Observational ISM and Star Formation

This Class (Lecture 15):
Nick Indriolo/Alfredo Zenteno

Next Class:
Brett Hayes & Duncan Christie

Music: *Sonne* – Rammstein

Outline

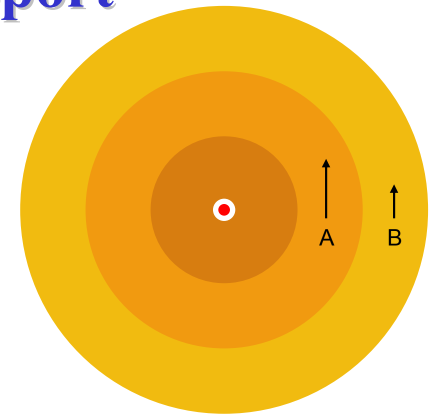
- Viscosity in the disk
- SED fits (more)
- Flaring Disks: Why do we need those anyway?

Disk Steps

- We established that due to a little of rotation, we expect to see a circumstellar disk surrounding the protostar.
- The outflow driving mechanisms focus on disk winds
  → disks are there in the youngest protostars!
- Nice.

- But, we also know that there is ongoing accretion in these systems.
- How does the disk accrete onto the star?
- Must depend on the rate of angular momentum transport in the disk. (kinda poorly understood)

Outward Angular Momentum Transport



Ring A moves faster than ring B. Friction between the two will try to slow down A and speed up B. This means: angular momentum is transferred from A to B.

Specific angular momentum for a Keplerian disk:

$$l = r v_\phi = r^2 \Omega_K = \sqrt{G M_* r}$$

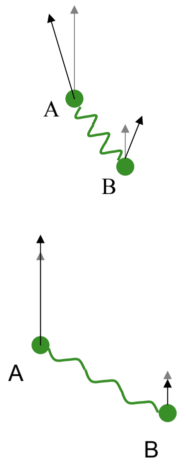
So if ring A looses angular momentum, but is forced to remain on a Kepler orbit, it must move inward! Ring B moves outward, unless it, too, has friction (with a ring C, which has friction with D, etc.).

Disk Viscosity

- Molecular viscosity is so small that disk evolution would be too slow ($t_{acc} \sim 10^{13}$ yrs).
- Have to consider other mechanisms for viscosity
  1. Turbulent Viscosity (Lin & Papaloizou 1995)
     - But may work the wrong way (transport angular momentum inward; e.g. Stone & Balbus 1996)
     - Also Keplerian motions tend to stabilize the disk (no turbulence)
  2. Current paradigm is magnetic instabilities in the disk
     - Developed for accretion disks by Balbus & Hawley (1991)

Magneto-rotational Instability (MRI)

(Also often called Balbus-Hawley instability)

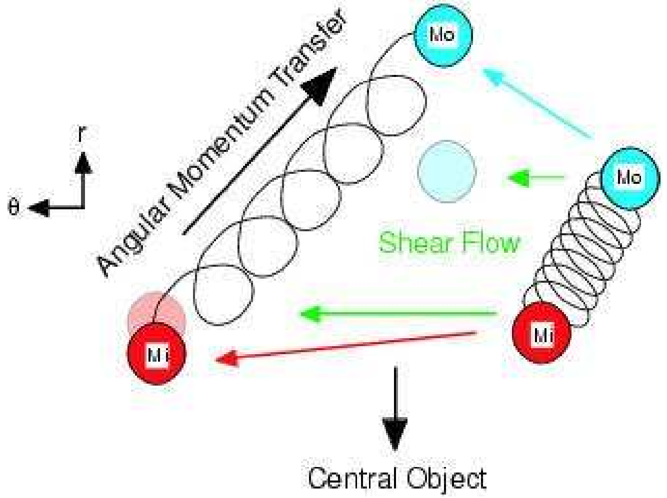


If a weak magnetic pull exists between two gas-parcels A and B on adjacent orbits, and the parcels are perturbed, and the magnetic tension increase. The effect is that A moves inward and B moves outward: a pull causes them to move apart!

The lower orbit of A causes an increase in its velocity, while B decelerates. This enhances their velocity difference! This is positive feedback: an instability.

