The Birth of High Mass Stars: 
Accretion and/or Mergers?

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ABSTRACT

The observational consequences of the merger scenario for massive star formation are explored and contrasted with the gradual accumulation of mass by accretion. In high density proto-star clusters, envelopes and disks provide a viscous medium which can dissipate the kinetic energy of passing stars, greatly enhancing the probability of capture. Protostellar mergers may produce high luminosity infrared flares lasting years to centuries followed by a luminosity decline on the Kelvin-Helmholtz time-scale of the merger product. Mergers may be surrounded by thick tori of expanding debris, impulsive wide-angle outflows, and shock induced maser and radio continuum emission. Collision products are expected to have fast stellar rotation and a large multiplicity fraction. Close encounters or mergers will produce circumstellar debris disks with an orientation that differs form that of a pre-existing disk. Thus, massive stars growing by a series of mergers may produce eruptive outflows with random orientations; the walls of the resulting outflow cavities may be observable as filaments of dense gas and dust pointing away from the massive star. The extremely rare merger of two
stars close to the upper-mass end of the IMF may be a possible pathway to hypernova generated gamma-ray bursters. In contrast with the violence of merging, the gradual growth of massive stars by accretion is likely to produce less infrared variability, relatively thin circumstellar accretion disks which maintain their orientation, and collimated bipolar outflows which are scaled-up versions of those produced by low-mass young stellar objects. While such accretional growth can lead to the formation of massive stars in isolation or in loose clusters, mergers can only occur in high-density cluster environments. It is proposed that the outflow emerging from the OMC1 core in the Orion molecular cloud was produced by a protostellar merger that released between $10^{48}$ to $10^{49}$ ergs less than a thousand years ago.

*Subject headings:* stars: formation – ISM:jets and outflows massive star formation: OMC1

1. Introduction

The birth of massive stars remains one of the outstanding problems in star formation (Stahler, Palla, & Ho, 2000; Larson 2003). Stars form from the gravitational collapse of turbulent molecular cloud cores (Elmegreen & Scalo 2004; Mac Low & Klessen 2004). There are two competing theories of massive star birth. The traditional view is that massive stars form in a quasi scaled-up version of low-mass star formation inside dense, turbulent, high-pressure hot-cores (Beech & Mitalas 1994; Bernasconi & Maeder 1996; Behrend & Maeder 2001; McKee & Tan 2002; Tan & McKee 2002; Yorke 2004). Alternatively, it has been suggested that massive stars form from the merging of lower mass protostars in high-density proto-star clusters (Bonnell, Bate, & Zinnecker 1998; Stahler et al. 2000; Bonnell 2002; Zinnecker & Bate 2002). In this paper, we explore observational approaches which may distinguish between the two formation scenarios.

There are several problems with the scaled-up version of the standard star formation scenario. Following the pioneering studies of Kahn (1974) and Yorke & Krügel (1977), Wolfire & Cassinelli (1986, 1987) argued that for a normal interstellar gas and dust mixture and stars more massive than about 10 to 20 $M_\odot$, radiation pressure may stop accretional growth. However, as the intense radiation field dissociates molecules, evaporates ice mantles, and sputters grains, the opacity of the accreting material can be greatly reduced. Nevertheless, radiation pressure tends to make accretion flows highly unstable and for the most luminous stars, even dust free envelopes can be blown away. Additionally, Lyman continuum radiation contributes to the reversal of inflow into outflow (Larson & Starrfield 1971). Some of these
difficulties can be circumvented by accretion from an envelope onto a circumstellar disk followed by accretion from the disk onto the star (Nakano et al. 1995; Jijina & Adams 1996, Yorke & Sonnhalter 2002; Yorke 2002). Furthermore, as shown by McKee & Tan (2002), accretion flows can overwhelm radiation pressure in high-density and high-pressure cloud cores. Nevertheless, observations indicate that many massive stars are born in clusters in which nearby objects can strongly alter the physical conditions from those expected for isolated star formation. Mutual interactions in such dense proto-clusters may be inevitable and merging may be an important process in some very dense star forming environments.

Predictions of the physical consequences of both accretion and merging are needed to establish a set of observational criteria that can discriminate between the models. While the behavior of stars forming by accretion are reasonably well understood, the consequences of merging have not been fully investigated. Therefore, in this paper, we explore possible consequences of protostellar merging sibling stars (Bonnell, Bate, Zinnecker 1998). In the next section (Section 2), the relevant physics of massive star formation is reviewed. In Section 3, plausible observable consequences are explored and we speculate that gamma-ray bursts may originate as a consequence of the merging of two massive stars in a tight binary system. In Section 4, the properties of the nearest massive star forming region, the OMC1 cloud core located behind the Orion nebula, are interpreted as the result of a recent merger.

2. High-Mass Star Formation Theories: Accretion vs. Mergers

In this section we review the salient features of the two competing high-mass star formation models relevant to observations designed to distinguish between them.

2.1. The Accretion Model

In the standard model of star formation, massive stars form in a manner similar to low-mass stars but with very high accretion rates (see reviews in Protostars & Planets IV, eds. Mannings, Boss, and Russell 2000). To assemble a \( \sim100 \, M_\odot \) star in \( 10^5 \) yr requires an average accretion rate of \( \dot{M} = 10^{-3} \, M_\odot \, yr^{-1} \). For an isothermal sphere with an \( r^{-2} \) radial density profile, the standard model of inside-out collapse predicts a mass accretion rate \( \dot{M} \sim \frac{c_s^2}{G} \) where \( c_s \) is the effective sound speed, and \( G \) is Newton’s gravitational constant (e.g. Hartmann 1998). An accretion rate \( \dot{M} = 10^{-3} \, M_\odot \, yr^{-1} \) requires \( c_s = 1.9 \, km \, s^{-1} \) which corresponds to a temperature of about 1,200 K for molecular gas (assuming a mean molecular weight of \( \mu = 2.7 \) since hydrogen is expected to be molecular). If a cloud core contains 100
M⊙ and collapses to form a massive star in $\tau = 10^5$ years, then the initial radius of the core must be about $R = 5 \times 10^{17}$ cm, its average $H_2$ density $n(H_2) = 3 \times 10^4$ cm$^{-3}$, the average pressure $P/k = 3 \times 10^8$ cm$^{-3}$ K, and its average column density $N(H_2) = R \times n(H_2) = 3 \times 10^{23}$ cm$^{-2}$ corresponding to about $A_V \sim 200$ magnitudes (Tan & McKee 2002; McKee & Tan 2002). Thus, growth by accretion requires very high pressure cores, large effective sound speeds, and high column densities.

It is possible that relatively isolated massive stars can be produced by radiation driven implosion (Klein, Sandford, & Whitaker 1983; Ho, Klein, & Haschick 1986). Several ultra-compact HII regions such as M17 UC1 are embedded in dense cores adjacent to ionization fronts that have partially enveloped them (e.g. Nielbock et al. 2001; Chini et al. 2000; Hanson, Howarth, & Conti 1997). The increased pressure generated by adjacent HII regions can compress the cloud core and trigger the large accretion rates needed to form a high-mass object (Bertoldi 1989; Kessel-Deynet & Burkert 2003). Such a scenario may be responsible for the large accretion disk recently found surrounding a massive protostar at the periphery of the HII region M17 (e.g. Chini et al. 2004).

A major difference between high- and low-mass star formation is that the pre-main sequence contraction time-scale is shorter than the accretion time-scale for $> 10$ M⊙. Thus, while low-mass stars always emerge from their natal cocoons as pre-main sequence objects, massive stars reach the zero-age main sequence and maturity while still embedded within their parent clouds, and while still accreting.

The effects of the forming star’s radiation pressure, abundant soft-UV, and ionizing Lyman continuum radiation must be included in models of its birth. For a normal interstellar gas and dust mixture, radiation pressure can reverse inflow and prevent growth for massive stars. However, as the intense radiation field dissociates molecules, evaporates ice mantles, and sputters grains, the opacity of the accreting material may be reduced greatly. Even with grain destruction, radiation pressure may halt the growth of massive stars by accretion for masses greater than 20 M⊙ (Wolfire & Cassinelli 1986, 1987). Tan & McKee (2002) and McKee & Tan (2002) argue that the high pressure of a collapsing massive cloud core can overwhelm the radiation pressure of a massive star forming at its center. For a star with a luminosity $L_* = 10^5$ L⊙, the radiation pressure is $P_{rad}/k = L_*/4\pi ckR^2 = 3 \times 10^7$ cm$^{-3}$ K, where R is the stellar radius, c is the speed of light, and k is Boltzmann’s constant. $P_{rad}$ is about an order of magnitude lower than the average pressure in the core discussed above. Therefore, the growth of an HII region can also stop accretion. But, Keto (2002) has shown that the gravity of the central star can confine an the HII region and bottle-up the destructive effects of Lyman continuum radiation field if its size is less than about $r_{II} = GM/c_{II}^2$ where $c_{II} \approx 10$ km s$^{-1}$ is the sound speed in the HII region. The ionized zone
surrounding a massive star can remain hyper-compact if there is a reservoir of gas with a density \( n(H) > (3L(\text{LyC})/4\pi a_B)^{1/2}r_{\text{II}}^{-3/2} \) within a distance \( r_{\text{II}} \) of the star. If an accretion flow or a circumstellar disk can provide this reservoir, the HII region can remain confined and the destructive effects of UV radiation can be mitigated. In a disk-confined HII region, some UV may escape and ionize gas at large distances orthogonal to the disk plane. However, an accretion flow in the disk plane can remain shielded. In rapidly rotating stars, the poles are hotter than the equator. Thus, most of the ionizing radiation is beamed towards the poles, reducing its destructive effects in the equatorial plane. Yorke & Sonnhalter (2002) modeled the formation of massive stars with the inclusion of these effects, demonstrating that direct accretion can produce stars up to 20 to 30 \( M_\odot \) by accretion from a disk. But, how do the most massive stars form?

