

PROTOSTELLAR DISK INSTABILITIES AND THE FORMATION OF SUBSTELLAR COMPANIONS

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ABSTRACT

Recent numerical simulations of self-gravitating protostellar disks have suggested that gravitational instabilities can lead to the production of substellar companions. In these simulations, the disk is typically assumed to be locally isothermal; i.e., the initial, axisymmetric temperature in the disk remains everywhere unchanged. Such an idealized condition implies extremely efficient cooling for outwardly moving parcels of gas. While we have seen disk disruption in our own locally isothermal simulations of a small, massive protostellar disk, no long-lived companions formed as a result of the instabilities. Instead, thermal and tidal effects and the complex interactions of the disk material prevented permanent condensations from forming, despite the vigorous growth of spiral instabilities. In order to compare our results more directly with those of other authors, we here present three-dimensional evolutions of an older, larger, but less massive protostellar disk. We show that potentially long-lived condensations form only for the extreme of local isothermality, and then only when severe restrictions are placed on the natural tendency of the protostellar disk to expand in response to gravitational instabilities. A more realistic adiabatic evolution leads to vertical and radial expansion of the disk but no clump formation. We conclude that isothermal disk calculations cannot demonstrate companion formation by disk fragmentation but only suggest it at best. It will be necessary in future numerical work on this problem to treat the disk thermodynamics more realistically.

Subject headings: hydrodynamics — instabilities — solar system: formation — stars: formation

1. INTRODUCTION

Protostellar disk instabilities have gained renewed interest as a possible mechanism for the formation of substellar companions to stars. As formulated by Kuiper (1951) and later Cameron (1978), instabilities in the solar nebula could lead directly to the early and rapid (orbital timescale) formation of clumps of material that eventually evolve into Jovian planets. The mechanism has the virtue of a short timescale, which has been perhaps the most serious problem for the currently favored core-accretion model for the formation of Jupiter (e.g., Mizuno 1980; Pollack 1984; Pollack et al. 1996). While many researchers have shown that protostellar disks are susceptible to a variety of instabilities (see references in Pickett et al. 1998, hereafter PCDLI), the conditions under which they lead to companion formation have yet to be defined. Numerical simulations that suggest the possibility of instability-induced companion formation have been conducted under rather idealized assumptions about the thermal conditions of the disks, and so the ultimate fate of fragments that do form has not been reliably determined.

We have previously studied how the disk thermal energetics controls the evolution of nonaxisymmetric structure in gravitationally unstable disks. In PCDLI and Pickett et al. (2000, hereafter PCDLII), we conducted a series of three-dimensional hydrodynamic evolutions of a gravitationally unstable disk subject to different assumptions regarding its thermal evolution. The final strength of the disturbances in the disk depended on the degree to which outwardly moving material could cool. In an adiabatic evolution that included artificial viscosity, a two-armed spiral grew quickly but saturated at low nonlinear amplitude because of the irreversible heating generated by the

spiral itself. No condensations formed. High-density fragments, in the form of arcs of disk material, resulted only for the extreme of locally isothermal conditions, i.e., evolutions in which the local disk temperature remains everywhere unchanged. Even in this case, only transient clumps formed; in fact, the disk was disrupted, with radial ejection of material, after 2 equatorial rotation periods. The destruction of subcondensations in the disk was a result of the gravitational interactions with other clumps and the remaining disk material and of the severe thermal and tidal effects experienced by clumps on eccentric orbits about the central star.

On the other hand, work by Boss (1997, 1998) has suggested that, under locally isothermal conditions, gravitational instabilities in disks can produce stable giant gaseous protoplanets (GGPPs) when the minimum value of the Toomre stability parameter Q is low enough. Direct comparison of our earlier results with those in Boss (1997, 1998) is difficult because of the differences in disk properties, specifically $Q(r)$, the disk-to-star mass ratio M_d/M_* , and the surface density distribution $\sigma(r)$. The PCDL model corresponds to a possible early stage in the development of a protostellar disk from the collapse of a prestellar cloud, whereas the Boss models represent older, more evolved disks with significantly flatter surface density distributions and unstable regions that are radially restricted. Consequently, more mass over a larger fraction of the disk is unstable in the PCDL model, leading to faster growth and a more complex interaction of the spiral structure than is seen in the Boss models.

