Can photo-evaporation trigger planetesimal formation?

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ABSTRACT

The majority of stars are born from giant molecular clouds in dense but transient OB associations such as Orion. Nearby O and B stars can photo-evaporate the outer parts of circumstellar disks surrounding low-mass stars on $10^5 - 10^6$ yr timescales. In this letter, we propose a method by which the radiation field may stimulate the formation of planetesimals. We present numerical model of disk evolution which includes photo-evaporation and vertical sedimentation. In our model, solid material grows and settles toward the midplane as in the model of Sekiya (1998). When a disk is exposed to photo-evaporation, mass-loss occurs from its outer shells where UV radiation can penetrate. Grain growth and settling cause these regions to be preferentially depleted of dust. The disk develops an increasing dust:gas ratio in its shielded interior and the dust becomes gravitationally unstable according to the criteria of Youdin & Shu (2002). Therefore, UV radiation fields may induce the rapid formation of planetesimals in disks where grain growth and sedimentation are important.

Subject headings: (stars:) planetary systems: protoplanetary disks – (stars:) planetary systems: formation – solar system: formation

1. Introduction

Several dozen disks with diameters from 100 AU to 1200 AU have been directly imaged around young stars embedded in the Orion nebula with the Hubble Space Telescope (HST) (O'Dell & Wong 1996; Bally et al. 1998, 2000). Excess near-infrared emission in the 2 to 10 μm wavelength region (Smith et al. 2004) provides indirect evidence that more than 80% of the several thousand low-mass young stars in the Orion nebula cluster are surrounded by disks of gas and dust. Disks which are not directly seen in images are either too small, are lost in the glare of their central stars, or are hidden inside externally ionized cocoons ('proplyds') produced by their own photo-evaporation. About half of these disks are being photo-evaporated by ultraviolet (UV) radiation from nearby O and B stars in the Trapezium cluster. Mass loss rates have been measured to be in the range $10^{-7} - 10^{-6} M_{\odot}$ yr^{-1} (Henney & O'Dell 1999), implying the loss of a disk within 10^4 to 10^6 years. It has been suggested that the formation of planets in regions such as Orion may be difficult – planets must form either rapidly, or rarely (Throop et al. 2001; Hester et al. 2004).

In this letter, we use a numerical model to study the loss of material from a photo-evaporating disk and to and examine the effects of sedimentation towards the disk midplane on the loss of the gas and dust components. Previous models of disk evaporation (Johnstone et al. 1998; Matsuyama et al. 2003; Adams et al. 2004) have examined only the gas component, assuming that gas and dust are well-mixed throughout and that the loss of gas implies the loss of dust. In our model, the evolution of the gas and dust components are treated individually. We explore the consequences of grain growth and sedimentation on planetesimal formation. Our model assumes that planetesimal formation begins by non-gravitational sticking in collisions (*e.g.* **?**), after which material sediments to the midplane where it can undergo gravitational instability *after sufficient gas is removed* (Goldreich & Ward 1973; Youdin & Shu 2002). The model presented here builds on our earlier work that did not include vertical sedimentation or gravitational instability (Throop 2000; Throop et al. 2001). In section 2, we discuss our model's structure, physics, and implementation. Section 3 reports on our results, and we discuss implications in section 4.

2. Disk Model

We have developed a numerical model which tracks the state of the disk's gas and dust components as they undergo vertical sedimentation and external photo-evaporation. We consider the effects of UV-induced photo-evaporation due to nearby massive stars, and we ignore the effects of self-irradiation by UV light from the low-mass stars embedded within the disks. Thus, our model is most applicable to the outer portions of disks, or to disks which are effectively shielded from self-irradiation.

Most disks around low-mass stars in OB associations formed well before photo-evaporation began. Low-mass stars in Orion have ages $10^5 - 10^6$ yr (Hillenbrand 1997). On the other hand, the large number of proplyds and their mass loss rates in the core of the Orion nebula implies that most have only been photo-evaporating for only a few 10^4 yr (Bally et al. 2000). Therefore, disks can evolve quiescently for up to about 10^6 yr. This is sufficient time to allow grains to grow and settle to the midplane as we show below. Photo-evaporation begins after this initial period.

