The Astrophysical Journal, 585:L143–L146, 2003 March 10

HALTING PLANET MIGRATION BY PHOTOEVAPORATION FROM THE CENTRAL SOURCE

Isamu Matsuyama,[1] Doug Johnstone,[2] and Norman Murray[3,4]
Received 2002 November 26; accepted 2003 January 31; published 2003 February 13

ABSTRACT

The recent discovery of Jupiter mass planets orbiting at a few AU from their stars complements earlier detections of massive planets on very small orbits. The short-period orbits strongly suggest that planet migration has occurred, with the likely mechanism being tidal interactions between the planets and the gas disks out of which they formed. The newly discovered long-period planets, together with the gas giant planets in our solar system, show that migration is either absent or rapidly halted in at least some systems. We propose a mechanism for halting type II migration at several AU in a gas disk. Photoevaporation of the disk by irradiation from the central star can produce a gap in the disk at a few AU, preventing planets outside the gap from migrating down to the star. This would result in an excess of systems with planets at or just outside the photoevaporation radius.

Subject headings: accretion, accretion disks — planetary systems: formation — planetary systems: protoplanetary disks — planets and satellites: formation — solar system: formation

1. INTRODUCTION

It is believed that gas giants do not generally form at small orbital distances from the central star (Boss 1995). Thus, a natural explanation for extrasolar planets orbiting close to the central star is that these planets formed farther away in the protoplanetary disk and migrated inward to where they are now observed. A variety of mechanisms have been proposed to explain planet migration: the interaction between a planet and a planetesimal disk (Murray et al. 1998), the gravitational interaction between two or more Jupiter mass planets (Rasio & Ford 1996), and the tidal gravitational interaction between the planet and the surrounding disk gas (Goldreich & Tremaine 1979, 1980). The last mechanism, focused on in this Letter, is expected to be dominant at early times, since the surrounding gaseous disk is required for the formation of planets.

If the perturbation exerted on the disk by the planet is small, the disk structure is not greatly altered, and the planet moves inward relative to the surrounding gas (Ward 1997). This type of migration is referred to as "type I." However, if the planet is large, it may open a gap in the disk (Goldreich & Tremaine 1980). The planet is locked to the disk and moves either inward or outward in lockstep with the gaseous disk. This slower migration is referred to as "type II."

We propose a mechanism for halting type II migration: photoevaporation driven by radiation from the central star. The planet's final location is consistent with the solar system and the growing class of extrasolar planets with nearly circular orbits outside of a few AU (see Tinney et al. 2002, Fig. 4). Photoevaporation by the central star was proposed by Shu, Johnstone, & Hollenbach (1993) and Hollenbach et al. (1994) as a way to remove a gas disk. Hollenbach, Yorke, & Johnstone (2000) generalized the discussion, describing the variety of possible disk removal mechanisms: accretion, planet formation, stellar encounters, stellar winds or disk winds, and photoevaporation by ultraviolet photons from the central source or massive external stars. Hollenbach et al. (2000) concluded that the dominant mechanisms for a wide range of disk sizes are viscous accretion and photoevaporation, operating in concert within the disk. In this Letter, we consider photoevaporation by the central source and viscous accretion.

2. MODEL

The model for disk removal used here is developed in a paper by Matsuyama, Johnstone, & Hartmann (2003) and is similar to that used by Clarke, Gendrin, & Sotomayor (2001). In addition, we assume a planet with a large mass, which opens a narrow gap in the disk, and assume that planet migration proceeds in lockstep with the disk evolution (type II migration). The gas disk orbiting the central star with the local Keplerian circular velocity is axisymmetric and geometrically thin. Considering angular momentum and mass conservation of a disk annulus at a radius, R, with kinematic viscosity, ν, the disk surface density evolution can be described by (Pringle 1981)

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}(\nu \Sigma R^{1/2})\right], \qquad (1)$$

where Σ is the disk surface density and t is the disk evolutionary time. We adopt the standard α-parameterization of Shakura & Sunyaev (1973) and write $\nu = \alpha c_s H$, where c_s is the sound speed at the disk midplane and H is the disk thickness. Hartmann et al. (1998) estimate $\alpha \sim 10^{-2}$–10^{-3} and a disk mass ~0.01–0.2 $M_\odot$ for T Tauri stars (TTSs). For the modeled disk temperature distribution, $T_d \propto R^{-1/2}$ (D'Alessio et al. 1998), the viscosity takes the simple form, $\nu(R) \propto R$. Given a solution for equation (1), we find the drift velocity,

$$v_R = -\frac{3}{\Sigma R^{1/2}}\frac{\partial}{\partial R}(\nu \Sigma R^{1/2}), \qquad (2)$$

and describe the evolution of the disk stream lines.