Henning et al. (2000) found a correlation between outflow mass-loss rate from high mass sources with their source luminosity. As a possible interpretation of this correlation, Behrend & Maeder (2001) suggest that the accretion rate onto massive stars may increase with time, contrary to the observed behavior of isolated low-mass stars. This feature can be incorporated into the direct accretion picture of massive star birth in several ways. First, the accretion rate will tend to increase with time if the slope of the parent cloud core density profile is shallower than the \( r^{-2} \) density profile of an isothermal sphere. Second, as the mass of a star increases, its Bondi accretion radius grows so that the star can accumulate mass at an increased rate from a given density environment. This effect, known as “competitive accretion”, can lead to run-away growth of the most massive objects in a forming cluster (Zinnecker 1982; Bonnell et al. 2001a, b). Third, massive objects tend to settle into the center of a forming cluster where the density of gas, and hence the accretion rate, is higher. However, Beuther et al. (2002) find evidence for steady outflow rates and argue that massive stars may indeed form via a scaled-up version of low mass star formation.

2.2. Mergers

Why consider alternative models for massive star birth? First, observations demonstrate that massive stars tend to form in clusters rather than in isolation (e.g. Lada & Lada 2003; De Wit et al. 2004). The central densities of young clusters sometimes exceed \( 10^5 \) stars per cubic parsec (e.g. the Trapezium cluster in Orion – Henney & Arthur 1998; IRS5 in W3 – Claussen et al. 1994). In such dense environments, perturbations by and interactions with sibling stars must be considered. Second, young OB associations and clusters expand and 5 to 30% of their members are ejected as high velocity stars (Gies 1987; Stone 1991; Kroupa 1995; Hoogerwerf, de Bruijne, & de Zeeuw 2000). Third, some outflows from very massive
stars are poorly collimated (e.g. OMC1 in Orion; McCaughrean & Mac Low 1997; Kaifu et al. 2000) and look like the result of an explosion (Allen & Burton 1993). Other outflows from massive proto-stars show evidence of abrupt flow-axis reorientation (e.g. IRAS 20126+4104 - Shepherd et al. 2000). Fourth, massive stars have a larger binary companion frequency (Mermilliod & García 2001; Zinnecker & Bate 2002) and faster rotation rates than low-mass stars. As discussed below, these trends can be interpreted as evidence that interactions with sibling stars may play important roles in the formation of some massive stars. Models of galactic collisions (e.g. Toomre & Toomre 1972) and interactions between stars and protostars (e.g. Soker et al. 1987; Benz & Hills 1992; Clarke & Pringle 1993; Hall, Clarke, & Pringle 1996; Larwood 1997; Boffin et al. 1998; Watkins et al. 1998a, b; Portegies Zwart et al. 1999; 2002; Lombardi et al. 2003) provide insights into the relevant physics of such interactions.

Bonnell, Bate, & Zinnecker (1998) proposed that massive stars form by a combination of competitive accretion and merging in forming star clusters. For star–star collisions to occur at a significant rate, a cluster requires a number density of about $10^8$ stars pc$^{-3}$ for low-mass stars. However, for 10 M$_\odot$ stars with a velocity dispersion of 5 to 10 km s$^{-1}$, merging may occur at densities as low as $10^6$ stars pc$^{-3}$. Though such high densities are not found in any observed star cluster, Bonnell et al. (1998) and Stahler et al. (2000) argue such extreme conditions may exist for a brief period of time during the highly embedded and obscured gravitational collapse and fragmentation phase of cluster forming cloud cores. As discussed next, gravitational focusing and dissipation by circumstellar matter can greatly enhance the merger rate in forming clusters, lowering the required density of stars during such a phase (e.g. Bally 2002; Bonnell 2002, Zinnecker & Bate 2002).

### 2.2.1. Gravitational Focusing

The cross-section for interactions among stars can be orders of magnitude larger than the projected area of a star because the typical velocity dispersion in young clusters is much smaller than the escape speed from a typical stellar surface. Consider a star of mass $m$ approaching a star with mass $M$ at a relative velocity $v$ (which at large separation is roughly given by the cluster velocity dispersion). The relative velocity at periastron is given by

$$v_p^2 = v^2 + \frac{2G(m + M)}{r_p}$$

where $r_p$ is the periastron separation. From the conservation of specific angular momentum it follows that $bv_{clus} = r_p v_p$ where $b$ is the impact parameter. When the separation between the centers-of-mass of the stars at perihelion is less than the sum of the stellar radii, the interaction results in a collision that may lead to the formation of a binary or possibly to a
merger. The cross-section for a grazing collision is given by

\[
\sigma_f = \pi r_f^2 = \pi (r_m + r_M)^2 \left[ 1 + \frac{2G(m + M)}{(r_m + r_M)v_0^2} \right] \approx \pi (r_m + r_M)^2 \left[ 1 + \frac{v_{esc}^2}{4v_{clus}^2} \right]
\]

where the subscript \( f \) refers to gravitational focusing, \( r_m \) and \( r_M \) are the radii of the stars, \( v_{esc} = \frac{2G(m + M)}{(r_m + r_M)} \) is the gravitational escape speed from the combined mass at periastron separation, and \( v_0 \approx 2v_{clus} \) is the relative speed of the two stars. Thus, gravitational focusing increases the collision cross-section by roughly a factor \( f_G = (1 + \frac{v_{esc}^2}{4v_{clus}^2}) \approx (\frac{v_{esc}}{2v_{clus}})^2 \). For the Orion Nebula cluster, \( v_{clus} \approx 1.5 \text{ km s}^{-1} \) (van Altena et al. 1988). Using \( v_{esc} \approx 300 \text{ km s}^{-1} \) corresponding to a slightly bloated pre-main-sequence star, gravitational focusing enhances interaction cross-sections by about a factor of \( 10^4 \).

### 2.2.2. Disk-Assisted Protostellar Capture

Massive circumstellar disks and/or envelopes can increase the cross-section for stellar capture by additional orders of magnitude. Disk mediated interactions were considered as a possible binary formation mechanism by Clarke & Pringle (1991; 1993), and Heller (1995). These authors considered collision partners having similar masses and concluded that such interactions can at most account for a small fraction of the observed binary star population in young clusters. The youngest clusters are much denser than those considered by Clarke and Pringle and often contain large amounts of interstellar and circumstellar gas. A careful re-assessment of the role of encounters during the embedded phases of young clusters is warranted.

Numerical modeling of close encounters indicates that disks are disrupted and truncated to a new outer radius equal to roughly 1/2 or 1/3 of the periastron separation (Clarke & Pringle 1993; Hall, Clarke, & Pringle 1996; Heller 1995; Larwood 1997; Hall et al. 1998; Watkins et al. 1998a,b; Boffin et al. 1998). The ejected portion of the disk can absorb the incoming star’s kinetic energy and facilitate the formation of a binary. A star of mass \( m \) can be captured by another star with mass \( M \) that is orbited by a disk with mass \( M_d \) if the two stars approach each other within roughly a disk radius and the disk has enough mass to lower the impactor’s velocity to below escape speed (Clarke & Pringle 1991). This condition is satisfied if the (negative) binding energy of the disk is larger than the excess kinetic energy (i.e. at infinite separation) of the impactor star. That is,

\[
\frac{1}{2}mv_m^2 < \frac{GM_dM}{r_d}
\]

where \( v_m \) is the velocity (at large separation) of the star with mass \( m \) with respect to star \( M \) (\( v_m \approx v_{clus} \), the cluster velocity dispersion) and \( r_d \) is the effective half-mass radius of the
disk (the radius at which a point mass with mass $M_d$ has the same gravitational potential energy as the disk). Thus, circumstellar matter-assisted capture is possible if the encounter velocity (at large separation) is

$$v_m < \left( \frac{2GM}{r_d} \right)^{1/2} \left( \frac{M_d}{m} \right)^{1/2} = v_{\text{esc}}(r_d) \left( \frac{M_d}{m} \right)^{1/2}$$

and periastron passage brings the impactor to within the half-mass radius of the disk. Thus a $M = 10 \, M_\odot$ star surrounded by a $M_d = 0.1 \, M_\odot$ disk (1% of the mass of its central star) having a radius $r_d = 10 \, \text{AU}$ can capture a star with a mass $m = 1 \, M_\odot$ if the relative velocity is less than about $6 \, \text{km s}^{-1}$ and the stars pass within about a disk radius. Because for typical parameters, $r_f \sim 1 \, \text{AU}$, direct collisions are much less likely than disk-mediated interactions which can occur for impact parameters as large as $100 \, \text{AU}$.

Numerical models (e.g. Pfalzner 2003) demonstrate that interactions excite strong spiral density waves and tidal tails which can efficiently transfer angular momentum and mass through the disk. Some of the disk mass is ejected from the system and some is accreted onto the central star. The impactor can also steal a portion of the impacted disk mass.

Disk-assisted capture of an intruder usually results in the formation of an eccentric binary. The initial orbit of the captured star tends to shrink somewhat as the outer parts of the disk are ejected. However, once the interaction truncates the disk(s) to an outer radius smaller than the separation of the stars during periastron passage, orbital decay stops (Moeckel & Bally 2005).

