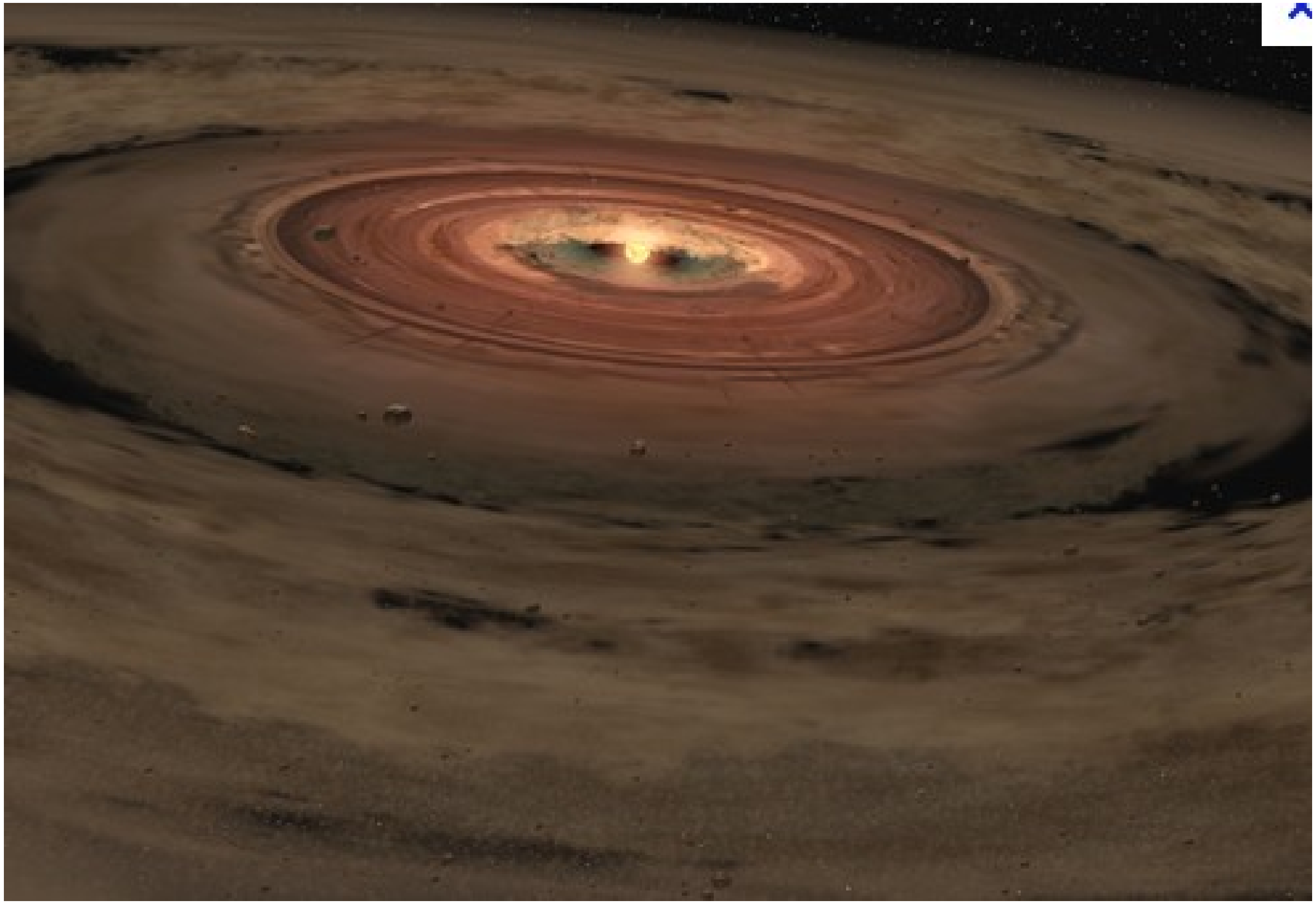
Disk clearing in low mass stars

Kedron Silsbee



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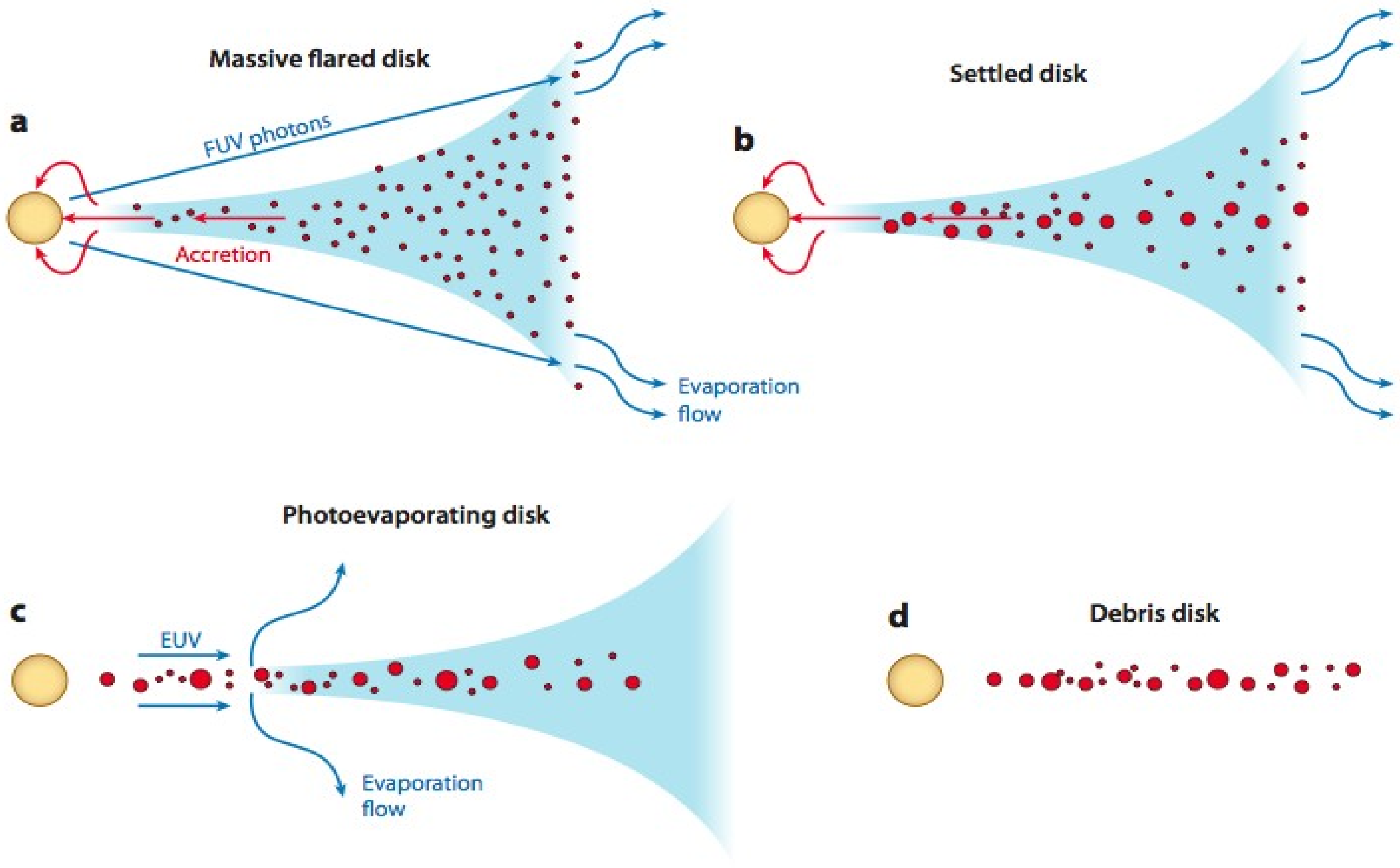
Outline

- Numbers / Observations
- Photoevaporation
    - theory, simulations
- Viscous draining
- 2 timescales
    - observational evidence
    - model



(from Williams and Cieza)