Ultimately, we wish to determine the realistic conditions, if any, under which the disk instability mechanism will succeed in the formation of companion objects. It seems clear that the locally isothermal assumption promotes the growth of a high-density nonaxisymmetric structure in disks (e.g., Laughlin & Bodenheimer 1994; Boss 1997, 1998, 2000; Nelson et al. 1998; Nelson, Benz, & Ruzmaikina 2000; PCDLI; PCDLII). However, our simulations have shown that the locally isothermal condition may not be sufficient by itself for the production of

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bound, long-lasting companion objects from the debris of a disrupted disk. In order to facilitate comparison with other work, we have generated a new axisymmetric model that more closely resembles the inner solar nebula in general and the Boss models in particular. While the basic structures of our new model and the Boss models are similar, the different simulation conditions may lead to different nonlinear outcomes. In particular, positive nonrotational velocities are severely damped for numerical stability in Boss (1997, 1998). Such a reduction in outward motion could prevent the expansion of the disk expected to occur as the result of gravitational instabilities, potentially enhancing the production and stability of GGPPs. In this Letter, we examine the effects of both the velocity restrictions and the disk thermal conditions on the ability of the Boss models to produce GGPPs. We present locally isothermal evolutions of our new solar nebula model with and without velocity conditions analogous to those in Boss (1997, 1998). Since these simulations represent one extreme assumption about the thermal physics of the disk, we also present an adiabatic evolution of the same model, in which artificial viscosity is used to produce irreversible heating, such as would occur in shocks.

2. NUMERICAL METHODS

2.1. Initial Model

The initial model is generated in a two-step process using a self-consistent field method to create an $n = 3/2$ polytropic equilibrium state, followed by axisymmetric cooling to produce the desired $Q(r)$ (Hachisu 1986; PCDLI). The M_*/M_d , $Q(r)$, and $\sigma(r)$ are comparable to the Boss models. The disk material is in near-Keplerian rotation. The disk extends radially from 0.76 AU to the disk equatorial radius $R_{\text{eq}} = 10$ AU and has a mass $M_d = 0.133 M_\odot$; the central star has a mass $M_* = M_\odot$. The resulting, cooled axisymmetric state has $Q \sim 1.1$ over the region $r/R_{\text{eq}} = 0.83\text{--}0.96$, which contains 31% of the disk mass. Like the Boss models, the low- Q region is located near the edge of the disk and is radially restricted. The $Q(r)$ rises steeply with decreasing radius inside $r/R_{\text{eq}} = 0.83$, e.g., from $Q(r = 5 \text{ AU}) = 3.5$ to $Q(r = 1 \text{ AU}) = 20$.

2.2. Three-dimensional Hydrodynamics

The three-dimensional hydrodynamics code is fully of second order and includes self-gravity (see PCDLII). The equations of hydrodynamics are solved in conservative fashion on a cylindrical grid with $(r, \phi, z) = (256, 64, 32)$; the initial equilibrium model extends to radial zone 210. The inner disk boundary is located at radial zone 16. In the adiabatic simulation, a von Neumann & Richtmeyer artificial viscosity scheme is used to treat and resolve shocks (Norman & Winkler 1986). Symmetry about the equatorial plane is assumed, and outflow boundary conditions are used.

We impose three conditions on the inner boundary. The material inside $R_{\text{inner}} = 0.76$ AU is not evolved in the hydrodynamics code, which allows a significantly longer computational time step to be used. The gravitational potential of material inside this radius is held fixed at the initial value. This is equivalent to treating the star as a central point mass. In order to prevent activity in the inner disk from dominating the behavior of the outer disk, all nonaxisymmetric structure inside $R_{\text{axi}} = 1.9$ AU is suppressed every time step by setting the nonaxisymmetric Fourier components of the density to zero. Similar suppression of the inner disk is used in Boss (1998). Finally, the disk is evolved using an adiabatic equation of state

inside $R_{\text{EOS}} = 3.8$ AU in all the simulations presented here. Outside this radius, we use either the locally isothermal assumption (denoted ISO) or an adiabatic evolution with artificial viscosity (denoted ADIAV). In Boss (1998), a set of equations of state are used, with $\gamma = 1\text{--}1.4$.

