SPATIAL HETEROGENEITY OF SHORT-LIVED RADIOISOTOPES AND OF STABLE OXYGEN ISOTOPES IN THE SOLAR NEBULA.

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In order for short-lived radioisotopes (SLRI) such as ^{26}Al to be used as precise chronometers for the early solar system, these SLRI must have been initially uniformly distributed throughout the solar nebula. The source of the SLRI ^{60}Fe appears to have been a nearby supernova [1] that was also the most likely source of the bulk of the solar nebula's ^{26}Al. These SLRI must then have been either injected into the presolar cloud [2] or onto the surface of the solar nebula [3] by the supernova shock front. The injection probably occurred through narrow Rayleigh-Taylor (R-T) fingers [2] that salted the disk's surface with highly nonuniform doses of SLRI, i.e., the SLRI were injected with a highly spatially heterogeneous distribution that must then have been homogenized by mixing in the solar nebula, if their chronometric role was to be preserved. Primitive meteorite components show evidence for both homogeneity [4] and heterogeneity [5] of SLRI in the the solar nebula, leaving the question of the degree of nebular homogenization highly uncertain.

The wide range in stable oxygen isotope abundances [6] appears to be best explained by self-shielding of molecular CO gas from UV photodissociation at the surface of the solar nebula [7]. This process results in the production of ^{16}O-poor ice grains, which are stable only in the outer solar nebula. Hence it is likely that the ^{16}O-^{17}O-^{18}O anomalies also started out with a strongly spatially heterogeneous distribution. These ^{16}O-poor ice grains must then have been transported inward to the initially ^{16}O-rich asteroidal region, where the refractory inclusions had already been forming, followed by chondrule formation after the nebular gas had evolved to a more ^{16}O-poor composition [8,9]. The transport of ^{16}O-poor ice grains formed at the outer disk surface inward to ~ 2.5 AU would have occurred on time scales of $\sim 10^3$ yr [9,10].

We present here the continuation of the nebular mixing and transport models published previously [9], continued now for well over two years of calculations on dedicated workstations. These models show that initially highly spatially heterogeneous distributions of tracers, such as SLRI sprayed onto the disk's surface, or oxygen isotope anomalies created by UV photodissociation, are transported inward and outward on time scales of $\sim 10^3$ yr and mixed on similar time scales, though the mixing leads only to homogenization at the level of $\sim 10\%$ about the mean value, a level determined by the granularity of large-scale gravitational torques.

Mixing and transport in these models is self-consistently calculated as a result of the evolution of spiral arms in a marginally gravitationally unstable disk. These calculations are relevant to the planet-forming midplane of protoplanetary disks, where magnetic fields are negligible because of low fractional ionizations (i.e., the "dead zone"). There is thus no need to assume some unknown level of turbulent viscosity (α) to evolve the disk.

Figures 1 and 2 present the ratios of the color density to the gas density (e.g., ^{26}Al/^{27}Al) at $\sim$ 3300 yrs after color field injection at 6 AU and 15 AU, respectively. Figures 1 and 2 show that in spite of starting off in an extremely heterogeneous state, after ~ 3300 yr the color field has been mixed quite well with the underlying disk gas. The exceptions are the regions near the artificial inner and outer boundaries of the calculation, where there is very little disk gas and hence anomalously high ratios of color to gas density.

Figures 3 and 4 show the evolution of the dispersion (or standard deviation) of an initially heterogeneous isotope ratio from its mean value. The injection transients die away on a time scale of $\sim 10^3$ yr and approach a steady dispersion level of $\sim 10\%$. This happens faster in Figure 4 than in Figure 3, because in the latter model (6 AU injection) the color field has to fight its way upstream against the overall inward flow onto the protostar. Gravitational torques are unable to homogenize the color fields below $\sim 10\%$ in either model.

References: [1] Tachibana, S. et al. (2006), ApJ, *639*, L87. [2] Vanhala, H. A. T., & Boss, A. P. (2002), ApJ, *575*, 1144. [3] Ouellette, N. & Desch, S. J. (2006), LPSC XXXVII, #2348. [4] Thrane, K., Bizzarro, M. & Baker, J. A. (2006), ApJ, *646*, L159. [5] Sugiura, N., Miyazaki, A. & Yin, Q.-Z. (2006), Earth Planets Space, *58*, 1079. [6] Clayton, R. N. (1993), AREPS, *21*, 115. [7] Lyons, J. R. & Young, E. D. (2005), Nature, *435*, 317. [8] Zanda, B. et al. (2006), EPSL, *248*, 650. [9] Boss, A. P. (2006), MAPS, *41*, 1695. [10] Boss, A. P. (2004), ApJ, *616*, 1265.

Conclusions: Mixing in a marginally gravitationally unstable disk naturally reduces spatial heterogeneities to the ~ 10% level, consistent with a chronological interpretation of initial ^{26}Al/^{27}Al ratios and with the observed range of ^{16}O-^{17}O-^{18}O ratios.