The EUV ($\lambda < 912$ Å) photons from the central star and the accretion shock (we refer to these photons as the EUV photons from the central source) are capable of ionizing hydrogen and evaporating material from the disk surface. Photoevaporation

[1] Department of Astronomy and Astrophysics, University of Toronto, 60 St. George Street, Room 1403, Toronto, ON M5S 3H8, Canada; isamu@astro.utoronto.ca.

[2] National Research Council Canada, Herzberg Institute of Astrophysics, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada; doug.johnstone@nrc.ca.

[3] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George Street, Toronto, ON M5S 3H8, Canada; murray@cita.utoronto.ca.

[4] Canada Research Chair in Astrophysics.

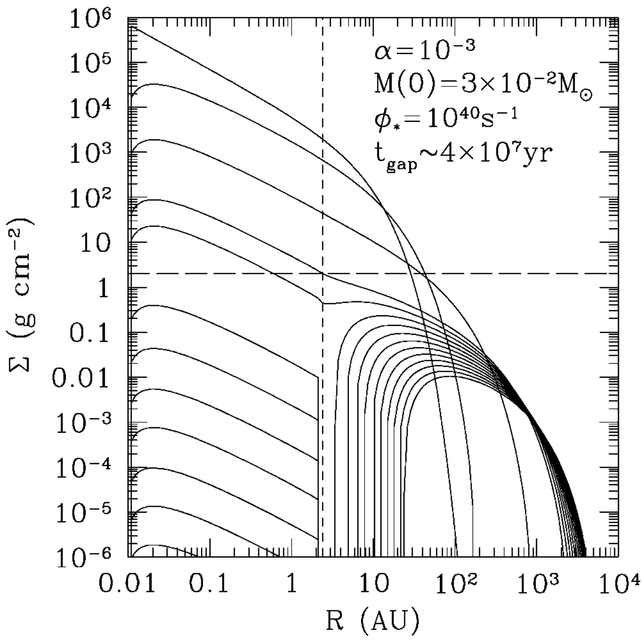

FIG. 1.—Snapshots of the surface density for a fiducial model under the influence of viscous diffusion and photoevaporation from the central source. The model corresponds to $\alpha = 10^{-3}$ and an initial disk mass, $M(0) = 0.03\ M_{\odot}$. The short-dashed line indicates the location of the gravitational radius, and the long-dashed line corresponds to the minimum surface density for gap formation by photoevaporation. The solid curves represent $t = 0$, 10^6, 10^7, 3.6×10^7, 4.2×10^7, 4.7×10^7, 5.2×10^7, 5.7×10^7, 6.2×10^7, 6.7×10^7, 7.2×10^7, 7.7×10^7, 8.2×10^7, 8.7×10^7, and 9.2×10^7 yr. The gap structure starts forming at $t_{\rm gap} \sim 4 \times 10^7$ yr, when the disk mass is $\sim 3\ M_{\rm J}$ and the surface density at the gravitational radius is $\Sigma_{\rm gap} \sim 2$ g cm^{-2} (*long-dashed line*).

forms an ionized atmosphere above the thin viscous disk. Hollenbach et al. (1994) found analytic solutions for the photoevaporation mass-loss rate by EUV photons from the central source. These photons are attenuated by recombined hydrogen atoms and scattered in the ionized atmosphere, providing a source of diffuse EUV photons that dominates the flux onto the disk at radii much larger than the size of the central star. Disk material is gravitationally bound to the central star inside the gravitational radius, $R_g = GM_*/3c_s'^2$, and it flows out of the disk surface at the sound speed of the heated material, c_s', beyond this radius. Given the number density of ionized hydrogen at the base of the ionized layer, $n(R)$, we can calculate the evaporation rate,

$$\dot{\Sigma}_{\rm ph}(R) = \begin{cases} 2\,\mu {\rm m}_p n(R) c_s', & \text{if } R > R_g; \\ 0, & \text{otherwise,} \end{cases} \qquad (3)$$

where $\mu = 0.68$ is the mean molecular weight for the ionized material.

