Theories of Massive Star Formation: Collisions, Accretion and the View from the “I” of Orion

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Abstract. I review the arguments motivating models for massive star formation via stellar collisions. I then describe how the standard accretion scenario, involving the collapse of a quasi-hydrostatic gas core, can produce high-mass stars in the pressurized regions of forming star clusters. I argue that the observational evidence, particularly in the Orion hot core, favors the standard accretion paradigm.

1. Introduction

Two basic models for how a massive star accumulates its mass are debated. The conventional case, which I refer to as the standard accretion model, involves the inside-out collapse of a gravitationally bound, pre-stellar gas core from approximate hydrostatic equilibrium. A small amount of angular momentum creates an accretion disk, via which mass reaches the star in an ordered manner. Low-mass stars appear to form in this way (Shu, Adams, & Lizano 1987).

The collisional model involves the coalescence of smaller stars or protostars in dense stellar clusters (Bonnell, Bate, & Zinnecker 1998). These lower-mass stars may first form via standard accretion from small gas cores that have fragmented from the protocluster gas clump. They may also build up their mass via Bondi-Hoyle accretion from the clump.

2. The Case Against Standard Accretion

Some of these points are discussed in the review by Stahler, Palla, & Ho (2000).

Long Formation Time: Assuming 100% efficiency, the accretion rate of a star forming from the collapse of a critically unstable isothermal sphere is 
\[ \dot{m}_* = 0.975 \sqrt[3]{c_{th}^3 / G} = 4.4 \times 10^{-6} (T/20 \text{K})^{3/2} M_\odot \text{ yr}^{-1} \] (Shu 1977), so the formation time is 
\[ t_{sf} = m_{sf} / \dot{m}_* = 6.9 \times 10^6 (T/20 \text{ K})^{-3/2} (m_{sf}/30 M_\odot) \text{ yr} \].

This timescale should be less than the main sequence lifetime (several Myr for massive stars) and the cluster formation time (\( \sim 1 \) Myr for the Orion Nebula Cluster (ONC); Palla & Stahler 1999), requiring large accretion rates and temperatures (e.g. \( \dot{m}_* > 10^{-4} M_\odot \text{ yr}^{-1} \) and \( T > 160 \text{ K} \) for \( m_{sf} = 100 M_\odot \) and \( t_{sf} < 1 \) Myr). Such temperatures are observed in massive star-forming regions, but are unlikely to occur until at least one massive star is present. Higher accretion rates result if a core has some nonthermal pressure support (Stahler, Shu, & Taam 1980). This does appear to be the case for massive cores since their line-widths correspond to supersonic velocities.
Radiation Pressure: The short Kelvin-Helmholtz times of massive stars allow them to reach the main sequence while they are still accreting (e.g. Palla & Stahler 1992). These protostars have high luminosity, $L$, and the radiation pressure may disrupt infall by acting on dust grains, which survive until temperatures of $\sim 2300$ K and are well-coupled to the dense gas. A necessary condition for infall is that the ram pressure of inward motion of the gas exceeds the outward radiation pressure from the direct radiation field of the star at the dust destruction front, $r_d \simeq 13(L/10^5L_\odot)^{1/2}(T_d/2300$K)$^{-2}(Q_a/0.1)^{-1/2}$AU, where $Q_a$ is the effective absorption efficiency of dust grains at the sublimation temperature. This implies $\rho v^2 > L/(4\pi r_d^2 c)$, where $\rho$ and $v$ are the density and infall velocity of the gas at $r_d$. In the spherical case we then have $\dot{m} > L/(4\pi r_d^2 c)$. For zero age main sequence (ZAMS) stars of mass 30, 60, 120 $M_\odot$, $L \simeq 1.2, 5.1, 18 \times 10^5 L_\odot$ (Schaller et al. 1992), and assuming free-fall conditions at $r_d$ we have $\dot{m} \gtrsim 0.4, 1.7, 6.2 \times 10^{-4} M_\odot$ yr$^{-1}$ (see also Wolfire & Cassinelli 1987). Nakano (1989) and Jijina & Adams (1996) have argued that these conditions are relaxed for accretion via a disk, since once gas reaches the disk (typically at radii $\gg r_d$), it is shielded from much of the stellar radiation. However, the ram pressure criterion should still apply in the disk at $r_d$. Consideration of this case (Tan & McKee 2002, in prep.) suggests that accretion rates $\sim 10^{-3} M_\odot$ yr$^{-1}$ are required to form the most massive stars. Radiation-hydrodynamic simulations (e.g. Yorke & Sonnhalter 2002) will ultimately provide the most accurate answer to this question.

