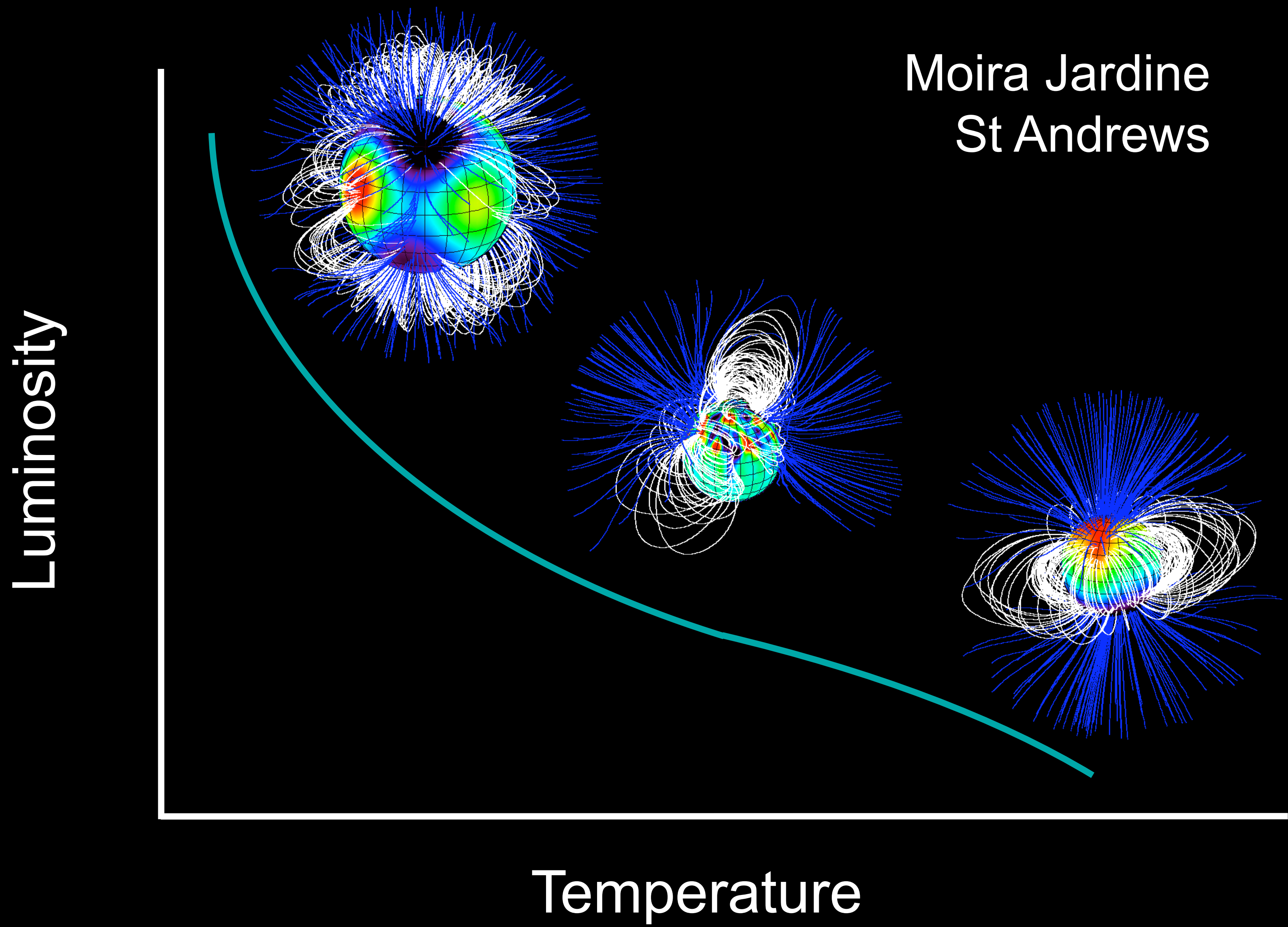
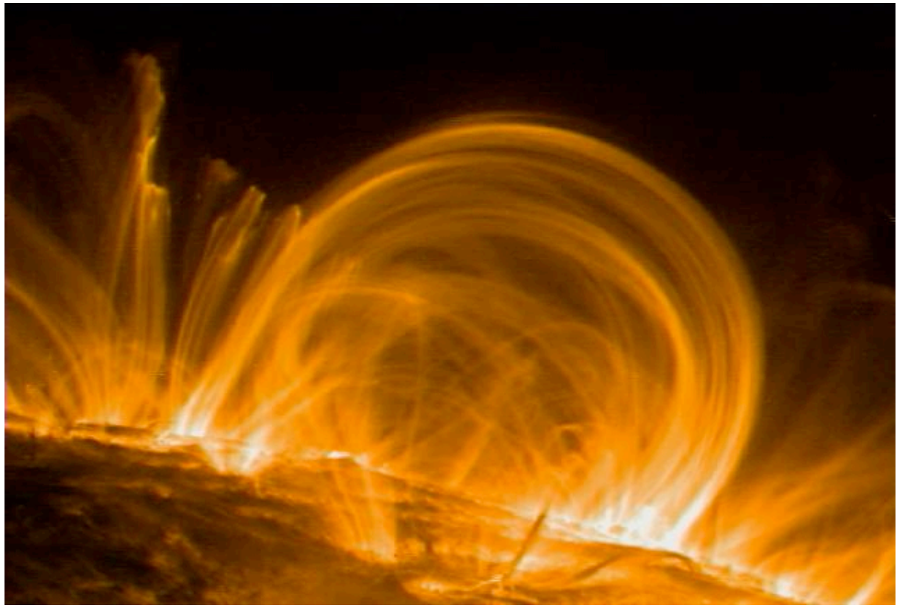
Stellar coronae

Moira Jardine
St Andrews



What do we mean by the term corona?

- White light (eclipse)
  - Scattering of optical photons off 10^6K electrons
  - Closed structures on scales of R_*
  - Magnetic cycle - interplanetary field resembles oscillating dipole (*Smith et al 2003*)

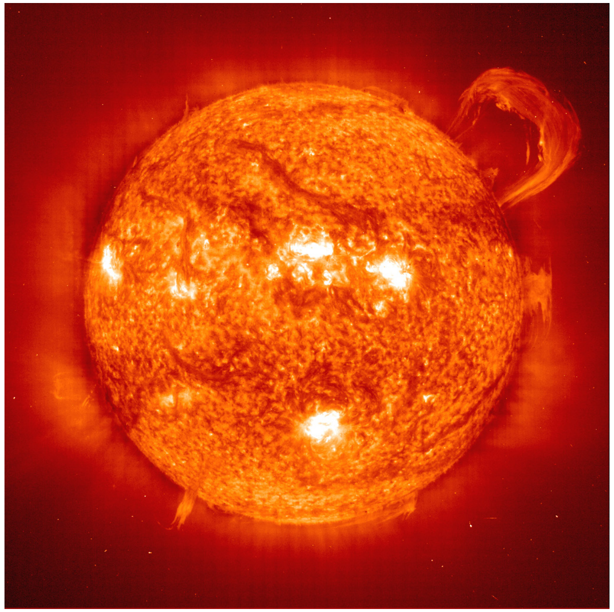


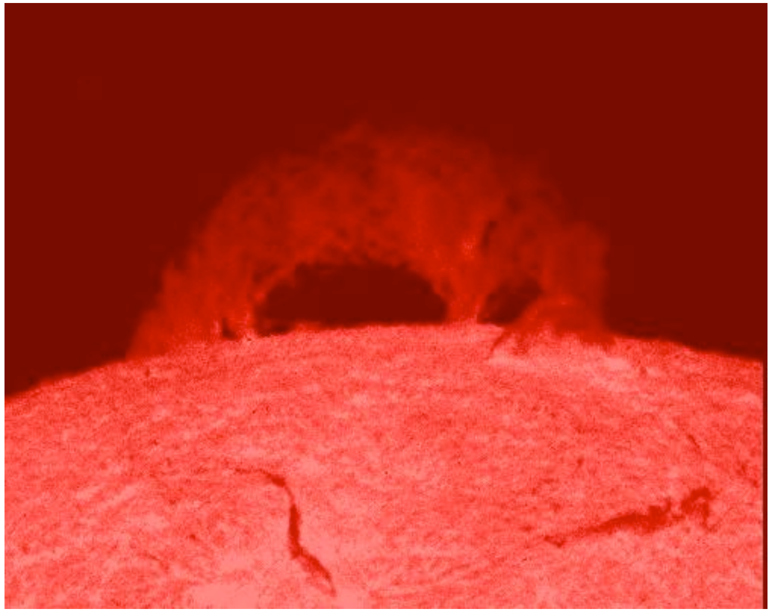
NASA: TRACE

- X-ray emission
  - Bremsstrahlung of 10^6K electrons
  - Closed structures on scales $<< R_*$
  - Cyclic variation

Solar Prominences

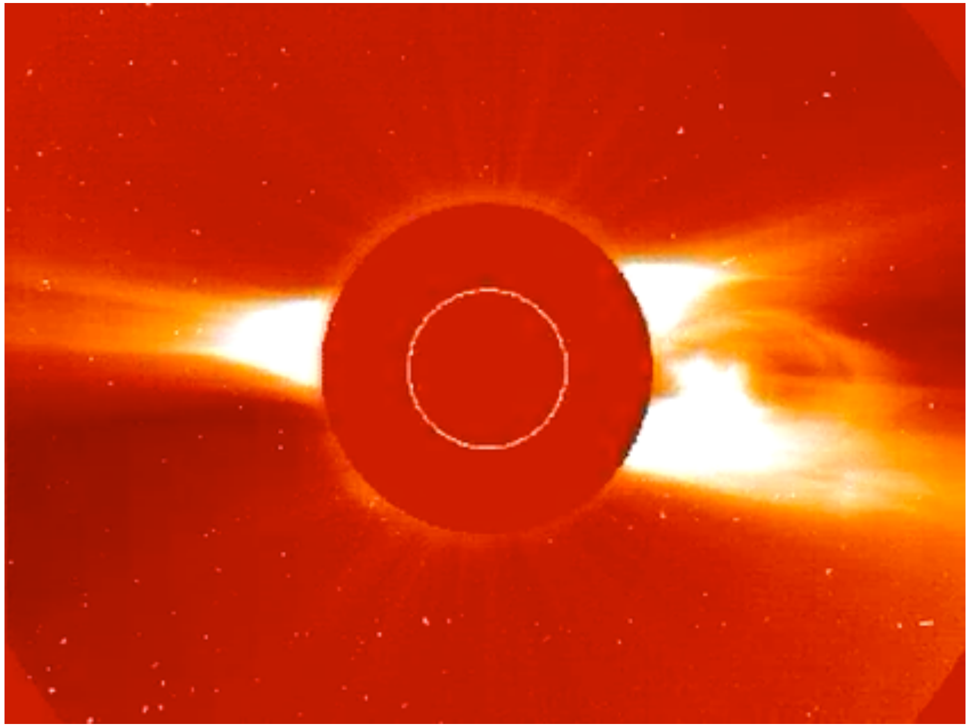
- Seen in $H\alpha$ as
  - absorption on the disk
  - emission off the limb





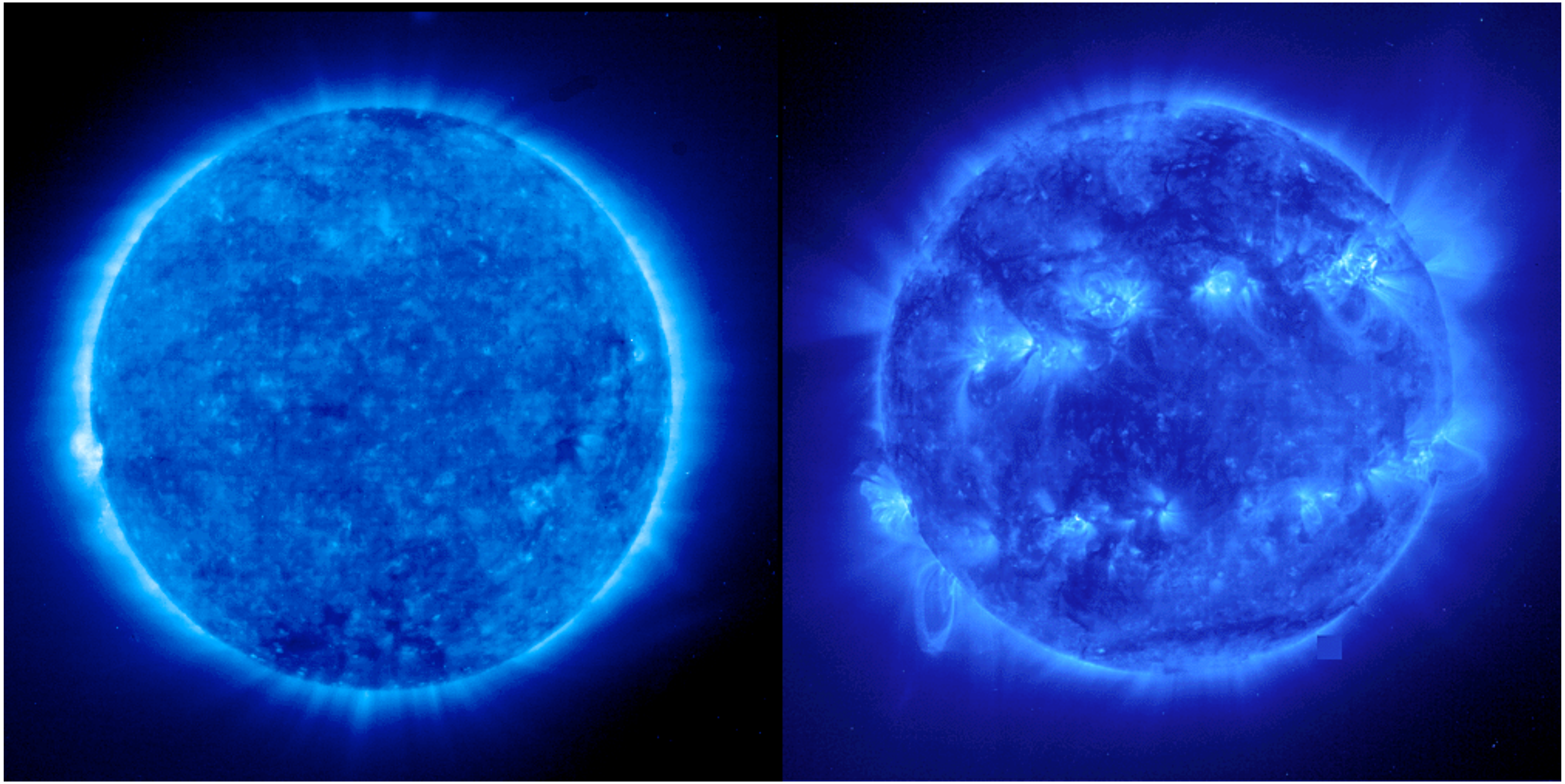
- Cool and dense implies
  - confinement and insulation by magnetic field

Coronal mass ejections



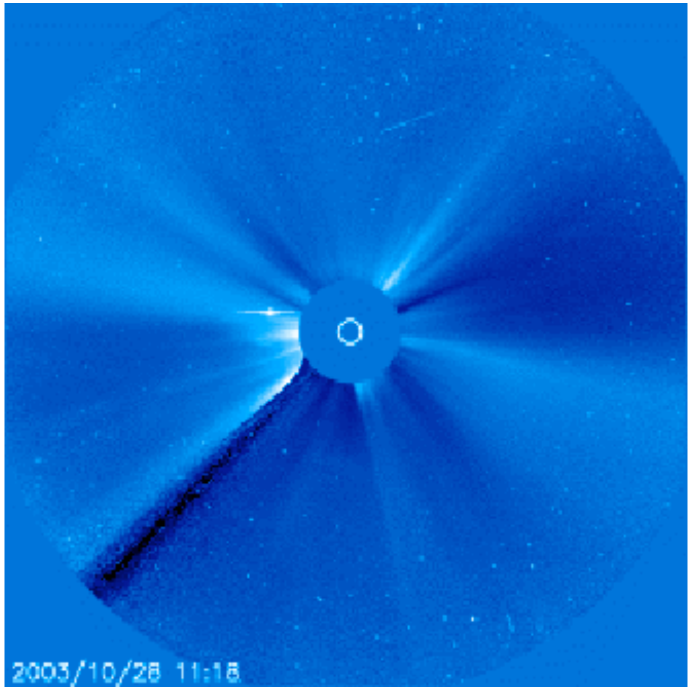
- Large-scale re-organisation of corona
- Note relation to spot belts

..bearing in mind that the Sun's activity varies over the cycle….



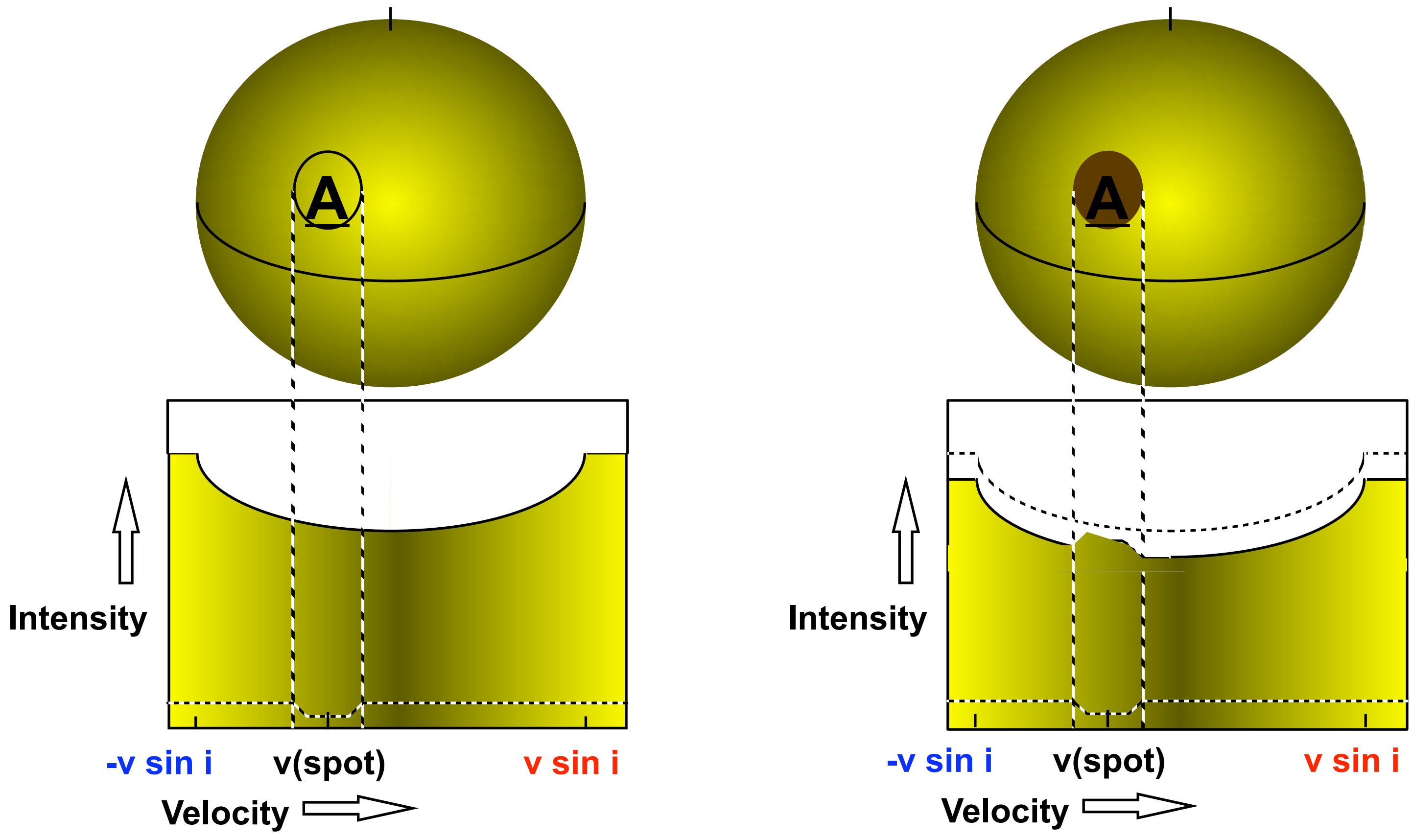
What is the impact on close-in planets?

- Stellar wind may
  - Erode planetary magnetosphere *(Griessmeier et al 2004, Stevens 2005)*
  - Lead to planetary orbital evolution *(Dobbs-Dixon 2004; Lovelace et al 2008)*
- Orbit of planet through stellar magnetosphere may
  - enhance stellar activity *(Shkolnik et al 2003, McIvor et al 2006, Saar et al 2006, Preusse et al 2007, Lanza 2008)*
  - Lead to orbital evolution (but too slow - *Papaloizou 2007*)



Both may induce radio emission *(Zarka, 2007; Jardine & Cameron 2008)*

Doppler Imaging: Basic Principles



How do we map magnetic fields?

