Evidence for Dust Grain Growth in Young Circumstellar Disks

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The agglomeration of interstellar dust grains within circumstellar disks orbiting extremely young stars represents the first stage of planet formation.[1] However, stars born in massive star-forming regions region such as the Orion Nebula are heated by intense UV radiation and the gas and dust in their disks can be lost in less than 100,000 years.[2] Planet formation may therefore be inhibited in such environments.[3] But, if agglomeration to meter-sized objects can occur prior to removal of the gas and small particles, planets may still eventually form from such disks. Here we provide observational evidence that centimeter-sized particles may exist around the young stars in the Orion Nebula. Furthermore, our models of circumstellar grain growth in photo-ablating disks demonstrate that these particles can grow to meter sizes on timescales shorter than the time in which disks evaporate. If planetary systems eventually form from

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the Orion Nebula disks, they may be dominated by rocky Earth-like planets. Cometary belts and giant planets such Jupiter may not exist in such systems unless they can form rapidly from the disks prior to gas removal.

The Hubble Space Telescope (HST) has found evidence for circumstellar disks around $\sim$ 150 stars embedded in the Orion Nebula.[4–10] These observations cover the wavelength range from λ = 233 nm to 2,220 nm with angular resolutions of about 0.07" (30 astronomical units, or AU, at a distance of 450 pc) and show that approximately two-thirds of the disks are surrounded by ionized skins photo-evaporated from disk surfaces by the nearby massive and luminous Trapezium stars. The existence of such disks was originally inferred from radio observations of ionized regions surrounding young stars in Orion.[11]

The disks are seen in silhouette against the bright emission from the Orion Nebula. The physical properties of their particulate matter can be probed by the wavelength-dependent attenuation of light that filters through their translucent outer edges. Normal sub-μm sized interstellar gains selectively scatter shorter wavelength light more efficiently than longer wavelengths. If they contain predominantly small grains, the translucent outer edges of circumstellar disks will be relatively more transparent and the apparent disk sizes will decrease with increasing wavelength. If the grains are larger than the observing wavelength, the apparent disk size will be independent of wavelength.

The largest disk in Orion, 114-426 is seen in silhouette against emission lines

in the nebula (Figures 1, 2, 3). It has an extended low-optical-depth edge at its eastern ansa with an approximate size 200 × 200 AU whose properties can be probed by the attenuation of bright background lines such as the 1,870 nm the Paschen α and 656 nm Hα lines. We convolved the Hα image with a synthetic TinyTIM Paschen α HST point spread function (PSF), and the Paschen α image with an Hα PSF so that the images have identical spatial resolutions. One-dimensional slices through the disk's midplane show that the extinction at 1,870 nm is only 15% lower than the extinction measured at 656 nm. The disk reddens background light much less than expected for normal interstellar material.[12] *The dust in this disk is achromatic to a level of* $\sim$ 15% *from 656 nm to 1,870 nm.* If the dust in 114-426 were composed of standard interstellar particles with typical radii of 100 nm, the ansa's optical depth would be a factor of ten lower at Paschen α than at Hα. The observations imply that most of the extinction is produced by particles larger than the wavelength. Assuming the particles to be silicate-ice Mie scatterers, the disk's lack of color requires these particles to be larger than 5 μm in radius, or at least 50 times larger than typical interstellar grains. Although previous observations of 114-426[9,13] indicated that the disk decreased in size by $\sim$ 20% with wavelength, this was likely due to the low signal-noise ratio obtained.[14] Because the translucent SW ansa was not detected, the earlier observation suggested a disk model with sharp edge truncation and small particles. In contrast to the disk's ansae, the disk's polar halo regions clearly decrease in size with wavelength, a result which is

consistent with a suspended population of relatively small particles above the disk's poles. These small particles have not yet settled to the disk midplane.

A second constraint on grain size comes from their millimeter-wavelength emission. Six Orion disks, including 114-426, were observed at a wavelength of 1.3 mm with the Owens Valley Radio Observatory millimeter interferometer. None were detected above of 21 mJy, which implied[15] a mass limit $M_{\rm disk} < 0.020 M_\odot$ (where $1 M_\odot$ = one solar mass), *assumimg dust with an opacity of* 0.02 cm^2 g^{-1} *at a wavelength of 1.3 mm, a typical value for an interstellar gas-dust mixture.* But, models of young disks suggest that grains quickly grow and decrease their opacity. Grains larger than the wavelength 'hide' material since they radiate less flux per unit mass than interstellar dust, causing the disk mass to be underestimated by approximately the ratio of the particle radius to the wavelength. Our evolutionary modeling[14] predicts that particle sizes can grow significantly larger than the wavelength throughout the disk in less than 10^5 yrs. The opacity of the disk may be as low as 2 10^{-3} cm^2 g^{-1}, implying disk masses ten times greater than those previously indicated.

