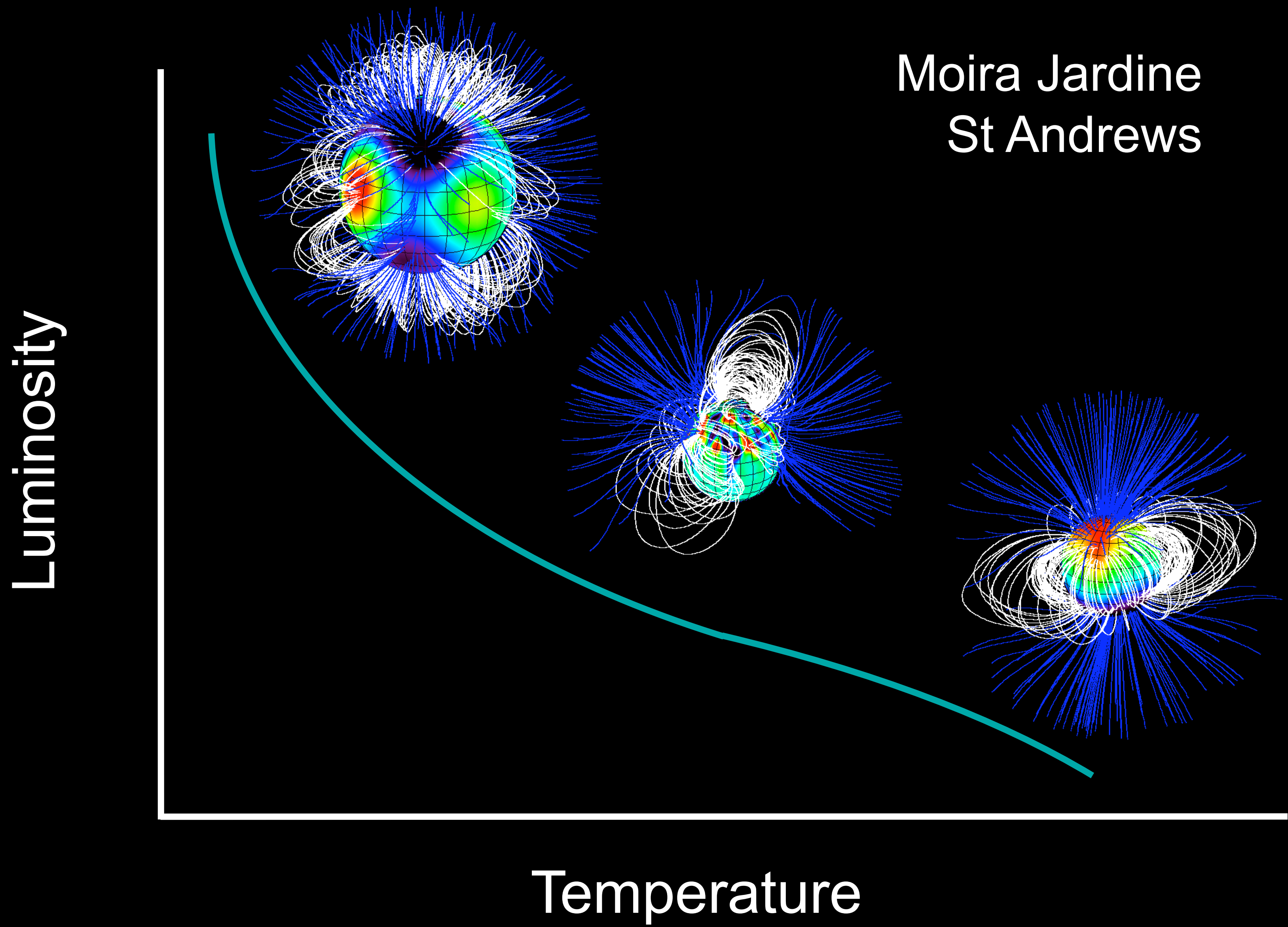
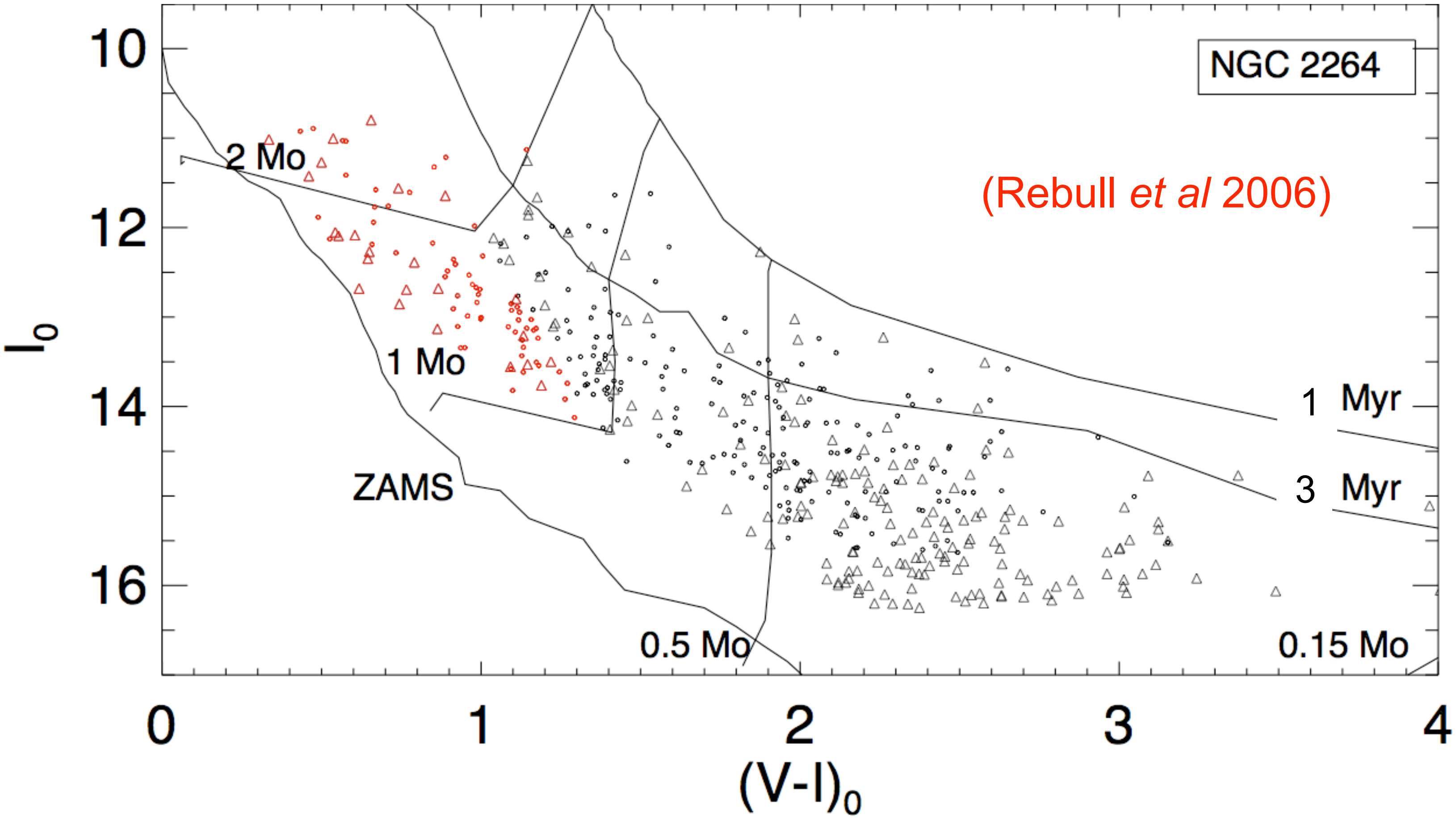
Magnetic properties of young stars

Moira Jardine
St Andrews



What are T Tauri stars?

- Pre-main sequence, solar mass
- Typically fairly slow rotators (~ 7days)
- Two classes:
  - *Classical* T Tauri stars (disks plus active accretion)
  - *Weak-lined* T Tauri stars (no disk and/or no active accretion)



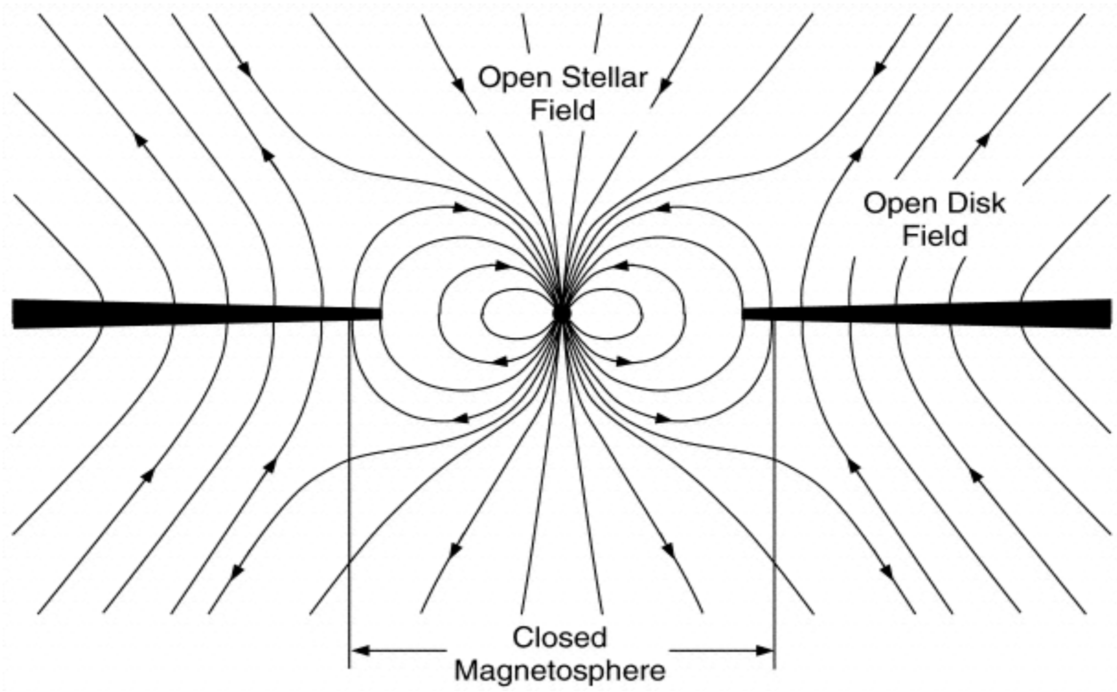
- Evolutionary tracks (*Seiss et al 2000*)
  - Dots: L_x detections; Triangles: L_x upper limits
  - Red: no longer fully convective

Outstanding questions

- *What is the mass accretion rate?*
  - *How long does the disk live for?*
  - *Is there time to build planets?*
- *Where does all the angular momentum go?*
  - *Why are most T Tauri stars slowly rotating?*
    - *They are still contracting*
    - *They are accreting from their disks - they experience an accretion torque (spin-up)*

The three-part corona

- Closed field:
  - Temperatures 10^6 -10^7K
  - Thermal speed > escape speed
  - Need closed magnetic loops to confine plasma
- Open field:
  - Hot plasma escapes to form stellar wind
  - Magnetically channelled
  - Mass+angular momentum lost
  - Specific angular momentum $L = \Omega (R_A)^2$

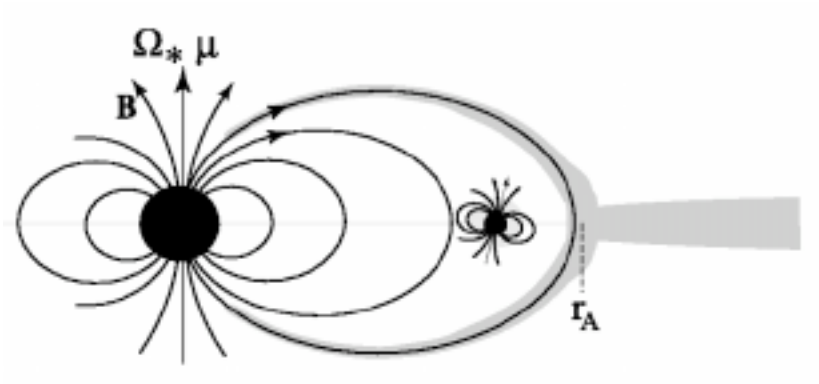


(Goodson et al. 1997)

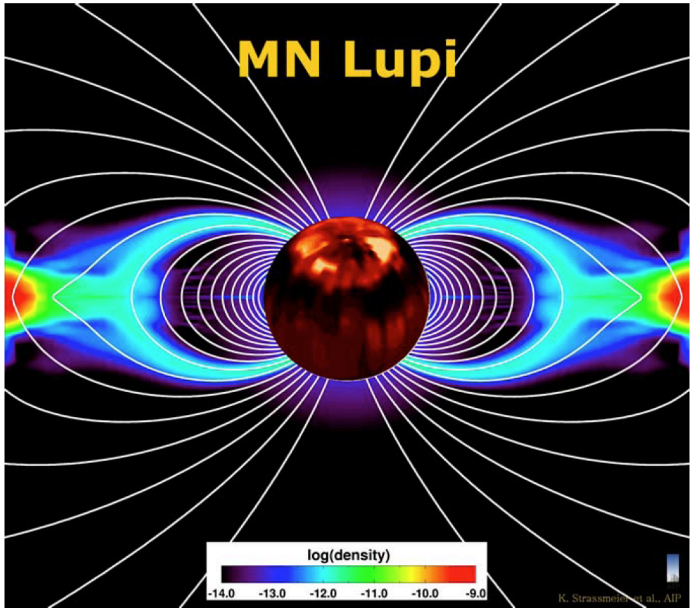
- Accreting field:
  - Stellar field lines penetrate disk, transmit magnetic torques (positive/spin up inside corotation, negative/spin down outside corotation).

Why does the field structure matter?

- It channels accretion, mediates torques
- It disrupts the disk (setting the inner edge of planet migration?)



(*Romanova et al. 2006*)

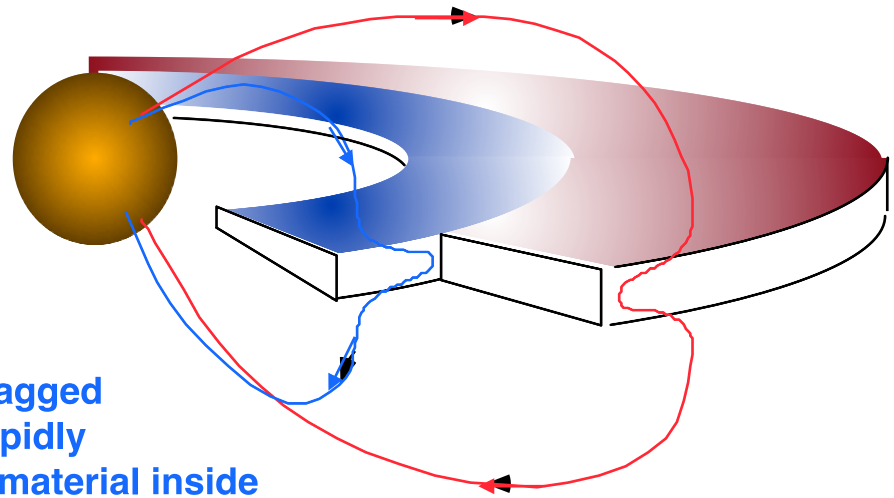


(*Strassmeier et al* 2005)

- Open field lines may carry a hot wind
- It powers a significant fraction of the X-ray emission

Can magnetic torques balance accretion torques?

- Disk locking *(Konigl 1991, Collier Cameron & Campbell 1993)*
- X-winds *(Shu, 1994)* and Ferreira *(2001)*



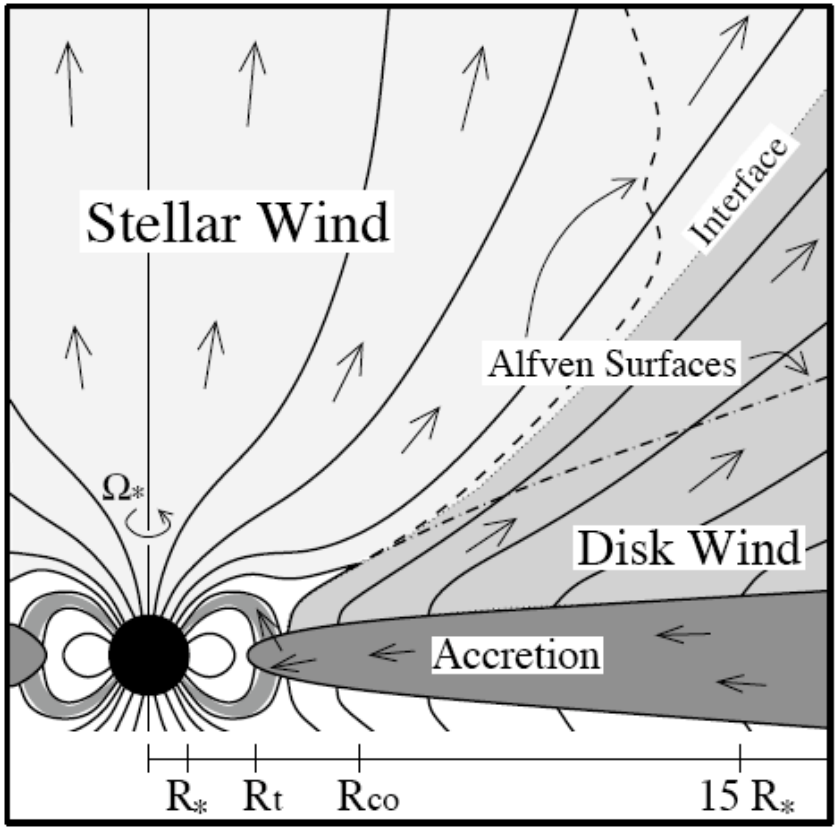
- Truncation radius by balancing differential accretion and magnetic torques:

$$r^2 B_z^2 = \frac{1}{2} \dot{M} \left(\frac{GM_*}{r} \right)$$

Can wind losses balance accretion torques?

- Disk comes in well inside corotation
- Need to transfer energy from accretion to wind
- Plausible wind models emerging (*Cranmer 2008*)
- *Weber & Davis (1968):* spherically-symmetric, isothermal wind, radial field
- Angular momentum loss rate:

$$-\dot{J} = \frac{8\pi}{3\mu_0}\frac{\Omega}{u_A}\left(B_0 r_*^2\right)^2$$



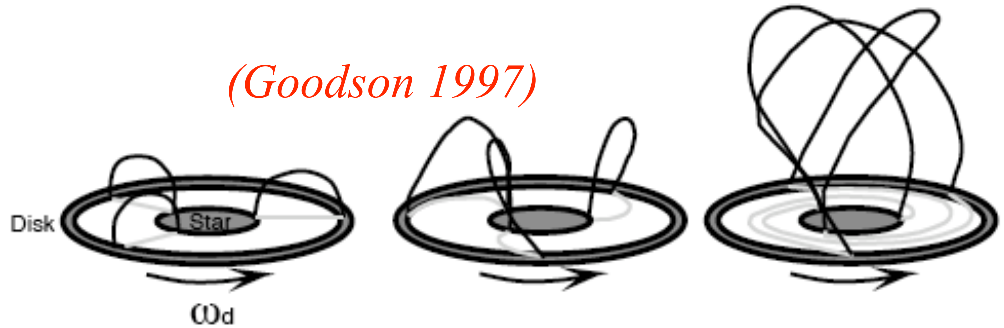
Matt & Pudritz 2005

Magnetic flux Φ through spherical surface

What determines the structure of the magnetosphere?

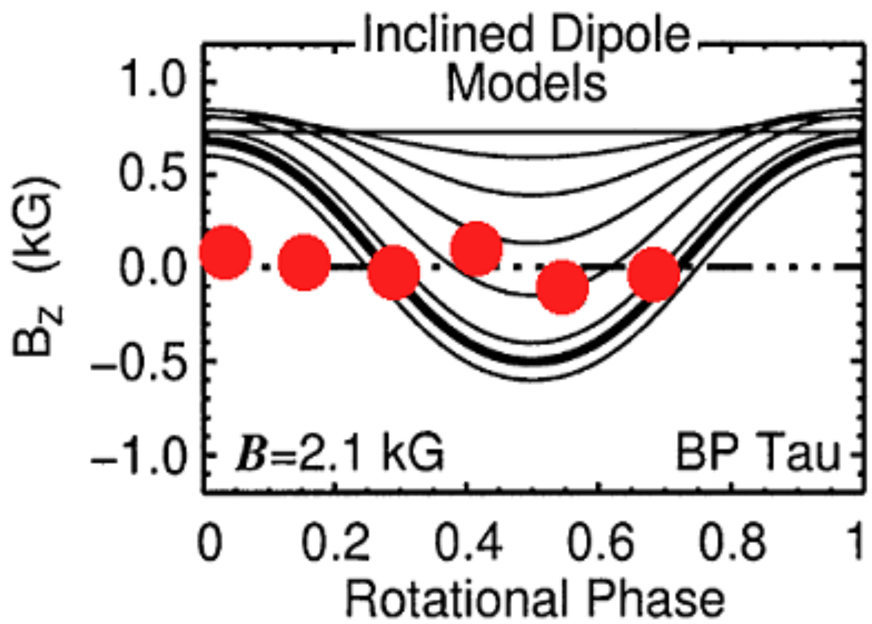
- Interaction with disk field?
  - Shearing of stellar field lines
    - Inflation/opening up of field lines (*Lynden-Bell & Boily 1994*)
    - Stressing of coronal field
  - Reconnection with disk field
    - Triggering large flares (*Favata et al 2005*)?
- Star
  - Interior dynamo
  - Surface transport

(Goodson 1997)



What are the observational indicators of structure?

