FRAGMENTATION IN ROTATING ISOTHERMAL PROTOSTELLAR CLOUDS

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1. INTRODUCTION

In this paper we report briefly the results of an extensive set of 3-D hydrodynamic calculations that have been performed during the past two and one-half years to investigate the susceptibility of rotating clouds to gravitational fragmentation. Because of the immensity of parameter space and the expense of computations, we have chosen to restrict this investigation to strictly isothermal collapse sequences. Isothermality is, fortunately, a fairly accurate description of the optically thin phases of collapse of protostellar clouds: a one solar mass, Jeans unstable interstellar cloud, having a temperature of 10 K and density $\sim 10^6$ particles/cm^3, for example, will collapse isothermally through about 6 orders of magnitude in density before heating up significantly (Gerola and Glassgold, 1978). The assumption also applies to protogalactic clouds (Silk, 1977). The results, therefore, should add specifically to our understanding of the dynamics of the earliest phases in a protostellar (or protogalactic) cloud's evolution. A much more complete discussion of these calculations can be found in Bodenheimer, Tohline and Black (1980), hereafter referred to as BTB.

2. THE NUMERICAL CODE

The 3-D hydrodynamic computer code that was used in this study is described in detail by Tohline (1980). Briefly, the code gives an explicit, first-order-accurate time-integration of the three-dimensional equation of motion and continuity equation on a moving-Eulerian, cylindrical computational grid. A solution of the three-dimensional Poisson equation at each time step permits the analysis of self-gravitating gas flows. In the model evolutions discussed here, a grid resolution of (32,16,32) in (R,Θ,Z) was used. The Z-axis was the rotation axis of

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each cloud. The 32 zones in the Z-direction resolved only the "northern" hemisphere of each cloud, as reflection symmetry through the equatorial plane was assumed in all cases. In most evolutions, the 16 azimuthal zones spanned the entire 2π radians; in some cases, however, the 16 zones were distributed over only π radians and a periodic boundary condition was used in order to double the azimuthal resolution--of course, only "even" non-axisymmetric modes could be followed in these "π-symmetry" runs. No magnetic fields or viscous forces are included in these calculations.

3. THE CALCULATIONS

3.1. Initial Models

Each initial model was chosen to be a uniform-density (ρ_0), uniform-temperature, spherical cloud in uniform rotation, on which a well-defined non-axisymmetric density perturbation was imposed. The models reported here were 1 $M_\odot$ clouds of pure molecular hydrogen at a temperature of 10 K; under the assumed isothermal behavior, however, the results can be scaled to any mass and temperature desired.

The axisymmetric initial models can be uniquely defined by a choice of the two parameters:

$$\alpha \equiv \frac{\text{total thermal energy}}{|\text{total gravitational potential energy}|} \quad ;$$

$$\beta \equiv \frac{\text{total rotational kinetic energy}}{|\text{total gravitational potential energy}|} \quad .$$

All of the discussion which follows centers around an analysis of whether or not gravitationally driven fragmentation in protostellar clouds is sensitive to variations in either one (or both) of these parameters.

In all of the model evolutions reported here, the density perturbation imposed on the initial models had the following form:

$$\rho = \rho_0[1.0 + A_0 \cdot f(R,Z) \cdot \cos(2\Theta)] \quad . \tag{1}$$

The function f(R,Z), whose exact description is given in BTB, simply produced two orbiting Gaussian-shaped "blobs" of maximum amplitude A_0 off-axis in the equatorial plane of the cloud. A_0 was chosen to be either 0.10 (10%) or 0.50 (50%) in these models.

3.2. Typical (Axisymmetric) Evolutions

Each model, being initially Jeans unstable to collapse, was followed for 1.5-2.0 initial free-fall times (τ_{ff}). The calculations were stopped in each case when density gradients became to severe in a part of the computational grid--hence, resolution became sufficiently poor--that a physically realistic representation of the fluid flow was no longer possible. Although these models include initial deviations from axial symmetry, little or no growth of non-axisymmetric features took place during the first free-fall time. As a result, the general behavior of each evolution is similar to that described by axisymmetric (2-D) models (see, e.g., Black and Bodenheimer, 1976). During the first free-fall time, each model evolved through a sequence of successively more flattened, centrally condensed spheroids, as rotational forces slowed collapse perpendicular to the rotation axis. At roughly 1 τ_{ff}, the cloud was sufficiently flat that isothermal pressure gradients were able to stop the collapse in the Z-direction, forming a centrally condensed disk structure. The meridional cross-section of one cloud, shown in figure 1, illustrates this structure. The axis ratio of the disk correlated with the initial value of α-- a smaller α leading to a flatter disk--while the absolute size of the disk correlated with β. If forced to remain axisymmetric, an off-axis density enhancement appeared in the disk and grew, via gravitational forces, to a well-defined toroidal (ring) structure with a density minimum at the cloud center. This ring grew in mass toward an "equilibrium" configuration analogous to that described by Ostriker (1964) for isothermal toruses. The ring, upon accretion of more material from the cloud, usually evolved beyond a critical mass-per-unit-length and collapsed upon itself toward an infinitesimally thin hoop.