Numbers

- Disk lasts 5*10^6 to 10^7 years
- Disk evaporates in a few * 10^5 years
- Star mass < 1.5 solar mass
- Total disk mass ~ a few * 10^-2 * star mass
- Flared – i.e. $\rho(R, Z) = \frac{\Sigma(R)}{\sqrt{2\pi} H} \exp\left(-\frac{Z^2}{2H^2}\right)$ where H ~ r^1.4

Observations

- Emission

  -Reprocessed starlight from dust

  -Longer wavelength as one moves out from star

  -Therefore observation at a certain wavelength is (sort of) equivalent to observation at a certain radius

- Absorption

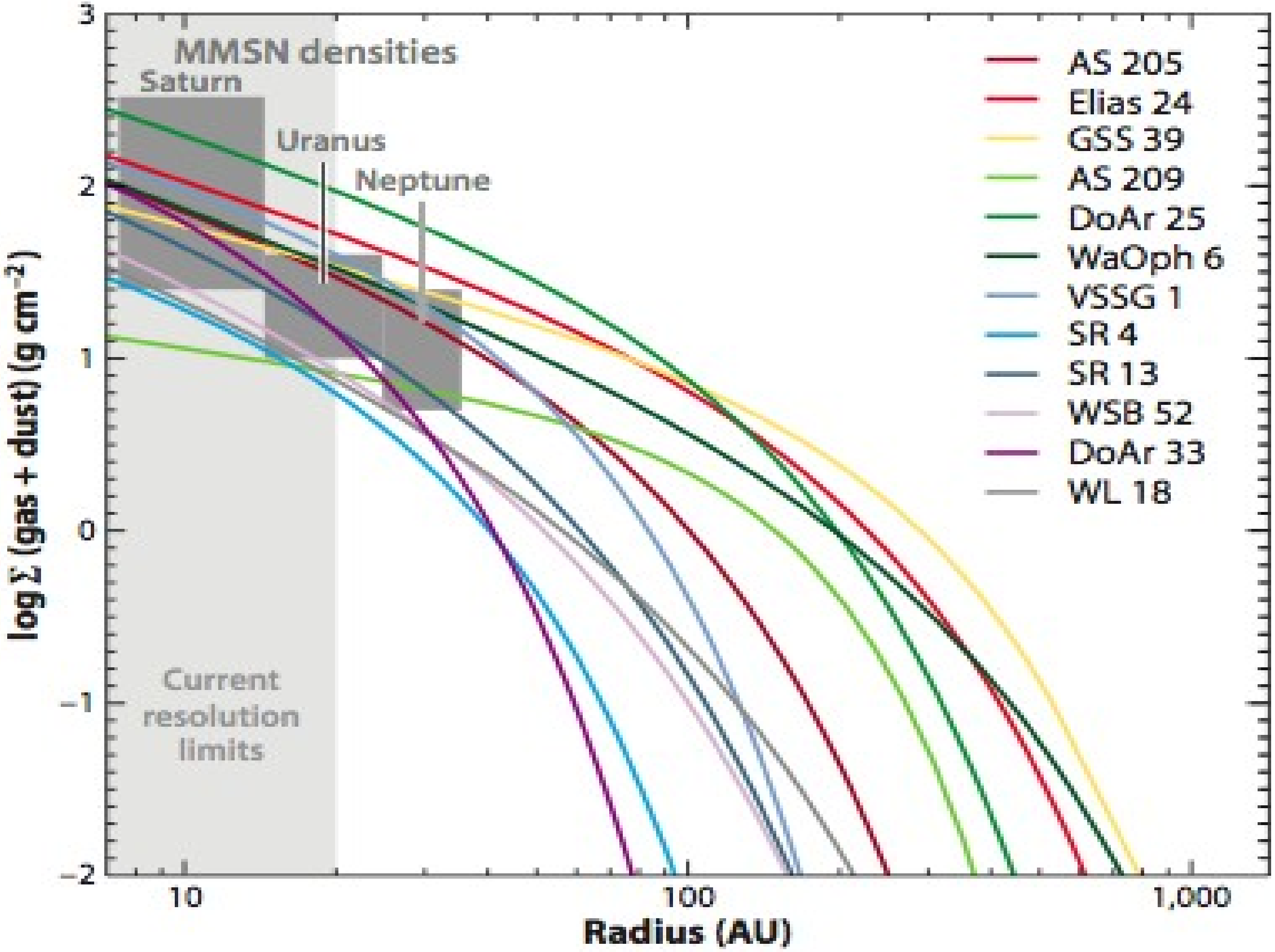
  Important for measuring disk radius if bright source behind disk, since outer parts cool and thin

