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Collapse, Fragmentation, and Accretion in Massive Cores

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Abstract. Recent observations indicate that the mass and spatial distributions of young star clusters are likely set by a process of initial fragmentation of a gas cloud into prestellar gas cores. In this paper I review the physical mechanisms by which a massive core produced in this fragmentation process collapses and forms a massive star or stellar system, with particular attention to the question of how such a core sub-fragments, and how the resulting fragments accrete mass from their environment. I show that, under the conditions that prevail in observed regions of massive star formation, cores fragment quite weakly as a result of radiative feedback. The few stars that form within them accrete primarily through massive unstable disks, in a process that continues until the parent core has been exhausted but not beyond that point. This process naturally explains the observed similarity between core and stellar mass and spatial distributions, and also reproduces the multiplicity properties of massive star systems.

1. Introduction

The origin of the mass and spatial distributions of stars in young clusters is an important unsolved problem, particularly for the most massive of those stars. Observationally, the outcome of the star formation process is reasonably well-constrained. The initial mass function of stars can be well fit either by a broken powerlaw or by a powerlaw plus a lognormal function (Kroupa 2002; Chabrier 2005). Massive stars lie on a powerlaw tail with a slope near -2.35, and the tail is featureless from $\sim 1-150\ M_{\odot}$. Stellar multiplicity is a strong function of stellar mass, ranging from a minority of stars being multiples near the peak of the IMF to near-universal binarity for O stars (Duchêne et al. 2001; Preibisch et al. 2001; Shatsky & Tokovinin 2002; Lada 2006). This multiplicity appears to be imprinted early, when massive stars are still embedded in their natal clouds (Apai et al. 2007). A significant fraction of massive stars also appear to be twins, with mass ratios near unity (Pinsonneault & Stanek 2006; however see Lucy 2006, who argues that this conclusion is questionable because it is based on a sample of eclipsing binaries, which is small and potentially biased), and WR20a, the most massive binary known, has a primary mass of 83 $M_{\odot}$ and a mass ratio of 0.99 ± 0.05 (Bonanos et al. 2004; Rauw et al. 2005).

Massive stars are also found primarily in clusters, and they tend to be strongly segregated toward the centers of those clusters (Hillenbrand & Hartmann 1998). It is unclear whether the stars form in the center, or whether they migrate there after formation but early in a cluster's lifetime (Bonnell et al. 1998; Tan et al. 2006; Huff & Stahler 2006; McMillan et al. 2007). There appears to be a small but statistically significant fraction of O stars that are neither members of clusters nor obvious runaways from them (de Wit et al. 2004, 2005), consistent with the overall statistical conclusion that the stellar and cluster mass functions are independent, and that the cluster mass function is unbroken down to clusters consisting of single massive stars (Oey et al. 2004; Elmegreen 2006; Parker & Goodwin 2007; however, see Weidner & Kroupa 2004).

The corresponding picture for the initial stages of star formation, particularly at high masses, is only now starting to come into focus. Star-forming clouds appear to have a small fraction of their mass in the form of dense cores – regions of high density that move coherently and sometimes harbor class 0 protostars at their centers (e.g. Goodman et al. 1998). Over the last 10 years, strong evidence has accumulated, over a wide variety of star-forming regions using several different observational techniques, that the mass distribution of these cores matches the functional form of the stellar IMF (Motte et al. 1998; Testi & Sargent 1998; Johnstone et al. 2001; Onishi et al. 2002; Beuther & Schilke 2004; Reid & Wilson 2005; Alves et al. 2007). The core mass function is simply shifted to higher masses by a factor of $2-4$. The most massive of these cores can be a few hundred $M_{\odot}$, a large enough mass reservoir to form even the most massive stars, and these cores appear strongly centrally concentrated (Beuther et al. 2007), suggesting that they are truly coherent objects. Equally intriguing, in at least one star-forming cloud the cores appear to be mass segregated just like stars in young clusters, with the most massive ones found exclusively toward the center (Elmegreen & Krakowski 2001; Stanke et al. 2006).

