THE BIRTH OF MASSIVE STARS 
AND STAR CLUSTERS 

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Abstract 
In the present-day universe, it appears that most, and perhaps all, massive stars 
are born in star clusters. It also appears that all star clusters contain stars drawn 
from an approximately universal initial mass function, so that almost all rich 
young star clusters contain massive stars. In this review I discuss the physical 
processes associated with both massive star formation and with star cluster for-
mation. First I summarize the observed properties of star-forming gas clumps, 
than address the following questions. How do these clumps emerge from giant 
molecular clouds? In these clustered environments, how do individual stars form 
and gain mass? Can a forming star cluster be treated as an equilibrium system or 
is this process too rapid for equilibrium to be established? How does feedback 
affect the formation process? 

1. Introduction 
Star clusters$^1$, are the fundamental units of star formation in galaxies. Most 
Galactic stars are born in clusters (Lada & Lada 2003): their figure 2 implies 
that equal numbers of stars are forming in each logarithmic interval of cluster 
mass, for cluster masses from $\sim 50 - 1000 \, M_\odot$. There is a dearth of star 
formation in clusters below $50 \, M_\odot$. The sample of Lada & Lada (2003) is too 
small to constrain the initial cluster mass function beyond $\sim 1000 \, M_\odot$. Hub-
ble Space Telescope observations have probed this range in external galaxies, 
finding a continuation of the mass function slope (Larsen 2002). For the dwarf 
starburst galaxy NGC 5253, Tremonti et al. (2001) have proposed a model in 
which all star formation occurs in clusters, which then dissolve on timescales 
of $\sim 10 \, \text{Myr}$ to create the sources of the observed diffuse UV light. 

The initial mass function of stars in clusters appears largely invariant (Kroupa 
2002) so that almost all relatively massive clusters will contain at least a few 

$^1$ I define a star cluster as a group of stars that forms together from a gravitationally bound gas clump.
high-mass stars. Thus a significant fraction of all stars form in proximity to massive stars, and may be affected by their strong feedback.

Locally, essentially all massive stars form in clusters (de Wit et al. 2005), so high-mass star formation seems to require an environment that will also produce a large number and mass of low-mass stars. In the present-day universe, massive star formation and star cluster formation are one and the same process.

It is clear that an understanding of massive star and star cluster formation is important to many areas of astrophysics, from galaxy evolution to planet formation.

2. Overview of physical properties

Figure 1 shows the masses, $M$, and mean surface densities, $\Sigma = M/(\pi R^2)$, of star clusters and interstellar gas clouds. For convenience $\Sigma = 1\,\text{g}\,\text{cm}^{-2}$ corresponds to $4800\,M_\odot\,\text{pc}^{-2}$, $N_H = 4.3 \times 10^{23}\,\text{cm}^{-2}$ and $A_V = 200\,\text{mag}$, for the local gas to dust ratio. Contours of constant radial size, $R$, and hydrogen number density, $n_H = \rho/\mu = 3M/(4\pi R^3\mu)$, where $\mu = 2.34 \times 10^{-24}\,\text{g}$ is the mean mass per H, are indicated. The density contours also correspond to free-fall timescales, $t_{\text{ff}} = \sqrt{3\pi/(32G\rho)} = 1.38 \times 10^6(n_H/10^3\,\text{cm}^{-3})^{-1/2}\,\text{yr}$.

For a virialized cloud with virial parameter $\alpha_{\text{vir}} \simeq 1$ (Bertoldi & McKee 1992) the signal crossing or dynamical timescale is $t_{\text{dyn}} = 2t_{\text{ff}}$.

The presence of molecules allows interstellar gas to cool to low temperatures, $\sim 10 - 20\,\text{K}$, effectively removing thermal pressure support. To survive the destructive local interstellar FUV radiation field requires a total column of $N_H = (0.4, 2.8) \times 10^{21}\,\text{cm}^{-2}$ for $\text{H}_2$ and CO, respectively (McKee 1999).

