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Massive Star Formation: A Tale of Two Theories

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Abstract. The physical mechanism that allows massive stars to form is a major unsolved problem in astrophysics. Stars with masses $\gtrsim 20\ M_\odot$ reach the main sequence while still embedded in their natal clouds, and the immense radiation output they generate once fusion begins can exert a force stronger than gravity on the dust and gas around them. They also produce huge Lyman continuum luminosities, which can ionize and potentially unbind their parent clouds. This makes massive star formation a more daunting problem than the formation of low mass stars. In this review I present the current state of the field, and discuss the two primary approaches to massive star formation. One holds that the most massive stars form by direct collisions between lower mass stars and their disks. The other approach is to see if the radiation barrier can be overcome by improved treatment of the radiation-hydrodynamic accretion process. I discuss the theoretical background to each model, the observational predictions that can be used to test them, and the substantial parts of the problem that neither theory has fully addressed.

1. Introduction

Observations indicate that stellar initial mass function (IMF) is an unbroken power law out to masses of about 150 $M_\odot$ (Elmegreen 2000; Weidner & Kroupa 2004; Figer 2005; Oey & Clarke 2005), and there is no evidence for variation of either the limit or the index of the mass function with metallicity or other properties of the star-forming environment (Massey 1998). Why the mass limit for stars is so high, what physics sets it, and why the mass spectrum seems to be universal are major unsolved problems in astrophysics. Their solution requires a model for how massive stars form, which at present is lacking due to both observational and theoretical challenges.

Massive stars form in the densest regions within molecular clouds. We detect these massive star-forming clumps as infrared dark clouds (e.g., Rathborne et al. 2005) or as millimeter sources (e.g., Plume et al. 1997; Shirley et al. 2003). The clumps have extremely high column densities and velocity dispersions ($\Sigma \sim 1$ g cm^{-2}, $\sigma \sim 4$ km s^{-1} on scales of $\lesssim$1 pc), and appear to be approximately virialized. However, the structures within the clumps that are the progenitors of single massive stars or small-multiple systems are only now becoming accessible to observations (Reid & Wilson 2005; Beuther et al. 2005). Observations

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continue to improve, but are hampered by large distances, heavy obscuration, and confusion due to high densities.

On the theoretical side the problem is perhaps even more difficult. Stars with masses $\gtrsim$20 $M_\odot$ have short Kelvin-Helmholtz times that enable them to reach the main sequence while still accreting from their natal clouds (Shu et al. 1987). The resulting nuclear burning produces a huge luminosity and a correspondingly large radiation pressure force on dust grains suspended in the gas surrounding the star. Early spherically symmetric calculations found that the radiation force becomes stronger than gravity, and sufficient to halt further accretion, once a star reaches a mass of roughly $20 - 40$ $M_\odot$ (Kahn 1974; Wolfire & Cassinelli 1987) for typical Galactic metallicities. More recent work has loosened this constraint by considering the effect of an accretion disk. Disks concentrate the incoming gas into a smaller solid angle, while shadowing most of it from direct exposure to starlight (Nakano 1989; Nakano et al. 1995; Jijina & Adams 1996). Cylindrically symmetric numerical simulations with disks find that they allow accretion to continue up to just over 40 $M_\odot$ before radiation pressure reverses the inflow (Yorke & Sonnhalter 2002).

Ionization from a massive star presents a second problem to be overcome. The escape speed in a massive star-forming core is considerably smaller than the sound speed of 10 km s^{-1} in ionized gas, so if a star is able to ionize its parent core into an HII region, the core will be unbound and accretion will stop (Larson & Starrfield 1971; Yorke & Kruegel 1977). Only if the ionization is quenched near the stellar surface, where the escape speed is larger than the sound speed, can accretion continue. Early work on the problem of massive star formation found that ionization was the dominant mechanism in setting an upper mass limit on stars, although the later realization that dust will absorb much of the ionizing radiation shifted theoretical attention more towards the effects of radiation pressure.

Today, there are two dominant models of massive star formation. In § 2., I present the competitive accretion model, in which stars are born small and grow by accretion of unbound gas and by collisions. In § 3., I discuss the turbulent radiation-hydrodynamic model, which suggests that massive stars form from massive, turbulent cores, and that neither radiation pressure nor ionization prevents accretion onto a massive star. Finally, I discuss the missing pieces of the picture that neither model is yet able to supply in § 4., and summarize the state of the field and future prospects in § 5.