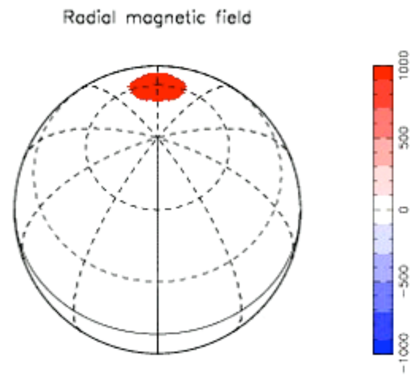
•In presence of magnetic field, lines split by Zeeman effect

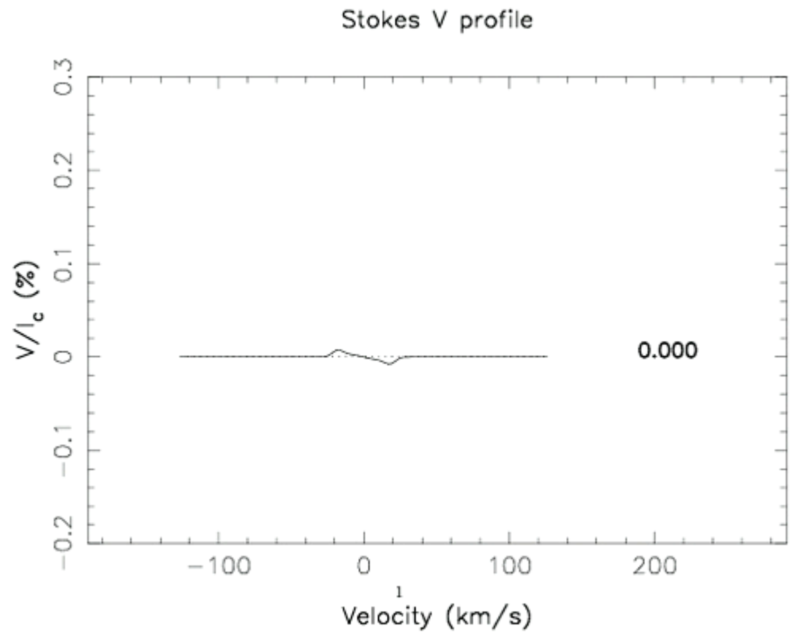
•Difference between left and right circularly polarised components is Stokes V

•Track Stokes V - get *line of sight* field

•Note max amplitude at disk centre

Radial field

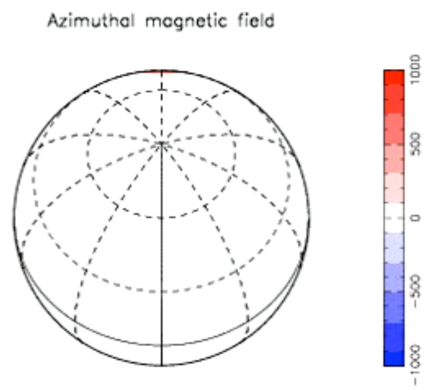


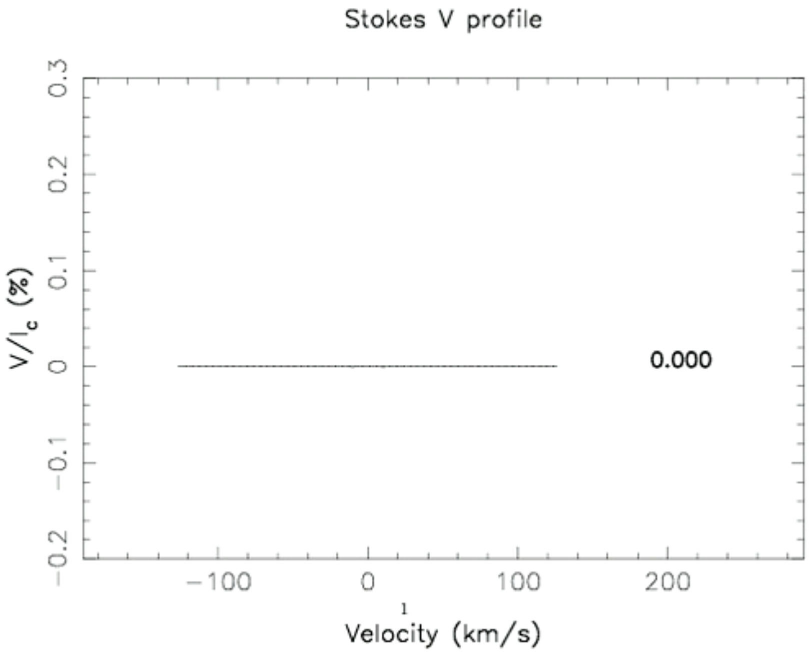


Azimuthal field

•Note max amplitude on the limb

•Note change of polarity at disk centre



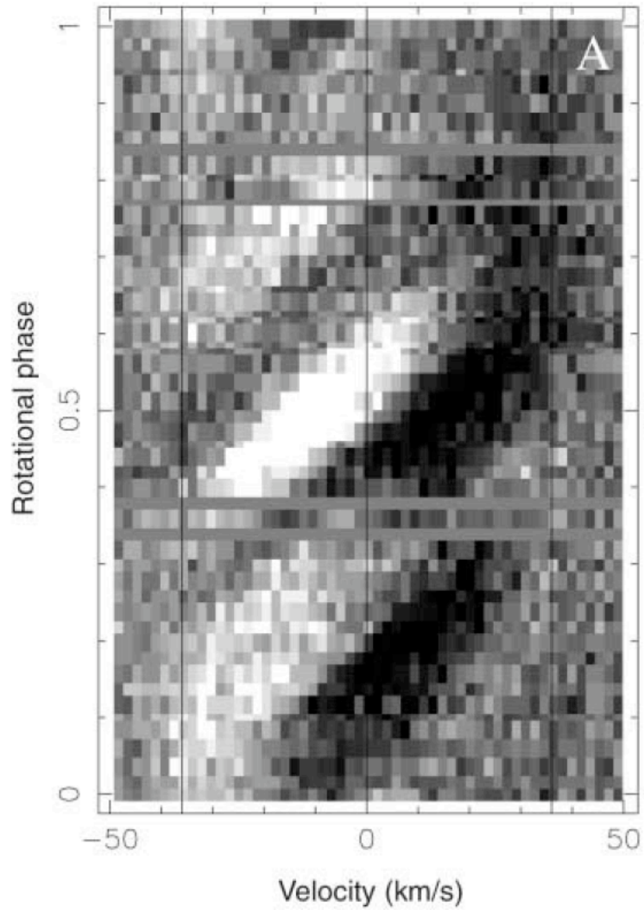


Imaging stellar magnetic fields

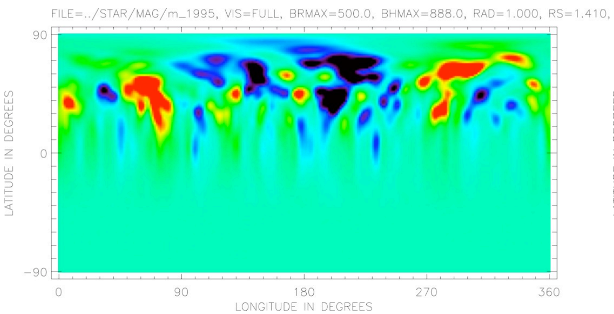
Fit Stokes profiles with spherical harmonics

$$
\begin{aligned}
B_r(\theta,\phi) &= -\sum_{\ell,m} \alpha_{\ell,m} Y_{\ell,m}(\theta,\phi) \\
B_\theta(\theta,\phi) &= -\sum_{\ell,m} (\beta_{\ell,m} Z_{\ell,m}(\theta,\phi) + \gamma_{\ell,m} X_{\ell,m}(\theta,\phi)) \\
B_\phi(\theta,\phi) &= -\sum_{\ell,m} (\beta_{\ell,m} X_{\ell,m}(\theta,\phi) - \gamma_{\ell,m} Z_{\ell,m}(\theta,\phi))
\end{aligned}
$$

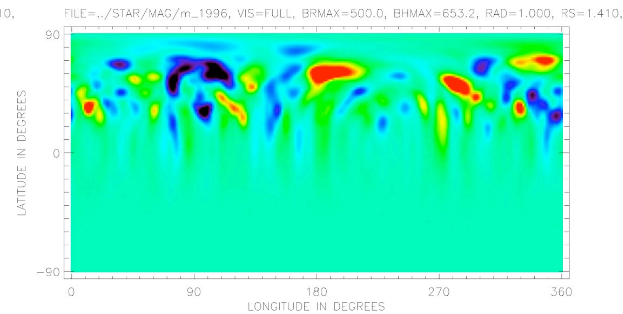
$\gamma_{l,m}$ = 0 for purely potential fields



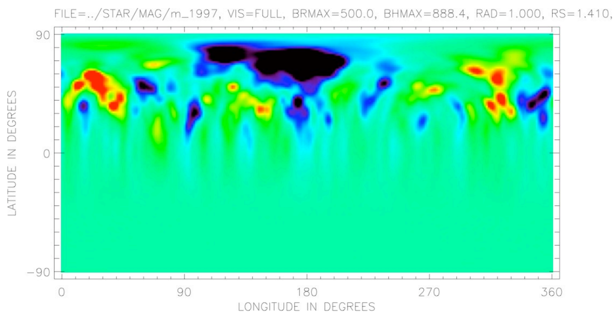
Stokes V



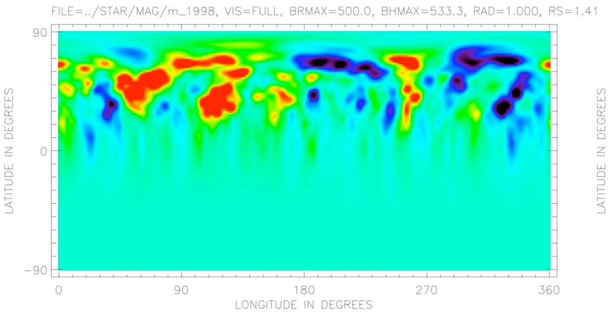
1995



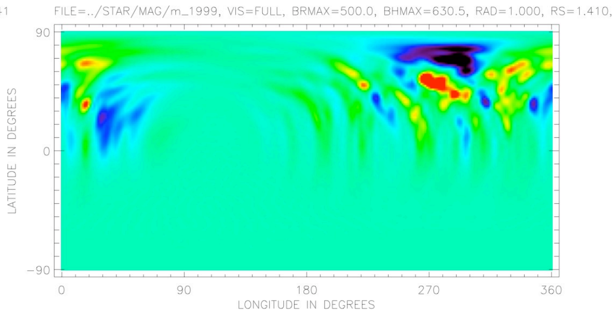
1996



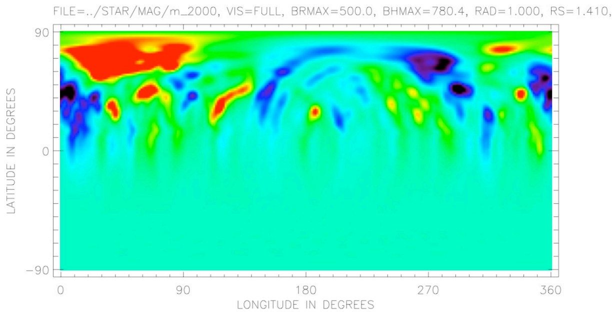
1997



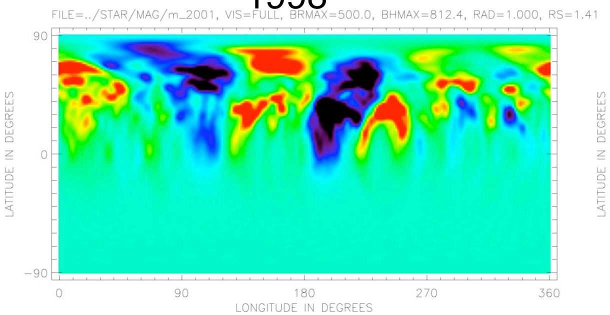
1998



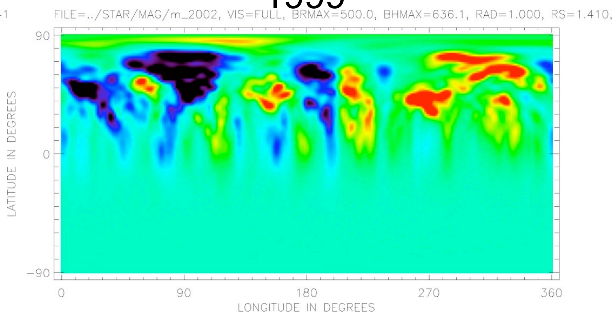
1999



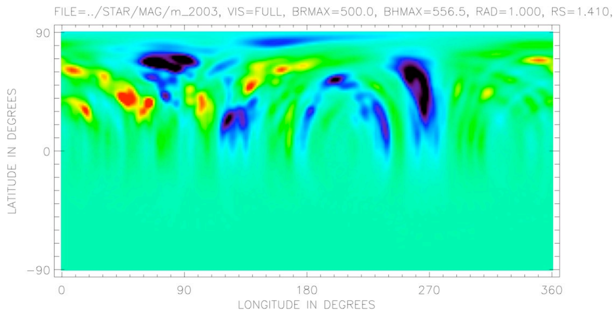
2000



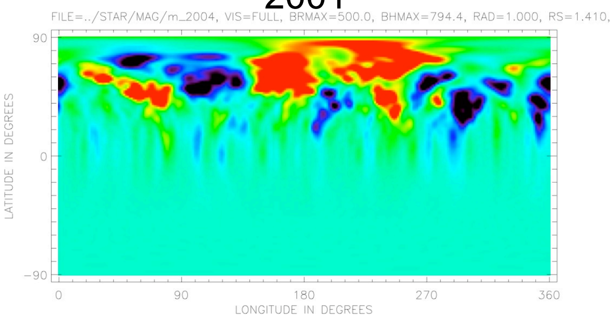
2001



2002



2003

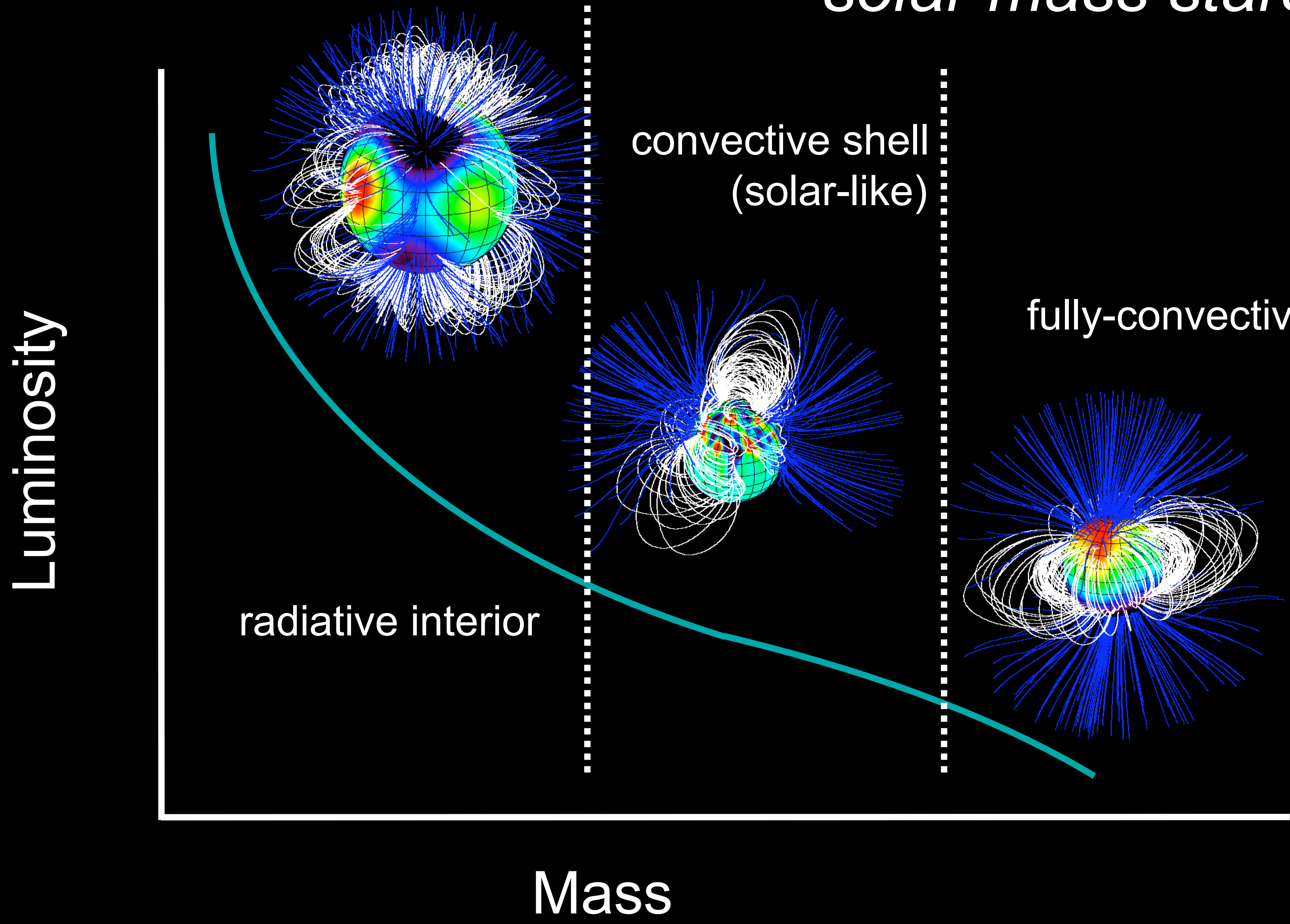


2004

AB Dor radial field from 1995 till 2004

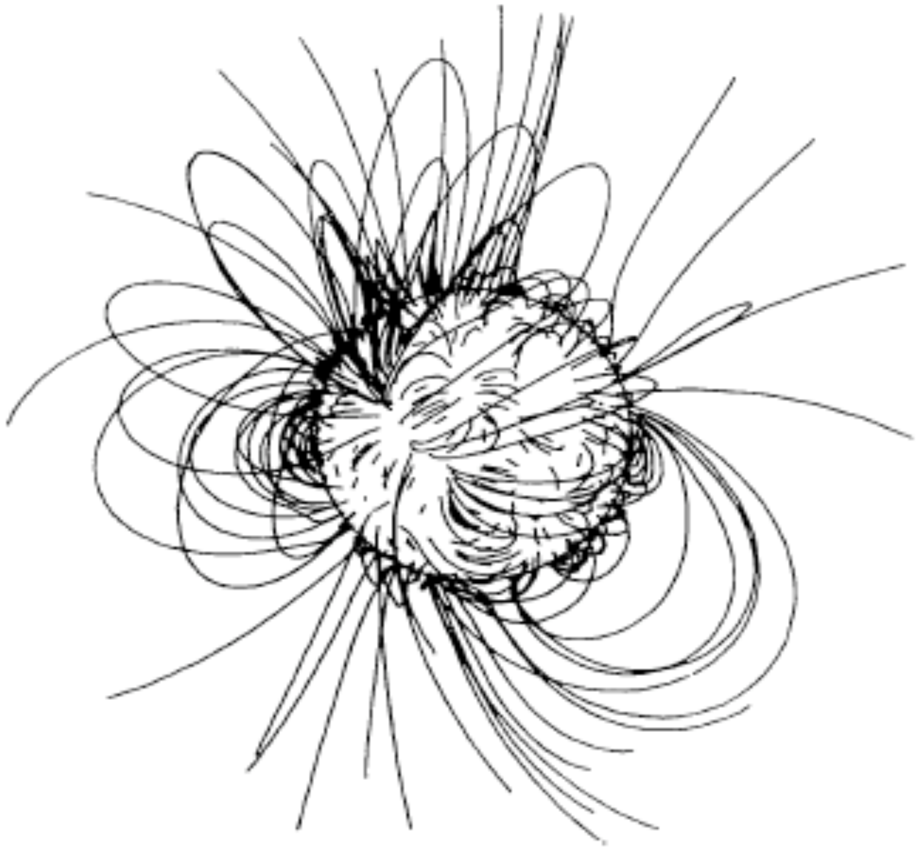
(Donati et al 1997,1999, 2003)

How do we determine coronal structure in solar mass stars?



