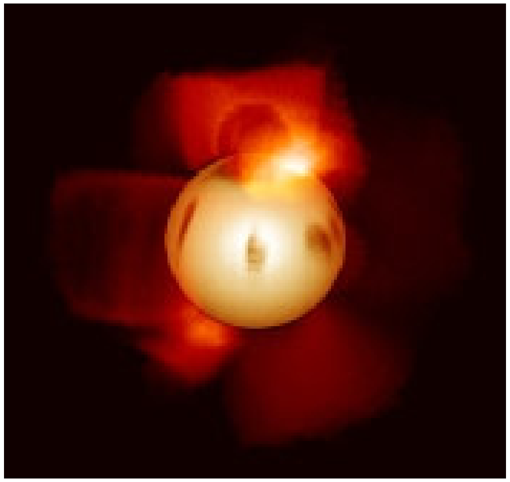
Heating Stellar Coronae



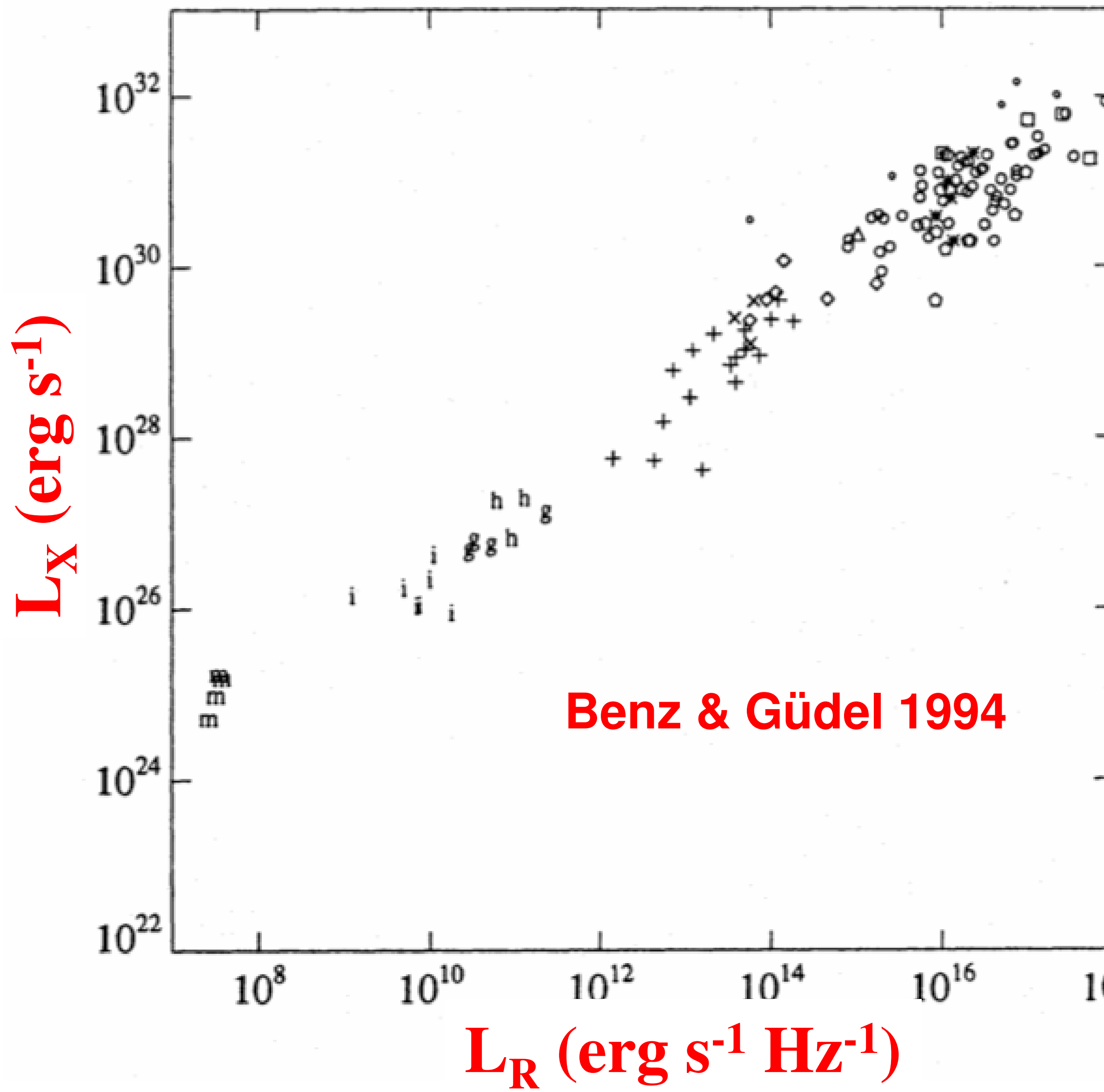
Moira Jardine

St Andrews

Is the Sun a typical star?

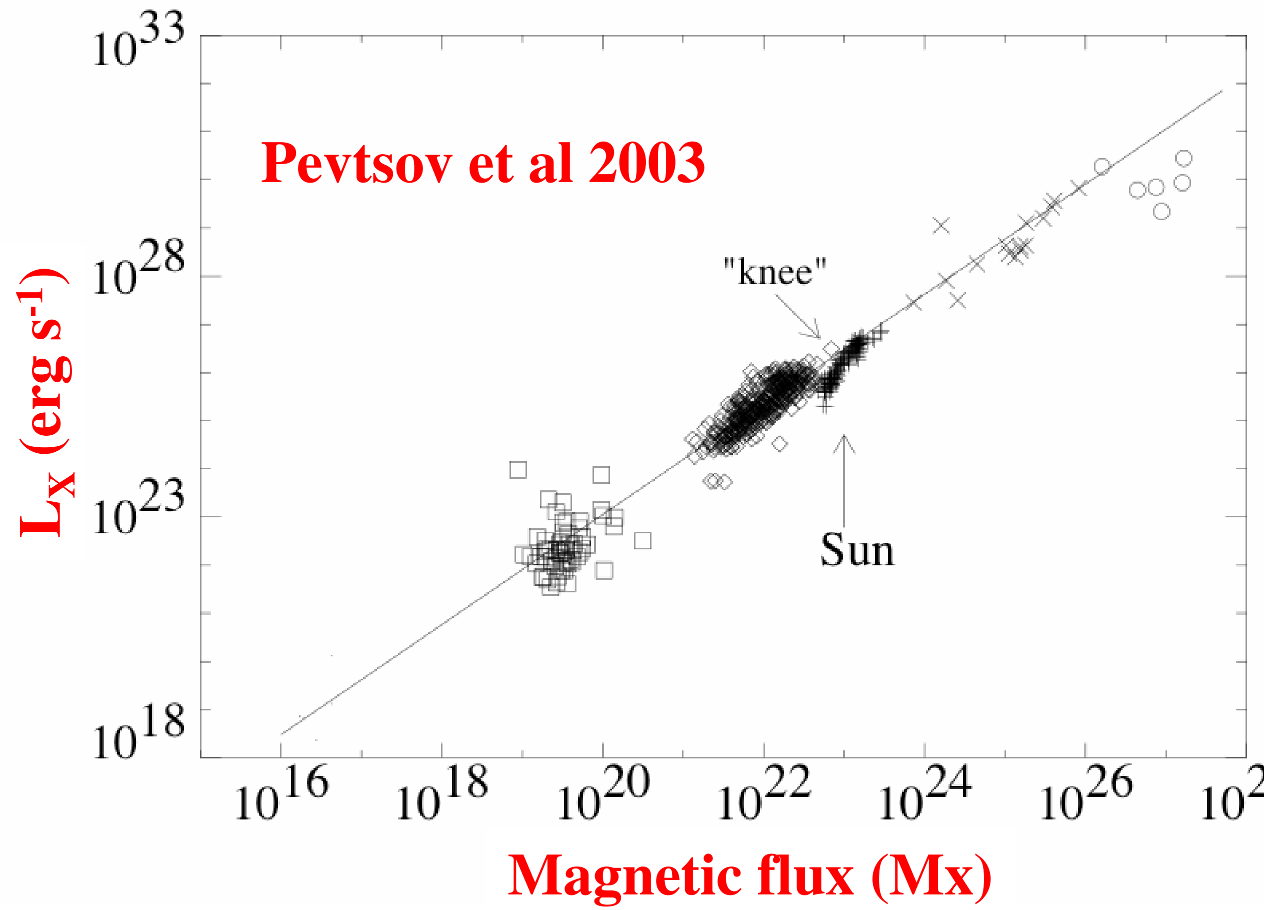
- For both solar flares (letters) and stellar global emission (symbols), X-ray flux is proportional to radio flux.