2. Competitive Accretion

2.1. The Model

The competitive accretion model for massive star formation begins with the premise that all stars are born small, with an initial mass ranging from as much as $\sim$0.5 $M_\odot$ (Bonnell et al. 2004) to as little as $\sim$3 Jupiter masses (Bate & Bonnell 2005), depending on the particular variant of the theory. These "seeds" are born in a dense molecular clump, and they immediately begin accreting gas to which they were not initially bound. Stars near the center of the clump are immersed in the highest density, lowest velocity dispersion gas, and accrete most rapidly (Bonnell et al. 2001a,b). The clump is globally unstable to collapse, and it contracts to stellar densities of $\sim 10^6 - 10^8$ pc^{-3}. At this point low mass stars begin to merge, either through direct collisions (Bonnell et al. 1998), or because gas drag and continuing accretion of low angular momentum gas causes binary systems to inspiral (Bonnell & Bate 2005). For example, a simulation of a 1000 $M_\odot$ clump with a radius of 0.5 pc by Bonnell et al. (2003) produces a nearly 30 $M_\odot$ binary system whose members approach within $\sim$20 AU of one another. In the simulation gravity is softened on scales of 160 AU, so it is unclear how the system would really evolve. However, Bonnell & Bate (2005) argue that it would likely merge, leading to the formation of a 20–30 $M_\odot$ star.

One particularly appealing feature of the merger scenario is that it provides a natural explanation for the observation that O and B stars form solely (or almost solely) in rich clusters (Lada & Lada 2003) that are strongly mass segregated (Hillenbrand & Hartmann 1998). Since the rates of competitive accretion and mergers are highest in cluster centers, and both processes can only occur in clusters, this model qualitatively reproduces the observations automatically. The model also naturally produces a high proportion of close, massive binaries, since for every binary that merges there are several more that come close (Bonnell & Bate 2005; Pinsonneault & Stanek 2006).

Most work on competitive accretion to date uses no physics beyond hydrodynamics and gravity. Dale et al. (2005) make a preliminary effort to include ionization effects, but they focus more on the scale of clusters than on individual stars, so their simulations do not have the resolution to study how photoionization might affect accretion onto a single star. No competitive accretion model to date includes either magnetic fields or radiation pressure. The latter omission is particularly important, since it means there is no evidence that competitive accretion by itself resolves the radiation pressure problem – only mergers do that. Indeed, simulations of Bondi-Hoyle accretion with radiation find that radiation pressure halts accretion onto stars with masses $\gtrsim 8\ M_\odot$ (Edgar & Clarke 2004) – although these results appear questionable in light of the more realistic simulations we discuss in § 3. If Edgar & Clarke's results do hold, though, so that radiation pressure limits Bondi-Hoyle accretion (but not accretion from a core) onto a massive binary, then the only way for massive stars to grow in a competitive accretion model is by direct collisions, rather than drag-induced binary mergers. This requires stellar densities of 10^8 pc^{-3}, $\sim$3 orders of magnitude larger than any observed to date in the Galactic plane.

2.2. Observational Evidence

There are several potential direct observational signatures of the competitive accretion scenario. Bally & Zinnecker (2005) suggest two approaches: collisions would produce both infrared flares lasting years to centuries and explosive, poorly-collimated outflows. At present there is no data set available where one could search for the flares. For the outflows, there is one known example that roughly fits the description that Bally & Zinnecker propose (the OMC-1 outflow), but there has been no detailed modeling of how the outflow from a collision would actually appear, and, as we discuss below, it is unclear how common such poorly collimated outflows are. A third direct test is to search for embedded clusters with densities of $\sim 10^8$ pc^{-3}, which are a required component of the competitive accretion picture. Such objects should be short-lived and therefore rare, but their high column densities would give them a distinct spectral shape that might be observable with Spitzer, and should be easily observable by JWST or SOFIA (S. Chakrabarti & C. F. McKee, 2006, in preparation).

One can also use more indirect tests to look for evidence of mergers, and here the competitive accretion picture runs into considerable difficulty. If massive stars form via collisions, the collision process should truncate their accretion disks or disrupt them entirely. The collision itself may give rise to a fat torus, but is unlikely to produce a thin disk (Bally & Zinnecker 2005). Thus, the collisional formation model predicts that massive stars should not have disks hundreds of AU in size, as are observed for low mass stars. However, there are now at least two known examples of massive stars with such large disks (Jiang et al. 2005; Patel et al. 2005). Since thin disks are probably required to create well-collimated MHD outflows, the collision scenario also predicts that massive protostars should lack well-collimated outflows. However, interferometric observations of young massive stars reveal that outflows for stars as massive as early B usually are well-collimated (Beuther & Shepherd 2005, and references therein). Position-velocity diagrams (Beuther et al. 2004) and near-IR images (Davis et al. 2004) of outflows, as well as correlations between outflow momentum and luminosity of the driving star (Richer et al. 2000), also point to a common driving mechanism for low mass and high mass protostellar outflows, inconsistent with the competitive accretion / collision scenario.