Photo-evaporation by the external ultraviolet radiation has been shown to be sufficient to erode the disks in the Orion core on 10^5 yr time-scales,[3,16] assuming the disks have the low mass limits indicated by earlier work. The radiation field of the Orion Nebula is dominated by the 10^5 solar luminosity Trapezium cluster of massive stars, whose most massive member is the O6 star θ^1 Ori C. Ultraviolet photons (91.2 nm $< \lambda <$ 200 nm) are absorbed by dust

in the disks and eject electrons that heat the surrounding gas to $T \sim 10^3$ K. The radiation-heated gas expands and a few-km/sec disk wind forms where the sound speed exceeds the gravitational escape speed from the disk. This neutral flow expands away from the disk and becomes fully ionized by the radiation field at a typical distance of several disk radii. This ionized gas is responsible for the bright regions surrounding many of Orion's disks, and allows the mass loss rates to be measured at about $\dot{M} = 4 \times 10^{-7} M_\odot$ yr^{-1}.[2,16] Although the outflow consists primarily of hydrogen gas, small dust grains far away from the central star will experience neutral-neutral drag forces greater than the force of gravity, and will be entrained in the escaping gas. At 500 AU, grains up to 1 mm in radius can be lost from the disk in this manner. Entrained dust in the photo-ablation flow has been observed in several HST images.[10]

While dust and gas is lost from the disk surface, the disk interior undergoes turbulent convection as heat from gravitational collapse and keplerian shear escapes from the midplane to the surface and is radiated away. Within the convective eddies dust grains collide and stick. Growth is fastest near the inner edge, where the disk temperature and density is highest and the overturn time is short.

Our model includes (a) grain growth due to turbulent convection;[17] (b) photo-evaporation of gas and entrained dust in an FUV-induced outflow;[3,16] and (c) photosputtering of ice particles.[18] The disk is vertically and azimuthally symmetric,[19] and the abundance and size distribution of ice, silicate, and gas

at each time-step is tracked. Sticky collisions between particles result in a new particle with the same density as the parent particles. The gas-to-dust mass ratio is initially 100, with a 2:1 silicate:ice mixture.[20] The initial grain population is assumed to have the size distribution of interstellar dust. The model begins when the ionizing source turns on, and is stopped after convection and photo-evaporation have ceased throughout the entire disk, typically after a few $\times$ 10^5 yr. We assume the disk to be convective throughout when the disk is opaque to its own thermal radiation.[17] After convection stops, grain growth becomes dominated by other processes such as settling and gravitational interactions, which we do not model.

Results for one typical run are shown in Figure 4. Figure 4a shows the evolution of grain sizes within the disk. Toward the disk center, grain growth is rapid and photo-evaporation does not remove large particles. Typical particle sizes after 10^5 yr are r = 1 m at 10 AU and r = 1 mm at 500 AU. Figure 4b plots the evolution of the edge-on optical depth. Grains at the inner disk edge agglomerate fastest, quickly reducing their optical depth and inhibiting further convection. Particles at the outer edge grow slowly and are readily entrained by the outflow and quickly lost from the disk. At the transition between these regimes an edge populated by large particles is left behind. In model disks, all ices and gas are lost within 10^6 yr due to photosputtering and photo-evaporation. Only silicates that grow large enough to resist photo-evaporative entrainment are retained. Therefore, only rocky planets can form

from the remaining debris. In the standard model of planet formation, giant planets such as Jupiter form by accreting hydrogen and helium rich gas from the disk onto a large rocky core. However, in Orion-like environments, there may not be sufficient time to grow the requisite cores prior to loss of the gas. Thus, to retain volatiles, Jovian planets can only form in these systems prior to disk photo-evaporation. The only viable mechanism for such rapid formation is gravitational collapse, which has been modeled to occur in massive disks ($M_{disk} > 0.13 M_*$) on 10^3 year timescales.[21] Furthermore, if icy bodies such as Kuiper belt objects, outer planet cores, and comets are to form, they must do so prior to disk loss.