Two velocity conditions are imposed on the simulations. In the first case, no restrictions are placed on velocities in the disk (i.e., the PCDL velocity conditions); the disk is free to expand under the influence of any gravitational instabilities that develop. In the other case, positive v_r and v_z are reduced by a factor of 2 every time step. This is roughly equivalent to the restrictions placed on positive r -components and negative θ -components of the velocity in Boss (1997, 1998) for spherical coordinates. The ADIAV evolution is conducted only under the free-velocity condition.

3. RESULTS

Each simulation begins with random cell-to-cell density perturbations in the range $\delta\rho/\rho = \pm 0.04$ for $r > 8$ AU. The simulations extend to 6.3–6.5 equatorial rotation periods (ERPs), or about 180 yr. In all three simulations, two- and three-armed

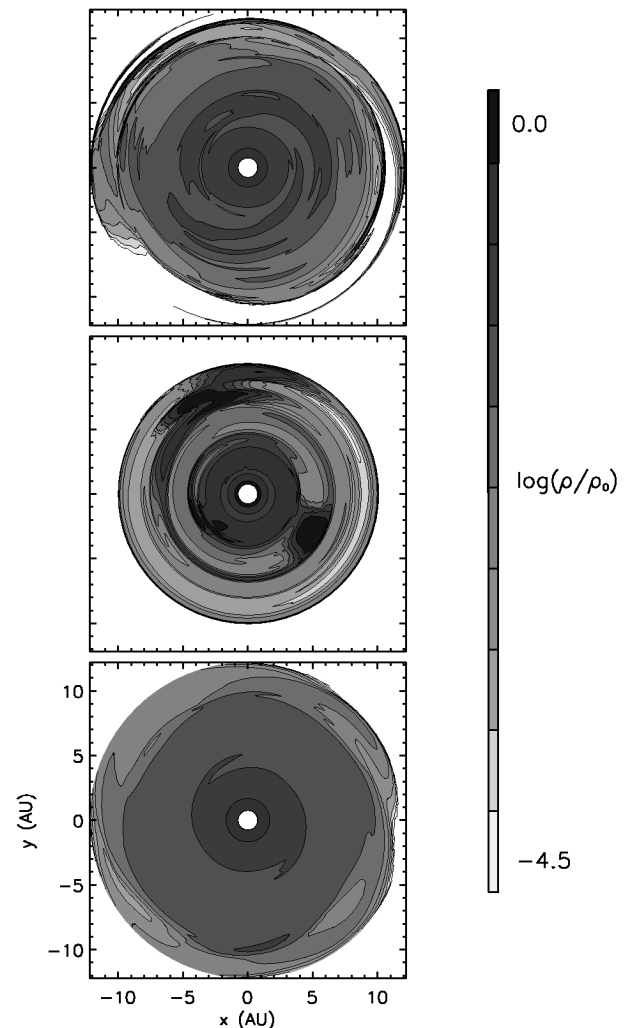


FIG. 1.—Comparison of the final equatorial plane mass density for the three simulations. *Top*: The free-velocity ISO simulation at 6.3 ERPs. *Middle*: The restricted velocity ISO-VR simulation at 6.3 ERPs. *Bottom*: The ADIAV simulation at 6.5 ERPs. The gray scale spans the range of $\log(\rho/\rho_0) = -4.5\text{--}0$, where $\rho_0 = 4 \times 10^{-9} \text{ g cm}^{-3}$. The contour/gray-scale interval is $\log(\Delta\rho/\rho_0) = 0.5$.

