NUMERICAL STUDIES OF THE FISSION HYPOTHESIS FOR ROTATING POLYTROPES

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The fission hypothesis suggests that close binary stars form due to global nonaxisymmetric instabilities in rotating, quasistatically contracting stars. We study this hypothesis by using an explicit, donor cell, finite difference 3-D hydrodynamic code with self-gravitation to follow dynamic two-armed instabilities in rapidly rotating polytropes. Typical grids are 32 x 16 x 16 in cylindrical coordinates (ϖ, ϕ, z) and assume reflection symmetry about the equator plane and rotation axis. Initial conditions are obtained by applying density perturbations $\delta\rho = a\rho \cos 2\phi$ with a = 0.10 or 0.33 to axisymmetric equilibrium models with the same angular momentum distribution but with various values of polytropic index n and of $\beta \equiv T/|W|$ where T = total rotational kinetic energy and W = total gravitational energy. We find dynamic growth of perturbations when $\beta \gtrsim 0.30$ for both n = ½ and 3/2. To within the limitations of our methods, this agrees well with the classical dynamic stability limit of $\beta \simeq 0.274$ for the bar modes of the Maclaurin spheroids. An unstable case with n = 3/2 and β = 0.33 is evolved for about ten initial central rotation periods. The part of the star inside corotation develops into a stable bone-shaped or dumbbell-shaped structure after about three pattern rotations. At about the same time, material outside corotation is ejected in the form of two trailing spiral arms. These arms wrap due to differential rotation, merge into a detached disk, and eventually narrow into a radially expanding ring with slight cos 2ϕ density enhancements. The ring contains 16% of the mass but more than half the angular momentum. The central bone-shaped object is an analog of the Riemann S-type ellipsoids. Fluid circulates dynamically and stably from one knob of the bone to the other. In this sense, the object is probably better described as a triaxial star than as a contact binary. Similar behavior is exhibited by an extensive n = ½ and β = 0.33 evolution. This work was supported by U.S. National Science Foundation Grant AST-7821449.

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DISCUSSION

Tscharnuter: How much mass and angular momentum is contained within the "bone-shaped" region?

Durisen: The final central bone-shaped object contains 84% of the mass but less than half of the angular momentum, and has a $T/|W|$ of about 0.19.

Kippenhahn: Your calculations show damping which you called "numerical" damping, and they show growth which you called "physical" growth. What are the time scales of these two phenomena compared to each other?

Durisen: For $T/|W| \lesssim 0.30$, the amplitude of the $\cos(2\phi)$ density perturbation decreases from 10% to about 1% in one to two pattern rotations. For $T/|W| \gtrsim 0.30$, the growth is roughly exponential in the linear regime with an e-folding time of one to two pattern rotations. The similarity of these time scales is probably responsible for the fact that our dynamic stability limit is 10% higher in $T/|W|$ than the classical Maclaurin spheroid value. We are planning to repeat our calculations with different azimuthal resolutions and with second-order instead of first-order transport. We also plan experiments on various other idealized problems to determine numerical diffusion coefficients and their dependence on the parameters of the numerical scheme. Comparison calculations using other 3-D codes are also underway. In this way, we hope to clarify which effects in our calculations are numerical and which are physical.

Gingold: Using the SPH particle code we also found that when the polytrope was of index 1.5 spiral arms formed, soaking up angular momentum. For an index of 0.5, however, we got a fission. Have you performed calculations with a lower polytropic index?

Durisen: Yes. We have carried out an evolutionary calculation with $n = 1/2$ and $T/|W| = 0.33$, and we have followed it for about three pattern rotations. Again, a central bone-shaped object forms, and material is ejected in the form of spiral arms. However, because of time-step size problems, we have not yet evolved this case beyond the phase of active spiral arm ejection. It is possible that the central bone might fragment at a later evolutionary stage.

Sørensen: How flat is your cloud at different stages?

Durisen: The starting axisymmetric equilibrium model with $n = 3/2$ and $T/|W| = 0.33$ has an equatorial to polar ratio of about six. During the intermediate, highly nonaxisymmetric phase of spiral arm ejection it is difficult to characterize the flattening uniquely because it depends on which meridional section is taken. Roughly speaking, the overall flattening from the tip of the arms to center increases due to expansion of the arms and contraction of the central bone. At the end of the evolution, it makes more sense to describe the ring and the bone separately. In computational units, the expanding ring has an inner radius of 14, a radial width of about 6, and a halfthickness in z of about 4. The central bone-shaped object has a semimajor axis of about 5.5 in computational units. We have not yet carefully scrutinized meridional sections of the bone, but it is centainly much less flattened than the starting model.