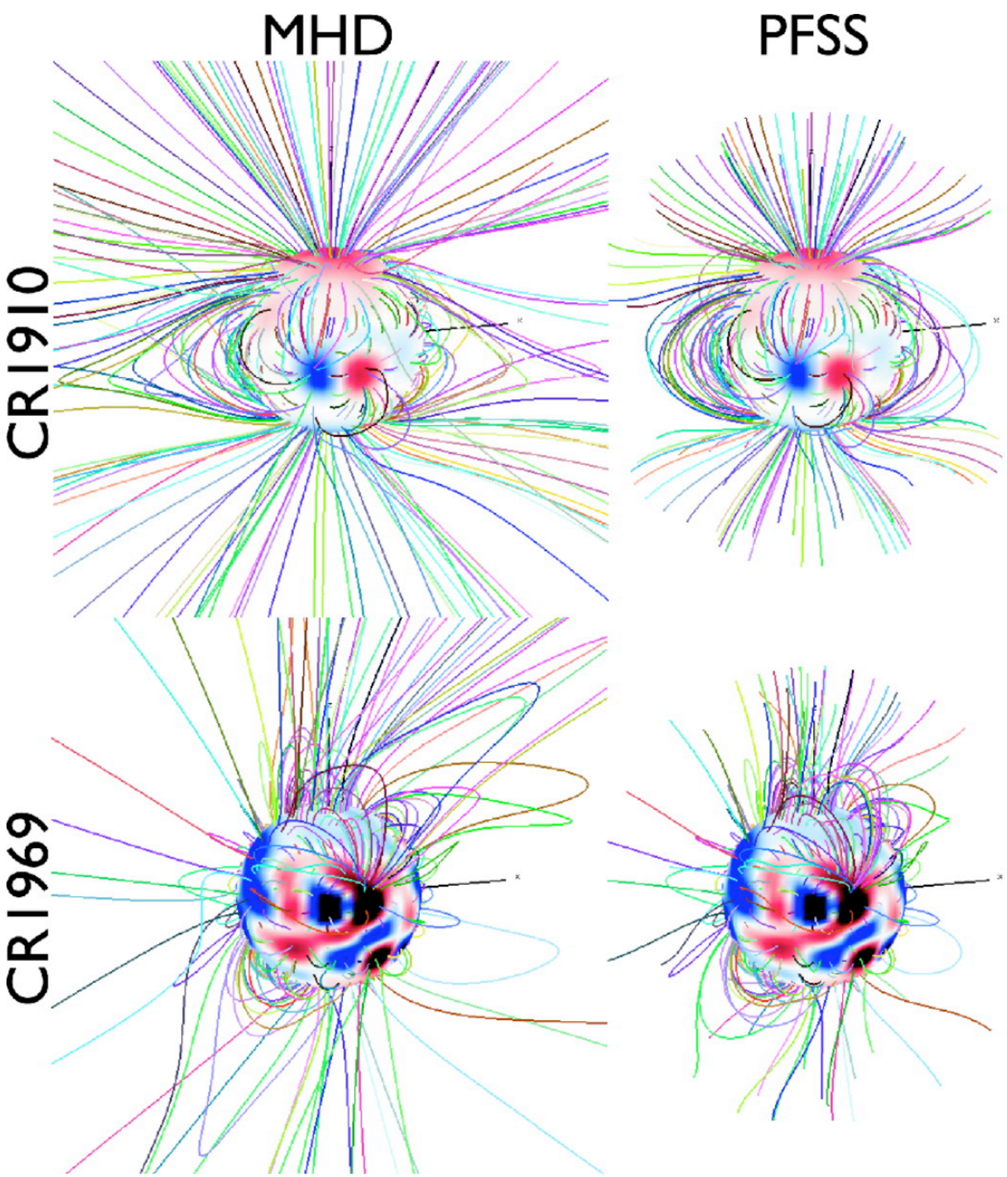
The shape of a stellar corona

- 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.



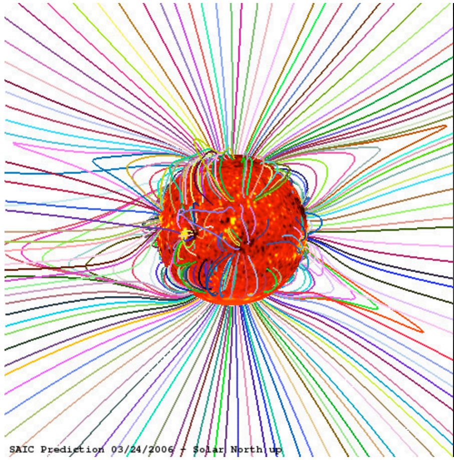
LONGITUDE OF DISK CENTER = 270 DEGREES

For the same surface fields, different “source surfaces” give different coronal fields.

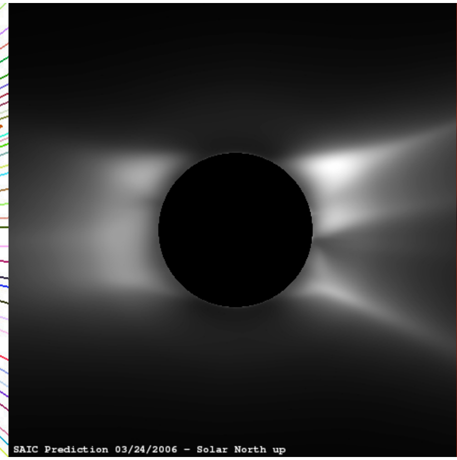


- Comparison between *potential field source surface* model and full MHD model is good for large scale structure *(Riley et al 2006)*

Comparison Between 3D MHD Model Prediction and Solar Eclipse Observation



Predicted Magnetic Field



Predicted Polarization Brightness

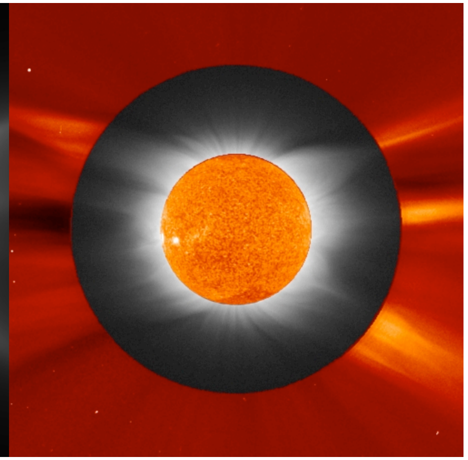
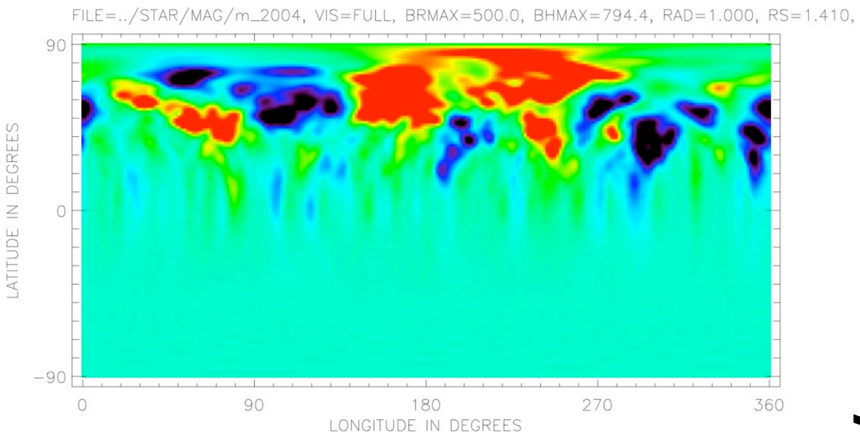


Image from Greece: Williams College Expedition*

http://imhd.net/corona/coronal_modeling.html

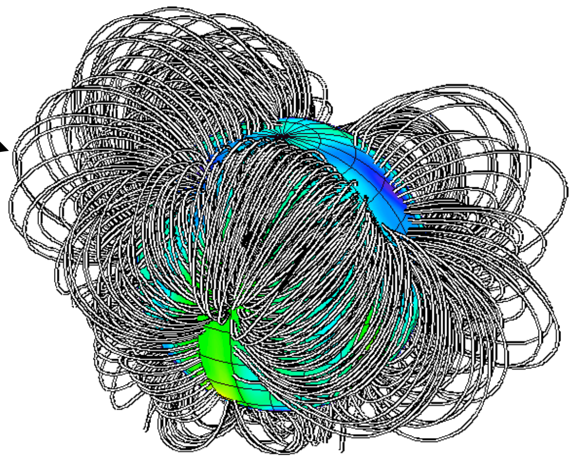
*Photo credit: The eclipse photo was taken by the Williams College Eclipse Expedition (Jay Pasachoff, Bryce Babcock, Steven Souza, Jesse Levitt, Megan Bruck, Shelby Kimmel, Paul Hess, Anna Tsykalova, and Amy Steele), with support from NSF/NASA/National Geographic.

How do we model stellar coronae?



Extrapolate surface field

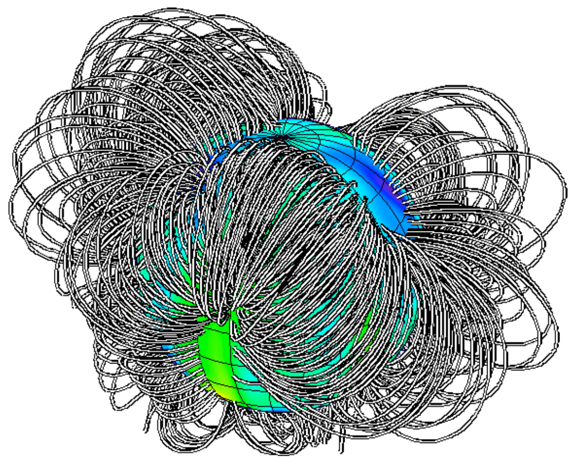
–*Potential Field Source Surface* model
(Altshuler & Newkirk 1969, Jardine et al, 1999)
–NB: extension to non-potential fields
(Hussain et al 2002)



Isothermal, hydrostatic corona

–(Jardine et al, 2002,Hussain et al 2007)

We can extrapolate the surface field…



Boundary conditions:

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

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

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

..and then determine the pressure structure…

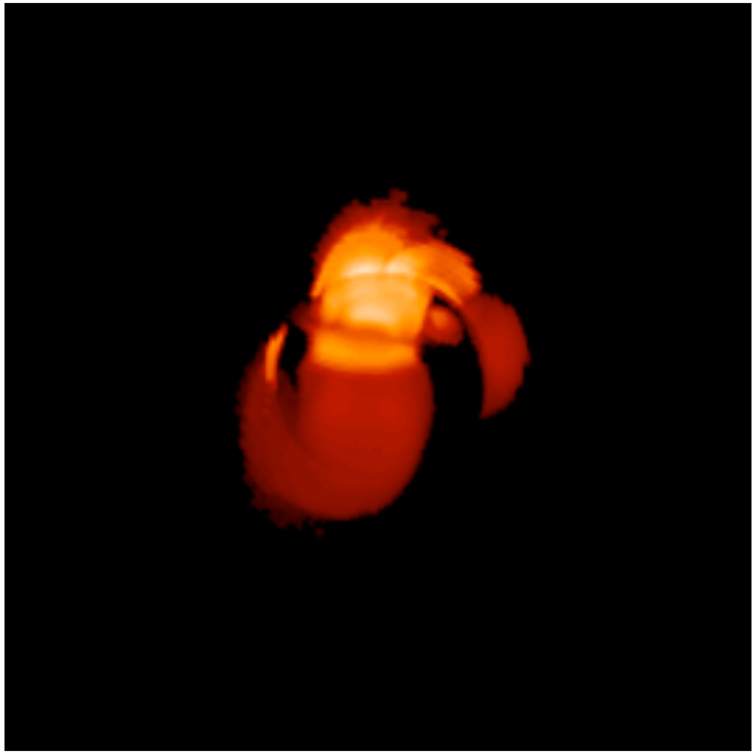
- Along each field line, assume a hydrostatic, isothermal gas at 10^6 or 10^7 K
- Base pressure $p_0 = K B_0^2$ (determine K by fitting to observed X-ray emission measure)
  – Hence for a stellar rotation rate ω:

$$p = p_0 e^{\frac{m}{kT}\int g_{\|} ds} \quad \text{and}$$

$$g(r,\vartheta) = \left(\frac{-GM_*}{r^2} + \omega^2 r \sin^2\vartheta\right)\hat{\mathbf{r}} + \left(\omega^2 r \sin\vartheta \cos\vartheta\right)\hat{\boldsymbol{\vartheta}}$$

- p = 0 if
  – field lines are open or $p > B^2/2\mu$
- Emissivity $\propto n_e^2$

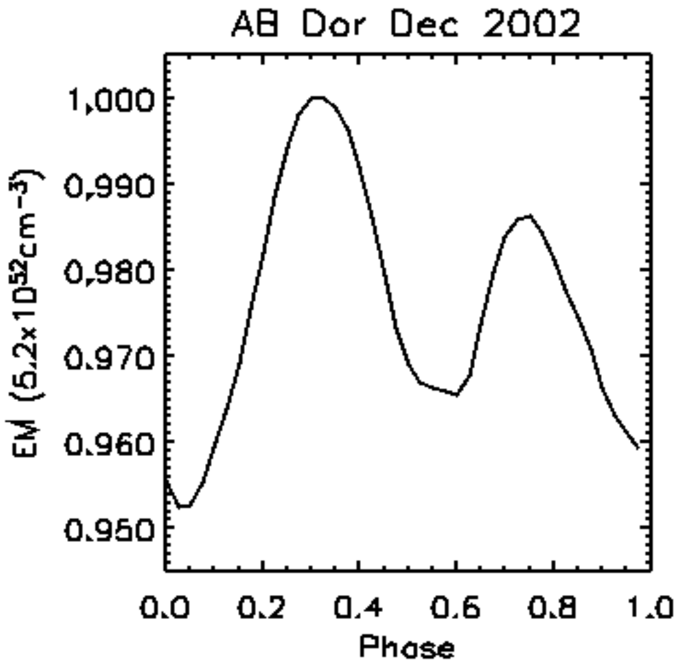
AB Dor, Dec 2002



- Emission measure ~ 10^{52} cm $^{-3}$
- Density: 0.6×10^{10}cm^{-3}

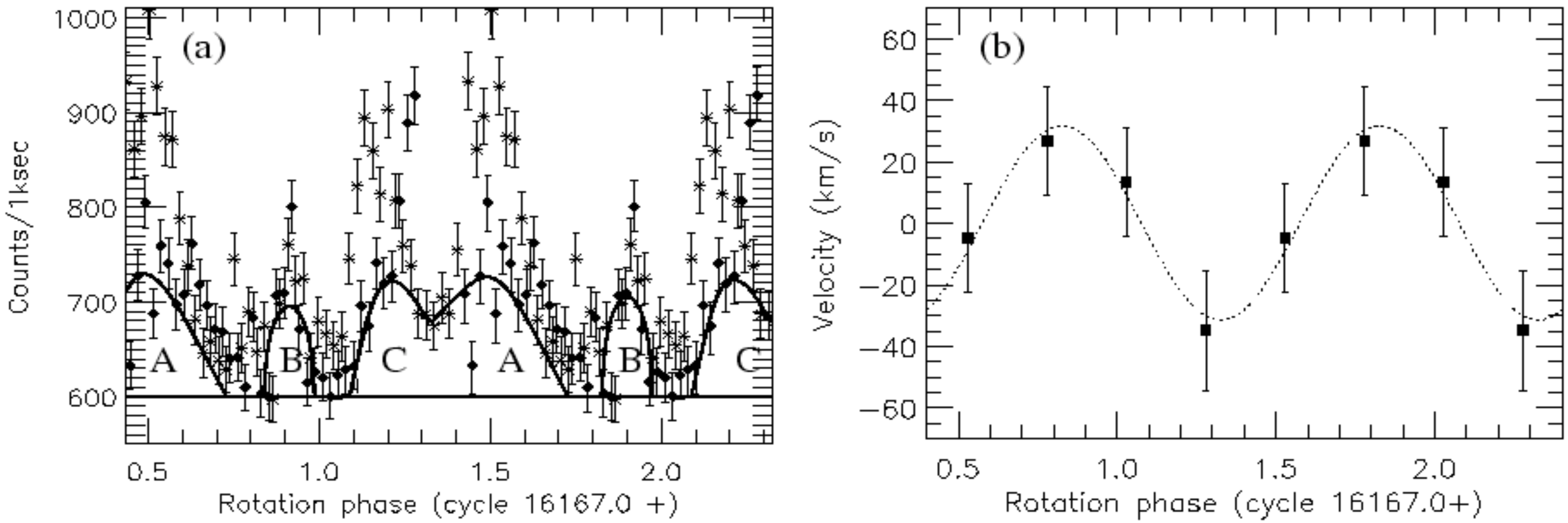
$$\overline{n_e} = \frac{\int n_e^3 dV}{\int n_e^2 dV}$$

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



..and compare with simultaneous X-ray observations…

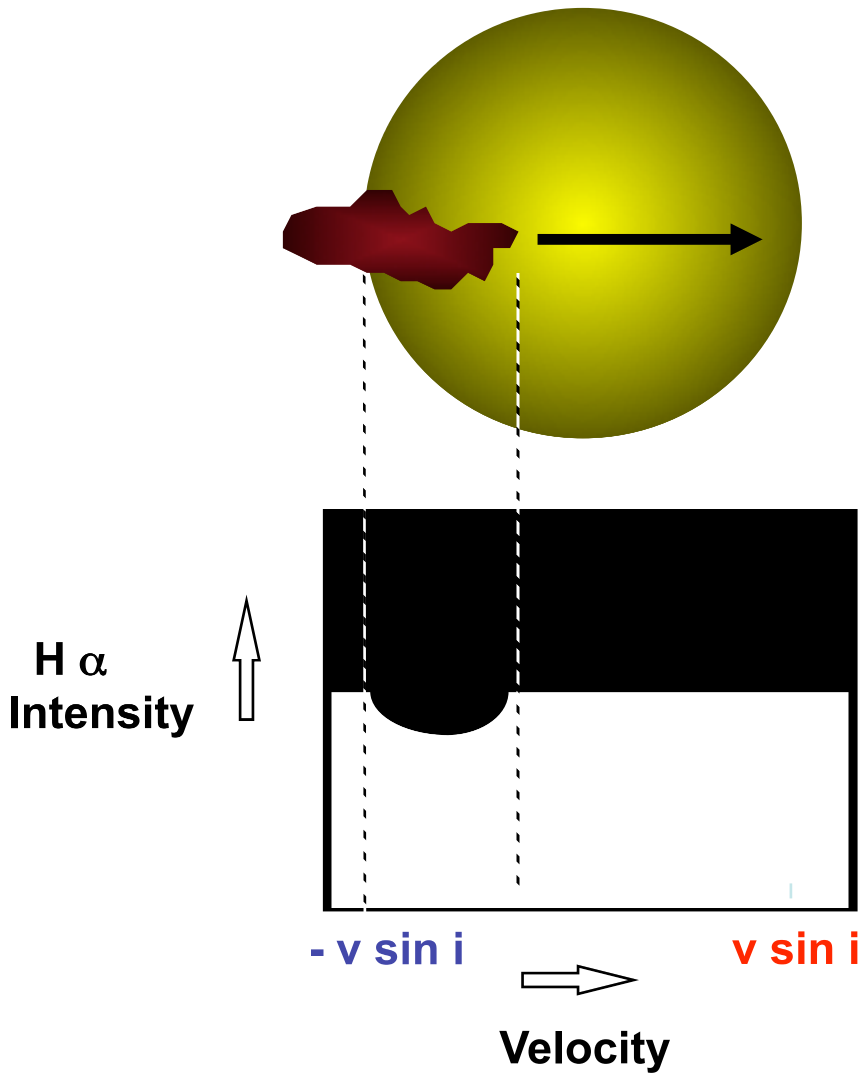
- Coordinated simultaneous observations with:
  - AAT/CTIO to obtain (Zeeman)-Doppler images (Cameron, Donati, Hussain)
  - Chandra (X-ray coronal spectrum: Hussain)

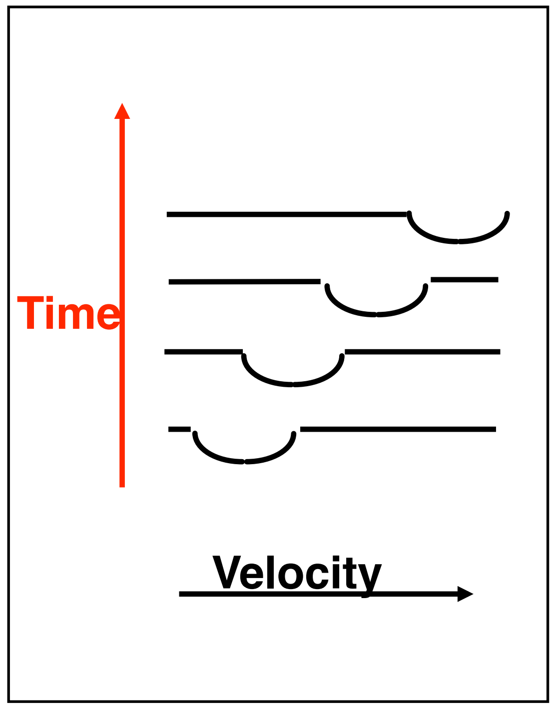


Hussain et al 2004, ApJ

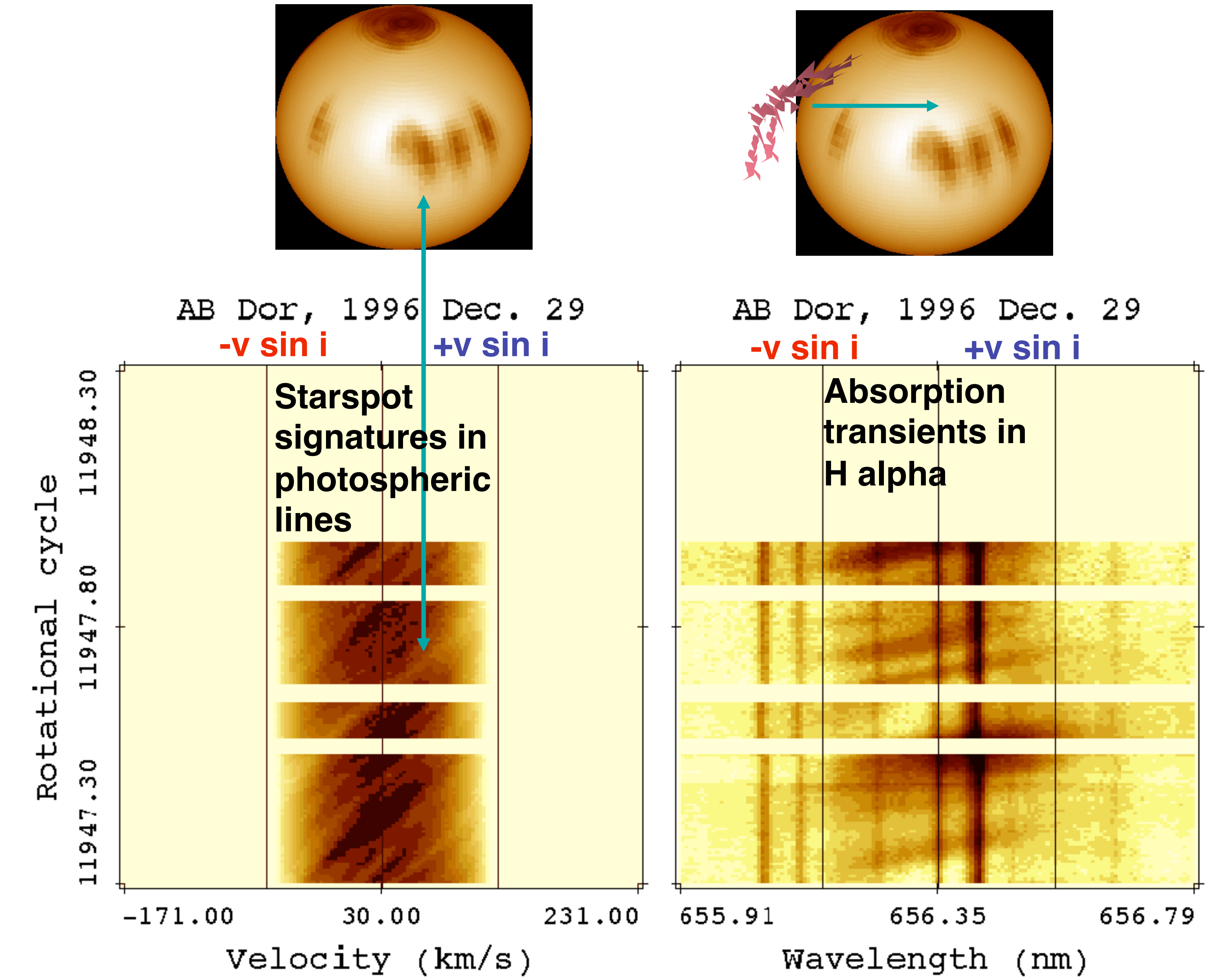
We can also observe stellar prominences….

