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RECENT ADVANCES IN THE COLLAPSE AND FRAGMENTATION OF TURBULENT MOLECULAR CLOUD CORES

R. I. Klein,[1,2] R. T. Fisher,[2] M. R. Krumholz,[3] and C. F. McKee[1,3]

RESUMEN

Observaciones de estrellas en la vecindad solar muestran que los sistemas binarios prevalecen y parecen ser un resultado general del proceso de colapso y fragmentación. Una de las metas principales de esta investigación es el entendimiento de la naturaleza de la formación de los sistemas estelares binarios y múltiples con estrellas de baja masa, típicamente ~ 0.2 a $3\,M_\odot$ y las propiedades físicas de estos sistemas. Preguntas básicas acerca de este proceso quedan sin respuesta. ¿Qué determina la fracción de una nube inestable que se fragmentará en objetos protoestelares? ¿Qué determina el patrón de agrupación estelar en sistemas binarios y múltiples? Además, aún después de que ocurre la fragmentación de la nube entendemos poco el subsecuente crecimiento de las protoestrellas mediante la acreción, y pérdida de masa a través de vientos estelares. En consecuencia, no es claro como la distribución de masas de los núcleos se relaciona con los fragmentos y por lo tanto a la distribución de masas estelares finales, lo cual es algo que debemos entender para poder explicar la función inicial de masas estelares.

Primero discutimos el desarrollo de la metodología numérica que contribuirá a dar respuestas a estas preguntas. Esta tecnología consta de un código paralelo radiativo-hidrodinámico autogravitante en tres dimensiones con malla adaptiva que hemos desarrollado. Presentamos nuevos resultados para el colapso gravitacional y la fragmentación de núcleos turbulentos de nubes moleculares marginalmente estables y seguimos el colapso de los fragmentos de alta masa a medida que interactúan con la radiación de las protoestrellas que se están formando en su interior. Discutimos las dificultadas teóricas en formar estrellas binarias y el papel de la turbulencia en su formación.

ABSTRACT

Observations of stars in the vicinity of the Sun show that binary systems are prevalent and appear to be a general outcome of the star-formation process. One of the major goals of this research is to understand the nature of the formation of binary and multiple stellar systems with typical low-mass stars (~ 0.2 to $3\ M_\odot$) and the physical properties of these systems. Basic questions concerning this process remain unanswered. What determines the fraction of an unstable cloud that will fragment into protostellar objects? What determines the pattern of stellar clustering into binaries and multiple systems? Even after fragmentation occurs, we have little understanding of the subsequent collapse. Consequently, it is unclear how the mass distribution of fragments maps onto eventual stellar masses, something we must understand to explain the stellar initial mass function.

We will first discuss the development of the numerical methodology that will contribute to answering these questions. This technology consists of a 3-D parallel, adaptive mesh refinement (AMR) self-gravitational, radiation-hydrodynamics code that we have developed. We will present new results for the gravitational collapse and fragmentation of marginally stable turbulent molecular cloud cores and follow the collapse of high-mass fragments as they interact with the radiation of the protostars forming at their centers. We will discuss the theoretical difficulties in forming binary stars and the role of turbulence in their formation.

Key Words: **HYDRODYNAMICS — ISM: CLOUDS — STARS: FORMATION — STARS: LOW MASS — TURBULENCE**

1. INTRODUCTION

The formation of giant molecular clouds (GMCs) sets the stage for the formation of protostellar systems by the gravitational collapse of dense regions

[1]Dept. of Astronomy, University of California, Berkeley, USA.
[2]Lawrence Livermore National Laboratory, University of California, USA.
[3]Dept. of Physics, University of California, Berkeley, USA.

within the GMC that fragment into smaller "core" components that in turn condense into stars. Developing a comprehensive theory of star formation remains one of the most elusive, and most important, goals of theoretical astrophysics. A major difficulty in achieving this goal is the fact that the gravitational collapse depends critically upon initial conditions within the cores.

Most stars exist in gravitationally bound binary and low-order multiple systems. Although several mechanisms have been put forth to account for binary star formation, over the past decade fragmentation has emerged as the leading mechanism (Boss 1993; Bodenheimer et al. 2000). This point of view has been strengthened by observations that have shown that the binary frequency among pre-main-sequence stars (Duchene, Bouvier, & Simon 1999) is comparable to, or greater than, that among nearby main-sequence stars (Duquennoy & Mayor 1991). These observations suggest that most binary stars are formed during the protostellar collapse phase. Moreover, the observed trend of decreasing fraction of binary and multiple systems with age strongly suggests that multiple star systems must have formed via fragmentation during the earliest stages of cloud collapse, rather than from capture of two or more stars formed individually.

