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FEEDBACK PROCESSES IN MASSIVE STAR FORMATION

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RESUMEN

Presentamos nuevos algoritmos para la inclusión eficiente de la retroalimentación radiativa en simulaciones hidrodinámicas de formación estelar masiva. La presión de radiación en polvo es estudiada en el contexto de acrecentamiento Bondi - Hoyle en cúmulos densos y la retroalimentación causada por fotoionización es incorporada en nubes moleculares altamente inhomogéneas.

ABSTRACT

We present new algorithms for the efficient inclusion of radiative feedback in hydrodynamic simulations of massive star formation. Radiation pressure on dust is studied in the context of Bondi Hoyle accretion in cluster cores and photoionisation feedback incorporated in highly inhomogeneous molecular clouds

Key Words: **H II REGIONS — ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

We describe new algorithms for modeling radiative feedback from massive stars that can be included in hydrodynamic star formation simulations. The two processes - radiation pressure on dust and photoionisation - are treated separately, as belonging to different evolutionary stages of the star formation process. (The former is generally effective during ongoing accretion onto the star, when the HII region is confined by ram pressure to small radii, whereas photoionisation becomes important after the cessation of accretion; see Lizano, this volume).

2. RADIATION PRESSURE ON DUST

Radiation from massive stars can melt dust in the surrounding flow out to a radius, r_d ($\sim$ a few hundred A.U.) where the dust temperature is $\sim 1500 - 2000$ K. At r_d, the incident radiation field is absorbed by dust within the short distance for which τ_{uv} (optical depth in the ultraviolet) of ~ 1, and, in this 'first strike', imparts to the dust/gas a momentum input rate of $\sim L_*/c$, where L_* is the luminosity of the central source. This stellar luminosity is re-emitted as thermalised infrared photons, which ultimately escape the dusty envelope around the star through radiative diffusion. This diffuse field causes a further momentum transfer between the central star and dust/gas at a rate of $\sim \tau_R L_*/c$, where τ_R is the Rosseland mean opacity of the envelope. Whereas τ_{uv} of the envelope is typically many hundreds, τ_R is of order unity. Thus the gas experiences two sources of momentum input of roughly comparable magnitude, one that is highly localised at the dust destruction radius, r_d, and the other that is distributed in the dusty envelope at larger radii.

Wolfire & Cassinelli 1986 (henceforth WC86) showed that use of grey opacity (such as the Rosseland mean) fails to reproduce the 'first strike' of the radiation at the inner edge of the dust shell. This is simply because the Rosseland mean formulation assumes thermal equilibrium between the radiation and the matter locally and thus ascribes to the dust at r_d an opacity appropriate to material that is a factor 10 cooler than the OB star's radiation field. Since the Rosseland mean dust opacity increases strongly with temperature , this severely under-estimates the opacity at r_d and the dynamical effect of the first strike of the radiation at r_d is artificially suppressed. Consequently, WC86 concluded that *radiative transfer calculations with grey opacity are likely to severely underestimate the efficacy of feedback through radiation pressure on dust.*

Nevertheless, most hydrodynamical studies of accretion onto OB stars have used grey opacities (e.g. Yorke & Kruegel 1977, Yorke & Bodenheimer 1999), since this has been, until recently, a computational necessity for 2D or 3D calculations. Most recently, Yorke & Sonnhalter (2002) presented the first 2D studies of disc accretion onto massive stars using full frequency dependent radiative transfer. Hopefully , despite the highly CPU intensive nature of such calculations, this initial study will be extended to a

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wider range of initial conditions.

Given the choice between the inadequacy of the Rosseland mean description and the computational costs of frequency dependent radiative transfer, Edgar & Clarke 2003 (henceforth EC03) proposed a simple algorithm which splits the radiation field into a component from the incident stellar field (attenuated with frequency dependent opacities) and remaining (diffuse) radiation field, treated by grey radiative diffusion . The algorithm reproduces the sharp deceleration of the flow at r_d, just as in the full frequency dependent calculations but is considerably cheaper than any involving full radiative transfer.