Causes turbulence in the disk

Spring Analogy



http://astsun.astro.virginia.edu/~tsi6a/research/mri_iap_jun_2005.pdf

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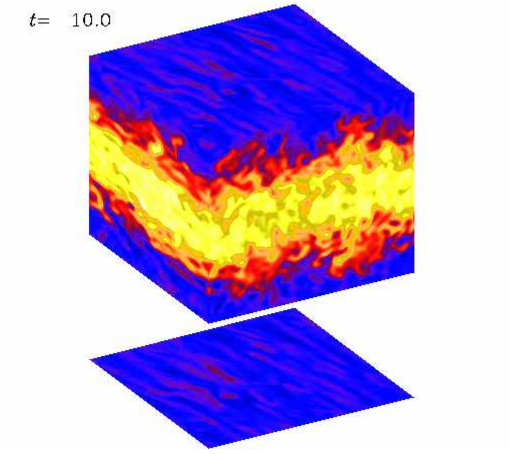
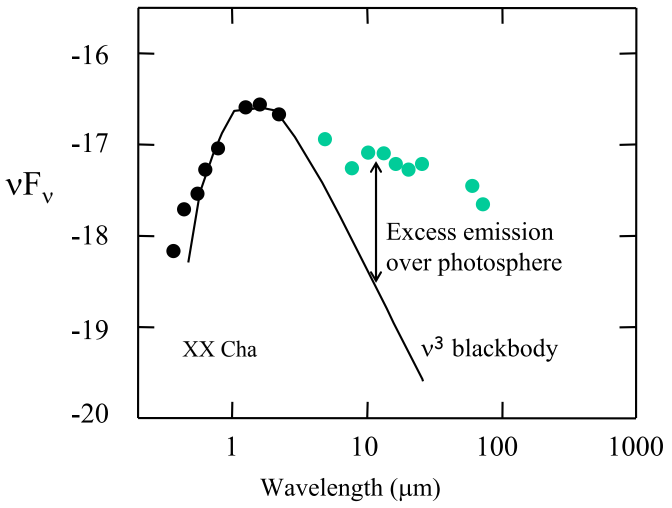
Magneto-rotational Instability (MRI)



However, there is still some debate on the importance of MRI (Hartmann et al. 2006)

Johansen & Klahr (2005)

Back to SEDs

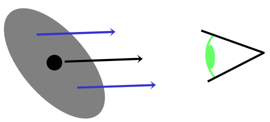


Far IR optical depth:
$\tau \sim 1$ at 100 μm
$\tau \sim 0.01$ at 1 mm

$\therefore\ \tau \geq 100$ at 1 μm
$\Rightarrow A_V \geq 300$

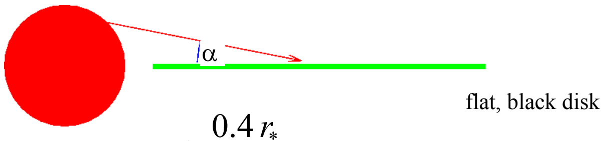
Observed $A_V \sim 3$

∴ clear line of sight to star and dust.



e.g. Adams, Lada, & Shu (1988)

Flat Irradiated Disks



$$\alpha \cong \frac{0.4\, r_*}{r}$$

Irradiation flux:

$$F_{\rm irr} = \alpha \frac{L_*}{4\pi r^2}$$

Cooling flux:

$$F_{\rm cool} = \sigma T^4$$

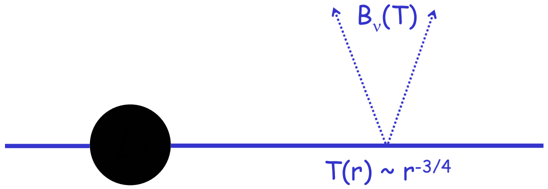
$$T = \left(\frac{0.4\, r_* L_*}{4\pi\sigma r^3} \right)^{1/4}$$

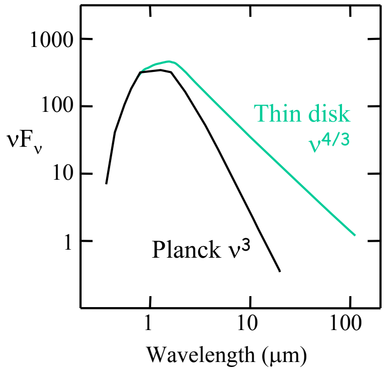
$$\boxed{T \propto r^{-3/4}}$$

Similar to active accretion disk, but flux is fixed.

