Stellar activity and its role in early evolutionary phases of stars and planets

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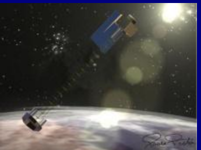
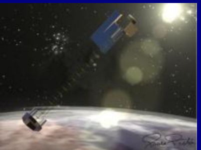


What physical phenomena

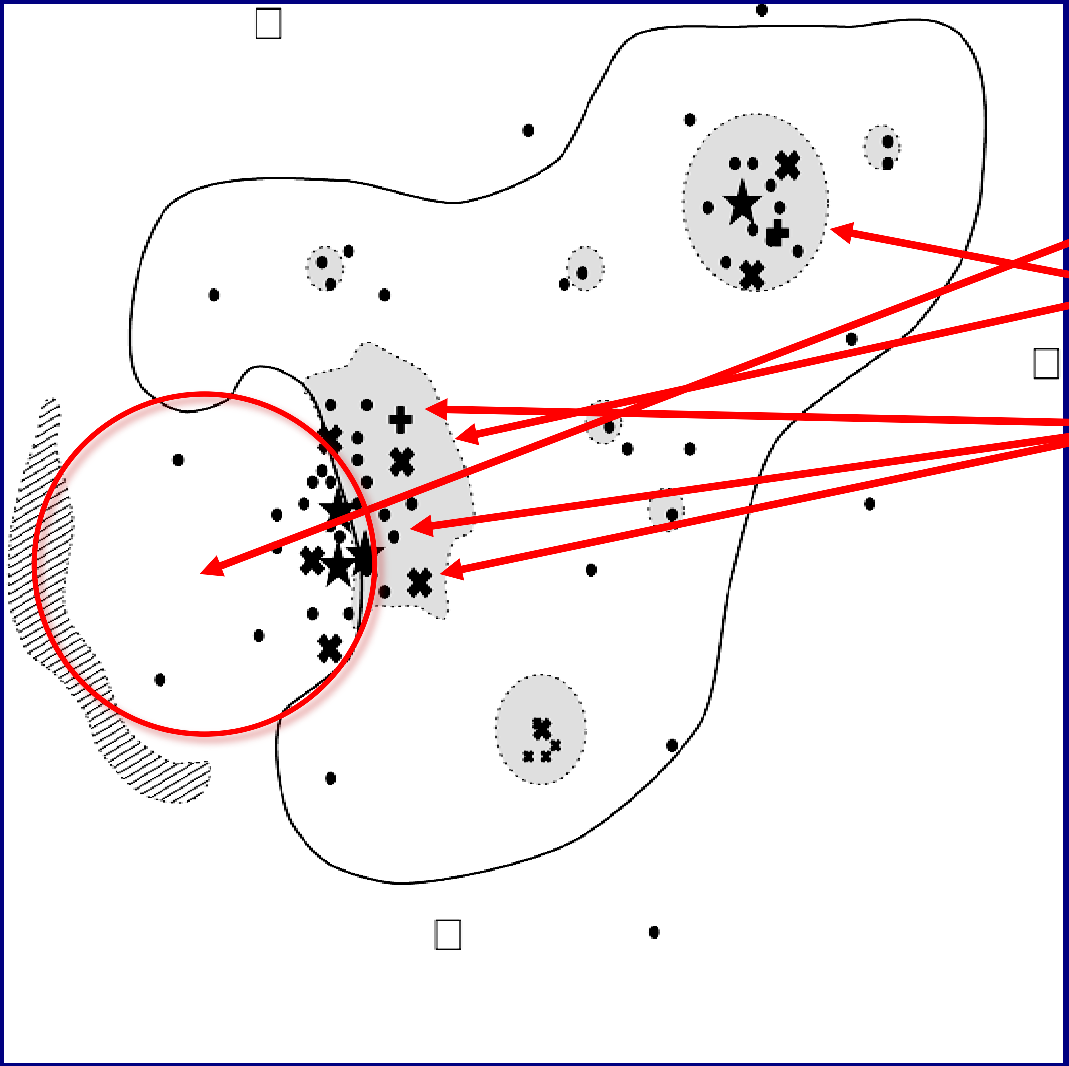
Stellar activity issues :

- Dynamo-generated magnetic fields
  - Strength, configuration, time cycle
  - Coupling with matter dynamics, instabilities
- Energetic phenomena
  - B field reconfiguration and plasma heating
  - Fast radiation and/or matter outputs
- High-energy radiation fields
  - Intensity, spectral hardness
  - Variability on stellar evolution time scales

A number of these issues could be addressed with NHXM

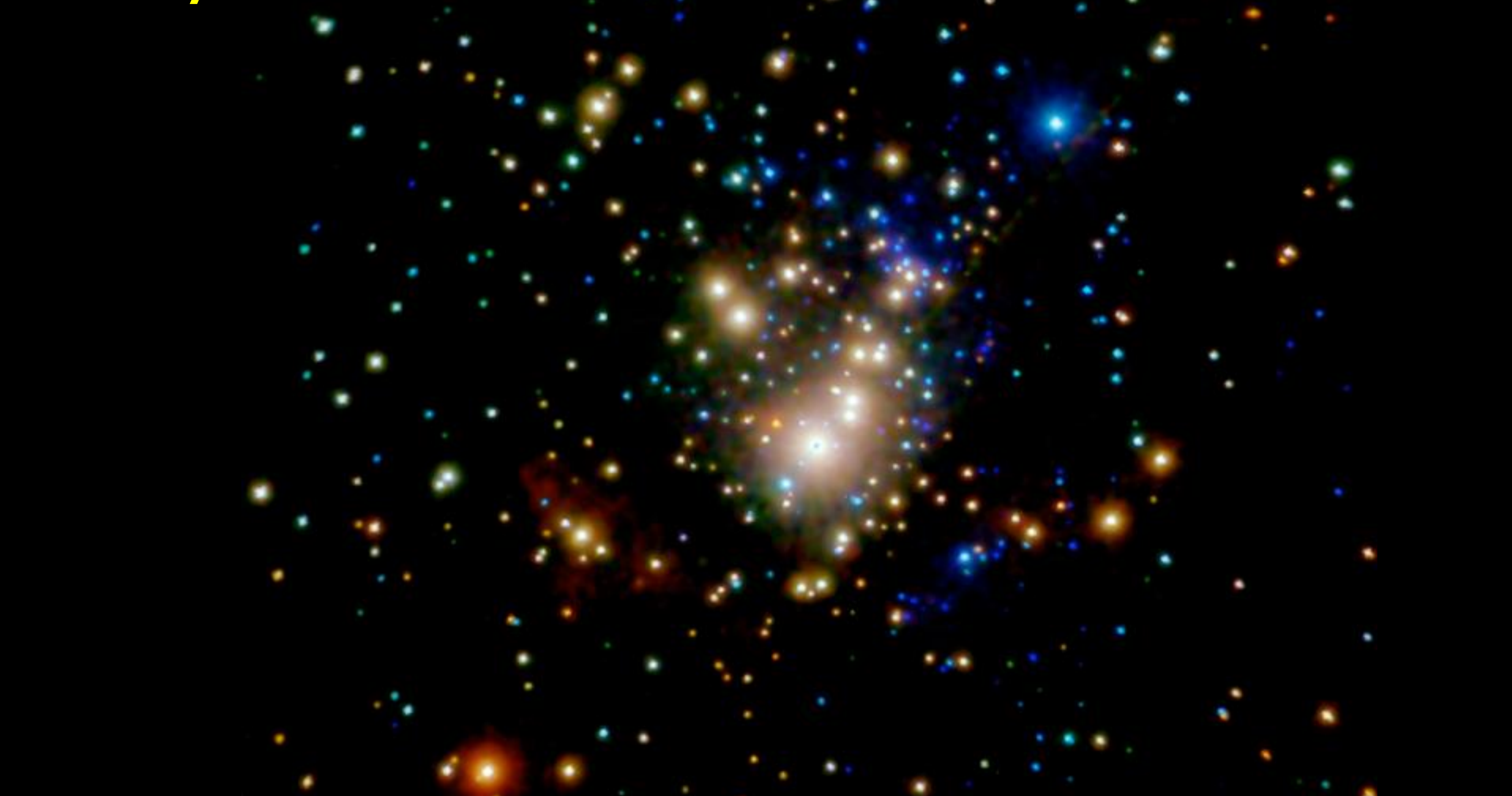


A typical stellar nursery



- Massive star forming regions are complex environments
  - Expanding SNRs
  - OB stars and associated wind shocks
  - Stars in different evolutionary stages (protostars, T Tauri stars, ecc.)
- Several hydro-dynamical and radiative effects may influence the early phases of stellar formation
- About 40 Star Forming Regions (SFRs) within 3 kpc already studied in X-rays
  - Best known SFRs, up to date: Orion, Taurus-Auriga, Ophiucus

X-ray view of the Orion Nebula Cluster



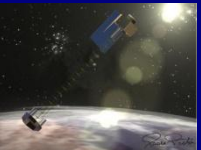
- About 1600 sources detected in 800 ks Chandra observattion, mostly Young Stellar Objects with ages $10^5 - 10^6$ yr

Observables vs. age

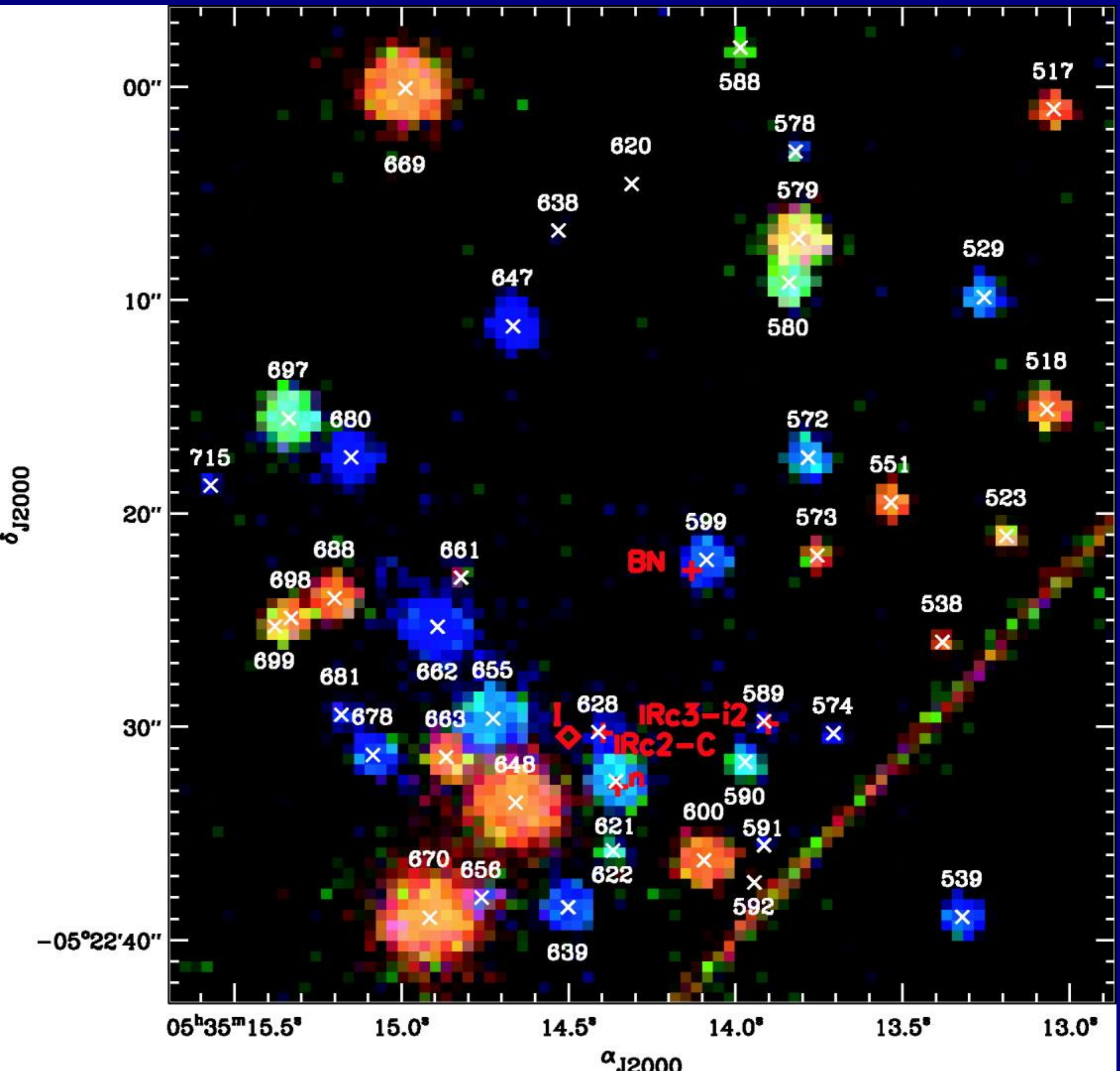
PROPERTIES	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
SKETCH					
AGE (YEARS)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-RAY	?	Yes	Strong	Strong	Weak
THERMAL RADIO	Yes	Yes	Yes	No	No
NON-THERMAL RADIO	No	Yes	No ?	Yes	Yes

