The X-Ray Universe

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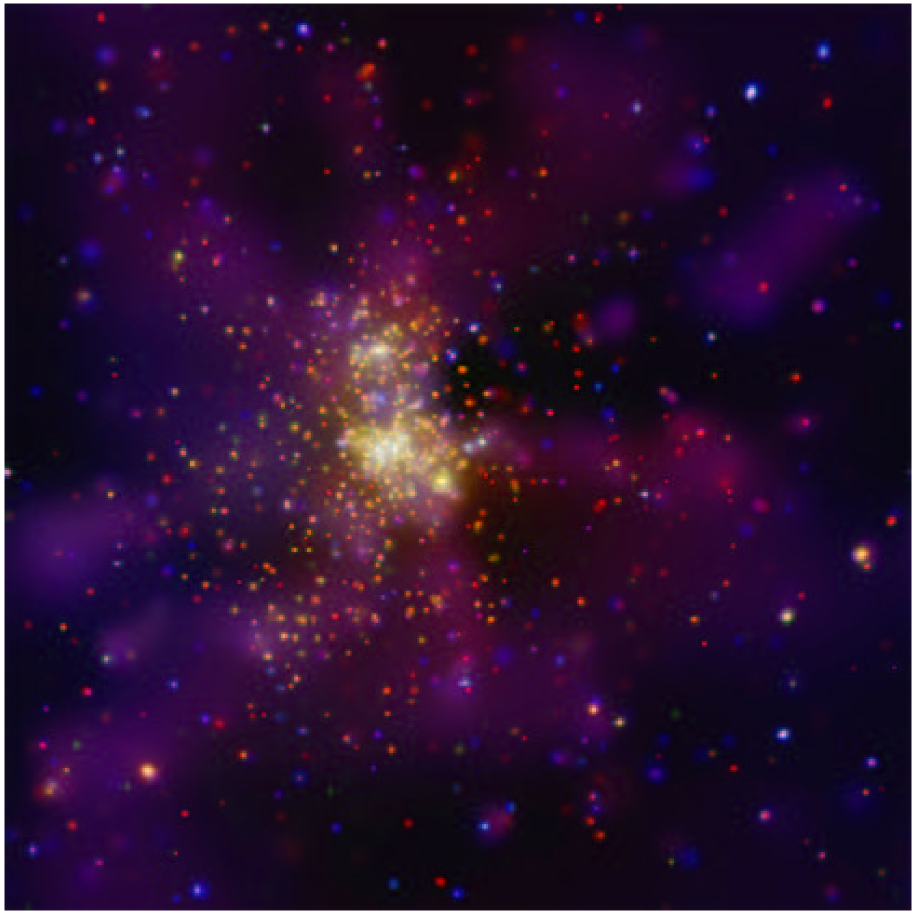
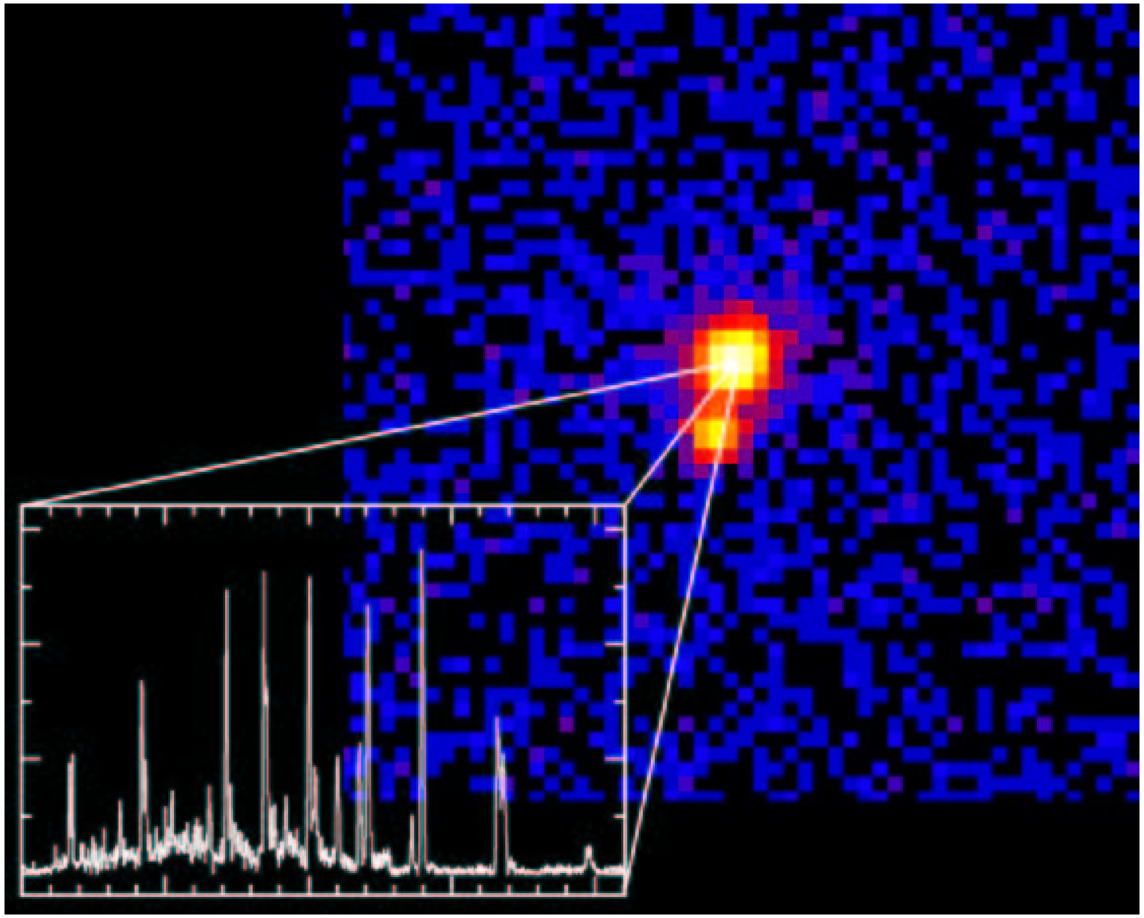


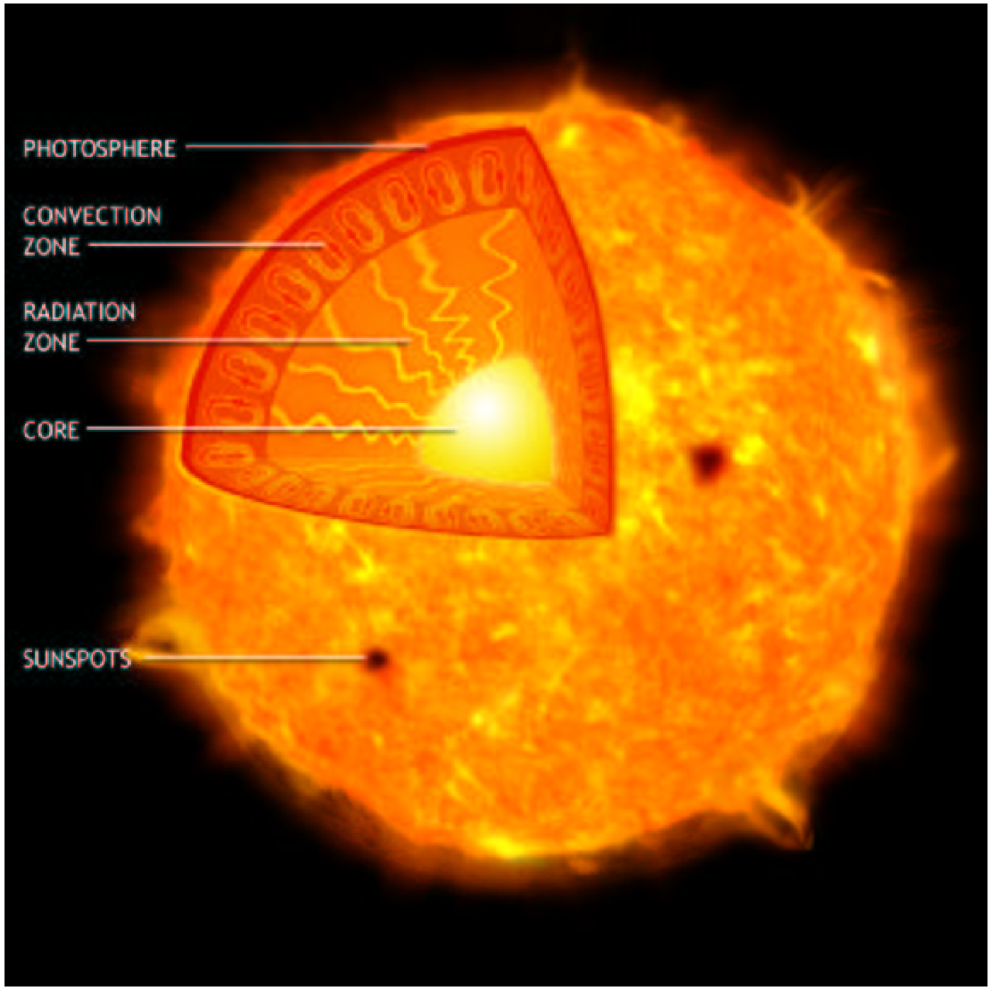
Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d= 2×10^4 ly

VI. X-rays from Normal Stars



NASA/EIT/W.Waldron, J.Cassinelli

Or not totaly abnormal



http://chandra.harvard.edu/photo/2005/neon/

VI. 1. Brief reminder: Stars

Low-mass stars on main sequence:

pp-cycle → $\varepsilon \sim T^6$

Radiative equilibrium core

Large temperature gradient outwards

Outer convection envelopes

Weak stellar winds

Massive stars on main sequence:

CNO-cycle → $\varepsilon \sim T^{15}$

Convective core

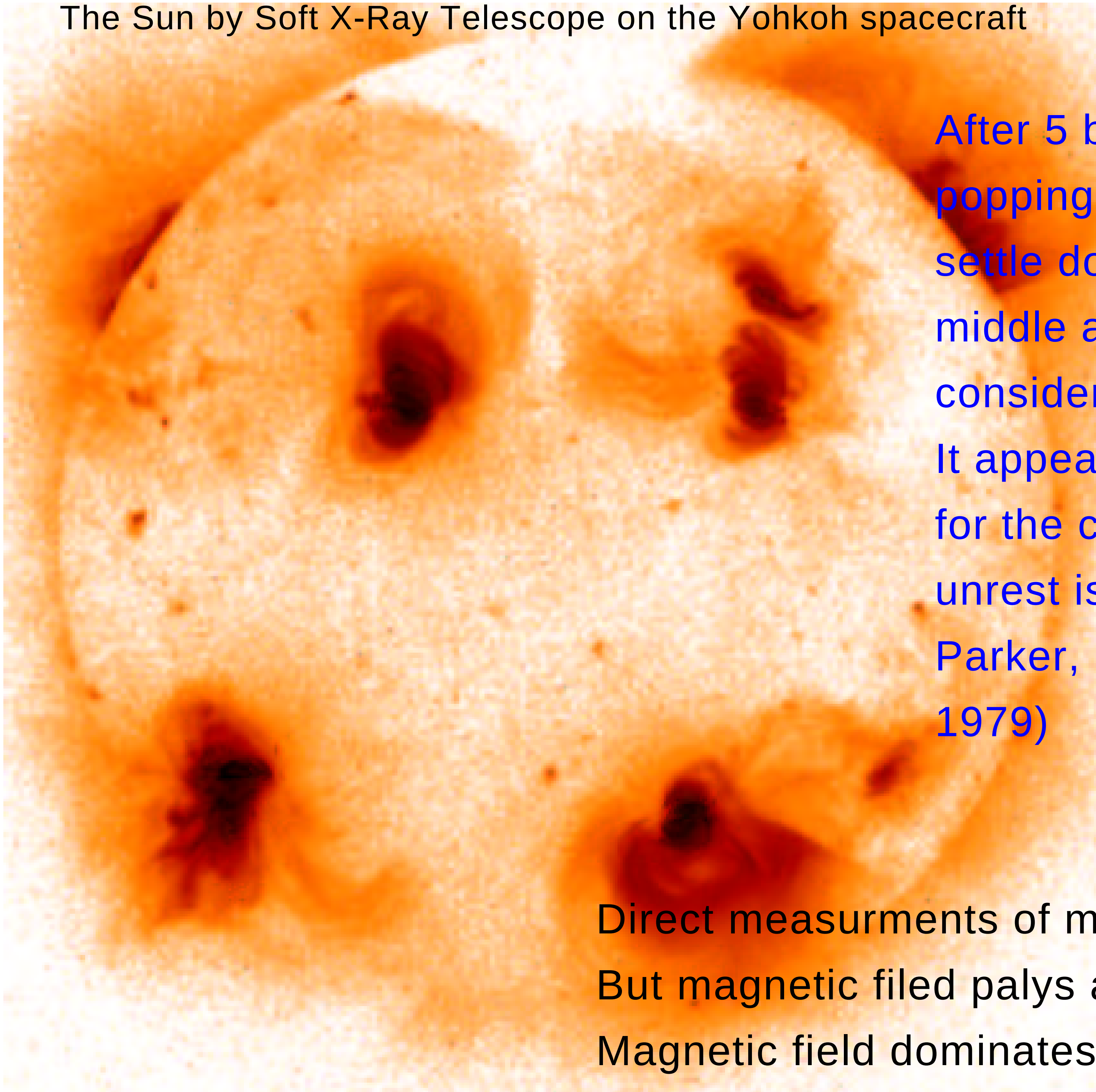
Outer radiative envelopes

Strong stellar winds

Sp	T_{eff}	$H\beta$	Other Fetures	$M/M_\odot$	$R/R_\odot$	$R/R_\odot$	T(MS)
O	>33000	weak	He^+, mb. emission	>20	>10	90,000-800,000	10-1 Myr
B	10,500-30,000K	med.	HeI absorption	3-18	3.0-8	95-52,000	400-11 Myr
A	7,500-10,000K	strong	H lines	2-3	2-3 8-55	3Gyr - 440 Myr	
F	6,000-7,200 K	med.		1-2	1-1.5	2.0-7.0	7-3 Gy
G	5,500-6,000 K	weak, Ca+ H	K, Na "D"	0.9-1	0.8-1	0.6-1.5	15-8 Gy
K	4,000-5,250 K	v. weak	a+, Fe, CH,CN	0.6-0.8	0.6-0.80	0.10-0.4	17 Gy
M	2,600-3,850 K	TiO, mol.		0.08-0.5	0.2-0.6	0.001-0.08	56 Gy
L			Brown dwarfs	<0.08			