Lynden-Bell & Pringle (1974)
Adams, Lada, & Shu (1988)

Disk SED: Multicolor Region





From before →

$$\boxed{\nu F_\nu \propto \nu^{(4q-2)/q}}$$

Using assumed temperature profile:

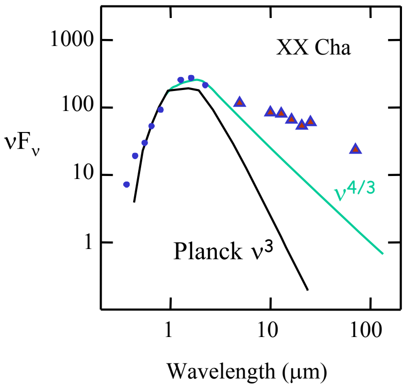
$$T(r) \propto r^{-q}$$

$q = 3/4 \ \Rightarrow\ \nu F_\nu \sim \nu^{4/3}$

Adams, Lada, & Shu (1988)

SED Fits

Thin disk $\nu F_\nu \sim \nu^{4/3}$

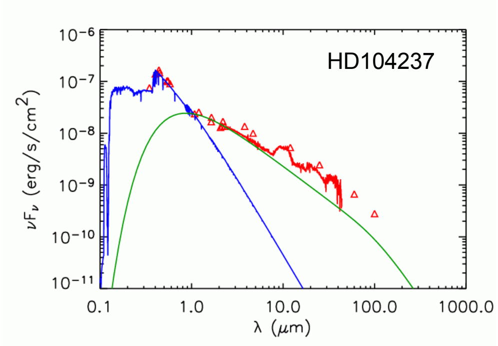


The SED from a theoretically thin black disk almost never fits the observations of young stars with excess infrared emission!

- most SEDs flatter than $\nu^{4/3}$
- some SEDs very flat, $\nu F_\nu \sim \nu^0$

Adams, Lada, & Shu (1988)
Beckwith *et al.* (1990)

SED Fits



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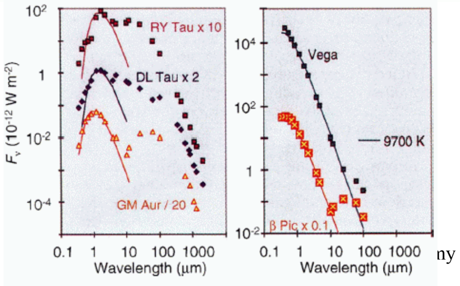

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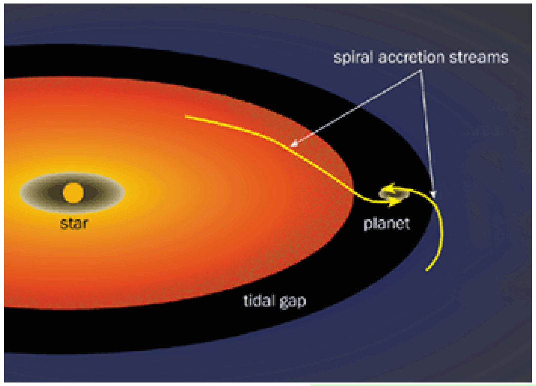
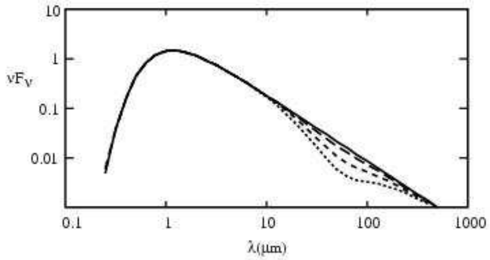
Beckwith et al. *(*1990 & 1999)