Feigelson & Montmerle, 1999

- X-ray emission signals the onset of stellar magnetic activity (but when?)
- Since then, stellar activity starts affecting the evolution of the environment
- Feedback on stellar evolution, disk longevity, planetary formation and primordial "space climate"



Heavily obscured protostellar cores



Red 0.5–1.7 keV Green 1.7–2.8 keV Blue 2.8–8.0 keV

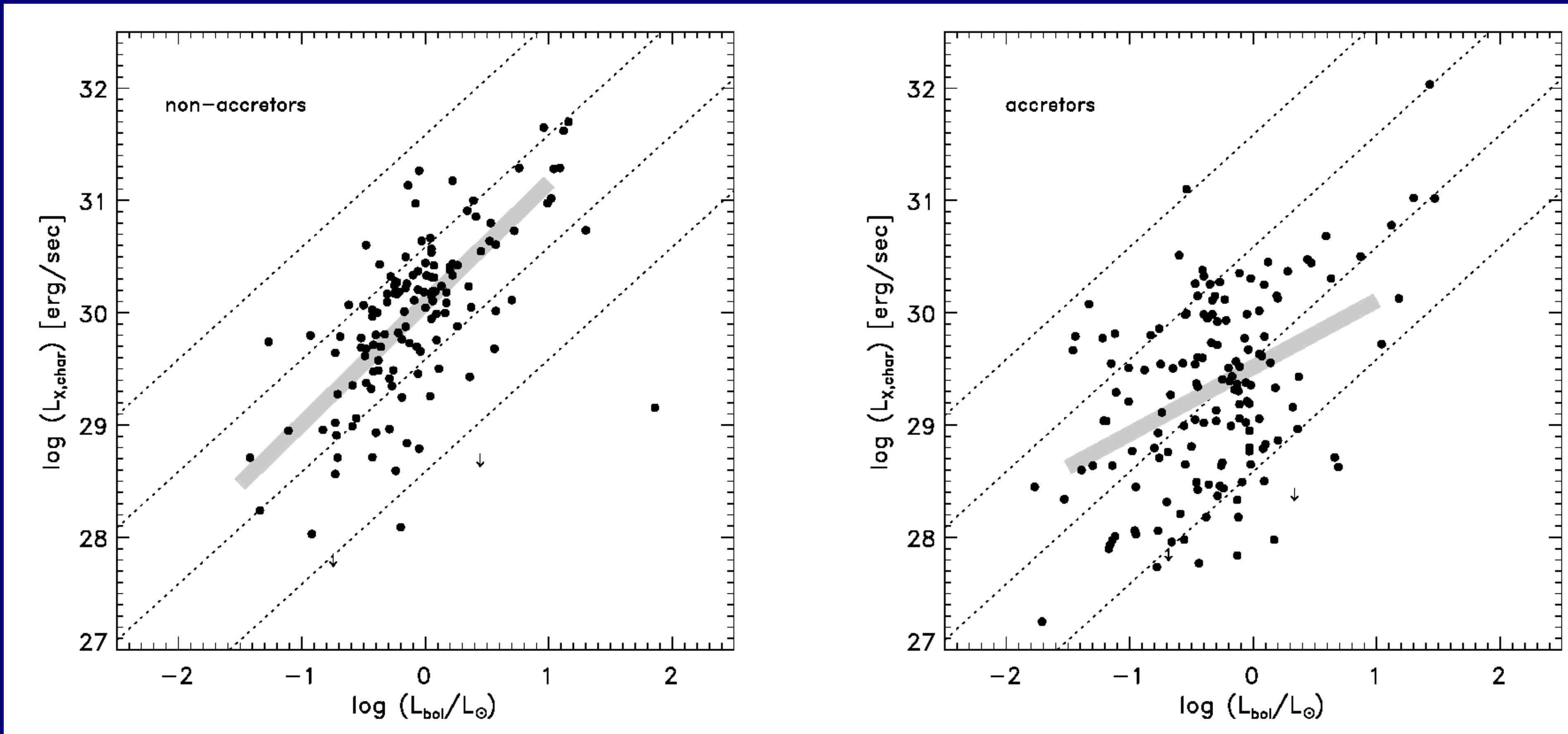
Grosso et al. (2005)

BN/KL region in the Orion Molecular Cloud:

Several new sources discovered, deeply embedded
$22.2 < \log N_H < 23.6$

(<u>sensitivity</u> in hard X-ray band and <u>resolution</u> required)

X-ray emission characteristics



Preibisch et al. (2005)

- Mean X-ray luminosity $L_x \approx 10^{-3.5}\ L_{bol}$ (saturated level) for non-accreting stars
- Depressed X-ray emission and large scatter for accreting stars

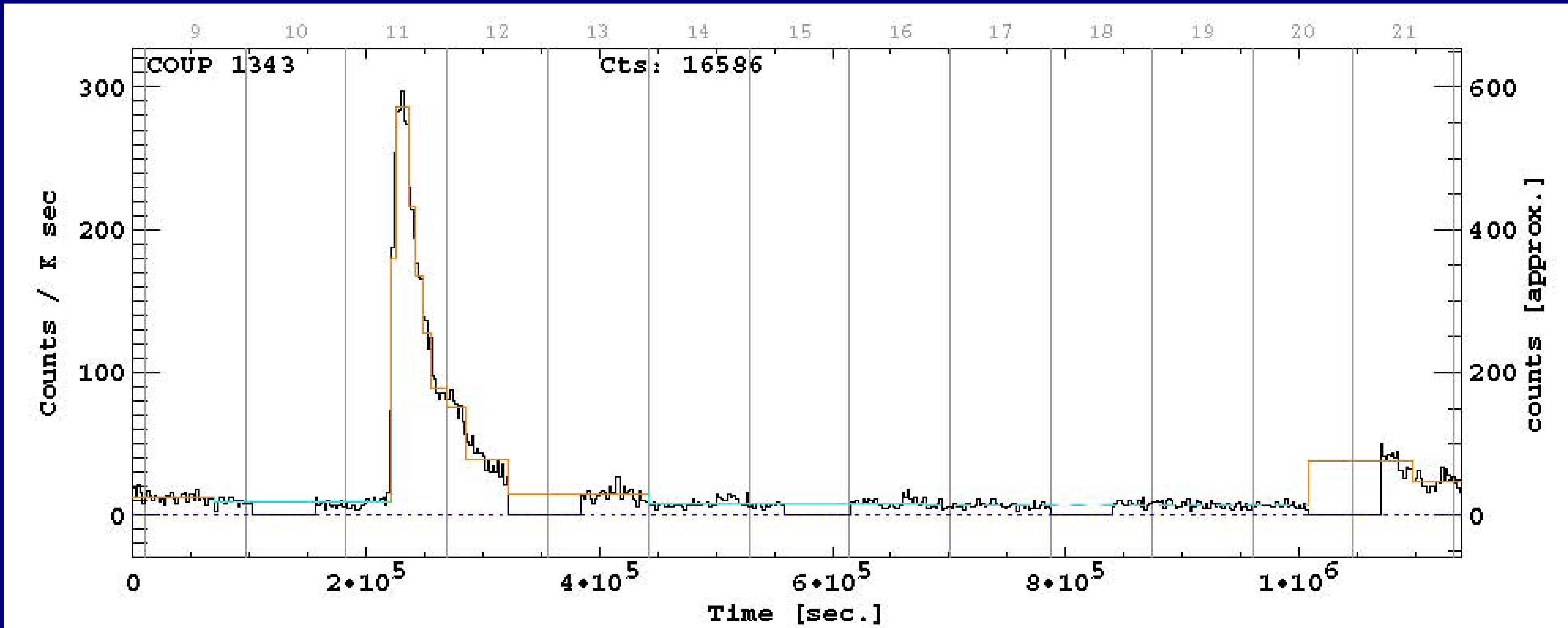
Orion Nebula Cluster: the COUP movie

Continuous flaring activity for essentially all sources

- Duration from minutes to days
- Peak X-ray luminosities $L_x \approx 10^{32}$ erg/s
- Total radiated energy up to $E \approx 10^{36.5}$ erg [0.5-8 keV]
- Frequency of largest flares: every few days per object

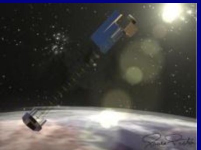
A. Maggio

X-ray Flare Characteristics

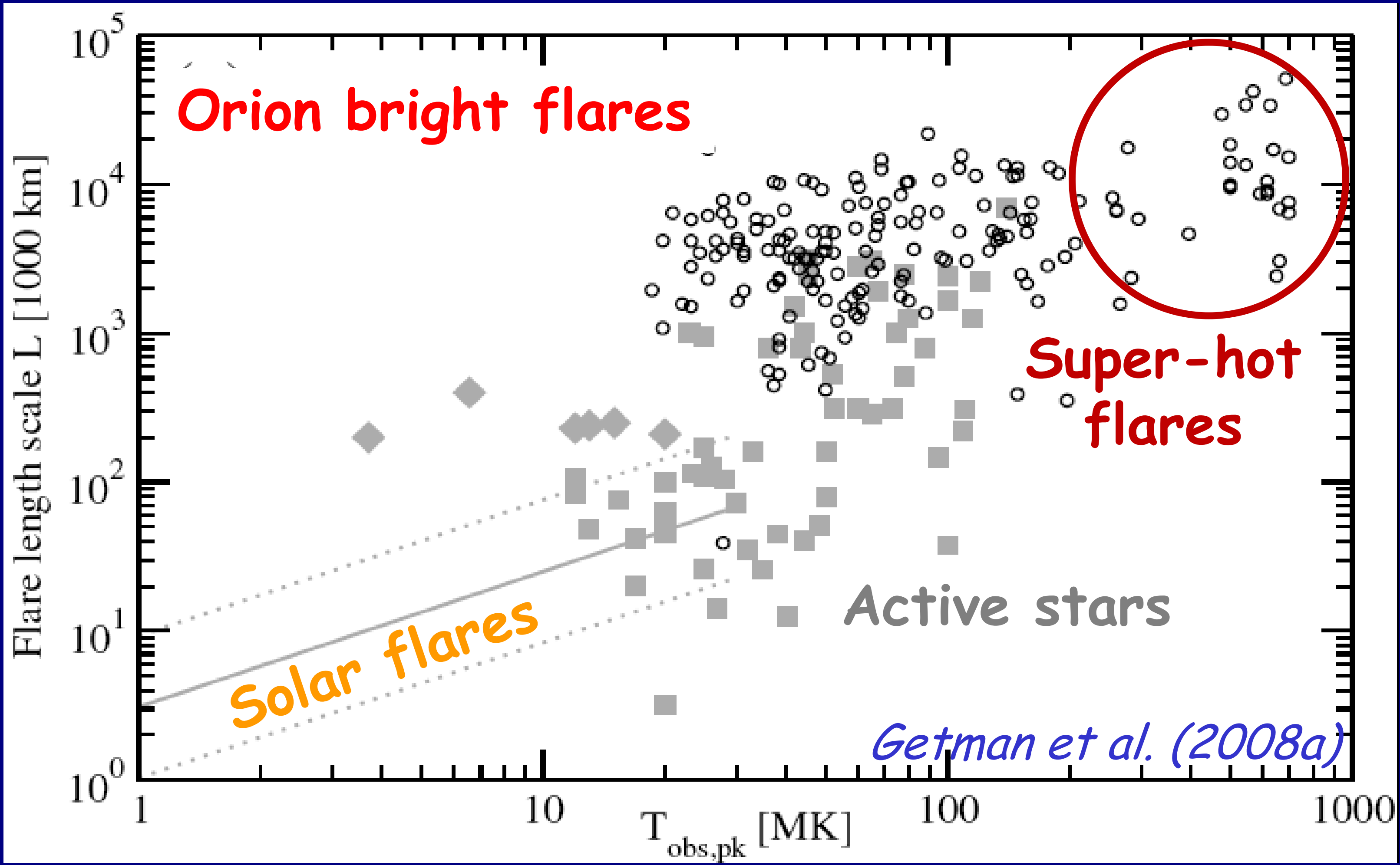


Favata et al. (2005)