Giant molecular clouds (GMCs) have an approximately constant column of $N_H = (1.5 \pm 0.3) \times 10^{22}\,\text{cm}^{-2}$ and typical masses $\sim 10^5 - 10^6\,M_\odot$ (Solomon et al. 1987). A sample of local ($d \lesssim 3\,\text{kpc}$) infrared-dark clouds (IRDCs), discussed in §3, have masses ranging from several hundred to $\sim 10^4\,M_\odot$ and $\Sigma \sim 0.1\,\text{g}\,\text{cm}^{-2}$ (Kirkland & Tan, in prep.), about a factor of 3 greater than the mean value of GMCs. The massive star forming clumps observed in the sub-mm by Mueller et al. (2002) have similar masses, but surface densities typically a factor of five greater still. More revealed star clusters, such as the Orion Nebula Cluster, have similar properties. More massive and higher surface density clusters are rare, but can be found in the Galactic center, e.g. the Arches and Quintuplet clusters (e.g. Kim et al. 2000). The most massive young clusters, so-called super star clusters, are often found in starburst environments, such as the Antennae galaxies, and in some dwarf galaxies, e.g. NGC 5253 (Turner et al. 2000) and NGC 1569 (Gilbert & Graham 2003).

All high-mass star-forming systems appear to be at about a constant density of $n_H \sim 2 \times 10^5\,\text{cm}^{-3}$, corresponding to $t_{\text{ff}} \sim 1 \times 10^5\,\text{yr}$. This is about the same as the density at which the cooling rate is a maximum (Larson 2005),
and thus gravitational collapse is easiest. A spherical self-gravitating cloud in hydrostatic equilibrium with mean surface density $\Sigma$ and density profile $\rho \propto r^{-k_\rho}$ with $k_\rho = 1.5$, similar to observed clumps, has a mean pressure of $4.3 \times 10^8 \Sigma^2$ K cm$^{-3}$ (McKee & Tan 2003). Massive stars and star clusters appear to form under pressures $\gtrsim 3 \times 10^7$ K cm$^{-3}$, much higher than that of the local diffuse ISM, i.e. $2.8 \times 10^4$ K cm$^{-3}$ (Boulares & Cox 1990).

3. Setting up initial conditions for star cluster formation

What causes a particular region of a GMC to form a star cluster? From Figure 1 we see that the surface density, pressures, and volume densities must increase by at least factors of 10, 100, and 1000, respectively. This occurs in only a small part of the GMC: typically only $\sim 1\%$ of the mass is involved.

Models for the cause of star formation can be divided into two groups: quiescent and triggered. In the former, star formation occurs in the densest, most unstable clumps of the GMC, and these form out of the general gravitational contraction of the entire cloud. This process may be regulated by the decay of turbulence, ambipolar (Mouschovias 1996) or turbulent diffusion of magnetic flux, or heating and ionization (McKee 1989) from newly-formed star clusters. In models of triggered star formation, the star-forming clumps are created by compression of parts of the GMC by external causes, such as: cloud collisions (Scoville et al. 1986; Tan 2000); convergent turbulent flows (e.g. Mac Low & Klessen 2004); or feedback from young stars with ionization (Elmegreen & Lada 1977; Thompson et al. 2004; Deharveng et al. 2005), stellar winds (e.g. Whitworth & Francis 2002), protostellar outflows, radiation pressure, and supernovae (e.g. Palous et al. 1994).

Elmegreen (2004) has noted that the compressions that result from most forms of stellar feedback are probably only efficient within particular GMCs or GMC complexes, i.e. young stars forming in one GMC are unlikely to trigger star formation in another. Oey et al. (2005) claim the age sequence of 3 regions of the W3/W4 complex is evidence for triggered star formation over an approximately 100 pc scale region.

A promising method for addressing the cause of star cluster formation is the study of infrared-dark clouds (IRDCs). These are regions that have surface densities high enough to obscure the Galactic infrared background. Large numbers of IRDCs have been found towards the inner Galaxy with the Midcourse Space Experiment (MSX) (Egan et al. 1998). These are associated with dense molecular gas (Carey et al. 1998; Teyssier, Hennebelle & Perault 2002). Carey et al. (1998) measured the following physical properties: radii $r \sim 0.2 - 8$ pc, column densities $\Sigma \sim 0.5 - 50$ g cm$^{-2}$, densities $n_H \gtrsim 2 \times 10^5$ cm$^{-3}$, masses $M \sim 10^3 - 10^5 M_\odot$ and temperatures $T \lesssim 20$ K. Kirkland & Tan (in prep.) identified a sample of relatively nearby IRDCs from the MSX infrared survey.
Figure 1. Surface density, $\Sigma$, versus mass, $M$, for star clusters and interstellar clouds. Contours of constant radius, $R$, and hydrogen number density, $n_{\text{H}}$, or free-fall timescale, $t_{\text{ff}}$, are shown with dotted lines. The minimum surface density for CO clouds in the local Galactic UV radiation field is shown, as are typical parameters of GMCs. Dense, cold clumps of GMCs known as infrared dark clouds are shown by small open squares (see text in §3). Large open squares are the star-forming clumps of Mueller et al. (2002): a triangle indicates the clump contains an HII region while the diagonal line from each point shows the effect of uncertain dust opacities on the mass estimate. The Orion Nebula Cluster, allowing for a contribution from gas of 50%, is shown by the solid diagonal line, which traces conditions from the inner to the outer parts of the cluster. Several more massive clusters are also indicated (see §2 for references). The condition for ionized gas to remain bound is indicated by the dashed line. The three solid circles are the conditions of feedback models discussed in §6.

