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The Formation of Companion Objects by Disk Instabilities

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Abstract

Numerical simulations of self-gravitating protostellar disks by another researcher have suggested that gravitational instabilities can lead to the production of stellar or substellar companions. In our own studies of small, massive protostellar disks, we found that thermal and tidal effects and the complex interactions of the disk material prevented permanent condensations from forming, despite vigorous instabilities. We here present new three-dimensional evolutions of an older, larger, but less massive protostellar disk. We show that, at least for the conditions described below, potentially long-lived condensations form only when severe restrictions are placed on the natural tendency of the protostellar disk to expand in response to gravitational instabilities.

1. Introduction

In Pickett et al. (1998, 2000, hereafter PCDLI and PCDLII, respectively), we conducted a series of three-dimensional hydrodynamic evolutions of a small (equatorial radius $R_{eq} \lesssim 0.1$ AU), massive (disk-to-star mass ratio $M_d/M_* \sim 2/3$) protostellar disk. The model was designed such that the value of the Toomre stability parameter Q in the disk was uniform and low ($Q = 1.5$), in order to allow the entire disk to participate in nonaxisymmetric instabilities. Four different assumptions about the disk thermal evolution were used to study how thermal energetics control the outcome of nonaxisymmetric instabilities. Regardless of thermal regime, the model was highly unstable to dynamic spiral disturbances. The final strength of the disturbances in the disk depended upon the degree to which outwardly moving material could cool. High density arcs of disk material resulted only for the extreme of locally isothermal conditions, i.e., evolutions in which the disk temperature at each radius retained its initial axisymmetric value. Nevertheless, only transient clumps formed, and in fact the disk was disrupted, with significant radial ejection of material, after two equatorial rotation periods (ERP's). The destruction of subcondensations in the disk was a result of the gravitational interactions with other clumps and the remaining disk material, and severe thermal and tidal effects experienced by clumps on eccentric orbits about the central star.

Recent work by Boss (1997, 1998) has suggested that, under locally isothermal conditions, gravitational instabilities in larger ($R_{eq} = 10$ AU), less massive ($M_d/M_* = 0.13$) disks can produce giant gaseous protoplanets (GGPP's) when the minimum value of Q is low enough. Direct comparison of our earlier results with those in Boss (1997, 1998) is difficult, due to differences in disk properties, specifically M_d/M_*, $Q(r)$, and the surface density distribution $\sigma(r)$. The PCDL model corresponds to an early stage in the development of a protostellar disk from the collapse of a pre-stellar 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 more complex interaction of spiral structure than is seen in the Boss models. Despite these differences, we feel that, based on the simulations in PCDLI and PCDLII, caution must be taken when attempting to evaluate the efficacy of the disk instability mechanism for the formation of stellar and substellar companions.

Ultimately, we wish to determine the realistic conditions, if any, under which the disk instability mechanism will succeed in the formation of companion objects. 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 boundary and velocity conditions may lead to different nonlinear outcomes. In particular, the 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 long-term stability of GGPP's. To test this idea, we present two locally isothermal evolutions of our new protostellar disk model. We find that, in the absence of any velocity damping, disk disruption occurs in a manner similar to that seen in the more massive PCDL disks, while candidate GGPP objects form only when the outward velocities are restricted. In the latter case, two massive fragments form and are similar to unstable cases in Boss (1998).

2. Numerical Methods

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 is in Keplerian rotation. The resulting, cooled axisymmetric state has $Q \sim 1.1$ over the region $r/R_{eq} = 0.83$ to 0.96, which contains 3.6% of the total mass; $Q(r)$ rises steeply with decreasing radius inside $r/R_{eq} = 0.83$. Table 1 lists some of the model parameters.

Table 1: Initial Model Parameters

M_{total}	1.133 $M_\odot$
M_d	0.133 $M_\odot$
$M(Q \sim 1.1)$	0.041 $M_\odot$
R_{inner}	0.76 AU
R_{Qmin}	8.6 AU
R_{eq}	10.0 AU
$Q(5AU)$	3.5
Q_{min}	1.07
$T_{mid}(5AU)$	100 K
$T_{mid}(10AU)$	38 K
$P(10AU) = ERP$	28.6 years

Hydrodynamics Code. The three-dimensional hydrodynamics code is fully second order and includes self-gravity (see PCDLII). The equations of hydrodynamics are solved in conservative fashion on a cylindrical grid with (r,ϕ,z) = (256,64,32); the initial equilibrium model extends to radial zone number 210. The inner disk boundary is located at radial zone number 16. Symmetry about the equatorial plane is assumed, and outflow boundary conditions are used.

Special Simulation Conditions. We impose three conditions on the inner boundary. The material inside R_{inner} is not evolved in the hydrodynamics code, which allows a significantly longer computational time step to be used and thus a more extensive simulation. 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. Further, all nonaxisymmetric structure inside $R_{axi} = 1.9$ AU is suppressed every time step, in order to prevent nonaxisymmetric activity in the inner disk from dominating the behavior of the outer disk. Boss uses similar suppression in his inner disks. Lastly, the disk is evolved using an adiabatic equation of state inside $R_{EOS} = 3.8$ AU; outside this radius, the locally isothermal condition from PCDLI and PCDLII is used.

3. Results

Two simulations are presented in this contribution. In the first simulation, no restrictions are placed on velocities in the outer 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 evolution, positive v_r and v_z are reduced by a factor of two every time step. This is roughly equivalent to the restrictions placed on positive r- and negative θ-components of the velocity in Boss (1997, 1998) for spherical coordinates. Each simulation begins with random cell-to-cell density perturbations ranging between $\delta\rho/\rho = \pm 0.04$ for $r > 8$ AU. The simulations extend to 6.3 ERP's, or about 180 years. Figures 1-3 compare the equatorial plane density greyscales at late times.

