X-rays and protoplanetary disks

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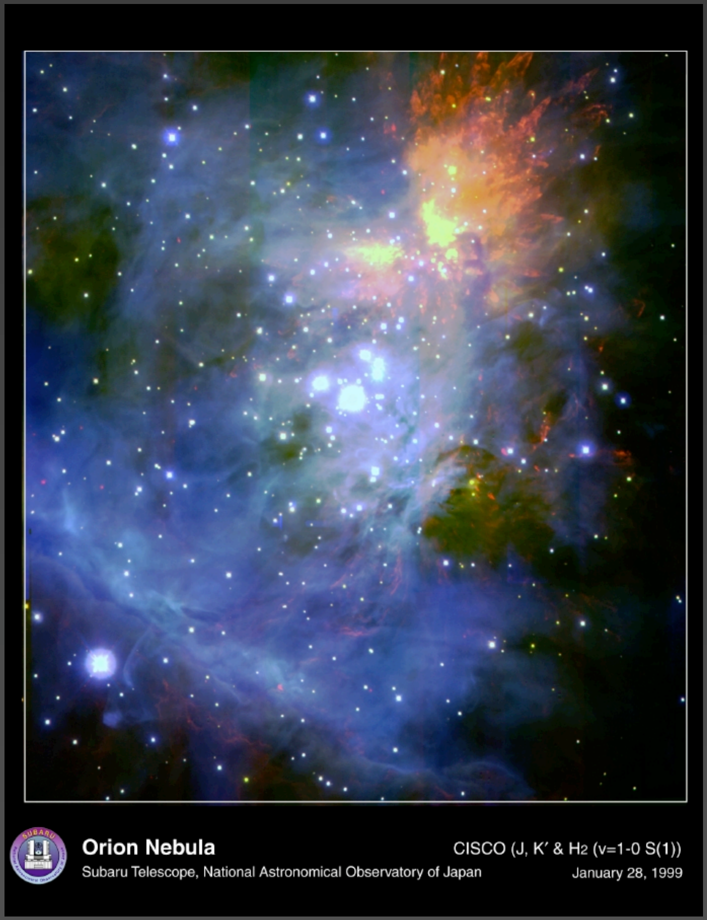
1. Stars ubiquitously exhibit high levels of flaring and hard X-ray emission throughout planet formation.

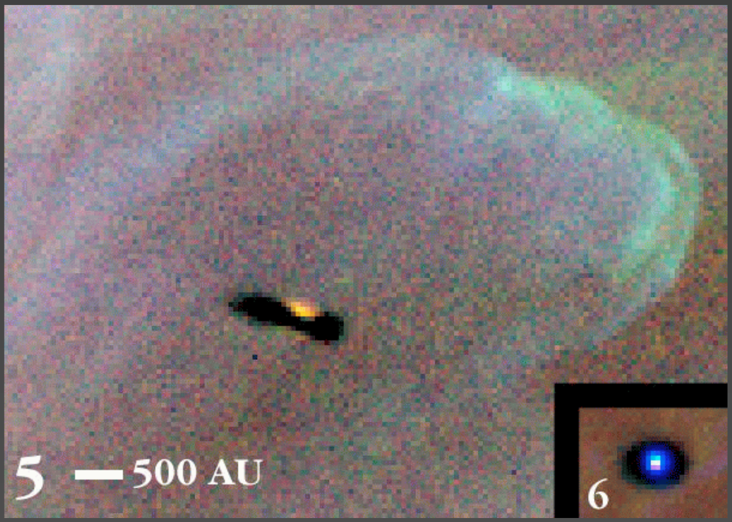
2. New evidence shows that these X-rays can efficiently irradiate protoplanetary disks.

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.

Introduction: X-rays and disks



Orion Nebula cluster & proplyd



Planet formation occurs in disks at T ~100-1000 K. This is neutral material (meV).

But high energy radiation is present in star/planet formation environments: keV photons & MeV particles are produced in violent magnetic reconnection flares.

Does this influence disk processes?
(heating, ionization, chemistry, turbulence, viscosity, shocks, melting & spallation of solids)

Theory looks very promising

Is there direct evidence for X-ray/flare effects in disk gases, solids & extrasolar planets?

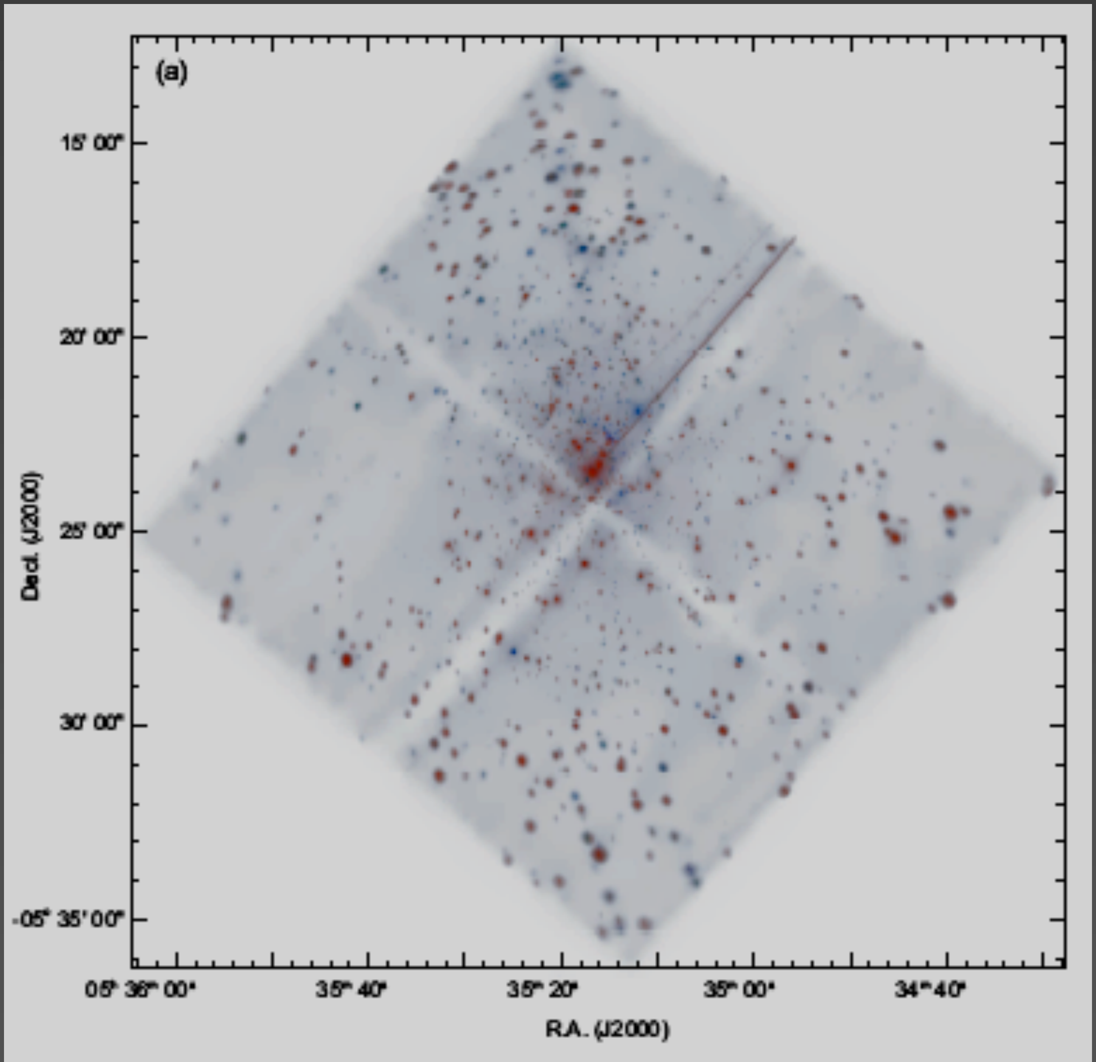
Perhaps some: disk gas excited H_2 & [NeII] lines; annealed disk grains & meteoritic chondrules; meteoritic isotopic anomalies