and the Galactic Ring Survey of $^{13}$CO (Simon et al. 2001). Surface densities and masses were estimated with three independent methods: infrared extinc-
tion, line strengths of $^{13}$CO, and virial arguments. The dispersion between these methods is a factor of a few due to systematic errors. The average properties of each cloud are shown in Figure 1. They have similar masses to the star clusters and surface densities that are somewhat smaller. Thus they are likely to be representative of the earliest stage of star cluster formation.

From a visual inspection of the sample, Kirkland & Tan (in prep.) find that the morphologies of the IRDCs are more varied, and in particular filamentary, than the star-forming clumps, that are often approximately spherical (Shirley et al. 2003). The line widths are several km/s, which is much greater than the sound speed of gas at $\sim 20$ K. Thus the initial conditions for star cluster formation probably involve supersonic turbulence, although not necessarily super-Alfvenic turbulence. There are often multiple velocity components. Some IRDCs are relatively isolated from other star-forming regions suggesting that their formation does not require triggering by feedback from young stars.

4. **How do stars form within clusters?**

We have seen that star clusters are born from turbulent gas, i.e. having velocity dispersions much greater than thermal. A basic question is how individual stars form in this environment. In particular do they grow inside quasi-equilibrium gas cores that collapse via accretion disks with relatively stable orientations? In this scenario (e.g. Shu, Adams, & Lizano 1987, McKee & Tan 2003) the initial mass of the core helps to determine the final mass of the star, modulo the effects of protostellar feedback. Alternative models involving competitive Bondi-Hoyle accretion (e.g. Bonnell et al. 2001) and direct stellar collisions (Bonnell, Bate, & Zinnecker 1998) have been proposed. These alternative models have been particularly motivated for the case of massive star formation since this occurs in the most crowded regions, radiation pressure feedback from massive stars on dust grains can cause problems for standard accretion scenarios, and the Jeans mass in these high pressure, high density regions is only a fraction of a solar mass.

**Formation of Cores**

First consider the formation of cores from a turbulent medium. Ballesteros-Paredes, Klessen, & Vazquez-Semadeni (2003) and Klessen et al. (2005) find that a substantial fraction of “cores” identified in their nonmagnetic SPH simulations of supersonic turbulence appear to be quiescent (i.e. line widths $\leq$ than thermal) and coherent (i.e. line widths are roughly independent of positional offset from the core center), but are in fact dynamic, transient entities. They argue that the inference of hydrostatic equilibrium, e.g. from radial profiles that appear similar to Bonnor-Ebert profiles (e.g. Alves, Lada, & Lada 2001), is not necessarily valid, since such profiles are also possible for dynam-
ically evolving cores. However, it is not clear if these artificial dynamic cores are consistent with the observations of Walsh et al. (2004), which find very small ($\lesssim 0.1$ km s$^{-1}$) velocity differences between the line centers of high ($n_H \sim 4 \times 10^5$ cm$^{-3}$) and low ($n_H \sim 2 \times 10^3$ cm$^{-3}$) density traces of starless cores: real cores do not appear to be moving with respect to their envelopes. Estimates of the ages of starless cores (e.g. Crapsi et al. 2005) are uncertain, but have the potential to constrain models of core formation.

The numerical simulations described above are nonmagnetic. Li et al. (2004) and Vázquez-Semadeni et al. (2005) have studied the properties of cores forming from turbulent, magnetized gas. The latter authors find in their periodic, fixed grid, isothermal, ideal MHD, driven turbulence simulations, that: magnetic fields reduce the probability of core formation; in the magnetically subcritical run, a bound core forms that lasts $\sim 5t_{ff}$ (defined at densities $\sim 50$ times the mean), which would be enough for ambipolar diffusion to affect the dynamics; in the moderately supercritical case, where magnetic fields are relatively weaker, bound cores form and then are able to undergo runaway collapse over about $2t_{ff}$, defined at the core’s mean density. These results suggest that the initial conditions for star formation are bound cores, and that the stronger the magnetic field, the more chance the cores have to attain a quasi-equilibrium structure. The marginally critical case is probably most relevant if star-forming clumps evolve from regions of GMCs that gradually lose magnetic support. The observations by Crutcher (1999) of the magnetic field strength in dense regions of GMCs imply that these regions are only marginally supercritical and that magnetic fields are important for the dynamics.