- Polarisation - complex structure (*Valenti et al 2003, John-Krull & Gafford, 2002, Symington et al 2005*)
- Complex structure also in X-ray (*Flaccomio et al 2005, Forbrich et al 2006, Schmitt & Robrade 2007*)
- Variability - (*Oliveira et al 2000; Bouvier et al 2003,2007; Barsony et al 2005; Forbrich et al 2006; Fischer et al 2008*)

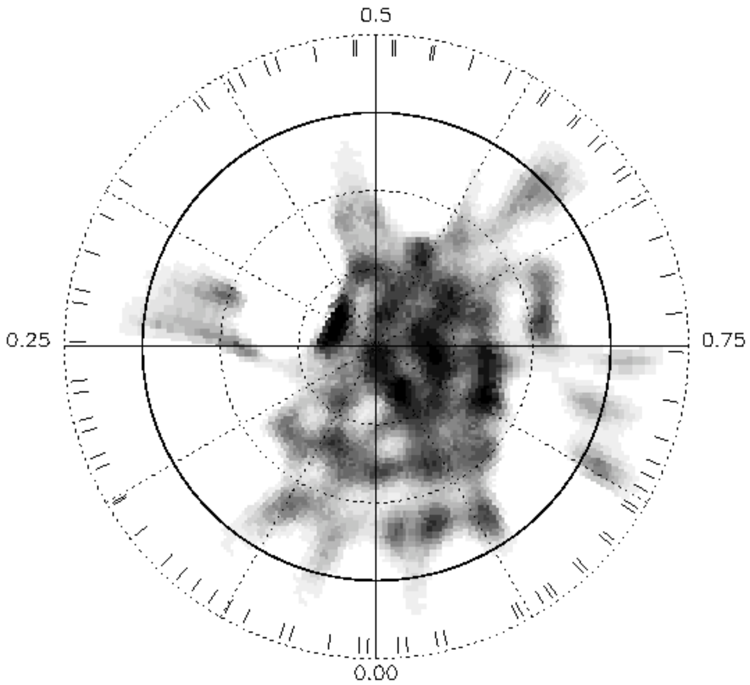


(Valenti & Johns-Krull 2004)

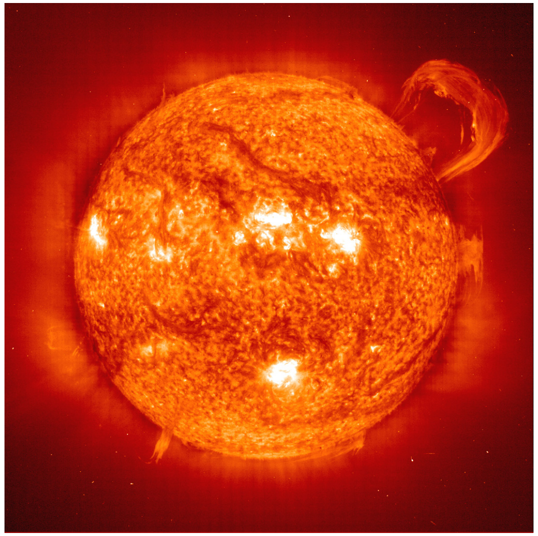
- Lack of correlation between
  - optical/X-ray variability (*Stassun et al 2006*) and
  - radio/X-ray (*Forbrich et al 2007*)

What are the observational indicators of structure?

- Stellar prominences seen in Hα

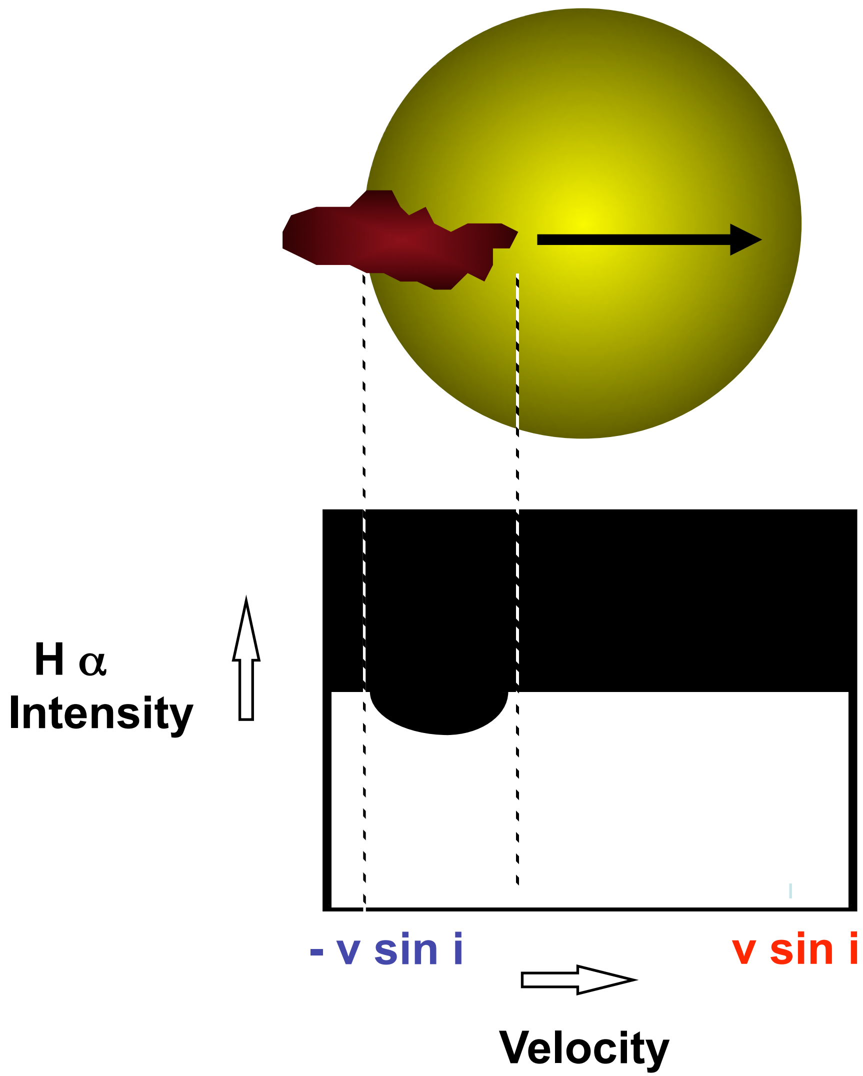


TWA6: Skelly et al 2008

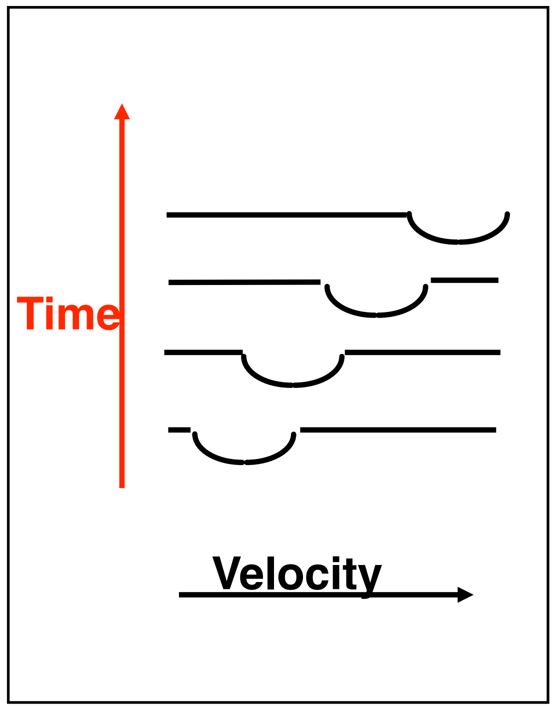


- Age ~ 8 Myr, P_{rot} = 0.54 days
- Radius ~ 1.05 R_{Sun}, Mass ~ 0.7 M_{sun}
- Negligible differential rotation
- Boundary between fully convective/ radiative core

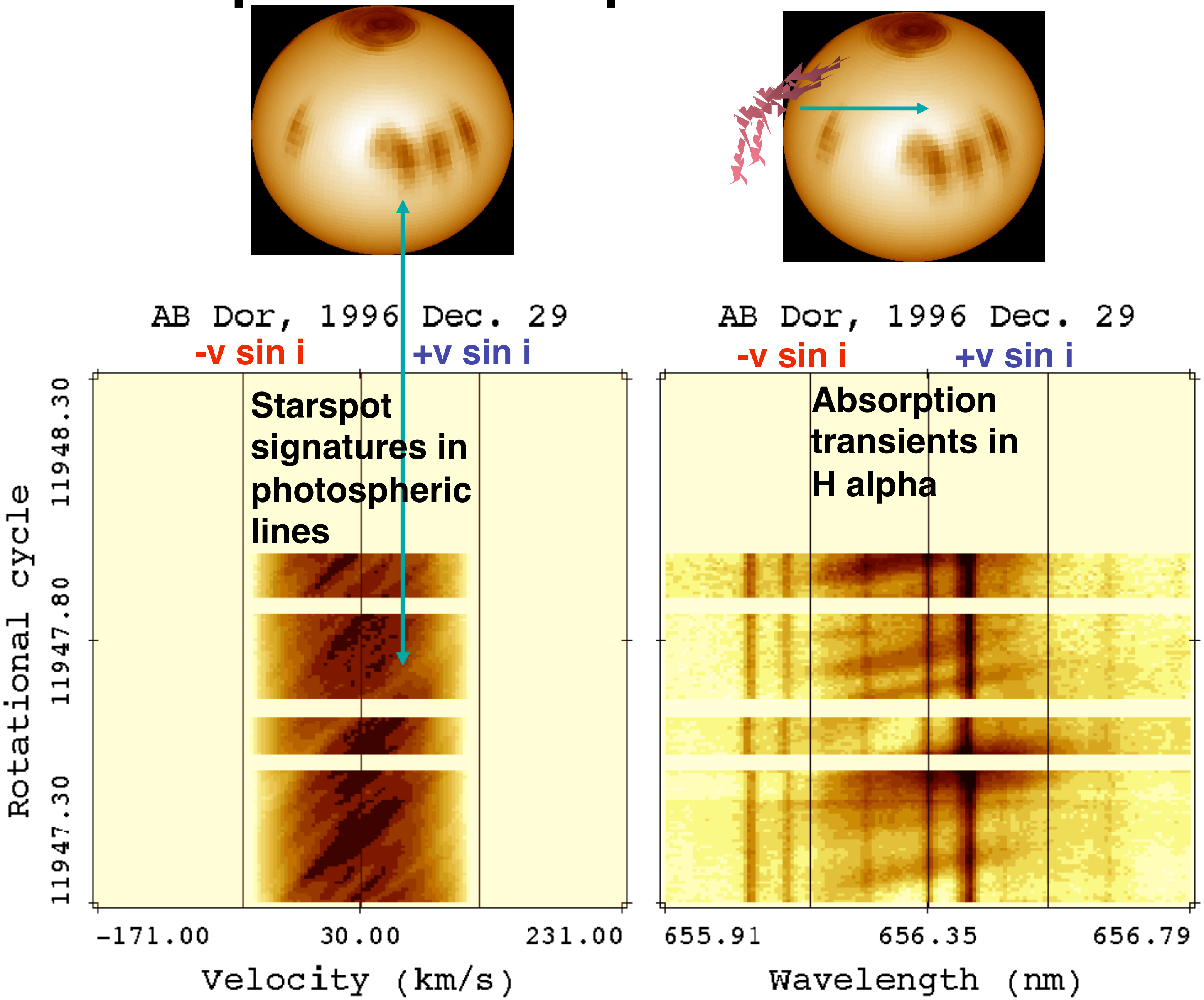
Observing stellar prominences



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

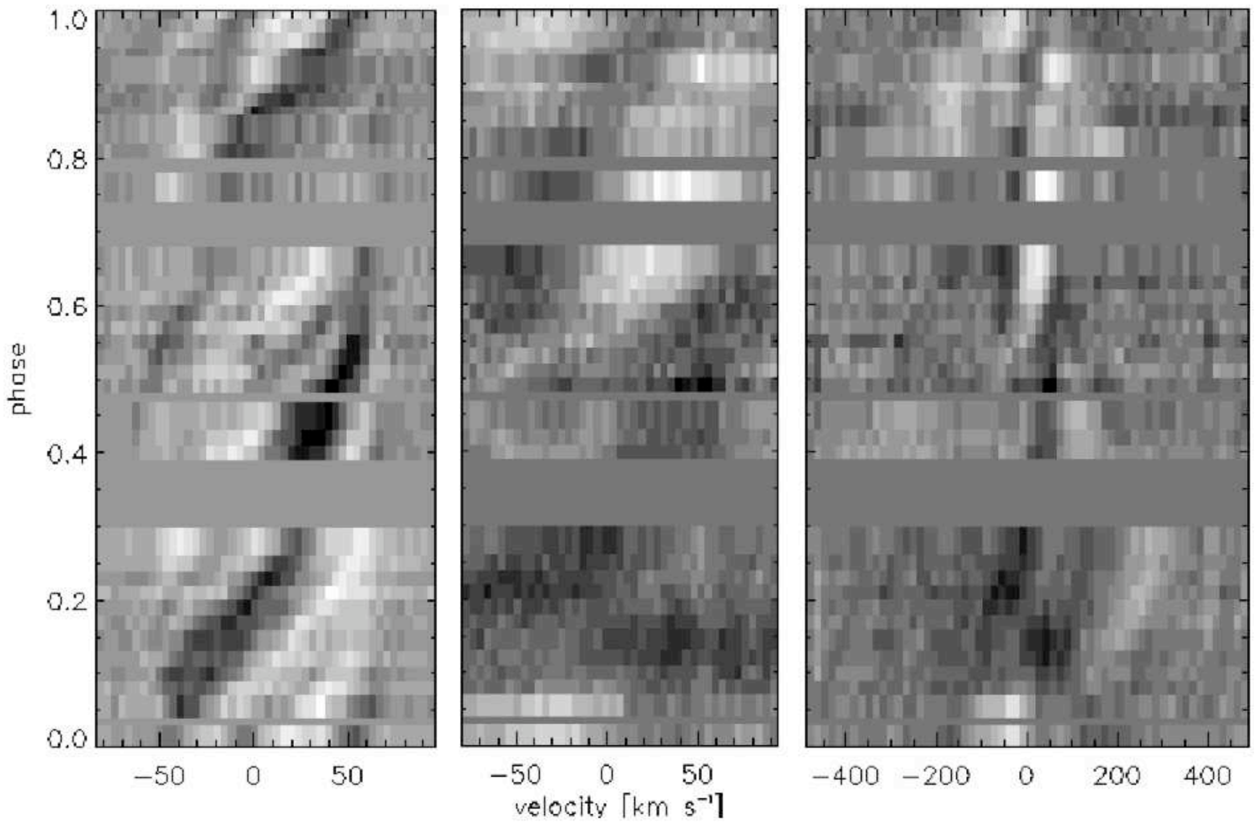


Spots and prominences



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_*

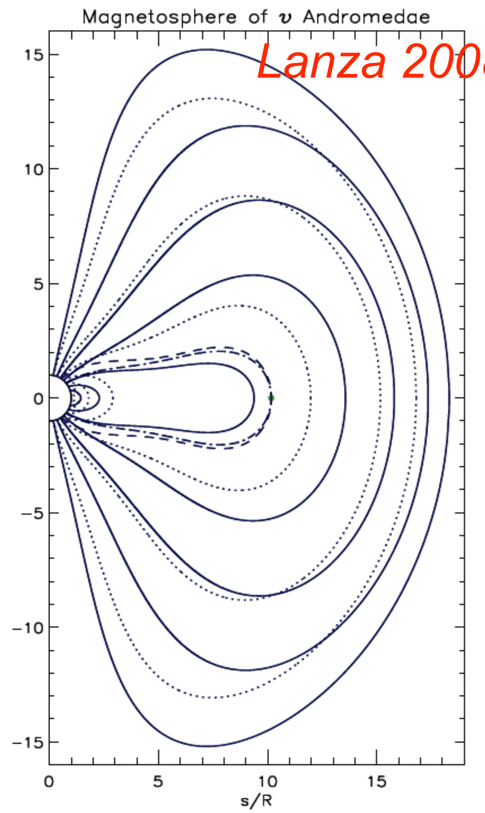


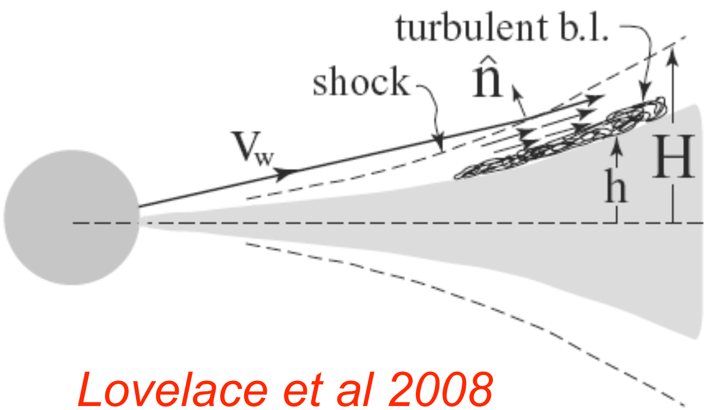
Spots seen in photospheric lines

Prominences seen in Hα

What is the impact on planets?