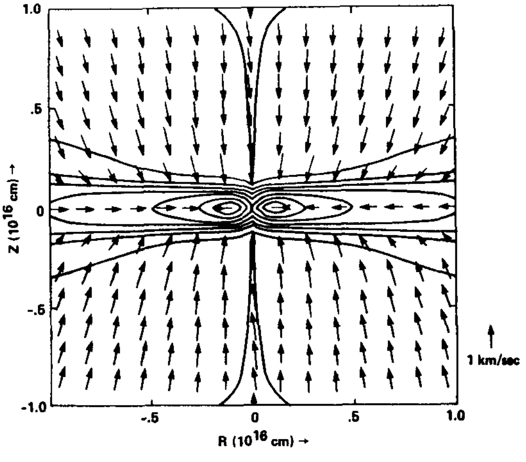

Figure 1. Density contours and velocity vectors in the meridional (R,Z) plane after 1.21 initial free-fall times for a model with $\alpha = 0.5$ and $\beta = 0.1$. Maximum density, 5×10^{-14} g cm^{-3}; contour interval, factor of 3.2. Most of the cloud mass is in the flattened disk and the ring structure is evident.

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3.3. Non-Axisymmetric Behavior

The evolution of non-axisymmetric features in these isothermal clouds can be described quite simply. For high α ($\gtrsim .3$) clouds--those clouds in which thermal pressure was initially important--the initial non-axisymmetric perturbation (NAP) underwent pressure-damping during the first free-fall time and the cloud evolved to a nearly axisymmetric ring structure. In all cases, the NAP began to grow after the ring formed, and in most instances this led to fragmentation of the ring into an equal mass binary system. A binary originating from "ring fragmentation" of this nature is shown in figure 2. In a few cases ($\alpha \cong .5$), the ring began to collapse axisymmetrically toward a thin hoop before the NAP had had time to amplify significantly. In these instances, no fragmentation was evident at the time calculations were stopped. It should be emphasized however, that fragmentation of the ring was observed in all other high α models -- models with $\alpha > .5$ as well as those with $\alpha < .5$.

In low α models, the NAP did not damp during the initial collapse phase and in most cases actually amplified somewhat. Upon formation of the disk, the NAP evolved directly into a well-defined, equal mass binary system without going through an intermediate ring formation stage. A binary system orginating from this type of "blob" fragmentation is illustrated in figure 3.

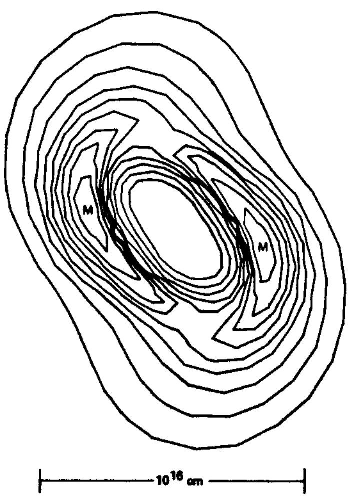

Figure 2

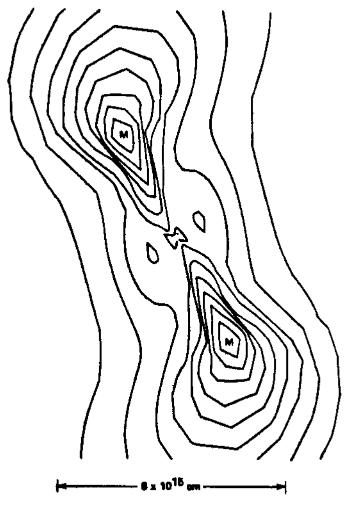

Figure 3

Density contours in the equatorial plane after "ring" fragmentation has occurred in one model (Fig. 2) and after "blob" fragmentation has occurred in another model (Fig. 3). Points of maximum density ($\sim 10^{-13}$ g cm^{-3}) are marked by "M"; contour interval, factor of 1.7.

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Of the 35 complete evolutions that we have followed, 12 started from initial models that had a Gaussian-shaped NAP of amplitude 50%. The final state of these 12 models is summarized pictorially in figure 4. A symbol is plotted for each model in this α-β plane, pinpointing its initial values of α and β. Squares locate models whose final configuration was a well-defined binary system (the number below each symbol tells the density contrast between a fragment's maximum and its surrounding); circles locate models that did not fragment significantly. "Marginal stability" occurs around $\alpha = 0.35$. This figure points out quite strongly two things:

a. The degree to which fragmentation occurs, that is, the rate at which a NAP grows, is sensitive to α.

b. Fragmentation of these isothermal clouds is practically independent of β.

