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Disk dispersal and photoevaporation

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Abstract. This article discusses protostellar disk dispersal due to photoevaporation by ultraviolet and X-ray photons from the central star. The current theoretical understanding of disk dispersal is summarised and observational constraints are discussed. Disk lifetimes due to photoevaporation are typically ∼ a few million years and depend on stellar mass, radiation field, disk viscosity, and dust evolution.

Keywords : stars: formation – protoplanetary disks; accretion: accretion disks

1. Introduction

Circumstellar disks play a critical role in star and planet formation. They form as a result of angular momentum conservation during the gravitational collapse of rotating cloud cores. The central star grows in mass via accretion of matter through the disk which receives mass from the surrounding envelope. The evolution of disks therefore directly affects star formation. Disks are often termed *protoplanetary*, as they are the birth-sites of planetary systems and planets assemble from disk material. Planet formation and disk evolution are thus closely tied.

Protoplanetary disks are inferred to have very short lifetimes ($\lesssim$ 10 Myrs), based on emission from their dust (solids) content. Excess emission over stellar photospheric levels at infrared wavelengths and longer is the main indicator of the presence of a dust disk and this excess is known to progressively decline with age (e.g., Lada & Wilking 1984). Young, primordial disks are massive and optically thick to stellar photons and typically surround classical, T Tauri stars (CTTS) that are actively accreting matter at rates of $\sim 10^{-5} - 10^{-8}$ $M_\odot yr^{-1}$. More evolved stars (weak-lined T Tauri stars, WTTS) show little or no accretion ($\lesssim 10^{-11} M_\odot yr^{-1}$) and are also seemingly bereft of disks (e.g., Cieza et al. 2007; Wahhaj et al. 2010). Some wTTS disks show evidence of relatively faint emission by *debris* dust, presumably consisting of second-generation dust generated by collisions of planetesimals. Disk lifetimes are derived from studies of young clusters which show that the fraction of stars with disks (or infrared excesses) decreases with mean cluster age (Haisch, Lada and Lada 2001; Hillenbrand 2008; Mamajek 2009 and Hernandez et al. 2009). Disk lifetimes are thus determined to be $\sim$ 5 Myrs, with evidence that very few disks are retained at ages $\gtrsim$ 10 Myr.

Gas dominates disk mass, however, and the readily observable dust is an almost negligible contributor to the disk mass (i.e., $\sim$1% of the parent cloud material). Gas disk evolution is not as well-studied, mainly because of the difficulty in observing the inherently weak line emission by gaseous species. This problem is compounded further by the very strong background continuum emission by dust above which lines must be detected. The limited number of existing gas observations suggest that gas disks also dissipate early. The seminal work on CO pure rotational lines from disks by Zuckerman et al. (1995), the *Spitzer* FEPS study by Pascucci et al. (2006) and other studies of individual disks have placed an estimate on the gas disk timescale at $\sim 5-30$Myr, but it is somewhat poorly constrained.

How then do disks disperse and what is the significance of short disk lifetimes? Viscous accretion onto the star, photoevaporation (thermal winds driven by stellar heating), and planet formation are some of the main agents believed to disperse disks and these also play a role in disk evolution. Although planets are abundant and the close correspondence between planet formation ($\sim 2-3$ Myr from core accretion theory; see Lissauer & Stevenson 2007) and disk dispersal timescales is suggestive of a causal link, it is unlikely that all disk mass is consumed by forming planets. At least in the Solar System, the solids/gas mass ratio is lower than that of the parent interstellar cloud material, suggesting more gas was present at early epochs. The Minimum Mass Solar Nebula (MMSN), formed by augmenting the solids in the Solar System with a gas complement of cosmic abundances (Weidenschilling 1977) has a mass of $\sim 0.01\ M_\odot$ within $\sim$ 40 AU, nearly a factor of 10 larger than the present value. Furthermore, exoplanet data indicate that the frequency of planetary systems among stars is $\sim$ 20% (e.g., Udry & Santos 2007; Wittenmyer et al. 2011; Latham et al. 2011), so all disks may not form planets before they are dispersed. Hence planet formation cannot be the main disk destruction mechanism. Truncation by stellar encounters (Scally & Clarke 2001), magnetic (MHD) disk winds (e.g., Shang et al. 2007; Suzuki & Inutsuka 2009) and ram pressure due to stellar winds (Matsuyama et al. 2009) are other proposed mechanisms that have been previously shown to be either nonviable or applicable only under specific circumstances. Disks are believed to be dispersed by being accreted viscously onto the star (e.g., Hartmann et al. 1998), or destroyed by photoevaporation (e.g., Hollenbach et al. 1994), or more likely, by a combination of the two (Clarke et al. 2001; Alexander et al. 2006; Gorti et al. 2009; Owen et al. 2010).