Initial Disk Structure. The initial surface density follows the model of Hayashi (1981). Surface densities for the gas, Σ_g, and dust, Σ_d, as a function of orbital distance r are defined by:

$$\Sigma_d = 30.1\ (r/\mathrm{AU})^{-k}\ [\mathrm{g\ cm^{-2}}] \tag{1}$$

$$\Sigma_g = 1700\ (r/\mathrm{AU})^{-k}\ [\mathrm{g\ cm^{-2}}], \tag{2}$$

implying a dust:gas mass ratio of 1:60. We assume a mass distribution exponent $k = 3/2$ and a disk size $r_d = 100$ AU, yielding a disk mass 0.02 $M_\odot$, with 0.01 $M_\odot$(a 'minimum-mass solar nebula') between 1 AU and 30 AU. In the vertical direction z, we distribute the gas using the Hayashi (1981) pressure-balance scale height H to calculate the gas density ρ_g,

$$H = 7.1 \times 10^{11} (r/\mathrm{AU})^{-5/4}\ [\mathrm{cm}] \tag{3}$$

$$\rho_g(r,z) = \frac{\Sigma(r)}{2H} e^{-(z/H)^2}\ [\mathrm{g\ cm^{-3}}], \tag{4}$$

where the factor of two accounts for the disk's top and bottom sides.

Grain growth and sedimentation. Dust grains in young disks are transported by small-scale turbulent eddies. Within these eddies, grains collide, stick, and grow (Cuzzi et al. 1996); as they grow, they sediment toward the disk midplane. Numerous studies have established that most of the disk's dust mass will have grown via collisions to sizes of mm to cm and sedimented to the midplane within a few $10^4 - 10^5$ yr (Throop 2000; Weidenschilling 1997; Weidenschilling & Cuzzi 1993; Mizuno et al. 1988). Since a typical disk may evolve for 10^6 yr before being photo-evaporated, it will have largely settled by this time. The existence of large grains at the disk outer edge is consistent with observations. Throop et al. (2001) used multi-band Hubble Space Telescope observations to show that at visual and near-infrared wavelengths, the translucent 600 AU outer edge of Orion's giant silhouette disk 114-426 produces grey extinction. The absence of reddening implied that grains had grown to at least several microns, and potentially much more. These observations indicated that grain growth could occur in Orion's disks, even at large disk radii.

Vertical structure. Local turbulence will prevent grains from settling to an infinitely thin plane. The equilibrium vertical distribution of dust in a proto-planetary disk has been studied by Sekiya (1998). In their model, the density is determined by an equilibrium between grain settling and grain lofting via Kelvin-Helmholtz instability – the mechanism responsible for lifting dust off a desert floor during a sandstorm. Because the gas disk has only a finite mass-loading capacity, the dust density increases rapidly toward the midplane. In some cases, the solution for midplane density becomes singular. Youdin & Shu (2002) interpreted this singularity as being indicative of the dust disk's susceptibility to a gravitational instability (GI). They did not model planetesimal formation from this instability, only the onset of the GI. They found that in the Hayashi (1981) disks, an increase in the dust:gas surface density of $\sim 2-10\times$ (varying with r) was sufficient to reach this instability, and it could be caused either by increasing Σ_d or decreasing Σ_g.

The Sekiya vertical profiles assume that the disks have no global turbulence. This condition has not been established in the Orion disks; indeed, many models describing turbulence from thermal convection and magneto-hydrodynamic instabilities have been published (*e.g.* Lin & Papaloizou 1980; Balbus et al. 1996). Because of their proximity to luminous sources of radiation, however, Orion's disks are expected to be relatively warm with temperatures of around 50 K. Thus, turbulence produced by thermal convection from the disk mid-plane is expected to be suppressed compared to that in similar disks in dark clouds such as Taurus where the disks may be as cold as 10 K. However, the precise nature of any turbulence remains an open issue.

