimeter telescopes (CCAT, LMT) will detect cold (10-20 K) clumps capable of forming isolated brown dwarfs out to distances of 1 kpc. Multiple wavelengths measures will further enable measurements of the dust temperatures and dust emissivity.

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