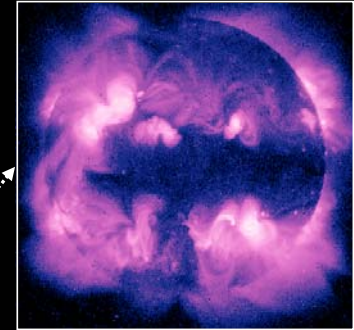
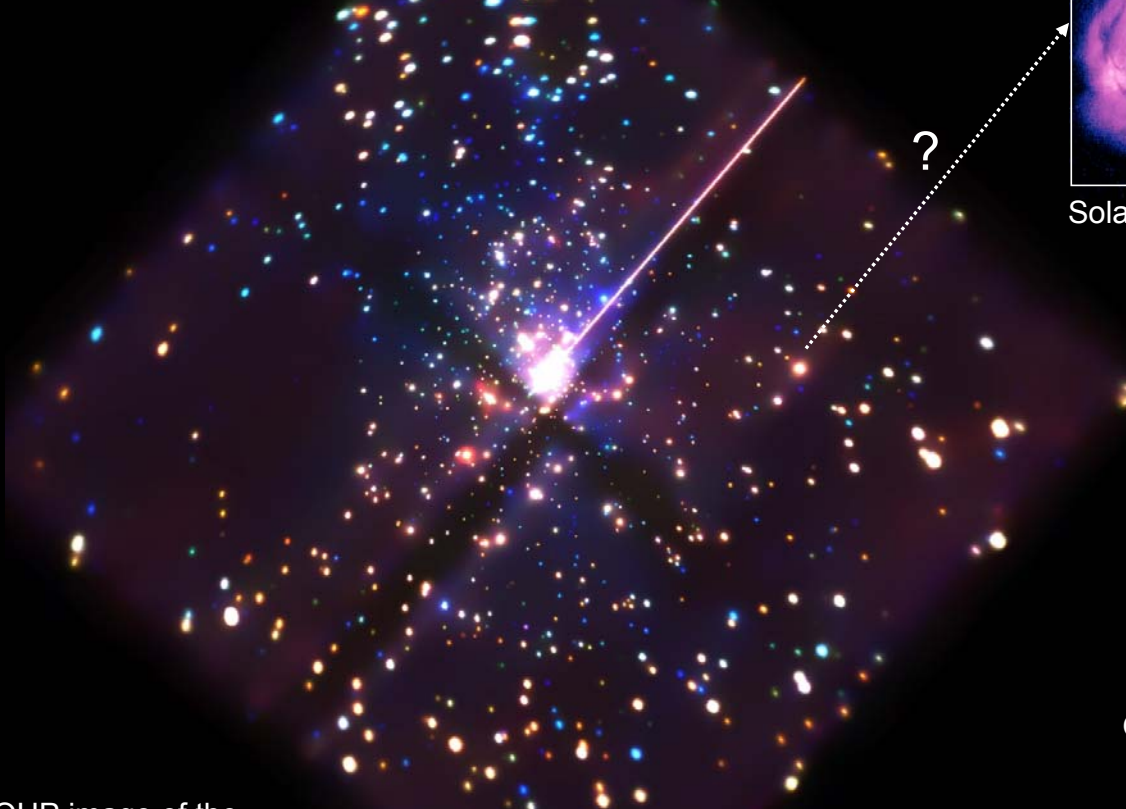
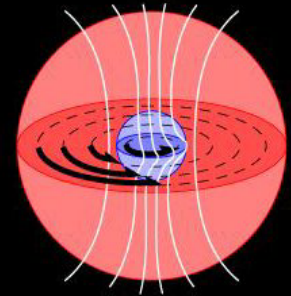


The Coronae of Very Young Stars

new insights from the
Chandra Orion Ultradeep Project



Solar – Stellar connection



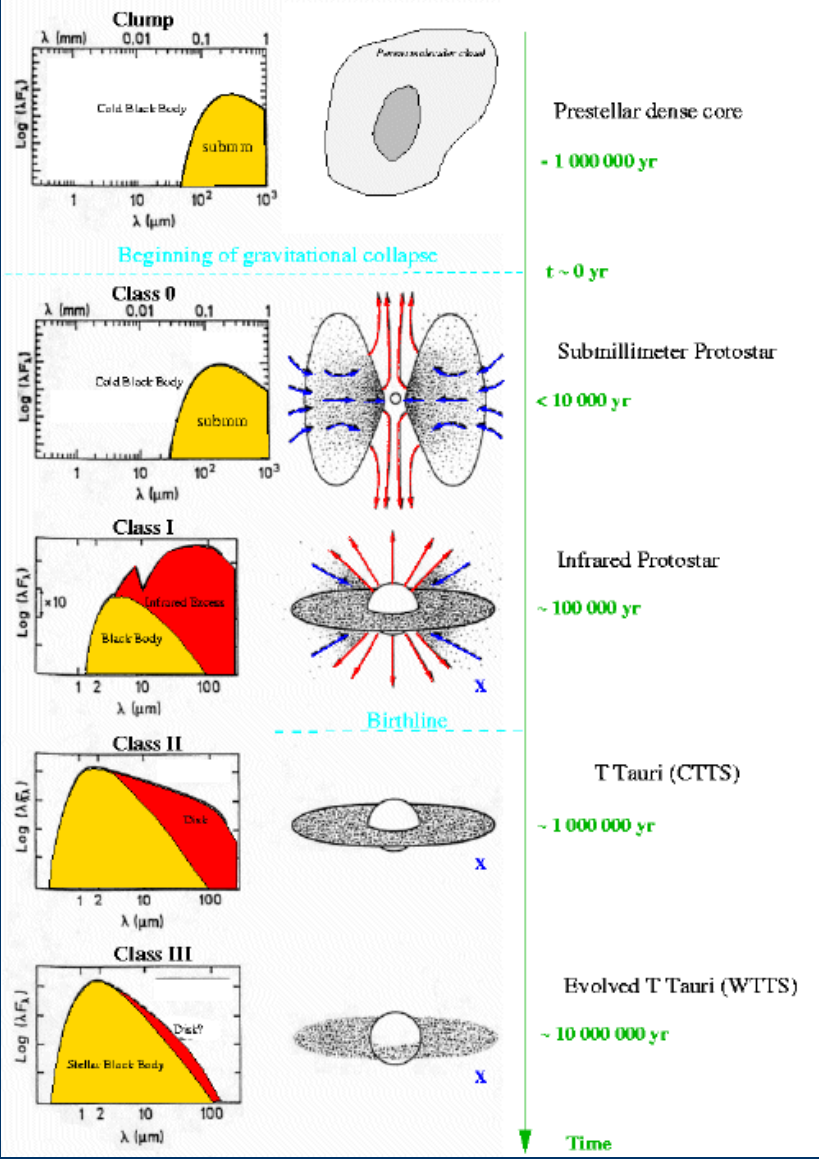
Origin of the X-ray emission

COUP image of the
Orion Nebula Cluster

Thomas Preibisch

Max-Planck-Institute for Radioastronomy, Bonn, Germany

Classification of young stellar objects



X-ray emission

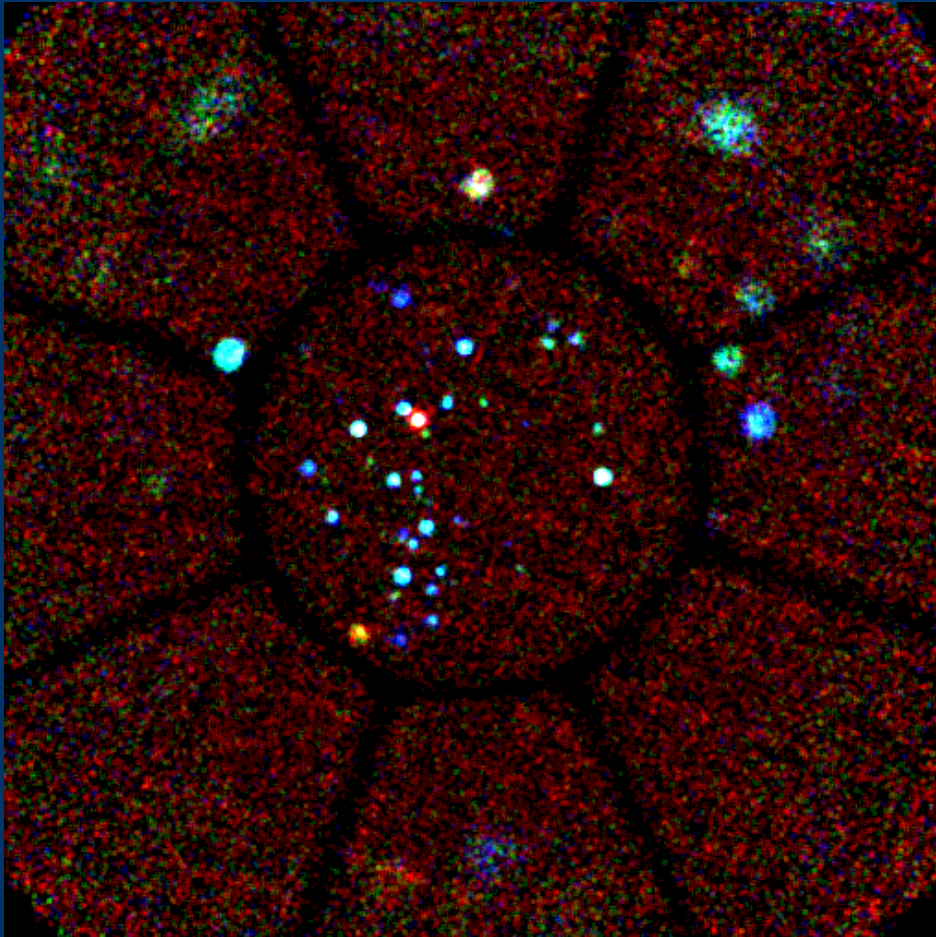
?

yes

yes

yes

EINSTEIN / ROSAT / ASCA observations of star forming regions



ROSAT X-ray image of the Chameleon I star forming region
age ~ 5 Myr

Many T Tauri stars are
strong X-ray sources

$$L_x \sim 10^{28} - 10^{31} \text{ erg/s}$$

$$T_x \sim 10 \text{ MK}$$

The solar-stellar connection

T Tauri Stars:

$$L_X \sim 10^{28} - 10^{31} \text{ erg/s}$$

$$L_X/L_{\text{bol}} \sim 10^{-5} - 10^{-3}$$

$$T_X \sim 5 - 50 \text{ MK}$$

(100 MK during flares)

100 - 10 000 ×

~ 10 ×

Sun:

$$L_X \sim 10^{27} \text{ erg/s}$$

$$L_X/L_{\text{bol}} \sim 10^{-6}$$

$$T_X \sim 2 \text{ MK}$$

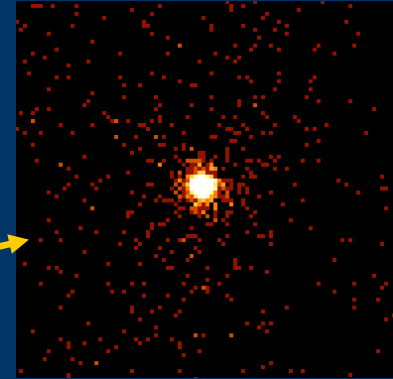
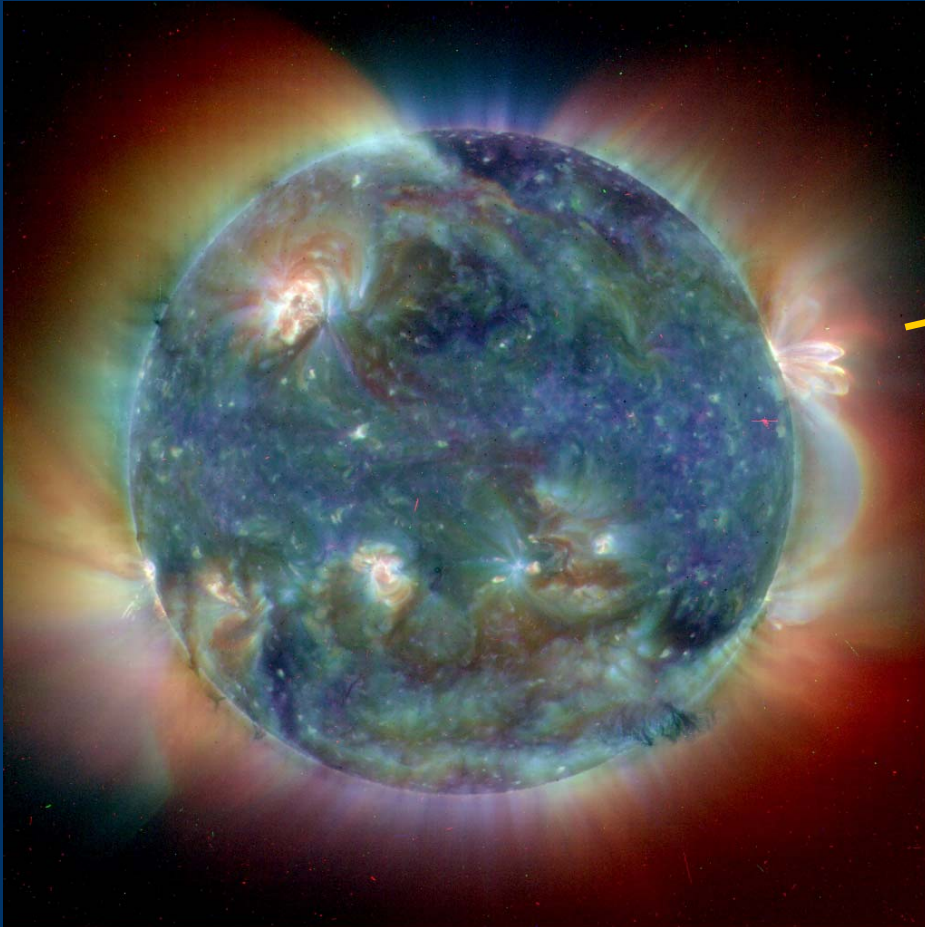
(≤10 MK during flares)

Is the strong X-ray activity of T Tauri Stars

- a) just scaled up solar-like magnetic activity ?
- b) or is there some other emission mechanism at work ?

