SIMULATIONS OF PROTOPLANETARY DISK EVOLUTION INCLUDING EXTERNAL PHOTO-EVAPORATION AND MRI VISCOSITY WITH DUST. A. Kalyaan[1] and S.J. Desch[1], [1]School of Earth and Space Exploration, Arizona State University, PO Box 871404, Tempe, AZ 85287-1404. (akalyaan@asu.edu)

Introduction: Planet formation models rely on knowledge of the distribution of mass in protoplanetary disks (PPDs), the surface density profile *Σ(r)* as a function of distance *r* from the star. Model disks are usually evolved using the equations of [1], assuming a viscosity ν = α *C H* [2], where *C* and *H* are the local sound speed and disk scale height. α is a dimensionless constant, usually taken to be ~ 0.01, but in fact it should be calculated from first principles after identifying the angular momentum transport mechanism in the disk. The magnetorotational instability (MRI) is increasingly recognized as this mechanism [3]. The MRI only operates where the ionization is high enough to couple the magnetic field to the gas of the disk, and the viscosity it generates will be non-uniform throughout PPDs, with α generally low in disk interiors, and high in their outer regions. [4]. The effect of non-uniform α on disk evolution has been little considered in the literature [5]. Another process only sometimes considered in such models [6-8] is external photoevaporation of the disk by the far-ultraviolet (FUV) radiation of nearby massive stars, which half of all disks are likely to experience [9]. These effects have never been considered simultaneously. In his update to the "minimum mass solar nebula", [10] argued that the solar system formed from a disk with p ≈ 2.2 between 5 AU and 30 AU, where $\Sigma(r) \sim r^{-p}$, He constructed analytical, steady-state solutions and showed that this steep slope was attributable to external photevaporation. He also pointed out that externally photoevaporated disks could experience outward transport beyond a few AU, throughout the disk's evolution, affecting volatile transport. Here we test these ideas, building on previous work [11], presenting the first simulations that simultaneously include external photoevaporation, non-uniform α(*r*) due to the MRI, and a calculation of ionization equilibrium including dust.

Methods: We perform 1D disk simulations, where the disk is divided into 60 radial zones between 0.1-100 AU. To incorporate ionization effects and dust chemistry, we further divide each annulus into 25 vertical zones in *z*. At each *(r,z)* a simple chemical network is solved balancing ionization by stellar x rays [12] and cosmic rays [13] against recombination of Na ions and electrons in the gas phase and on grain surfaces. A grain size of a=1μm is assumed. We calculate steady-state abundances of ions and electrons, using the collision cross sections from [14], which includes the effects of grain charging. From the calculated ion abundances, we estimate α(*r,z*) using the formulations of [15] that include the non-ideal magnetohydrodynamic effects of ambipolar diffusion; we assume a saturated state of turbulence. From α(*r,z*), we calculate a vertically integrated mass-weighted <α>*(r)*. We impose a floor of 10^{-5} on α in the inner disk, to assist the slow inner disk evolution. We also incorporate photoevaporation via the disk outer edge, using the treatment of [6], and evolve the disk for 5 Myr.

We perform a parameter study varying the global gas-to-dust (g/d) mass ratio in the disk, and the extent of photoevaporation via the G_0 parameter (FUV flux in units of the background interstellar flux, 1.6 Habings). High g/d is a proxy for grain growth.

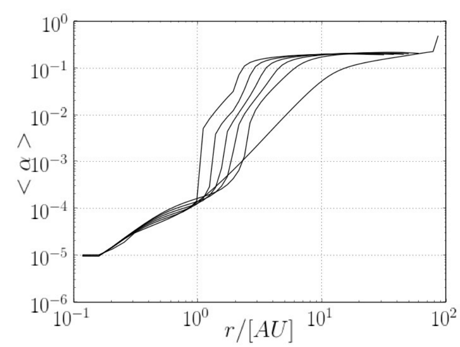

Figure 1: <α>*(r)* at times 0 Myr, 1 Myr, … , 5 Myr (from right to left) for the low-dust (g/d=10000) run.

Results: We discuss results from three runs: 1. uniform α; 2. non-uniform α due to MRI with low dust (g/d=10000); and 3. non-uniform α due to MRI with a canonical amount of dust (g/d=100). G_0=1000 in each.

α profile: (Fig. 1) <α> calculated from MRI viscosity is found to vary significantly with r, varying from ~10^{-5} in the inner disk to 10^{-1} in the outer disk, unlike the constant value of 0.01 that is usually adopted. For the low-dust run, a sharp transition from low to high α occurs at 3AU, moving inward with time. A similar sharp transition in the high-dust run occurs farther out at 10-20 AU, also moving inward with time. This important transition region that can have significantly effects on planet growth is not seen with uniform α simulations.