2.3. Theoretical Difficulties

The apparent conflict between competitive accretion models and observations has led to theoretical reconsideration of the problem. For competitive accretion to be effective a small "seed" protostar in a molecular clump must be able to accrete its own mass or more within a dynamical time of its parent clump. The process by which the protostar gathers gas from the clump is Bondi-Hoyle accretion in a turbulent medium, a process for which Krumholz et al. (2005a, 2006b) give a general theory supported by simulations. Using this result, together with an analysis of the possibility that protostars might gain mass by capturing other cores in their parent clump, Krumholz et al. (2005c) determine what properties a star-forming molecular clump must have for competitive accretion within it to be effective. They show that competitive accretion only works in clumps with $\alpha_{\rm vir}^2 M \lesssim 10\ M_\odot$, where M is the clump mass and $\alpha_{\rm vir}$ is the clump virial parameter (Bertoldi & McKee 1992; Fiege & Pudritz 2000), roughly its ratio of kinetic energy to gravitational potential energy. For observed star-forming clumps, $\alpha_{\rm vir} \sim 1$ and $M \sim 1000\ M_\odot$, so competitive accretion will not operate. It occurs in simulations only because the regions simulated have smaller virial parameters and masses than observed regions. In some cases the virial parameters are too small to begin with (Bonnell et al. 2001a,b), and in others the virial parameters start near unity, but decay of turbulence quickly reduces them to smaller values (Bonnell et al. 2004; Bate et al. 2002a,b, 2003). The results of Krumholz et al. (2005c) strongly suggest that competitive accretion plus mergers cannot be the mechanism by which massive stars form.

3. Turbulent Radiation Hydrodynamic Models

Given the difficulties with the competitive accretion scenario, one must ask whether it might be possible to form massive stars in roughly the same way as low mass stars, via collapse from a coherent core and disk accretion. Such a scenario must overcome three serious challenges: one requires a plausible model for the origin and structure of massive cores, a method to allow accretion to occur despite radiation pressure feedback, and an explanation for why ionization does not destroy the protostellar core before the massive star is fully assembled.

3.1. Massive Cores

Theoretical arguments predict that fragmentation in a turbulent medium produces a spectrum of bound fragment masses that resembles the stellar IMF (Padoan & Nordlund 2002). If these arguments are correct, then massive cores are simply the tail of the distribution of core masses. Simulations of fragmentation in a turbulent medium do roughly concur with analytic models (Li et al. 2004), and observations also support the idea that cores have a mass distribution that parallels the stellar IMF, and that cores with masses $\gg M_\odot$ exist (e.g., Motte et al. 1998; Testi & Sargent 1998; Johnstone et al. 2001; Reid & Wilson 2005; Beuther et al. 2005). Thus, massive cores may naturally arise from turbulent fragmentation.

Massive cores, however, must be structured somewhat differently than the cores that give rise to low mass stars. The thermal Jeans mass in star forming regions is $\sim$1 $M_\odot$, so massive cores cannot be supported primarily by thermal pressure. Instead, they must be turbulent. McKee & Tan (2003) present a self-similar model of massive, turbulent cores that are in rough pressure balance with the high pressure environments they form. This gives them surface densities $\sim$1 g cm^{-2} and pressures $P/k \sim 10^8$ K cm^{-3}, much larger than the mean column density and pressure in giant molecular clouds. These high pressures cause the cores to be extremely compact, with radii $\lesssim$ 0.1 pc, and the correspondingly high density produces accretion rates of $\sim 10^{-3}$ $M_\odot$ yr^{-1} onto embedded stars, allowing massive stars to form in $\sim 10^5$ yr.

One important question for models of massive cores is whether they will produce one or a few massive stars, or fragment to produce numerous low mass stars instead. Dobbs et al. (2005) simulate centrally condensed turbulent cores with structures that follow the McKee & Tan (2003) model, and find that they form many low mass stars rather than a single massive star. However, their simulations do not include radiation. Krumholz et al. (2006a) perform similar simulations including radiative transfer, and find that the combination of high accretion luminosity and high optical depth that occur in high-density cores produce rapid heating that inhibits fragmentation. Of course the massive core models used by both Dobbs et al. and Krumholz et al. are highly idealized, so the question of to what extent real massive cores fragment remains open.

3.2. Accretion with Radiation Pressure

The Flashlight Effect Once a massive protostar reaches $\sim$15 $M_\odot$, the pressure exerted by its radiation field will begin to have a significant effect on the accretion flow. Two dimensional radiation-hydrodynamic simulations by Yorke &

Sonnhalter (2002) find that, once the radiation field becomes significant, it begins to reverse inflow along the poles. Accretion continues through an accretion disk in the equatorial plane, and the disk serves to collimate the radiation field and beam it preferentially in the polar direction. This collimation is called the flashlight effect. However, in Yorke & Sonnhalter's simulations this is not enough to allow very massive stars to form. As the protostellar mass and luminosity increase, inflow stops over a wider and wider range of angles about the pole. Eventually, no more material is able to fall onto the disk, and soon thereafter the radiation field disperses the disk itself. Yorke & Sonnhalter find a maximum final mass of the star of $\approx 20\ M_\odot$ in simulations with gray radiation, and $\approx 40\ M_\odot$ in simulations with a multi-frequency treatment of the radiation field. The difference in outcome is likely due to enhancement of the flashlight effect by the more realistic multi-frequency radiation model.