Assuming ionization equilibrium, Hollenbach et al. (1994) found the number density at the base of the ionized layer, for $R > R_g$:

$$n(R) = 3.1 \times 10^5 \left(\frac{\phi}{10^{40}\ {\rm s^{-1}}}\right)^{1/2} \left(\frac{R_g}{1\ {\rm AU}}\right) \times \left(\frac{R}{1\ {\rm AU}}\right)^{-5/2}\ {\rm cm^{-3}}, \qquad (4)$$

where ϕ is the total ionizing flux from the central source. We assume that half of the accretion luminosity is radiated as hot continuum from accretion shocks and that the EUV flux can be characterized as blackbody emission at $T_{\rm as} = 10^4$ K (Gullbring et al. 2000; Johns-Krull, Valenti, & Linsky 2000; Kenyon et al. 1989). There are currently no strong observational constraints on the ionizing flux from the central star, ϕ_*. The EUV flux for the sun is $\sim 2.6 \times 10^{37}\ {\rm s^{-1}}$ (see Wilhelm et al. 1998, Fig. 10*b*). Since TTSs are chromospherically active (D'Alessio et al. 1998), their EUV fluxes must be higher by a few orders of magnitude. We estimate the ionizing flux from the far-ultraviolet (FUV) spectra of TTSs (Valenti, Johns-Krull, & Linsky 2000, Fig. 3) and the corresponding distances to the star (Johns-Krull et al. 2000, Table 1). The typical values are $\sim 10^{39}\ {\rm s^{-1}}$ for classical TTSs. Extrapolating the FUV flux underestimates the EUV flux; thus, the EUV flux might be as high as $10^{40}\ {\rm s^{-1}}$.

Combining photoevaporation with viscous accretion is done numerically. At each time step, photoevaporation-induced mass loss and viscous diffusion–induced disk evolution are solved. For details on the disk dispersal calculation, refer to Matsuyama et al. (2003). The simulation is stopped when the disk mass is $1\ M_{\rm J}$.

3. DISCUSSION

At a given disk radius, a gap forms when the mass transported by viscous accretion is equal to the mass removed by photoevaporation. This occurs when the photoevaporation timescale, $\Sigma/\dot{\Sigma}_{\rm ph}$, is equal to the viscous diffusion timescale, $R^2/3\nu$. Therefore, we can estimate the surface density for gap formation at the gravitational radius,

$$\Sigma_{\rm gap} \sim 2 \left(\frac{\alpha}{10^{-3}}\right)^{-1} \left(\frac{\phi_*}{10^{40}\ {\rm s^{-1}}}\right)^{1/2} \left(\frac{R_g}{2.4\ {\rm AU}}\right)^{-1}\ {\rm g\ cm^{-2}}. \qquad (5)$$

Figure 1 shows snapshots of the disk surface density distribution for a disk with initial mass $M(0) = 0.03\ M_{\odot}$ and $\alpha = 10^{-3}$. A gap starts forming at the gravitational radius when the surface density reaches $\Sigma_{\rm gap} \sim 2$ g cm^{-2} during the last stages ($t_{\rm gap} \sim 4 \times 10^7$ yr) of the disk evolution and the disk is divided into two annuli. The subsequent evolution is dominated by two competing effects; viscous diffusion attempts to spread both annuli and remove the gap structure while photoevaporation removes material predominantly at the gravitational radius, reopening the gap. The material in the inner annulus is quickly removed both at the inner edge, by accretion onto the central star, and at the outer edge, by the combination of viscous spreading and photoevaporation. In contrast, the outer annulus loses material primarily from its inner edge. The inner edge of the outer annulus recedes from the star as photoevaporation removes disk material, thereby reducing the mass removal rate in accordance with equations (3) and (4).

We model a planet that has opened a narrow gap in the disk. The migrating planet will open a gap if its mass is greater than the critical mass, $M_c \sim M_* (81\pi\alpha c_s^2/8v_k^2)$ (see, e.g., Lin & Papaloizou 1993). The planet is initially tidally locked to the disk and moves with the gas, migrating outward or inward depending on its initial location. This migration may stop for two reasons. First, the combination of photoevaporation from the central source and viscous spreading removes disk mass, reducing the gravitational interaction between the planet and the disk and allowing the planet to decouple its orbit from that of the gas. Second, the planet will stop if it reaches the gap created by photoevaporation, as the tidal torques are unable to influence