In a dense cluster forming environment, two processes may lead to further orbit evolution; ongoing accretion from the surrounding envelope, and an interaction with another star (Bate, Bonnell, & Bromm 2002; Bonnell, Bate, & Vine 2003; Moeckel & Bally 2005). Accretion adds mass to the system and therefore leads to orbital decay. The resulting decrease in periastron separation can lead to further dissipative interaction with remnant disks and hardening of the binary. Interaction with a second intruder star can re-configure the binary and sometimes may lead to a merger. Three-body encounters leading to mergers were observed in the simulations of Bonnell & Bate (2002). Numerical simulations are needed to identify the parameters which lead to mergers or captured binary companions. In the rest of this paper, we restrict our attention to those encounters which do lead to merging.

### 2.2.3. Merger Types

In most models of star formation, the gravitational collapse of a pre-stellar cloud core leads to the formation of a magnetically or rotationally supported disk; outward angular
momentum transport in the disk then drives accretion onto a central protostar. Thus, there are three different types of entity in star formation; cores, disks, and (proto)stars. To form a star cluster, a portion of a giant molecular cloud must fragment before or during its collapse phase. Since the resulting cores may collapse at different times and evolve at different rates, a forming cluster is expected to consist of a mixture of cores, disks, and protostars (e.g. Klessen 2001; Bate et al. 2003; Schmeja, Klessen, & Froebrich 2005).

In principle, six types of mutual interactions are possible among these three entities. The top row of Figure 1 shows the interactions that involve cores. Since cores are diffuse, mutual interactions between these objects will be relatively low-energy events. Nevertheless, a massive star, with or without its own circumstellar disk, can potentially gain additional mass by merging with a passing core. However, the addition of more mass to the envelope of a massive star does little to overcome potential problems with radiation pressure and ionization. High velocity collisions with cores can strip a protostar of its own core or disk, bringing accretional growth to a halt (Price & Podsiadlowski 1995). These events are likely to have considerably less spectacular consequences than disk-disk, disk-star, or star-star interactions. Star-star collisions (bottom row in Figure 1) are likely to be very energetic, but are the least likely in the star formation environment. Interactions between young stars surrounded by circumstellar disks (middle row in Figure 1) are likely to be the most interesting interactions in nascent clusters. A massive protostar is most likely to have an encounter with the most common type of object in such a forming cluster – a low-mass star, disk, or core. However, in a mass-segregated cluster, the most common type of encounter may be a massive protostar with another massive or intermediate mass star.

### 2.3. Merger Energetics

The energy released by a merger of a low-mass object of mass $m$ with a more massive object having mass $M$ is $E = \eta G m M / R$ where $R$ is radius of the collision product and $\eta$ is a factor of order unity that takes into account details of the density distributions of the stars and the additional mass of circumstellar material. For $M = M_{10} = 10 \, M_\odot$, $m = m_1 = 1 \, M_\odot$, and $R = 10^{12} \, $ cm, we find $E = 2.5 \times 10^{48} \eta$ ergs. The range of energies can cover more than 6 orders of magnitude; while the merger of two 0.1 $M_\odot$ dwarf protostars produces only $3 \times 10^{45}$ ergs, the much rarer merger of two 100 $M_\odot$ stars would release more than $10^{51}$ ergs. The estimated energies of observed protostellar outflows lie within the range produced by mergers.

The most probable encounters have large impact parameters and therefore have high angular momenta. Such interactions can efficiently convert impactor kinetic energy into
rotational energy. As discussed below, some of this spin energy can be carried away by the ejection of the outer disk and some can be carried away by an outflow emerging along the axis of the system.

### 2.3.1. The Merger Luminosity

Most of the gravitational potential energy is released when the stars merge and the peak energy release rate can reach values as high as

\[
L \approx \frac{(GM)^{3/2} m / 2\pi R^{5/2}}{1.2 \times 10^{9} m_{10} M_{10}^{3/2} R_{12}^{-5/2}} \text{ L}_{\odot}
\]

where \( R \) is the orbital radius just before merging (comparable to the radius of the collision product) and \( R_{12} \) is in units of \( 10^{12} \text{ cm} \).

The released gravitational potential energy is deposited in the merger product and surrounding debris. The luminosity of the merger product will be limited by the radiative time-scale which can be estimated from

\[
L_{\text{max}} \approx G\eta m \frac{\tau_{c} R}{\tau_{4}} = 2.1 \times 10^{3} m_{10} M_{10} \tau_{4}^{-1} R_{12}^{-1} \text{ (L}_{\odot})
\]

(for \( \eta = 1 \)) where \( \tau_{c} \) is the radiative cooling time of the debris cloud surrounding the merger product and \( \tau_{4} \) is this cooling time in units of \( 10^{4} \text{ years} \). Though \( \tau_{c} \) is likely to be a complex function of the debris geometry and the stellar masses involved, it can be estimated in several ways.

The radiative cooling time of the collision product is likely to be comparable to its Kelvin-Helmholtz time given by \( \tau_{K-H} \approx GM^{2}/RL \). Using the main-sequence mass-luminosity relationship, \( L \propto M^{3.3} \), and mass-radius relationship, \( R \propto M^{2/3} \) implies that the Kelvin-Helmholtz time scales as \( \tau_{K-H} \approx 1.1 \times 10^{5} M_{10}^{-2} \text{ years} \) where \( M_{10} \) is the mass of the product in units of \( 10 \text{ M}_{\odot} \).

However, immediately after its formation, the merger product is likely to have a photospheric radius considerably larger than a main-sequence star with the same mass. Numerical models of stellar collisions leading to the formation of blue stragglers in globular clusters (Lombardi et al. 2002, 2003; Fregeau et al. 2004) indicate that merger products have radii up to 30 times larger than an equivalent main sequence star. Thus, \( \tau_{K-H} \) for a merger product is likely to be shorter than the above estimate for a main sequence star by at least one order of magnitude. Thus \( \tau_{c} \) may be in the range \( 3 \times 10^{3} \) to \( 5 \times 10^{4} \text{ years} \) for a \( 10 \text{ M}_{\odot} \) product and less than 100 years for a \( 100 \text{ M}_{\odot} \) product.

The cooling time can also be estimated from the time required for photons to diffuse from the merger product and its surrounding debris field. The diffusion time-scale \( \tau_{\text{diff}} = (l/c)N \) where \( l \) is the photon mean free path, \( c \) is the speed of light, and \( N \approx (R/l)^2 \) is the
number of scatterings the photon experiences during its random-walk to the surface. Thus, \( \tau_{\text{diff}} \approx \kappa M/cR \) where \( \kappa \) is the opacity per unit mass, \( M \) is the mass of the merger product or its debris field, and \( R \) is the size-scale.

The merger product is likely to be surrounded by a debris field that has been shock heated by the merger. This material will have an even shorter cooling time because it will be spread over a region larger than the product. Additionally, debris will tend to be confined to a flattened structure preferentially lying in the encounter plane. Thus, there may be two distinct radiative cooling time-scales for a merger product. The shorter time-scale associated with the larger but less massive debris field, and a longer time-scale for the merger product. While a 10 M\( \odot \) collision product may relax in \( 10^4 \) to \( 10^5 \) years, a 100 M\( \odot \) remnant may relax in less than \( 10^3 \) years leading to the peak emergent luminosities ranging from \( 10^4 \) to nearly \( 10^7 \) L\( \odot \).

Mergers are most likely to occur during the short-lived, high-density, embedded phase of a forming cluster. Thus, most of the emergent radiation is likely to be obscured and re-processed to far-infrared or longer wavelengths by the surrounding medium.

2.3.2. Ionizing Radiation

Stars more massive than about 15 M\( \odot \) contract to the main-sequence faster than they can accrete their mass in most models (e.g. Yorke 2003). Thus, accreting or merging stars more massive than this can be treated as main-sequence objects with a well determined Lyman continuum luminosity. Their H\( \text{II} \) regions can be confined by gravity when the density of the surrounding medium is sufficiently large and the radius of the ionized zone is sufficiently small to make the escape speed from this radius larger than the sound speed in photo-ionized plasma. The radius, \( r_g \), at which the escape speed from a star of mass \( M \) is given by the sound speed, \( c_{\text{II}} \), is given by \( r_g = GM/c_{\text{II}}^2 \). Combining this with the Stromgren radius of an H\( \text{II} \) region, given by \( r_S = (3L(LyC)/4\pi\alpha_Bn_e^2)^{1/3} \), where \( L(LyC) \) is the Lyman continuum luminosity of the ionizing star, \( \alpha_B \) is the case-B recombination coefficient, and \( n_e \) is the electron density, gives the critical density above which the gravitational field of the star can confine the plasma. That is, a uniform density H\( \text{II} \) region may be bound by the gravity of the UV-emitting star if \( n_e > (3L(LyC)/4\pi\alpha_B)^{1/2}(GM)^{-3/2}c_{\text{II}}^3 \) (e.g. Keto 2002). Thus, a 10 M\( \odot \) star with \( L(LyC) = 10^{45} \) photons s\(^{-1} \) has a gravitational radius, \( r_g = 90 \) AU and a critical density \( n_e = 6 \times 10^5 \) cm\(^{-3} \) above which the H\( \text{II} \) region will be confined by gravity. The corresponding numbers for a 100 M\( \odot \) star with \( L(LyC) = 10^{50} \) photons s\(^{-1} \) are \( r_g = 900 \) AU and \( n_e = 6 \times 10^6 \) cm\(^{-3} \).
If a core or disk with a much higher density than this critical density penetrates to a distance $d$ of a massive star, the characteristic radius of the resulting HII region will become comparable to $d$. The density of the photo-ionized plasma can be estimated from photo-ionization equilibrium since to first order, recombinations in a layer of thickness comparable to $d$ must consume the incident flux of Lyman continuum photons. The density of the photo-ionized plasma between the massive star and the dense intruding body will adjust itself to satisfy the Stromgren criterion, $n_e \approx (3L(LyC)/4\pi a_B)^{1/2}d^{-3/2}$. This plasma will be confined by gravity when $d < r_g$. Thus, the collision of a massive star with an ultra-dense cloud core fragment or a lower-mass star surrounded by a dense disk may result in a gravitationally confined hyper-compact HII region which can smother the star’s Lyman continuum radiation field.

