X–rays, protoplanetary disks and planet formation

Eric Feigelson (Penn State)

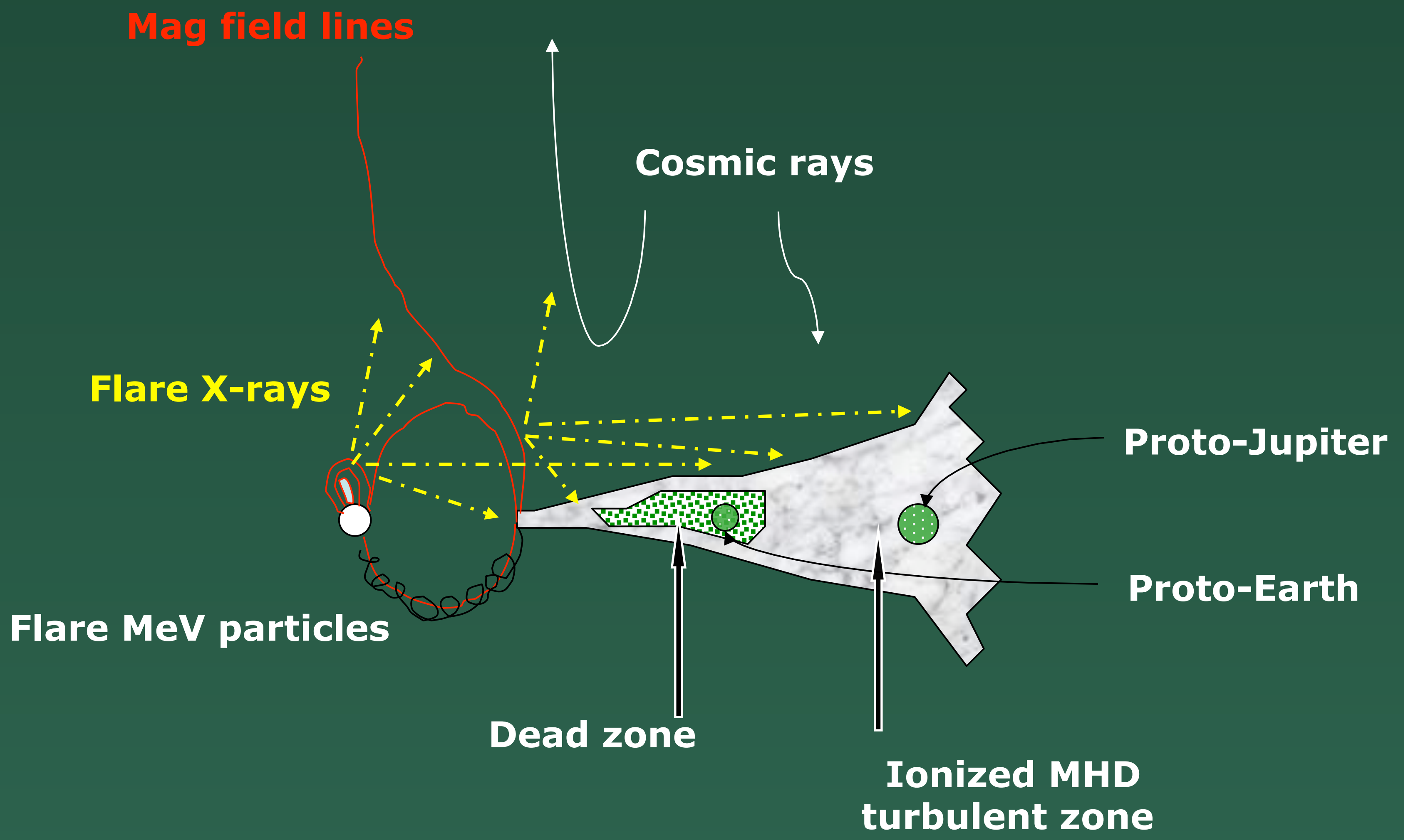
1. **Stars ubiquitously exhibit high levels of flaring and hard X-ray emission throughout planet formation.**

2. **Evidence shows that these X-rays can efficiently irradiate protoplanetary disks.**

3. **Theoretical studies indicate that the resulting ionization may significantly affect disk thermodymanics, chemistry, dynamics (esp. turbulence) and solids, thereby influencing the processes of planet formation.**

CONSTELLATION School `X-rays from Star Forming Regions' 2009

X-ray influence on planet formation



Feigelson 2003, 2005

X-rays can irradiate protoplanetary disks

1. Some systems show evidence of reflection of X-rays off of the disk: the fluorescent 6.4 keV iron line

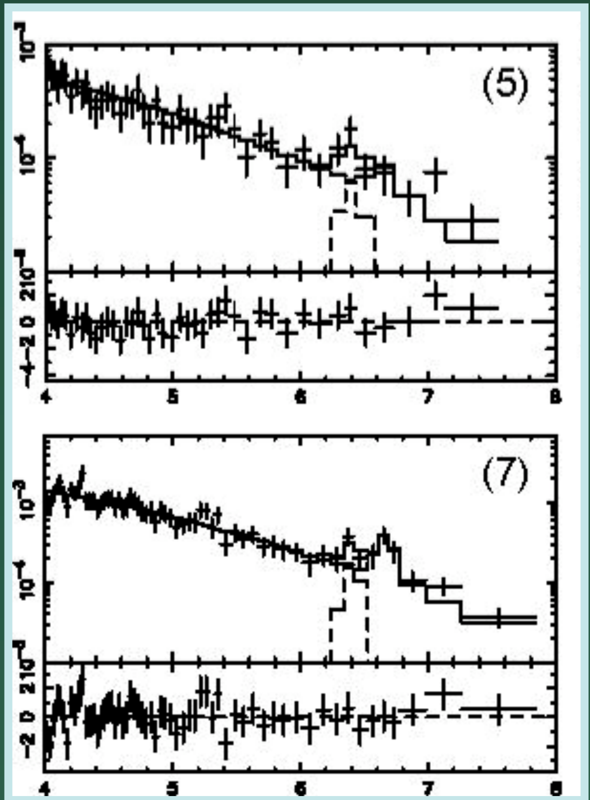
2. Some systems show soft X-ray absorption attributable to gas in the disks