VI. 2. Magnetic fields

The Sun by Soft X-Ray Telescope on the Yohkoh spacecraft



After 5 billion years, the Sun is still popping and boiling, unable to settle down into the decadent middle age that simple theoretical considerations would suggest. (...) It appears that the radical element for the continuing thread of cosmic unrest is the magnetic field. (E N Parker, Cosmical Magnetic Fields, 1979)

Direct measurments of magnetic fileds: photsphere

But magnetic filed palys a minor role in ph.

Magnetic field dominates in the corona: X-rays

coronal heating, flares, CMEs, wind acceleration

http://solar.physics.montana.edu/ypop/

VI. 3. Dynamo theory

Cosmic Magnetic Fields are omnipresent. Seeded in Big Bang??

Dynamo: mechanism for flux generation starting from a small initial seed field

A fully consistent and predictive theory is still lacking

The basics of modern dynamo theories (Parker 1970)

- Dynamo problem: solution of Maxwell eqs. + Ohm's law + hydrodynamic eqs. Finitite kinetic energy and gradients, no magentic filed at
- Two anti-dynamo theorems: Cowling's theorem: rotationally symmetric magnetic field cannot be maintained by dynamo; Elsasser's theorem: differential rotation alone cannot drive dynamo.
- Thus, working dynamo rrequires a complex 3-D and non-axisymmetric structure of both the generated magnetic filed and the driving velocity field.
- In the Sun, differential rotation and convective flows are the most importnat ingridients. Parker loop:1 Convective up- andf down flows in rotating system generate meridional flux lops through twisting of the field lines due to the action of Coriolis force.

Located in the layer between convection and radial zones tacholine

VI. 4. αΩ-Dynamo

The Parker mechanism has been mathematically formalized and generalized by mean-field theory (Krause, Rädler, Steenbeck 1966).

Evolution of a suitably averaged magnetic field in a turbulent flow of an electrically conducting fluid.

$$\frac{\partial \langle B \rangle}{\partial t} = \nabla \times (\langle u \rangle \times \langle B \rangle + \alpha \langle B \rangle) - \nabla \times [(\eta + \beta) \nabla \times \langle B \rangle$$

$\alpha \langle B \rangle$ drives a mean current parallel or anti-parallel to the mean magnetic field.

α-effect generates a meridional field from an azimuthal and vs.

Ω-effect describels differential rotation, Ω is angular velocity

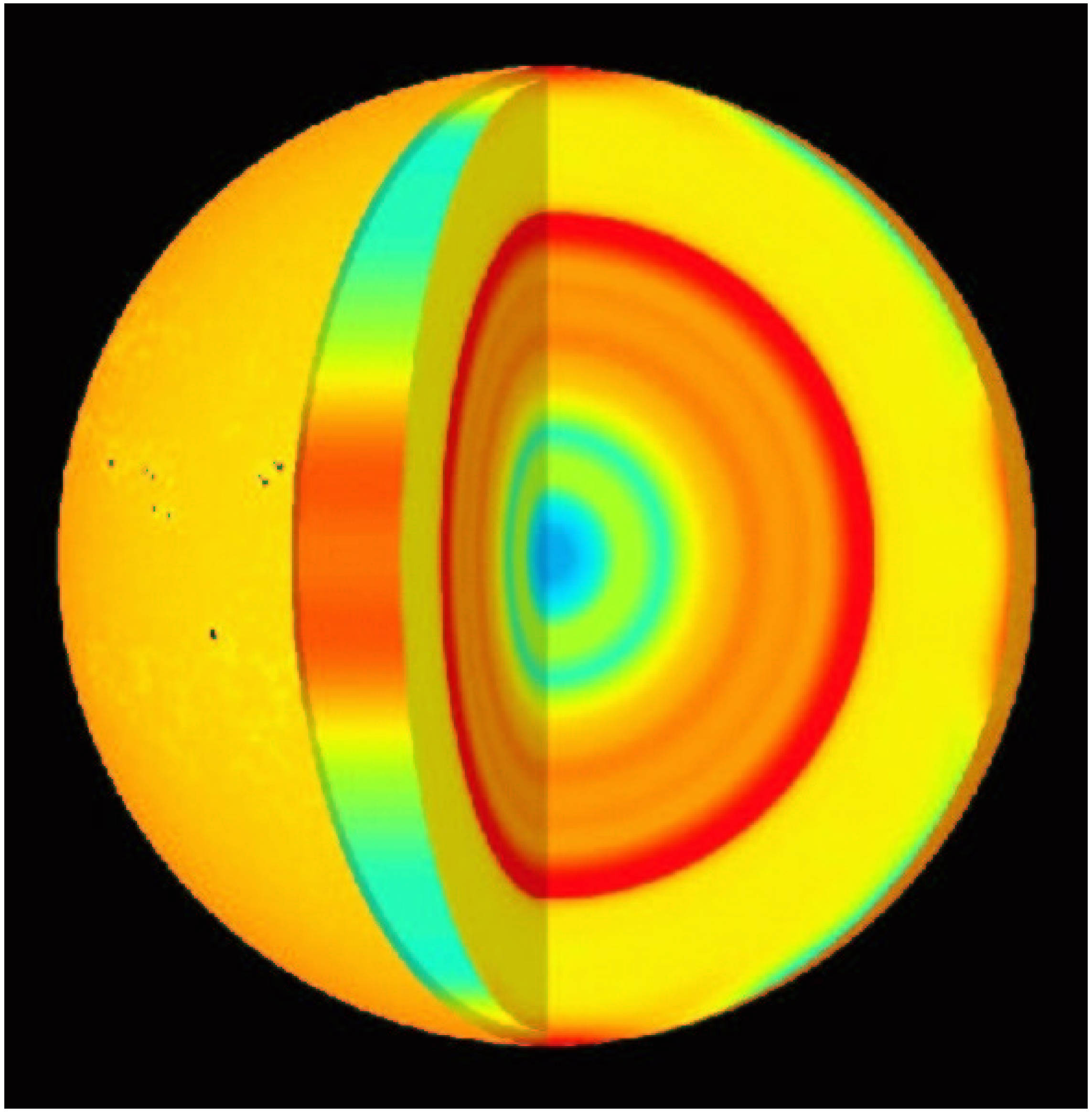
$\alpha \frac{\partial \Omega}{\partial r}$ describes dynamo waves

Dynamo Waves propagate latitudinally, equatorwards or polewards

Mean-field αΩ-dynamo reproduces many of the key features of the solar cycle: the periodic filed reversals, the polarity of sun-spot groups, the equatorwards drift of the activity zones.

However the equatorwards drift requires radially inward fast increase of the angular velocity. This is in direct conflict with the results of helioseismology.

VI. 5. The rotation of the Sun



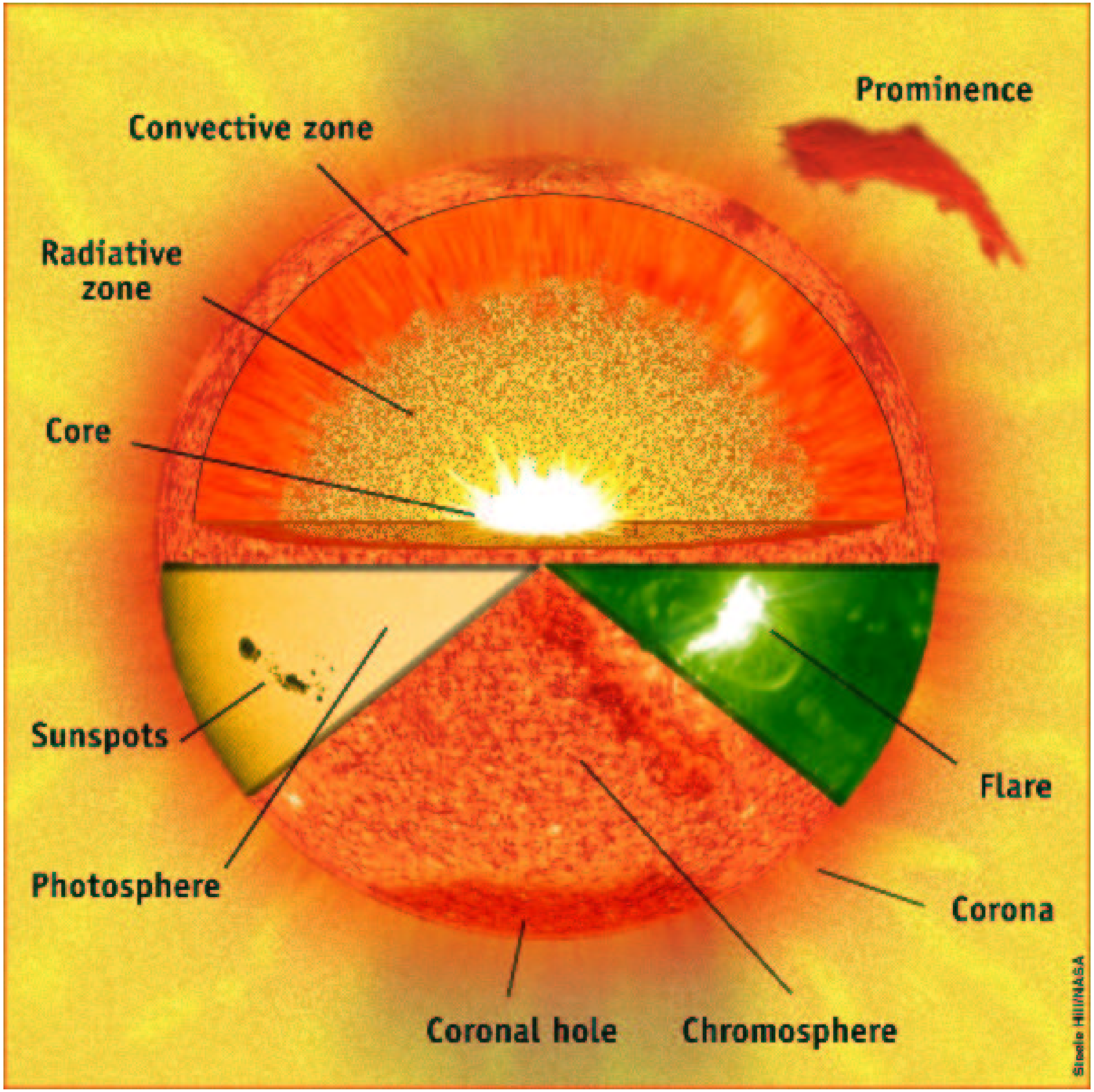
http://sohowww.nascom.nasa.gov/

Solar rotation and polar flows of the Sun as deduced from measurements by SOHO. The cutaway reveals rotation speed inside the Sun. The left side of the image represents the difference in rotation speed between various areas on the Sun.

Red-yellow is faster than average and blue is slower than average. The light orange bands are zones that are moving slightly faster than their surroundings.