Crowding: It appears that massive stars form almost exclusively in clusters containing many more low-mass stars, which dominate the total stellar mass. The central stellar densities can be very high—Hillenbrand & Hartmann (1998) find $n_\ast \simeq 1.7 \times 10^4$ pc$^{-3}$ in the ONC corresponding to separations of about 0.04 pc. The hydrostatic cores invoked in standard accretion would have to form and survive in such a crowded environment.

Small Jeans Mass: The Jeans mass (or more appropriately the Bonnor-Ebert mass, which is the maximum mass of a stable isothermal sphere) becomes very small in regions of high pressure, such as high-mass star-forming clumps where $P \sim 10^8 - 10^9$ K cm$^{-3}$ (McKee & Tan 2002b [MT02b]). The Bonnor-Ebert mass is $M_{BE} = 0.046(T/20$K)$^{2}(P/10^9$K cm$^{-3})^{-1/2}M_\odot$. If gas forms bound structures only on this scale, then to form a massive star, most of the mass would have to be accumulated via Bondi-Hoyle accretion or mergers.

3. The Case for Collisions and Competitive Accretion

A model of massive star formation by collisions of lower-mass stars (Bonnell et al. 1998), whose masses may be augmented by competitive Bondi-Hoyle accretion (Bonnell et al. 2001a), can automatically circumvent three of the four difficulties faced by standard accretion. Firstly, the coalescence of stars, or any optically thick mass unit, is not prevented by radiation pressure. However, Bondi-Hoyle accretion is suppressed, i.e. for $m_\ast \gtrsim 10 M_\odot$. Rates of Bondi-Hoyle accretion are enhanced in dense regions and collisions are favored in crowded regions—just the locations where massive stars are observed to form. Bonnell & Davies (1998) have shown that there has not been enough time for the Trapezium stars in the ONC to have reached their central location by dynamical relaxation. Either
they formed in the center (half of the massive stars forming within 30% of the half-mass radius) or they formed with much smaller velocity dispersions than the lower mass stars. Bondi-Hoyle accretion and mergers can potentially build up sub-solar Bonnor-Ebert masses to the massive star regime. A simulation of competitive accretion (Bonnell et al. 2001b) has reproduced the observed stellar IMF from an initial cluster of a 1000 identical $0.1 \, M_\odot$ stars embedded in a cold gas clump that makes up 90% of the mass. Note, however, that in some star-forming regions pre-stellar gas cores are observed to have a mass spectrum similar to that of stars (up to at least 5 $M_\odot$) (e.g. Motte et al. 2001).

It has been proposed that run-away OB stars, which are ejected from clusters with velocities $\sim 50 - 150 \, \text{km s}^{-1}$, and the small primary to secondary mass ratios of massive star binaries, may be the by-products of massive star formation by collisions (Stahler et al. 2000). Both phenomena are expected to result from close three body interactions of massive stars—the least massive star tends to be ejected leaving the remaining stars in a tightened binary. Such encounters should be common if massive star mergers are occurring. An alternative mechanism for producing run-away OB stars (from clusters that are at least several Myr old) is a supernova in a double massive star binary system. Hoogerwerf, de Bruijne, & de Zeeuw (2001) have identified the ejected stars from single examples of both of these types of event.

It is clear that collisions and strong dynamical interactions can occur in the crowded environments of star clusters, but the real question is whether the rate is great enough to be relevant for the star formation process. The collisional timescale in a cluster of equal mass stars in the strong gravitational focusing limit is (Binney & Tremaine 1987)

$$t_{\text{coll}} = 1.44 \times 10^{10} \left( \frac{10^4 \text{pc}^{-3}}{n_*} \right) \left( \frac{\sigma}{2 \, \text{km s}^{-1}} \right) \left( \frac{10R_\odot}{r_*} \right) \left( \frac{M_\odot}{m_*} \right) \text{yr}$$

(1)

where $\sigma$ is the 1D velocity dispersion, and $r_*$ and $m_*$ the stellar radius and mass. In the above equation we have normalized the variables to values typical of the central region of the ONC and allowed for a generous increase in the stellar radius due to pre-main sequence activity. For collisions to be important we require the collisional timescale to be $\lesssim 10^6$ yr, which requires a substantial change in one or more of the above parameters.

