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Photoevaporation and Disk Dispersal

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Abstract. Protoplanetary disks are depleted of their mass on short timescales by viscous accretion, which removes both gas and solids, and by photoevaporation which removes mainly gas. Photoevaporation may facilitate planetesimal formation by lowering the gas/dust mass ratio in disks. Disk dispersal sets constraints on planet formation timescales, and by controlling the availability of gas determines the type of planets that form in the disk. Photoevaporative wind mass loss rates are theoretically estimated to range from $\sim 10^{-10}$ to 10^{-8} $M_\odot$ yr^{-1}, and disk lifetimes are typically $\sim$ few Myr.

Keywords. Accretion, Planetary systems: Protoplanetary Disks, Formation

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1. Disk Dispersal

Several lines of evidence point to dispersal mechanisms that operate in protoplanetary disks and remove most of their mass. In the solar system, gas is heavily depleted with only ∼10% of the initial disk mass remaining—the total mass of solids ($\sim 10^{-4}$ $M_\odot$) in planets and planetary objects is high relative to the total gas ($\sim 10^{-3}$ $M_\odot$), almost all of which is contained in the giant planets. Protoplanetary disks in star-forming regions show evidence for dispersal of dust; Haisch *et al.* (2001) first determined that the frequency of disk-bearing stars in clusters declines with cluster age on $\sim 3 - 5$ Myr timescales. Concurrent exoplanetary studies have further revealed the ubiquity of planet formation in disks around low and intermediate-mass stars, and the close correspondence between the minimum mass required to form our solar system and measured dust disk masses suggests that most of the dust in disks is depleted very quickly into planets. Gas disk dispersal is less well constrained, but is believed to also occur rapidly after star and disk formation.

Disks are initially composed of interstellar material with gas dominating their masses, and their primordial evolutionary phase ends with gas dispersal. Studies of a few nearby young disks by Zuckerman *et al.* (1995) found that CO emission was only detected from objects younger than 10 Myr, setting the earliest constraints on gas disk lifetimes. Later surveys by the Spitzer and Herschel space telescopes set upper limits on the mass of gas present in more evolved disks, $< 0.1 M_J$ within ~ 40 AU at ages $\sim 5-30$ Myr and $< 1 M_J$ gas within ~ 100 AU at ages $\sim 4 - 6$ Myr, respectively (Pascucci *et al.* 2006, Dent *et al.* 2013). Observations are thus consistent with gas dispersal times that are at least as long as, or similar to, dust disk dispersal times. The prevalence of gaseous envelopes around exoplanets and the low orbital inclinations of close-in Kepler planets both suggest that gas typically survives past planet formation epochs; in fact, migration in a gas disk may have shaped the architecture of many exoplanetary systems. In the light of all the above constraints, gas disk lifetimes are likely to be $\lesssim 10$ Myr.

Although several disk dispersal theories have been previously considered (e.g., see review by Hollenbach *et al.* 2000), viscous accretion and photoevaporation by stellar high energy photons are believed to be primarily responsible for removal of disk material. Viscosity depletes both gas and dust via loss of angular momentum; radial drift, if efficient, may also remove substantial amounts of larger dust and solids as the disk evolves. If all disks undergo planet formation, then most of the solids may be assembled into planetary objects. A large fraction of the gas, especially in the outer disk, is probably removed by photoevaporation whereby stellar heating of gas drives thermal winds from the disk surface.

2. Photoevaporation theory

Young stars generate intense high energy radiation fields at ultraviolet (FUV, $6 - 13.6$eV; EUV, $13.6 - 100$eV) and X-ray wavelengths. These photons irradiate the disk surface and can heat gas to escape temperatures when the combined thermal pressure and angular momentum support exceed gravitational pressure. Thermal winds are launched when the gas at a given radius (r_{AU}) is heated up to a critical temperature, $T_{crit} > (1 - 1.8) \times 10^4\ r_{AU}^{-1}$ K for ionized/atomic flows. Typically, flows are subsonic and escape temperatures are lower than T_{crit}.

