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RESOLUTION ISSUES IN THE COLLAPSE AND FRAGMENTATION OF TURBULENT MOLECULAR CLOUD CORES

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RESUMEN

La formación de nubes moleculares gigantes (GMCs) dispone el escenario para la formación de sistemas protoestelares inducidos por el colapso gravitacional de regiones densas interiores a la GMC que se fragmentan en condensaciones más pequeñas que a su vez se colapsan en estrellas. Inherente a la dificultad en alcanzar este gol, está el que el colapso gravitacional y la fragmentación que le sigue dependen críticamente de las condiciones iniciales en las condensaciones así como de mantener la exactitud en las simulaciones a medida que las condensaciones se colapsen. Uno de las metas de esta investigación es el entender la naturaleza y las propiedades físicas de la formación de binarias y de sistemas estelares múltiples con estrellas de baja masa típicas (~ 0.2 a 3 $M_{\odot}$). Hemos desarrollado un poderoso código numérico dirigido a los aspectos clave de la formación de estrellas de baja masa. Esta tecnología consiste de un esquema de hidrodinámica radiativa auto-gravitatoria con una red computacional paralela adaptable (AMR). Esta metodología nos permite una eficiencia computacional sobre códigos convencionales aplicados a problemas que involucran el colapso gravitacional a través de varios ordenes de magnitud en densidad y en radio. En este breve artículo, discutimos resultados preliminares sobre la formación de estrellas para el espacio de parámetros marginalmente estables, condensaciones de nubes moleculares turbulentas que evolucionan hacia protoestrellas en un rango de turbulencia y tasa de rotación. Contrastamos nuestros resultados con simulaciones recientes en SPH y mostramos cuando la falta de resolución en estas simulaciones puede empezar a afectar al resultado, llevando probablemente a la falsa fragmentación y a propiedades inexactas de la distribución de masa y de agrupamiento.

ABSTRACT

The formation of Giant Molecular clouds (GMCs) sets the stage for the formation of protostellar systems by the gravitational collapse of dense regions within the GMC that fragment into smaller core components that in turn condense into stars. Inherent in the difficulty in attaining this goal is that the gravitational collapse and ensuing fragmentation depend critically upon initial conditions in the cores as well as the maintenance of accuracy in the simulations as the cores collapse. One of the goals of this research is to understand the nature and physical properties of the formation of binay and multiple stellar systems with typical low mass stars (~ 0.2 to 3 $M_{\odot}$). We have developed a powerful numerical code that is addressing the key issues surrounding the formation of low mass stars. This technology consists of a parallel adaptive mesh refinement (AMR) self-gravitational radiation-hydrodynamics code. This methodology allows us to obtain considerable computational efficiency over conventional codes when applied to problems involving gravitational collapse across many orders of magnitude in density and radius. In this brief paper, we discuss preliminary results of the formation of stars for the parameter space of marginally stable, turbulent molecular cloud cores as they evolve to protostars over a range of turbulence and rotational rate. We contrast our results with recent SPH results for similar initial conditions. We survey current SPH simulations and show where the lack of resolution in these simulations may begin to affect the outcome, possibly leading to false fragmentation and an inaccurate picture of the stellar mass distribution and clustering properties.

Key Words: **HYDRODYNAMICS — ISM: MOLECULES — ISM: STRUCTURE — ISM: TURBULENCE — STARS: LOW MASS**

1. INTRODUCTION

The extreme variations in length scale inherent in the star formation process have made it difficult to perform accurate calculations of fragmentation and collapse. In order to address the fundamental issues we have developed a robust, parallel adaptive meshrefinement (AMR) self-gravitational hydrodynamics code including the effects of multi-fluids, radiation transport, self gravity and most recently

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magnetic fields and have applied it to the study of low mass star formation (Truelove et al. 1997, Klein 1999, and Klein et al. 2004).

Over the last few years, we have begun to investigate the properties of marginally stable, turbulent molecular cloud cores (Klein, Fisher, Krumholz & McKee 2003, Klein, Fisher & McKee, 2001). In addition to starting with initial models that faithfully describe the high resolution observations of molecular cloud cores, one must ensure that the simulations are convergent – that is, they are run at a level of resolution that faithfully resolves the key physics in the star formation process and avoid the false fragmentation first noted by Truelove et al. 1997. The conditions for avoidance of such false fragmentation were worked out in detail in Truelove et al. 1997 for grid based (Eulerian) codes, and by Bate and Burkert in 1997 (here after BB97) for SPH codes. We point out, for the first time, the significant discrepancy between these two criteria.