Absorption dips move through Hα profile as prominence crosses the disk.

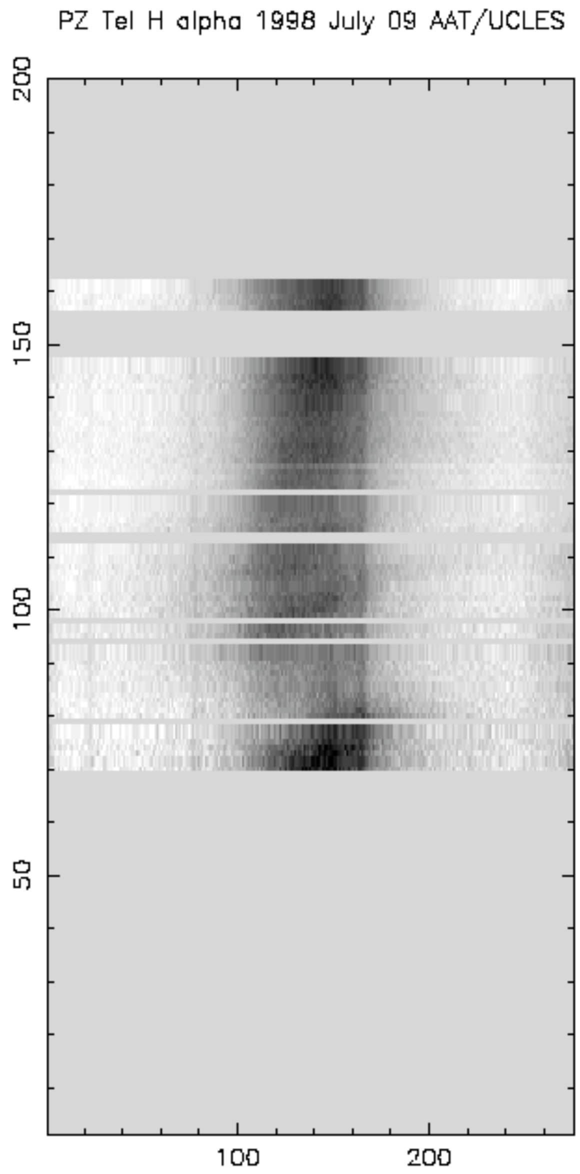




Spots and prominences



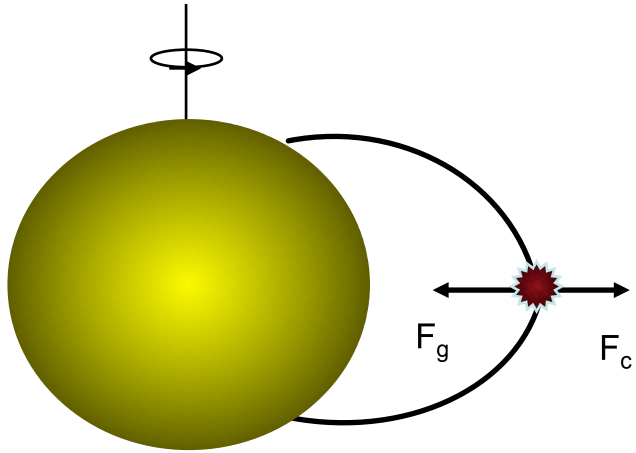
- Prominences are detected in 90% of young (pre-) main sequence stars with P_{rot}<1 day
  - AB Dor (K0V): *(Collier Cameron &Robinson 1989)*
  - HD 197890 ="Speedy Mic" (K0V): *(Jeffries 1993)*
  - 4 G dwarfs in α Per cluster: *(Collier Cameron & Woods 1992)*
  - HK Aqr = Gl 890 (M1V): *(Byrne, Eibe & Rolleston 1996)*
  - RE J1816+541: *(Eibe 1998)*
  - PZ Tel: *(Barnes et al 2000)* (right) P_{rot} = 1 day (slowest yet)
  - Pre-main sequence G star RX J1508.6-4423 *(Donati et al 2000)* -- prominences in emission!



Prominence Characteristics for AB Dor

- Formation site: co-rotation radius (gravity balances centrifugal forces)
- Areas: 3×10^{21} cm^2
- Column densities: 10^{20}cm^{-2}
- Masses: 2-6 x 10^{17} g (cf solar quiescent prominences M ~ 10^{15} g)
- Temperatures: 8000-9000K
- Number: about 6 in observable hemisphere
- Co-rotation enforced out to about $5R_*$

Why do prominences form at the co-rotation radius?



Force balance: $\underline{\nabla} p = \underline{\boldsymbol{j}} \times \underline{\boldsymbol{B}} + \rho \underline{\boldsymbol{g}}$

(zero along the field)

On the equator $g(r) = -\frac{GM_*}{r^2} + \omega^2 r$

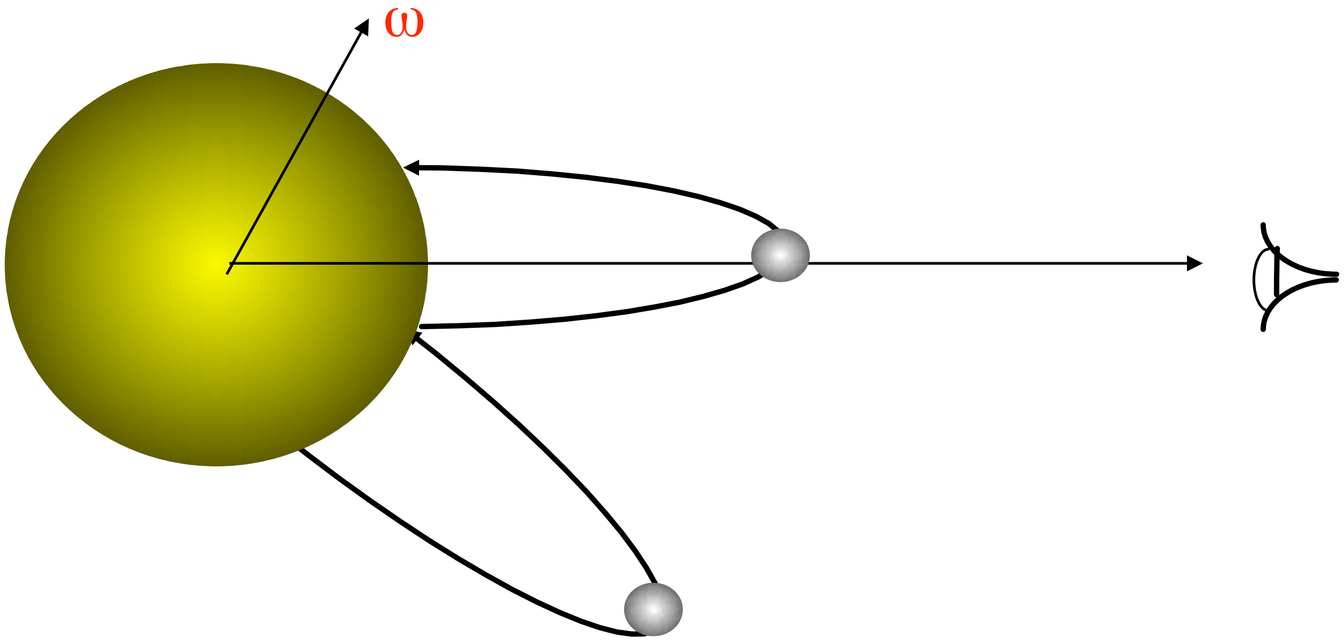
g=0 at the co-rotation radius $r_K = \left(\frac{GM_*}{\omega^2}\right)^{1/3}$

beyond this, pressure and density rise

$$p = p_0 \exp\left\{ {}^{m}\!/_{kT} \int g(r)\,dr \right\}$$

What can we learn from prominences?

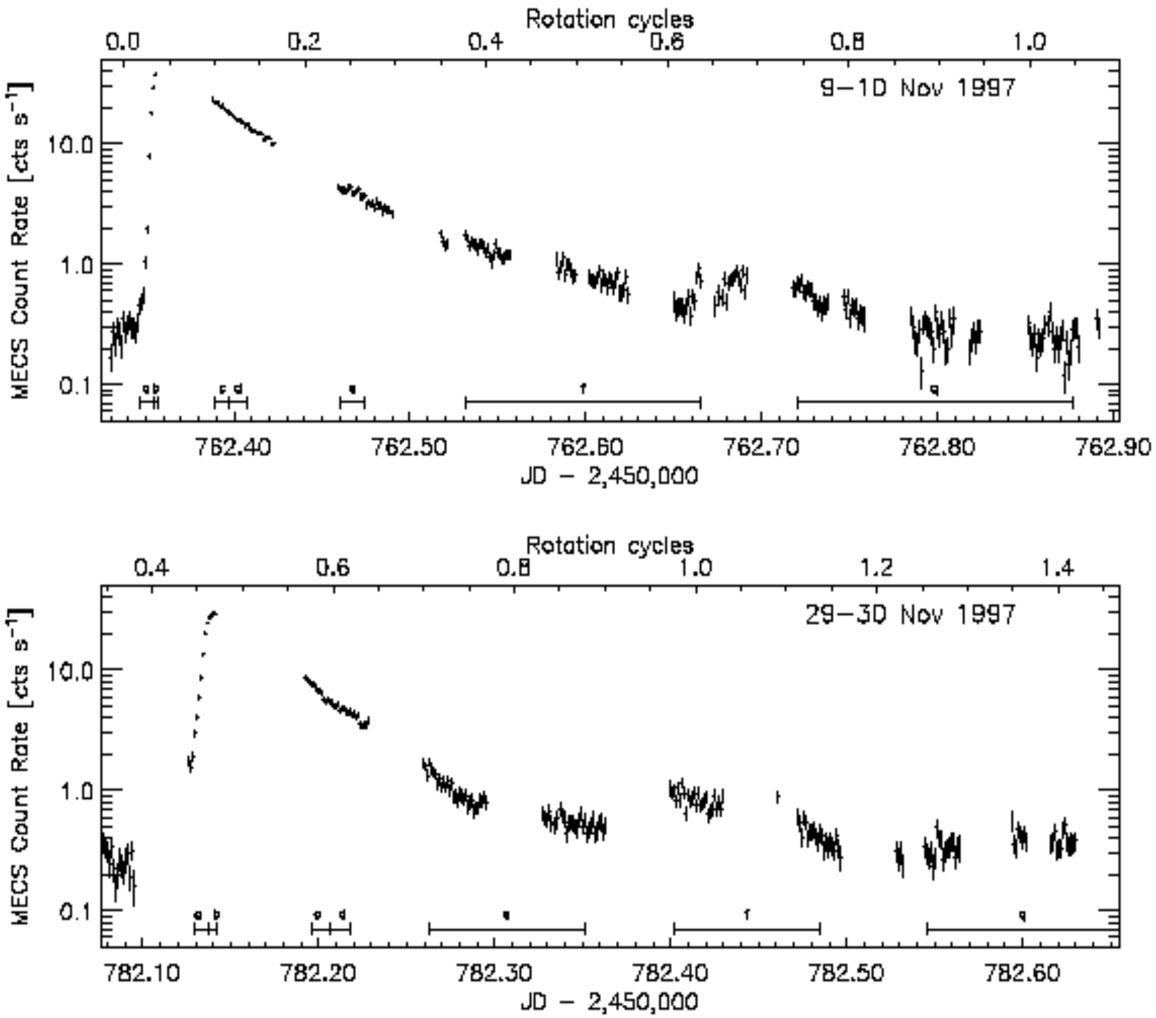
- The number and distribution of prominences tells us about the degree of field complexity



- Modelling is in its infancy! *(Collier Cameron 1988, Jardine & Collier Cameron 1991, Ferreira & Jardine 1995, van den Oord & Zuccarello 1996, Unruh & Jardine 1997, Ferreira & Mendoza-Briceno 1997, Ferreira 2000, Jardine & van Ballegooijen 2006)*

The amazing unobscured flares

- 1997 BeppoSAX observations of AB Dor: flare decay time (~ 14h) > 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?

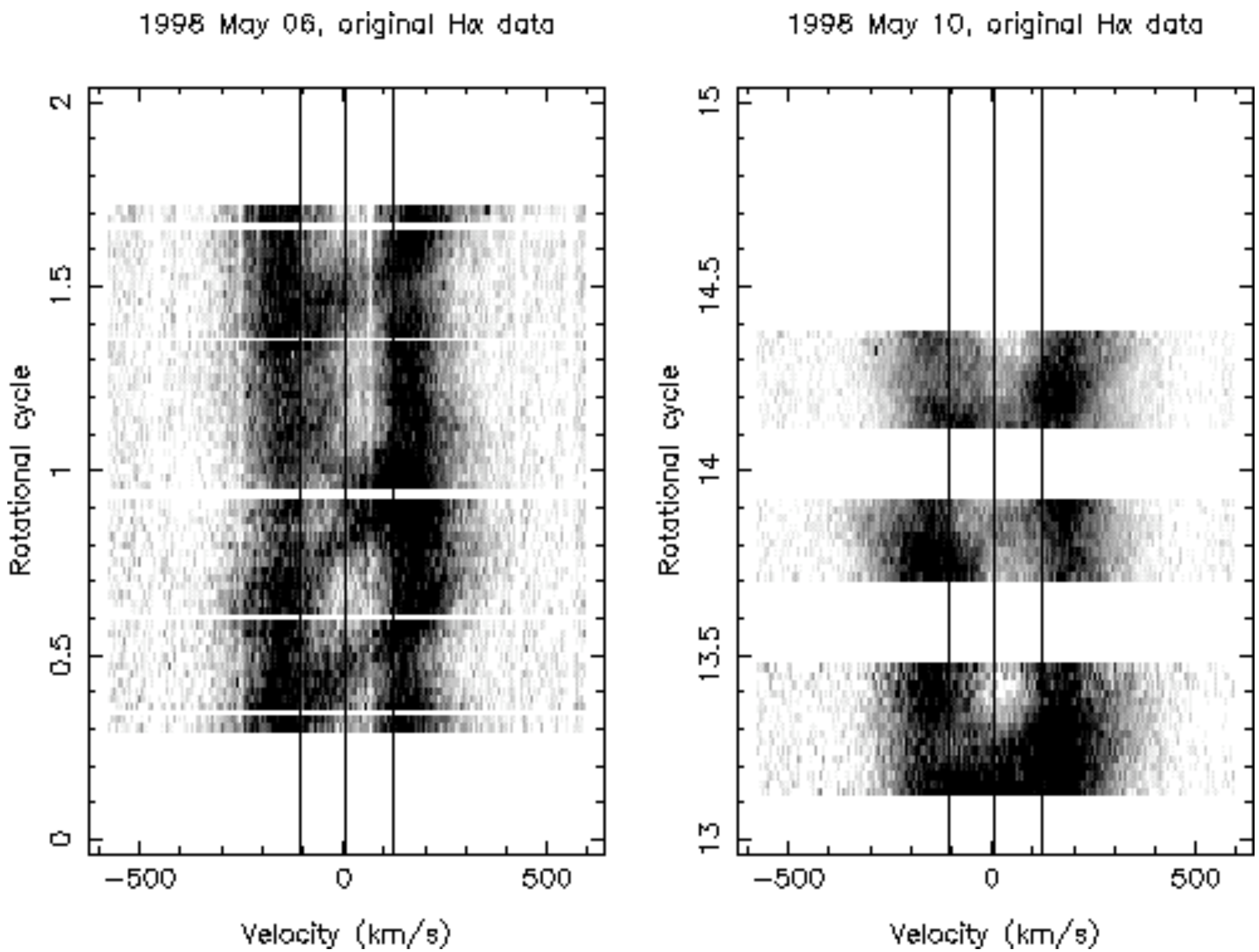


Maggio et al (2000)

Prominences seen in emission off the limb…

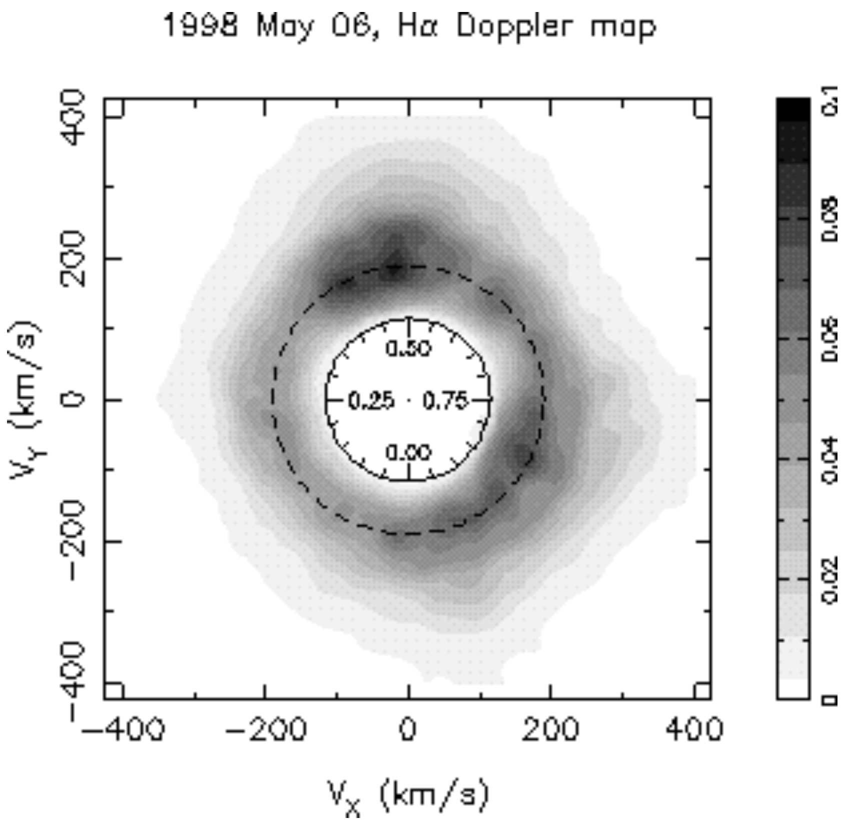
RX J1508.6 -4423
(Donati et al 2000):

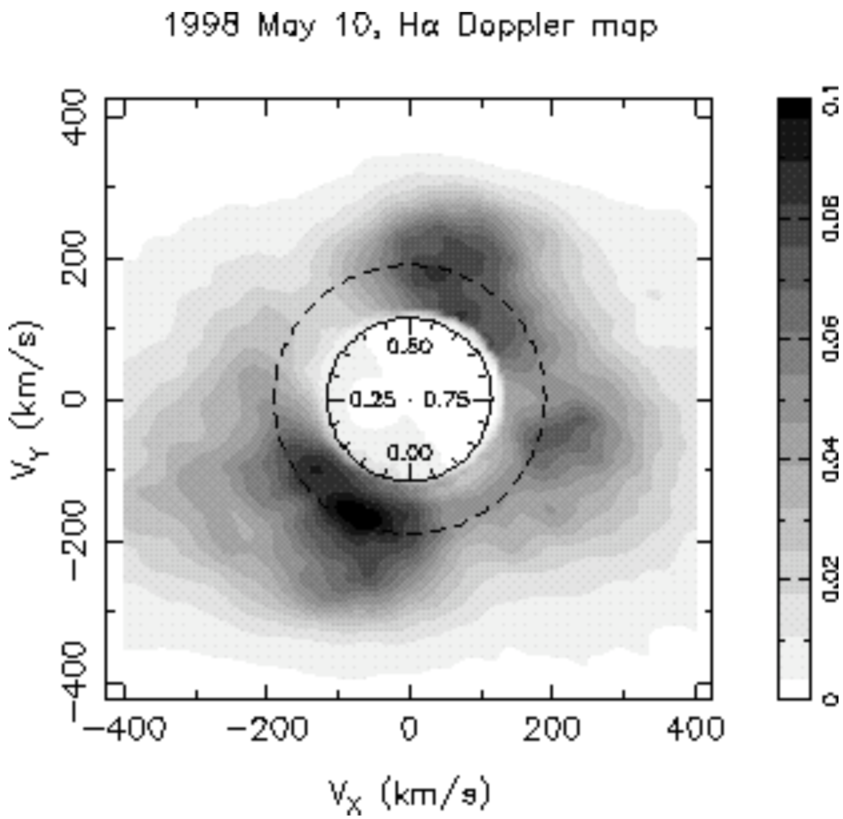
Star is viewed at low inclination; uneclipsed Hα-emitting clouds trace out sinusoids