More recent three-dimensional radiation-hydrodynamic simulations, however, demonstrate a qualitatively new effect that allows accretion to higher masses than two-dimensional work suggests. Krumholz et al. (2006a) find that at masses $\lesssim 17\ M_\odot$, the radiation field is too weak to reverse the inflow, and massive cores evolve much as Yorke & Sonnhalter (2002) find. At larger masses, the radiation field begins to inhibit accretion along the poles, driving bubbles into the accreting gas. However, the three-dimensional simulations show that bubbles grow asymmetrically due to an instability that is suppressed in Yorke & Sonnhalter's two-dimensional, single quadrant (i.e. assuming symmetry about the xy plane) simulations. Figure 1a shows this effect. Since the gas is extremely optically thick to stellar radiation, the bubbles are able to collimate the radiation field and beam it preferentially in the polar direction, as shown in Figure 2a. At the time shown in the Figure, the flux of radiation in polar direction at the edge of the bubble is larger than the flux in the equatorial plane by more than an order of magnitude. The strong flux in the polar direction deflects gas that reaches the bubble walls to the side. As the velocity field in Figure 1a shows, it then travels along the bubble wall and falls onto the disk, where it is shielded from the effects of radiation by the disk's high optical depth. The gas then accretes onto the star.

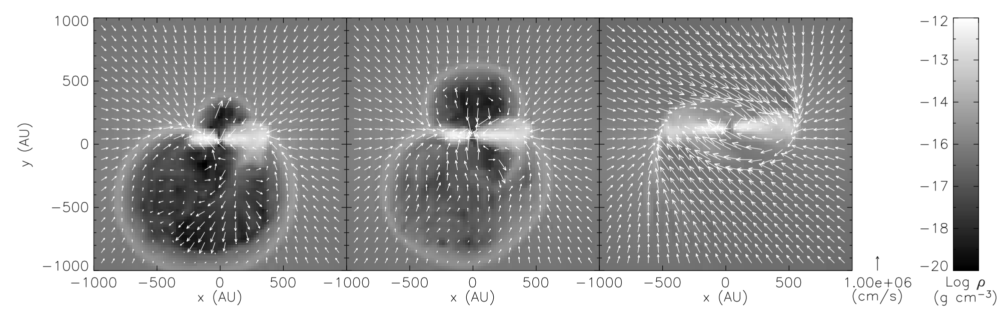

Figure 1. The plot shows a simulation of the collapse of a 100 $M_\odot$ core by Krumholz et al. (2006a). Each panel is a slice in the XZ plane at a different time, showing the density (grayscale) and velocity (arrows). The times of the three slices are 1.5×10^4 (*left*), 1.65×10^4 (*center*), and 2.0×10^4 yrs (*right*), and the stellar masses at those times are 21.3 $M_\odot$, 22.4 $M_\odot$, and 25.7 $M_\odot$.

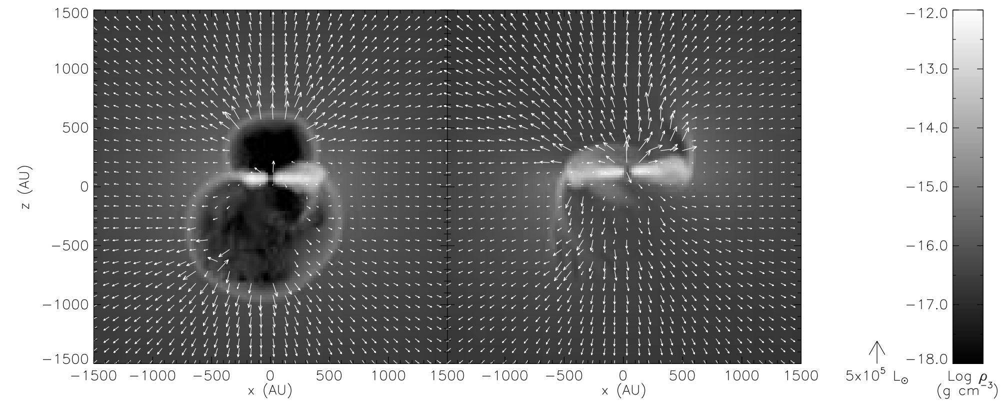

Figure 2. The plot shows a simulation by Krumholz et al. (2006a). The panels show the same times as the center and right panels of Figure 1, but the arrows show radiation flux rather than velocity. The flux vectors are multiplied by $4\pi r^2$, where r is the distance from the central star. For clarity, flux vectors from inside the optically thin bubble interior in panel (a) have been omitted.