3. Some disks show [NeII] 12.8μm line from X-ray ionization

4. Many disks show a non-equilibrium hot molecular layer, excited H_2, H_2O and CO from X-ray or UV irradiation

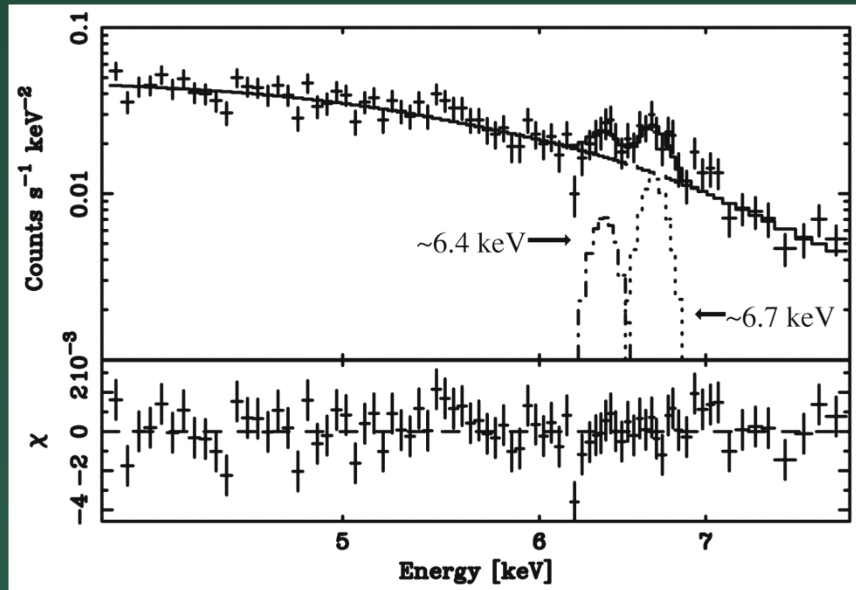
Iron fluorescent line
Cold disk reflects flare X-rays

COUP spectra

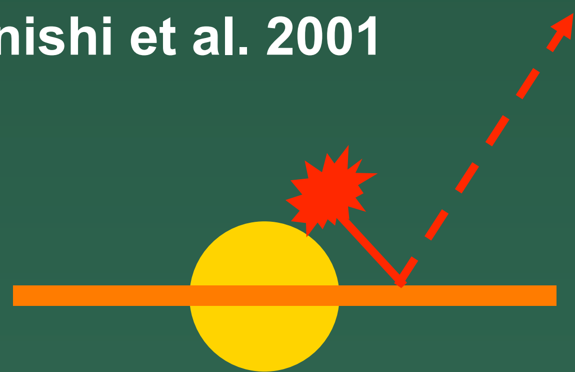


Tsujimoto & 7 others 2005 COUP #8

YLW 16A: protostar in Oph

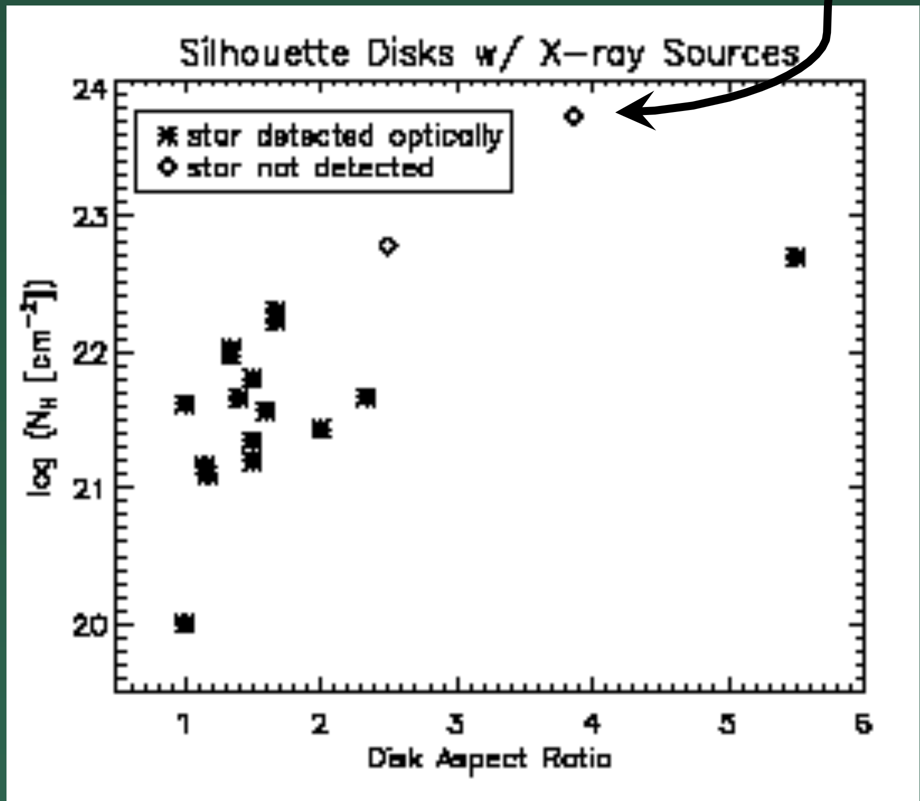


Imanishi et al. 2001



also Favata et al. 2006, Giardino et al. 2007, Skinner et al. 2007, Czesla & Schmitt 2007