- Fast rise and slower exponential decay
- Can be modelled as compact solar flares
- Analysis of broad-band X-ray spectroscopy data yields size of magnetic structures confining the flaring plasma

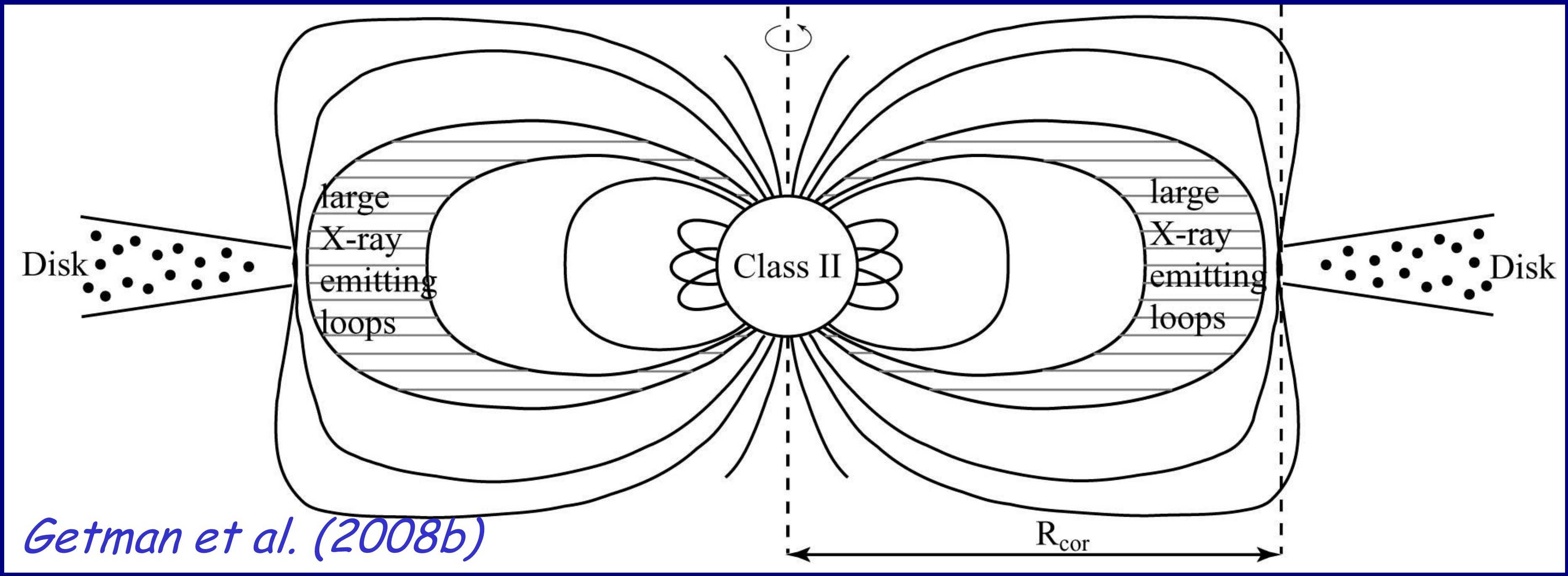


Flare sizes and temperatures



- Scale lengths from 5 x 10^{11} to 5 x 10^{12} cm, i.e. up to 10 – 20 R_*
- Plasma peak temperatures up to 7 x 10^8 K (but extreme values are poorly constrained)

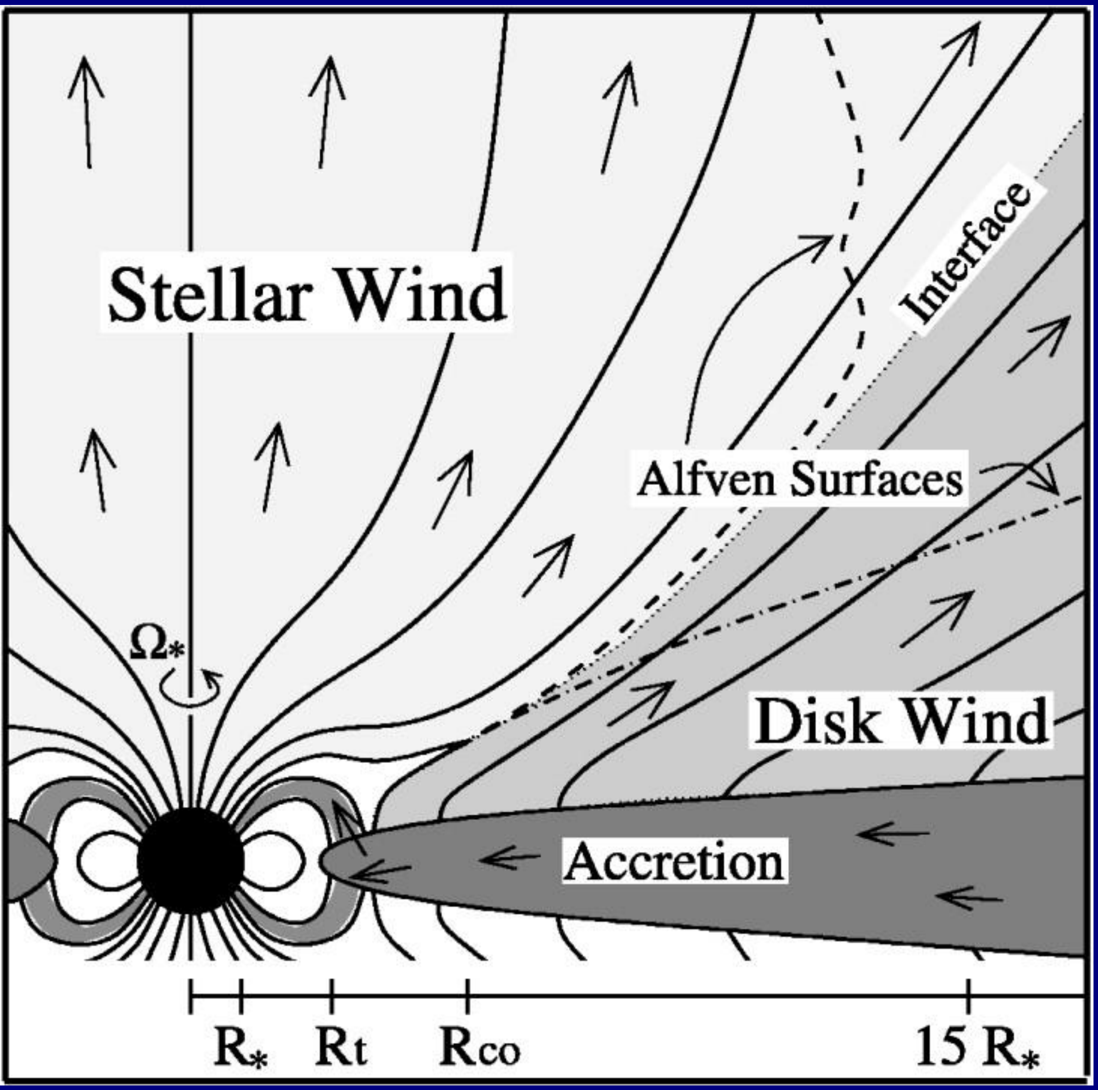
What kind of stellar magnetospheres?



- In accreting T Tauri stars, coronal extent limited by the disk (truncated at the co-rotation radius)
- Closed field ⇒ hot plasma ⇒ X-ray emission, flares
- Open field ⇒ stellar wind ⇒ mass & angular momentum losses
- Star-disk field ⇒ accretion ⇒ shocks ⇒ soft X-ray excess

⇒ giant flares? Open issue...

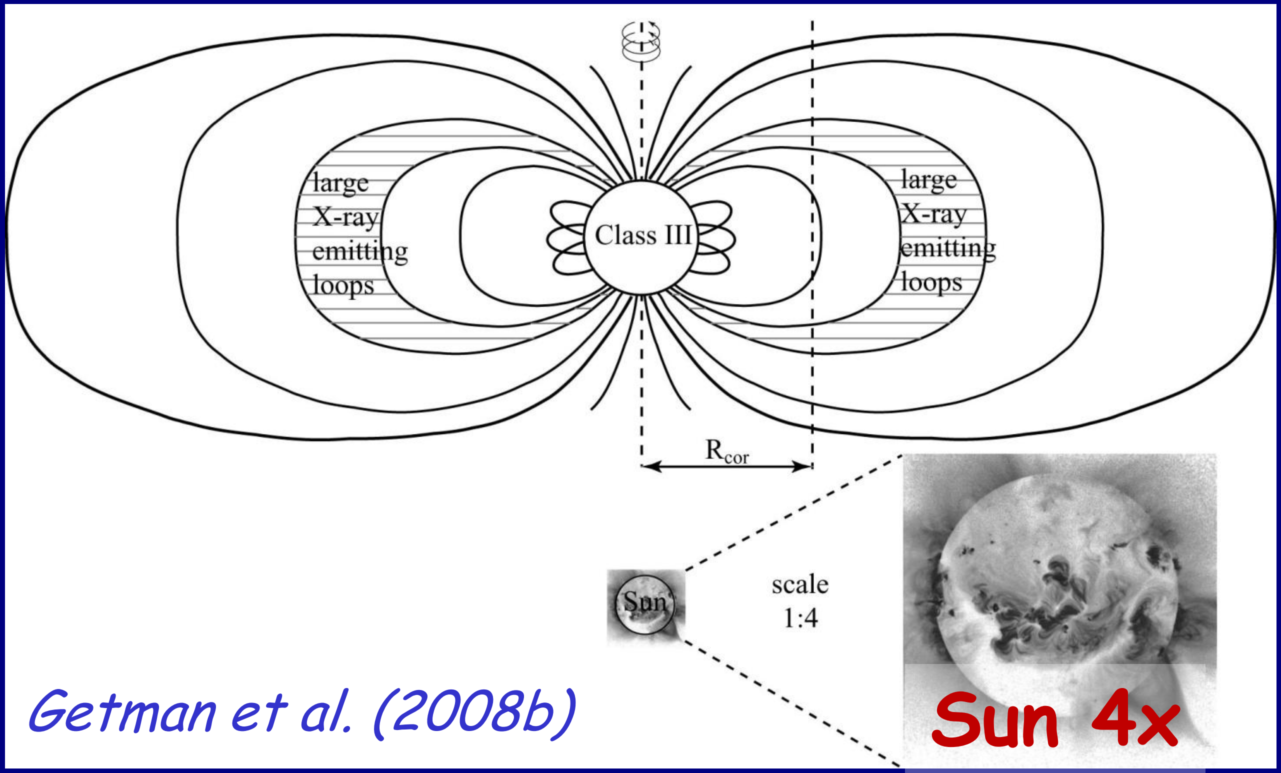
Role of Magnetic Fields



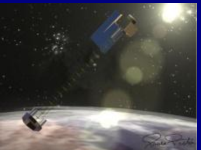
Matt & Pudritz (2005)

- In accreting T Tauri stars, magnetic fields determine
- ⇒ hot plasma confinement and heating
- ⇒ steady X-ray emission and flares
- ⇒ mass inflow and outflow
- ⇒ angular momentum balance
- ⇒ star-disk locking and magnetic torques?
- ⇒ disk disruption
  - ⇒inner edge for planet migration?