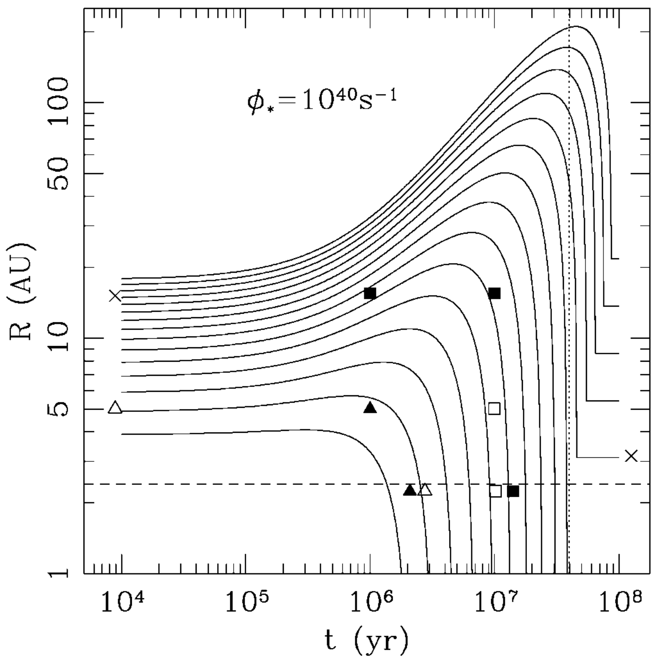

FIG. 2.—Disk stream lines for the fiducial model with $M(0) = 0.03\ M_\odot$ and $\alpha = 10^{-3}$. The initial spacing (at $t = 10^4$ yr) between the stream lines is 1 AU, covering the disk from 4 to 18 AU. The short-dashed line indicates the location of the gravitational radius, $R_g = 2.4$ AU, and the dotted line represents the time when the photoevaporation gap starts forming, $t_{\rm gap} \sim 4 \times 10^7$ yr. Planets forming at $R \sim 5$ AU and tidally locking to the disk early ($t = 10^4$ yr) (*open triangles*) or late (*filled triangles*) fall onto the central star at $t \sim 2.5 \times 10^6$ yr. In contrast, a planet starting with initial semimajor axis $R \sim 15$ AU at $t = 10^4$ yr (*crosses*) stops migrating when it reaches the photoevaporation gap.

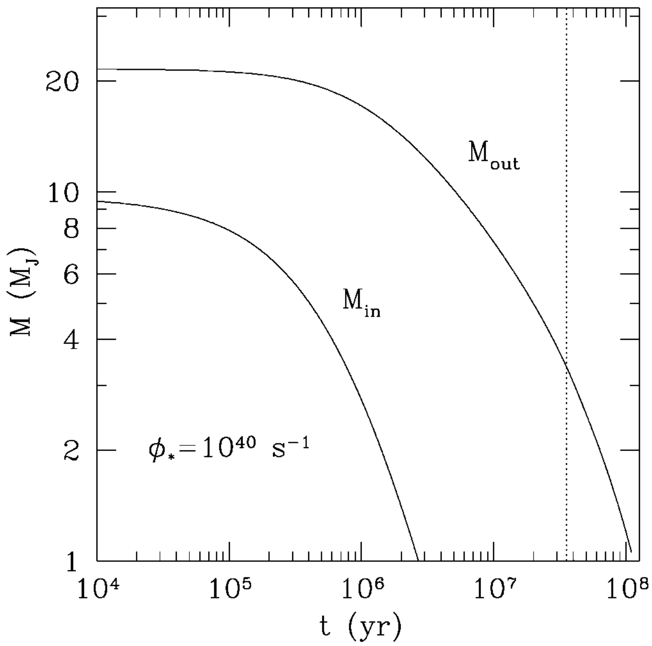

FIG. 3.—Disk mass outside the gravitational radius, $M_{\rm out}$, and disk mass inside the gravitational radius, $M_{\rm in}$, as a function of disk lifetime for the fiducial model. The dotted line indicates the time, $t_{\rm gap} \sim 4 \times 10^7$ yr, when the gap structure starts forming.

the planet across such a large opening. In order to describe planet migration, we show in Figure 2 the disk stream lines that start between 4 and 18 AU, at $t = 10^4$ yr, where there is enough mass to form a Jupiter mass planet in an annulus of width 4 AU. After the planet opens a gap, it migrates along the disk stream lines; therefore, we can follow planet migration in Figure 2 for different planet gap opening locations and times. The disk mass outside the gravitational radius is reduced to Jupiter's mass in $\sim 10^8$ yr (see Fig. 3); therefore, a migrating planet with Jupiter's mass stops migrating at any disk location soon after this time. However, a migrating planet may reach the inner disk boundary ($R = 10^{-2}$ AU) or the photoevaporation gap before the disk mass is reduced to Jupiter's mass.