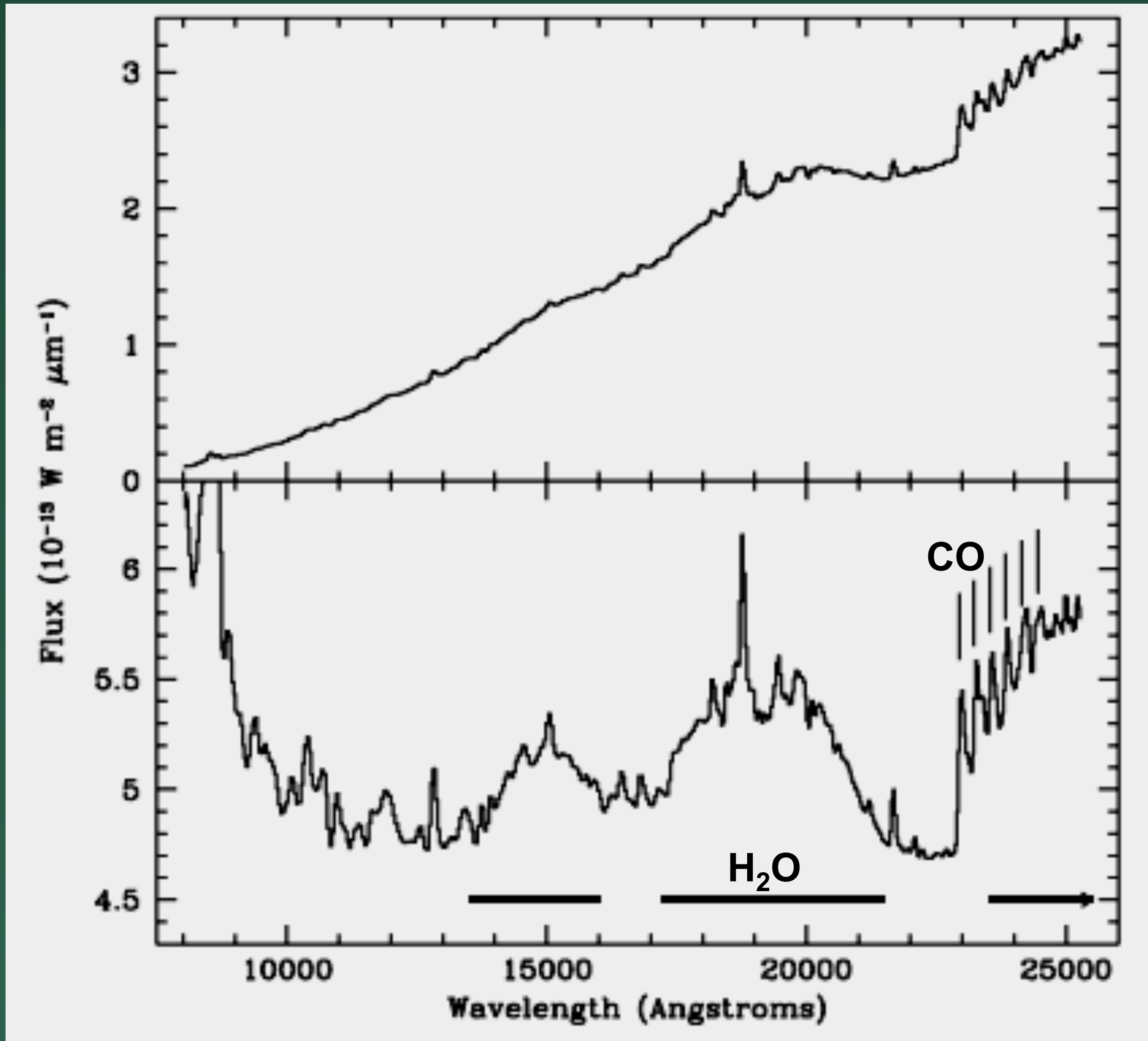
X-ray absorption by gas in edge-on Orion proplyds



First measurement of <u>gas</u> content of UV-irradiated photoevaporating disks?