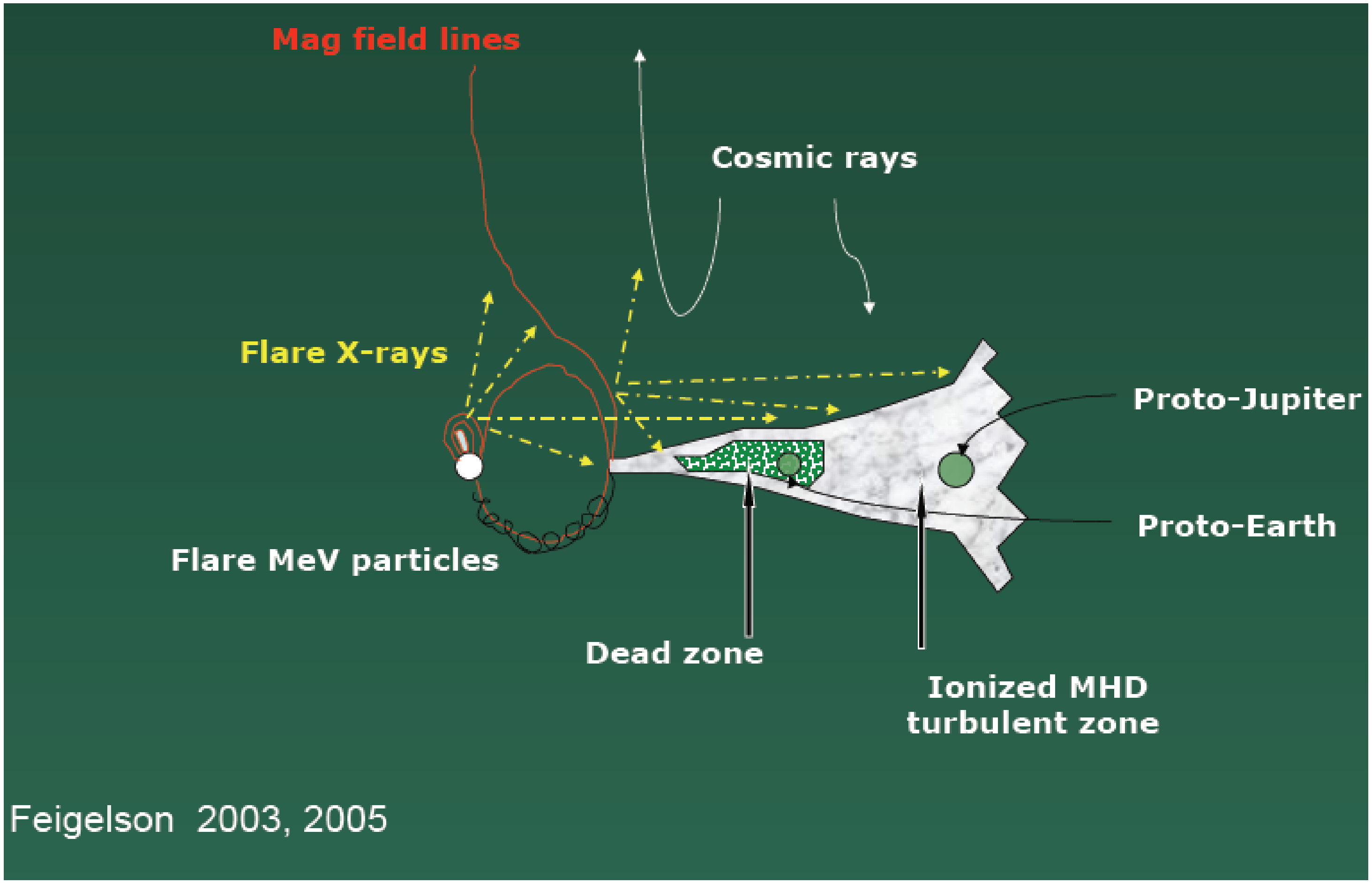
Magnetospheres in non-accreting stars



- Coronal extent limited by gas/B-field pressure ratio
- Fast rotation ⇒ efficient dynamo ⇒ enhanced magnetic activity
- Intense high-energy irradiation of young planetary bodies
- Coronal Mass Ejections and Stellar Energetic Particle flows
    - Star-planet magnetospheric interaction?



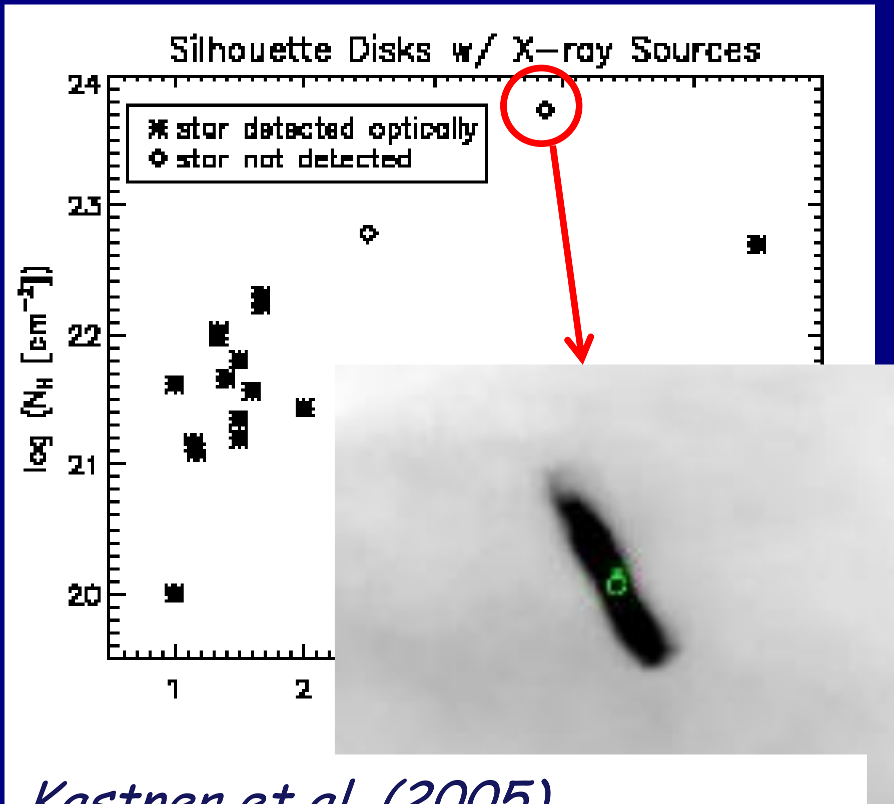
Stellar activity effects on Circumstellar/Protoplanetary Disks



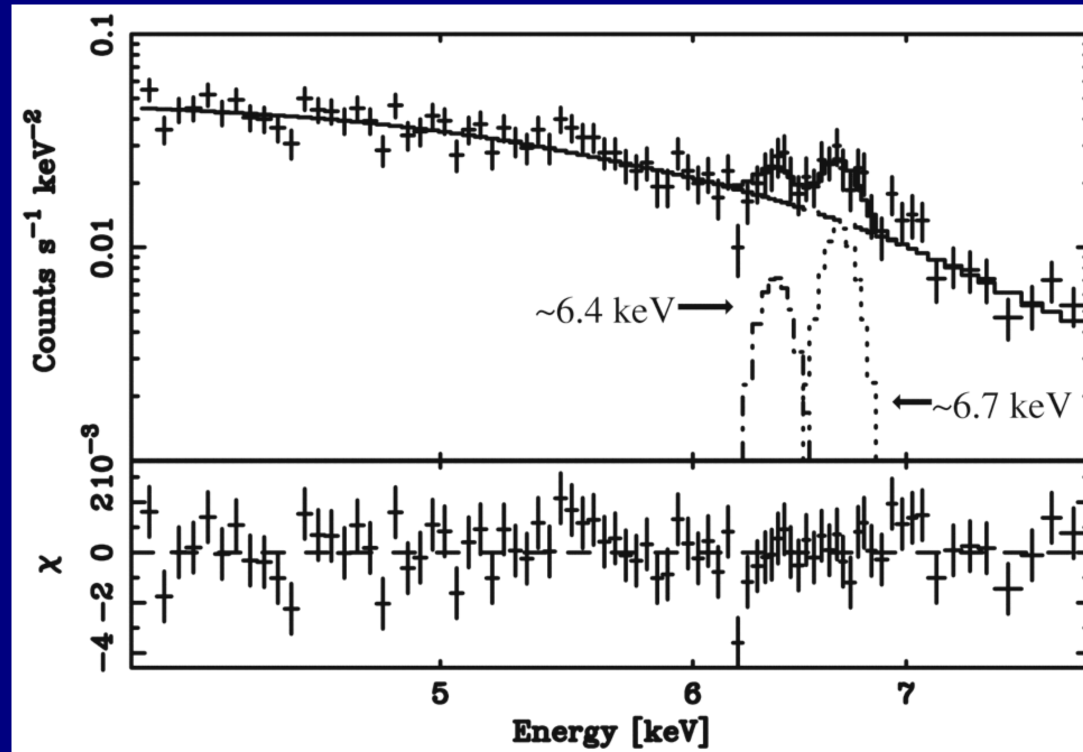
Circumstellar disks are subject to high-energy radiation, winds, and energetic particles originating from the central star ⇒ heating, ionization, evaporation

How is planetary formation affected?

X-ray Diagnostics of X-rayed Disks



Kastner et al. (2005)



Imanishi et al. (2001)

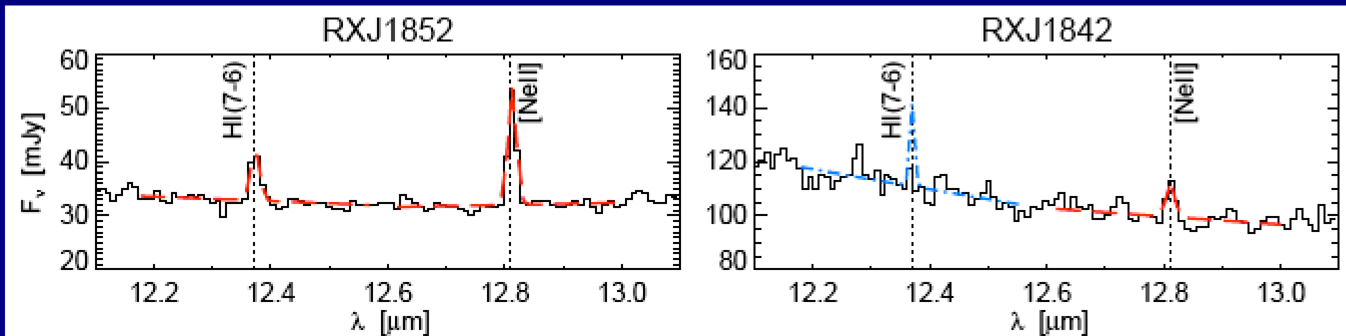
- X-ray absorption of gas in edge-on proplyds

(<u>broad-band spectroscopy</u>)

- Reflection of X-rays off the disk ⇒ Fluorescent 6.4 keV iron emission line

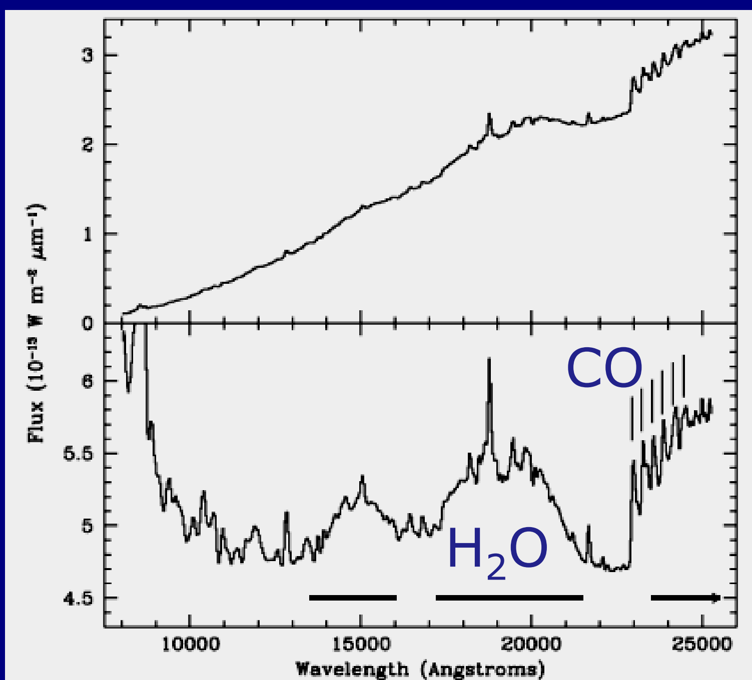
($E/\Delta E \geq 40$ @ 6 keV and <u>sensitivity</u> required)

IR Diagnostics of X-rayed Disks



Pascucci et al. (2007)