Stahler et al. (2000) pointed out that the collisional cross section is substantially increased for protostars that are still embedded in dense gas cores or have massive disks (see also McDonald & Clarke 1995). However, it is also possible that such encounters separate the stars from their gas without leading to a collision (Price & Podsiaedowski 1995), which would reduce the efficiency of this mechanism. Zwart et al. (2001) have found that mass segregation and binarity can boost the collision rate. It may also be increased if stars are swollen by the energy release from a recent collision. Nevertheless, even for an optimistic collision radius of 1AU = $215R_\odot$ (for each star) and for stellar masses $m_* = 10M_\odot$ equation (1) shows that densities of order $10^6 \text{pc}^{-3}$ are needed for $t_{\text{coll}} \sim 10^6$ yr. More realistic cross sections suggest the densities need to be $\gtrsim 10^8 \text{pc}^{-3}$.

Bonnell et al. (1998) have presented a model in which extreme densities can result in a cluster of lower-mass stars that are accreting from their protocluster gas cloud. The velocity dispersion of the stars decreases as they accrete,
lowering the total energy of the system and causing the cluster to contract. In a subsequent version of this model (Bonnell 2002) the initial gas cloud, which dominates the total mass, is in free-fall collapse. The cloud is seeded with various spatial distributions of low-mass stars. Gas densities increase rapidly at the center and low-mass stars that happen to be here grow quickly with large rates of Bondi-Hoyle accretion (Bonnell et al 2001a,b). After one free-fall time the central stellar density can increase from its initial value by factors of about $10^5$. However, this dramatic increase appears to depend on the assumption of free-fall collapse of the entire gas cloud. It is argued that if the initial conditions for this simulation are taken to be the present-day densities of the ONC, then collisional massive star formation is likely to occur.

Finally, it has been suggested that filamentary structure in the collapsing gas could provide a means of weakly collimating any outflows that are produced in the star formation process (Bonnell 2002). It would be difficult for the collisional model to produce coherent and symmetric outflows.

Two key observational predictions of the collisional model are the sporadic release of large amounts of energy from stellar collisions and the brief existence of dense ($\gtrsim 10^6 - 10^8\text{pc}^{-3}$) stellar clusters around each forming massive star. Neither of these have been observed, although they may be obscured by the high extinction ($A_V \gtrsim 200$) typical of massive star-forming regions.

4. Turbulent Core Accretion

In spite of the difficulties facing the standard accretion model (§2), the presence of coherent and massive gas cores in high-mass star-forming regions (Garay & Lizano 1999; Kurtz et al. 2000) suggests that a model for massive star formation should start by considering the collapse of such structures (McLaughlin & Pudritz 1997; Osorio et al. 1999; McKee & Tan 2002a [MT02a]; MT02b). Massive stars do not form in isolation and in the model of MT02a,b we assume the cores, which may form individual or binary stars, are part of a self-similar hierarchy of structure. We term the gas cloud that forms a star cluster a clump. The density distributions of clumps and cores, averaging over internal clumpiness, are consistent with approximately spherically symmetric power law density profiles, with $\rho \propto r^{-k_P}$ and $k_P \simeq 1.5$ (Evans et al. 2002). Such structures can result from the hydrostatic equilibrium of gas with an equation of state $P \propto \rho^{\gamma_p}$, with $\gamma_p = 2/3$. Since the gas is observed to be cooler than the virial temperature, it must be supported by nonthermal forms of pressure. The signal speed, $c \equiv (P/\rho)^{1/2}$, is therefore supersonic and so the cores and the clumps should be turbulent and clumpy, as is observed. In the fiducial case of $k_p = 3/2$, $c \propto r^{1/4}$ and $P \propto r^{-k_P}$, with $k_P = 1$. We define the surface of a core to be where the pressure has decreased to the ambient pressure in the clump. This is set by self-gravity and is $P_{cl} \simeq 0.88 G \Sigma_{cl}^2 = 8.5 \times 10^8 \Sigma_{cl}^2 \text{K cm}^{-3}$ in the central regions where massive stars typically form. In this expression $\Sigma_{cl} \equiv M_{cl}/(\pi R_{cl}^2)$ is the mean surface density of the clump, with characteristic value $\sim 1.0 \text{g cm}^{-2}$ (Plume et al. 1997).