- -> common underlying process responsible for both



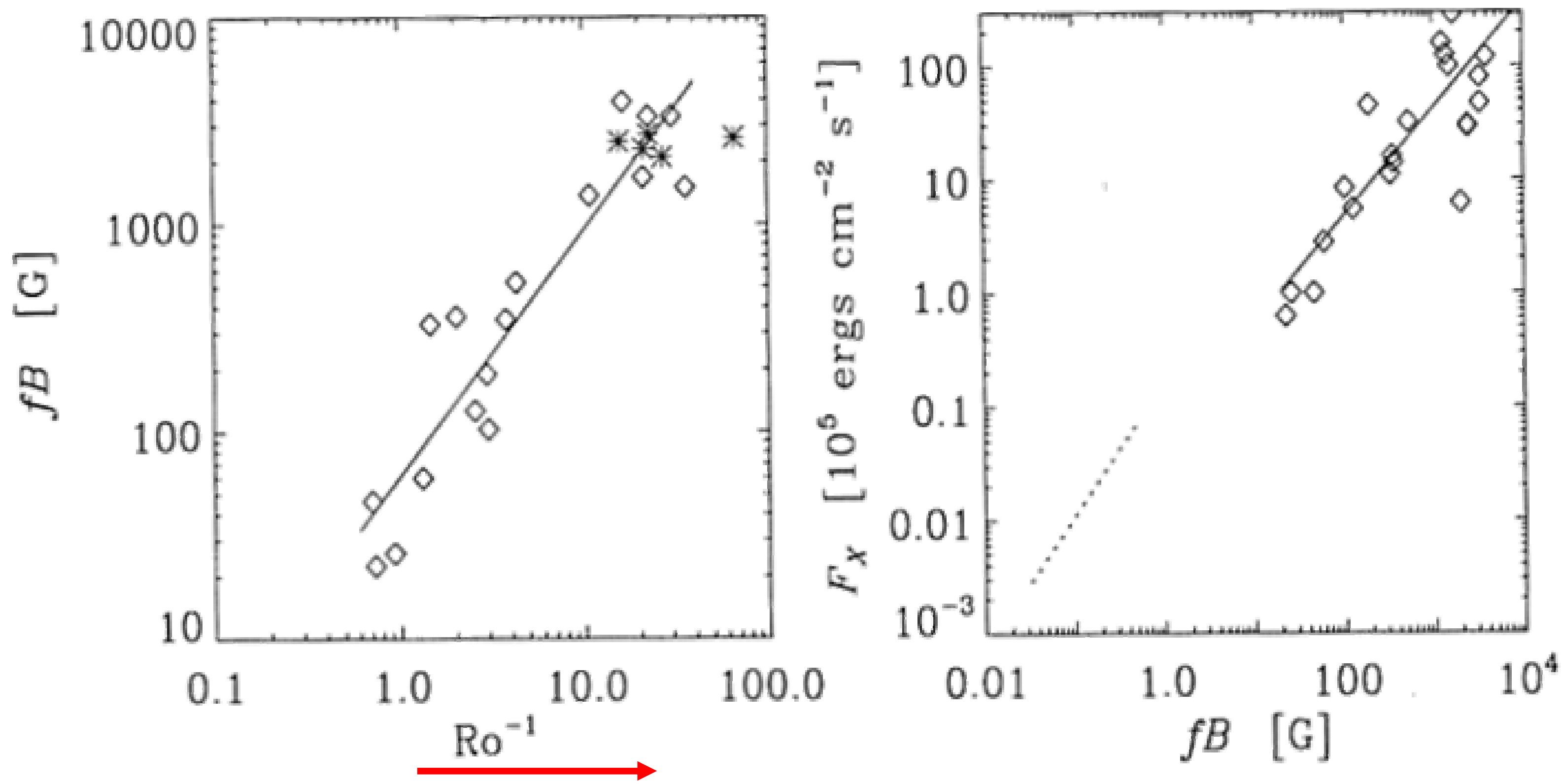
How are stellar coronae heated?

- X-ray flux increases with mean magnetic flux (Fischer et al 1998, Saar 1996, Benevolenskaya et al 2002)
- $L_x \sim \Phi^n$
- n =1 => volume heating rate ~ B/L



Rotation is a key parameter

- Field strengths and X-ray flux increase with increasing rotation rate (Saar, 2001)
- Hence both B *and* L may be functions of rotation rate

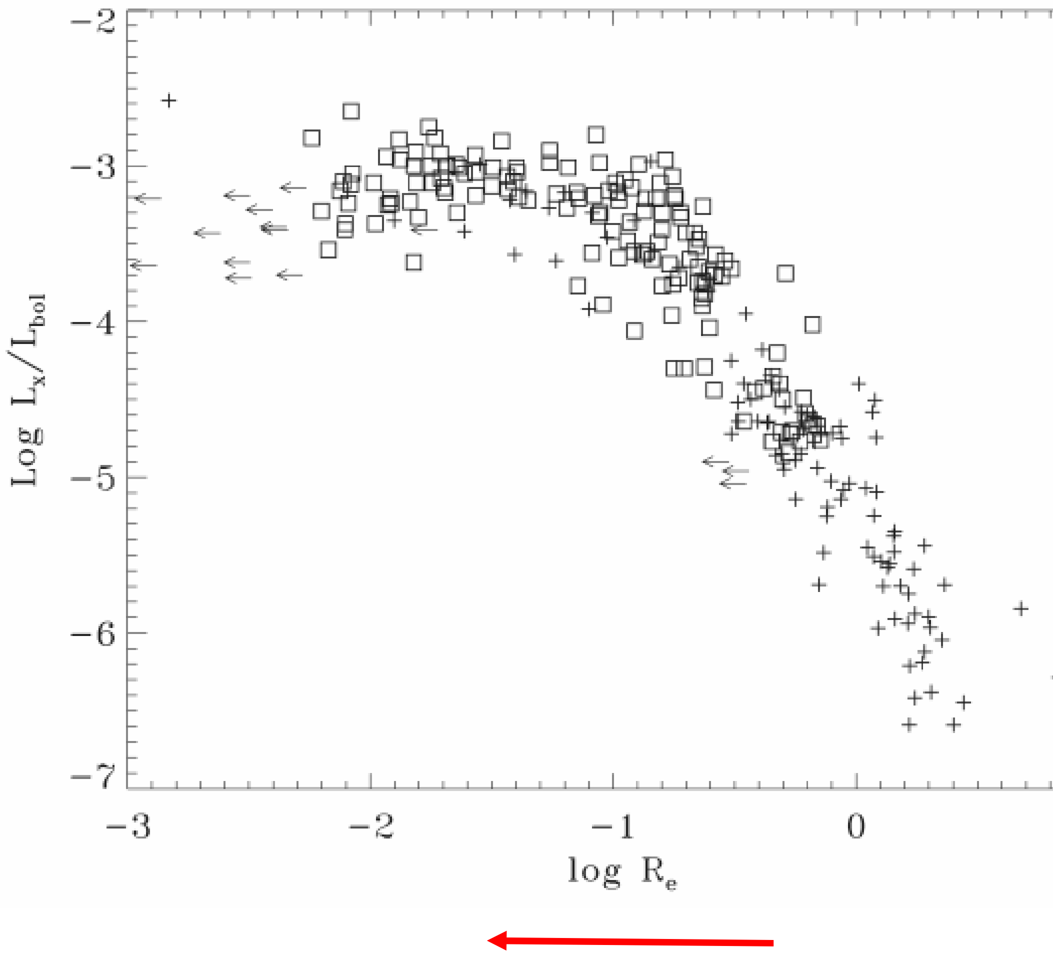


Increasing rotation rate

(inverse Rossby number $R^{-1} = t_c / P_{rot}$)

What about (Super) saturation?

- L_x / L_{bol} saturates then declines towards extreme rotation rates in young open cluster stars (Stauffer et al 1997, Randich 1998, Pizzolato et al 2003, Feigelson et al 2003).
- Has the coronal heating (or the dynamo process) saturated?
- Is the stellar surface full to capacity ?

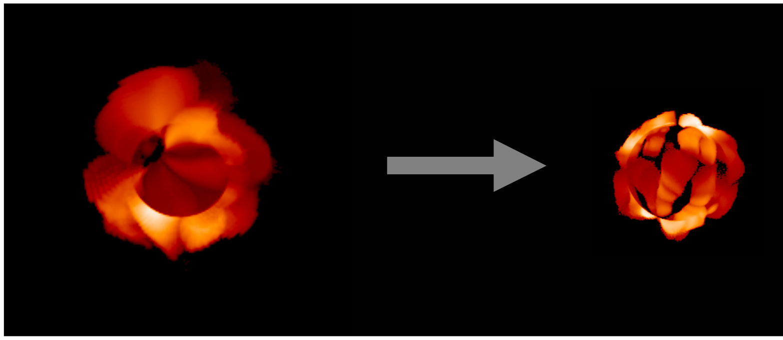


(Pizzolato et al 2003)

Centrifugal stripping of coronae?

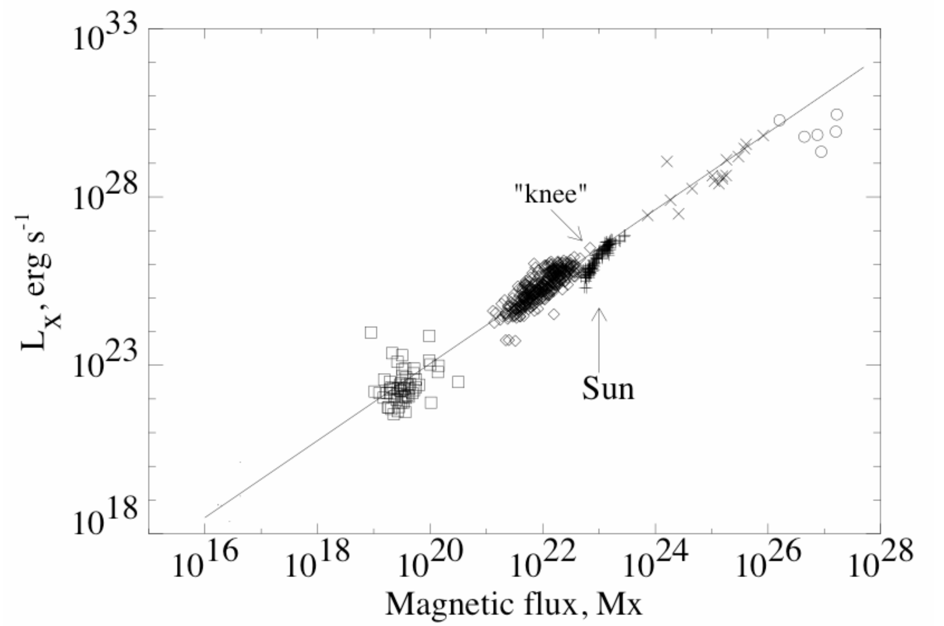
- Consistent with breaking-open of closed corona beyond the co-rotation radius where centrifugal forces balance gravity (Jardine & Unruh 1999).

- Also explains the high (30%) X-ray rotational modulation of VXR45: a supersaturated star in IC2391 (Marino et al 2003).



Jardine 2004

If $L_x \sim \Phi^n$ what determines n?



