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Theory of Formation of Massive Stars via Accretion

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Abstract. The collapse of massive molecular clumps can produce high mass stars, but the evolution is not simply a scaled-up version of low mass star formation. Outflows and radiative effects strongly hinder the formation of massive stars via accretion. A necessary condition for accretion growth of a hydrostatic object up to high masses $M \gtrsim 20\,\mathrm{M}_\odot$ (rather than coalescence of optically thick objects) is the formation of, and accretion through, a circumstellar disk. Once the central object has accreted approximately 10 $\mathrm{M}_\odot$ it has already evolved to core hydrogen-burning; the resultant main sequence star continues to accrete material as it begins to photoevaporate its circumstellar disk (and any nearby disks) on a timescale of $\sim 10^5$ yr, similar to the accretion timescale. Until the disk(s) is (are) completely photoevaporated, this configuration is observable as an ultra-compact HII region (UCHII). The final mass of the central star (and any nearby neighboring systems) is determined by the interplay between radiation acceleration, UV photoevaporation, stellar winds and outflows, and the accretion through the disk.

Several aspects of this evolutionary sequence have been simulated numerically, resulting in a "proof of concept". This scenario places strong constraints on the accretion rate necessary to produce high mass stars and offers an opportunity to test the accretion hypothesis.

1. Introduction

Massive stars play a key role in the sequence of events after the Big Bang that ultimately result in the development of life on Earth. They are the principal source of heavy elements and of UV radiation and are an important source of dust grains. Through a combination of winds, massive outflows, champagne flows, and supernova explosions they provide an important source of turbulence in the ISM of galaxies. This turbulence in combination with differential rotation presumably drives galactic dynamos. The galactic magnetic fields thus produced, interacting with supernova shock fronts, accelerate cosmic rays. Cosmic rays, UV radiation, and dissipation of turbulence are the principal sources of heating in the ISM, whereas heavy elements found in dust, molecules, and in atomic/ionic form ultimately are responsible for its cooling. Massive stars thus profoundly affect the star and planet formation process as well as the physical structure of galaxies.

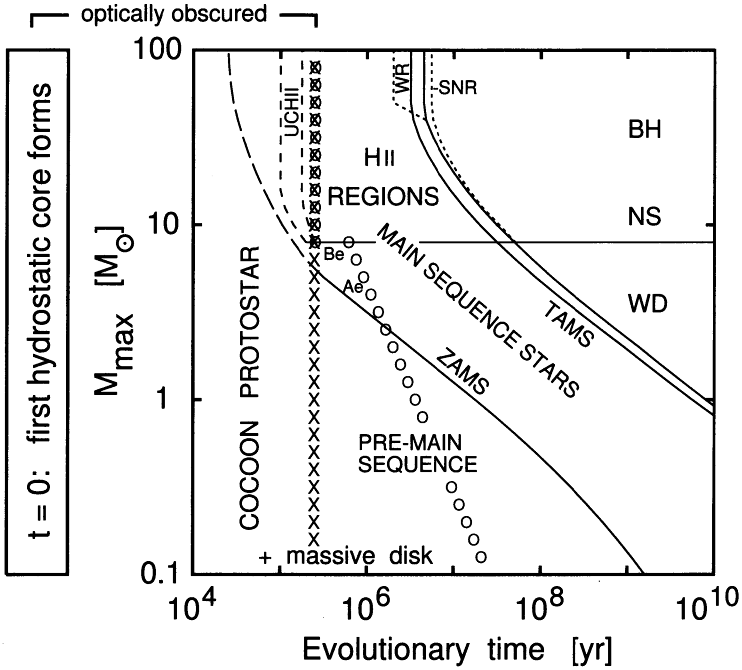

Figure 1. Relevant time scales of stars attaining a maximum mass $M_{\rm max}$. Symbols have the following meaning: WR: Wolf-Rayet star, TAMS: end of core hydrogen-burning, ZAMS: begin of hydrogen-burning, Ae & Be: Herbig Ae/Be stars; circles: dissipation of gaseous disks (my guess); crosses: end of rapid accretion onto accretion disk (assumed independent of mass). The end of nuclear burning (unmarked line parallel to the TAMS) results in a WD (white dwarf) or – for massive stars – in an SNR (observable supernova remnant) and either a BH (black hole) or NS (neutron star) [adapted from Yorke 1986].

In spite of the key role that these relatively short-lived massive stars play in the shaping of galactic structure and evolution, our understanding of their formation is still rather limited. The reason for this is three-fold: they are difficult to observe during the critical formation phases, they are rare, and the theoretical problem is extremely complex. Their formation is obviously not merely a scaled-up version of low mass star formation and obviously much more complex because of the proximity of high mass stars (among these the forming star itself), resulting in mutual interactions via gravitational torques, powerful winds and ionizing radiation.

