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How Radiation Feedback Affects Fragmentation and the IMF

Mark R. Krumholz

Astronomy Department, Interdisciplinary Sciences Building, University of California, Santa Cruz, CA 95064, USA

Abstract. The stellar initial mass function (IMF) is determined by a process of fragmentation and accretion in the opaque, dense center of a giant molecular cloud. This environment effectively traps radiation from newborn stars, and the interaction between the gas and the radiation is the dominant feature controlling the thermodynamics and in some extreme cases the bulk motion of the gas. Not surprisingly, radiation feedback therefore plays a dominant role in determining how gas fragments to produce the IMF. In this contribution I focus on simulations exploring two radiative effects particularly relevant to the formation of massive stars: suppression of fragmentation by radiative heating, and interruption of accretion by radiation pressure. Contrary to past theoretical expectations, simulations show that the former is a dominant effect that may ultimately control when and where massive stars form, while the latter does not appear to have a significant effect on stellar masses.

1. Introduction

For much of the past decade of star formation simulations, it has been common to assume either that the molecular gas out of which stars form is isothermal, that its temperature can be described as a simple function of density, or that its temperature is controlled by radiative heating and cooling rates that are a function only of local gas properties (e.g. see the review by Klessen et al. 2009). These models have the virtue of being easy to compute, since they involve no non-local physics other than gravity. However, they also have a major weakness, in that they neglect the spatially and temporally non-uniform effects of heating by stars.

This neglect creates two problems, one applicable to all stars and the other specific to massive stars. First, as I discuss in § 2, the fragmentation of a molecular cloud into stars is strongly influenced by the gas temperature, and how the temperature varies with density. In the clustered environments where most stars form, radiation from embedded stars plays a dominant role in determining this, and thus it cannot be ignored if we are to obtain the correct initial mass function (IMF). As I discuss in § 3, for massive stars neglect of radiative feedback is particularly problematic because it means ignoring the classic problem of the radiation pressure barrier. To put it simply, massive stars can exert an outward radiation force on the dusty gas around them that is larger than the inward force of their gravity. Naively, this would seem to imply that sufficiently massive stars cannot form, or that there should be an upper limit to their masses. Obviously only simulations including radiation feedback can study this effect.

2. Thermal Feedback and Fragmentation

2.1. The Importance of Non-Isothermality

It has been clear since the work of Low & Lynden-Bell (1976) that the fragmentation of collapsing gas clouds is associated with departures from the isothermal regime that applies, at least approximately, in most molecular gas. The importance of deviations from isothermality in setting the stellar mass scale can be seen by considering the dimensionless numbers that describe the behavior of a cloud of magnetized, self-gravitating isothermal turbulent gas. (A more thorough discussion of this topic is given in McKee et al. 2010). Such a cloud possesses four types of energy: gravitational potential, thermal, bulk kinetic, and magnetic. From these we can form three dimensionless ratios, for example

$$\mathcal{M} = \frac{\sigma}{c_s} \qquad \beta = \frac{8\pi\rho c_s^2}{B^2} \qquad n_J = \frac{\rho L^3}{c_s^3/\sqrt{G^3\rho}}, \tag{1}$$

where c_s is the isothermal sound speed, σ is the non-thermal velocity dispersion, ρ is the mean density, B is the mean magnetic field, and L is the characteristic size of the cloud. These three numbers are the Mach number, the plasma β, and the Jeans number, describing the ratios of bulk kinetic energy to thermal energy, thermal energy to magnetic energy, and gravitational energy to thermal energy, respectively. All other dimensionless numbers commonly used to describe such clouds can be computed from these. For example the Alfvén Mach number (describing the ratio of kinetic to magnetic energy), the mass to flux ratio (gravitational over magnetic energy), and the turbulent virial ratio (kinetic over gravitational) are given by

$$\mathcal{M}_A = \mathcal{M}\sqrt{\frac{\beta}{2}} \qquad \mu_\Phi = \sqrt{\frac{\pi\beta}{2}} n_J^{1/3} \qquad \alpha_{\mathrm{vir}} = \frac{5}{6\pi}\left(\frac{\mathcal{M}}{n_J}\right)^2 \tag{2}$$