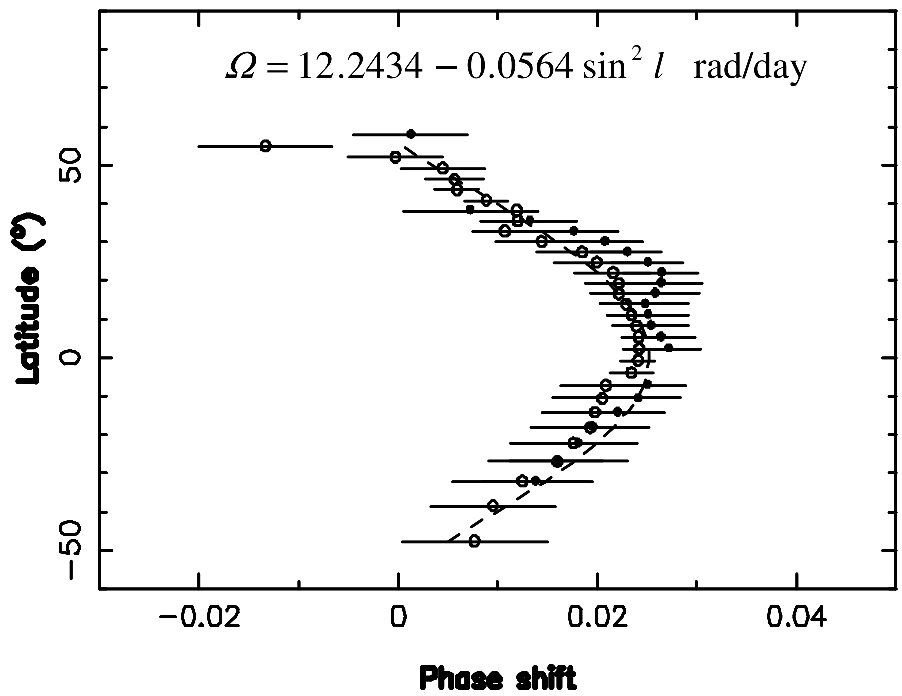
- Phase of magnetic cycle (Benevolenskaya et al 2002)
  - Are cycles on more active stars similar to the Sun's?

- Ratio of closed/open flux (Lockwood et al 1999, Wang et al 2000, Solanki et al 2000, MacKay et al 2002)
  - Is this different for other stars? (Jardine et al 2002, McIvor et al 2004, Wood 2004) (Note problems with unresolved stellar flux)

- Both of these are probably function of stellar rotation rate (and hence age)

Doppler imaging of AB Dor

- d = 16 ± 1 pc (HIPPARCOS)
- Young K0 dwarf, age 20-30 Myr (Cameron & Foing 1997)
- Spin period 12.3 hours (Innis et al 1988)
- Inclination 60 degrees
- Equator laps high latitudes every ~110 days.
  - cf. Sun: ~120 days
- Circumstellar prominence system (Cameron & Robinson 1989)

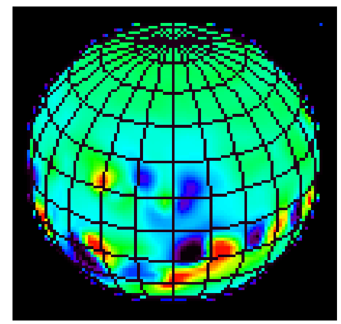


Stellar magnetograms: AB Dor

- (Zeeman)-Doppler imaging -> high latitude flux of mixed polarity (Donati & Cameron 1997, Donati 1999)

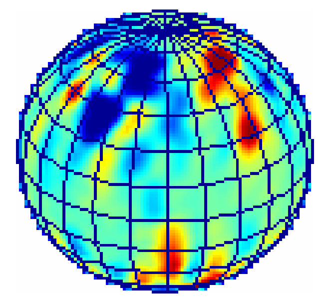
- Active longitudes (Jetsu 1993, Berdyugina 2002, Benevolenskaya et al 2002, Bigazzi & Ruzmaikin 2004)

- High X-ray emission measure (~10^{53}cm^{-3}), but low rotational modulation of 5-13% (Kürster 1997)



Sun at max

P=26 days

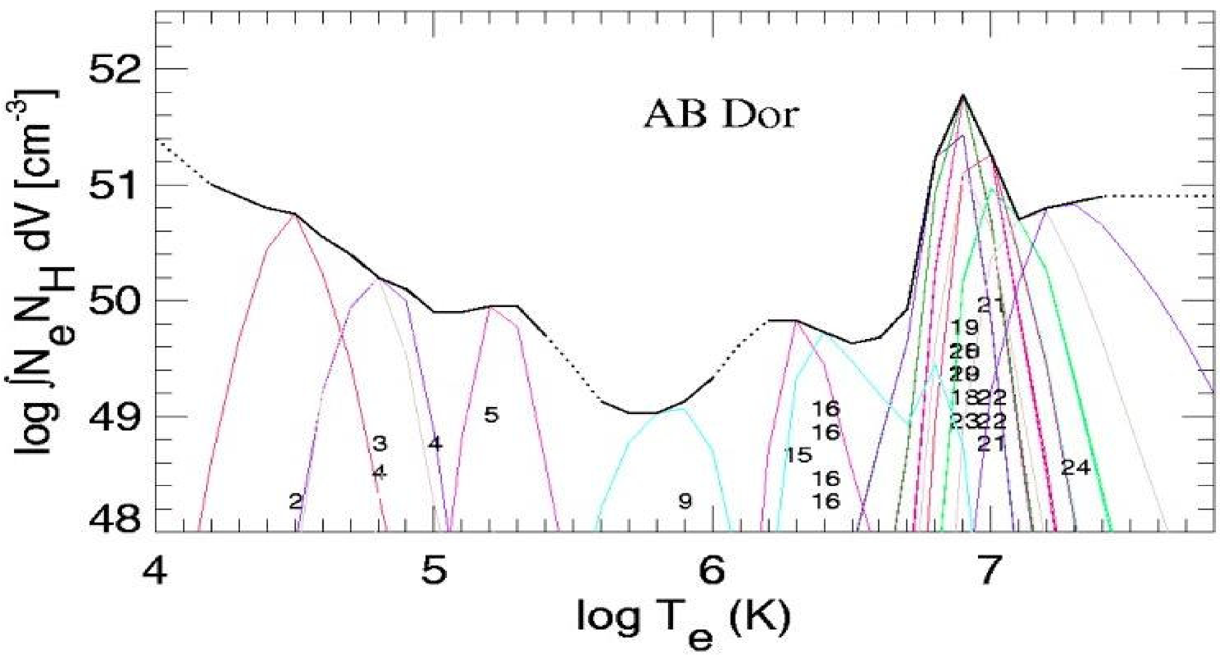


AB Dor

P=0.5 days

Hot dense coronae?

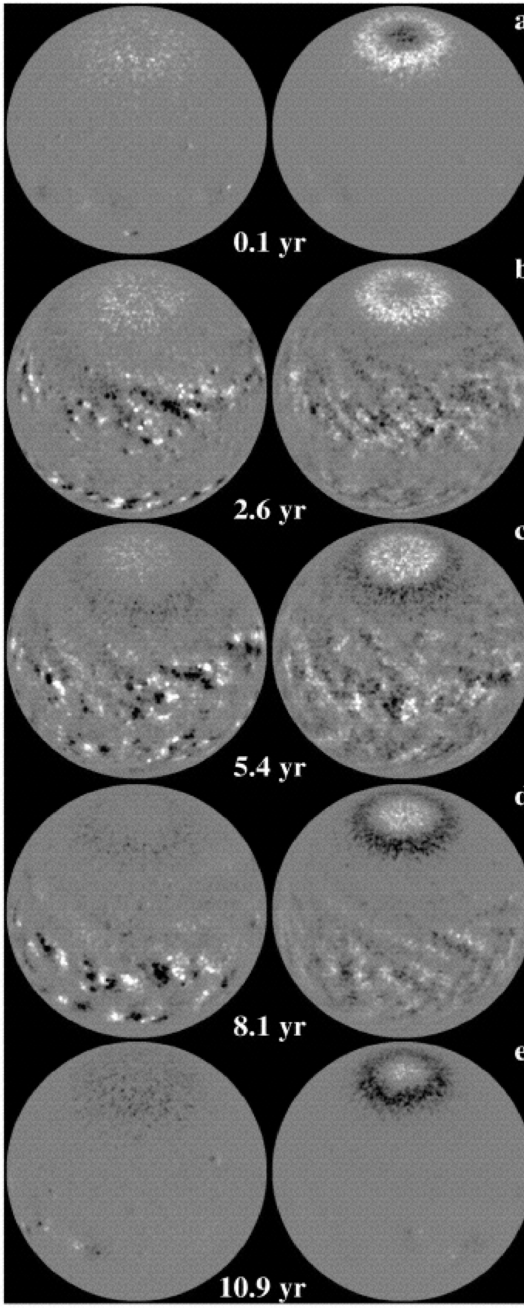
- High temperature peak at 10^7K in Differential Emission Measure
  - Only seen on Sun during flares
- High densities from Chandra/XMM/EUVE:
  - Capella, σ Gem, 44i Boo ~10^{13}cm^{-3} (Dupree et al 1993, Schrijver et al 1995, Brickhouse & Dupree 1998).
  - AB Dor: 10^9-10^{12} cm^{-3} (Maggio et al 2000, Güdel et al 2001, Sanz-Forcada et al 2003)