The striking similarity between the functional form of the core and stellar mass distributions, and the similarity in mass segregation for both cores and stars, are highly suggestive of a model in which a single core forms a single star or star system with an efficiency of $25-50\%$. This idea is the basis of the massive core model proposed by McKee & Tan (2002, 2003), and will form the basis of the remainder of these proceedings. The goal is to sketch out a physical theory for how a massive core turns into a massive star. We focus on objects like the millimeter cores IRDC 18223-3 (Beuther et al. 2005) or IRAS 05358+3543 – mm1 (Beuther et al. 2007), which typically have masses $\sim 100\ M_{\odot}$, radii ~ 0.1 pc, and roughly powerlaw density profiles $\rho \propto r^{-k_\rho}$ with $k_\rho \approx 1.5$. § 2. examines the initial collapse and fragmentation of these objects, § 3. examines how they form disks and tight binaries, and § 4. examines what happens to the resulting stars after such a core has been fully accreted. Finally, I summarize in § 5. In this contribution I do not grapple in any detail with the physics of massive protostellar disks and the interaction of accretion with radiation feedback. These topics are explored in the contributions by Kaitlin Kratter and Richard Klein.

2. The Initial Collapse of Massive Cores

The first problem to face in determining how a massive core evolves is how and whether it subfragments into smaller cores that produce low mass stars. Since massive cores contain many thermal Jeans masses of gas at the ~ 10 K temperatures typically found in dense clouds before star formation begins, one might expect rapid and complete fragmentation that precludes any formation of massive stars (Bate & Bonnell 2005; Dobbs et al. 2005). However, analytic and numerical calculations including the effects of radiation show that estimates

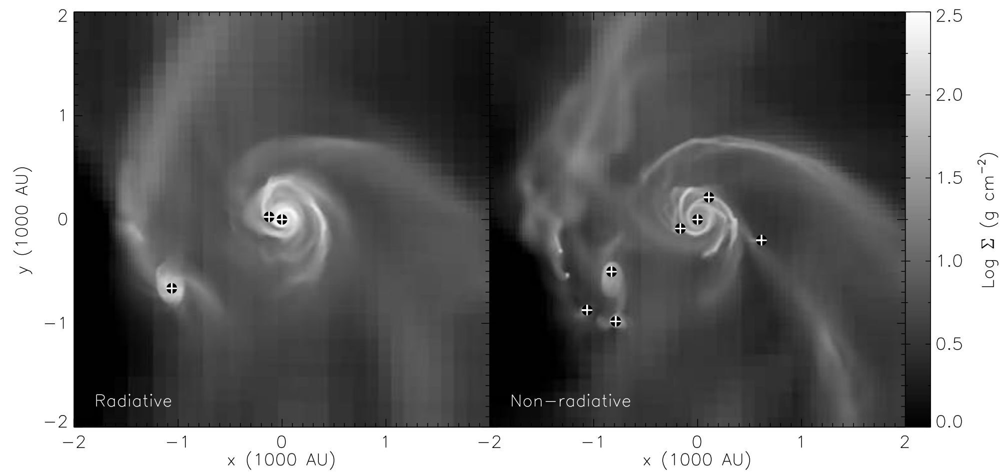

Figure 1. Column densities in a 2000 AU region in two simulations of the collapse and fragmentation of a massive core from Krumholz et al. (2007b). The simulation on the left includes radiation, while the one on the right does not, but they are otherwise identical in initial conditions, resolution, and evolution time. The plus signs show the positions of protostars. This figure is adapted from Krumholz et al. (2007b), and appears by kind permission of the American Astronomical Society.

of fragmentation based solely on the initial Jeans mass are misleading. In the dense environments where massive stars form, accretion luminosity produced by infall onto the first low mass objects to form in a gas cloud will rapidly reach $\sim 10-100\ L_\odot$ and overwhelm all other sources of heating, warming the gas well above its initial temperature (Krumholz 2006). Simulations using the Orion adaptive mesh refinement code (Krumholz et al. 2007c) that take this heating into account find that it dramatically suppresses fragmentation in massive cores (Krumholz et al. 2007b). Fig. 1 demonstrates this effect by comparing the results of two simulations with identical initial conditions and resolution, one using radiative transfer and one without it.