Magnetic fields are likely to affect the masses of cores that are present in a given environment. One argument against massive star formation from cores has been that the thermal Jeans mass in the high pressure, high density regions associated with massive star formation is very small. However this argument is irrelevant if massive cores derive most of their pressure support from either magnetic fields or turbulent motions. Observations suggest that the mass function of cores is fairly similar, within large uncertainties, to that of stars and that there are some massive pre-stellar cores (Testi & Sargent 1998; Motte et al. 2001; Li, Goldsmith, & Menten 2003; Beuther & Schilke 2004).

**Accretion to Stars**

It is computationally expensive to follow gravitational collapse to the high densities and short timescales associated with protostars and their accretion disks. A common numerical technique is to introduce sink particles in bound regions of high density, which can then accrete gas from their surroundings (Bate, Bonnell, & Price 1995). Bonnell & Bate (2002) modeled star cluster formation with SPH, isothermal, non-periodic, no feedback, nonmagnetic simula-
tions, with initial setup of static gas and sink particles about to undergo global collapse. Stars gained mass via competitive accretion and stellar collisions and the final mass spectrum was similar to the Salpeter mass function. Using similar simulations, except now with an initially turbulent velocity field with no later driving, Bonnell, Vine, & Bate (2004) showed that the most massive star at the end of their calculation had gained mass that was initially very widely distributed. Dobbs, Bonnell, & Clark (2005) found that a massive turbulent core, such as envisaged by McKee & Tan (2003), can fragment into many smaller cores and protostars if the equation of state is isothermal. However, their non-isothermal model suffered much less fragmentation, while the results of Vázquez-Semadeni et al. (2005) suggest that less fragmentation would also occur if magnetic fields are allowed to affect the dynamics. Schmeja & Klessen (2004) simulated star cluster formation with SPH simulations with periodic boundaries, driven turbulence, no magnetic fields, no feedback, sink particle diameters of 560 AU, and an isothermal equation of state, finding highly variable accretion rates for their protostars.

We have seen that SPH simulations, by lacking magnetic fields, probably do not accurately model the fragmentation process of real star-forming regions, particularly with regard to core formation. Another difficulty is that in SPH simulations with sink particles, “stars” acquire most of their mass by competitive Bondi-Hoyle accretion and this process is not adequately resolved. In theory, gas is gravitationally focused by a passing star so that streamlines collide, shock and dissipate their energy. Eulerian grid simulations, including sink particles (Krumholz, McKee, & Klein 2004) and adaptive mesh refinement of small scale structures, have been used to simulate the interaction of sink particles with surrounding turbulent gas: the accretion rate is much smaller than the classical analytic estimate of accretion from a uniform medium (Krumholz, McKee, & Klein 2005a). Stellar feedback should also reduce this accretion rate, particularly to massive stars (e.g. Edgar & Clarke 2004). Thus the importance of Bondi-Hoyle accretion may be grossly over-estimated in SPH simulations.

Assumptions and Predictions of the McKee-Tan Model

McKee & Tan (2002; 2003) modeled massive star formation by assuming an initial condition that is a massive core in approximate pressure equilibrium with the surrounding protocluster medium, i.e. the star-forming clump. Tan & McKee (2002) modeled star cluster formation by extending this assumption to every star. To derive the pressure in the clump, the system was assumed to be in approximate hydrostatic equilibrium so that the mean pressure is related to the surface density, i.e. \( P \sim G\Sigma^2 \). How valid are these assumptions?
The mean pressure in the clump sets the overall density normalization of each core and thus its collapse time and accretion rate. The McKee-Tan model allows for deviations from exact pressure equilibrium with the parameter $\phi_P$, although the expectation is that these deviations will be factors of order unity. Although the core is treated as collapsing in isolation, this is also an approximation: McKee & Tan (2003) estimate that during the collapse time the core will interact with an amount of mass similar to the initial core mass, although not all of this will become bound to the core. Thus in reality one would expect for a given initial core mass somewhat greater final stellar masses than under the assumption of isolated cores. The particular density structure of cores assumed by McKee & Tan (2003) is $\rho \propto r^{-k_\rho}$ with $k_\rho = 1.5$ set from observed cores. This choice affects the evolution of the accretion rate during the collapse: $k_\rho < 2$ implies accretion rates accelerate. However, this is a secondary effect compared to the overall normalization of the accretion rate that is set by the external pressure. In any case since the pressure support is nonthermal with significant contributions from turbulent motions, one does not expect a smooth density distribution in the collapsing core, and the accretion rate will show large variations about the mean.