Since the core mass inside a distance $r$ from its center is $M(<r) = k_p c^2 r/G$, then for higher ambient pressures (larger values of $c^2$ at the core surface), the equilibrium state for a given core mass becomes smaller and denser. The efficiency ($\epsilon_{core} \equiv m_{sf}/M_{core}$) of star formation from a core is typically quite
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high for low-mass stars (~ 50%–Matzner & McKee 2000), if set by magneto-
centrifugally driven bipolar outflows such as disk-winds or X-winds (Königl &
Pudritz 2000; Shu et al. 2000) that launch a fraction \( f_w \sim 0.1 \) – 0.3 of the
accreted mass with force \( p_w = m_w v_w = f_w m_* v_w = \phi_w m_* v_K \). Here \( v_K \) is the Ke-
plerian velocity at the equatorial stellar radius and \( \phi_w = 0.6 \) is a fiducial value.
These winds sweep up and eject gas from polar regions of the core. Similarly
high efficiencies hold for massive stars for the same values of \( f_w \) and \( \phi_w \) (Tan &
McKee 2002, in prep.). For \( \epsilon_{core} = 0.5 \) we have (MT02b)

\[
\begin{align*}
\rho_{\text{core}} &= 0.057 \left( \frac{m_{\text{sf}}}{30 M_\odot} \right)^{1/2} \frac{\Sigma_{\text{cl}}^{-1/2}}{\text{pc}}. \tag{2}
\end{align*}
\]

Recall the mean stellar separation in the center of the ONC of about 0.04 pc.
Comparison with the expected size of a massive core shows that crowding is not
necessarily a problem, particularly since during a typical stage of formation half
the stars observed today were not yet present, in the central part of the ONC
there has been time for some relaxation and density increase since formation,
and most stars are low-mass and have little dynamical impact on a massive core.

When a core does collapse it must be from a configuration at least as dense
as implied by equation (2). The high pressures of massive star-forming clumps
require dense cores, which have short free-fall times. Inside-out collapse proceeds
as in the model of Shu (1977), but now, since \( c \propto r^{1/4} \), the accretion rate grows:

\[
\dot{m}_* = 4.6 \times 10^{-4} \left( \frac{m_{\text{sf}}}{30 M_\odot} \right)^{3/4} \frac{\Sigma_{\text{cl}}^{3/4}}{M_\odot \text{ yr}^{-1}}, \tag{3}
\]

where \( m_* \) is the instantaneous protostellar mass. It will fluctuate because of
core clumpiness. These mean accretion rates are large enough to overcome
the radiation pressure of massive stars (Tan & McKee 2002, in prep.). The
corresponding formation timescales,

\[
\tau_{\text{sf}} = 1.29 \times 10^5 \left( \frac{m_{\text{sf}}}{30 M_\odot} \right)^{1/4} \frac{\Sigma_{\text{cl}}^{-3/4}}{\text{yr}}, \tag{4}
\]

are short compared with the age constraints of the ONC (Palla & Stahler 1999).

In these models the mass of a star is determined by the initial core mass
and the efficiency of star formation, \( \epsilon_{\text{core}} \). Since we find \( \epsilon_{\text{core}} \) to be relatively
constant with stellar mass, the shape of the stellar IMF should reflect that of
the cores. This is consistent with observations (e.g. Motte et al. 2001). Such a
mass function may result from the coagulation of cores or from fluctuations in
the turbulent velocity field that produce unstable condensations, but we have
not attempted to predict it. We do not expect much hierarchical fragmentation
of collapsing cores if the collapse happens quite quickly after formation (i.e.
within a few dynamical times) and if most turbulent fluctuations do not produce
unstable cores. The central concentration of the cores (\( \rho \propto r^{-1.5} \)) may suppress
fragmentation (Bodenheimer et al. 2000). Once a protostar has formed, its tidal
field will also stabilize the collapsing core against fragmentation.

