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From Massive Cores to Massive Stars

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Abstract. The similarity between the mass and spatial distributions of pre-stellar gas cores in star-forming clouds and young stars in clusters provides strong circumstantial evidence that these gas cores are the direct progenitors of individual stars. Here, I describe a physical model for the evolution of massive cores into stars, starting with the initial phases of collapse and fragmentation, through disk formation and fragmentation, the later phases of stellar feedback, and finally interaction of the newly formed stars with their environments. This model shows that direct mapping from cores to stars is the natural physical outcome of massive core evolution and thereby allows us to explain many of the properties of young star clusters as direct imprints of their gas-phase progenitors.

1. Introduction

Massive stars form in regions of extremely high column density, hidden behind hundreds of magnitudes of visual extinction. As radio and submillimeter interferometers have matured over the past decade, they have revealed the properties of these regions with ever higher detail, to the point where today it is not entirely unreasonable to speak of observationally determined "initial conditions" for the problem of star formation. One of the most striking results of this exploration has been the extent to which the properties of young star clusters are directly mirrored in the conditions found in pre-stellar molecular gas.

At the most basic level, young clusters and the molecular clumps from which they form have similar bulk properties, such as column density ($\sim 1\,\mathrm{g\,cm^{-2}}$), size ($\sim 1$ pc), and velocity dispersion (a few $\mathrm{km\,s^{-1}}$) (McKee & Tan 2003). More interestingly, the dense cores within these clumps also mirror the properties of stars. Cores are bound, centrally condensed objects with characteristic sizes ~ 0.1 pc or smaller and masses comparable to those of individual stars (Sridharan et al. 2005; Beuther, Sridharan, & Saito 2005). Observations in many regions with a variety of techniques find that the core and star mass functions have the same shape, differing only in that cores are a factor of 2–4 more massive (e.g., Motte, André, & Neri 1998; Johnston et al. 2001; Reid & Wilson 2006; Alves, Lombardi, & Lada 2007; Alves, this volume, p. 72). Moreover, cores appear to be mass-segregated: cores with masses greater than a few $M_\odot$ are found only in the centers of their parent clumps, but the core mass function is otherwise independent of position (Elmegreen & Krakowski 2001; Stanke et al. 2006). This is remarkably similar to the pattern in young clusters, where there is no segregation for stars smaller than a few $M_\odot$, but more massive stars are almost exclusively in cluster centers (Hillenbrand & Hartmann 1998; Huff & Stahler 2006).

The coincidence in both the mass and spatial distributions of cores and stars makes a strong circumstantial case that young stars' properties might be direct imprints of core properties. (The somewhat higher core masses are to be expected, since outflows should prevent $\sim 50\%$ of a core's mass from reaching a star—Matzner & McKee 2000.) However, we cannot make such an inference without a theoretical understanding of how cores might evolve into stars. The goal of this paper is to summarize work in the last few years that has focused on the most problematic part of this process, understanding the evolution of massive cores. In the following sections I sketch a model for the evolution of these objects, beginning with observed core properties and using numerical and analytical arguments to understand how they collapse into stars.

2. Initial Collapse and Fragmentation

The first phase of evolution for a massive core begins when it starts to collapse but has not yet formed any stars. One might initially suspect that there is no plausible way for a massive core to collapse to a single star or a small multiple system, since the Jeans mass in cold molecular clumps is only roughly solar. If massive cores do truly fragment into Jeans mass-sized objects once their collapse begins, then there can be no direct mapping from cores to stars. Such behavior is exactly what purely hydrodynamical numerical simulations find: as objects collapse and their density rises, the Jeans mass falls, and the objects break into smaller and smaller pieces that always have masses comparable to the Jeans mass at their current density. The fragmentation process ceases only when the assumed equation of state stiffens, so massive cores generate numerous small stars (e.g., Bate & Bonnell; Dobbs, Bonnell, & Clarke 2005).