The wind mass loss rate, and hence the importance of photoevaporation in removing disk gas, depend on the density and temperature in the thermal wind; these in turn depend on the heating agent. The rate of change of surface density $\dot{\Sigma}_{pe} \propto \rho_b \sqrt{T_{gas}}$, where ρ_b and T_{gas} are the density and temperature in the flow respectively. EUV and soft X-ray ($\sim 0.1-0.3$ keV) photons can heat the gas to high temperatures ($\gtrsim 10^4$ K) but are easily absorbed due to their low attenuation columns and the densities of such flows are typically low. However, the physics is relatively simple as the temperature is either nearly constant in the case of EUV or can be parametrized in terms of the ionization parameter for optically thin soft X-rays. FUV and hard X-rays ($\gtrsim$ 1keV) heat the gas to lower temperatures ($<$ few 1000 K) but have significantly higher penetration depths and hence higher flow densities. In this case, the determination of gas temperature is complicated by the chemistry of trace coolant species and the radiative transfer of cooling line emission that is often optically thick.

Mass loss rates estimated from theoretical models are low for EUV-driven photoevaporation ($\sim 10^{-10}\ M_{\odot}\ \mathrm{yr}^{-1}$), but $\sim 10 - 100$ times higher in the FUV and soft X-ray case. Although the mass loss rate derived differs depending on model assumptions and stellar/disk parameters, for fields typical of T Tauri stars Gorti & Hollenbach (2009) find that photoevaporation is mainly driven by FUV photons. This is partly due to the fact that accretion produces shocks on the stellar surface that generate a significant FUV flux in addition to the chromospheric/coronal flux; FUV fields are typically high around young, low and intermediate-mass stars. High EUV and X-ray fluxes can, however, also produce higher mass loss rates and could in principle dominate under certain conditions.

Mass loss rates due to photoevaporation are thus uncertain by $\sim 1 - 2$ orders of magnitude, mainly because of difficulties in assessing the amount of flux irradiating the disk surface. EUV luminosities are unknown as they are easily absorbed and nearly impossible to measure directly; this is also true for soft X-rays. However, gas irradiated by EUV and soft X-rays will be partly or fully ionized ($x_e \sim 0.1 - 1$) and Pascucci *et al.* (2014) recently placed constraints on the ionization levels of a few disks based on the expected free-free emission. They found that the implied EUV photon luminosity is low, even if all of the observed cm excess is attributed to free-free emission from ionized gas. EUV-driven photoevaporative mass loss rates in their disk sample are hence too low to explain inferred disk lifetimes. The role of soft X-rays is still inconclusive, as the flux of free-free emission depends on the gas temperature. The absence of a clear correlation between X-ray luminosity and free-free emission flux and the low cm excess from a known soft X-ray source, TW Hya, together suggest that soft X-rays are unimportant in driving

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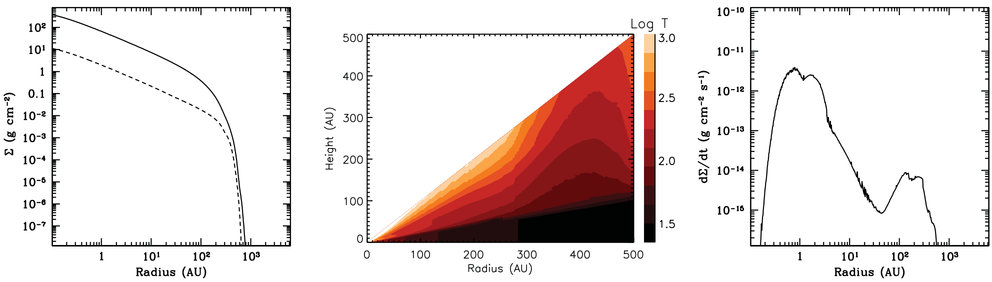

(a) Surface Density ($\Sigma(t)$) (b) Disk Temperature (c) Photoevaporation rate

Figure 1. The first panel shows the instantaneous gas surface density (solid line) of a model disk at an epoch 1 Myr after the beginning of the simulation. The dashed line is the total solid surface density which is distributed into a number of dust size bins, this distribution is calculated using the gas surface density at that epoch. At each time t, a thermochemical disk structure model is calculated from this $\Sigma(r,t)$ and the dust opacities, the corresponding temperature structure is shown in panel (b). From the temperature and density structure (not shown), we evaluate the height at which the photoevaporation rate ($\dot{\Sigma}_{pe}$) peaks for each radius as shown in the next panel (c). This rate is then used in the surface density evolution equation to advance Σ to the next time step.

mass loss, but it remains to be seen if the Pascucci *et al.* (2014) results hold for a larger disk sample.