We demonstrate the relatively low resolution typically adopted in a survey of current SPH simulations. We will suggest that the lack of resolution in these simulations seriously affects the outcome, possibly leading to false fragmentation and an inaccurate picture of the stellar mass distribution.

2. COLLAPSE AND FRAGMENTATION OF TURBULENT CORES

2.1. *Recent Results with AMR Over a Range of Turbulence and Rotation Rates*

We have followed the collapse and fragmentation of a range of turbulent cores spanning transonic cores with Mach number 1 to supersonically turbulent cores with Mach number 3 and spanning a large dynamic range in rotational values of β from $4 \times 10^{-4} \leq \beta \leq 10^{-1}$. We have found that transonic cores typically result in the formation of single stars whereas moderately supersonic turbulent cores result in low multiplicity systems (single or binary). We have found this to betrue over the observed range of rotation rates.

Ward-Thompson 2004, and Delgado-Donate, Clarke, and Bate 2004 (hereafter DDCB04). In the case of Goodwin et al. 2004, the collapse and fragmentation of transonic coreswith $\mathcal{M} \sim 1$ formed 4-8 low mass stars while DDCB04, with $\mathcal{M}$ =3.75 formed 20 low mass stars (Figure 1). In contrast, our AMR turbulent core simulations with $\mathcal{M}$ =1-3 typically form one to (at most) several stars, with no further evidence of fragmentation of the disks that form around each star (Figure 2).

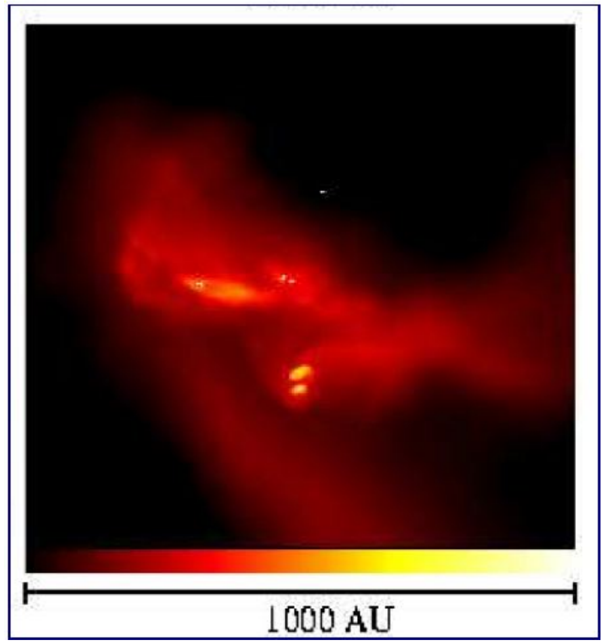

Fig. 1. Column density of DDCB04 turbulent core, drawn from their paper.

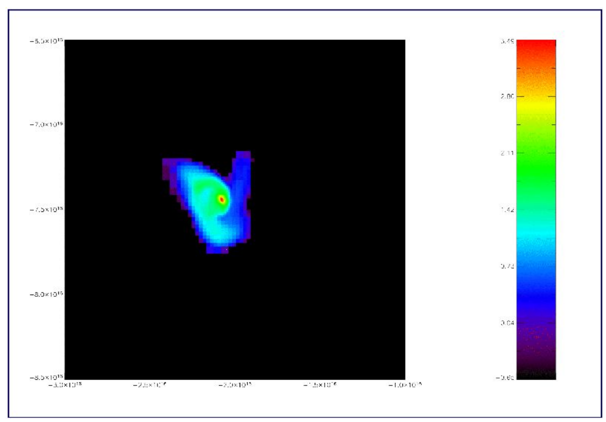

Fig. 2. Column density of AMR result using the same initial conditions, shown on a similar scale at a similar time. Note that unlike the SPH simulations, the AMR simulation produces a smooth disk with no signs of fragmentation.