The inclination angle (and thus thickness) of the Orion disks is unknown and their vertical mass structure cannot be fully probed by optical observations. However, Johnstone et al. (1998) estimate from model fits that the disks' outer shells are characterized by a UV penetration depth $N_D = 3\times10^{21}$ cm^{-2} – that is, the outer shell is depleted by ~ 3 from the classical value of $N_D = 1\times10^{21}$ cm^{-2}. The Orion disks therefore appear at least partially settled; it is likely that an atmosphere of small, micron-sized grains remains suspended in order to maintain the photo-evaporation.

Photo-evaporation. UV radiation heats the disk surface to a depth N_D where the radiation is predominantly absorbed by dust. Wherever the sound-speed in the heated layer exceeds the local gravitational escape speed, mass-loss occurs. Mass-loss occurs in two distinct regimes (Johnstone et al. 1998). FUV radiation (912Å $< \lambda <$ 2,000Å) produces a warm (~ 1000 K) neutral hydrogen outflow for radii $r_I > GM/2c_I^2$ where $c_I \sim 3$ km s^{-1} is the sound-speed, and the factor of roughly two accounts for the effects of pressure gradients within the outflow. For a 1 $M_\odot$ star, $r_I \sim 50$ AU. For most disks, the resulting mass loss prevents ionizing EUV radiation ($\lambda < 912$ Å) from reaching the disk surface. But, as a disk loses mass and shrinks to a size less than r_I, FUV-induced mass-loss declines and stops entirely. At this point, the ionizing EUV radiation can reach the disk surface, ionize its skin, and raise its sound-speed to $c_{II} \sim 10$ km s^{-1} . Mass loss-resumes in the form of a fully ionized wind until a radius of about $r_{II} \sim GM/2c_{II}^2 \sim$5 AU.

We incorporate the mass loss rates of Johnstone et al. (1998) from their eqs. (5) and (23). We assume an outflow wind speed $v_0 = 3$ km s^{-1}, and a UV penetration depth $N_D = 3 \times 10^{21}$ cm^{-2} (*i.e.*, their $\epsilon = 3$). We assume that small, micron-sized dust grains produced as collisional byproducts will remain well-mixed with the gas and therefore continue to provide efficient heating of the gas as they absorb UV radiation, even as larger grains settle to the midplane. The external star is assumed to have an output of 10^{49} photons s^{-1} and be at a distance $d = 0.1$ pc, roughly corresponding to the case of Orion's HST10 disk. The central star's mass is taken to be 1 $M_\odot$.

Following Johnstone et al. (1998), we assume that the mass loss rate is constant across the disk; that is,

$$\dot{\Sigma} = \frac{\dot{M}}{\pi r_d^2} \ . \tag{5}$$

We assume that mass is lost from the top down (decreasing z), and that the mass loss occurs symmetrically on both sides of the disk. If the disk material re-settles vertically on a timescale faster than the photo-evaporation time, then the disk will maintain a general symmetry in the z direction, regardless of asymmetry in the illumination source. This condition is met (for dust and gas respectively), if

$$\frac{\Sigma(r)}{\dot{\Sigma}} > t_{\rm set}(a(r)) \tag{6}$$

and

$$\frac{\Sigma(r)}{\dot{\Sigma}} > \frac{H(r)}{v_0} \ . \tag{7}$$

Using typical grain sizes $a(r)$ due to coagulative growth, and settling times $t_{\rm set}$ (*e.g.* Mizuno et al. 1988; Weidenschilling 1997; Throop 2000), we find that these conditions are satisfied throughout our simulation.

Dust entrainment. When gas is lost to the UV-induced outflow, small grains are entrained and dragged along with the flow. We assume, by analogy with the gas's finite mass-loading described by Youdin & Shu (2002), that gas can entrain its own mass density of dust grains, but no more. The entrained dust volume-density in the outflow ρ_{de} is therefore

$$\rho_{de}(r,z) = \mathrm{Min}(\rho_\mathrm{d}(\mathrm{r,z}), \rho_\mathrm{g}(\mathrm{r,z}))\ . \tag{8}$$

In most cases, the vertical location in the disk where these densities are equal occurs slightly above the midplane, causing a preferential removal of gas.