Not only are massive stars formed less often than their low mass counterparts, their relevant time scales (contraction to hydrogen-burning and nuclear burning timescales) are shorter (see Fig. 1). Both effects result in fewer examples of high mass stars to be found in a given (early) evolutionary phase within a given volume. The low number statistics of high mass stars is partially offset by their higher luminosities, which allow us to study high mass stars at greater distances. However, insufficient spatial resolution is an issue — an entire cluster is often contained in a single observing pixel.

In the following I will not argue for or against the "accretion scenario" versus the "coalescence scenario" for high mass star formation, but rather investigate conditions under which accretion of material onto a massive star via an accretion disk is theoretically possible. The basic questions to be addressed are:

1. How is it possible to compress sufficient material to form a massive star into a sufficiently small volume within a sufficiently small time period?
2. How does the forming massive star influence its immediate surroundings, eventually limiting the final mass?

As McKee & Tan (2003) have argued, turbulent and pressurized clouds permit sufficient material to be available in the cores of giant molecular clouds for high mass star formation. Here, we address the issue of further concentrating this material into a region of a few $R_\odot$ within a few 10^5 yr.

2. The basic problem

A necessary condition to accrete sufficient material to produce a massive star ($M \gtrsim 10\ \mathrm{M}_\odot$) is: $M_* = \int_0^t \left[\dot{M}_{\mathrm{acc}}(t') - \dot{M}_{\mathrm{out}}(t')\right] dt' \gtrsim 10\ \mathrm{M}_\odot$, i.e., the infall (accretion) rate $\dot{M}_{\mathrm{acc}}$ must greatly exceed the outflow rate $\dot{M}_{\mathrm{out}}$ during a significant proportion of the formation process. For this to occur the acceleration due to gravity must exceed the outward directed radiative acceleration of the embryo source. Whereas gravity GM_*/r^2 increases linearly with mass, the radiative acceleration of dusty material $\kappa L/4\pi r^2 c$ is proportional to the stellar luminosity which increases as a high power of stellar mass (roughly $L_* \propto M_*^{3.2}$ in the range $0.01 \lesssim M_*/\mathrm{M}_\odot \lesssim 100$). Thus, to allow infall we require $\kappa_{\mathrm{eff}} L/4\pi r^2 c < GM_*/r^2$ with $L = L_* + L_{\mathrm{acc}}$, which translates into

$$\kappa_{\mathrm{eff}} < 130\ \mathrm{cm}^2\,\mathrm{g}^{-1} \left[\frac{M_*}{10\ \mathrm{M}_\odot}\right] \left[\frac{L}{1000\ \mathrm{L}_\odot}\right]^{-1} \tag{1}$$

This condition defines the maximum effective opacity κ_{eff} of accretable material. The (proto-)star's luminosity is given by the sum of its intrinsic luminosity L_* and the luminosity L_{acc} emitted by the dissipation of kinetic energy of the material being accreted.

Dusty material generally has a very high opacity (Fig. 2); for the "hardness" of radiation expected from main sequence stars of 5 $\mathrm{M}_\odot$ and higher, the net force on typical dusty interstellar material ($\kappa \sim 100\ \mathrm{cm}^2\mathrm{g}^{-1}$) is directed away from the star (Fig. 3).

3. How does Nature solve this Problem?

To allow further growth of an already existing stellar embryo at least one of the following conditions must be met: a) κ_{eff} must be significantly lower than its ISM value for optical/UV radiation; b) the effective luminosity must be reduced;

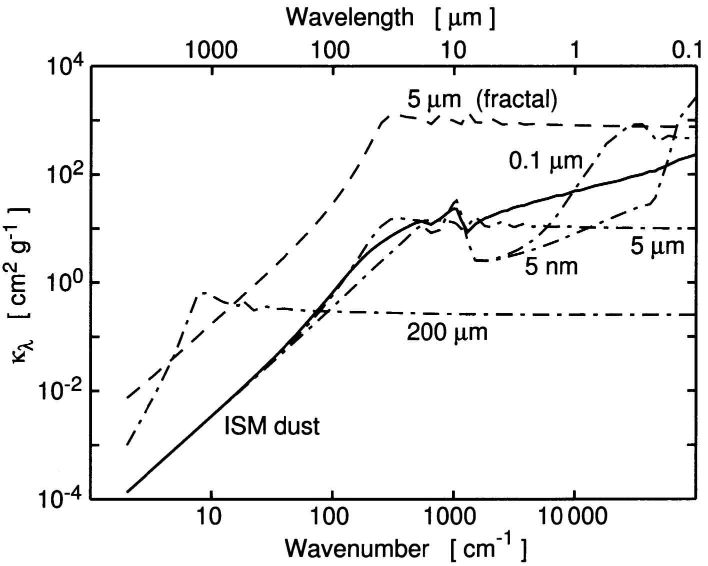

Figure 2. Specific extinction coefficients of dusty gas with a dust to gas mass ratio of 0.01 under the assumption of compact silicate grains of given radius (*dashed-dotted lines*). For comparison the opacity of fractal 5 μm silicates (*dashed lines*) and "ISM Dust" (*solid line*; Preibisch et al. 1993) are also given.