Several SPH calculations of cluster formation have resulted in the formation of numerous low mass or brown dwarf systems after collapse and fragmentation of turbulent clouds (Klessen, 2001; Bate, Bonnell, and Bromm, 2002). All of these SPH simulations have been performed with similar or lower resolution to that suggested in BB97. One should appropriately ask whether the resolution used in these simulations is sufficient to achieve a converged result. All of our AMR calculations satisfy the Jeans condition (Truelove et al. 1997, Klein, Truelove and

McKee, 1997), which requires that the resolution element of the grid $\Delta x < J\lambda_J$ where J (the Jeans number) $= 0.25$ and λ_J is the local Jeanslength. However, many recent SPH calculations in star formation may be significantly far from satisfying an equivalent constraint. BB97 proposed that 2 $N_{\rm neigh} = 100$ particles per Jeans mass is a sufficient resolution requirement for an SPH calculation, where $N_{\rm neigh} \simeq 50$ is the typical number of particles in an SPH smoothing kernel. They cited the work of an earlier paper by Navarro & White (1993) as a justification for their criterion. However Navarro & White(1993) studied adiabatic ($\gamma > 4/3$), *not* isothermal collapse. The Jeans mass, M_J is an increasing function of density in this case, and therefore is not relevant during the important isothermal collapse phase of star formation. In the significantly more demanding case of isothermal collapse, the initial resolution of an SPH calculation will severely diminish in time in instability to resolve the local Jeans mass. This is easily seen if we consider that the SPH resolution is the number of smoothing kernels per Jeans mass (Fisher, Klein & Mckee 2004), or

$$\frac{\pi^{5/2}}{6}(\frac{c_s}{G^{1/2}})^3 \frac{1}{N_{neigh} m_{SPH}} \frac{1}{\rho^{1/2}} .$$

Thus, the effective AMR resolution remains constant in time, but the SPH resolution decreases in time as $\rho^{1/2}$. Similarly Fisher, Klein & McKee (2004) have considered the ratio of effective resolution per Jeans mass of AMR to SPH and have found the density at which the AMR effective resolution is equal to the SPH effective resolution:

$$\rho_{crit} = \frac{J^6 \pi^3 c_s^6}{G^3 (N_{neig} m_{SPH})^2} .$$

At densities lower than ρ_{crit}, the effective resolution of an SPH code is higher than that of an AMR calculation with Jeans number J. At higher densities, the effective resolution of an SPH code is *lower*. This fact is the essential problem in SPH collapse simulations with the typical resolutions adopted. Here we briefly discuss some of the consequences of SPH work that has used the Bate criterion for effective resolution.

In Figure 3 we consider the effective resolution comparsion between AMR and the recent SPH calculation of DDCB04, which used the resolution recommended by BB97. We plot the log ratio of effective SPH to AMR resolution as a function of log density as described above. The three lines correspond to the effective resolution ratio of an SPH simulation to an AMR simulation using Jeans numbers J of 1/2, 1/4 and 1/8 respectively for AMR. We also plot the dotted horizontal line corresponding to the critical density ρ_{crit}. The point of intersection of any of the J curves with the ρ_{crit} line is that density at which the SPH resolution equals the AMR resolution. For collapse that reaches higher densities, the SPH resolution falls below the AMR resolution. The dashed vertical line corresponds to the "stiffening" density at which the simulations make the transition from isothermal collapse to adiabatic collapse. For a typical AMR simulation with $J = 0.25$, we note that the calculation of DDCB04 begins to fall *below* the AMR simulation at densities of 6.0×10^{-16}. This density is several orders of magnitude *below* the stiffening density 1.0×10^{-13}. This means that the SPH simulation of DDCB04 is at lower resolution than what is required for AMR stability against artificial fragmentation over seveal decades of collapse in the isothermal regime. One can see the same conclusion applies even if one were to have required an even lower Jeans number of $J = 0.5$.

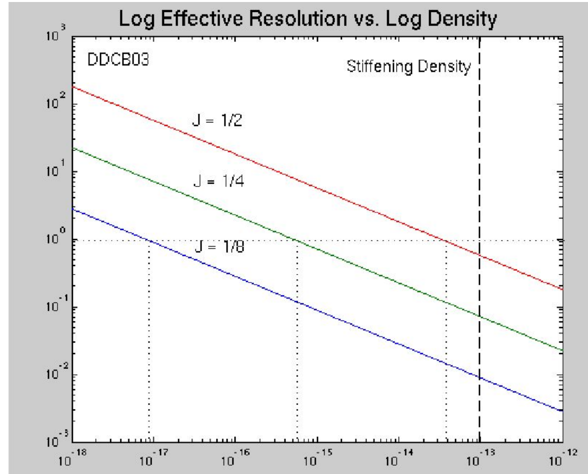

Fig. 3. Log effective resolution vs. log compression, shown for the DDCB04 problem. Solid lines indicate the ratio of effective mass resolution for the SPH simulation to AMR resolution, adopting AMR Jeans numbers of $J = 1/2$, $J = 1/4$, and $J = 1/8$ (see text). Dotted lines indicate where the SPH simulation drops beneath a given J value. Long-dashed line indicates the density at which the EOS stiffens.