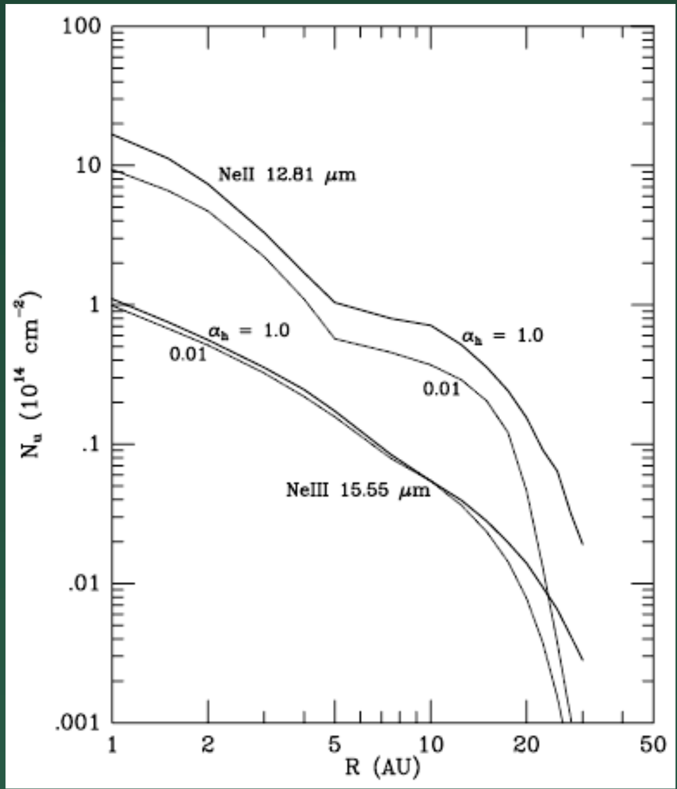
Kastner & 7 others 2005 COUP #9

Hot CO and H_2O seen in some PPDs



Carr et al. 2004

This `hot molecular layer' may be produced by X-rays, UV or shocks

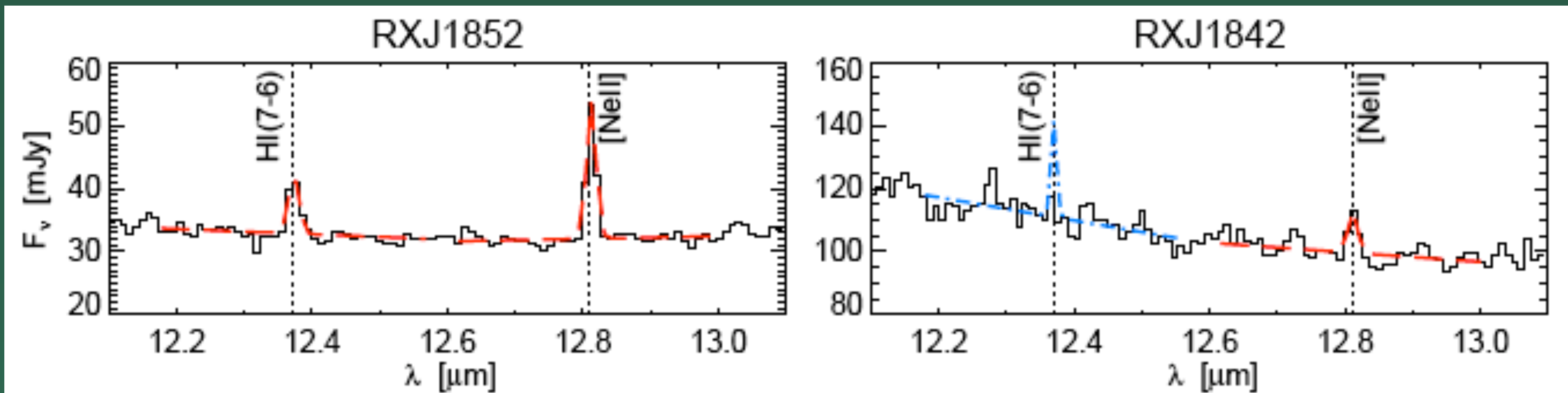


Stellar X-rays ionize and heat outer disk atmospheres out to several AU. [Ne II] 12.81 um line predicted

(Glassgold et al. 2006; Meijerink et al. 2008; Ercolano et al. 2008; Gorti & Hollenbach 2008; Alexander 2008)

[Ne II] line detected with Spitzer and Keck

(Pascucci et al. 2007; also Lahuis et al. 2007; Herczeg et al. 2007)



X-rays & disk ionization

YSO X-ray ionization *rate* dominates CRs in the disk by 10^8 for $1M_o$ PMS star at 1 AU:

$$\zeta = 6\times10^{-9}\,(L_x/2\times10^{30}\text{ erg s}^{-1})\,(r/1\text{ AU})^{-2}\ \text{s}^{-1}$$

The ionization *fraction* is uncertain due to recombination processes. Hard (5-15 keV) X-rays should penetrate 1-100 g/cm^2.

Igea & Glassgold 1997 & 1999; Fromang, Terquem & Balbus 2002; Matsumura & Pudritz 2003, 2006, 2008; Alexander, Clarke & Pringle 2004; Salmeron & Wardle 2005; Ilgner & Nelson 2006; … …

Reviews: Glassgold et al. 2000 & 2006; Balbus 2003

Plausible X-ray/flare effects on protoplanetary disks

- **PMS X-ray ionization will heat gas and change chemistry in disk outer layers**

  Aikawa & Herbst 1999 & 2001; Weintraub et al. 2000; Markwick et al. 2001 & 2002; Najita et al. 2001; Ceccarelli et al. 2002; Bary et al. 2003; Alexander et al. 2004; Glassgold et al. 2004; Semenov et al. 2004; Doty et al. 2004; Greaves 2005; Stauber et al. 2006ab; Ilgner & Nelson 2006abc; Kamp et al. 2006; Nomura et al. 2007; Chiang & Murray-Clay 2007; Henning & Semenov 2008; Agundez et al. 2008

- **PMS X-rays may be an important ionization source at the base of bipolar outflows**

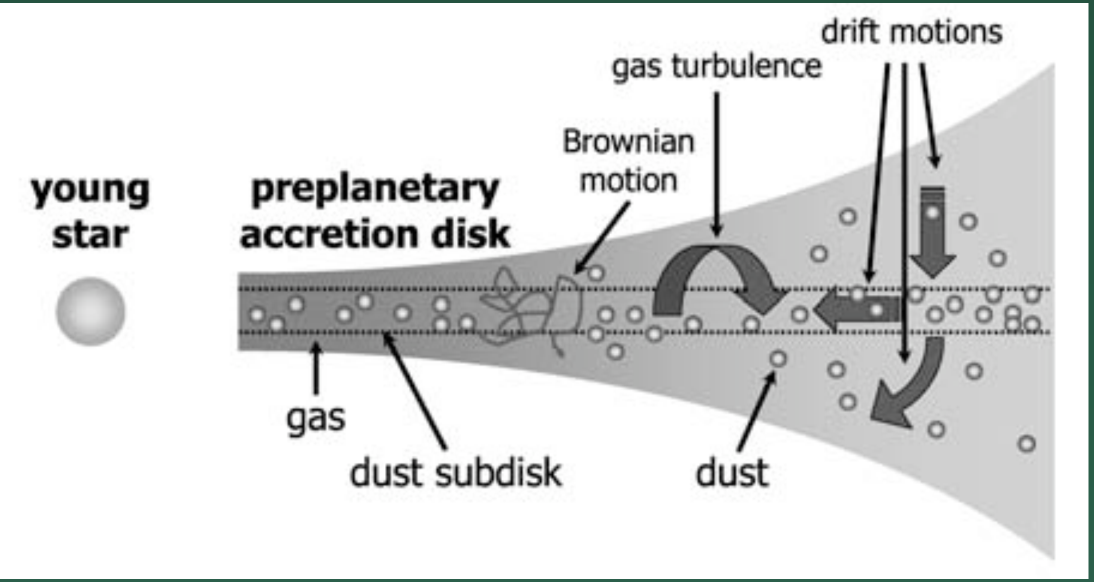
  Shang et al. 2002 & 2004; Fero-Fontan et al. 2003; Liseau et al. 2005