Tomographic back-projection

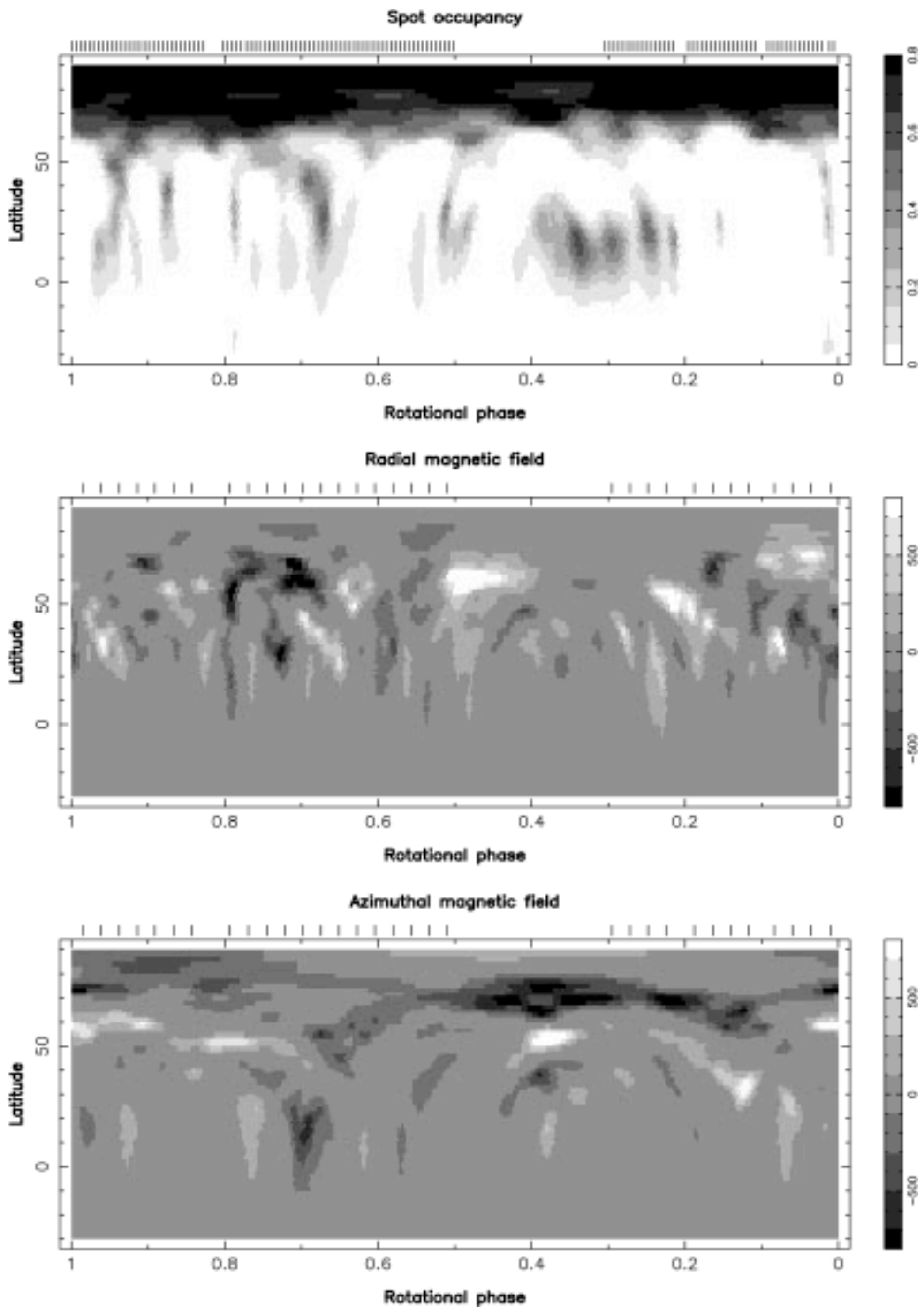
- Clouds congregate near co-rotation radius (dotted).
- Little evidence of material inside co-rotation radius.
- Substantial evolution of gas distribution over 4 nights.





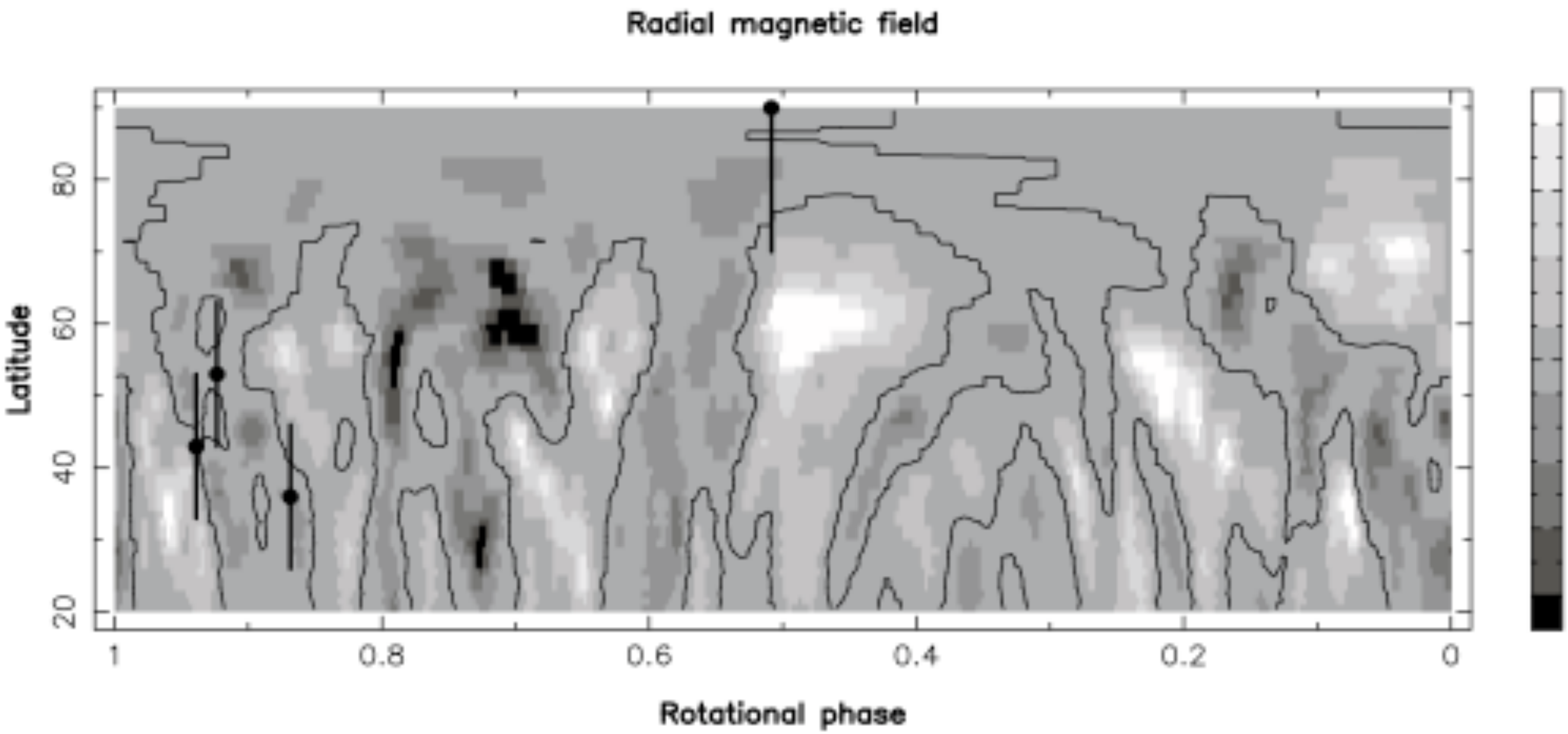
Prominence positions

- (Zeeman)-Doppler images of AB Dor in 1996 Dec *(Donati et al 99)*
- Tick marks show rotation phases observed
- Where were the prominences?



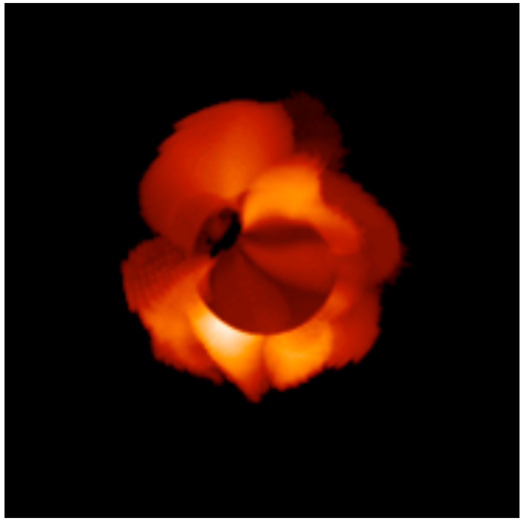
Pin the tail on the donkey

- Black dots show prominence positions
- Contour shows neutral polarity line
- Are the prominence locations related to neutral lines?



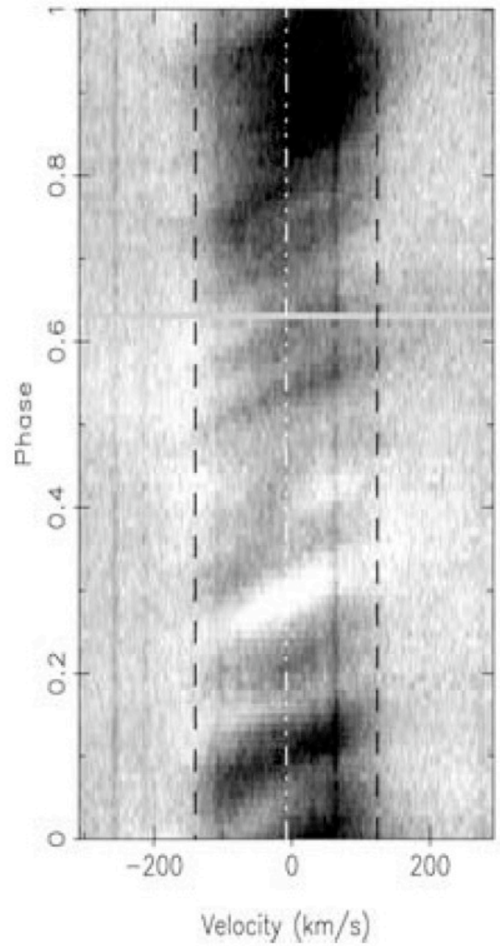
How extended are the coronae of active stars?

- High densities imply compact coronae
  - 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)

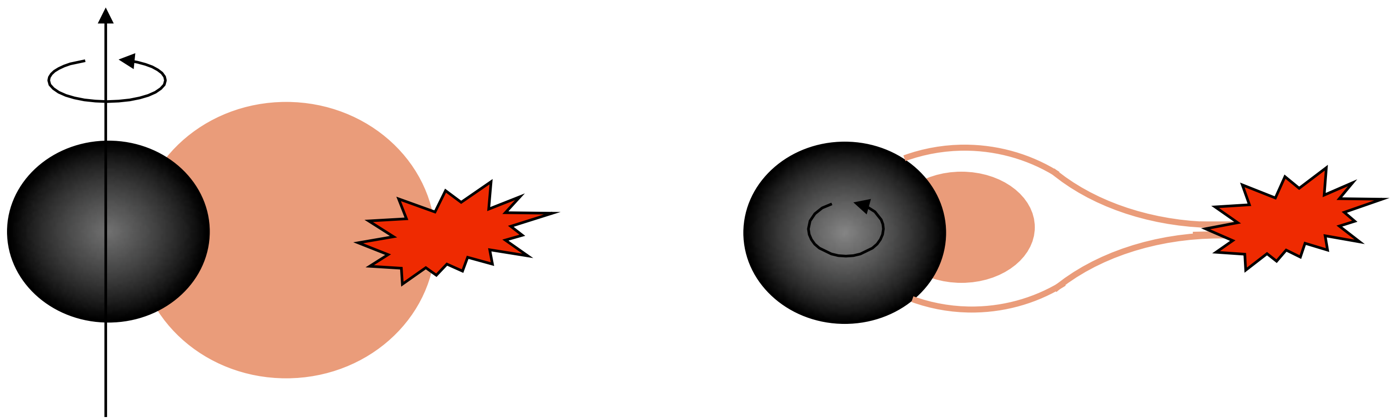


Jardine et al (2002)

- But…. prominences co-rotating out to 3-6 R* imply extended coronae
  - Cool clouds of neutral hydrogen observed as moving absorption features in Hα

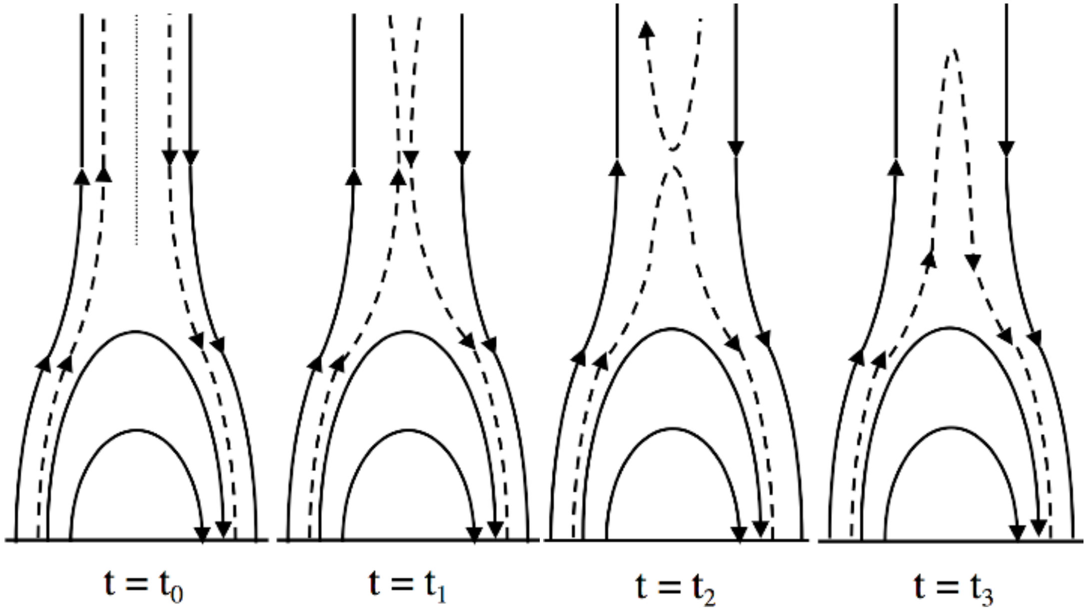


- *Do the prominences lie in the X-ray emitting corona or in the wind?*



Blowin' in the wind

- Current sheet above helmet streamers can reconnect
- Stellar wind blows until back-pressure builds up
- New long thin loop has max height determined by the co-rotation radius R_k

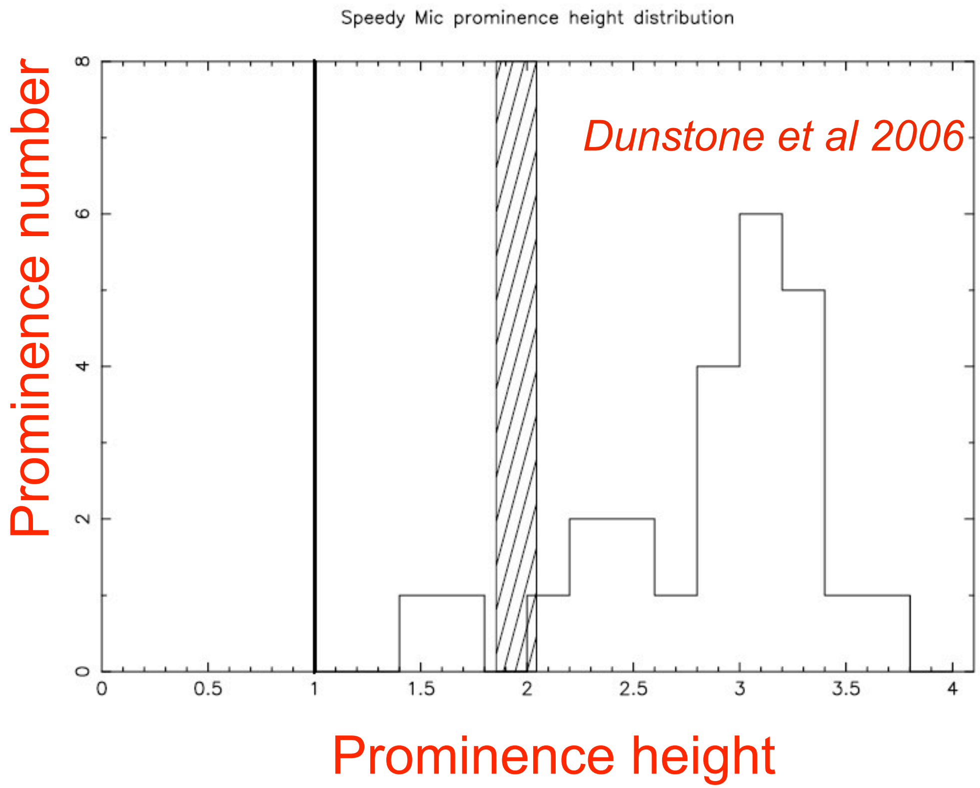


$$\frac{y_m}{R_*} = \frac{1}{2}\left\{-1 + \sqrt{\left[1 + 8\left(\frac{R_k}{R_*}\right)^3\right]}\right\}$$

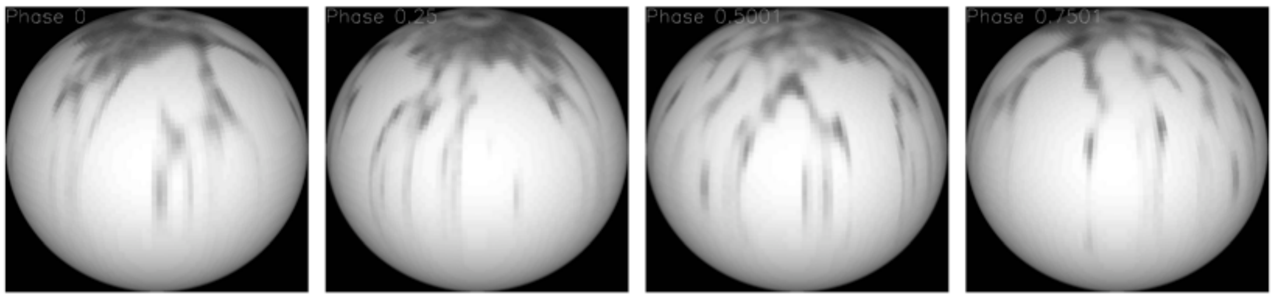
Jardine & van Ballegooijen 2006

How does this compare with observations?