Gaps in Disk SEDs

http://www.mpia.de/homes/beuther/lecture_ss06.html

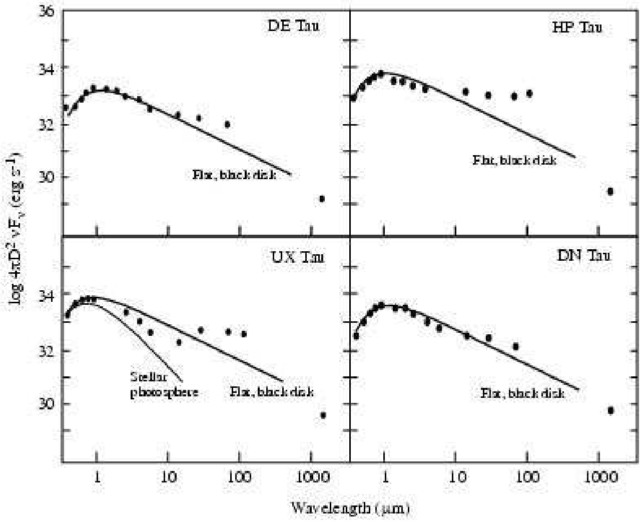




Full line: no gap
Long-dashed: gap 0.75 to 1.25 AU
Short-dashed: gap 0.5 to 2.5 AU
Dotted: gap 0.3 to 3 AU

To become detectable gap has to cut out at least a decade of disk size.

Additional FIR excess



- Larger inner or smaller outer disk radii even increase the discrepancy.
- Data indicate that outer disk region is hotter than expected from flat, black disk model → Disk flaring

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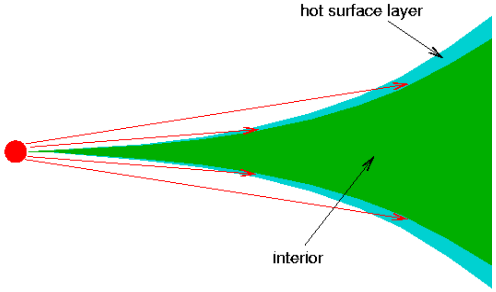
Flared disks

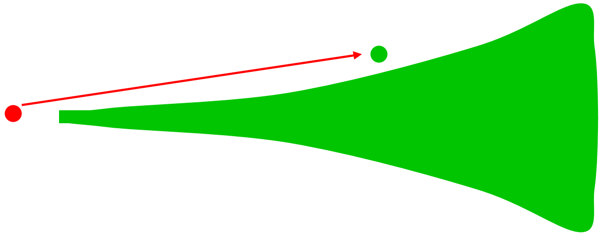


flaring

vertical structure

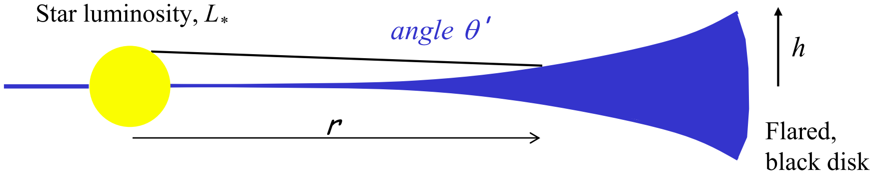
irradiation

heating vs cooling



- Kenyon & Hartmann 1987
- Calvet et al. 1991; Malbet & Bertout 1991
- Bell et al. 1997;
- D'Alessio et al. 1998, 1999
- Chiang & Goldreich 1997, 1999; Lachaume et al. 2003

Flaring Disk: Geometry



- Absorbed radiation ~ $\sin\theta' \gg \sin\theta$
- $T_{flare}(r) > T_{flat}(r)$, especially at large r

$$\frac{h}{r} \sim r^{2/7}$$

$$T_i(r) \sim r^{-6/15}$$

BUT

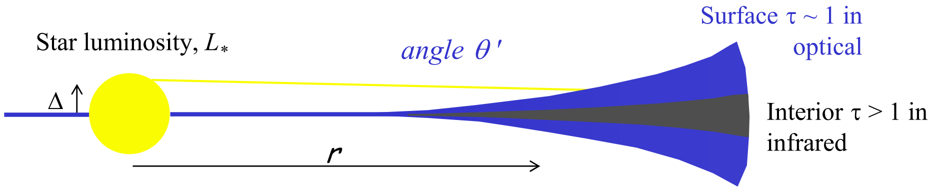
→ Cannot account for *flat* SEDs (6/15 < 1/2)