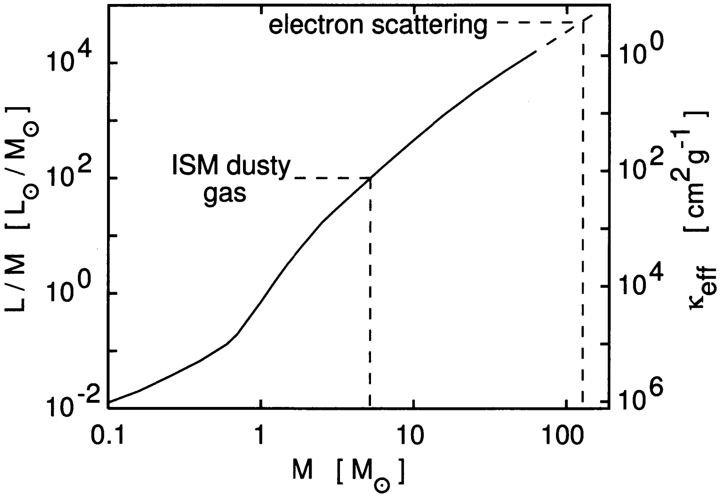

Figure 3. Luminosity to mass ratio (*solid line, left axis*) for main sequence stars. Using equation 2 this translates into a critical effective opacity for main sequence stars that allow accretion of material (*right axis*). The dotted lines show how two extreme values for opacity translate into upper mass limits of 5 M$_\odot$ (ISM dusty gas) and 130 M$_\odot$ (electron scattering).

or c) "gravity" must be increased.

a) Reduce κ_{eff}:

As evident in Fig. 2 κ_{eff} can be significantly lower than its ISM value if the radiation field "seen" by the accreting material is shifted from the optical/UV into the far infrared, if the average size of dust grains increases (but remains "compact" rather than becoming "fractal") or if most of the dust is destroyed. In their pioneering efforts Kahn (1975) and Wolfire & Cassinelli (1987) studied the 1D spherically symmetric accretion problem for massive star formation with emphasis on the dust opacity. Indeed, the latter authors concluded that massive stars can only form if the dust has been significantly modified, assuming an accretion flow that is steady-state and spherically symmetric. Of course, accretion may be non-steady and/or non-spherically symmetric and this basic premise may be invalid.

Another possibility to reduce the effective opacity is the accretion of optically thick "blobs". In this case

$$\kappa_{\text{eff}} = \pi R_{\text{blob}}^2 / M_{\text{blob}} \tag{2}$$

As a particular subset of this family of solutions Bonnell et al. (1998) considered building up massive stars by coalescence of lower mass stars within a stellar cluster (see also Bonnell 2002).

Modifications to the opacity due to coagulation of dust and dust destruction processes during the collapse phase were calculated by Suttner & Yorke (2001) for three different detailed dust models (compact spherical particles, fractal BPCA grains, and fractal BCCA grains). Using a 2D (axial symmetry assumed) code that followed the dynamics of gas + 30 individual dust components, they find that even during the early collapse and the first $\sim 10^4$ yr of dynamical disk evolution, the initial dust size distribution is strongly modified (Fig. 4). Close to the disk's midplane coagulation produces dust particles of sizes of several $10\,\mu$m (for compact spherical grains) up to several mm (for fluffy BCCA grains), whereas in the vicinity of the accretion shock front (located several density scale heights above the disk), large velocity differences inhibit coagulation. Dust particles larger than about $1\,\mu$m segregate from the smaller grains behind the accretion shock. Due to the combined effects of coagulation and grain segregation the infrared dust emission is modified. Within the accretion disk a MRN (Mathis, Rumpl, & Nordsieck 1977) dust distribution provides a poor description of the general dust properties. Nevertheless, the radiative force acting on the *infalling* material is hardly affected.

b) Reduce the effective luminosity:

Yorke & Krügel (1977) solved the time dependent non-steady state accretion problem in spherical symmetry and were able to produce stars of masses 17 $M_\odot$ and 36 $M_\odot$ from clouds of masses 50 $M_\odot$ and 150 $M_\odot$ respectively — due to the effects of oscillatory "super-Eddington" accretion. Accretion was permitted during quiescent low luminosity phases. Also, the sheer weight of the entire dusty envelope forced material upon the star, even when the Eddington criterion was not fulfilled locally.