- 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*)



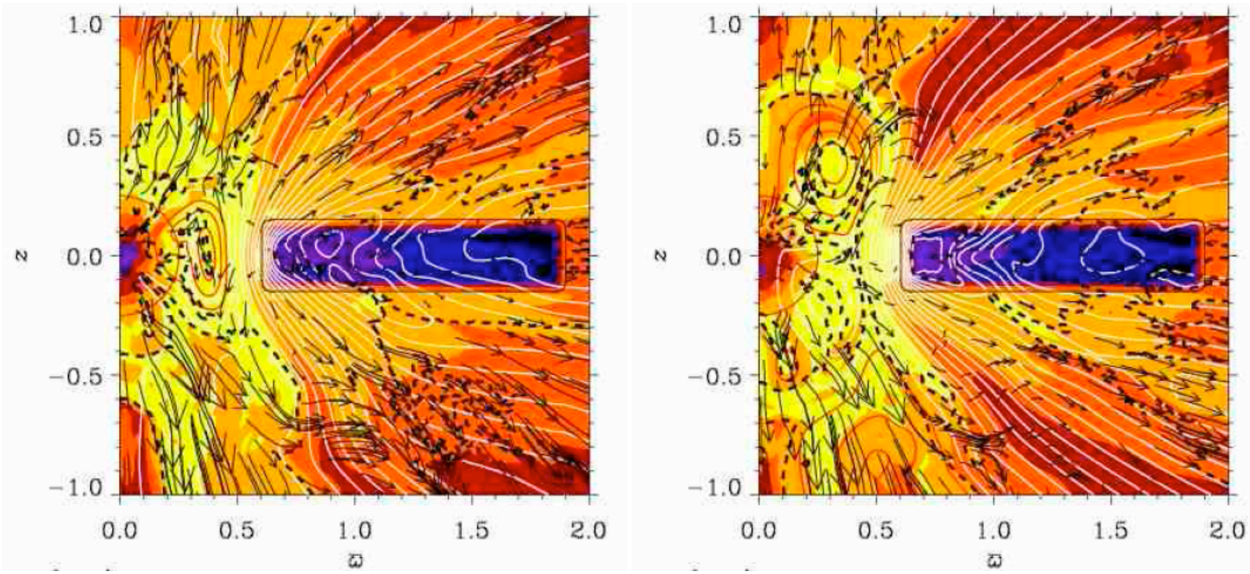


Lovelace et al 2008

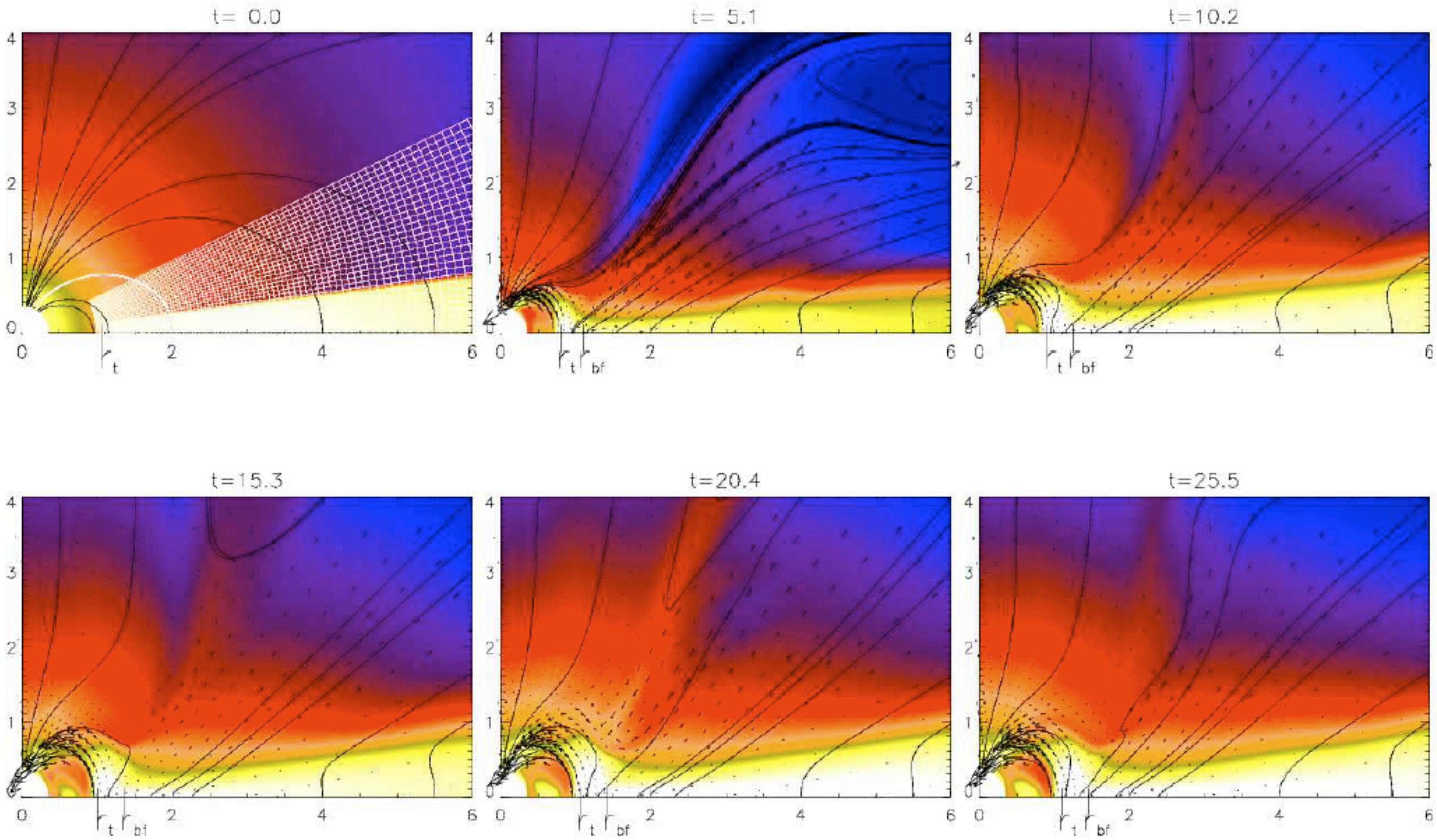
- Stellar wind may
  - Erode planetary magnetosphere *(Griessmeier et al 2004, Stevens 2005)*
  - Lead to planetary orbital evolution *(Dobbs-Dixon 2004; Lovelace et al 2008)*

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

What about theory?



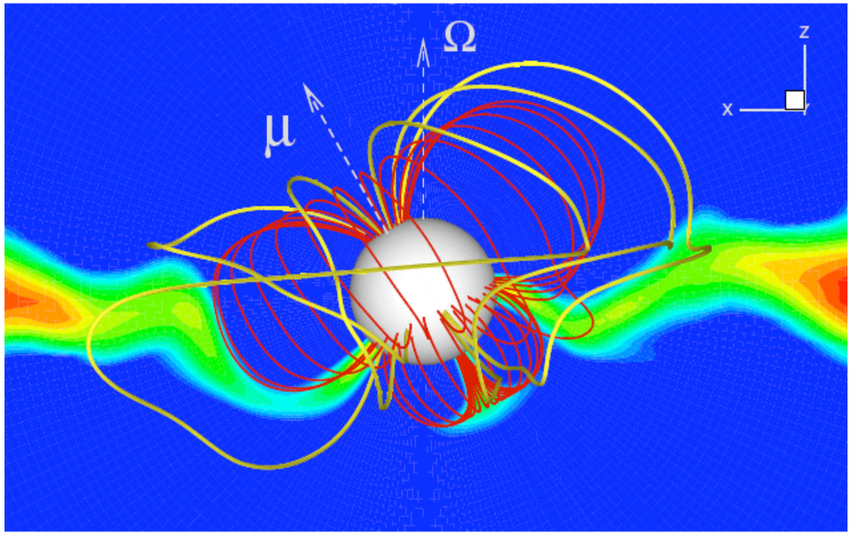
- Field generated by disk + stellar dynamo
- Wind angular momentum losses balance accretion torque (*von Rekowski & Brandenburg 2004*)



Bessolaz *et al* 2007

- Accretion funnels form when stellar field interact with disk
- Weak stellar fields -> low accretion rates
- No winds (either from disk or X-point) produced

What about theory?



- Stellar field prescribed: dipole + quadrupole
- *Open* field lines contribute to accretion torque (*Long et al 2006*)

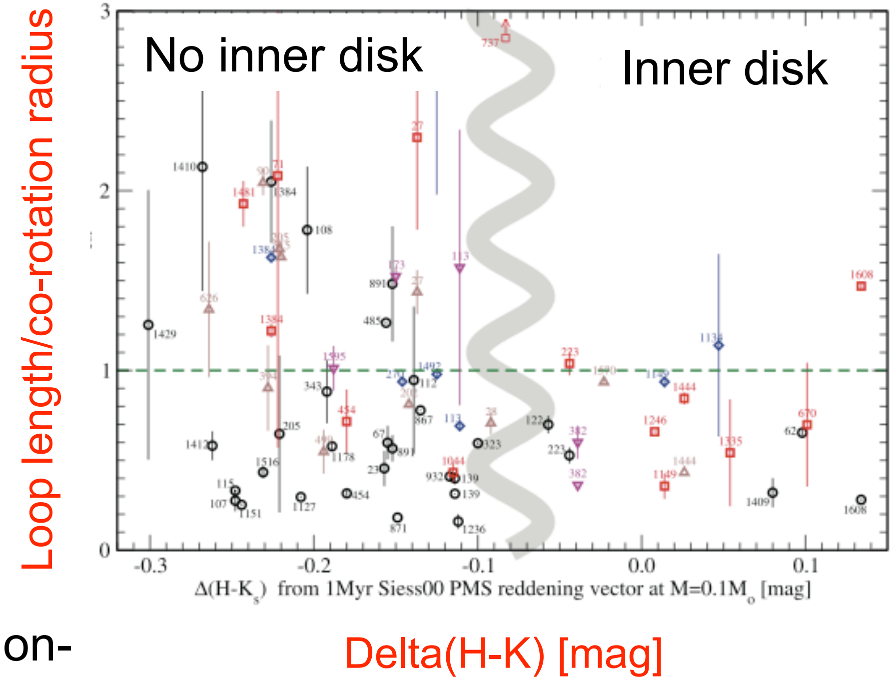
Monster flares: disk ionisation?

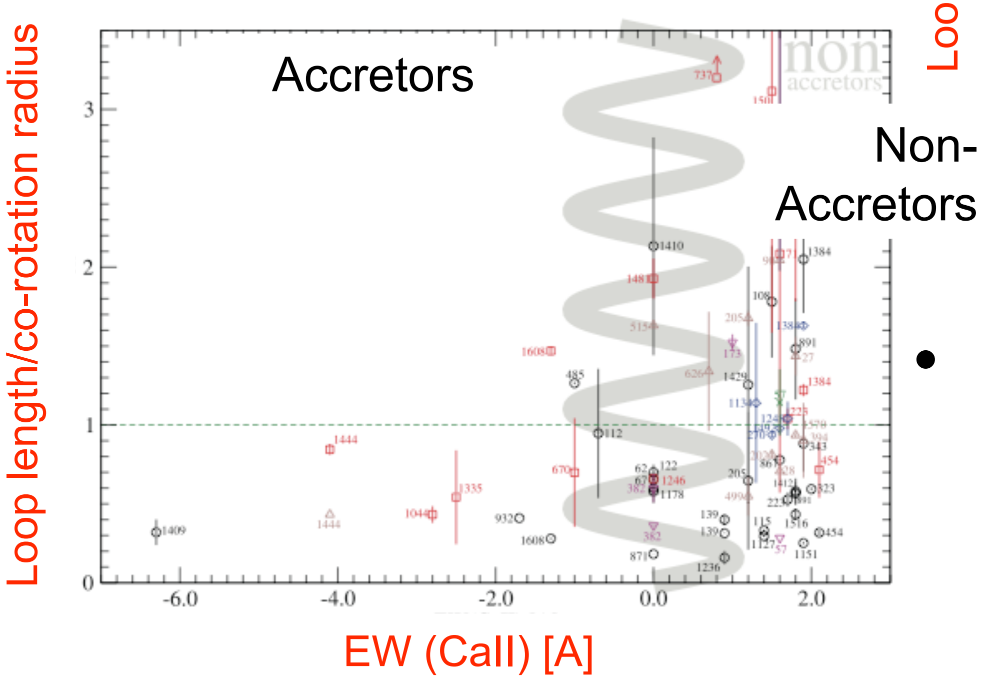
- Many large flares detected during COUP *(Favata et al 2005).*
- Large flares detected from HL Tau *(Giardino et al 2006),* and T Tau South *(Lionard et al 2005).*
- Flaring lengths ~5R$_*$, but many may be longer ~10-20R$_*$.

Credit: NASA/CXC/A.Hobart

What determines the size of the corona?

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



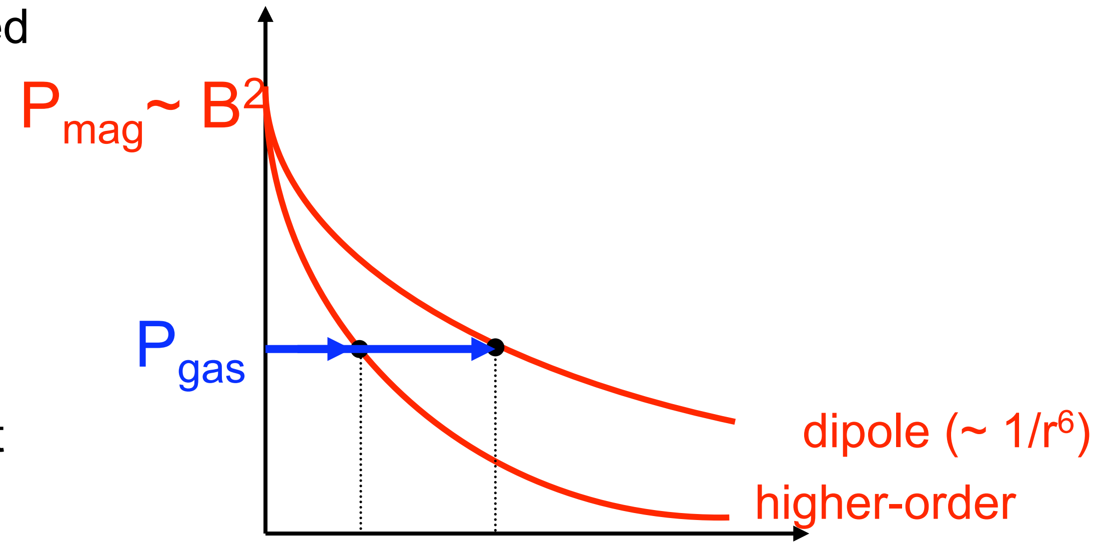


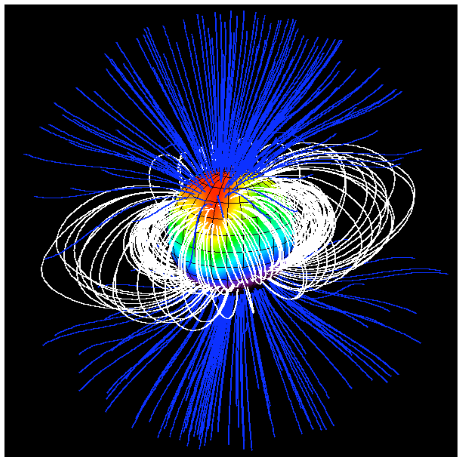
- ….and those that are not accreting….

Getman et al 2008a,b

…what role does the magnetic structure play?

- If coronal extent determined by balance of gas and magnetic pressure…
- Dipolar fields -> extended coronae
- Compact fields -> compact coronae



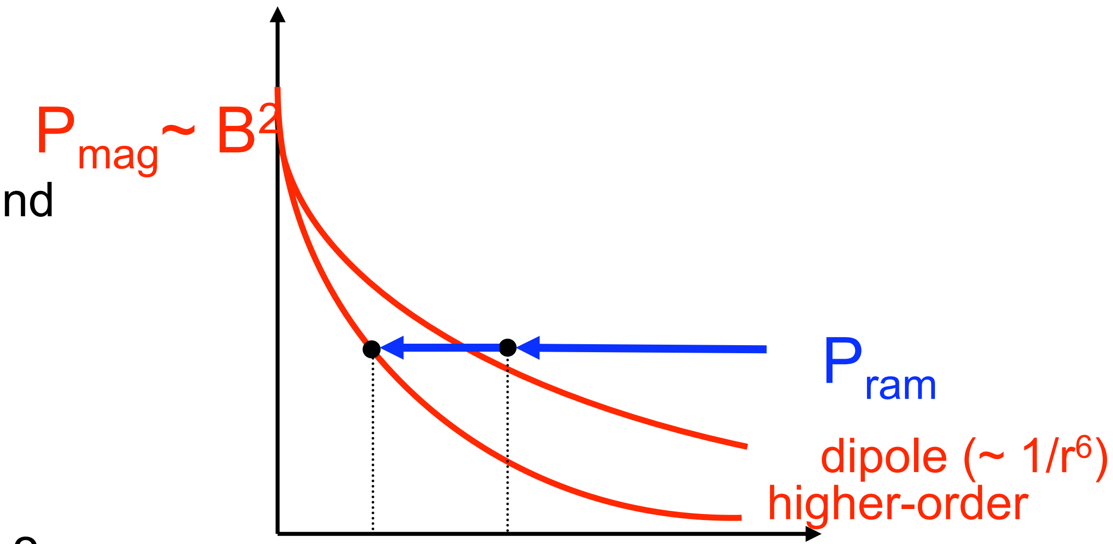


$$p = p_0 e^{\frac{m}{kT}\int g_{\|} ds}$$ and in the equatorial plane

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

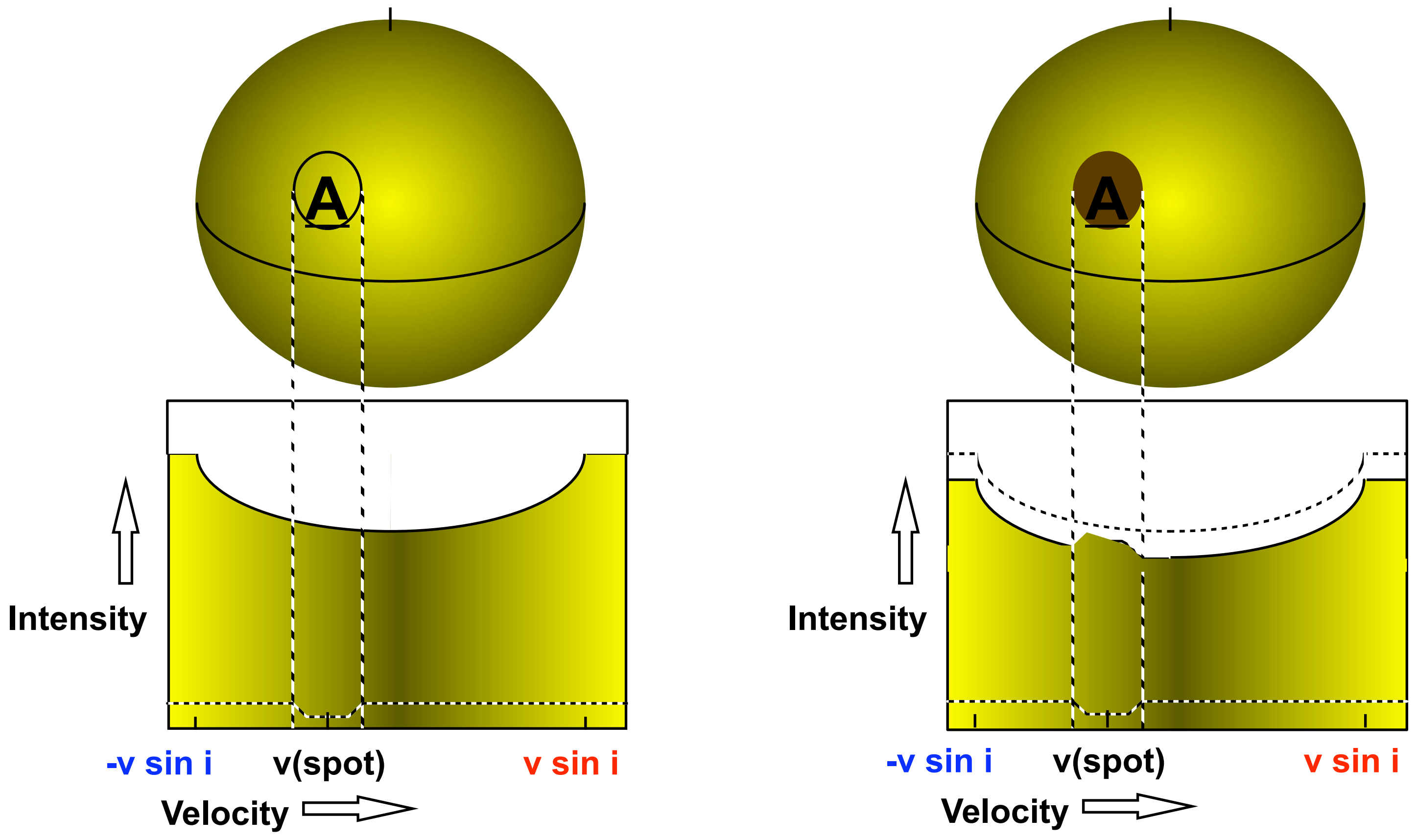
This also influences disk disruption radius..

- Disk disrupted at some radius determined by interaction between disk and magnetosphere
- Dipolar fields -> larger disruption radius?
- What if field lines are open?

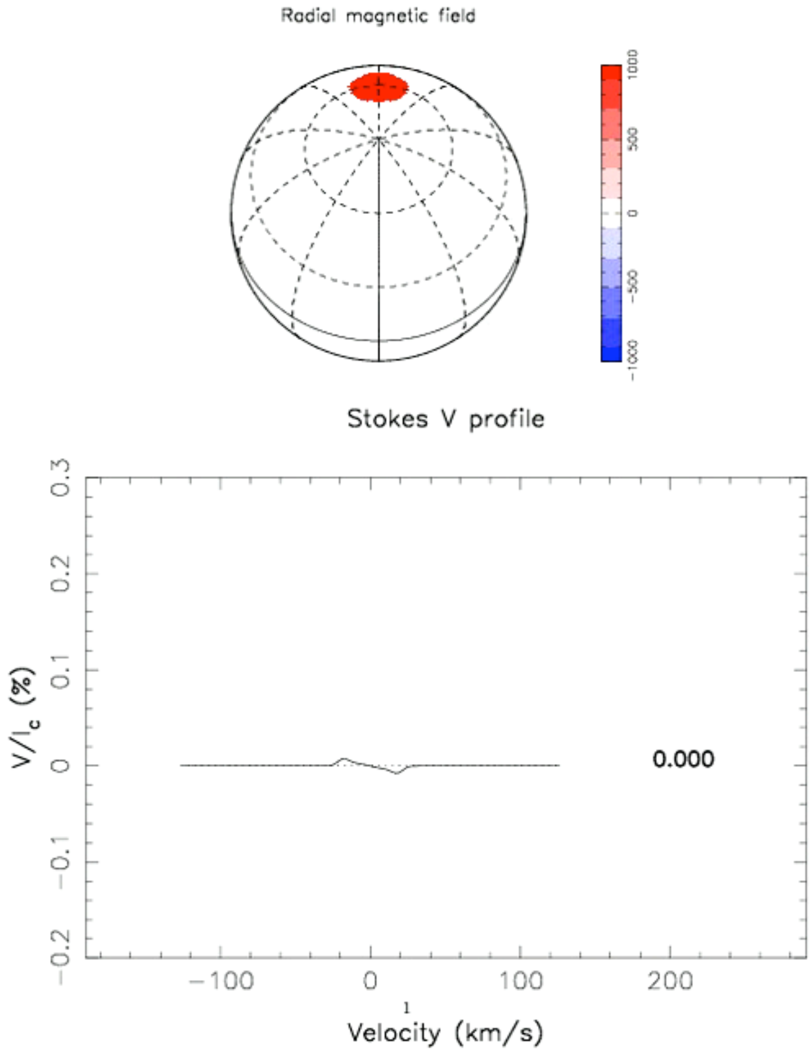


How do we determine the magnetic field structure?