2.4. Merger Evolution

Detailed consideration of the merger process will require numerical modeling in which the hydrodynamics, effects of gravity, magnetic fields, and radiation are considered carefully. Here, we break the problem into sub-processes and speculate about the likely behavior of the system. If a merger does occur, there are likely to be three distinct phases; an in-spiral phase following the initial encounter during which the system evolves toward a more compact configuration, the merger itself during which the bulk of the gravitational potential energy is released, and the post-merger outflow phase during which some circumstellar matter is ejected by this energy and the collision product settles into a new configuration.

2.4.1. Inspiral

Though the most common star in a typical star forming region is likely to be a low-mass dwarf, such objects are not likely to be the most common partners in merger. Low mass objects have small gravitational radii and thus interact effectively only with a small part of the disk or envelope surrounding a massive collision partner. Additionally, mass segregation and competitive accretion in a dense cluster-forming cloud core are likely to lead to a relatively large median mass in the region where mergers are possible. Thus, the most common interactions leading to a merger are likely to involve relatively massive stars. The most massive stars in the densest proto-clusters may experience multiple merging events.

A typical merger is expected to start with the dissipative passage of a star through the outer parts of a massive star’s circumstellar disk. The order of magnitude of the density and
column density of the circumstellar debris field can be estimated by assuming that an initial
disk with a mass $M_d = 0.1 \, M_\odot$ is ejected into a spherical volume. If ejected with a speed
characterized by a fraction of the orbital speed at the impactor periastron distance – say 10
to 20 km/s corresponding to one quarter to one half of the Kepler speed at 10 AU from a
20 $M_\odot$ star, the outer edge of the debris field would reach a radius of 1000 AU in 200 – 400
years. At an outer radius of 1000 AU, the volume-averaged density of the debris produced
by the disruption of a 0.1 $M_\odot$ disk is $n(H_2) \sim 2 \times 10^6 \, \text{cm}^{-3}$, and its column density is order
$N(H_2) \sim 5 \times 10^{22} \, \text{cm}^{-2}$. The density distribution will probably be very inhomogeneous.
The encounter may form an eccentric binary in which one or both stars are surrounded by
truncated disks.

Merging requires orbital decay. As discussed above, accretion from a surrounding cloud
adds mass to the system, shrinks the orbits of binary companions, and forces further dis-
sipative interactions with circumstellar material. The resulting disk perturbations during
periastron can increase accretion form the disk onto its central star, temporarily increasing
its luminosity. In high density proto-clusters, interactions of single (or binary) stars with
binary systems can also also lead to merging (Bonnell & Bate 2002).

2.4.2. Merging

The actual merger is likely to be a very short-lived event with a duration comparable
to the orbital time-scale at the tidal radius. Stellar collisions have been modeled by several
groups (e.g. Lombardi et al. 2003; Freitag & Benz 2004). The merger parameters are likely
to be similar to the case of the collision between two main sequence stars at a high impact
parameter where the velocity-at-infinity is small compared to the escape speed from the
stellar surface (e.g. Figures 23 and 24 in Freitag & Benz, 2004). Most of the energy of a
merger is released during this short phase. While the collision product will cool and relax
to a new main-sequence configuration on a Kelvin-Helmholtz time-scale as discussed above,
the energy injected into the surrounding circumstellar debris can emerge on a much shorter
time-scale, especially if this debris has a roughly disk-like geometry.

Most of the merger energy is likely to be radiated by the outer surface of the merger
envelope at infrared and sub-mm wavelengths. The observable luminosity peak is likely to
last for an envelope cooling time which can range from years for small envelopes to centuries
or more for massive envelopes. There may be additional reprocessing of this radiation by
dense gas and dust surrounding the collision product.
2.4.3. Outflow

Observations show that accretion tends to be accompanied by outflow, typically with a speed comparable to the gravitational escape speed from the launch region (for reviews, see Reipurth & Bally 2001; Königl & Pudritz 2000; Shu et al. 2000). Thus, the rapid release of gravitational potential energy by a merger is likely to drive a powerful outflow into the surrounding medium. The acceleration of such a flow must involve radiation fields and/or magnetic fields.

If outflow of mass $M_{\text{out}}$ were to be accelerated only by mechanical means, energy conservation implies that that the outflow kinetic energy at infinity $E_{\text{out}}$ must be less than the potential energy released by the mass accreted, or $E_{\text{out}} < GM(m - M_{\text{out}})/R$. Thus, the kinetic energy of an outflow powered only by mass motion can at most be $E_{\text{KE}} = 0.5mv_{\text{clus}}^2 \approx 10^{45}m_1v_{10}^2$ erg.

The energy produced by a merger may be transported by radiation or magnetic fields from where it is released deep in the potential well of the collision product to material at larger distances. In this case, a significant fraction of the gravitational binding energy released by mass accretion onto the collision product can be coupled to matter far away where it does not need to climb out of the gravitational potential well.

The high luminosities of mergers involving at least one massive star, combined with the large opacity of circumstellar debris, are likely to make radiation effects an important ingredient for merger induced outflow acceleration. Assuming that a typical debris disk surrounding a collision product contains $1 \, M_\odot$ and is 100 AU in radius, its (spherical) average column density as seen from its center is $N(H_2) > 5 \times 10^{25}$ cm$^{-2}$ and $n(H_2) \approx 3 \times 10^{10}$ cm$^{-3}$. Thus the circumstellar environment of the collision product will be opaque in most directions.

An absorbing layer with a column density of order $10^{21}$ cm$^{-2}$ at the inner edge of this envelope will be compressed and accelerated by the radiation field. The accelerated layer will slam into gas in the envelope, driving a shock wave away from the collision product. The radial velocity of this layer can be estimated from the balance between radiation pressure and the ram pressure of the advancing shock along each radial direction from the merger product. If the pre-shock mass density along each radial direction at a distance $r$ from the merger remnant is $\rho(r)$, the radiatively accelerated shell along that direction will have a velocity

$$v_{\text{shell}}(r) = \left[ \frac{L}{4\pi c \rho(r)} \right]^{1/2} \frac{1}{r} \approx 32.5 \left[ \frac{L}{10^5 L_\odot} \right]^{1/2} \left[ \frac{n(H_2)}{10^7 \text{cm}^{-3}} \right]^{-1/2} \left[ \frac{r}{100 \text{AU}} \right]^{-1} \text{ (km/s)}$$

This debris is likely to be flattened with a higher density in its equatorial plane than along its poles. Thus, the radiatively driven shell may develop into a roughly bipolar pattern. In
the dense disk, the radiatively driven layer will stall with a speeds of less than $1 \text{ km s}^{-1}$. However for a merger product luminosity of $L > 10^5 \text{ L}_\odot$, a density less than $10^7 \text{ cm}^{-3}$, and a radius of 100 AU, the shell speed will be greater than 30 km s$^{-1}$. The radiatively accelerated shell will have a mass $M_{\text{shell}} \approx 4\pi r^2 \mu m_H N_{21} \sim 6 \times 10^{-5} r_{100}^2 M_\odot$ where $r_{100}$ is the shell radius in units of 100 AU. Thus, a high-luminosity pulse of radiation may produce an impulsive bipolar outflow.

The shocks driven into circumstellar debris will produce high-density compressed layers and possibly the products of “hot core” chemistry such as H$_2$O and SiO in the shock-heated gas. Infrared radiation from grains heated by shocks or the radiation field of the collision product may also excite maser emission.

Magnetic acceleration of an outflow is likely to be considerably more efficient than radiative acceleration. Massive star forming molecular cloud cores are thought to be threaded by relatively strong magnetic fields in excess of 100 $\mu$G (e.g. Lai et al 2003). UV radiation from stars and shocks likely provide the minimum level of ionization required to couple these fields strongly to the entangled medium. Fields threading the individual circumstellar environments of merging protostars are likely to be entrained and amplified by differential rotation and turbulent dynamo action during a merger. Expansion of the debris disk during the late phases of a merger may stretch entrained magnetic fields. Thus, it is reasonable to expect that strong magnetic fields thread the debris surrounding a collision product. Magnetic fields may convert a significant portion of the merger-released gravitational potential energy into the kinetic energy of an outflow by either the transient acceleration modes proposed by Uchida & Shibata (1983; 1985), or the steadier disk-wind solutions of Pudritz & Norman (1983).

If the outflow is predominantly accelerated by the magneto-centrifugal mechanism, it likely to start during the early phases of inspiral. As the magnetic field gets increasingly wrapped-up and the impactor spirals closer to the more massive star, the launch point will migrate deeper into the gravitational potential well of the system. Under the assumption that the flow terminal velocity is proportional to the escape speed from the wind launch point, the speed of the ejecta is likely to increase as the stars spiral towards each other, reaching a maximum value as the merger completes. Thus, an eruptive, wide-angle outflow, with increasing mass loss rate and speed that peak immediately after the merger is expected. As faster ejecta overtakes slower moving debris launched earlier during the inspiral phase, Rayleigh-Taylor instabilities are likely to develop (Stone, Xu, & Lee 1995; McCaughrean & Mac Low 1997). Such instabilities may produce the multiple fingers of high-velocity shock-excited H$_2$ and [Fe II] emission observed in Orion’s OMC1 outflow (see below).