The assumption of approximate pressure equilibrium in the protocluster requires star formation to occur over at least several dynamical timescales, and this is examined in the next section. The basic picture of star cluster formation then involves: a turbulent, self-gravitating gas clump in which bound cores occasionally form (most gas at any given time is not in bound, unstable cores); a core mass function fairly similar to stars, i.e. massive cores form but are rare; an approximate equilibrium of cores with their surroundings; the collapse of cores quite rapidly in one or two free-fall timescales to form stars or binaries; the orbiting of newly-formed stars in the still star-forming clump, but negligible growth via competitive accretion.

Some of the key predictions of the McKee-Tan model are the properties of the cores and accretion disks of massive stars. The core size is $R_{\text{core}} \simeq 0.06(M_{\text{core}}/60M_\odot)^{1/2}\Sigma^{-1/2}$ pc. Recall that $\Sigma$, the surface density of the clump, is related to the pressure of clump via $P \sim G\Sigma^2$. These small, pressure-confined cores have relatively small cross-sections for close interactions with other stars, although such interactions may still become important in the later stages of cluster formation once the stellar density has been built up to a high enough level. The rate of core collapse leading to accretion to the star, via a disk, is $\dot{m}_* = 4.6 \times 10^{-4} f_\star^{1/2} M_{60}^{3/4} \Sigma_{60}^{3/4} M_\odot$ yr$^{-1}$, where $f_\star$ is the ratio of $m_*$ to the final stellar mass and a 50% formation efficiency is assumed.

Thus the collapse time, $1.3 \times 10^5 M_{60}^{1/4} \Sigma_{60}^{-3/4}$ yr, is short and quite insensitive to $M$, allowing coeval high and low mass star formation. The disk size is $R_{\text{disk}} = 1200(\beta/0.02)(f_\star M_{60})^{1/2}\Sigma^{-1/2}$ AU, where $\beta$ is the initial ratio of rotational to gravitational energy of the core, and the normalization is taken
from typical low-mass cores (Goodman et al. 1993), although there is quite a
large dispersion about this value. These estimates allow quantitative models
of the protostellar evolution, disk structure and outflow intensity. These have
been compared to observations of the Orion KL protostar (Tan 2004a), also
discussed briefly below. First I review other observational evidence of massive
star formation from cores and accretion disks.

**Observational Evidence for Massive Star Formation from
Cores and Accretion Disks**

The issue of the mode of star formation, particularly massive star formation,
is most likely to be resolved by observations. What observations are required?
A common approach has been to search for disks around massive stars. How-
ever, these by themselves do not distinguish between the models, unless they
are seen in conjunction with a collapsing pre-stellar core and it can be shown
that the star accumulated most of its mass by accretion from the core through
the disk. One would also like to show that the disk has maintained a fairly sta-
ble orientation, perhaps by looking at the impact of past outflow activity, during
the accretion process, although even this is not necessarily to be expected from
the collapse of a very turbulent core.

There are a number of claims for disks around massive protostars and mas-
sive young stars. Cesaroni et al. (1999) made mm and IR observations of
IRAS 20126+4104, concluding the system showed the expected signatures
of a massive ($\sim 24 \, M_\odot$) protostar, forming from a Keplerian accretion disk
inside a dense gas core. Shepherd, Claussen, & Kurtz (2001) used 7 mm
observations to marginally resolve the driving source, G192.16, of a power-
ful molecular outflow, which from luminosity arguments is thought to be a
$\sim 10 \, M_\odot$ protostar. They interpreted the elongation, which is roughly per-
collard to the outflow, to be evidence for a $\sim 100 \, AU$, $\sim 10 \, M_\odot$ disk.
However, much of the elongation is asymmetric, and so they also invoked a
second protostar. Sandell, Wright, & Forster (2003) used 3.4 mm continuum
and molecular line observations of NGC7538S to infer the presence of a rotat-
ing, massive ($\sim 100 \, M_\odot$), and exceptionally large ($r_d \sim 14000 \, AU$) disk about
a $\sim 10^4 \, L_\odot$ protostar, again driving a powerful outflow. This source is also pe-
culiar in that, if it is a massive protostar, it is relatively isolated. Beltran et al.
(2004) used 1.4 mm continuum and molecular line observations to identify 4
massive protostellar disks by searching for velocity gradients perpendicular to
outflows. They found disk sizes of several thousand AU. Chini et al. (2004)
used NIR imaging and CO line observations in M17 to find an elongated struc-
ture $\sim 2 \times 10^3 \, AU$ across with a mass of $\geq 100 \, M_\odot$ and a velocity gradient
of $1.7 \, km \, s^{-1}$. In the above systems the velocities measured from molecular
lines are typically on quite large scales that barely resolve the disk: the velocity
differences are only a few km s\(^{-1}\), since the inner regions are not resolved. It is possible that some of these sources, particularly those where there is little evidence for a luminous central source or outflow, may simply be flattened or filamentary structures with a velocity gradient.