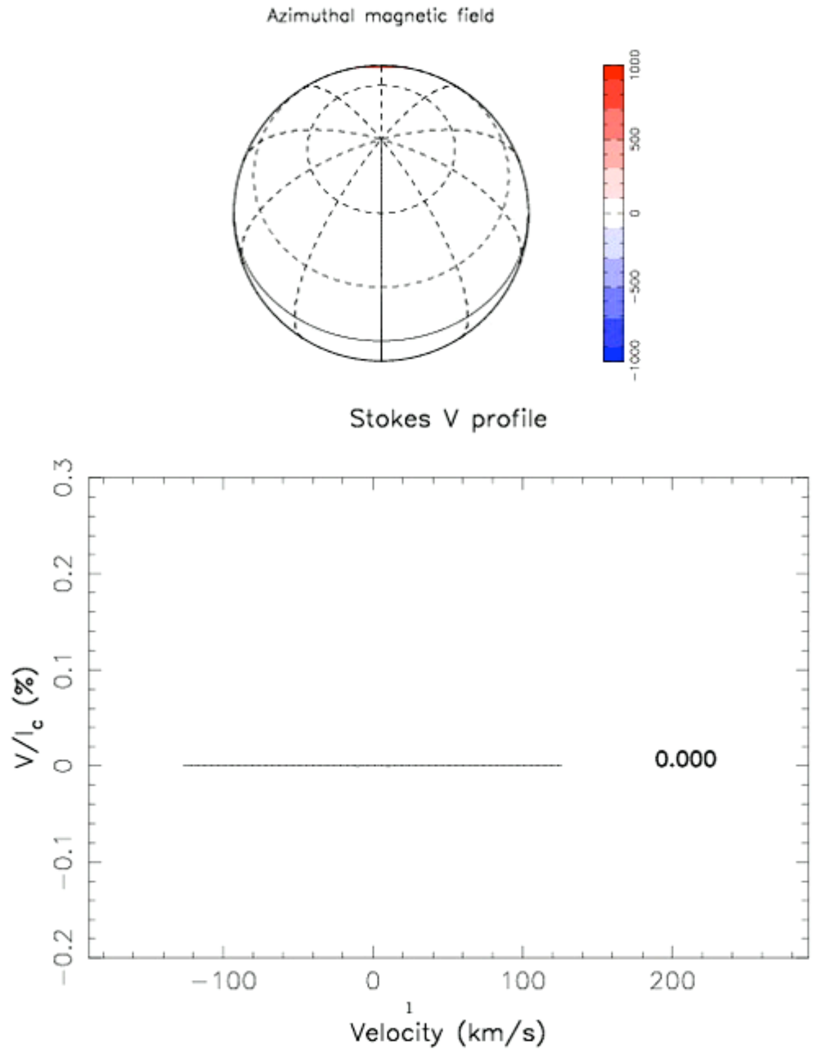
Doppler Imaging: Basic Principles



Radial field



Azimuthal field



Imaging stellar magnetic fields

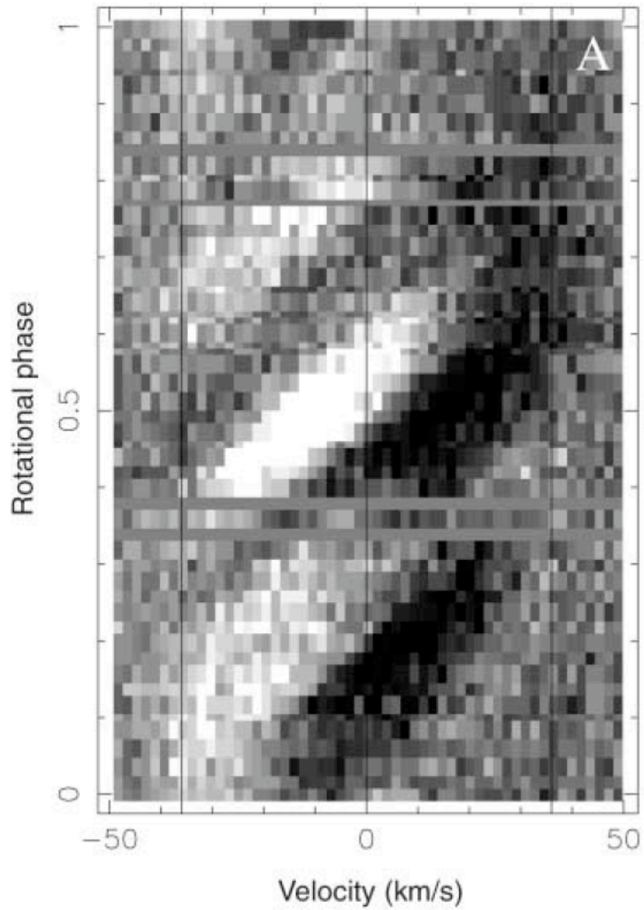
Fit Stokes profiles with spherical harmonics

$$B_r(\theta,\phi) = -\sum_{\ell,m} \alpha_{\ell,m} Y_{\ell,m}(\theta,\phi)$$

$$B_\theta(\theta,\phi) = -\sum_{\ell,m} (\beta_{\ell,m} Z_{\ell,m}(\theta,\phi) + \gamma_{\ell,m} X_{\ell,m}(\theta,\phi))$$

$$B_\phi(\theta,\phi) = -\sum_{\ell,m} (\beta_{\ell,m} X_{\ell,m}(\theta,\phi) - \gamma_{\ell,m} Z_{\ell,m}(\theta,\phi))$$

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

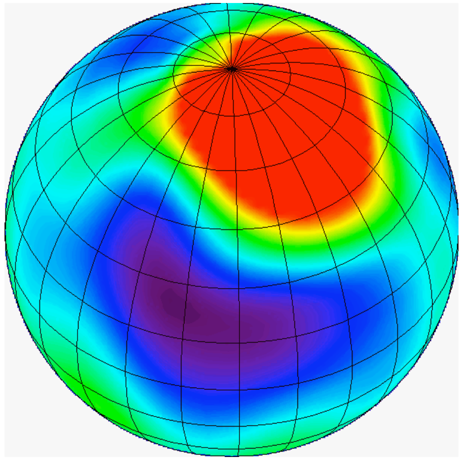


Stokes V

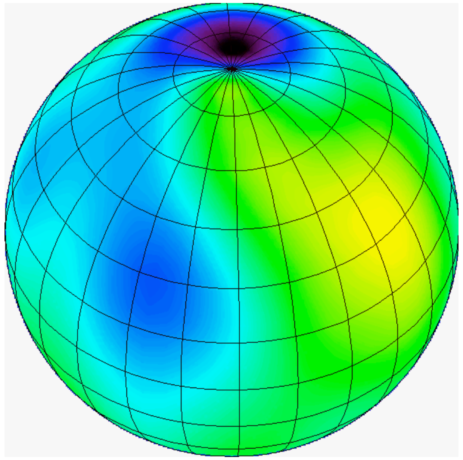
The magnetic field of v2129 Oph

- A young (1.5 - 3.0 Myr) moderately-accreting T Tauri star
- Mass ~ 1.35 +/- 0.15M_{Sun}, Radius ~2.4 +/- 0.3R_{Sun}
- Period = 6.5d, vsini = 14.5 +/- 0.3 kms^{-1}

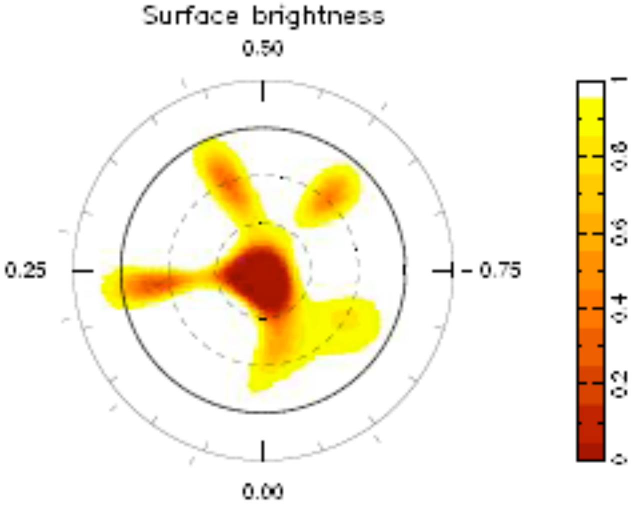
- ESPADONS spectropolarimetry (*Donati et al 2007*)
- Maps in photospheric lines, Ca II IRT, HeI λ587.562
- 1.2kG (tilted) octupole, 0.35kG dipole



Radial field

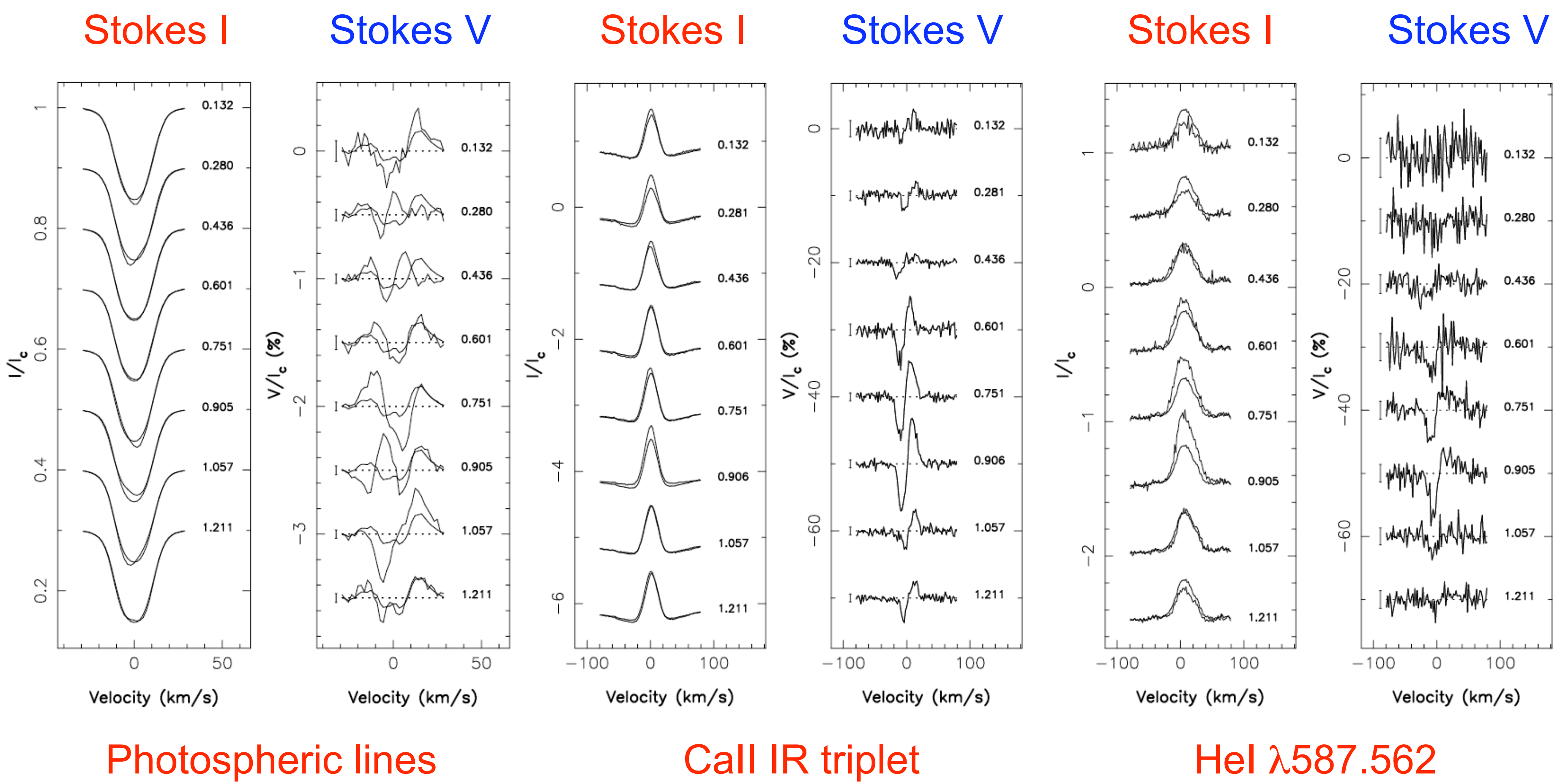


Azimuthal field



Signatures of accretion of v2129Oph

- He I emission excess at same phase as strong positive field

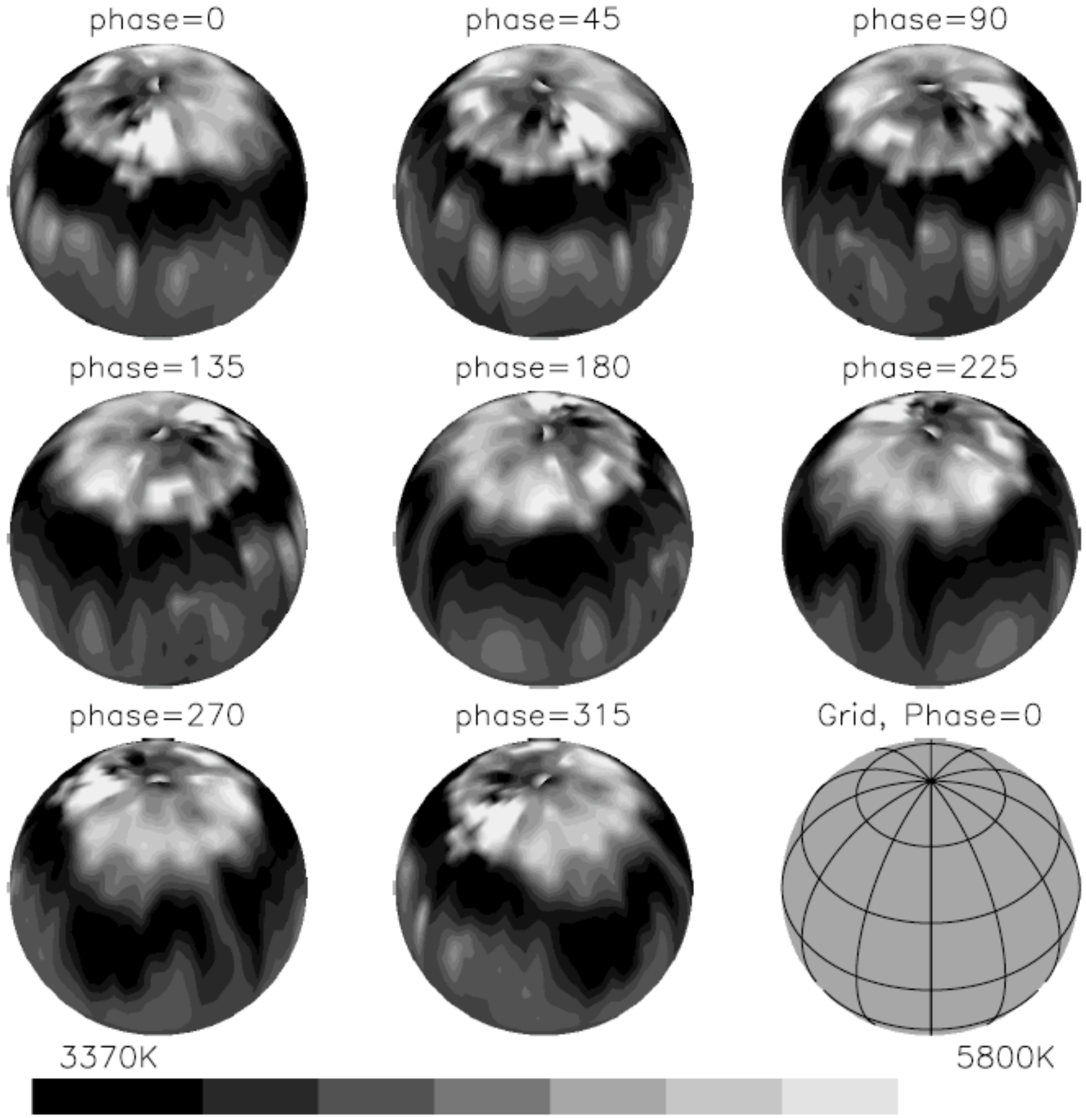


What is the field structure in surface dark/bright regions?

Where are the regions of

1) open
2) closed
3) accreting

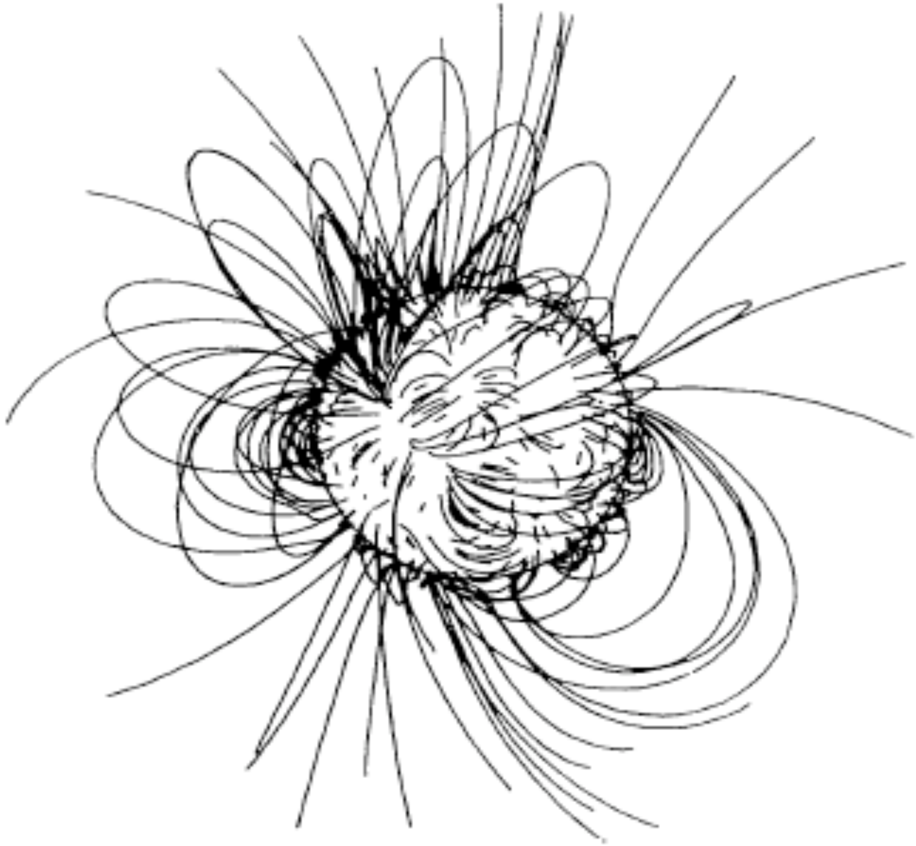
field lines?



