Photoevaporation of Viscous Protoplanetary Disks by EUV, FUV and X-rays

Uma Gorti[1,2] , Kees Dullemond[3] & David Hollenbach[1]

[1] SETI Institute, Mountain View CA **[2]** NASA Ames Research Center, Moffett Field, CA, **[3]**Max-Planck Institute, Heidelberg

email: Uma.Gorti-1@nasa.gov)

Abstract

We present simple 1-D models of viscously evolving protoplanetary disks that are being photoevaporated by the EUV, FUV and X-ray radiation from the central star. In our time evolutionary sequence, the disk accretion is initially high, and when the opacity in the accompanying wind becomes low enough, at $dM_{acc}/dt \sim< 4x10^{-7} M_o/yr$, FUV and X-rays begin to irradiate the disk. The surface is heated to temperatures ranging from a few 100K to a few 1000K, and the disk photoevaporates. As the disk mass and hence the accretion rate (for constant viscosity parameter α) declines, the wind mass loss rate declines, and EUV photons penetrate the disk wind and begin to heat the disk surface. EUV and X-rays are capable of creating gaps in the disk at ~1-3 AU and then erode the remaining outer disk. For values typical of a solar-mass star, an initially massive $0.1M_o$ disk is completely dispersed on a timescale of $3x10^6$ yrs.

We find that FUV and X-ray heating is responsible for removing the bulk of the disk mass, renders the disk optically thin and determines disk lifetimes. EUV and X-rays may affect the inner planet-forming regions of disks by creating gaps, as seen in transition disks.

Model Features

- 1-D model for viscous evolution (Lynden-Bell & Pringle 1974)
- Constant viscosity parameter α (=0.01)
- Constant EUV, X-ray luminosities
- Time-dependent FUV luminosity calculated from accretion rate added to a constant chromospheric component.
- 1+1D Dust Radiative Transfer (Dullemond, Dominik & Natta 2001)
- Gas temperature set equal to dust temperature at extinction to the star $A_v > 1$; Thermal balance at surface
- Separate gas and dust temperature calculation in flow regions
- Chemistry restricted to disk surface (No molecules)
- Thermal Balance - Self consistent vertical structure
  - *Heating:* Dust collisions, FUV, X-rays & EUV
  - *Cooling:* Dust collisions, OI, [NeI], [ArII], Lyα

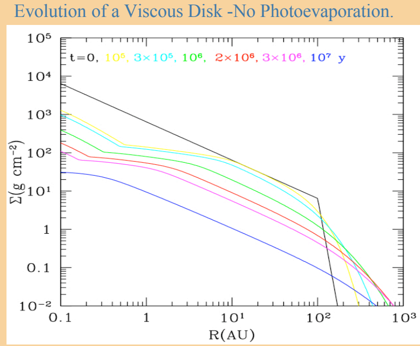
Model Parameters and Initial conditions

- $M_* = 1 M_o$, $R=2R_o$, T=4300K
- $L_{EUV} = 4x10^{30}$ erg s^{-1} ($\Phi_{EUV}=6x10^{41}$ s^{-1})
- $L_X = 2.0x10^{30}$ erg s^{-1}; Chromospheric $L_{FUV}= 2x10^{30}$ erg s^{-1}
- Accretion Luminosity = $0.8\ G\ M_*\ dM_{acc}/dt\ /R_*$
- FUV component of L_{FUV} calculated assuming blackbody emission from shock at 9000K, in the range 912-2000Å (Calvet & Gullbring 1998)

- Initial disk mass = $0.1M_o$
- At t=0; Disk extends from 0.1-200AU , $\Sigma(r) \sim r^{-1}$
- Dust grain size: 50Å < a < 200μm

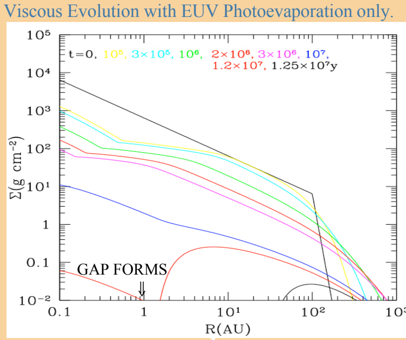
- Disk wind mass loss rate assumed to be 0.1 times the accretion rate
- Minimum accretion rate for penetration of disk wind by
  - FUV & X-rays: $dM_{acc}/dt< 4x10^{-7} M_o\ yr^{-1}$
  - EUV: $dM_{acc}/dt < 10^{-9}\ M_o\ yr^{-1}$

Evolution of a Viscous Disk -No Photoevaporation.