- **X-ray ionization is likely to induce MRI turbulence affecting accretion, dust coagulation, migration, gaps**

  >60 studies

Some issues in planet formation theory

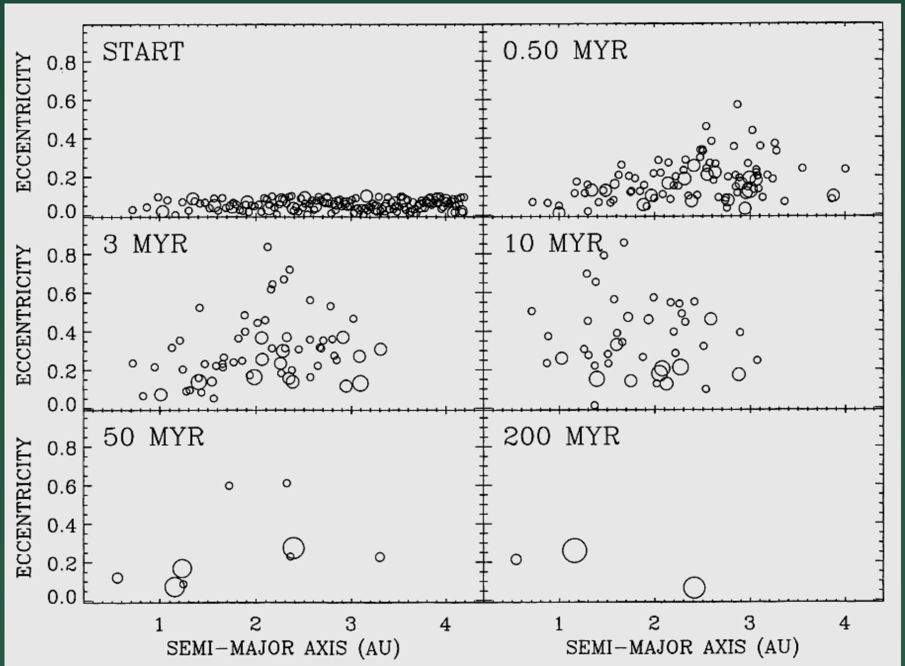
- How does growth occur from interstellar grains to larger bodies? Traditional theory requires calm dynamics and gravitational settling towards the midplane (Dominik/Dullemond 2005).



- How do m-size bodies avoid inspiral due to headwind from gas?

No consensus answer. (Weidenschelling 1977)

•Rapid `oligarchic growth' from km-size to Earth-size occurs by gravitationally focused growth. Not a problem (Ida, Chambers …)



•How do Jovian mass planets grow? Rapid gravitational instability? (Debate: Boss, Durisen, …) Slow gas accretion onto ~10x-Earth planet? (Pollack et al. 1996)

•How to prevent all Jovians from inspiral due to torque from gas? (Goldreich & Tremaine 1981)

X-ray effects on disk dynamics and protoplanet migration … turbulence!

X-rays --> MRI --> MHD turbulence --> inhomogeneities producing gravitational torques which overwhelm the Goldreich-Tremaine torque, so protoplanets undergo random walks rather than inward Type I migration. Gap formation is also suppressed, so Type II migration is delayed. Planet formation at edge of dead zone.

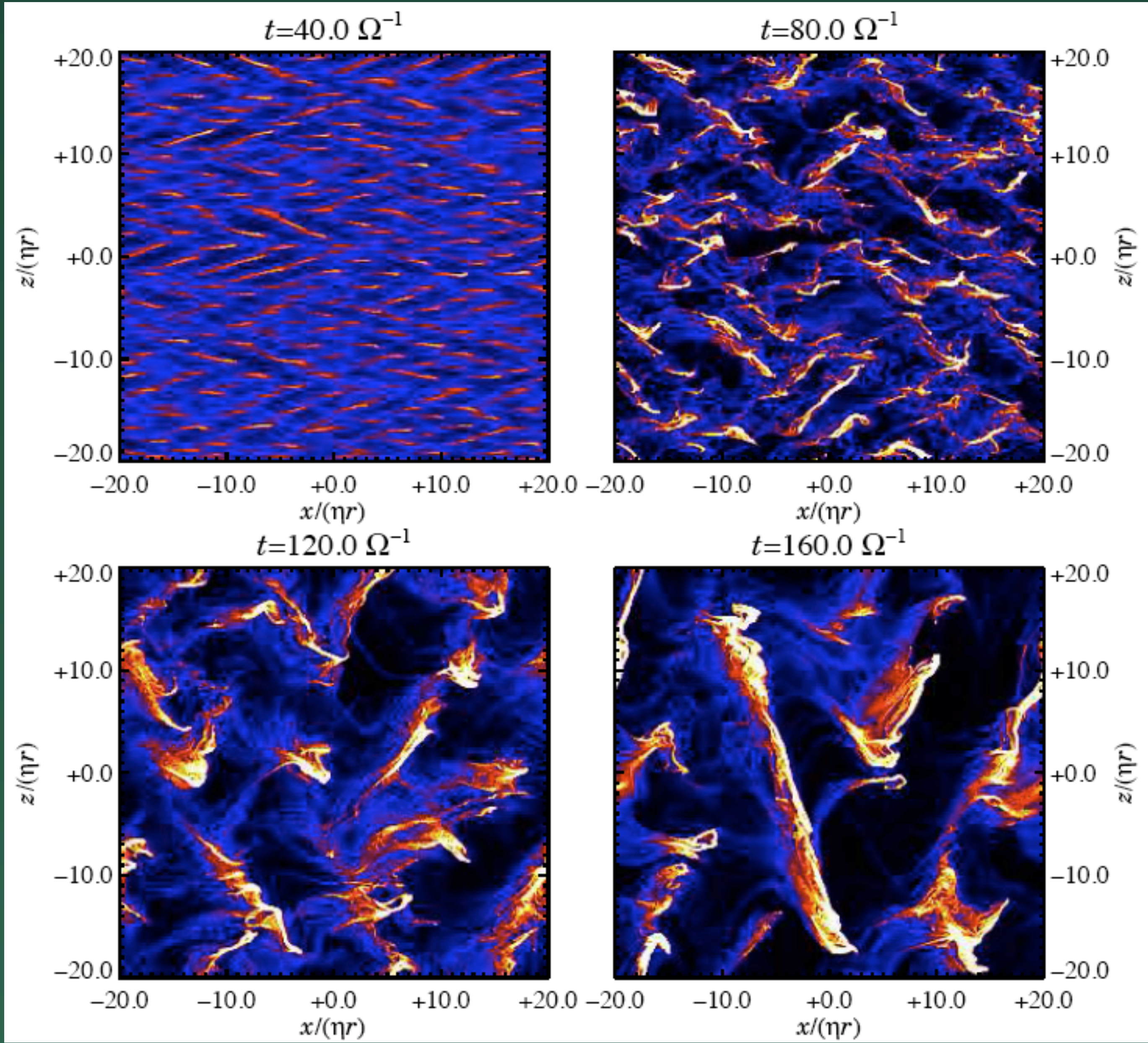
(Work by many theory groups)