→ Still assumes "black" disk (no radiative transfer)

http://feps.as.arizona.edu/pub_presentations/kobe_2005/

Kenyon & Hartmann 1987

Flaring Disk: Radiative Transfer



- Optical light absorbed $\tau_V \sim 1$, $\tau_{IR} << 1$
- Small grains "bare" => $T_{grain} > T_{blackbody}$
- Disk emission $\tau_{IR} < 1$ (5 - 100 μm)

$$\frac{h}{r} \approx 0.9 \left(\frac{r}{209\ AU}\right)^{\frac{13}{45}}$$

Still cannot account for *very flat* SEDs, but does fit majority.

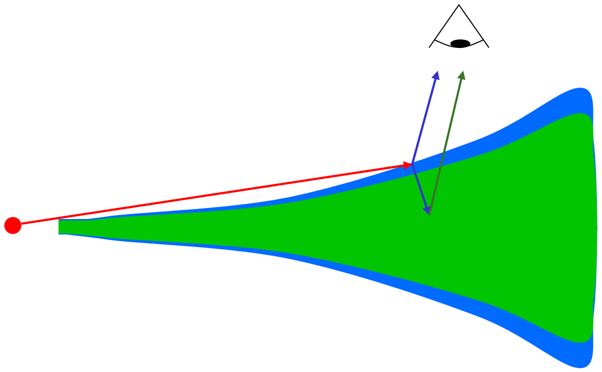
$$T_i(r) \approx 21\ \mathrm{K} \left(\frac{r}{209\ AU}\right)^{\frac{19}{45}}$$

Prediction: disk surface emission is optically *thin*

http://feps.as.arizona.edu/pub_presentations/kobe_2005/

Chiang & Goldreich 1997

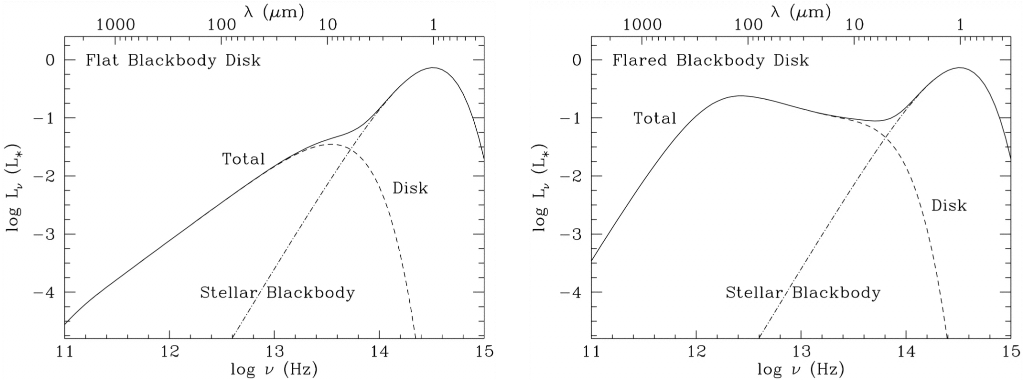
The Surface Layer



Disk has a hot surface layer which absorbs all stellar radiation.

Half of it is re-emitted upward (and escapes); half of it is re-emitted downward (and heats the interior of the disk).