However, while a purely hydrodynamical approach to fragmentation is analytically very simple and numerically very cheap, it neglects the important effect of radiation feedback from embedded, forming protostars. Krumholz (2006) points out that, even before embedded stars begin nuclear burning, just the gravitational energy released as gas accretes onto them can significantly heat the surrounding gas, raising the Jeans mass and suppressing fragmentation. Krumholz, Klein, & McKee (2007c) follow up this point by simulating the collapse of turbulent, massive cores whose initial masses, sizes, central concentrations, and levels of turbulence are chosen to match those of observed cores (as seen, for example, by Sridharan et al. 2005 and Beuther et al. 2005). The simulations combine a protostellar evolution model with a new adaptive mesh refinement gravity–radiation–hydrodynamics algorithm (Krumholz, Klein, & McKee 2004; Krumholz et al. 2007a) to model accurately the effects of radiative heating. The simulations show that radiative heating strongly suppresses fragmentation of massive cores, allowing the great majority of the mass in a core to collapse into one or two stars. In contrast, a control run omitting radiative heating qualitatively reproduces the earlier hydrodynamical result that massive cores collapse into dozens of small fragments. Figure 1 illustrates the difference made by the inclusion of radiative heating.

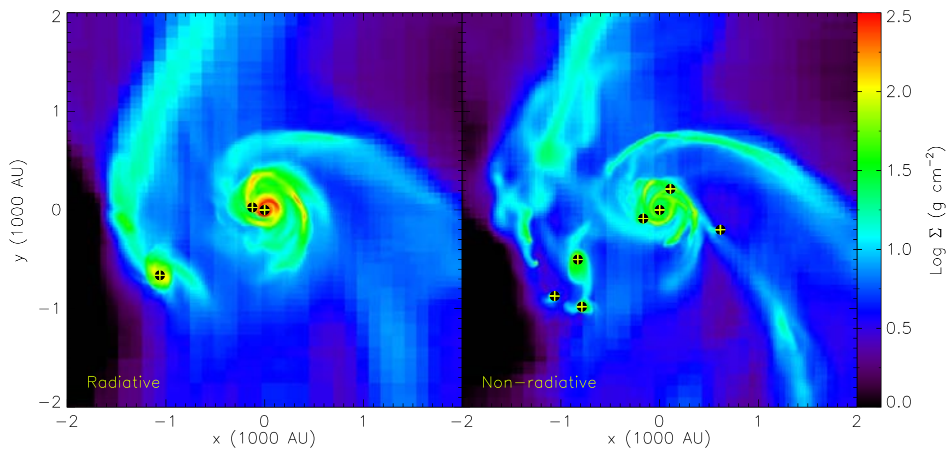

Figure 1. Column density in two simulations of the collapse and fragmentation of a $100\,M_\odot$ core. The left and right panels show two runs from Krumholz et al. (2007c, runs 100A and 100ISO) at 20 kyr of evolution; one uses radiative transfer and one does not, but otherwise the simulations have identical initial conditions and resolution. The plus signs indicate the positions of stars. Note the significantly greater number of stars in the non-radiative run, with several more condensations on the verge of collapse to stars.

The most important point to take from this is that when more detailed physics than simple hydrodynamics is included, simulations and analytical arguments both show that the observed massive cores are unlikely to fragment into many pieces. Thus, a model in which there is a direct mapping from the masses and positions of massive cores to those of massive stars passes its first test: the cores will collapse largely monolithically, rather than fragmenting into small stars. A secondary point is that we must be careful about drawing conclusions based on simulations with very simple physics. Models that do not include radiative transfer produce qualitatively different results from those that do.