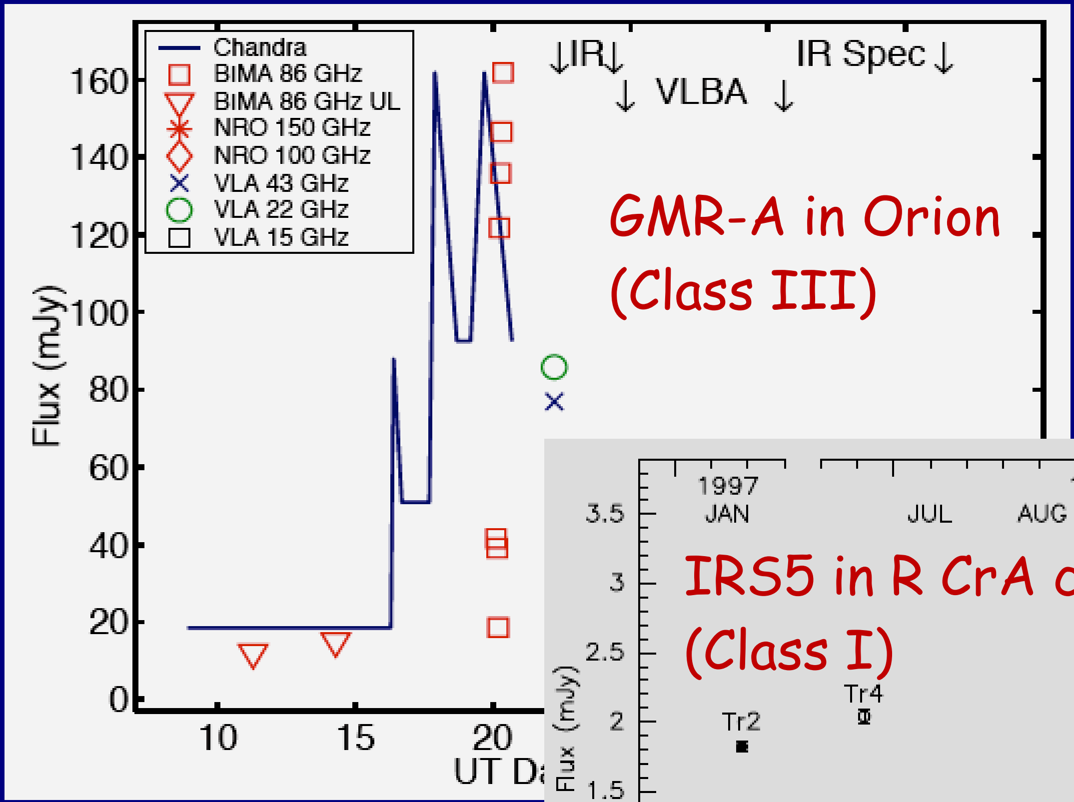
- Detection of [Ne II] 12.81 μm line emission



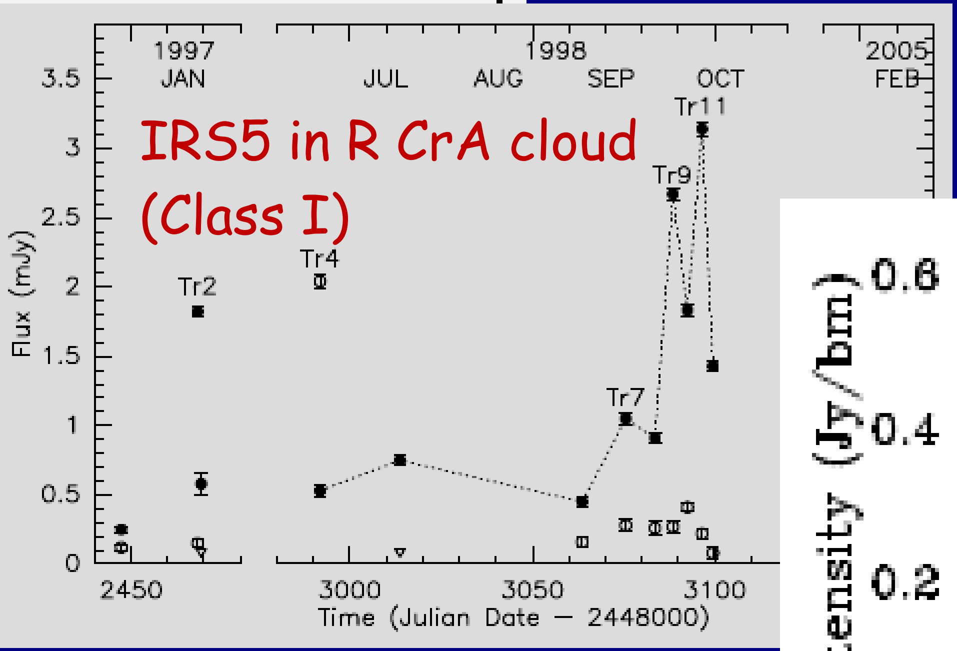
Carr et al. (2004)

- Hot H_2O and CO molecular layer observed is some YSOs

Evidence of MeV particles

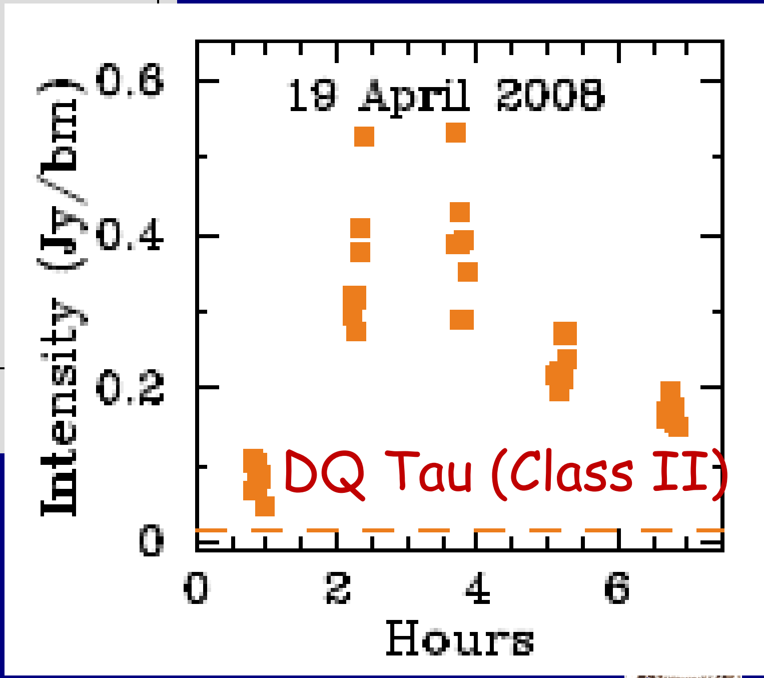


Bower et al. (2003)



Choi et al. (2008)

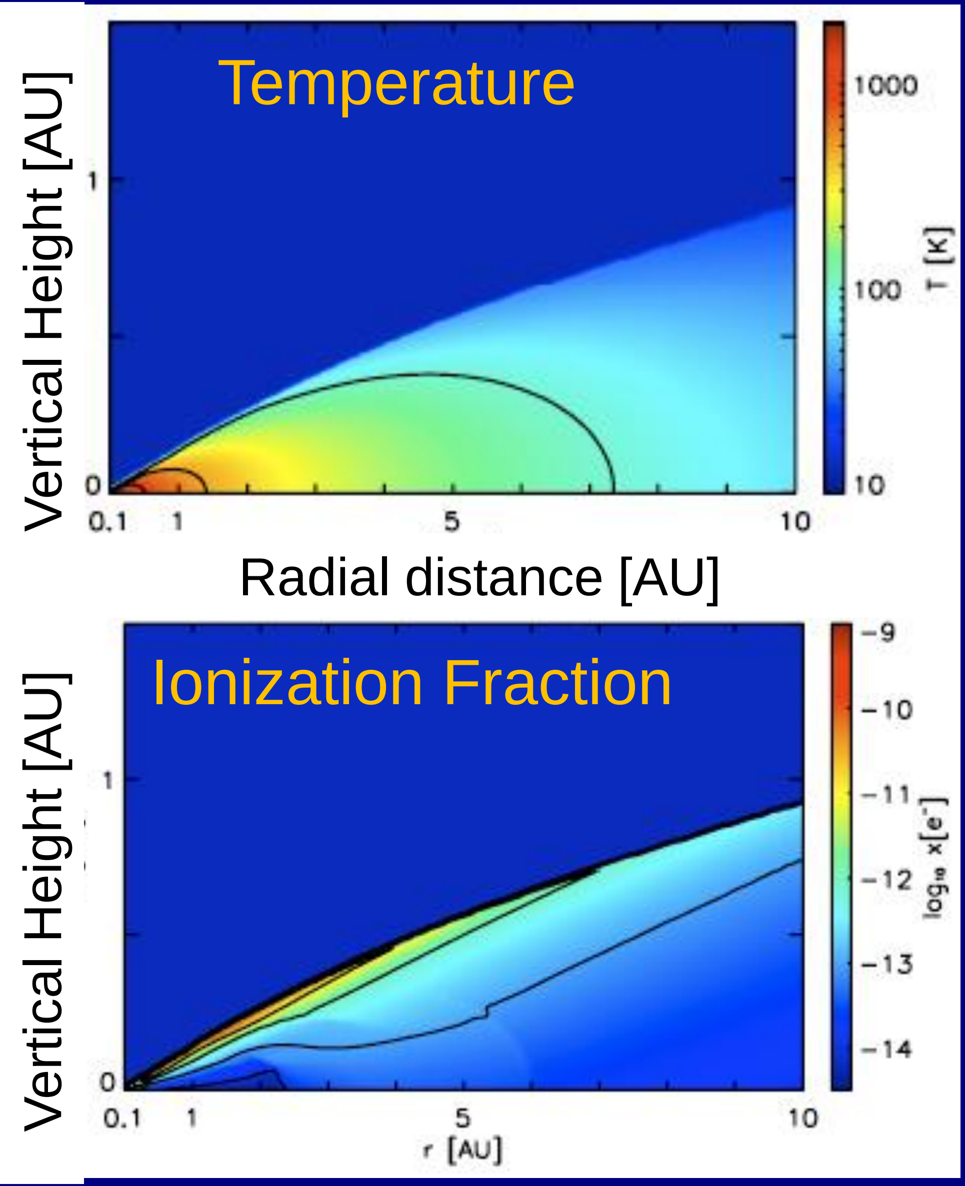
- Radio gyrosynchrotron emission with high variability and strong circular polarization detected in several YSOs



Salter et al. (2008)

Any polarization in the X-ray band?

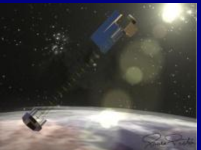
XUV Irradiation of Circumstellar Disks



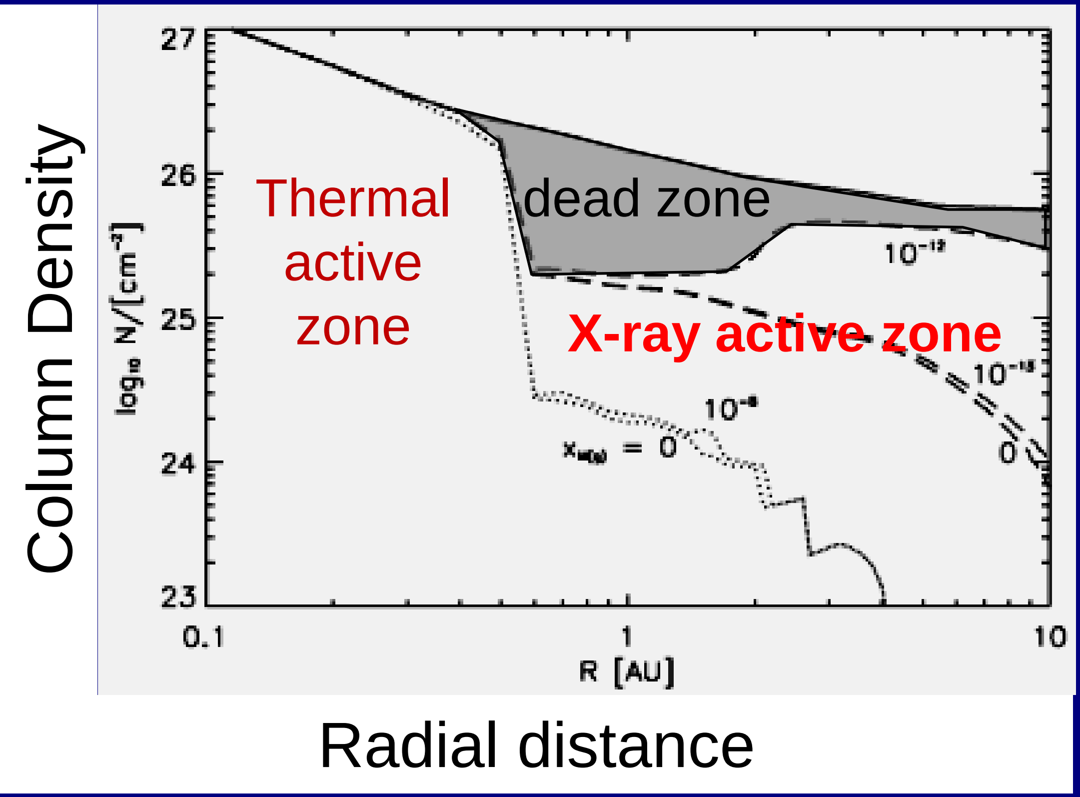
Ilgner & Nelson (2006)

- Heating and ionization of gas in disk outer layers out to several AU
  - ➢ B-field freezing
  - ⇒ disk truncation
  - ➢ MRI turbulence
  - ⇒ angular momentum transport
  - ⇒ mass accretion
  - ⇒ planetary migration?
- Out of equilibrium molecular chemistry in the disk interior

What the role of hard X-rays during flares, and ejection of Energetic Particles?



