Radiative Transfer Simulations: Low-Mass Cores, Disks, and Protostars

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Abstract

Although radiative feedback is a key element in star formation, few simulations have included radiation transfer and studied its effects. Using the Orion adaptive mesh refinement (AMR) code, we simulate low-mass star formation in a turbulent molecular cloud. The 3D hydrodynamic simulations include both self-gravity and gray radiative transfer. We compare the distribution of stellar masses, accretion rates, and disk properties in the cases with and without radiation feedback. We find that the influence of radiative heating is mainly confined to a few thousand AU around the source. However, an increase of only a factor of two in gas temperature is sufficient to suppress disk fragmentation that would otherwise result in very low-mass stars or brown dwarfs. Finally, we present spectral energy distributions (SEDs) of the sources calculated with RADISHE. We compare these with SEDs of low-mass embedded protostars observed with Spitzer.

Introduction

Star formation occurs exclusively in dense turbulent molecular clouds. Simulations have shown that radiative transfer can have an important effect on the gas temperature and density configuration (Boss et al. 2000, Whitehouse & Bate 2006). Simulations have also shown that radiative heating from pre-existing high-mass sources can suppress the formation of nearby stars (Krumholz et al. 2007a). Krumholz et al. contrasted simulations of collapsing, turbulent high-mass cores using an isothermal equation of state to those using grey flux-limited diffusion (GFLD) radiation transfer. The isothermal calculation produced many low-mass fragments and no massive star, while the simulations with radiative transfer produced one star containing the majority of the mass and few companions. Comparisons of the temperature distribution, assuming a barotropic equation of state instead of radiative transfer, showed significant underestimation of the amount of heated gas and a lower maximum gas temperature. For massive cores, temperature discrepancies make the difference between producing a high-mass star versus a multiple system of low-mass stars. On this poster, we present adaptive mesh refinement (AMR) simulations with the code Orion including GFLD radiative transfer in order to investigate the role of radiative feedback on low-mass star formation.

Methodology

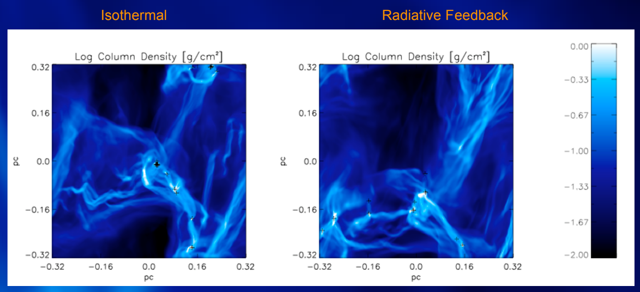
The simulations are performed using the parallel AMR code, Orion, which uses a conservative second order Godunov scheme to solve the equations of compressible gas dynamics (Truelove et al. 1998; Klein 1999). Orion solves the Poisson equation using multi-level elliptic solvers with multi-grid iteration. We model radiative transfer using the gray flux-limited diffusion approximation (Krumholz et al. 2007b). Throughout our calculations, we use the Truelove criterion to determine the addition of new AMR grids (Truelove et al. 1997), and we adopt a Jeans number of J=0.25. We insert sink particles in regions of the flow that have exceeded this density on the maximum level (Krumholz et al. 2004). Sink particles serve as numerical markers of collapsing regions and also, after sufficient mass accretion and lifetime, protostellar objects.

Parameters and Initial Conditions

$L = 0.65$ pc
$T = 10$ K
$M = 165$ Msun
$\rho = 4.46 \times 10^{-20}$ g/cm^3
$M_{1D} = 3$
$k = 1..2$
$dx_{max} = 30$ AU
Base $= 256^3$

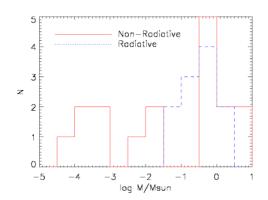
In addition to the calculation with radiative transfer we perform a calculation with the same initial conditions and an isothermal equation of state. We chose initial values such that the cloud falls on the linewidth-size relation (Heyer & Brunt 2004) and satisfies energy equipartition. We generate the initial turbulent conditions by applying perturbations with wavenumbers between k=1..2 to an initially constant density field. We use periodic boundary conditions for hydrodynamics and self-gravity, while using Marshak boundary conditions for the radiative transfer. This allows the shock heated gas to cool rather than trapping the radiation in the box. At three crossing times, we turn on gravity and follow the evolution of the cores with continued energy injection to maintain virial equilibrium.

