PLANET FORMATION PROCESSES IN A MARGINALLY GRAVITATIONALLY UNSTABLE DISK AROUND A SOLAR-MASS PROTOSTAR.

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Introduction: Marginally gravitationally unstable disks provide a natural mechanism for the rapid transport radially inward and outward of short-lived radioactivities and refractory grains, as well as the ability to largely homogenize any initial spatial heterogeneity [1,2]. However, such a disk might also be expected to possibly form giant planets by the disk instability mechanism, which requires a gaseous disk that is massive enough to become gravitationally unstable and able to cool fast enough for robust clumps to form and survive. Here we present a set of four models with three-dimensional radiative hydrodynamics [3] that investigate the extent to which disk instability can lead to rapid giant planet formation in a disk with half the mass of previous disk instability models [4].

Models: Recent observations imply low-mass stars form with disk masses in the range from 0.05 $M_\odot$ to 0.4 $M_\odot$ [5]. The models calculate the 3D evolution of a disk with a mass of $0.043 M_\odot$ from 4 to 20 AU in orbit around a $1 M_\odot$ protostar [3]. Four different models have been computed with the same disk density distribution but with different combinations of outer disk temperature T_o (20 and 25 K) and envelope temperature T_e (30 and 50 K). Model A had T_o = 20 K and T_e = 50 K, model B had T_o = 25 K and T_e = 50 K, model C had T_o = 20 K and T_e = 30 K, and model D had T_o = 25 K and T_e = 30 K. The initial disk temperatures inside 7 AU computed for this disk density distribution yield a midplane temperature of T_m = 339 K at 4 AU and decreasing monotonically to T_m = 100 K at 7 AU; thereafter, T_m is assumed to decrease smoothly to T_o = 20 or 25 K. In order to err on the side of stability, the temperature is not allowed to drop below this initial distribution. These choices lead to initial Toomre Q gravitational stability criteria decreasing monotonically outwards from values greater than 10 inside 5 AU to minimum Q values Q_{min} = 1.74 for models A and C and 1.95 for models B and D at the outer grid boundary of 20 AU.

Results: Figure 1 shows the equatorial density distribution of model A after 129 yr of evolution. Strong spiral arms are apparent from the inner boundary at 4 AU out to $\sim$ 10 AU, as well as a number of clumps, often still aligned with their parental spiral arms. Figure 2 depicts the midplane temperature distribution, which rises rapidly inside $\sim$ 7 AU to a maximum of $\sim$ 340 K at 4 AU. The maximum midplane density of 5.5×10^{-10} g cm^{-3} occurs for the clump seen at about 6 o'clock in Figure 1. The mass of the clump at this time is $\sim 0.26 M_J$, slightly above the Jeans mass of $\sim 0.24 M_J$ at the mean density (1.1×10^{-10} g cm^{-3}) and mean temperature (26 K) of the clump. This mass estimate implies that the clump is self-gravitating. The most promising clump in model B at 119 yr occurs at 5 o'clock in Figures 3 and 4. The estimated clump mass is $\sim 0.21 M_J$, below the Jeans mass of $\sim 0.35 M_J$ at the mean density (1.9×10^{-10} g cm^{-3}) and mean temperature (40 K) of the clump. The clump at 7 o'clock in Figures 3 and 4 suffers from the same problem; model B appears to be close to, but not quite capable of forming self-gravitating clumps. Only models A and C were able to form self-gravitating clumps that are likely to succeed in forming gas giant planets [3].

Conclusions: Previous work [4] showed that robust disk instabilities could occur inside 20 AU in disks with a mass of $\sim 0.091 M_\odot$. The present models [3] show that when the disk mass inside 20 AU is halved, the ability of disk instability to produce viable, self-gravitating clumps is signficantly compromised, when self-consistently-calculated disk cooling rates are employed. Disk instability thus appears to be only a marginally effective process in a disk with $\sim 0.04 M_\odot$, and is unlikely to lead to giant planet formation around solar-mass protostars with disks significantly less massive than $\sim 0.04 M_\odot$. Core accretion remains as the favored formation mechanism for giant planets in such lower mass disks. Nevertheless, the mixing and transport properties of marginally gravitationally unstable disks [1,2] are expected to remain similar to those in more massive disks, implying that gravitational torques are likely to play an important role in the earliest phases of planetary system formation, even if they do not lead directly to giant planet formation.

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References: [1] Boss, A. P. 2007, ApJ, *660*, 1707. [2] Boss, A. P. 2008, EPSL, *268*, 102. [3] Boss, A. P. 2010, ApJ,, *725*, L145. [4] Boss, A. P. 2002, ApJ, *576*, 462. [5] Isella, A. et al. 2009, ApJ, *701*, 260.

