# CLOUD COLLAPSE AND FRAGMENTATION

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ABSTRACT. Interstellar clouds are thought to undergo a rapid phase of collapse in the process of contracting to form stars. Break-up during this collapse phase is termed *fragmentation*. Computer codes capable of calculating the hydrodynamics of cloud collapse in three spatial dimensions have been used to study the fragmentation process. Fragmentation into binary or multiple protostellar systems is the preferred outcome of collapse; only very slowly rotating, high thermal energy clouds, or clouds starting from power-law initial density profiles, avoid fragmentation and form single stars.

## 1. Introduction

This review focuses on the aspects of interstellar cloud collapse of most interest for the formation of binary systems. Break-up of a cloud during its dynamic, self-gravitational collapse toward stellar densities is termed *fragmentation*, in contrast to *fission*, which refers to break-up of a quasi-equilibrium, rapidly-rotating configuration (see reviews by Durisen and Lebovitz, this volume). Fragmentation intrinsically involves the nonlinear, time evolution of a self-gravitating, three dimensional (3D) fluid undergoing rapid, dynamical collapse, and as a consequence is not amenable to detailed analytical study. However, substantial progress in understanding fragmentation has come from the use of numerical codes developed for this problem. A brief summary of protostellar dynamics and thermodynamics is given, followed by the results of the standard test case for 3D codes and a description of the outcomes of isothermal and nonisothermal 3D collapse.

## 2. Protostellar Dynamics and Thermodynamics

Once interstellar clouds become sufficiently dense, exterior ionizing radiation is unable to penetrate to the cloud center, leading to loss of the magnetic field support that appears to dominate diffuse clouds. Shielding from external radiation also allows the cloud temperature to decrease to $\sim$ 10K. The combination of decreased magnetic and thermal support is thought to produce a phase of dynamic collapse, where self-gravitational forces overwhelm thermal and magnetic forces. This first collapse phase occurs nearly isothermally, until densities of $\sim 10^{-13}$ g cm$^{-3}$ are reached, whereupon the center is dense enough to trap IR radiation that previously escaped. Thereafter the evolution at the center is more nearly adiabatic, or more properly, *nonisothermal*, to stress the fact that at least initially, continued radiative losses preclude the assumption of strict adiabaticity. Because of rising thermal pressure, an *outer* core forms, and this core begins to collapse itself once temperatures high enough to dissociate molecular hydrogen ($\sim$ 2000K) are reached. The second



*D. McNally (ed.), Highlights of Astronomy, Vol. 8, 123–126.*

collapse leads to formation of the *inner* core with densities comparable to stellar densities ($\sim 1$ g $cm^{-3}$). Tscharnuter (1987) has shown that the inner core can disappear and reappear in a series of explosive rebounds (driven by reassociation and dissociation of molecular hydrogen). However, we are interested here in binary formation, which means we must consider the collapse of rotating clouds, and Tscharnuter's 'hiccups' are stabilized by rotation. Larson (1972) showed that when rotation is included, axisymmetric (2D) protostellar collapse can lead to flattened structures (rings) that are likely to fragment in a fully 3D calculation.

## 3. Standard Test Case

Because of the absence of analytical solutions for 3D collapse, one of the most important means of testing the accuracy of 3D codes is through mutual comparisons on a standard test case. Boss and Bodenheimer (1979) presented results obtained with two separate finite-difference (FD) codes applied to the same initial conditions. They found good agreement, both qualitatively and quantitatively: with both codes, the initial cloud collapsed (isothermally) and formed an intermediate bar that fragmented into a binary protostar. The properties of the binary thus formed are typical of all succeeding calculations: e.g., each binary member contains about 15% of the total mass and spins with a specific angular momentum reduced by about a factor of 20 from that of the initial cloud. However, when Gingold and Monaghan (1981) used their smoothed-particle hydrodynamics (SPH) code to study the standard test case, a different evolution ensued: the binary decayed back into a bar. Efforts to resolve this disagreement failed (Bodenheimer and Boss 1981; Gingold and Monaghan 1982), until a refined SPH method (Monaghan and Lattanzio 1985) coupled with a greatly increased number of particles led to an evolution that is very similar to that of the FD codes (Monaghan and Lattanzio 1986). The independent SPH code of Miyama, Hayashi, and Narita (1984) also produces results similar to that of the FD codes with initial conditions close to that of the standard test case. This mutual agreement between four independent numerical codes using greatly differing techniques gives strong support for the credibility of these 3D collapse calculations.

## 4. Isothermal Fragmentation

All published results for 3D isothermal collapse are summarized in Figure 1. Both FD calculations (Narita and Nakazawa 1977; Boss and Bodenheimer 1979; Tohline 1980; Boss 1980; Bodenheimer, Tohline, and Black 1980; Różyczka, Tscharnuter, and Yorke 1980; Boss 1981a,b) and SPH calculations (Larson 1978; Wood 1982; Gingold and Monaghan 1983; Miyama, Hayashi, and Narita 1984) are included. Figure 1 shows whether fragmentation (formation of two or more fragments) resulted from isothermal collapse of an initially uniform density cloud with initial ratios of thermal to gravitational energy ($\alpha_i$) and rotational to gravitational energy ($\beta_i$) designated by location on Figure 1.