As the collision product relaxes, both stellar luminosity and outflow activity are expected
to decline. Thus, merger-generated outflows may be impulsive when compared to the typical ages of protostellar outflows from low to intermediate mass stars which range from $10^4$ to over $10^5$ years. When observed just after the merger event, merger generated outflows may resemble explosions. After the eruption, but before the outflow has suffered significant deceleration by the surrounding medium, the ejecta may be characterized by a Hubble law with $v \propto d$.

### 2.4.4. Disk Regeneration

Two distinct mechanisms can lead to the re-formation of a circumstellar disk following a merger. First, as the merging stars approach within their tidal radii, the lower mass pre-main-sequence star will be tidally sheared (see the simulations shown in Zinnecker & Bate 2002). The resulting debris will form a torus surrounding the collision product. Merging of the two stars requires that orbital angular momentum be carried away. Angular momentum can be transferred from the merging stellar cores to the outer portion of the debris surrounding the merger by gravitational torques. Thus, as the stars spiral into each other, the outer edge of the surrounding debris disk must expand to larger radii. Some of this material may survive in orbit around the collision product as a disk and may serve as the dissipative medium for subsequent encounters. Second, if the merger occurs inside a dense cloud core, continued infall may re-build a new post-merger accretion disk at a rate roughly given by $\dot{M} \sim c^3/G$ where $c$ is the sound speed in the core. Disk regeneration by either or both mechanisms leads to the development of a dissipative circumstellar medium that sets the stage for additional mergers with any additional stars or binaries that wonder too close to the collision product.

The toroidal debris disk will partially collimate the outflow emerging from the center into a roughly bipolar pattern. Debris expanding into the plane defined by the in-spiral orbit is likely to encounter the densest material and suffer the greatest deceleration, while debris launched along the axis of the system will encounter the least resistance. The entire debris disk is likely to expand radially due to the combined effects of dynamical heating, radiation pressure, and the impact of fast ejecta from the core.

### 3. Observable Consequences

Protostellar merging events have several observable consequences resulting from the release of gravitational potential energy and the nature of the environment. The energy released emerges in one of three forms; radiation, kinetic energy of an expanding high velocity
outflow ejected mostly in the polar direction, and an expanding lower velocity equatorial torus or debris disk. Mergers are most probable in ultra-dense proto-clusters and are likely to be highly obscured.

3.1. Infrared Flares

Heating of remnant circumstellar disks during the capture and subsequent inspiral phases and the terminal merging event are expected to produce luminous flares in the thermal-infrared to sub-mm wavelength region that last an envelope cooling time which may range from years to millenia. This prompt emission may be followed by a slower decline in luminosity as the collision product relaxes on a Kelvin-Helmholtz time-scale and its radiation is reprocessed by the circumstellar medium. These considerations suggest that massive stars produced by merging may exhibit infrared light curves similar to FU Ori type outbursts experienced by low-mass young stars. An abrupt increase in luminosity, perhaps preceded by a series of lower amplitude events triggered by pre-merger periastron passages, will be followed by first a rapid decline with a time-scale given by the envelope cooling time, followed by a much longer decline to the collision product main-sequence luminosity on a Kelvin-Helmholtz time-scale.

Infrared flares should be most common in the densest cluster-forming regions in ultra-dense environments near galactic nuclei, in recently merged galaxies supporting high rates of star formation, and in regions producing super star clusters. Monitoring of the 5 µm to 1 mm wavelength fluxes produced by massive star forming regions in the Milky Way over several decades may provide one test of the merging hypothesis. The event rate for infrared flares ought to be comparable to the formation rate of massive stars by this channel. As discussed above, the merging of two 100 M⊙ protostars can release over 10^{51} ergs, comparable to a supernova explosion. If radiated on a 10^3 year time-scale, this results in a flare with a luminosity larger than 10^7 L⊙. However, such high luminosity events will be very rare compared to the lower luminosity events.

The rate of merger-produced flares should be proportional to the merger rate. If merging is an important pathway to the formation of massive stars, then it is expected that some high luminosity IRAS sources in our galaxy have brightened or faded since the IRAS observations were made. Monitoring of starburst regions in nearby galaxies such as M82 or NGC 253 may also reveal a class of time-variable infrared sources. Merger induced flares might be distinguished from other types of stellar variability by their high luminosity, long decay time, and absence of expanding supernova remnants. Mergers should be highly confined point sources. Therefore, they would be best studied with large aperture telescopes such as
the James Webb Space Telescope or with future 30–100 meter class ground based facilities equipped with advanced AO systems.

In summary, mergers are expected to generate high luminosity infrared flares at a rate comparable to the birth rate of massive stars by this mechanism. Such flares may have rapid rise times, followed by a relatively prompt decay lasting years to decades, followed by slow decline to the main-sequence luminosity of the collision product on a Kelvin-Helmholtz time-scale.

### 3.2. Impulsive Wide-Angle Outflows

If 10% of the energy released by the merger of a 1M$_\odot$ star with a 20 M$_\odot$ star to form a merger product with a radius of $10^{12}$ cm is converted into bulk kinetic energy of motion of 1 M$_\odot$ of the surrounding medium, this medium can be accelerated to a terminal velocity of about 200 km s$^{-1}$. Outflows along the merger axis and merger plane are likely to behave quite differently. The portion of the outflow that erupts orthogonal to the dense debris in the merger plane will experience less resistance and is likely to be partially collimated by the debris disk. If so, collimation is likely to be very poor and defined mostly by the geometry of the torus. Each lobe of such a mechanically collimated bipolar outflow (as opposed to magnetically confined flows) is likely to subtend an opening angle of about a radian or more. As the collision product relaxes, the merger-generated luminosity and outflow activity will decline. Thus, merger-generated outflows are expected to be dominated by the energy release occurring on a time-scale very short compared to the time required to form a star; such flows will resemble explosions.

In summary, merger generated bipolar outflows are expected to be impulsive and poorly collimated. The flow velocity is expected to increase as the merger progresses, perhaps triggering the formation of instabilities in the ejecta.

### 3.3. Expanding Thick Disks

A portion of the outflow energy will be coupled to the circum-merger torus. The above energy estimates for the merger of 1 and 20 M$_\odot$ protostars indicate that much of a 1 to 10 M$_\odot$ torus can be accelerated away from the collision product to well above escape speed. For example, if the thick torus intercepts 10% of the total outflow energy (corresponding to 1% of the energy released by the merger) of a 1 M$_\odot$ object merging with a 20 M$_\odot$ star, a 10 M$_\odot$ torus can be accelerated to about 20 km s$^{-1}$. The result would be an expanding field of
relatively low velocity debris in the merger plane.

Shocks driven into the circum-merger torus will produce very high-density shock- and infrared-heated layers having conditions ideal for the excitation of maser emission. The resulting maser spots should trace the expansion of the inner disk away from the forming massive star. Thus, the debris disk and outflows produced by mergers may be sites of expanding clusters of OH, H$_2$O, SiO, and methanol masers. Orbital motion may shear these layers into arcs centered around the central collision product. These shocks may produce arcs-of maser emission such as those observed in Cepheus A (Torrelles et. al. 2001a,b).

In summary, post-merger disks are expected to be dynamically heated thick tori which may exhibit large expanding motions and contain shocks which may be detectable as expanding arcs of maser spots.

3.4. Uncorrelated Orientation of Multiple Eruptions

Massive stars formed by a sequence of mergers with several lower mass stars may produce multiple widely-separated (in time) explosions of outflow activity with randomly oriented tori and outflow axes. Thus, the outflow axis of a merger-grown massive star should meander chaotically over time. Multiple uncorrelated (in orientation) outflow episodes may leave behind outflow cavities whose walls consist of filaments of dense gas pointing away from the collision product. In OMC1, dozens of low-velocity NH$_3$ and dust filaments point radially away from the cloud core, perhaps tracing the walls of cavities left behind by successive periods of outflow activity (e.g. Wiseman & Ho 1998; Johnstone & Bally 1999).

In summary, the formation of the most massive stars by protostellar mergers may involve multiple merging events. The orientations of the eruptive outflows and expanding tori will exhibit a random walk in orientation.

3.5. Decaying Compact Radio Continuum Sources

The hot plasma generated by a protostellar merger may produce a short-lived ultra-compact HII region which decays on the time-scale of the event. Though the central portion of such a source will be sufficiently dense to be optically thick at all radio frequencies, plasma that escapes orthogonal to the debris disk, or which is entrained by the MHD outflow may become optically thin at high frequencies.

The combination of magnetic fields and strong shocks may lead to in-situ particle accel-
eration. Thus mergers may also excite some non-thermal radio emission. Some time-variable radio sources observed in nearby galactic nuclear starbursts such as M82 and NGC 253 (Kronberg et al. 2000) may be powered by proto-stellar mergers. If a large fraction of massive stars form from mergers, the merging rate could be comparable to the SN rate. The high-mass star formation rate in the nucleus of M82 appears to be about 1 $M_\odot$ $yr^{-1}$, leading to a supernova rate of about 1 every 10 to 30 years, consistent with the number and decay rates of the observed time variable-radio sources. It is also possible that fast shocks in the circumstellar environment of a merger may produce some X-ray emission. However, the expected large column density of this environment is should absorb most of this radiation. Hard, penetrating radiation may however contribute to partial ionization of the medium which may lock associated magnetic fields to the medium.