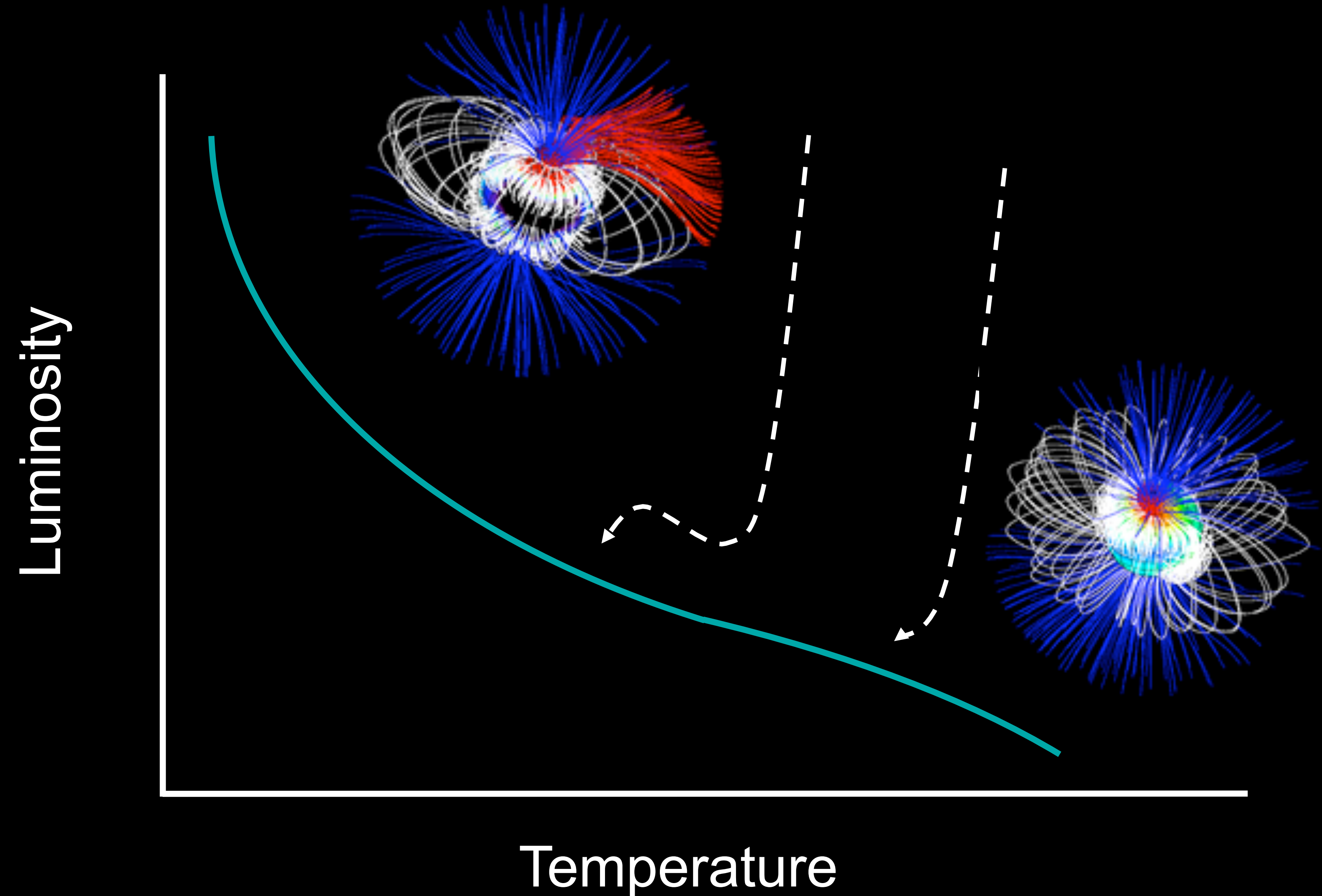
- Speedy Mic (P_{rot}=0.38 d)
- Highly structured
  - Surface brightness (spots)
  - X-ray corona *(Wolter et al 2008)*
- 25 prominences in total
- Calculated max height of 3.4R*

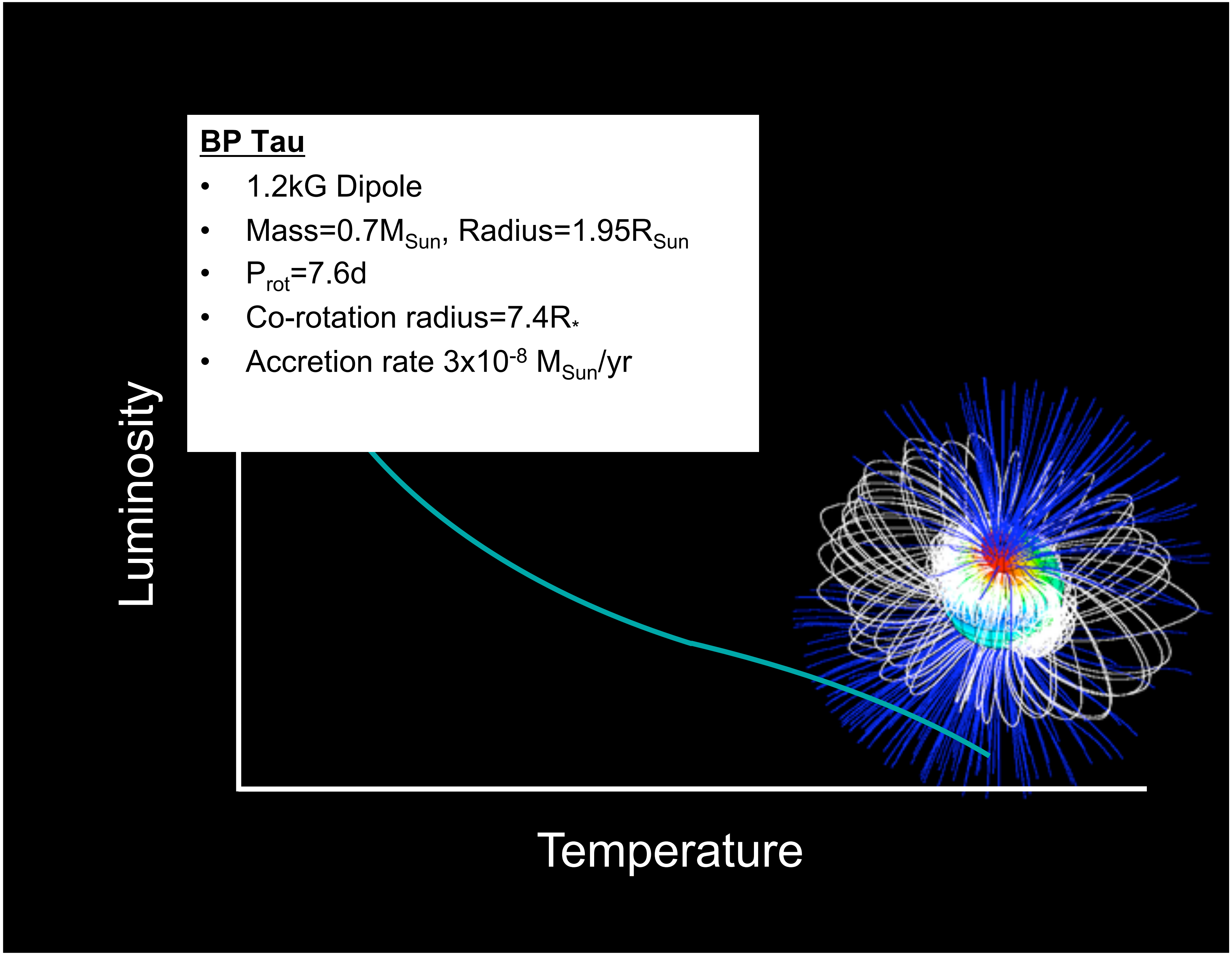


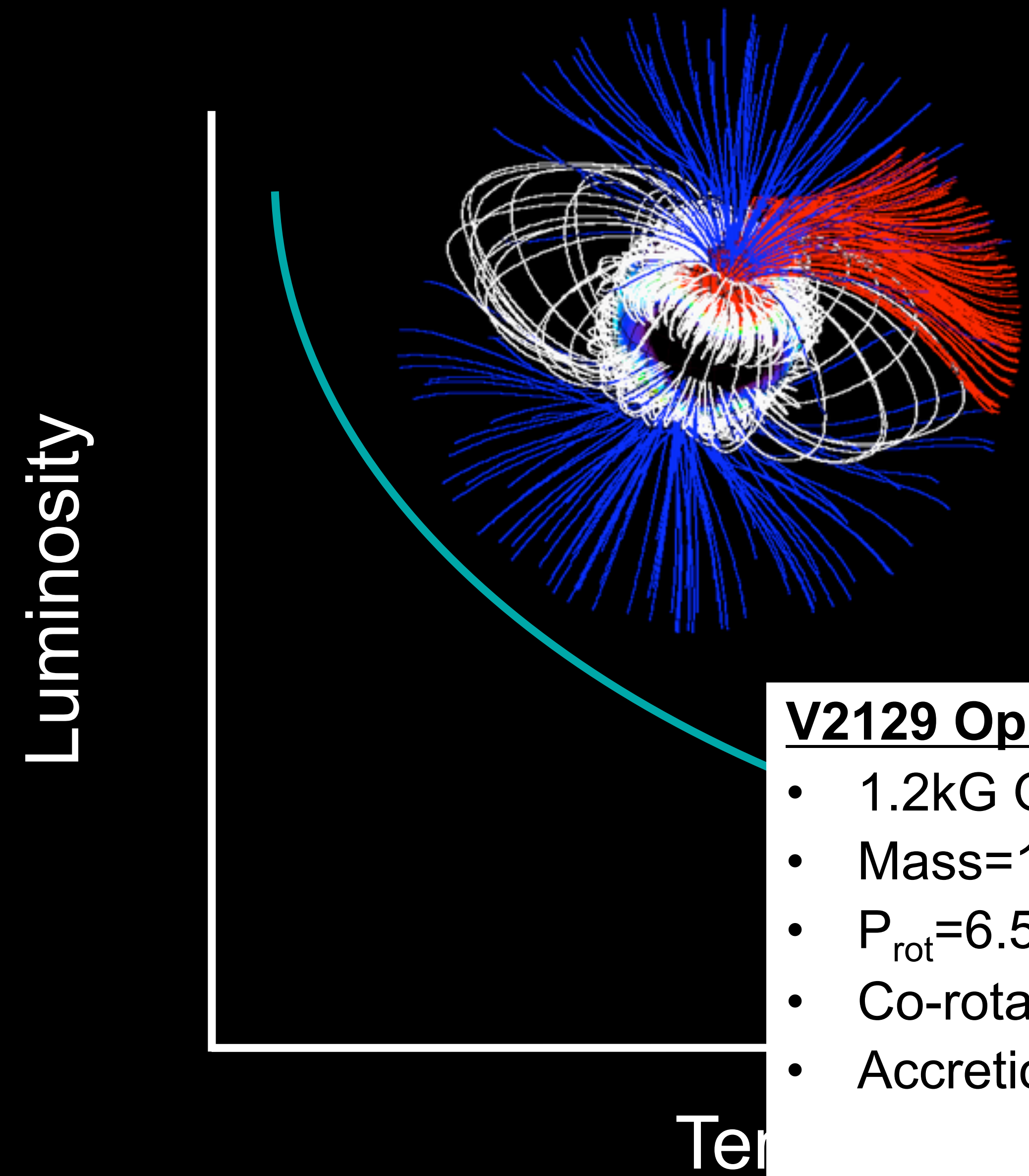
Barnes (2005)



What is the coronal structure of young stars?




BP Tau
- 1.2kG Dipole
- Mass=0.7M_{Sun}, Radius=1.95R_{Sun}
- P_{rot}=7.6d
- Co-rotation radius=7.4R_*
- Accretion rate 3x10^{-8} M_{Sun}/yr
Luminosity
Temperature

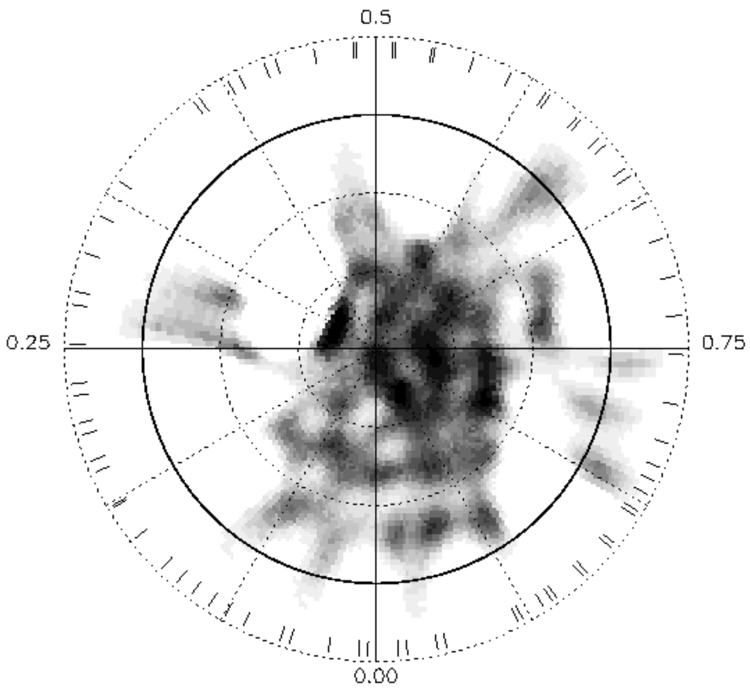


<u>V2129 Oph</u>

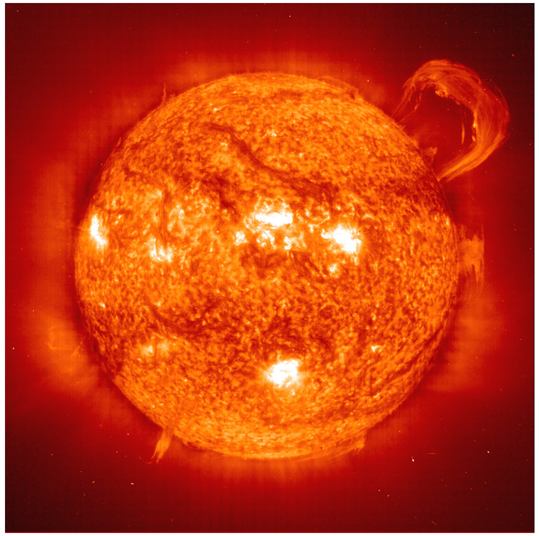
- 1.2kG Octupole (dipole ~ 0.35kG)
- Mass=1.35M_{Sun}, Radius=2.4R_{Sun}
- P_{rot}=6.53d
- Co-rotation radius=6.7R_*
- Accretion rate 10^{-8} M_{Sun}/yr

What are the observational indicators of structure?

- Stellar prominences seen in Hα



TWA6: Skelly et al 2008

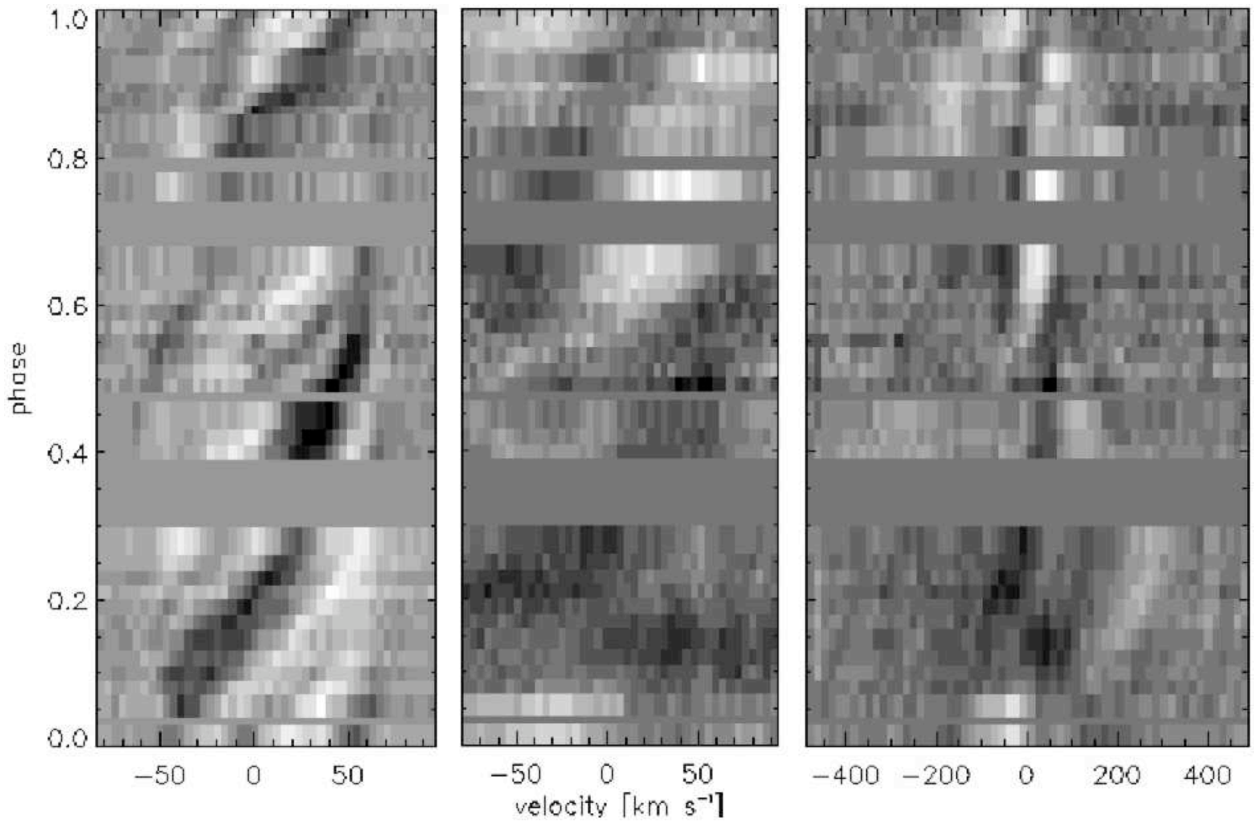


- Age ~ 8 Myr, P_{rot} = 0.54 days
- Radius ~ 1.05 R_{Sun}, Mass ~ 0.7 M_{sun}
- Negligible differential rotation
- Boundary between fully convective/ radiative core

Where are the prominences?

- At least one prominence (lifetime > 3 days) at 4 R_*

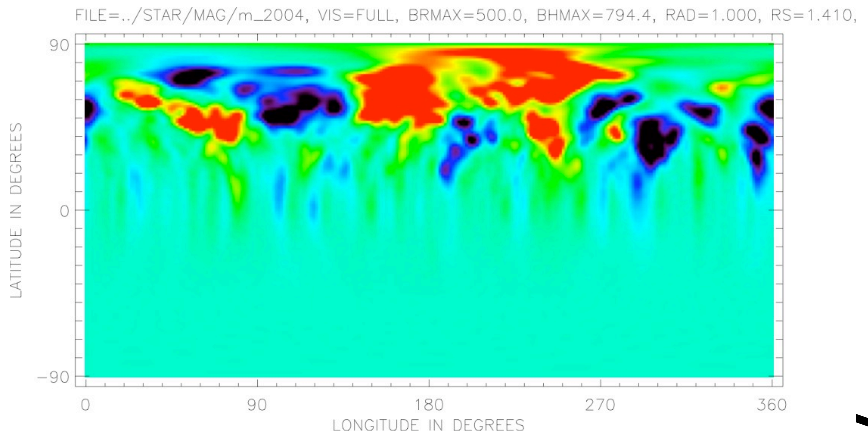
- Max height predicted by Jardine & van Ballegooijen (2006) is 4.8 R_*



Spots seen in photospheric lines

Prominences seen in Hα

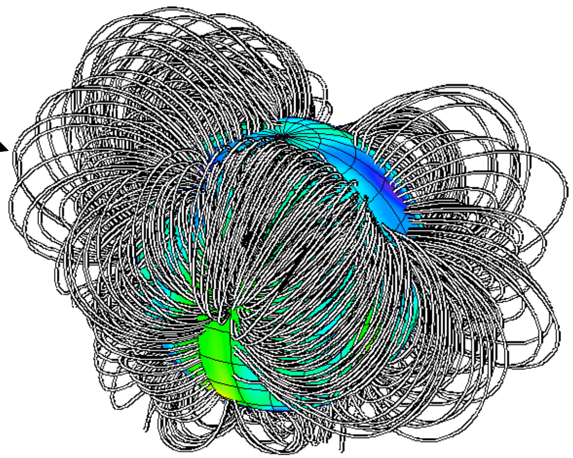
Does the stellar corona extend out to the prominence locations?



