NONAXISYMMETRIC MODELS OF COLLAPSING, ROTATING PROTOSTARS. A. P. Boss and S. J. Peale, Univ. of California, Santa Barbara, CA 93106

The problem of the origin of the solar system and of stellar and planetary systems in general is intimately connected to the question of the distribution of angular momentum in collapsing gas clouds. The collapse of rotating clouds restricted to axial symmetry has been followed numerically and found to produce an off-axis density maximum or "ring". It is then tempting to alleviate the classical angular problem of stellar and planetary system formation by proposing that this ring should fragment into several blobs, thereby transforming the spin angular momentum of the original rotating cloud primarily into the orbital angular momentum of a multi-protostellar system. This hypothesis has been confirmed in a slightly different form by calculations performed with the full three spatial dimension hydrodynamic code which is capable of following nonaxisymmetric motions such as the fragmentation of a ring. These calculations reveal that the collapsing cloud may indeed fragment into several dense, self-gravitating objects, but without necessarily first passing through a distinct ring phase. A comprehensive theory of planetary formation is dependent upon the results of such calculations that may yield a mechanism for the formation of a single star and the accompanying protoplanetary nebula. In particular a multi-protostellar system can be expected to eject single protostars and the properties of such objects should provide a realistic estimate of the initial conditions in the solar and photoplanetary nebula. Such estimates are of course crucial to the numerical modeling of the early solar system (e.g. Cameron and Pine, 1973; Cameron, 1977).

The hydrodynamical code employs explicit time differencing on an Eulerian spherical coordinate grid, based on the donor cell hydrodynamics scheme. The grid may be refined in the inner regions in order to more accurately follow the collapse. The Poisson equation for the gravitational potential is solved using an expansion in spherical harmonics. The spherically symmetric version of the code has undergone extensive testing, including the collapse of a pressureless cloud, the equilibrium state of a Bonnor-Ebert isothermal sphere, isothermal collapse, and nonisothermal collapse including the full effects of radiative transfer in the diffusion approximation. The nonisothermal calculations include an ideal gas equation of state, specific internal energy equation, and an opacity routine specialized to low temperatures (based on one obtained from W. DeCampli), and are in agreement with results previously obtained by Larson (1969) and Black and Bodenheimer (1975). We have also tried the Lax-Wendroff two-step scheme and several conservative, space-centered difference schemes, some of which are superior to the donor cell scheme in depicting various test cases. The performance of such schemes in the multi-dimensional collapse problems is currently under investigation.

The axially symmetric version of the code has been found to consistently produce a ring-like structure similar to those

previously encountered by Larson (1972) and Black and Bodenheimer (1976). The formation of such rings has been disputed by Kamiya (1977) who instead obtains a disk-like structure. This ring-like structure appears to be a consistent outcome of the numerical collapse, since calculations with varying numbers of radial grid points and with varying degrees of grid refinement produce rings of equivalent size and density. The rings so obtained are often close to the equilibrium states calculated by Ostriker (1964) for thin, self-gravitating isothermal rings. The axially symmetric code produces a ring-like structure and behavior similar to that found by Bodenheimer and Tscharnuter (1978).

The full three-dimensional code has been run with axially symmetric initial conditions but did not produce a ring. Instead an off-axis condensation developed in the first cell out from the rotation axis and grows strongly while rotating about this axis. A ring can be formed instead by increasing the amount of artificial viscosity to large values. However, due to the poor resolution of this single blob, and to possible pathologies in the difference scheme that might result in spurious advection of mass, this result is tentative and is also currently under investigation.

When the nonaxisymmetric version of the code was run with a large bar-shaped perturbation in the initial density, a well-defined binary system resulted, in fair agreement with the result obtained by Bodenheimer (private communication) for the same initial conditions. In this run the binary essentially formed directly out of the initial density perturbation without going through a distinct phase of ring formation, contrary to Tohline (1978) who has found for different initial conditions that his calculations proceed through a ring phase and generally do not fragment. Norman and Wilson (1978) studied the breakup of a ring obtained from axially symmetric calculations and found them to fragment so easily that they doubted that the ring could survive intact to the phase where they initiated their calculations.

The full three-dimensional code was also run with an initially axially symmetric density distribution in the presence of a tidally distorting point object of equal mass two radii away in the equatorial plane. The tidal forces produced a slightly lopsided bar-shaped density distribution, with the larger end oriented towards the tidal distorter but carried past that direction by the general cloud rotation. This configuration collapsed into a single self-gravitating object (centered on this larger end) with specific angular momentum reduced by about a factor of ten from the initial conditions. The center of mass being still roughly along the rotation axis implies that eventually other concentrations must form out, though the calculation could not be taken this far. This calculation suggests that tidal forces may be an effective means of fragmenting a collapsing, rotating protostellar cloud into a system of nonsimultaneously forming blobs, one of which could be ejected along with its slowly accreting nebula to serve as a prototype for the presolar nebula.

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