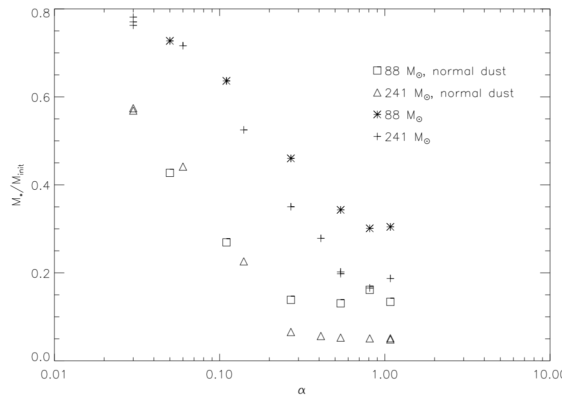

Fig. 1. Fraction of cloud mass ending up in star as a function of the initial ratio of thermal energy to gravitational energy. Symbols denote different cloud masses and normal or reduced dust opacities. (From EC03)

2.1. *Case Studies*

2.1.1. *Spherical collapse calculations*

In an influential paper, Wolfire & Cassinelli (1987) (henceforth WC87) argued that OB star formation is inhibited by radiation pressure on dust unless the grain opacity is reduced by an order of magnitude relative to its value in the ISM. This was based on their steady state accretion calculations onto massive stars , which require that the net acceleration is inwardly directed at the flow's outer edge.

EC03 used the above algorithm to re-examine the formation of OB stars in spherical symmetry, but unlike WC87, conducted *time dependent* hydrodynamic simulations. In this case, the outer edge of the flow does not need to always experience a net inward acceleration, as the cloud can collapse freely, prior to the switch on of a luminous object at its centre. Once the central object switches on, the infalling envelope *may* be able to accrete on to the star even when subject to a net outward force from radiation pressure on dust. How much this aids the formation of massive stars depends on the time history of the assembly of the central object. Efficient star formation (i.e. where a high fraction of the cloud mass can accrete onto the star) is most favoured by cold, initially homogeneous conditions, where the collapse is nearly homologous and a large fraction of the cloud mass arrives at the origin almost simultaneously. For warmer collapses, pressure gradients cause a larger spread in arrival times at the origin and more of the initial cloud mass is still slowly infalling when the central star switches on. Consequently, the efficiency is lower for warmer collapses (see Figure 1).

Figure 1 shows that arbitrarily high stellar masses can be attained (even for full interstellar dust opacity) if one starts with sufficiently cold and massive clouds. Otherwise, final masses tend to cluster around $10M_\odot$, due to the steep rise in the ultraviolet luminosity of stars in this mass range. The observed IMF, by contrast, is featureless in this region. This suggests that, though these simulations show that massive star formation in spherical symmetry is less affected by radiation pressure on dust than hitherto thought, the actual star formation process is still less sensitive to this effect than our simulations. It has yet to be shown that other modes of OB star formation (e.g. disc accretion) can avoid over-producing stars with masses close to $10M_\odot$.

2.1.2. *Accretion in Bondi Hoyle geometry*

Given the debate as to whether radiation pressure on dust is fatal to accretion models for massive star formation, Bonnell et al 1998 suggested that massive stars instead form through collisions in the cores of massive clusters. Collisions require that the centres of clusters can - albeit briefly - achieve very high stellar densities ($\sim 10^8$ stars pc $^{-3}$). In the hydrodynamical simulations of Bonnell & Bate 2002, high central densities result from shrinkage of the cluster core due to mass loading of central stars by accretion of inflowing gas. In such calculations (which omit feedback) the dominant accretion mode is Bondi Hoyle (BH) accretion (Bonnell et al 2001).

