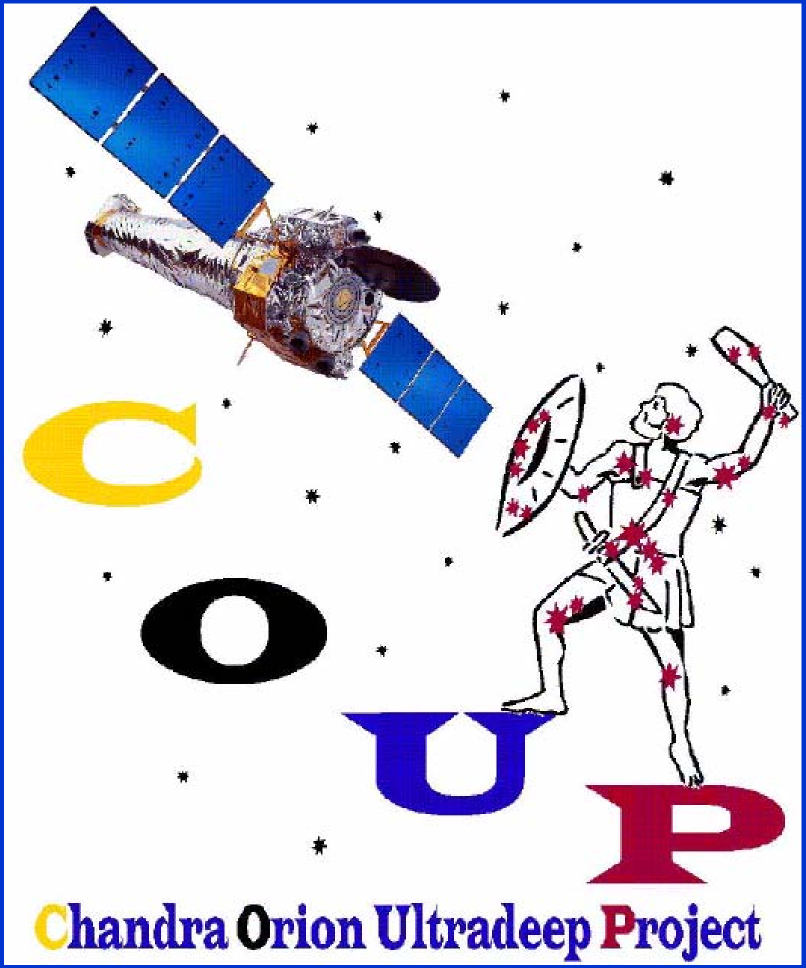


The Chandra Orion Ultradeep Project

Eric Feigelson
(Penn State)
& the COUP Team

Outline of talk

1. Introduction to COUP

2. X-ray flares & the magnetic geometry of YSOs

3. Implications of X-rays for star & planet formation

COUP: Chandra Orion Ultradeep Project

9.7 day nearly-continuous exposure of the Orion Nebula, Jan 2003

Principal Investigator: Eric Feigelson (Penn State)

Group leaders:

Data reduction & catalog	Kosta Getman (Penn State)
X-ray spectra & variability	Giusi Micela (INAF-OA Palermo)
Optical variability	Keivan Stassun (Vanderbilt)
Origin of T Tauri X-rays	Thomas Preibisch (MPIfR)
Embedded stars	Nicolas Grosso (Grenoble)
Brown dwarfs	Mark McCaughrean (AIP)
Massive stars	Thierry Montmerle (Grenoble)
Effects of X-rays	Francesco Palla (Arcetri)

Participating COUP scientists:

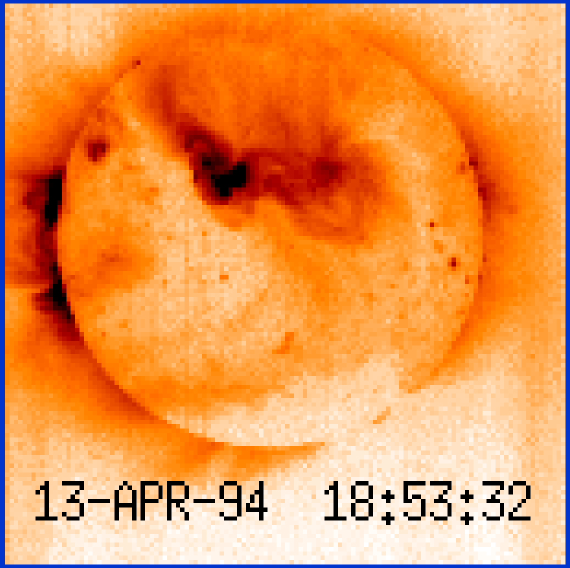
John Bally	Patrick Broos	Paola Caselli	Francesco Damiani
Fabio Favata	Ettore Flaccomio	Gordon Garmire	Alfred Glassgold
Rick Harnden	William Herbst	Lynne Hillenbrand	Joel Kastner
Charles Lada	Andrea Lorenzani	Antonio Maggio	Gwendolyn Meeus
Thierry Morel	Gus Muench	Fabio Reale	Norbert Schulz
Salvotore Sciortino	Hsieh Shang	Beate Stelzer	Leisa Townsley
Yohkoh Tsuboi	Masahiro Tsujimoto	Maureen van den Berg	Saku Vrtilek
Scott Wolk	Hans Zinnecker		

13 papers with COUP results will appear in a special issue of ApJ Suppl, Oct 2005

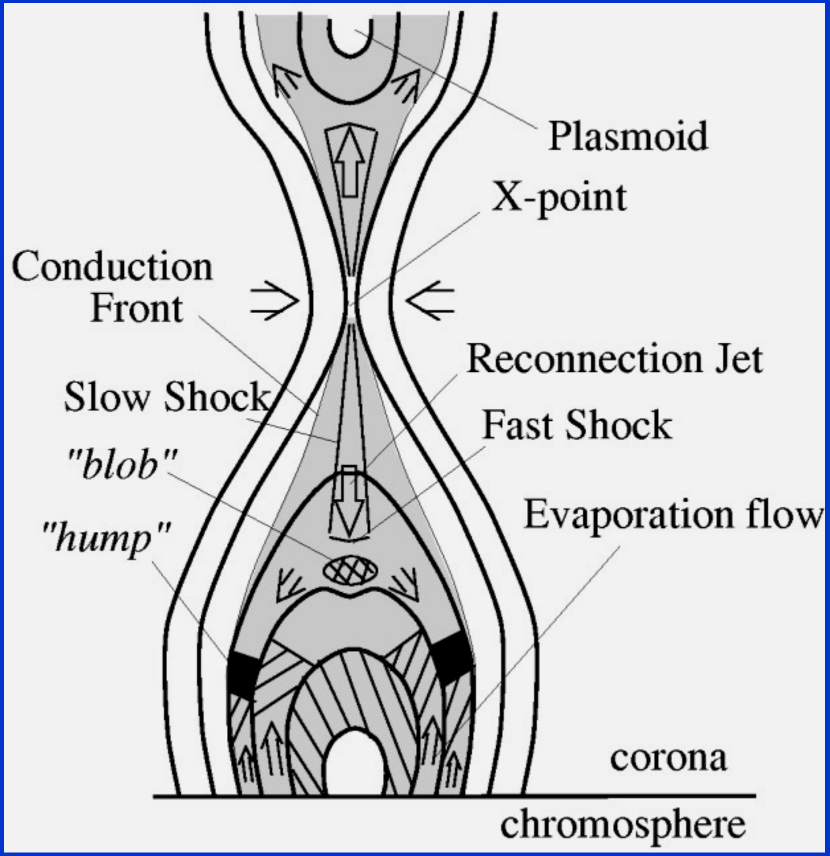
Visuals, full text papers, source lists/properties, and the 1616-page Source Atlas are available on-line at

www.astro.psu.edu/coup

Stellar X-rays arise from magnetic reconnection events and thus trace the MHD of stellar interiors