3. Disk and Binary Formation

Since collapsing turbulent cores have non-zero angular momentum, they naturally form protostellar disks. Observationally, these are a potential signpost of the star formation process. Both the simulations described above and analytical models (Kratter & Matzner 2006) find that the disks formed by massive cores are likely to be strongly gravitationally unstable. This instability causes the disks to develop large amplitude $m = 1$ spiral modes, and potentially even fragment to form companions to the primary star (although a majority of the mass still goes into the primary, not the fragments). Krumholz, Klein, & McKee (2007b) show that the strong $m = 1$ spiral structure present in such unstable disks should be observable with next-generation telescopes such as ALMA and the EVLA, and that a systematic offset between the disk's "zero" velocity and the central star's velocity produced by the instability might also be detectable. The detection of a disk with these signatures inside a massive core would be strong evidence

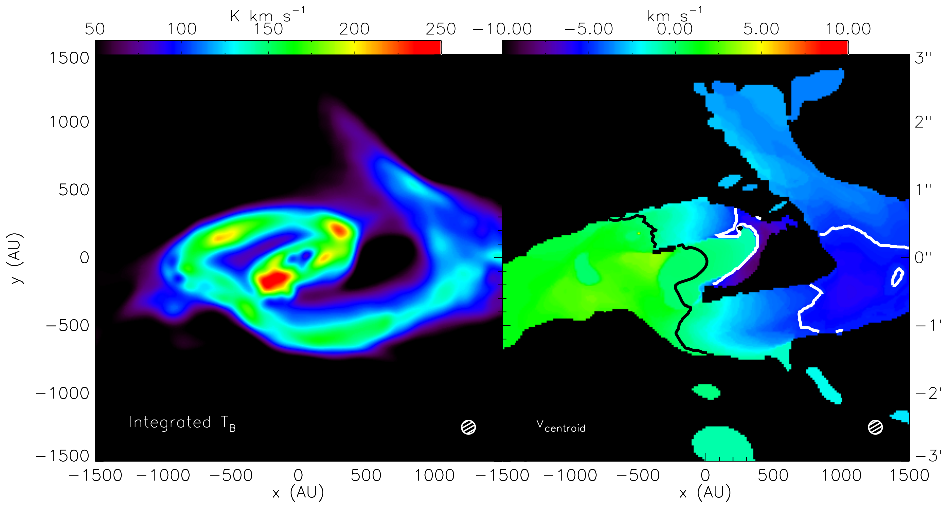

Figure 2. The velocity-integrated brightness temperature (*left panel*) and centroid velocity (*right panel*) in a simulated 0.1 arcsec resolution ALMA observation of a massive protostellar disk 500 pc away in the CH_3CN 220.7472 GHz line. The disk is from the simulation illustrated in the left panel of Fig. 1 at an evolution time of 27 kyr, when the central star is $8.3\,M_\odot$ in mass. The white contour in the right panel corresponds to $-5\,\mathrm{km\,s^{-1}}$, and the black contour shows $0\,\mathrm{km\,s^{-1}}$, measured relative to the velocity of the central star. The disk is systematically offset to negative velocities relative to the star, so while there is a large region with velocity $< -5\,\mathrm{km\,s^{-1}}$, there are no pixels with velocities $> 5\,\mathrm{km\,s^{-1}}$. Black pixels correspond to locations where ALMA would not detect the line at $> 3\sigma$ confidence.

in favor of the model that massive cores collapse to form massive stars. Figure 2 shows a simulated ALMA observation of such a disk, computed using the technique of Krumholz et al. (2007b).

Disks around massive stars are also important for their role in forming companions to massive stars. Most massive stars have close companions (Lada 2006), and gravitational instability in massive protostellar disks provides a natural explanation for this because even radiatively heated massive disks suffer some fragmentation (though vastly less than if radiation is omitted). These fragments initially form with masses around solar at distances > 100 AU from the primary (Kratter & Matzner 2006; Krumholz et al. 2007c), but they subsequently migrate inward to separations < 10 AU as the disk accretes. The final separations of these disk-formed companions from the primary, and whether some of them merge with it, has not yet been determined.