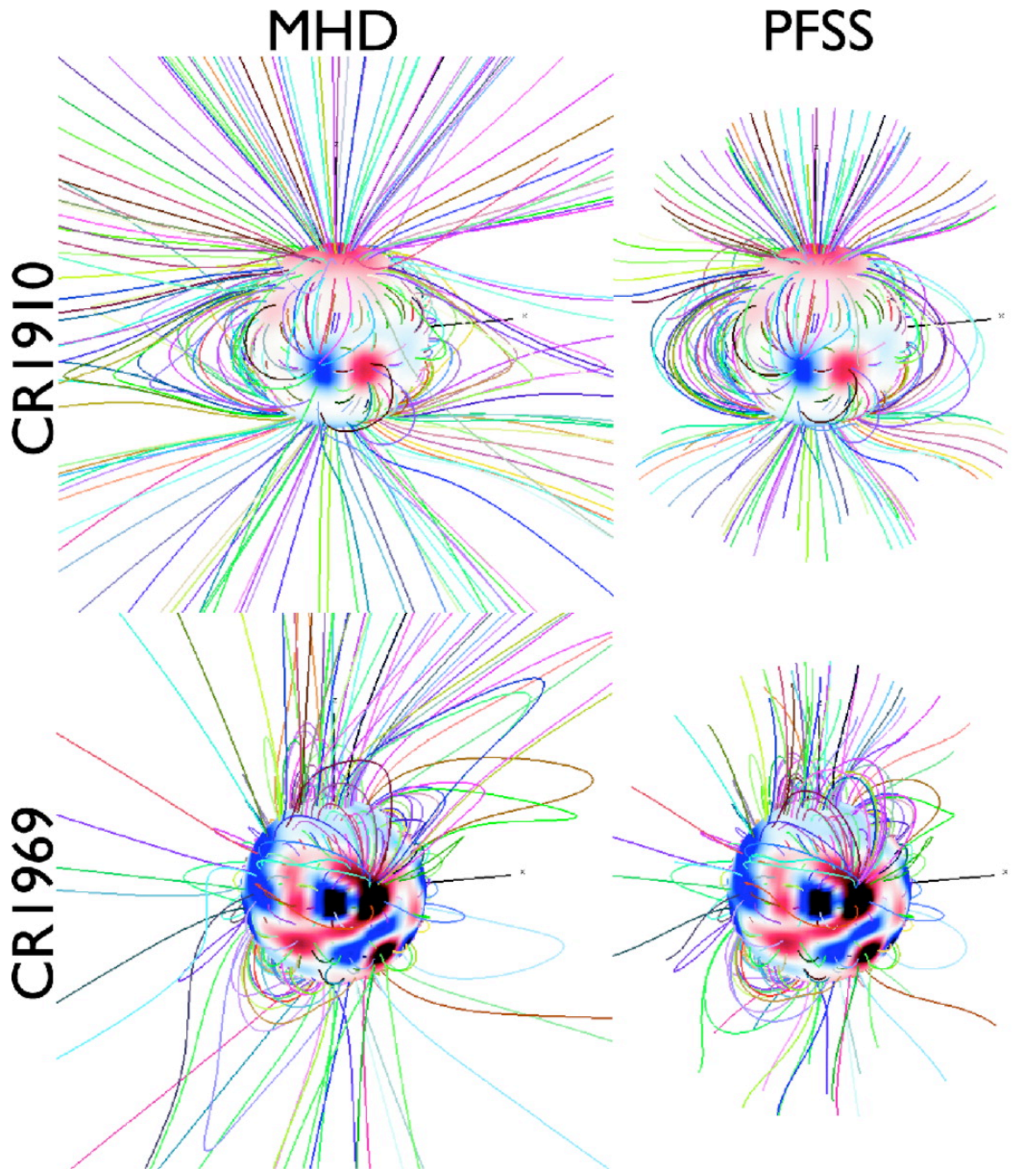
- *MN Lupi: Strassmeier et al 2005*

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.

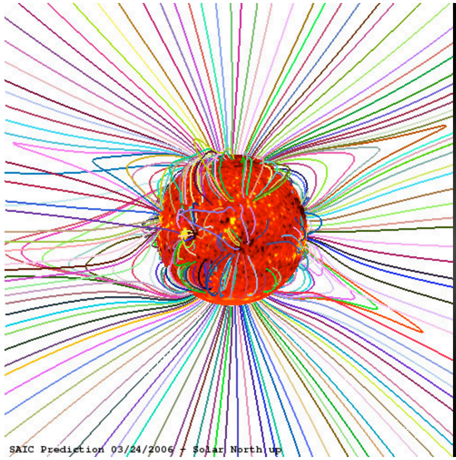


For the same surface fields, different “source surfaces” give different coronal fields.

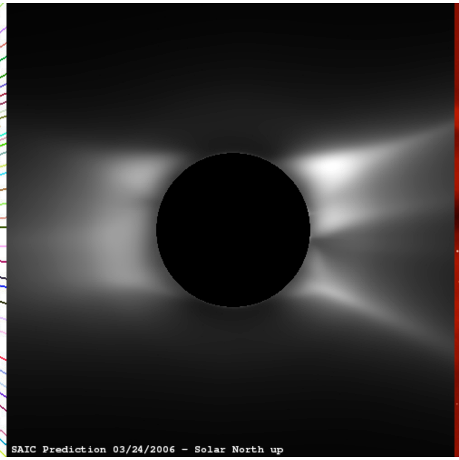


- Comparison between *potential field source surface* model and full MHD model is good for large scale structure *(Riley et al 2006)*

Comparison Between 3D MHD Model Prediction and Solar Eclipse Observation



Predicted Magnetic Field



Predicted Polarization Brightness

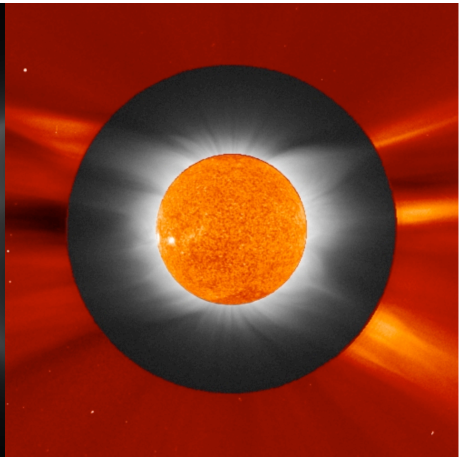
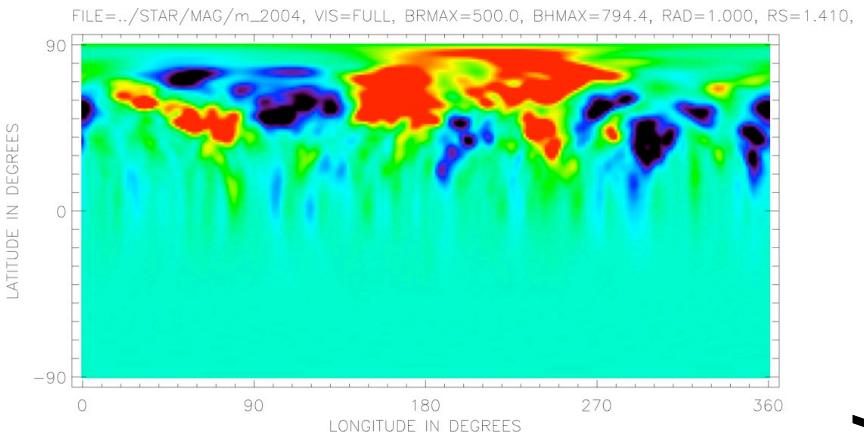


Image from Greece: Williams College Expedition*

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.

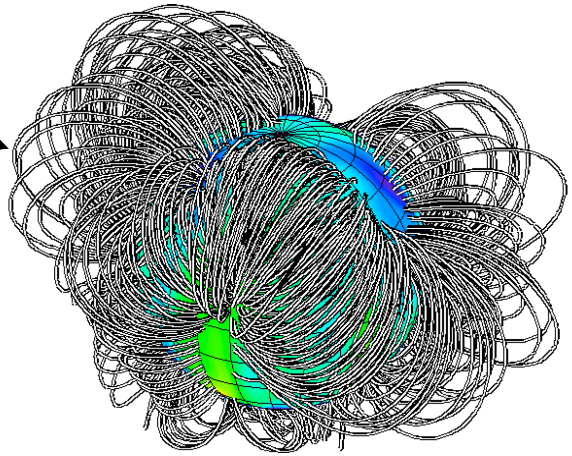
How do we model stellar coronae?



Extrapolate surface field

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

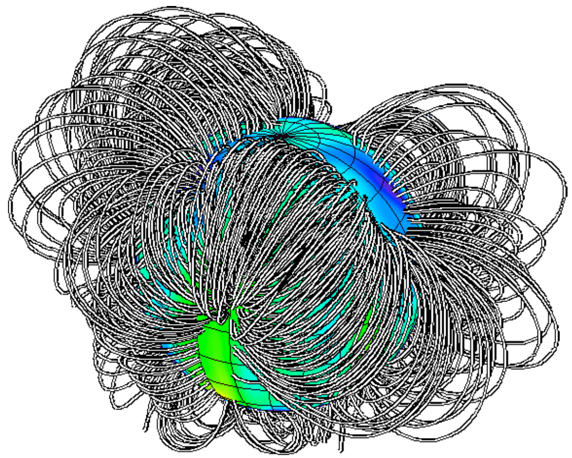
–NB: extension to non-potential fields (Hussain *et al* 2002)



Isothermal, hydrostatic corona

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

Extrapolating the surface field



- 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)

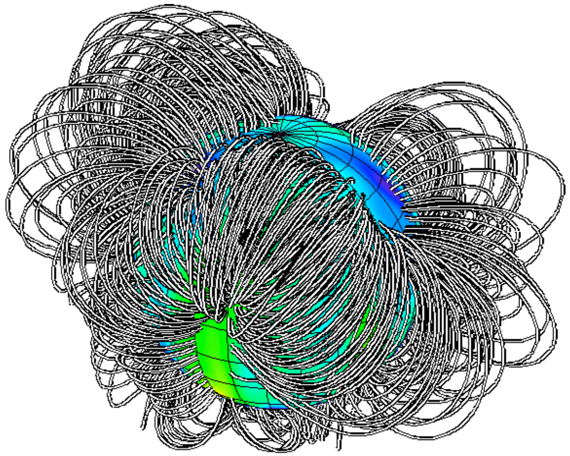
Boundary conditions:

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

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

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

Determining the pressure structure

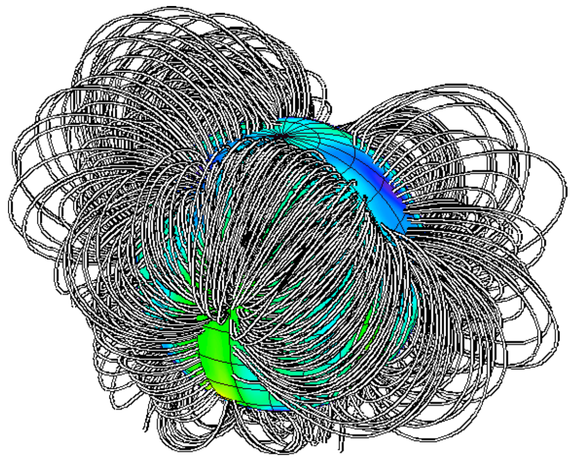


- Along each field line, assume a hydrostatic, isothermal gas at 10^6 or 10^7 K
- Base pressure $p_0 = K B_0^2$ (determine K by fitting to observed X-ray emission measure)
  - Hence for a stellar rotation rate ω:

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

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

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

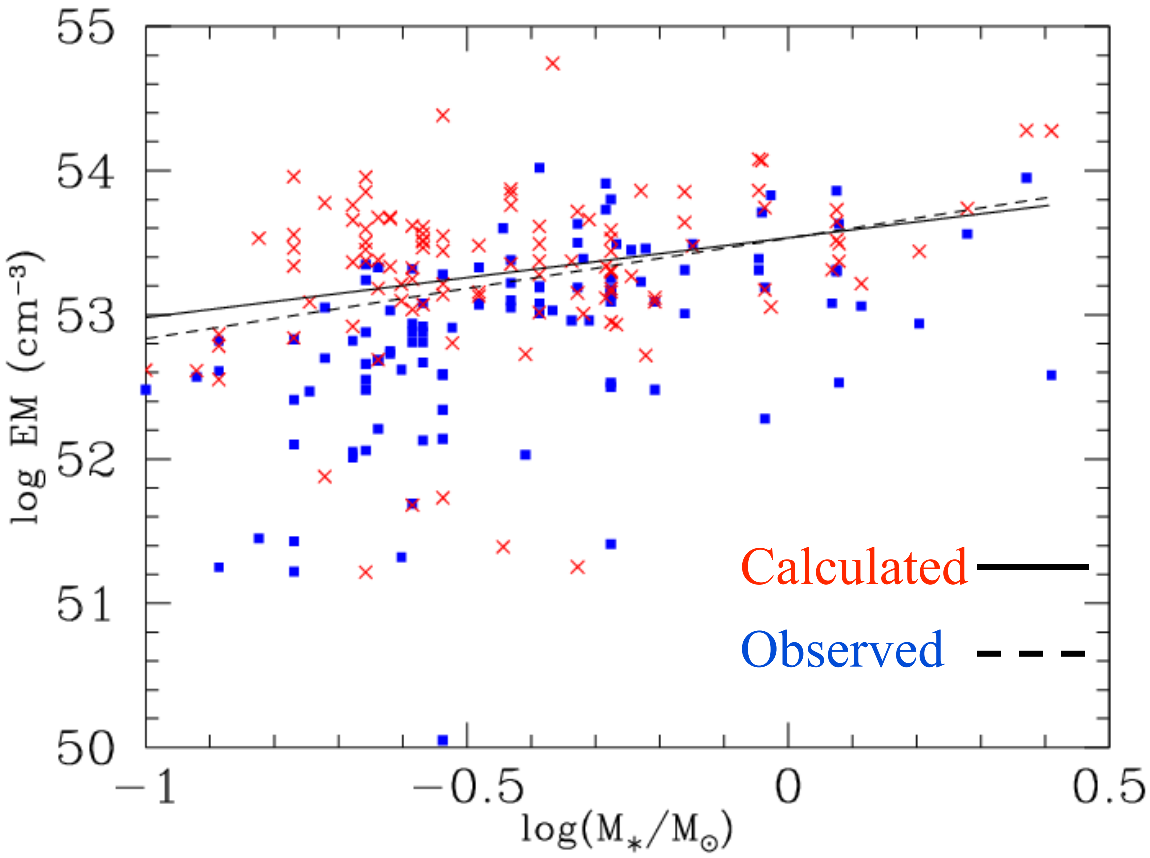


- All field lines that pass through the disk beyond the co-rotation radius are opened up

- Emissivity $\propto n_e^2$

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)

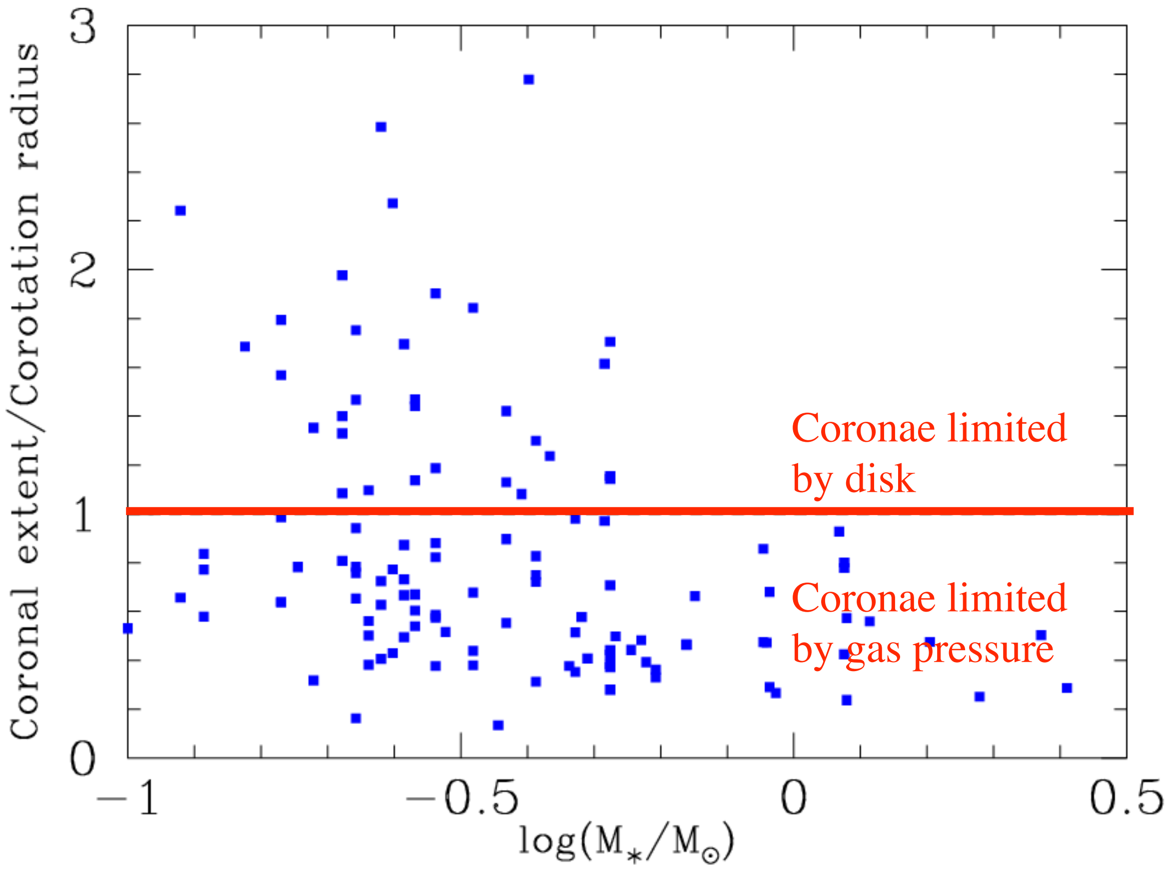
Where does the corona end?

- 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?

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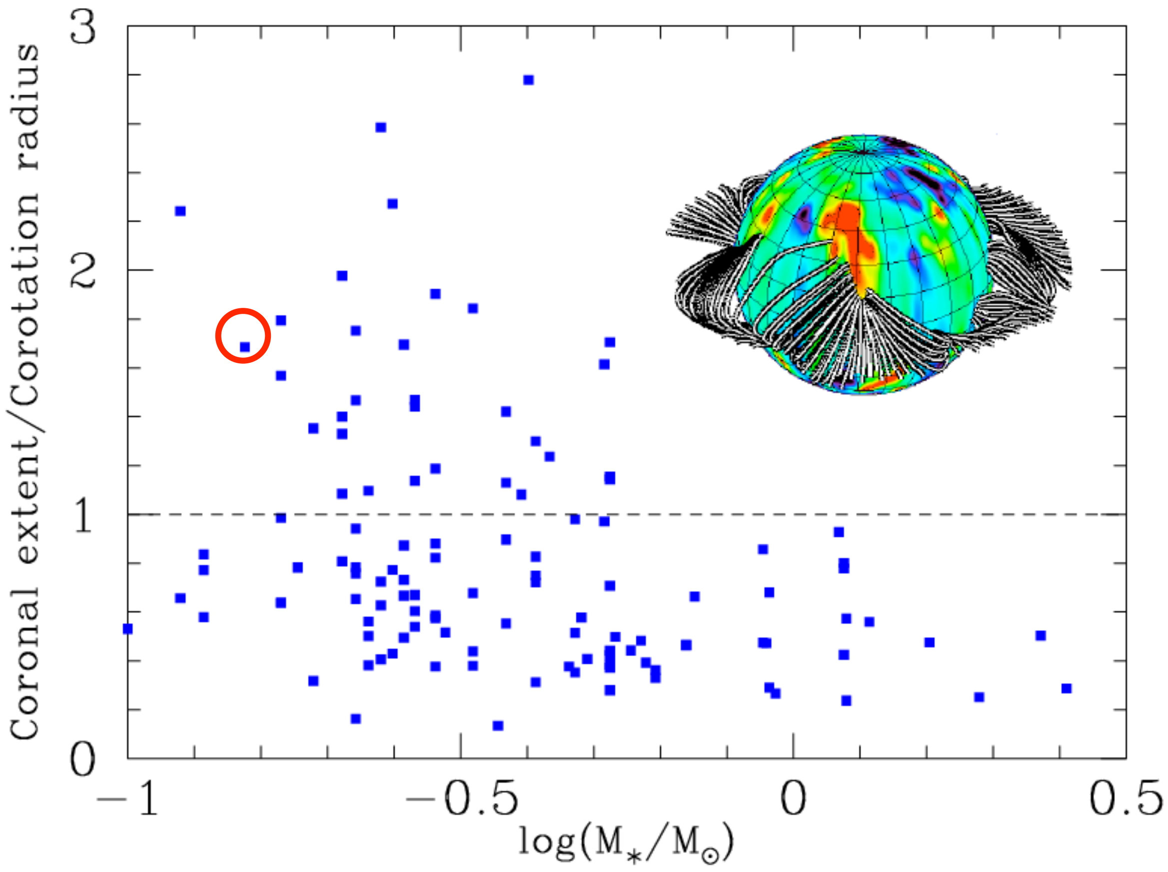


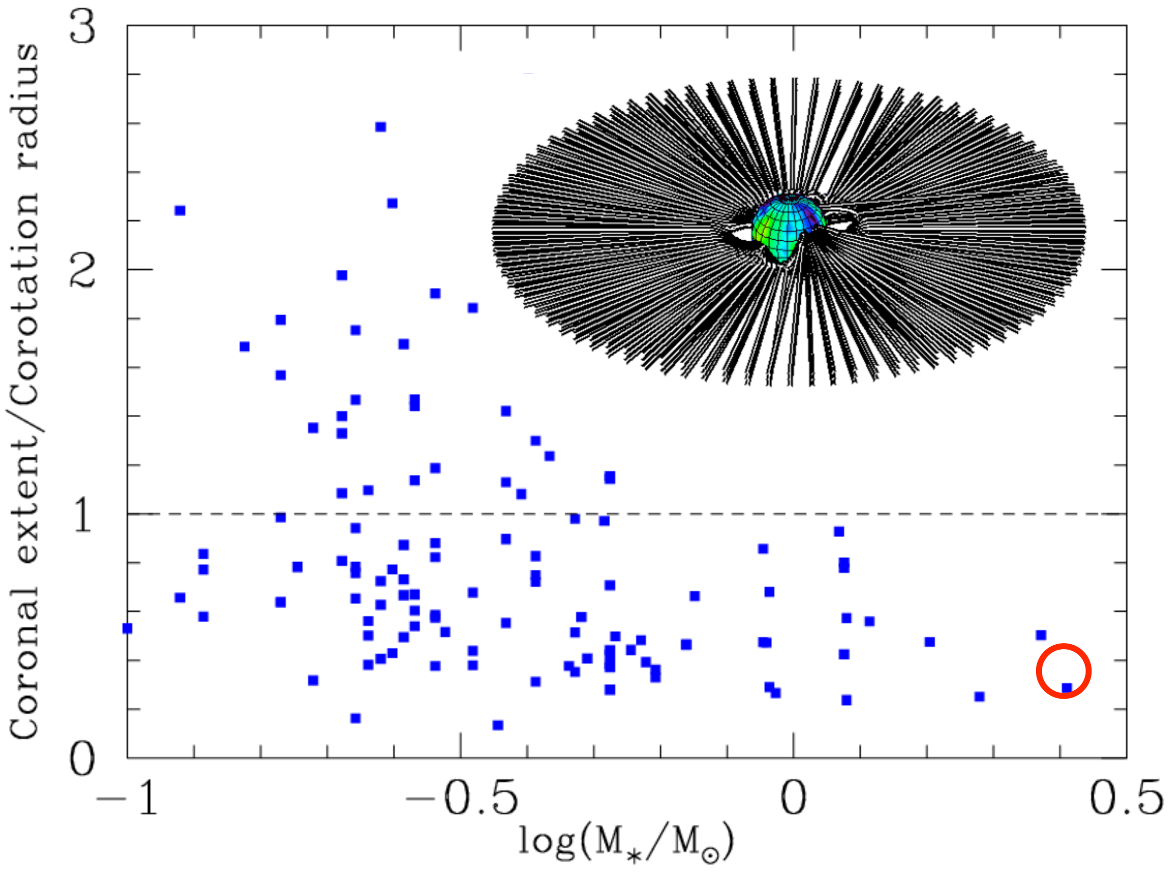
Where does the corona end?