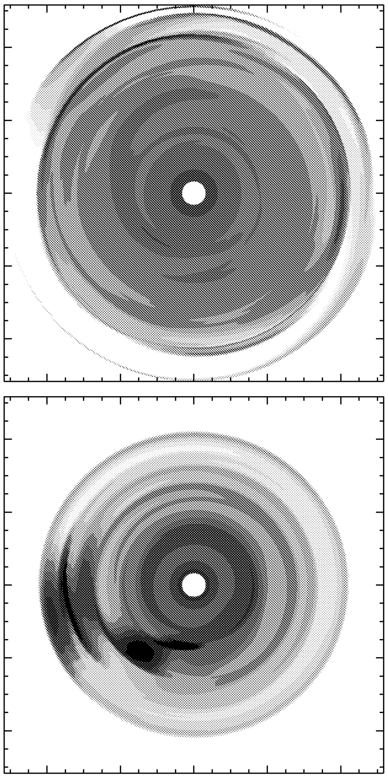

Fig. 1.— Equatorial plane density greyscales for both simulations at 5.8 Equatorial Rotation Periods (ERP's). Top: No velocity restrictions. Bottom: The simulation in which all positive r- and z-velocities are damped. The greyscales span seven orders of magnitude in density; the box encloses the total radial computational grid

3.1. Free Velocity Case

In the simulation without velocity restrictions, the disk behaves much like the unstable locally isothermal 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 significant nonlinear amplitude in less than 2 ERP's. By about 3 ERP's, 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 has been ejected. Although many transient, high density structures appear, no single object survives the length of the calculation as a potential GGPP. Note, too, that the spiral instabilities are quite widespread throughout the disk (Figures 1-3).

3.2. Restricted Velocity Case

The evolution of the protostellar disk subject to the velocity conditions is at first more quiescent than the free velocity case. Two- and three-armed spirals take longer to reach significant nonlinear amplitude and are more narrowly confined to the initially unstable (low

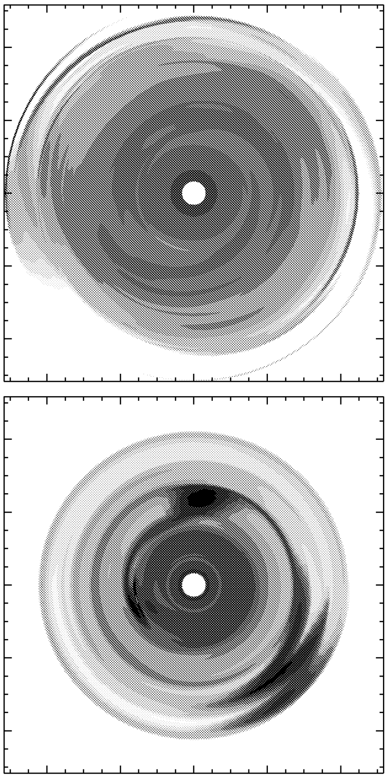

Fig. 2.— Same as Figure 1, at 6.0 ERP's.

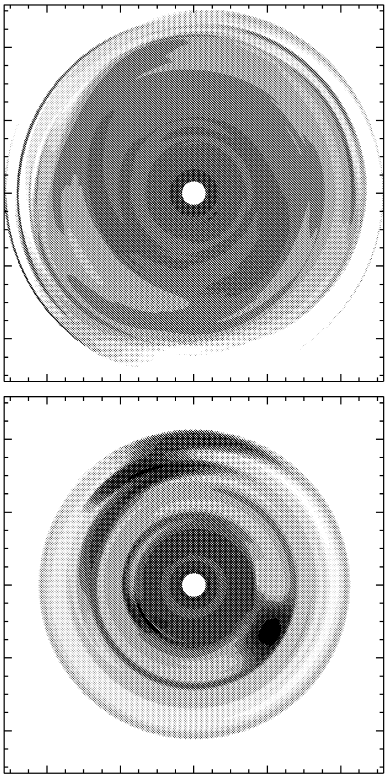

Fig. 3.— Same as Figure 1, at 6.3 ERP's.

Q) regions. At 3 ERP's, 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 ERP's, a large, high density clump of material forms near 5.4 AU. By the end of the calculation, the clump has completed two 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 AU to 6.2 AU (Figure 3). The final mass of the clump is 0.034 $M_{\odot}$, and its central density is about two orders of magnitude higher than the gas in the gap. The disk has not expanded appreciably during the simulations. We note that this configuration is qualitatively similar to the evolution of an unstable model shown in Figure 15 of Boss (1998). A larger, less coherent structure is also evident outside about 7 AU.

4. Conclusions

This paper presents preliminary three-dimensional hydrodynamic evolutions of a protostellar disk under two velocity conditions. When the outward velocity is unrestrained, instabilities generated in the colder outer disk eventually lead to the expansion and disruption of the disk, with no long-lived condensations surviving. When the positive radial and vertical motions are damped, similar instabilities lead to the formation of a massive, dense clump of material on a roughly 5 AU orbit. We stress that, while the clump survives two complete orbits, it would be difficult to predict its long-term survival under more realistic thermal conditions. In future calculations, we will relax the assumption of local isothermality with an improved equation of state, as well as follow ejected material by expanding the initial computational grid. Our results serve as a cautious reminder that the energetics of a protostellar disk can greatly affect the outcome of nonlinear instabilities (see also Nelson et al 2000). In particular, restricting the outward flow of material in an unstable disk can artificially enhance the ability of the disk to form GGPP's and, once formed, may aid in their survival.

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