FRAGMENTATION OF MOLECULAR CLOUDS: THE INITIAL PHASE OF A STELLAR CLUSTER

RALF S. KLESSEN, ANDREAS BURKERT, AND MATTHEW R. BATE
Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

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ABSTRACT

The isothermal gravitational collapse and fragmentation of a region within a molecular cloud and the subsequent formation of a protostellar cluster are investigated numerically. The clump mass spectrum that forms during the fragmentation phase can be well approximated by a power-law distribution \(dN/dM \propto M^{-1.5}\). In contrast, the mass spectrum of protostellar cores that form in the centers of Jeans-unstable clumps and that evolve through accretion and \(N\)-body interactions is described by a lognormal distribution with a width that is in excellent agreement with observations of multiple stellar systems.

Subject headings: ISM: kinematics and dynamics — ISM: structure — methods: numerical — stars: formation

1. INTRODUCTION

Understanding the processes leading to the formation of stars is one of the fundamental challenges in astronomy and astrophysics. With the advent of new observational techniques and instruments, especially in the IR and radio wave bands, a vast amount of astronomical data about star-forming regions has been accumulated. However, on the theoretical side, not much progress has been made yet. Analytical models of the star formation process are restricted to describing the collapse of isolated, idealized objects (for an overview, see Whitworth & Summers 1985). Much the same applies to numerical studies (see, e.g., Bonnell & Bastien 1993; Boss 1997; Burkert & Bodenheimer 1996; Burkert, Bate, & Bodenheimer 1997; Nakajima & Hanawa 1996). Star formation is a complex self-gravitating, magnetohydrodynamic problem, which includes the effects of heating and cooling and the feedback processes from newly formed stars. Furthermore, it is influenced by the Galactic environment. Taking into account all these processes with high spatial resolution far exceeds the present computational capabilities.

Previous numerical simulations of the collapse and fragmentation of molecular cloud regions have shown that a large number of condensed objects can indeed form on a dynamical timescale as a result of gravitational fragmentation (see, e.g., Larson 1978; Monaghan & Lattanzio 1991; Keto, Lattanzio, & Monaghan 1991). In these studies, the clouds were treated as isolated gaseous spheres that collapsed completely onto themselves. Instead, we study a small region embedded in a large, stable molecular cloud complex where only the overdense regions are able to contract as a result of self-gravity. We assume that the molecular cloud is supported on large scales by turbulence and/or other processes. Previous numerical models were also strongly constrained by numerical resolution. Larson (1978), for example, used just 150 particles in a smoothed particle hydrodynamics–like simulation. Whitworth et al. (1995) and Turner et al. (1995) were the first to address star formation on larger scales in detail, using high-resolution numerical models. However, they studied a different problem: fragmentation and star formation in the shocked interface of colliding molecular clumps. While clump-clump interactions are expected to be abundant in molecular clouds, the rapid formation of a whole star cluster requires gravitational collapse on a larger scale that contains many clumps and dense filaments.

In this Letter, we extend previous studies of the collapse of isolated objects to the regime of the isothermal collapse and fragmentation of a gravitationally unstable region embedded in the interior of a molecular cloud. We present a high-resolution numerical model of the dynamical evolution and follow the fragmentation into dense protostellar cores. The temperature and the density are chosen such that the region is highly gravitationally unstable and forms a hierarchically structured protostellar cluster. The results of this study (i.e., the properties of the dense clumps and of the newly formed protostellar cores) are compared with observations.

2. NUMERICAL TECHNIQUE

To follow the time evolution of the system, we use smoothed particle hydrodynamics (SPH; for a review, see Monaghan 1992), which is intrinsically Lagrangian and can resolve very high density contrasts. The code is based on a version originally developed by Benz (1990). We adopt a standard description of artificial viscosity (Monaghan & Gingold 1983) with the parameters \(\alpha_v = 1\) and \(\beta_v = 2\). The smoothing lengths are variable in space and time such that the number of neighbors for each particle remains at approximately 50. The system is integrated in time using a second-order Runge-Kutta-Fehlberg scheme, allowing individual time steps for each particle (Bate, Bonnell, & Price 1995). Once a highly condensed object has formed in the center of a collapsing cloud fragment and has passed beyond a certain density, we substitute it with a “sink” particle, which then continues to accrete material from its infalling gaseous envelope (Bate et al. 1995). By doing so, we prevent the time steps of the code from becoming prohibitively small. This procedure implies that we cannot describe the evolution of gas inside such a sink particle. However, at some stage of the gravitational collapse, the SPH resolution limit (Bate & Burkert 1997) would be reached in the fragment anyway. For a detailed description of the physical processes inside a protostellar core (i.e., its further collapse and fragmentation), a new simulation that concentrates just on this single object, with the appropriate initial conditions taken from the larger scale simulation, would be necessary (Burkert, Klessen, & Bodenheimer 1998).

