SHORT-LIVED RADIOISOTOPE HOMOGENEITY AND STABLE OXYGEN ISOTOPE HETEROGENEITY: SINGLE SHOT VERSUS CONTINUOUS INJECTION AT THE SURFACE OF THE OUTER SOLAR NEBULA. A. P. Boss, Carnegie Institution (boss@dtm.ciw.edu).

Most of the solar system's live ^{26}Al may have been injected into the presolar cloud [1,2] or the solar nebula [3,4] by a supernova shock wave. In either case, injection occurred as a single event that was spatially heterogeneous, which would reduce the usefulness of ^{26}Al as a chronometer [4]. Previous models [2,5] have shown how such initial spatial isotopic heterogeneity can be substantially reduced in a marginally gravitationally unstable (MGU) disk, as a result of the large-scale inward and outward transport of gas and particles small enough to move with the gas [6]. Stable oxygen isotopes, on the other hand, appear to have been spatially heterogeneous in the solar nebula, e.g., small particles from the Wild 2 comet have normalized ^{17,18}O/^{16}O ratios that span the entire solar system range of $\sim 6\%$ variations [7]. The leading explanation for generating these oxygen anomalies is UV photodissociation of CO molecules at the surface of the outer solar nebula, where self-shielding would lead to isotopic fractionation between gas-phase and solid-phase oxygen atoms [8]. CO self-shielding on the irregular outer surface of the disk would also lead to initial spatial heterogeneity, though the process would be continuous in time, rather than a single event. We present here a new set of 3D models that examine the time evolution of isotopic heterogeneity introduced in the outer solar nebula, either by a single event or by a continuous process.

The fully 3D hydrodynamical models begin with a $1 M_\odot$ central protostar surrounded by a protoplanetary disk with a mass of 0.13 $M_\odot$ between 10 and 40 AU at a fixed temperature of 50 K, resulting in a disk that is initially MGU ($Q_i \sim$ 1.4 to 2). MGU disks are likely to be the cause of the FU Orionis outbursts experienced by young solar-type stars [9], when protostellar mass accretion rates soar. A 3D color field is introduced, representing small particles or gases containing short-lived radioactivities or oxygen anomalies. The color field is added to the surface of the initial disk in an azimuthal sector spanning 90 degrees in a narrow ring of width 1 AU, centered at either 20 AU (model 40B) or 30 AU (model 40A). These models are intended to represent one-time injections of isotopic heterogeneity, such as supernova-induced Rayleigh-Taylor fingers carrying live ^{26}Al [1]. Models 40cB and 40cA are the same as models 40B and 40A, except that the color is added continuously to the disk surface throughout the evolution, simulating ongoing photodissociation of CO [8].

The Figures show the time evolution of the dispersion of the ratio of the color density to the gas density, i.e., the ratios ^{26}Al/^{27}Al and ^{17,18}O/^{16}O. The root of the sum of the squares (RSS) of the differences between the local ratio and the azimuthal average ratio is plotted as a function of radial distance for all four models.

Isotopic dispersion is a strong function of orbital radius and time in all the models, with the dispersion initially being large (black) as a result of the isotopes beginning to travel downward and radially inward and outward. The dispersion decreases dramatically over time scales of $\sim 5 \times 10^3$ yr (red), and continues to drop toward $\sim$ steady state values after $\sim 10^4$ yr (green, blue) in the middle of the disks. Higher dispersions seen near the outer disk boundaries ($\sim$ 40 AU) are caused by the unphysical pile-up of disk mass and should be discounted. Minimum dispersions drop to less than $\sim 1\%$ in models 40B and 40A, implying homogeneity for isotopes derived from a one-time event. However, for continuous injection, dispersions even after $\sim 10^4$ yr can be $\sim$ 2-5% in model 40cA, and even higher in 40cB, consistent with the larger variation in stable oxygen isotope ratios. While these models are restricted to the outer disk, previous models of single injection events have shown similar radial variations in the dispersion in disks spanning 1 AU to 10 AU [5] over even shorter time intervals ($< 5 \times 10^2$ yr).

Conclusions: A MGU disk phase driving a FU Orionis outburst is astronomically likely and cosmochemically convenient for explaining the relative homogeneity of ^{26}Al/^{27}Al ratios derived from supernova injection and the range of ^{17,18}O/^{16}O ratios derived from UV self-shielding at the surface of the outer solar nebula.

References: [1] Boss, A. P., & Keiser, S. A. 2012, ApJ, *756*, L9. [2] Boss, A. P. 2012, AREPS, *40*, 23. [3] Ouellette, N., et al. 2007, ApJ, *662*, 1268. [4] Dauphas, N., & Chaussidon, M. 2011, AREPS, *39*, 351. [5] Boss, A. P. 2011, ApJ, *739*, 61. [6] Boss, A. P., et al. 2012, EPSL, *345-348*, 18. [7] Nakashima, D., et al. 2012, EPSL, *357-358*, 355. [8] Lyons, J. R., & Young, E. D. 2005, Nature, *435*, 317. [9] Zhu, Z., et al. 2010, ApJ, *713*, 1143.