Disk lifetimes have a direct bearing on planet formation because if planets are to form from disk matter, they must necessarily do so before the disk is dispersed. In their *Kepler* study, Latham et al. (2011) found that rocky Super-Earths and Neptunesized objects (with a low gas content) are more common and that gas-rich, Jupiter-type objects are quite rare. If gas disk lifetimes are short, there may be enough time for rocky protoplanetary cores to form and perhaps accrete small amounts of gas, but insufficient time for the core to reach the runaway phase of gas accretion and form gas giant planets (e.g., D'Angelo et al. 2010). The relative profusion of rocky planets and ice giants compared to gas giants may then indicate rapid gas depletion in disks. Disk evolution therefore also influences the nature of the planetary objects being formed.

In this paper, I will discuss disk dispersal by primarily photoevaporation and viscous evolution. Current theoretical understanding will be summarized in §2, followed by a discussion of how theoretical predictions compare with observations and how future progress can be made (§3).

2. Disk dispersal: theory

Viscous evolution. The basis for viscous accretion disk theory is that disks must transport angular momentum radially outward to enable star formation (e.g., Pringle 1981). Viscous diffusion in the disk drives mass inwards due to a loss of energy and simultaneously spreads angular momentum outward allowing accretion. In its simplest form, all uncertainties in the microphysics are parametrized by a parameter, α, and the kinematic viscosity expressed as $\nu(r) = \alpha c_s^2(r)/\Omega_K(r)$ where c_s is the local sound speed and Ω_K is the local Keplerian angular velocity (Shakura & Sunyaev 1973). Although α is largely an unknown parameter and may vary with time and spatial location in the disk, it is generally assumed to be a constant. Its value has been estimated to be $\lesssim 0.01$ from disk accretion rates (e.g., Hartmann et al. 1998) and from MHD simulations (e.g., Brandenburg et al. 1995; Stone et al. 1996).

In accretion disk theory, the stellar mass accretion rate ($\dot{M}_{acc}$) is proportional to the product of the viscosity $\nu(r)$ and surface density $\Sigma(r)$, i.e., $\dot{M}_{acc} \sim 3\pi\nu(r)\Sigma(r)$, and the steady-state solution for $\Sigma(r)$ is such that $\dot{M}_{acc}$ is *independent* of r. $\dot{M}_{acc}$ declines through the disk as $\Sigma(r)$ decreases due to viscous spreading. Measured stellar accretion rates in fact do decrease by up to 4-5 orders of magnitude as stars evolve from CTTS ($\sim 10^{-8} - 10^{-6}\mathrm{M_\odot yr^{-1}}$) to wTTS ($\lesssim 10^{-11}\mathrm{M_\odot yr^{-1}}$). Viscous spreading also implies, however, that disk size increases with age and this is not observed (e.g., Andrews et al. 2010). Moreover, as $\dot{M}_{acc}$ falls and the disk expands, the dispersal time due to viscous evolution grows longer ($\sim 1/t$, and $\sim 10^8$ years for a purely viscous disk, Gorti et al. 2009). Observations of disk lifetimes do not show such a linear behaviour (e.g., Mamajek 2009). The predicted steady evolution of the disk also does not match the "two-timescale" nature of disk dispersal, where disks undergo a prolonged phase of mass depletion followed by a shorter clearing phase at all radii (e.g., Clarke et al. 2001).

Photoevaporation. Stellar high energy photons irradiate and heat gas at the disk surface to high temperatures ($\sim 500 - 10^4$K). Thermal speeds higher than local escape velocities are attained and the unbound gas flows away from the system, steadily depleting the disk. This process is called photoevaporation (e.g., Dullemond et al. 2007). In photoevaporation theory, gas outside of a characteristic disk radius (r_g) can be potentially heated to drive mass loss flows, whereas gas within r_g remains gravitationally bound. Here r_g is defined as GM_*/c_s^2 where M_* is the stellar mass, c_s the local sound speed and G is the gravitational constant. For gas at 10^4K, $r_g \sim 7$AU for a $1M_\odot$ star. The mass of gas subject to photoevaporation is substantial, as typically, $\Sigma(r) \propto r^{-1}$ (e.g., Pringle 1981; Andrews & Williams 2005), implying that the outer disk ($r > r_g$) constitutes the main mass reservoir. When the rotational support of disk gas is taken into account, this critical radius is found to be even smaller, ~0.1-0.2 r_g (e.g., Liffman et al. 2003; Adams et al. 2004). Photoevaporation can therefore drive mass flows that disperse bulk of the disk mass.