Problem:
for stellar X-ray
astronomy

Stellar observations are time- and space-averages
over a very dynamic and highly structured corona

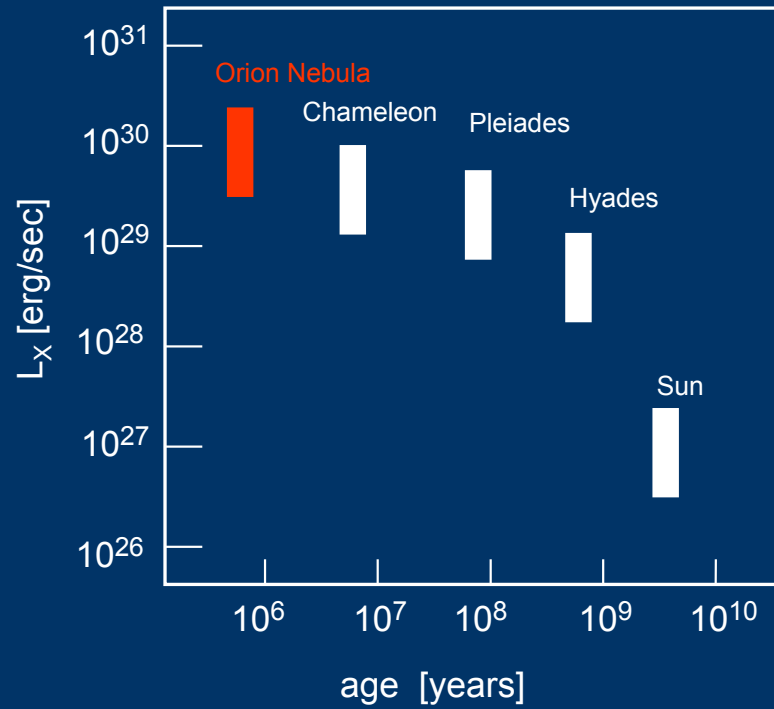
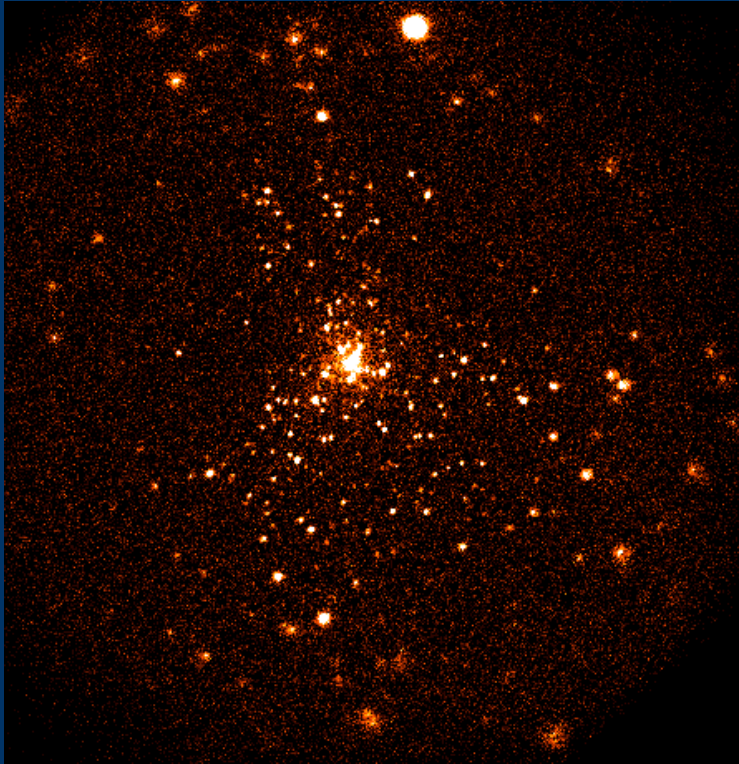


$$I \propto \int G(T) N_e^2(T) \frac{dV(T)}{d \log T} d \log T$$

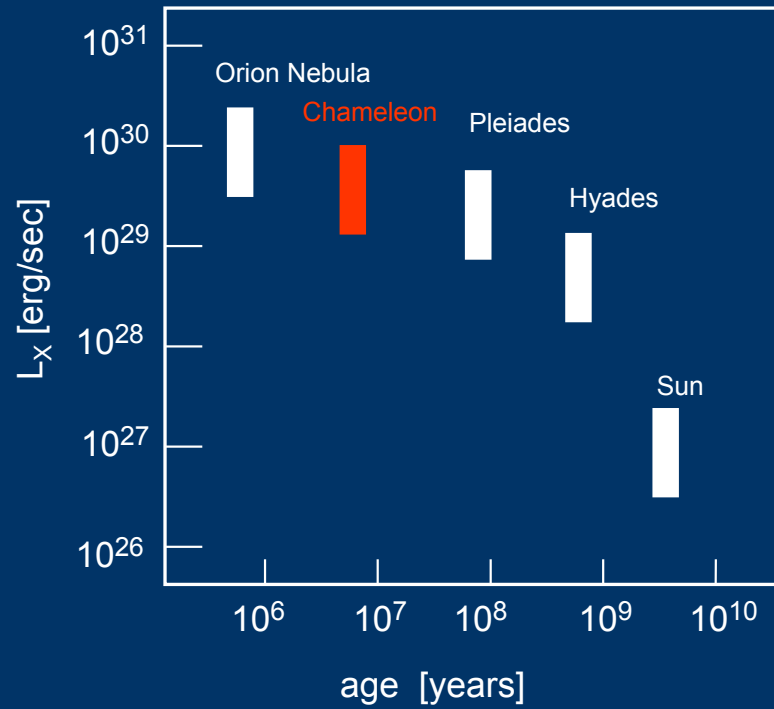
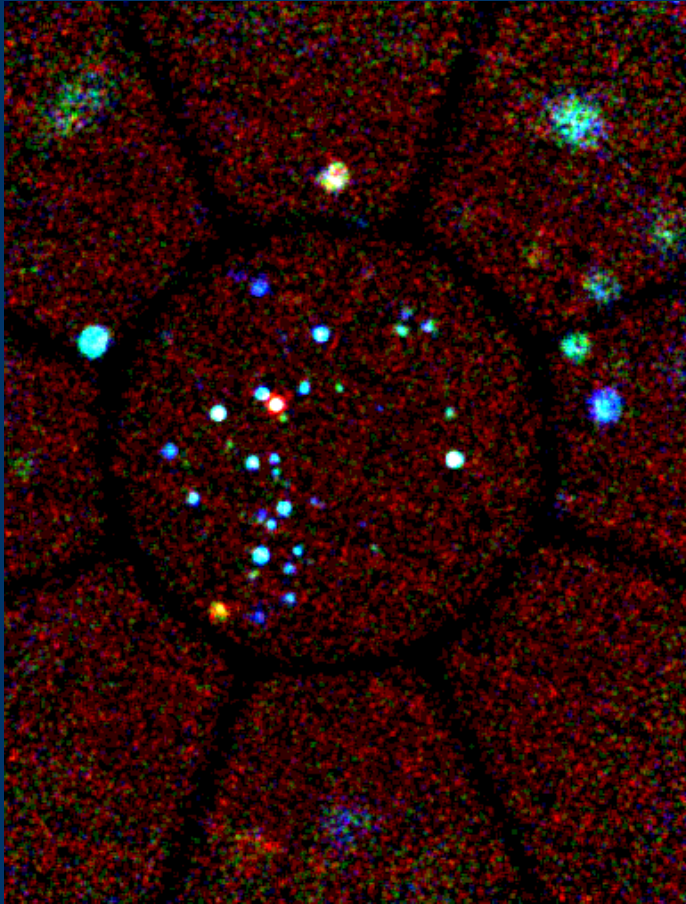
Advantage
of stellar X-ray
astronomy

1 Sun
↕
many stars

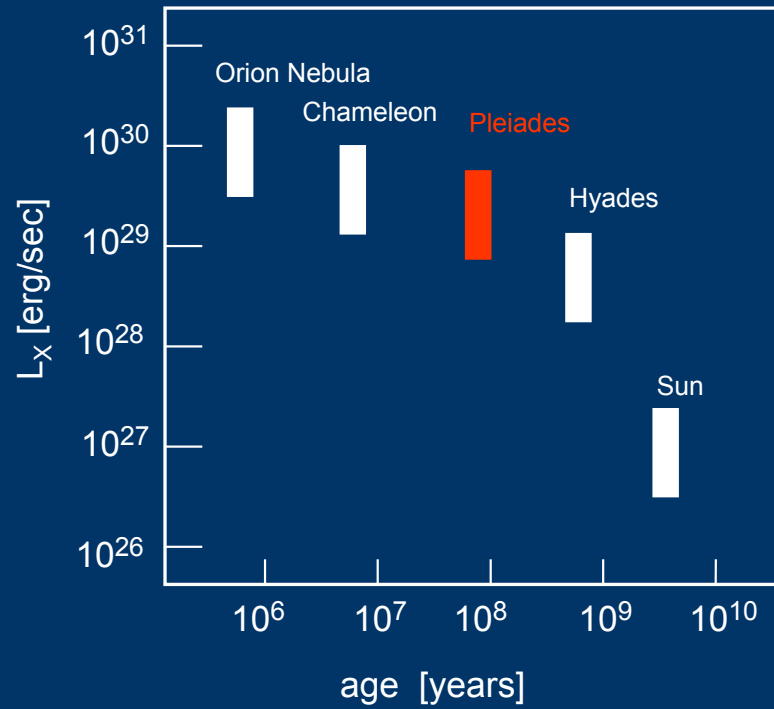
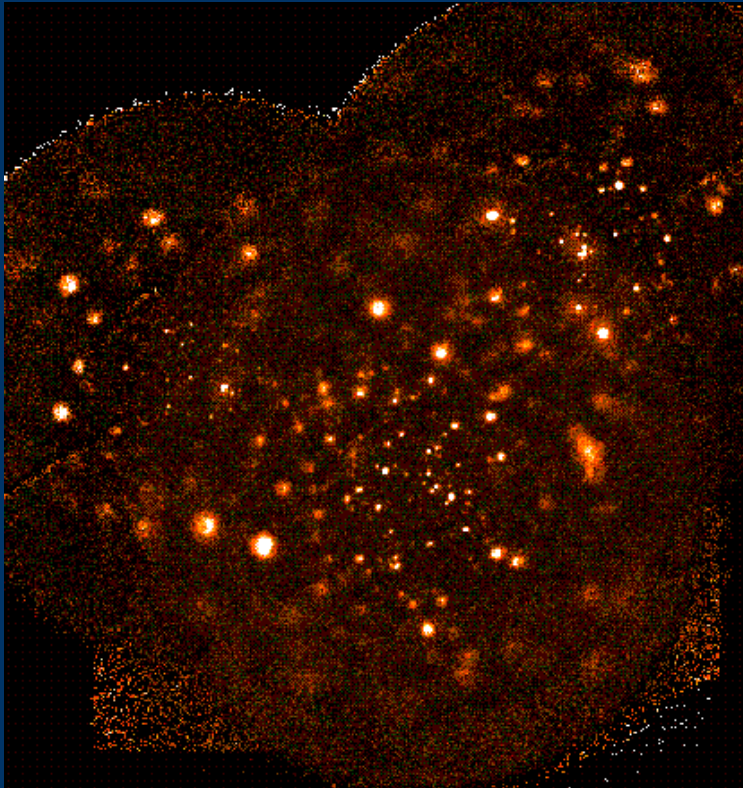
Temporal evolution of the X-ray
activity of solar mass stars