Hereafter, we assume that FUV photons (and hard X-rays, although see Gorti & Hollenbach 2009) are more relevant for photoevaporation and disk dispersal.

3. FUV-driven photoevaporation

FUV heating critically depends on the evolving abundance of very small grains (VSGs) and polycyclic aromatic hydrocarbons (PAHs) in the disk. Gas is indirectly heated by FUV photons via collisions with energetic electrons produced by photoelectric ejection from small dust. As the gas surface density decreases and dust grains collide, coagulate and fragment in the disk, the abundance of small grains is expected to evolve. If there are fewer small grains, the heating rate and resulting gas temperature would be lower, but on the other hand, the FUV opacity would also be reduced. Higher penetration of FUV photons would then result in higher densities in the flow. Since the photoevaporation rate $\dot{\Sigma}_{pe}$ depends on both density and temperature, the effect of a reduced or enhanced small grain abundance on the mass loss rate is not immediately apparent.

Motivated by the above, Gorti *et al.* (2015) recently investigated the effects of dust evolution on photoevaporation. Using a multi fluid (gas+solids) EUV, FUV and X-ray photoevaporation model combined with a dust grain evolution framework based on coagulation/fragmentation equilibrium, they solved for the evolution of gas and solid surface densities with time. Figure 1 shows the calculation of photoevaporation rate for one such model at a given instant of time in these simulations. A 1+1D disk structure model is used to calculate the disk structure at every epoch using the instantaneous surface density distribution as determined by a 1-D viscous evolution and disk photoevaporation model. See Gorti *et al.* (2015) for more details.

Although the dust grain size distribution significantly changes with time, photoevaporation timescales for these models are comparable to models with no dust evolution. Disk lifetimes change by less than a factor of 2, which is not significant given the uncertainties in other model input parameters (e.g., stellar spectrum, disk viscosity). Figure 2 shows the decrease in gas mass with time for models with and without dust

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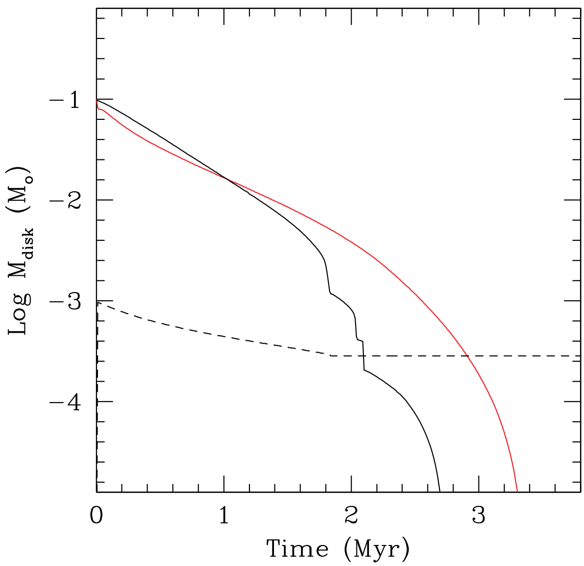

Figure 2. The disk gas (solid) mass and dust mass (dashed line) is shown in black for the dust evolution model and in red for a model without dust evolution. The dispersal time scales for gas in both models are similar. In the model without dust evolution, gas and dust are assumed to be always well-mixed and dust is carried along with the gas. Note that in the model with dust evolution, most of the dust is left behind after photoevaporation as very little dust is collisionally coupled to the flow.

evolution. As discussed in Gorti *et al.* (2015), the relative insensitivity of the photoevaporation rate to small grain abundance is due to the opposing effects of heating and opacity on $\dot{\Sigma}_{pe}$.

An interesting outcome of combining dust evolution with photoevaporation is that the gas/dust mass ratio in the disk changes as the disk evolves and disperses. As shown in Figure 2, most of the dust in the disk remains after the gas is removed. This result is due to two effects: (i) gas densities in the photoevaporative flow are too low for all but the smallest dust grains to be collisionally coupled with the gas, and (ii) mass loss due to photoevaporation is comparable to mass loss due to accretion (see Gorti *et al.* 2015). Low gas/dust ratios are a requirement for many planetesimal formation mechanisms (see review by Johansen *et al.* 2015), and preferential removal of gas by photoevaporation may thus aid planet formation. Although these disk evolution models do not consider planet formation and solids are restricted to sizes $<$ 1 cm, the remnant dust may potentially constitute the mass reservoir out of which planetesimals and eventually planets form.