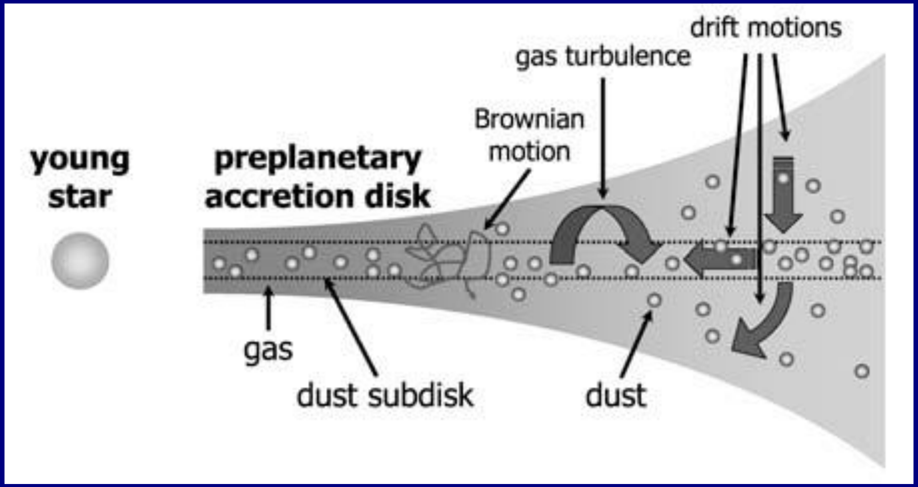
Disk ionization models



Ilgner & Nelson (2006)

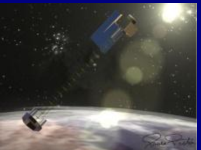
- Ingredients: X-ray photo-ionization, viscous heating, radiative cooling, and turbulent mixing of gas, dust and grain phases, with given chemical composition
- Boundary between active (= turbulent) and dead (= laminar) zone occurs at very low ionization fraction, log X_e ~ -12
- The size of the dead zone depends on the frequency, energetics, and hardness of stellar flares (statistical studies required)

Effects on planets

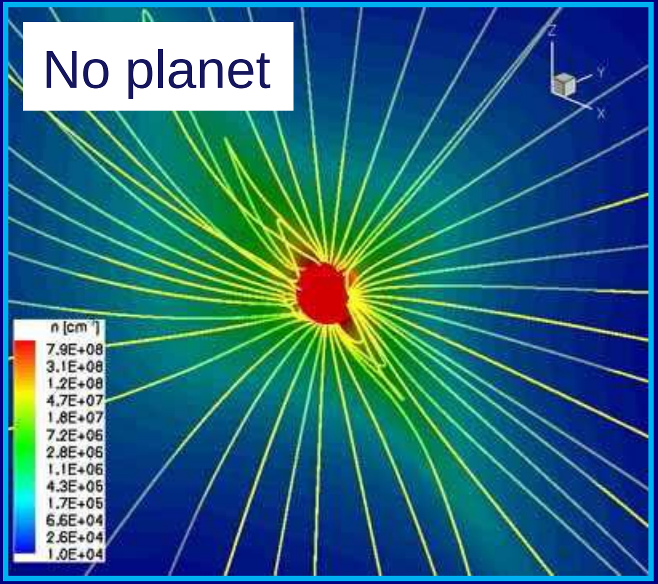


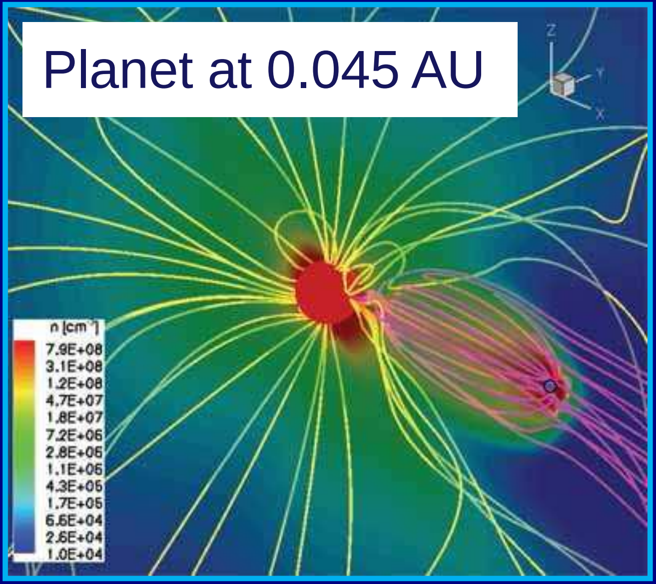
- Traditional theory of growth from interstellar grains to larger bodies requires calm dynamics and gravitational settling towards the disk midplane

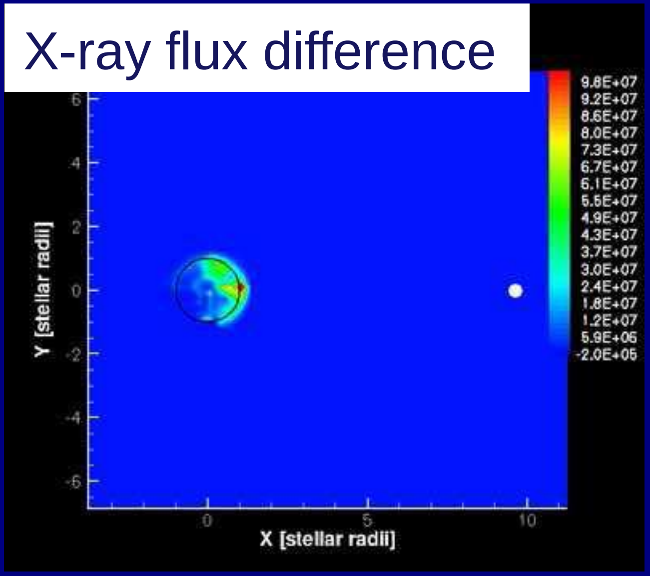
- X-ray induced MRI turbulence produces inhomogeneities and gravitational torques ⇒ inhibited sedimentation of solids ⇒ planetary formation in dead zones only?
- When formed, planetesimals undergo random walks, rather than simple migration
- Close-in gaseous planets have magnetosphere which interact with the stellar one ⇒ enhanced activity
- Planet atmospheres are subject to high-energy irradiation and stellar winds ⇒ heating, evaporation



Star-Planet Interaction



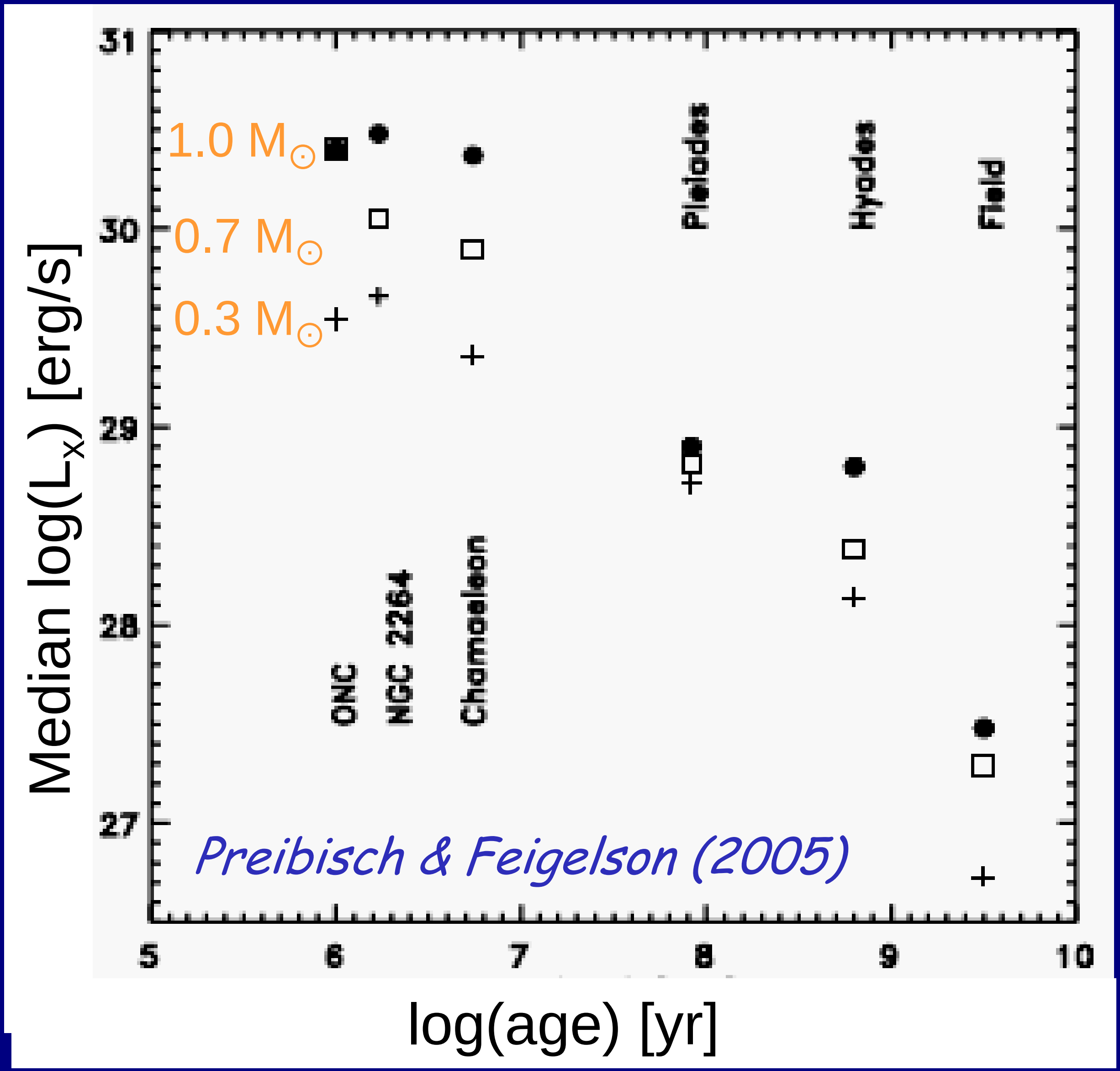




Cohen et al. (2009)