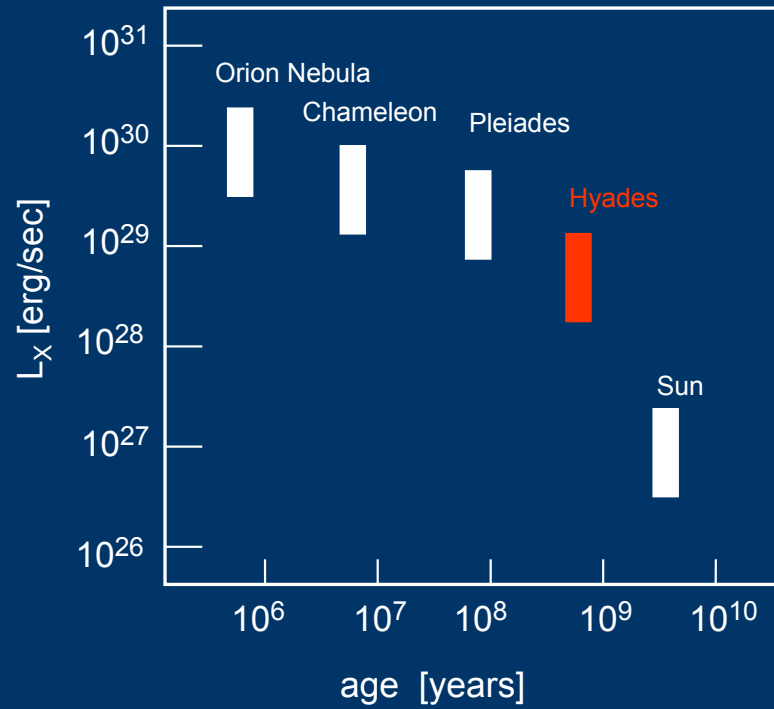
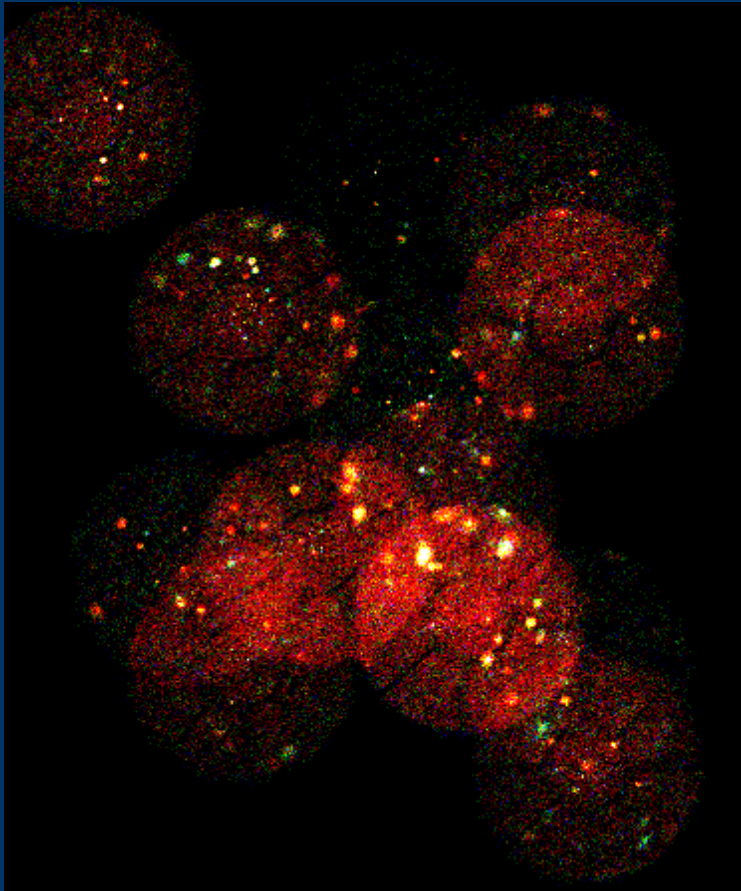
Temporal evolution of the X-ray activity of solar mass stars



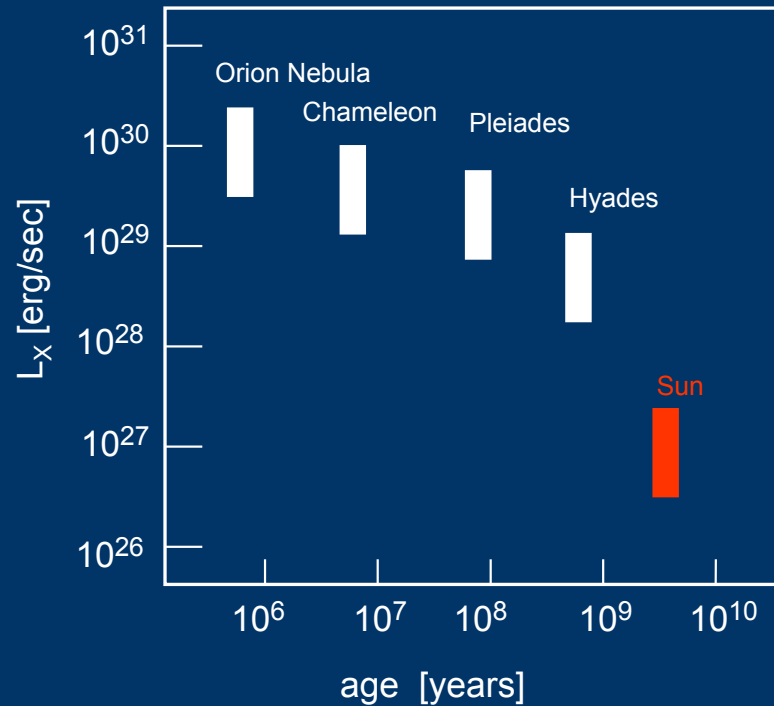
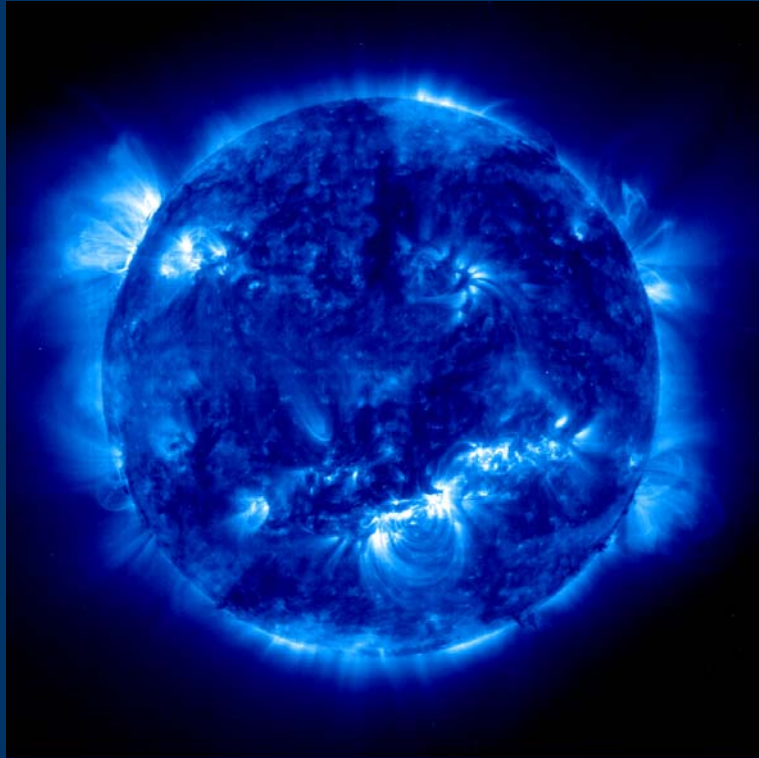
Temporal evolution of the X-ray activity of solar mass stars



Temporal evolution of the X-ray activity of solar mass stars

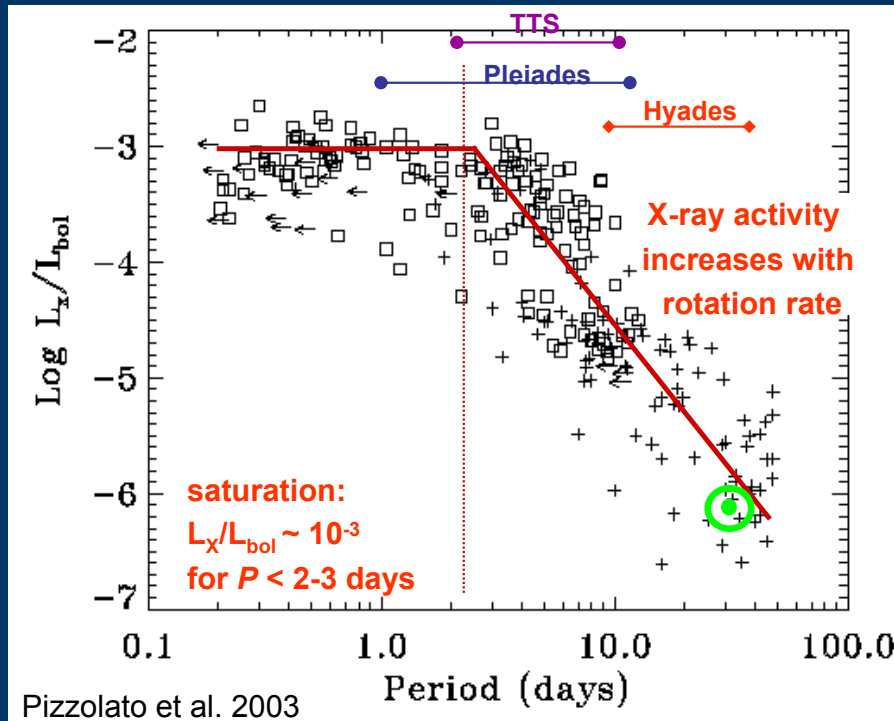


Temporal evolution of the X-ray activity of solar mass stars



→ smooth decrease of L_x with age
no sudden changes

The activity – rotation relation for *main-sequence stars*



L_x/L_{bol} (TTS) \sim L_x/L_{bol} (coronally active main-sequence stars)

usual explanation: **scaled up solar-like magnetic activity:**

faster rotation \rightarrow stronger dynamo action \rightarrow higher activity

Problem: *Solar analogy cannot reproduce the high X-ray luminosities*

Surface filled completely with solar-type loops: $\log(L_X/L_{\text{bol}}) \leq -5$

T Tauri stars: $\log(L_X/L_{\text{bol}})_{\text{max}} \sim -3$

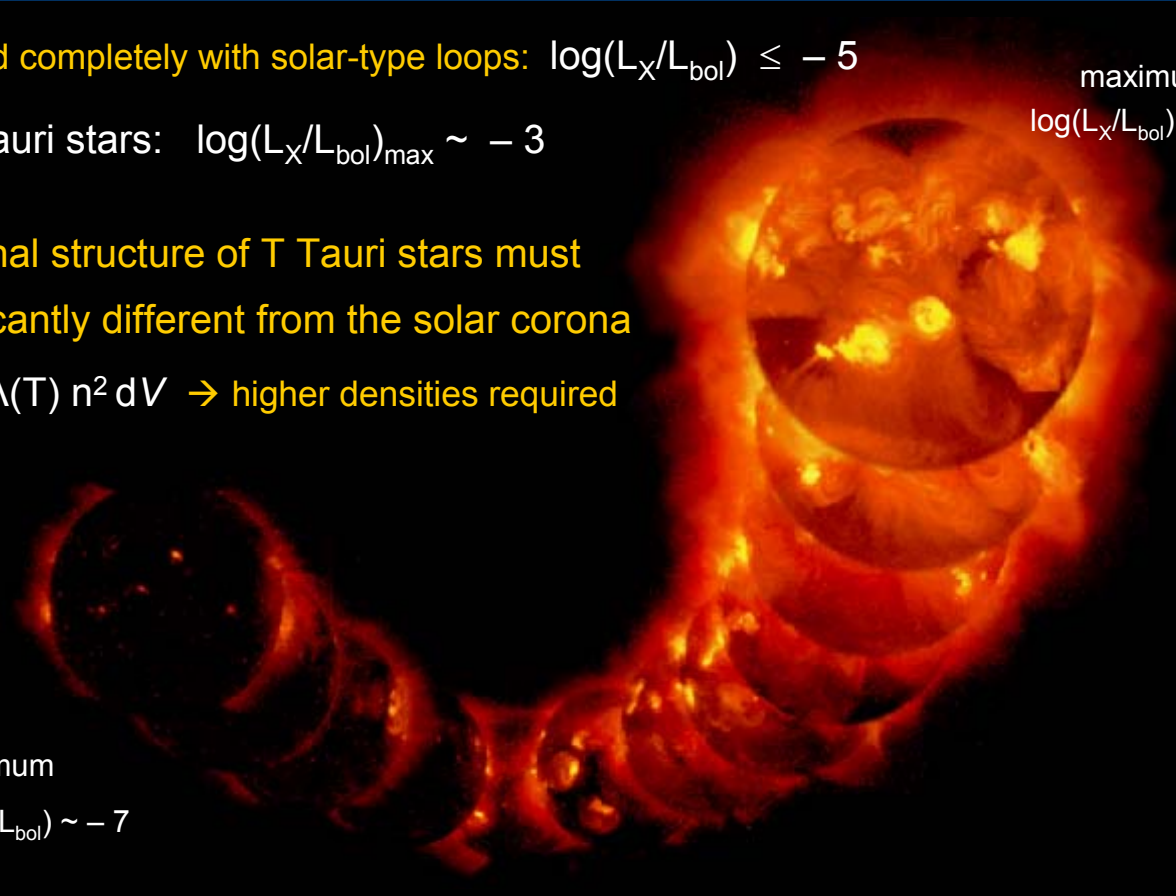
maximum
 $\log(L_X/L_{\text{bol}}) \sim -6$

The coronal structure of T Tauri stars must be significantly different from the solar corona

$L_X \propto \int \Lambda(T) n^2 dV \rightarrow$ higher densities required

minimum

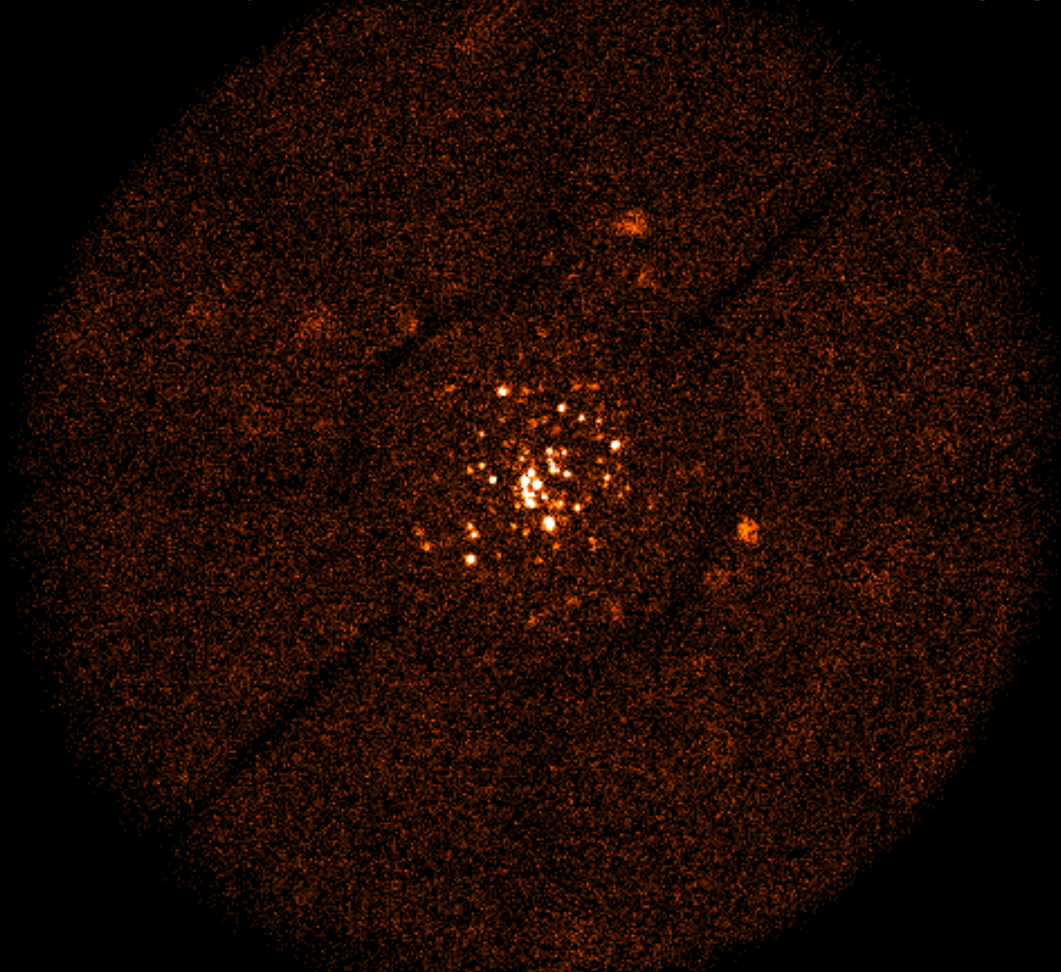
$\text{Log}(L_X/L_{\text{bol}}) \sim -7$



High S/N spectra of a large TTS sample could provide valuable constraints

\rightarrow More/better data are needed !