Yohkoh view of the X-ray Sun



Yokohama & Shibata 1998

The Orion Nebula

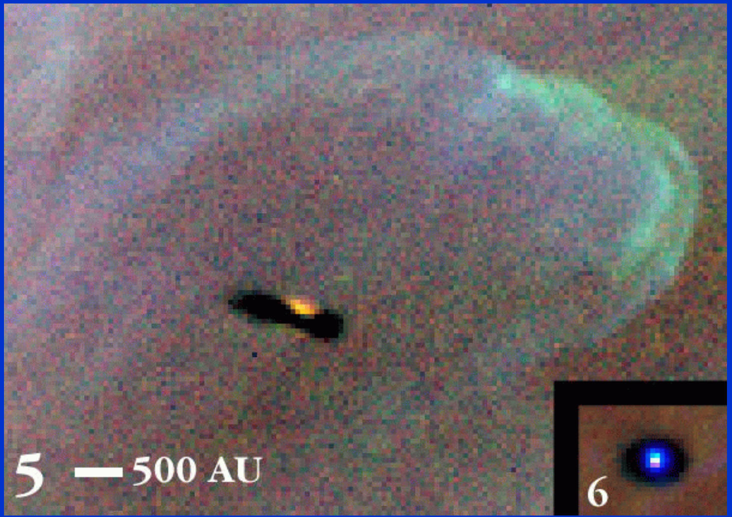
Orion Nebula Cluster

~2000 members

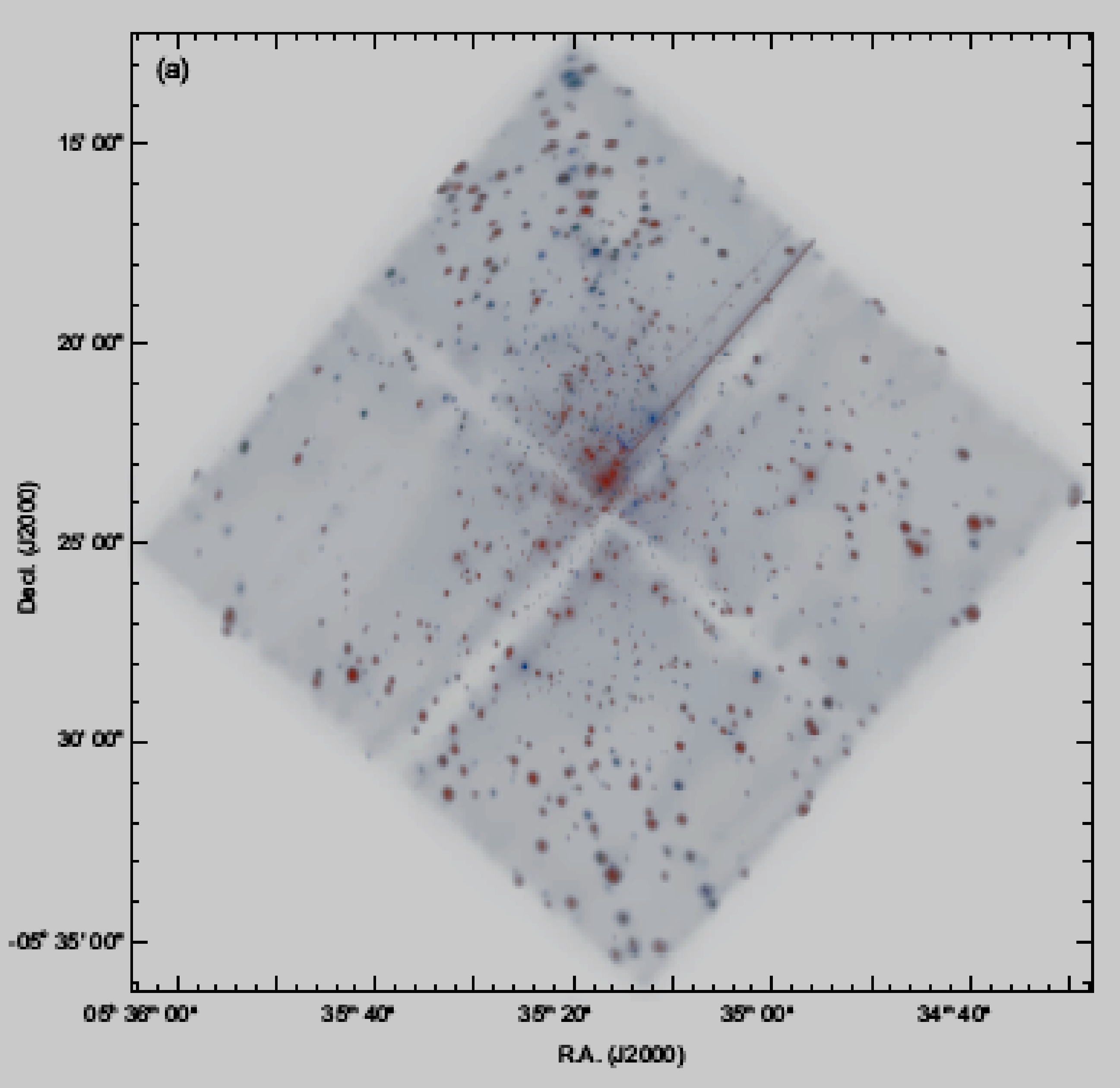
$0.003 < M < 45\ M_o$

Active star formation in the OMC 1 clouds

Likely planet formation in proplyds

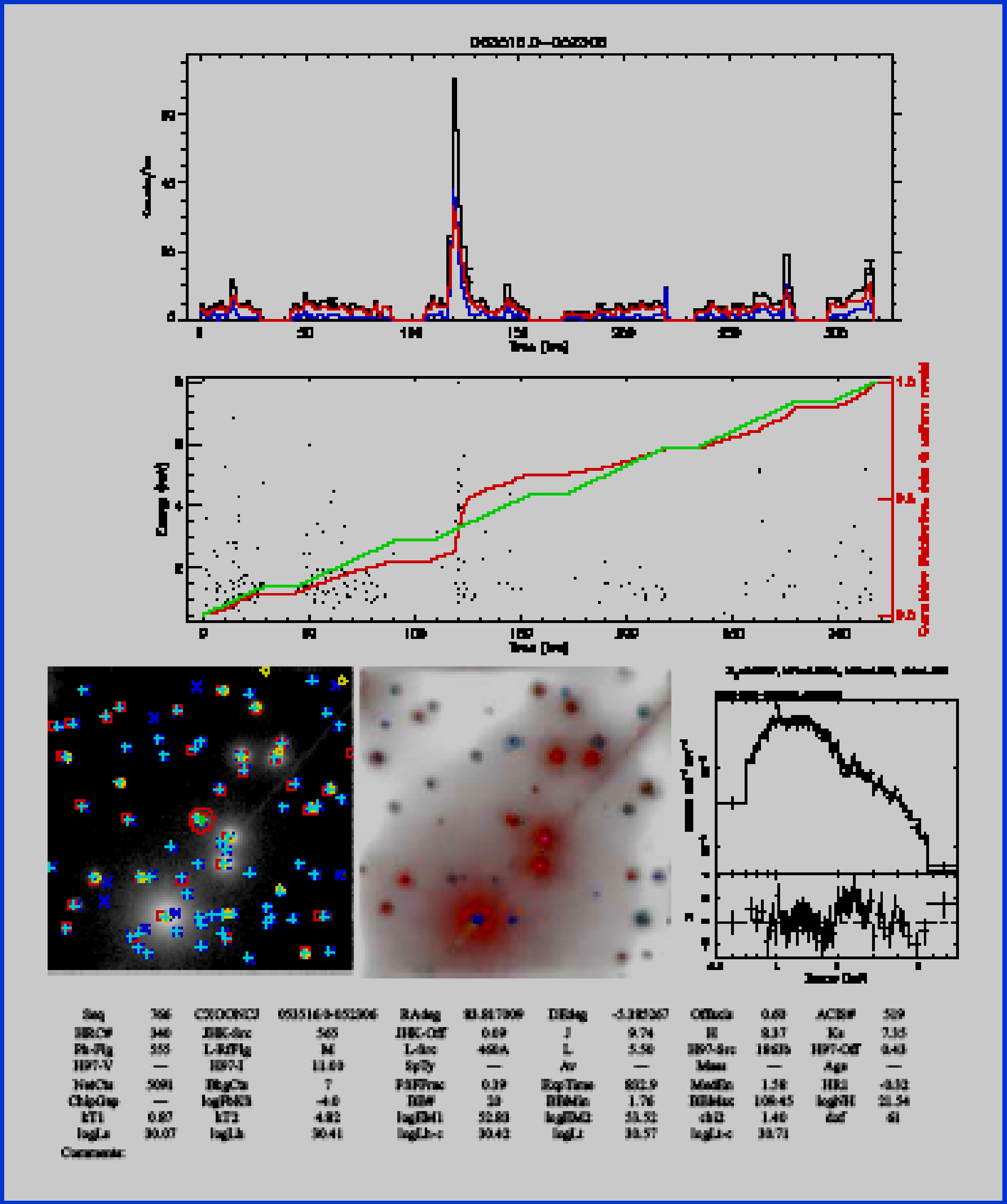


The
COUP
Image



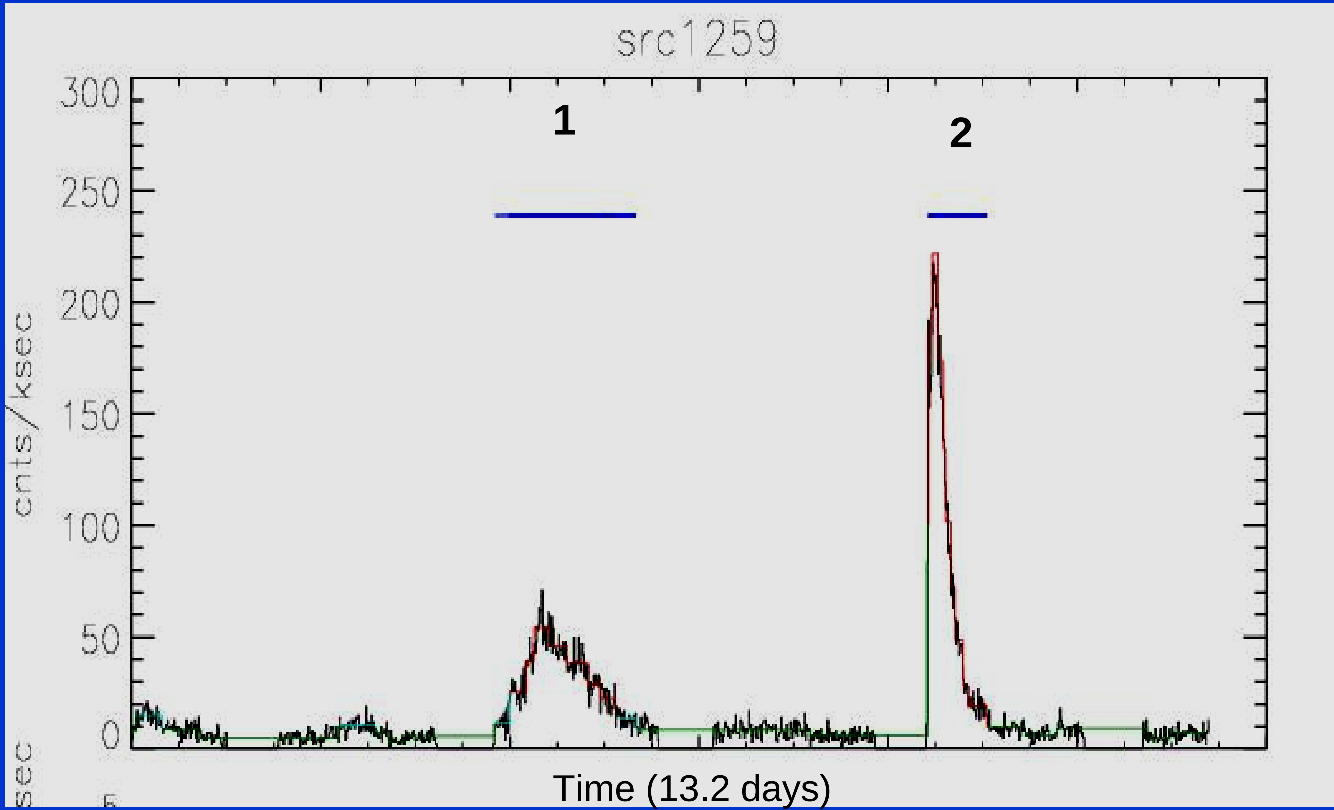
Getman & 22 others 2005 COUP #1

Example of the 1616 COUP Source Atlas pages




Chandra X-ray

Extraordinary flares in analogs of the young Sun



JW 738

V=15.7 K=10.5
Age ~ 10 Myr

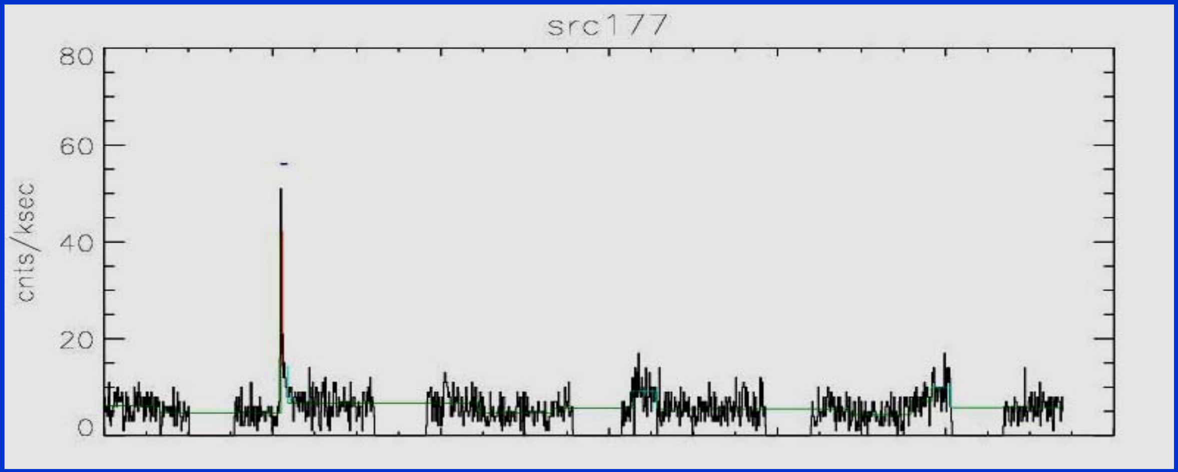
log Lc = 30.7 erg/s
log Lp = 32.6 erg/s

Flare 1: Unusual slow-rise slow-decay morphology.

Flare 2: One of the most powerful X-ray flares ever seen in any late-type star with $E_x \sim 10^{36.8}$ erg.