Figure 2 provides information on which initial locations and times allow a planet tidally locked to the disk to survive. It is difficult to time the gaseous disk removal in such a manner as to maintain planets at large distances from the central star. A planet that opens a narrow gap at $t = 10^4$ yr survives only if its initial disk location is greater than the critical radius ~14 AU, because the planet reaches the outer edge of the photoevaporation gap after the gap has formed. Since the disk expands rapidly at early times, this critical radius increases with later planet gap opening timescales; i.e., the later the planet forms, the farther away from the central star it has to be in order to survive. However, this behavior changes after the photoevaporation-induced gap forms. If the planet forms at a time similar to when the photoevaporation gap forms, $t_{\rm gap} \sim 4 \times 10^7$, it survives as long as it originates outside the gravitational radius.

4. CONCLUSIONS

In this Letter, we have studied different scenarios in which a planet undergoing type II migration survives because of the formation of a gap by photoevaporation from the central source. If the planet gap opening occurs close to when the photoevaporation gap forms (at $t \sim 4 \times 10^7$ yr for our fiducial model), the final semimajor axis of the planet is near the gravitational radius (~2.4 AU) for a wide range of initial semimajor axes. This scenario requires long timescales for planet formation (10^6–10^8 yr), similar to those predicted by the core accretion model (Pollack et al. 1996; Bodenheimer, Hubickyj, & Lissauer 2000).

We can also predict the final semimajor axis when considering rapid planet formation by disk instability (Boss 2000). Our disk initially spreads outward under the influence of viscosity, allowing planets that form early at small radii to move out beyond R_g before the photoevaporation gap opens and enhancing their survival rate. The rate and amount of viscous spreading in real disks depends on the initial surface density profile and any continuing accretion onto the disk. If the planet-induced gap opening occurs at early stages of the disk evolution (for example, at $t \sim 10^4$ yr), all the planets initially located inside ~14 AU will reach the disk inner boundary at the central star. The only planets that survive are those that form at a narrow range of semimajor axes (14 AU $\lesssim R \lesssim$ 18 AU). However, viscous diffusion spreads this narrow range during planet migration, and the final semimajor axis distribution is 3 AU $\lesssim R \lesssim$ 22 AU. This final distribution of planets has similarities to our own solar system, and it suggests that the gas giants could have formed at ~14–18 AU and migrated to their current locations. Furthermore, the initial planet locations are in agreement with recent simulations of planet formation by disk fragmentation (Mayer et al. 2002).

The minimum surface density for gap opening by photoevaporation, $\Sigma_{\rm gap}$, and the disk size, R_d, determine the disk mass outside the gravitational radius. In our fiducial model, the mass outside the gravitational radius at the time of gap opening is $2\pi\Sigma_{\rm gap}R_g(R_d - R_g) \sim 3\ M_{\rm J}$; therefore, it is possible to consider migration of a Jupiter mass planet. However, for lower ionizing fluxes (i.e., $\phi_* \lesssim 10^{40}\ {\rm s}^{-1}$), the minimum surface density for gap opening by photoevaporation becomes smaller (see eq. [5]) and the halting of planet migration becomes marginal. For example, for $\phi_* = 10^{38}\ {\rm s}^{-1}$, the minimum surface density for gap opening and the disk mass outside the gravitational radius are smaller by 1 order of magnitude ($\Sigma_{\rm gap} \sim 0.2$ g cm^{-2} and $M_{\rm out} = 0.3\ M_{\rm J}$).

We note that the gravitational radius R_g roughly coincides with the location of the asteroid belt in the solar system. It is well known that the surface density of heavy elements reaches a severe local minimum in the asteroid belt; this is usually attributed to long-term gravitational effects from Jupiter, although it is not clear that the amount of depletion that results is sufficient (Liou & Malhotra 1997; Holman & Murray 1996). Simple estimates show that the planetesimal formation timescale is much shorter than the gap formation time, so it is not clear that the formation of a photoevaporation gap would significantly reduce the surface density of planetesimals, but the coincidence is intriguing.

The photoevaporation gap opening timescale ($\sim 4 \times 10^7$ yr) is long compared to the typically observed gaseous disk lifetimes (10^6–10^7 yr). However, the disk lifetime for stars outside stellar clusters is considerably longer than the disk lifetime for stars in the hostile stellar clusters (Matsuyama et al. 2003). In addition, there is evidence that some stars retain disks between 10^7 and 10^8 yr (see Hillenbrand 2003, Fig. 2).