Sanz-Forcada *et al* 2002

The forward problem: simulating moderate activity

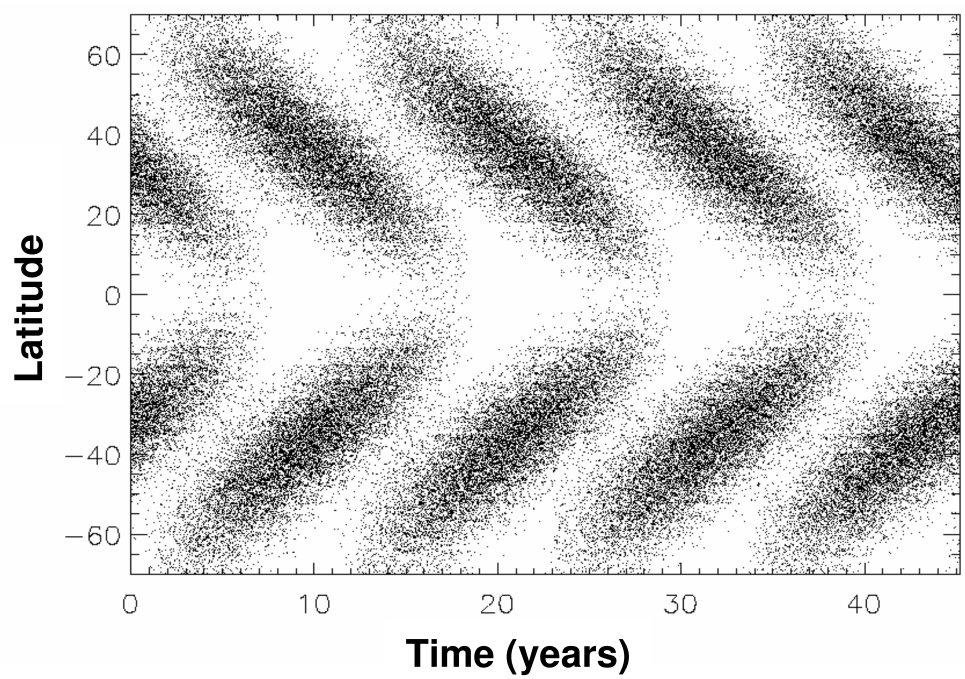
- Simulate flux emergence/transport with solar values of:
  - Flux emergence pattern (butterfly diagram)
  - Surface transport due to differential rotation, meridional flow and supergranular diffusion
- But…rate of flux emergence enhanced to 30 times solar

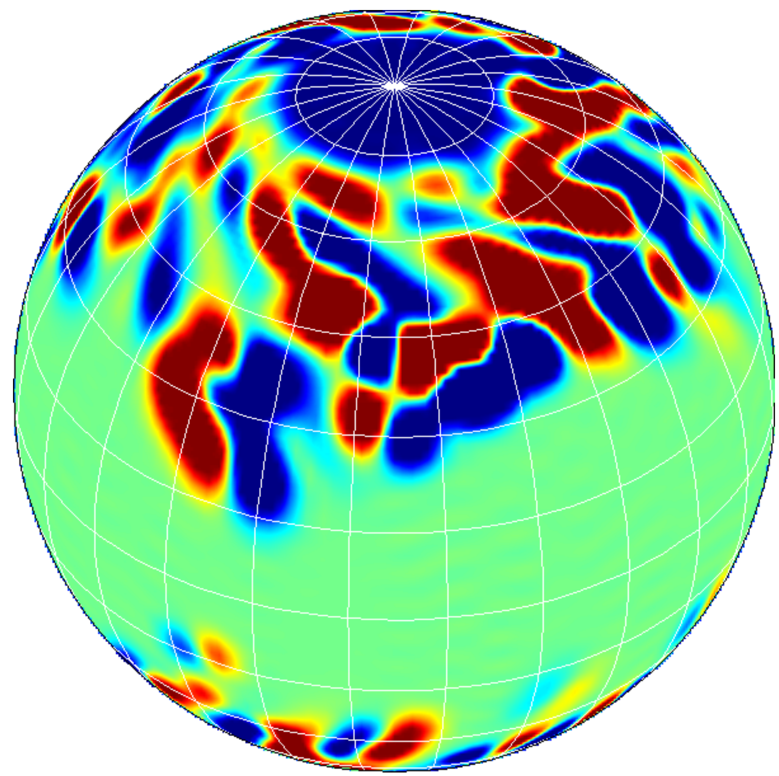


(Schrijver & Title 2001)

Simulating high activity

•Enhanced flux emergence latitude (10^o-70^o) and meridional flow (100m/s)

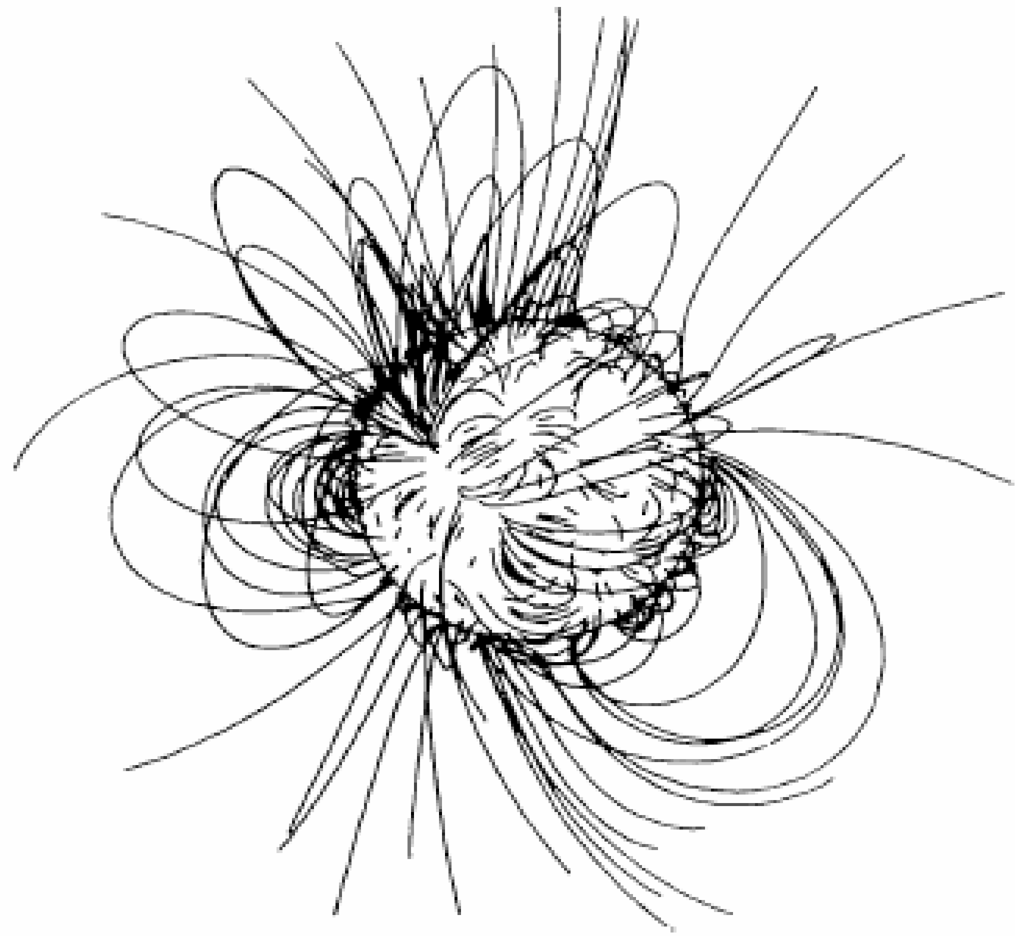




(Mackay et al 2004)

The shape of a stellar corona

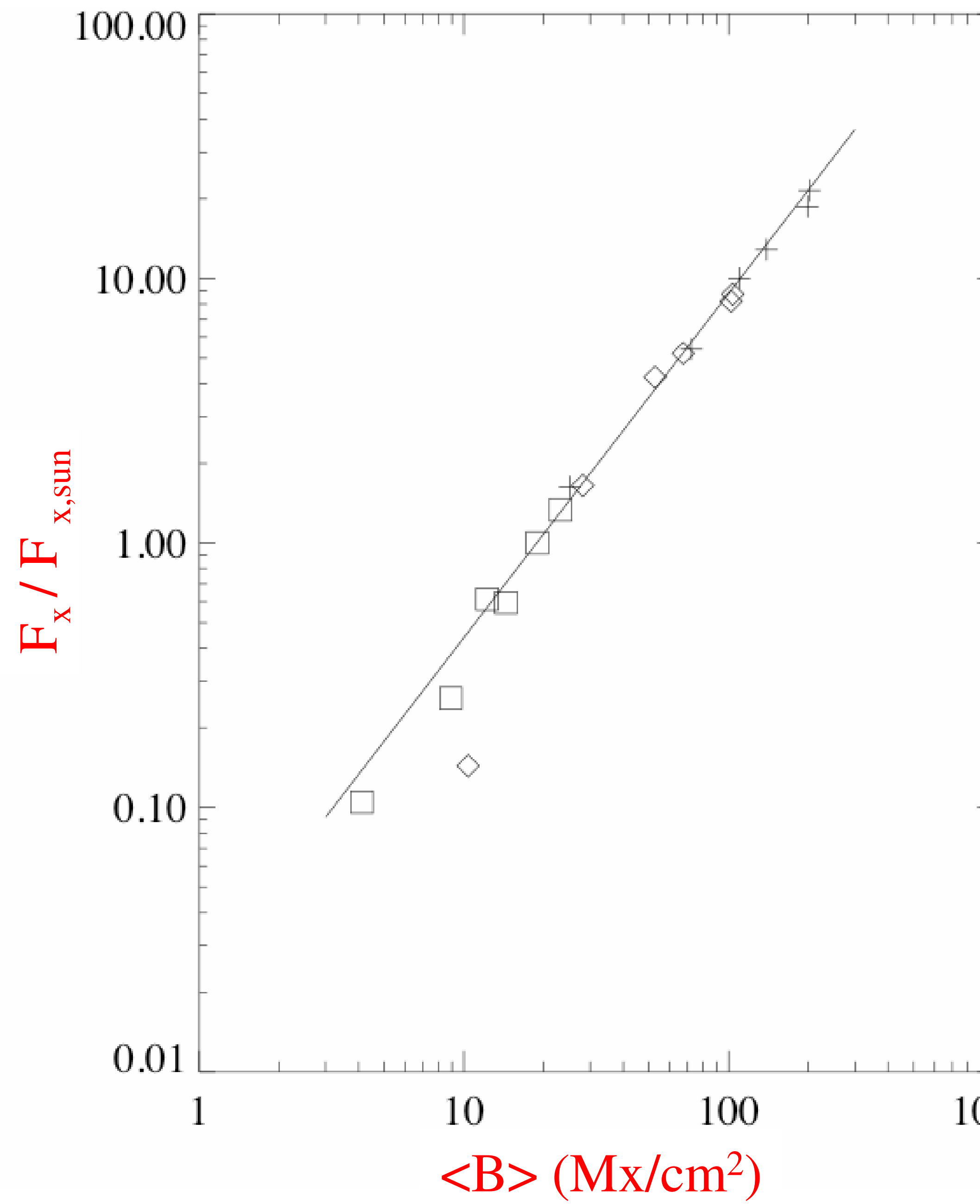
- Altshuler & Newkirk (1969):
  - fitted potential field models to solar surface magnetograms.
  - Mimic transition from closed corona to solar wind by imposing a “source surface” at several solar radii. Field beyond source surface is radial.
- Can we do this for other stars?



