STRUCTURE AND EVOLUTION OF EXTERNALLY PHOTOEVAPORATED PROTO-PLANETARY DISKS. **A. Kalyaan**[1], **S. J. Desch**[1], **N. Monga**[1] [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287. (akalyaan@asu.edu).

Background: Protoplanetary disks (PPDs) are large ($\sim 10^2$ AU) rotating systems of gas and dust, formed during the early stages of star formation. They are the sites of planet formation. Models of planet formation rely on knowledge of the surface density, $\Sigma(r)$, the mass per area in the disk as a function of distance r from the star. Models of how the surface density evolves usually model it as a power law: $\Sigma(r) = \Sigma_0(r/r_0)^{-p}$, where $p = -d\ln\Sigma/d\ln r$ (which technically can vary with r). Likewise the temperature of the disk is often modeled as a power law with radius: $T(r) = T_0(r/r_0)^{-q}$ with $q \approx 0.5$ [1]. It is assumed that most of the disk is marked by an inward radial velocity of gas, i.e., $V_r < 0$, and behaves as an accretion disk. Yet, disk models commonly recognize that gas can move outward, too. It has been shown that disks with $p + q > 2$ (perhaps only locally) are marked by outward transport [2].

Models of $\Sigma(r)$ over time account for viscous dissipation in the disk, accretion onto the star. Only recently external photoevaporation—loss of mass from the outer disk by UV heating from a nearby massive star—has been recognized to significantly influence the evolution of $\Sigma(r)$ and the radial velocity of gas V_r through a PPD [3-5]. Desch (2007) [4] has predicted that external photoevaporation would lead to a very steep steady-state profile with $p > 2$, and therefore outward transport $V_r > 0$, throughout much of the outer portions of the disk (beyond a few AU). **Here we present numerical calculations to test this hypothesis and we discuss implications for planet formation.**

Models of Externally Photoevaporated PPDs External photoevaporation of PPDs occurs when their outer surface layers absorb far-ultraviolet radiation from a nearby massive star, heating to temperatures of a few $\times 10^2$ K, sufficient to escape the central star's gravity. It is a well observed phenomenon in star-forming regions such as the Orion Nebula [6,7], and it is well understood that photoevaporation truncates the disk at an outermost radius r_d, typically ~ 50 AU, from which most of the loss occurs [3]. But the role of photoevaporation in changing the structure $\Sigma(r)$ of disks has only recently been considered.

[4] was motivated to study the evolution of $\Sigma(r)$ in the face of external photoevaporation because of his finding that updating the Minimum Mass Solar Nebula model of [8] accounting for the starting positions of the planets in the Nice model [9] led him to infer a steep outer disk profile $\Sigma(r) = \Sigma_0(r/r_0)^{-p}$ with $p > 2.2$. [4] showed that such a steep profile was potentially a steady-state solution to the equations of disk evolution, provided the PPD was being externally photoevaporated, implying that our Sun formed in a high-mass star-forming region. Numerical simulations of disk evolution were conducted by [5] to test this analytic solution. They numerically calculated the evolution of an externally photoevaporated disk using the equations of disk evolution [10] and assuming a viscosity $\nu = \alpha C^2/\Omega_\mathrm{K}$, where C is the sound speed, Ω_K is the Keplerian orbital frequency, and α is a fixed parameter [11]. They found that disks could be characterized by $p \approx 1.8$, much steeper than previous models, but did not completely substantiate the findings of [4]. We hypothesize that their results may be attributable to assumptions about how viscosity in the disk varies with r. In particular, [5] assumed a uniform α throughout the disk, whereas we hypothesize that if α increases with r that steeper profiles may result.

Our Numerical Model We numerically calculate the evolution of an externally photoevaporated disk using the same equations of disk evolution [11]. Appropriate boundary conditions allow accretion onto the central star and loss of gas from the outer edge at mass loss rates that are functions of the strength of the radiation field, as determined by [3]. The strength of the radiation field is G_0 times the interstellar radiation field strength. $G_0 = 1$ denotes no nearby massive star, while $G_0 = 300$ corresponds to a B0 star at a distance of 2.5 pc. In contrast to [5], we do not assume uniforma α, instead calculating how α would vary if it disk viscosity were attributable to the magnetorotational instability (MRI).

We calculate α by first calculating the ionization chemistry in the PPD, balancing ionizations by Galactic cosmic rays [12] and central star X-rays [13] against recombinations in the gas phse and on grain surfaces, assuming a monodispersion of neutral grains 1 μm in radius. Further details of this simple ionization chemistry are described by [14]. The ion density is calculated as a function of r and of height, assuming a Gaussian, isothermal density profile.