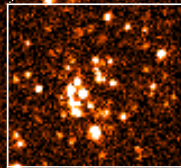
From ROSAT to Chandra: IC 348 (2 Myr)



ROSAT PSPC resolution = 15"

From ROSAT to Chandra: IC 348 (2 Myr)

215 X-ray sources detected



ROSAT PSPC resolution = 15"

Chandra ACIS resolution ~ 1"

Numerous Chandra and XMM observations
of star forming regions and young clusters

Persisting problems:

- ◆ limited sensitivity: objects at the solar activity level

$$L_X \sim 10^{27} \text{ erg/s}, L_X/L_{\text{bol}} \sim 10^{-6} \text{ remain undetected}$$

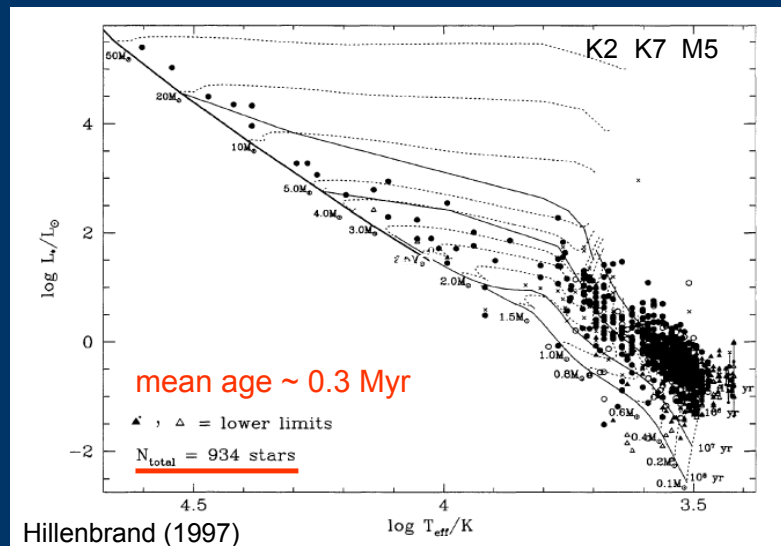
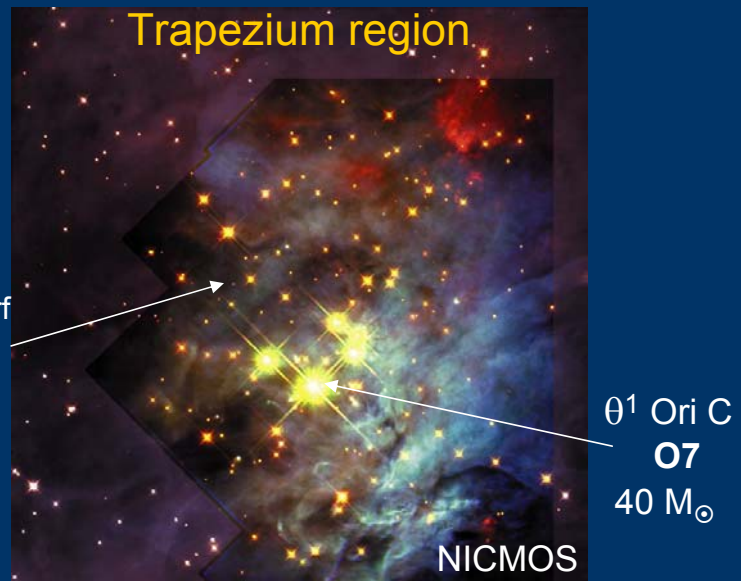
- ◆ spectra only for brightest sources
- ◆ many different small samples of T Tauri stars → statistical errors

Solution: Ultradeep observation of a selected, well investigated region

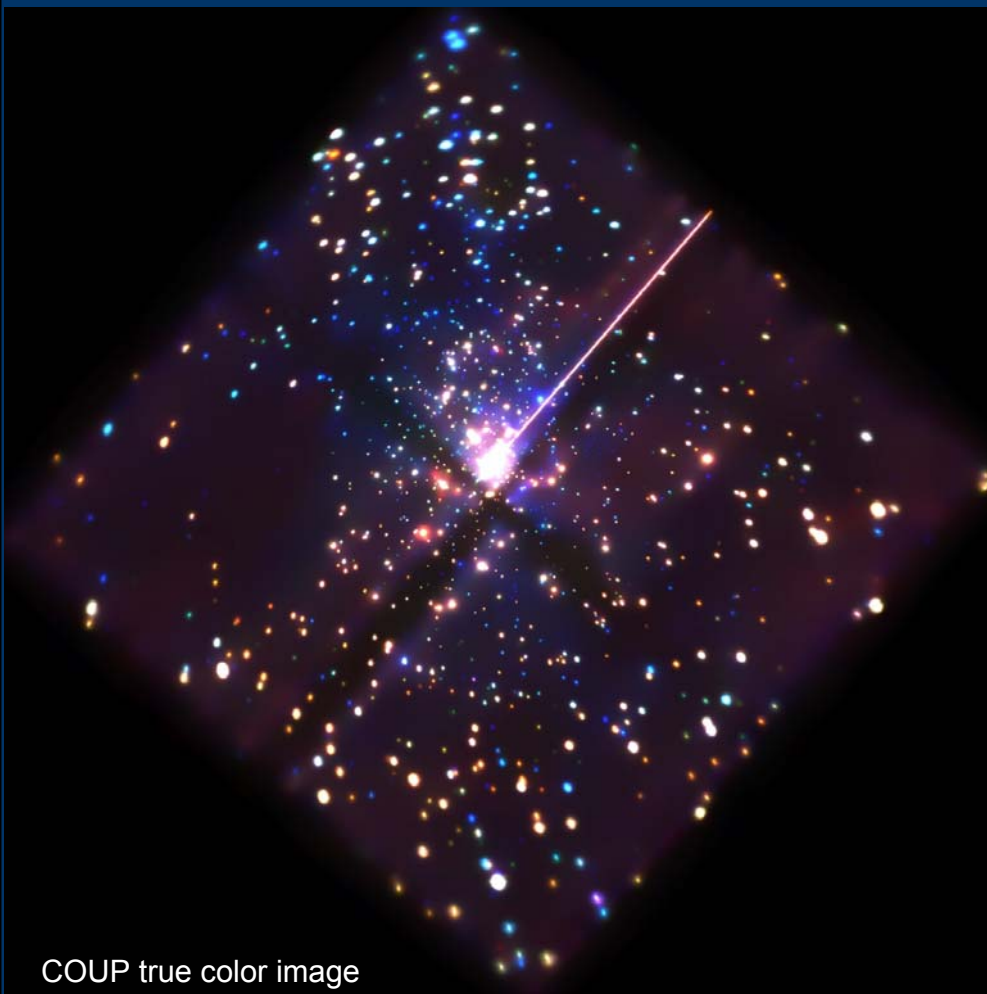
Target: **Orion Nebula Cluster (ONC)**

one of the most nearby, rich, and best studied regions
of low- and high-mass star formation

>1000 T Tauri stars, very well studied at optical/infrared,
stellar parameters known for hundreds of objects



The Chandra Orion *U*ltradeep *P*roject (COUP)



COUP true color image

PI: Eric Feigelson

8-21 January 2003:
Orion Nebula Cluster
observed with ACIS for
850 ksec = 10 days

10 × deeper than any previous
X-ray observation of the ONC

1616 sources detected

Unique aspects of **COUP**:

- high sensitivity:**
- $L_{X,lim} \sim 10^{27}$ erg/s \rightarrow sensitive to $L_X/L_{bol} = 10^{-7}$ for $1 M_{\odot}$
 - X-ray emission from brown dwarfs
 - good spectra for > 1000 sources \rightarrow plasma temperatures

11 day quasi-continuous exposure:

- reveals variability on timescales from seconds to 10 days (factor 10^6)
- hundreds of flares \rightarrow flare properties & statistics

Scientific analysis:

Science groups (Group leaders):

Data reduction & catalog (Getman) [finished 20 Nov. 2003]

X-ray spectra/variability (Harnden)

Origin of TTS X-rays (Preibisch)

Embedded stars (Grosso)

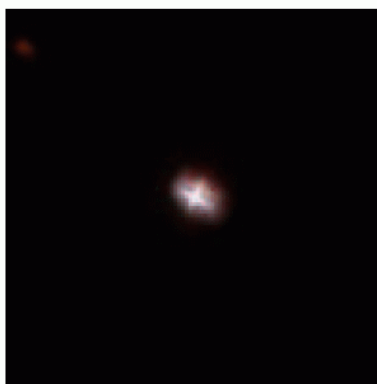
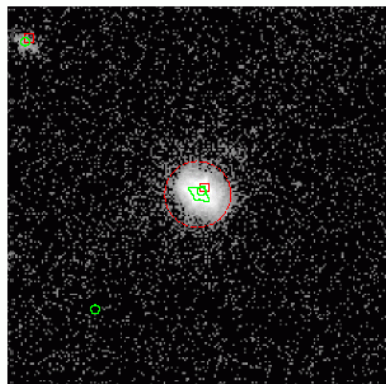
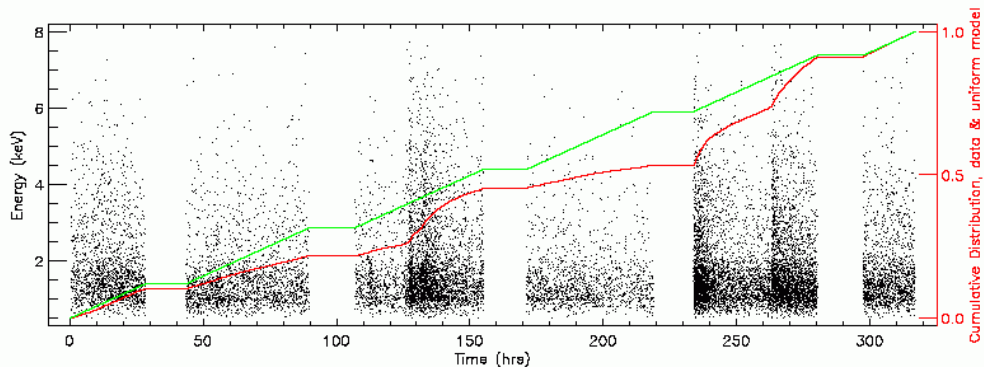
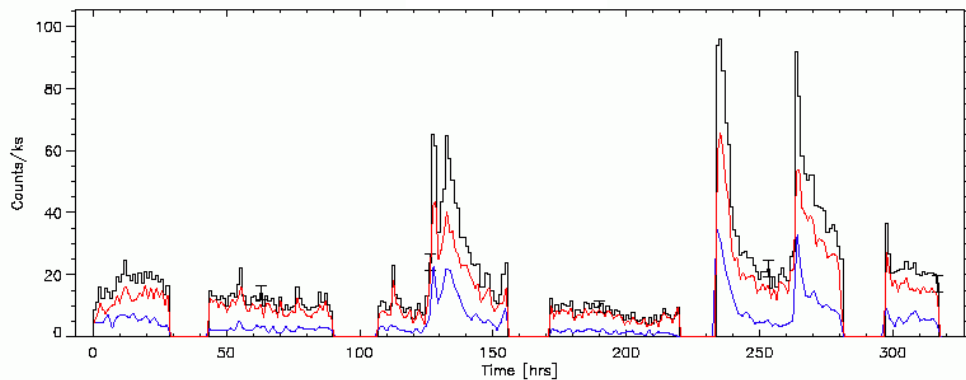
Brown Dwarfs (McCaughrean)

High-mass stars (Montmerle)

Effects of X-rays (Palla)