LONGITUDE OF DISK CENTER = 270 DEGREES

L_x for moderate activity

- Simulate flux emergence/transport
- Extrapolate potential coronal field with source surface
- Construct atmosphere: base heating flux density/unit area $F \sim B^{\alpha}/L^{\beta}$
- Determine X-ray emission (folded through instrument response)

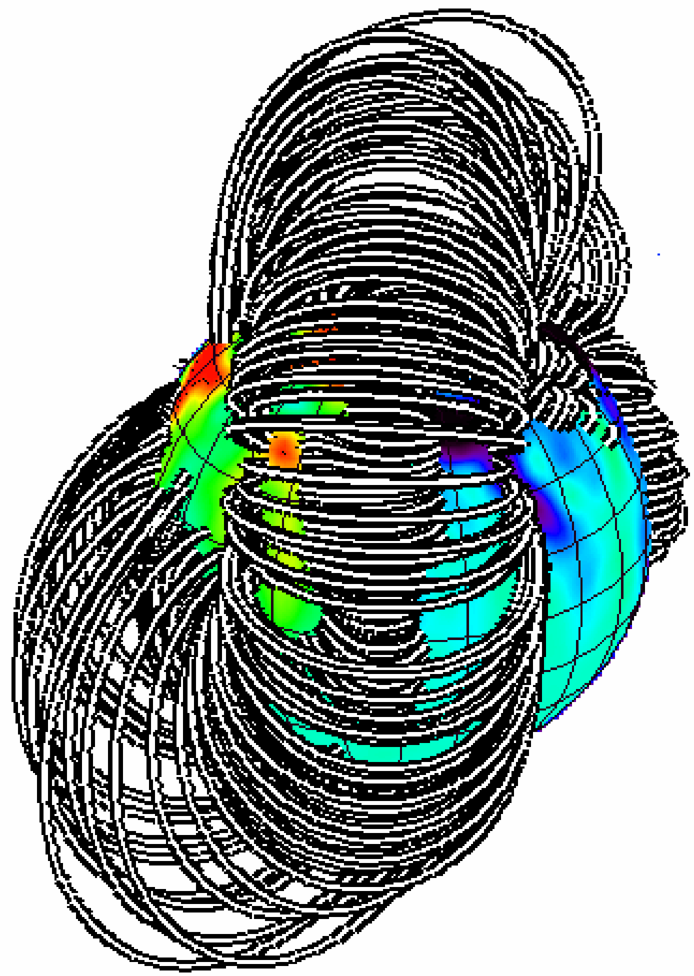


- Best fit to solar X-ray data -> $F \sim B/L$

(Schrijver & Aschwanden 2002, Schrijver et al 2004)

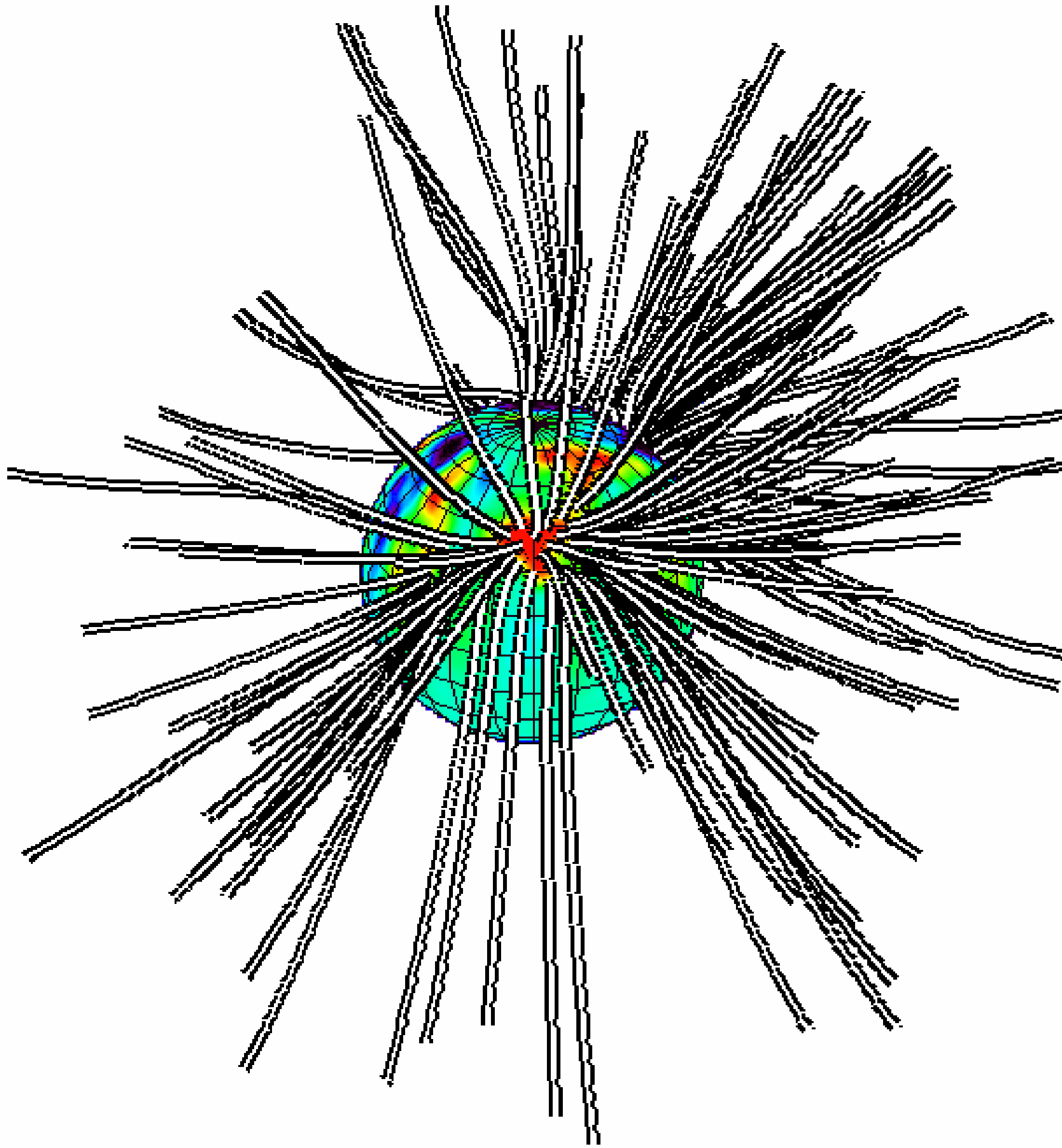
The forward problem: data

- AB Dor 2002 Dec
- Use Zeeman-Doppler maps to give surface radial field distribution
- Potential field + source surface extrapolation
- Note extension to non-potential fields (Hussain et al 2002)



Open field AB Dor 2002

- Two open field regions found.
- These will be dark in X-rays.
- Winds emerge from mid to low latitudes, not the poles (Holzwarth 2004)



X-ray Emission

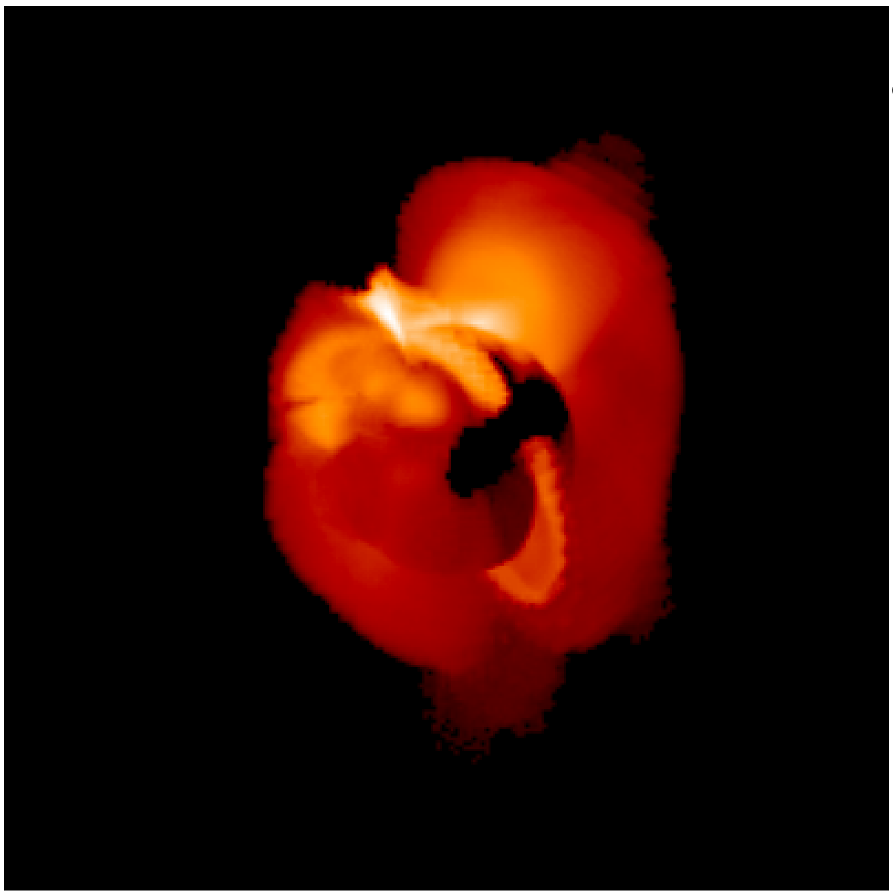
- Hydrostatic balance *along* each field line
- Isothermal corona at 10^6 or 10^7 K
- Base pressure $p_0 \alpha B_0^2$
- $p = 0$ if
  - field lines are open or
  - $p > B^2/2\mu$
- Emissivity $\propto n_e^2$
- Monte Carlo radiative transfer code by K. Wood