To achieve high computational speed, we have combined SPH with the special-purpose hardware device GRAPE (GRAvity PipE) (Sugimoto et al. 1990; Ebisuzaki et al. 1993), following the implementation described by Umemura et al. (1993) and, in greater detail, by Steinmetz (1996). Since we wish to describe a region in the interior of a globally stable
molecular cloud, we have to prevent global collapse. Therefore, we use periodic boundaries, applying the Ewald (1921) method in a Particle Mesh–like scheme (Klessen 1997). In this Letter, we present a simulation with 500,000 SPH particles.

3. INITIAL CONDITIONS FOR CLOUD FRAGMENTATION

The structure of molecular clouds is very complex, consisting of a hierarchy of clumps and filaments on all scales (for a review, see Blitz 1993). Many attempts have been made to identify the clump structure and derive its properties (Stutzki & Güsten 1990; Williams, De Geus, & Blitz 1994). As starting conditions, we choose density fields with Gaussian random fluctuations that follow a power spectrum \( P(k) \propto 1/k^2 \); i.e., large-scale fluctuations have, on average, large amplitudes, whereas the amplitudes of short-wavelength modes decay quadratically. The fields are generated by applying the Zeldovich (1970) approximation to an originally homogeneous gas distribution: we compute a hypothetical field of density fluctuations in Fourier space and solve Poisson’s equation in order to obtain the corresponding self-consistent velocity field. These velocities are then used to advance the particles in one big step \( \Delta t \).

4. A CASE STUDY

As a case study, we present the time evolution of a region in the interior of a molecular cloud containing a total mass of 222 Jeans masses, determined from the temperature and mean density of the gas. Figure 1 depicts snapshots of the system initially and when 10%, 30%, and 60% of the gas mass has been accreted onto the protostellar cores. Note that this cube has to be seen periodically replicated in all directions. Initially, pressure smears out small-scale features, whereas large-scale fluctuations start to collapse on themselves and into filaments and knots. After \( t \approx 0.9 \), the first highly condensed cores form in the centers of the most massive and densest Jeans-unstable gas clumps and are replaced by sink particles. Soon, clumps of lower initial mass and density follow, altogether creating a hierarchically structured cluster of accreting protostellar cores.

4.1. Scaling Properties

The gas is isothermal. Hence, the calculations are scale free, depending only on one parameter: the dimensionless temperature \( T \equiv E_{\text{int}} / |E_{\text{pot}}| \), which is defined as the ratio between the internal and gravitational energy of the gas. The model can thus be applied to star-forming regions with different physical properties. In the case of a dark cloud with mean density \( n(H_2) \approx 100 \text{ cm}^{-3} \) and a temperature \( T \approx 10 \text{ K} \) like Taurus-Auriga, the computation corresponds to a cube of length 10 pc and a total mass of 6300 \( M_\odot \) (with the Jeans mass being \( M_\text{J} = 28 M_\odot \)). The dimensionless time unit corresponds to \( 2.2 \times 10^4 \text{ yr} \). For a high-density star-forming region like Orion, with \( n(H_2) \approx 10^3 \text{ cm}^{-3} \), these values scale to 0.32 pc and 200

1 Time is measured in dimensionless units, with \( t = 0 \) being defined by the start of the SPH simulation. For adequate timing, the Zeldovich shift interval \( \Delta t = 1.5 \) has to be added. As a reference, the free-fall time of the isolated cube would be \( t_\text{ff} = 1.4 \).

2 In the case of isotropic turbulence, the nonthermal (turbulent) contributions can also be accounted for in this expression: \( E_{\text{int}} \approx E_{\text{therm}} + E_{\text{turb}} \).
close encounters lead to the formation of unstable triple or higher order systems and alter the orbital parameters of the cluster members. As a result, a considerable fraction of the “protostellar” cores gets expelled from their parental clump. Suddenly bereft of the massive gas inflow from their collapsing surroundings, they effectively stop accreting, and their final mass is determined. Ejected objects can travel quite far and resemble the weak-line T Tauri stars found via X-ray observations in the vicinities of star-forming molecular clouds (see, e.g., Neuhaüser et al. 1995 and Wichmann et al. 1997).