Model structure. Our numerical model uses a 100×100 2D grid to track the densities $\rho_g(r,z)$ and $\rho_d(r,z)$. We use logarithmically-spaced bins in the vertical and radial directions, and assume azimuthal symmetry. The model uses a self-adjusting variable timestep to evolve the system; typical timesteps are 10^3 yr at the outer edge and 10 yr at the inner. The timesteps chosen are more than sufficient to assure numerical convergence. At each timestep, photo-evaporation and grain entrainment act on the disk as described above. Our simulation begins when the disk first becomes exposed to UV radiation from nearby massive stars; it ends when the disk has been eroded in to $r_d \leq r_{II}$, stopping all photo-evaporation.

3. Results

Figure 1 shows the output from our model run. The disk is gradually eroded from the outside edge inward, first by FUV radiation and then by EUV. After 1.25×10^5 yr, the gas disk has been removed entirely outward of 5 AU, and continued UV flux will remove no additional gas inward of this distance. Dust throughout the disk is partially but not fully removed: between 5 and 50 AU, the disk is left with roughly 4 Earth masses of dust. This dust has condensed to the midplane and is not entrained in the photo-evaporative outflow. It meets the instability criteria of Youdin & Shu (2002), indicating that planetesimals could form. Standard models indicate the initial planetesimals from such an instability to be of size ~ 0.1 km (Goldreich & Ward 1973). Beyond 50 AU the dust density is not high enough to meet the instability criteria. Between 1 and 5 AU, an additional 20 Earth masses of solid material remains; this material is unaffected by external photo-evaporation and thus although it has settled, does not become unstable because gas motions inhibit collapse.

We have performed a second run on a disk with all of the same characteristics, except that the gas and dust densities Σ_g and Σ_d were increased to three times their nominal values, giving a disk mass of $0.06 M_\odot$. In this run, the general behavior was similar to that shown in our nominal run. However, between 5 and 50 AU nearly 140 Earth masses of material remained, all of which was unstable after photo-evaporative gas removal. The highly non-linear dependence on the initial dust mass is due to the fact that nearly all the additional mass settles preferentially to the midplane, rather than being distributed uniformly. Initial results indicate that this trend continues with even higher dust masses.

4. Discussion

If a disk has more than a few 10^5 years to evolve before it is exposed to UV radiation, grains throughout the disk can grow sufficiently large to settle toward the disk mid-plane. Thus, a gradient in the vertical distribution of the dust:gas ratio can be established: the disk surface layers become relatively dust-depleted while the disk mid-plane becomes dust-enriched. Because photo-evaporation preferentially removes the gas component, the settled dust subdisk remains and the gas no longer inhibits a gravitational instability. The subsequent formation of planetesimals by gravitational instability addresses a size scale (cm to km) that has been difficult for purely accretional growth models, because bodies in this size range have neither the self-gravity nor the internal strength to maintain integrity after collisions of more than several m s^{-1} (*e.g.* Weidenschilling & Cuzzi 1993).

Planetesimal formation by means of gravitational instability may be enhanced by any process that sufficiently concentrates dust. For example, Youdin & Shu (2002) presented another method for enhancing the dust:gas ratio – the inward radial drift of cm-to-meter-scale bodies in the nebula. They demonstrated that local instabilities could be created on timescales of 10^5-10^6 yr in the 1-100 AU region. The methods presented in both our work and theirs operate on roughly comparable distances and timescales.

Our model is simplistic and ignores some important processes. Hollenbach et al. (1994) found that the central star's own UV radiation can drive photo-evaporation. Because we have ignored such self-irradiation in our models, the results presented here apply to the outer regions of disks (beyond several AU), or to disks shielded from illumination from their central stars. Self-illumination acts in a similar way to external illumination and will also preferentially remove gas, so we expect that the effect in the inner region will be similar to that demonstrated here. Additionally, the inner disk will be affected by viscous transport of material toward the central star. Our model does not include these processes; Matsuyama et al. (2003) found that self-irradiation and viscous transport together formed gaps near the inner gravitational radius. Such gaps may halt the inward radial drift of solid material, further spurring the onset of instability at that location.