Now consider transforming a cloud by scaling the density, magnetic field, and size from their original values ρ, B, L to new values ρ', B', L' following

$$\rho' = x\rho \qquad B' = x^{1/2}B \qquad L' = x^{-1/2}L. \tag{3}$$

Examining equation (1), we see that such a scaling leaves all the dimensionless numbers for the system unchanged, and so the physical evolution of the system under this scaling must be similarly unchanged. Note, however, that the *mass* of the cloud, and of all the structures within it, does not remain unchanged by this scaling:

$$M' = \rho' L'^3 = x^{-1/2}\rho L^3 = x^{-1/2}M. \tag{4}$$

Thus we see that an isothermal cloud possesses no characteristic mass scale. Any evolutionary path that leads to the formation of 1 $M_\odot$ objects in such a cloud (or a simulation of such a cloud) can be rescaled to produce objects with a mass of 1 kg or 10^{10} $M_\odot$ equally well. We therefore learn an important lesson: the characteristic mass of stars must depend somehow on the way in which star-forming gas clouds deviate from isothermality.

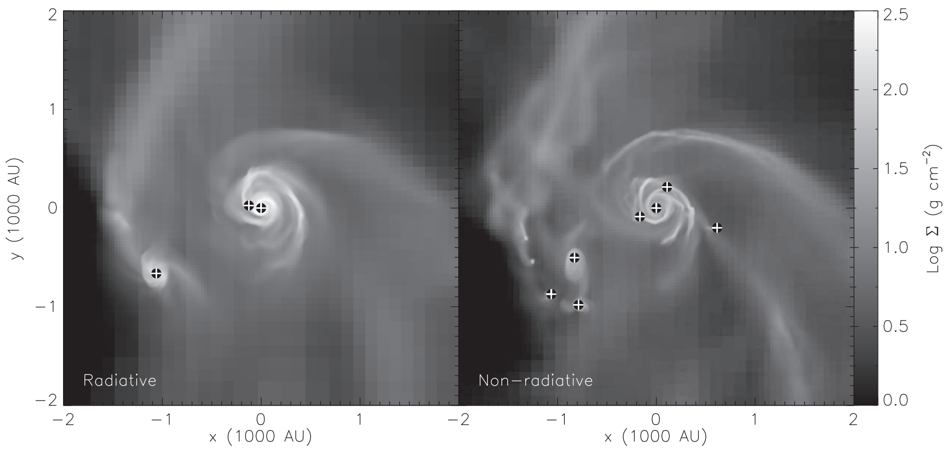

Figure 1. The two panels show the column density in the central region of two simulations of the collapse and fragmentation of a 100 $M_\odot$ protostellar core. Plus signs indicate the positions of stars. The simulations use identical initial conditions and numerical resolution, and differ only in that the one on the right uses an isothermal equation of state, while the one on the left includes stellar radiative feedback. For full details on the simulations, see Krumholz et al. (2007).

2.2. Radiative Feedback and Non-Isothermality

In low-density regions deviations from isothermality can arise due to subtle changes in molecular cooling or dust-gas coupling (Larson 2005). In dense regions, however, Krumholz (2006) points out that heating due to the accretion luminosity produced by the first few stars to form in the cluster is likely to be a far larger effect. This heating changes the effective equation of state from isothermal to steeper than isothermal, and this in turn suppresses fragmentation. Subsequent numerical simulations have confirmed this effect, both for individual massive protostellar cores (Krumholz et al. 2007) and for clusters of lower mass stars (Bate 2009; Offner et al. 2009; Urban et al. 2010). Figure 1 shows an example of a simulation in which, as a result of radiation feedback, a massive protostellar core is able to undergo monolithic collapse to a massive star rather than fragmenting. In the simulations of low mass, low density star cluster formation, radiation also suppresses the formation of brown dwarfs, solving the problem of overproduction of brown dwarfs observed in earlier simulations.