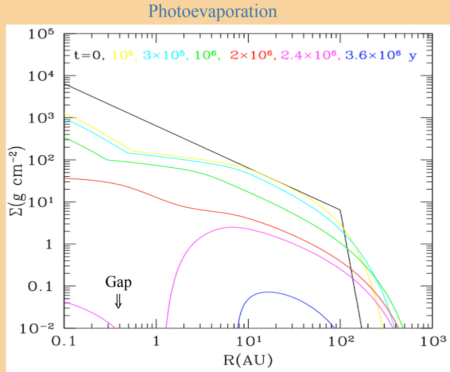
Disk mass steadily declines with time, expanding while approximately maintaining surface density $\Sigma \sim r^{-1}$.

Viscous Evolution with EUV Photoevaporation only.



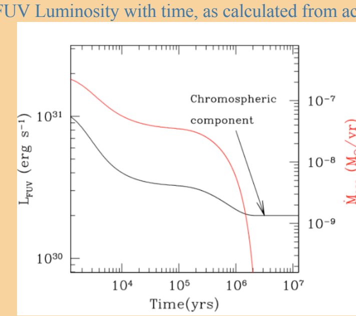
Disk evolves viscously until EUV irradiation. Gap forms in disk at a few AU at ~ $1.2x10^7$ yrs. Viscous draining rapidly removes mass interior to the gap forming a hole. Disk mass at this epoch is quite low, EUV subsequently removes outer disk in ~ few 10^5 yrs. Disk lifetime is ~ $1.25x10^7$ years.

Viscous Evolution with EUV, FUV and X-ray Photoevaporation

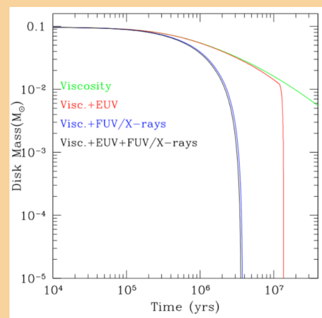


Disk surface density decreases with time rapidly due to FUV/X-ray photoevaporation. The gap is therefore created earlier in disk evolution at ~ $2x10^6$ years. Entire disk is dissipated on a timescale of few Myrs.

FUV Luminosity with time, as calculated from accretion rate



Disk mass with time for all the different models



Timescales for disk destruction by FUV and X-rays are a factor of ~3-4 **shorter** than for EUV alone. For EUV, FUV and X-ray photoevaporation, lifetimes are calculated to be ~$3.5x10^6$ years for a disk around a solar-type star. EUV may not affect disk mass removal, but may play an important role in creating gaps such as those seen in transition disks by Spitzer. X-rays may also create gaps at ~ a few AU, a result that needs further investigation. Such transition-type disks may be more massive, as X-rays create gaps at relatively earlier epochs in disk evolution.

Summary

- Disk lifetimes due to FUV/X-ray photoevaporation and viscous evolution are comparable to observed disk lifetimes of a few 10^6 yrs.
- EUV may be important later in the evolution of disks, when the disk mass has fallen below ~ $0.01M_o$, when a gap can be formed. Viscous draining then leads to the formation of a hole, which may explain the observed holes in some transition disks.
- X-rays may also create gaps at ~ 1 AU where gas is heated to 10^4K.

Caveats and Future work

- We assume photoevaporative flows that are launched subsonically from the base remain isothermal to the sonic point (Adams et al. 2004). This assumption needs to be confirmed by a detailed hydrodynamic solution that includes thermal balance of gas.
- We use a simple 1+1D model for the dust radiative transfer, 2D models are needed to investigate the effects of possible disk shadowing in a disk with an evolving surface density distribution.
- A more detailed chemical network may be needed for an exact calculation of the disk evolution, as the mass loss rates are very sensitive to the gas temperature and density.