Pestalozzi et al. (2004) interpreted VLBI observations of methanol masers in NGC7538 IRS N1 in terms of an edge-on Keplerian disk extending to a radius of $\sim 1000$ AU and orbiting a $30 M_\odot$ protostar. While some methanol maser systems may trace accretion disks, it appears that many are in fact signatures of outflows (De Buizer 2003).

In more evolved and revealed systems, NIR spectra of CO and Br\(\gamma\) emission have been used to infer the presence of disks, the emission coming from inside a few AU from the star (Blum et al. 2004; Bik & Thi 2004). Vink et al. (2002) used H\(\alpha\) spectropolarimetry to show that Herbig Ae/Be stars are surrounded by flattened, presumably disk-like, structures. While studies of revealed systems are useful for probing the properties and lifetimes of remnant accretion disks, they do not directly test the different formation scenarios, since even stellar collisions would be expected to leave remnant material that would form a disk.

Most of the aforementioned systems are at distances of $\sim 2$ kpc or more. The closest massive protostar is in the Orion KL region, only $\sim 450$ pc away. Wright et al. (1996), Greenhill et al. (1998) and Tan (2004) have interpreted the system as containing a $r \sim 1000$ AU accretion disk, as traced by SiO (v=0; J=2-1) maser emission, centered about the thermal radio source $I$ (Menten & Reid 1995) and aligned perpendicular to the large scale molecular outflow that flows to the NW and SE. However, from SiO (v=1,2; J=1-0) masers within several tens of AU from source $I$, Greenhill et al. (2003) have interpreted the disk as being aligned parallel to the large scale outflow. In this case either the source is unrelated to the large scale outflow, or the orientation has changed in the last $\sim 10^3$ yr, the timescale of current outflow activity. Normally one would regard this last possibility as extremely unlikely, however, the motion of a $\sim 10 M_\odot$ young star (the BN object) through the region occurred only 500 years ago (Plambeck et al. 1995; Tan 2004b). Several pieces of evidence point to an ejection of BN from the already-formed $\Theta^1 C$ binary system, however it is not possible to exclude an origin at source $I$ itself (Bally & Zinnecker 2005; Rodriguez et al. 2005).

Outflows are common from regions of high-mass star formation (see Beuther & Shepherd 2005, these proceedings) for a review. However, because massive stars tend to be forming in clusters it is not always clear which sources are responsible for driving the outflows. Nevertheless there seems to be a multitude of collimated, powerful outflows, that appear to be scaled-up versions of those from low-mass protostars. The continuity in outflow properties from the low to high mass regimes suggests that there is a single driving mechanism (Beuther et al. 2002).
One difference between outflows from low-mass and high-mass protostars is the presence of high flux of ionizing radiation in the latter. This should create an “outflow-confined”, hyper-compact HII region (Tan & McKee 2003). This model can account for the radio spectrum and morphology of source I in Orion KL, and perhaps also for the radio sources in CRL 2136 (Menten & van der Tak 2004), W33A, AFGL 2591 and NGC 7538 IRS9 (van der Tak & Menten 2005). An alternative model is the gravitationally-confined ionized accretion flow (Keto 2003), however this requires spherical accretion all the way to the star. Another model is the ionized flow from a photo-evaporated neutral disk (Hollenbach et al. 1994), however, if normal MHD outflows are present from the inner disk, they should block ionization of the outer disk.

5. The timescale of star cluster formation

The timescales of star cluster formation have been reviewed by Tan (2005). Two independent pieces of evidence suggest that in the Orion Nebula Cluster, stars have been forming for at least 10 dynamical timescales, or 20 free-fall timescales. First ages of stars derived from pre-main-sequence tracks show a spread from 0 to at least 3 Myr (Palla & Stahler 1999). Second, the age of a dynamical ejection event of 4 massive stars ejected from a region coincident with the ONC is about 2.5 Myr (Hoogerwerf et al. 2001).

