TRANSIENT CLUMPS AND HIGH-TEMPERATURE PROCESSING IN THE OUTER DISK.

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Protoplanetary disks in Class 0 and I objects are subject to heavy infall from their surrounding envelopes for $\sim 10^5$ yr following the collapse of their natal clouds [1,2]. This infall not only supplies new interstellar medium material to the disk, but can drive violent and episodic bursts of gravitational instabilities (GIs) [3]. At disk distances $r \lesssim$ tens of AU, GIs will likely be able to self-regulate and avoid disk fragmentation, even during periods of heavy envelope infall. In contrast, at $r \gtrsim$ tens of AU, clumps with a few to ~ 10 M_J may form [4]. In some cases, fragments may survive to become massive gas giants, brown dwarfs, or even, with prodigious mass growth, stellar companions. However, this survival is not guaranteed, and many clumps may become tidally destroyed [5].

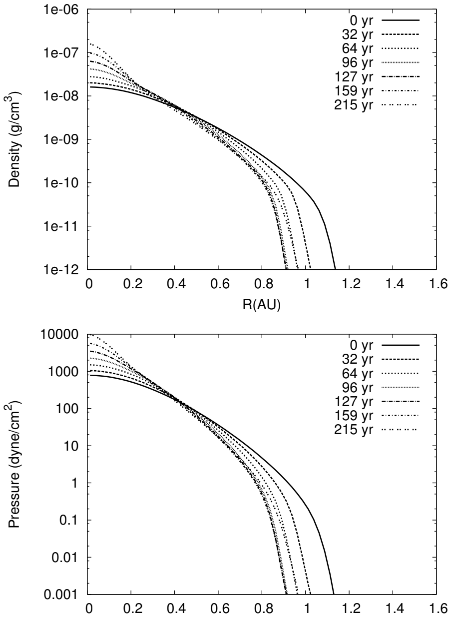

Figure 1: Radial profiles, averaged over mass shells, for density and pressure in the 10 M_J clump. The high-density, high-pressure environment is in stark contrast to typical conditions in the cometary regions of protoplanetary disks.

When clumps first form at distances ~ 100 AU, their radial extent will be many AU in size, filling a substantial fraction of their Hill sphere [6]. If clumps are born on eccentric orbits or move inward through clump-clump scattering [5] or rapid migration [7,8], a clump's Hill sphere can decrease faster than the clump can contract, leading to its destruction [9]. Gas, ices, and dust in these clumps will have been exposed to temperatures and pressures that would otherwise not occur at large orbital

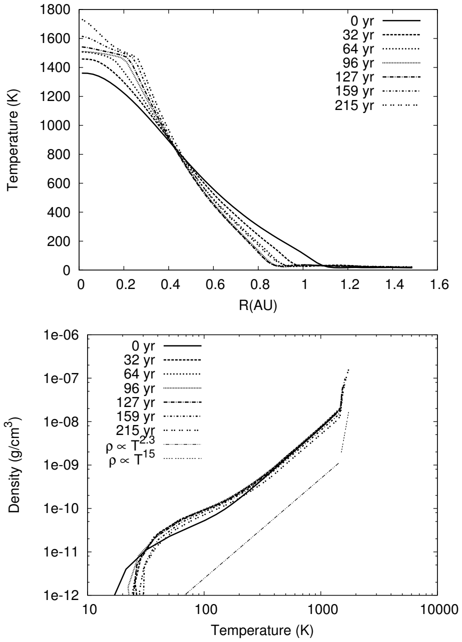

Figure 2: Similar to Figure 1, but for the temperature profile (top), as well as each snapshot on the density-temperature plane (bottom). Upon reaching $T \sim 1450$ K, the sudden drop in the opacity in these hot regions allows radiative transport to become much more efficient than in the regions where dust has not sublimated. A radiative core develops, with the radiative/convective boundary at the opacity transition. The bottom panel demonstrates that the overall structure of the clump is well approximated by an $n = 2.3$ polytrope, switching to $n \sim 15$ at the core/envelope boundary.

