

**SNOWLINES OF EXTERNALLY PHOTOEVAPORATED PROTOPLANETARY DISKS WITH NON-UNIFORM VISCOSITY DUE TO MAGNETOROTATIONAL INSTABILITIES** A. Kalyaan<sup>1</sup> and S. J. Desch<sup>1</sup>, <sup>1</sup>School of Earth and Space Exploration, Arizona State University, PO box 871404, Tempe AZ 85287-1404 (akalyaan@asu.edu)

**Introduction:** A snowline represents a region in the solar nebula at 2.7 AU, corresponding to the sublimation temperature of water ( $\sim 170$  K), inside of which water is believed to have existed only as water vapor and outside of which it exists as ice [1]. Spectral observations of farther ( $>2.7$  AU) water-rich C-type and closer-in ( $<2.7$  AU) water-poor S-type main belt asteroids seems to be consistent with this scenario [2]. However several sophisticated disk models place the snowline much closer at  $\sim 1$  AU [3]. This dichotomy reveals that temperature only does not determine where the snowline is, but as [4][5] have argued, radial dynamics of volatiles, such as the outward diffusion of water vapor, and the inward drift of ices also does. When undisturbed, these inward and outward volatile transport processes can settle into a steady cyclical flow of water across the snowline. However, external processes such as photoevaporation of the protoplanetary disk (due to FUV radiation from nearby massive stars) can upset this equilibrium, shift the snowline, and cause more water to flow out of the inner disk, giving rise to the formation of water-poor planets.

While some recent studies have considered the effect of external photoevaporation on disk evolution and planet formation [6][7], rarely do disk models go beyond the simplistic  $\alpha$ -parameterization of viscosity where viscosity  $\nu = \alpha C H$  [8] [ $C$  and  $H$  are the local sound speed and disk scale height, respectively].  $\alpha$ , a dimensionless constant, usually assumed to be uniformly  $\sim 0.01$ , is not attributable to any realistic physical mechanism. Our work describes results of numerical simulations that not only include the effects of external photoevaporation, but also a unique viscosity treatment derived directly from magneto-rotational instabilities [9] and a calculation of ionization equilibrium including dust, as an important precursor step before incorporating the radial transport processes to understand the distribution of volatiles in the nebula.

**Methods:** We perform 1.5D disk simulations, where the disk is divided into 60 radial zones between 0.1-100 AU and each annulus is further divided into 25 zones across height  $z$ . At each  $(r, z)$  a simple chemical network is solved balancing ionization by stellar x rays [10] and cosmic rays [11] against recombination of Na ions and electrons in the gas phase and on grain surfaces. From the calculated ion abundances, we estimate  $\alpha(r, z)$  using the formulations of [9] that include the non-ideal magnetohydrodynamic effects of ambipolar

diffusion. We also incorporate photoevaporation via the disk outer edge, using the treatment of [12].

**Results and Conclusions:**  $\alpha$  calculated from MRI viscosity is found to vary significantly with  $r$ , varying from  $\sim 10^{-5}$  in the inner disk to  $10^{-1}$  in the outer disk, unlike the constant value of 0.01 that is usually adopted. Dust affects disk evolution by absorbing charges and causing the inner disk to evolve much more slowly. Mass therefore accumulates in the inner and middle disk. Photoevaporation causes mass loss through the outer disk edge and steepens  $\Sigma$  profiles in the outer disk. While  $r_T$  (transition radius where the directionality of mass flow changes from inward to outward) moves outward with time in the non-photoevaporated viscous spreading disk [13],  $r_T$  moves *inward* in a photoevaporated disk, driving more and more volatiles out of the inner disk with time. From our simulations, we find that disk structure and evolution are dramatically altered when subject to both non-uniform  $\alpha$  and external photoevaporation, leading to very steep outer disks (5-30 AU) [Fig 1] with outward transport of volatiles. These aspects will have dramatic implications for planet formation and volatile transport.

**References:** [1] Hayashi, C., (1981) *PThP. Supp.* 70, 35-53 [2] Gradie, J., & Tedesco, E., (1982) *Science* 216, 1405-1407 [3] Sasselov, D.D., & Lecar, M., (2000) *ApJ* 528, 995-998 [4] Cuzzi, J. N., & Zahnle, K. J., (2004) *ApJ* 614, 490-496 [5] Ciesla, F. J., & Cuzzi, J. N. (2006) *Icarus* 181, 178-204 [6] Mitchell, T.R. and Stewart, G.R. (2010) *ApJ* 722, 1115-1130. [7] Anderson, K.R. et al. (2013) *ApJ* 774, 9-22. [8] Shakura, N.I. and Sunyaev, R.A. (1973) *A&A* 24, 337-355 [9] Bai, X.N. and Stone, J.M. (2011) *ApJ* 736, 144-160. [10] Glassgold, A.E. et al (1997) *ApJ* 480, 344-350 [11] Umebayashi, T. and Nakano, T. (1981) *PASP* 33, 617-635 [12] Adams, F.C. et al. (2004) *ApJ* 611, 360-379. [13] Hartmann, L, et al, (1998) *ApJ*, 495, 385-400

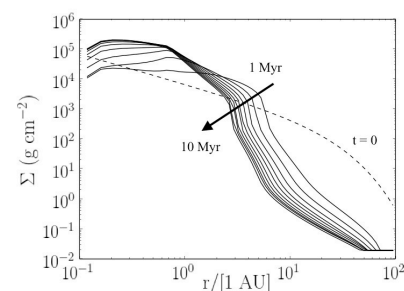


Fig1:  $\Sigma$  profiles at  $t=0$  (dashed), 1 Myr, 2 Myr, ... 10 Myr