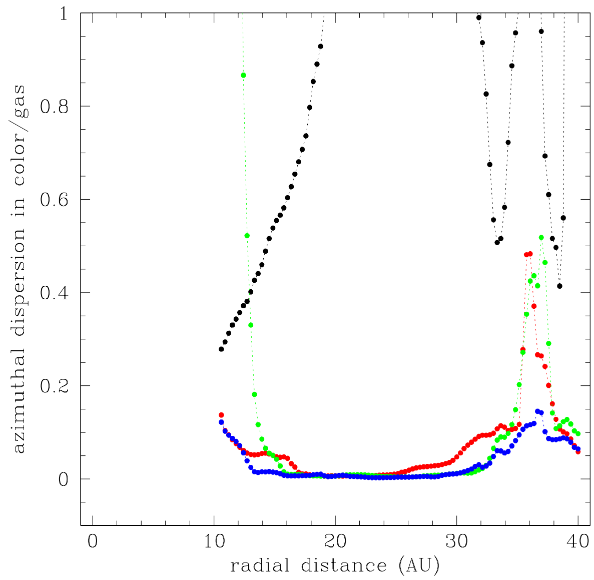

Fig. 1. Model 40B after 200 yr (black), 5800 yr (red), 14500 yr (green), and 24000 yr (blue).

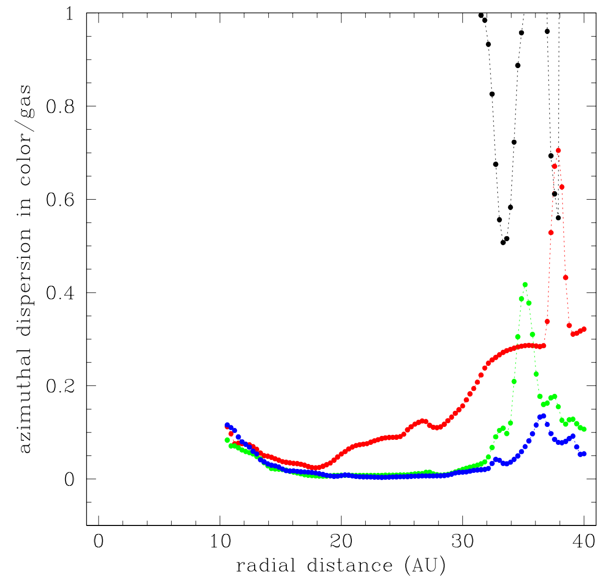

Fig. 3. Model 40A after 200 yr (black), 3500 yr (red), 8100 yr (green), and 15000 yr (blue).

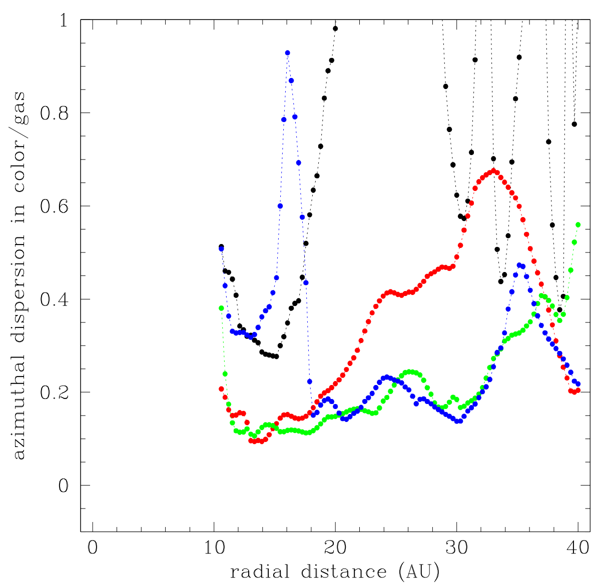

Fig. 2. Model 40cB, plotted as in Figure 1, with continuous injection at the disk's surface at 20 AU.

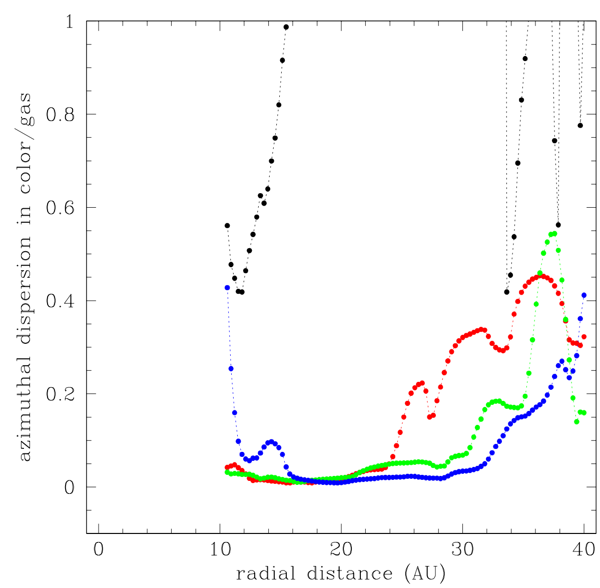

Fig. 4. Model 40cA, plotted as in Figure 3, with continuous injection at the disk's surface at 30 AU.