In summary, protostellar mergers may produce relatively transient ultra-compact thermal and possibly non-thermal radio sources that decay on time-scales of years to centuries.

3.6. Binaries and the IMF

The origin of the initial mass function (IMF) has been extensively debated in the literature (e.g. Larson 2005; Mac Low & Klessen 2004; Padoan & Nordlund 2002; Kroupa 2001, 2002; Elmegreen 2000; Bonnell et al. 1997, 2004). While initial conditions in the cloud core and feedback in the form of outflows and radiation may determine the masses of stars formed in isolation, in clusters other factors may dominate. Massive objects accrete at higher rates from a given environment than less massive ones (competitive accretion). Furthermore, objects near the high density center of a core accrete faster than those in lower density environments. Protostellar merging provides an additional mechanism which can alter the IMF (Bonnell, Bate, & Zinnecker 1998; Stahler et al. 2000). Since a large fraction of field stars form in clusters that dissolve soon after formation, these various processes are all likely to contribute to the shape of the field IMF. The more high-density clusters contribute to the field-star population, the larger the role of mergers in determining the IMF. Mergers may be the dominant process in ultra-dense regions where systems such as 30 Doradus and protoglobular clusters form. Numerical simulations indicate that the expected mass-spectrum of massive stars is consistent with the predictions of the merger hypothesis (Bonnell & Bate 2002).

An environment where the stellar density is sufficient to lead to mergers is also expected to produce a large number of multiple star systems through three-body dynamical interactions and by means of captures of intruder stars that fail to merge (Bonnell & Bate 2002; Bate, Bonnell, & Bromm 2002). Indeed, multiple systems are more common among O and
B stars than among lower mass objects (Preibisch et al. 1999; Zinnecker & Bate 2002). A remarkable feature of the four massive stars in the Trapezium in Orion is that at least three of the four members ($\theta^1$ Ori A, B, and C) are resolved multiples (Weigelt et al. 1999; Schertl et al. 2003). Additionally, the brightest components of members A and B are also eclipsing binaries. Thus, the number of companions to the four massive Trapezium stars is unusually large; at sub-arcsecond scales, they consist of at least 13 individual objects.

In summary, if merging dominates the birth of stars above a certain mass, then one possible signature of this mass is the presence of a break in the IMF at this mass, above which the IMF is steeper (e.g. Kroupa 2004). Additionally, the multiple star fraction will increase above this mass scale.

### 3.7. Clustering and Run-away Stars

Mergers can only occur in ultra-high density protostellar environments with over $10^7$ YSOs per cubic parsec. The observed densities of visible star clusters are never this high. However, such high densities are only expected during the highly embedded phase of cluster formation. By the time most clusters become visible at visual or near-IR wavelengths, they may have expanded significantly. Deep thermal-IR or high angular resolution radio wavelength surveys of dense cores such as the IRc2 region in Orion are needed to determine the peak cluster density reached between formation and re-expansion. A rough estimate of the peak cluster densities prior to proto-cluster expansion can be made by assuming that such clusters form from the densest molecular cloud cores which are observed to have $n(H_2) \approx 10^7$ cm$^{-3}$. For a star formation efficiency $\epsilon$, a median stellar mass $M$, the density of a cluster formed from a cloud with mean density $n(H_2)$ is $N_\star = 2 \times 10^6 \epsilon_{0.5} M_{0.3}^{-1} n_7$ stars pc$^{-3}$ where $M_{0.3}$ is the median stellar mass in units of 0.3 $M_\odot$, $n_7$ is the density of molecular hydrogen in units of $10^7$ cm$^{-3}$, and $\epsilon_{0.5} = 0.5$ is the star formation efficiency (the ratio of the total mass of stars formed, divided by the initial mass of gas).

Runaway high-velocity stars are thought to be produced by the break-up of binaries in which one member exploded (Blaauw 1991) or from three- and four-body (single–binary and binary–binary) interactions. The contribution of the latter process grows in importance with increasing cluster density. The massive run-away stars AE Aurigae and $\mu$ Columbae apparently originated from a binary–binary interaction which 2.6 Myr ago produced two fast run-away stars and the binary star $\iota$ Orionis located in the Orion OB1c subgroup in front of Orion’s Trapezium cluster (Hoogerwerf et. al. 2000). Only such dynamical interactions can produce high-velocity runaway stars before the first supernova (SN) explosion in a group (Kroupa 2004). Clusters dense enough to promote merging will develop higher velocity
dispersions than groups that do not allow it. Thus, clusters which produce large numbers of high-velocity run-away stars and stars with velocities much larger than the escape speeds from cluster-forming molecular cloud cores provide indirect evidence for a prior epoch during which stellar densities were sufficiently high to promote dynamical interactions. Lower cluster densities would result in fewer and slower runaway stars generated by three- and four-body interactions, few interaction-formed binaries, and fewer rapid rotators.

In summary, the statistics of run-away stars can be used as an indicator of the high cluster densities required for merging to occur. Deep, high angular resolution radio and far-IR wavelength studies can be used to directly measure the stellar densities of embedded cluster during their formation.

3.8. Gamma-ray Bursters and Hypernovae

Gamma-ray bursters (GRBs) are known to be associated with massive star forming regions in galaxies (see Meszaros 2002 for a review). The collapsar model for GRBs requires a rapidly rotating and very massive progenitor star (Woosley 1993; Proga et al. 2003). The off-axis collisions and merging of stars near the top of the stellar mass spectrum may result in the production of GRBs. The rare merger of two (or more) stars at the very top of the stellar mass spectrum are most likely to occur in the most extreme star formation environments such as those which produce super star-clusters in galactic starbursts (e.g. the Antennae) and dwarf galaxies (e.g. 30 Dor in the LMC). Such events can release more than $10^{51}$ ergs of gravitational potential energy.

The merging of massive stars may produce super-massive ($> 100 \, M_\odot$) collision products with rapid rotation since the most probable collisions occur at high impact parameter. Rapidly rotating super-massive stars are likely to be near the Eddington limit, radiate most of their luminosity at short ultraviolet wavelengths, and be hotter at their poles and darker at their equators. Radiation, and the resulting line-driven stellar winds, will tend to emerge from the poles of the rotationally flattened object (von Zeipel 1924; Owocki et al. 1998; Smith et al. 2003). Thus, surrounding interstellar gas will be cleared most efficiently along the stellar rotation axis.

The cores of massive stars are convective. The combination of rapid spin and convection may lead to the generation of a strong internal magnetic field. The super-massive object may be eventually disrupted by an unusually violent supernova explosion (a hypernova) soon after formation. During the hypernova, the rapidly spinning core of the collapsing star may form a transient, magnetized toroid before its mass plunges into the black hole forming at its
center. As matter spirals toward and into the black hole, some of its gravitational potential energy may be efficiently converted into relativistic jets launched by the magnetic field along the spin axis. These conditions may be ideal for the production of relativistic jets that blast through the remains of the star and into relatively clear regions along the object’s spin axis. As these jets slam into residual gas in the cavities along the merger product’s rotational axis, they may emit hard gamma and X-ray radiation. Thus, the extremely rare merger of massive stars may produce gamma-ray bursters (GRBs).

The delay between the formation of a super-massive star and its death in a hypernova explosion is likely to be comparable to the nuclear time-scale for the star. This delay can be estimated from \( \tau_{\text{nuc}} \approx 0.007 \epsilon M c^2 / L \) years where \( \epsilon \) is the fraction of the star involved in nuclear energy release before detonation. For \( \epsilon = 0.25 \) (probably a severe upper limit), \( M = 120 \, M_\odot \), and \( L = 1 \times 10^6 \, L_\odot \), \( \tau_{\text{nuc}} \) is about 3 Myr.

A very rough estimate of the rare merger rate of a pair of stars near the top end of the IMF can be obtained either by considering the rate of bound cluster formation in the Milky Way or the formation rate of the most massive stars. The bound cluster birth rate has been estimated to be in the range 0.1 to 0.4 kpc\(^{-2}\) Myr\(^{-1}\) in the Solar vicinity (e.g. Lada & Lada 2003). Assuming that most such clusters form in the Molecular Ring which has an area of about 170 kpc\(^2\), about 17 to 70 such clusters form somewhere in the Milky Way every million years. If 10% of these bound clusters produce very massive stars near the upper mass limit of around 120 \( M_\odot \), the birth rate of such stars is around 1.7 to 7 Myr\(^{-1}\). Such stars live only about 3 Myr. Thus, there will be of order 10 such stars in the Galaxy at any one time, consistent with the number known in the 100 \( M_\odot \) range. GRBs are thought to have a beaming angle of about 4° (Frail et al. 2001) so that only about 0.1% of all GRBs will be visible from Earth. If all super-massive stars are merger remnants with fast rotation that produce hypernovae, and 0.1% of the resulting GRBs are oriented towards us, then we would expect to see one Galactic GRB every 0.1 to 1 billion years. If only 10% of super-massive stars form by merging, the GRB rate would be 10 times lower. However, the star formation rate may have been 10 times higher in the past (e.g. at a redshift of \( \sim 1 \)). There are \( 10^{11} \) similar galaxies in a Hubble volume. Under these assumptions, the total GRB rate is expected to be between \( 10^2 \) to \( 10^3 \) events per year, not inconsistent with the actual detection rate of GRBs.