Eventually the instability becomes violent enough for the bubbles to start collapsing (Figure 1b), leaving behind remnant bubble walls (Figure 1c). These dense walls serve to collimate the radiation and shield the gas from it, as shown in Figure 2b, allowing it to reach the accretion disk and then the star. The collapse is in essence a radiation Rayleigh-Taylor instability, caused by the inability of radiation, a light fluid, to hold up the heavy gas. Simulations to date have reached masses of $\approx 34\ M_\odot$ onto the star, with $5-10\ M_\odot$ in the disk. Thus far there are no sign of accretion being reversed, and the simulations are continuing as of this writing. Note that these calculations use gray radiative transfer, a case for which Yorke & Sonnhalter (2002) found a limit of $\approx 20\ M_\odot$; Yorke & Sonnhalter's results suggest collimation of the radiation field would be even more effective, and accretion correspondingly easier, with multi-frequency radiation.

Protostellar Outflows The simulations discussed above all ignore the presence of protostellar outflows. However, Krumholz et al. (2005b) point out that outflows can also have a strong effect on the radiation field. Outflows from massive stars are launched from close to the star, where radiation heats the gas to the point where all the dust sublimes. As a result, outflows are dust-free and very optically thin when they are lunched. Because outflows leave the vicinity of the star at high speeds ($\gtrsim 500$ km s^{-1}), there is no time for dust within the outflow cavity to re-form before the gas is well outside the collapsing core. Because the core around it is very optically thick, the outflow cavity collimates radiation and carries it away very efficiently. It effectively becomes a pressure-release valve for the radiation. Monte Carlo radiative transfer calculations show that, for outflow cavities similar to those observed from massive protostellar outflows, the presence of a cavity can reduce the radiation pressure force on infalling gas by an order of magnitude. This can shift the inflow from a regime where radiation pressure is stronger than gravity to one where it is weaker. Krumholz et al.

(2005a) show that, even for a 50 $M_\odot$ star embedded in a 50 $M_\odot$ envelope, an outflow cavity would make radiation pressure weaker than gravity over a quarter of the solid angle onto the star.

It is unclear how radiation collimation by outflows will interact with the radiation bubbles and Rayleigh-Taylor instability that occur in simulations where an outflow is not present. However, the overall conclusion one may draw from both effects is that, in an optically thick core, it is very easy to collimate radiation. Collimation reduces radiation pressure over much of the available solid angle, and allows accretion to continue to higher masses than naive estimates suggest. Radiation pressure is not a significant barrier to accretion.

3.3. Ionization

The third puzzle to solve in an accretion mechanism for massive star formation is ionization. For spherically symmetric accretion, Walmsley (1995) shows that accretion above a critical rate

$$\dot{M}_{\rm crit} = \sqrt{\frac{4\pi G M S m_H^2}{\alpha^{(2)}}} \approx 2\times 10^{-5} \left(\frac{M}{10\ M_\odot}\right)^{1/2} \left(\frac{S}{10^{49}\ {\rm s}^{-1}}\right)^{1/2}\ M_\odot\ {\rm yr}^{-1}, \quad (1)$$

where M is the stellar mass, S is the ionizing luminosity (in photons s^{-1}), and $\alpha^{(2)}$ is the recombination coefficient to excited levels of hydrogen, will trap all ionizing photons near the stellar surface. Since estimated accretion rates for massive stars are much higher than this, if accretion is spherically symmetric then the star will be unable to ionize its parent core.

Observations support the idea that HII regions can be confined near their source stars for long periods, and that they are therefore not able to stop accretion. The argument comes from statistics: ultracompact HII regions (roughly those $\lesssim$ 0.1 pc in size) have dynamical times $\sim 10^3$ yr, but a census of the number of HII regions versus their size implies that ultracompact HII regions must survive for times closer to $\sim 10^5$ yr (Wood & Churchwell 1989; Kurtz et al. 1994). An extended phase during which HII regions are confined by accretion, and which lasts for a time comparable to the star formation time ($\sim 10^5$ yr), is consistent with the data, while the idea that HII regions expand dynamically and halt accretion is not. In addition, observations of inflow signatures in ionized gas in some systems (Sollins et al. 2005) provide direct evidence that accretion can continue even after the formation of an HII region.

The exact mechanism by which HII regions are confined is still uncertain. Keto (2002, 2003) presents spherically symmetric hydrodynamic accretion models with ionizing radiation. In the models, when the ionizing luminosity is low, accretion traps all ionizing photons at the stellar surface and there is no HII region. As the stellar mass and ionizing luminosity increase, the HII region is able to lift off the stellar surface, but it remains trapped in a region where the thermal pressure of the ionized gas is insufficient to escape. Accretion continues through the ionization front for a long time, but eventually the ionizing luminosity rises high enough for the HII region to expand outward and reach the point where it halts further accretion. While this model seems to be consistent with the observational data, there are two possible problems. First, it is spherically symmetric, while massive stars form primarily in very turbulent regions. Second, the long trapped HII region phase requires that the ionizing luminosity and the accretion rate rise together. Ionizing luminosity rises sharply with stellar mass, and in Keto's models (which assume Bondi accretion) so does the accretion rate. However, if the accretion rate were a weaker function of mass, as is expected for more realistic core models (e.g., McKee & Tan 2003), then it is unclear the confinement would work.