The Chandra Orion Ultradeep Project

13-day observation of the Orion Nebula

1616 COUP sources:
849 low-N_H ONC stars
559 high-N_H stars, incl. 75 new members

16 foreground stars
159 probable AGN
23 uncertain



Getman & 22 others 2005 COUP #1 & #2

COUP: The Movie

Some useful references

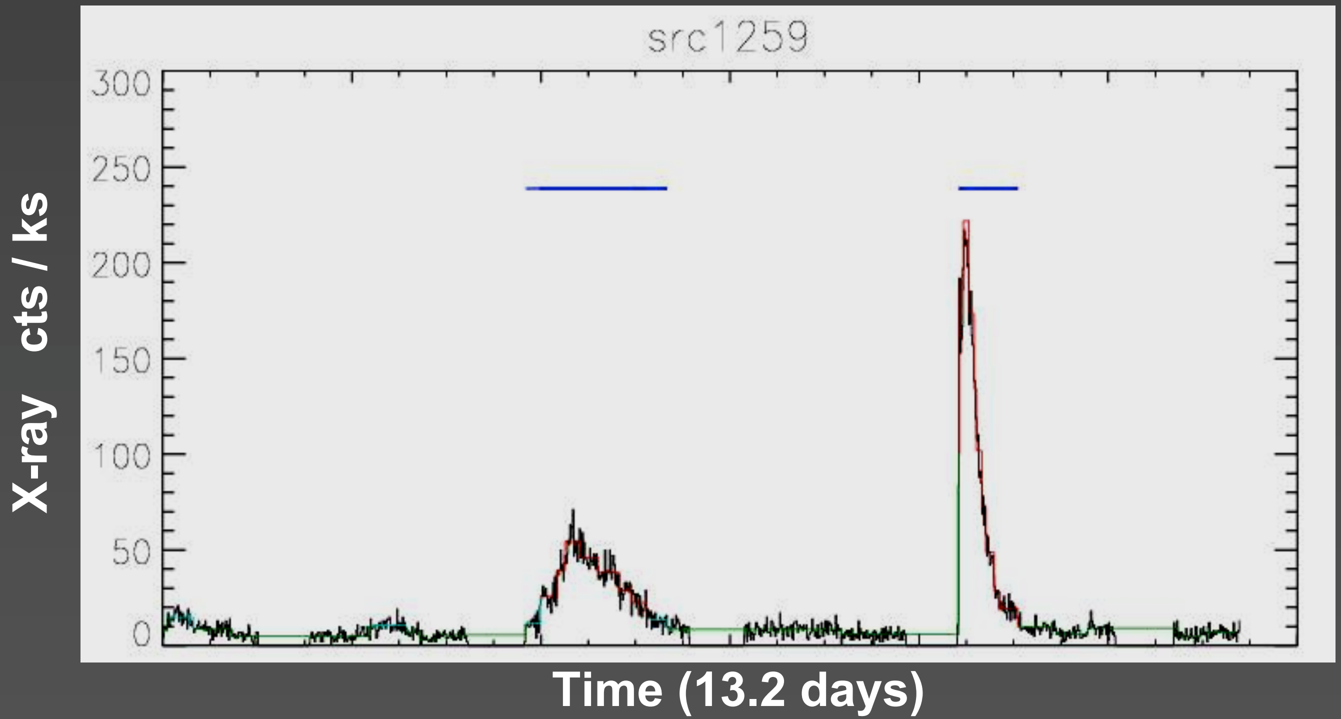
- "X-rays from young stars & stellar clusters"
  Review article in Protostars & Planets V 2007
  Feigelson, Townsley, Guedel & Stassun

- ~20 papers from Chandra Orion Ultradeep Project (COUP, Feigelson PI)
  ApJ Suppl Special Issue October 2005 + others 2006-07

- ~15 papers from XMM-Newton Extended Survey of the Taurus molecular cloud (XEST, Guedel PI)
  As&Ap Special Issue 2007