Assuming a magnetic field locally at equipartition strength everywhere, we then calculate the parameters β and A_m, and then α as described in [15]. We find that in general the vertically, mass-weighted average α is uniform and $\sim 10^{-5}$ for $r < 3$ AU, then rising as a power of r to a value $\sim 10^{-1}$ near the disk edge at $r_{\rm d} \approx 50$ AU.

We have run the disk evolution code and present two results here, both assuming $G_0 = 300$: one with uniform $\alpha = 10^{-2}$, and one with the α we calculate above. In Figure 1 we show for the second case $\Sigma(r)$ at 1 Myr time intervals over 10 Myr. A steep profile in the outer disk develops because of the photoevaporation of the outer edge of the disk. In Figure 2 we show the average slope p across the interval 5 to 30 AU, over the course of 10 Myr, for the two cases. The non-uniform α case yields a steeper profile.

Conclusions: We draw the following conclusions. External photoevaporation of PPDs can yield steep profiles in their outer regions, with $p > 2$, leading to outward transport. As predicted by [4], these steep surface density profiles exist in near steady state, as evidenced by Figure 2 after 2 Myr. We confirm the hypothesis that a variable α, with α increasing with r in the disk, does indeed lead to a steeper profile. We attribute this to the fact that the 5-30 AU region is resupplied by gas more slowly at its inner edge but is depleted at its outer edge at the same rate. We plan further simulations to test whether steady-state profiles with $p = 2.2$, as predicted by [4], are possible.

References: [1] EI Chiang & P Goldreich 1997 ApJ 490, 368. [2] T Takeuchi & DNC Lin 2002. ApJ 81, 1344. [3] FC Adams et al. 2004 ApJ 611, 360. [4] SJ Desch 2007 ApJ 671, 878. [5] TR Mitchell & GR Stewart 2010 ApJ 722, 1115. [6] MJ McCaughrean & CR O'Dell 1996 AJ 111, 1977. [7] D Johnstone et al. 1998 ApJ 499, 758. [8] SJ Weidenschilling 1977 PSS 51, 153. [9] R Gomes 2005, Nature 435, 466. [10] D Lynden-Bell & JE Pringle 1974 MNRAS 168, 603. [11] Shakura & Sunyaev 1973 [12] T Umebayashi & T Nakano 1981 PASP 33, 617. [13] AE Glassgold et al. 1997 ApJ 480, 344. [14] Desch 2004 [15] XN Bai & JM Stone 2011 ApJ 736, 144.

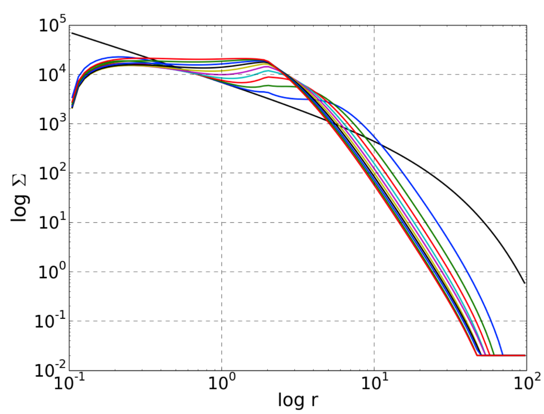

Figure 1: $\Sigma(r)$ at various time intervals in disk with $G_0 = 300$ and spatially varying α.

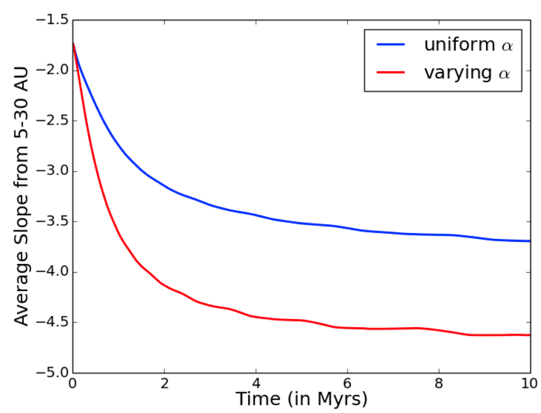

Figure 2: Average slope p between 5 and 30 AU in two disks with $G_0 = 300$, as a function of time from 0 to 10 Myr. Both cases yield steep ($p > 2$) near-steady-state solutions, but the variable α case is steeper.