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Non-isothermal gravoturbulent fragmentation: effects on the IMF

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Abstract. Identifying the processes that determine the initial mass function of stars (IMF) is a fundamental problem in star formation theory. One of the major uncertainties is the exact chemical state of the star forming gas and its influence on the dynamical evolution. We study the effect of a piecewise polytropic EOS on the formation of stellar clusters in turbulent, self-gravitating molecular clouds using three-dimensional, smoothed particle hydrodynamics simulations. In these simulations stars form via a process we call gravoturbulent fragmentation, i.e., gravitational fragmentation of turbulent gas. To approximate the results of published predictions of the thermal behavior of collapsing clouds, we increase the polytropic exponent γ from 0.7 to 1.1 at some chosen density n_c, which we vary from $4.3 \times 10^4\,\mathrm{cm}^{-3}$ to $4.3 \times 10^7\,\mathrm{cm}^{-3}$. The change of thermodynamic state at n_c selects a characteristic mass scale for fragmentation $M_{\rm ch}$, which we relate to the peak of the observed IMF. A simple scaling argument based on the Jeans mass $M_{\rm J}$ at the critical density n_c leads to $M_{\rm ch} \propto n_c^{-0.95}$. Our simulations qualitatively support this hypothesis, but we find a weaker density dependence of $M_{\rm ch} \propto n_c^{-0.5\pm0.1}$. Our investigation generally supports the idea that the distribution of stellar masses depends mainly on the thermodynamic state of the star-forming gas. The thermodynamic state of interstellar gas is a result of the balance between heating and cooling processes, which in turn are determined by fundamental atomic and molecular physics and by chemical abundances. Given the abundances, the derivation of a characteristic stellar mass can thus be based on universal quantities and constants.

Key words. stars: formation – methods: numerical – hydrodynamics – turbulence – equation of state – ISM: clouds

1. Introduction

One of the fundamental unsolved problems in astronomy is the origin of the

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stellar mass spectrum, the so-called initial mass function (IMF). Observations suggest that there is a characteristic mass for stars in the solar vicinity. The IMF peaks at this characteristic mass which is typically a few tenths of a solar mass. The IMF has a nearly power-law form for larger masses and declines rapidly towards smaller masses (Scalo 1998; Kroupa 2002; Chabrier 2003).

Although the IMF has been derived from vastly different regions, from the solar vicinity to dense clusters of newly formed stars, the basic features seem to be strikingly universal to all determinations (Kroupa 2001). Initial conditions in star forming regions can vary considerably. If the IMF depends on the initial conditions, there would thus be no reason for it to be universal. Therefore a derivation of the characteristic stellar mass that is based on fundamental atomic and molecular physics would be more consistent.

There are many ways to approach the formation of stars and star clusters from a theoretical point of view. In particular models that connect stellar birth to the turbulent motions ubiquitously observed in Galactic molecular clouds have become increasingly popular in recent years. See, e.g., the reviews by Larson (2003) and Mac Low & Klessen (2004). The interplay between turbulent motion and self-gravity of the cloud leads to a process we call gravoturbulent fragmentation. The supersonic turbulence ubiquitously observed in molecular gas generates strong density fluctuations with gravity taking over in the densest and most massive regions (e.g. Larson 1981; Fleck 1982; Padoan 1995; Padoan et al. 1997; Klessen et al. 1998, 2000; Klessen 2001; Padoan & Nordlund 2002). Once gas clumps become gravitationally unstable, collapse sets in. The central density increases until a protostellar objects form and grow in mass via accretion from the infalling envelope.

However, current results are generally based on models that do not treat thermal physics in detail. Typically, they use a simple equation of state (EOS) which is isothermal with the polytropic exponent $\gamma = 1$. The true nature of the EOS remains a major theoretical problem in understanding the fragmentation properties of molecular clouds.

Recently Li et al. (2003) conducted a systematic study of the effects of a varying polytropic exponent γ on gravoturbulent fragmentation. Their results showed that γ determines how strongly self-gravitating gas fragments. They found that the degree of fragmentation decreases with increasing polytropic exponent γ in the range $0.2 < \gamma < 1.4$ although the total amount of mass in collapsed cores appears to remain roughly consistent through this range. These findings suggest that the IMF might be quite sensitive to the thermal physics. However in their computations, γ was left strictly constant in each case. In this study we extend previous work by using a piecewise polytropic equation of state changing γ at some chosen density. We investigate if a change in γ determines the characteristic mass of the gas clump spectrum and thus, possibly, the turn-over mass of the IMF.