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

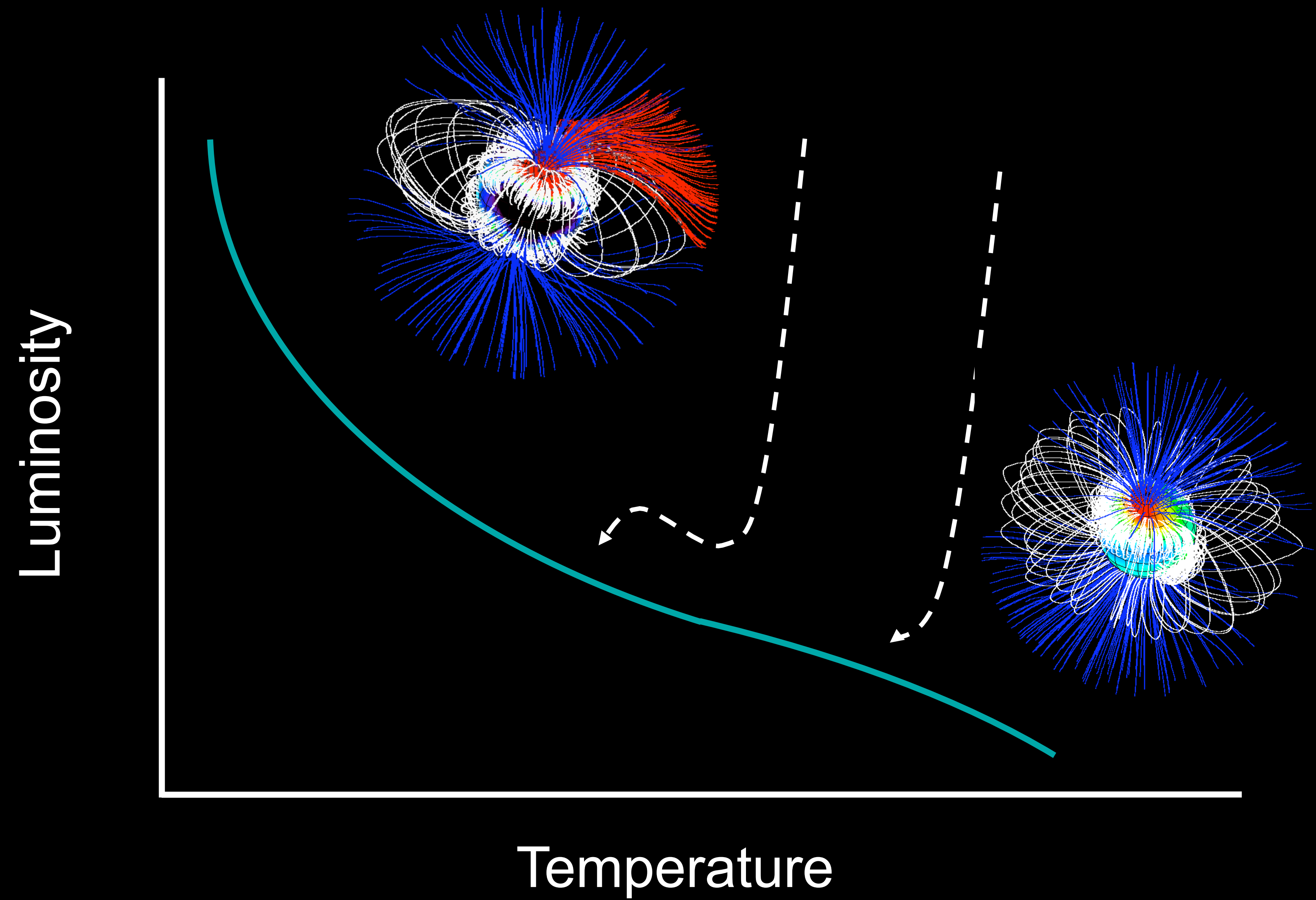
=> *Coronal extent limited by disk*

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

- *=> Coronal extent limited by pressure balance*



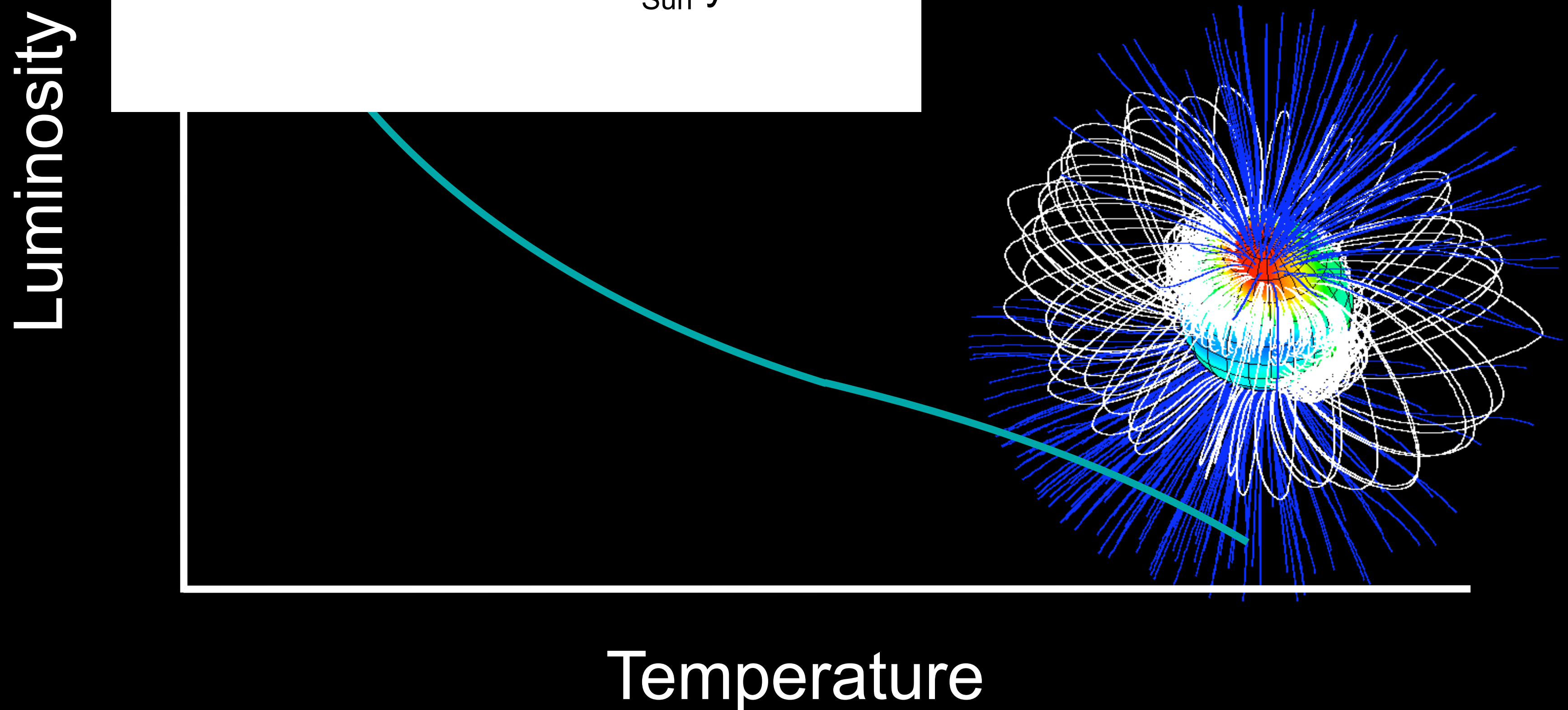
Pre-main sequence coronal structure



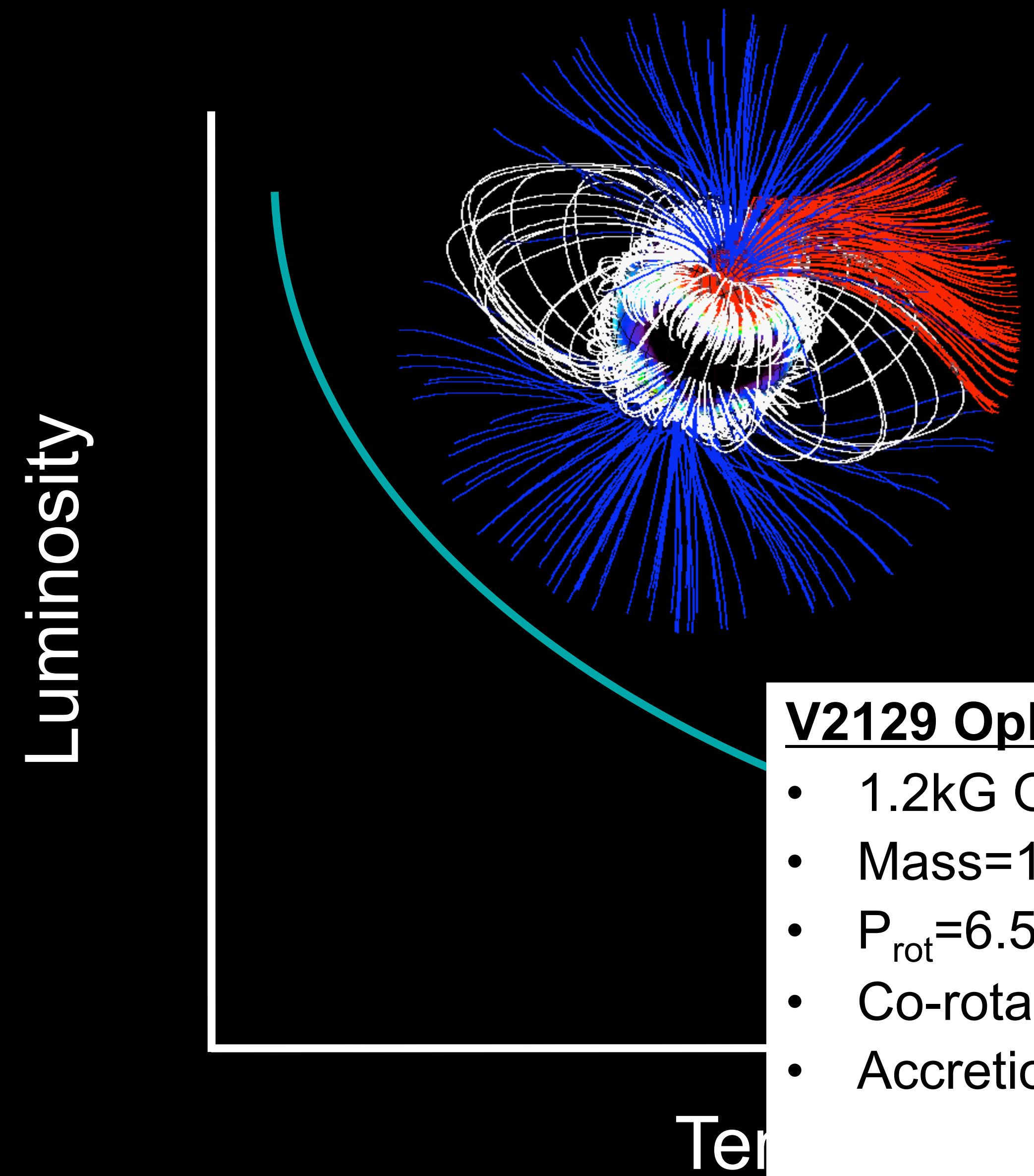
Coronal structure approaching the main sequence

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



Coronal structure approaching the main sequence

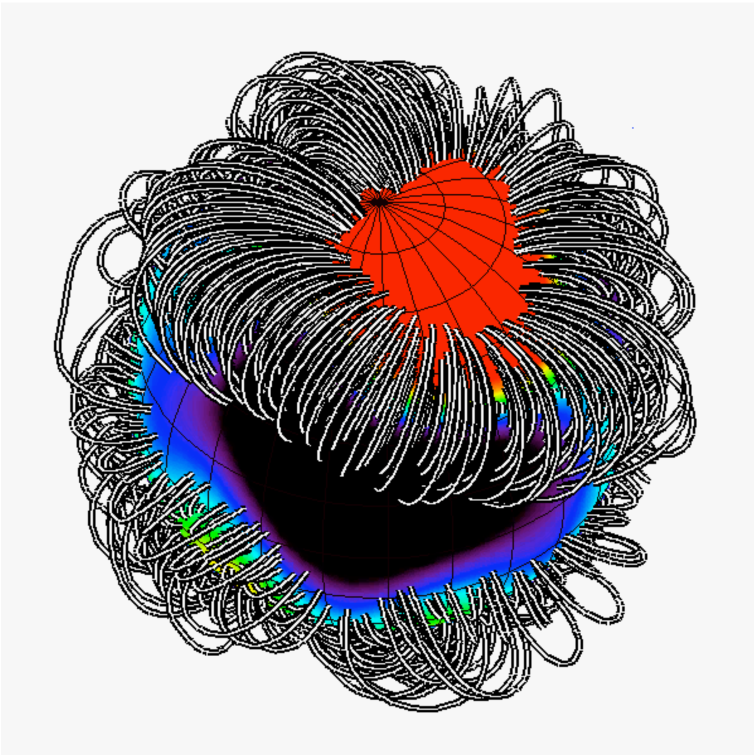


<u>V2129 Oph</u>

- 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

Magnetic structure of v2129 Oph on different scales

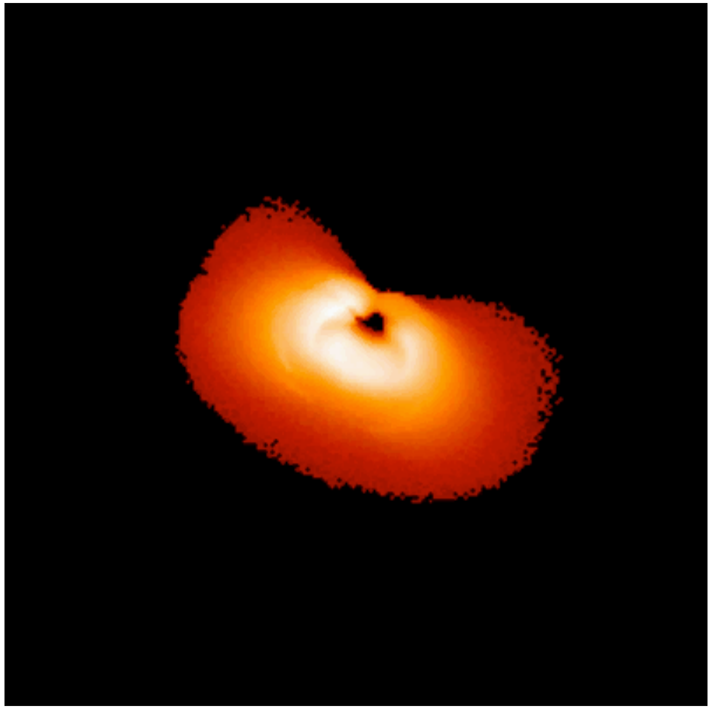
Small scale

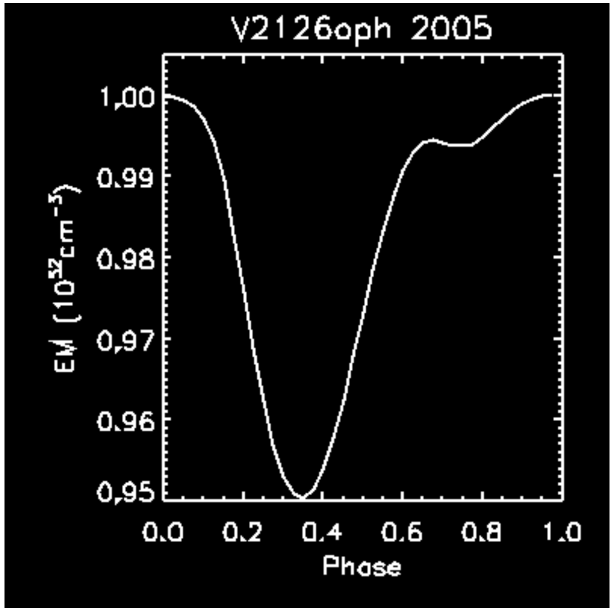


Larger scale

The X-ray emission of v2129Oph

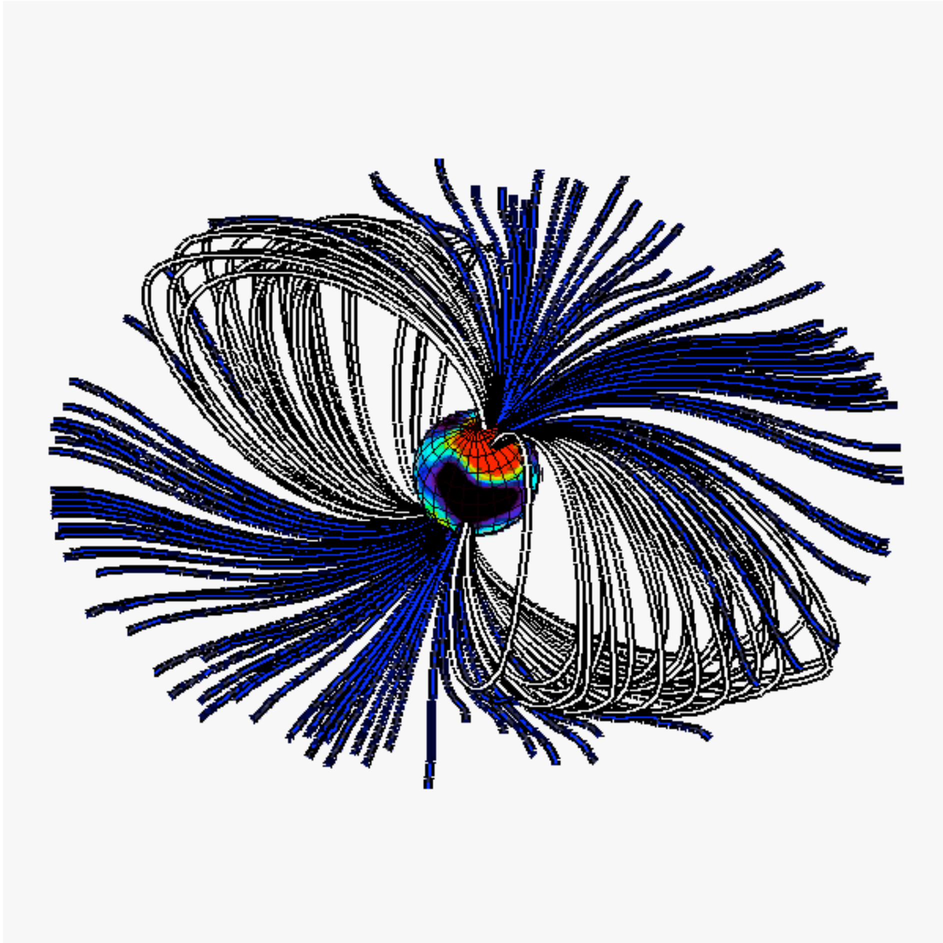
- Corona at 2×10^7K is compact
- Emission measure 4×10^{52} cm $^{-3}$ ($L_x = 4 \times 10^{30}$ erg s^{-1})
- Emission measure-weighted density 5×10^9 cm $^{-3}$
- Always in view -> low rotational modulation ~ 5%





Where is the accretion located?

