**COMETARY REFRACTORIES, CRYSTALLINE SILICATES, SHORT-LIVED RADIOISOTOPES, STABLE OXYGEN ISOTOPES, AND THE SOLAR NEBULA.** A. P. Boss, DTM, Carnegie Institution of Washington (boss@dtm.ciw.edu).

The discovery of refractory grains amongst the particles collected from Comet 81P/Wild 2 by the Stardust spacecraft [1] provides the ground truth for large-scale transport of materials formed in high temperature regions close to the protosun outward to the comet-forming regions of the solar nebula. Observations of disks around young stars often find evidence for crystalline silicate grains at distances ranging from inside 3 AU to beyond 5 AU, in both the disk's midplane and its surface layers [2]. These grains could have been produced through thermal annealing of amorphous grains by hot disk temperatures reached only within the innermost disk, well inside 1 AU. Crystalline and amorphous silicate grains thus appear to require large-scale transport as well. While accretion disk models driven by a generic turbulent viscosity have been invoked as a means to explain large-scale transport [3,4], the detailed physics behind such an "alpha" viscosity remains unclear, especially considering that the magneto-rotational instability (MRI) is unable to drive evolution in the magnetically dead midplane regions [5] of most interest for planetary formation.

We present here an alternative physical mechanism for large-scale transport in the solar nebula: gravitational torques associated with the transient spiral arms in a marginally gravitationally unstable disk, of the type that appears to be necessary to form gas giant planets. Three dimensional models are presented of the time evolution of self-gravitating disks [6,7,8], including radiative transfer and detailed equations of state, showing that small dust grains will be transported upstream and downstream inside the disk on time scales of less than 1000 yr inside 10 AU. These models furthermore show that any initial spatial heterogeneities present (e.g., in short-lived isotopes such as $^{26}$Al) will be homogenized by disk mixing down to a level of $\sim$ 5%, preserving the use of short-lived isotopes as accurate nebular chronometers [9], while simultaneously allowing for the spread of stable oxygen isotope ratios [10,11]. This finite level of nebular spatial heterogeneity appears to be related to the coarse mixing achieved by spiral arms, with radial widths of order 1 AU, over time scales of $\sim$ 1000 yrs [7,8].

The models consist of a $1 M_\odot$ central protostar surrounded by a protoplanetary disk with a mass of 0.047 $M_\odot$ between 1 and 10 AU. The underlying disk structure is the same as that of the disk extending from 4 AU to 20 AU in previous models [6,7,8]. Disks with similar masses and surface densities appear to be necessary to form gas giant planets by either core accretion or disk instability. Protoplanetary disks are often believed to have masses in the range of 0.01 to 0.1 $M_\odot$ [12], but recently it has become apparent that these disk masses may be underestimated by factors of up to 10 [13].

The color field represents particles consisting of refractories or silicates or containing short-lived radioactivities or oxygen anomalies. Particles smaller than $\sim$ 1 cm will move along the gas during the times depicted in these models. Figure 1 shows that within 385 yrs after a color field was sprayed onto the surface of the disk at a distance of 2 AU (model 2S), the color field has been transported both inward to the central protostar as well as outward to the disk boundary at 10 AU. Figures 2 and 3 plot the ratio of the color density to the gas density (e.g., $^{26}$Al/$^{27}$Al) for model 2S, showing that the initially highly heterogeneous distribution is homogenized to a high degree within 385 yrs. Figure 4 quantifies the mixing process, by showing the evolution of the dispersion (or standard deviation) of the initially spatially heterogeneous color fields from its mean values for models 2S and 2M (2 AU midplane injection). The initial transients disappear on a time scale of $\sim$ 300 yrs and approach a steady dispersion level of $\sim$ 2% in model 2S. In models where the injection occurred at 9 AU instead of 2 AU, the dispersion approaches a steady value of $\sim$ 5%.

**References:** [1] Brownlee, D. E. et al. (2006), Science, *314*, 1711. [2] Merín, B., et al. (2007), ApJ, *661*, 361. [3] Gail, H.-P. (2002), A&Ap, *390*, 253. [4] Ciesla, F. J. (2007), Science, *318*, 613. [5] Matsumura, S., & Pudritz, R. E. (2006), MNRAS, *365*, 572. [6] Boss, A. P. (2004), ApJ, *616*, 1265. [7] Boss, A. P. (2006), MAPS, *41*, 1695. [8] Boss, A. P. (2007), ApJ, *660*, 1707. [9] Thrane, K., Bizzarro, M., & Baker, J. A. (2006), ApJ, *646*, L159. [10] Clayton, R. N. (1993), AREPS, *21*, 115. [11] Lyons, J. R. & Young, E. D. (2005), Nature, *435*, 317. [12] Kitamura, Y., et al. (2002), ApJ, *581*, 357. [13] Andrews, S. M., & Williams, J. P. (2007), ApJ, *659*, 705.