From the standpoint of the upper end of the IMF, the most interesting aspect of this work is that the effectiveness of radiation feedback in suppressing fragmentation and encouraging massive stars to form is a function of the star-forming environment. Radiation feedback is more effective in denser environments for two reasons. First, denser environments are more optically thick, so they trap radiation more effectively, allowing the same amount of stellar radiation output to heat more matter. Second, high density corresponds to short dynamical times. Since the mass accreted onto stars appears to be a roughly fixed fraction of the available mass per dynamical time (Krumholz & Tan 2007), mass accretes onto stars more rapidly in a denser environment. Since the energy release per gram of matter accreted onto stars is nearly independent of accretion rate or mass distribution for stars with masses $\sim 0.1 - 1$ $M_\odot$, this means that the higher

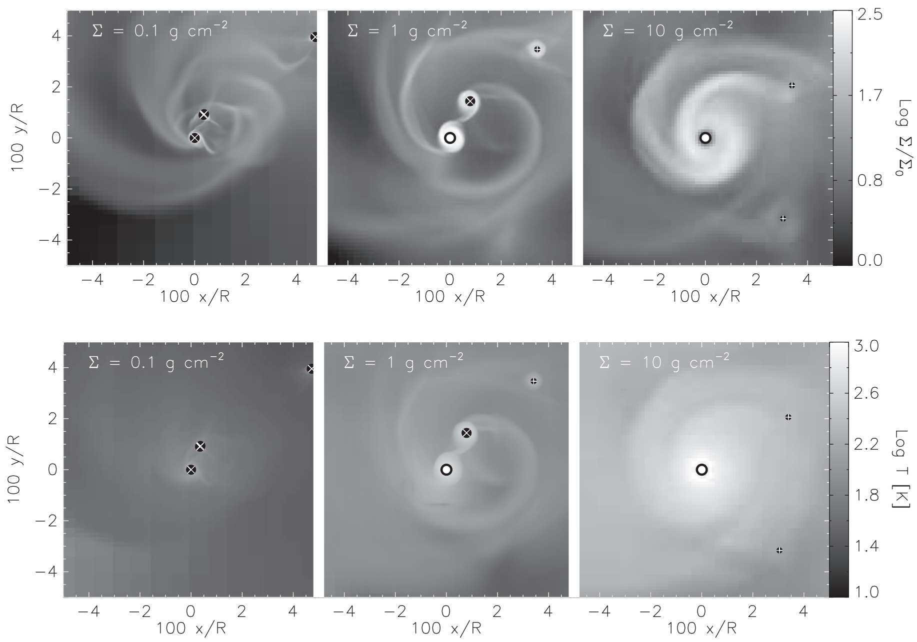

Figure 2. The three panels show the column density (top) and column density-weighted temperature (bottom) in three simulations of a 100 $M_\odot$ core with three different initial column densities, as indicated in the plot. Each simulation has been evolved for the same number of free-fall times at the initial mean density. The region shown is 10% of the initial cloud radius, centered at the system center of mass, and the color scale indicates column density relative to the initial mean value. Symbols indicate low mass stars (0.05 – 1 $M_\odot$, plus signs), intermediate mass stars (1 – 8 $M_\odot$, x's), and high mass stars (> 8 $M_\odot$, filled circles). Notice the absence of high mass stars in the low column density run. For full simulation details, see Krumholz et al. (2010).

accretion rates found in denser environments produce larger accretion luminosities and thus heat more matter. Combining these effects, Krumholz & McKee (2008) estimate that massive stars should begin to form as a result of suppressed fragmentation once cores reach surface densities of ~ 1 g cm^{-2} or more.

Numerical calculations by Krumholz et al. (2010) confirm this effect, finding that simulations starting from clouds with identical masses, virial ratios, and turbulent velocity fields, but different initial column densities, have very different fragmentation histories. Those with column densities well below 1 g cm^{-2} produce clusters of low mass stars but no massive stars, while those with column densities well above 1 g cm^{-2} produce massive stars. Figure 2 shows an example. The density distributions on large scales in these simulations are nearly identical, but on small scales the amount of fragmentation is radically less in the high column density case than in the low column density case. The obvious cause is the far higher gas temperature.

Intuitively, we can understand this effect by imagining that every accreting protostar has a sphere of influence around itself wherein its radiation suppresses further fragmentation. This sphere of influence includes more mass in a denser environment both because the star itself is brighter and because the radiation is trapped within the matter more effectively. At a critical column density of ~ 1 g cm^{-2}, a low mass star's sphere of influence can contain a mass many times its own. In this case, if a massive gas core surrounds that low mass star, it will fragment little or not at all, and it will instead be accreted onto the low mass star at the core center. The mass of the final star becomes limited by the mass supply in the core, not by fragmentation.