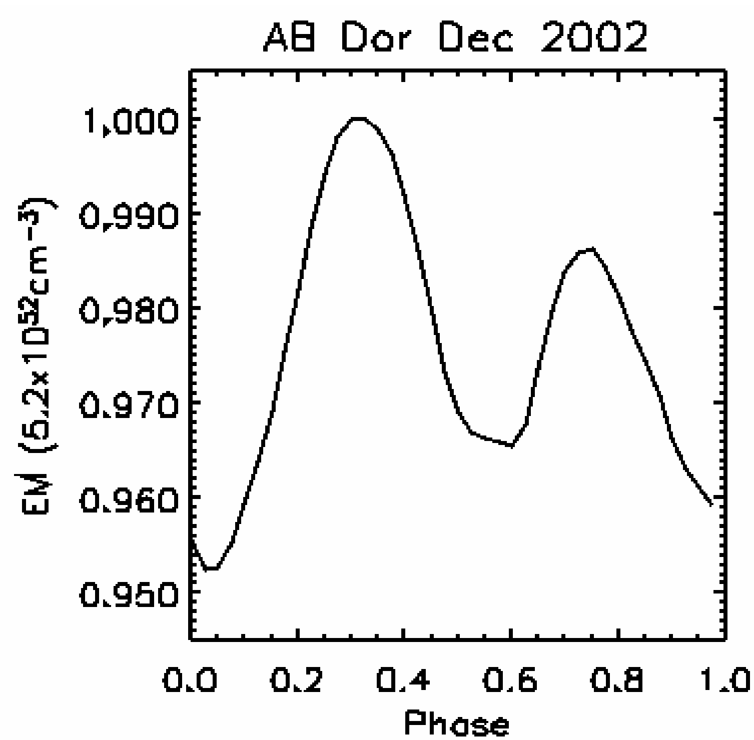
AB Dor 2002 Dec

- Emission measure ~ 10^{52} cm $^{-3}$
- Density: $0.6\times10^{10}\,cm^{-3}$

$$\overline{n_e} = \frac{\int n_e^3 dV}{\int n_e^2 dV}$$

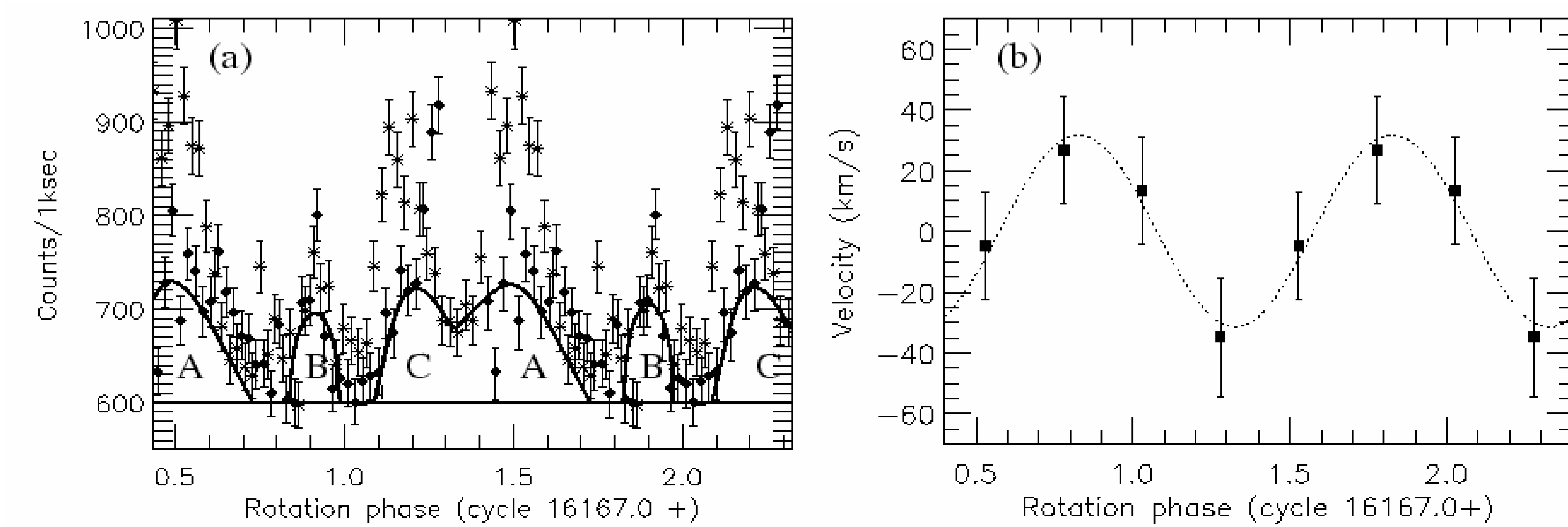
- Always in view -> low rotational modulation ~ 5%





AB Dor in different wavelengths

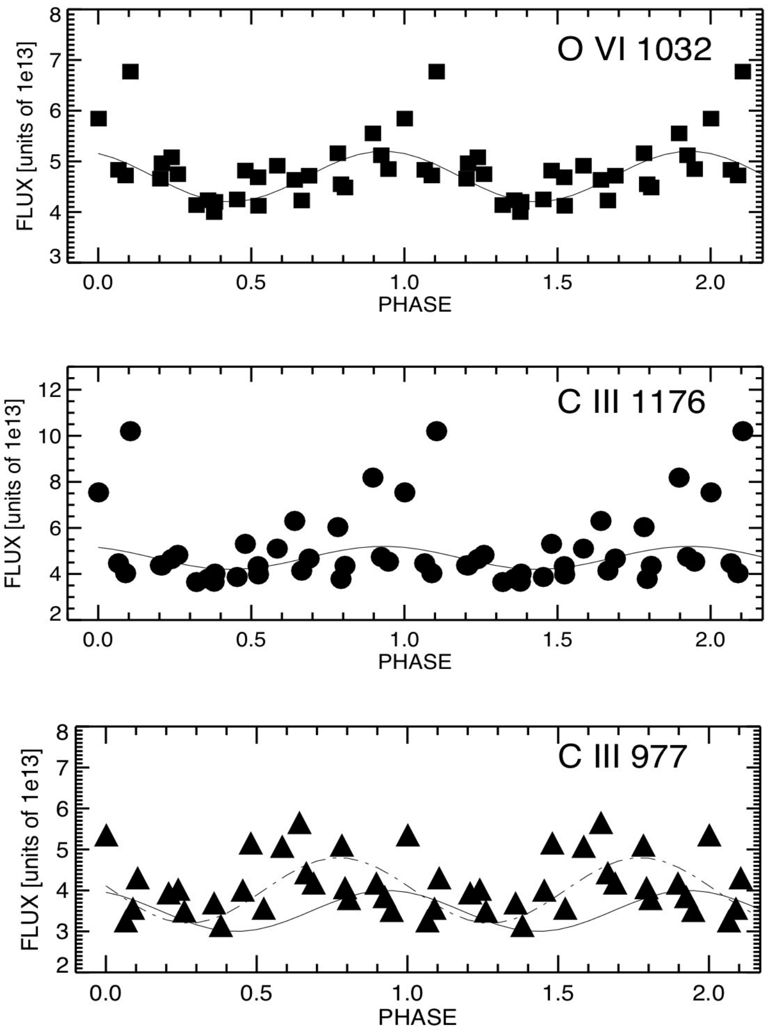
- Coordinated simultaneous observations with:
  - AAT/CTIO to obtain (Zeeman)-Doppler images (Cameron, Donati, Hussain)
  - Chandra (X-ray coronal spectrum: Hussain)
  - FUSE (wind-sensitive lines: Dupree)



Hussain et al 2004, ApJ

Tracking the open field

- FUSE results (Dupree et al 2005)
- Phases of low flux correspond to regions of open field (lines narrower then too)