A relatively long formation timescale is also consistent with the observed morphologies of protoclusters in CS molecular lines: Shirley et al. (2003) find approximately spherical and centrally concentrated morphologies for a large fraction of their sources, suggesting they are older than a few dynamical times.

Formation timescales longer than a dynamical time allow the clump gas to virialize and come into pressure equilibrium: self-gravity is countered by internal sources of pressure. Numerical simulations (Mac Low et al. 1998; Stone et al. 1998) suggest that turbulence decays in one or two dynamical timescales (however, see Cho & Lazarian 2003). In this case, in order for turbulence support of the clump to be maintained, energy must be injected, most probably from internal sources such as protostellar outflows.

Such long formation timescales would also allow for significant dynamical relaxation of the forming star cluster: for \( N \) equal mass stars the relaxation time is \( t_{\text{relax}} \simeq 0.1 N/(\ln N) t_{\text{dy}} \), i.e. about 14 crossing timescales for \( N = 1000 \). Using numerical experiments, Bonnell & Davies (1998) found that the mass segregation time (of clusters with mass-independent initial velocity dispersions) was similar to the relaxation time. The presence of gas should shorten these timescales (Ostriker 1999). Therefore at least a part of the observed central concentration of massive stars in the Orion Nebula Cluster, in particular the Trapezium stars, may be due to mass segregation rather than preferential formation at the center.
It should be noted that a star cluster formation timescale of a few Myr is similar to the dynamical timescale of individual GMCs. Star formation appears to be rapid when compared to these timescales, but not when compared to the timescales of the star-forming clumps themselves. This is a major difference between the clustered (e.g. Orion) and distributed (e.g. Taurus, Hartman 2002) mode of star formation. Note also that even if the star cluster formation timescale is similar to the GMC dynamical timescale, this does not imply GMC lifetimes are this short (e.g. Tassis & Mouschovias 2004; §6).

6. How does feedback affect the formation process?

Feedback processes that act against gravitational collapse and accretion of gas to protostars include radiation pressure (transmitted primarily via dust grains), thermal pressure of ionized regions and ram pressure from stellar winds, particularly MHD-driven outflows from protostars that are still actively accreting. If star cluster formation takes longer then \( \sim 3 \) Myr, then there is a chance of supernova feedback clearing out any remaining gas.

Feedback in Individual Cores

For individual low-mass star formation from a core, bipolar protostellar outflows, accelerated from the inner accretion disk and star by rotating magnetic fields, appear to be the dominant feedback mechanism, probably preventing accretion from polar directions and also diverting a fraction, up to a third, of the material accreting through the disk. This leads to star formation efficiencies from the core of order 50% (Matzner & McKee 2000).

For massive protostars, forming in the same way from a core and accretion disk, one expects similar MHD-driven outflows to be present leading to similar formation efficiencies. In addition, once the massive protostar has contracted to the main sequence (this can occur rapidly before accretion has finished), it starts to produce large a flux of ionizing photons. The HII region is unlikely to be impeded by an accretion flow with reasonable angular momentum. However, it is likely to be confined, at least equatorially, by the bipolar outflow (Tan & McKee 2003). As the protostellar mass and ionizing flux increase, then eventually the HII region can spread through the outflow and start to ionize the disk surface. If the disk is ionized out to a radius where the escape speed is about equal to the ionized gas sound speed, then a photo-evaporated flow is set up, further reducing accretion to the star (Hollenbach et al. 1994).

Radiation pressure on dust grains (well-coupled to the gas at these densities) is also important for massive protostars. It has been suggested, in the context of spherical accretion models, that this leads to an upper limit to the initial mass function (Kahn 1974; Wolfire & Cassinelli 1987). However, these constraints are relaxed once a disk geometry is allowed for (Nakano 1989; Jijina & Adams
Yorke & Sonnhalter (2002) used 2D axially symmetric simulations to follow massive star formation from a core collapsing to a disk, including radiation pressure feedback: accretion stopped at $43 \, M_\odot$ in their most massive core. They showed the accretion geometry channeled radiative flux into the polar directions and away from the disk, terming this the “flashlight effect”. Krumholz, McKee, & Klein (2005b) found that cavities created by protostellar outflows increase the flashlight effect, allowing even higher final masses.