Xie et al. (1996) offer another possibility: HII regions may be confined by turbulent pressure, which far exceeds thermal pressure in the dense regions where massive stars form. However, Xie et al.'s model is purely analytic, and it is unclear if turbulent confinement of ionization can work in reality. Recent simulations by Dale et al. (2005) of collapsing regions suggest that it will not, because ionizing radiation will escape through low-density regions of the turbulent flow. In Dale et al.'s simulations the turbulent pressure is far lower than it should be due to turbulent decay (§ 2.3.), but the results suggest at a minimum that turbulent confinement of HII regions needs further study. Tan & McKee (2003) offer the alternative model that HII regions may be confined by the dense outflows of massive stars. In this picture, the ionized region is confined to the dense walls of an outflow cavity that has been largely evacuated of gas by magnetic fields. They find that the ionization stays confined near the star as long as the star is type B or later. However, it is unclear what this model predicts will happen for more massive stars.

Regardless of which model for trapping is correct, it is important to note that *some* mechanism for confining HII regions for many dynamical times seems to be required by the observational data. All the proposed explanations thus far involve accretion, winds, or turbulence in some form. There is no plausible solution for the long lifetimes of HII regions in the competitive accretion picture, which lacks these elements and generally predicts gas (as opposed to collisional) accretion rates onto massive stars that are too low to confine ionization (Dale et al. 2005; Dobbs et al. 2005). This is another serious argument against competitive accretion.

4. Missing Pieces

Thus far, I have argued that the turbulent radiation hydrodynamic model provides a good solution to the problem of massive star formation. However, there are several elements of the problem for which neither that model nor the competitive accretion model have made much progress.

4.1. Magnetic Fields

None of the simulations of massive star formation performed to date have included magnetic fields, and analytic models have included them only in the most cursory fashion. It is unclear how serious an omission this is. The dynamical importance of the magnetic field is determined by the mass to magnetic flux ratio, M/Φ. For a given flux there is a maximum mass M_Φ than flux can support against gravitational collapse, so for a cloud of mass M it is natural to define the magnetic support parameter $\lambda = M/M_\Phi$. Values of $\lambda > 1$ are termed supercritical, and correspond to configurations where magnetic support cannot prevent the cloud from collapsing dynamically; in the subcritical regime, $\lambda < 1$, magnetic support can prevent collapse. If typical massive star forming cores are subcritical or critical, then omission of magnetic fields is a serious error.

In principle one can determine λ directly from observations. In practice, however, magnetic fields are extremely difficult to detect even in low-mass star forming regions, which are generally closer and suffer much less from confusion and extinction than massive regions. Crutcher (2006) reviews the observations of magnetic fields in massive star-forming regions that exist, and concludes that $\lambda \approx 1$ is typical, indicating the magnetic effects are significant.

However, this conclusion is plagued by large systematic uncertainties. First, to determine λ from observations, one must assume a geometry for the cloud. Crutcher's conclusion assumes that cores are two-dimensional disks. However, observations show that cores are roughly triaxial (Jones et al. 2001), with ratios of long to short axis of $\sim 2:1$. This would give $\lambda > 1$ for the vast majority of observed regions. A second difficulty stems from uncertainty in where within a core one is measuring a magnetic field. The most common and reliable way to detect magnetic fields in molecular gas is via Zeeman splitting in OH or CN. However, both of these molecules are biased tracers of the mass, due to excitation threshold effects and freeze-out onto dust grains (Tafalla et al. 2002). It is unclear what systematic biases observing the field in these biased tracers might produce. Methods such as the Chandrasekhar-Fermi effect, which are based on polarization of dust grains, are not affected by freeze-out, but are affected by uncertainty as to where along a line of sight a polarized signal is arising. It is not clear whether these effects will systematically increase or decrease λ. A third bias is that in many cases observations do not detect a magnetic field at all, and at least some non-detections remain unpublished. If such regions are not properly included in statistical analyses, this can artificially raise estimates of λ (Bourke et al. 2001). In summary, observations are quite ambiguous as to whether magnetic fields are dynamically significant in regions of massive star formation. Ideally they should be included in models, but limitations of algorithms have prevented their inclusion thus far.

4.2. Masers

Decades ago observations established that massive star forming regions are often host to water, methanol, OH, and SiO masers. Although they were originally thought to arise from shocks at the edges of HII regions, high resolution observations show that they are generally offset from HII regions, and are more closely associated with infrared sources (Hofner & Churchwell 1996). Masers are particularly useful because they provide spatial resolutions of milliarcseconds, far higher than any other technique possible for deeply embedded sources. The resolution in space and time is sufficiently high that multi-epoch observations can often detect proper motions of individual maser spots.

