

CAN PHOTOEVAPORATION TRIGGER PLANETESIMAL FORMATION?

HENRY B. THROOP

Department of Space Studies, Southwest Research Institute, Suite 400, 1050 Walnut Street, Boulder, CO 80302; throop@boulder.swri.edu

AND

JOHN BALLY

Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389

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ABSTRACT

We propose that UV radiation can stimulate the formation of planetesimals in externally illuminated protoplanetary disks. We present a numerical model of disk evolution including vertical sedimentation and photoevaporation by an external O or B star. As solid material grows and settles toward the disk midplane, the outer layers of the disk become dust-depleted. When such a disk is exposed to UV radiation, heating drives photoevaporative mass loss from its surface, generating a dust-depleted outflow. The dust-to-gas surface density ratio in the disk interior grows until dust in the disk midplane becomes gravitationally unstable. Thus, UV radiation fields may induce the rapid formation of planetesimals in disks where sedimentation has occurred.

Subject headings: planetary systems: formation — planetary systems: protoplanetary disks — solar system: formation

1. INTRODUCTION

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 photoevaporate the outer parts of circumstellar disks surrounding low-mass stars on 10^5 – 10^6 yr time-scales. Several dozen disks with diameters from 100 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 2–10 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 that are not directly seen in images either are too small, are lost in the glare of their central stars, or are hidden inside externally ionized cocoons (“proplyds”) produced by their own photoevaporation. About half of these disks are being photoevaporated by 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} to $10^{-6} M_{\odot} \text{ yr}^{-1}$ (Henney & O’Dell 1999), implying the loss of a disk within 10^4 – 10^6 yr. 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 photoevaporating disk and to examine the effects of sedimentation toward 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 nongravitational sticking in collisions (see, e.g., Chokshi et al. 1993), 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, which did not include vertical sedimentation or gravitational instability (Throop 2000; throop et al. 2001).

2. DISK MODEL

We have developed a numerical model that tracks the state of the disk’s gas and dust components as they undergo vertical sedimentation and external photoevaporation. We consider the effects of UV-induced photoevaporation 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 that are effectively shielded from self-irradiation.

Most disks around low-mass stars in OB associations formed well before photoevaporation began. Low-mass stars in Orion have ages of 10^5 – 10^6 yr (Hillenbrand 1997), while most appear to have been photoevaporating for only a few tens of thousands of years (Bally et al. 2000). Therefore, disks can evolve quiescently as grains grow and settle for up to about 10^6 yr, after which photoevaporation begins.

Initial disk structure.—The initial surface density follows the model of Hayashi (1981). Surface densities for the gas and dust as a function of distance r are set by

$$\Sigma_d = 30.1 \left(\frac{r}{1 \text{ AU}} \right)^{-k} \text{ g cm}^{-2}, \quad \Sigma_g = 1700 \left(\frac{r}{1 \text{ AU}} \right)^{-k} \text{ g cm}^{-2}, \quad (1)$$

implying a dust-to-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 half of this between 1 and 30 AU. In the vertical direction z , we use the Hayashi (1981) pressure-balance scale height $H = 7.1 \times 10^{11} [r/(1 \text{ AU})]^{-5/4}$ cm and calculate the gas density,

$$\rho_g(r, z) = \frac{\Sigma_g(r)}{2H} e^{-(z/H)^2} \text{ g cm}^{-3}, \quad (2)$$

where the factor of 2 accounts for the disk’s top and bottom sides. The central star has $1 M_{\odot}$.

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 by means of collisions to sizes of centimeters or beyond and sedimented to the midplane within a few times 10^4 – 10^5 yr. Weidenschilling (1997) found that by 7×10^4 yr, typical bodies at 30 AU had grown to meter sizes and settled to the midplane. Mizuno et al. (1988) found that typical grains at 40 AU grew to nearly centimeter sizes after 2400 yr, and Throop (2000) found that grains grew to centimeter sizes at 100 AU within 10^5 yr. *HST* observations directly support grain growth, even at the 600 AU outer edge of Orion’s largest known disk (Throop et al. 2001). Assuming a settling time

$$t_s \approx 10^6 \left(\frac{r}{1 \mu\text{m}} \right)^{-1} \text{ yr} \quad (3)$$

(e.g., Youdin & Shu 2002), a typical disk will easily be settled to beyond 100 AU in the 10^6 yr for which it can evolve before the onset of photoevaporation.