Mass of disk as a function of radius

- M(r) = disk mass enclosed in radius r

$$M(r) = \int_{r_0}^{r} 2\pi r \Sigma(r) dr$$

- Note that we require that that majority of the mass is outside the radius at which the viscous timescale is short compared with the disk lifetime, else entire disk drains on viscous timescale for inner disk, since it is initially fed by the outer disk



(from Williams and Cieza)

Minimum Solar Mass Nebula

- Looking at composition of planets in our solar system, and comparing with expected abundances in the disk
- .01-.07 solar mass (since compositions uncertain)
- Minimum, since heavier elements were presumably blown away to some extent as well
- Other systems have larger planets, so larger minimum masses to their protostellar disks, assuming same composition

Considered, but disfavored ideas

- Planet formation
  - -why at all radii simultaneously?
  - -why simultaneously all grain sizes?
  - -our solar system - where is all the hydrogen?
- Close stellar encounters
  - -can't eliminate entire disk at once
  - -infrequent on such short length scales
- Magnetospheric models
  - -doesn't kill emission at all wavelengths simultaneously (Armitage et. al. 1999)

Photoevaporation

- Important distance for given T: $R > \frac{15}{T_4} * \frac{\mathrm{M}}{\mathrm{M_{sun}}}\mathrm{AU}$

    - radius where thermal speed of hydrogen equal to escape velocity

    - factor of 2 less for ionized hydrogen

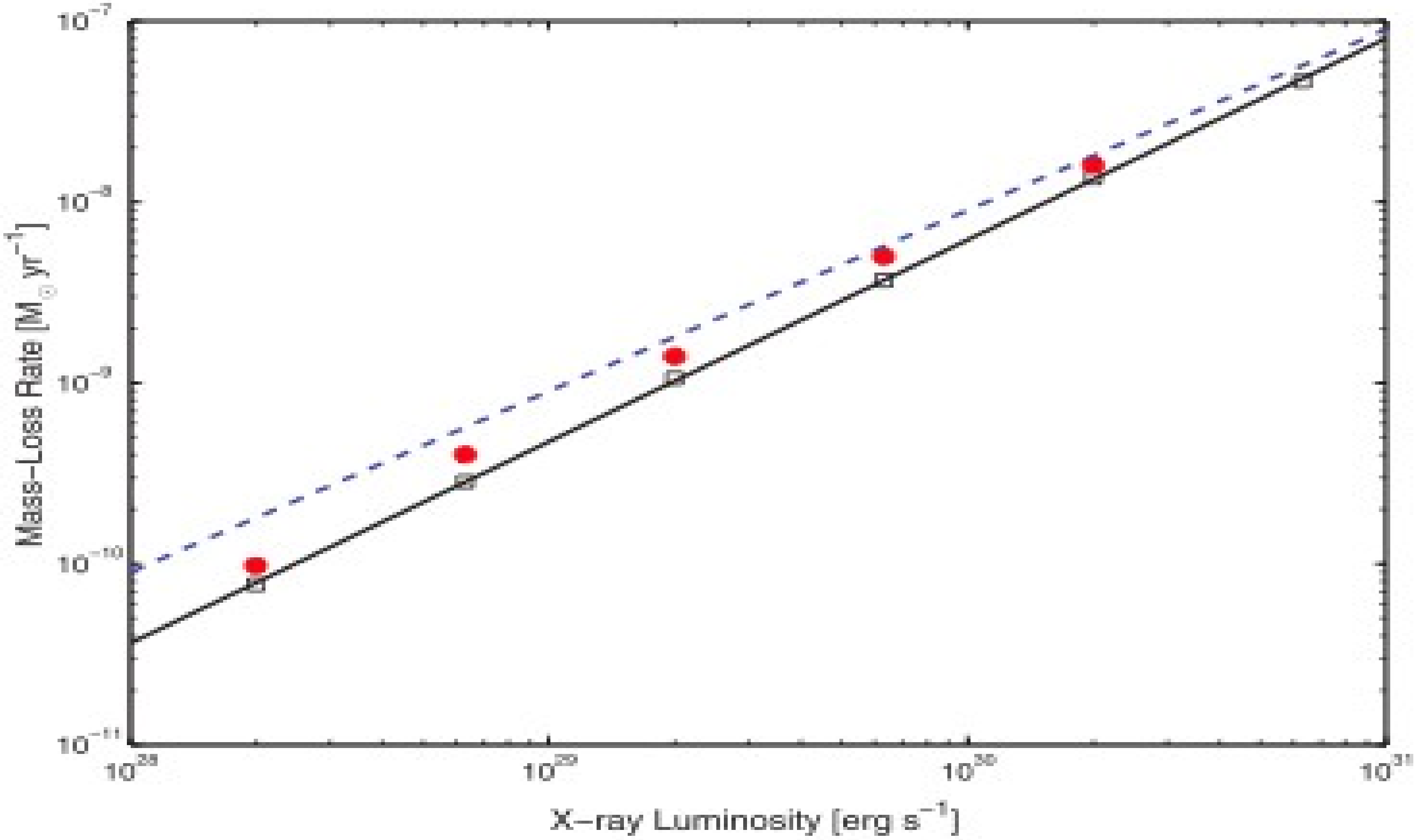
- High energy photons important because of large interaction cross-section