Extrapolate surface field

–*Potential Field Source Surface* model
(Altshuler & Newkirk 1969, Jardine et al, 1999)

–NB: extension to non-potential fields
(Hussain et al 2002)



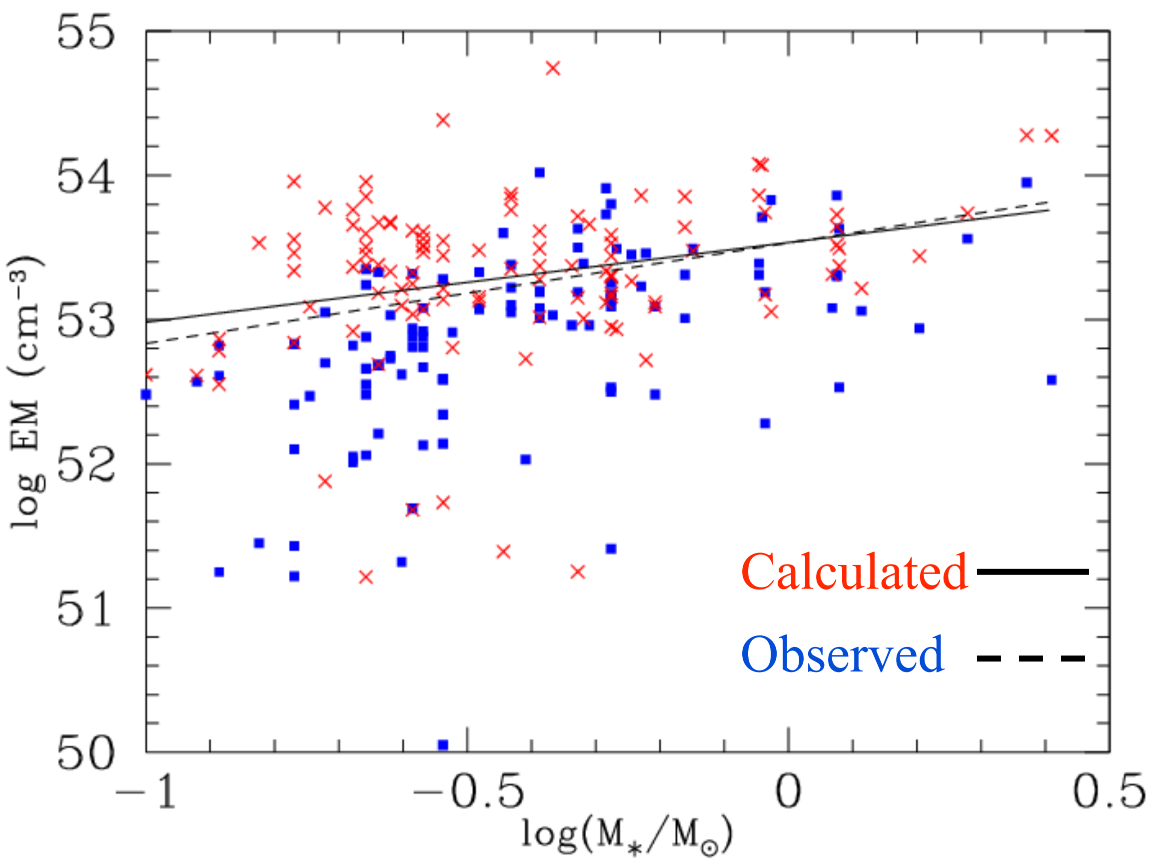
Isothermal, hydrostatic corona

(Base pressure $p_0 = K B_0^2$)

–(Jardine et al, 2002,Hussain et al 2007)

Finding the base pressure

- *Calculate* emission measure for each star in COUP sample for a range of K values
- Determine which K best fits all the *observed* emission measures
- This also gives densities similar to those derived from X-ray data



(Jardine et al 2006)

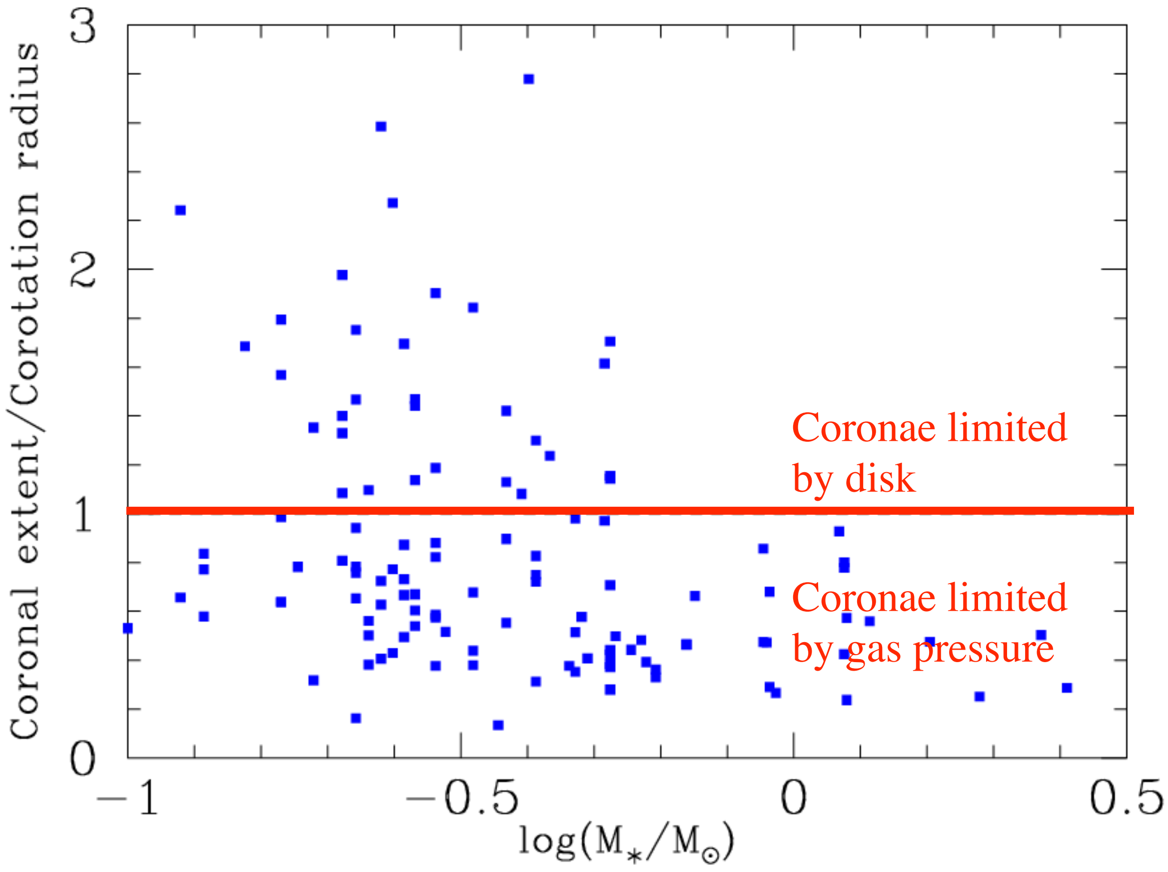
Where does the corona end?

- Low mass stars have coronae that extend beyond the co-rotation radius

=> *Coronal extent limited by disk*

- Higher mass stars have coronae that do not extend to the co-rotation radius.

- *=> Coronal extent limited by pressure balance*



(Jardine et al. 2006; Gregory et al 2006)

Where does the corona end?

- Low mass stars have coronae that extend beyond the co-rotation radius

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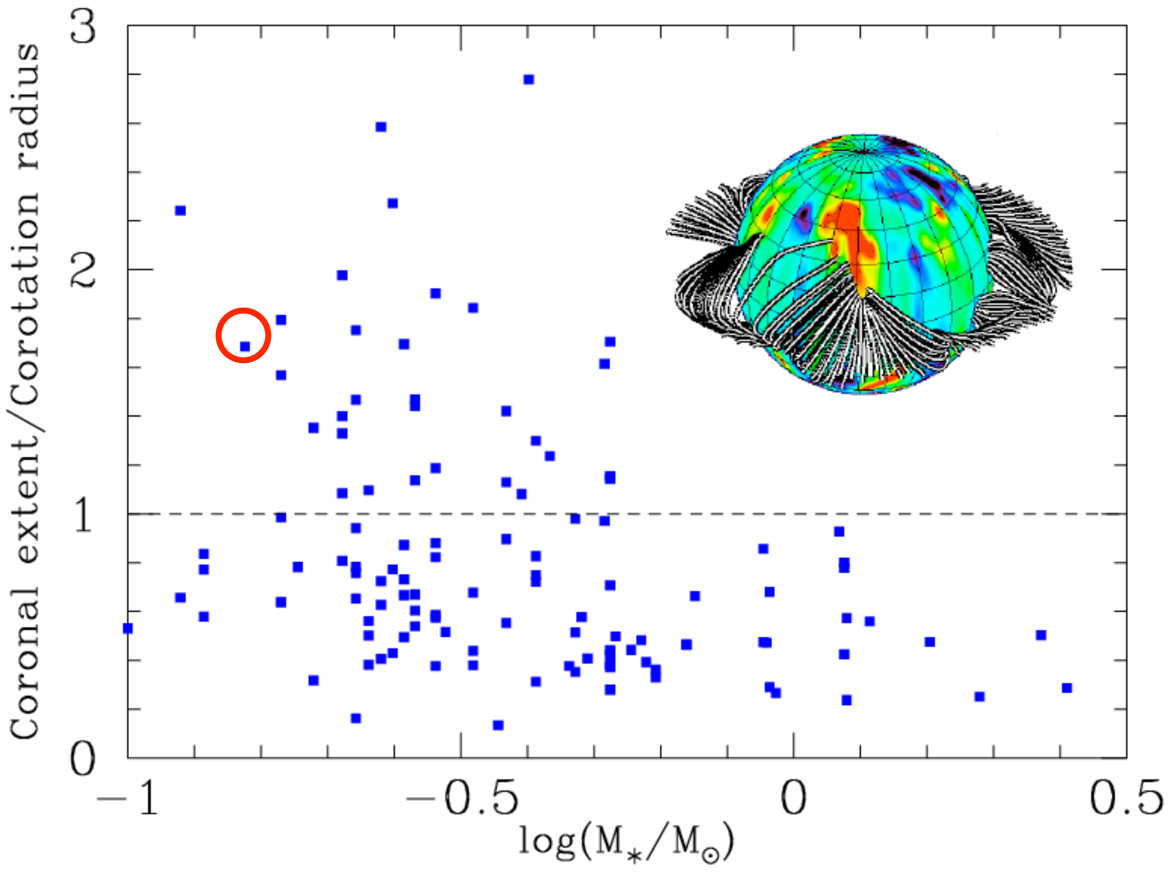

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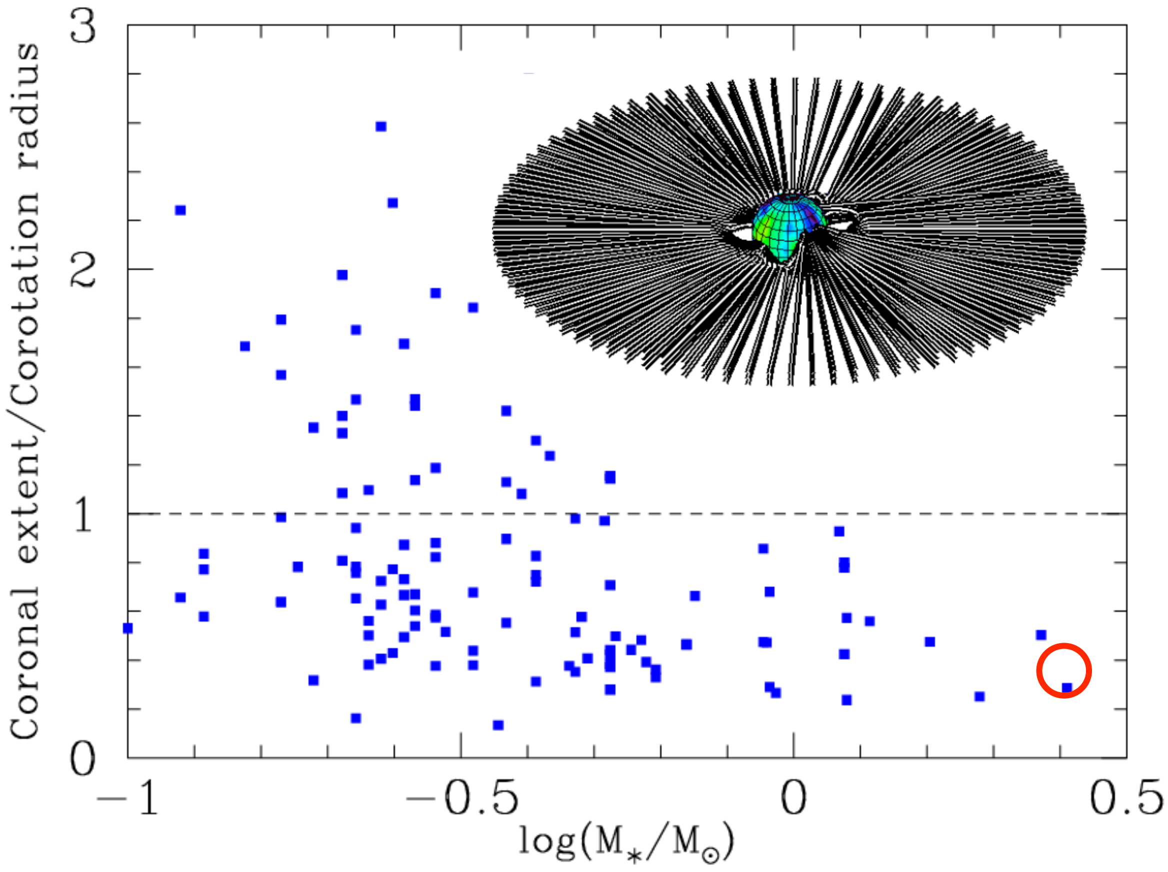
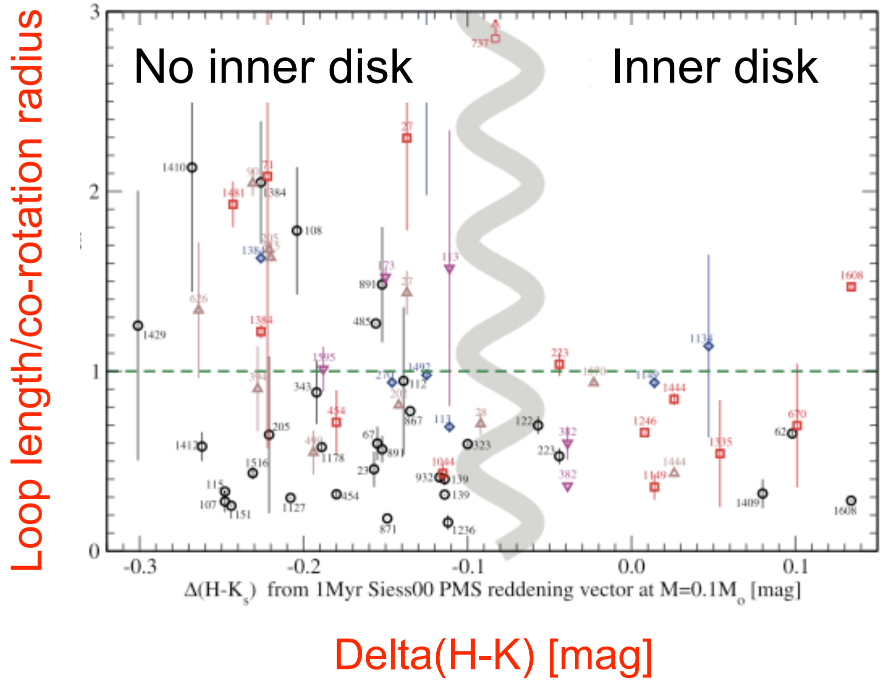


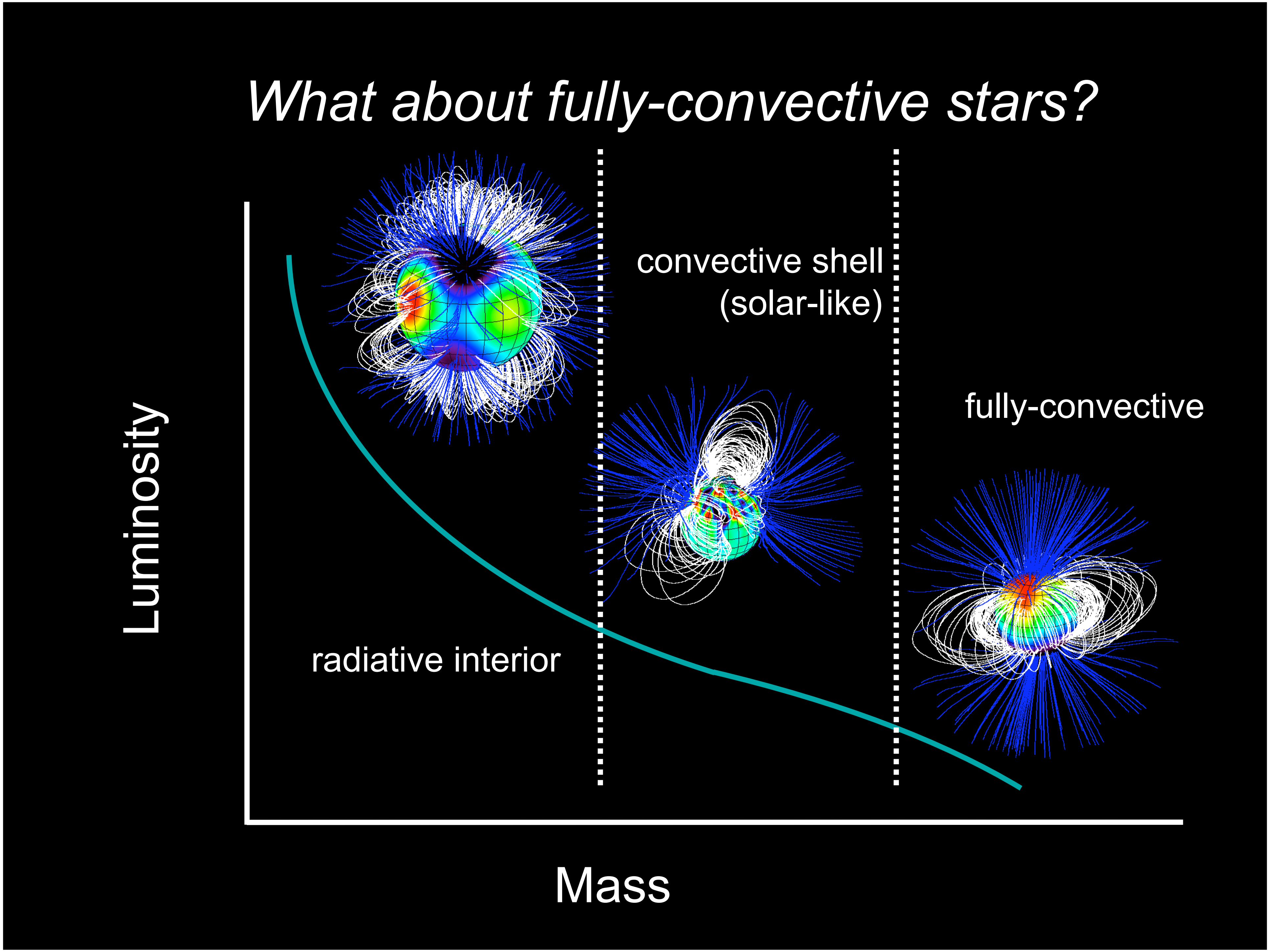
What determines the size of the corona?

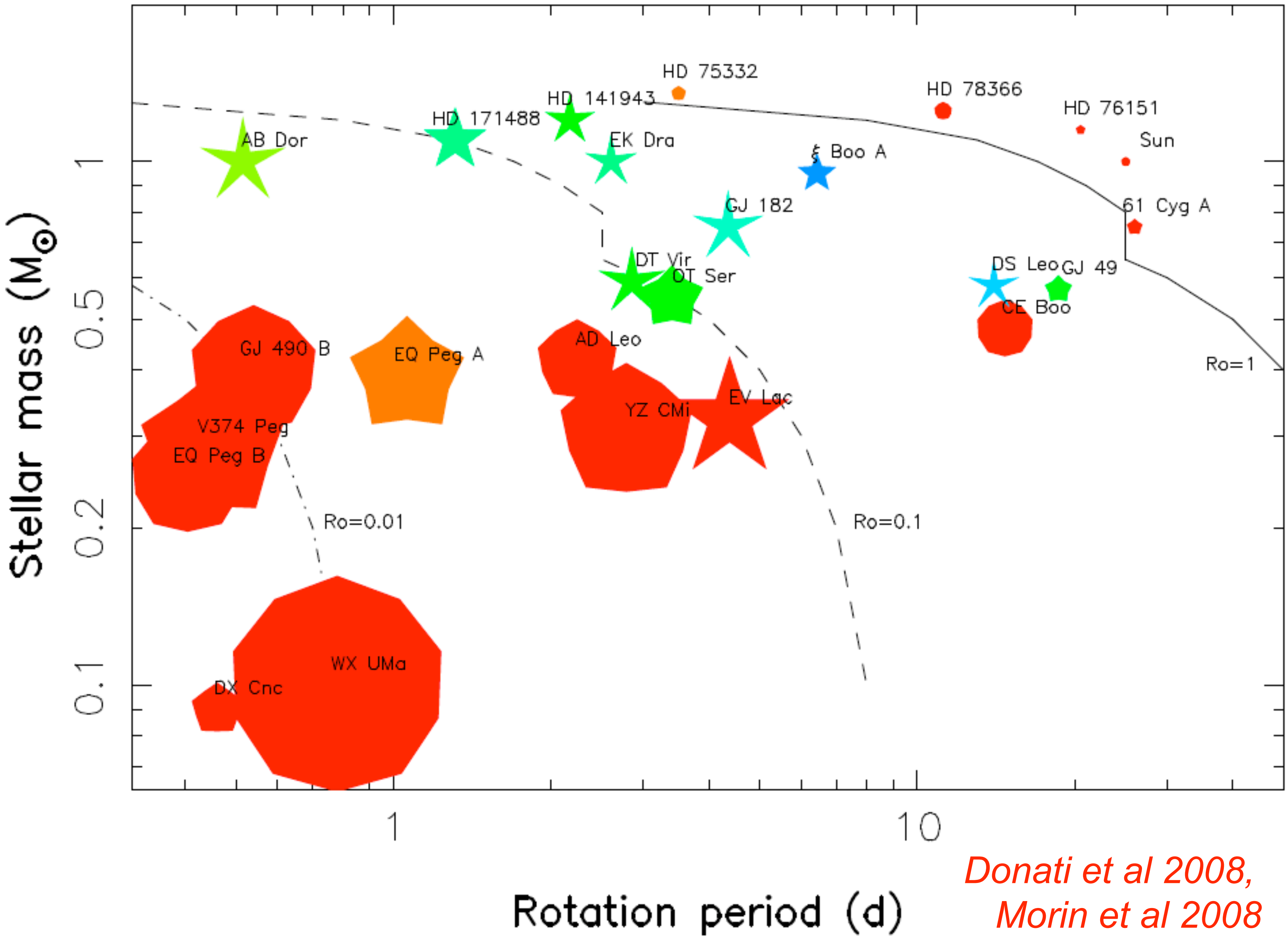
- Largest flaring loops appear on stars with no inner disk….