Light-orange bands down to 20000 km

VI. 6. Magnetic fields in and out

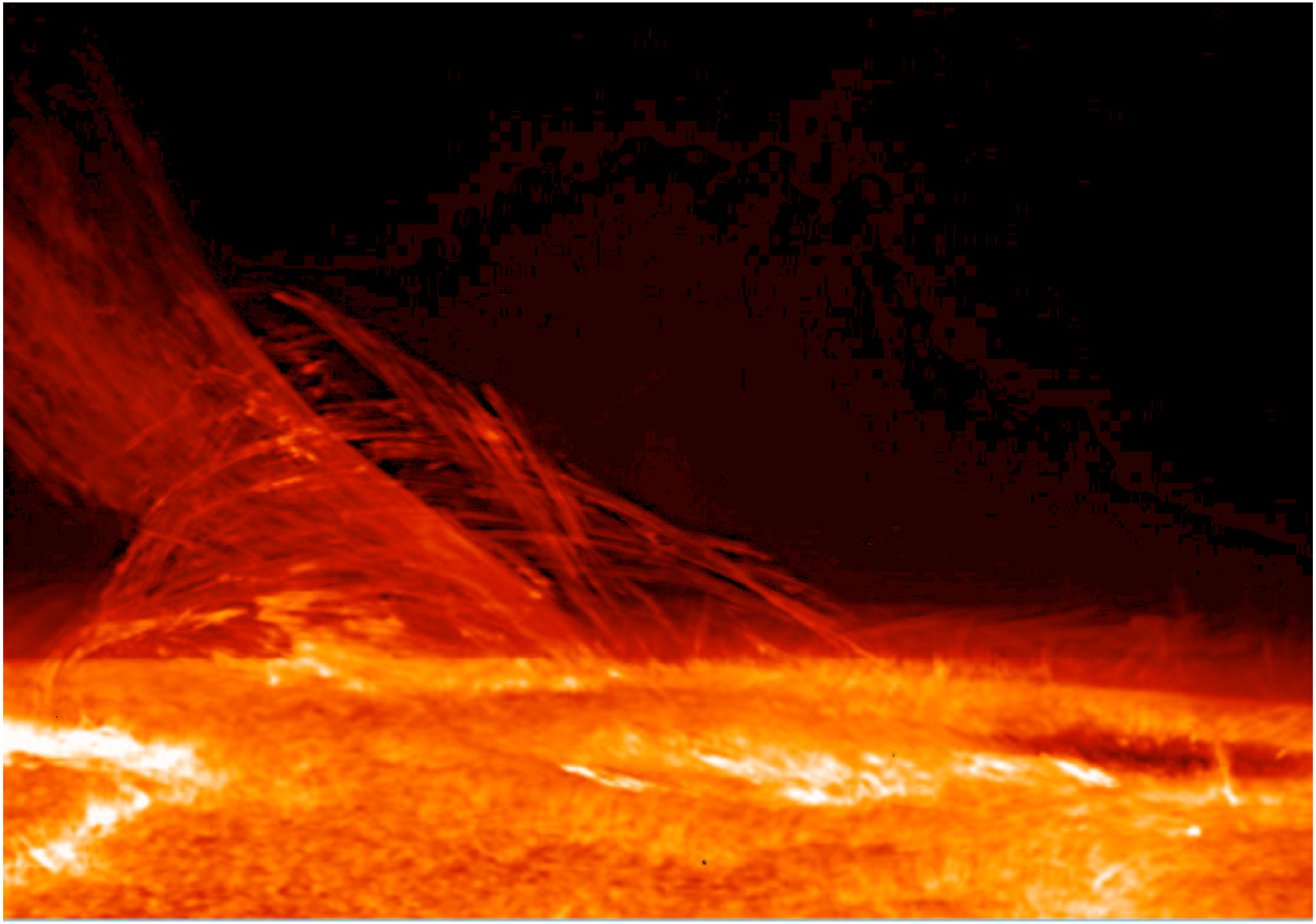


http://sohowww.nascom.nasa.gov/

Convection brings the magnetic field lines on the surface. Lines are always closed, the relative role of gas and magnetic filed pressure changes with height

VI. 7. Hinode image of the Chromosphere

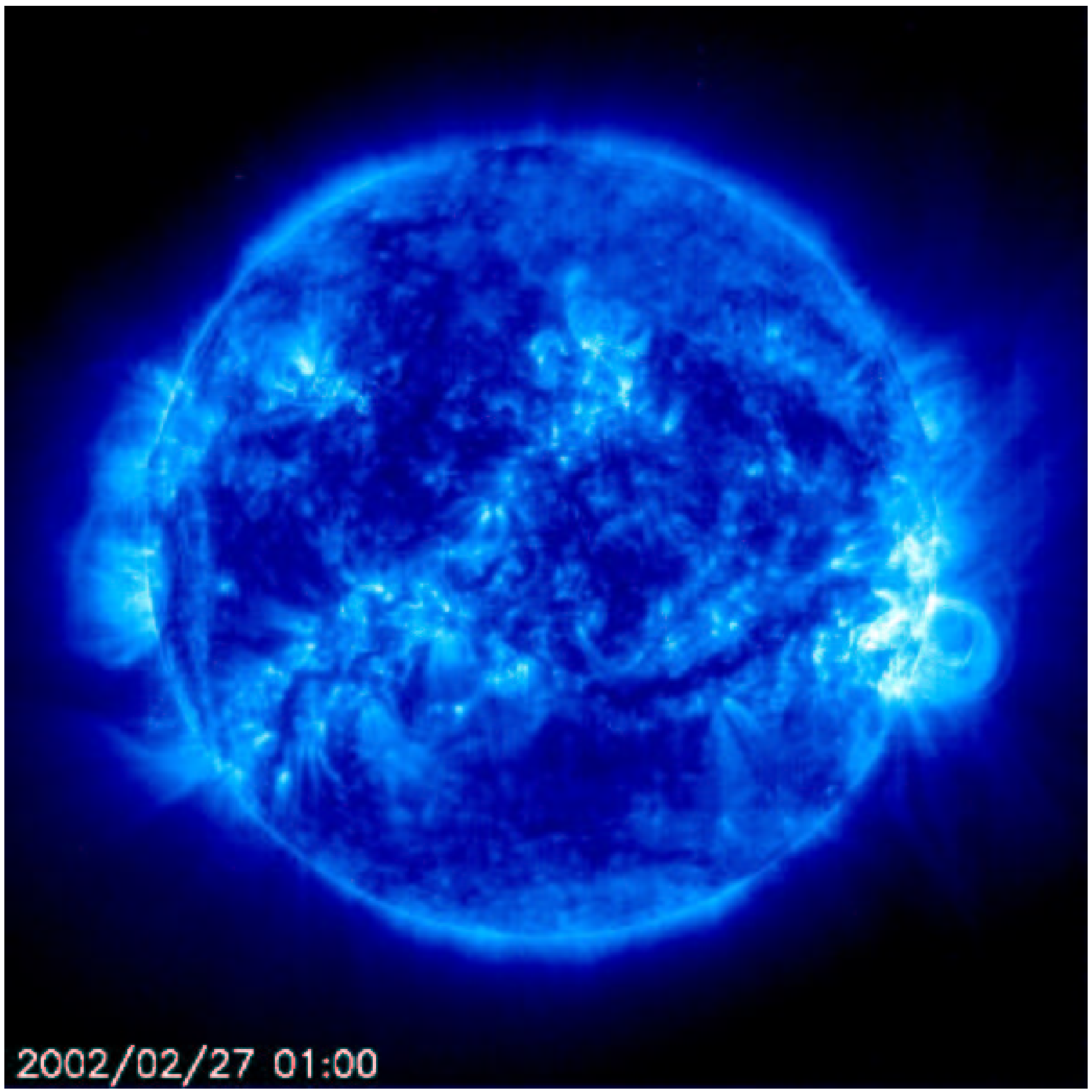
D=2500 km thick, ρ(r) decreases, T(r) from 4500 to 10 000 K.

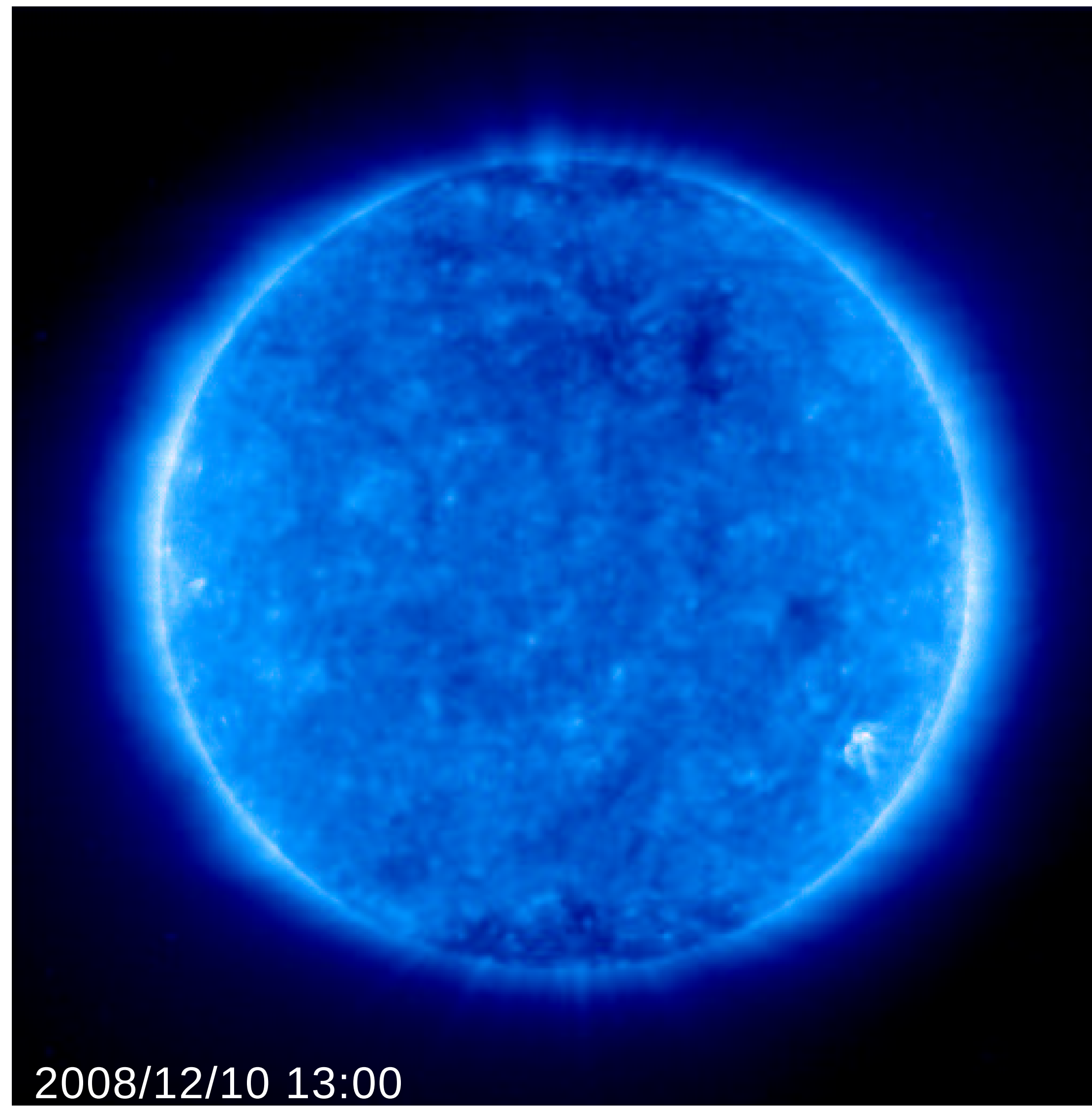


http://www.nasa.gov/mission_pages/solar-b

VI. 8. Lower corona: now and then

SOHO images in Fe IX/X 171Å line. Lower corona, plasma temperature 1MK.