    - deposit their energy in concentrated region

More photoevaporation

- To order of magnitude, $\frac{d\Sigma}{dt} = \rho c_s$
- $n_s = \frac{L_X}{R^2}\left[f^{-1}\left(\frac{GM_*\mu m_h}{2k_B R}\right)\right]^{-1}$
- $c_s^2 = \frac{k_B f\left(L_X/n_s R^2\right)}{\mu m_h} = \frac{GM_*}{2R}.$
- dM/dt = $8 \times 10^{-9}\left(\frac{L_X}{1 \times 10^{30}\,\mathrm{erg\,s^{-1}}}\right) M_\odot\,\mathrm{yr}^{-1}$
- Good to the factor of 2 level
- To get better quantitative results, must consider radiative transfer and hydrodynamics
- subsonic (mach number ~.1-.2) flows can be initiated and then accelerated by pressure gradients
- Find mass loss rate scales with the square root of the radius to the inner disk edge

Importance of X-ray Luminosity



Owen, Clarke & Ercolano, 2012

energies

- “FUV”, “EUV”, X-ray
- EUV → “Extreme Ultraviolet”, which is ionizing radiation, heats everything to 10^4 K (since it heats to ionization, then penetrates further), only penetrates very narrowly
- FUV, X-ray, penetrate further, evaporate more gas.

  - timescale 10^2 times faster when FUV + X-rays included

What works where when

- Viscous accretion more effective close to sun

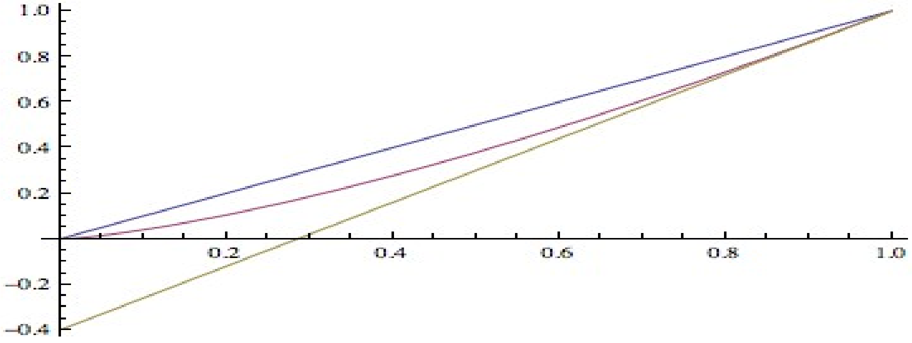
  - higher viscosity,

  - higher velocity gradient

- Photoevaporation more effective further out

  - less gravitational potential to overcome

  - not counting inner surface, actually more projected area since scale height ~ r^1.4, so using small angle approximations