The conclusion that one draws is that the SPH simulation of DDCB04 is most likely seriously underresolved. This low resolution, in turn, is likely to cause artifical fragmentation leading to the high multiplicity found in their work.

In Figure 4, we summarize several recent SPH papers. We list the range of particles used in the simulation; the typical number of particles used per

Authors	Range N	Typical number particles per minimum Jeans mass / N_neigh	Initial M / M_J	Compression at Stiffening	Typical ρ_{crit} / ρ_{init} for J = 1/4 & for J = 1/2
Bate & Burkert (1997)	10^4 - 8 10^4	2	~ 3	3 10^3 - 3 10 ^4	90 6 10^3
Tsuribe & Inutsuka (1999)	10^5 - 3 10^5	~ 30	~ 1 - 10	10^6	4 10^6 2.4 10^8
Klessen (2001)	2 10^5 - 5 10^5	0.4 - 0.5	100 - 200	10^4	1.3 90
Bate, Bonnell, & Bromm (2002)	3.5 10^6	1.5	50	1.6 10^6	4 10^3 2 10^5
Goodwin, Whitworth, & Ward-Thompson (2003)	2.5 10^4 - 10^5	1	1	3 10^4	1 70
Delgado-Donate, Clarke, Bate (2003)	3.5 10^5	2	10	10^5	5 10^2 10^4

Fig. 4. Table showing a survey of recent SPH simulations. Columns shown (left to right) for each paper are the range of particles used, typical mass resolution (in terms of smoothing kernels per minimum Jeans mass), initial number of thermal Jeans masses, compression at stiffening, and the ratio of the critical density (see text) to initial density for $J = 1/4$ and $J = 1/2$, respectively.

minimum Jeans mass normalized to $N_{neigh} \approx 50$; the number of initial Jeans masses used in the simulation; the stiffening compression (ρ_{stiff}/ρ_{init}) and ρ_{crit}/ρ_{init} for corresponding values of $J = 0.25$ and 0.5. A first glance at this table indicates that with the sole exception of Tsurible and Inutsuka (1999),most of the SPH simulations to date use a resolution that is at best that suggested by BB97 to resolve the minimum Jeans mass. In the case of Klessen (2001), this simulation is almost an order of magnitud *below* that suggested by BB97.

We note that for each of the aforementioned SPH simulations with the exception of Tsuribe and Inutsuka 1999, the critical compression for SPH to fall below there solution necessary for AMR to be stable to artificial fragmentation occurs at densities *well below the stiffening density* for each of the simulations; even when the lesser demanding $J = 0.5$ criterion is used.

We note that the Goodwin et al. simulation reached its critical density at only 70 times initial density and this is 2-3 orders of magnitude below the density that stiffening to adiabatic compression occurs. Thus the opportunity for this simulation to artifically produce multiple fragments is large. In SPH simulations of clusters by Klessen (2001) and Bate, Bonnell and Bromm (2002) the situation is particularly severe as artificial fragmentation is likely to occur several orders of magnitude before the stiffening transition is reached. This would in turn imply that many of the small scale stars or brown dwarfs found in these simulations are generated by numerical instability and may not be real.

3. CONCLUSION

Our results demonstrate that with well resolved AMR simulations, we can currently form single or binary systems in the regime of $\mathcal{M} \sim 1 - 3$ and $\beta \sim 10^{-4} - 10^{-1}$. Introducing turbulence naturally produces seeds from which fragments may grow, while at the same time also producing more realistic initial molecular cloud core models which correspond more closely to observation than previous models. We have also shown that the particle resolution used in many recent SPH simulations suggested by the criterion of Bate and Burkert 1997, is severely short of the resolution dictated by the Jeans condition described by Truelove et al. 1997 and is likely to produce artificial fragmentation leading to a false multiple fragmentation. In particular we demonstrate with an AMR simulation that the recent work of Delgado-Donate et al. is likely to be numerically contaminated and its conclusions regarding multiple low mass star and brown dwarf formation are likely incorrect.

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