Clouds that collapse from high $\alpha_i, \beta_i$ initial conditions do not fragment, but instead undergo relatively little collapse before settling into a diffuse, rotating, isothermal equilibrium state, termed a *Bonnor-Ebert ellipsoid*, the triaxial analogue of the Bonnor-Ebert isothermal sphere. Clouds with lower $\alpha_i, \beta_i$ undergo a sustained collapse that nearly always leads to fragmentation into a binary or multiple system (the one calculation at $\alpha_i = 0.1$, $\beta_i = 0.05$ was only taken to 1.0 free fall times, insufficiently far to allow fragmentation to occur). The oblique line shows the fragmentation criterion ($\alpha_i \times \beta_i < 0.12$) advanced by Hayashi, Narita, and Miyama (1982) on the basis of the stability of 2D rotating, isothermal equilibrium models. Figure 1 shows that Hayashi's criterion represents well the results for rapidly rotating clouds, but the criterion appears to fail for slowly

https://doi.org/10.1017/S1539299600007589 Published online by Cambridge University Press

rotating clouds (see below and the one model with $\alpha_i = 0.55$ and $\beta_i = 0.02$).

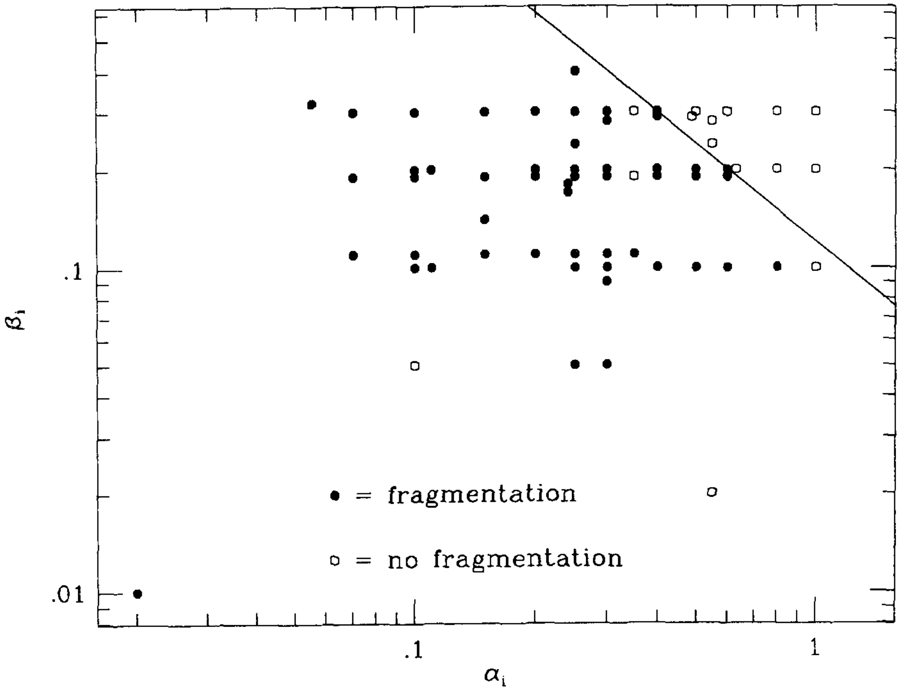


Figure 1. Results of all 3D isothermal collapse calculations.

It should be noted that while the FD and SPH codes largely agree on whether fragmentation should occur, agreement on the number of fragments produced may not always be so good. In general, FD codes produce smaller numbers of fragments than SPH codes for a given set of initial conditions. This is undoubtedly because FD codes model a continuum that resists fragmentation (through numerical viscosity), while SPH codes model a swarm of $N$ particles that can become $N$ fragments if they are separated sufficiently far apart. Reality is hopefully somewhere in between, and this point alone emphasizes the need to continue to compare results obtained with both types of codes.

## 5. Nonisothermal Fragmentation

In the previous section we asserted that very slowly rotating clouds are unlikely to undergo fragmentation. Isothermal calculations are unable to properly address this point, because slowly rotating clouds collapse to nonisothermal densities prior to undergoing rotationally-induced fragmentation. Calculation of evolution through this phase requires detailed thermodynamics and 3D radiative transfer. Boss (1985) used a 3D Eddington approximation code to show that very slowly rotating clouds collapsing from high $\alpha_i$ initial conditions do *not* undergo fragmentation, though they may become bar-like. Hence these initial conditions appear to lead to single star formation.

There are two other physical situations in which binary formation is prevented. One is the collapse of progressively smaller mass clouds, which is equivalent to initiating collapse at progressively higher densities. Increased initial densities means less collapse can occur before nonisothermality sets in and thermal pressures prohibit fragmentation; the minimum protostellar mass that can be produced through the fragmentation of a collapsing cloud is $\sim 0.01 M_{\odot}$ (Boss 1986). The other is the collapse of clouds that are initially strongly centrally condensed; clouds with power-law initial density profiles cannot fragment into binaries (Boss 1987). In contrast, changes in the dust grain opacity by factors of 3 to 100 have relatively little effect on protostellar fragmentation (Boss 1988a).

## 6. Conclusions

This review has shown that fragmentation during protostellar collapse into a binary or multiple system is a natural, even preferred outcome, strongly suggesting that fragmentation is a likely means for explaining the formation of binary stars. Fragmentation also appears to be uniquely capable of explaining the ubiquity and wide range in dynamical properities of binary systems (see Bodenheimer 1978 and Boss 1988b for details).

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