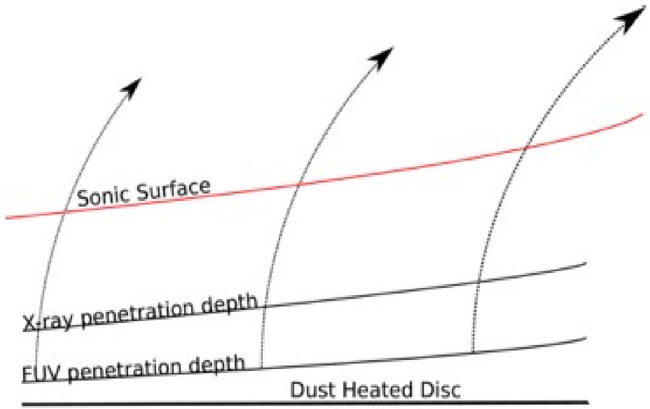


$$\theta = \frac{dh}{dr} - \frac{h}{r} \sim r^{.4}$$

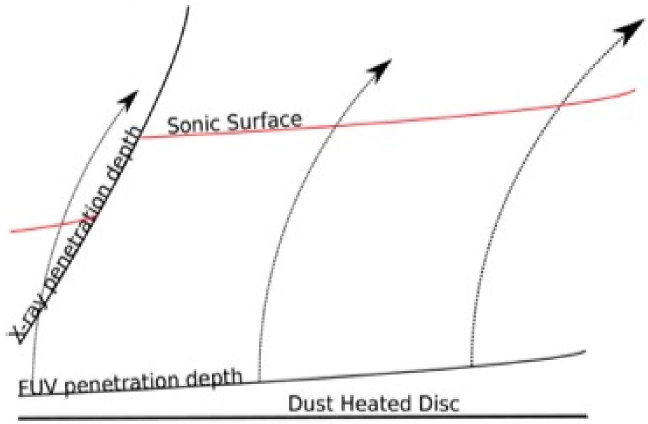
Sources of high energy photons

- low mass stars produce negligibly few FUV photons in photosphere
- One source is accreting material
- Not consistent with previously discussed model if this is the only source
- Apparently x-rays from magnetosphere important, at least in late stages of disk clearing