Turbulence inhibits settling towards midplane.

But particle density concentration due to two-stream instability in turbulent protoplanetary disk

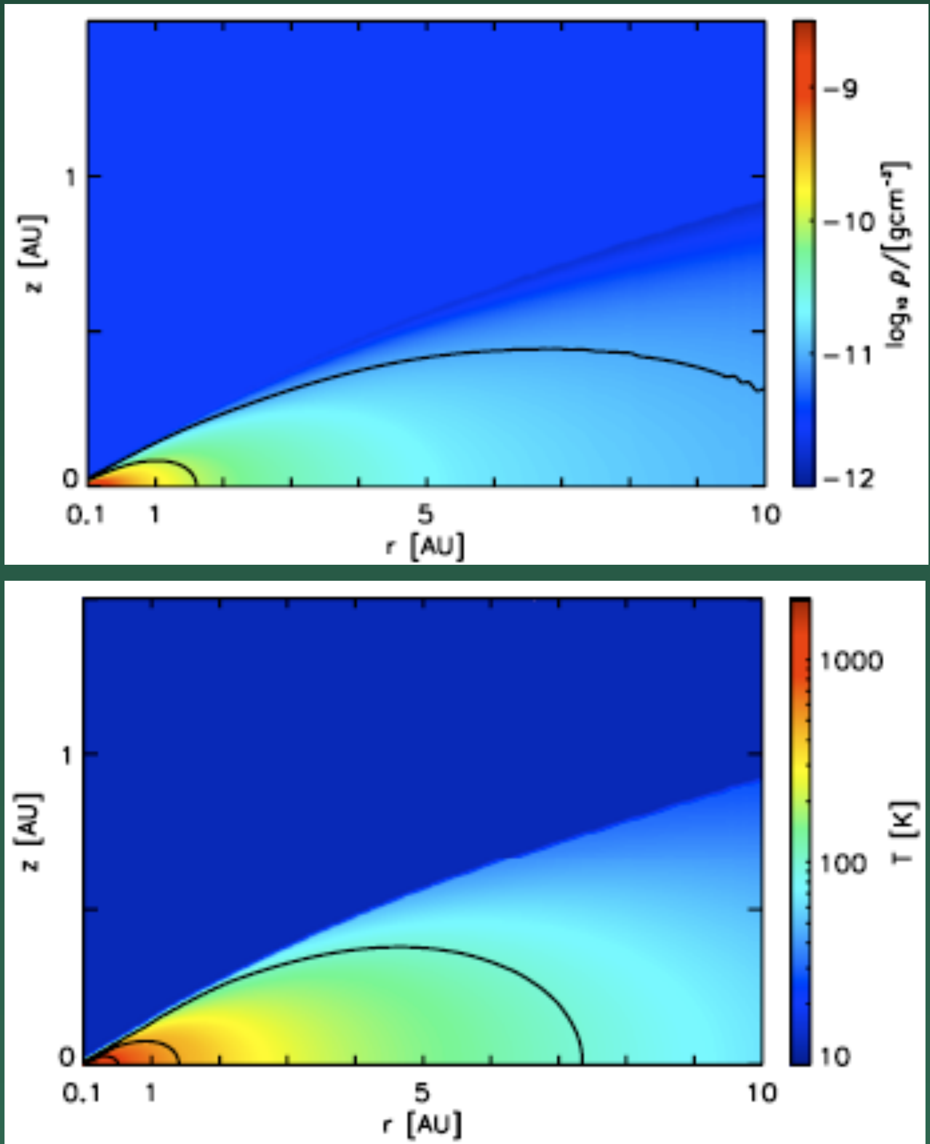
A solution to particle growth and inspiral dilemmas?