Once fragmentation occurs, collapse proceeds largely unimpeded for low-mass stars. Until very recently, the extreme variations in length scale inherent in the star-formation process have made it difficult to perform accurate calculations of fragmentation and collapse, which are intrinsically three-dimensional in nature. In order to address several central questions of multiple low-mass star formation, over the last several years we have developed a powerful new 3-D parallel, adaptive mesh refinement (AMR) hydrodynamics code that includes multifluids, radiation transport, and self-gravity. Our work with a related, older code resulted in the discovery of a physically motivated constraint on the resolution (the Jeans condition) that must be met to suppress artificial fragmentation (Truelove et al. 1997).

Over the last few years, we have begun to investigate the properties of marginally stable, turbulent molecular cloud cores. Using turbulent simulations, we have generated models with radii, masses, density contrasts, turbulent linewidths, and projected velocity gradients consistent with observations of molecular cloud cores (Klein, Fisher, & McKee 2001; Burkert & Bodenheimer 2000). This work represents a significant improvement over the previous theoretical work on such cores, which typically assumed a uniform spherical core with an artificially imposed perturbation (i.e., 10% $m = 2$ or white-noise density perturbations), and rigid solid-body rotation. The turbulent spectrum imposes a characteristic scale on the models, which is the scale at which the core linewidth becomes supersonic. In the past year, we have successfully integrated and tested flux-limited radiative diffusion and self-gravity into our fully three-dimensional, parallel, multifluid AMR hydrodynamics code. In § 2 we briefly describe the AMR methodology. In § 3 we present recent results of the collapse of turbulent cores with radiation transport. We discuss conclusions and future directions of this work in § 4.

2. COMPUTATIONAL METHODOLOGY AND ALGORITHMS

Following the evolution of a collapsing molecular cloud as regions within it increase in density across many orders of magnitude is a formidable task. Conventional grid-based codes require that the finest-resolution gridding be applied over large volumes that may evolve to be devoid of fragments and thus not require the small zoning. Our 3-D adaptive code overcomes this problem.

First, the code employs a conservative higher-order Godunov scheme to solve the Euler equations of multi-fluid compressible gas dynamics using an optimized approximate Riemann solver (Toro 1997). The algorithm is second-order accurate in both space and time for smooth flow problems, and it has a robust and accurate treatment of shocks and contact discontinuities.

The second major component of the code is a self-gravity solver. At each time step we solve a Poisson problem on the adaptive grid hierarchy to obtain the gravitational potential; we then apply the gradient of this potential as a source term in the momentum and energy equations (Truelove et al. 1998). A multigrid iteration scheme is used to solve the linear system of equations resulting from the discretization of the Poisson equation on a given level. These level solutions are then iterated to convergence to obtain a solution for the gravitational potential on all levels. The gravity solver utilizes the same linear solver as the radiative diffusion.

The third component is an adaptive, coupled, radiation-hydrodynamics solver using single-frequency flux-limited diffusion. First, the code solves a fully implicit system consisting of the emission/absorption and diffusion parts of the radiation and gas energy equations (Howell & Greenough

1999). It uses a Newton-Raphson iteration method, with an adaptive parallel multigrid method to find provisional solutions in each loop of the iteration. Once the implicit system reaches convergence, the algorithm updates the gas and radiation states using explicit forms of the radiation-pressure force, work and advection terms.

These solvers for hydrodynamics, self-gravity, and radiative transfer are coupled together within the adaptive mesh refinement infrastructure of our code. The adaptive mesh refinement scheme employs an automatic, dynamic regridding strategy based on an underlying rectangular discretization of the spatial domain (Berger & Oliger 1984; Berger & Colella 1989; Bell et al. 1994). The overall algorithm conserves total energy, mass, and momentum.

3. COLLAPSE AND FRAGMENTATION OF TURBULENT CORES

Binary stars have a wide range of periods, ranging from less than a day to more than 10^6 yr (Bodenheimer et al. 2000). The median period is 180 yr; for a total binary mass of $1\,M_\odot$, the corresponding separation is about $30\,\mathrm{AU} = 4.5 \times 10^{14}$ cm.

It is crucial that the initial models that one uses faithfully describe those present in nature. High-resolution observations of molecular cloud cores (e.g., Motte & André 2001) indicate that the mean column density of pre-stellar molecular cloud cores is close to that of a centrally condensed isothermal sphere supported primarily by thermal pressure. Moreover, observations of linewidths in star-forming regions indicate that the non-thermal linewidths are typically transonic on the scale of cores, and obey a power-law linewidth–size relation (Larson 1981). In the past year we have, for the first time, generated self-consistent, initial conditions for cores in virial balance between gravity and thermal and turbulent pressures, which incorporate density fluctuations in addition to those present in the velocity field, and which match these key known observational properties of cores. In contrast, nearly all calculations which appear in the literature deal with initial cores unrealistically far from equilibrium (e.g., Boss & Bodenheimer 1979; Boss 1991; Burkert & Bodenheimer 1993), without any turbulent support, leading to highly supersonic collapse velocities, and artificially symmetric collapses.