Radiative Transfer vs. Isothermal Equation of State



The isothermal (left) and radiative transfer (right) simulations at 0.8 of a freefall time. The black crosses mark the locations of stars. Note that on the image scale some crosses overlap.

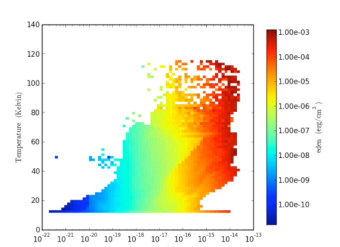
Initial Mass Function



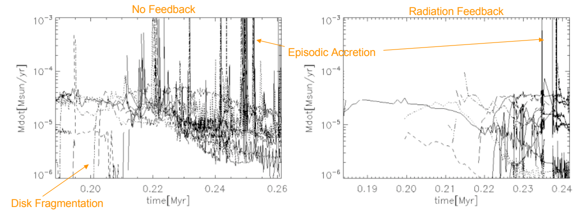
- Radiation suppresses disk fragmentation (i.e. no BDs are formed in the disks).
- Accretion rates are lower with radiation feedback.
- The star formation efficiency is lower in the simulation with radiative feedback (4% vs. 9%).

Radiative Heating

The scatter plot on the right shows the distribution of gas temperatures vs. densities with the colorbar indicating the total energy. The highest gas temperatures are around 120 K and the minimum temperature is 10 K, a value which is set by the radiation boundary conditions. Since the densest cells are generally near stars, they tend to be hot and contain larger velocities either because they are infalling or part of an accretion disk. Hence, the highest density cells correspond to the largest energies and comprise most of the heated gas.



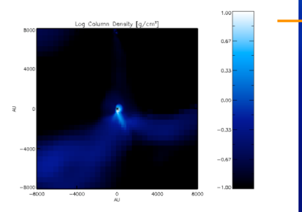
Accretion Rates



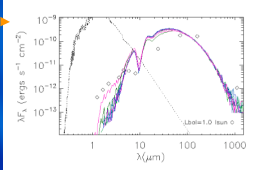
- Each line style represents a different protostar.
- Typical observed Class 0-1 accretion rates are 2 x 10^{-6} Msun/yr.
- About 5% of such sources have high accretion (Enoch et al. 2008).

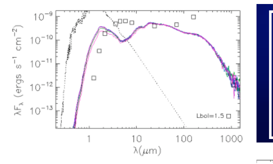
SEDs of Embedded Protostars

We use the Monte Carlo radiative transfer code RADISHE to post-process the simulations to order to obtain spectral energy distributions (Chakrabarti & Whitney 2009). For the core envelope, we adopt the dust model of Whittet et al. (2001). The disk dust grains are described by Cotera et al. (2001), where we define the disk as gas with density greater than $n_{H2} = 2 \times 10^7$ cm^{-3}. Note that we do not include outflows, which may affect the SED shape depending upon their orientation and opening angle.



L* = 9 Lsun
M* = 1.6 Msun
R* = 5 Rsun
T* = 4200 K
Menv = 2.1 Msun
Σ = 1.0 g/cm^2
Rdisk ~ 350 AU

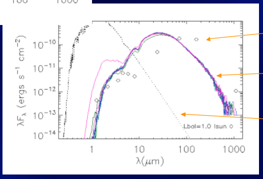




L* = 1 Lsun
M* = 0.4 Msun
R* = 6 Rsun
T* = 3000 K
Menv = 3.0 Msun
Σ = 0.9 g/cm^2
Rdisk ~ 200 AU

The colored lines give the SED for 10 different inclination angles. The dotted black line shows the spectra for a stellar atmosphere of 3500 K. A Class I source from Enoch et al. (2008) is overplotted, where the source bolometric luminosity, Lbol, is labeled and the calculated SED is scaled to that luminosity for comparison.

L* = 7 Lsun
M* = 1.5 Msun
R* = 10 Rsun
T* = 3000 K
Menv = 0.6 Msun
Σ = 2.5 g/cm^2
Rdisk ~ 350 AU



Enoch et al. (2008) data for a source in Perseus

Simulation post-processed with RADISHE

Stellar atmosphere of 3500 K

Conclusions

- Radiative transfer produces a significantly different result than an isothermal equation of state in simulations of low-mass star formation.
- Radiative feedback heats the accretion disks, suppressing disk fragmentation and lowering the average accretion rate.
- Heating is mainly confined to the core envelope, and hence star formation in nearby areas is not affected.
- Post-processing with RADISHE yields SEDs similar to Class I sources in local star-forming regions.

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