**Feedback during Star Cluster Formation**

One of the primary goals for models of feedback in star clusters is a prediction of the star formation efficiency, since this determines whether the cluster remains bound: Lada, Margulis, & Dearborn (1984) find from numerical models that clusters can remain bound with efficiencies as low as $\sim 30\%$ if the gas is removed gradually. Lada & Lada (2003) conclude that 90-95\% of Galactic embedded clusters emerge from their GMCs unbound, although the mass associated with these systems is a somewhat lower percentage.

One can make some simple analytic estimates of the effects of massive star feedback on real protoclusters using Figure 1. The dashed line shows the condition that the escape speed at a distance $2R$ from the clump center is equal to the ionized gas sound speed ($\sim 10 \text{ km s}^{-1}$). To the right and above this line ionizing feedback is much less effective since even if cluster gas is ionized it will be relatively difficult to be expelled. The Arches cluster in the Galactic center and super star clusters are in this region. If star clusters form relatively slowly, e.g. in $20t_\text{ff}$ as may be the case in Orion (§5), then we can see that the clusters forming massive stars, which have approximately constant densities and free-fall timescales ($\sim 10^{5} \text{ yr}$), would not be affected by supernova feedback, since this only starts after at least $\sim 3 \times 10^{6} \text{ yr}$. However, the rate of star formation is uncertain, particularly in the more massive and distant clusters.

Matzner & McKee (2000) modeled protostellar outflow feedback in clusters of low-mass stars, estimating formation efficiencies of 30-50\%. Adding high-mass stars to these particular models would presumably reduce the efficiency.

Tenorio-Tagle et al. (2003) presented a 1D model of star cluster formation in the presence of stellar wind and ionizing feedback, assuming an initial burst of massive star formation that creates a compressed shell from the infalling neutral gas, where more stars can form. They achieved high star formation efficiencies, allowing the build-up of very massive clusters, comparable to super star clusters. However, it is not clear how their model would fare in a more realistic turbulent and clumpy medium.

Scoville et al. (2001) considered radiation pressure feedback as a mechanism for limiting star cluster masses at $\sim 10^{3} \, M_\odot$. However, their model is 1D and it would be more difficult to disrupt gas if it were in optically thick clumps.
Tan & McKee (2001; 2004) used an idealized model to investigate feedback in a turbulent and clumpy medium. This structure was approximated by dividing the gas into cores and an intercore medium. The dynamics of the cores are affected by the potential of the overall protocluster and feedback effects from a stellar population at the cluster center, including radiation pressure, stellar winds and ionization, which can photo-evaporate cores. The main conclusion was that a clumpy, turbulent medium is much more capable of confining feedback, particularly ionizing feedback. HII regions are confined because they are continually injected with neutral cores that then suffer high photo-evaporation rates. This mass loading keeps the density and recombination rate relatively high. Such effects are likely to be important for Galactic ultra-compact (\(\lesssim 0.1\) pc) HII regions, whose long lifetimes have been a puzzle. Figure 1 shows the parameters of three models, A, B, and C. Model A formed a cluster that dispersed its gas in 2 Myr, while B and C took about 3 Myr. Estimates of the star formation efficiency are somewhat uncertain as protostellar outflows were omitted. Within the limitations of the model, the efficiencies were \(\sim 30\%\) for model A, and \(\sim 50\%\) for models B and C.

**Feedback on GMCs**

Once star clusters have formed, their feedback will impact the larger scale interstellar medium. In particular they may contribute to the destruction of GMCs. Williams & McKee (1997) considered the destruction of Galactic GMCs by photo-evaporation from ionizing photons from OB associations, finding destruction timescales of \(\sim 30\) Myr for the most massive clouds. Matzner (2002) estimated slightly shorter destruction timescales for the same feedback process. Monaco (2004) considered the effects of supernova feedback on clouds that have already been shaped by ionization.

Alternatively, Ballesteros-Paredes (2004) argued that GMCs are transient phenomena and that their disruption is simply due to dynamical processes. Clark & Bonnell (2004) modeled star formation in such transient GMCs.

Observationally, Leisawitz, Bash & Thaddeus (1989) found that open star clusters older than about \(\sim 10\) Myr were not associated with molecular clouds, which is consistent either with post-star-formation cloud lifetimes shorter than this age, i.e. only a couple of dynamical timescales, or with relative velocities of star clusters and their parent clouds of about \(10\) km s\(^{-1}\), which are to be expected from photoionization feedback (Williams & McKee 1997). The important question of GMC lifetimes remains open.

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