We can analytically estimate what properties a core must have to avoid fragmenting (Krumholz & McKee 2008). A massive core that is being heated by one or more accreting low mass stars near its center is only likely to avoid fragmentation if the resulting luminosity is enough to dominate its thermal structure and heat it to above the "background" temperature of ~ 10 K over most of its volume. Chakrabarti & McKee (2005) give an approximate analytic solution for the temperature structure of a spherical, centrally-heated gas cloud, and using this formalism it is possible to derive a critical luminosity per unit cloud mass $\eta_{\rm halt}$ for which this condition will be met and fragmentation will cease.

Accretion onto low mass stars releases $\psi \approx 0.1 GM_\odot/R_\odot$ erg per gram of mass accreted, roughly independent of both the accretion history and, for masses below a few $M_\odot$, the mass of the accreting star. At early times in a turbulent massive core, low mass stars will form and accrete at a rate of a few percent of the core mass per free-fall time (Krumholz & McKee 2005; Krumholz & Tan 2007a), and this star formation rate plus ψ determines the luminosity

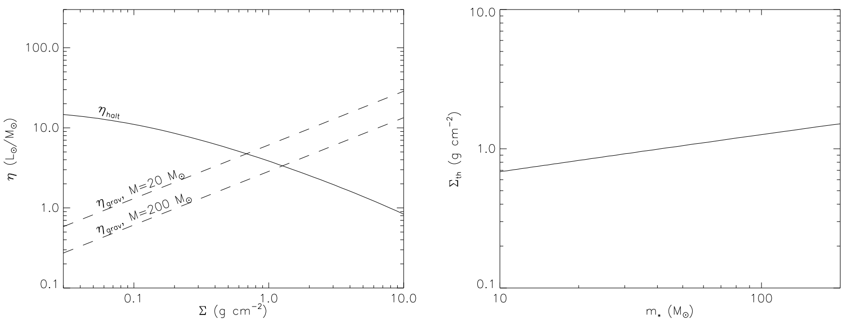

Figure 2. The plot on the left shows the minimum light to mass ratio $\eta_{\rm halt}$ required to halt fragmentation in a core, overplotted with the light to mass ratio $\eta_{\rm grav}$ produced by accretion onto low mass stars in that core. The plot on the right shows the column density Σ at which $\eta_{\rm halt} = \eta_{\rm grav}$, as a function of the mass of the star to be formed, m_*, which is taken to be half the core mass M. This figure is adapted from Krumholz & McKee 2008, and appears by kind permission of the Nature Publishing Group.

per unit core mass $\eta_{\rm grav}$ produced by release of gravitational potential energy as a function of the core column density Σ and mass M. We show $\eta_{\rm halt}$ and $\eta_{\rm grav}$ in the left panel of Fig. 2. By finding the values of Σ and M for which $\eta_{\rm halt} = \eta_{\rm acc}$, one can derive the necessary condition for accretion feedback to halt fragmentation in a massive core. As Fig. 2 shows, this condition takes the form of a minimum column density that depends weakly on the mass. This result has several interesting implications. First, since the minimum column density is $\Sigma \approx 1$ g cm^{-2}, the existence of this threshold naturally explains why regions of massive star formation all have such unusually high column densities (McKee & Tan 2003). Second, it suggests that there should be variations in the stellar IMF on small scales in very high column density clouds, with regions where $\Sigma < 1$ g cm^{-2} being systematically deficient in massive stars compared to regions where $\Sigma > 1$ g cm^{-2}.