To summarise…

Solar-like stars have coronae that are…

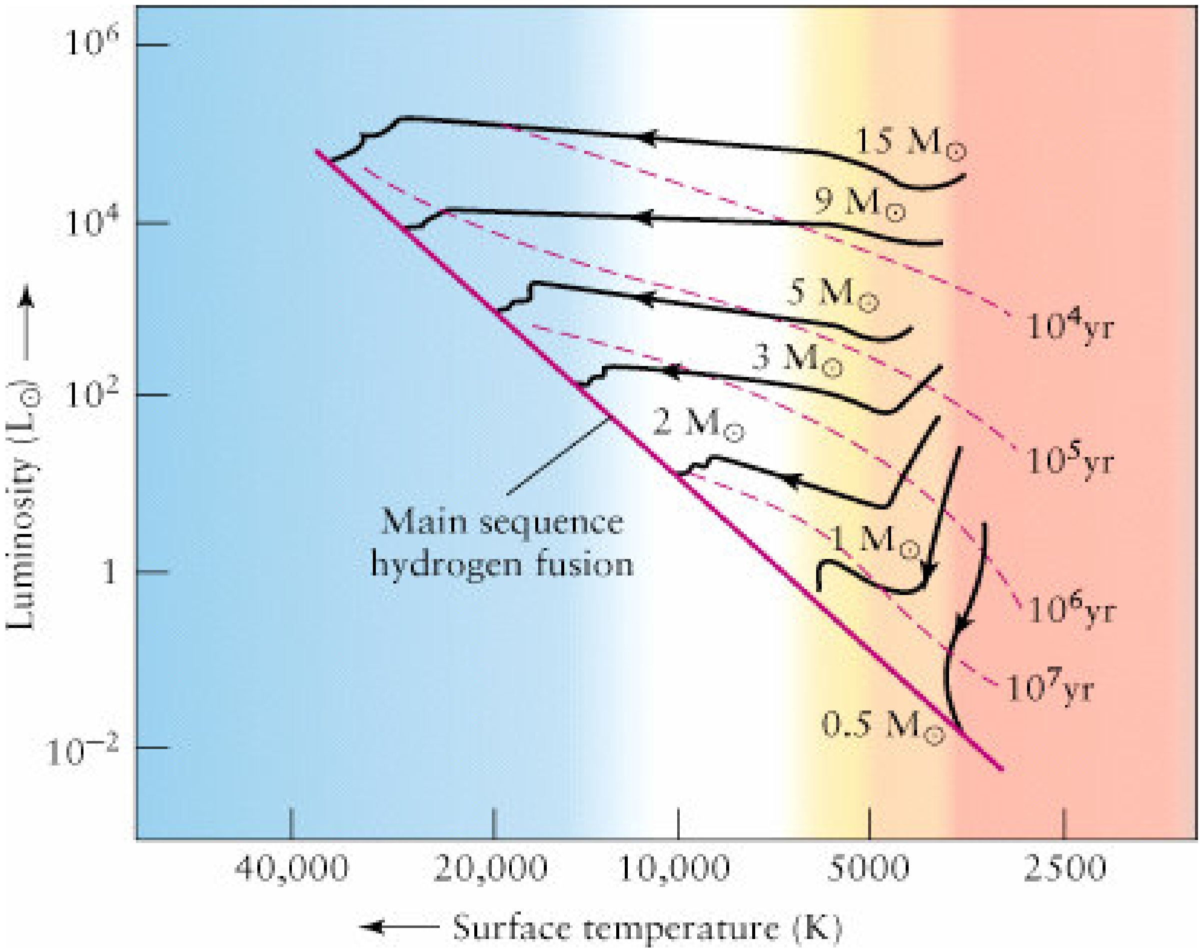
Hotter and denser

than the Sun, but just as

highly structured and compact

What if stars don't have a solar-like dynamo?

- Both pre-main sequence and very low mass stars are fully-convective
- Hence no interface dynamo



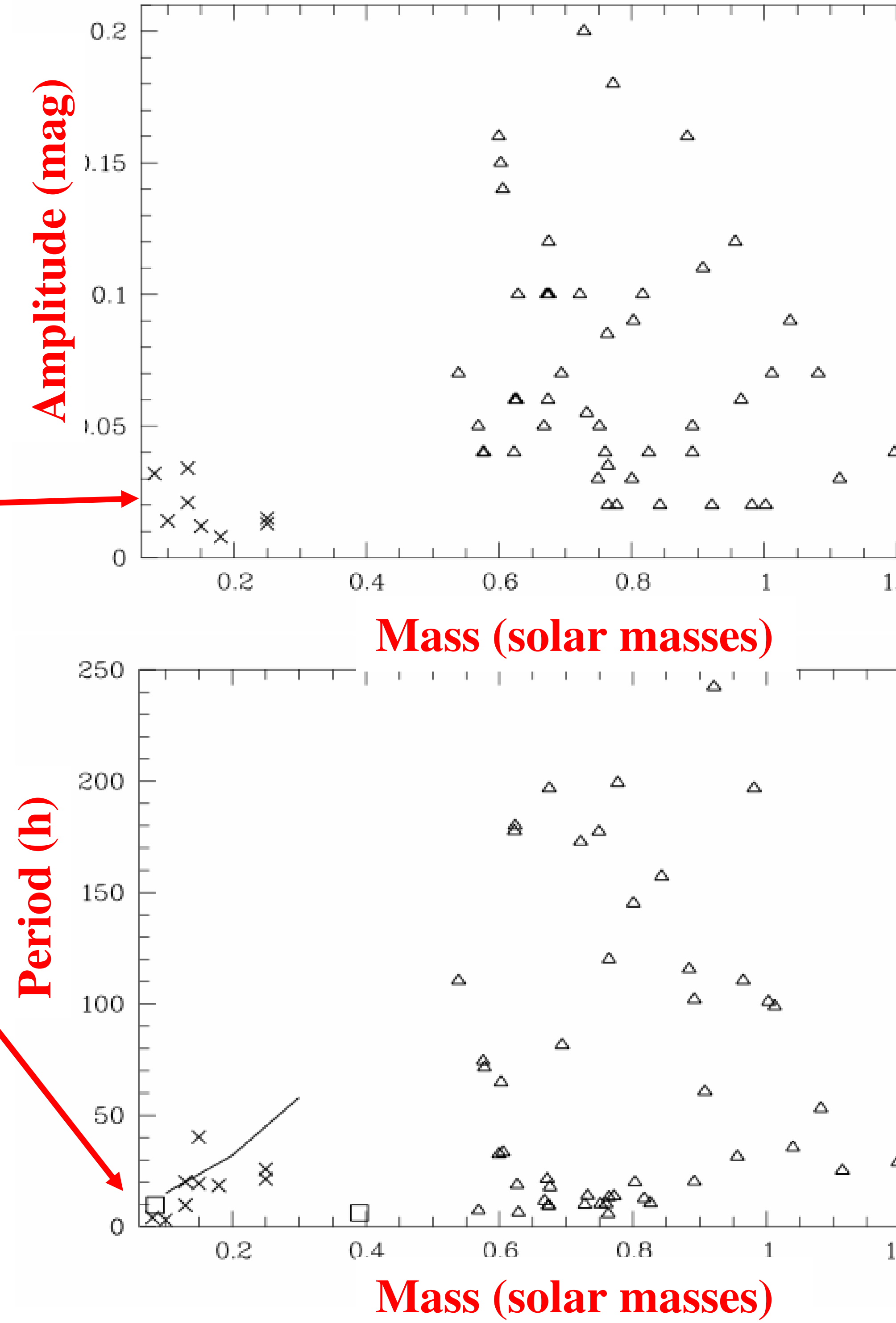
Low mass stars in Pleiades have:

- the smallest amplitude photometric variations

- the lowest periods (most rapid rotators)

- Are their fields inefficient at losing angular momentum (Durney 1993, Barnes 2003)?

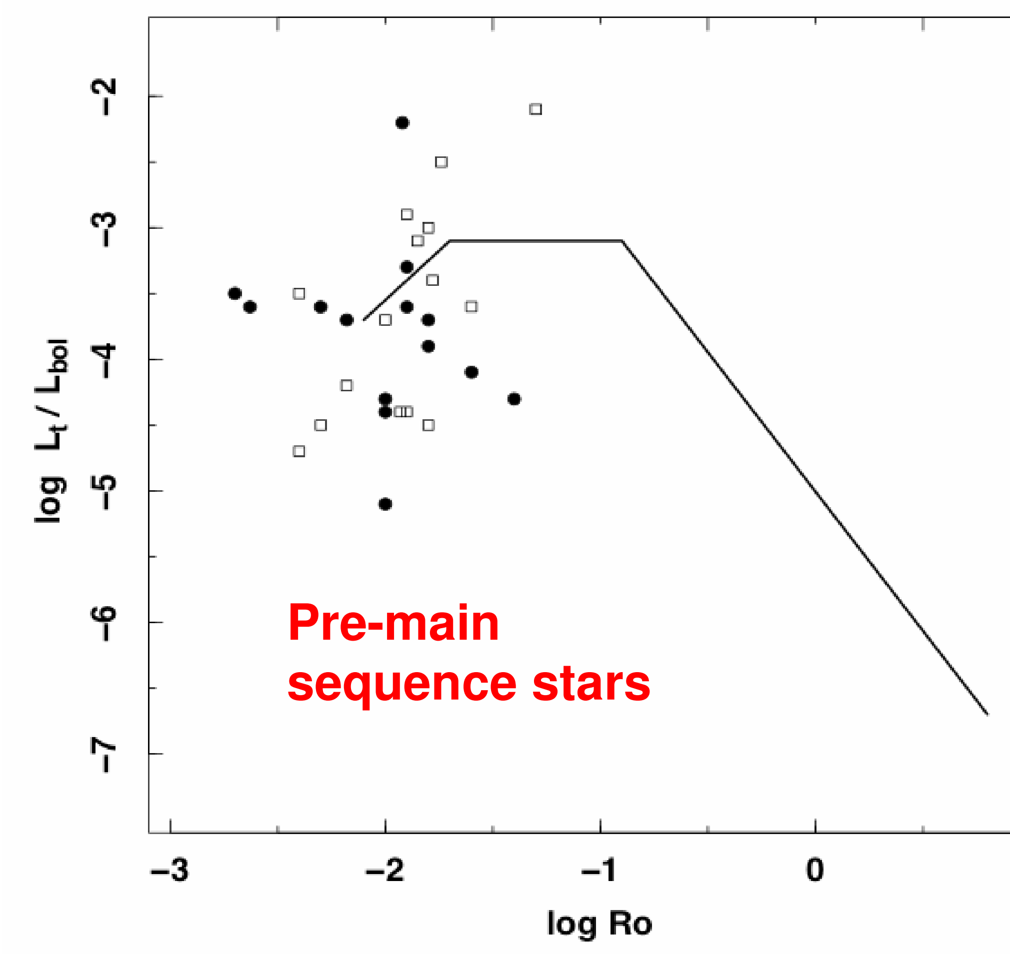
Scholz & Eisloffel 2004



Pre-main-sequence stars

- Study of Orion Nebula Complex showed no L_x-rotation relation (Feigelson et al 2003, Flaccomio et al 2003, Stassun et al 2004)
- Possible effect of star-disk interaction?
- Zeeman-Doppler Imaging with ESPADONS on CFHT coming *soon* in 2005

