RADIAL TRANSPORT OF FIRST SOLIDS OF THE SOLAR SYSTEM BY X-WINDS. Renyu Hu. Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, hury@mit.edu.

Introduction: X-winds are high-speed bipolar-collimated jet around young stellar objects powered by enhanced magnetic activities and disk-magnetosphere interactions [1,2]. X-winds could have provided the thermal conditions for the formation of refractory inclusions, notably calcium-aluminum-rich inclusions (CAIs), as well as effective mechanism for the radial transport of these solids from the inner Solar System and the outer Solar System [3]. The X-wind model for the formation of chondrules and CAIs has been critically examined against isotopical and mineralogical evidence [4], however, it is still essential to perform detail modeling on the trajectories of solid particles entrained in the X-wind outflow and see if the X-wind can transport particles to proper annuli of the protoplanetary disk. The recent discovery of CAI-type inclusions in a short period commet [5,6] also calls for efficient large-scale radial transport mechanisms.

Model: We extend previous X-wind transport models [1,7] to investigate the effect of the protoplanetary disk's gravity and vertical extent.

We track trajectories of solid bodies launched from the X-region, at an initial angle of θ_0 with respect to the disk mid-plane. In the equation of motion, we consider the contribution of protosun's gravity, protoplanetary disk's gravity, and aerodynamic drag of the wind. We assume the disk mass profile as the minimum mass solar nebula [8], multiplied by a factor f. The efficiency of aerodynamic drag depends on the product of solid body radius and density, denoted as η.

We consider the vertical extenson of the protoplanetary disk to be the scale height of the disk [9]. The flared disk may intercept trajectories of solid bodies and we cease to trace a particle after it enters the disk. We define the "re-entering radius" as the radius where the solid body re-enters the disk.

The configuration of X-winds is described by three parameters: mass of the protosun, magnetic dipole moment of the protosun, and accretion rate of the protoplanetary disk. We consider both the "embedded" stage, when the protosun is still embedded in its natal envelope of gas and dust, and the "revealed" stage, when the outflowing wind has reversed the infall of the envelope and revealed the central star [1]. For each stage, mass of the protosun and accretion rate of the protoplanetary disk are specified as [1]. For both stages we consider three configurations of X-winds, depending on the magnetic dipole moment of the protosun. We compute the velocity field of X-winds in each configuration from a set of hydrodynamic equations assuming the streamlines to be straight lines originating from the X-region and the open angle of the winds to be $\theta_w=45^o$ [7].

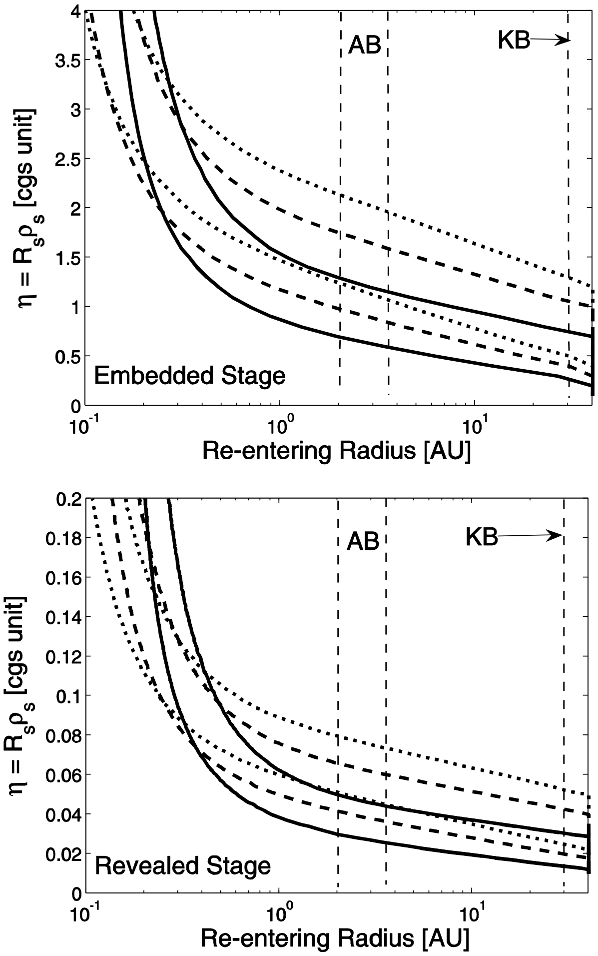

Figure 1: Relation between the solid body size and density (η) and the radius where it re-enters the protoplanetary disk. Vertical dashed lines indicate the radii of the asteroid belt and the Kuiper belt. For both stages, the solid, dashed, and dotted curves describe the magnetic high, average, low states, respectively. Each state is described with two curves: the higher curve corresponds to f=0 and $\theta_0=\theta_w$, and the lower curve corresponds to f=5 and $\theta_0=\theta_w/2$.

