THE FORMATION OF COMMON-ENVELOPE, PRE-MAIN-SEQUENCE BINARY STARS

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1. Introduction

Recent observational investigations of the frequency of occurrence of pre-main-sequence binary stars have reinforced earlier suspicions that "binary formation is the primary branch of the star-formation process" (Mathieu 1994). As Bodenheimer *et al.* (1993) have reviewed, a number of different theories have been proposed to explain the preponderance of binary stars. Klein *et al.* (1998) show how the direct fragmentation of protostellar gas clouds may occur in early phases of collapse (at cloud densities $n \sim 10^3 - 10^{10}\text{cm}^{-3}$). But at higher densities, clouds are unable to cool efficiently upon contraction. Consequently, direct fragmentation becomes problematical. Because higher mean densities are associated with systems having shorter dynamical times, one is led to consider mechanisms other than direct cloud fragmentation for forming binary systems with orbital periods less than a few hundred years. Here we investigate whether such binaries can form by spontaneous fission of rapidly rotating protostars.

2. The Classical Fission Hypothesis

As Chandrasekhar (1969) has reviewed (see also Durisen & Tohline 1985), if protostellar objects are assumed to be self-gravitating, incompressible fluids with uniform vorticity, one can show analytically that their allowed equilibrium configurations are defined by spheroids or ellipsoids. Classically, models describing the slow contraction of rotating protostellar gas clouds have been formulated around such analytically prescribable equilibrium configurations. For example, a large, slowly rotating gas cloud with a relatively small ratio of rotational to gravitational potential energy $T/|W|$ will resem-

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ble a Maclaurin spheroid. As it contracts conserving angular momentum and mass, its evolution will proceed along the Maclaurin sequence through progressively flatter configurations of higher $T/|W|$. At a sufficiently high $T/|W|$, one finds that the axisymmetric configuration is no longer the lowest energy state available. Instead, there is an ellipsoidal configuration to which the gas cloud will prefer to evolve. Furthermore, if one follows evolution along a more and more distorted ellipsoidal sequence (such as the Jacobi sequence or any one of the Riemann sequences), one finds that eventually other configurations with even higher order surface distortions become energetically favorable. For example (see Fig. 3 of Durisen & Tohline 1985), there is a "dumbbell-binary sequence" that branches smoothly off of the Jacobi ellipsoid sequence. One might imagine, therefore, that binary stars form from the slow contraction of a rapidly rotating gas cloud along the Maclaurin, then Jacobi (or Riemann), then dumbbell-binary sequences. In reality, the picture is not this clear. Most significantly, detailed work on ellipsoidal figures of equilibrium has only been completed for incompressible fluid systems. It is not at all clear to what extent the results carry over to more realistic structures having compressible equations of state.

3. Problems Promoting the Fission Hypothesis

While examining the structure of rotating gas clouds that form the compressible analogues of Maclaurin spheroids, Ostriker & Bodenheimer (1968) showed that models with reasonable degrees of compressibility must incorporate a significant degree of differential rotation if they are to possess reasonably high values of $T/|W|$ and, therefore, be physically interesting in the context of the fission hypothesis. Employing 3D numerical hydrodynamics techniques, Durisen *et al.* (1986), Williams & Tohline (1988), and Houser *et al.* (1994) have examined the relative stability of rapidly rotating, compressible gas clouds that are initially in axisymmetric equilibrium but which reside just past a critical bifurcation point along the axisymmetric sequence according to Ostriker & Bodenheimer (1968). Invariably these simulations have shown that models with $T/|W| > 0.27$ are dynamically unstable toward the growth of a nonaxisymmetric deformation but, unlike their uniformly rotating, incompressible counterparts, the eigenmode to which these structures appear to be unstable has a spiral character.

