# PARTICLE TRAJECTORIES DURING FU ORIONIS OUTBURSTS BY THE PROTOSUN.

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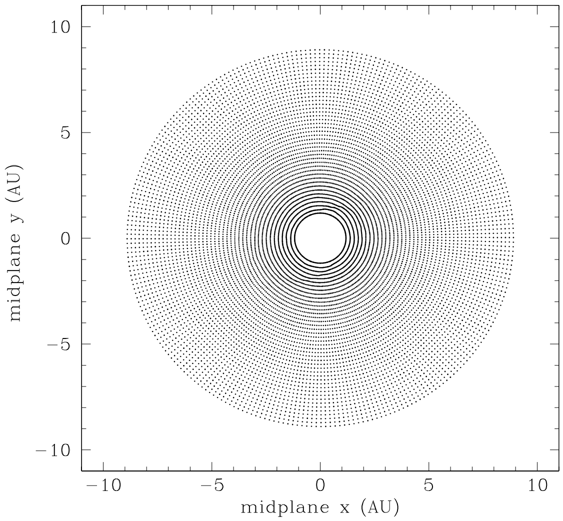
**Introduction:** Solar-type young stars undergo $\sim$ 100-year-long FU Orionis outbursts roughly every $\sim 10^4$ yr [1] during their early evolution. Such outbursts are thought to be caused by rapid mass accretion by the protostar during phases when the disk is marginally gravitationally unstable (MGU) [2]. We study here the trajectories of particles embedded in the solar nebula during a MGU phase of disk evolution. These trajectories have profound cosmochemical consequences [3], ranging from large-scale outward transport of refractory grains, such as the calcium, aluminum-rich inclusions (CAIs) found in Comet Wild 2 by the Stardust Mission [4], to an explanation [3] for a CAI found in Allende whose variations in oxygen isotopes imply repeated passages both inward and outward in the disk [5], to time scales ($\sim$ 10 yr) for sublimation of CAIs similar to those inferred for a Leoville CAI [6].

**Models:** We present here new results for MGU disk models [3] where the particles are represented as finite-size bodies that interact with the disk gas by gas drag [7], while moving on Keplerian orbits, subject to the gravity of the protosun and of the simultaneously evolving MGU protoplanetary disk. While the disk is fully 3D [8], the particles are limited to trajectories in the disk midplane. The particles are assumed to have fixed radii of 1 mm, 1 cm, 10 cm, or 1 m, and are initially distributed uniformly in the disk midplane (Fig. 1), with one particle located in the center of each of the midplane cells, away from the innermost and outermost disk boundaries at 1 AU and 10 AU, respectively. With 50 radial and 256 azimuthal grid cells, that means a total of 48 x 256 = 12288 particles. In order to speed the disk evolutions, the initial disk temperature distribution is held fixed, while the disk gas evolves temporally in three spatial dimensions. As in our previous models [3], the midplane temperature distribution decreases monotonically from 1550 K at 1 AU to 60 K beyond $\sim$ 6 AU, resulting in a minimum value of the Toomre Q parameter of Q = 1.8 in the outer disk.

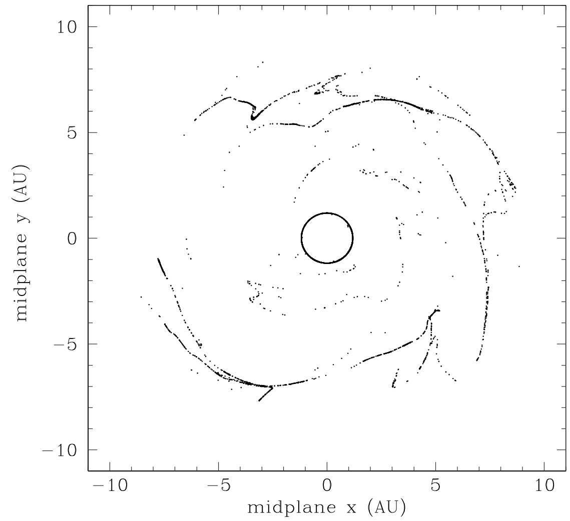
**Results:** Fig. 2 shows that after 122 yr of evolution, the cm-sized particles have become strongly clumped by the gas drag and gravitational forces associated with the gaseous spiral arms that are driving the MGU disk's inward flow of mass onto the central protostar at a rate of $\sim 2 \times 10^{-5} M_\odot$ yr$^{-1}$, as occurs in FU Orionis outbursts [1]. Because gas drag can result in both inward or outward motion in a disk with spiral arms [7], the particles are not all lost to the protosun, though a large fraction do eventually reach the inner boundary at 1 AU and are thereafter frozen in place (as seen in the inner ring in Fig. 2). The results for 1 mm-, 10 cm- and 1 m-sized particles after 122 yr are similar to those for the 1 cm-sized particles shown in Fig. 2, with the locations of the 1 cm- and 10 cm-sized particles being essentially the same. The surface densities of the particle clumps seen along the spiral arms in Fig. 2 are as high as 5 times the initial density. This significantly enhanced dust to gas ratio is underestimated by these calculations, which have a relatively coarse numerical grid. A higher dust to gas ratio, and hence higher oxygen fugacity, can be expected in models with higher spatial resolution. Figs. 3 and 4 show that individual particles can move inward and outward in the disk repeatedly on eccentric orbits, sampling a wide range of nebular densities and temperatures, as we found in our previous models [3]. Substantial sublimation and recondensation of water ice and silicate mantles and rims can be expected for such trajectories [3].