Johansen & Youdin 2007

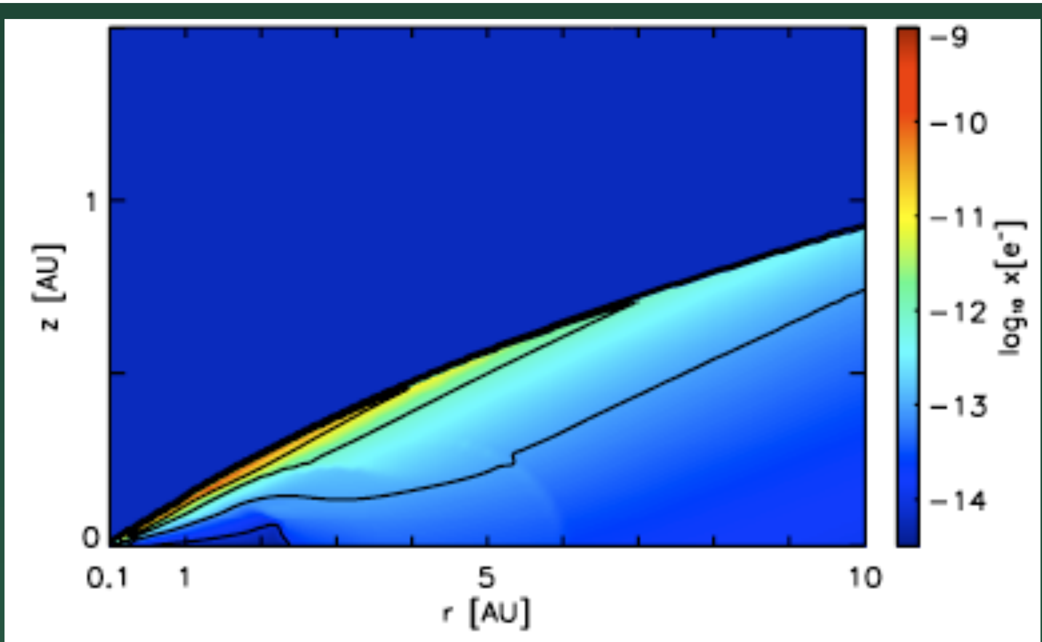


Sophisticated model with gas, dust & X-rays

Time-dependent ion-induced chemistry: Ilgner & Nelson 2006abc



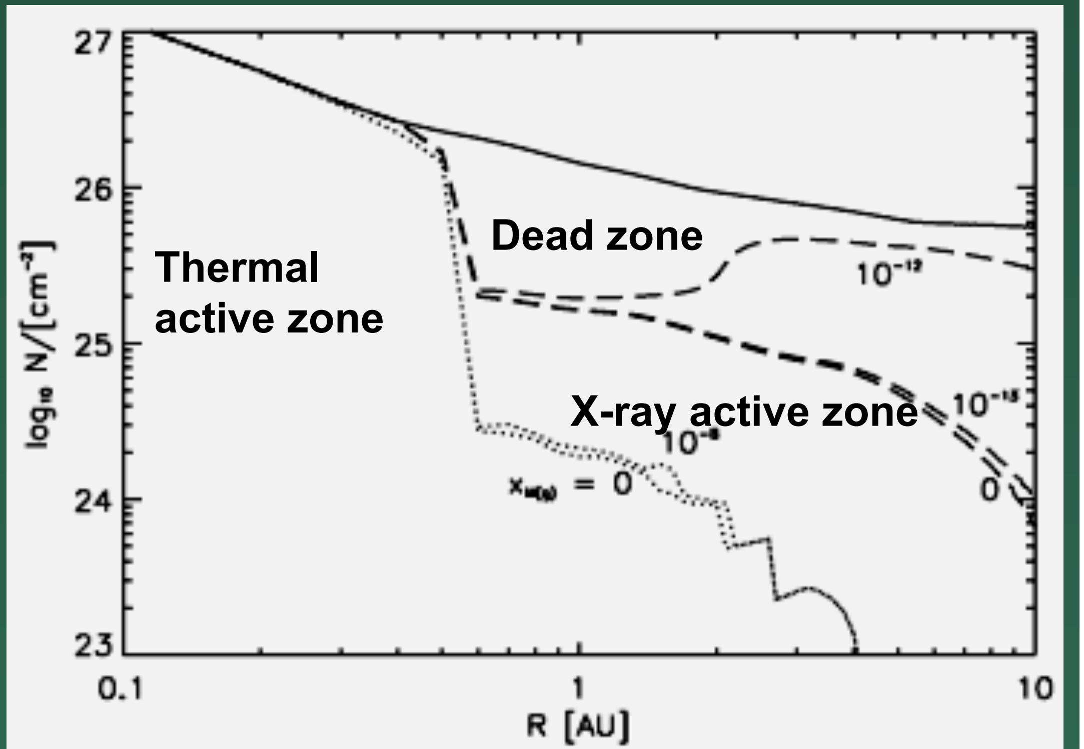
Density & temperature distribution in the assumed α−disk model



Ionization fraction throughout disk for a X-ray irradiated model

Boundary between active (= turbulent) and dead (= laminar) zone occurs at very low ionization fraction, log X_e ~ -12

Active vs. dead zones with grains (dashed) and without grains (dotted)



Periodic X-ray flares ($\log L_{x,p}$=32 erg/s) increase the size of the active zone considerably, and higher temperatures during flares (kT=7 vs. 3 keV) can increase midplane ionization rates by 1000x further.

- r<0.5 AU is fully active due to thermal ionization of potassium.

- 0.5<r<2 AU has dead zone fluctuating during/between flares, and may disappear entirely if X-ray flare temperature is high

- r>2 AU does not change during flares due to slower recombination timescale, but dead zone is still sensitive to X-ray temperature. Electrons and gases may desorb/adsorb onto grains during flare cycles.