Earliest theories of photoevaporation considered heating by EUV (13.6 – 100eV) photons from massive OB stars that ablated their own disks and also those around nearby stars (e.g., Hollenbach et al. 1994, Johnstone et al. 1998, Richling & Yorke 1997, 1998, 2000, Font et al. 2004). Recent theories combine the effects of photoevaporation and viscous evolution. Clarke et al. (2001) were the first to find that a gap forms in the disk (at $\sim 0.1 - 0.2r_g$) where the local photoevaporation rate ($\dot{M}_{pe}$) exceeds the viscous mass accretion rate. The outer disk is removed by photoevaporation and the (gravitationally bound) mass inside the gap is accreted onto the star. Alexander et al. (2006) refined this theory further to consider direct illumination by EUV photons of the inner rim of the outer disk after the hole forms and found that this illumination reduced disk lifetimes considerably. More recently, Gorti & Hollenbach (2008), Ercolano et al. (2008), Gorti et al. (2009) and Owen et al. (2010) extended photoevaporation theory to include heating by FUV (6 – 13.6eV) and X-ray (0.1 – 10keV) photons from the central star. While the EUV flux from the star is not easily measured, young stars are known to be strong emitters of FUV and X-rays. Accretion generates $\sim 10^4$K hotspots on the surface of the star and shock emission in the FUV bands can be almost as high as $0.01 - 0.1L_*$ throughout disk evolution. Strong chromospheric activity also generates X-rays (including FUV), which can be very high for young stars, $\sim 10^{-3.3}L_*$ (e.g., Preibisch et al. 2005). The disk intercepts a fair fraction of this high energy radiation. As FUV and X-rays penetrate deeper, they heat surface gas to high temperatures and result in more vigorous flow compared to EUV-driven photoevaporation. Calculated mass loss rates ($\dot{M}_{pe}$) range from $\sim 10^{-10}M_\odot yr^{-1}$ for EUV heating (Alexander et al. 2009) to $\sim 10^{-9}M_\odot yr^{-1}$ for FUV/X-ray heating (Gorti et al. 2009) and $\sim 10^{-8}M_\odot yr^{-1}$ for a soft X-ray spectrum (Ercolano et al. 2008; Owen et al. 2010).

Evolution of a photoevaporating, viscous disk. Disk evolution begins with the collapse of a rotating, prestellar core to form a central object and a flattened structure. Initially, the star rapidly builds up most of its mass by bursts of accretion driven by gravitational instabilities in the massive disk (e.g., Vorobyov & Basu 2010). As the disk accretes, its mass reduces and it becomes gravitationally stable at a mass of $\sim 0.1M_*$. Accretion continues and is accompanied by outflows at a rate $\sim 0.1\dot{M}_{acc}$ (e.g., White & Hillenbrand 2004). Matter in the outflow absorbs high energy radiation from the central star and initially shields the disk (Gorti et al. 2009). As $\dot{M}_{acc}$ falls, the outflow material eventually becomes tenuous enough to first allow FUV and high energy X-ray photons (columns $\sim 10^{22}\mathrm{cm}^{-2}$) to pass through and strike the disk surface. Photoevaporative flows are now set up, and accretion and photoevaporation act to deplete mass in the disk. This phase lasts for $\sim 1-2$Myrs for a typical disk around a $1\mathrm{M}_\odot$ star. The disk mass decreases, and therefore the $\dot{M}_{acc}$ declines and the outflow becomes weaker to allow soft X-rays (hν < 0.3keV) and EUV photons to also penetrate the outflow and irradiate the disk. During this stage of disk evolution, FUV photons deplete the outer disk of its mass reservoir, where the binding energy of gas is low and lower gas temperatures are sufficient to drive flows. The steady loss of mass in the outer disk also prevents the disk from expanding significantly due to viscosity. After the disk mass has been sufficiently depleted, a gap opens in the disk. At every radial annulus, matter is lost by photoevaporation and replenished by viscous accretion as long as the local $\dot{M}_{acc}$ is higher than $\dot{M}_{pe}$. As Σ decreases due to the mass loss, $\dot{M}_{acc}$ also decreases until, at some location in the inner disk ($\sim 1-10$AU for a $1M_\odot$ star), $\dot{M}_{acc}$ drops below $\dot{M}_{pe}$ (Fig. 1). At this instant, the inner and outer disk become decoupled as mass is removed faster by photoevaporation than can be supplied by viscous transport. The inner disk drains onto the star on the viscous timescale at the gap location, typically $\lesssim 10^5$ years. Once the inner disk is accreted, the inner rim of the outer disk is now directly illuminated by stellar high energy photons, and $\dot{M}_{pe}$ is significantly increased as photons are no longer obliquely incident on the disk. The remainder of the disk now is eroded both at the inner rim by FUV/X-ray/EUV photons and at the outer edge by FUV photons. The disk evolves into a torus, loses mass, and