OB associations have been accused of being hazardous to planetary formation (*e.g.* Throop et al. 2001; Hester et al. 2004). On the contrary, our results indicate that UV radiation fields in an OB association may actually stimulate a critical step in planet formation – the growth of kilometer-size planetesimals. If our Solar System formed via the method described here, the initial disk mass must have been greater than our nominal $0.02M_{\odot}$ disk mass, because that disk leaves insufficient material outward of 5 AU from which to form the giant planet cores, assuming the standard core-and-envelope scenario of Pollack et al. (1994). These planets have cores totaling roughly 40 Earth masses; our simulation leaves only a total of 4 Earth masses. If the disk were only several times more massive, however, the non-linear dependence between initial and final dust masses would imply that sufficient mass for the cores would remain. We note that the formation of planetesimals in our model depends on the loss of most of the disk's gas envelope, after which there would be insufficient material from which to form the giant planets' atmospheres; therefore, if giant planets form near OB associations, they may have formed by more rapid methods (*e.g.* Boss 2003; Mayer et al. 2004).

Our model may underestimate the amount of solid material left in the disk, for two reasons. First, as grains continue to settle out, the dust:gas ratio in the outer shells where photo-evaporation occurs will decrease, causing a corresponding decrease in the amount of dust entrained. Because N_D is considered a constant in our model, we do not account for this decrease in the fractional dust loss rate. Second, our dust entrainment criterion has no grain size dependence. In reality, as grains grow they will become more difficult to entrain, and our method will overestimate their loss rate. In both cases, more detailed modeling of the gas-grain interaction is necessary; we estimate that after these factors are included, the disks may retain up to several times more material than indicated here. A future paper will present a more complete model of grain growth and entrainment. Additional work remains to be done to examine the stability and evolution of volatiles in these systems.

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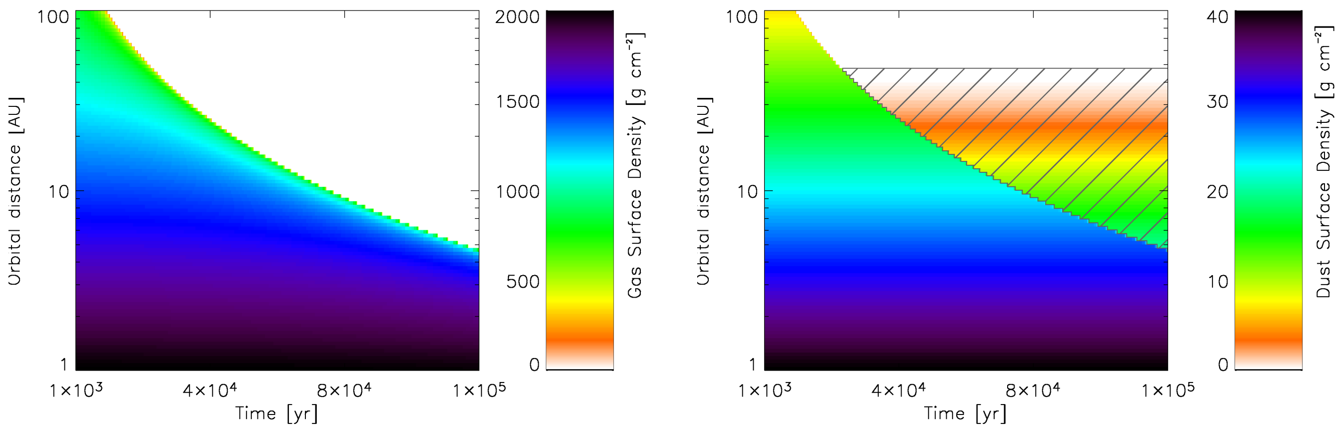

Fig. 1.— Evolution of our model circumstellar disk. Before the model begins, dust grains have grown and settled toward the midplane via Sekiya's vertical distributions. Photo-evaporation preferentially removes gas, increasing the dust:gas surface density ratio until the dust reaches a critical level for gravitational instability (hatched region, right).