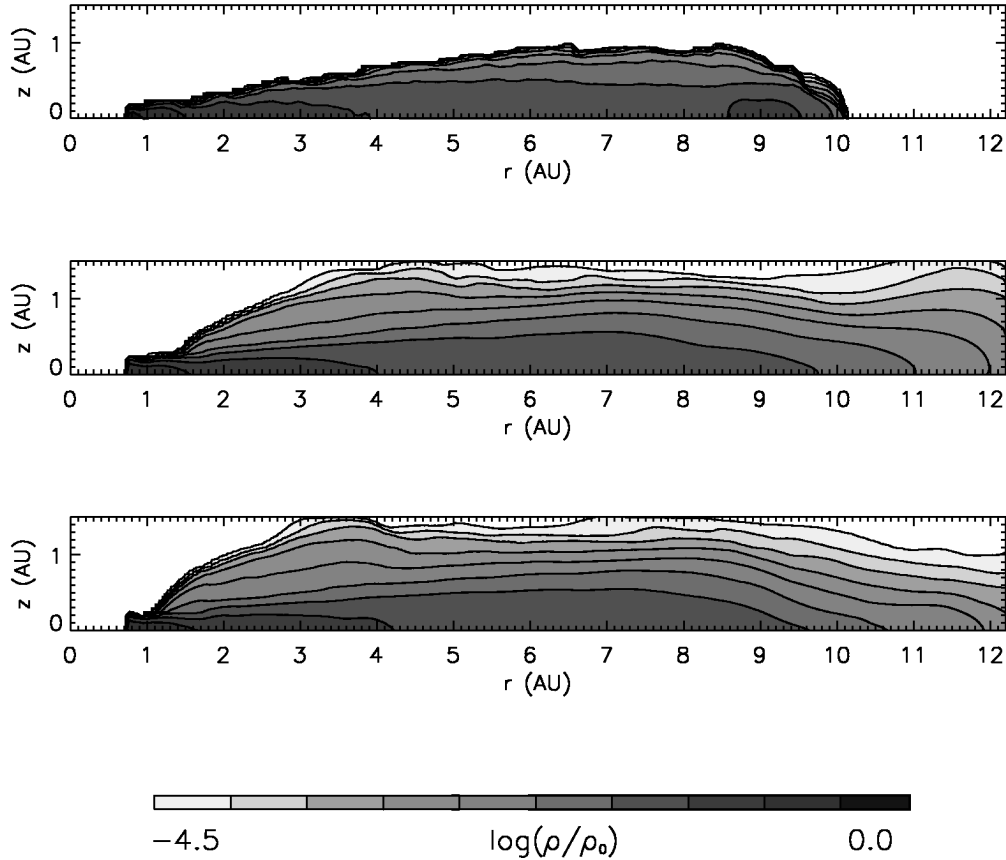


FIG. 2.—Evolution of meridional density for the ADIAV simulation. From top to bottom, the azimuthally averaged densities for the ADIAV simulation at 0.0, 3.25, and 6.5 ERPs are shown. The gray scale is the same as in Fig. 1.

spirals grow in the outer regions of the disk, reaching a significant nonlinear amplitude between 2 and 3 ERPs. The subsequent evolution of the instabilities and their impact on the disk depend on both the imposed velocity restrictions and the thermal regime. Figure 1 shows equatorial gray scales of the mass density at the end of the three simulations.

3.1. Locally Isothermal Case: Free-Velocity Conditions (ISO)

In the free-velocity isothermal simulation, the disk behaves much like the ISO evolution of the PCDL model. Two- and three-armed spirals quickly grow to nonlinear amplitude and shred the disk into a collection of long, high-density arcs. The spiral instabilities reach a significant nonlinear amplitude in less than 2 ERPs. The disturbances are quite widespread throughout the disk. By about 3 ERPs, the model has expanded significantly, and mass leaves the computational grid. At the end of the simulation, about 1% of the total mass and 14% of the total angular momentum have been ejected. Although transient, high-density structures appear, and no single object survives the length of the calculation as a potential GGPP. Note that by the time shown in Figure 1, most of the high-density arcs have already left the computational grid. Future calculations will use higher resolution and a larger grid in order to explore the fate of the ejected material.