An interesting fate awaits migrating stars that get close to the primary but do not merge with it. Massive protostars go through a phase of deuterium shell burning, during which their radii swell to tenths of an AU in size. Krumholz & Thompson (2007) point out that this may lead a primary to overflow its Roche lobe and transfer mass onto close companions. Such mass transfer is almost always unstable, terminating only once the mass ratio of the system reaches unity. This provides a natural mechanism for the origin of the heretofore unexplained massive "twins", binaries consisting of two massive stars with a mass ratio of almost exactly unity (e.g., Pinsonneault & Stanek 2006).

4. Radiation Pressure Feedback

A direct core-to-star mapping is possible only if most of a core's mass is able to accrete onto the massive star forming within it. However, spherically symmetric calculations indicate that the huge radiation output of massive stars should exert a force stronger than gravity on dust grains suspended in the gas around them for stars of $\sim 20\,M_{\odot}$ or larger (Larson & Starrfield 1971; Yorke & Kruegel 1977; Wolfire & Cassinelli 1987). How massive stars can form despite this radiation barrier is a classical problem in astrophysics. Fortunately, rotation and the formation of a disk can significantly mitigate this effect, because gas in a disk self-shields against the radiation due to high optical depths (Nakano 1989; Nakano, Hasegawa, & Norman 1995; Jijina & Adams 1996), while at the same time a disk collimates the radiation field and beams it away preferentially in the polar direction, thereby reducing the radiation force felt by gas in the equatorial plane (Yorke & Sonnhalter 2002). However, even with these effects it is not entirely clear that stars can grow to arbitrary masses by accretion.

Two additional effects may help. First, radiation hydrodynamic simulations show that the first effect of radiation pressure is that massive stars blow radiation bubbles above and below accretion disks (Yorke & Sonnhalter 2002; Krumholz, Klein, & McKee 2005a). However, in three dimensions these bubbles do not halt accretion, because gas that reaches the bubble wall flows along the wall onto the accretion disk. Bubbles may also collapse due to Rayleigh–Taylor instability, allowing accretion to continue through optically thick channels while radiation escapes through optically thin regions around them (Krumholz et al. 2005a). If magnetic fields are present and sufficiently strong, this effect will be enhanced by photon bubble instability (Turner, Quataert, & Yorke 2007), which arranges the gas into dense lumps separated by low density gaps through which radiation leaks, effectively reducing the radiation pressure force experienced by the bulk of the gas.

Second, protostellar outflows provide a third escape valve for radiation. Massive protostars appear to generate hydromagnetic outflows just like low mass stars, with the difference that for massive stars the outflow cavities are largely dust-free because the base of the outflow is close enough to the star for the dust within it to have been destroyed by sublimation. Such outflow cavities therefore present optically thin channels through which radiation can leak out of the optically thick cores. Radiative transfer calculations show that this can lead to order-of-magnitude reductions in the radiation force on accreting gas near the equatorial plane, again allowing accretion to continue where it might otherwise have been halted (Krumholz, McKee, & Klein 2005b).

While a definitive numerical simulation including the effects of radiation forces, magnetic fields, and protostellar outflows in three dimensions has not yet been done and is probably at best barely within the capabilities of present-day supercomputers, it seems clear that each of these effects will help massive stars form by accretion. Thus, we can tentatively say that there is no barrier to most of the gas in a protostellar core accreting onto a massive star. Conversely, however, simulations of massive star formation that do not include radiation force effects are simply ignoring this problem entirely. Preliminary simulations indicate that models of star formation that depend on Bondi–Hoyle accretion are likely to fail once radiation pressure is included (Edgar & Clarke 2004), so models of this sort must be viewed with caution.

5. Competitive Accretion

Thus far we have seen that massive protostellar cores will not fragment strongly, that what fragmentation they do show is consistent with the observed multiplicity properties of massive stars, and that radiation pressure will not prevent most of the mass in a core from accreting onto a star. There remains, however, one more way in which a direct mapping from cores to stars could fail: if, once stars accrete their parent cores, they were subsequently to accrete a great deal more mass, then there would be no direct relationship between core and stellar masses. This process of accretion onto stars from gas that was not originally part of a bound core is known as competitive accretion (Bonnell et al. 2001a,b).