Nakano et al. (1995), however, point out that even a small amount of rotation leads to the formation of a circumstellar disk, and we thus expect

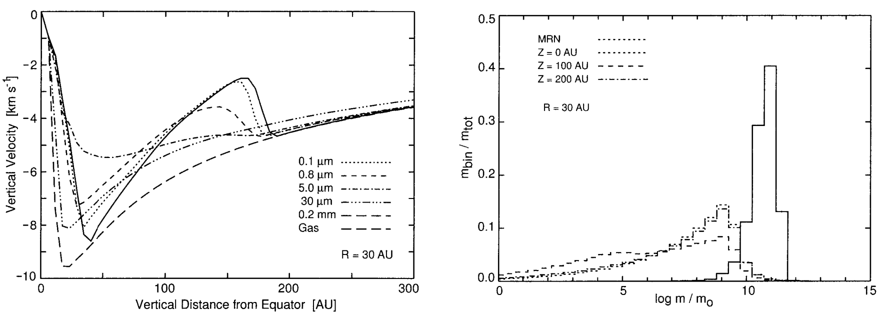

Figure 4. Evolution of compact spherical grains in a rotating, collapsing 3 $M_\odot$ protostellar clump at 11,400 yr (Suttner & Yorke 2001). **Left:** Velocities of selected grains through the accretion shock at $r = 30$ AU; **Right:** Grain mass spectrum at selected positions along $r = 30$ AU compared to initial MRN spectrum.

accretion to proceed in 2D through an accretion disk, i.e. radiation pressure could blow away the tenuous polar regions but not the massive disk. Yorke & Bodenheimer (1999) studied this effect quantitatively. They find that whereas the central object may emit radiation isotropically, the radiation field quickly becomes anisotropic further from the center. For an outside observer and in particular for a dust grain attempting to accrete onto an existing protostellar disk, the radiative flux close to the equatorial plane can be much smaller than the component parallel to the rotation. This so-called "flashlight effect" (the "beaming" of radiation in the polar direction) occurs whenever a circumstellar disk forms.

As an example of the flashlight effect Fig. 5 displays the angle-dependent SEDs of a 2 $M_\odot$ protostellar clump at two evolutionary times. The edge-on bolometric fluxes are a factor of 0.2 and 0.07 (respectively) less than what they would be for an isotropic source, whereas the pole-on bolometric fluxes are a factor of 2.6 and 2.9 greater. Moreover, the edge-on flux is dominated by the far infrared, which is far less effective at radiatively accelerating dusty gas than the mid- and near-infrared seen pole-on.

Although the flashlight effect allows dusty material to come close to the central source via a circumstellar disk, the material to be accreted eventually encounters optical and UV radiation from the central source. A necessary requirement for this material to be accreted rather than "blown out" by radiation is that the dust has been largely destroyed (or it has coagulated into larger particles) so that the opacity is dominated by the gaseous component.

Even though no massive disk has yet been directly observed around a main sequence massive star, there is much indirect evidence that such disks exist (Shepherd, Claussen, & Kurtz 2002). In their radio recombination maser studies and CO measurements Martin-Pintado et al. (1994) do find indirect evidence for both an ionized stellar wind and a neutral disk around MWC349. Moreover, several other high luminosity FIR sources — suspected embedded young OB stars — have powerful bipolar outflows associated with them (e.g., Eiroa et al. 1994; Shepherd et al. 2002). Such massive outflows are probably powered by

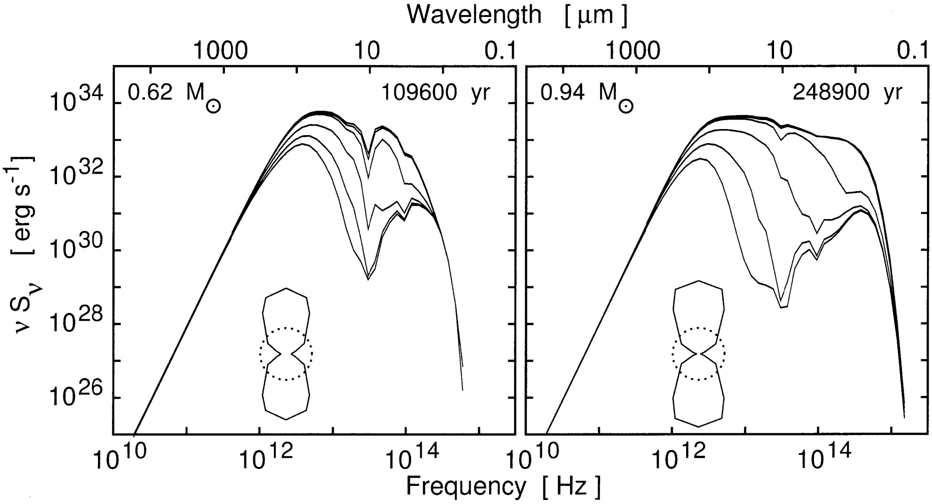

Figure 5. SEDs of a 0.13 pc protostellar clump at viewing angles: 0° (pole-on), 20°, 30°, 60°, 75°, and 90°. Accreted core mass (*upper left*) and time after hydrostatic core formation (*upper right*) are given in each frame. In insets the "beam pattern" of the bolometric luminosity (vertical corresponds to pole-on) is compared to that of an isotropic source (*dotted line*) *[adapted from Yorke & Bodenheimer 1999]*.

disk accretion, and, similar to their low mass counterparts, the flow energetics appear to scale with the luminosity of the source (see Cabrit & Bertout 1992; Shepherd & Churchwell 1996; Richer et al. 2000).