- ~1 paper/month on theory studies of ionized & turbulent protoplanetary disks

Extraordinary flares in Orion pre-main sequence stars



JW 738

K=10.5

Age ~ 10 Myr

Mass ~ 1 Mo

log Lp = 32.6 erg/s

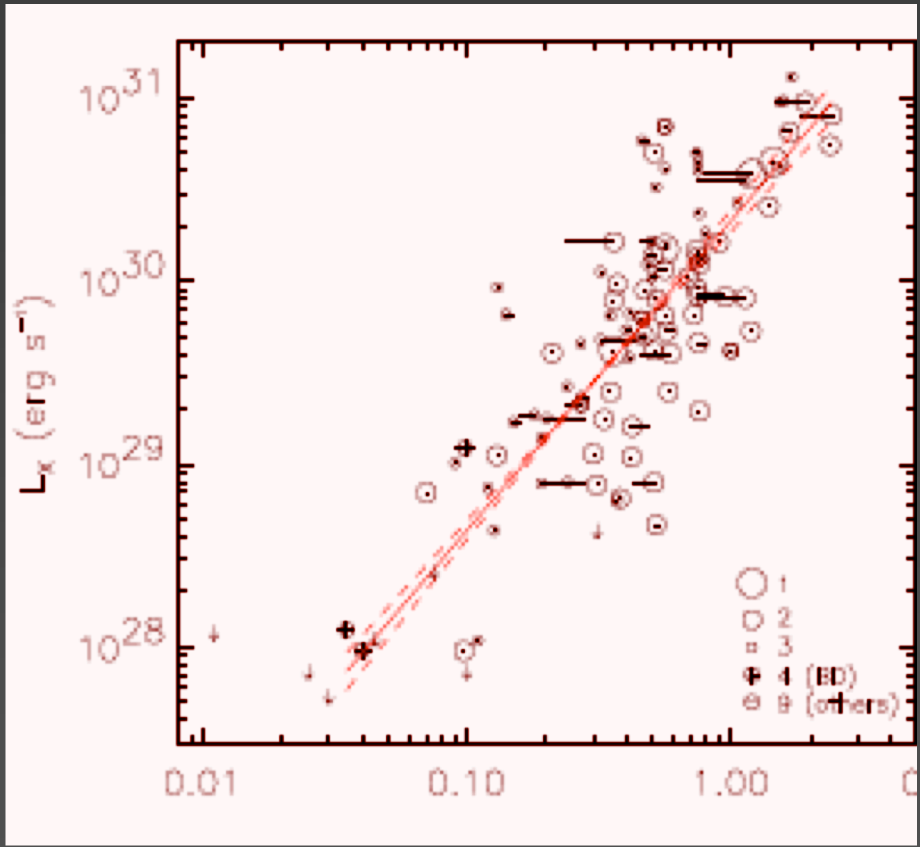
Wolk & 7 others 2005 COUP #6

X-ray characteristics of young stars

- Powerful flares releasing up to 10^{36} erg in the 0.5-8 keV band occur every few days. Many weaker flares dominate the "quiescent" emission.

- X-ray luminosity scales strongly with stellar mass but weakly with age for 0.1 < t < 10 Myr.

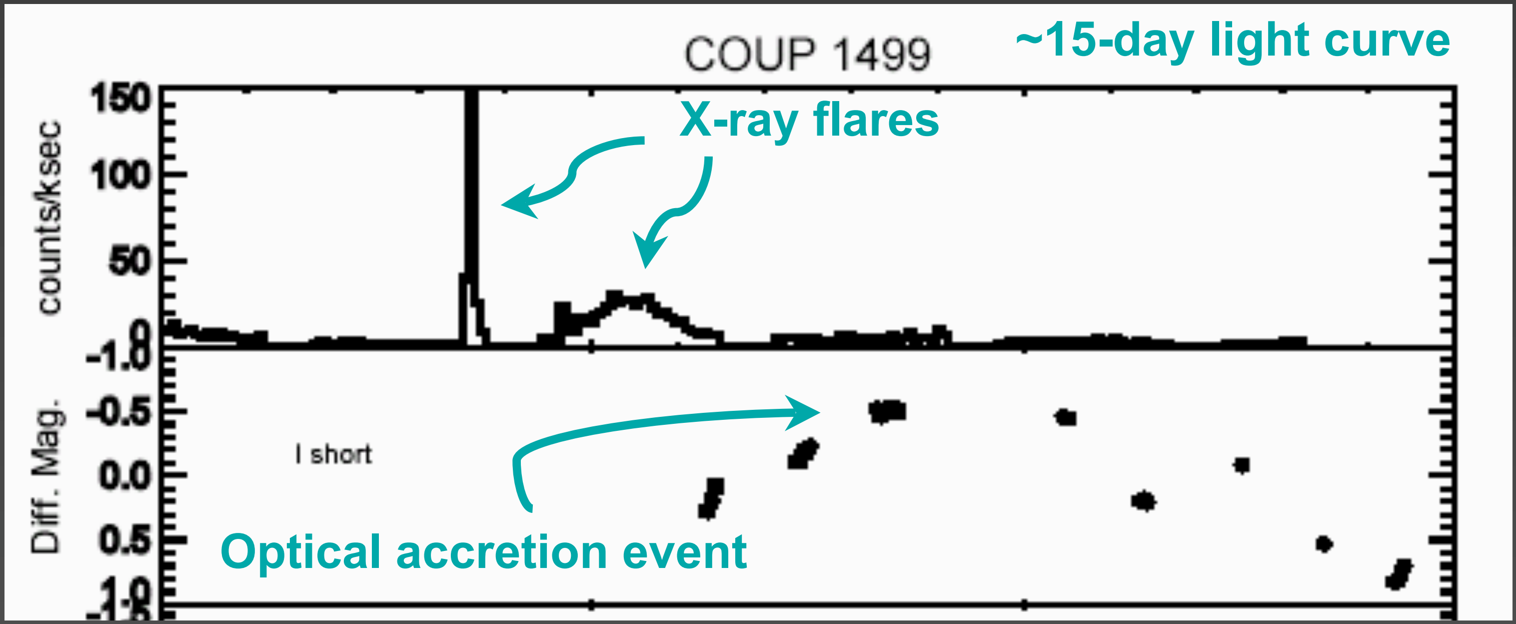
- Flare lightcurves are well-modeled by solar-like magnetic loops with lengths 0.1< r < 10 R_*.