Purely hydrodynamic simulations of star cluster formation show that this process is the dominant mechanism by which stars gain mass. In effect, all stars are born at masses of the order of the Jeans mass, but some of them fall to the center of the collapsing gas cloud, and the deep potential well then channels gas to them. They subsequently accrete this gas and grow in mass, producing a full range of initial masses (Bonnell, Vine, & Bate 2004; Bonnell & Bate 2006).

However, direct observational estimates of the rate of competitive accretion generally find that it is too small to make a significant contribution to final stellar masses (André et al. 2007). Krumholz, McKee, & Klein (2005c, 2006) point out that competitive accretion is possible in simulations only because the simulated gas clumps are in the process of global collapse, which creates deep potential wells within which the gas is dense and non-turbulent and Bondi–Hoyle accretion is rapid. These deep, dense, quiescent gas wells have not been observed, however. This is probably because clumps are not in a state of global collapse. Such a collapse necessarily converts order unity of the mass in a gas clump into stars and ends star formation in 1–2 free-fall times (e.g., Bonnell et al. 2004). However, there is strong evidence that the star formation process cannot be anywhere near that fast. The gas clump from which the ONC formed likely had a density $\sim 10^5\,\mathrm{cm}^{-3}$ (Elmegreen 2000), implying a free-fall time of 0.1–0.2 Myr, but the estimated ages of the stars in Orion point to a formation process lasting 1–3 Myr, implying a minimum formation timescale of five free-fall times even if one assumes the fastest plausible formation time, with ~ 15 free-fall times being more likely (Tan, Krumholz, & McKee 2006). Furthermore, the total galactic mass of infrared dark clouds, which have densities $\sim 10^3\,\mathrm{cm}^{-3}$, is such that, if they were collapsing to form stars on a free-fall timescale, the total galactic star formation rate would have to be ~ 100 times higher than its observed value. The same conclusion holds for dense gas clumps traced by HCN($1 \rightarrow 0$) emission, which have densities $\sim 10^4$–$10^5\,\mathrm{cm}^{-3}$ (Krumholz & Tan 2007). This implies that, even in regions with mean densities of $10^5\,\mathrm{cm}^{-3}$ star formation cannot be anywhere near as rapid as would be required for competitive accretion to occur.

The final piece of evidence against competitive accretion comes from simulations that include more detailed physics. Li & Nakamura (2006) and Nakamura & Li (2007) simulate the formation of a star cluster using magnetohydrodynamics rather than simple hydrodynamics, and including the effects of outflows driven by the protostars forming within the cluster. They find that the protostellar outflows drive turbulent motions, preventing global collapse and ensuring that conditions are too turbulent for competitive accretion processes to alter the masses of protostars significantly after they have consumed their parent cores. Moreover, these simulations, unlike ones where competitive accretion occurs, produce star formation rates in good agreement with observations. We can therefore tentatively conclude that the core accretion hypothesis passes this final test: once stars have accreted their parent cores, they will not gain much additional mass from the gas to which they were not bound at birth. A direct core to star mapping will survive.