Wolk & 7 others 2005 COUP #6

Short flares in solar analogs



JW 223a

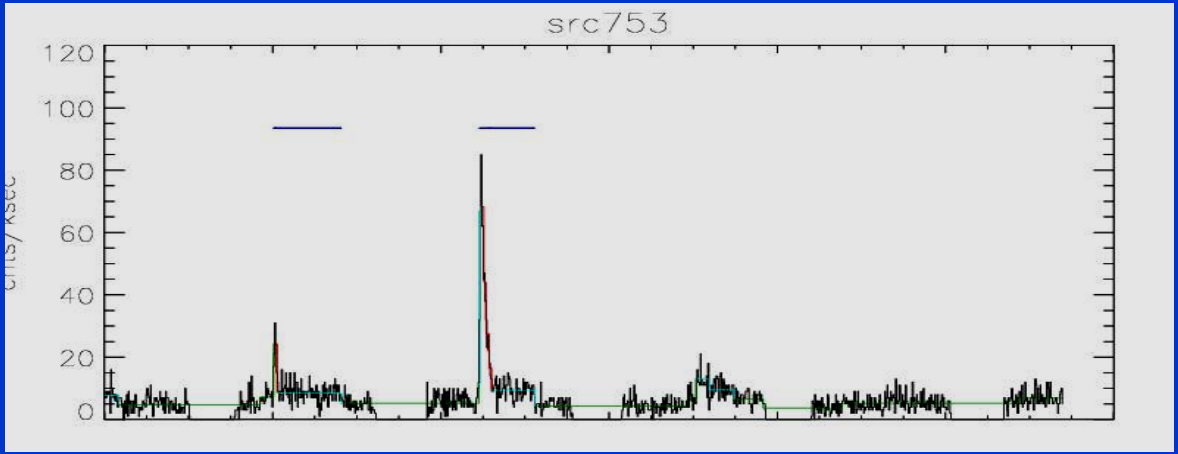
V=16.1 K=10.1

Age=2 Myr

K excess

log Lc = 30.3 erg/s

log Lp = 31.2 erg/s



JW 487

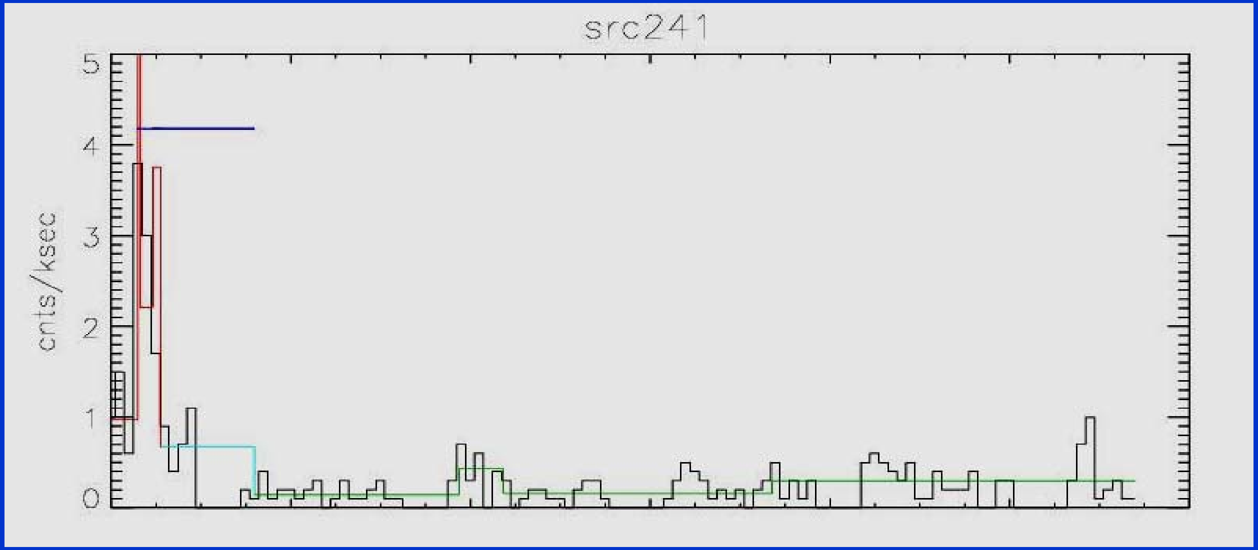
V=14.6 K=10.3

Age=2 Myr

log Lc = 30.1 erg/s

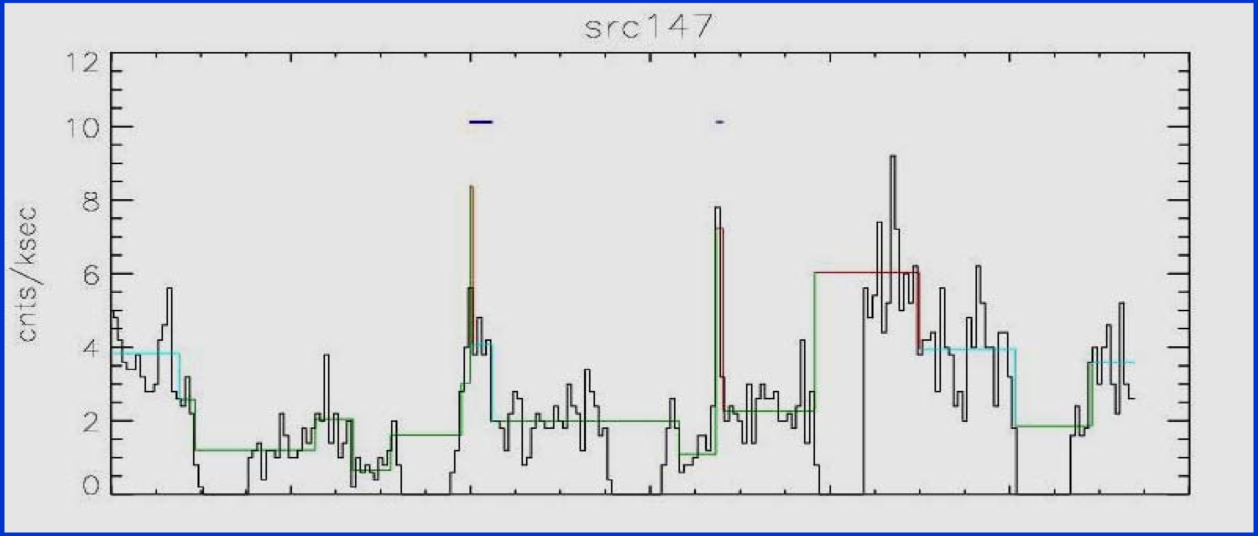
log Lp = 31.4 erg/s

Two weaker solar analogs



JW 268
V=14.5 K=10.8
Age=3 Myr

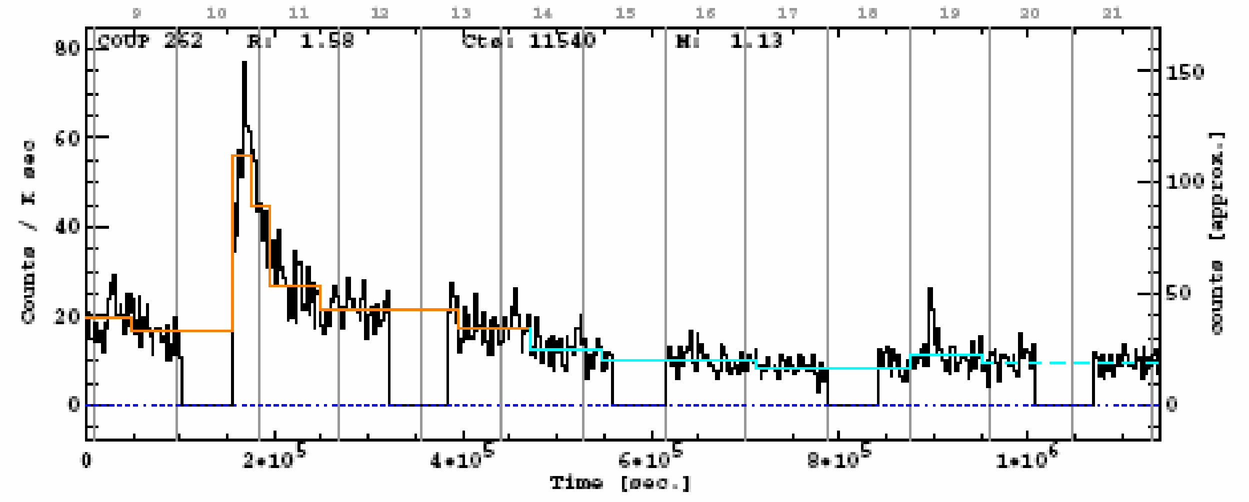
log Lc = 29.0 erg/s
log Lp = 29.5 erg/s



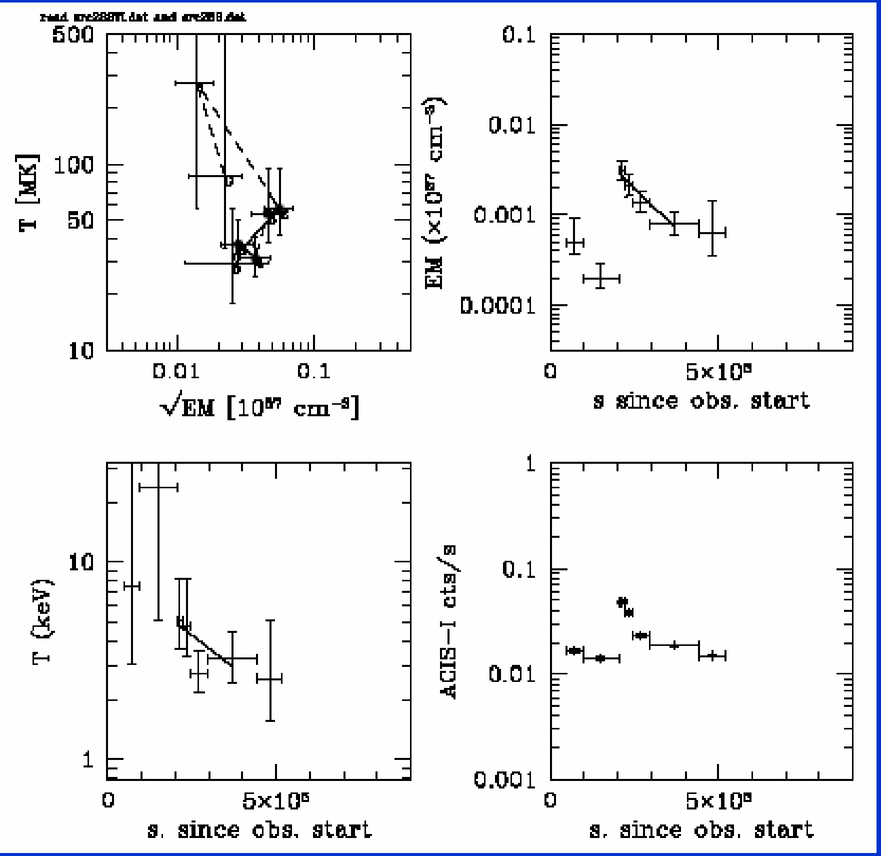
JW 198
V=15.4 K=10.4