Our observational results complement several previous studies of particle sizes in young disks. Near-infrared observations of disks orbiting other young stars such as GM Aurigae[22] and HR4796A[23] provide some evidence for particles larger than several microns based on the spectrum of light reflected from their central stars. Sub-millimeter observations of several disks in NGC2024[24] and Taurus[25] reveal relatively flat spectral indices perhaps indicating large grains. However, there are other systems that show no evidence for grain growth. Near-IR observations of the disk in HH30[26] show normal dust opacities from small grains, and sub-mm observations of the HL Tau disk[1] are inconclusive at best. Grain growth in disks appear to vary environmentally and temporally, beginning as early as the collapse phase in some systems,[27] while other systems show no evidence for growth even after several Myr.

Observations indicate that most stars in our galaxy form in dense but transient groups ('OB associations') which contain young, luminous O- and B-type stars that emit large amounts of ultraviolet radiation.[28] For example, the Orion OB1 association, may have formed $\sim 20{,}000$ low-mass stars in the past 12 Myr. Although smaller dark clouds like those in Taurus-Auriga are more common, they contain a smaller fraction of the Galaxy's molecular gas mass and therefore form far fewer stars. Such dark clouds are expected to have produced only a few thousand stars within 500 pc of the Sun in the last 12 Myr. Thus, the large majority of stars form in giant regions like the Orion molecular cloud.[29] Within the OB associations, the majority of stars form in clusters within a few parsecs of massive stars. Once exposed to UV radiation, disks are destroyed on timescales of 10^5 years, significantly faster than $10^6 - 10^7$ yr times[30] believed to be required for the formation of the Jovian planets. If most stars form in regions like the Orion Nebula, planetary formation models must be revised to consider the destructive effects of these environments.

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Figure 1: Images of the 114-426 disk in two wavelengths, in silhouette against the Orion Nebula. The images have been rotated and scaled to the same size. The left image is taken with the HST Wide Field/Planetary Camera-2 at a pixel size of 0.0225" with filter F656N (Hα, 656 nm) for 1600 s during program GO6603, while the right image is taken with the HST Near-Infrared Camera and Multi-Object Spectrograph at a pixel size of 0.0215" with filter F187N (Paschen α, 1870 nm) for 288 s during program GO7367. Both images were created from sub-pixel dithered observations at four pointings, and the pixel sizes of the instruments are double those indicated.

Figure 2: One-dimensional intensity slices through the 114-426 circumstellar disk in the Orion Nebula. The slices are taken along the disk's major axis and average together three adjacent pixel columns. Variations in the local background brightness are not sufficient to affect the slopes. The curves have been normalized to match the background flux at each ansa in both wavelengths, and have been convolved to the same resolution as described in the text. At both wavelengths, the disk's SW ansa is sharp-edged and well-matched by a sharp-edged disk convolved with both PSFs. In contrast, the disk's NE ansa is extended and translucent. Slices through the disk clearly indicate that this region has similar optical depth profiles at both wavelengths, a result that cannot be explained with extinction caused by standard interstellar dust particles of radius 0.1 μm.

Figure 3: Wavelength dependence of light transmission through several

populations of dust particles. The data points for the ansa of Orion 114-426 are marked, and show that the particles are more grey than those seen elsewhere. The three curves show extinction laws for diffuse material observed towards three lines of sight.[31] A indicates the extinction in magnitudes at wavelength λ. The standard color ratio $R_{\rm V}$ is defined as $A_{\rm V}/(A_{\rm V} - A_{\rm B}$. Other single letters indicate the standard photometric bands.

Figure 4: Evolutionary models showing grain growth in the presence of grain loss processes. a) Typical particle size, based on cross-section per bin. Particles grow quickly at the inner edge due to higher collision velocities, densities, and slower loss processes. Growth is terminated when infrared optical depth drops below unity, inhibiting convection. b) Grains at the outer edge are rapidly blown away, while grains at the inner disk grow rapidly. This leaves behind a disk populated by large particles. Time-steps are spaced logarithmically. For this run, the following disk parameters are assumed, which correspond to the 114-426 disk at a time when it was closer to the Orion core, where the majority of disks are found: surface density[32] $\Sigma \sim R^{-3.5}$, vertical height $z = R/10$, sputtering rate $(dr/dt)_{\rm s} = 1$ μm yr^{-1}, sticking efficiency $\epsilon = 0.1$, outflow column density $n_0 = 3 \times 10^{22}$cm^{-2}, viscosity parameter $\alpha = 10^{-2}$, outflow temperature $T_{\rm o} = 1000K$, central star mass $M_{\rm s} = 1M_{\odot}$, disk inner and outer radii $R = [10$ AU$, 500$ AU$]$, UV source distance $d = 0.1$ pc, and grain density $\rho = 1$g cm^{-3}. The model parameters used here emphasize rapid photoevaporation; similar effects are seen for a variety of input conditions, with a