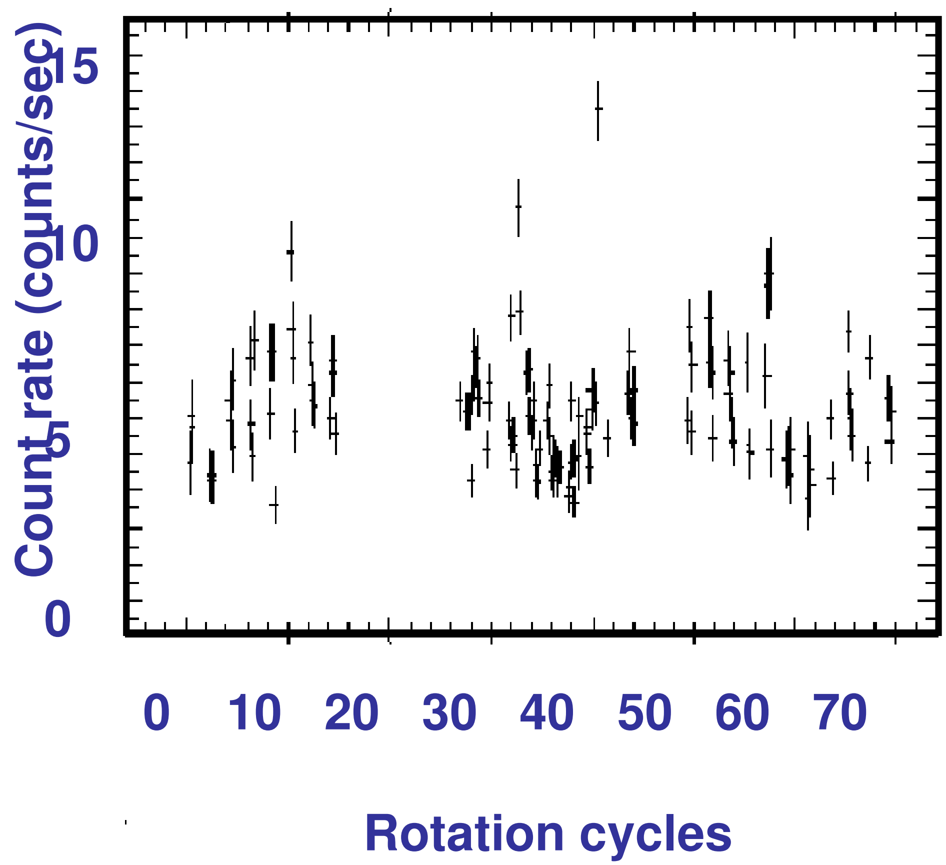
Feigelson et al 2003



Increasing rotation rate

Stellar soft X-ray emission

- ROSAT PSPC data of AB Dor (K0 dwarf, P=0.5 days)
- Lx ~ 1000 times solar!
- Flares + Weakly modulated (5-13%) “baseline” emission + flares (Kürster et al 1997)
- cf other studies (eg Güdel 1995, Siarkowski 1996, Singh 1999)



Linking surface magnetograms to X-ray emission

- Source surface model (Altshuler & Newkirk 1969, van Ballegooijen *et al* 1998, Jardine *et al* , 1999)
  - NB: extension to non-potential fields (Hussain *et al* 2002)

Boundary conditions:

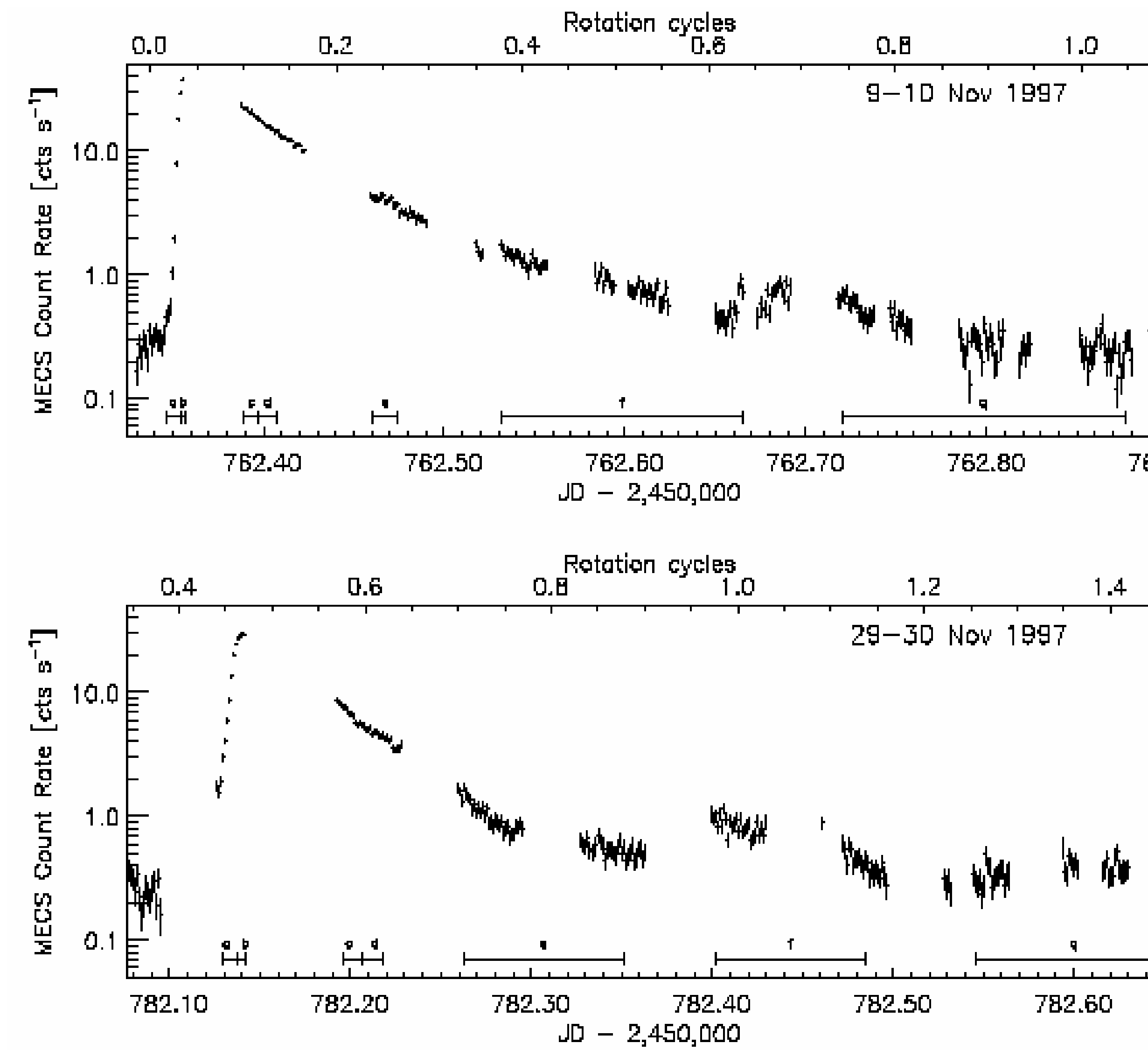
- B_r (stellar surface)= observed
- B_ϕ (source surface) = 0

$$\mathbf{B} = -\nabla\psi, \qquad \nabla\times\mathbf{B} = 0, \qquad \nabla\cdot\mathbf{B} = 0 \quad \Rightarrow$$

$$\psi(\mathrm{r},\theta,\phi) = \sum_{l=0}^{N}\sum_{m=-l}^{l}\left(a_{lm}r^{l} + b_{lm}r^{-(l+1)}\right)Q_{lm}(\theta)e^{im\phi}$$

The amazing unobscured flares

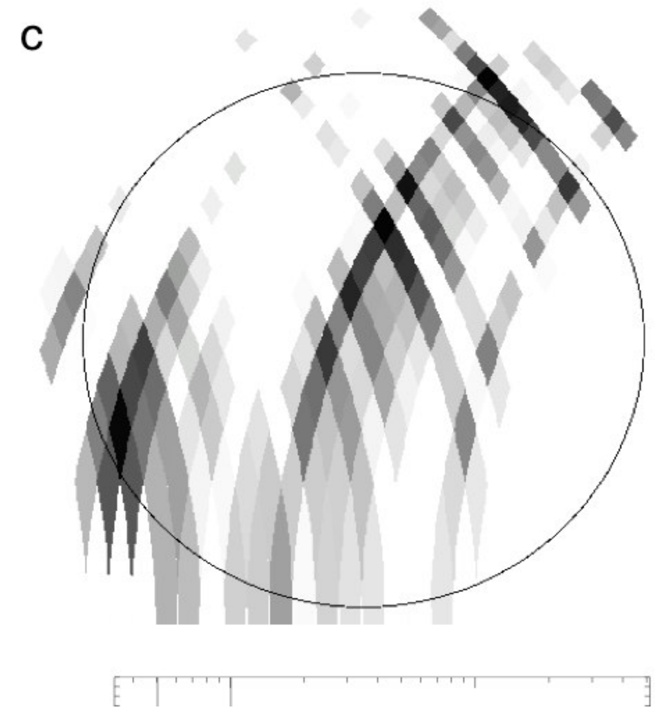
- 1997 BeppoSAX observations: flare decay time (~ 14 hours) > spin period.
- So why didn't the flare region rotate out of view?
- Was it far out in the corona?
- Modelling suggested flaring loop(s) small (~0.3R*)
- Circumpolar?



Maggio et al (2000)

Eclipse mapping stellar coronae

- Binary system α Cr B
- G5V "solar analogue" (age ~10^8 years) + X-ray dark A0
- XMM-Newton observations during eclipse allow reconstruction of 2D image of coronal gas
- Discrete patches of emission at all latitudes
- Densities 10^9 - 3×10^{10} cm^{-3}



Güdel et al 2003