3.1. *Initial Conditions*

Truly accurate simulations for collapse must begin from realistic initial conditions, with self-consistent turbulence in both velocity and density. To generate such initial conditions, we would ideally start from a large turbulent box simulation of a cloud and allow the cloud to form dense sub-regions that become the molecular cloud cores whose properties are well studied with high-resolution observations. These turbulent cores would then be evolved through the first gravitational collapse and fragmentation phase to protostellar formation, and the subsequent distribution of single, binary, and multiple stars would be analyzed. As a preliminary step to investigate such realistic initial conditions, we start instead with a smooth Bonnor-Ebert sphere and perturb only the velocity field with Gaussian perturbations on large scales; we adjust the energy injection rate of the perturbation to achieve the desired turbulent Mach number. This naturally produces the 3-D turbulent power spectrum $P(k) \propto k^{-4}$ predicted by theory and by Larson's law (Larson 1981). After a few sound-crossing times, we take the resulting object as our initial condition for a collapse calculation of a molecular cloud core. We simulate observations of our cores in an optically thin tracer, and compare the results to observed cores using four tests. We simulate observations of these cores to determine: the axis ratio (Myers et al. 1991); β, the ratio of rotational kinetic to gravitational potential energy (Goodman et al. 1993); and γ, the exponent of the single-object linewidth–size relation (Ossenkopf & Mac Low 2002). The cores' aspect ratio must match the observed value of roughly 0.5, or slightly higher for isolated cores (Myers et al. 1991). Typical aspect ratios of cores produced in our simulations are 0.6 to 0.9. The ratio of rotational kinetic energy to gravitational potential energy must match the observed distribution, with a mean of 0.02 and a mode of 0 to 0.02 (Goodman et al. 1993). Our simulated cores show values of 0.001 to 0.03. Ossenkopf & Mac Low (2002) find an exponent of 0.5 ± 0.04 for the linewidth–size relation over a wide range of length scales. Our simulated observations produce exponents of 0.42 to 0.55. We find excellent agreement between the properties of our simulated cores and observations. We have found (to be published elsewhere) that if we are simulating a barotropic cloud that obeys Larson's laws, and if the initial thermal temperature is fixed, then the initial conditions for a typical case are determined by a single number $\mathcal{M}$, the turbulent Mach number in the cloud. Thus, our initial cores can be thought of as a sub-region of the

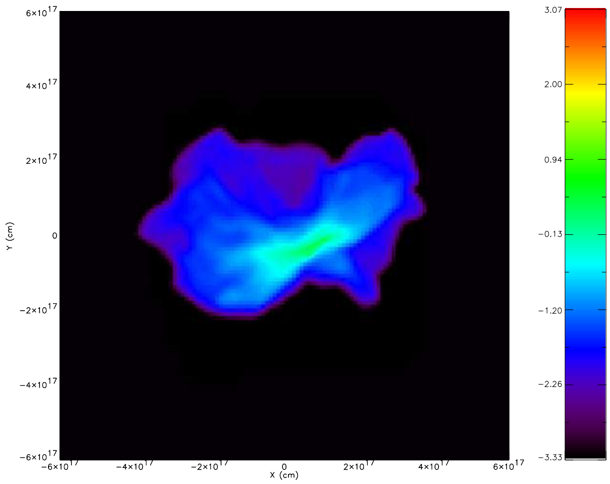

Fig. 1. Log of column density at $t = 3.84 \times 10^{12}$ s for a radiative run with $\mathcal{M} = 3$.

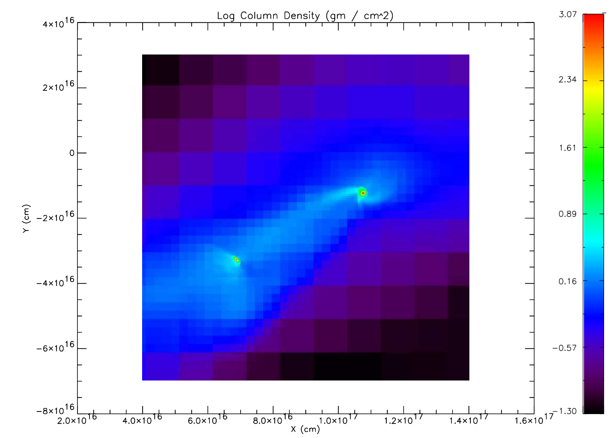

Fig. 2. Zoom-in on binary system: log of column density shown at $t = 4.13 \times 10^{12}$ s.

larger turbulent cloud, characterized in scale by the Mach number of the gas in the sub-region. We are currently performing more self-consistent, detailed collapse simulations of fully turbulent clouds with perturbations affecting both the velocity and density fields, and this will be reported elsewhere.