If the primary source of the massive star's material is from the surrounding molecular clump via accretion, then a circumstellar disk should be the natural consequence of the star formation process even in the high mass case. However, it should be difficult to observe disks around massive stars. The high FUV and EUV fluxes associated with high mass stars will begin to photoevaporate the disks on timescales of $\sim 10^5$ yr (Hollenbach et al. 2000), which will be observable as deeply embedded UCHIIs with comparable lifetimes (Richling & Yorke 1997).

c) Increase Gravity: For completeness I mention the fact that the gravitational acceleration is enhanced with respect to radiative acceleration when massive stars form within a dense cluster of not so brightly radiating objects. For this to have a dominant effect we require that $\rho_{\rm objects} \gg \rho_{\rm gas}$. In this scenario one requires a density-peaked cluster of low mass objects embedded within a molecular cloud. The effective gravity near the cluster's center is enhanced relative to an isolated molecular cloud without the cluster and relative to off-center regions of the molecular cloud. If this were the only way to form massive stars, isolated massive stars may not exist at all or only in very exceptional cases.

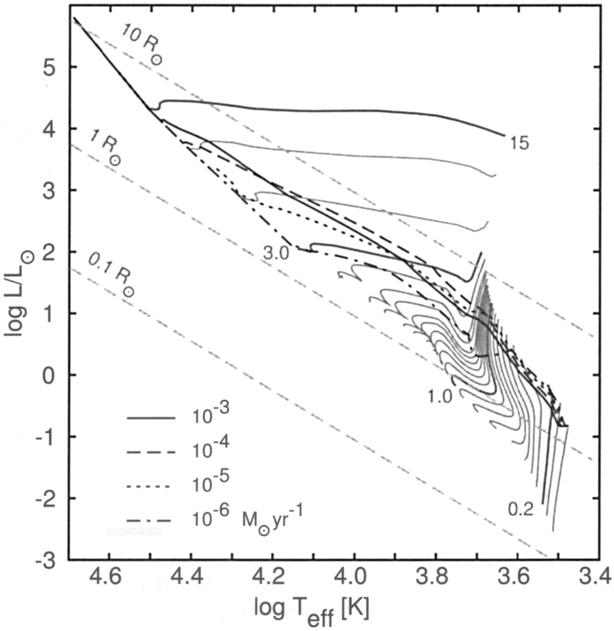

Figure 6. Pre-main sequence tracks of accreting (proto-)stars in the HR diagram for the given constant accretion rates are compared to published tracks (*grey lines*) of non-accreting pre-main sequence stars (D'Antona & Mazzitelli 1994; Iben 1965). All "accreting" tracks are assumed to begin at the "birthline" of an equilibrium deuterium burning 0.1 M$_\odot$ pre-main sequence star [adapted from Yorke 2002].

4. What happens to the central (Proto-)Star during Accretion?

Because the luminosity is so critical during accretion up to high stellar masses, one must also consider the luminosity evolution of the accreting object. As discussed by Maeder (2002) and Yorke (2002) an initially low mass object that gains mass through accretion evolves substantially differently in the Hertzsprung-Russell (HR) diagram than a non-accreting protostar would (see Fig. 6).

Yorke's (2002) tracks are qualitatively similar to the more detailed calculations by Behrend & Maeder (2001) and Meynet & Maeder (2000). Differences can be attributed to the starting mass, 0.1 M$_\odot$ instead of 1 M$_\odot$, and the differing accretion rates. In all cases published to date, not only do the tracks of accreting objects consistently lie slightly below the equilibrium deuterium burning "birthline", but the qualitative effect of more rapid accretion is to shift the tracks to even smaller radii away from the "birthline". Indeed, the concept of "birthline" is no longer valid for stars more massive than $M_* \gtrsim 0.7$ M$_\odot$, because deuterium is consumed faster than it can be accreted. The tracks of accreting stars eventually converge to the main sequence and follow along the ZAMS as more material is added. For e.g. an accretion rate of 10^{-3} M$_\odot$, hydrogen-burning begins at $t \simeq 1.3 \times 10^4$ yr, after ~13 M$_\odot$ have accreted.