Telleschi et al. 2007 XEST #2

Preibisch et al. 2005 COUP #4 Preibisch et al. 2005 COUP #5 Wolk et al. 2005 COUP #6 Favata et al. 2005 COUP #7 Flaccomio et al. 2005 COUP #8 Guedel et al. 2007 XEST #1 Maggio et al. 2007 COUP #17 Stelzer et al. 2007 XEST #5

Pre-main sequence X-rays are generally not produced by the accretion process

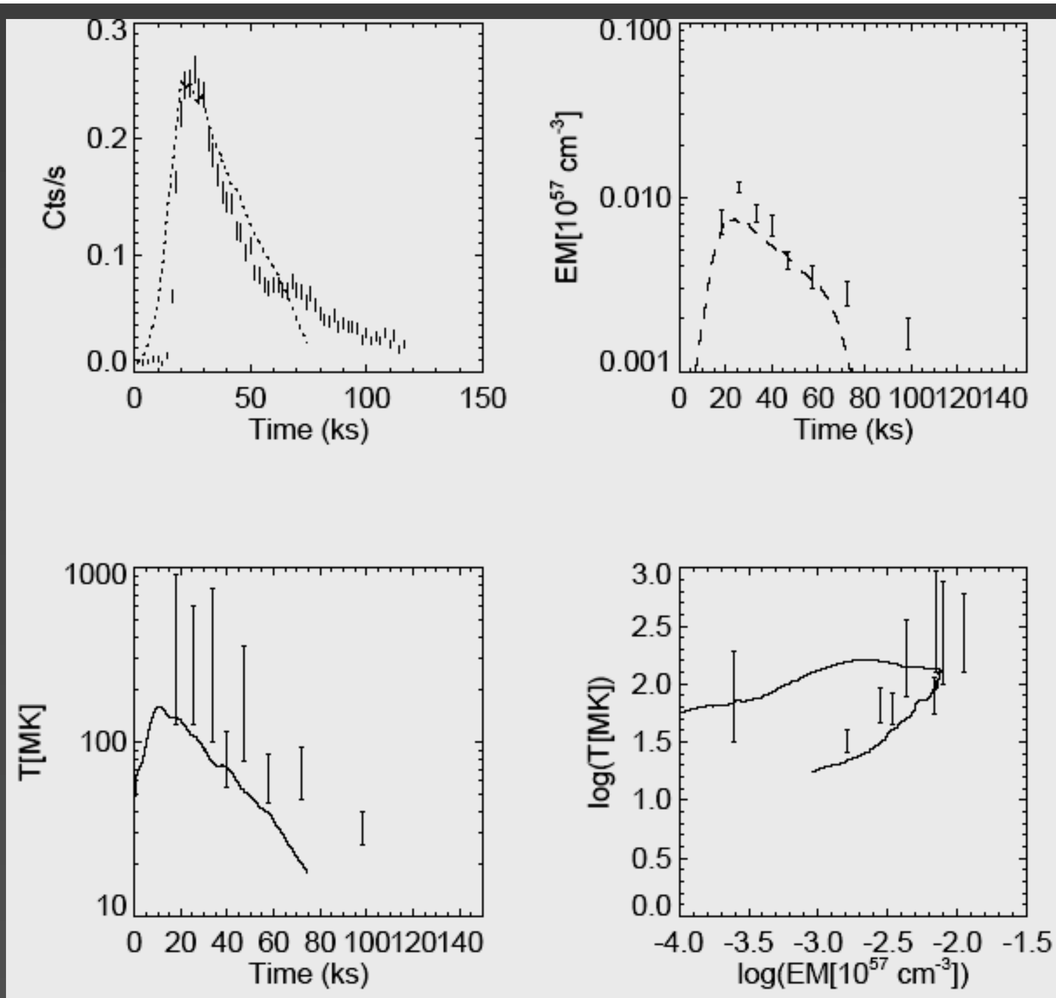


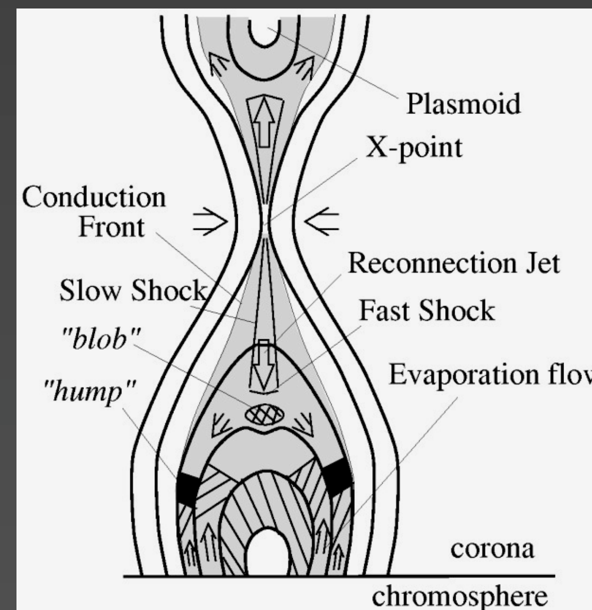
No relation seen between X-ray flares and accretion variations in ~800 simultaneously monitored Orion stars.

No difference in X-ray flaring of ~100 accreting (CTT) and non-accreting (WTT) Taurus stars.

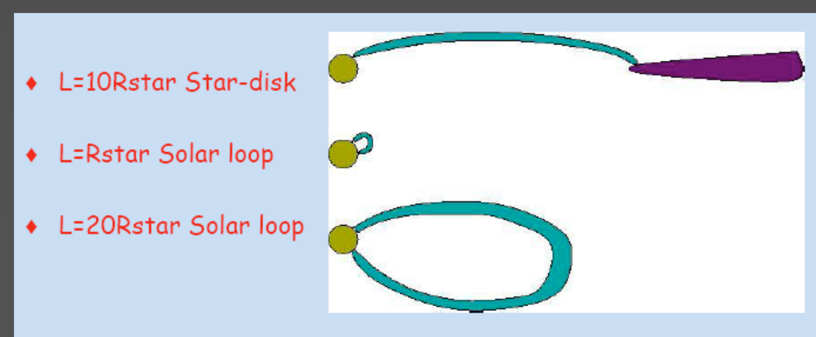
Stassun et al. 2006 & 2007 Stelzer et al. 2007

Radiative/hydrodynamic models of powerful COUP flares are well-fit by solar plasma loop model



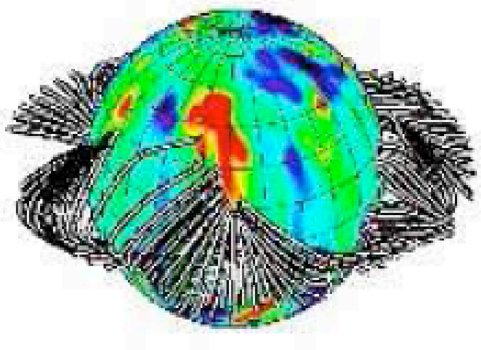


Brightest COUP flares require giant loops ~10 R_* Star/disk magnetic fields?