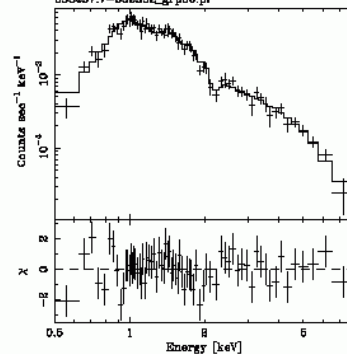
The COUP X-ray atlas

Typical example:
K8 T Tauri Star



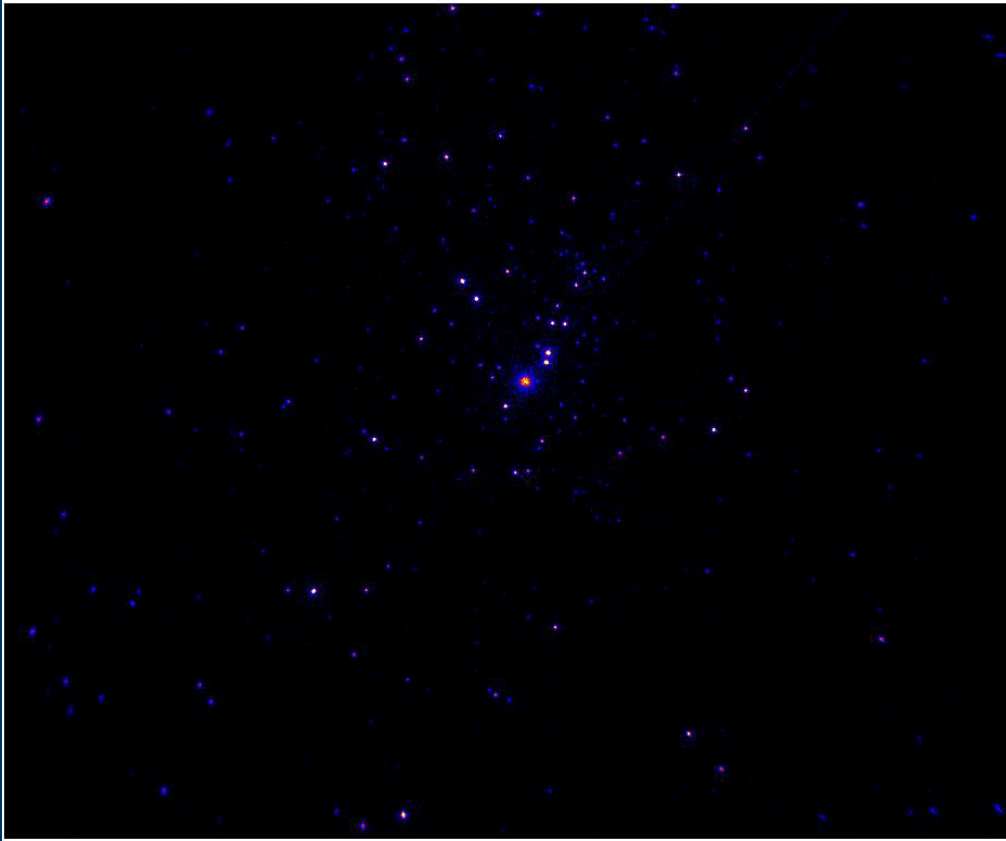
$N_G=0.1385$, $kT1=0.7852$, $kT2=3.042$, $chi=0.975$

053457.7-052352_grp80.pl

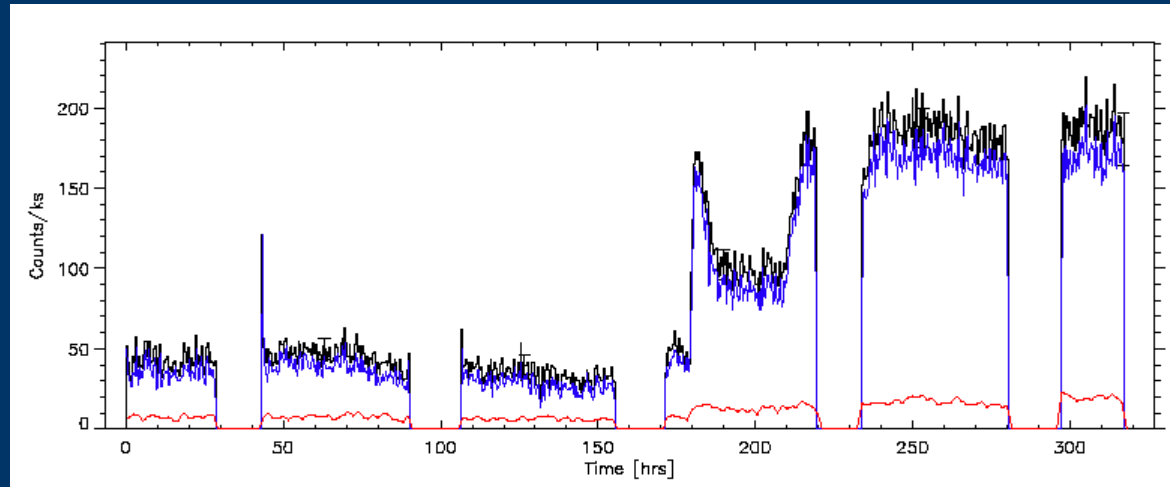


1.) Variability

The COUP movie

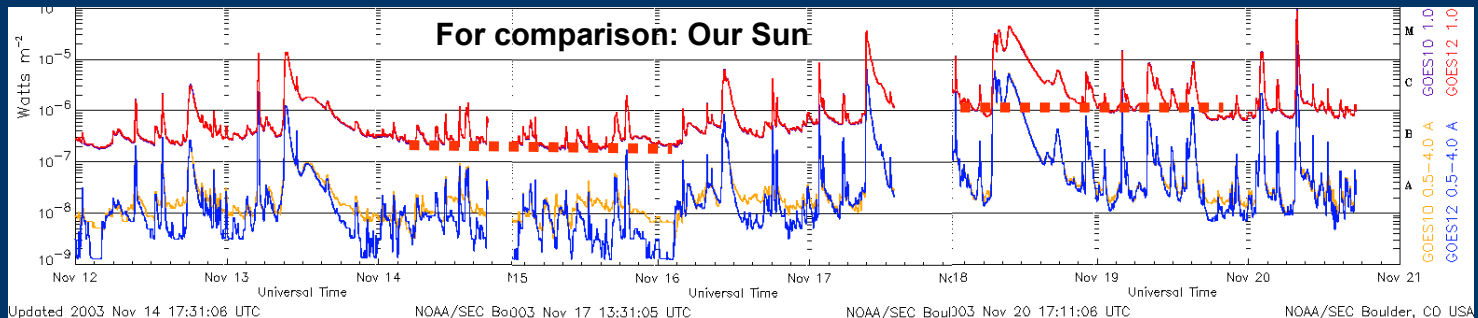


Some interesting light curves

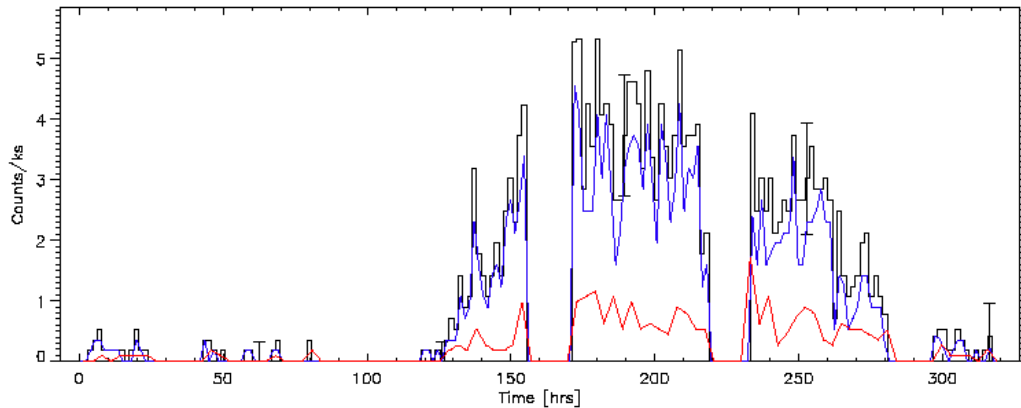


X-ray flux increases by factor of ~ 4 within ~ 2 days

Possible interpretation: single active region appears due to rotation

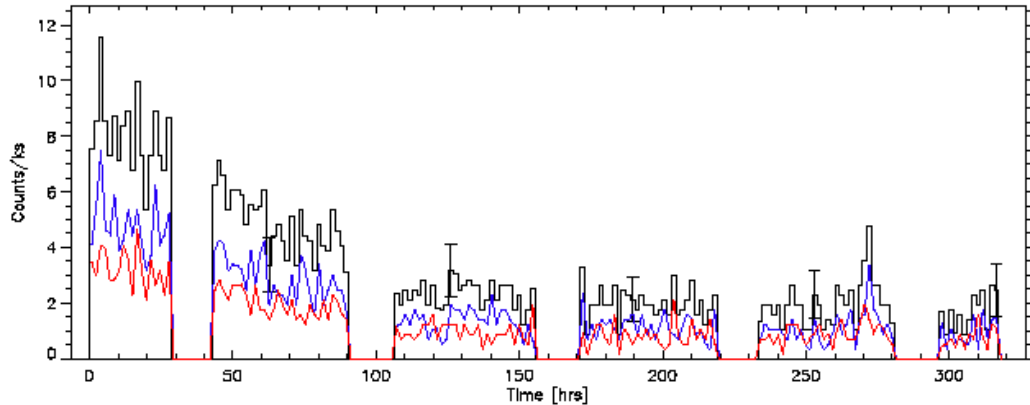


Some interesting light curves



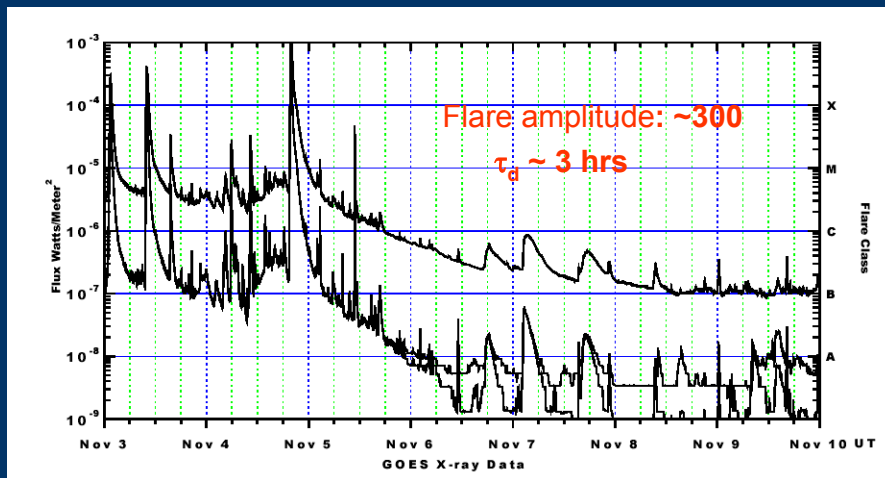
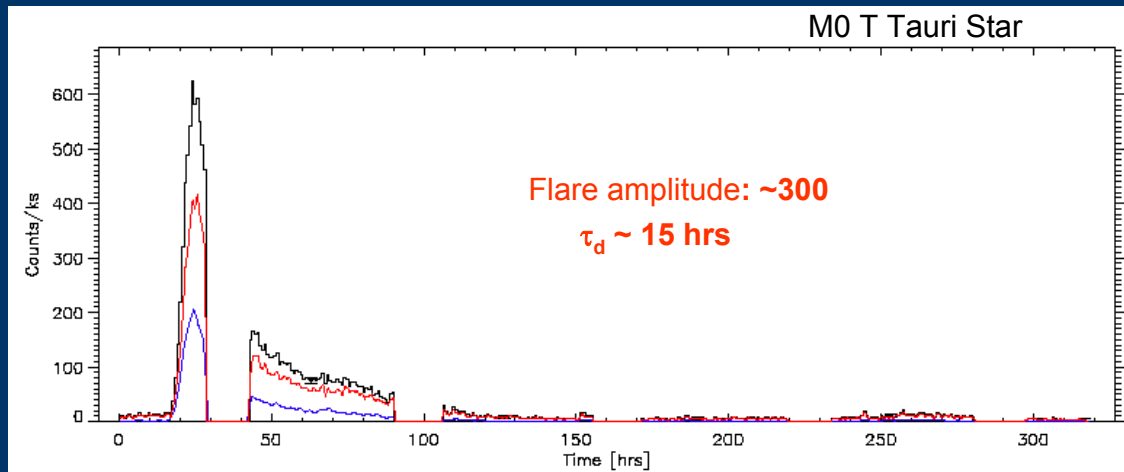
strong indications for rotational modulation

→ X-ray emission is dominated by a few active regions



→ no completely filled corona

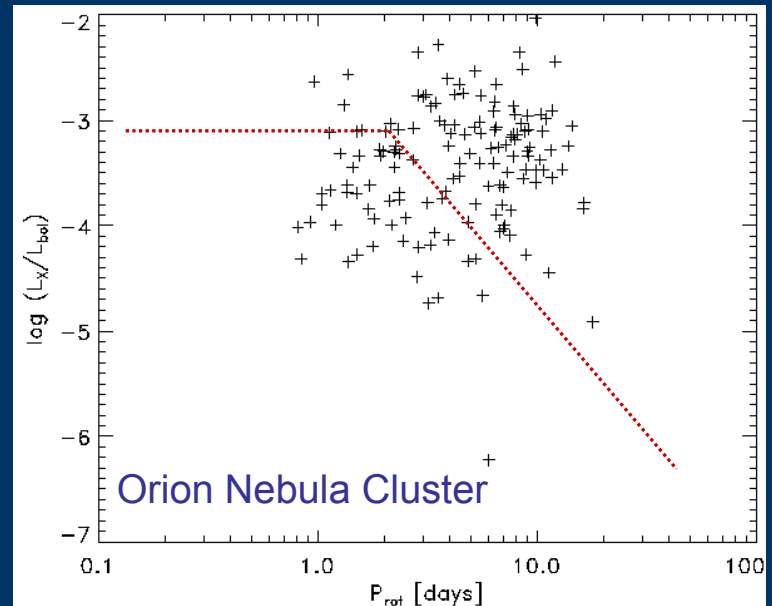
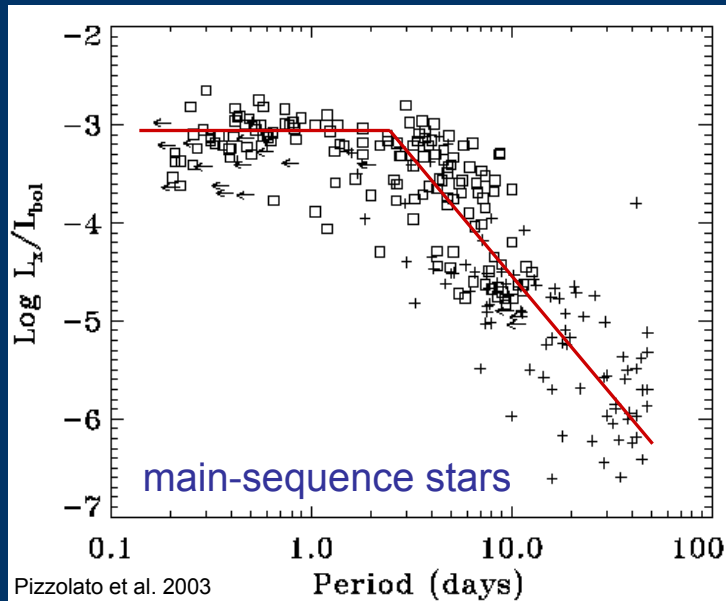
Some interesting light curves