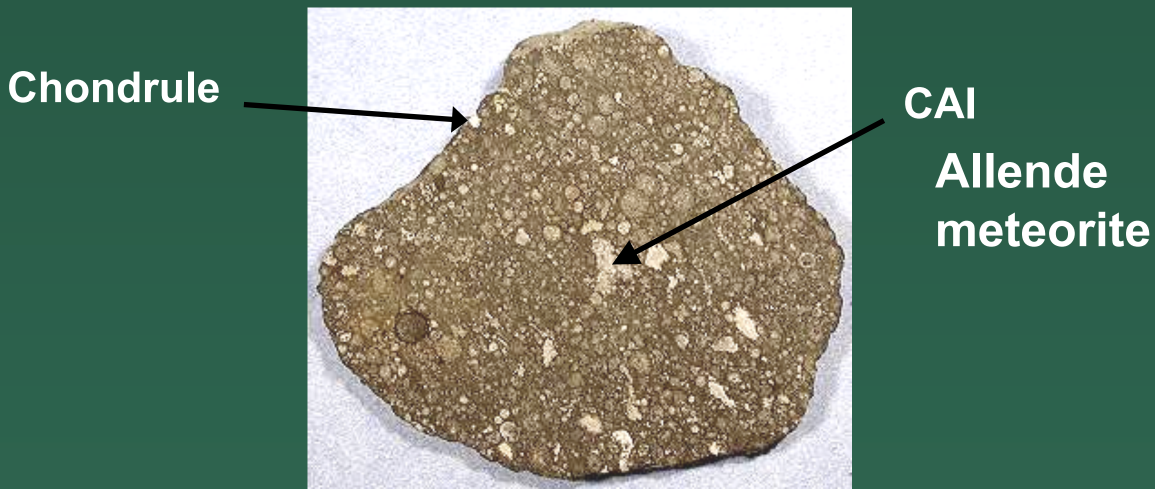
(Ilgner & Nelson 2006c)

Magnetic reconnection flares may affect disk solids

1. *Flare MeV protons may have produced some short-lived radio nuclides in CAIs by spallation (^{10}Be, ^{21}Ne, ^{41}Ca, ^{53}Mn, …)*
   Clayton et al. 1977; Lee 1978; Feigelson 1982; Caffee et al. 1987; Gounelle et al. 2001; Feigelson et al. 2002; Leya et al. 2003; Gounelle et al. 2006

Chandra measurements of X-ray flare rates in Orion Nebula solar analogs quantitatively supports the local spallation origin of meteoritic isotopic anomalies *Feigelson et al. 2002*

2. *Flare X-rays may have melted meteoritic CAIs close to star and/or melted chondrules at Asteroid Belt* Shu et al. 2001; Miura & Nakamoto 2007

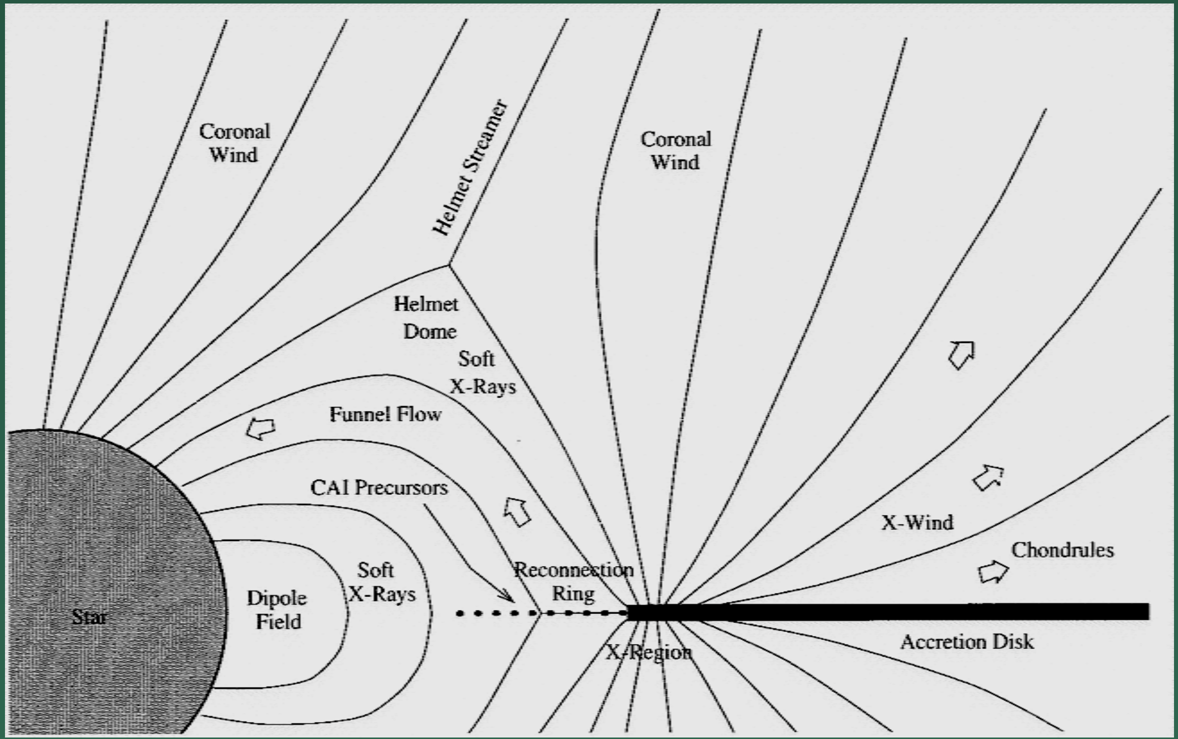


X-ray flares & chondrule formation

The causes of the flash melting of meteoritic chondrules and CAIs has been a major problem for >100 years. Meteoritic literature was surprisingly unaware of X-ray/radio flare findings.

Shu et al. (1997, 2001) develop a (controversial) model for flare flash melting of CAIs

Miura & Nakamura (2007) suggests flare shocks melt dustballs lofted by turbulence at ~3 AU



Conclusions

- The X-ray studies of young stars show that powerful magnetic flares are ubiquitous throughout the epoch of planet formation, 10^3 above solar levels. The astrophysics resembles gigantic solar flares.

- X-rays can efficiently irradiate protoplanetary disks.

X-ray evidence: Fe fluor lines Absorption

IR evidence: [NeII] line Mol. excitation

Possible consequences on planet formation processes: MRI, turbulence, viscosity, dead zones

Gas heating & ion-molecular chemistry

Ionization of outflows

Spallation of isotopes, chondrule melting

Planetary systems form in

cool dark disks ….

which are irradiated by 10^8 violent

magnetic reconnection flares