- Select those field lines that
  - pass through the equatorial plane
  - have inward-pointing gravity
- Accretion funnels onto positive polarity region
- Accretion lights up the large scale field *that cannot be detected in X-ray emission*
- Accretion flow models can predict line shifts

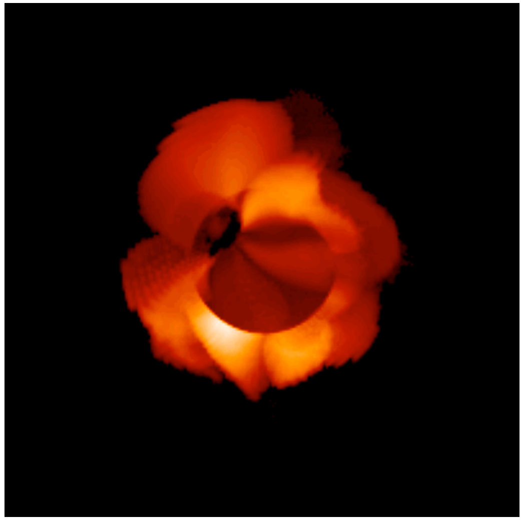


What are the outstanding questions?

- Understanding disk/magnetosphere interaction for stars of different masses, ages, and rotation rates.
- Does the change in internal structure when the radiative core develops lead to a change in the magnetic structure?
  - Does this affect X-ray emission/wind loss?
- Impact on planets (angular momentum loss, star-planet interaction).
- Spin-down as a measure of stellar age (gyrochronology)

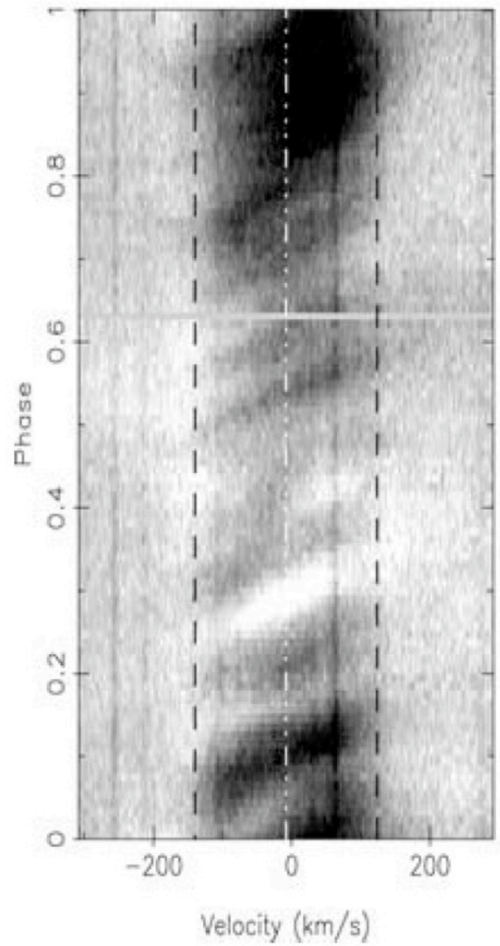
How extended are the coronae of active stars?

- 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)

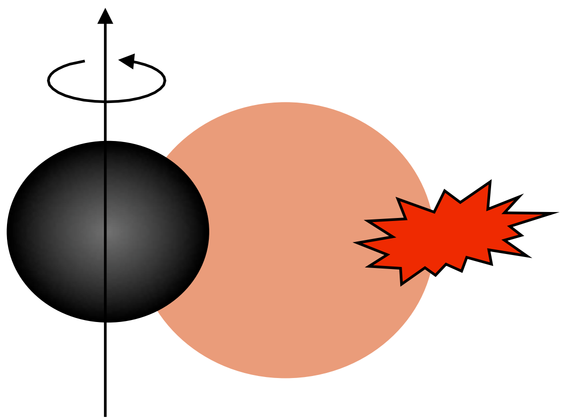


Jardine *et al* (2002)

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

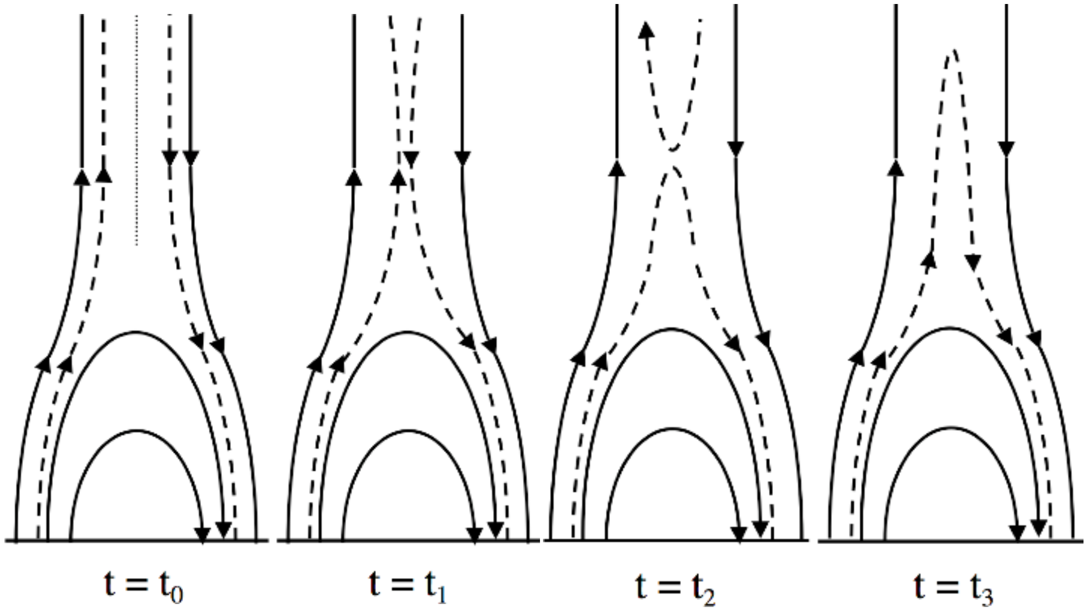


- *Do the prominences lie in the X-ray emitting corona or in the wind?*



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

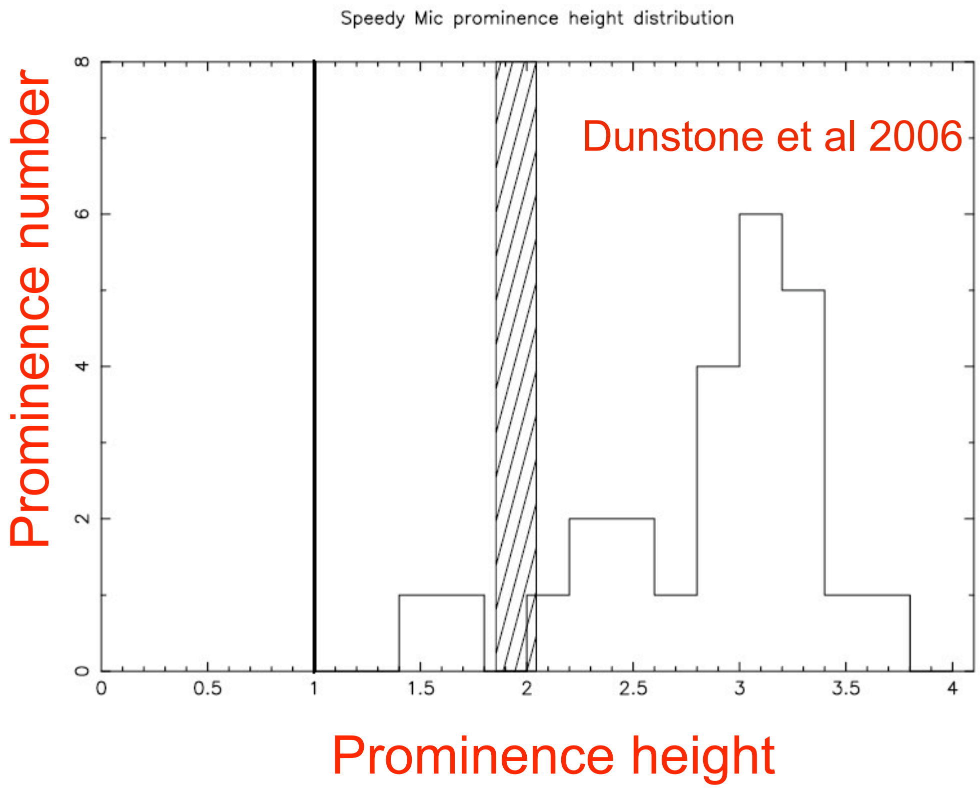


$$\frac{y_m}{R_*} = \frac{1}{2}\left\{-1 + \sqrt{\left[1 + 8\left(\frac{R_k}{R_*}\right)^3\right]}\right\}$$

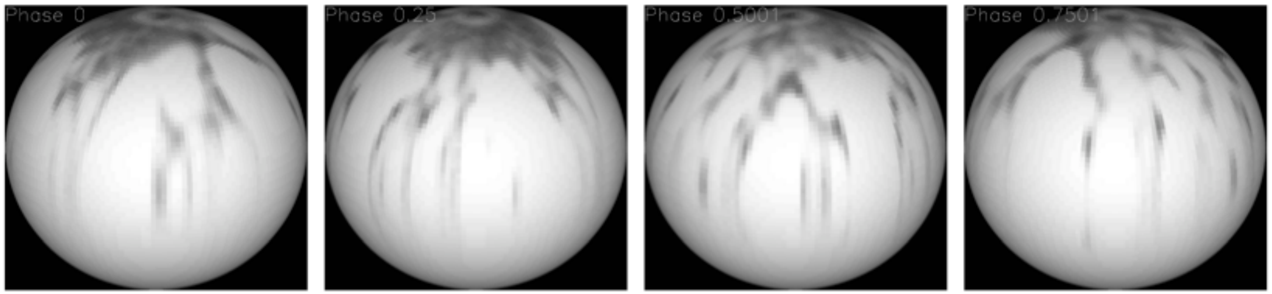
Jardine & van Ballegooijen 2006

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)

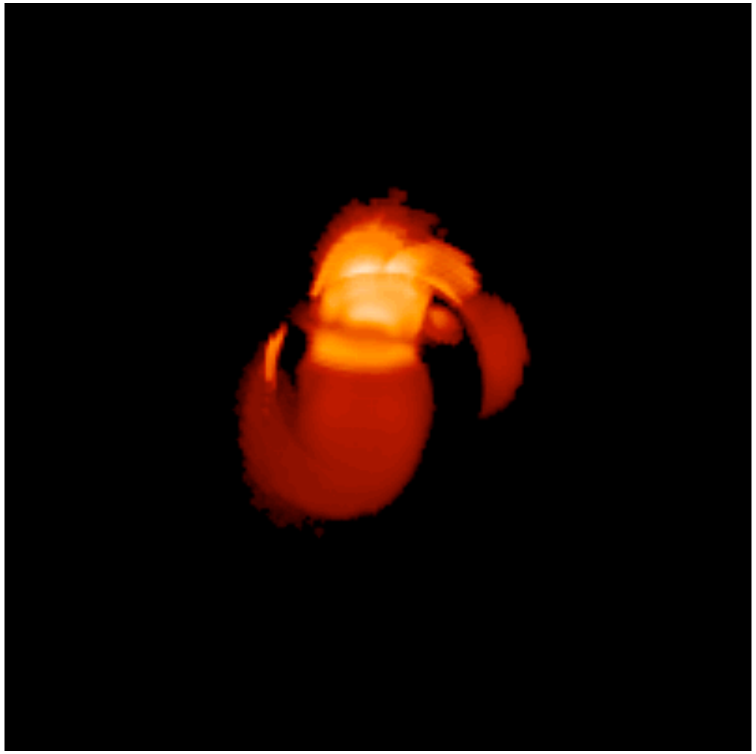


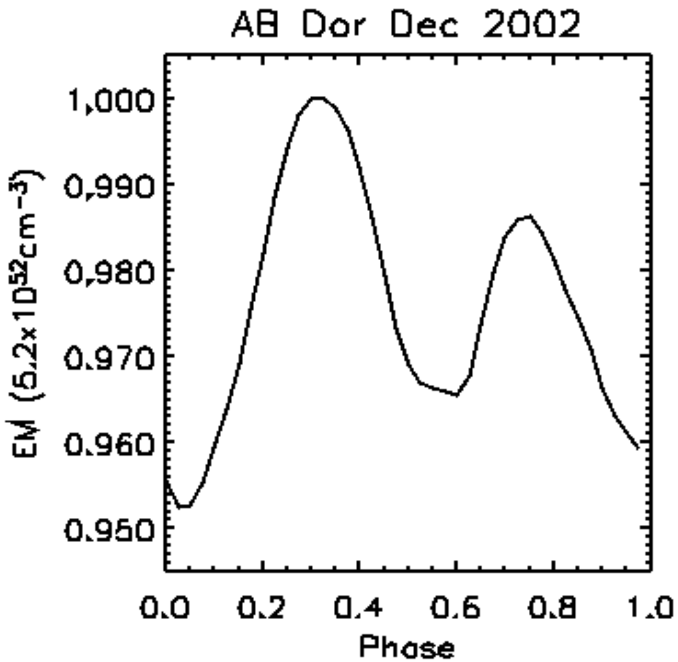
AB Dor 2002 Dec

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

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

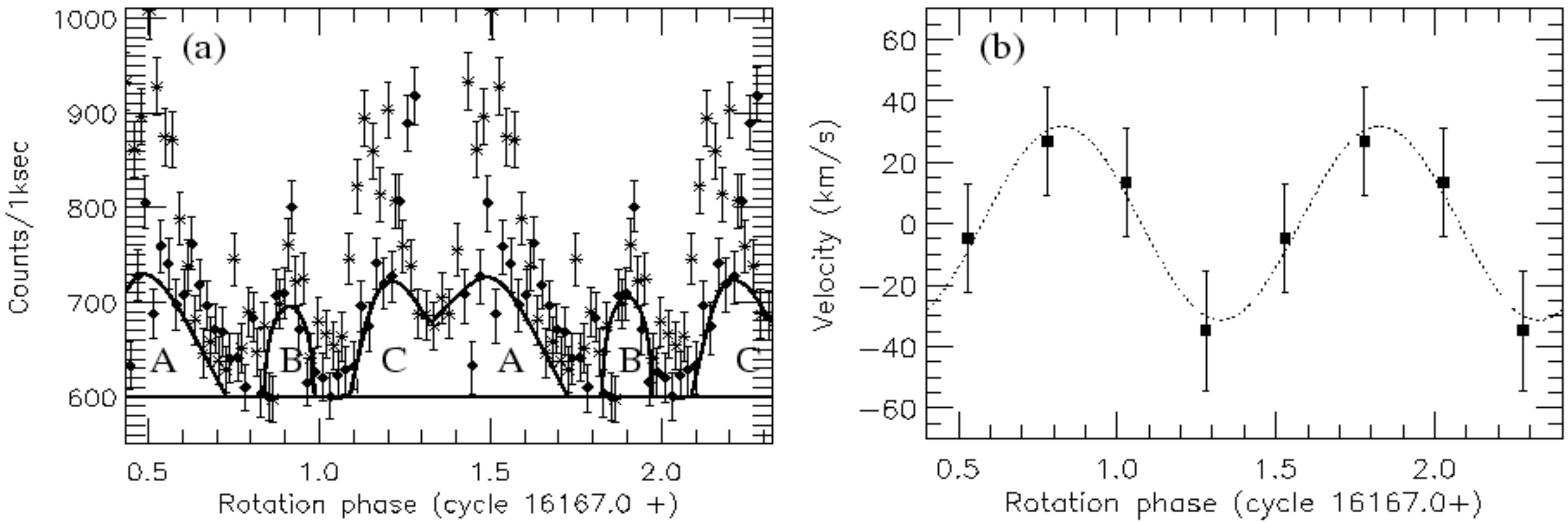
- Always in view -> low rotational modulation ~ 5%





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)

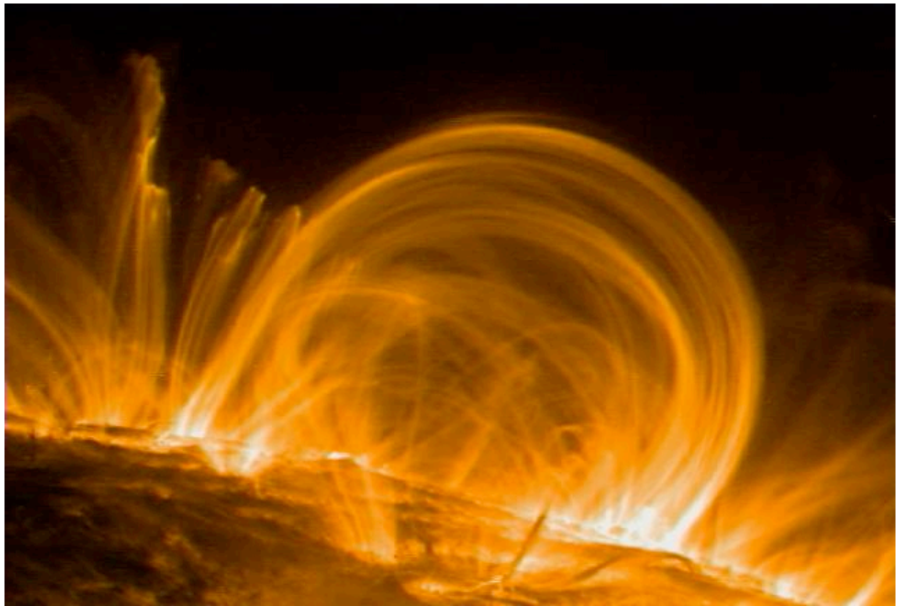


Hussain et al 2004, ApJ

$$
\begin{aligned}
Y_{\ell,m}(\theta,\phi) &= c_{\ell,m} P_{\ell,m}(\theta)\; e^{im\phi} \\
Z_{\ell,m}(\theta,\phi) &= \frac{c_{\ell,m}}{\ell+1} \frac{\partial P_{\ell,m}(\theta)}{\partial\theta}\; e^{im\phi} \\
X_{\ell,m}(\theta,\phi) &= \frac{c_{\ell,m}}{\ell+1} \frac{P_{\ell,m}(\theta)}{\sin\theta}\; im\; e^{im\phi} \\
c_{\ell,m} &= \sqrt{\frac{2\ell+1}{4\pi} \frac{(\ell-m)!}{(\ell+m)!}},
\end{aligned}
$$

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*)



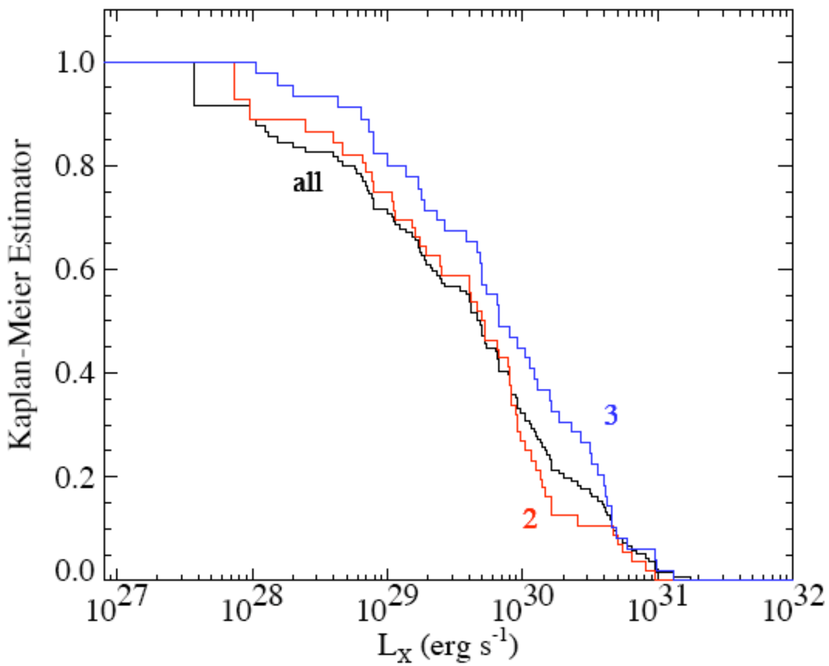
NASA: TRACE

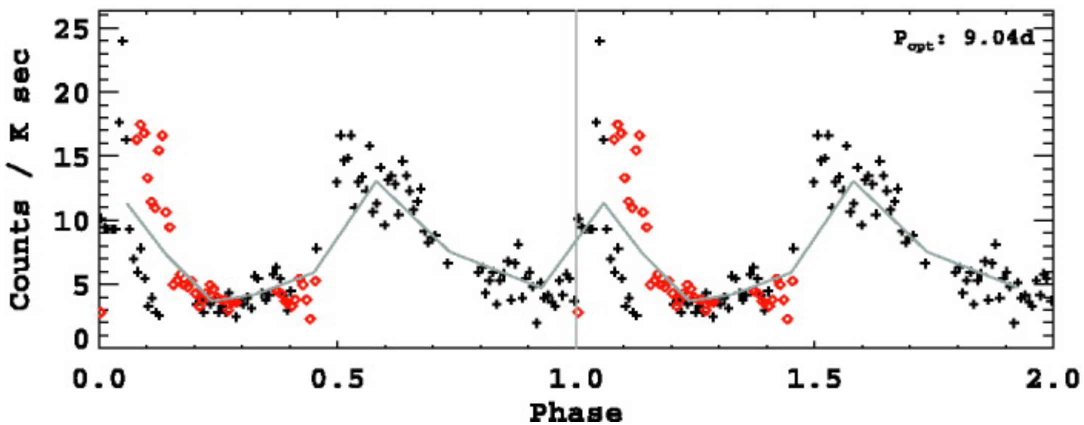
- X-ray emission
  - Bremsstrahlung of 10^6K electrons
  - Closed structures on scales $<< R_*$
  - Cyclic variation

What is the effect of accretion?