Solar X-class
flare on Nov 4

2.) Origin of the X-ray emission

No activity - rotation relation for the T Tauri Stars

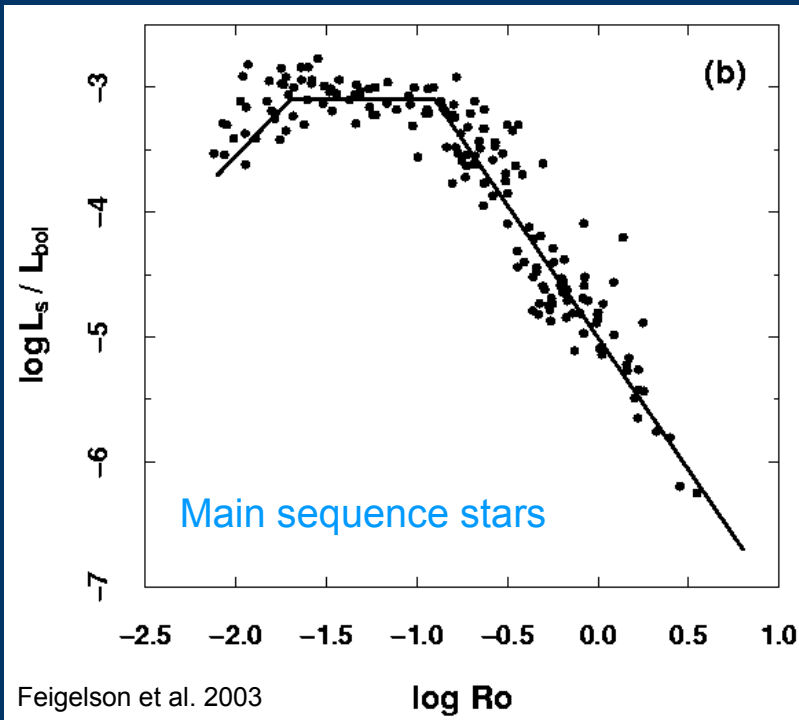


Fast rotators are highly active,
slow rotators show weak activity

Even slow rotators are highly active

A closer look to the activity – rotation connection

$$\text{Rosby Number } R_0 = \frac{\text{Rotation period } P_{\text{rot}}}{\text{Convective turnover time } \tau_c}$$



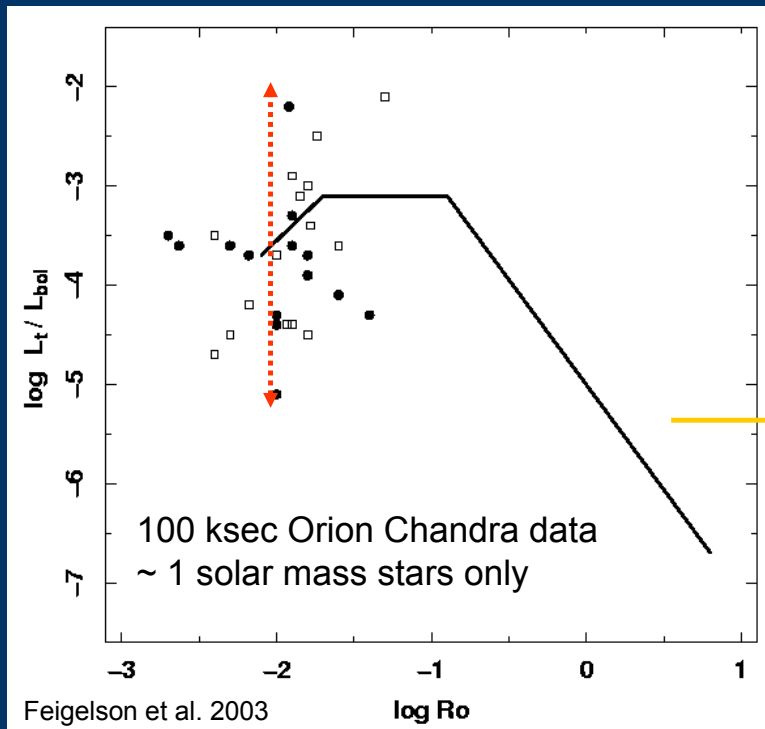
Dynamo saturation for $R_0 \leq 0.1$

1 M_{\odot} main sequence star:

$\tau_c \sim 20$ days (Kim & Demarque 1996)

→ saturation for $P_{\text{rot}} \sim 2$ days

A closer look to the activity – rotation connection



1 M_{\odot} T Tauri star:

$$\tau_C \sim 700 \text{ days}$$

→ saturation for $P_{rot} \sim 70$ days

→ all T Tauri stars are saturated

→ should have $L_X/L_{bol} \sim 10^{-3}$

wide spread of activity levels
at a given Rosby number

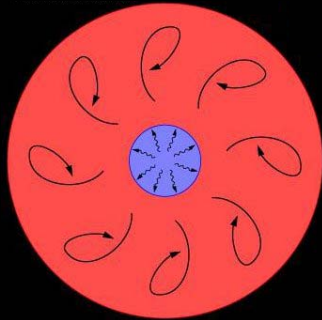
**Rotation is *not* the dominant factor
in the generation of X-rays (???)**

→ more data soon available

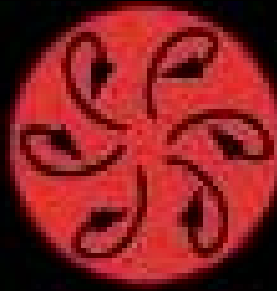
Problem **T Tauri Stars are fully convective**

→ **solar-type α - Ω dynamo cannot work**

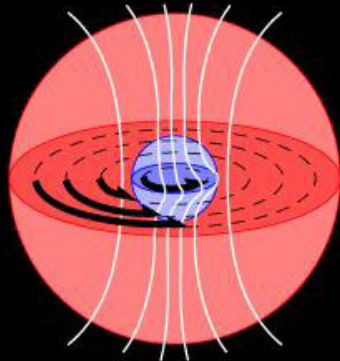
Late-type MS stars:



T Tauri stars:

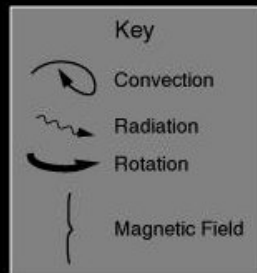


Rotation and Magnetic Dynamo
Standard Model



No α - Ω dynamo

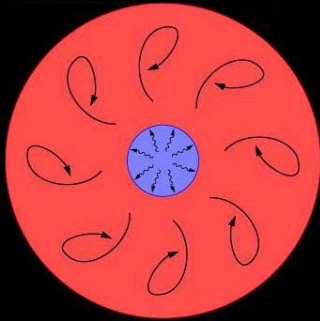
α - Ω dynamo



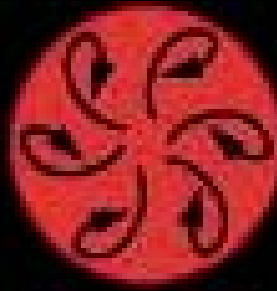
Problem T Tauri Stars are fully convective

→ solar-type α - Ω dynamo cannot work

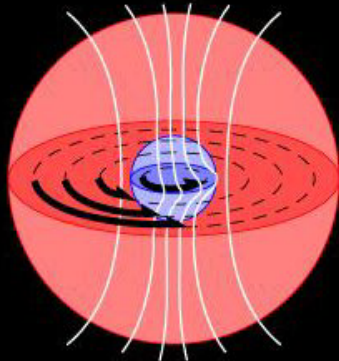
Late-type MS stars:



T Tauri stars:

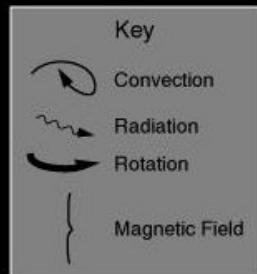


Rotation and Magnetic Dynamo
Standard Model



α - Ω dynamo

No α - Ω dynamo



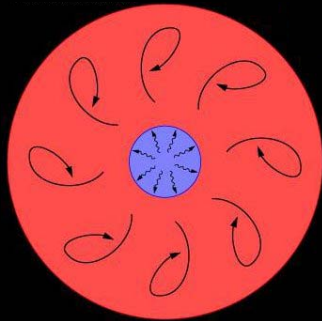
Alternative models for
magnetic field generation:

- α^2 dynamo ✗
strongly rotation-dependent

Problem T Tauri Stars are fully convective

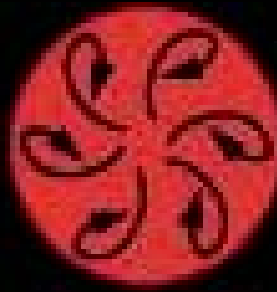
→ solar-type α - Ω dynamo cannot work

Late-type MS stars:

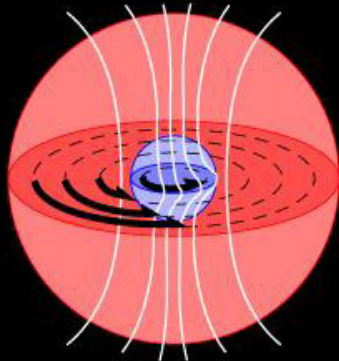


Rotation and Magnetic Dynamo
Standard Model

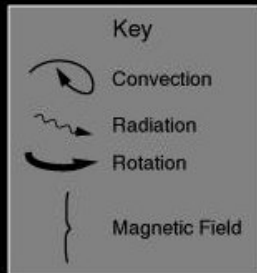
T Tauri stars:



No α - Ω dynamo

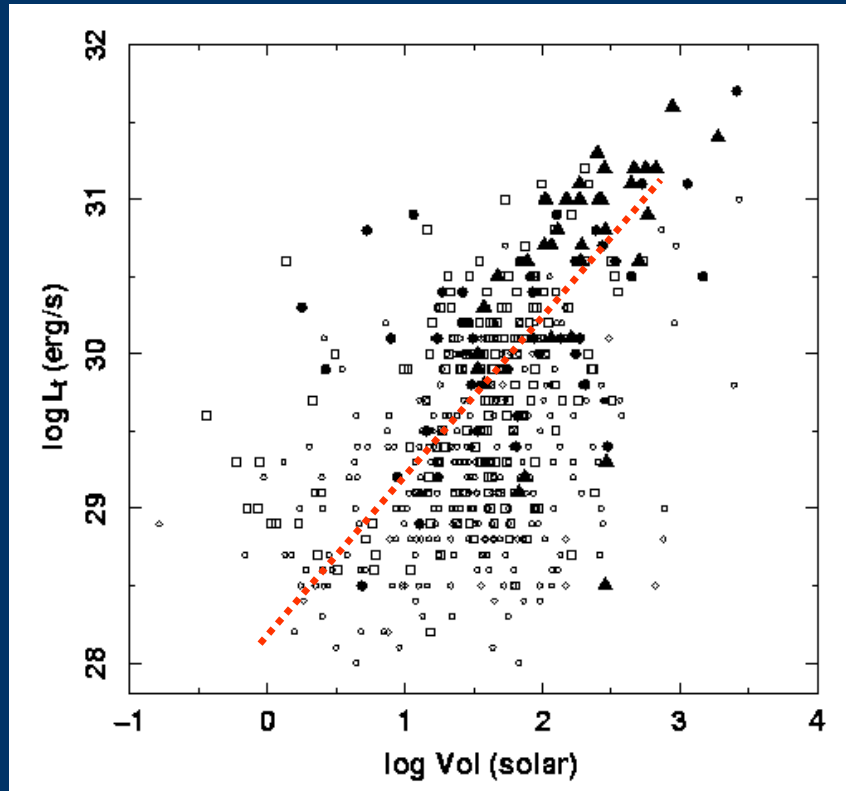


α - Ω dynamo



Alternative models for
magnetic field generation:

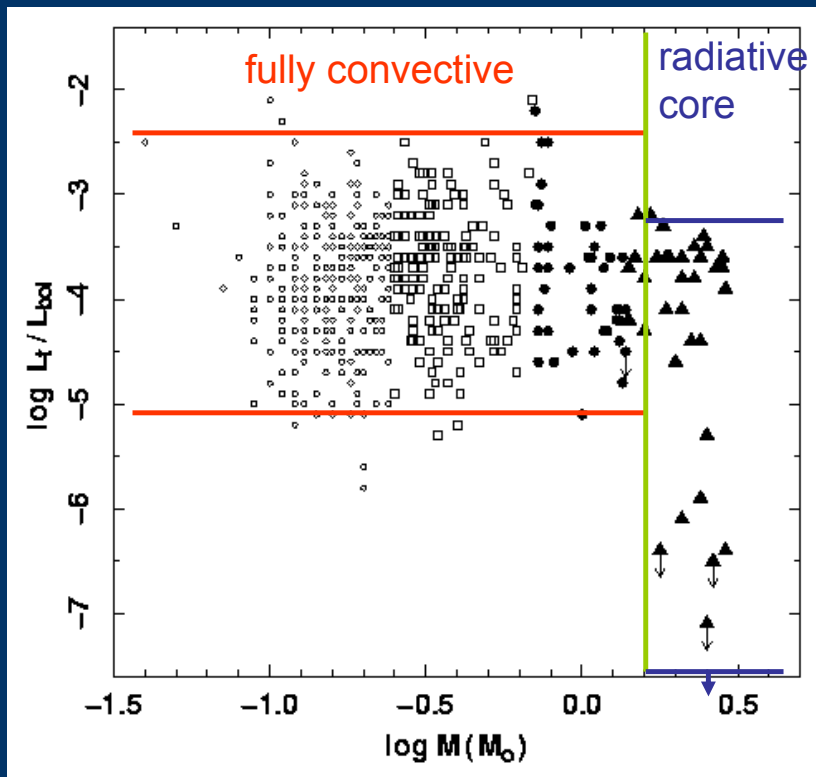
- α^2 dynamo
strongly rotation-dependent
- turbulent dynamo
works throughout the whole
convection zone
only weakly dependent
on rotation



T Tauri stars are fully convective

X-ray luminosity \propto stellar volume = volume of convection zone

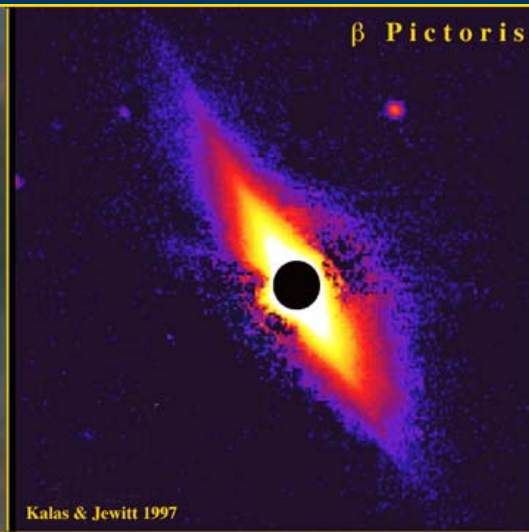
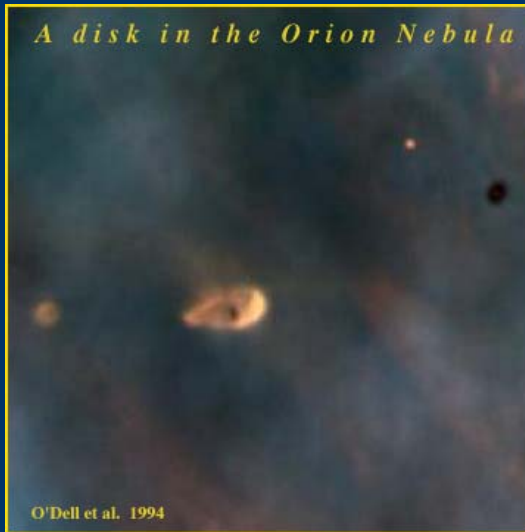
\rightarrow may support turbulent dynamo theory



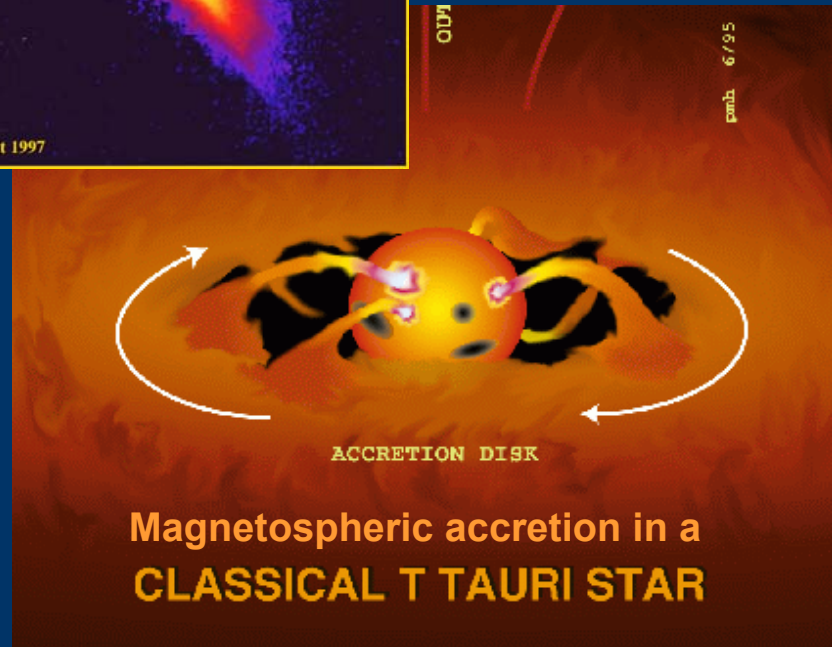
Clear difference between fully convective stars and stars with radiative cores

→ Changes in the stellar interior structure
cause changes in the dynamo activity

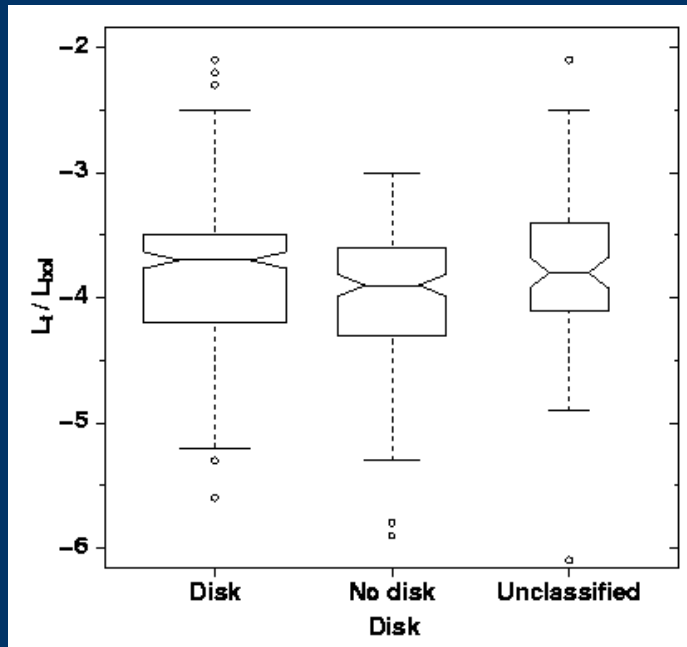
3.) X-ray emission and accretion disks



Are the X-ray properties related to the presence/absence of disks or the accretion process?



X-ray luminosities and circumstellar disks



The presence or absence of a disk does *not* affect the X-ray activity

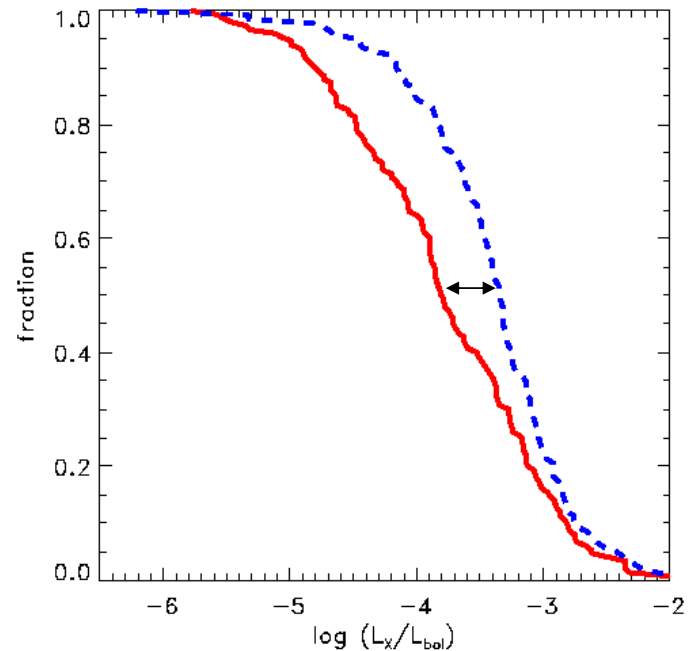
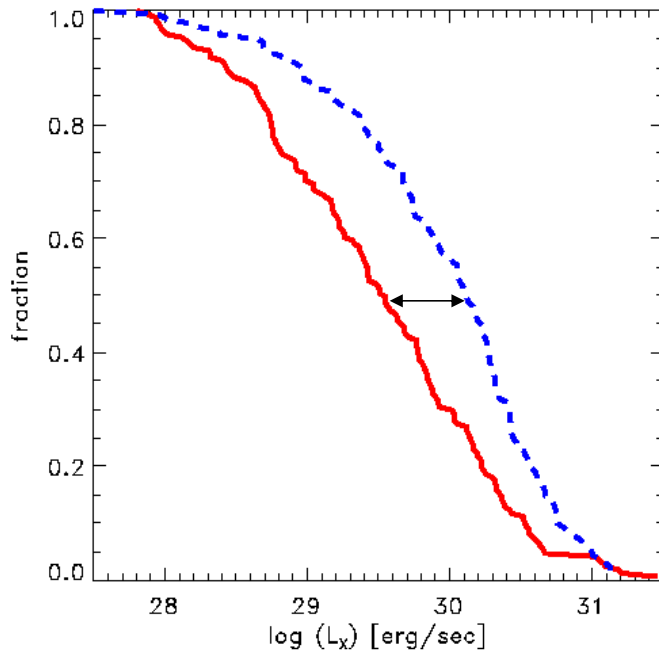
→ X-ray are not primarily produced in disk fields

X-ray luminosities and accretion

Ca II line emission traces accretion rate

$EW(\text{Ca II}) > 1 \text{ \AA} \rightarrow$ no accretion

$EW(\text{Ca II}) < -1 \text{ \AA} \rightarrow$ strong accretion



\rightarrow accreting stars have ~ 3 times *lower* X-ray luminosities

WHY ?

Scenario I:

accreting stars are magnetically locked to their disk:

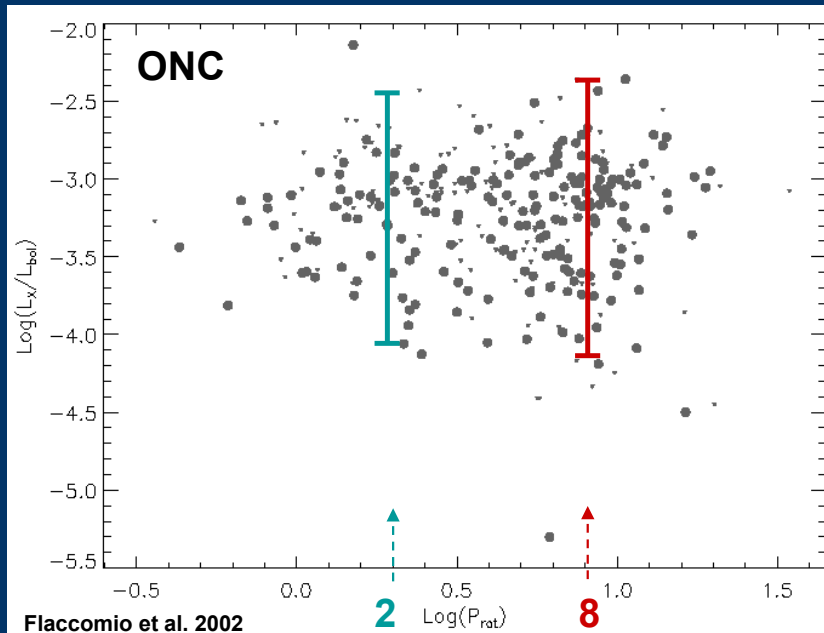
→ slower rotation → weaker dynamo ??

Herbst et al. 2002:

stars with disks: $\langle P_{\text{rot}} \rangle \sim 8$ days

stars without disks: $\langle P_{\text{rot}} \rangle \sim 2$ days

BUT: there is no rotation-activity relation for T Tauri Stars !!!!



non- accreting

accreting

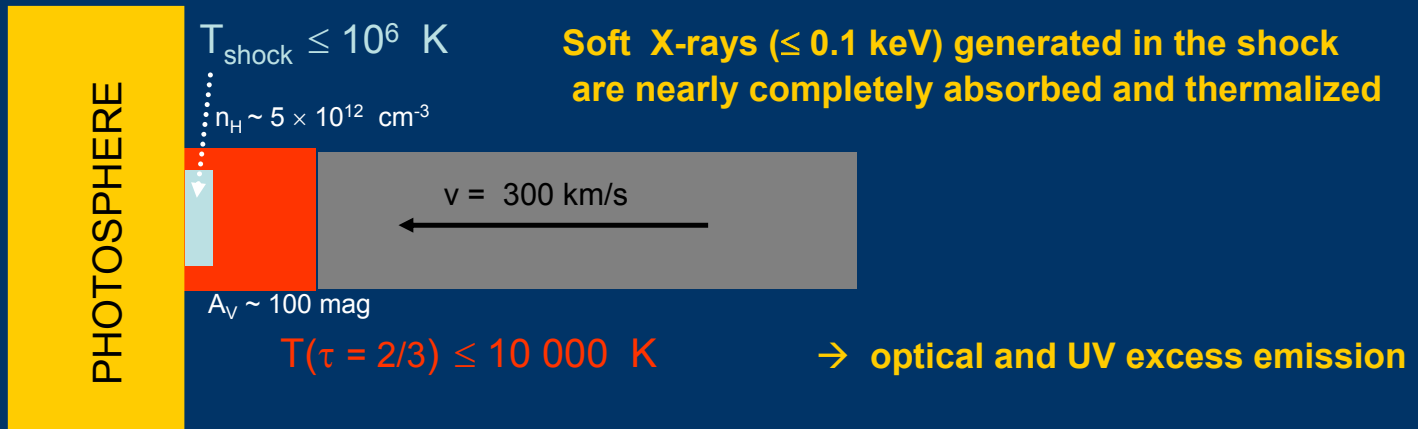
Scenario II:

Different X-ray emission process in accreting stars

Magnetospheric accretion:
X-ray emission from the accretion shock ???