We have calculated the evolution of protostellar radius and luminosity (bolo-
metric, outflow-mechanical, and ionizing) for the accretion rates predicted from
Figure 1. Models of protostellar evolution: bolometric luminosity (top panel), outflow force (middle panel), and ionizing luminosity (bottom panel) versus protostellar mass. Solid lines show model predictions for $m_{*f} = 7.5, 15, 30, 60, 120 \ M_\odot$ stars forming in a $\Sigma_{cl} = 1 \ g \ cm^{-2}$ clump. Dashed and long-dashed lines show a 30 $M_\odot$ star forming from $\Sigma_{cl} = 0.32, 3.2 \ g \ cm^{-2}$ clumps respectively. The dotted line shows the ZAMS bolometric (Schaller et al. 1992) and ionizing luminosities (Schaerer & de Koter 1997; W. Vacca, private comm.). Constraints on the properties of several nearby protostars are derived from the luminosities of their hot molecular cores (see Osorio, Lizano, & D’Alessio 1999 for additional modeling and observational references).
the turbulent core collapse model. Before reaching the ZAMS, the radius is determined by deuterium core and shell burning (e.g. Palla & Stahler 1992). Our model is based on that of Nakano et al. (1995), but extended to include shell burning with a simple prescription that matches the results of Palla & Stahler. With the protostellar radius and accretion rate we calculate the accretion luminosity, which adds to the internal luminosity to give the total. The outflow force, \( \dot{p}_w \), is calculated assuming \( \phi_w = 0.6 \), as described above. The rate of emission of H ionizing photons, \( S \), is calculated with contributions from the star and the accretion shock and utilizing models of Schaerer & de Koter (1997) for solar metallicity. The models are shown in Fig. 1. From the observed bolometric luminosities of hot molecular cores, we constrain masses and accretion rates of embedded protostars, assuming \( \Sigma_{cl} = 1 \text{ g cm}^{-2} \). This also constrains \( \dot{p}_w \) and \( S \).

If the mechanism of magneto-centrifugal outflow generation remains qualitatively similar to that operating in lower-mass stars, where theoretical models (Shu et al. 2000; Königl & Pudritz 2000) predict \( f_w = \dot{m}_w / \dot{m}_* \sim 0.1 - 0.3 \) with most of the outflow originating from the inner \( (r \lesssim 10r_*) \) accretion disk, then the large accretion rates predicted by equation (3) imply a high density of the outflowing gas rising from the disk. For fiducial parameters, we find that the ionizing fluxes of protostars at least as massive as \( \sim 60M_{\odot} \) are confined by their outflows in directions approximately in the plane of the accretion disk. Thus we do not expect disk photoevaporation (Hollenbach et al. 1994) to be an important process during the accretion phase of most massive stars.

Ionizing photons can more readily escape along the polar directions of the flow, where MHD-outflow models predict the existence of “dead-zone” cavities that the outflow does not penetrate. These regions should be occupied by a more diffuse conventional stellar wind. The angular extent of the cavity as viewed from the star decreases with distance as the outflow is collimated by the hoop stresses of the toroidal magnetic field component. Outside the cavity, the density of the outflow may be derived given the angular distribution of the outflow force and assuming a constant terminal velocity. For the force distribution of Matzner & McKee (1999), which includes the small angle softening parameter \( \theta_0 \), we have

\[
n_w = \frac{4.34 \times 10^5}{\sin^2 \theta + \theta_0^2} \left( \frac{f_w}{0.1} \frac{10 \text{AU}}{r} \right)^2 \left( \frac{0.6 \ln(200)}{\phi_w \ln(2/\theta_0)} \right) \left( \frac{\dot{m}_*}{10^{-4} M_{\odot}/\text{yr}} \right)^{1/2} \frac{30 M_{\odot}}{m_*} \frac{r_*}{10 R_{\odot}} \text{ cm}^{-3}.
\]

A test of this model is the presence of very compact H II regions, embedded in the outflows of massive protostars. These regions will initially be elongated along the outflow axis, but should eventually ionize the entire flow as the star’s luminosity grows and the accretion and outflow rates finally diminish. This transition should be quite rapid for a flow density distribution declining as \( (r \sin \theta)^{-2} \).

Of the hot cores in Fig. 1, No centimeter emission is seen (to \( \sim 0.5 \text{ mJy} \)) from IRAS 23385+6053 and G34.24+0.13MM, perhaps because of their lower luminosities and further distances. The Orion hot core contains a very compact thermal source (“I”), discussed below. W3(H_2O) contains a narrow radio jet (Wilner et al. 1999). Shepherd & Kurtz (1999) and Zhang et al. (2002) report radio and SiO jets aligned with outflows in G192.16-3.82 and AFGL 5142. See also Garay & Lizano (1999).
5. The Orion Hot Core and Source “I”