3. Massive Disks and Binaries

Since massive cores have non-zero angular momentum, massive star formation proceeds through an accretion disk. These disks tend to be massive ($\sim 30 -$ 50% of the mass of the central star), extended ($\sim$ 1000 AU in radius) rapidly accreting (effective $\alpha \sim 1$), and highly gravitationally unstable ($Q = 1$, with strong fragmentation). The basic physical processes in these disks, and the underlying reasons they have these properties, are summarized in Kratter et al. (2007) and in Kaitlin Kratter's contribution to this volume.

Instead, it is interesting to note that these disks and their properties are a potentially observable signpost of the massive star formation process. Krumholz et al. (2007a) simulate molecular line observations of massive disks from the radiation-hydrodynamic simulations of Krumholz et al. (2007b), and find that they should be detectable in submillimeter lines with ALMA out to distances of

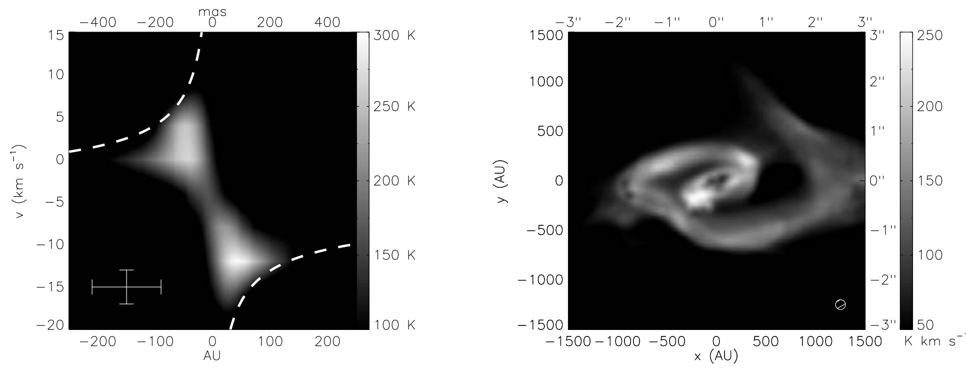

Figure 3. Simulated observations of a massive protostellar disk in the NH_3 (*left panel*) and CH_3CN (*right panel*) lines at 23.7226 GHz and 220.7472 GHz, respectively. The NH_3 observation shows brightness temperature as a function of position and velocity along a line through the plane of a disk seen edge-on; the dashed lines are Keplerian rotation profiles. The CH_3CN observation shows velocity-integrated brightness temperature as a function of position. The crosshair on the left and circle on the right indicate the resolution of the simulated beam. This figure is adapted from Krumholz et al. 2007a, and appears by kind permission of the American Astronomical Society.

~ 2 kpc, a typical distance for massive embedded protosotars, and in radio lines with the EVLA out to ~ 0.5 kpc, the distance to the nearest region of massive star formation. Fig. 3 shows some simulated observations at 0.5 kpc.

Massive disks present a potential test of models of massive star formation. In competitive accretion models (Bonnell et al. 2007, and references therein), almost all massive stars have close encounters that remove their disks at radii larger than ~ 30 AU. While continuing accretion causes them to grow back, it seems likely that the typical disk mass, and the fraction of massive stars with disks, should both be lower in competitive accretion models than in the massive core models described here. However, quantitative predictions of massive disk properties from competitive accretion models are not yet available. Moreover, it seems unlikely that these predictions could be reliable without the inclusion of radiative transfer in the simulations, since Krumholz et al. (2007b) show that its omission leads to a factor of $\sim 3-5$ underestimate of the disk mass due to unphysical fragmentation in the disk in the non-radiative models.