2. Thermal Properties of Star-Forming Clouds

Observed prestellar cores typically show a rough balance between gravity and thermal pressure (Benson & Myers 1989; Myers et al. 1991). Thus, the thermal properties of the dense star-forming regions of molecular clouds must play an important role in determining how these clouds collapse and fragment into stars.

As can be seen in Fig. 2 of Larson (1985), observational and theoretical studies of the thermal properties of collapsing clouds both indicate that at densities below about $10^{-18}\,\mathrm{g\,cm^{-3}}$, roughly corresponding to a number density of $n = 2.5 \times 10^5\,\mathrm{cm^{-3}}$, the temperature generally decreases with increasing density. This is due to the strong dependence of molecular cooling rates on density (Koyama & Inutsuka 2000). The resulting temperature-density relation can be approximated by a power law with an exponent of about −0.275, which corresponds to a polytropic equation of state with $\gamma = 0.725$.

At densities above $10^{-19}\,\mathrm{g\,cm^{-3}}$, star-forming cloud cores become opaque to the heating and cooling radiation that determines their temperatures at lower densities, and at densities above $10^{-18}\,\mathrm{g\,cm^{-3}}$ the gas becomes thermally coupled to the dust grains, which then control the temperature by their far-infrared thermal emission. The balance between compressional heating and thermal cooling by dust results in a temperature that increases slowly with increasing density, and the resulting temperature-density relation can be approximated by a power law with an exponent of about 0.075, which corresponds to $\gamma = 1.075$.

Thus the temperature-density relation can be approximated with a polytropic exponent γ that changes at a certain critical density n_c from a value below unity to a value above unity (Larson 1985; Spaans & Silk 2000).

3. Numerical Approach

To gain insight into how the characteristic stellar mass may depend on the critical density we carry out simulations of turbulent molecular cloud fragmentation. During gravoturbulent fragmentation it is necessary to follow the gas over several orders of magnitude in density. The method of choice therefore is smoothed particle hydrodynamics (SPH). Excellent overviews of the method, its numerical implementation, and some of its applications are given in reviews by Benz (1990) and Monaghan (1992). We use the parallel code GADGET, designed by Springel et al. (2001). SPH is a Lagrangian method, where the fluid is represented by an ensemble of particles, and flow quantities are obtained by averaging over an appropriate subset of SPH particles. The method is able to resolve large density contrasts as particles are free to move, and so naturally the particle concentration increases in high-density regions. We use the Bate & Burkert (1997) criterion for the resolution limit of our calculations. It is adequate for the problem considered here, where we follow the evolution of highly nonlinear density fluctuations created by supersonic turbulence.

Our version of the code replaces high-density cores with sink particles (Bate, Bonnell, & Price 1995). Sink particles accrete gas from their surroundings while keeping track of mass and momentum. This enables us to follow the dynamical evolution of the system over many local free-fall timescales. We include turbulence in our version of the code that is driven uniformly on large scales, with wave numbers k in the range $1 \leq k \leq 2$. The driving strength is adjusted to yield a constant turbulent Mach number $\mathcal{M}_{\mathrm{rms}} = 3.2$.

We compute models where the polytropic exponent changes from $\gamma = 0.7$ to $\gamma = 1.1$ at critical densities in the range $4.3 \times 10^4\,\mathrm{cm^{-3}} \leq n_c \leq 4.3 \times 10^7\,\mathrm{cm^{-3}}$. Each simulation starts with a uniform density distribution. The global free-fall timescale is $t_{\mathrm{ff}} \approx 10^5$ yr. We run our simulations with 1 million, 2 million or 5.2 million particles . For further details see Jappsen et al. (2004).

4. Dependence of the characteristic mass on the equation of state

Further insight into how the characteristic stellar mass may depend on the critical density can be gained from the mass spectra of the collapsed cores, which we show in Fig. 1. We plot the mass spectra at different times, when the fraction of mass accumulated in protostellar cores has reached approximately 10% and 30%. We used the same initial conditions, parameters and driving fields in all models shown. Dashed lines indicate the specific mass resolution limits.