It is also possible to halt both type I and type II migration in stellar clusters by removing the disk. This is a likely situation for the disks surrounded by ionization fronts in the Trapezium cluster (Johnstone, Hollenbach, & Bally 1998; Störzer & Hollenbach 1999; Bally, O'Dell, & McCaughrean 2000). Störzer & Hollenbach (1999), Hollenbach et al. (2000), and Matsuyama et al. (2003) show that the disk lifetime due to photoevaporation by external stars is in the range 10^5–10^6 yr in the neighborhood of massive O stars and between 10^6 and 10^7 yr at reasonable distances (~0.03–0.3 pc) from external O stars. These timescales are in agreement with observational estimates for the lifetime of protoplanetary disks in stellar clusters (Haisch, Lada, & Lada 2001). This scenario is possible when considering the rapid planet formation by disk instability; on the other hand, it is uncertain whether gas giant planets form by core accretion in these short-lived disks.

The research of I. M. is supported by a University of Toronto fellowship and the international recruitment award. The research of D. J. is partially supported through an NSERC grant held at the University of Victoria. The research of N. M. is supported by the Canada Research Chair Program and by NSERC.

REFERENCES

Bally, J., O'Dell, C. R., & McCaughrean, M. J. 2000, AJ, 119, 2919
Bodenheimer, P., Hubickyj, O., & Lissauer, J. J. 2000, Icarus, 143, 2
Boss, A. P. 1995, Science, 267, 360
———. 2000, ApJ, 536, L101
Clarke, C. J., Gendrin, A., & Sotomayor, M. 2001, MNRAS, 328, 485
D'Alessio, P., Canto, J., Calvet, N., & Lizano, S. 1998, ApJ, 500, 411
Goldreich, P., & Tremaine, S. 1979, ApJ, 233, 857
———. 1980, ApJ, 241, 425
Gullbring, E., Calvet, N., Muzerolle, J., & Hartmann, L. 2000, ApJ, 544, 927
Haisch, K. E., Lada, E. A., & Lada, C. J. 2001, ApJ, 553, L153
Hartmann, L., Calvet, N., Gullbring, E., & D'Alessio, P. 1998, ApJ, 495, 385
Hillenbrand, L. A. 2003, in Origins 2002: The Heavy Element Trail from Galaxies to Habitable Worlds, ed. C. E. Woodward & E. P. Smith (San Francisco: ASP), in press (astro-ph/0210520)
Hollenbach, D., Johnstone, D., Lizano, S., & Shu, F. 1994, ApJ, 428, 654
Hollenbach, D. J., Yorke, H. W., & Johnstone, D. 2000, Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 401
Holman, M. J., & Murray, N. W. 1996, AJ, 112, 1278
Johns-Krull, C. M., Valenti, J. A., & Linsky, J. L. 2000, ApJ, 539, 815
Johnstone, D., Hollenbach, D., & Bally, J. 1998, ApJ, 499, 758
Kenyon, S. J., Hartmann, L., Imhoff, C. L., & Cassatella, A. 1989, ApJ, 344, 925
Lin, D. N. C., & Papaloizou, J. C. B. 1993, Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. Arizona Press), 749
Liou, J. C., & Malhotra, R. 1997, Science, 275, 375
Matsuyama, I., Johnstone, D., & Hartmann, L. 2003, ApJ, 582, 893
Mayer, L., Quinn, T., Wadsley, J., & Stadel, J. 2002, Science, 298, 1756
Murray, N., Hansen, B., Holman, M., & Tremaine, S. 1998, Science, 279, 69
Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y. 1996, Icarus, 124, 62
Pringle, J. E. 1981, ARA&A, 19, 137
Rasio, F. A., & Ford, E. B. 1996, Science, 274, 954
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shu, F. H., Johnstone, D., & Hollenbach, D. 1993, Icarus, 106, 92
Störzer, H., & Hollenbach, D. 1999, ApJ, 515, 669
Tinney, C. G., Butler, R. P., Marcy, G. W., Jones, H. R. A., Penny, A. J., McCarthy, C., & Carter, B. D. 2002, ApJ, 571, 528
Valenti, J. A., Johns-Krull, C. M., & Linsky, J. L. 2000, ApJS, 129, 399
Ward, W. R. 1997, Icarus, 126, 261
Wilhelm, K., et al. 1998, A&A, 334, 685