Age=15 Myr
Proplyd, K excess

log Lc = 29.5 erg/s
log Lp = 29.9 erg/s

Even these weak COUP flares are ~10x stronger than the most powerful flares from the contemporary Sun.



COUP 262

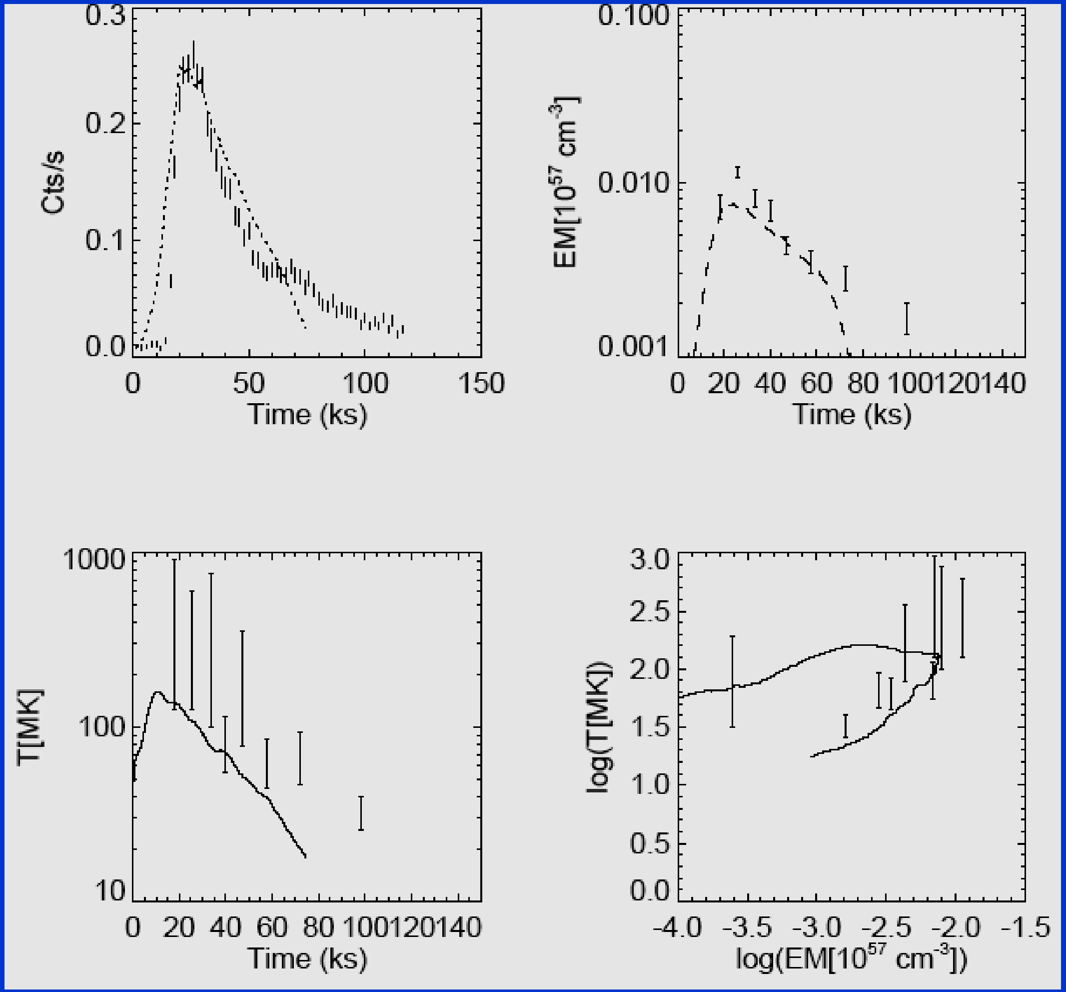


This is a M=1.1 M_o solar analog with strong IR excess.

Flare peak logL_x=31.6 erg/s with slow decay and sustained heating with derived loop

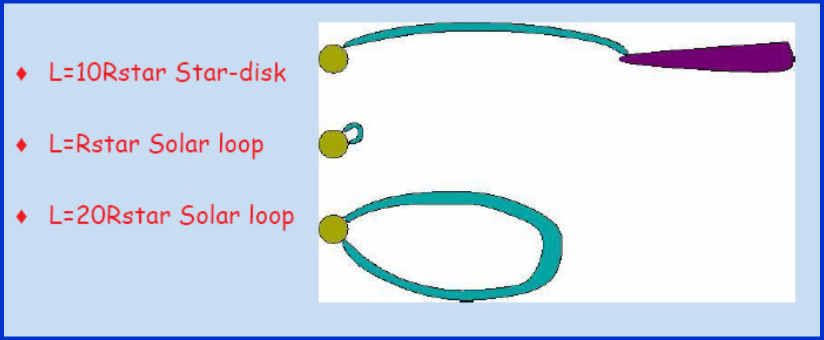
L ~ 28 R_o ~ 3 R_*

Favata & 8 others 2005 COUP #8



Detailed hydrodynamic modeling of COUP 1343 flare shows good fit to solar-like flare model.