4. Disks around nearby young stars

Disk dispersal theory is qualitatively well understood; the main uncertainties pertain to the poorly quantified mass loss rates. If disk mass loss rates are high ($\sim 10^{-9}$ to 10^{-8} $M_\odot$ yr^{-1}), then photoevaporation has the potential to trigger the formation of planetesimals by lowering the gas/dust ratio and plays a pivotal role in planet formation. If mass loss rates are low ($\sim 10^{-11}$ to 10^{-10} $M_\odot$ yr^{-1}), then planet formation is not affected by photoevaporation; however, the dynamics and orbital architecture of planetary systems will still be influenced by the presence (or absence) of gas at these late stages.

A more accurate determination of mass loss rates is hindered by our ignorance of key inputs: the level of viscosity in the disk, stellar high energy spectra and their variation with accretion rate, disk chemistry and associated micro-physics, dust size evolution and dynamics and finally, the effect of planet formation on disk evolution.

Studies of nearby young stars provide the best opportunities to resolve some of these outstanding issues. Better determination of the stellar high energy spectra, including any possible contribution of accretion to EUV and X-ray fluxes and the variability of the high energy flux with accretion rate through high resolution, monitoring campaigns would help in better informing the theoretical models. Detailed multi-wavelength disk observations with high spatial resolution can characterize dust emission and probe particles from sub-micron to cm sizes. Gas line emission studies can help validate chemical models and shed light on heating/cooling processes. Spatial and velocity resolved observations can detect blue-shifts and asymmetries in line profiles due to photoevaporative winds and perhaps directly measure disk mass loss rates.

TW Hydra is an example of such a nearby, but perhaps atypical, system with abundant observational data and has been successfully used to develop detailed models of its gas disk structure and evolutionary status (e.g. Gorti *et al.* 2011). Similar detailed observations for other nearby disks from the X-ray to radio wavelengths will help us understand how disks evolve, form planets and eventually disperse.

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References

Dent, W. R. F., Thi, W. F., Kamp, I., *et al.* 2013, *PASP*, 125, 477
Gorti, U. & Hollenbach, D. 2009, *ApJ*, 690, 1539
Gorti, U., Hollenbach, D., Najita, J., & Pascucci, I. 2011, *ApJ*, 735, 90
Gorti, U., Hollenbach, D., & Dullemond, C. P. 2015, *ApJ*, 804, 29
Haisch, K. E., Jr., Lada, E. A., & Lada, C. J. 2001, *ApJ*, 553, L153
Hollenbach, D. J., Yorke, H. W., & Johnstone, D. 2000, Protostars and Planets IV, 401
Johansen, A., Jacquet, E., Cuzzi, J. N., Morbidelli, A., & Gounelle, M. 2015, arXiv:1505.02941
Pascucci, I., Gorti, U., Hollenbach, D., *et al.* 2006,*ApJ*, 651, 1177
Pascucci, I., Ricci, L., Gorti, U., *et al.* 2014, *ApJ*, 795, 1
Zuckerman, B., Forveille, T., & Kastner, J. H. 1995, *Nature*, 373, 494

Discussion

Question: How would X-ray flares affect dispersal?

Author: Heating and cooling timescales are at least of the order 100 years, therefore variability on smaller timescales would get averaged out. However, if X-rays and UV were to vary on longer timescales, for example due to accretion, then this variability would impact dispersal times. For FUV, this is taken into account by including an accretion-generated field, but we do not have information to include an accretion generated component for X-rays.

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Question(van der Marel): What about transition disks?

Author: Transition disks are difficult to explain as photoevaporating disks in our models because the calculated disk lifetimes are at least a few Myrs, and the viscous timescales at gap opening are short, thus we would only expect to see a few % of disks transitioning because of photoevaporation. However, other groups find different results, and at least a few of the non-accreting transition disks may have been created by photoevaporation.