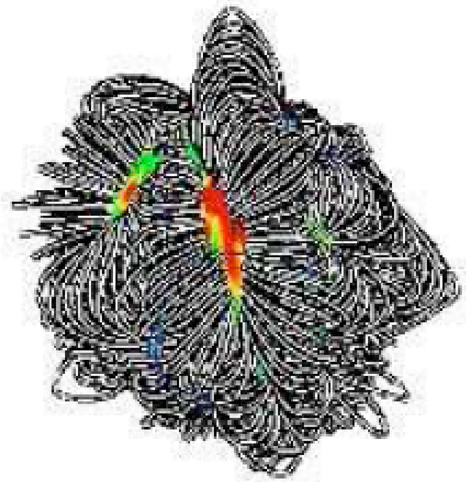


Favata & 7 others 2005 COUP #7

T Tauri X-rays thus arise from magnetic reconnection events in the corona



Open accreting field lines

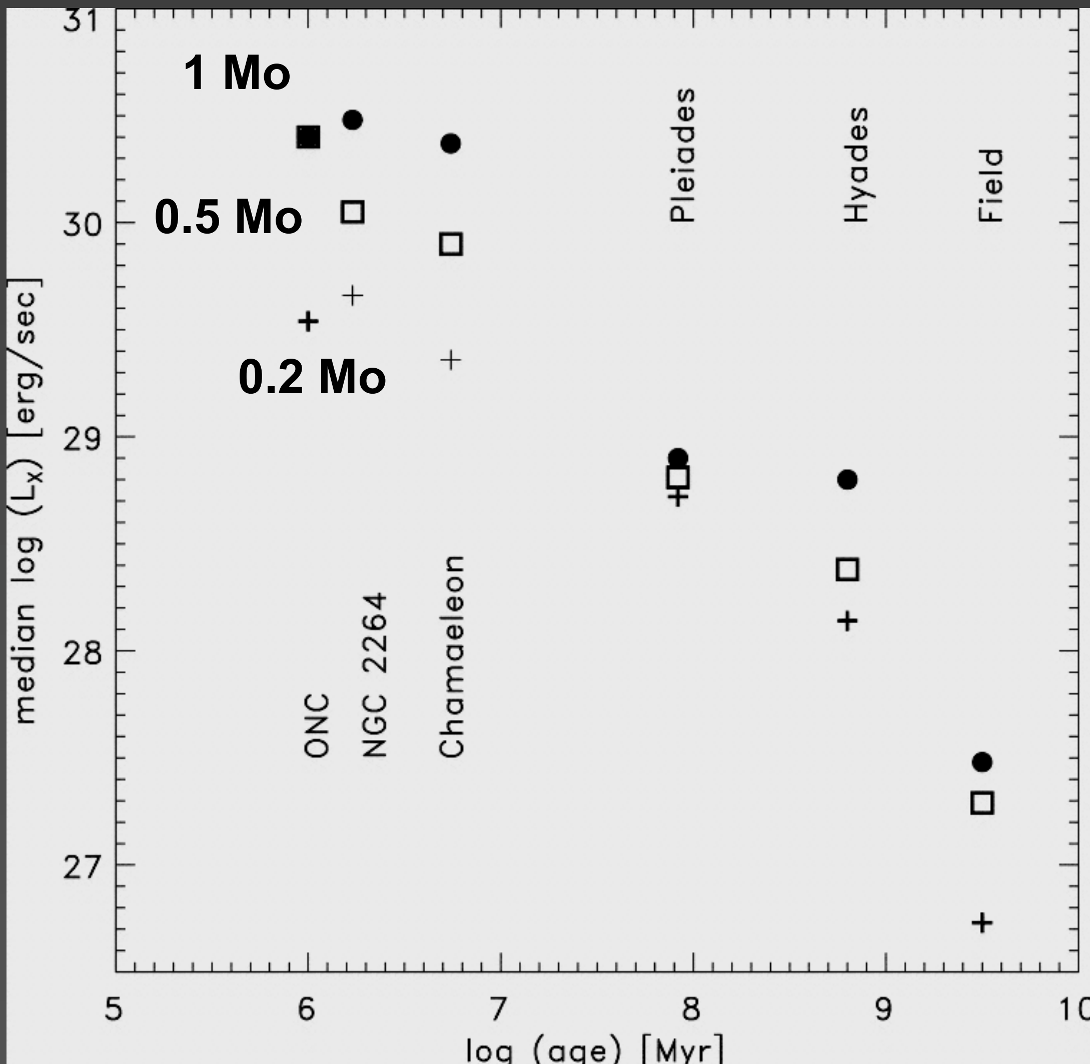


Closed plasma-filled field lines

Resulting X-ray corona (without flares)