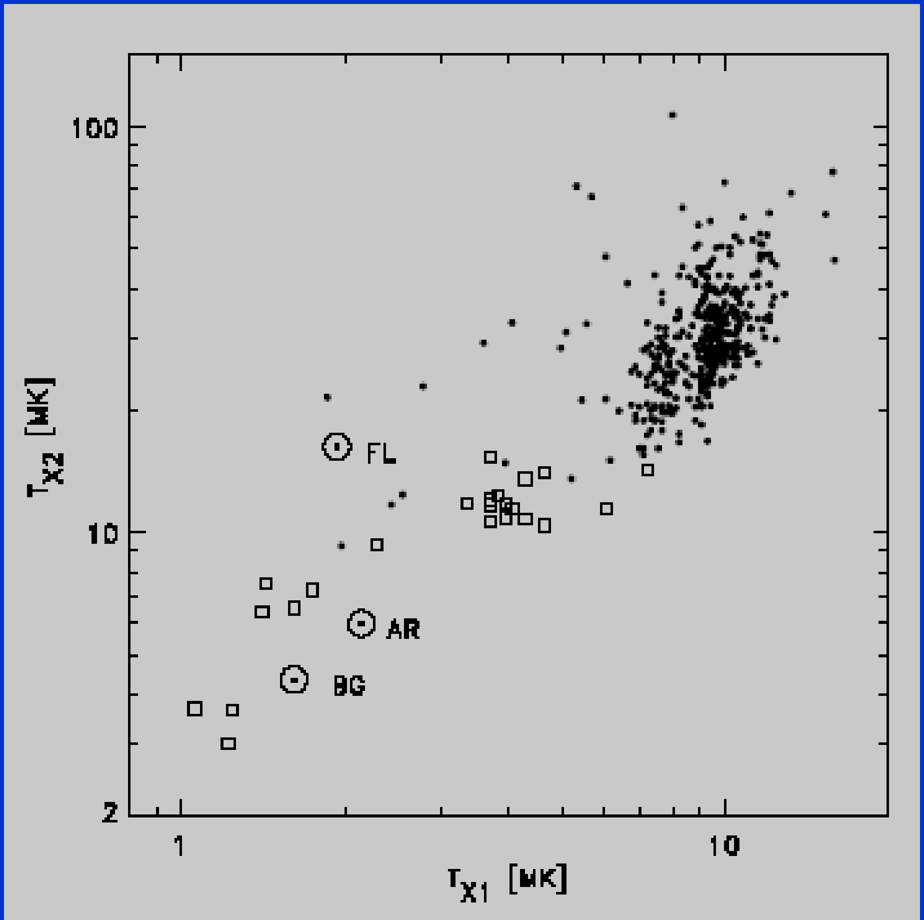
Is this direct evidence for star-disk magnetic fields? Is the flare plasma fed by the disk?



Micela 2005

Other COUP flare properties resemble older stars

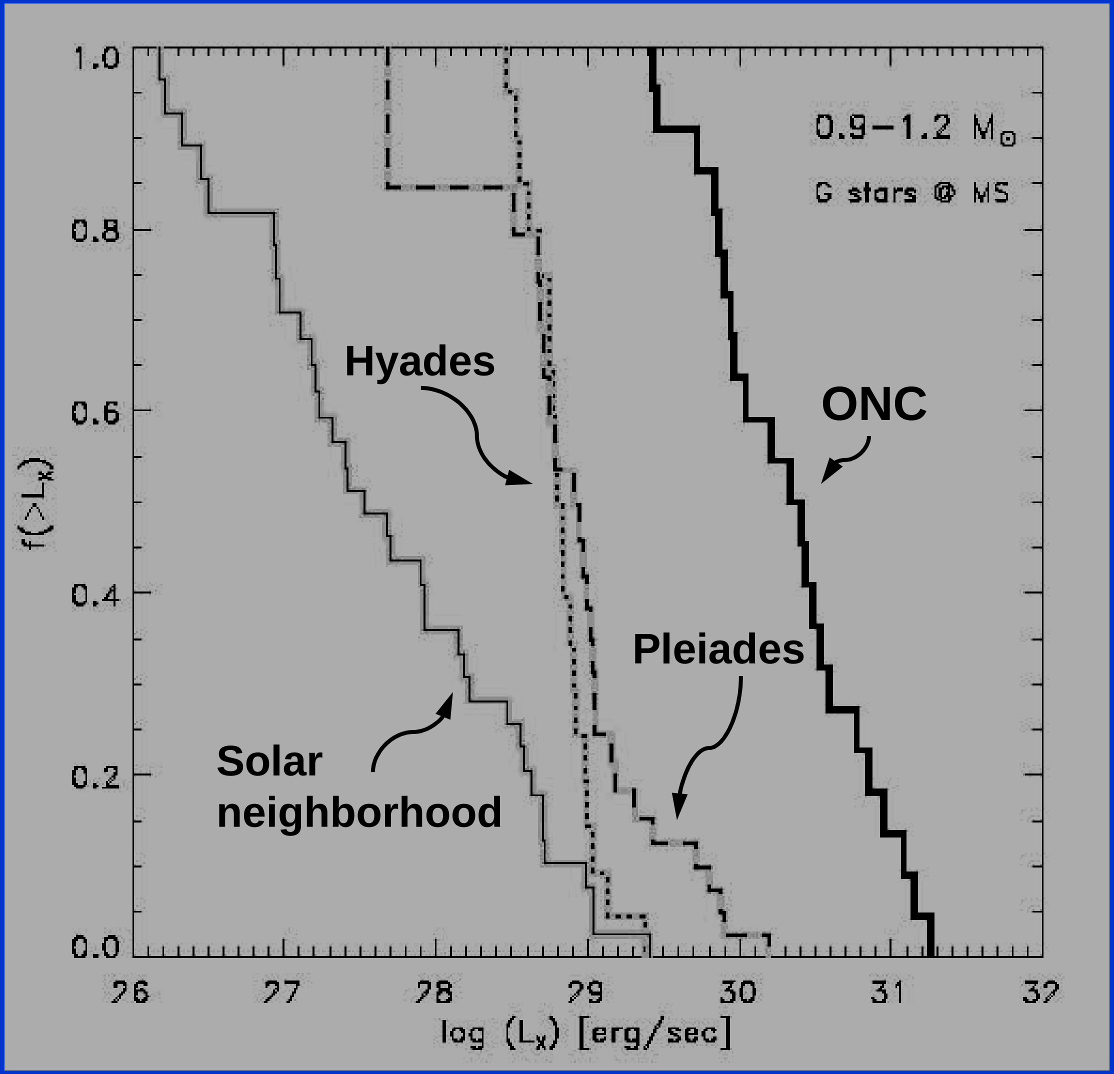
Plasma temperatures of PMS stars extend relationship seen for active MS stars (squares) and Sun (circles).



Preibisch et al. 2005, COUP #5

Plasma abundance anomalies are the same as in older magnetically active stars (Maggio et al. 2005; poster here)

The evolution of X-ray emission in late-type stars



COUP clarifies the decay of magnetic activity for ages 1-100 Myr.

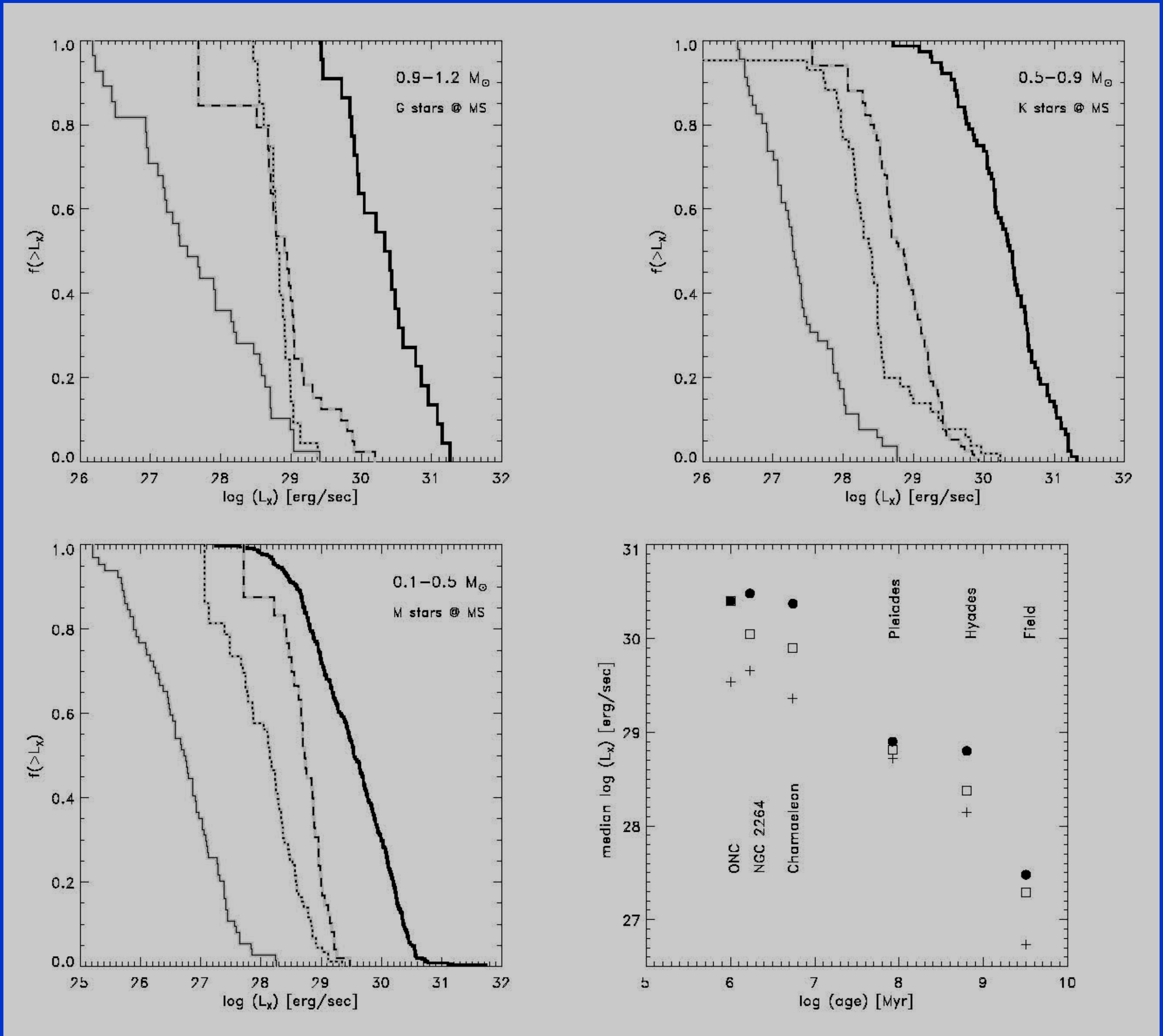
Explanation not obvious in light of complex rotational evolution history.