In summary, it is possible that the merging of the most-massive stars lead to hypernovae and the production of one class of gamma-ray bursters.
3.9. Distinguishing Mergers from Accretion

Several types of observations can be used to distinguish between the accretion and merger scenarios. While accretion can in principle produce massive stars in isolation, mergers can only occur in very dense clusters that presumably can only form in very dense and massive cloud cores. Neglecting segregation of stars and gas and contraction, the formation of a cluster density of $10^6 \text{M}_\odot \text{pc}^{-3}$ requires a pre-star-formation cloud core gas density of $n(H_2) \approx 10^7 \text{cm}^{-3}$. However, as shown by Bonnell et al. (2003), gravitational collapse of a fragmenting core with an initial density of $n(H_2) = 10^5 \text{cm}^{-3}$ can lead to stellar densities of $10^6$ to $10^8$ stars per cubic pc for a brief period. It is during this transient ultra-dense and highly embedded phase that mergers are most likely. A corollary to the high density is that interactions will truncate disks. In the Bonnell et al. (2003) simulations, one-third of all stars and virtually all massive stars, suffer interactions with periastron separations of less than 100 AU.

Circumstellar disks are expected to have very different properties in the merger and accretion scenarios. Accretional growth of a protostar is expected to be associated with the presence of quiescent, geometrically thin, accretion disks. Close-encounters and mergers will disrupt such disks. One expected signature of a recent merger is the presence of a dynamically heated, expanding torus of debris surrounding the collision product. Dynamical stirring and the increasing rate of energy dissipation as a system evolves towards a merger may launch shocks into this expanding debris field. The dense and hot environment of a merger may be ideal for the production of maser emission. The merger and subsequent reprocessing of radiation to longer wavelengths by the circumstellar debris may produce a high luminosity flare at far infrared wavelengths that lasts from years to centuries. In the merger scenario, some encounters will lead to the formation of captured binaries and when the merger is completed, the resulting product will have rapid spin. Thus, a high multiplicity fraction and fast rotation among massive stars may be one signature of interactions and merging. Large numbers of high-velocity ($> 50 \text{ km s}^{-1}$) as well as moderate-velocity (10 to 50 km s$^{-1}$) run-away stars originating in OB associations and young star clusters can provide indirect evidence for extremely high stellar densities during their birth.

Outflows produce one of the most easy to observe signs of the birth of a young star. Disk accretion in forming low-mass stars produces highly collimated jets (e.g. Reipurth & Bally 2001). Such jets have been observed to be produced by moderate mass protostars with luminosities larger than $10^4 \text{L}_\odot$. However, as discussed below, the outflow from the nearest $10^5 \text{L}_\odot$ class protostar, OMC1, has a very different morphology indicating an explosive origin. While massive stars growing by accretion from a disk may produce collimated outflows which are quasi scaled-up versions of those driven by low-mass protostars, mergers are expected to
drive wide-angle, eruptive outflows. The formation of the most massive stars may involve multiple protostellar merging events. The orbital planes defined by a series of in-spirals are likely to be random. Thus, the orientations of the outbursts produced by a series of merging events are likely to be un-correlated with each other. The series of eruptions would likely leave behind a set of outflow lobes and cavities which point radially away form the massive collision product. These different expectations of accreting and merging protostars are summarized in Table 1.

4. The OMC1 Outflow: Evidence for a Recent Merger?

The Orion region contains the nearest region of on-going massive star formation (e.g. O’Dell 2001). The Trapezium cluster associated with the Orion nebula, one of the youngest clusters near the Sun, contains over 2000 mostly low-mass young stars less than about 10^6 years old (Hillenbrand 1997; Hillenbrand & Hartmann 1998) The density of stars in the cluster core currently is in the range 5 \times 10^4 stars pc^{-3} (McCaughrean and Stauffer 1994) to 2 \times 10^5 stars pc^{-3} (Henney & Arthur 1998), implying a nearest-neighbor distance between low-mass stars of only a few thousand AU (e.g. Bally et al. 1998).

Over 50% of the young stars in the Trapezium cluster are surrounded by disks with radii up to 500 AU. The intense UV radiation field of the Trapezium stars is photo-evaporating these disks, making them visible as Orion’s ‘proplyds’ (O’Dell, Wen, & Hu 1993; O’Dell & Wong 1996; Bally et al. 1998, 2000; Johnstone, Hollenbach, & Bally 1998; McCaughrean, Stapelfeldt, & Close 2000). In this cluster, the present ratio of the average interstellar separation to the typical disk radius is only 10 to 100. Since these disks are losing mass at rates around 10^{-7} to 10^{-6} M⊙ per year, they were more massive in the recent past. Since star formation in the Orion nebula is finished (except in dense cores such as the BN/KL region behind the nebula) the visible portion of the cluster is likely to be in a state of expansion as the surrounding molecular cloud that dominates the mass in the region is photo-ablated. Thus, when the massive Trapezium stars formed, the cluster was probably denser, and its low-mass stars had more massive disks. A 3 km s^{-1} velocity dispersion for the Trapezium cluster and a core radius of 0.1 pc implies a crossing-time of about 3 \times 10^4 years. So, this cluster could have expanded significantly in the recent past. These factors make it plausible that mutual interactions and cannibalism might have occurred prior to the emergence of the massive Trapezium stars. Indeed, the large multiplicity of the massive Trapezium stars and the gap in the radial distribution of low-mass stars surrounding \theta^1 Ori C (Hillenbrand 1997) may be evidence that this star has merged with its neighbors while it was forming.

Massive star formation is still occurring within the luminous (10^5 L⊙) OMC1 core located
immediately behind the Orion nebula. Though many individual peaks of thermal infrared (7 to 24 µm) emission have been identified (Lonsdale et al. 1982), many may not be self-luminous. The VLA studies of Menten & Reid (1995) indicate that, in addition to the Becklin-Neugebauer object (BN), the region contains at least two other ultra-compact radio sources, I and n, separated by about 3″ (1,500 AU in projection) from each other.

Radio sources I and n in OMC1 are both associated with strong OH, H$_2$O, and SiO maser emission (Johnston et al. 1989; Genzel et al. 1981; Greenhill et al. 2003; 2004). An expanding arcminute-scale complex of high velocity ($v = 30$ to $100$ km s$^{-1}$) H$_2$O masers surround the entire OMC1 region. The expansion center coincides within several arcseconds of source n (Genzel et al. 1981). In addition to this high velocity flow, a low velocity ($v = 18\pm 2$ km s$^{-1}$) cluster of much brighter maser spots is associated with this expansion. As shown by Gaume et al. (1998), the so-called 22 GHz H$_2$O ‘shell’ masers, which were mostly resolved-out in the VLBI observations of Genzel et al. (1981), are concentrated in a 2″ by 0.5″ strip centered on source I and oriented roughly orthogonal to the bipolar CO outflow emerging from OMC1 (Chernin & Wright 1996). Additionally, bright SiO maser emission lies within 0.1″ of source I. These masers consist of four clusters of emission having velocities very similar to those of the H$_2$O shell masers. Greenhill et al. (1998) and Doeleman, Lonsdale, & Pelkey (1999) found that these masers are concentrated into four linear chains fanning out to the North, East, South, and West from source I. The North and West clusters are redshifted while the south and east clusters are blueshifted. Thus, these SiO maser chains have Doppler shifts opposite to the CO flow emerging from this region.

A fast (30 to 100 km s$^{-1}$), poorly collimated bipolar outflow emerges from this region orthogonal to the ‘shell’ maser disk with a blueshifted lobe towards the northwest. The OMC1 outflow has a mass of about 10 $M_\odot$ and a kinetic energy of about $4 \times 10^{47}$ ergs (Kwan & Scoville 1976). The OMC1 outflow and the H$_2$ fingers (Allen & Burton 1993; Stolovy et al. 1998; Schultz et al. 1999; Kaifu et al. 2000) indicate that a powerful explosion occurred in OMC1. The H$_2$ finger system consists of over a hundred individual bow-shocks which delineate a relatively wide-angle bipolar outflow towards PA $\approx 315^\circ$ with an opening angle of more than 1 radian in each lobe. Some of the H$_2$ fingers are visible in Hubble Space Telescope images and thus have known proper motions. The proper motion vector field (Lee & Burton 2000; Doi, O’Dell, & Hartigan 2002) indicates an explosive origin about 1010±140 years ago, assuming no deceleration. Greenhill et al. (1998) interpreted the ‘shell’ water masers and the 18 km s$^{-1}$ outflow as tracers of an expanding disk surrounding source I with a northeast–southwest major axis that lies orthogonal to the fast wide-angle bipolar outflow that emerges along a northwest–southeast axis. However, Greenhill et al. (2003) presented an argument, based on new VLBA and 7 mm VLA data, that the disk is oriented southeast–northwest and that the “shell” masers trace a jet. In this picture,
the four SiO maser chains trace the surface of the disk, which produces a ridge of 7 mm radio continuum emission along the disk plane. However, this new re-interpretation leaves the H$_2$ fingers and associated CO flow without a known driving source. Furthermore, it is possible that the 7 mm radio emission actually traces a thermal radio jet rather than dust emission from a disk. Thus, we believe the interpretation in which the “shell” and SiO masers surrounding source I trace a thick, expanding disk, and the 7 mm emission traces a jet oriented northwest-southeast which drives the H$_2$ fingers and associated CO outflow provides a simpler explanation for the various phenomena in OMC1.

The kinematics, energetics, and morphology of the OMC1 region can be explained by a recent merger suffered by source I. A 20 M$_\odot$ star swallowing a 1 M$_\odot$ object will release about $3 \times 10^{48}$ ergs of gravitational potential energy, more than enough to drive an outflow such as that observed in the OMC1 cloud core. Merger-generated outflows are expected to be highly impulsive, poorly collimated, and may exhibit an ejection speed that increases with time. Such accelerating flows may readily produce the instabilities that are required to explain the multiple fingers of H$_2$ emission in Orion (Stone et al. 1995; McCaughrean & Mac Low 1997).