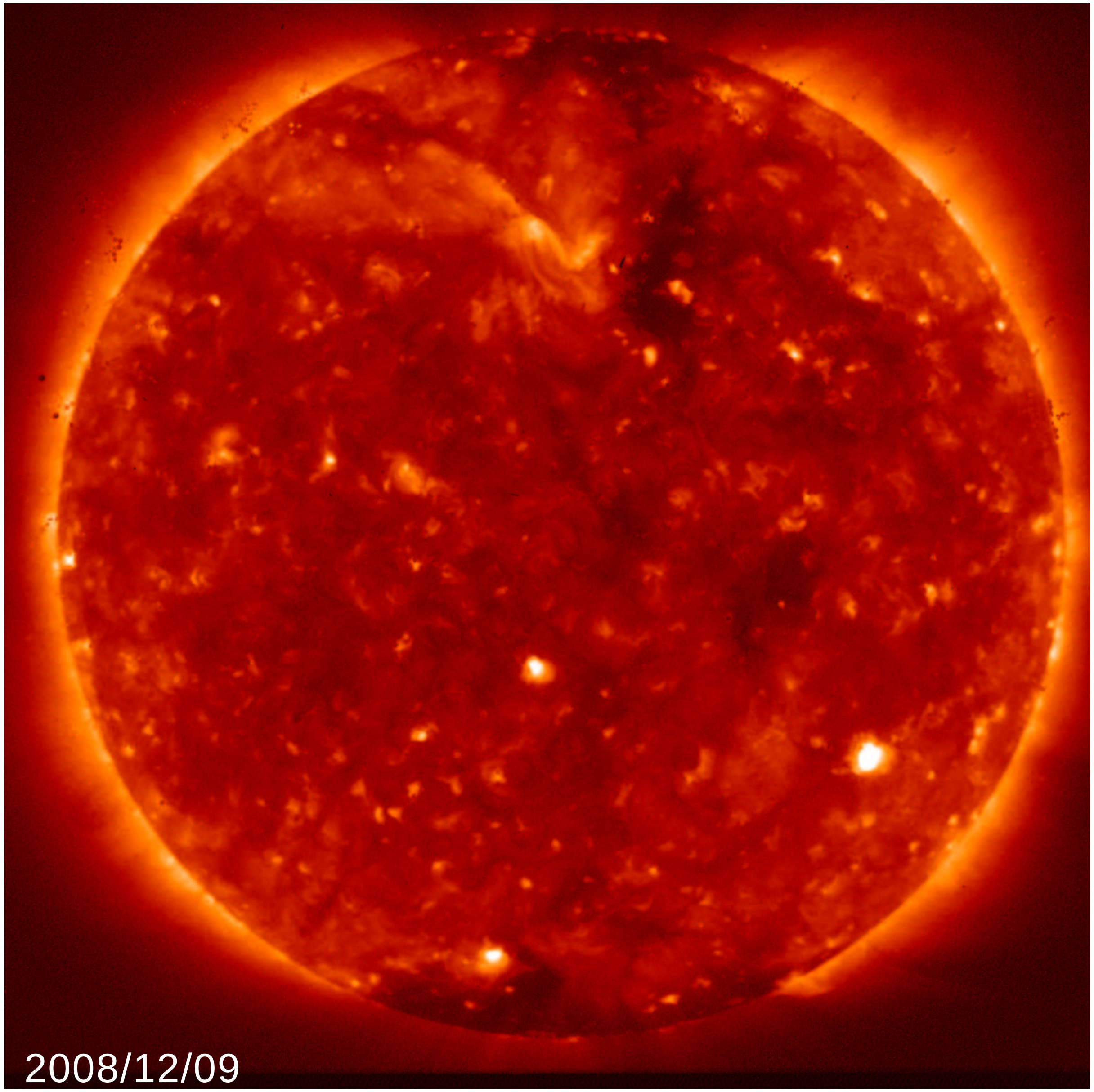


http://sohowww.nascom.nasa.gov/

VI. 9. Upper and lower corona: Hinode mission

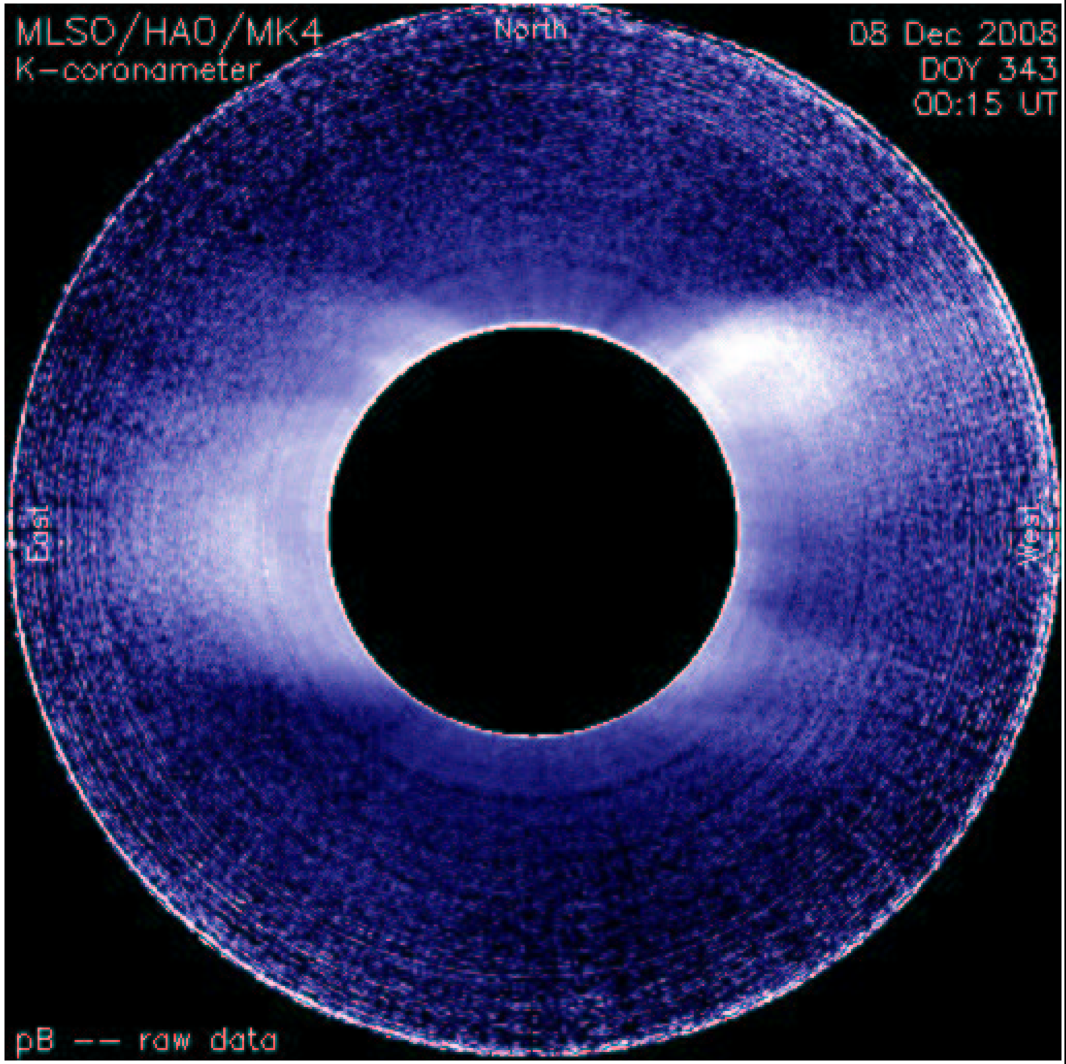
Corona is optically thin CIE plasma T=1..10MK

13Å, 45Å, 116Å, 304Å filters, T=1-100MK



http://solar-b.nao.ac.jp

The latest optical image of the corona



http://umbra.nascom.nasa.gov/images

VI. 10. Flares

Solar flares are an explosions in the solar atmosphere:

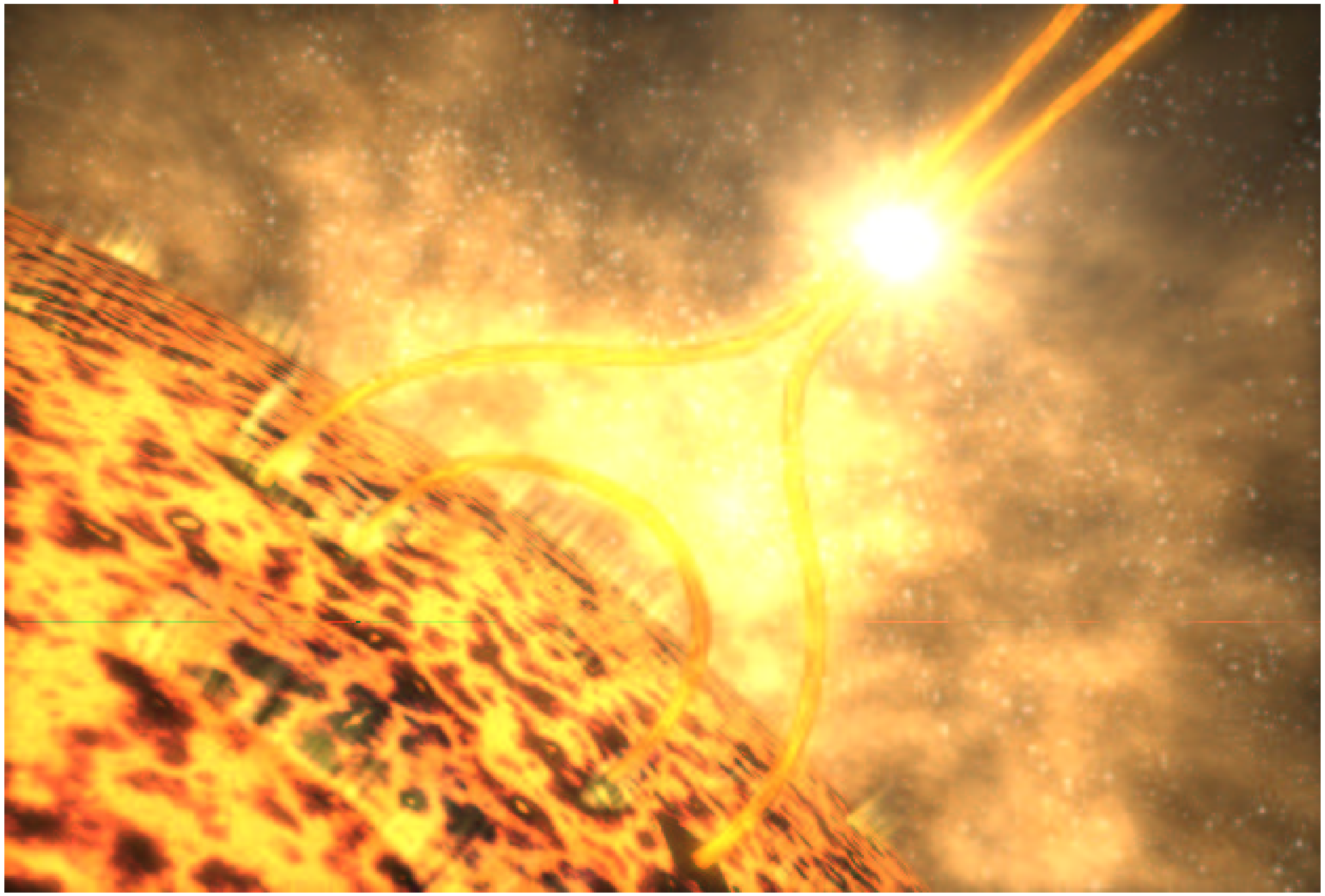
Sudden bursts of particle acceleration, plasma heating, and bulk mass motion.

Release of energy stored in the magnetic fields that thread the corona.

In the largest flares $>10^{32}$ ergs can be released in a few minutes.

Largest flares observed around solar maximum

There is a continious spectrum of flare sizes $dN/dE=kE^{-\alpha}$, α=1.6 ... 2.6