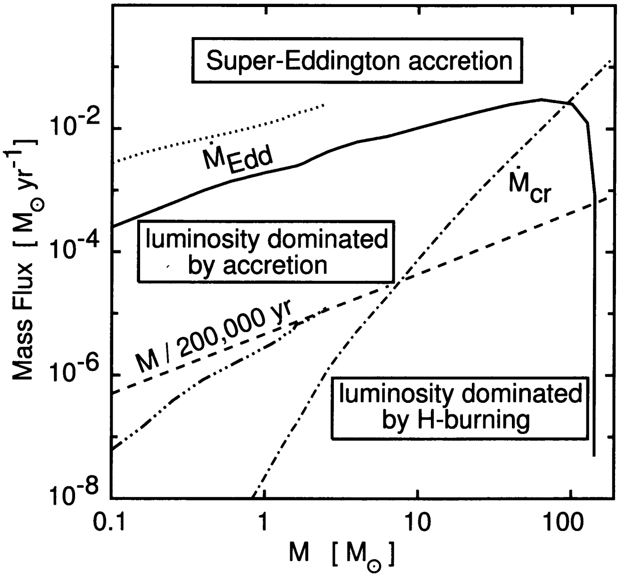

Figure 7. Relevant mass accretion rates onto existing stars of mass M as discussed in text.

I remind the reader that these tracks in the HR diagram do not reflect the actual observable bolometric luminosities of accreting protostars. Much of the accretion luminosity $L_{\rm acc}$ will be indistinguishable from the intrinsic luminosity L_* of the star. The importance of accretion luminosity, $L_{\rm acc} \sim GM\dot{M}/r$ is exemplified in Fig. 7. At $\dot{M}_{\rm cr} = L_* r/GM$ accretion luminosity and intrinsic luminosity are equal (*dash-dotted line* for core hydrogen-burning stars and *dash-triple dotted line* for birthline stars). Above this line the luminosity is dominated by accretion; below the line it is dominated by the intrinsic stellar luminosity.

What order of magnitude of mass accretion rate can be expected? In order to produce a star of mass M within, say 200,000 yr, an average accretion rate 5×10^{-5} $M_\odot$ yr^{-1} $[M/M_\odot]$ is necessary (*dashed line* in Fig. 7). Assuming this average accretion rate during the main accretion phase, we note that the luminosity of low mass stars is dominated by accretion luminosity, whereas for high mass stars the luminosity is initially determined by accretion but is eventually dominated by the intrinsic stellar luminosity. Of course the actual accretion rate may vary strongly from this average (see example given in Fig. 8). The maximum accretion rate possible onto a core hydrogen-burning star, assuming electron scattering and the effects of both the intrinsic stellar luminosity and accretion luminosity is given by the *solid line*. This maximum allowable accretion rate is modified for low mass stars if "birthline" stellar radii and luminosities are assumed (*dotted line*).

Yorke & Sonnhalter (2002) consider the collapse of isolated, rotating, nonmagnetic, massive molecular clumps of masses 30 $M_\odot$, 60 $M_\odot$ and 120 $M_\odot$ using an improved frequency-dependent radiation hydrodynamics code (see Fig. 8). The flashlight effect discussed in section 3 allows material to enter into the

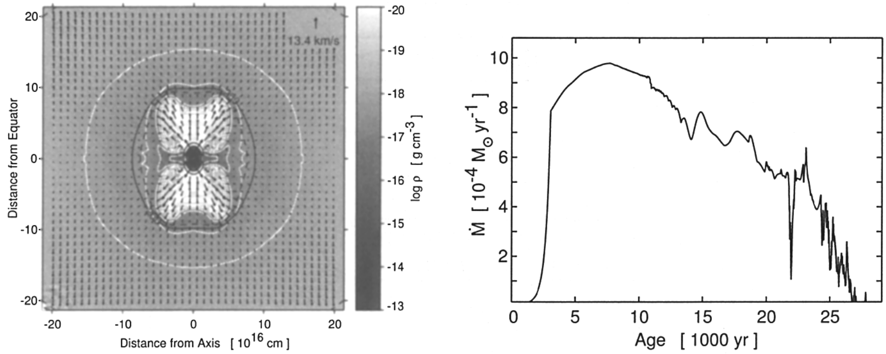

Figure 8. **Left:** Distribution of density (*grey-scale*), velocity (*arrows*), temperature of amorphous carbon grains (*solid black contour lines*), and temperature of silicate grains (*dotted contour lines*) for the 60 $\mathrm{M}_\odot$ case of Yorke & Sonnhalter (2002) at $t = 25,000$ yr, after which 33 $\mathrm{M}_\odot$ have accreted onto the core. **Right:** Time dependent mass accretion rate of central object for 60 $\mathrm{M}_\odot$ case shown at left.

central regions through a disk. For massive stars it is important to take into account the frequency dependent nature of the opacity and the flux within the disk (rather than assuming either Rosseland or Planck “grey” opacities). For their 60 $\mathrm{M}_\odot$ case Yorke & Sonnhalter find that 33.6 $\mathrm{M}_\odot$ are accreted in the central regions as opposed to 20.7 $\mathrm{M}_\odot$ in a comparison “grey” calculation. Because these simulations cannot spatially resolve the innermost regions of the molecular clump, however, they cannot distinguish between the formation of a dense central cluster, a multiple system, or a single massive object. They also cannot exclude significant mass loss from the central object(s) which may interact with the inflow into the central grid cell. With the basic assumption that all material in the innermost grid cell accretes onto a single object, they are only able to provide an upper limit to the mass of stars which could possibly be formed.

