X-rays and protoplanetary disks

Eric Feigelson (Penn State)

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 thermodynamics, chemistry, dynamics (esp. turbulence) and solids, thereby influencing the processes of planet formation.

ALMA: Through Disks to Stars and Planets June 2007
Planet formation occurs in disks at $T \sim 100-1000$ 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)

- ~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 $0.1 < r < 10 R_*$. 

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 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.
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**

**YLW 16A: protostar in Oph**

**Imanishi et al. 2001**

**Tsujimoto & 7 others**
2005  COUP #8

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

First measurement of gas content of UV-irradiated photoevaporating disks?

Kastner & 7 others 2005 COUP #9
X-ray influence on planet formation

Mag field lines

Cosmic rays

Flare X-rays

Flare MeV particles

Dead zone

Ionized MHD turbulent zone

Proto-Jupiter

Proto-Earth

Feigelson 2003, 2005
X-rays & disk ionization

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

$$\xi = 6 \times 10^{-9} \left( \frac{L_x}{2 \times 10^{30} \text{ erg s}^{-1}} \right) (r/1 \text{ AU})^{-2} \text{ s}^{-1}$$

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


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**
  

- **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 $T>3000$K 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* (\(^{10}\text{Be},^{21}\text{Ne},^{41}\text{Ca},^{53}\text{Mn}, \ldots\))
   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

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