- Suppression of X-ray emission (*Guedel et al 2006)*
  - Also for radiative stars (*Rebull et al 2006*)
- Soft excess (*Telleschi et al 2006*)

X-ray luminosity function for cTTS and wTTS

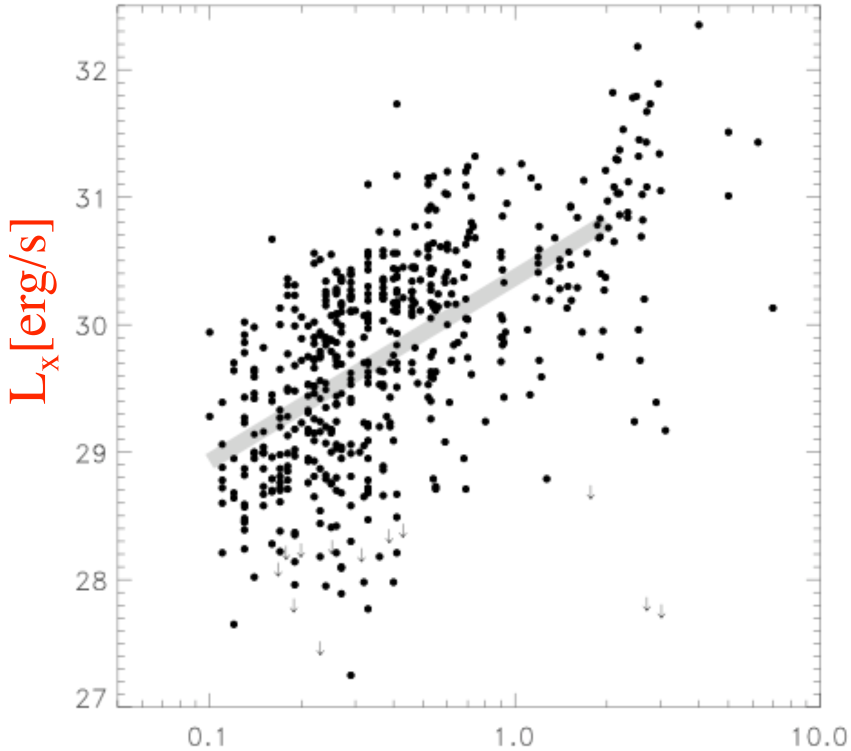




- Rotational modulation (*Flaccomio et al 2005*)

...issues with X-rays…

- $L_x \sim M_*$
- But note large scatter in L_x at each mass
- Drop in L_x as stars develop radiative cores (*Rebull 2006*)
- Suppression of L_x in cTTS?

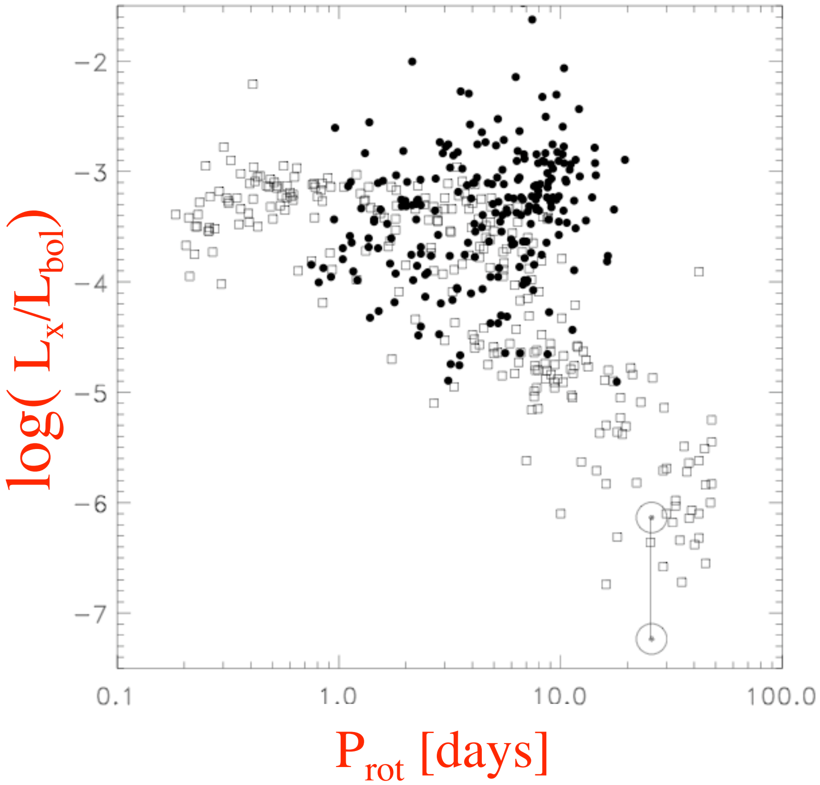


Stellar mass [solar masses]

(*Preibisch et al 2005, Feigelson et al 2006, Getman et al 2006, Guedel et al 2006*)

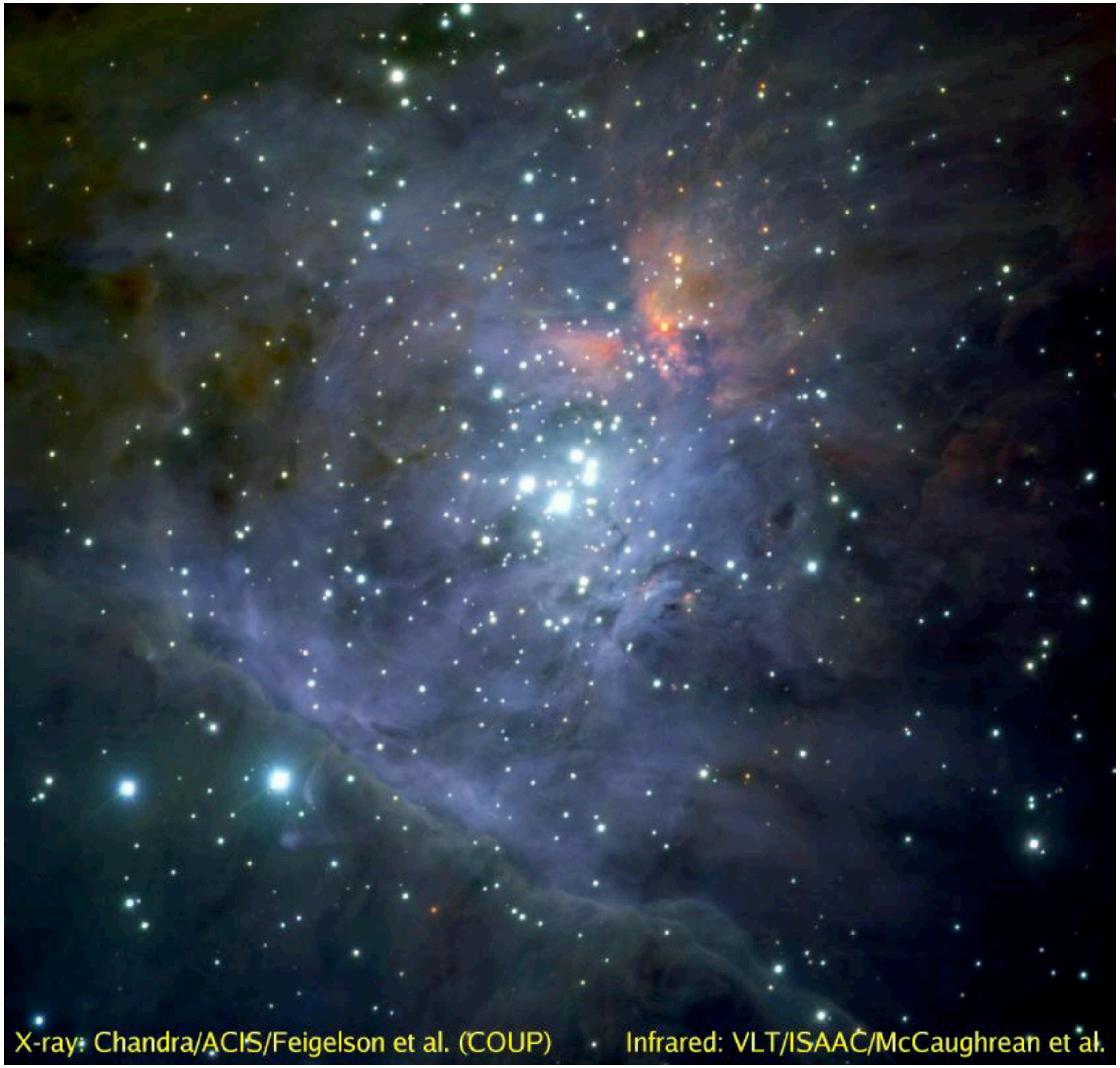
...issues with X-rays…

- No Period-Activity relation!
- Rotational modulation - compact coronae?
- Monster flares (l >> R_*) - field lines connecting to disk?

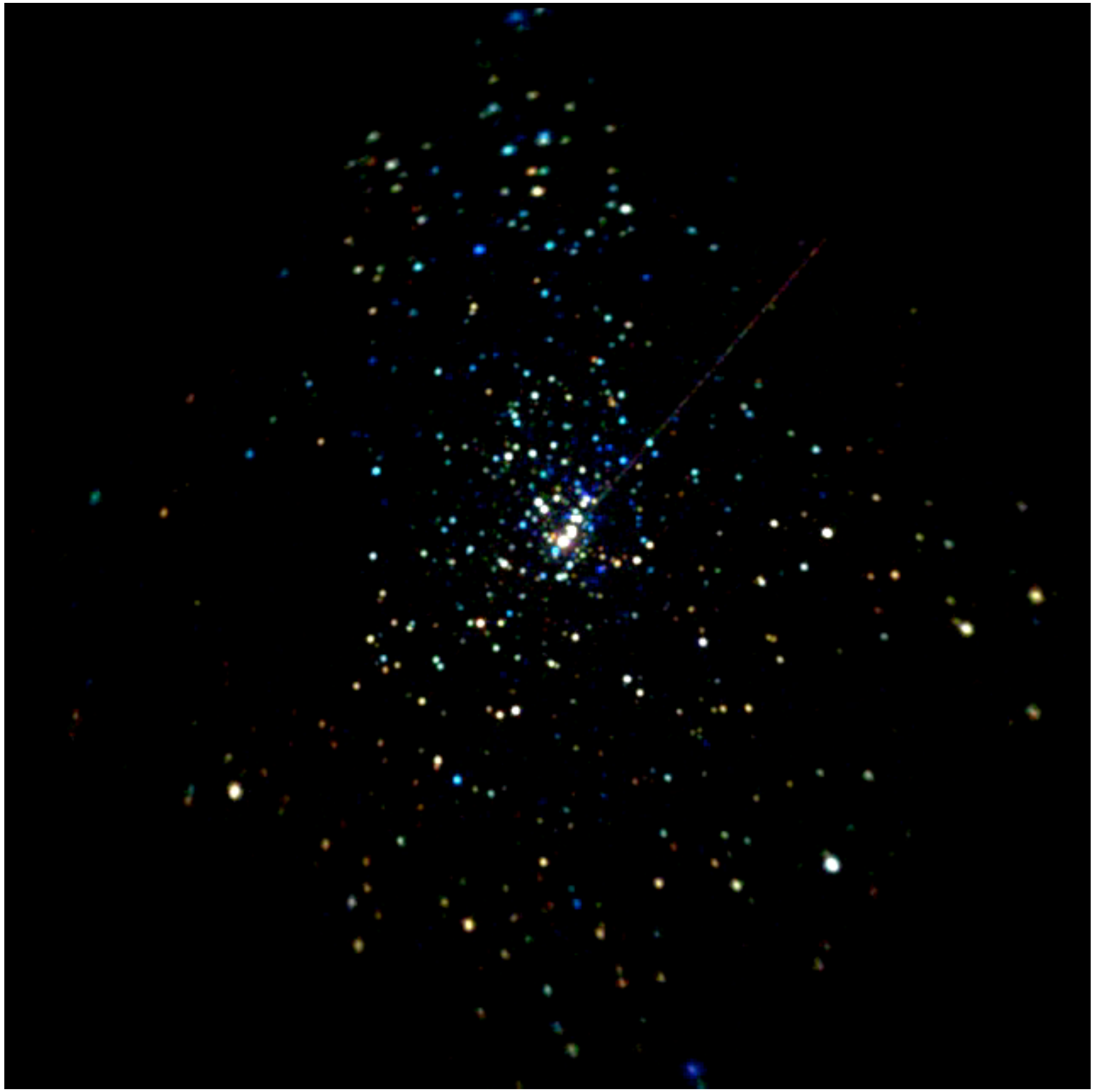


(*Preibisch et al 2005, Feigelson et al 2006, Flacommio et al 2005, Favata et al 2005, Getman et al 2006, Franciosini et al 2006,Guedel et al 2006*)

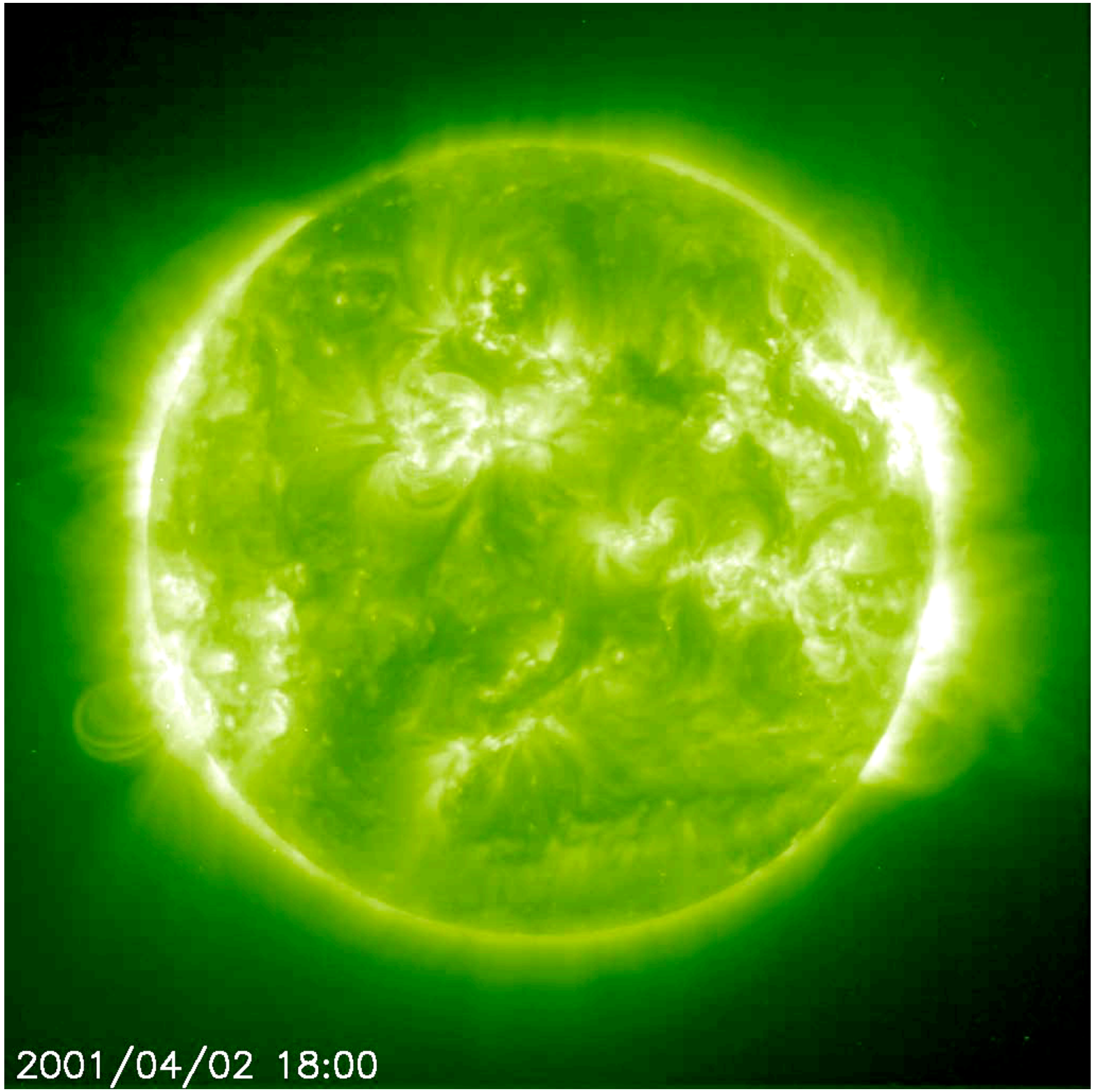
Christmas lights in Orion

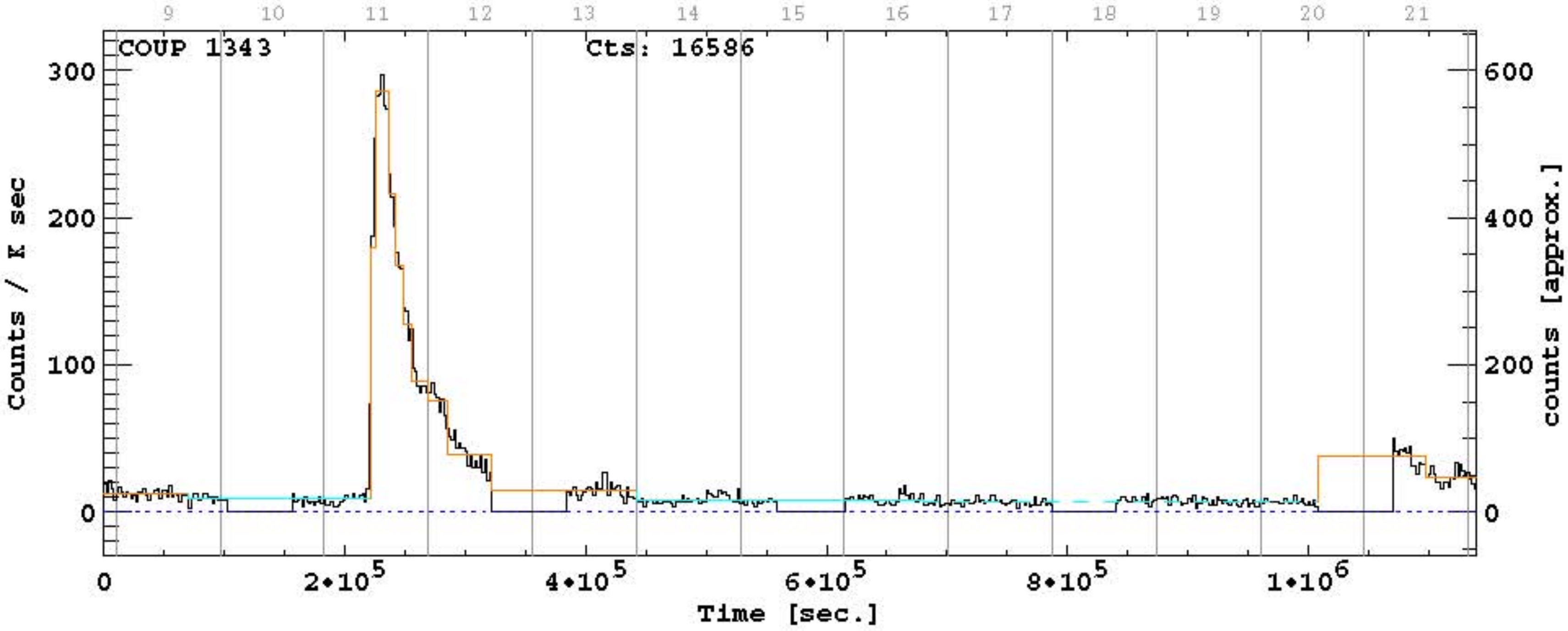


- Flaring on timescales of mins-> days



- EIT image of large solar flare





Favata et al 2005

- Note rapid rise and exponential decay
- More powerful than any solar flare (10^{32} $ergs^{-1}$)
- Typical lengthscale ~ 5 R_* (~ co-rotation radius)
- BUT…some of the largest flares must be contained in loops ~ $10R_*$