One can speculate on the affect that outflows will have on the accretion through an accretion disk. The inner part of the accretion disk could well look like the configuration shown in Fig. 9. Radiation and the stellar wind from the central star (presumably already hydrogen-burning) evacuate a cavity in the polar direction as shown in the example depicted in Fig. 8. At the interface between the supersonic outflowing stellar wind and the denser subsonic HII disk atmosphere some disk material will be removed but it is unlikely that this can prevent inward flow of disk material. Inward radial flow of dusty molecular gas is allowed in the equatorial plane of the disk (assuming angular momentum is transfered outward) because of the low radially directed radiation flux (flashlight effect). Angular momentum transfer could result from either magnetic fields in the disk or from the tidal effect of nearby stars. Indeed, rapid accretion through a disk may be a direct consequence of having nearby companions, thus explaining why massive stars are generally members of multiple systems.

Once the disk material crosses $r_{\mathrm{dust}} \sim 25\,\mathrm{AU}\,[M_*/30\,\mathrm{M}_\odot]^{1.6}$, the radius of dust destruction, its opacity decreases and it is not easily stopped by radiation.

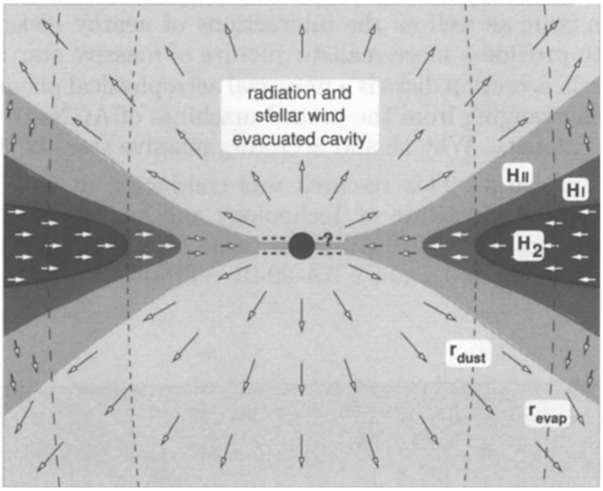

Figure 9. The inner accretion disk: inward radial flow is allowed in the equatorial plane. A polar cavity is evacuated by a combination of radiation and the stellar wind. The disk itself is self-shielded from the intense EUV field by an ionization front separating HII and HI gas and from the FUV field interior to the HI/H_2 interface by dust, molecular hydrogen, and CO. The dust is destroyed at $r_{\rm dust}$. Interior to $r_{\rm evap}$ even the ionized gas is gravitationally bound.

It is, however, still unclear how the disk material ultimately flows onto the star. Surely, the disk "puffs up" close to the star, in analogy to the accretion disks in AGNs. Outside of $r_{\rm evap} \sim 130\,{\rm AU}\,[M_*/30\,{\rm M}_\odot]$, where the escape velocity is less than 10 km s^{-1}, the disk loses material via photoevaporation on a time scale of $\sim 10^5$ yr. This is of the same order as the accretion time scale; these competing effects will determine the final mass of the star.

5. Discussion and Conclusions

Massive stars can in principle be formed via accretion through a disk. An accreting star quickly evolves to the main sequence after about 10 $M_\odot$ have accreted, but the star is not readily observable as such. Still obscured by the material in the vicinity, the appearance will be that of an UCHII region. Radiative acceleration, photoevaporation, and stellar winds eventually destroy the disks, but prior to this accretion onto the star provides an additional source of luminosity. This accretion is expected to be highly variable and episodic. A powerful radiation-driven outflow in the polar directions and a "puffed-up" (thick) disk result from the high luminosity of the central source. The details of how disk material ultimately flows onto the star is still unclear — as is often the case for accretion disks in general.

In this report I have not addressed the issues of embryo multiple systems (binaries, etc.) which compete for accretable material. Future studies will have to address this issue as well as the interactions of nearby disks with multiple massive stars to provide a more realistic picture of massive star formation.

Accretion via accretion disks is a universal astrophysical phenomenon, which operates at scales ranging from the central machines of AGNs to X-ray binaries and perhaps to planets. Why should accreting massive stars be an exception?