In Figure 2, we plot the accretion history of 14 representative protostellar cores in the simulation. The objects are numbered according to their time of formation. The figure illustrates the following trends: (a) The cores that form first tend to have the largest final masses. They emerge from the initial clumps with the highest densities. The mass of the initial clumps composes a considerable fraction of the final mass of the cores. (b) Matter that contracts into dense cores at later times (say $t \approx 2$) has already undergone considerable dynamical evolution. Small initial clumps stream toward each other along filaments. At the intersections of filaments, they merge and may undergo rapid collapse, when enough mass is accumulated. (c) Once dense cores have formed, they evolve as a result of accretion, competing for gas from the surrounding reservoir and interacting dynamically, as described above. For example, at $t \approx 1.8$, core 19 is expelled from a dense clump at the intersection of two massive filaments by a triple interaction with cores 1 and 17. It stops accreting. However, it still is bound to the gas knot, which grows in mass as a result of continuous infall. It falls back onto the clump of gas and resumes accreting at $t = 2.0$. Cores 9 and 41 are also expelled from their parental clumps, but unlike core 19, their accretion is terminated completely. These dynamical interactions between cores are an important agent in shaping the mass distribution.

4.3. Mass Spectrum—Implications for the Initial Mass Function

Figures 3a–3d describe the mass distribution of identified gas clumps (thin lines) and of protostellar cores (thick lines). To identify individual clumps, we have developed an algorithm similar to the method described by Williams et al. (1994) but based on the framework of SPH. As a reference, we also plot
the observed canonical form for the clump mass spectrum, \( dN/dM \propto M^{-\alpha} \) (Blitz 1993), which has a slope of \(-0.5\) when plotting \( N \) versus \( M \). Note that our initial condition does not exhibit a clear power-law clump spectrum but instead consists preferentially of small-scale fluctuations. However, these are quickly damped by pressure forces, and during the subsequent nonlinear gravitational collapse, a power-law mass spectrum is formed with a slope that is similar to the observed clump mass spectrum (Figs. 3b and 3c). In all panels, the vertical lines indicate the SPH resolution limit for 500,000 particles (Bate & Burkert 1997).

A common feature in all our simulations is the broad mass spectrum of “protostellar” cores; this spectrum peaks slightly above the overall Jeans mass of the system. This is somewhat surprising, since the initial fluctuations span a vast range of masses and peak densities and the evolution of each core is heavily influenced by complex merging and collapse processes. However, in a statistical sense, the system retains “knowledge” of its (initial) average properties. The present simulations cannot resolve subfragmentation in condensed cores. However, detailed simulations show that perturbed cores tend to break up into multiple systems (see, e.g., Burkert & Bodenheimer 1996 and Burkert et al. 1997). Here we can only determine the mass function of multiple systems without breaking them down into a mass function of single stars. Our simulations predict an initial mass function (IMF) with a lognormal functional form, if the mass of a multiple system that forms within a condensed core is roughly proportional to the core mass, \( M_\ast = \eta M_{\text{core}} \). Figure 3e compares the results of our calculations with the observed IMF for multiple systems (Kroupa, Tout, & Gilmore 1990). The maximum of the observed IMF is located at 0.23 \( M_\odot \). The calculated core mass distribution peaks at \(-2M_\odot\). In § 4.1, we found that when we scale the simulation to the conditions in low-density (e.g., Taurus) and high-density star-forming regions (like Orion), we obtain Jeans masses of 28 and 0.9 \( M_\odot \), respectively. Thus, to reproduce the observed peak in the IMF, we take \( \eta \approx 0.005 \) for Taurus and \( \eta \approx 0.125 \) for Orion; i.e., the implied star formation efficiency for a low-density Taurus-like region is much lower than for cloud regions of high density like Orion. With these star formation efficiencies, the agreement between the observed IMFs for multiple systems (thick dashed line; values from Kroupa et al. 1990) is excellent. Note that although the peak depends on our choice of \( \eta \), the agreement in the width of the distribution does not depend on this scaling. For comparison, the IMF corrected for binary stars (Kroupa, Tout, & Gilmore 1993) is indicated as a thin solid line, together with the mass function from Salpeter (1955) indicated as a thin dashed line.

### 5. Summary and Discussion

Since collapse and fragmentation in molecular clouds is an extremely complex and dynamical process, many authors have sought to understand the stellar initial mass function as resulting from a sequence of statistical events that may naturally lead to a lognormal IMF (see, e.g., Zinnecker 1984 and Adams & Fatuzzo 1996; also Price & Podsadiłowski 1995, Murray & Lin 1996, and Elmegreen 1997). However, using numerical simulations, it is possible to identify underlying processes that may contribute to the form of the stellar initial mass function. In the calculations presented here, we find several trends. The “protostellar” cores that form first are generally formed in the clumps with the highest initial density, and they tend to have the highest final masses. Cores that form later originate from gas that was initially in low-density clumps or from distributed gas that converged to form a higher density clump before quickly collapsing. Overlaid on these general trends, dynamical interactions between individual cores can act to terminate accretion onto a core by ejecting it from a clump, thus setting its final mass. The excellent agreement between the numerically calculated mass function and the observed IMF for multiple stellar systems (Kroupa et al. 1990) strongly suggests that these gravitational fragmentation and accretion processes dominate the origin of stellar masses. In a subsequent paper, the results from calculations spanning a larger range of the parameter space relevant for molecular clouds shall be discussed in detail.