http://svs.gsfc.nasa.gov/vis/a000000/a002700/a002750/index.html

No consistent theory of flares

Reconnection, 3D-topologies

VI. 11. RHESSI

3keV-17MeV

Significant fraction

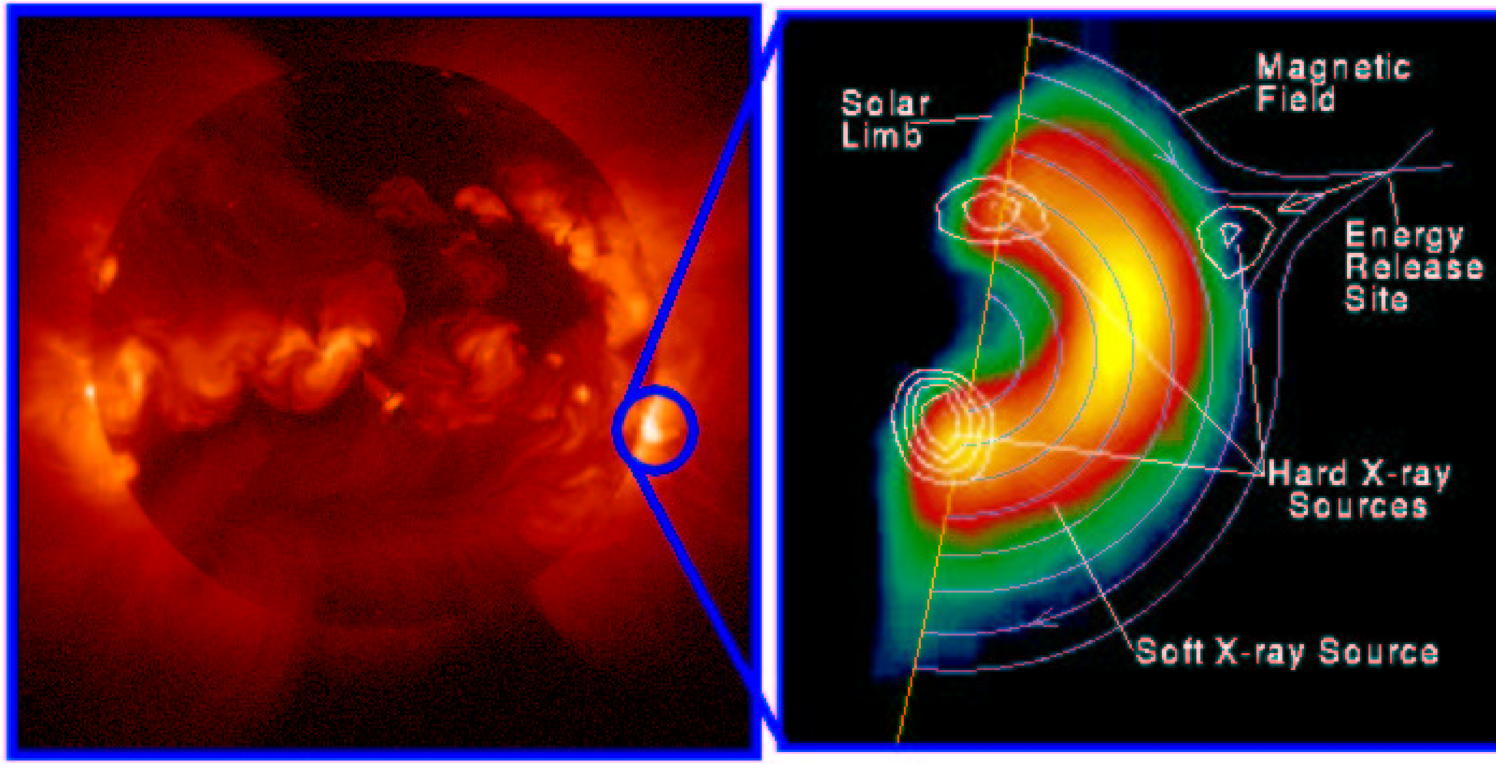
of released energy

→ accelerating paricles

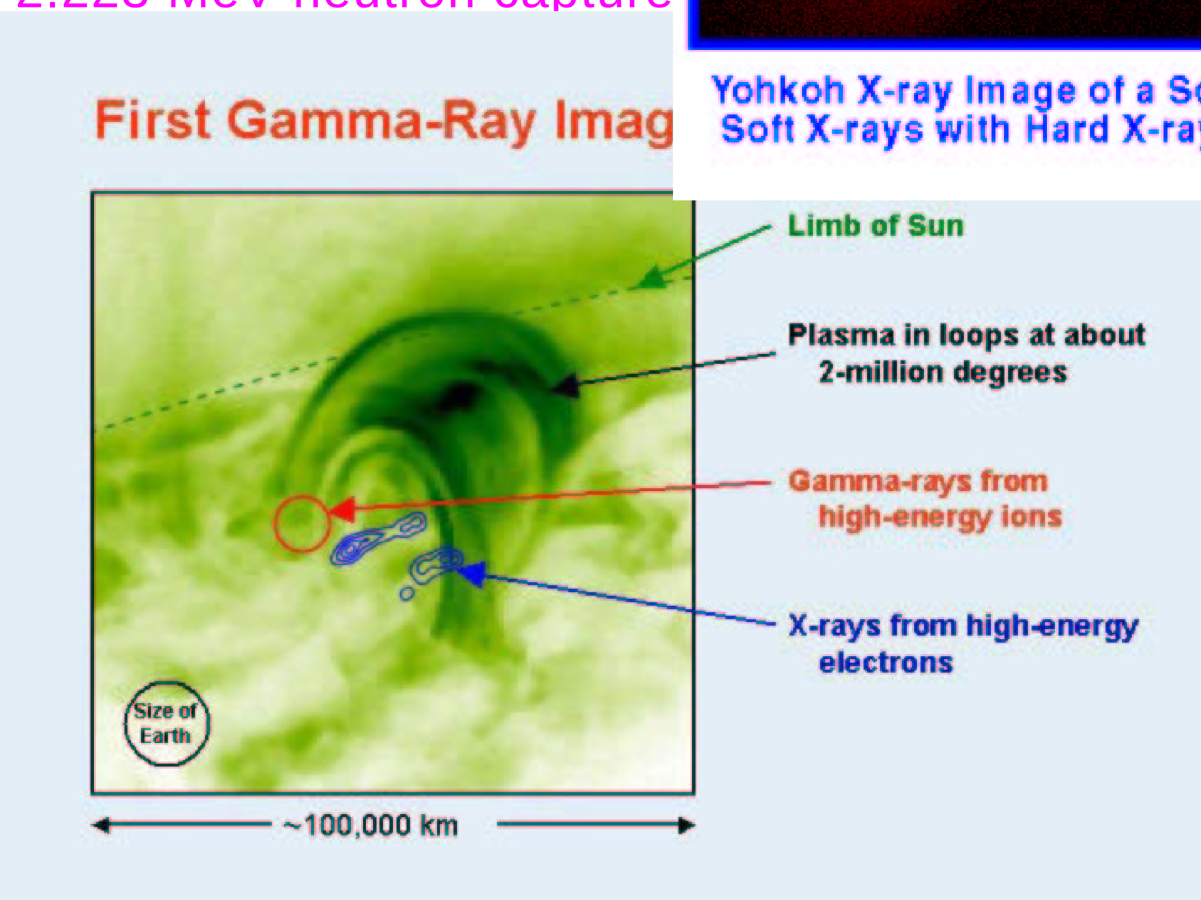
Flare 23 July 2002

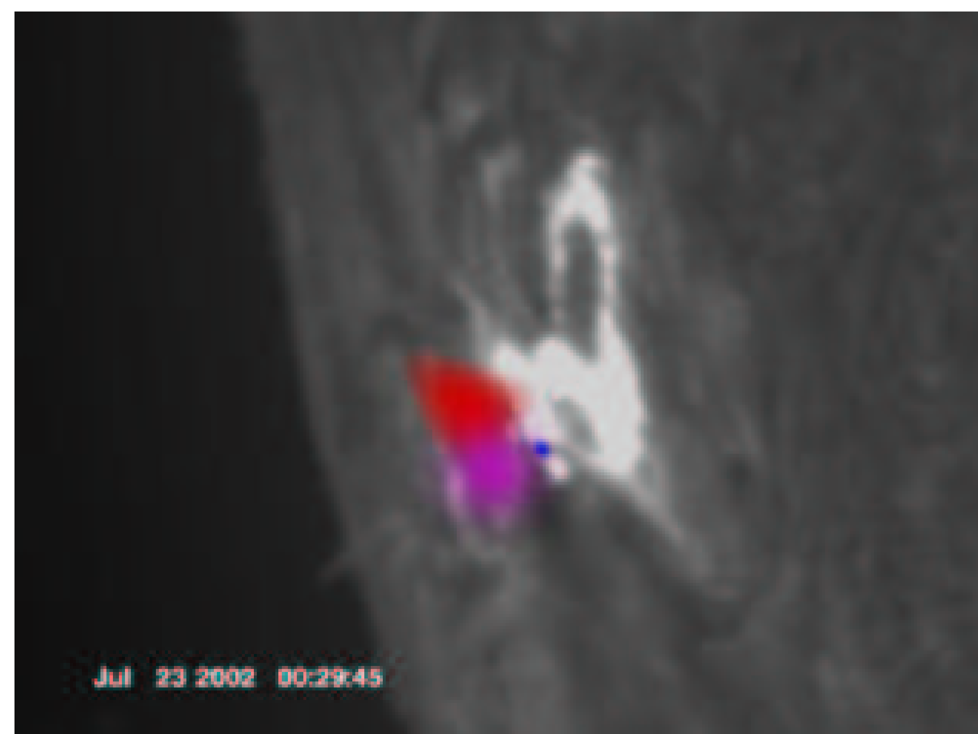
511keV e-p annihilation

2.223 MeV neutron capture



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.





http://svs.gsfc.nasa.gov/vis/a000000/a002700/a002750/index.html

VI. 11. How corona is heated?

Coronal activity scales with magnetic activity, 11 yr cycle

Corona never disappears:

$L_X = 10^{26}$ erg/s in min activity, 10^{27} erg/s in max activity (+ very strong flares)

It is now established that any energy release mechanism is magnetic in origin - the challenge posed is to determine what specific heat input is dominating in a given coronal feature throughout the solar cycle.

Leading theories:

* Sound wave dissipation (Walsh & Ireland 2003)
* Differential heating by plasmakinetic processes (Vocks & Marsch 2002)
* Nanoflare heating: small scale reconnection events (Parker 1988)

Model shall describe physical conditions in the corona:

density, temperature, velocity

Corona heating and dynamo theory should be consistent

Sun offeres only a limited range of parameters.

VI. 11. Solar-Stellar connections

All low- and solar-type stars posses magnetic fileds and are X-ray active

Is Sun an average star?

The Sun in time?

How dynamo and heating processes differ among stellar types?

In some cases, the magnetic filed can be directly measured through the Zeeman effect, but in general X-ray emission is used to infer stellar activity.

See recent review M. Güdel A&AR 2004, 12, 71

In accordance with dynamo theory the magnetic activity of cool stars is related to their rotation rate: faster spinning stars are more active (α-effect increases with rotation rate).

For solar type stars (M< 1.5Msun) and ages of > 100 Myr, angular momentum loss by a stellar wind brakes rotation: rotation nearly uniquely determined by the stellar age.

Late type stars, M and brown-dwarfs are fully convective. How their activity level differ from solar-type stars?

VI. Coronal activity cycles in solar analog stars

The Sun 11-yr cycle is the global manifestation of its activity.

The behavior of HD 81809 (G2 + G9) is a simple extension of the solar case.

Two more studied stars show cyclic activity as well.

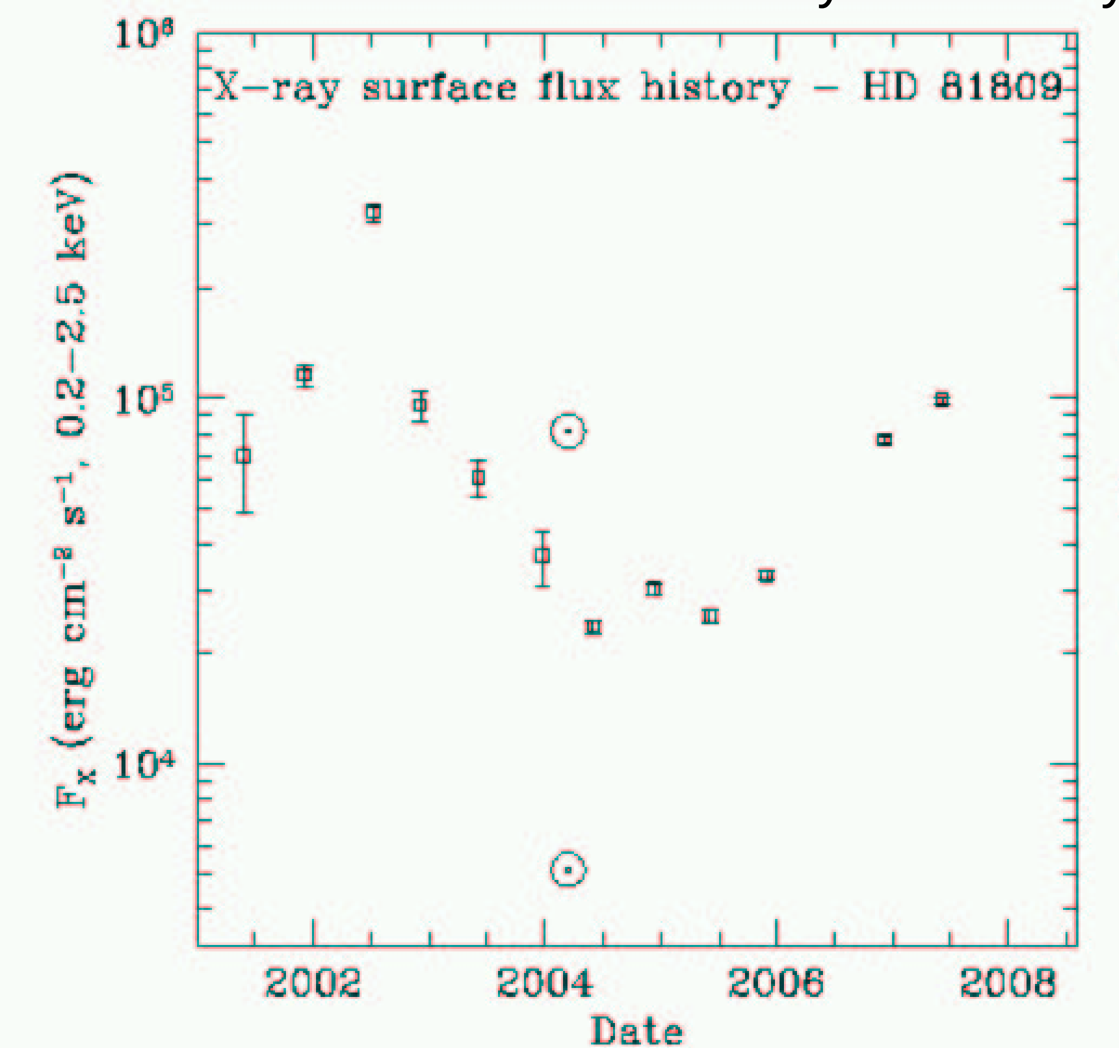


Fig. 3. Evolution of the X-ray surface flux (in the 0.2–2.5 keV band) of HD 81809 from April 2001 to May 2007. The typical X-ray surface flux of the Sun at minimum and maximum of the cycle, in the ROSAT band, is also plotted.