Jardine et al. 2006

X-ray levels elevated throughout planet formation epoch



X-ray levels decline only slightly during Class I-II-III phases

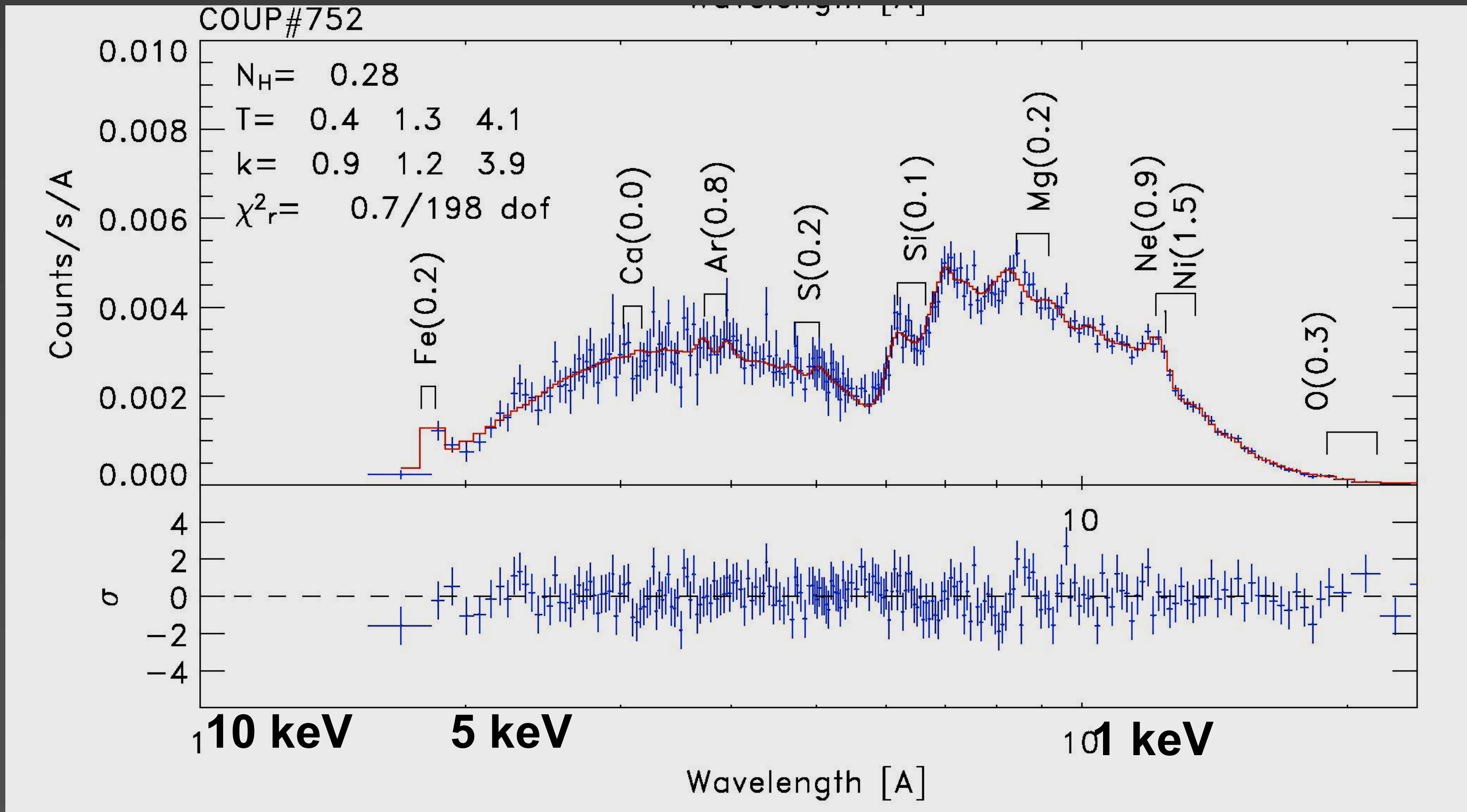
…

but drop rapidly on the main sequence

Preibisch & Feigelson 2005
COUP #4

X-ray spectra often extend to very high energies

with abundance anomalies similar to older flaring stars



Maggio et al. 2007 COUP #17

Note that pre-2000 studies showed only <2 keV due to poor telescopes. Chandra/XMM see <8 keV and models sometimes infer X-rays out to 15-20 keV.

X-rays can irradiate protoplanetary disks

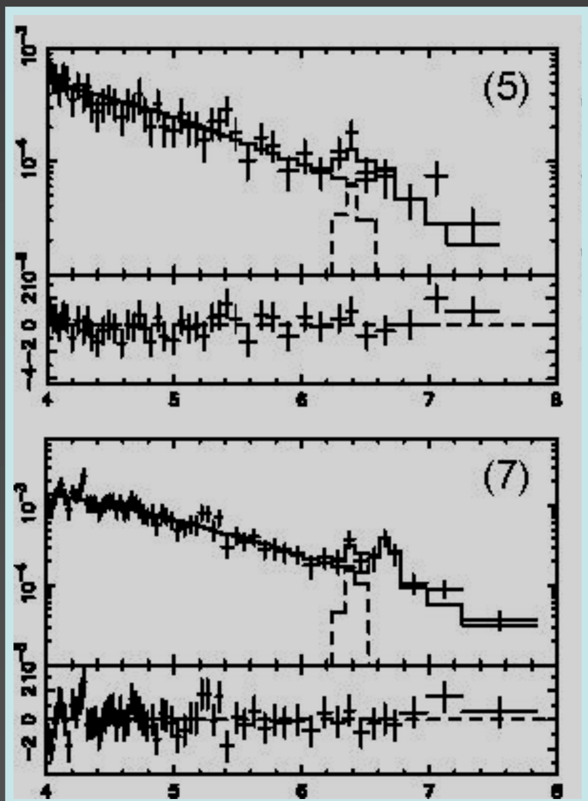
1. Some systems show evidence of reflection of X-rays off of the disk: the fluorescent 6.4 keV iron line