Preibisch & Feigelson 2005, COUP #4

Mass-stratified activity evolution relation

G stars

K stars

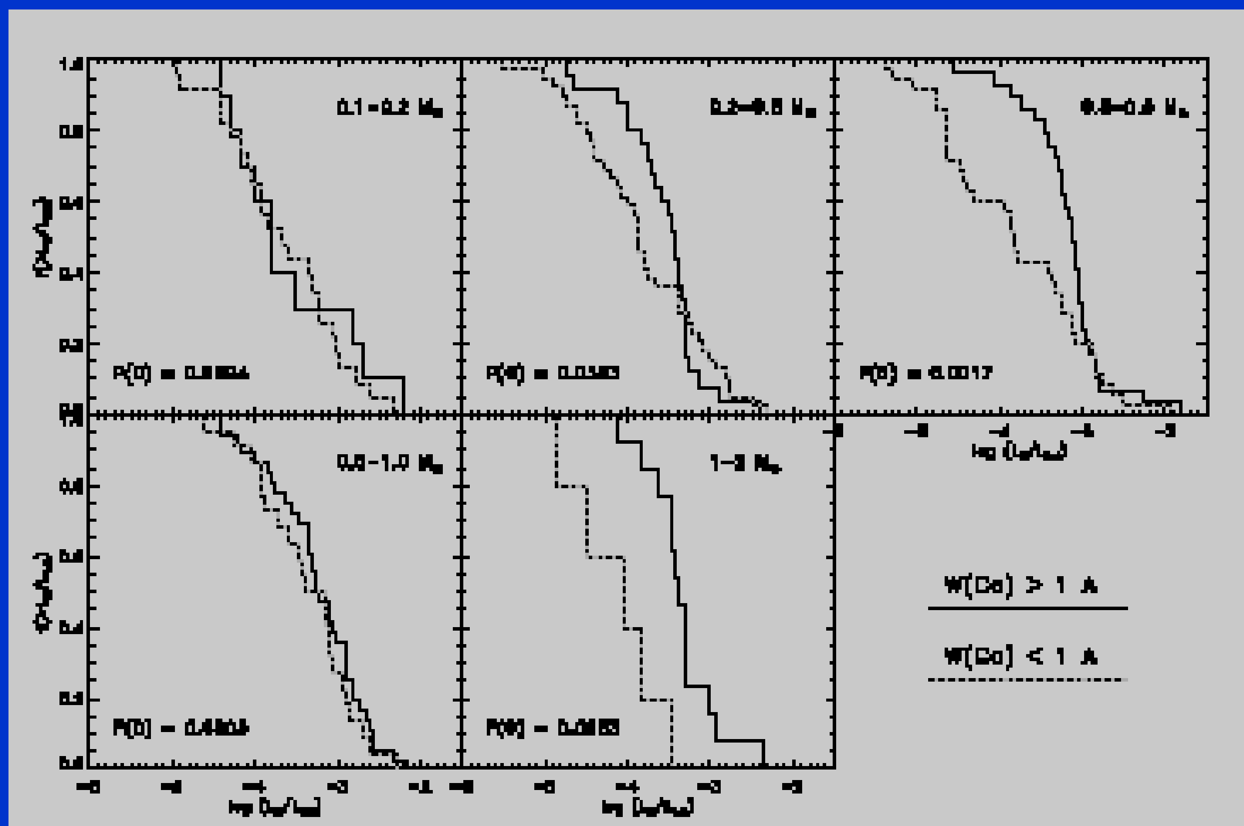


M stars

Evol of $\langle \log L_X \rangle$

Preibisch & Feigelson 2005, COUP #4

X-ray emission is statistically slightly (factor of 2) suppressed by accretion from disk onto star. Reason uncertain, but does not support model of X-ray <u>production</u> in the accretion shock.



Preibisch et al. 2005, COUP #5

Simultaneous sparse optical photometry simultaneous with COUP shows hundreds of stars with high-amplitude variations due to time-dependent accretion.

But none of these variations coincide with X-ray flares

Stassun et al. 2005

COUP, flares & magnetic geometry of YSOs

Flare morphologies, spectral evolution, temperatures, & abundances closely match solar-flare model

Flare behaviors not related to disk, and emission is suppressed by accretion

BUT …

Some (but not all) flare loops are longer than seen in other stars, perhaps extending to the disk

X-rays and star/planet formation

Star formation occurs in molecular cloud cores at T~10-100 K. Planet formation occurs in disks at T ~100-1000 K. These are thermodynamically neutral material (meV) with covalent bonds emitting IR-mm radiation.

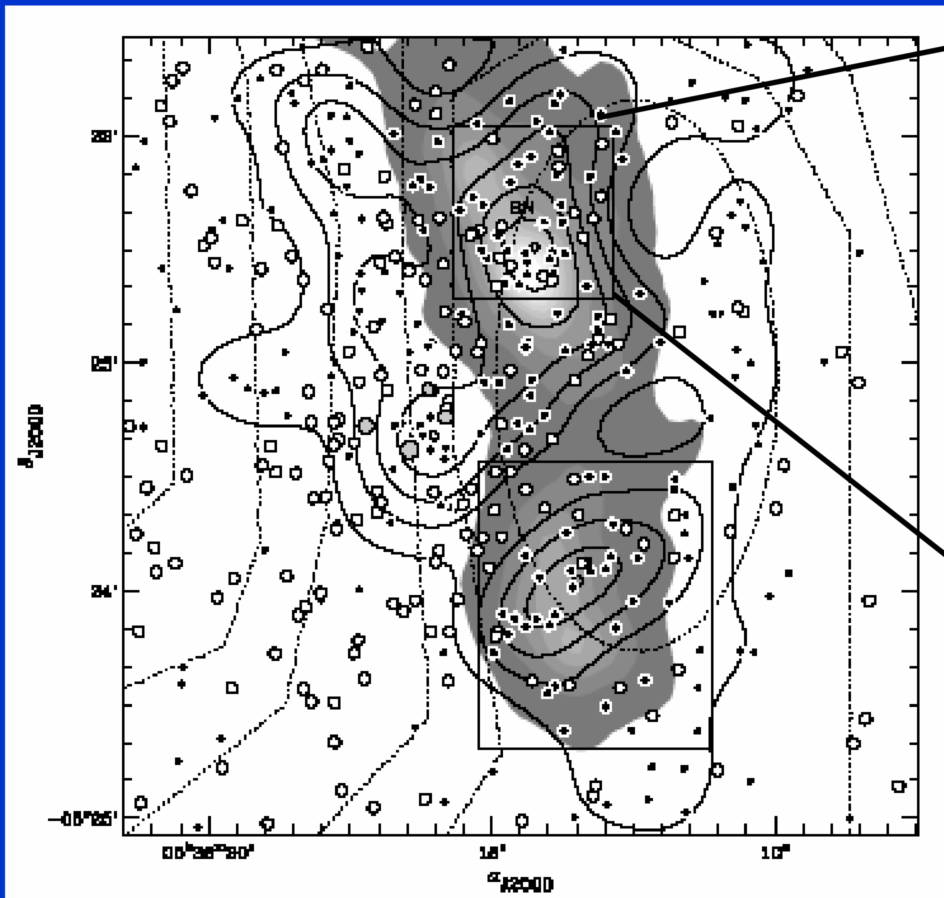
But high energy radiation is present in star/planet formation environments: keV photons & MeV particles produced in violent magnetic reconnection flares:

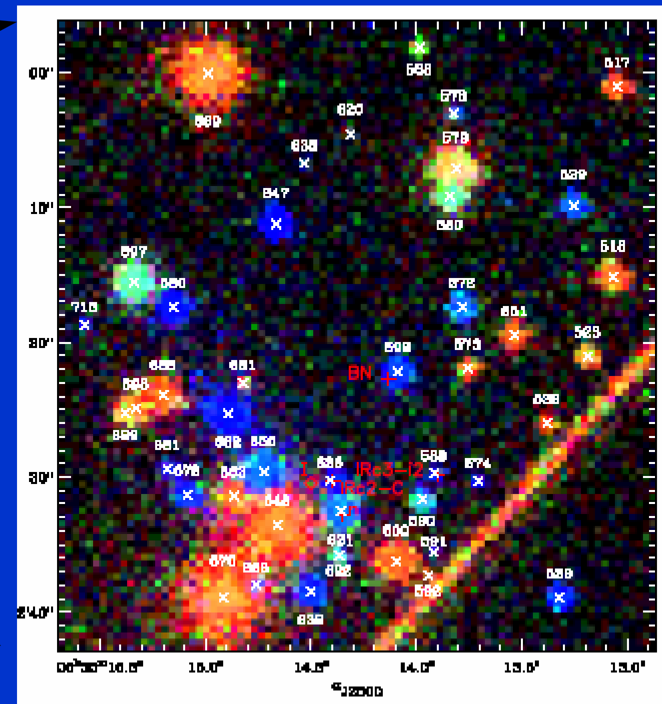
Do they non-trivially affect cloud/disk processes?
(heating, ionization, chemistry, turbulence, viscosity, shocks, melting & spallation of solids, ...)

Is there evidence for these effects in clouds, protoplanetary disks, extrasolar planets, the meteoritic record?