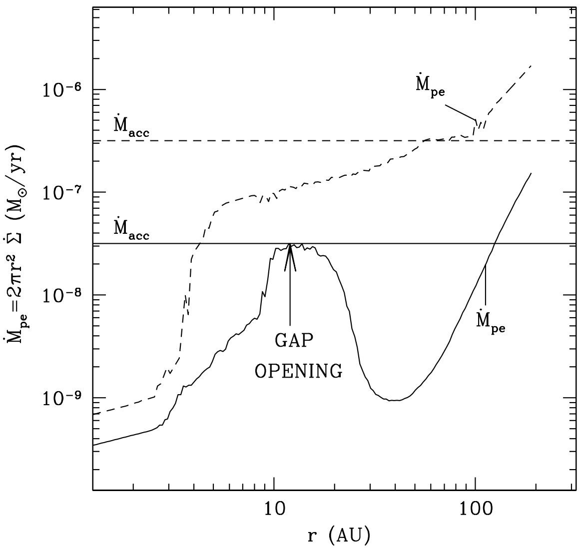

Figure 1. The accretion and photoevaporation rates are shown for a model disk at two epochs, the dashed lines are at an earlier epoch and the solid lines show the rates at a later epoch when a gap begins to form at $\sim$ 10AU.

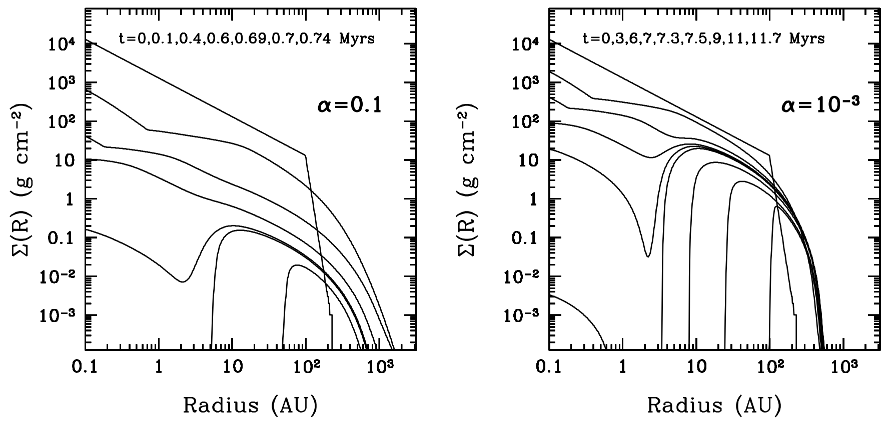

Figure 2. Gas surface density distribution in the disk for two values of the viscosity parameter, α. In panel (a) $\alpha = 0.1$ and the disk evolves rapidly, while in panel (b) $\alpha = 10^{-3}$ and the disk is seen to remain extended and dissipate slowly.

is destroyed. Disk lifetimes depend on other parameters besides the radiation field, mainly the stellar mass, viscosity and dust properties. Disks around stars $\lesssim 3M_\odot$ have lifetimes $\sim$ 5Myr independent of mass, while disks around more massive stars are short-lived due to their intense radiation fields (Gorti et al. 2009, Ercolano et al. 2011). The choice of the viscous parameter α also affects disk evolution. Disks with low α evolve slowly and disks with higher values of α evolve on faster timescales, due to changes both in the dispersive effects of viscosity and accretion-related FUV luminosity (Fig. 2). For α values of $10^{-3}, 10^{-2}$ and 0.1, Gorti et al. (2009) calculate typical disk lifetimes of 12Myr, 4Myr and 0.7Myr respectively. Dust settling and grain growth also affect photoevaporation timescales. As the dust disk evolves, settling causes a change in the flaring angle of the disk and reduced interception of stellar photons by the disk surface, affecting its evolution. Dust settling and grain growth also change the penetration depth of FUV photons and higher column densities of gas are heated. Including dust evolution in photoevaporation models results in an accelerated rate of evolution at initial stages due to enhanced FUV penetration, but a relative decrease in photoevaporation rates at later stages as the disk settles and flaring decreases (Gorti et al., in preparation).