Employing a significantly improved finite-difference simulation code and improved spatial resolution (128^3 grid zones), we recently have repeated the simulation that was first reported in Durisen *et al.* (1986). Moviel (on the accompanying CD-ROM) shows the nonlinear development of the two-armed, spiral-mode instability. The evolution is shown in the inertial reference frame and covers 20 central initial rotation periods. Each frame of

Movie1 displays four nested isodensity contours at $\rho/\rho_{\max} = 0.8$, 0.4, 0.04, and 0.004. Via the trailing spiral structure, gravitational torques are able to effectively redistribute angular momentum on a dynamical time scale; a relatively small amount of material is shed into an equatorial disk (this disk material is not visible in Movie1 because $\rho_{\rm disk} < 0.004\rho_{\max}$); and the central object (containing most of the initial object's mass) settles down into a new equilibrium configuration. Clearly, evolution to a binary star system as suggested by the classical fission hypothesis does not occur. It is primarily because simulations of this type have not produced a binary star system that the classical fission hypothesis has lost favor within the star formation community over the past decade (Bodenheimer *et al.* 1993).

4. Fission Hypothesis Revived

Interestingly, the instability illustrated by Movie1 produces a final steady-state object (hereafter referred to as the "final bar") that is dynamically stable, has a $T/|W| \sim 0.25$, and has a decidedly nonaxisymmetric structure. In many respects this final bar appears to be a compressible analog of a Riemann ellipsoid but, as Movie2 illustrates, the configuration possesses nontrivial internal motions. In the first frame of Movie2, 108 test particles have been lined up along the major axis of the final bar. Thereafter the particles are followed as they move along equatorial-plane streamlines of the flow, as viewed in a frame of reference that is rotating with the overall pattern speed of the final bar. The illustrated flow is entirely prograde and largely differential, but there is a small volume near the center of the configuration that is moving harmonically. In Movie3 we illustrate the 3D flow-field of the final bar. In the first frame of Movie3, a vertical *sheet* of test particles has been aligned with the major axis of the final bar. The subsequent motion of these particles illustrates that there is relatively little vertical fluid motion and, although it varies with R and θ, the angular velocity $\omega(\mathbf{x})$ is almost independent of z. It may be possible, therefore, to understand this and similar systems in terms of the properties of simpler, 2D nonaxisymmetric structures.

Andalib (1998) recently has developed a self-consistent-field technique that can be used to construct equilibrium models of infinitesimally thin, self-gravitating gaseous disks with (a) compressible equations of state, (b) nonaxisymmetric structures, and (c) nontrivial internal motions. By demanding that the disks have uniform vortensity $\zeta \equiv (\nabla \times \mathbf{v})/\rho$, Andalib has successfully constructed equilibrium disks with polytropic indices $0 \leq n \leq 1.3$ and minor-to-major axis ratios in the range $0.80 \geq b/a \geq 0.06$. Movie4 illustrates the internal flow of four of Andalib's compressible disks with nonaxisymmetric structures: one with fully retrograde internal motions (R); one with fully prograde internal motions (P); one with vortices sandwiched between separate regions of prograde and retrograde flow (V); and a common-envelope binary (dumbbell-shaped) configuration (D).

The similarity between the flow illustrated in Movie2 and the flow in Andalib's model P (Movie4) is striking. Apparently Andalib's model provides a good 2D analog of the 3D "final bar" that formed as a result of our fully hydrodynamic simulation of the two-armed, spiral mode instability (Movie1). Furthermore, Andalib's work demonstrates that model P is just one among a series of compressible models with nontrivial internal flows that defines a smooth elliptical-dumbbell-binary sequence. We suspect, therefore, that the final bar sits on an analogous (3D) sequence and that, if it is cooled slowly, it will evolve along the sequence to a common-envelope binary configuration such as the one illustrated by model D in Movie4. Additional support for this conjecture comes from New & Tohline (1997) who have demonstrated that stable, equal-mass common-envelope binaries can be constructed for fully 3D fluid systems with a sufficiently compressible equation of state.

In summary, it seems clear that a wide variety of rapidly rotating, nonaxisymmetric systems can be constructed with compressible equations of state. This work gives us renewed confidence that fission offers a viable route to binary star formation. Future investigations designed to model the slow cooling and contraction of initially nonaxisymmetric configurations like the final bar described above should demonstrate whether or not this scenario is correct. This research has been supported in part by the U.S. National Science Foundation (AST-9528424), and in part through grants of computing time at the San Diego Supercomputer Center and the NAVOCEANO Major Shared Resource Center.

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