**Conclusions:** Mixing in a marginally gravitationally unstable disk rapidly transports tracers both inward and outward and homogenizes spatial heterogeneities to the $\sim 2\%$ to $\sim 5\%$ level inside 10 AU, consistent with refractories in comets, initial homogeneity of $^{26}Al/^{27}Al$ ratios, and a range of $^{16}O$-$^{17}O$-$^{18}O$ ratios in the inner solar system.

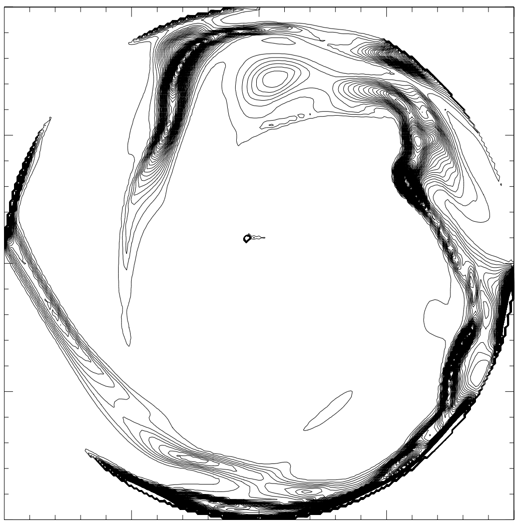


Fig. 1. Contours of the color field in the midplane of model 2S after 385 yrs (10 AU radius disk).

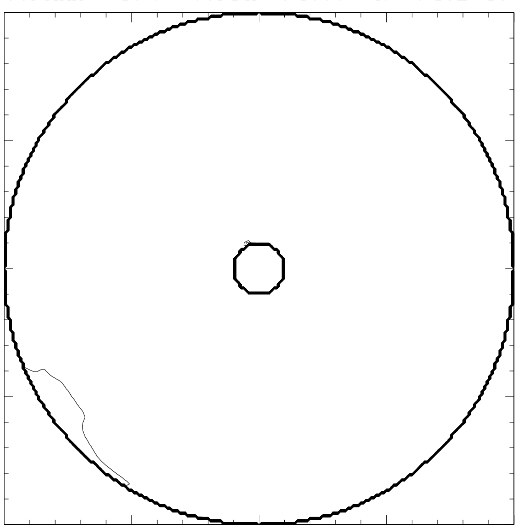


Fig. 3. Same as Fig. 2 at 385 yr: homogeneity.

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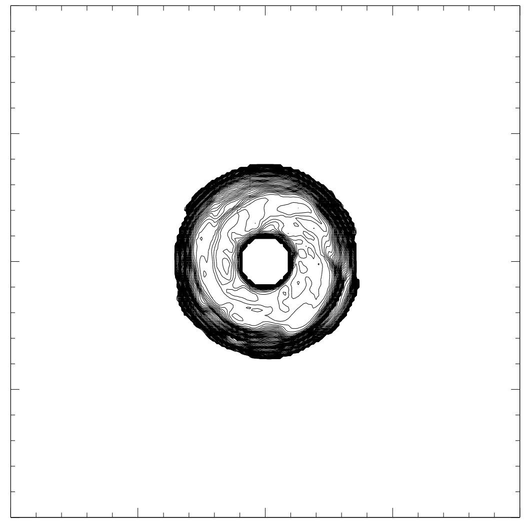


Fig. 2. Contours of the color field divided by the gas density in the midplane of model 2S after 8.4 yrs, showing initial heterogeneity.

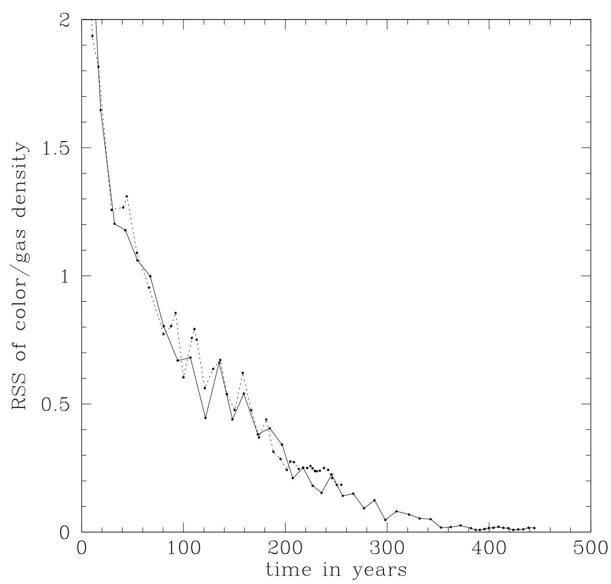


Fig. 4. Time evolution of the square root of the sum of the squares (RSS) of the color field divided by the gas density minus the mean value for models 2S (solid) and 2M (dashed).