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

Iron fluorescent line

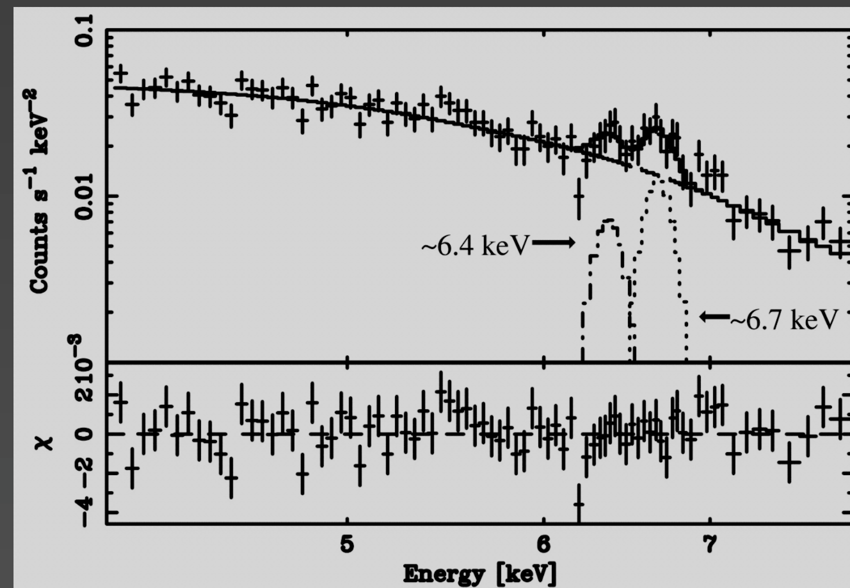
Cold disk reflects flare X-rays

COUP spectra

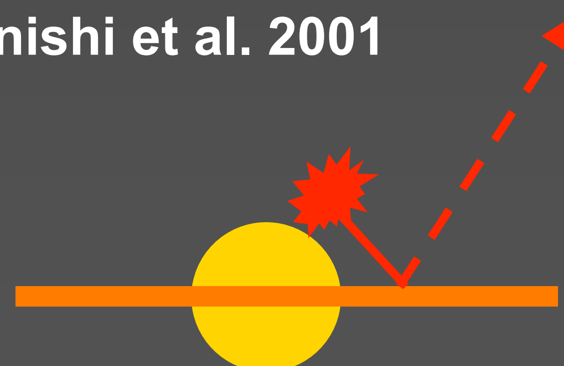


Tsujimoto & 7 others 2005 COUP #8

YLW 16A: protostar in Oph

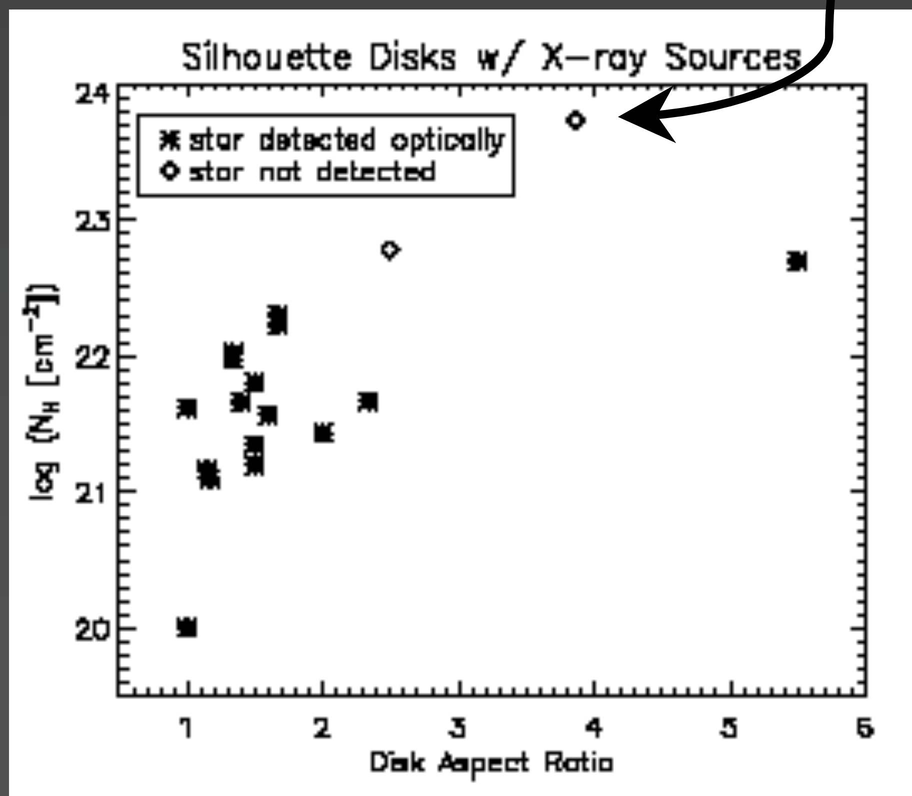


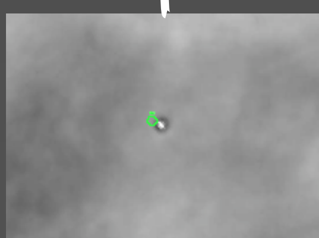
Imanishi et al. 2001



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

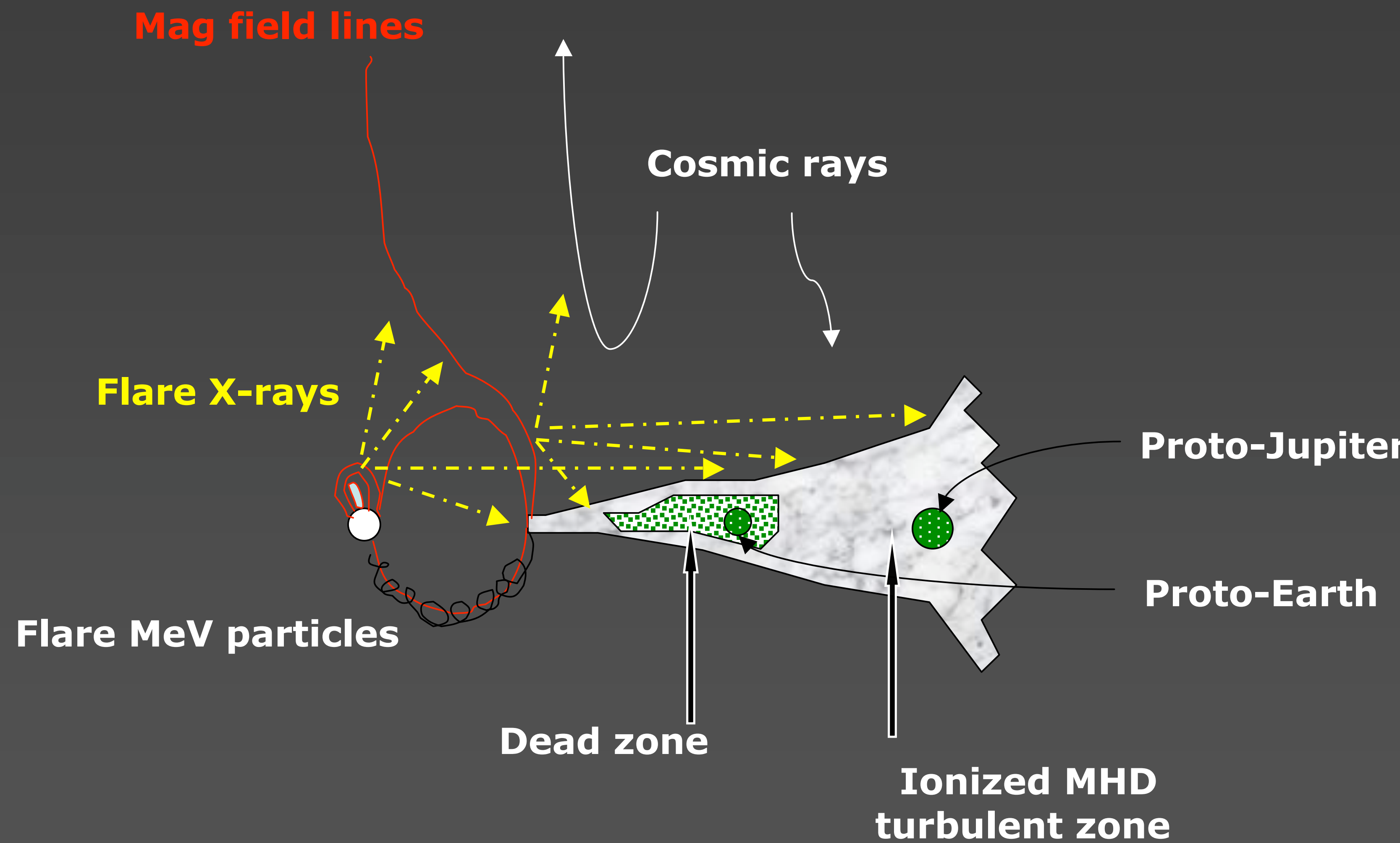




First measurement of <u>gas</u> content of UV-irradiated photoevaporating disks?

Kastner & 7 others 2005 COUP #9

X-ray influence on planet formation



Feigelson 2003, 2005

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:

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

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; 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

- **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**

  >50 studies

Protoplanet migration in a turbulent disk

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.

Laughlin et al. 2004 and other groups