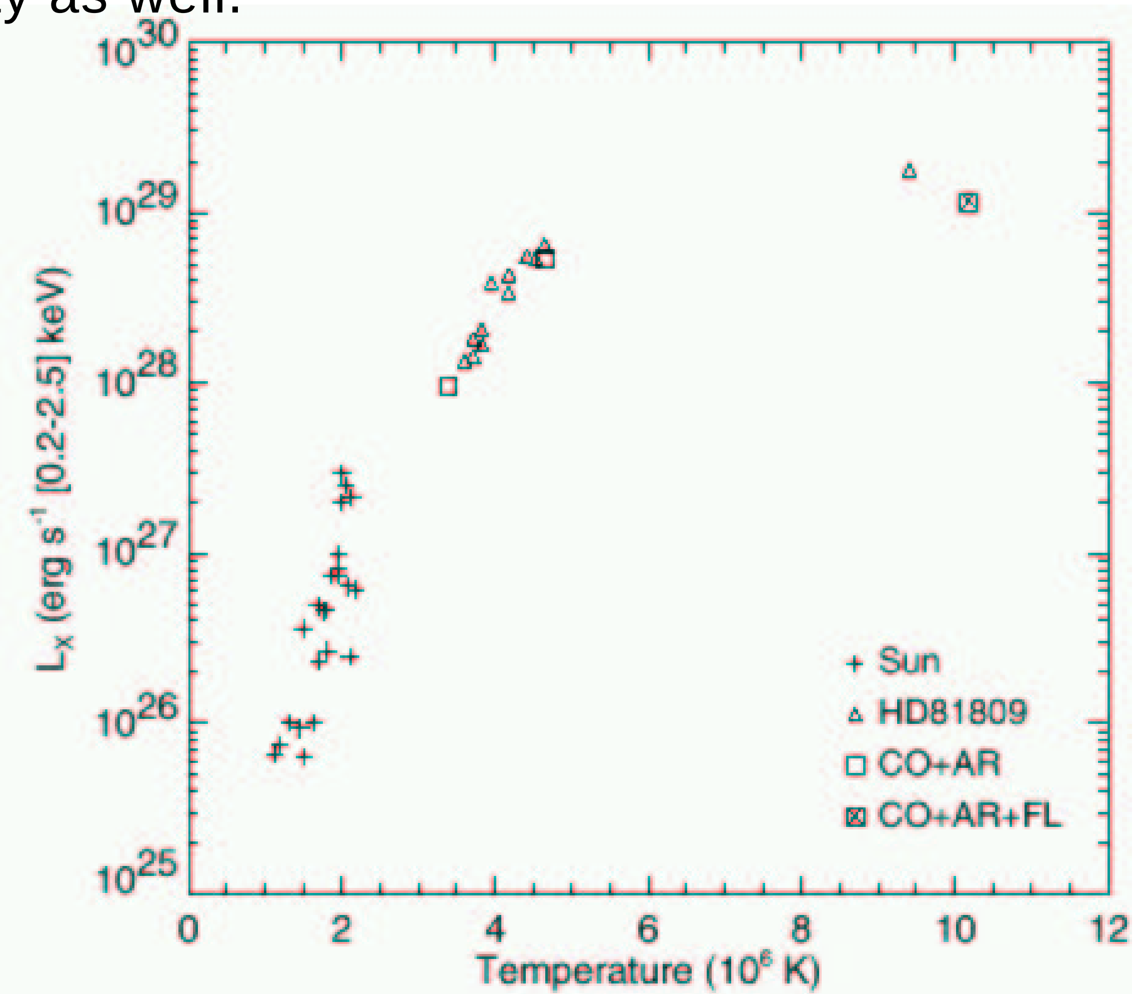
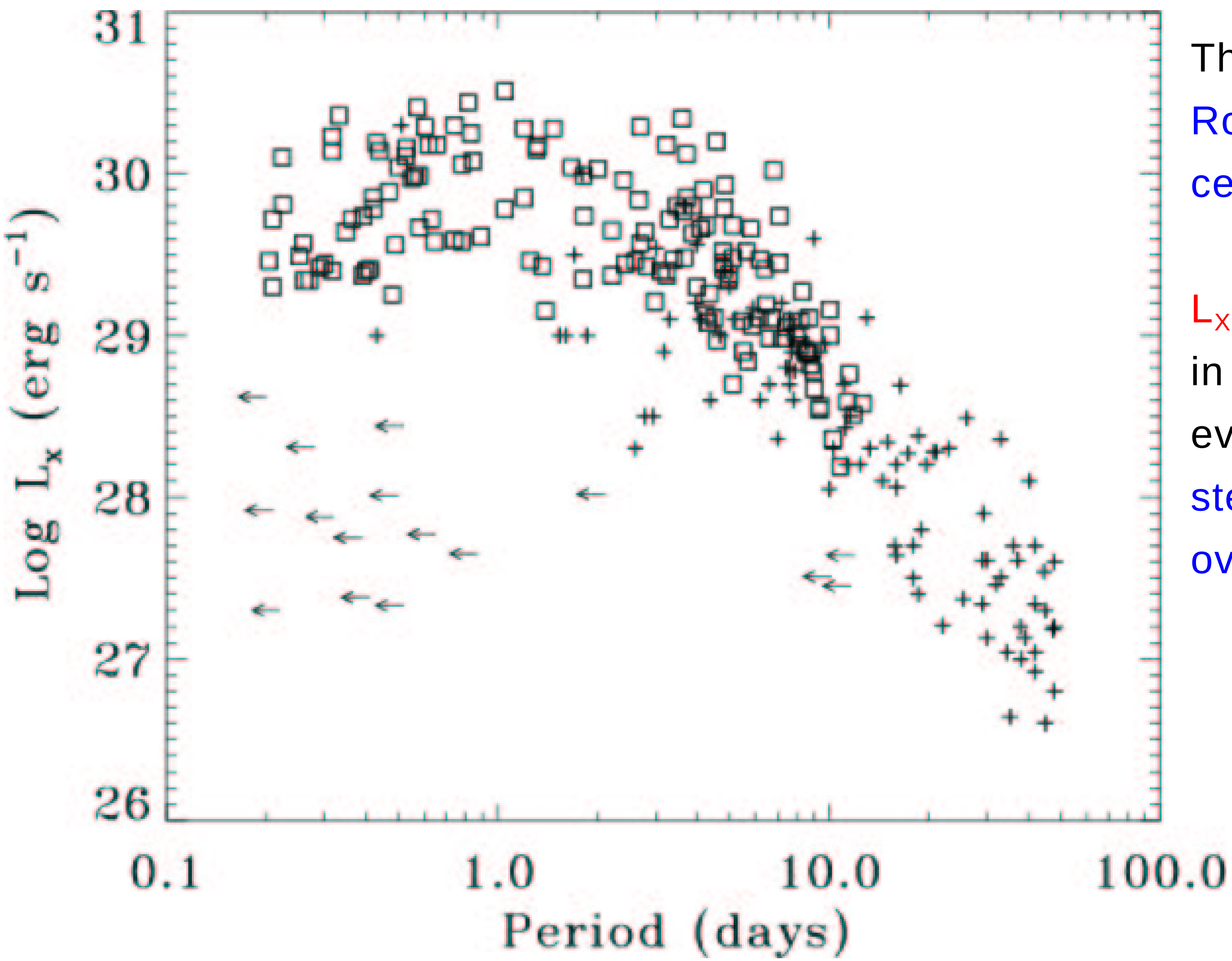


Fig.4 The evolution of the coronal X-ray temperature and luminosity along the cycle in both the Sun (crosses) and HD 81809 (triangles).

Favata etal. 2008 A&A 490, 1121

VI. The stellar activity-rotation relationship

The relationship between coronal X-ray emission and stellar rotation in late-type main-sequence stars. Two emission regimes: I) P_{rot} is a good predictor of the total X-ray luminosity, II) constant saturated X-ray to bolometric luminosity ratio.



Pizzolato etal. 2003 A&A 397, 147

The scaling with P_{rot} is secondary

Rossby number R_o: the ratio of centrifugal to Coriolis acceleration:

$L_X \sim P^{\alpha}_{rot}$ independ. on M_* or Sp in non-saturated stars even with M<0.5Msun

stellar rotation dominates over convection

L_X from saturated stars depends only on L_{bol} → dependent on the characteristics of the stellar structure.

VI. High-Resolution X-ray spectroscopy

CIE plasma: I^{q}/I^{q-1} depends on T

collisional ionization is balanced by radiative recombination

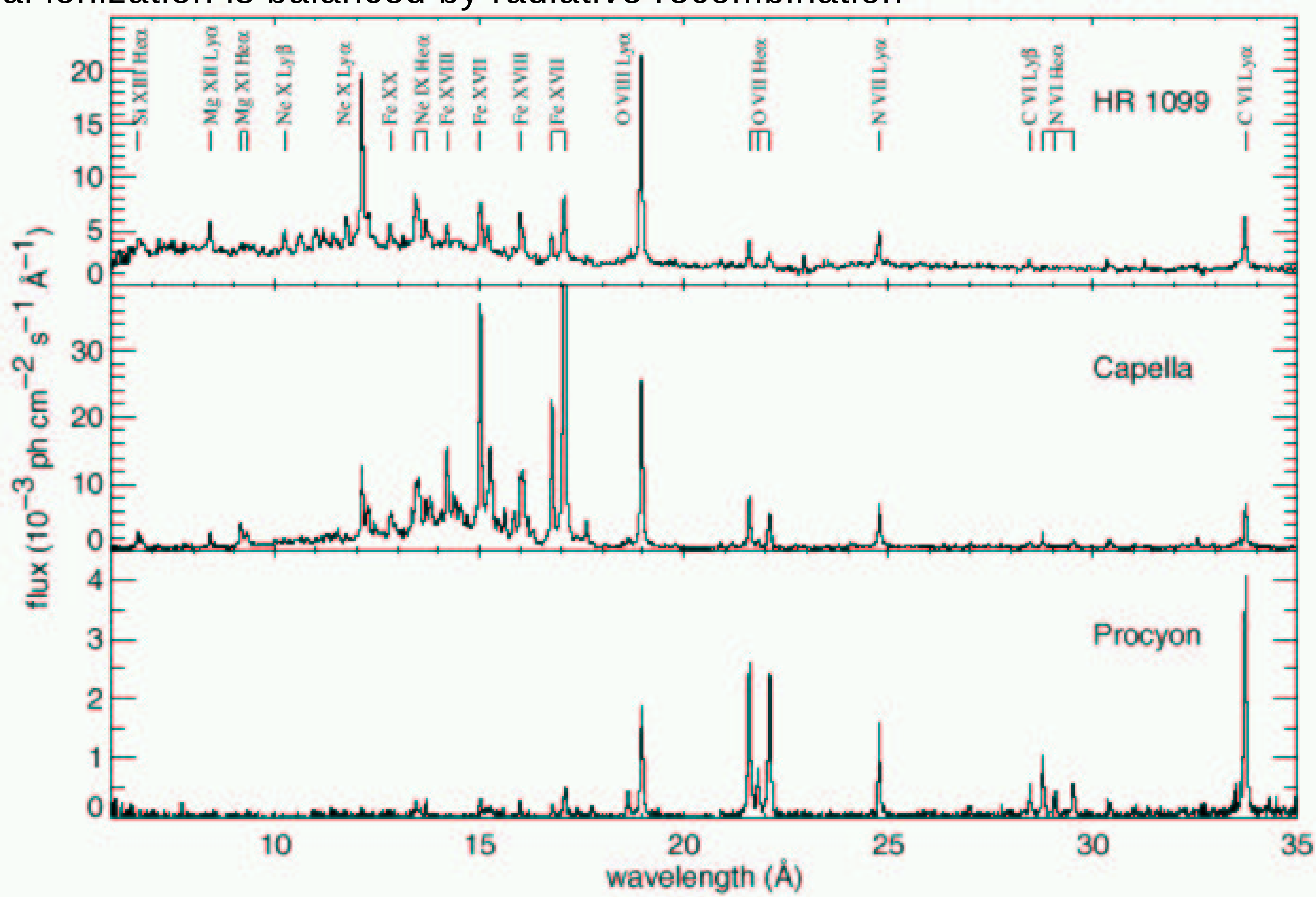


Fig. 6. Three high-resolution X-ray spectra of stars with largely differing activity levels: HR 1099, Capella, and Procyon. Data from *XMM-Newton* RGS

from Güdel 2004, A&AR, 12, 71

VI. The differential emission measure distribution

From observed spectrum we can measure flux ϕ_i in a line that correspond to some atomic transition i

$$\phi_i = \frac{1}{4\pi d^2} \int A G_i(T) \frac{n_e n_H dV}{d \ln T} d \ln T$$

d distance, G_i cooling function that depends on atomic parameters, A abundance of the element. For a fully ionized plasma with cosmic abundance $n_H=0.85n_e$

Differential emission measure $Q(T) = \frac{n_e n_H dV}{d \ln T}$

DEM contains information on the plasma T and the density-weighted plasma mass that emits X-rays at this T. It provides important constraints on heating theories and on the range of coronal structures.