The primary difficulty with maser observations is that they are difficult to interpret. Maser spots often show linear or arc-like arrangements, which early observers interpreted as tracing edge-on disks (Norris et al. 1993). This would have been interesting, because at the time no disks around massive stars were known. Even today, it would provide us with a powerful tool for tracing the dynamics of massive accretion disks on very small scales. However, more recent work that has combined maser data with observations in other wavelengths provides little support to the disk hypothesis. In a few cases, such as Orion BN/KL (Greenhill et al. 2004), linear arrangements of maser spots are perpendicular to molecular outflows, as one would expect were masers tracing a disk. More often, however, maser spots are parallel to the direction of outflows (De Buizer 2003; De Buizer & Minier 2005; De Buizer et al. 2006), suggesting that they trace outflows rather than disks. The primary lesson is that masers cannot be used as diagnostics of the massive star formation process without more complete models of how and where maser emission arises.

While difficult, making such models is likely to yield new insights into the star formation process, particularly when applied to some of the more unusual arrangements of masers that appear consistent with neither a disk nor an outflow. For example, Figure 3 reproduces Figure 1a of Torrelles et al. (2001). The dots show the positions of water maser spots observed in three epochs in the Cepheus A region, a site of massive star formation. At each epoch the spots fit a circle roughly 62 AU in radius around the same center to an accuracy of 0.1%. The change in radius with time implies that the circle is expanding at 9 km s^{-1}. The best explanation for this geometry is that we are seeing a limb-brightened, expanding spherical shell, and there is no obvious way that either a disk or an ordinary bipolar outflow could explain the data. One intriguing possibility is that the masers could be tracing the wall of a radiation bubble, as seen in the simulations of Krumholz et al. (2006a). The bubbles are quite spherical when they are at such small radii, the expansion velocities are roughly consistent with what is seen in the simulations, and the densities and temperatures in the bubble walls are roughly what would be needed to produce maser emission.

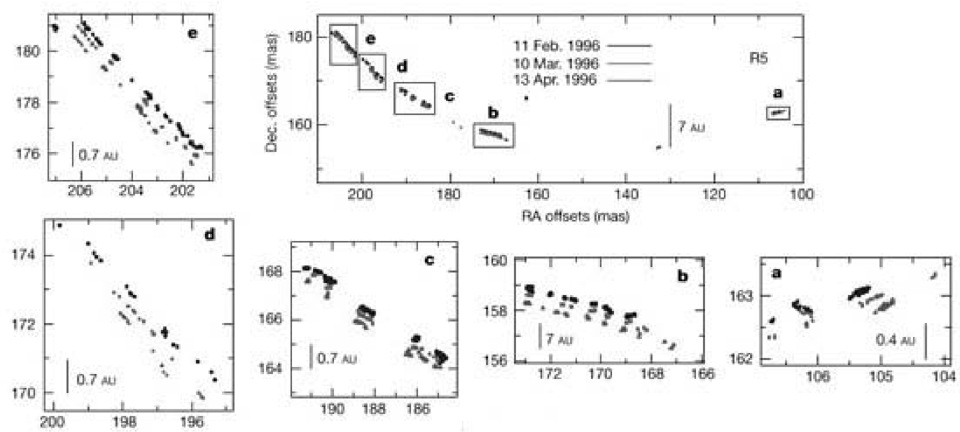

Figure 3. Dots show spots of water maser emission observed by Torrelles et al. (2001) in the Cepheus A star-forming region. Figure appears by the kind permission of the Nature Publishing Group.

4.3. The Stellar Mass Limit

A final observational result that neither model has been able to incorporate or explain thus far is the existence of an upper mass limit to the stellar IMF. Statistical arguments applied to the Galaxy as a whole (Elmegreen 2000; Oey & Clarke 2005) and direct star counts in individual massive clusters (Weidner

& Kroupa 2004; Figer 2005) both show that the IMF cannot continue to have a Salpeter slope out to arbitrarily high masses. Instead, there must be a fairly sharp turn-down at around 150 $M_{\odot}$. It is difficult to see how such a cutoff could occur in the competitive accretion model. Collisions between point particles should be a scale-free process, producing a featureless power-law distribution of masses. It is possible that the "microphysics" of the collision process could provide a break in the power-law – for example collisions between stars with a total mass above 150 $M_{\odot}$ might lead directly to intermediate mass black holes rather than to stars that we could observe – but there is at present no evidence to support this hypothesis.