3.2. Locally Isothermal Case: Velocity Restrictions (ISO-VR)

The ISO-VR evolution is at first more quiescent than the ISO case. Two- and three-armed spirals take longer to reach a

significant nonlinear amplitude and are more narrowly confined to the initially unstable (low- Q) regions. At 3 ERPs, a moderately nonlinear two-armed spiral contains high-density knots of material at the ends of the spiral arms. The subsequent evolution of the spiral and the rest of the disk does involve the appearance and disappearance of short-lived high-density arcs. However, by 5.4 ERPs, a large, high-density clump of material forms near 5.4 AU. By the end of the calculation, the clump has completed almost three orbits about the central regions and, in the process, has become more coherent, gained mass, and cleared a large gap in the disk from about 4.1 to 6.2 AU (Fig. 1). The final mass of the clump is $0.034 M_{\odot}$, and its central density is about 2 orders of magnitude higher than the gas in the gap. The disk has not expanded appreciably during the simulation. We note that this configuration is qualitatively very similar to the evolution of the unstable model shown in Figure 15 of Boss (1998). A larger, less coherent structure is also evident outside about 7 AU. While it is difficult to determine whether the object at 5.4 AU would survive over longer timescales, we note that (1) the clump does not appear to weaken like the dense structures seen in the ISO simulation and (2) the condensation lasts for at least as many orbital periods as the GGPPs reported by Boss (1998) under similar simulation conditions.

3.3. Adiabatic Case (ADIAV)

The ADIAV evolution of the protostellar disk resembles the evolution of the smaller, more massive PCDL disk under the same thermal conditions (PCDLII). A three-armed spiral reaches a high nonlinear amplitude by about 2 ERPs and is the dominant

player until about 4 ERPs, when it competes with a global two-armed spiral. The late evolution of the disk is then dominated by this two-armed spiral, which becomes widespread throughout the disk (Fig. 1). Unlike the isothermal simulations, no condensations form as a result of the instabilities. The disk expands because of irreversible heating, leading to gradual mass loss off the top and outer edge of the grid (Fig. 2). The amount of material and angular momentum lost in this fashion is about an order of magnitude smaller than in the free-velocity ISO case. By the end of the simulation near 6.5 ERPs, the spiral disturbances are still evident but are much weaker compared with the ISO evolutions.

4. CONCLUSIONS

The ISO condition is more favorable to clump formation than are adiabatic conditions, and the clumps appear more likely to survive if the disk material resists radial expansion, artificially or otherwise. This last point has been confirmed by Boss (2000) in recently revised, high-resolution ISO simulations of the solar nebula with a larger ($R_{\text{eq}} = 20$ AU) and less massive ($M_d = 0.09 M_{\odot}$) disk than in the models presented here and in Boss (1997, 1998). When the velocity restrictions from Boss (1997, 1998) are lifted, the disk evolution is chaotic and reminiscent of the ISO evolutions reported here and in PCDLII. A $5 M_J$ clump does form on an elliptical orbit and completes two orbits, but it eventually dissipates against the complex background of strong spirals and spiral fragments. This occurs in spite of the fact that the clump far exceeds its local Jeans mass, and so it seems initially bound (Boss 2000). In a violently unstable, locally isothermal disk, the fate of any condensation that forms may be regarded as an artifact of its orbit and is therefore difficult to determine with certainty if the disk ma-

terial is allowed to expand naturally and if the region where nonaxisymmetric structure grows is not confined radially.

As attractive as the locally isothermal evolutions are from the viewpoint of companion formation, they are less realistic than the ADIAV evolution because the ISO condition is not likely to remain valid as dense structures form. While the assumption of local isothermality in the cool, initially optically thin regions of the solar nebula may be justified, the assumption breaks down locally as dense spirals or clumps form, continue to grow, and become optically thick. For example, assuming a Rosseland mean opacity of $\kappa \sim 1 \text{ cm}^2 \text{ g}^{-1}$ for 100 K (Pollack et al. 1994), the approximate temperature at 5 AU for our initial solar nebula model, the $34 M_J$ object that forms there in the ISO-VR case has a final optical depth of 4×10^4 . The dense condensation in Boss (2000) has an optical depth of about an order of magnitude higher than this. We stress that the ADIAV conditions themselves are somewhat idealized and that a reliable determination of the effects of nonaxisymmetric structure will require the proper inclusion, in three dimensions, of the stabilizing effects of heating as seen in the ADIAV case (see also Nelson et al. 2000; Nelson 2000; PCDLII) as well as the destabilizing effects of cooling, for example, by radiation (e.g., Nelson et al. 2000).

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