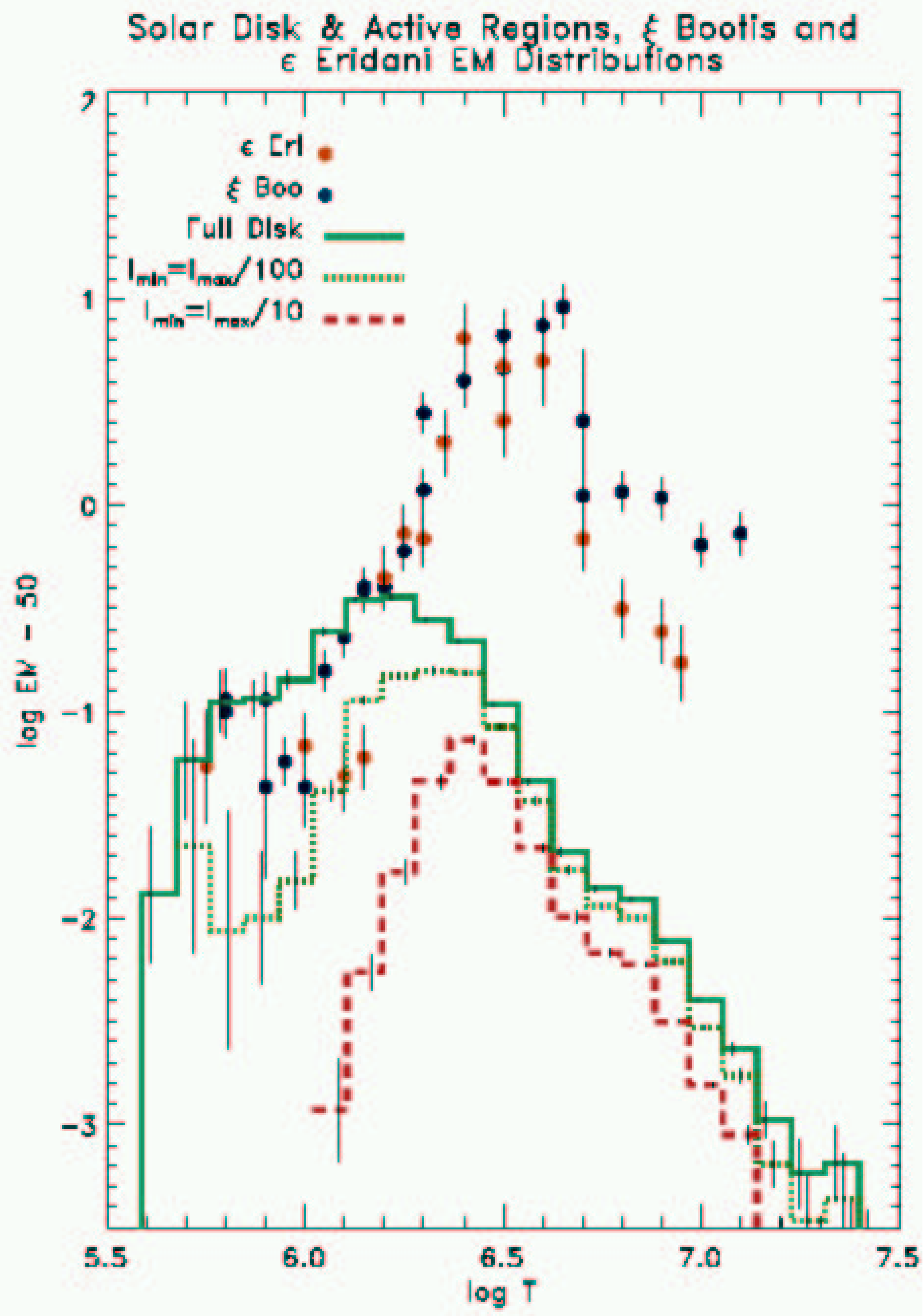
In the Sun, $Q(T) \propto T^s$, s=2 for quiet Sun, s=3 for flares

Deriving DEMs from X-ray spectra has been one of the central issues in observational stellar X-ray astronomy.

Problems with inverse problems

On top of it: inaccurate atomic physics parameters, uncertainties in the instrument calibration and imprecise flux determinations, line blends, **unknown element abundances.**

VI. Stars at higher activity levels support hotter coronae



[EM]=10^{50} cm^{-3}, [T]=K

Histograms are for the Sun

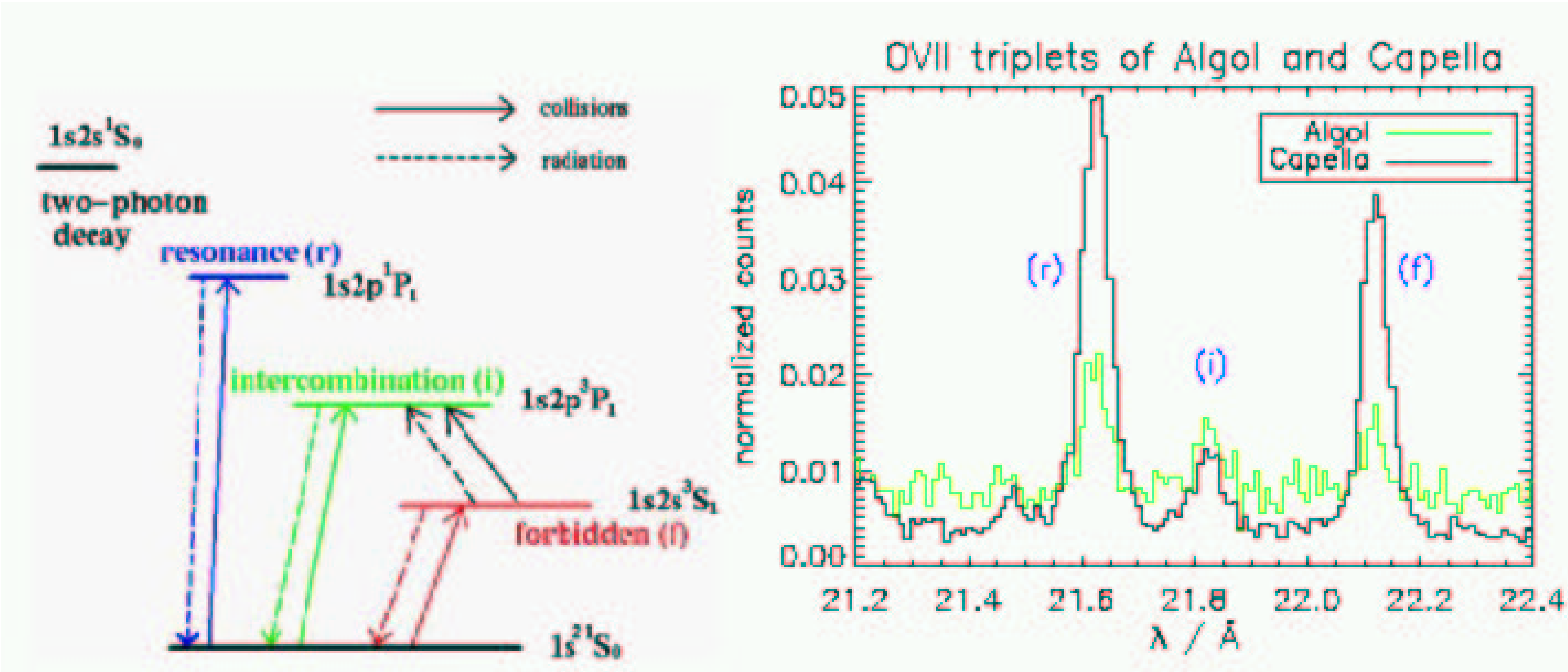
Sun's active regions - red

It can be because:

- As the activity on * increases, more active regions in corona
- More heating: interactions between adjacent field structures
- Higher rate of large flares.
- Coronal heating directly relates to the production rate of magnetic fields, then magnetic pressure would scale with the thermal coronal pressure → EM $\propto T^3$ g