X-ray vs FUV dominated regimes



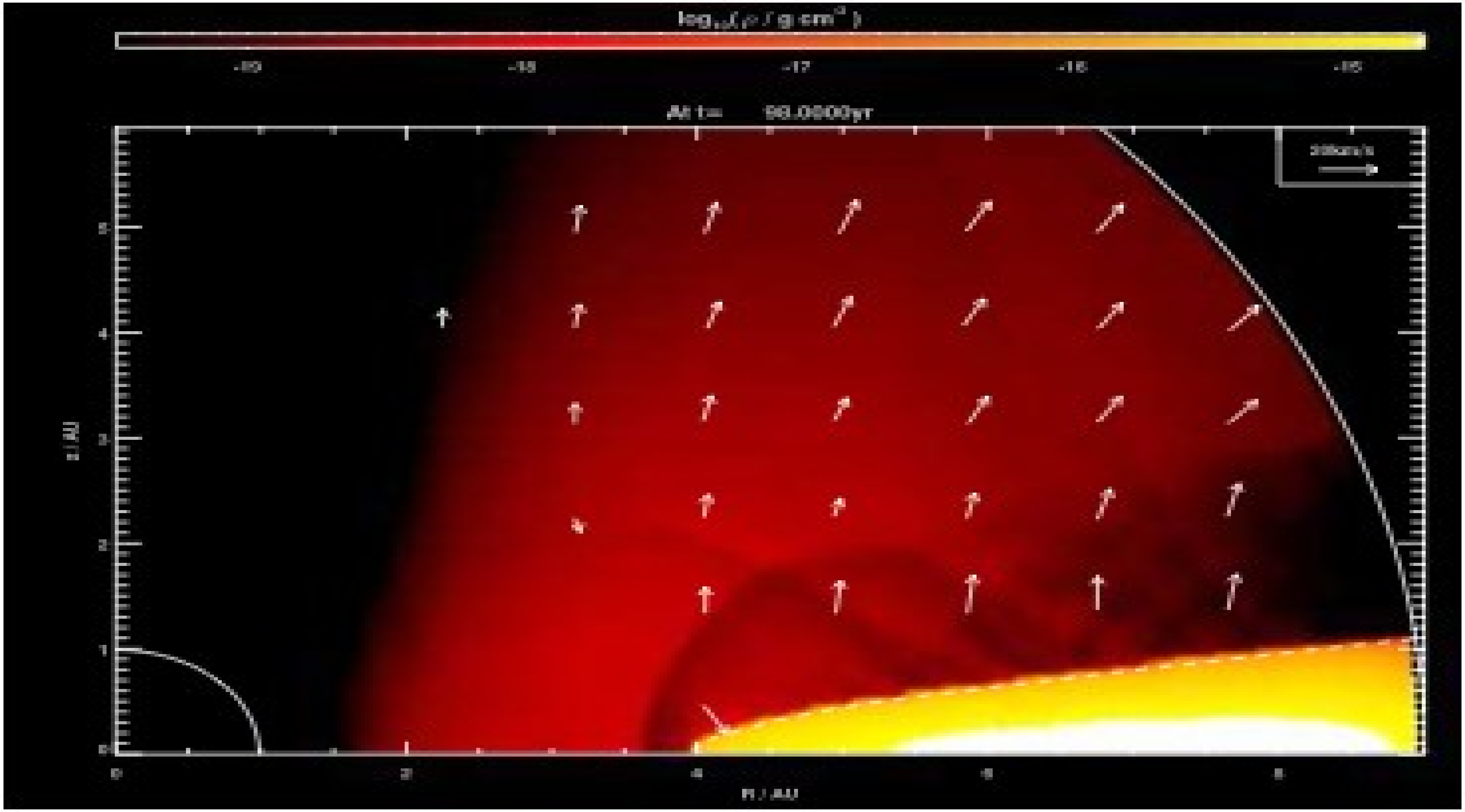
(a) X-ray dominated photoevaporation



(b) FUV dominated photoevaporation

Owen, Clarke & Ercolano, 2012

Gas Flow



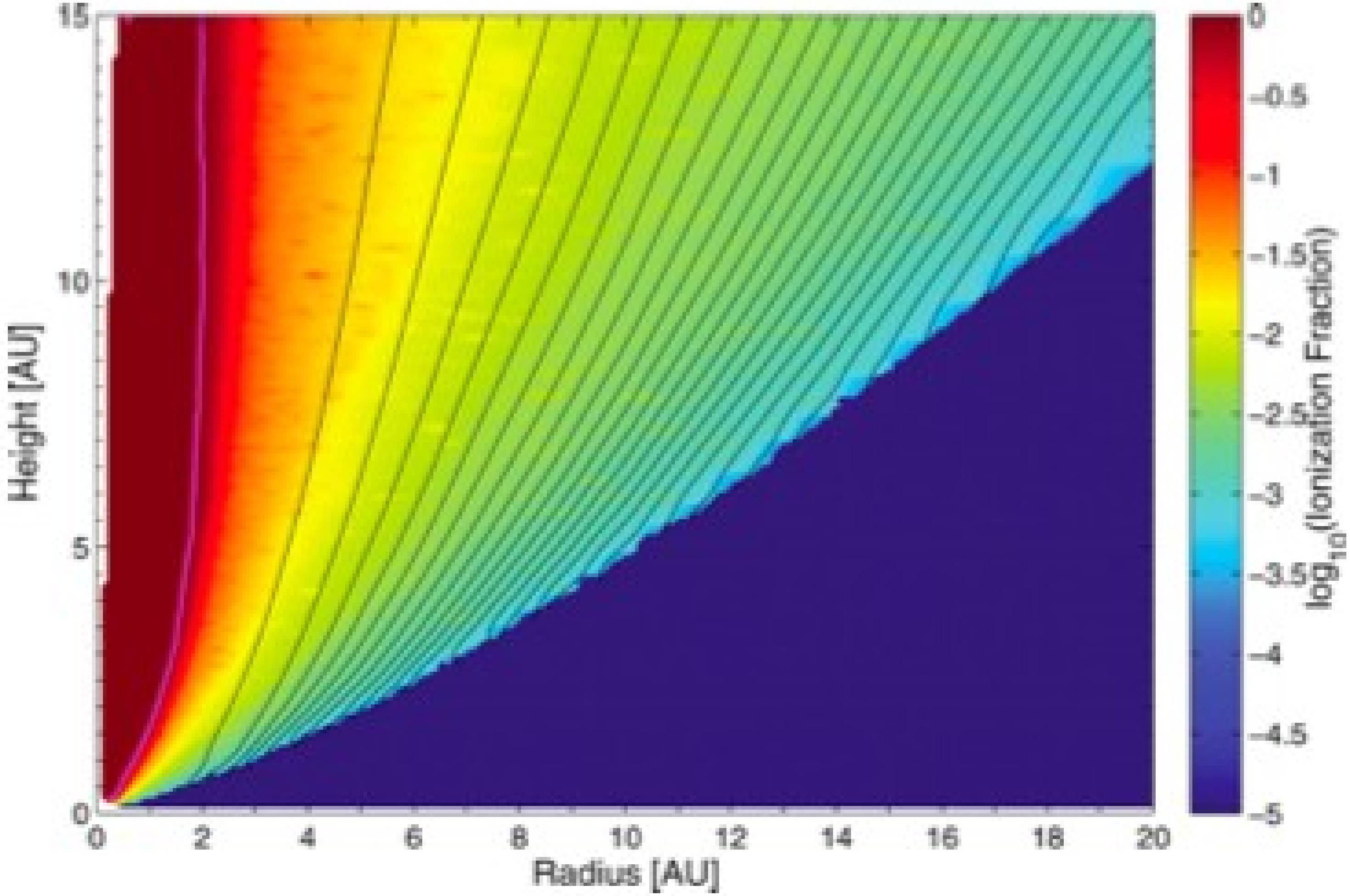
Alexander, Clarke & Pringle, 2006

Approximations

- Difficult to handle radiative transfer and hydrodynamics
- “OTS” approximation

  - recombination photons either assumed to be absorbed locally (if optically thick) or escape
- Dust opacity in inner disk ignored
- Assume all lateral motion of material in the boundary layer between ionized/neutral gas is neutral

Optically thick wind



Owen, Clarke & Ercolano, 2012

Viscous accretion

- Assume circular Keplerian orbits, dv/dr <0, so
  - -Angular momentum out
  - -Material in
- Sources of effective viscosity
  - - turbulent eddies
  - - gravitational torques
  - - hydromagnetic instabilitites

Two timescale model

- Two processes
    - Photoevaporation
    - Viscous draining
- Outer disk is eventually thinned so can't feed inner disk (i.e. gap develops)
- Inner disk drains on its viscous timescale
- Outer disk blown away by photoevaporation

What Happens to the dust?

- Small grains(<1 mm) blown out by the photoevaporative wind (do not have enough thermal energy to escape independently of gas)
- shorter scale-height than the gas, so grains which are large enough to move independently of the gas clump together in the middle, and form coplanar planets

Conclusions

- Unlike high mass stars, somewhat difficult to remove disk quickly
- Somewhat unusual system in that evaporative timescale factor of 10 shorter than lifetime
- Needs combination of viscous accretion and photoevaporation
- Models differ on the importance of various wavelength from UV to X rays in photoevaporation

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