Edgar & Clarke (2004) (henceforth EC04) examined how radiation pressure on dust affects BH accretion using the ZEUS 2D code (Stone & Norman 1992) coupled to the above feedback algorithm. In the absence of feedback, BH accretion causes streamlines to be gravitationally focused and undergo a shock downstream of the star. Fluid elements within a critical impact parameter can then accrete onto the star by way of a radial accretion column (Bondi & Hoyle 1944). The fact that accretion is concentrated over a small range of solid angles, and thus involves a

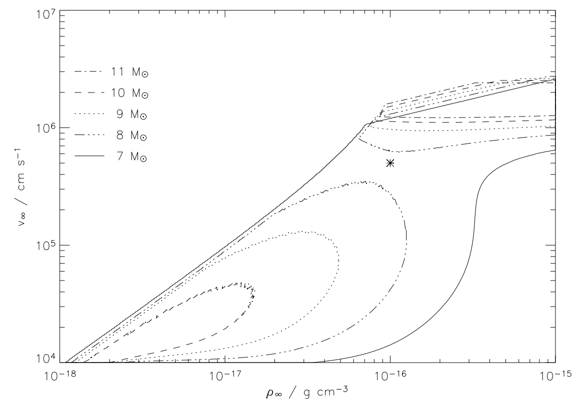

Fig. 2. Regions of parameter space of density v. velocity permitting Bondi Hoyle accretion (from EC04)

large radial ram pressure, suggests that BH geometry might be more favourable to accretion than spherical geometry (just as disc accretion is known to be more favourable than spherical accretion geometry; Yorke & Sonnhalter 2002).

The simulations of EC04 however demonstrated the opposite effect, since there are streamlines which, before reaching the accretion shock downstream of the star, intercept the dust destruction radius nearly tangentially. Such streamlines are thus very susceptible to deflection into outward flowing trajectories by even a modest impulse at r_d. The consequent density enhancement in the rear hemisphere of the dust destruction front further enhances the absorption of momentum from the diffuse field and the code fails to find an accretion solution.

EC04 used such simulations to show that a good criterion for successful BH accretion in the presence of feedback is to compare the ram pressure of the unperturbed flow in the upstream direction with the product of the photon momentum flux and the Rosseland optical depth in that direction. (Recall that the diffuse field deposits momentum into the flow at a rate $\sim \tau_R L_*/c$ and that for accretion to occur, the associated momentum flux must be at least matched by the radial ram pressure in the flow).

Figure 2 depicts the areas of parameter space that permit successful BH accretion. The upper left of the diagram is excluded, since the accretion timescale is then too long to create an OB star in 10^6 years. The other contours show how the permitted regions of parameter space shrink as stellar mass is increased, forming two islands of lower optical depth, either due to lower densities or higher velocities (which reduces the central concentration of the flow). Nevertheless, for normal dust abundances (as shown), there are apparently no accretion solutions for stars more massive than $\sim 11 M_\odot$.

We thus find that BH accretion geometry is much less favourable to massive star formation than even spherical geometry. EC04 thus concluded that *stars cannot grow to beyond* $\sim 10 M_\odot$ *by BH accretion, and that all more massive stars must instead* (in these models) *form through stellar collisions.* This feedback effect is shortly to be incorporated in cluster simulations, which will determine whether the driving of the cluster core to ultra high densities requires continued mass loading of stars above $10 M_\odot$. If it does not, further stellar growth can ultimately result from stellar collisions. A strong observational constraint on this scenario is that it must not leave behind an excess of objects with masses $\sim 10 M_\odot$.

3. RADIATIVE FEEDBACK THROUGH PHOTOIONISATION

Photoionisation dominates feedback on parsec scales in massive star forming regions. In particular, the expulsion of ionised gas from shallow potentials is likely to determine whether gravitationally bound clusters can form (e.g. Lada et al 1984, Tenorio Tagle et al 1986, Goodwin 1997, Geyer & Burkert 2001).

To date the evolution of HII regions has been extensively studied in a number of Eulerian simulations (Yorke et al 1989, Franco et al 1990, Garcia-Segura & Franco 1996). The use of grid based codes has however encouraged the study of rather idealised systems (i.e. the introduction of an already formed source into a smoothly varying medium with spherical or axial symmetry) Thus, despite our detailed knowledge of the complex density structure of molecular clouds, we still rely on estimates of how photoionisation limits star formation efficiency based on uniform cloud models (Whitworth 1979).