**Conclusions:** These models imply that FU Orionis phases, driven by a MGU disk, may explain the cosmochemical facts that small, refractory grains can be transported outward [8,9] to great distances [4] and can take walkabout trajectories back and forth throughout the nebula, leading to extensive mineralogical and isotopic alterations [3] similar to those found in certain CAIs [5,6].

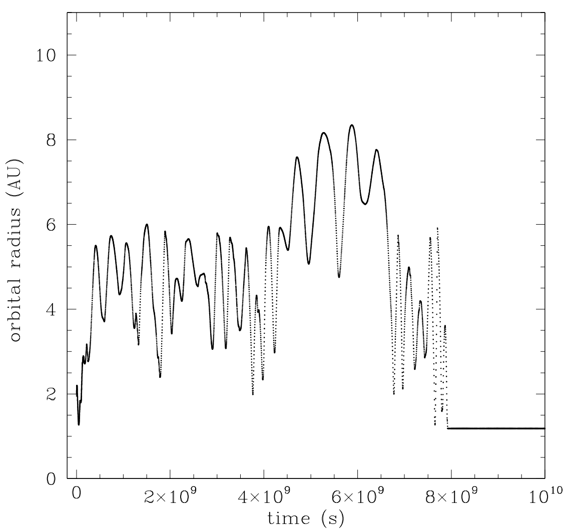
**References:** [1] Hartmann, L., & Kenyon, S. J. 1996, ARAA, *34*, 207. [2] Zhu, Z., Hartmann, L., & Gammie, C. 2010, ApJ, *713*, 1143. [3] Boss, A. P., Alexander, C. M. O'D., Podolak, M., & Ebel, D. 2012, Science, in preparation. [4] Brownlee, D. E., et al. 2006, Science, *314*, 1711. [5] Simon, J. I., et al. 2011, Science, *331* , 1157. [6] Shahar, A., & Young, E. D. 2007, EPSL, *257*, 497. [7] Haghighipour, N., & Boss, A. P. 2003, ApJ, *583*, 996. [8] Boss, A. P. 2007, ApJ, *660*, 1707. [9] Boss, A. P. 2008, EPSL, *268*, 102.



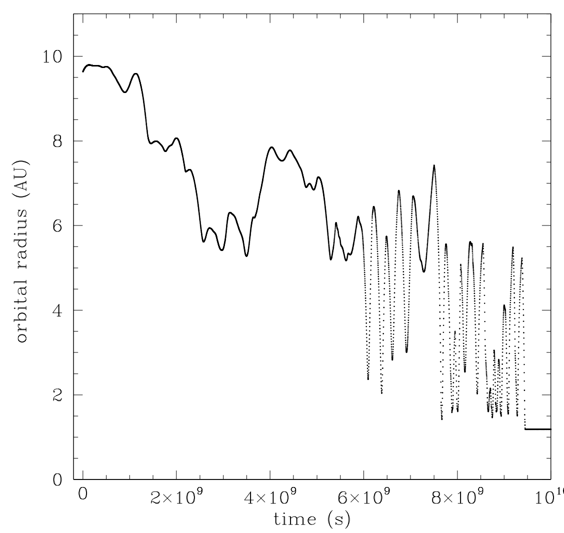

1. Initial midplane locations of 12288 particles.




2. Location of 1-cm-radius particles after 122 yr.




3. Evolution of 1-cm-radius particle #1174.




4. Evolution of 1-cm-radius particle #11925.