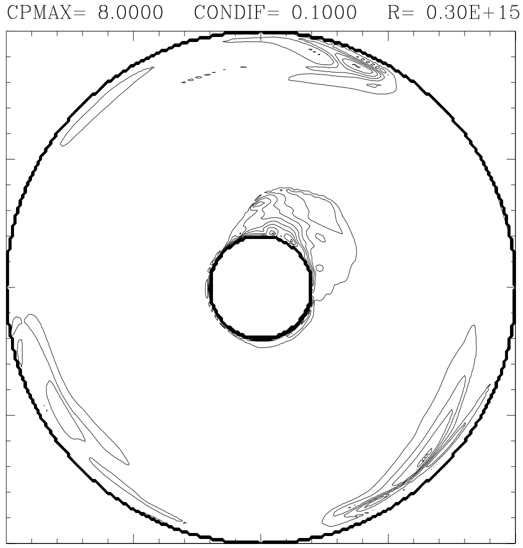

Fig. 1. Contours of the color field divided by the gas density in the midplane of the 6 AU injection model after 3484 yrs (20 AU radius disk).

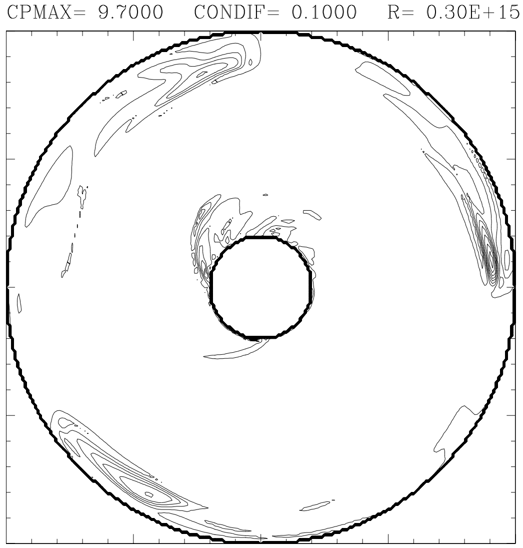

Fig. 2. Same as Fig. 1 but after 3491 yrs of evolution with injection at 15 AU.

Acknowledgments: Supported in part by NASA's PG&G and OSS Programs.

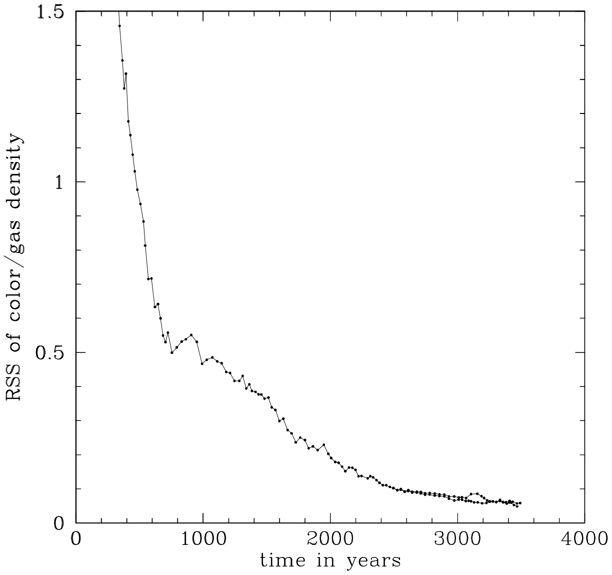

Fig. 3. Time evolution of the square root of the sum of the squares (RSS) of the color field divided by the gas density minus the mean value for the model with color injected at 6 AU at $t = 200$ yrs.

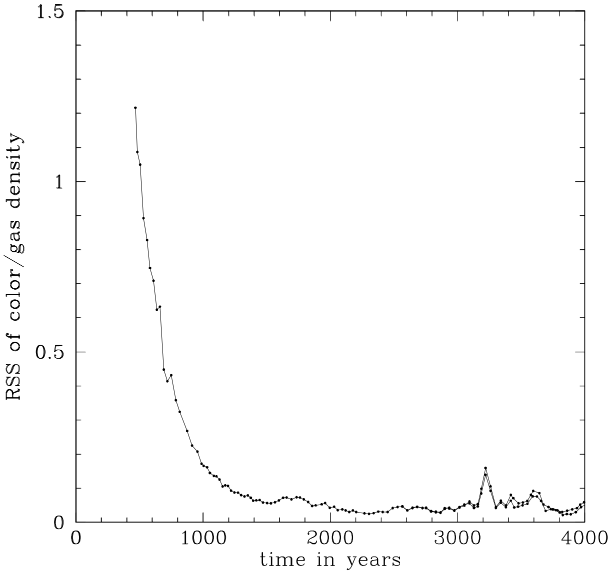

Fig. 4. Same as Fig. 3 but for the 15 AU model. In both models the isotopic dispersion approaches a value of ~ 10%, which appears to be a consequence of mixing driven by large-scale gravitational torques.