from Drake et al.2000

VI. Electron densities in stellar coronae



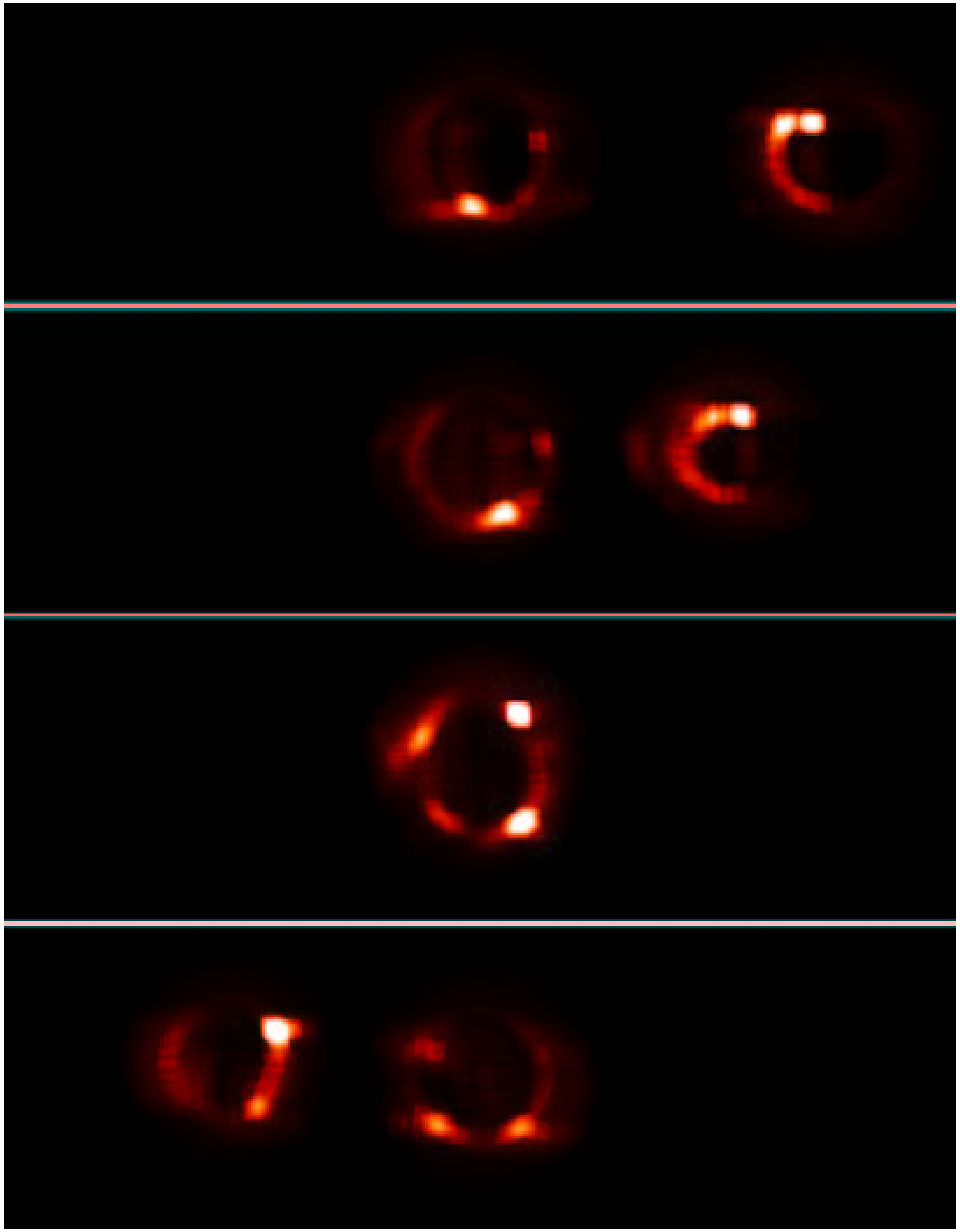
from Güdel 2004, A&AR, 12, 71

He-like ions allow to measure density

Interpretation is not strightforward, because coronae are not homogeneous

VI. Imaging of coronae with eclipsing binaries

YY Gem: short-period spectroscopic binary



The light-curve, i.e. F_X(time), is measured

Image is reconstracted from the analysis of X-ray light-curve

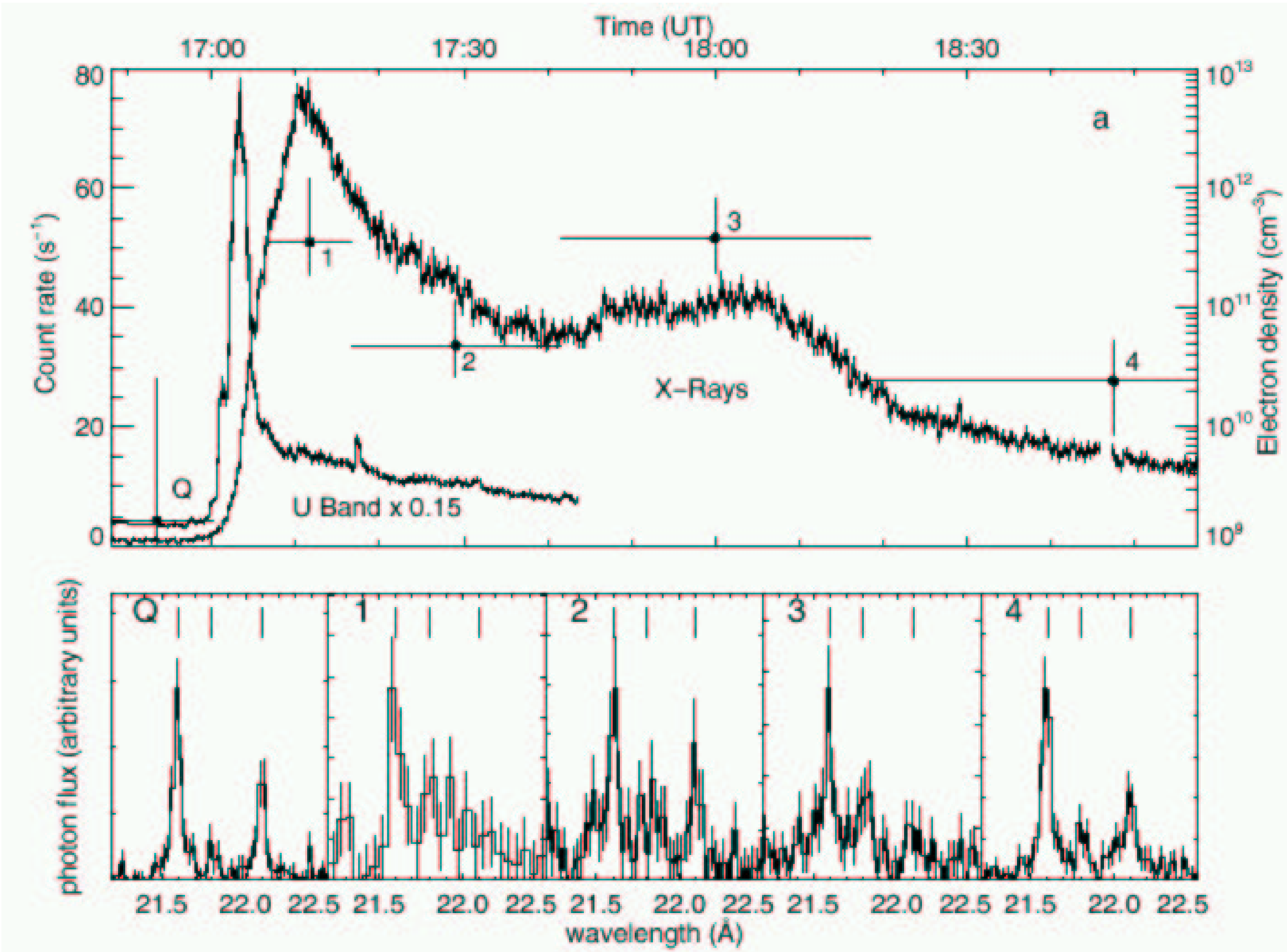
The coronal plasma is inhomogeneous

Most bright areas are at mid-latitudes

from Güdel et al.2001

VI. Stellar flares

Flare on Proxima Centauri,observed with XMM-Newton



from Güdel et al.2002

VI. Stellar flares: common properites

* Flares are universaly observed
* Theoretically: When the flare energy release evaporates plasma into the corona, heating and cooling effects compete simultaneously,depending on the density and temperature profiles in a given flare.
* Obsevrationsllly: correlation between flare EM and T: larger flares are hotter.
* The Neupert Effect Soft X-rays is due to the cooling of thermal gas in the loop time scale hours. Hard non-thermal X-rays and radio synchrotron due to high-energy particles, time scale seconds.
* The distibution is similar to the Sun: → $\frac{dN}{dE} \propto E^{-\alpha}$. But it apperas that later stars are flaring more

VI. The elemental composition of stellar coronae

- The Sun: The First Ionization Potential (FIP) Effect C,N,O,Ne,Ar (FIP>10eV) photospheric abundance ratios with respect to hydrogen, Si,Mg,Ca,Fe (FIP<10) are overabundant. Observed also in cosmic rays?!
- Inverse First Ionization Potential (FIP) Effect in more active stars

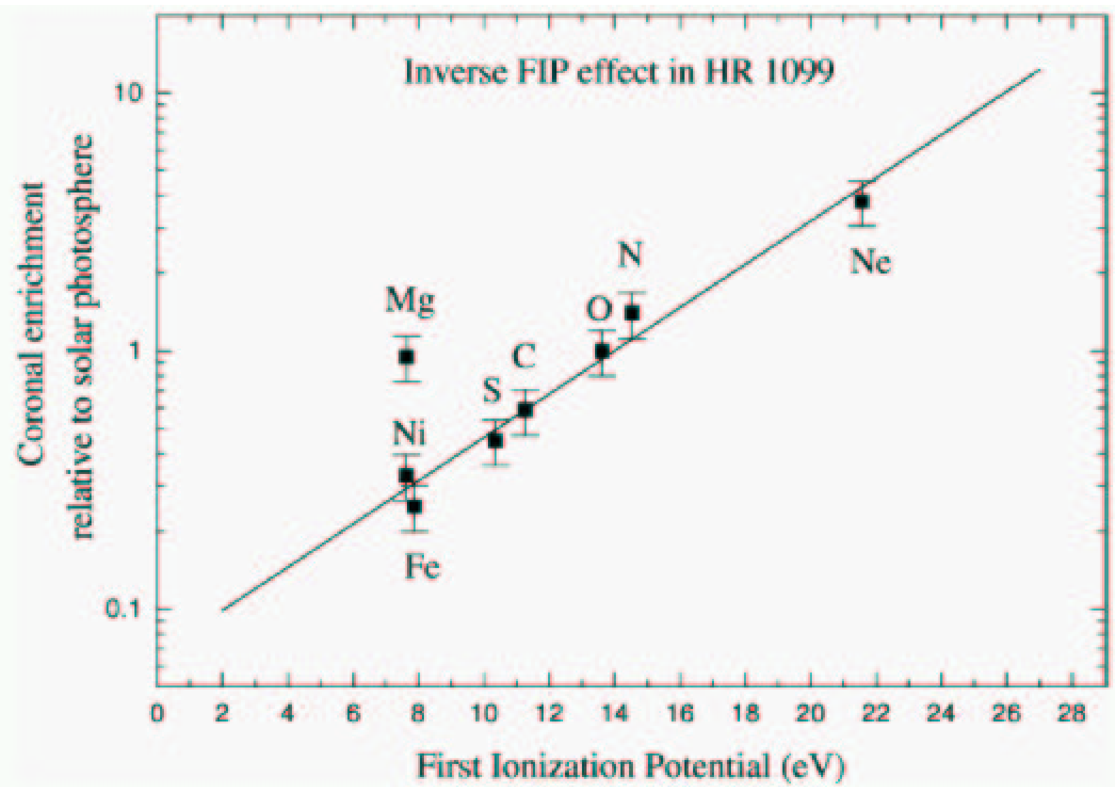
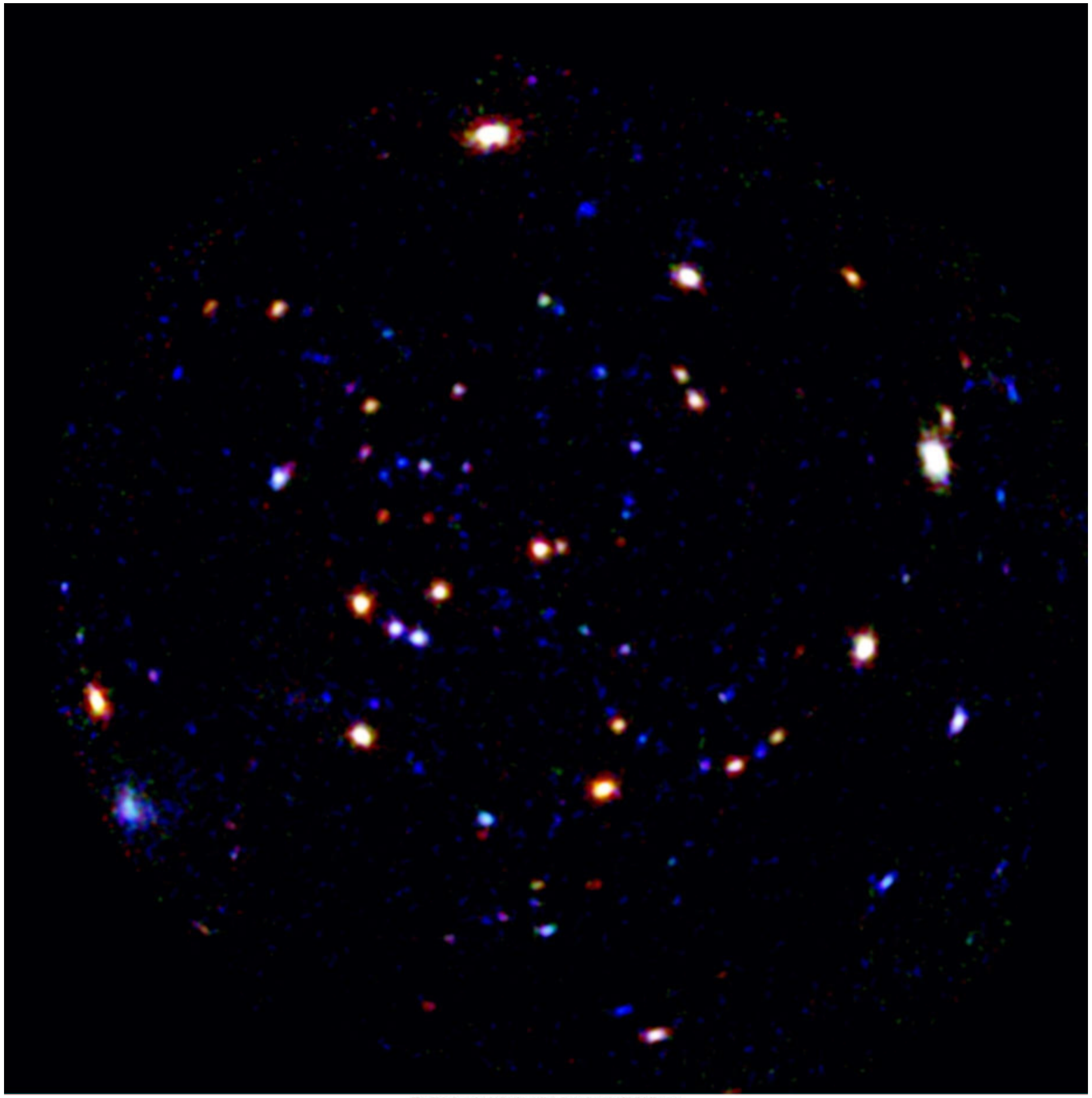


Fig. 35. Inverse FIP effect in the corona of HR 1099. The coronal element abundance ratios with respect to oxygen and normalized to the solar photospheric ratios are plotted as a function of the FIP of the respective element (after Brinkman et al. 2001)

from Güdel et al.2002

VI. General properties



The Pleiades open (galactic) stellar cluster seen by XMM-Newton

Image courtesy of Rosemary Willatt, Pedro Rodriguez (ESAC)

European Space Agency

http://xmm.esac.esa.int/external/xmm_science/gallery/

- Age-luminosity correlation for M~1Msun $L_X \approx 3 \times 10^{28} t^{-1.5}$ erg/s, [t]=Gyr
- Sun and its near-twin α Cen A behave very much alike → Sun is a star !
- Low-mass stars stay active for a longer time.
- Saturation limit of $L_X/L_{bol}=10^{-3}$
- **Dynamo rules it all!**

- Pleiades (100 Myr), an open stellar cluster. The image is false-coloured: soft (0.2 - 1 keV), medium (1 - 1.3 keV), hard (1.3 - 10 keV).