

**SECOND-ORDER ACCURATE MODELS OF SOLAR NEBULA FORMATION.** A. P. Boss, DTM, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015.

**INTRODUCTION.** Previous work has demonstrated the possible occurrence in the early solar nebula of nonaxisymmetric structures such as bars and spiral arms that could efficiently transport angular momentum outward [1]. These three dimensional models [2] along with two dimensional models by other workers [3,4] have also shown that the early solar nebula might have had relatively high temperatures ( $\sim 1500K$ ) in the terrestrial planet region. Considering the possible importance of these conclusions, it is worthwhile to attempt to refine the numerical aspects of these calculations as much as possible and see if the previous results are still obtained. With this end in mind, the hydrodynamics code used in [1,2] has been improved in several respects, one of the most important being the use of second-order accurate finite differences to represent the hydrodynamical fluxes. Models calculated with the new codes have begun to reveal differences from the older results, primarily with respect to the tendency toward fragmentation.

**NUMERICAL METHODS.** The new code features second-order accurate hydrodynamical fluxes, obtained using consistent advection and a spherical coordinate extension of van Leer monotonic interpolation [5]. At present, the code is still first-order accurate in time, but this should be quite adequate considering the large number ( $\sim 10^5$ ) of time steps typically used in a single model. The spatial resolution has been increased to 51 grid points in radius, to effectively 45 in colatitude (assuming symmetry through the equatorial plane), and to 64 in azimuth (with no symmetry about the rotation axis being assumed). The hydrodynamical equations are still solved in conservation law form, ensuring global conservation of mass and angular momentum. The code has again been designed to conserve angular momentum locally, as measured by the preservation of the initial angular momentum spectrum during axisymmetric collapse [6]. The radial momentum fluxes have been corrected for the effects of volume centering in spherical geometry [7]; this correction is necessary in order to achieve a high degree of accuracy during the pressureless sphere test case. The diagonal components of the artificial viscosity tensor are used as needed to stabilize the scheme against shocks [8]; the artificial viscosity is designed to vanish during homologous collapse. Radiative transfer in both the Eddington and diffusion approximations has been added to the codes, allowing the study of nebula models that contain both optically thick and thin regions or only optically thick regions, respectively. The second-order nature of the hydrodynamics in the code has been demonstrated through convergence testing [9] on both purely spherical as well as three dimensional test cases. The code's ability to reach and maintain a stable polytropic equilibrium has been verified; the latter test shows that the level of nonaxisymmetric 'noise' is no more than about 1%.

**RESULTS.** The most basic astronomical constraint on a solar nebula model is that it must produce a single rather than a binary protostar. Previous modeling has determined initial conditions for which binary protostars can form through fragmentation, that is, through break-up during the dynamic collapse phase [10]. It is thus of interest to see how the criteria for binary fragmentation change when a second-order three dimensional hydrodynamics code is employed. Hence a series of four models was run, with each model starting from the same initial conditions as models run with the old code [10]. The new models assumed isothermal thermodynamics for computational efficiency and because only a negligible amount of nonisothermal heating occurs in these particular models. Each model started with  $\beta_i = E_{\text{rotational}}/|E_{\text{gravitational}}| = 0.16$ ,  $M = 1.0M_{\odot}$ , and  $T_i = 10K$ , but with varied  $\alpha_i = E_{\text{thermal}}/|E_{\text{gravitational}}|$ ; C1:  $\alpha_i = 0.40$ , C4:  $\alpha_i = 0.26$ , C7:  $\alpha_i = 0.13$ , and C10:  $\alpha_i = 0.060$ . Each model started in solid body rotation and with

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a radial density profile ( $\rho_i \propto \exp[-(r/r_1)^2]$ ) with a central density 20 times higher than the boundary density.

Models C1 and C4 are initially the closest to virial equilibrium ( $\alpha + \beta = 1/2$ ) and so may best represent clouds that begin collapse following loss of magnetic field support through ambipolar diffusion; models C7 and C10 may better represent clouds that are induced to collapse by rapid compression. Models C10 and C7 collapsed and formed intermediate bar configurations before fragmenting into binary protostars, in much the same manner as before [10]. However, models C1 and C4 behaved quite differently from the older models, where C1 and C4 did not undergo fragmentation after the same time had elapsed. With the new code, models C1 and C4 collapsed to form an intermediate disk configuration, which subsequently began to undergo binary fragmentation; model C4 was evolved far enough to undergo sub-fragmentation into a hierarchical system. The difference in outcomes between models C1-C4 and C7-C10 must be attributed to the differing initial conditions. Models C7-C10 started with considerably lower thermal pressure than C1-C4, and as a consequence the initial bar-like perturbation was able to grow rapidly and produce a narrow spindle. Model C4 started much closer to virial equilibrium, and as a consequence did not encounter significant growth of nonaxisymmetry until after a rotationally flattened disk began to form, allowing higher order modes to participate in the fragmentation.

Model C4 has shown that the old code [10] could err in favor of single star formation. A suspicion that this would be the case arose during the development of the new code, when the pressureless collapse test revealed that the old code had a systematic tendency to produce elevated densities in the central regions when the density should have remained uniform. The new code, being free of this tendency, is not similarly biased in favor of single stars.

Finally, another comparison model has been run with the new code, using the same initial conditions as model 10 of [2]; the old model had a  $0.05 M_\odot$  nebula when the sun's mass reached  $0.99 M_\odot$  and a temperature of  $\sim 1500$  K in the terrestrial planet region. However, the new model led to considerably higher temperatures, because the new method preserves the uniform density central plateau, resulting in a sudden burst of accretion onto the central protostar and hence a much larger luminosity. The peak mass accretion rate ( $\sim 1 M_\odot/\text{yr}$ ) is much too large to be realistic for the solar nebula. The mass accretion rate would be quite a bit lower in a model starting from more realistic, centrally condensed initial conditions, as in [10]. With respect to temperatures, the original models [2] are actually more realistic because that numerical scheme resulted in lower mass accretion rates ( $< 10^{-2} M_\odot/\text{yr}$ ).

**IMPLICATIONS.** The new models have shown that binary fragmentation and nebula temperatures can depend on the hydrodynamical scheme. Hence it will be important to use the new, more accurate code to re-examine issues such as binary versus single star formation, and to calculate models of solar nebula formation with mass accretion rates closer to the suspected values ( $\sim 10^{-6} - 10^{-4} M_\odot/\text{yr}$ ).

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