In order to study the photoionisation process as part of hydrodynamical star formation simulations, we need a method that can deal with the dynamically evolving and inhomogeneous conditions in simulations like those of Bate et al 2003. To this end, Dale (PhD thesis, 2004) has developed an algorithm for plumbing photoionisation feedback in a Smoothed Particle Hydrodynamic (SPH) code, loosely based on that of Kessel-Deynet et al 2000. The ionisation front is located at each timestep of the SPH code (and the temperature of the gas adjusted) using a Stromgren volume technique: i.e. the integrated recombinations along the path from the source to a particle are compared with the number of ionising photons emitted in the direction of that particle.

The method reproduces standard solutions for the evolution of HII regions in simple geometries

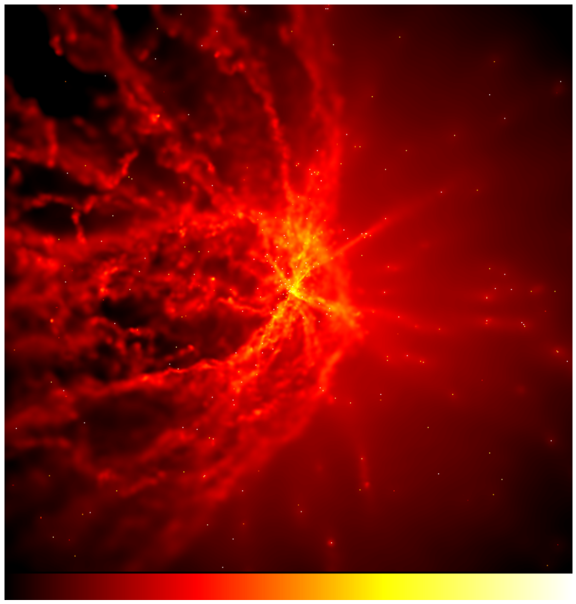

Fig. 3. Photoionised cloud structure from Dale et al 2004

(Spitzer 1978), and compares reasonably well (for complex density fields) with results from the MOCASSIN Monte Carlo radiative transfer code (Ercolano et al 2003). This shows that the diffuse radiation field is unimportant at the high densities of the simulation, and justifies the use of this algorithm (which is many orders of magnitude faster than the Monte Carlo code) in hydrodynamic codes.

Dale et al 2004 applied this photoionisation algorithm to a simulation of Bonnell & Bate (2002) of the formation of a massive star cluster. When the ionising source is switched on in the cluster core, the gas distribution is highly inhomogeneous, with several dense filaments converging radially on the central region. (Only one ionising sourve is introduced in this calculation, although the method can readily handle multiple radiation sources).

Ionising radiation exaggerates the anisotropic initial conditions (Figure 3), and, in the left hemisphere, has eroded several lower density channels, creating loosely collimated outflows. The opening angles, velocities and mass flow rates are similar to those observed near OB stars (Churchwell 1999), in support of Bonnell & Bate's surmise that such outflows are collimated by anisotropic cloud structure.

The simulation demonstrates both positive and negative feedback. Whilst photoionisation clearly lowers the mass inflow rate into the central regions (compared with a control simulation, without feedback), there is also considerable extra fragmentation due to lateral compression of dense (neutral) filaments between adjoining ionised outflow channels. The latter process is however under-resolved, so we cannot yet judge whether the net effect of feedback on the star formation rate is positive or negative.

It is particularly interesting to compare Figure 3 with a comparable simulation with an azimuthally smoothed density field, in which the HII region is entirely confined to the cluster core. In Figure 3, larger volumes of the cloud are influenced by photoionisation and the gas has absorbed enough thermal and kinetic energy to unbind the cluster. However, the unbound mass fraction is a mere few per cent, as this energy is absorbed by a small fraction of the mass in the low density channels, and the bulk of the cloud mass is hardly affected. Although much more effective feedback results in lower density simulations, we here stress the qualitative conclusion - that in realistically inhomogeneous clouds, the deposition of many times the cluster's binding energy in the gas does *not* necessarily imply that the cluster becomes unbound.

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