### References

- Adams, R. C., & Fatuzzo, M. 1996, ApJ, 464, 256
- Bate, M. R., Bonnell, I. A., & Price, N. M. 1995, MNRAS, 277, 362
- Bate, M. R., & Burkert, A. 1997, MNRAS, 288, 1060
- Benz, W. 1990, in The Numerical Modeling of Nonlinear Stellar Pulsations, ed. J. R. Buchler (Dordrecht: Kluwer), 269
- Blitz, L. 1993, in Protostars and Planets III, ed. E. H. Levy & J. J. Lunine (Tucson: University of Arizona Press), 125
- Bonnell, I. A., & Bastien, P. 1993, ApJ, 406, 614
- Bonnell, I. A., Bate, M. R., Clarke, C. J., & Pringle, J. E. 1997, MNRAS, 285, 201
- Boss, A. 1997, ApJ, 483, 309
- Burkert, A., Bate, M. R., & Bodenheimer, P. 1997, MNRAS, 289, 497
- Burkert, A., & Bodenheimer, P. 1996, MNRAS, 280, 1190
- Burkert, A., Klessen, R. S., & Bodenheimer, P. 1998, in ASP Conf. Ser, The Orion Complex Revisited, ed. M. J. McCaughrean & A. Burkert (San Francisco: ASP), in press
- Ebisuzaki, T., Makino, J., Fukushige, T., Taiji, M., Sugimoto, D., Ito, T., & Okumura, S. 1993, PASJ, 45, 269
- Elmegreen, B. G. 1997, ApJ, 486, 944
- Ewalt, P. P. 1921, Ann. Phys., 64, 253
- Keto, E. R., Lattanzio, J. D., & Monaghan, J. J. 1991, ApJ, 383, 639
- Klessen, R. 1997, MNRAS, 292, 11
- Kroupa, P., Tout, C. A., & Gilmore, G. 1990, MNRAS, 244, 76
- Kroupa, P., Tout, C. A., & Gilmore, G. 1990, MNRAS, 244, 76
- Larson, R. B. 1978, MNRAS, 184, 69
- Monaghan, J. J. 1992, ARA&A, 30, 543
- Monaghan, J. J., & Gingold, R. A. 1983, J. Comput. Phys., 52, 135
- Monaghan, J. J., & Lattanzio, J. C. 1991, ApJ, 375, 177
- Murray, S. D., & Lin, D. N. C. 1996, ApJ, 467, 728
- Nakajima, Y., & Hanawa, T. 1996, ApJ, 467, 321
- Neuhauser, R., Sterzik, M. F., Torres, G., Latham, D., & Martin, E. L. 1995, A&A, 299, L13
- Price, N. M., & Podsadiłowski, Ph. 1995, MNRAS, 273, 1041
- Salpeter, E. E. 1955, ApJ, 121, 161
- Steinmetz, M. 1996, MNRAS, 278, 1005
- Struck, J., & Güsten, R. 1990, ApJ, 356, 513
- Sugimoto, D., Chikada, Y., Makino, J., Ito, T., Ebisuzaki, T., & Unemura, M. 1990, Nature, 345, 33
- Turner, J. A., Chapman, S. J., Bhattal, A. S., Disney, M. J., Pongracic, H., & Whitworth, A. P. 1995, MNRAS, 277, 705
- Unemura, M., Fukushige, T., Makino, J., Ebisuzaki, T., Sugimoto, D., Turner, E. L., & Loeb, A. 1993, PASJ, 45, 311
- Whitworth, A. P., Chapman, S. J., Bhattal, A. S., Disney, M. J., Pongracic, H., & Turner, J. A. 1995, MNRAS, 277, 727
- Whitworth, A. P., & Summers, D. 1985, MNRAS, 214, 1
- Wichmann, R., Krautter, J., Covino, E., Alcala, J. M., Neuhauser, R., & Schmitt, J. H. M. M. 1997, A&A, 320, 185
- Williams, J. P., De Geus, E. J., & Blitz, L. 1994, ApJ, 428, 693
- Zeldovich, Y. B. 1970, A&A, 5, 84
- Zinnecker, H. 1984, MNRAS, 210, 43