6. Summary and Conclusion

For the past decade observations have increasingly pointed to an intimate link between young stars and the dense stellar-mass gas clouds known as pre-stellar cores. Cores and stars have very similar mass and spatial distributions, so it is tempting to explain the properties of young star clusters as imprinted at birth. However, this hypothesis requires that cores map directly onto stars. Here, I provide a physical model for such a mapping. When massive cores first collapse, they do not fragment strongly because the first stars that form within them heat the gas and suppress fragmentation. As a result, massive cores collapse to only a few stars. Most of the fragmentation that does happen occurs in unstable self-gravitating disks, which should be directly observable. Disk fragmentation ensures that massive stars will essentially always have companions, and some of these companions will turn into twins of the primary star. As the massive star grows, it will begin to generate a huge radiation force opposing accretion. However, a combination of instabilities and the leakage of radiation through protostellar outflow cavities allows the radiation to escape and accretion to continue unimpeded to high masses. Finally, once stars have accreted their parent cores, they will be unable to gain additional mass that was not originally part of the core. Thus, the hypothesis that stars come directly from cores, with a one-to-one mapping of core mass to star mass, is in agreement with a physical model for how massive cores evolve. The best explanation for many properties of young star clusters appears to be that they are set at birth, when the cluster is still a dark cloud.

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Discussion

Bonnell: Comment: I am concerned that the information on the densest regions comes from the most distant (extragalactic) sources. Question: The disk fragmentation produces wider, low mass companions. How do they evolve to within 0.1 AU?

Krumholz: 1) While the original Gao & Solomon HCN work was indeed on extragalactic sources, Wu et al. (2005, ApJ, 635, L173) followed this up with Galactic HCN observations. They find that individual HCN clumps in the Milky Way, which are resolved, fall on the same HCN mass star formation rate law. This strongly suggests that the results do not depend much on resolution. 2) The fragments are at ∼300 AU, and have masses smaller than $0.5\,M_\odot$, when they first form. However, they are embedded in a disk that is rapidly accreting and much more massive than the embedded fragment. As a result, the fragment is dragged inward by the disk while simultaneously gaining mass from it. I don't have the resolution in my simulations to follow the migration in to 0.1 AU, but I can say that the disk-formed stars migrate inward to the smallest radius I can resolve. I see no physical reason why the migration would stop inside that.

Shlosman: Whether the disk fragments depends how deep one can drive Q below unity. Gravitational viscosity will turn on new source viscosity. So the efficiency of this heating will depend on such sensitive issues as the viscosity of a numerical code. To what extent have you tested the code in this respect? Do you reproduce the energy cascade and to what spatial scales?

Krumholz: In our simulations numerical viscosity is negligible compared to angular momentum transport by gravitational torques, except in the inner ∼10 cells where we resolve the disk very poorly. This statement is based on detailed tests of the code against analytical solutions published in Krumholz, McKee & Klein (2004). However, in the massive star simulations, the dominant heating source is illumination by the central star, not viscous dissipation. We resolve the heating and cooling reasonably well in the outer disk where the fragmentation occurs: about 30–40 cells per disk radius, ∼10–15 cells per disk scale height. Fragmentation can occur because, at a given radius, the disk is essentially isothermal. This favors fragmentation.

Hensler: There is a fundamental debate as to what extent turbulence affects clump formation and collapse. How do you insert turbulence? Do you maintain it from external sources? How does decascading of turbulence change the evolution on small scales, i.e., core mass, accretion, accretion disk formation, etc.?

Krumholz: My simulations mostly focus on single cores, so I don't artificially drive turbulence at all. I insert it as an initial condition, at a level such that my initial cores are virialized, but then let it decay freely. In the simulations

I used to test competitive accretion, I did artificially drive the turbulence to set up the box, but I stopped driving once I began the test. In that run, the turbulence was critical to halting competitive accretion. In the Nakamura & Li simulation I showed, there is no artificial driving, just whatever turbulent driving is provided self-consistently by outflows from stars forming in the simulation box. In this run, the turbulence is again critical in keeping the gas clump in equilibrium, forming stars at a slow rate consistent with observations. Without the turbulence, the star formation rate is much too high; this is seen in the competitive accretion simulations.

Caricature of John Beckman, drawn by Eduardo Battaner in 1983, and kept all those years by Mike Edmunds. It was made during the course "Current topics on galaxies", in Granada, organized jointly by the Royal Greenwich Observatory and the Instituto de Astrofísica de Andalucía.