• X-ray effects on molecular cloud cores

COUP results on OMC-1: BN/KL & OMC1-S



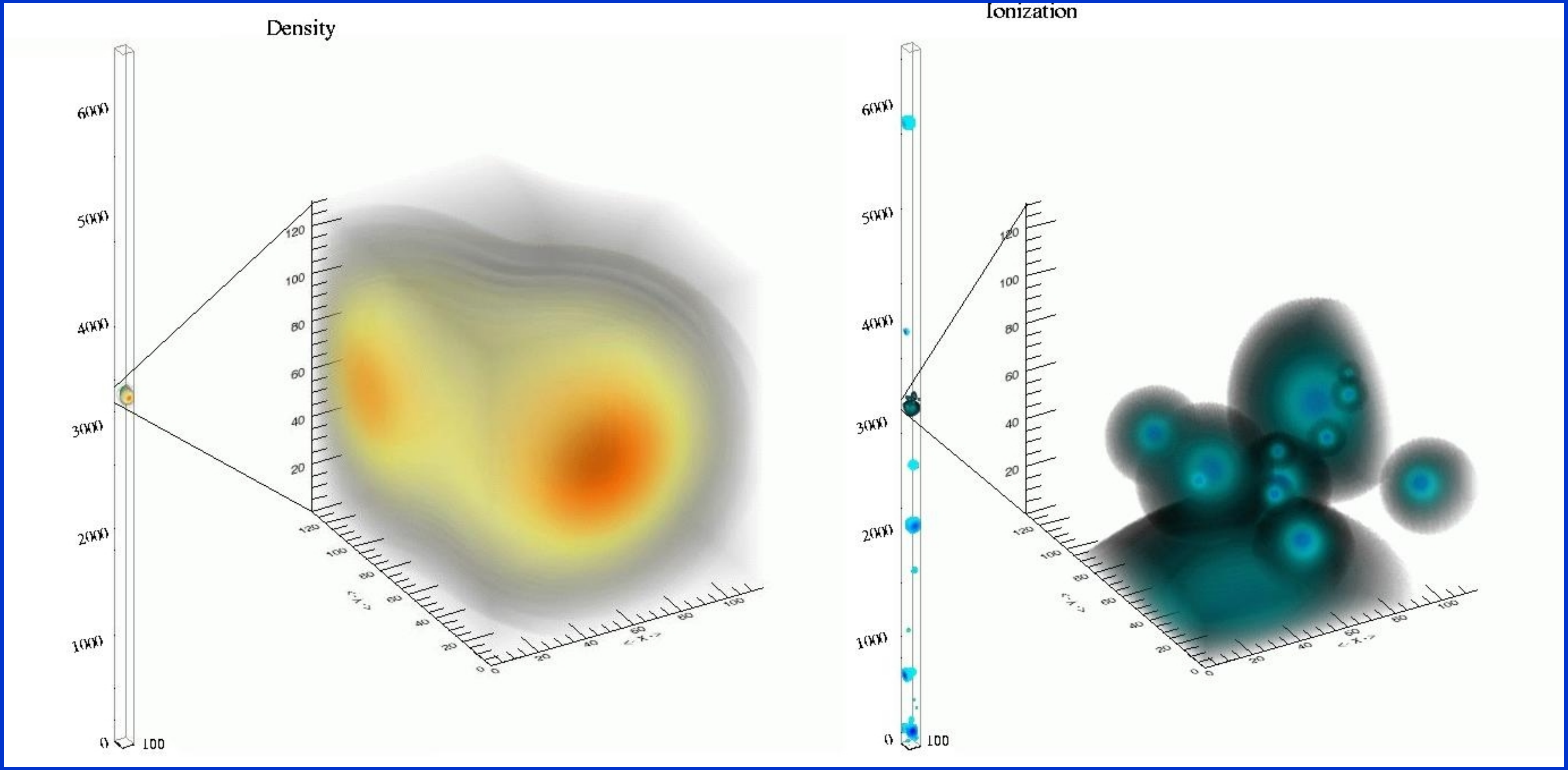


Open circles: logNH<22.0
Filled circles: log NH>22.0
Greyscale map: SCUBA

Low-mass population of BN/KL is surprisingly small for the nearest high-mass star forming region

Grosso & 14 others 2005 COUP #11

Three-dimensional calculation of X-ray Dissociation Regions in BN/KL



Result: X-ray ionization dominates CRs in ~20% of BN/KL core. Only 1-2% for OMC-1 South.

Lorenzani & Palla, in prep

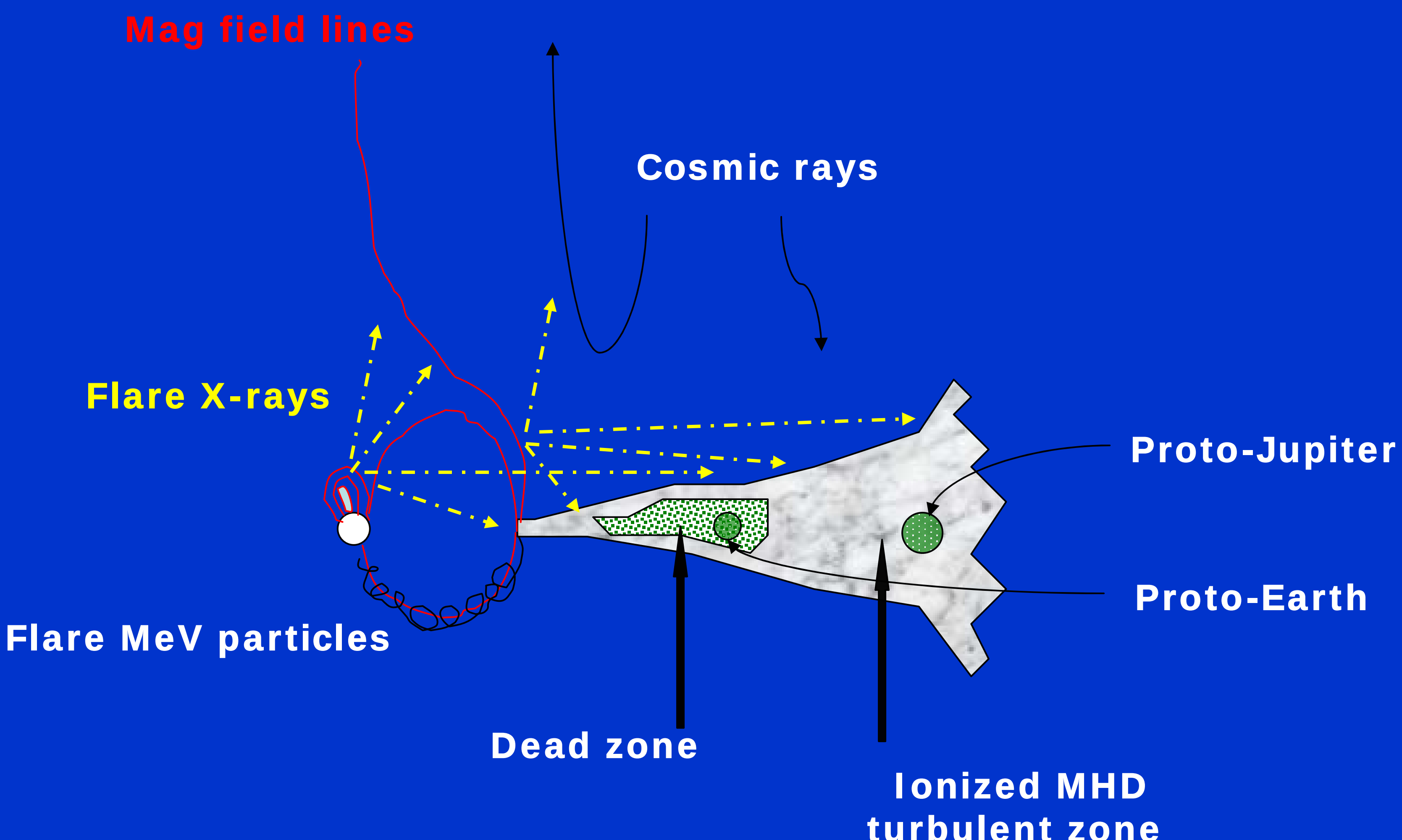
Tentative conclusions on XDRs

XDRs will significantly ionize cloud cores when a cluster (N > 20 stars with $M > 1\ M_\odot$) is embedded.

If XDRs suppress ambipolar diffusion, they may terminate growth of clusters and inhibit future SF in their vicinity.

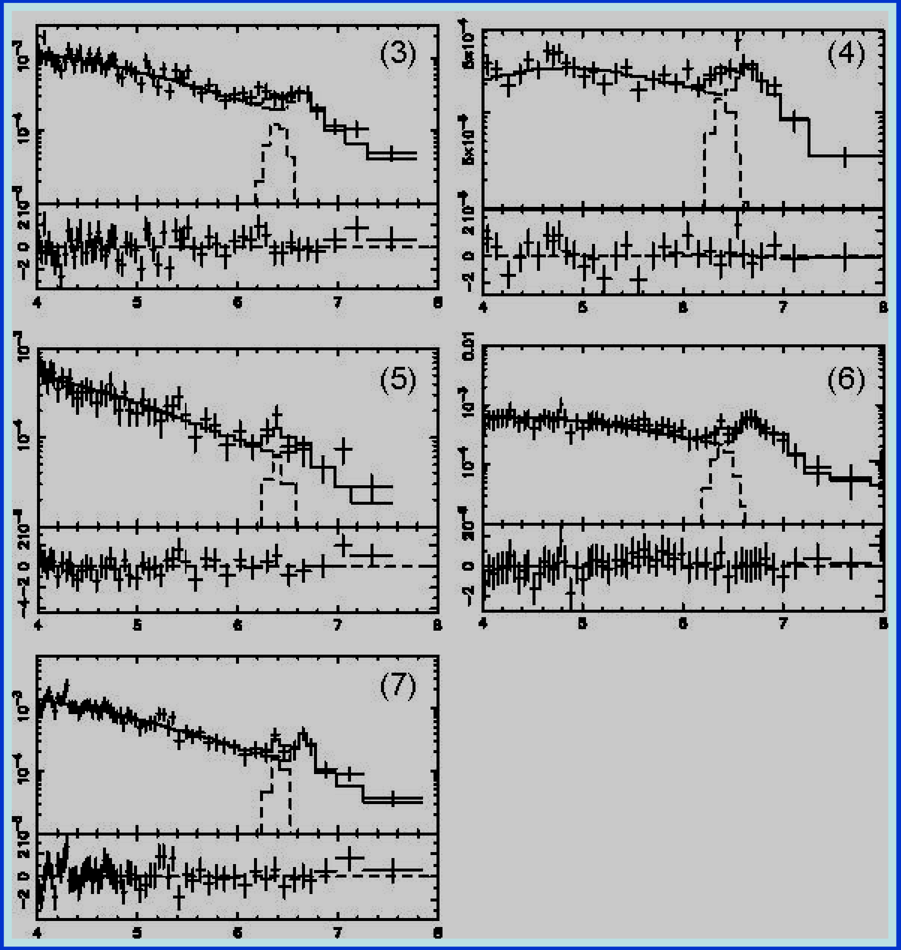
Thanks to Andrea Lorenzani & Francesco Palla of Arcetri Observatory for sharing these unpublished results

