DESTRUCTION OF STELLAR DISKS BY PHOTOEVAPORATION

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RESUMEN

El resumen será traducido al español por los editores. Photoevaporation may provide an explanation for the short lifetimes of disks around young stars. With the exception of neutral oxygen lines, the observed low-velocity forbidden line emission from T Tauri stars can be reproduced by photoevaporating models. The natural formation of a gap in the disk at several AU due to photoevaporation and viscous spreading provides a possible halting mechanism for migrating planets and an explanation for the abundance of observed planets at these radii.

ABSTRACT

Photoevaporation may provide an explanation for the short lifetimes of disks around young stars. With the exception of neutral oxygen lines, the observed low-velocity forbidden line emission from T Tauri stars can be reproduced by photoevaporating models. The natural formation of a gap in the disk at several AU due to photoevaporation and viscous spreading provides a possible halting mechanism for migrating planets and an explanation for the abundance of observed planets at these radii.

Key Words: **ACCRETION — ACCRETION DISKS — STARS: FORMATION**

1. INTRODUCTION

Most low-mass stars form surrounded by circumstellar disks. Observations of infrared excess (e.g., Haisch, Lada, & Lada 2001) suggest disk lifetimes $\tau_{\rm disk} \approx 6 \times 10^6$ yr, requiring an efficient mechanism for disk dispersal.

Hollenbach, Yorke, & Johnstone (2000) considered a variety of disk dispersal mechanisms and concluded that viscous accretion of the disk onto the central star (e.g. Hartmann et al. 1998) together with photoevaporation of the disk at moderate radii (Shu, Johnstone, & Hollenbach 1993; Hollenbach et al. 1994; Johnstone, Hollenbach, & Bally 1998) must act together efficiently to remove the entire disk. Numerical calculations by Clarke, Gendrin, & Sotomayor (2001) and Matsuyama, Johnstone, & Hartmann (2003a) have shown that these processes may remove the disk in 10^{5-7} yr.

The photoevaporation model fits observational data well in the case of external heating via nearby massive stars (Bally et al. 1998; Johnstone, Hollenbach, & Bally 1998; Störzer & Hollenbach 1998). With the exception of a few cases (e.g., MWC349A), evidence for disk photoevaporation due to the central star (Shu et al. 1993; Hollenbach et al. 1994) is largely circumstantial. Observations of blue-shifted, low-velocity emission from forbidden lines of oxygen, nitrogen, and sulfur in the spectra of many T Tauri stars (Hartigan, Edwards, & Ghandour 1995) provide useful diagnostics. Font et al. (2004) calculated the flow properties of the photoevaporative disk wind and found them to compare reasonably with the strengths and profiles of the nitrogen and sulfur lines. The oxygen lines, however, are underabundant in the model.

Along with disk dispersal, photoevaporation and viscous accretion produce structure in the disk such as gaps and rings. Matsuyama, Johnstone, & Murray (2003b) showed that the formation of gaps within the gaseous disk during the dispersal era places constraints on the migration of planetary orbits.

The following sections review the key results of Matsuyama et al. (2003a,b) and Font et al. (2004).

2. PHOTOEVAPORATING DISKS

The evolution of a stellar disk under the influence of viscous accretion and photoevaporation from the central source or external stars has been studied by Clarke et al. (2001) and Matsuyama et al. (2003a). The key parameter in these studies is the source and strength of the ionizing radiation ϕ_*. Clarke et al. assumed that the ionizing flux was due to super-solar activity on the surface of the star and constant with time. Matsuyama et al., however, treated the photoionizing flux from the central source as arising from both the quiescent star and accretion shocks at the

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base of stellar magnetospheric columns. In the latter study, therefore, the ionizing flux was calculated self-consistently from the accretion mass-loss rate.

Alexander, Clarke, & Pringle (2004) raised objections to the use of accretion energy to produce ultraviolet photons, showing that such photons would be absorbed in the dense accretion flow and may not escape the shock front. Furthermore, both stellar and accretion shock ultraviolet photons may be trapped by the strong protostellar jet which launches from the inner disk. Shang et al. (2002) were unable to ionize completely the jet using only photons from the central star due to the high optical depth of the jet itself. It may be that the source of ultraviolet radiation ionizing the disk is the disk-jet boundary, in which case the photon flux still scales as the accretion energy. Other possibilities include enhanced stellar surface activity (but only in stars with weak or absent jets) or nearby massive stars.