Plambeck et al. (1995) and Tan (2004) found that the BN star, located about 10” northwest of the OMC1 core, has a large proper motion of $38.7 \pm 4.7$ km s$^{-1}$ towards P.A. $-37.7 \pm 5^\circ$. Additionally, Scoville et al. (1983) found that this source is moving about +12 km s$^{-1}$ with respect to the OMC1 cloud core in the radial direction. Tan (2004) interpreted this motion as the result of ejection from the Trapezium some 4,000 years ago. He notes that BN passed within 1” of source I about 500 years ago.

One problem with the interpretation that BN is a runaway star expelled from the Trapezium is that it exhibits traits of a star much younger than any of the Trapezium members. While none of the Trapezium stars are surrounded by obvious circumstellar environments, BN is surrounded by an envelope that produces 600 – 900 K dust continuum and absorption/absorption in the near-infrared vibrational bands of CO (Scoville et al. 1983). Hot (3,500 K) CO band-head emission emission is formed by a dense ($n(H_2 = 10^{11}$ to $10^{13}$ cm$^{-3}$) molecular layer having a very small (<0.7 AU) area. Scoville et al. (1983) suggested that this emission may trace a shock front, or possibly a disk surrounding a low-mass companion. In addition to a large infrared excess, and infrared emission from CO, BN is surrounded by an ultra-compact ($\sim 20$ AU radius) HII region, and exhibits Brackett-series emission lines that have been interpreted as a decelerating stellar wind with a mass loss rate of $\dot{M} \approx 4 \times 10^{-7}$ to $10^{-7}$ M$_\odot$yr$^{-1}$ and a relatively low terminal velocity of less than a hundred km s$^{-1}$. Furthermore, redshifted absorption in CO indicates infall onto BN from beyond 25 AU at rates of $\dot{M} \approx 4 \times 10^{-6}$ M$_\odot$yr$^{-1}$. Thus, this ejected high-velocity star must be dragging along a substantial (> $10^{-4}$ M$_\odot$) reservoir of dense circumstellar gas. If BN originated from the
Trapezium, then it is puzzling why it is surrounded by such a rich circumstellar environment when none of the Trapezium stars exhibit such media or other youthful traits.

We consider the possibility that BN was expelled not from the Trapezium, but from the OMC1 cloud core, possibly by source I. If the outer parts of the OMC1 outflow for which proper motions have been measured have been decelerated by a factor of about two, then the true age of the outflow is about 500 years. Proper motions indicate that BN passed within 1″ of source I about 500 years ago. It would be a remarkable coincidence for a high velocity star to pass so close to another massive star, and to have this occur just when a remarkable outflow is launched. A physical interaction with source I might explain the OMC1 outflow, the ejection of BN, and by its moving through the gas-rich environment of the OMC1 cloud core, the presence of a co-moving circumstellar environment.

If BN was ejected from the vicinity of source I, its +12 km s$^{-1}$ radial velocity with respect to the stationary CO emission from OMC1 and proper motion towards the northwest would place it behind the northwest lobe of the OMC1 outflow. Indeed, Scoville et al. (1983) found CO absorption at the velocity of the blueshifted lobe of the OMC1 outflow towards BN. The ejection of BN requires the involvement of a third star. This star either survives as a close companion of source I, or may have spiraled into and merged with this star. Either interaction may have triggered the “explosion” responsible for the powerful OMC1 outflow and associated H$_2$ fingers.

The NH$_3$ and dust filaments in the OMC1 cloud core (e.g. Wiseman & Ho 1998; Johnstone & Bally 1999) point radially away from the vicinity of the BNKL core. These features may trace the walls of cavities left behind by earlier episodes of outflow activity in OMC1. Some of these events may have been triggered by earlier protostellar interactions.

5. Conclusions and Summary

Stellar merging is possible in forming clusters during a very short-lived and transient phase during which cluster densities exceed $10^7$ stars pc$^{-3}$. On the other hand, it is possible that in low stellar density environments or in isolated small cloud cores, stars of most masses form by direct accretion without the perturbations caused by sibling protostars. Thus, there may be multiple pathways by which moderate to high-mass stars form. High resolution infrared and radio wavelength observations of forming star clusters are needed to determine the significance of mutual interactions and mergers.

Merging rates can be greatly enhanced by gravitational focusing in low velocity dispersion clusters and by the presence of circumstellar material in the form of envelopes and disks.
which can provide a dissipative medium. Protostellar mergers can release between $10^{45}$ ergs for the most common low-mass events to over $10^{51}$ ergs when a pair of 100 M$_\odot$ stars merge.

The formation of massive stars by proto-stellar mergers can be distinguished from the standard scenario of disk accretion by several types of observation. Mergers are expected to produce unique phenomena including:

1] Luminous infrared flares with rise-times comparable to the orbital time-scale of the merging protostars, followed by a fast decline dominated by the cooling time of circumstellar debris, and the longer lasting decline on the Kelvin-Helmholtz time-scale of the merger product.

2] Eruptive, wide-angle bipolar outflows which may be subject to instabilities resulting from the collision of accelerating winds powered by the increasing energy-release of the merger.

3] Expanding thick tori of debris produced by the merging of circumstellar disks and the tidal disruption of the lower-mass collision partner. Shocks driven into this debris disk by the inspiraling protostars may drive ‘hot core’ chemistry, excite maser emission, and non-thermal radio emission.

4] Multiple merging and mass-loss episodes producing uncorrelated outflow lobe orientations. Such multiple eruptions may leave behind radial fingers of swept-up gas and dust pointing away from the merger product.

5] Capture-formed binaries due to incomplete or failed mergers. Merging is expected to deplete the immediate vicinity of a forming massive star of lower mass sibling stars.

6] Clusters with sufficient density to allow mergers may produce high stellar multiplicity, stars with fast rotation, and large numbers of high-velocity run-away stars.

7] It is possible that the merging a pair of stars close to the top end of the IMF produce hypernova explosions which lead to gamma-ray bursts.

8] The BNKL outflow in the OMC1 cloud core behind the Orion nebula is interpreted in terms of a merger model. Several observed properties of this source fit the expectations of the merger model.

High resolution observations of infrared to radio-wavelength emission from active sites of massive star formation are needed to distinguish between the direct accretion and merger scenarios. Studies of the disks, outflows, kinematics, and infrared photometric variability of high luminosity protostellar sources in the Milky Way will determine if mergers play a role in massive star formation. The morphology of shock-excited H$_2$ and [Fe II] emission in the near-infrared, fine-structure cooling lines in the mid-infrared, molecular tracers in the
sub-millimeter and millimeter parts of the spectrum will be used to trace outflow and disk structure. Such observations will be feasible in the near future with Gemini, VLT, Keck, JWST, and aperture synthesis instruments such as ALMA and CARMA. Monitoring of the thermal infrared and radio emission from point sources in massive star forming regions in starburst regions will provide an additional test of massive star formation models. Such observations and determinations of stellar densities in highly obscured cloud cores may become feasible at thermal-infrared imaging with JWST, and at radio and sub-mm wavelengths with ALMA and E-VLA. In the far future, adaptive-optics assisted near infrared imaging with 30 to 100 meter telescopes may be able to penetrate the extremely large \( A_V > 100, \) or \( A_K > 10 \) extinction of cluster-forming cores as distance of a few kpc.

Though the standard accretion scenario may well explain the formation of most massive stars, the existence of blue-stragglers in globular clusters indicates that mergers do occur in nature. The formation phases of massive stars and clusters are still hidden from us by high extinction and source confusion. Thus, merging in protostellar environments is a plausible pathway to at least some massive stars. It is important to explore possible observable consequences that may distinguish the merging from the accretion scenarios. This paper is intended to stimulate further work on the various possibilities.

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6. References

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Table 1. Predictions of Massive Star Formation Mechanisms

| Type of Study      | Direct Accretion                          | Mergers                        | Proposed Observation                                      |
|--------------------|-------------------------------------------|--------------------------------|-----------------------------------------------------------|
| Cores              | isolated, non-interacting                 | clustered, interacting         | cm, mm, sub-mm interferometry                              |
| Disks              | stable, thin, accreting                   | transient, thick, expanding     | IR, radio imaging                                          |
| Outflows           | collimated, quasi-steady                  | wide-angle eruptions            | H₂, [FeII], CO, SiO, radio continuum                      |
| Massive YSOs       | stable IR, can be isolated                | flaring IR & radio in dense clusters only | thermal IR and radio continuum, comparison with older data |
| Young Clusters     | low star density, moderate stellar spin, small binary fraction | high star density, fast stellar spin, high binary fraction | wide-field IR imaging                                      |
| Remnant Associations | low σᵥ, few runaways till first SN      | high σᵥ, runaways prior to first SN | 2MASS, Spitzer, MSX archives                               |

Notes:
Fig. 1.— A cartoon showing six types of interactions possible in a high density cluster environment. It is assumed that there are three types of recognizable entity in such an environment distinguished by increasing densities and diminishing dimensions; pre-stellar cloud cores, disks containing stars, and naked stars. Each entity can interact with the other two. The interactions of cores, disks, or stars with starless cores tend to be low-energy, long-duration events. This process is unlikely to contribute to significant growth of massive stars due to the radiation effects. Star-star interactions are likely to be extremely rare. The most likely interactions which lead to merging are between disks or between disks and naked stars. As discussed in the text, these interactions may produce capture-formed binaries. On-going accretion from a core, or subsequent interactions of the binary with other stars or disks are most likely to lead to merging.