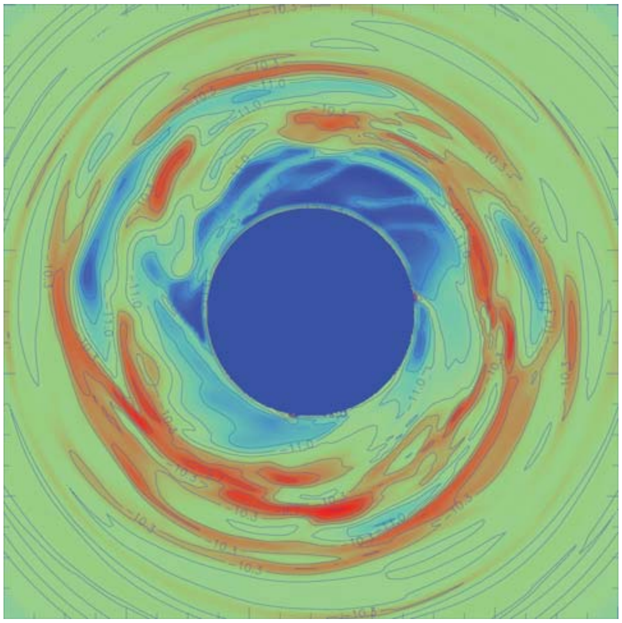

Figure 1. Equatorial log density for model A after 129 yr. Colors span a rainbow running from blue (low density) to red (high density). Contours are spaced by factors of ~ 2 in density. Region shown is 24 AU wide; inner region (blue) is 4 AU in radius.

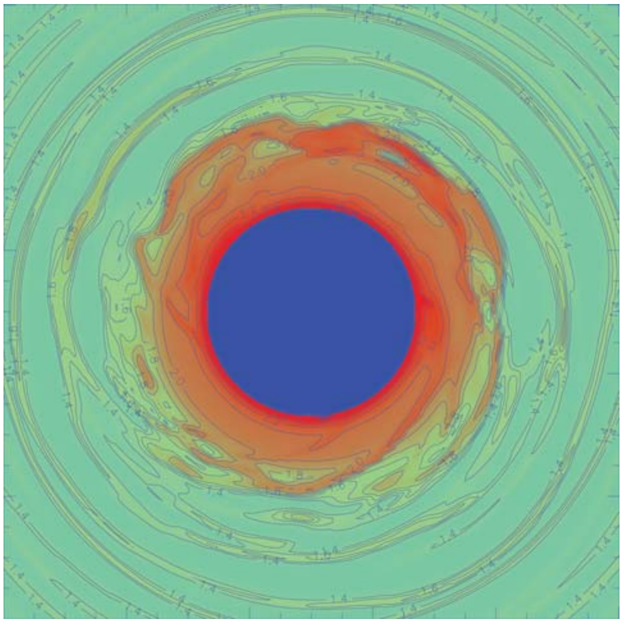

Figure 2. Equatorial log temperature for model A after 129 yr, plotted as in Figure 1, except that the contours are spaced by factors of ~ 1.3 in temperature. Midplane temperatures rise to 339 K at 4 AU and fall to 20 K in the outer disk.

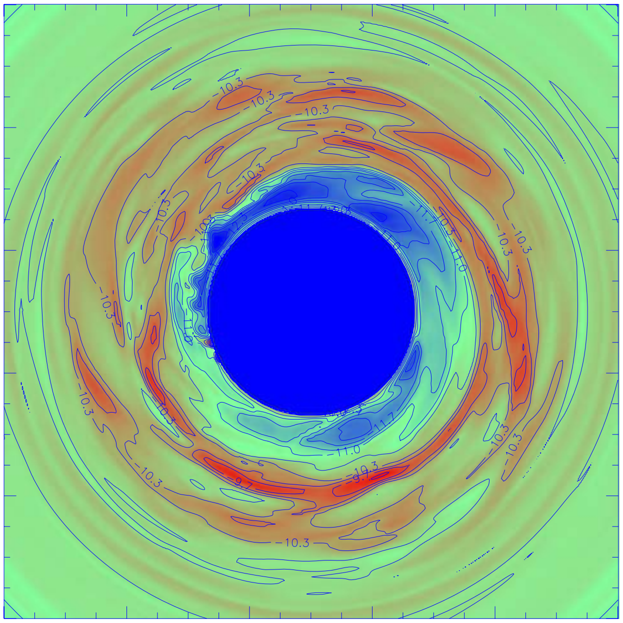

Figure 3. Equatorial log density for B (119 yr).

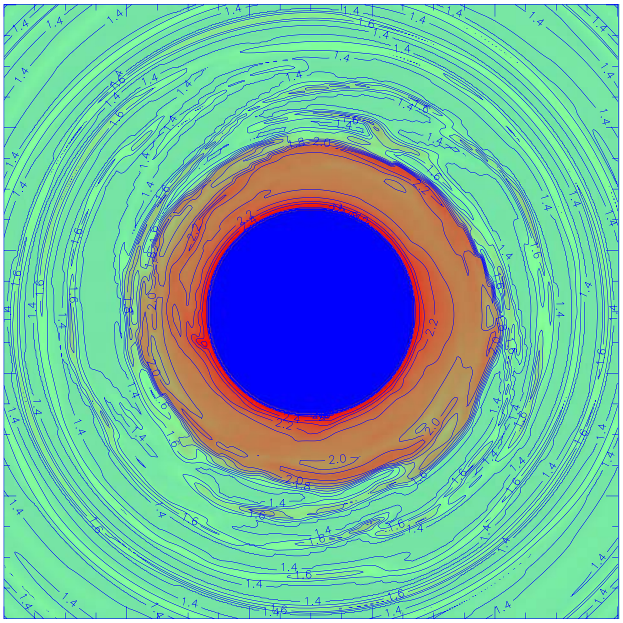

Figure 4. Equatorial log temperature for B (119 yr).