At a distance of 450 pc, the Orion hot core is the closest example of a massive star in formation. The core is self-luminous ($L_{\text{bol}} \sim 1 - 5 \times 10^4 L_\odot$, Gezari et al. 1998 [G98]; Kaufman et al. 1998). A weak radio continuum source (“I”) (e.g. Menten & Reid 1995), located within a few arcseconds of the core center, as traced by dust and gas emission (Wright, Plambeck & Wilner 1996), almost certainly pinpoints the location of the massive protostar. Note that the Becklin-Neugebauer (BN) object ($L \sim 10^4 L_\odot$; 0.02 pc to the NW in projection) is likely to be a runaway B star (Plambeck et al. 1995; Plambeck 2002, private comm.), that did not form close to the hot core; radio source “L” (0.007 pc to the SW in projection; sometimes referred to as “n”) is not particularly embedded or luminous (G98) and may be an intermediate mass protostar. Note also that bright near and mid-infrared features (e.g. IrC2) often result from inhomogeneous extinction (G98). X-ray observations (Garmire et al. 2000) can detect lower-mass protostars to $A_V \sim 60$ and reveal several sources (including “L”) within about 0.02 pc projected distance of source “I”, which itself is not detected.

A large scale, wide-angle bipolar outflow extends to the NW and SE of the core (Chernin & Wright 1996, and references therein). These authors have modeled the flow as being inclined at 65° to our line of sight. At 22 GHz, source “I” appears elongated ($0''.145$ by $<0''.085$, Menten 2002, private comm.) parallel to the large scale outflow axis. In a perpendicular direction, SiO emission forms a “bow-tie” feature centered on “I”, that may be an inclined or flared disk (Wright et al. 1995). SiO should be abundant where dust grains are destroyed.

We model the thermal radio emission from source “I” assuming the ionized gas has a density given by equation (5) for two jets of fixed half-opening angle $\theta_i = 10^\circ$ and length $l_i = 30$ AU, inclined at 65° to our line of sight. These dimensions are consistent with the 22 GHz size of $0''.145$ and the lower frequency fluxes being due to optically thick emission at temperature $T_i = 10^4$ K. We investigate
models with $\theta_0 = \theta_i$ and $\dot{m}_* = 1, 2, 4 \times 10^{-4} M_\odot$ yr$^{-1}$. Fig. 2 lists other parameters. A consistent, but not unique, model accounts for the radio spectrum with an outflow from a $20 M_\odot$ protostar accreting at $\dot{m}_* \simeq 2 \times 10^{-4} M_\odot$ yr$^{-1}$. More realistic geometries of the ionized region, derived from the predicted ionizing flux, are considered in a future paper (Tan & McKee 2002, in prep.).

6. Conclusions

The collisional model for star formation can account qualitatively for some of the observational properties of massive stars, such as their tendency to form in the centers of clusters. However, it is difficult to achieve the necessary stellar densities ($\sim 10^8$ pc$^{-3}$) for this process to be efficient. The standard accretion model, modified to account for the high pressures and turbulent, nonthermal conditions of massive star-forming clumps can achieve the high-accretion rates necessary to overcome radiation pressure and achieve short formation timescales. Crowding is not a serious problem. Nearby massive star-forming regions show signatures of disks and collimated outflows, suggesting the accretion picture is relevant to the formation of stars with masses up to at least $\sim 20 - 30 M_\odot$.