Vertical structure.—Local turbulence will prevent grains from settling to an infinitely thin plane. The equilibrium vertical distribution of dust in a protoplanetary disk has been studied by Sekiya (1998). In Sekiya’s model, the density is determined by an equilibrium between grain settling and grain lofting by means of the Kelvin-Helmholtz “sandstorm” instability. 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-to-gas surface density of ~ 2 – 10 (varying with r) was sufficient to reach this instability, and it could be caused by either 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 magnetohydrodynamic 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 midplane is expected to be suppressed compared with 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.

Observations provide indirect evidence that the Orion disks have settled. Johnstone et al. (1998) estimate from model fits that the disks’ outer shells are characterized by a UV penetration depth $N_D = 3 \times 10^{21} \text{ cm}^{-2}$ —that is, the outer shell is depleted in dust by at least a factor of 3 from the classical N_D . This would be expected in a disk in which solids had partially sedimented to the midplane.

Photoevaporation.—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). Far-UV radiation (FUV; $912 \text{ \AA} < \lambda < 2000 \text{ \AA}$) produces a warm 10^3 K neutral hydrogen outflow for radii $r_1 > GM/2c_1^2$, where $c_1 \sim 3 \text{ km s}^{-1}$ is the sound speed and the factor of 2 roughly accounts for the effects of pressure gradients within the outflow. For a $1 M_\odot$ star, $r_1 \sim 50 \text{ AU}$. For most disks, the resulting mass loss prevents ionizing extreme-UV radiation (EUV; $\lambda < 912 \text{ \AA}$) from reaching the disk surface. But, as a disk loses mass and shrinks to a size less than r_1 , FUV-induced mass loss declines and stops entirely. The ionizing EUV radiation can then reach the disk surface, ionize its skin, and raise its sound speed to $c_{\text{II}} \sim 10 \text{ km s}^{-1}$. Mass loss resumes in the form of a fully ionized wind until a radius of about $r_{\text{II}} \sim GM/2c_{\text{II}}^2 \sim 5 \text{ AU}$.

We incorporate the mass-loss rates of Johnstone et al. (1998) from their equations (5) and (23). We assume an outflow wind speed $v_0 = 3 \text{ km s}^{-1}$ and a UV penetration depth $N_D = 3 \times 10^{21} \text{ cm}^{-2}$ (i.e., their $\epsilon = 3$). We assume that small, micron-sized, dust grains produced as collisional by-products 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 $d = 0.1 \text{ pc}$, roughly corresponding to Orion’s 182–413 (*HST* 10) disk.

Following Johnstone et al. (1998), we assume that the mass-loss rate per area is constant across the disk. 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 resettles vertically on a timescale faster than the photoevaporation 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

$$\Sigma(r)/\dot{\Sigma} > t_s(a(r)) \quad (4)$$

and

$$\Sigma(r)/\dot{\Sigma} > H(r)/v_0. \quad (5)$$

Using typical grain sizes $a(r)$ due to coagulative growth and settling times t_s (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 (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 is therefore

$$\rho_{\text{de}} = \min [\rho_d(r, z), \rho_g(r, z)]. \quad (6)$$

In most cases, these densities are equal near roughly $H/100$, causing a preferential removal of gas above this location.