Results: We find a threshold value of η of solid bodies for any particular X-wind configuration, disk's mass and intial launching angle, denoted as η_t, below which the solid bodies will be expelled from the Solar System. More importantly, only the solid bodies whose η are larger than but very close to η_t of a particular X-wind configuration can be launched to the annuli of the asteroid belt (AB) or the Kuiper belt (KB). As a result, in any particular state of protosun and proplanetary disk, the location of the AB, where we envisage the parent bodies of carbonaceous chondrites, can only receive solid bodies with size larger than but very close to the threshold size. Moreover, the variation of initial launching angle θ_0 affects the threshold size significantly (see Figure 1 and 2) and enlarges the acceptable range of particle size to the AB significantly. Omitting the uncertainties of initial launching angle, the size distribution can be very sharp in a constant outflow [10]. We suggest that the variation of θ_0 may make the size distribution of CAIs or chondrules in chondrites wider.

During the revealed stage, an annulus of the protoplanetary disk receives 1 order of magnitude smaller solid bodies (assuming density is generally the same) than during the embedded stage (See Figure 1). It has been shown that only the embedded stage can host the thermal conditions required for the formation of CAIs [1]. We note that η_t during the revealed stage is compatible with the typical size range of chondrules in meteriotes. If X-wind is the radial transport mechanism for both CAIs and chondrules, CAIs would be larger than chondrules in any chondritic group due to the X-wind transport. Such difference could not be found in chondrites [11].

The threshold particle size critically depends on the mass of the protoplanetary disk. The disk's gravity modifies the trajectories and makes the re-entering radius lower significantly. As shown in Figure 2, the threshold size for the retention of solids decreases significantly with the disk mass parameter *f*. Previous calculations [1] did not consider the disk gravity and vertical extent, and were therefore imperfect in estimating the re-entering radius.

Discussion: Although blurred by the uncertainty in θ_0, the size sorting effect of X-winds may have significant implications in our understanding of CAI and chondrule populations. If we assume chondrules mainly formed during the revealed stage, our X-wind transport model predicts the maximum chondrule radius to be 0.04 cm, compatible with all carbonaceous chondrite groups except the CV class [12]. Chondrules in CV chondrites may form earlier, probably during the transition from the embedded stage to the revealed stage. CAIs in all chondritic groups are lighter than the threshold η_t of $\theta_0=\theta_w/2$ during the embedded stage. Therefore, for the tiny primitive grains to be retained in the disk, the current X-wind model requires that they are launched preferably at low angles ($\theta_0<\theta_w/2$).

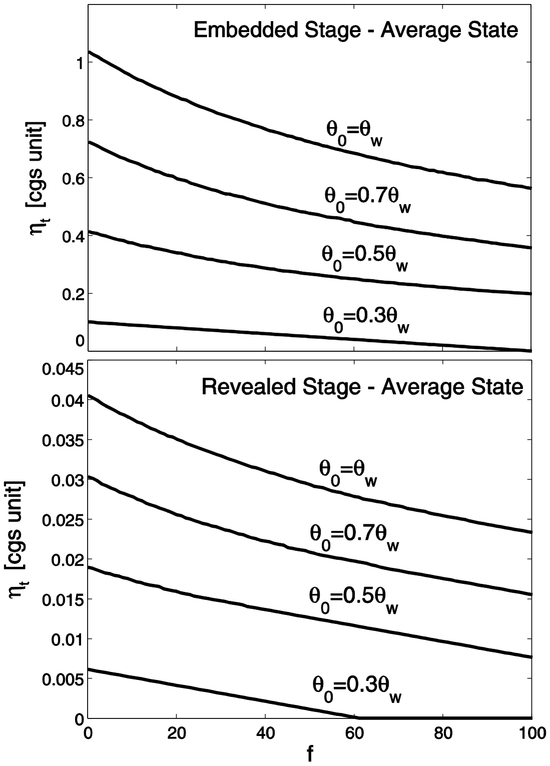

Figure 2: Sensitivity of the threshold particle size on the protoplanetary disk's mass (*f*) and initial launching angle (θ_0). For each line we fix the value of θ_0, vary *f*, and find the corresponding η_t.

Conclusions: We find that the protoplanetary disk's gravity has a non-negligible effect on the trajectories of solid bodies entrained in X-winds. We find that size sorting by the X-wind is so effective that only solid bodies with size larger than but very close to the retention threshold size can be delivered to the radius of the asteroid belt. In general, the size distribution of CAIs and chondrules in chondrites could be determined from the initial size distribution as well as the distribution over the intial lauching angle.

References: [1] Shu F. H. et al. (1996) *Science*, 271, 1545. [2] Shu F. H. et al. (1997) *Science*, 277, 1475. [3] Shu F. H. et al. (2001) *ApJ*, 548, 1029. [4] Desch S. J. et al. (2010) *LPSC Abstracts*, 41, 2200. [5] Brownlee D. et al. (2006) *Science*, 314, 1711. [6] Nakamura T. et al. (2008) *Science*, 321, 1664. [7] Shang H. (1998) *Doctoral Dissertation*. [8] Hayashi, C. (1981) *Prog. Theor. Phys. Suppl.*, 70, 35. [9] Hartmann L. (2009) *Accretion Processes in Star Formation* 2^{nd}., Cambridge University Press, Cambridge, UK. [10] Liffman K. (2005) *Meteorit. Planet. Sci.*, 40, 123. [11] Scott E. R. D. (2007) *Annu. Rev. Earth. Planet. Sci.*, 35, 577. [12] Wurm G., Krauss O. (2006), *Icarus*, 180, 487.