Structure and emission of the accretion shock Calvet & Gullbring 1998, ApJ 509,802



→ in general, no observable X-ray emission from accretion shock expected

Furthermore: accreting stars are weaker X-ray emitters than non-accretors

Scenario III: Eric Feigelson (priv. communication):

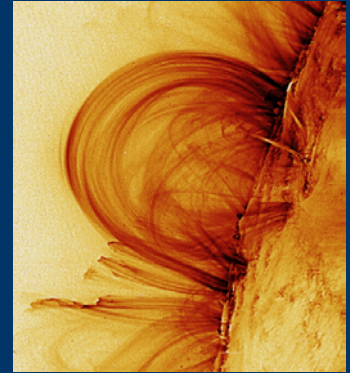
Changes in the stellar surface magnetic field due to accretion

Non-accreting stars (WTTS):

stellar magnetic field lines have low plasma density

$$n \sim 10^{10} - 10^{11} \text{ cm}^{-3}$$

explosive injection of energy from reconnection raises temperatures above 10^7 K \rightarrow X-ray emission



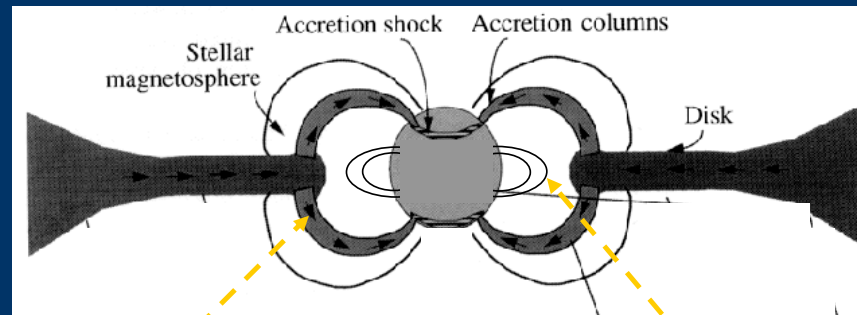
Accreting stars (CTTS):

field lines are mass loaded with accreting material

$$n \sim 10^{12} - 10^{13} \text{ cm}^{-3}$$

The same amount of reconnection energy raises temperatures only to $\sim 10^5 \text{ K}$

\rightarrow no X-ray emission

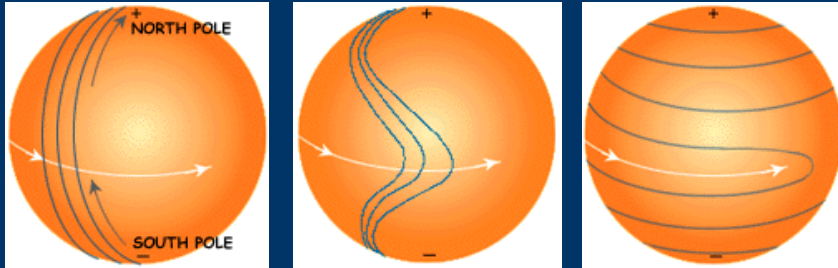


High-density accretion loops

Low-density loops

Scenario IV: Accretion changes the internal stellar structure, rotation pattern and the magnetic field generation process

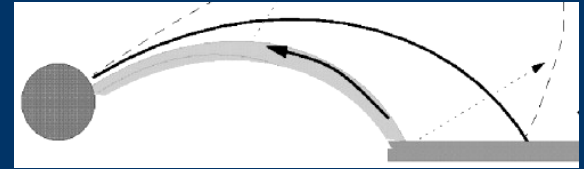
Differential rotation in the Sun



Differential rotation generates a strong toroidal field
out of a weak poloidal field

Rotational shear is the main source of magnetic field energy

Magnetospheric coupling and disk breaking



Hartmann 2002, ApJ 566,L29

Magnetospheric accretion model:

Magnetic star-disk coupling brakes stellar rotation at (or near) the equator

→ reduces differential rotation → weaker dynamo action

→ less magnetic field generation → weaker X-ray emission (???)

Conclusion: It is unclear how accretion influences the X-ray activity

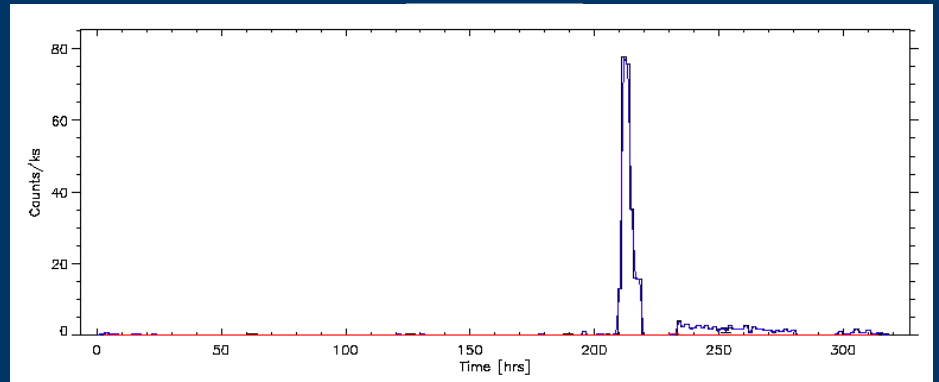
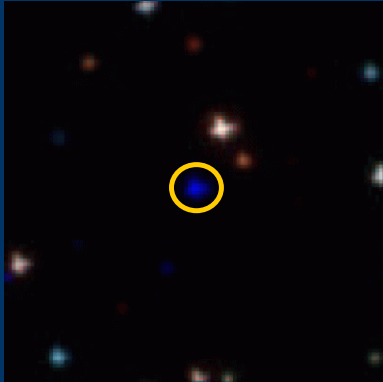
4.) Detection of >100 unidentified hard X-ray sources

Most blue sources:

- no optical counterparts
- no near-infrared counterparts (even in deep ($K \sim 20$) VLT images)
- clearly clustered on the molecular cloud



Example of an
optical/infrared invisible
hard X-ray source

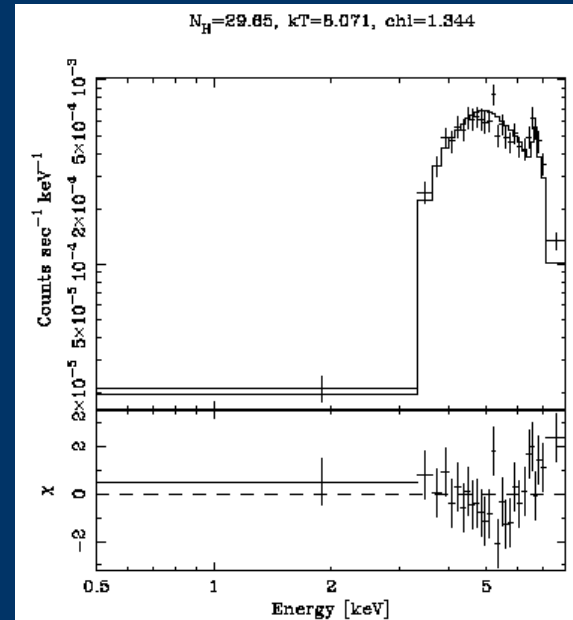


Spectral fit:

$$A_V = 150 \text{ mag}$$

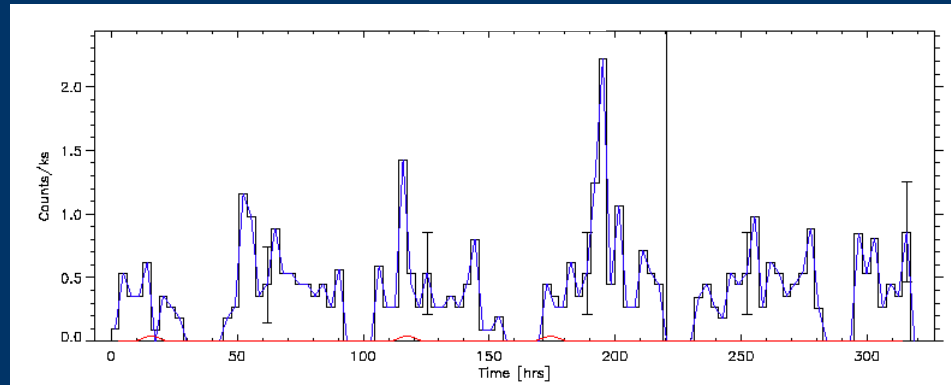
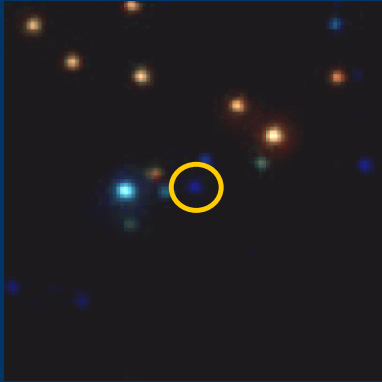
$$T_X = 90 \text{ MK}$$

$$L_X = 1.4 \times 10^{31} \text{ erg/sec}$$



→ typical for class I protostars

Non-flaring
optical/infrared invisible
hard X-ray source

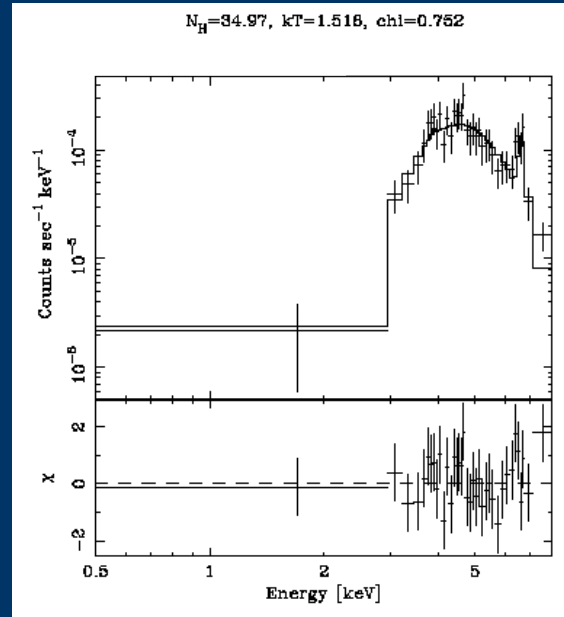


Spectral fit:

$$A_V = 170 \text{ mag}$$

$$T_X = 17 \text{ MK}$$

$$L_X = 1.8 \times 10^{31} \text{ erg/sec}$$



→ Probably a deeply embedded protostar

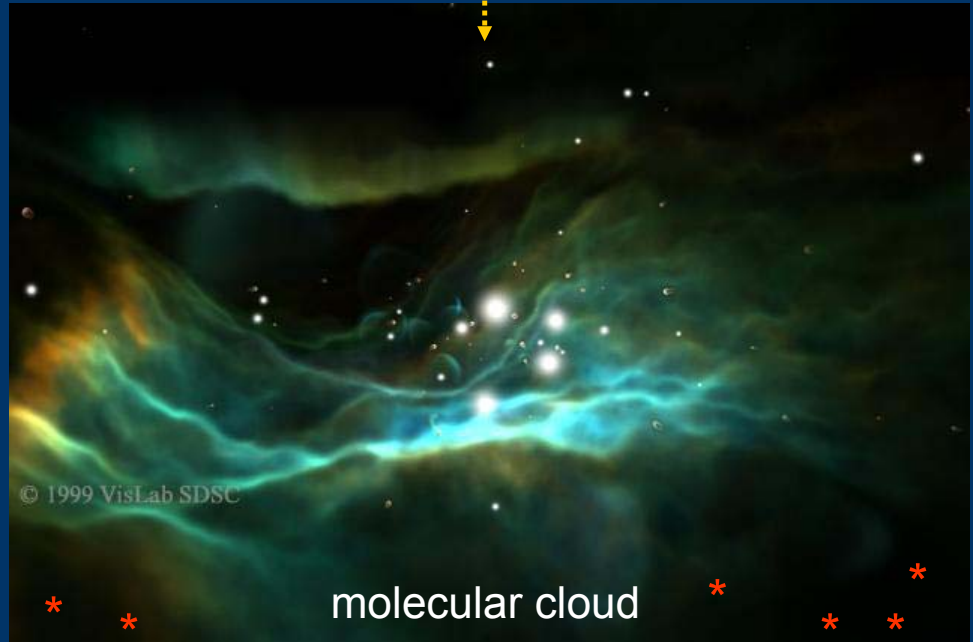
3D geometry of the Orion Nebula Cluster



view from earth



simulated side view



molecular cloud

→ ongoing star formation in the molecular cloud behind the optical Orion Nebula

we see probably only a small fraction ($\leq 10\%$???) of these protostars:

→ >1000 stars are forming (probably more than the known ONC members)

Only seen in X-rays, not in any other wavelength

Conclusions

- Origin of the strong X-ray activity of T Tauri stars:
 - ``scaled-up Sun`` picture cannot be (fully) correct
 - no rotation-activity relation for T Tauri stars
 - some kind of magnetic dynamo is at work (turbulent dynamo ?)
 - accreting T Tauri stars have lower X-ray luminosities, detailed mechanism is still unclear

Analysis of the COUP data will solve many open questions

- Large population of protostars in the molecular cloud behind the Orion Nebula detected by their X-ray emission

More interesting detections expected in the COUP data