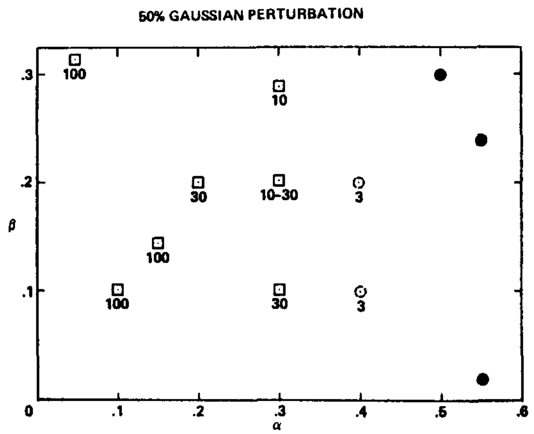

Figure 4. The (α,β) plane indicating, for each initial α, β, the final outcome of the evolution. Symbols are explained in the text.

Several models were run from identical initial conditions but with "π-symmetry" imposed, in order to double the resolution in the azimuthal coordinate. These evolutions showed that coarse zoning can lead to some artificial numerical damping of non-axisymmetric features, but that the qualitative results described above are correct. With improved resolution and, hence, less numerical damping, only a couple of minor modifications arose: (1) The "marginal stability" line in the α-β plane moved to slightly higher α, and (2) models near the marginal stability line that had previously fragmented through the ring mode, changed and fragmented directly via the "blob" mode.

Several models were also run with $f(R,Z) = 1$ (see eq. 1) and with a 10% initial NAP amplitude rather than the general 50% amplitude; all of these runs also used "π-symmetry" in order to avoid excessive damping. The lower amplitude models also evolved qualitatively in the manner described above. The only differences were minimal and were related to the fact that at a given time in an evolution, the amplitude of the NAP was (understandably) lower. Fragmentation into a binary system was the general outcome.

4. SUMMARY

From the extensive set of numerical calculations briefly described above, it seems apparent that rotating, isothermal gas clouds are unstable to fragmentation under a wide range of conditions. (CAUTION: This result for isothermal clouds cannot be generalized to all clouds, as is shown, for example, by Boss's analysis [these proceedings] of the stability of collapsing, adiabatic clouds.) It is of importance to note, however, that no fragmentation is apparent during a cloud's initial dynamic collapse toward a disk structure; rather it is the rotationally flattened disk/ring configuration that undergoes fragmentation. This is a considerably different picture of fragmentation than has been presented, for example, by Hoyle (1953).

The degree of instability and the mode (ring vs. blob) of fragmentation is sensitive to α, but insensitive to β. The initial amplitude of a perturbation does not appear to be crucial--fragmentation should occur eventually even for low amplitude initial NAPs.

Finally, it is of some interest to know what the properties are of the fragments that break out of these isothermal clouds. Before outlining these properties we emphasize that in this set of calculations we have specifically excited the m = 2 (binary) non-axisymmetric mode; hence we have in some sense suppressed the development of other modes and we have promoted the development of equal mass components in the binary systems. In these evolutions, a typical fragment contained $\sim$ 15% of the initial cloud mass; had a specific angular momentum $\cong$ 25-30% that of the original cloud; had a ratio of spin angular momentum to orbital angular momentum $\cong 0.2$; and itself had a ratio of thermal to gravitational energy $\alpha_{frag} < 0.1$. The formation of a binary system has therefore resulted in a conversion of some of the original cloud's spin angular momentum into orbital angular momentum, and has produced "protostars" with reduced specific angular momenta. It is also evident that each fragment is unstable to further collapse (having low α) under the isothermal assumptions imposed here.

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DISCUSSION

TSCHARNUTER: What would happen if there was a 10% perturbation instead of a 50% one?

TOHLINE: We ran some 10% perturbations, and the only differences were that it took somewhat longer to get fragmentation, the marginal stability line moved a little, and the fragmentation did not always occur through a ring stage.

J. COX: Can you say anything about the formation of a planetary system?

TOHLINE: With our present resolution the mass ratio of the fragment is always near unity. The $m = 2$ perturbation is therefore frequently used. For $m = 1$ or a spectrum of perturbations there may be non-equal masses, but extreme mass ratios cannot be seen. Certainly there is enough mass outside the fragments which could go into planets.

PERCY: How do you envision that these perturbations develop?

TOHLINE: Observations of interstellar clouds indicate that all are extremely lumpy to begin with. Our calculations really start artificially too uniform. A spectrum of perturbations would be nice to use.

WINKLER: I think a planetary system is easier formed by turbulence than the $m = 1$ mode.

TOHLINE: I firmly believe that the $m = 1$ mode can give large mass ratios, but I doubt that you can get to a Jupiter-Sun ratio.