The upper mass limit is not much easier to understand in the context of the turbulent radiation hydrodynamic model. One might think that the increasing strength of radiation pressure feedback with mass could produce a cutoff, but this explanation faces two serious objections. First, at masses $\gtrsim 100$ $M_{\odot}$, stellar luminosity is almost directly proportional to mass, since at such masses stars are supported primarily by internal radiation pressure. Thus, the ratio of radiation pressure force to gravitational attraction does not change significantly for stars larger than $\sim$100 $M_{\odot}$. Why, then, should be there be a change in the IMF at 150 $M_{\odot}$? A second problem with an explanation based on radiation pressure is the absence of evidence for a variation in the stellar IMF with metallicity. Since the strength of the radiation pressure force is directly proportional to the metallicity, if radiation pressure set the stellar mass limit then one would expect the high mass end of the IMF to change with metallicity, which should be observable as a change in IMF with Galactocentric radius. Such a change has not been observed (Massey 1998).

One possible way out would be if the mass limit is unrelated to the formation process, and is instead set by stellar stability. Humphreys & Davidson (1979, 1994) investigate the structure of very massive stars, and find that they are often pulsationally unstable. This instability can cause rapid mass loss, which might set a stellar upper mass limit. However, whether such a limit really exists, and if so whether it coincides with the observed mass limit, is at present unknown.

5. Conclusions and Prospects

Our knowledge of the physical mechanism of massive star formation is still quite limited, as evidenced by the fact that for the last decade there have been two very different models for it that observations could not definitively distinguish. However, theoretical and observational work over the last year or two have advanced the field to the point where we can begin to decide between the models. Observations of disks and outflows from young massive stars point to accretion from a core rather than collision as the mechanism by which massive stars form, and theoretical work strongly suggests that competitive accretion does not operate in observed star-forming clouds, consonant with observations favoring accretion from cores. Moreover, the problem of how to make massive stars despite radiation feedback, one of the original motivations for the competitive accretion and collision model, seems to be receding. Recent simulations and analytic work show that both radiation pressure force and ionization are much less effective at inhibiting accretion than had previously been assumed.

In the next decade, observations should be able to settle definitively the issue by searching for more direct indicators of collision, such as very high column density embedded clusters and infrared flares from collisions. They also promise to give us a window into the massive star formation process on much smaller scales, where the effects of radiation pressure and ionization should be more obvious. Masers have started to provide data with high resolution in space and time, but interpreting maser data still requires much theoretical work. The next generation of millimeter interferometers, such as ALMA, will enable us to resolve disks around massive stars, and possibly to see dense shells of material shaped by protostellar radiation and outflows on $\lesssim 1000$ AU scales. These observations should be much easier to interpret.

On the theoretical side, progress will depend primarily on improving computational models, and should focus on four problems with the current generation of simulations. First, no simulation of massive star formation to date has included outflows. This is a major omission, since we know that outflows are present, and that they can have profound effects on the formation process. Outflows may also be responsible for driving turbulence in star-forming clumps, and should therefore be included in simulations of cluster formation to avoid the problem of unphysically small virial parameters identified by Krumholz et al. (2005c). Improving the computations from hydrodynamics to magnetohydrodynamics is a second potential advance. The major difficulty here is knowing what initial conditions to use, since the strength and geometry of the magnetic field in regions of massive star formation is so poorly known. Third, simulations could be improved by starting from larger scales. Both competitive accretion and turbulent radiation hydrodynamic simulations of massive star formation start with extremely unrealistic initial conditions. A better approach would be to simulate a cluster-forming clump $\sim$4000 $M_\odot$ in size, typical of the Plume et al. (1997) sample, follow the formation of a massive core, and then simulate the subsequent collapse of the core at high resolution using adaptive mesh refinement or adaptive smoothed particle hydrodynamics.

A final area ripe for improvement is radiative transfer. Thus far simulations have either used multi-frequency radiation in two dimensions (Yorke & Sonnhalter 2002), or gray radiation in three dimensions (Krumholz et al. 2006a). Since the simulations show that both multi-frequency and three-dimensional effects are important, it is critical to do three-dimensional multi-frequency radiative transfer simulations. A natural outgrowth of this is modeling ionization, since in principle one can treat Lyman continuum photons as just another frequency group and then add a chemistry update step to recompute the ionization fraction after a radiation update. A final improvement to the radiation would be to use an approximation better than flux-limited diffusion, which may produce errors inside low optical-depth radiation bubbles. The major obstacle here is computational cost. Three-dimensional gray flux-limited diffusion calculations require months of supercomputer time on present computers, and improvements to the radiation physics without significant advances in processor or algorithmic speed would make the problem impossible to run.

Perhaps the best opportunities for progress now come not purely from theory or from observation, but from work that makes detailed comparisons of the two. Hopefully in the future more observers and theorists will collaborate to post-process simulations so that they can make definite comparisons to observations, and use the results of those comparisons to refine theoretical models. In the next decade, work of this sort should be able to provide us with at least the basic outline of how massive stars form.

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Jackie Kessler-Silacci and Shardha Jogee share a laugh.