Differences in the SED

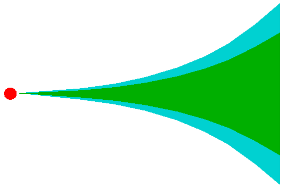


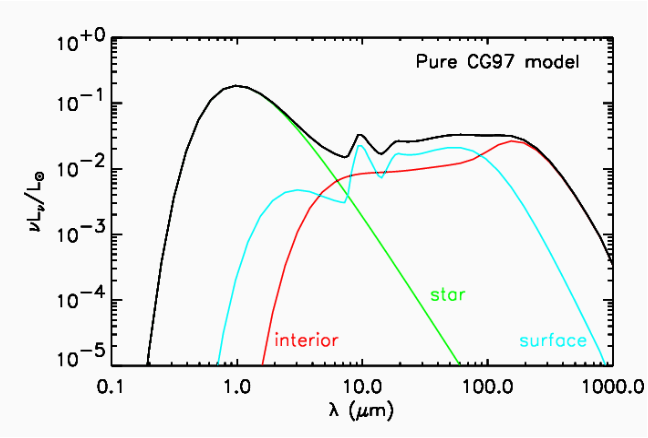
Chiang & Goldreich 1997

Two layers

Model has two components:

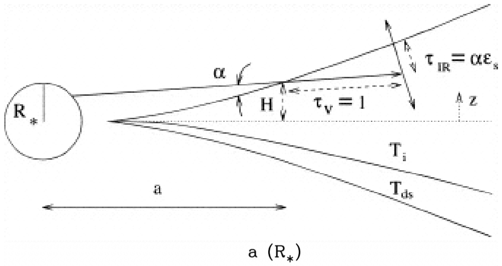
- Surface layer
- Interior



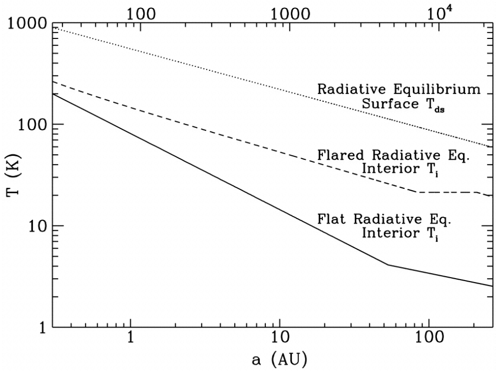


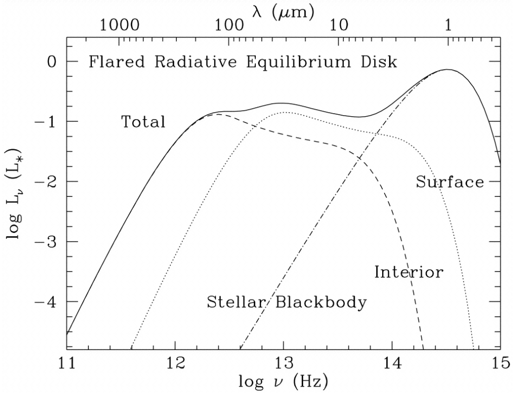
Chiang & Goldreich 1997

Affecting the SED



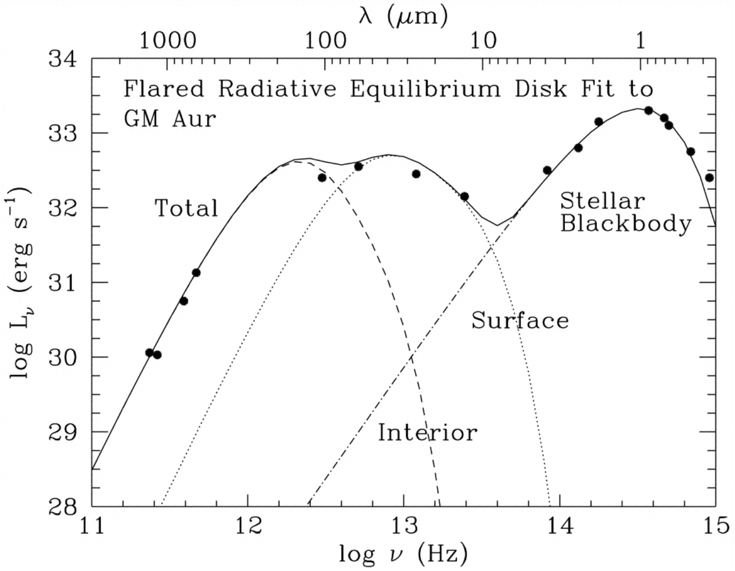
$n_{vert} \sim \exp(z^2/2h^2)$





Chiang & Goldreich 1997

Fitting GM Aur



Chiang & Goldreich 1997