We find closest correspondence with the observed IMF (see, Scalo 1998; Kroupa 2002; Chabrier 2003) for a critical density of $4.3 \times 10^6\,\mathrm{cm^{-3}}$ and for stages of accretion around 30% and above. At high masses, our distribution follows a Salpeter-

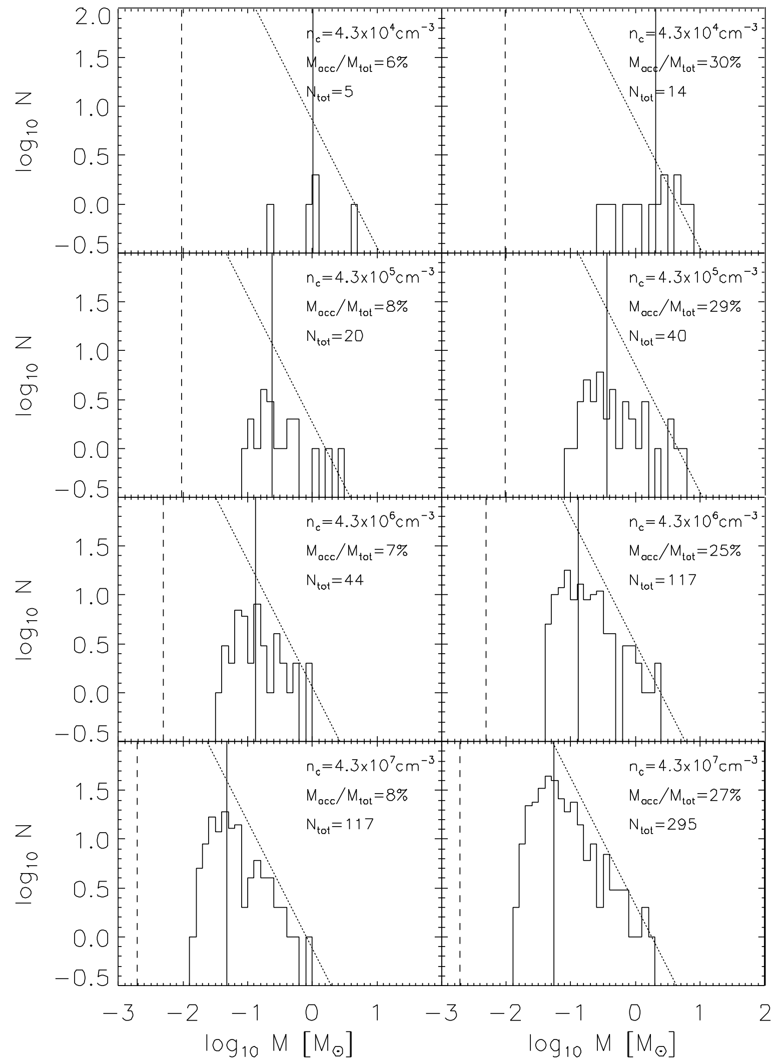

Fig. 1. Mass spectra of protostellar cores for four models with critical densities in the range $4.3 \times 10^4\,\mathrm{cm}^{-3} \leq n_\mathrm{c} \leq 4.3 \times 10^7\,\mathrm{cm}^{-3}$. We show two phases of evolution, when about 10%, 30% of the total mass has been accreted onto protostars. The *vertical solid line* shows the position of the median mass. The *dotted line* serves as a reference to the Salpeter value (Salpeter 1955). The *dashed line* indicates the mass resolution limit.

like power law. For comparison we indicate the Salpeter slope $x \approx 1.3$ (Salpeter 1955) where the IMF is defined by $\mathrm{d}N/\mathrm{d}\log m \propto m^{-x}$. For masses about the median mass the distribution exhibits a small plateau and then falls off towards smaller masses.

The top-row model where the change in γ occurs below the initial mean density, shows a flat distribution with only few, but massive cores. They reach masses up to $10\,M_\odot$ and the minimal mass is about $0.3\,M_\odot$. The distribution becomes more peaked for higher n_c and there is a