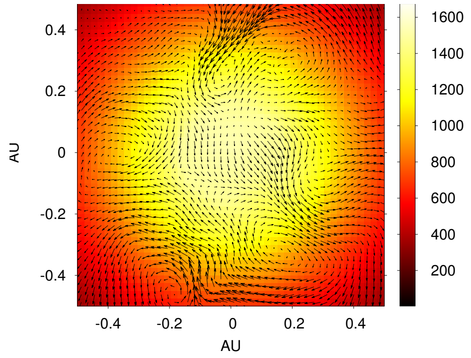

Figure 3: A $10M_J$ clump after 64 yr of evolution. The full radius of the clump extends to $\sim$ 1 AU. Convective cells have fully developed throughout the clump, allowing for mass to be exposed to a wide ration of temperatures, pressures, and densities. Colorbar indicates temperature in Kelvin.

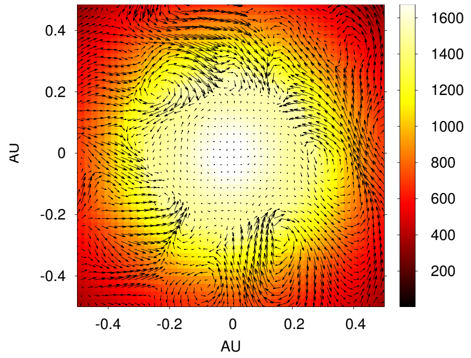

Figure 4: Same as Figure 3, but at the end of the simulation, corresponding to 215 yr. As the clump contracts, the central temperature rises above 1450 K. For the Pollack et al. [14] opacities used here, dust sublimates and allowing radiation to carry energy over greater distances. As a result, the core transitions from convective to radiative, and well-mixed layers always have a maximum temperature $T \sim 1450$ K. The clump at this snapshot is near dynamical collapse due to H_2 dissociation, and the radiative core contains nearly half of the clump's mass.

separations.

We investigate the conditions in a 10 M_J clump using 3D radiation hydrodynamics simulations. Radiation transport is treated by combining flux-limited diffusion with Monte Carlo techniques. The initial clump model is constructed from an $n = 2.5$ polytrope. We have assumed that substantial evolution from cooler temperatures has already taken place. The hydrodynamics code[1] includes the rotational and vibrational states of molecular hydrogen for a fixed ortho:para ratio of 3:1 [10]. After the initial clump is loaded onto the grid, there is an adjustment phase that lasts $\sim$ 15 yr. We take $t = 0$ yr in the following figures to refer to the time following this adjustment period. Figures 1 and 2 show density, pressure, and temperature profiles for the clump, as well as profiles on the density-temperature plane, at seven different times. Material is mixed throughout the clump by strong convection (Figure 3). Between 64 and 96 yr, the central temperature increases to $\sim$ 1450 K, and dust sublimates. This allows a radiative core to develop, which remains surrounded by a convective envelope until the end of the simulation. After the radiative core forms, a substantial fraction of the clump's mass will be locked at high temperatures and pressures, while the rest will continue to circulate between temperatures of tens and 1450 K (Figure 4).

If this clump were to be on an eccentric orbit about a $\sim \mathrm{M}_\odot$ star with a pericenter inside 13 AU, the clump would undergo tidal mass striping, which can ultimately lead to full tidal disruption. This would release material in icy regions of the protoplanetary disk that has been exposed to remarkably different thermal histories, as suggested by [5,11]. Most of the material from this epoch will be accreted onto the growing protostar, but as long as the processed material is not preferentially lost, low-mass, non-self-gravitating disks could contain relics of a disk's younger, violent past.

References: [1] Watson, D. M. et al. 2007, Nature, 448, 1026. [2] Calvet, N., Hartmann, L., Kenyon, S. J., & Whitney, B. A. 1994, 434 330. [3] Vorobyov, E. I., & Basu, S. 2006, 650, 956. [4] Boley, A. C. 2009, ApJ, 695, L53. [5] Boley, A. C., Hayfield, T., Mayer, L., & Durisen, R. H. 2010, Icarus, 207, 509. [6] Boley, A. C., & Durisen, R. H. 2008, ApJ, 724, 618. [7] Michael, S., Durisen, R. H., & Boley, A. C. 2011, ApJ, 737, L42. [8] Baruteau, C., Meru, F., & Paardekooper, S.-J. 2011, MNRAS, in press. [9] Cha, S. H., & Nayakshin, S. 2011, MNRAS, 415, 3319. [10] Boley, A. C., Hartquist, T. W., Durisen, R. H., & Michael, S. 2007, ApJ, 656, 89L. [11] Nayakshin, S., Cha, S. H., Bridges, J. C. 2011, MNRAS, 416, L50. [12] Pollack et al. 1994, ApJ, 421, 615.

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[1] Astrohoneycomb will be described in a future manuscript.