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References

Binney, J., & Tremaine, S. 1987, *Galactic Dynamics*, (Princeton)
Blake, G. A., et al. 1996, ApJ, 472, L49
Bodenheimer, P., Burkert, A., Klein, R.I., & Boss, A.P. 2000, *Protostars & Planets IV*, eds. V.Mannings,A.Boss,S.Russell (Tucson:U.of Arizona),675
Bonnell, I. A. 2002, in *Hot Stars Workshop III: The Earliest Phases of Massive Star Birth*, ed. P. A. Crowther (ASP)
Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 2001a, MNRAS,323,785
Bonnell, I. A., Clarke, C. J., Bate, M. R. & Pringle, J. E. 2001b, MNRAS,324,573
Bonnell, I. A., Bate, M. R., & Zinnecker, H. 1998, MNRAS, 298, 93
Bonnell, I. A., & Davies, M.B. 1998, MNRAS, 295, 691
Chandler, C. J., & Wood, D. O. S. 1997, MNRAS, 287, 445
Chernin, L. M., & Wright, M. C. H. 1996, ApJ, 467, 676
Evans, N.J.,II, Shirley, Y.L., Mueller, K.E., & Knez, C. 2002, in *Hot Stars Workshop III: The Earliest Phases of Massive Star Birth*, ed.P.Crowther(ASP)
Garay, G., & Lizano, S. 1999, PASP, 111, 1049
Garmire, G., et al. 2000, AJ, 120, 1426
Gezari, D. Y., Backman, D. E., & Werner, M. W. 1998, ApJ, 509, 283 (G98)
Hillenbrand, L.A., & Hartmann, L.W. 1998, ApJ, 492, 540
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
Hoogerwerf, R., de Bruijne, J. H. J., & de Zeeuw, P. T. 2001, A&A, 365, 49
Jijina, J., & Adams, F. C. 1996, ApJ, 462, 874
Kaufman, M. J., Hollenbach, D. J., & Tielens, A. G. G. M. 1998, ApJ, 497, 276
Königl, A., & Pudritz, R. E. 2000, Protostars & Planets IV, eds. V. Mannings, A. Boss, & S. Russell (Tucson: U. of Arizona), 759
Kurtz, S. Cesaroni, R., Churchwell, E., Hofner, P., & Walmsley, C.M. 2000, Protostars & Planets IV, eds. V. Mannings, A. Boss, S. Russell (Tucson: U. of Arizona), 299
Matzner, C. D., & McKee, C. F. 1999, ApJ, 526, L109
Matzner, C. D., & McKee, C. F. 2000, ApJ, 545, 364
McDonald, J. M., & Clarke, C. J. 1995, MNRAS, 275, 671
McKee, C. F., & Tan, J. C. 2002a, Nature, 416, 59 (MT02a)
McKee, C. F., & Tan, J. C. 2002b, ApJ, submitted (MT02b)
McLaughlin, D. E., & Pudritz, R. E. 1997, ApJ, 476, 750
Menten, K. M. & Reid, M. J. 1995, ApJ, 445, L157
Motte, F., André, P., Ward-Thompson, D., & Bontemps, S. 2001, A&A, 372, L41
Murata, Y. et al. 1992, PASJ, 44, 381
Nakano, T. 1989, ApJ, 345, 464
Nakano, T., Hasegawa, T., & Norman, C. 1995, ApJ, 450, 183
Osorio, M., Lizano, S., & D'Alessio, P. 1999, ApJ, 525, 808
Palla, F., & Stahler, S. W. 1992, ApJ, 392, 667
Palla, F., & Stahler, S. W. 1999, ApJ, 525, 722
Plambeck, R.L., Wright, M.C.H., Mundy, L.G., & Looney, L.W. 1995, ApJ, 455, L189
Plume, R., Jaffe, D.T, Evans, N.J, Martin-Pintado, J., & Gomez-Gonzalez, J. 1997, ApJ, 476, 730
Price, N. M., & Podsiałowski, Ph. 1995, MNRAS, 273, 1041
Schaerer, D., & de Koter, A. 1997, A&A, 322, 598
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Shepherd, D. S., & Kurtz, S. E. 1999, ApJ, 523, 690
Shu, F. H. 1977, ApJ, 214, 488
Shu, F. H., Najita, J., Shang, H., Li, Z.-H. 2000, Protostars & Planets IV, eds. V. Mannings, A. Boss, & S. Russell (Tucson: U. of Arizona), 789
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Stahler, S. W., Shu, F. H., & Taam, R. E. 1980, ApJ, 241, 637
Stahler, S. W., Palla, F., & Ho, P. T. P. 2000, Protostars & Planets IV, eds. V. Mannings, A. Boss, & S. Russell (Tucson: U. of Arizona), 327
Wilner, D. J., Reid, M. J., & Menten, K. M. 1999, ApJ, 513, 775
Wolfire, M. G., & Cassinelli, J. 1987, ApJ, 319, 850
Wright, M.C.H., Plambeck, R.L., Mundy, L.G., & Looney, L.W. 1995, ApJ, 455, L185
Wright, M.C.H., Plambeck, R.L., & Wilner, D.J. 1996, ApJ, 469, 216
Yorke, H. W., & Cordula, S. 2002, ApJ, 569, 846
Zhang, Q., Hunter, T.R., Sridharan, T.K., & Ho, P.T.P. 2002, ApJ, 566, 982
Zwart, S. F. P., Makino, J., McMillan, S. L. W., & Hut, P. 1999, A&A, 348, 117