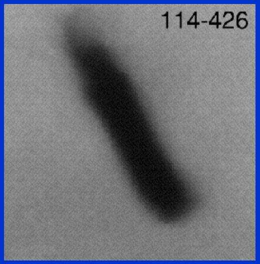
X-ray irradiation of disks

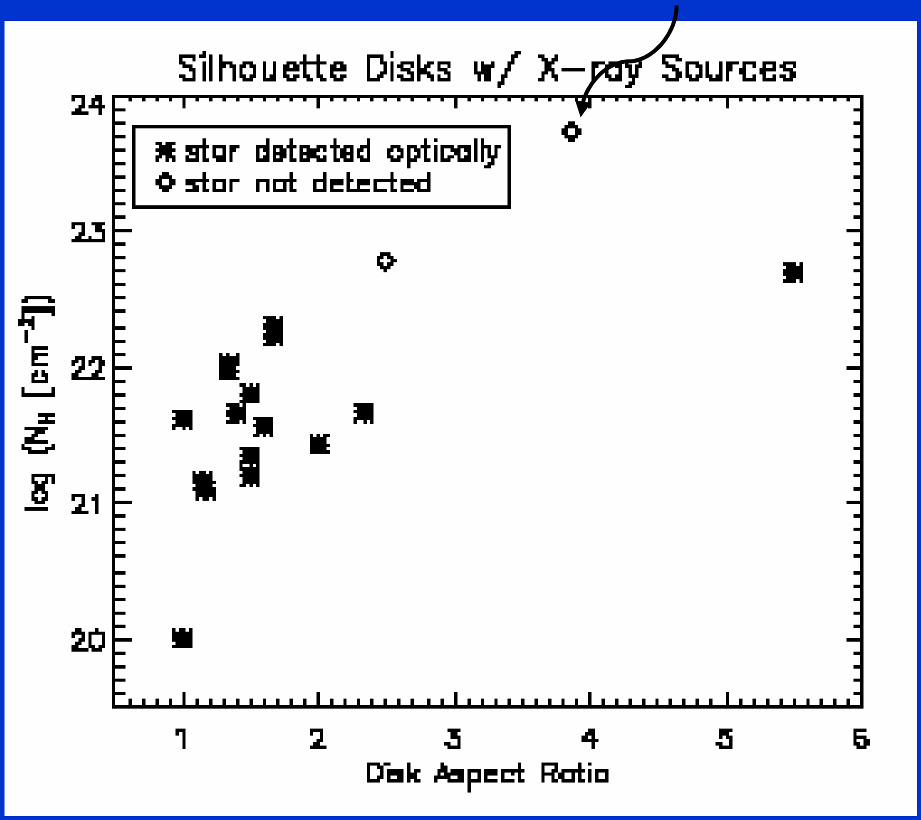


Feigelson 2003, 2005a, 2005b

Evidence for X-ray irradiation of disks



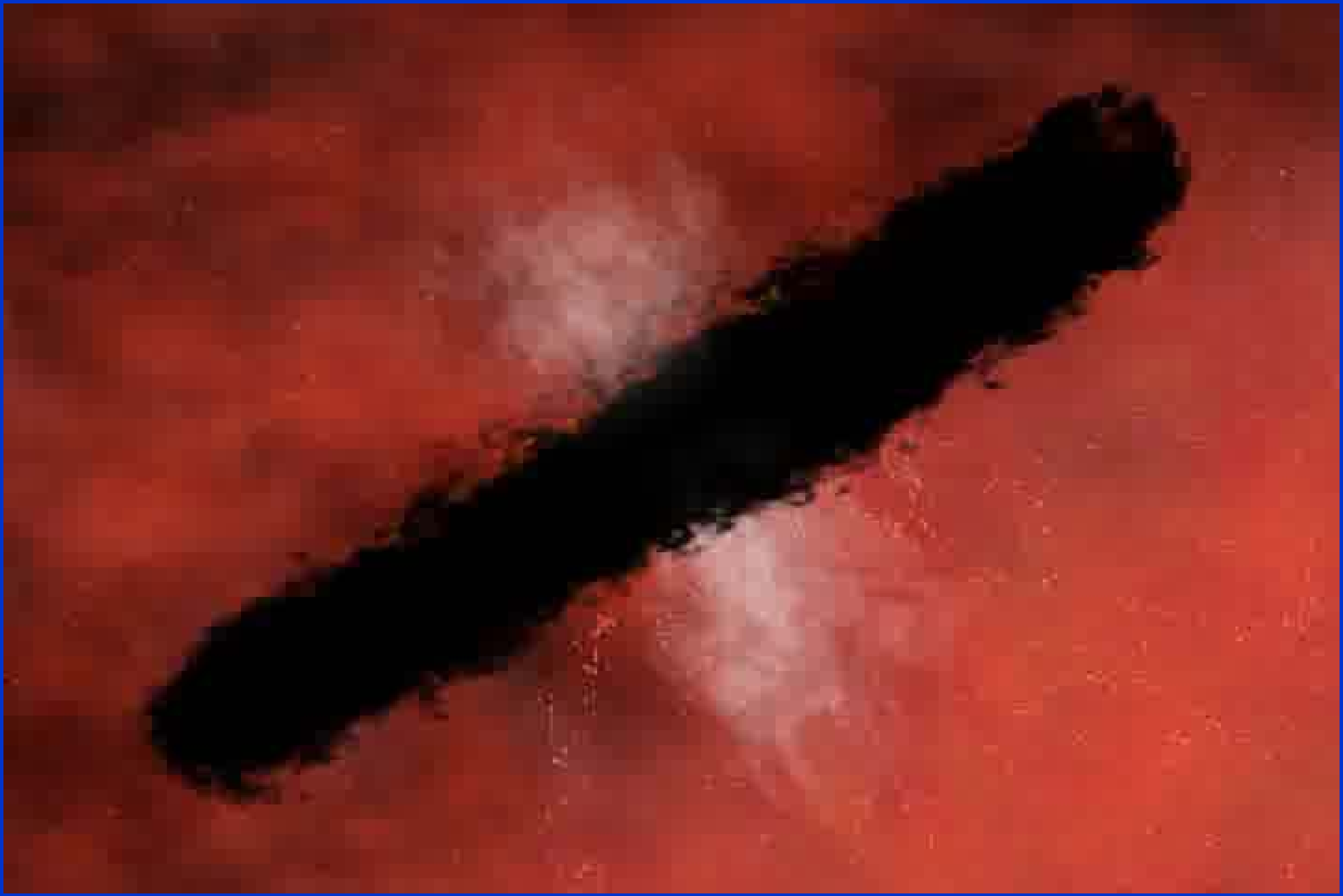




Tsujimoto & 7 others 2005 COUP #8

Kastner & 7 others 2005 COUP #9

Artist's view of X-ray superflares illuminating the protoplanetary disk



NASA press release May 2005

X-rays & disk ionization

YSO X-ray ionization *rate* dominates CRs out to 10^3-10^4 AU

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

for early Sun, 10^8 above cosmic ray levels. Chandra shows spectrum has hard penetrating component. The ionization *fraction* is uncertain due to recombination processes.

X-ray ionization penetrates to midplane in Jovian zone, leaves `dead zone' in terrestrial zone. Igea & Glassgold (1997, 1999), Sano et al. 2000, Fromang et al. 2002 Matsumura/Pudritz 2003 Blackman & Tan 2003

Magneto-rotational instability (MRI) is probably triggered. Salmeron/Wardle 2003 Kunz/Balbus 2004 Desch 2004

MRI induces turbulence which suppresses Type I migration. Matsumura/Pudritz 2003 & 2005 Nelson/Papaloizou 2003 & 2004 Winters et al. 2003 Menou/Goodman 2004 Laughlin et al. 2004 Hersant et al. 2004 Gammie 2005

Other likely X-ray/flare effects on protoplanetary disks

- PMS X-rays are an important ionization source at the base of bipolar outflows, necessary for coupling disk material to the collimating magnetic fields. *Shang et al. 2002 & 2004 Fero-Fontan et al. 2003*
- PMS X-ray ionization will change abundances of chemical species in protoplanetary disks. *Aikawa & Herbst 1999 & 2001 Markwick et al. 2001, Semenov et al. 2004, Gorti & Hollenbach 2004*
- PMS X-rays will heat gas in disk outer molecular layer. *Ceccarelli et al. 2002, Alexander et al. 2004, Glassgold et al. 2005a*
- Flares may help explain two enigmas of the meteoritic record: chondrule melting, and the production of short-lived radionuclides in CAIs. *Gounelle et al. 2001, Feigelson et al. 2002, Glassgold et al. 2005b, …*

Conclusions on star/planet formation

- Solar-type stars exhibit their highest levels of magnetic activity during their PMS phases.
- XDRs will dominate CR ionization of molecular cloud cores if a stellar cluster is present.
- COUP shows X-rays can efficiently irradiate proto-planetary disks (Fe fluorescent line & proplyd absorption).
- X-rays dominate disk ionization and may alter disk structure, dynamics & chemistry. If MHD turbulence is induced, planet formation processes may be substantially affected. The X-ray data support models of particle irradiation of meteoritic solids.

Solar systems form in cool dark disks ….

which are irradiated by 10^8 violent

magnetic reconnection flares