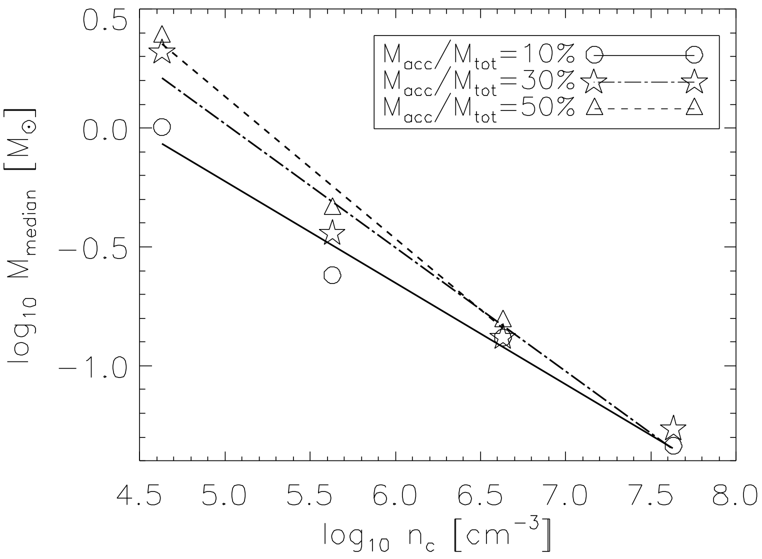

Fig. 2. Plot of the median mass of the protostellar cores $M_{\rm median}$ over critical density $n_{\rm c}$. We display results for different ratios of accreted gas mass to total gas mass $M_{\rm acc}/M_{\rm tot}$ and fit our data with straight lines. The slopes take the values: -0.43 ± 0.05 (*solid line*), -0.52 ± 0.06 (*dashed-dotted line*), -0.60 ± 0.07 (*dashed line*).

shift to lower masses. This change of median mass with critical density $n_{\rm c}$ is depicted in Fig. 2. The median mass $M_{\rm med}$ decreases clearly with increasing critical density $n_{\rm c}$. We fit our data with a straight line. The slope takes values between -0.4 and -0.6.

5. Discussion and Summary

Using SPH simulations we investigate the influence of a piecewise polytropic EOS on fragmentation of molecular clouds. We study the case where the polytropic index γ changes from a value below unity to one above at a critical density $n_{\rm c}$, and consider a range of different $n_{\rm c}$.

We investigate this relation numerically by changing γ from 0.7 to 1.1 at different critical densities $n_{\rm c}$ varying from $4.3 \times 10^4\,{\rm cm}^{-3}$ to $4.3 \times 10^7\,{\rm cm}^{-3}$. A simple scaling argument based on the Jeans mass $M_{\rm J}$ at the critical density $n_{\rm c}$ leads to $M_{\rm ch} \propto n_{\rm c}^{-0.95}$ (see Jappsen et al. 2004). If there is a close relation between the average Jeans mass and the characteristic mass of a fragment, a similar relation should hold for the expected peak of the mass spectrum. Our simulations qualitatively support this hypothesis, however, with the weaker density dependency $M_{\rm ch} \propto n_{\rm c}^{-0.5\pm0.1}$. The density at which γ changes from below unity to above unity selects a characteristic mass scale. Consequently, the peak of the resulting mass spectrum decreases with increasing critical density. This spectrum not only shows a pronounced peak but also a power-law tail towards higher masses. Its behavior is thus similar to the observed IMF.

Altogether, supersonic turbulence in self-gravitating molecular gas generates a complex network of interacting filaments. The overall density distribution is highly inhomogeneous. Turbulent compression sweeps up gas in some parts of the cloud, but other regions become rarefied. The fragmentation behavior of the cloud and its ability to form stars depend strongly on the EOS. If collapse sets in, the final mass of a fragment depends not only on the local Jeans criterion, but also on additional processes. For example, protostars grow in mass by accretion from their surrounding material. In turbulent clouds the properties of the gas reservoir are continuously changing. In a dense cluster environment, furthermore, protostars may interact with each other, leading to ejection or mass exchange. These dynamical factors modify the resulting mass spectrum, and may explain why the characteristic stellar mass depends on the EOS more weakly than expected.

Our investigation supports the idea that the distribution of stellar masses depends, at least in part, on the thermodynamic state of the star-forming gas. If there is a low-density regime in molecular clouds where temperature T sinks with increasing density ρ, followed by a higher-density phase where T increases with ρ, fragmentation seems likely to be favored at the transition density where the temperature reaches a minimum. This defines a characteristic mass scale. The thermodynamic state of interstellar gas is a result of the balance between heating and cooling processes, which in turn are determined by fundamental atomic and molecular physics and by chemical abundances. The derivation of a characteristic stellar mass can thus be based on quantities and constants that depend solely on the chemical abundances in a molecular cloud. The current study using a piecewise polytropic EOS can only serve as a first step. Future work will need to consider a realistic chemical network and radiation transfer processes in gas of varying abundances.

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