The disk cannot be entirely removed using only viscous accretion and photoionization from the disk-star accretion shock because the photoionizing flux decreases too quickly with time (Matsuyama et al. 2003a). When 6-13.6 eV far-ultraviolet (FUV) photons from relatively nearby massive stars can be included, however, the disk is removed in 10^{6-7} yr. In addition, when ionizing photons from close massive stars can be included the disk is removed in 10^{5-6} yr.

An intriguing consequence of photoevaporation by the central star is the formation of a gap in the disk at late stages of the disk evolution (Figure 1). The gap forms near $r_g \sim G M_*/a^2$, where the sound speed a of the 10^4 K photoevaporated disk gas matches the escape velocity from the central star. Interior to this radius, material from the disk is bound to the system and forms a hot disk corona. Exterior to this radius, the ionizing radiation is less intense due to divergence. The gap forms when the surface density at r_g drops to $\Sigma(r_g) \sim 2\,\mathrm{g\,cm^{-2}}$, for typical ionization and viscous parameters.

When viscous accretion and photoevaporation by both the central star and nearby massive stars are considered simultaneously, the disk shrinks and is truncated at an outer radius, set by the temperature in the FUV photoevaporated disk gas ($T \sim 10^3$ K) or the temperature in the ionizing photon photoevaporated flow ($T \sim 10^4$ K). At typical distances ($d \gg 0.03$ pc) from massive stars the disk is evaporated by both external FUV photons and internal ionizing photons. This produces both an outer limit for the disk size and an inner disk gap during the last stages of disk evolution (Figure 2).

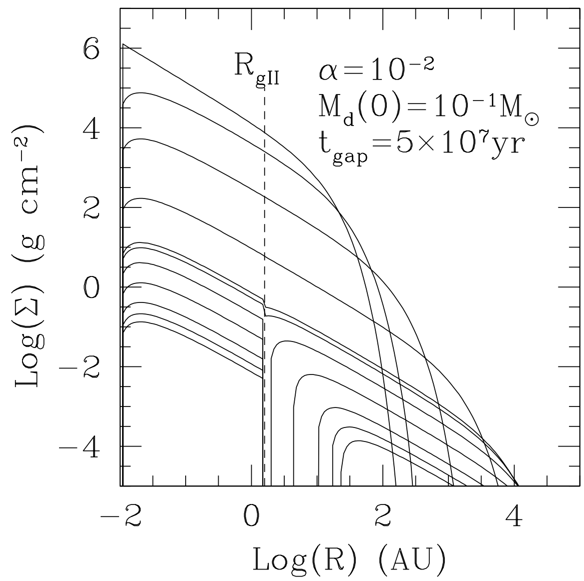

Fig. 1. Snapshots of the disk surface density for a representative model with both viscous evolution and photoevaporation from the central star. R_{gII} refers the gravitational radius for 10^4 K gas. See Matsuyama et al. 2003a for details.

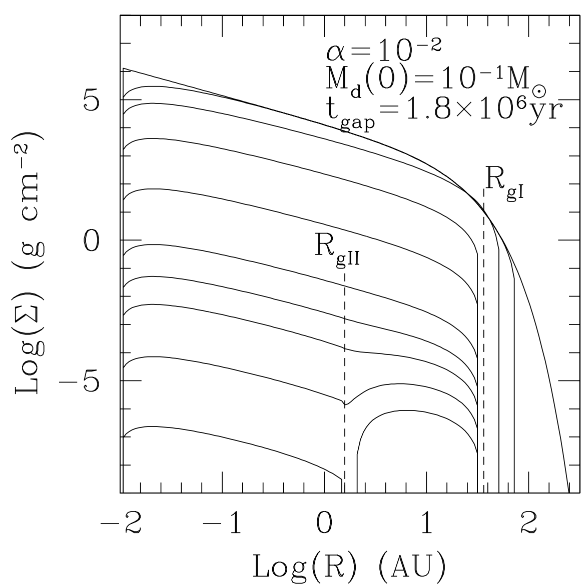

Fig. 2. Snapshots of the disk surface density with viscous evolution, internal photoevaporation, and evaporation due to a nearby massive star. R_{gI} refers the gravitational radius for 10^3 K gas. See Matsuyama et al. 2003a for details.