resultant change in the location of the outer edge.

Figure 1:

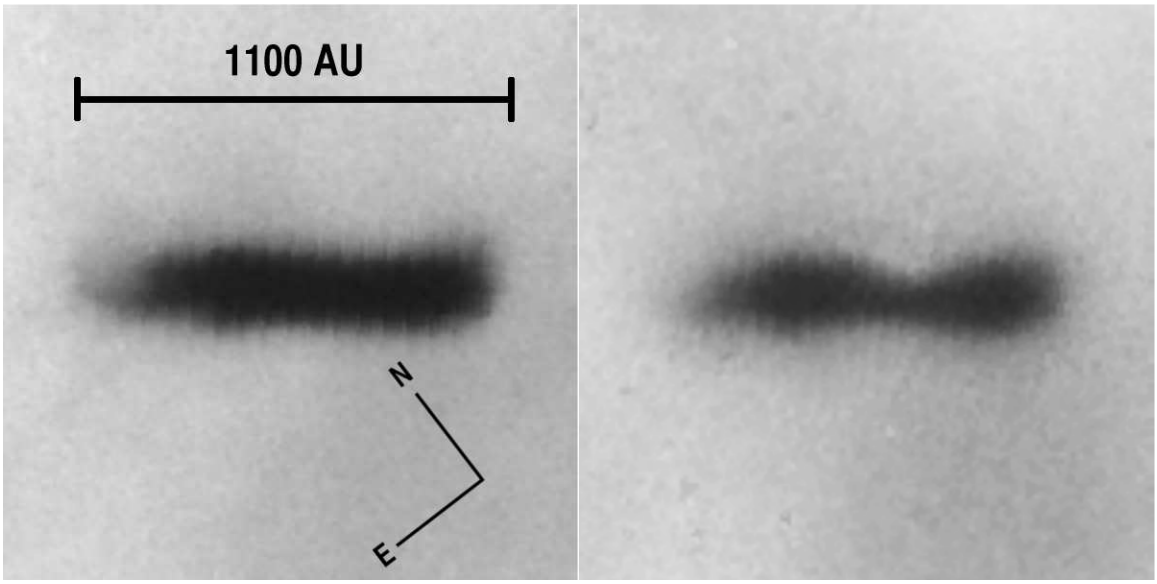


Figure 2:

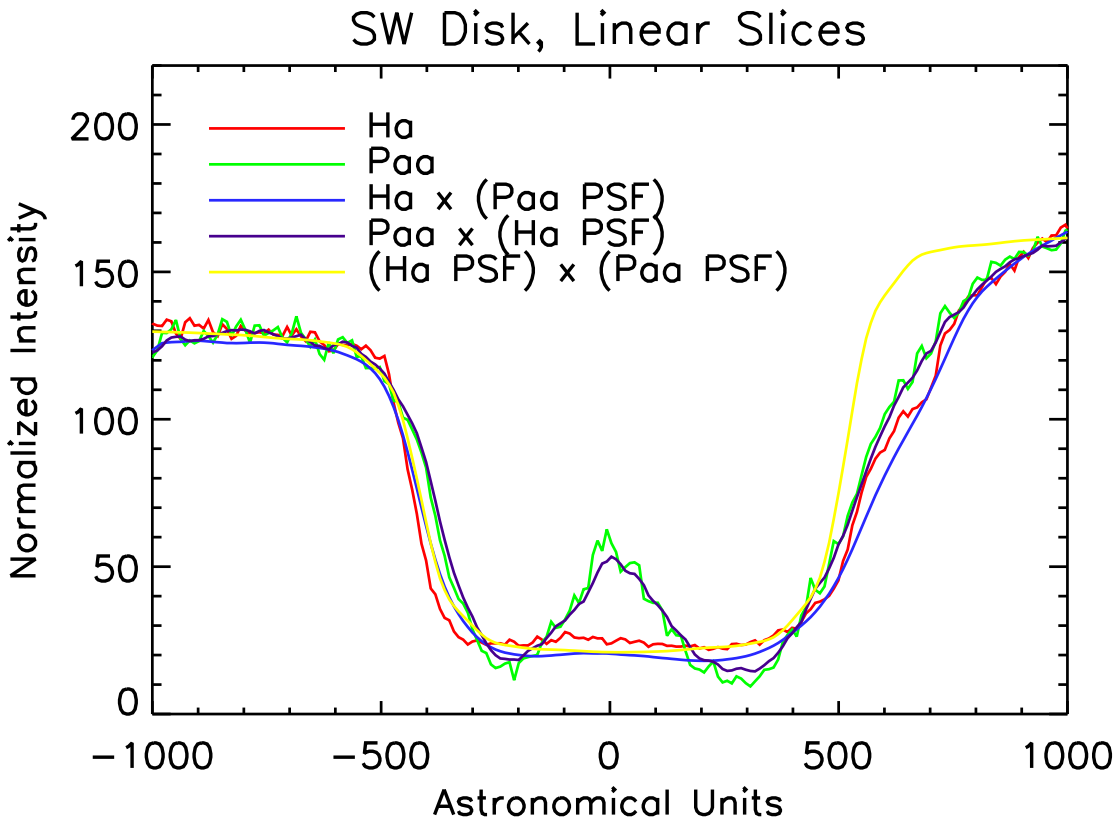

SW Disk, Linear Slices
Ha
Paa
Ha x (Paa PSF)
Paa x (Ha PSF)
(Ha PSF) x (Paa PSF)
Normalized Intensity
200
150
100
50
0
−1000
−500
0
500
1000
Astronomical Units

Figure 3:

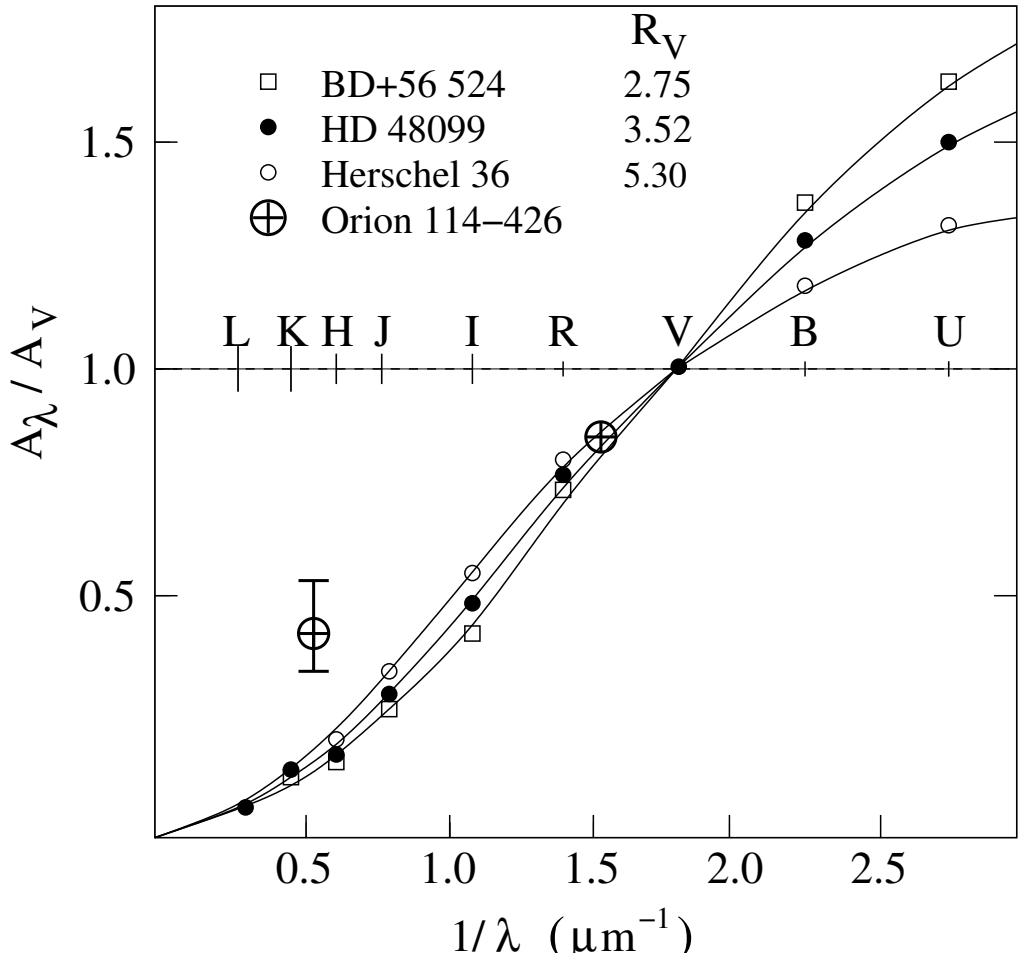
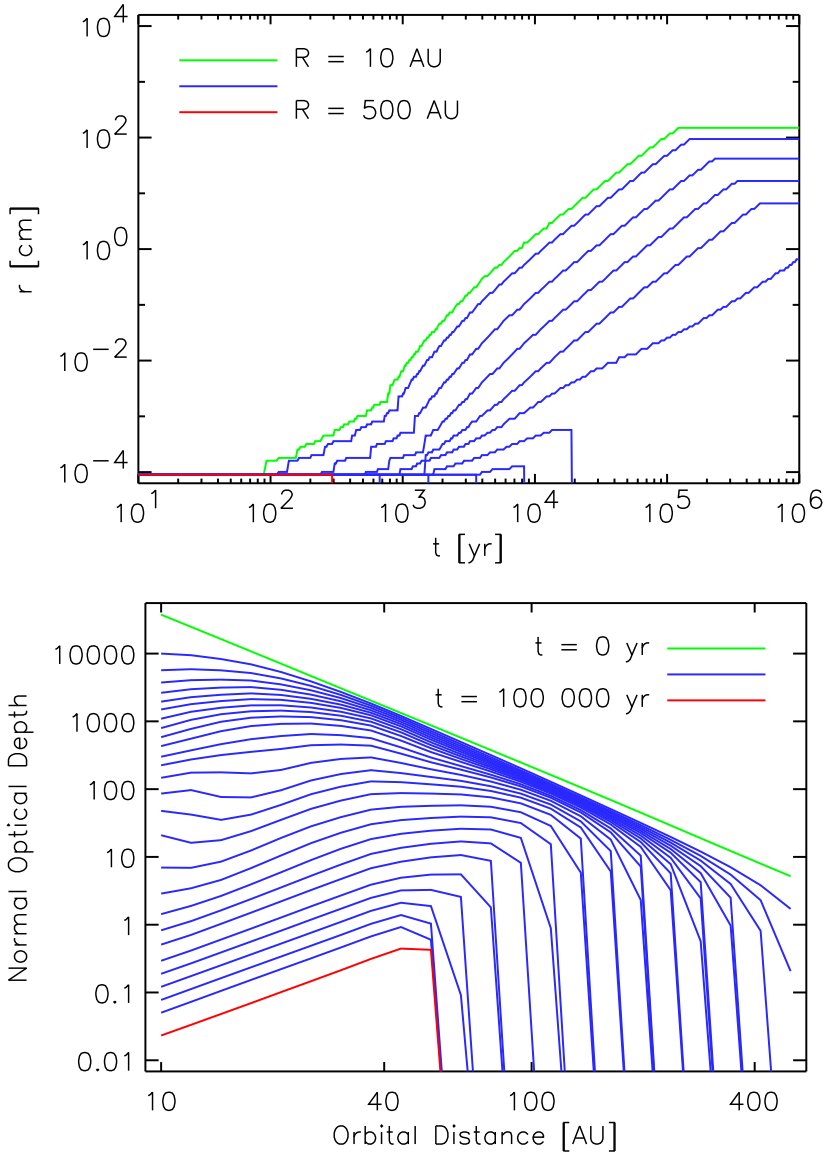

R_V
BD+56 524 2.75
HD 48099 3.52
Herschel 36 5.30
Orion 114–426
L K H J I R V B U
Aλ / AV
1.5
1.0
0.5
0.5 1.0 1.5 2.0 2.5
1/λ (μm^-1)

Figure :5


R = 10 AU
R = 500 AU
r [cm]
t [yr]
t = 0 yr
t = 100 000 yr
Normal Optical Depth
Orbital Distance [AU]