3. Discussion: theory vs. observations

Disk observations have tremendously surged over the past few years, especially due to the FEPS and c2d Legacy Science Programs of *Spitzer* (led by M. Meyer and N. Evans respectively) and more recent *Herschel* studies. Statistics of dust disks in different stages of evolution have significantly improved and direct detection of gas by line emission is becoming possible with space and ground-based instruments of increasing sensitivity and spectral resolution. For a recent review of disk observations, see Williams & Cieza (2011).

The best observational diagnostic of photoevaporation has been the recent discovery of blue-shifted [NeII]12.8μm emission (Herczeg et al. 2007; Pascucci & Sterzik 2009)). This line arises from either fully ionized EUV-heated gas or partly-ionized X-ray heated gas that participates in the photoevaporative flow. Blue-shifts of $\sim$ 10km s^{-1} have been observed, as expected for a photoevaporative wind (Alexander 2008) and calculated line profiles match well with observations (Pascucci et al. 2011). Blue-shifts in the [OI]6300Å lines have been predicted by Ercolano & Owen (2010) as the hot, neutral gas in the wind is luminous in forbidden line emission in their models. Hollenbach & Gorti (2009) and Gorti et al. (2011), however, argued against thermal [OI] emission. High resolution observations of the disk around TW Hya showed a blueshifted [NeII] line but no shift in the [OI] line (Pascucci et al. 2011), supporting a non-thermal origin for [OI]6300Å emission and perhaps suggesting that the mass loss rates in the wind are lower than predicted by the XEUV models. Earlier observations of blue-shifted forbidden line emission by Hartigan et al. (1995) are indicated in other sources, however, and suggest XEUV photoevaporation may work in those cases.

Photoevaporation theories reproduce observed disk lifetimes reasonably well, and estimate $\sim 1-5$Myrs (Alexander et al. 2006; Gorti et al. 2009; Owen et al. 2010). There is a wide dispersion in observed values, however, with some older objects still possessing optically thick, massive disks (e.g., the 10 Myr disk around TW Hya), and others that lose their disks at a very young age of $\lesssim$ 1 Myr. This variation is not surprising as disk initial properties and stellar properties are very diverse.

Are X-rays or FUV photons more relevant for disk dispersal? This question is important as different evolutionary pathways are predicted in the two cases and these have implications for planet formation in the disk. FUV and hard X-rays penetrate deeper in the disk and can drive denser flows (Gorti et al. 2009) while soft X-rays (and EUV) can heat lower density gas to high temperatures (Owen et al. 2010), even though they may be absorbed very easily, perhaps in the wind itself. FUV photoevaporation models predict that the outer disk will be depleted of mass and that the gas disk will shrink as it evolves. As large dust grains ($\gtrsim$ 100μm) are not well coupled to the gas, these may still be retained as extended dust disks (Gorti et al., in prep.). On the other hand, XEUV photoevaporation proceeds mainly from inside-out as the outer disk evolves viscously and spreads but does not get depleted of its gas. There are some indications that the outer disk does lose mass. Wahhaj et al. (2010) found that the 24μm excess observed in disks survives the longest, as there is a correlation between it and the far-infrared and sub-mm excesses (i.e., disks without excesses at long wavelengths do not have an excess in the MIR). Although this result is suggestive of the "torus-like" evolution predicted by the FUV models, note that the 24μm excess in these faint disks cannot be distinguished from debris emission. Andrews et al. (2010) surveyed disks with faint emission in the sub-mm and found that the disk characteristic radius (a measure of disk size) decreases with disk mass, and that disks with holes (transition disks) have shorter characteristic radii. Such a correlation is expected of an FUV photoevaporating disk where the disk gets progressively truncated as it evolves and loses mass. There is no clear dependence of disk mass on FUV luminosity, but in disks with inner holes, accretion rates are often low and the corresponding accretion-generated component of the FUV luminosity will be reduced.

Photoevaporation theories will better tested in the future with forthcoming observations by *Herschel*, SOFIA, ground-based high resolution data and especially with the high sensitivity and spatial resolution of ALMA. Further theoretical studies are needed to assess the relative important of X-rays, EUV and FUV, although it is quite likely all three are important in disk dispersal in different disk environments. Disk evolution is also influenced by other processes such as planet formation and dust evolution including grain growth and settling, and future photoevaporation models need to address these effects for more comprehensive theories.

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