3. HYDRODYNAMIC MODELS

Low-velocity (e.g. $\sim 10\,\mathrm{km\,s^{-1}}$) blue-shifted forbidden lines are observed in the spectra of T Tauri

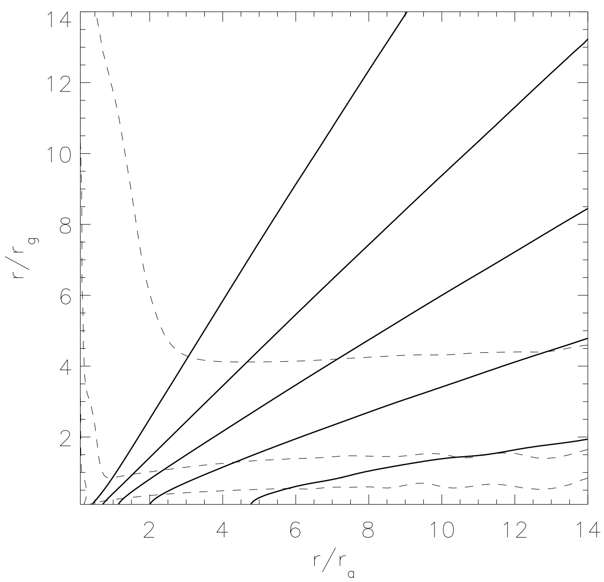

Fig. 3. Steady-state flow results for the photoevaporative disk wind model. The solid lines are streamlines and indicate how the ionized gas travels. The dashed lines indicate where $v_{\rm tot}/a$ equals 1, 2, and 3. See Font et al. (2004) for details.

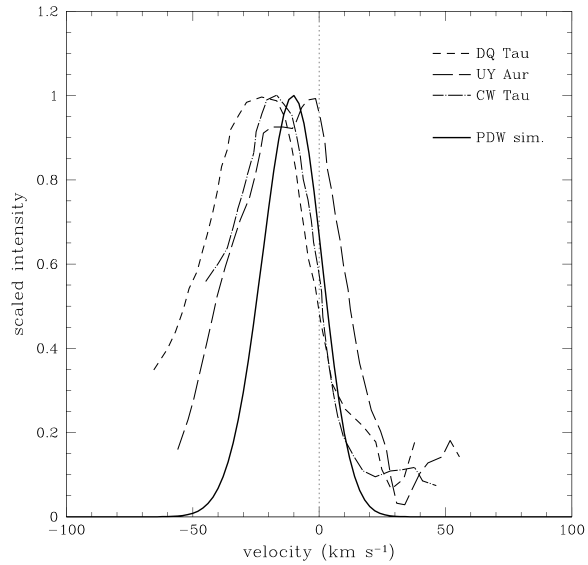

Fig. 4. Comparison of [SII]λ6731 line profiles. The photoevaporative disk wind (PDW) model profile is calculated assuming $\phi_* = 10^{41}\,{\rm s}^{-1}$, $M_* = 1\,M_\odot$ and a face-on disk. See Font et al. (2004) for details.

stars (Hartigan et al. 1995). The similarity between the blue-shift of the low-velocity component and the sound speed in 10^4 K gas has led to speculation that this feature may be an observational signature of photoionized disk winds.

Using the analytic model of Shu, Johnstone, & Hollenbach (1993) and Hollenbach et al. (1994) as a basis, Font et al. (2004) examined the characteristics of photoevaporative outflows using hydrodynamic simulations. Figure 3 shows the streamlines and isotachs of the resultant disk wind. Near the disk surface, the radial density gradient forces the streamlines to bend outward significantly and the flow accelerates. At larger distances from the disk, however, the flow becomes radial and approaches the classical Parker wind solution (Parker 1963).