3.2. *Preliminary Results*

We have begun simulating turbulent low-mass cores, including the effects of radiative transfer in the flux-limited diffusion approximation. To the best of our knowledge, these are the first astrophysical simulations in star formation incorporating flux-limited radiation diffusion on an adaptive mesh. We begin with an initial $8\,M_{\odot}$ core with a turbulent Mach number of $\mathcal{M} = 3$. In Figure 1, we view the log of the column density of the core at $t = 3.84 \times 10^{12}$ s,

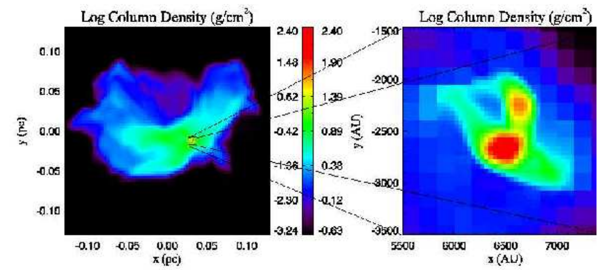

Fig. 3. Blow-up of binary: log of column density shown at $t = 4.63 \times 10^{12}$ s.

corresponding to 0.086 edge free-fall times after the start of the collapse. Note the formation of a binary embedded in a highly irregular core with an orbital separation of 3700 AU. A similar calculation using a barotropic approximation for the equation of state produces almost identical results. At this time, the core structure is still optically thin and we would not expect any significant results of the radiation on the fragmentation. Figure 2 shows the binary at $t = 4.13 \times 10^{12}$ s. The binary has a separation distance of 2800 AU. Each member of the binary appears to be surrounded by a disk with one component of the binary showing a 2 arm spiral. The binary appears to form inside the structure of a filament in the cloud core. Some differences are noted with a pure barotropic calculation in which the binary has a somewhat smaller separation of 2400 AU. Figure 3 shows the full scale of the core with the binary present at $t = 4.63 \times 10^{12}$ s and a blow-up of the binary star system with an orbital separation of $\simeq 836$ AU. This model used the barotropic approximation. Radiative models are currently being evolved to this time. The binary is formed within a filamentary structure and at this time is too close to adequately resolve. By the endpoint of the simulation, roughly 20% of the mass of the original core had been accreted. An interesting result of this particular model is that the filamentary structure of the turbulent cloud remained optically thin throughout the duration of the simulation. It remains to be seen which models build up optically thick turbulent density structures, and precisely what impact radiative transfer has on the fragmentation process in general.

4. CONCLUSION

Our results demonstrate that we can currently form binary systems in the transonic regime of $\mathcal{M} \sim 2$ to 3. Introducing turbulence naturally produces seeds from which fragments may grow, while at the same time also producing more realistic initial molecular cloud core models that correspond more closely to observation than previous models. However, several outstanding theoretical and computational challenges remain before we may make a more quantitative assessment of how well our turbulent models fare in comparison with observation.

In particular, it remains an open question whether our models can explain *in detail* the observed frequency of binaries and multiple stars, as well as the known orbital element distributions of binary systems. A key unresolved issue in this determination is precisely how the measured properties of molecular cloud cores (typically determined by observers through measurements in one or more molecular emission lines, or continuum dust emission) relate to the one free parameter—the Mach number—of our models. For instance, while extensive catalogs of cores seen in NH_3 and other lines have been gathered (Jijina et al. 1999), these results are sensitive only to molecular gas at densities high enough to be above the critical density of that species, and low enough to remain optically thin. As a result, they present a biased picture of the gas participating in the star-formation process, and do not directly correspond to our simulated cores. It will be crucial to understand the nature of this bias through a combination of further modeling and multi-line observations. It will also be equally crucial to work from the opposite direction, and map our theoretical cores onto observables using detailed radiative transfer models. A corresponding computational challenge will be to evolve our collapse calculations for self-consistent initial condiitons far enough in time to allow most of the mass of the initial core to form stars and thus to determine the final distrbution of stellar masses for a typical core. The end result of this program will be the first detailed comparison of a theoretical model of multiple star formation with observation, and will represent a major advance in our understanding of the fundamental physics of the star-formation process itself.

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Robert Fisher and Richard I. Klein: Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California, CA 94550, USA (rklein@astron.berkeley.edu, rfisher@llnl.gov).
Richard I. Klein and Christopher F. McKee: Department of Astronomy, University of California, Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA (rklein,cmckee@astron.berkeley.edu).
Mark Krumholz and Christopher F. McKee: Department of Physics, University of California, Berkeley, CA 94720 (mkrumholz,cmckee@astron.berkeley.edu).