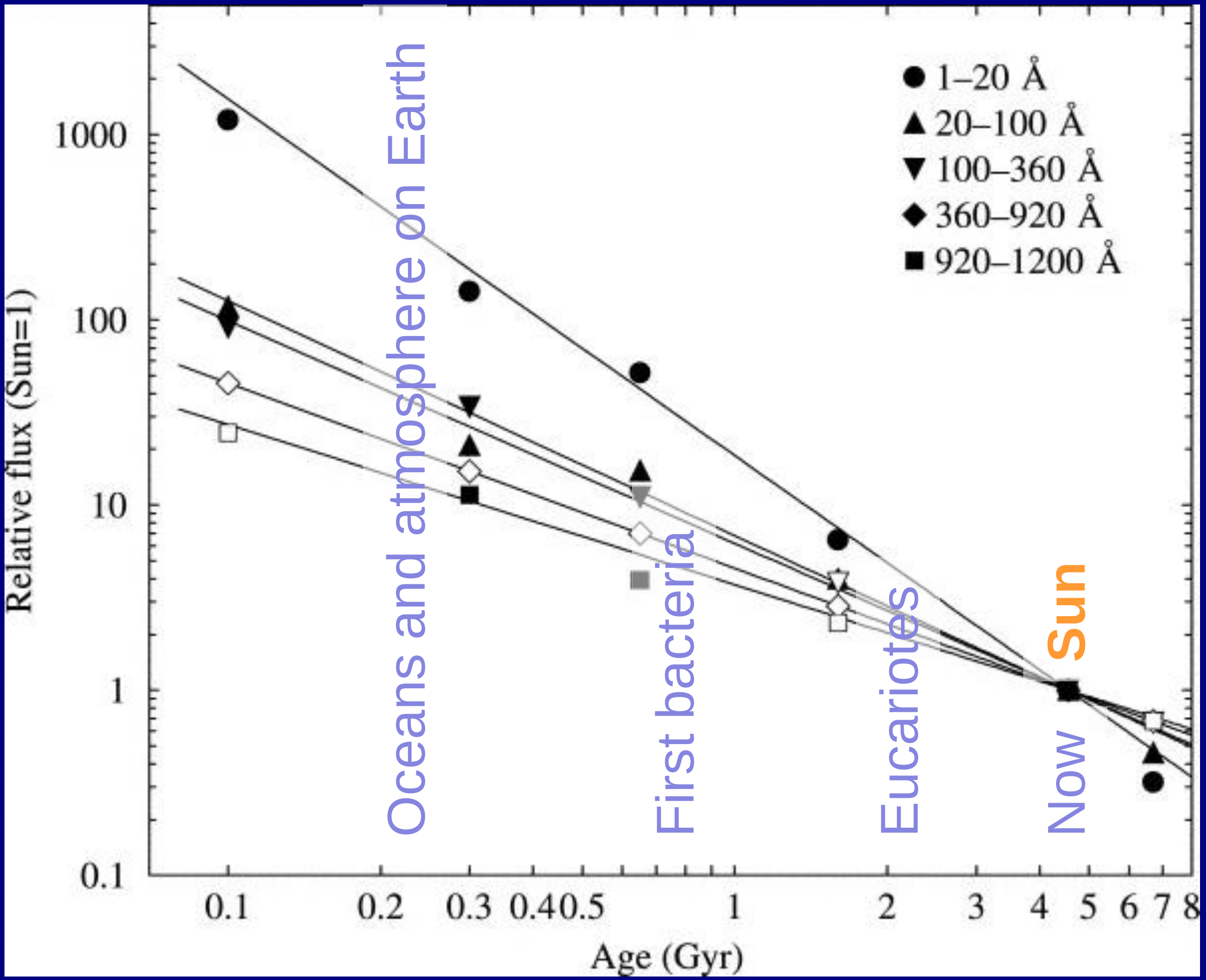
- Observational indications from stars with close-in Jovian-mass planets (Shkolnik et al. 2003, Kashyap et al. 2008)
  - Variation of chromospheric CaII H&K emission with orbital period
  - Phase-shift of the hot spot from sub-planetary longitude
  - Statistically higher X-ray emission level
- Recent 3-D MHD simulations with realistic magnetospheres reproduce observations

X-ray emission at later epochs



- X-ray luminosity decreases with age
  - Wind-driven stellar spin-down, less effective dynamo action
- Stellar coronae become cooler
  - Softening of the spectrum
- Decreasing flaring activity

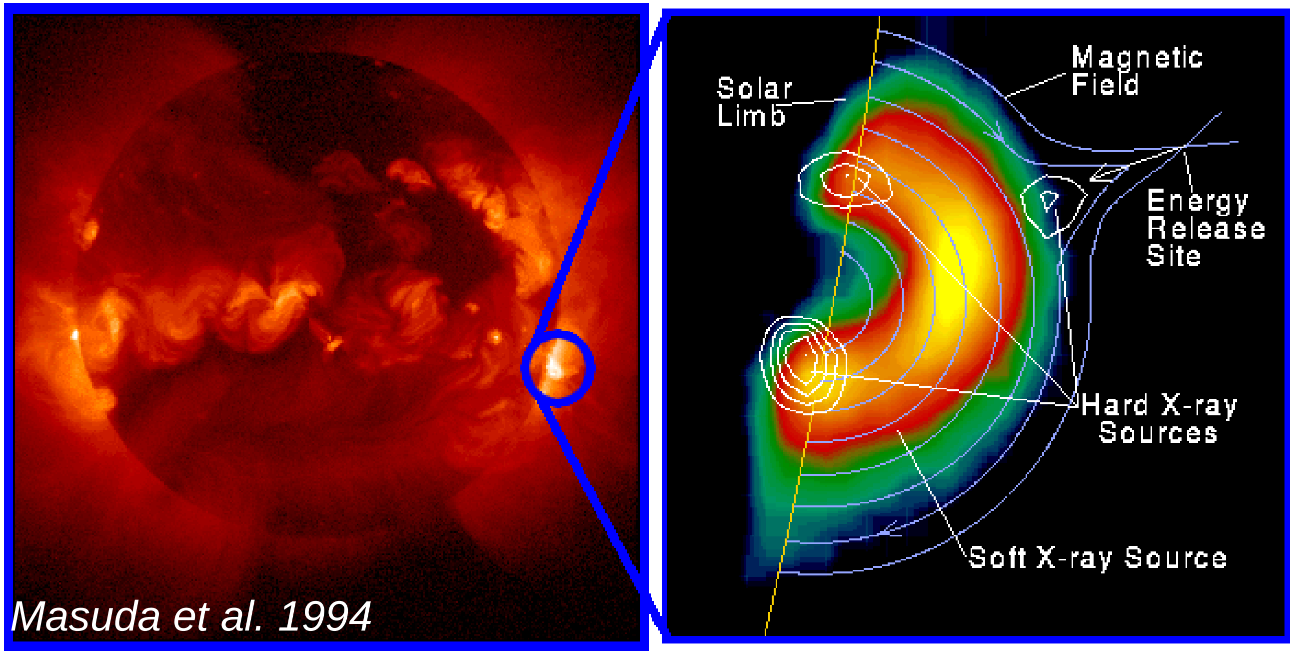
X-ray emission at later epochs



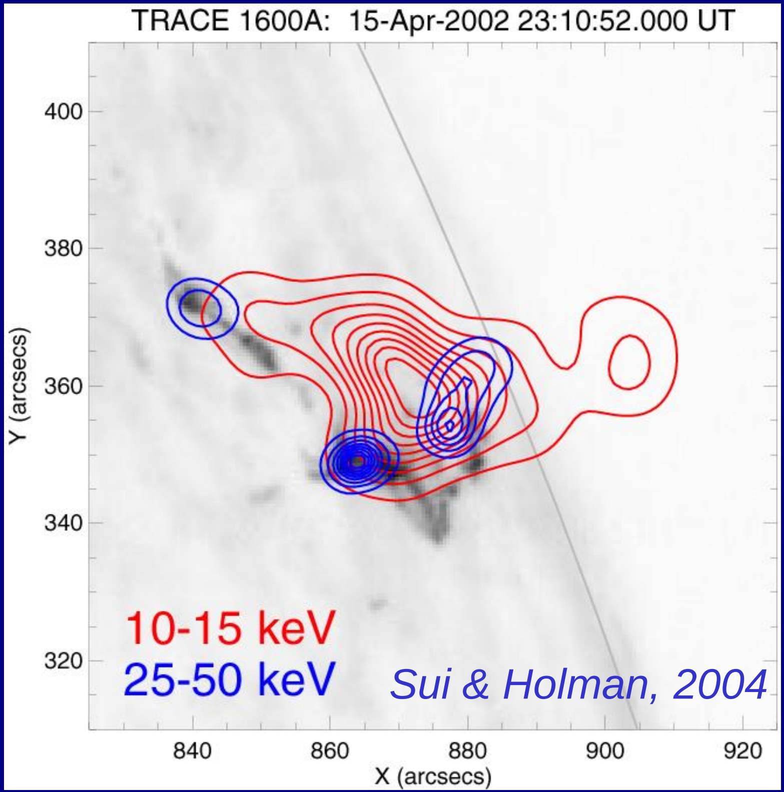
Ribas et al. (2005)

- X-ray luminosity decreases with age
  - Wind-driven stellar spin-down, less effective dynamo action
- Stellar coronae become cooler
  - Softening of the spectrum
- Decreasing flaring activity

The hard X-ray Sun today

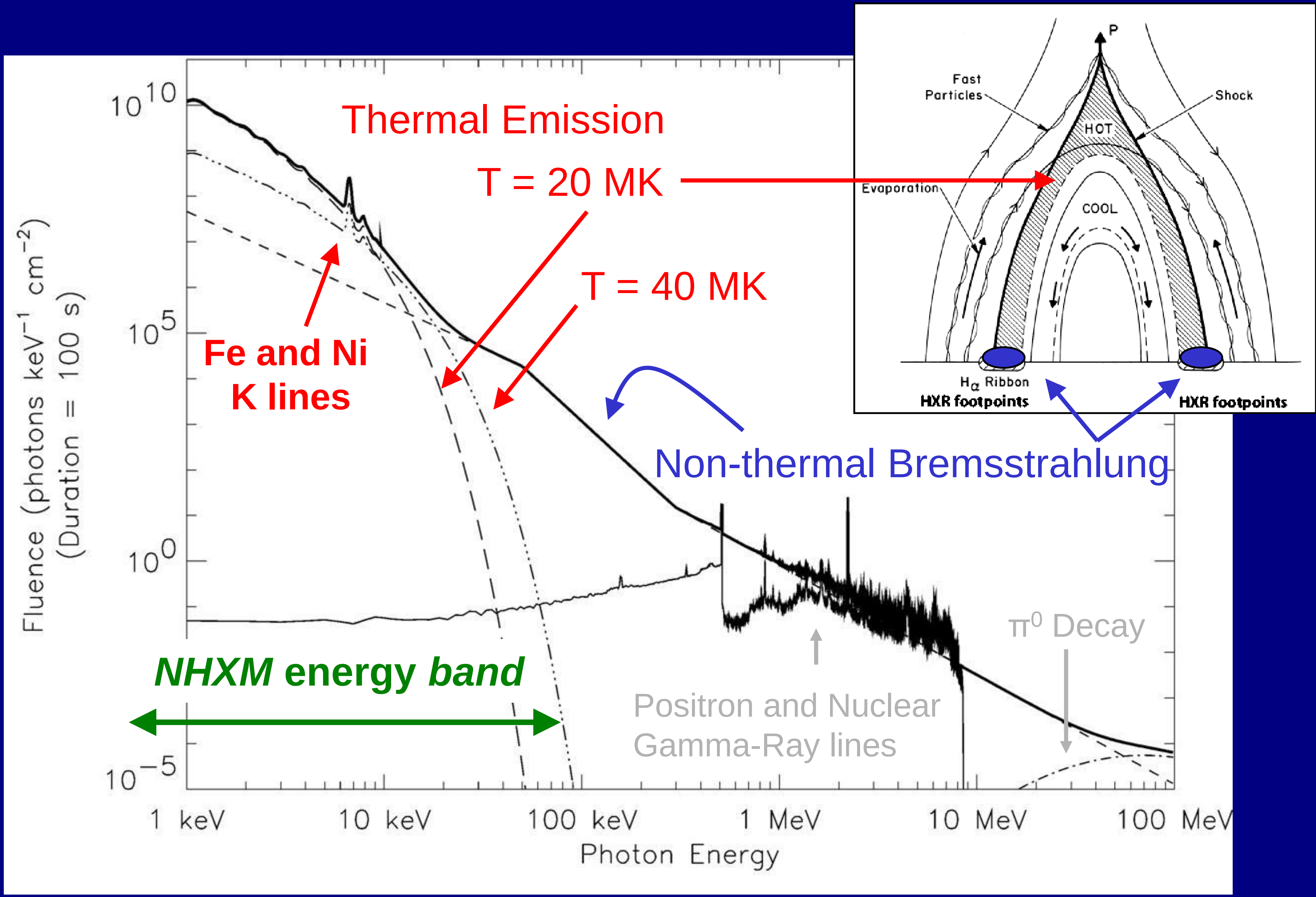


Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.



- Spacially-localized hard X-ray emission (10–50 keV) from solar flares routinely observed with RHESSI
- Associated gyro-synchrotron radio emission from mildly relativistic electrons with a power-law energy distribution
- Explained (partially) with models of magnetic reconnection, particle acceleration, and non-thermal emission

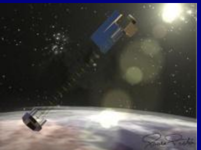
Large solar flares: X-ray and γ-ray spectrum



Courtesy H. Hudson

Sun compared with Active Stars

	Sun	Young Active Stars
X-ray luminosities	$L_x/L_{bol} \sim 10^{-6}$ (quiescent) $L_x/L_{bol} \sim 10^{-5}$ (large flares)	$L_x/L_{bol} \sim 10^{-3}$ (quiescent) $L_x/L_{bol} \sim 10^{-1}$ (large flares)
Occurrence of large flares	1 every 10 days (at max of solar cycle)	A few per day (no magnetic cycle?)
Flare time scales	up to a few hours	up to a few days
Coronal plasma temperatures	$\approx 10^6$ K (quiencent) $\approx 10^7$ K (flaring)	$\approx 10^7$ K (quiencent) $\approx 10^8$ K (flaring) !!!