*Effects of dust: (*Figs. 2, 3) Dust affects disk evolution by absorbing charges and drastically reducing the ion fraction in the dense disk interior. This lowers α and causes the inner disk to evolve much more slowly.

For uniform α, $\Sigma(r)$ retains the shape of the initial $t=0$ profile (dashed curve, Fig. 2) for many Myr. In the low-dust run, infall onto the star is steady at 10^{-8} $M_\odot$ yr^{-1} but the outer disk evolves very quickly, and the inner disk gains considerable mass. In the high-dust run, α is so low in the inner disk it practically doesn't evolve; infall onto the star plunges below 10^{-9} $M_\odot$ yr^{-1} (Fig. 3). Mass instead accumulates in the middle disk (2 -10 AU). Grain growth appears necessary for the inner disk to evolve. Mass may be depleted from > 10 AU and accumulate at 2-10 AU early on, then move inward as grains grow.

Effects of photoevaporation: Fig. 3 shows profiles of $\dot{M}$ (r). Mass moves inward toward the star in the inner disk, but beyond the transition radius r_T, typically at 8-20 AU, mass moves outward due to photoevaporation. In contrast to the uniform α case, r_T moves *inward* with time, causing more and more mass from the inner disk to flow outward. Fig. 4 shows the average slope $<p>$ of the surface density profile between 5-30 AU for the low-dust run, but with different values of G_0. It is evident that due to more mass flowing outward, external photoevaporation causes steep slopes ($<p> \approx 2.2$ for low-dust runs, ≈ 6 for high-dust runs) in the outer disk during the first few Myr.

Conclusions: From our simulations, we find that disk structure and evolution are dramatically altered when subject to non-uniform α and external photoevaporation. Combination of both effects lead to outer disks (5-30 AU) that are much more steeper than the MMSN profile, and in some annuli mass *increases* with time. Outward transport is more common in such disks.These aspects will have dramatic implications for planet formation.

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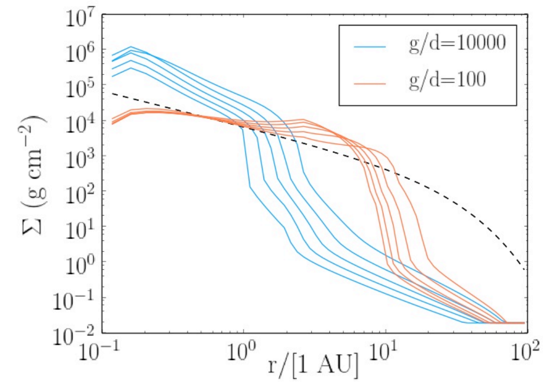

Figure 2: $\Sigma(r)$ profiles for the low-dust and high-dust runs for times t=0 Myr (dashed), 1 Myr …, 5 Myr.

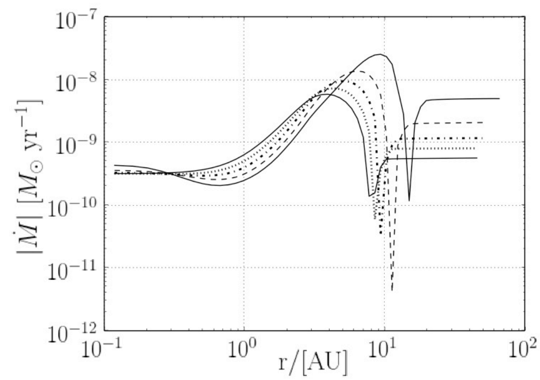

Figure 3: Profiles of $|\dot{M}(r)|$ due to accretion in the inner disk and outflow driven by photoevaporation in the outer disk, for times 1 Myr, 2 Myr, .. , 5 Myr (solid, dashed, dash-dotted, dotted, solid), for the high-dust run. The dip in each curve denotes r_T beyond which mass flows outward due to photoevaporation.

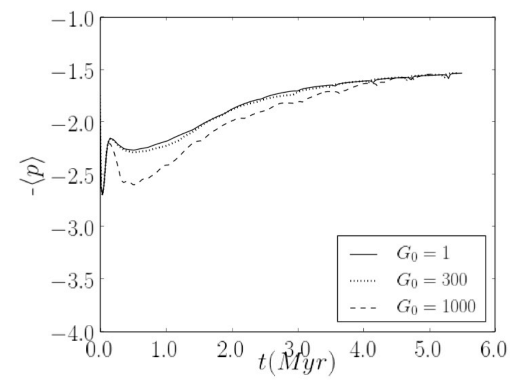

Figure 4: Average slope <p> between 5-30 AU versus time, for low-dust simulations with different G_0. Higher G_0 steepens the slope during first few Myr.