It is also interesting to point out that massive disks provide a natural explanation for the high companion fraction of massive stars, because these disks are strongly unstable to fragmentation. Fragments form at a variety of masses and separations from the parent star (Krumholz et al. 2007b; Kratter et al. 2007), and tend to migrate inward along with the disk as it accretes. Many of these probably merge with the central star, but some likely park in close orbits. At that point, they will accrete from a circumbinary disk, growing along with the primary, a process that pushes the mass ratio toward unity (Bate 2000). This will be strongly enhanced by a second effect: rapidly accreting massive protostars experience a phase in which their radii swell to ~ 1 AU (see Takashi

Hosokawa's contribution to this volume), and this will cause them to overflow their Roche lobes and transfer mass onto close companions. Since many massive binaries are quite close (for example WR20a has an orbital separation of 0.25 AU), this process may affect many massive binaries. Krumholz & Thompson (2007) show that the resulting transfer runs away and only stabilizes once the system reaches $q \approx 1$, explaining massive twin systems such as WR20a.

4. Post-Core Accretion onto Massive Stars

The final factor that could destroy the proposed link between prestellar cores and stars is if a star, once its has accreted its parent core, then accreted a significant amount of additional mass. This is the competitive accretion model. Whether or not this happens depends on whether or not star formation occurs over one dynamical time in process of free-fall collapse, or whether it is impeded by feedback or external driving and takes a longer time (Krumholz et al. 2005, 2006; Bonnell & Bate 2006). In the former case, then the turbulence with which a cloud is born decays away, and the resulting low levels of turbulence permit rapid Bondi-Hoyle accretion (the rate for which varies as the inverse cube of the velocity dispersion). In the latter case, the turbulence does not decay, and in a turbulent medium the Bondi-Hoyle accretion rate is so low that stars gain a completely negligible amount of mass once they have accreted their parent cores.

The first simulations of star cluster formation to include realistic feedback seem to favor extended formation with turbulence maintained by feedback (Li & Nakamura 2006; Nakamura & Li 2007), but this work is preliminary. However, the question can also be tackled observationally. If the competitive accretion scenario is correct, then the dense gas clouds from which star clusters form should collapse into stars in roughly a free-fall time, and therefore when averaged over an entire galaxy the total mass of these clouds, divided by their free-fall time, should be roughly the total star formation rate. On the other hand, if clusters do not form in free-fall collapse, then the total mass of dense gas clouds divided by their free-fall time should be much larger than the total star formation rate.

Gao & Solomon (2004) and Wu et al. (2005) provide the data necessary for a strong test of these predictions, by measuring the luminosities of galaxies and local gas clouds in the HCN($1 \rightarrow 0$) line, which traces gas at densities $\sim 10^5$ cm^{-3}. From the luminosity one can estimate the total mass of gas in such clouds, and by comparing this to a star-formation rate indicator such as the far-infrared luminosity, one can determine how the mass over free-fall time compares to the star formation rate. Krumholz & Tan (2007b) perform this test, and find that the mass divided by the free-fall time is always roughly 100 times larger than the observed star formation rate. Other tracers of dense gas yield similar results. This appears to be strong observational evidence ruling out the possibility that cluster formation occurs in free-fall collapse, and therefore that stars gain their mass from post-core, competitive accretion.

5. Summary

From this work it is possible to see the beginnings of a coherent theory of how cores, at least at the high mass end of the spectrum, evolve into stars. The mass and spatial distributions of cores are set by an initial process of turbulent fragmentation, and once formed the cores begin to form stars with an efficiency that is roughly independent of their mass. Thus, the stellar IMF and the mass segregation of clusters is imposed at birth, in the gas phase.

Collapsing massive cores do not fragment strongly because radiation from accreting low mass stars within them suppresses fragmentation. Suppression occurs only at high column densities, which is consistent with the observation that massive stars form in high column density regions. While fragmentation is reduced by radiation, it is not halted completely, and most massive stars end up as members of multiple systems. In particular, these companions and form out of massive, unstable protostellar disks, or can be captured by these disks, and can then migrate inward. Those that find themselves close to the primary star can become twins when the primary undergoes rapid expansion and overflows its Roche lobe. Once the entire core has been accreted, the star formation process is largely complete. Because regions of massive star formation are turbulent, and remain so for extended periods, stars cannot capture significant amounts of additional mass once their parent core is gone. Their masses are fixed by the supply of gas available in the coherent core from which they initially form.

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