Model structure.—Our numerical model uses a 100×100 two-dimensional 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 we assume azimuthal symmetry. The model uses a self-adjusting variable time step; typical steps are 10^3 yr at the outer edge and 10 yr at the inner. The time steps chosen

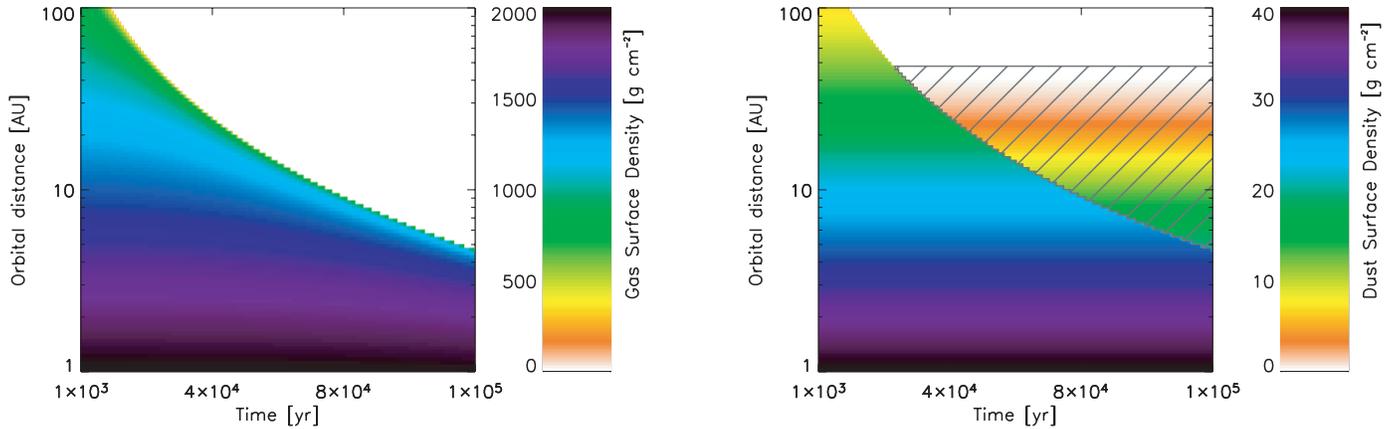


FIG. 1.—Evolution of our model circumstellar disk of mass $0.02 M_{\odot}$. Before the model begins, dust grains have grown and settled toward the midplane by means of Sekiya’s vertical distributions. Photoevaporation fully removes gas inward of 5 AU (*left*), while leaving substantial amounts of dust in this same region (*right*). The dust-to-gas surface density ratio through much of this region increases to a level where the dust is unstable against gravitational collapse (*hatched region, right*).

are more than sufficient to ensure numerical convergence. At each time step, photoevaporation 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 $r_d \leq r_{\text{II}}$, stopping all photoevaporation.

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, or 3% of its original dust mass. This dust has condensed to the midplane and is not entrained in the photoevaporative outflow. It meets the instability criteria of Youdin & Shu (2002), indicating that kilometer-scale planetesimals could spontaneously form. 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 photoevaporation 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 3 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, or 40% of the original dust mass. The entire remaining disk met the instability criteria. The highly nonlinear dependence between the disk mass and the fraction of dust retained is due to the fact that nearly all the additional mass goes directly to the midplane. Initial results indicate that this trend continues with even higher dust masses.

4. DISCUSSION

If a disk has more than a few hundred thousand years to evolve before it is exposed to UV radiation, grains throughout the disk can grow sufficiently large to settle toward the disk

midplane. A gradient in the vertical distribution of the dust-to-gas ratio is established, and the disk surface layers become dust-depleted while the disk midplane becomes dust-enriched. Because photoevaporation 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 (centimeter to kilometer) 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 meters per second (see, 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-to-gas ratio—the inward radial drift of centimeter- 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 photoevaporation. 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. In addition, 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 form 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 by means of the method

described here, the initial disk mass must have been greater than $0.02 M_{\odot}$, 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 nonlinear dependence between initial and final dust masses would imply that sufficient mass for the cores would remain. 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). Partial retention of the gas envelope, enabling giant planet formation, could occur if photoevaporation ceases as a result of the short lifetimes of the illuminating stars, or if the gravitational radius r_{II} is moved outward from 5 AU.

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-to-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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