2.3. Implications for the Large-Scale IMF

An obvious implication of this work is that regions of star cluster formation with mean column densities significantly below ~ 1 g cm^{-2} should show systematic differences in their stellar mass distributions. In comparison, the typical galactic cluster-forming gas clumps has a mean surface density slightly below this value (e.g. see the data compiled in Figure 1 of Fall et al. 2010), and the cores, which should have somewhat higher column densities, probably reach this value. However, there is a large scatter about this mean, so that there are a minority of star-forming regions with low column densities. If we combine this with the observation that the protostellar core mass distribution appears identical in functional form to the observed stellar IMF (e.g. see Alves et al. 2007; Enoch et al. 2008; Rathborne et al. 2009, among many others), we arrive at a schematic picture for how the IMF will develop in different regions. In the typical star-forming cluster, cores have large enough column densities to avoid fragmentation, and the result is an IMF with the same functional form as the core mass function. In unusually low column density star-forming regions, on the other hand, massive cores may be present, but they fragment into many low mass stars rather than forming a single massive star. The result is an IMF that is systematically deficient in massive stars in protocluster of low column density.

It is not entirely clear how this effect translates to the galactic scale. The simulations discussed above all cover regions no more than a few pc in size, and often considerably less, and it is not clear how the column density on these small scales is related to the much lower column densities of giant molecular clouds averaged on $\sim 10 - 100$ pc size scales. Nonetheless, we might expect a general effect that large regions in which the mean column density is lower, such as outer galaxy disks, may be deficient in small-scale regions of high column density that are capable of generating massive stars.

3. Radiation Force Feedback for Massive Stars

A potential complication to this picture is that radiation not only suppresses fragmentation, it also provides a force that can oppose accretion onto sufficiently massive stars, a process first pointed out by Larson & Starrfield (1971) and Kahn (1974), and subsequently studied in one dimension by Yorke & Kruegel (1977) and Wolfire & Cassinelli (1987). The problem is simple to understand: as one ascends to higher stellar masses, stars are supported to an ever greater extent by radiation pressure rather than gas pressure. The force density exerted by radiation is $\kappa\rho F/c$, where κ is the specific opacity of the material, ρ is its density, F is the radiative flux, and c is the speed of light. Inside the star, the opacity is mostly electron scattering, corresponding to $\kappa = 0.34$ cm^2 g^{-1} for a Solar mix of H and He. Once light leaves the stellar surface, however, it encounters dusty interstellar matter for which κ is a factor of ~ 10 larger. (This is a typical opacity in the infrared for gas with a Milky Way dust to gas ratio. The opacity to direct ultraviolet starlight is far higher, but photons of this wavelength are all absorbed in a thin layer near the star and then down-converted to infrared, so the IR opacity is the important one.) If the radiation force is comparable to gravity within the star, this means it must greatly exceed the gravitational force outside the stars.

At first glance, this would seem to imply that massive stars cannot form out of normal interstellar material, and this is what spherically symmetric calculations indeed find. Since massive stars clearly do form, something must be wrong with this argument, but it does leave open the question of whether stellar masses are in fact limited by radiation pressure feedback. If so, one might expect this limit to depend on quantities such as the interstellar dust to gas ratio, and this would have dramatic implications for the IMF.

Fortunately, real life is not spherically symmetric, and in the 1980s and 1990s a number of researchers pointed out using analytic models that, in the presence of angular momentum, a collapsing massive core inevitably forms a disk. The disk helps reduce the effects of radiation pressure, because the stellar radiation is absorbed in a thin layer at the disk inner edge but is then re-radiated isotropically, allowing most of it to escape rather than hinder the inflow (e.g. Nakano 1989; Nakano et al. 1995; Jijina & Adams 1996). Protostellar outflow cavities enhance this beaming effect still further, potentially reducing the radiation force in the equatorial plane by a factor of ~ 4, comparable to the effect of the disk itself (Krumholz et al. 2005). However, none of the simulations published to date include outflows.

In two-dimensional numerical simulations, Yorke & Sonnhalter (2002) found that beaming by the disk allowed stars to grow to $\sim 20\ M_\odot$ in simulations using gray radiative transfer, and to $\sim 40\ M_\odot$ using a multi-group treatment of the radiation. After this point the radiation pressure reversed the infall. Very recently, Kuiper et al. (2010) have argued that this reversal of infall was a result of Yorke & Sonnhalter's limited numerical resolution, and that two-dimensional simulations with a very similar setup but higher resolution do not produce a reversal of the infall. Instead the star is able to continue to accrete unabated up to masses as high as any observed.