The role of NHXM

1. Detection of deeply embedded YSOs
   (deep sensitivity and hard X-ray fine imaging required:
   NXHM OK, NuSTAR No, ASTRO-H No)

2. X-ray spectroscopy during super-hot flaring events
   (broad energy band required:
   NXHM OK, NuSTAR No, ASTRO-H OK)

3. Determine frequency and amplitude of energetic events
   (long stares at Star Forming Regions required:
   possible with NXHM)

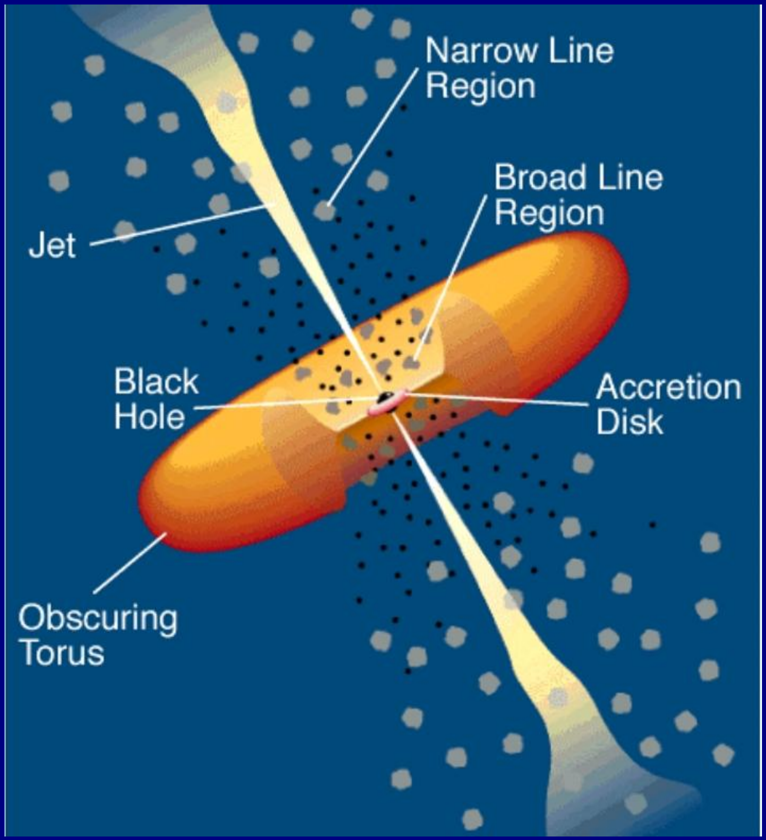
4. Study the decline of hard X-ray emission with age for solar-type and lower mass stars (**NXHM OK**)

5. Search for fluorescent Fe line emission ($E/\Delta E \geq 40$ @ 6 keV required: **NXHM OK**, NuSTAR No, ASTRO-H OK)

6. Fishing for X-ray polarization during long-duration flaring events (MDP $<$ 40% in 10–50 ksec integration time:
   possible with NHXM only, but how many events?)

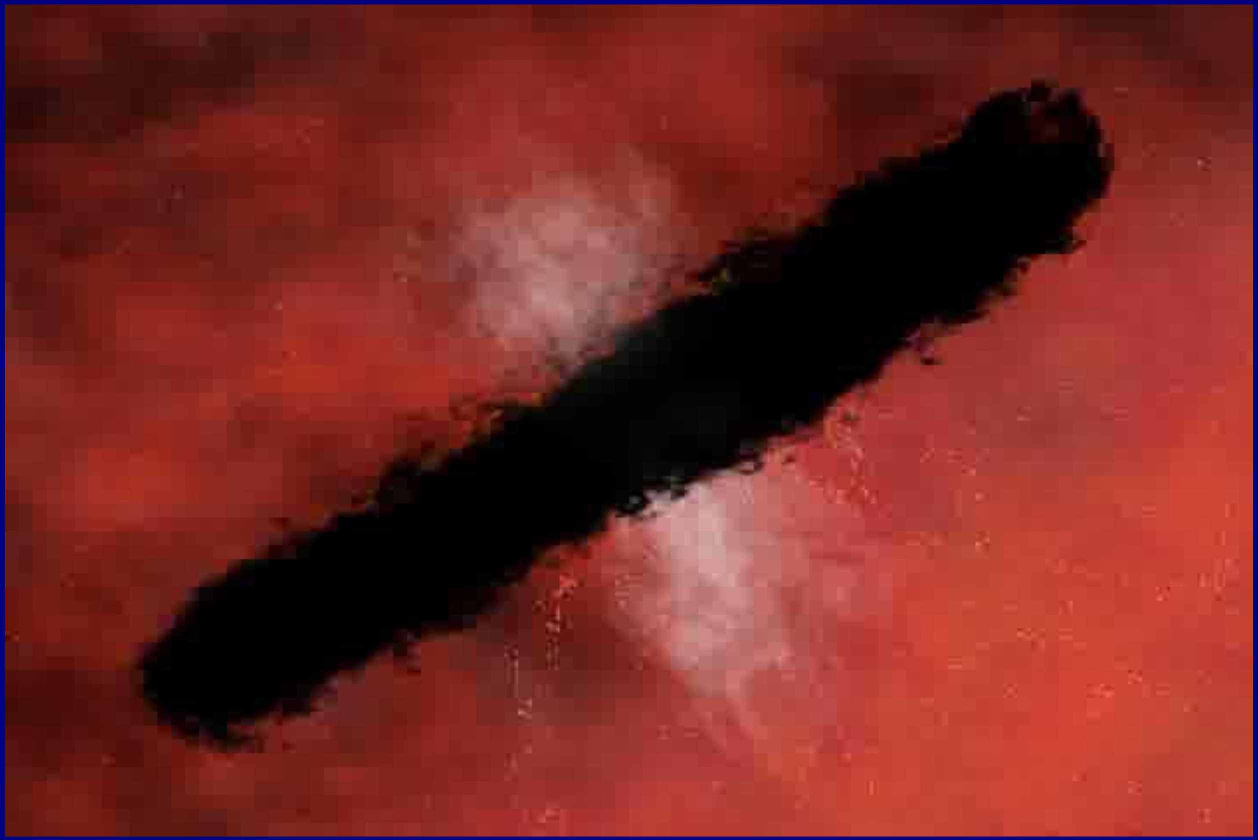
A provocative "unifying" scheme for AGNs and YSOs (as NHXM targets)

Radio-loud AGN



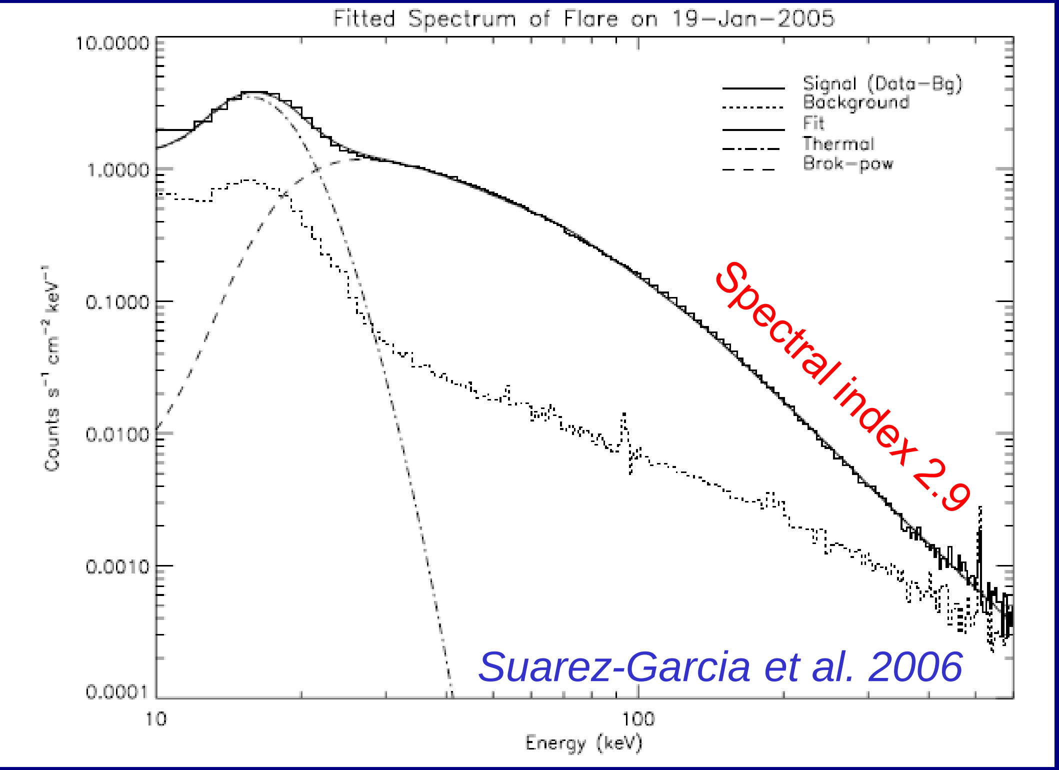
Urry and Padovani 1995

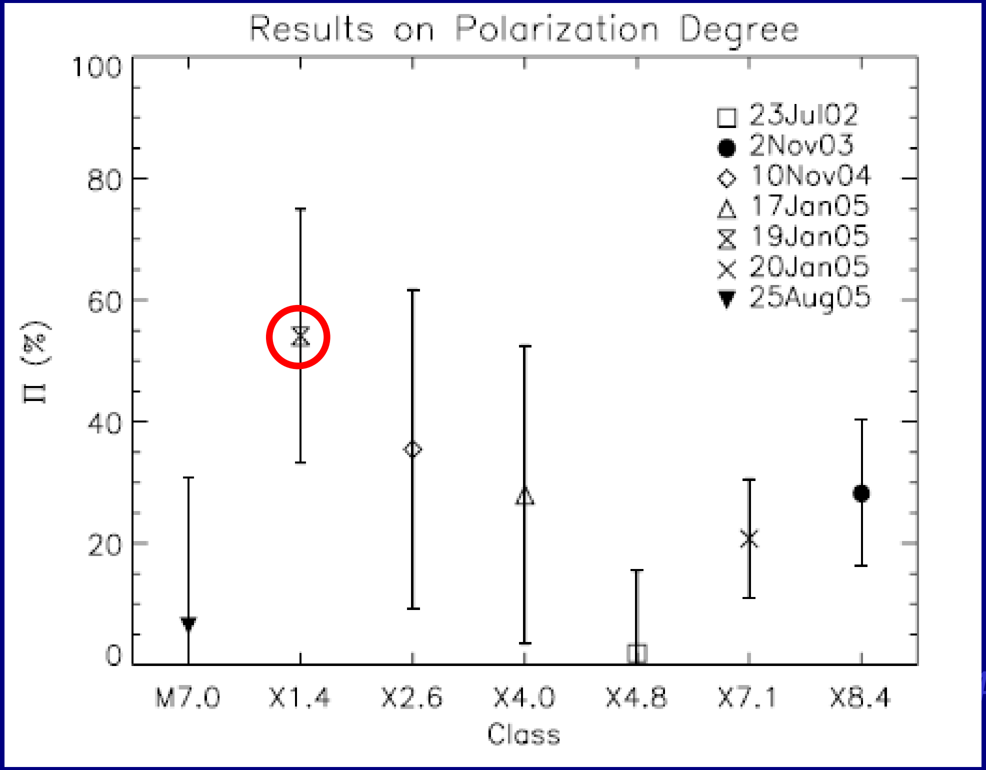
Accreting T Tauri star with flare



Feigelson and the COUP Team (2005)
Credit: A. Hobart, NASA/CXC

Solar X-ray polarization





- X-ray polarization searched in 7 large solar flares observed with RHESSI (rise times 60–240 s, 10^3–10^4 events in 100–350 keV)
- Significant (1–3 σ) polarization found in 5 cases, but large uncertainties and range of polarization degree (10–60%)
- Independent analyses of a few flares observed with RHESSI and Coronal-F yield consistent results within uncertainties
- These results have little predictive power, however