General results from the simulations were found to agree well with the analytic predictions, although some small differences were present. Most importantly, the flow of material from the disk surface develops at a somewhat smaller radius than in the analytic approximations ($r_g = G\,M_*/3\,a^2$) and the flow-velocity from the disk surface is only one-third the sound speed.

Assuming the gas to be almost entirely ionized and adding contributions from each cell in the hydrodynamic simulation, Font et al. (2004) computed the widths, velocities, and luminosities of sulfur and nitrogen forbidden lines. The simulated line shapes were found to be in relatively good agreement with observations (Figure 4).

Font et al. (2004) also demonstrated that the model line strengths are in agreement with observed low-velocity forbidden line emission of ionized species from T Tauri stars. This is in contrast with magnetic wind models (Garcia et al. 2001a, 2001b), which systematically under-predict these line luminosities. The photoevaporative model, however, cannot account for the luminosities of neutral oxygen lines in T Tauri stars since almost all oxygen in the model is ionized.

4. MIGRATION OF PLANETARY ORBITS

The recent discovery of Jupiter-mass planets orbiting at 3-5 AU from their stars complements earlier detections of massive planets with very small orbits. The short period orbits suggest that migration has occurred, possibly due to tidal interactions between the planets and the gas disk. The newly discovered long period planets (and our own solar system) show that migration is either absent or rapidly halted in at least some systems.

Matsuyama et al. (2003b) proposed a novel mechanism for halting disk coupled planet migration at several AU in a gas disk. As mentioned in §2, photoevaporation of the disk may produce a gap in the disk at r_g (e.g. a few AU). Such a gap would pre-

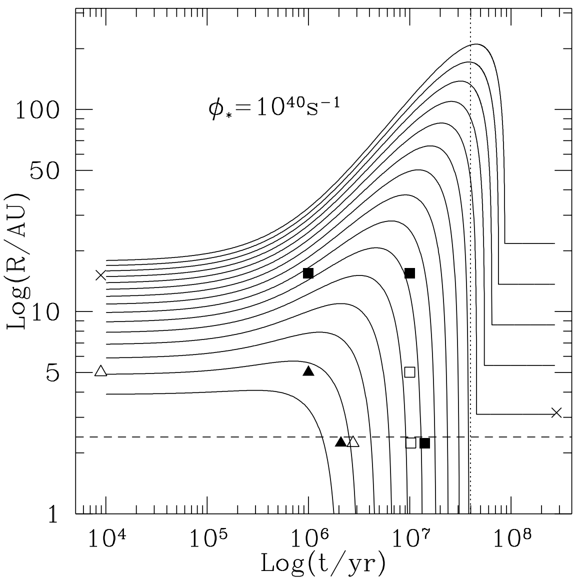

Fig. 5. Planet streamlines in a viscously evolving and photoevaporating disk. See Matsuyama et al. (2003b) for details.

vent outer planets from migrating inward toward the star, resulting in an excess of systems with planets at or just outside r_g. Figure 5 plots the streamlines of planets moving in tandem with their viscously evolving disk. Planets which form in the inner disk migrate with the viscous disk toward the central star. In contrast, planets from the outer disk are halted by the gap near r_g, fixing their orbits at several AU. Almost all planets which tidally lock themselves to the disk early will first migrate outward in the disk before viscously accreting toward the star.

5. CONCLUSIONS

Photoevaporation of disks around young stars may be responsible for short observed disk lifetimes, especially when powered by FUV or ionizing radiation from nearby massive stars. Together, photoevaporation and viscous accretion naturally lead to the formation of gaps and ring structures within disks, without the need to invoke unseen planets.

Hydrodynamic models of the photoevaporative disk wind reveal that the launching point for the flow, r_g, has been overestimated in the analytic models by a factor of ~ 3 and that the launch velocity has been also somewhat overestimated. While most observed low-velocity forbidden line profiles are reasonably matched by the model, the predicted neutral oxygen forbidden line flux is too low since almost all oxygen in the model is ionized. Interestingly, a hot 10^4 K wind which is not photoionized would contain mostly neutral oxygen and the line strengths would produce an excellent fit to the observations.

The existence of a gap in the disk at r_g provides a halting mechanism for migrating planets. Given the predicted location of r_g at several AU from the central star, such gaps might explain the recent abundance of observed planets with these radii.

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