The only three-dimensional simulations of this process published to date are those of Krumholz et al. (2009), who also find that accretion is not halted by radiation. In the three dimensional simulations a $70\ M_\odot$ binary forms out of a $100\ M_\odot$ core, at at the end of the simulation $\sim 15\ M_\odot$ remained in the circumstellar environment and continued to accrete. In the simulation radiation is able to drive an expanding bubble above and below the accretion disk, but this bubble becomes unstable, breaking up into a series of optically thin channels through which radiation escapes, and optically thick fingers that channel matter onto the accretion disk (Figure 3). Radiation flows around rather than through the optically thick fingers, so that, even though the radiation force exceeds the gravitational force when averaged over 4π sr, the gravitational force is stronger than the radiation force over those solid angles through which the matter preferentially accretes. In this respect, the behavior is analogous to a Rayleigh-Taylor instability, but with radiation playing the role of the light fluid that is unable to hold up a heavy fluid (gas).

As a side note, these simulations also show that the accretion disk becomes gravitationally unstable and invariably produces a binary system rather than a single star.

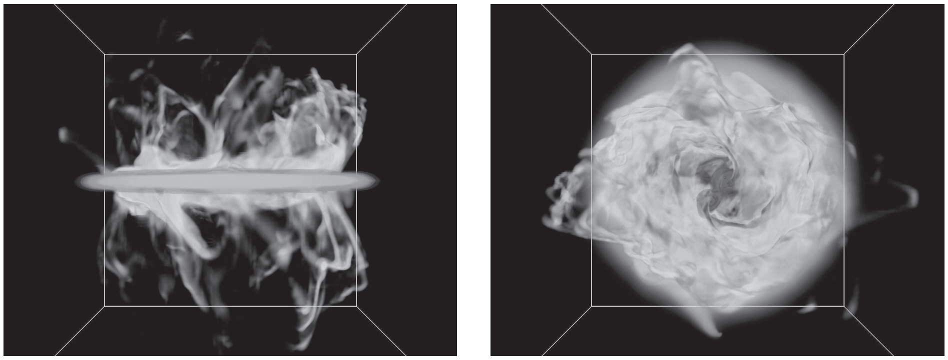

Figure 3. The two panels show edge-on (left) and face-on (right) volume renderings of the density structure around a high mass binary system formed in a simulation by Krumholz et al. (2009). Notice the dense fingers of gas above and below the accretion disk that channel matter onto the disk and thence onto the stars.

Fragmentation in the disk is reduced by radiation as it is in the core, but the buildup of matter in the disk is so large, and radiation is sufficiently excluded from the disk, that the disk is able to fragment even while the core is not. This nicely explains why massive stars are essentially always members of multiple systems, and it is possible that the orbital motion of the stars plays some role in driving the instability, by producing a rapidly time-varying radiation field at the bubble walls.

The bottom line of this numerical work is that there is no evidence that radiation pressure is capable of inhibiting accretion, even at very high stellar masses. Consequently, radiation force does not seem to play a role in setting the IMF. Instead, the masses of stars will be limited by the mass supply available in their parent cores (if they are sufficiently dense to avoid fragmentation) or by fragmentation choking off the mass supply (if they are not sufficiently dense).

4. Conclusions

Radiation feedback is crucial to determining the IMF, but the numerical simulations of it that have been performed over the past few years show that its role is quite the opposite of what one might naively have expected. As discussed in § 3, the classical problem of radiation pressure limiting accretion onto massive stars appears to be a mirage created by over-reliance in spherically symmetric models. When one simulates real three-dimensional clouds, or even two-dimensional ones at sufficient resolution, the result is that radiation pressure does not prevent accretion of gas onto massive stars. If the mass supply is sufficient, stars appear to grow without limit.

Indeed, rather than inhibiting accretion and the formation of massive stars, radiation seems to enhance it. That is because the gravitational fragmentation of gas is largely determined by how it deviates from being purely isothermal; fragmentation is suppressed in regions where the effective equation of state is stiffer than isothermal. In the clustered environments where most stars forms, radiation feedback is the dominant driver of non-isothermality, and it is capable of rendering large masses of gas hostile to fragmentation. The result is that, in sufficiently dense regions, the masses of stars end up being determined by the available mass supply in their parent cores. The IMF is therefore determined by the core mass function.

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