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References

Behrend, R., Maeder, A. 2001, A&A, 373, 190

Bonnell, I.A., Bate, M.R., Zinnecker, H. 1998 MNRAS, 298, 93

Bonnell, I.A., 2002, PASP, 267, ed. P.A. Crowther, 193

Cabrit, S., Bertout, C. 1992, A&A, 261, 274

D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467

Eiroa, C., Casali, M. M., Miranda, L. F., Ortiz, E. 1994, A&A, 290, 599

Hollenbach, D., Yorke, H.W., Johnstone, D. 2000, in *Protostars and Planets IV*, eds. Mannings, Boss, Russell, (Tucson: Univ. Ariz. Press), p. 401

Iben, I., Jr. 1965, ApJ, 141, 993

Kahn F.D. 1974, A&A, 37, 149

Maeder, A, 2002, In: Highlights of Astronomy, Vol. 12, ed. H. Rickman, p. 170

Mathis, J.S., Rumpl, W., Nordsieck, K.H. 1977, ApJ, 217, 425

Martin-Pintado, J., Neri, R., Thum, C., Planesas, P., Bachiller, R. 1994, A&A, 286, 890

McKee, C.F., Tan, J.C., 2003, ApJ, 585, 850

Meynet, G., Maeder, A. 2000, A&A, 361, 101

Nakano T., Hasegawa T., Norman C. 1995, ApJ 450, 183

Preibisch, T., Ossenkopf, V., Yorke, H.W., Henning, T., 1993, A&A, 279, 577

Richer, J. S., Shepherd, D. S., Cabrit, S., Bachiller, R., Churchwell, E. 2000, in *Protostars & Planets IV*, ob. cit., p. 867

Richling, S., Yorke, H.W. 1997, A&A, 327, 317

Shepherd, D.S., Churchwell, E. 1996, ApJ, 472, 225

Shepherd, D.S., Claussen, M.J., Kurtz, S.E., 2002, PASP, 267, ed. P.A. Crowther, 415

Suttner G., Yorke H.W. 2001, ApJ, 551, 461

Wolfire M.G., Cassinelli J.P. 1987, ApJ, 319, 850

Yorke, H.W., 1986, ARAA, 24, 48

Yorke, H.W., 2002, PASP, 267, ed. P.A. Crowther, 165

Yorke, H.W., Bodenheimer, P. 1999, ApJ, 525, 330

Yorke, H.W., Krügel, E. 1977, A&A, 54, 183

Yorke, H.W., Sonnhalter, C., 2002, ApJ, 569, 846

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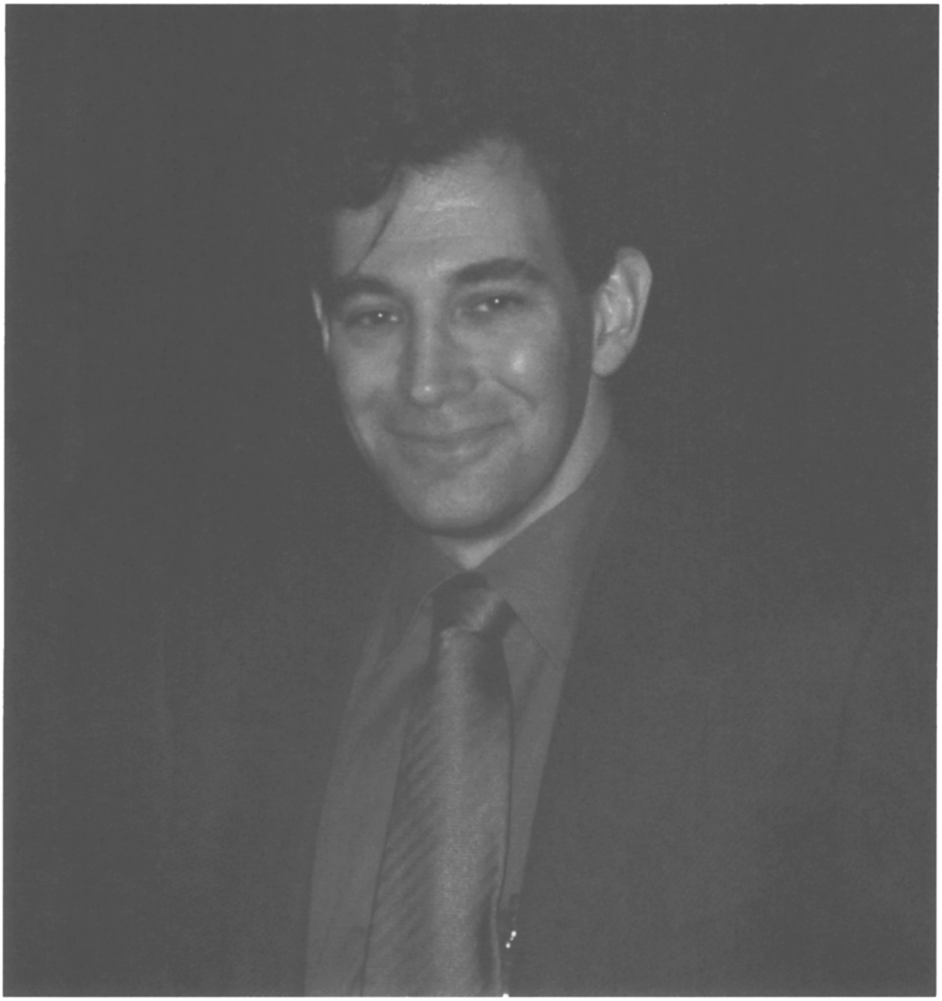

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