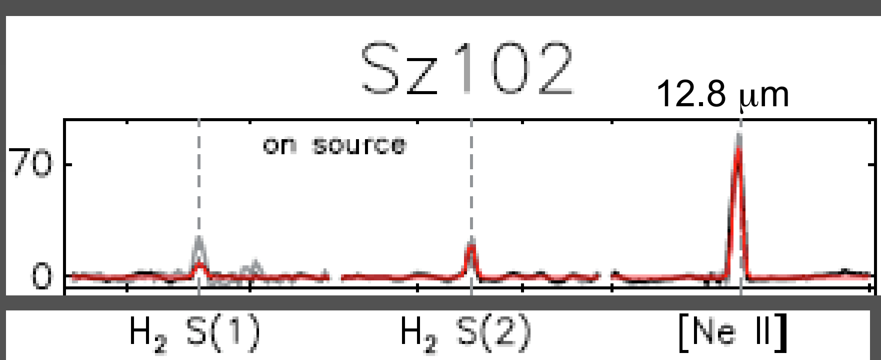
X-ray irradiation effects on disk gases

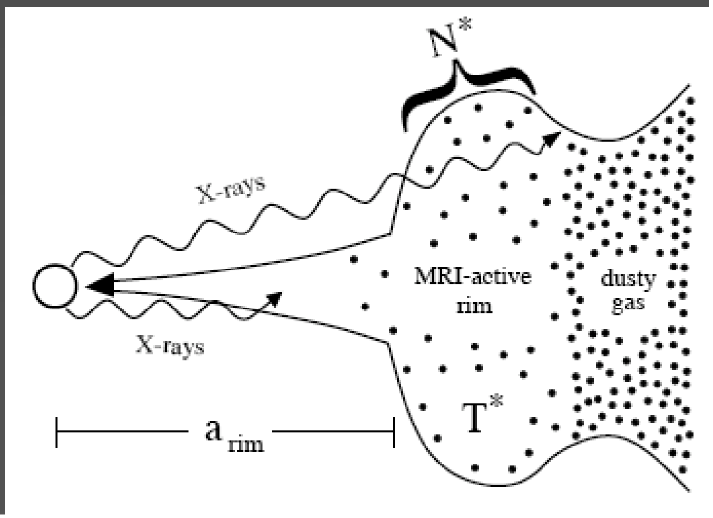
Heating of outer gas to T>3000K causing excitation of H_2, H_2O, CO lines
Najita et al. 2003; Bary et al. 2003; Carr et al. 2004; Glassgold et al. 2004; Alexander et al. 2004; Bitner et al. 2007; Stauber et al. 2007

Ionization of outer gas and emission of mid-IR [NeII] lines
Glassgold et al. 2007; Pascucci et al. 2007; Lahuis et al. 2007

Sublimation of ices & destruction of H_2O
Greaves 2005; Ceccarelli et al. 2005; Stauber et al. 2006

Evacuation of inner disk edge in transitional disks
Chiang & Murray-Clay 2007

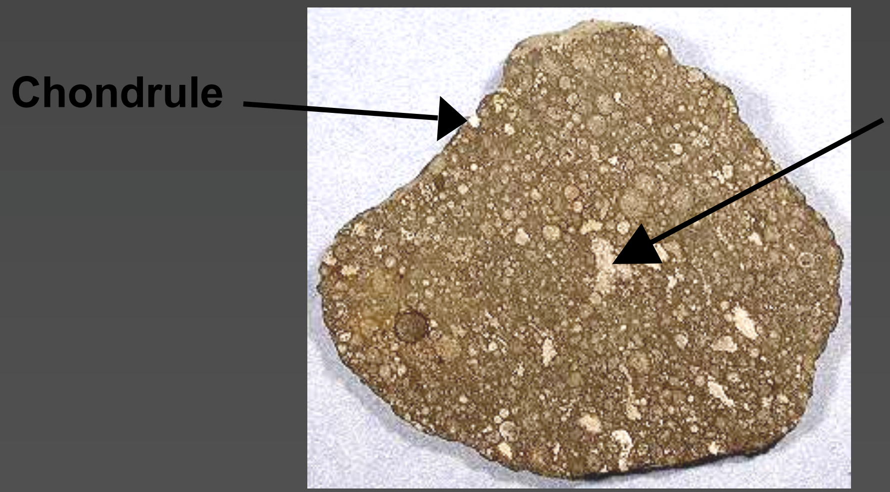




Magnetic reconnection flares may affect disk solids

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

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



Allende meteorite

3. *Flare X-rays may have annealed amorphous dust into crystalline silicates in T Tauri disks* Watson et al. 2007

Planetary systems form in

cool dark disks ….

which are irradiated by 10^8 violent

magnetic reconnection flares