- Does any associated prominence ejection contribute to angular momentum loss? *(Aarnio et al 2009)*



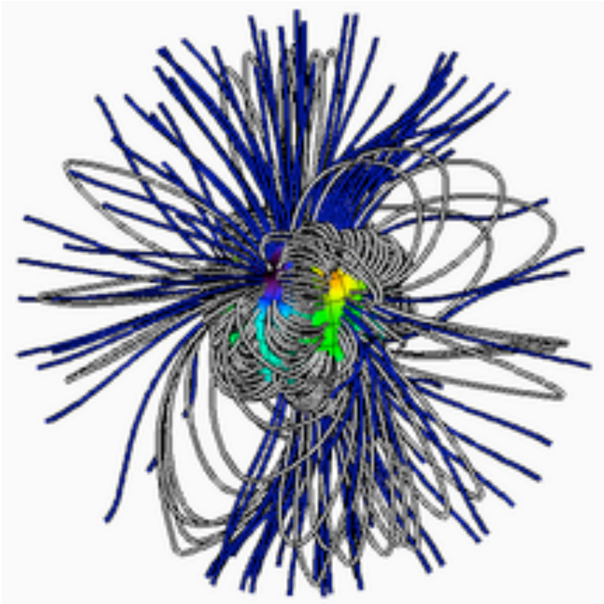
Getman et al 2008a,b


What about fully-convective stars?
convective shell
(solar-like)
fully-convective
radiative interior
Luminosity
Mass

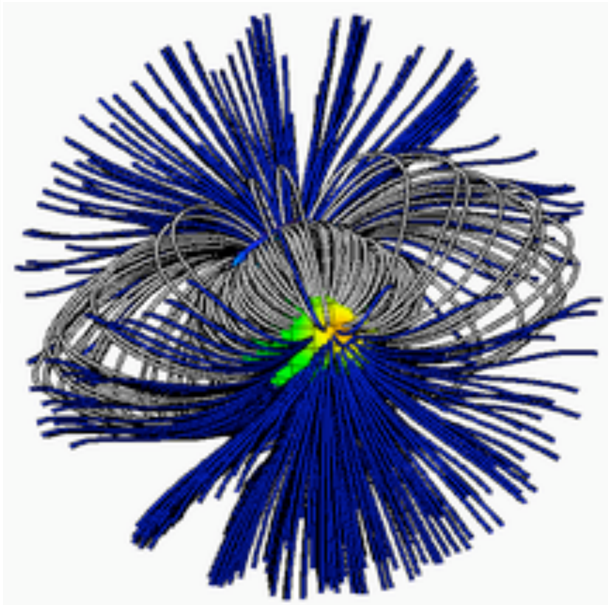


Donati et al 2008,
Morin et al 2008

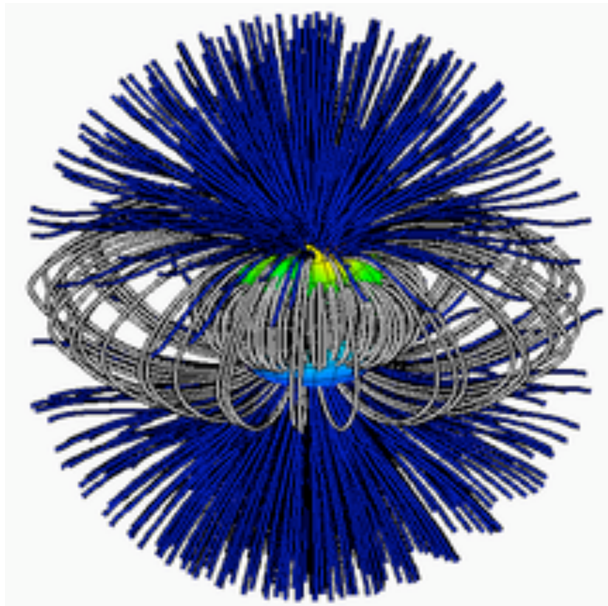
Coronal structure appears to change across the fully-convective boundary



GL 494



EV Lac



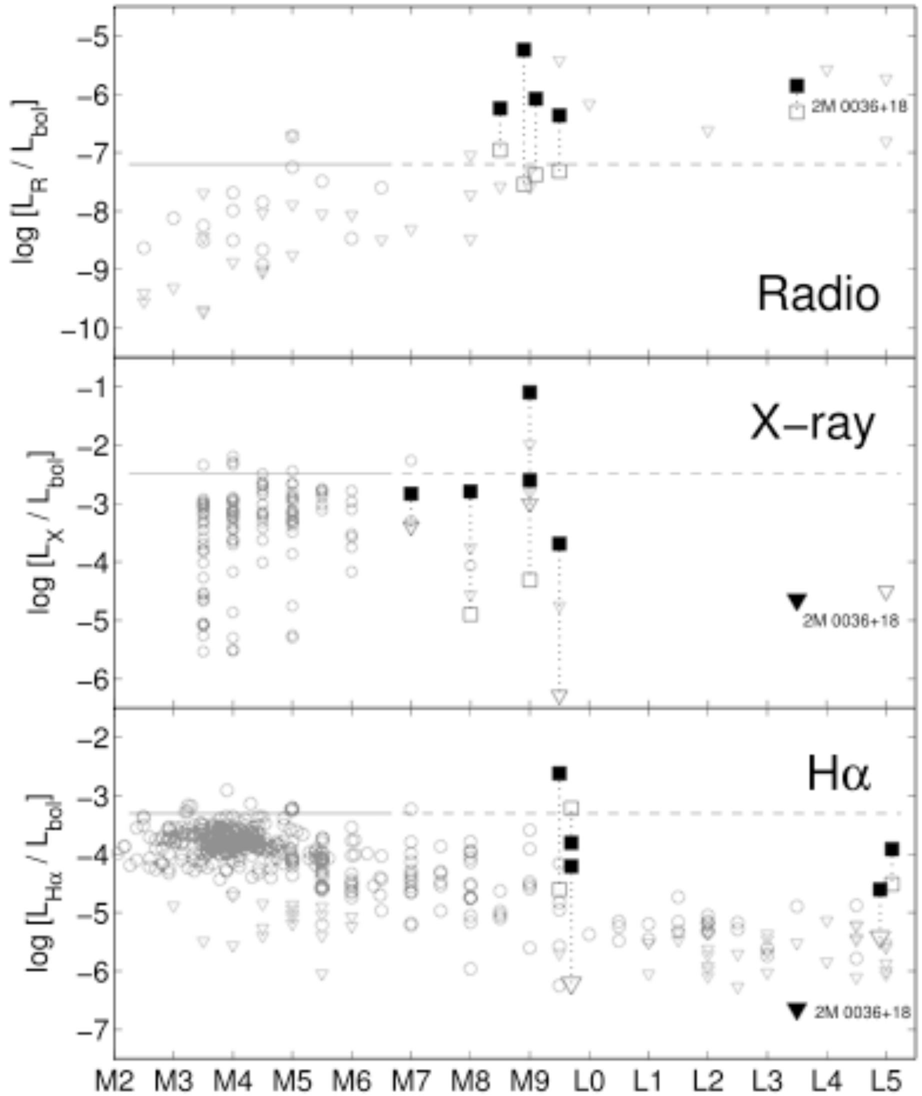
EQ Peg b

Low mass stars possess active coronae

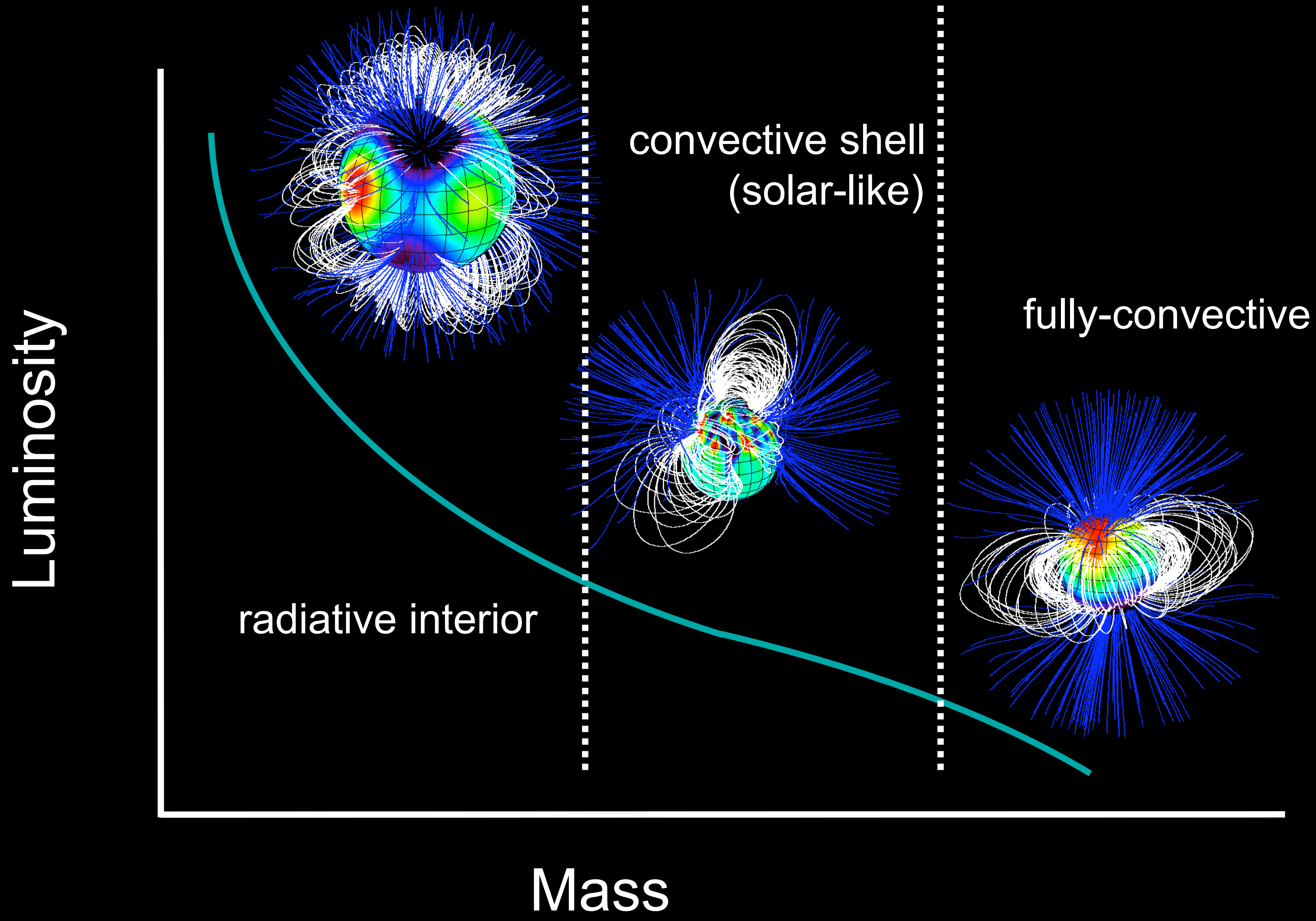
- The change in magnetic structure is *not* accompanied by a dramatic change in X-ray emission

- But radio emission increases!

Berger et al 2005

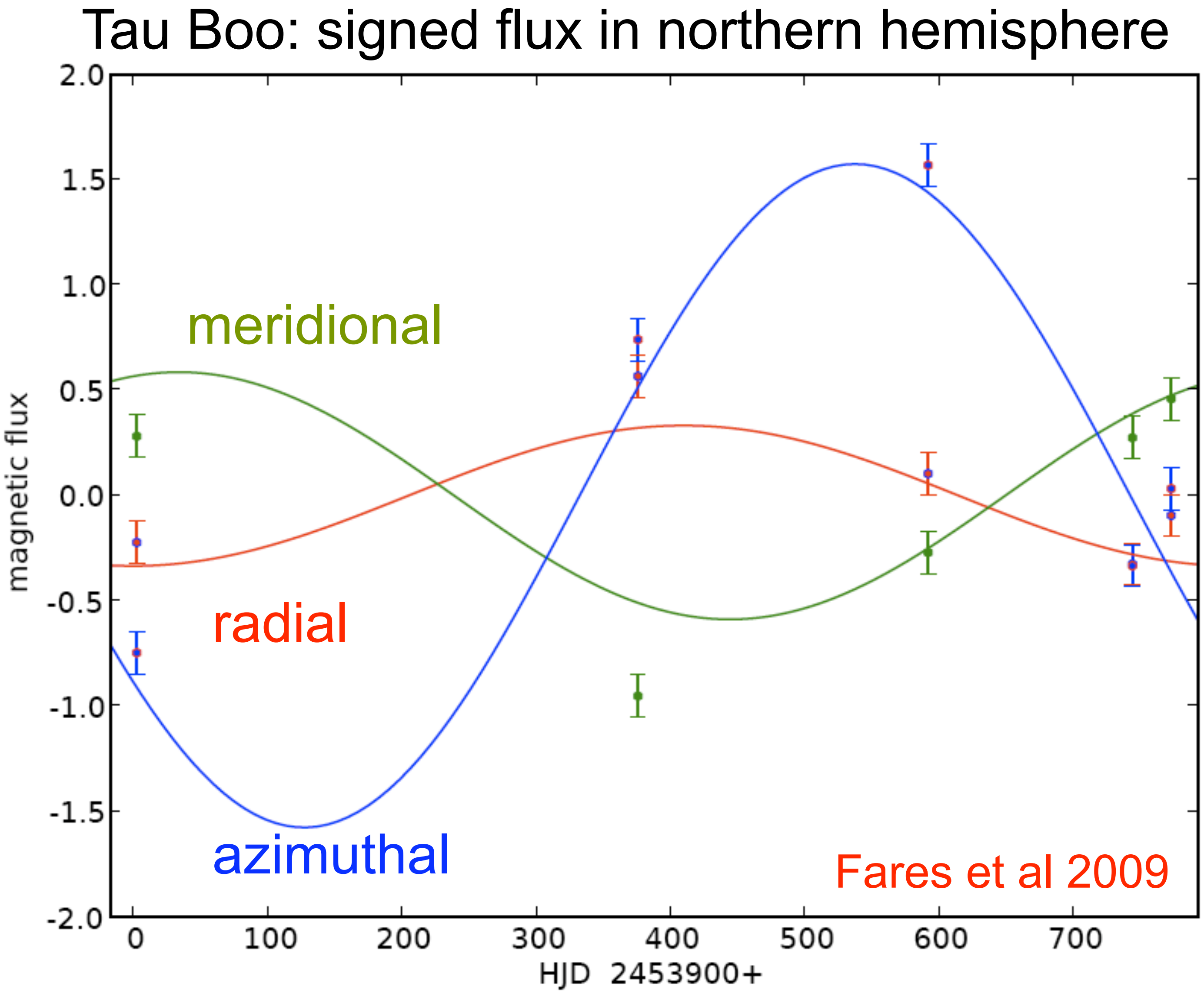


What about magnetic cycles?

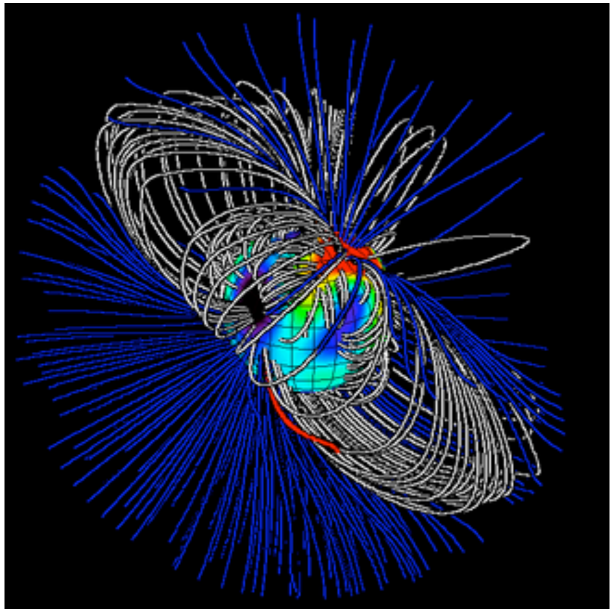


Can the planet affect the stellar magnetic cycle?

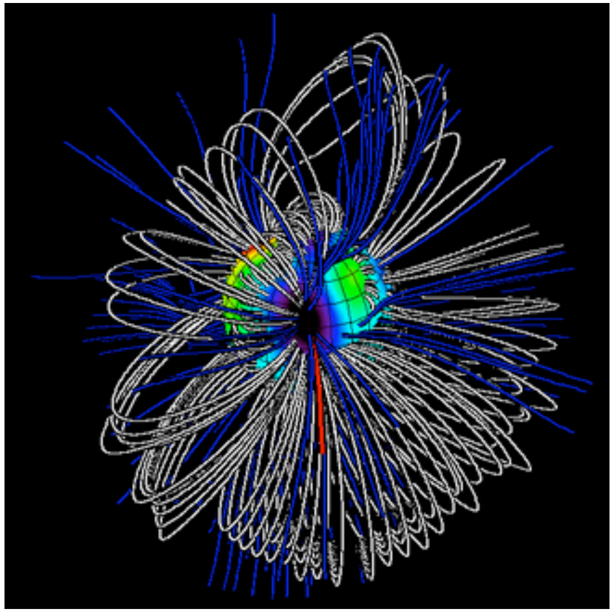
- Shallow stellar convective zone
- Best fit periods:
  - – 820 days (2.25 years)
  - –250 days (8 months)
- Azimuthal flux variation leads radial



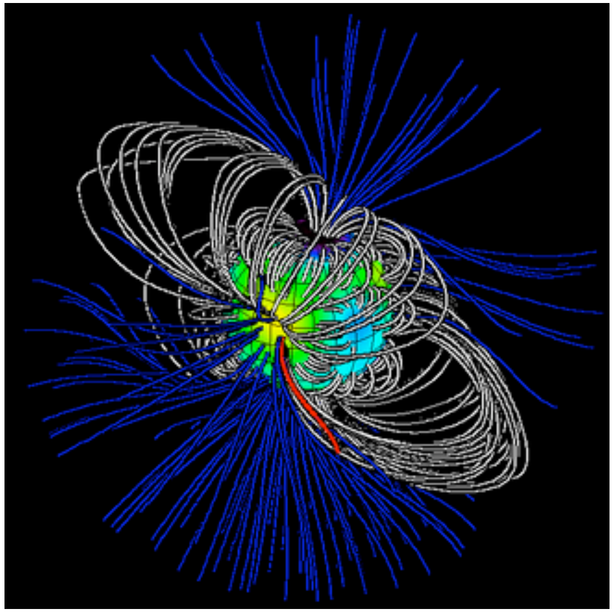
Note change of polarity over 1 year



June 2007

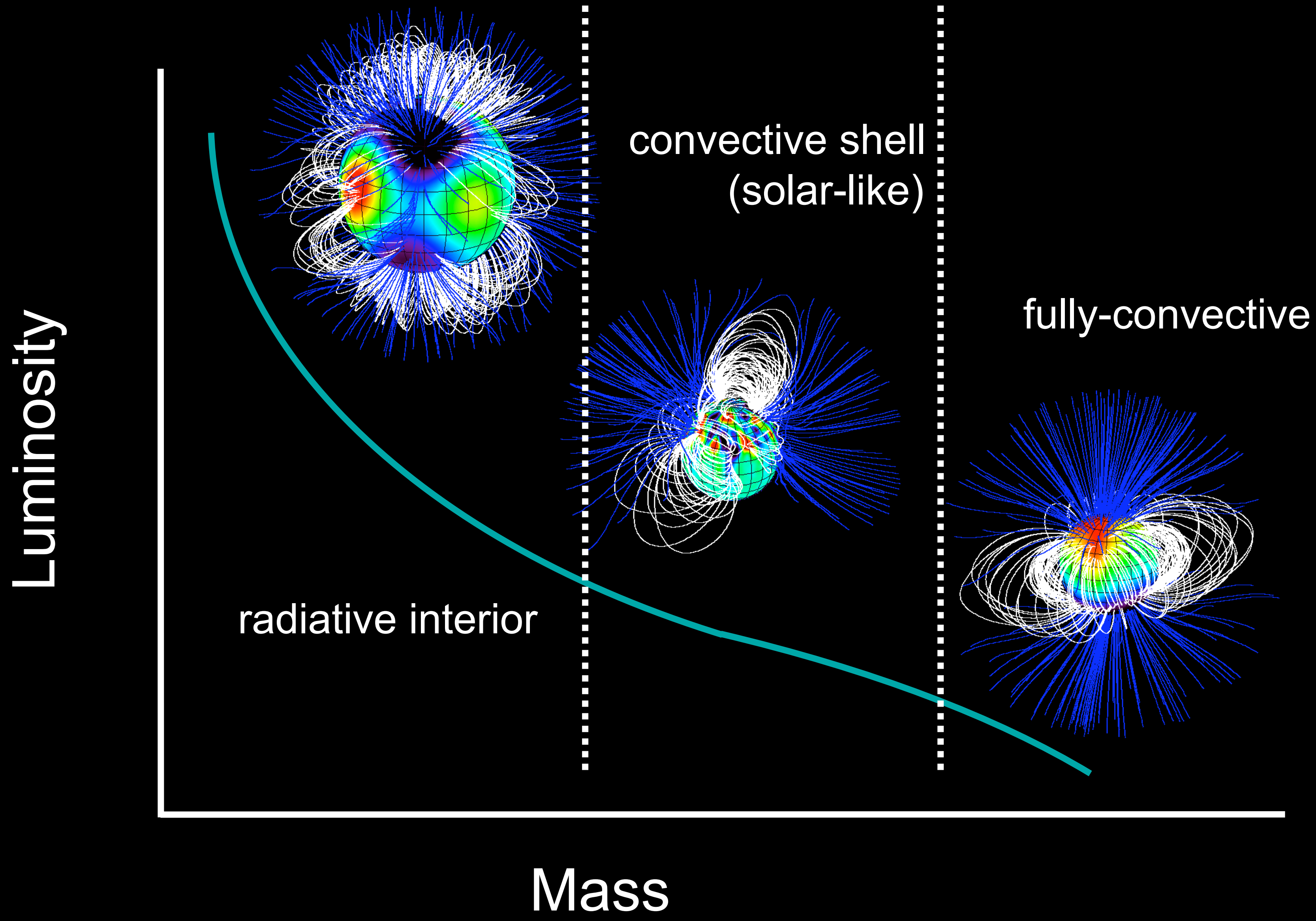


Jan 2008



July 2008

Questions?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Luminosity
Mass