Stellar coronae

Moira Jardine
St Andrews
What do we mean by the term corona?

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

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

NASA: TRACE
Solar Prominences

• Seen in Hα 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
  - Lead to orbital evolution (but too slow)
    - Papaloizou 2007)

Both may induce radio emission (Zarka, 2007; Jardine & Cameron 2008)
Doppler Imaging: Basic Principles

Intensity

Velocity

-\( v \sin i \)

\( v(\text{spot}) \)

\( v \sin i \)
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
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{align*}
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{align*}

\(\gamma_{\ell, m} = 0\) for purely potential fields

Stokes V
AB Dor radial field from 1995 till 2004

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.

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

Isothermal, hydrostatic corona

We can extrapolate the surface field...

Boundary conditions:

- $B_r$ (stellar surface) = observed
- $B_\phi$ (source surface) = 0

$$B = -\nabla \psi, \quad \nabla \times B = 0, \quad \nabla \cdot B = 0 \quad \Rightarrow$$

$$\psi (r, \theta, \phi) = \sum_{l=0}^{N} \sum_{m=-l}^{l} \left( a_{lm} r^l + b_{lm} r^{-(l+1)} \right) Q_{lm} (\theta) e^{im\phi}$$
..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 $\omega$:
    
    $$ p = p_0 e^{m/kT} \int_{\text{gl}ds} \text{and} $$
    $$ g(r,\theta) = \left(-\frac{GM_*}{r^2} + \omega^2 r \sin^2 \theta \right) \hat{r} + (\omega^2 r \sin \theta \cos \theta) \hat{\theta} $$

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

- Emissivity $\propto n_e^2$
AB Dor, Dec 2002

- Emission measure $\sim 10^{52}$ cm$^{-3}$
- Density: $0.6 \times 10^{10}$ cm$^{-3}$
  $$n_e = \frac{\int n_e^3 dV}{\int n_e^2 dV}$$
- Always in view -> low rotational modulation $\sim 5\%$
..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)

We can also observe stellar prominences.... Absorption dips move through Hα profile as prominence crosses the disk.
Spots and prominences

AB Dor, 1996 Dec. 29

-v sin i  +v sin i

Starspot signatures in photospheric lines

Rotational cycle

11947.30  11947.80  11948.30

-171.00  30.00  231.00

Velocity (km/s)

Absorption transients in H alpha

Wavelength (nm)

655.91  656.35  656.79
• Prominences are detected in 90% of young (pre-) main sequence stars with $P_{\text{rot}} < 1$ day

- AB Dor (K0V): (Collier Cameron & Robinson 1989)
- HD 197890 = “Speedy Mic” (K0V): (Jeffries 1993)
- 4 G dwarfs in $\alpha$ 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) $P_{\text{rot}} = 1$ 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**: $3 \times 10^{21}$ cm$^2$
- **Column densities**: $10^{20}$ cm$^{-2}$
- **Masses**: $2-6 \times 10^{17}$ 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: \[ \nabla p = j \times B + \rho g \]

(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

\[ p = p_0 \exp \left\{ \frac{m}{kT} \int g(r) dr \right\} \]
What can we learn from prominences?

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

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?

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, $\sigma$ Gem, 44i Boo $\sim 10^{13}\text{cm}^{-3}$ (Dupree et al 1993, Schrijver et al 1995, Brickhouse & Dupree 1998).
  - AB Dor: $10^9-10^{12}\text{ cm}^{-3}$ (Maggio et al 2000, Güdel et al 2001, Sanz-Forcada et al 2003)

- But…. prominences co-rotating out to 3-6 $R^*$ imply extended coronae
  - Cool clouds of neutral hydrogen observed as moving absorption features in $\text{H}\alpha$

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 $R_k$

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

*Jardine & van Ballegooijen 2006*
How does this compare with observations?

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

Barnes (2005)

Dunstone et al 2006
What is the coronal structure of young stars?
BP Tau
- 1.2kG Dipole
- Mass=$0.7M_{\text{Sun}}$, Radius=$1.95R_{\text{Sun}}$
- $P_{\text{rot}}=7.6\text{d}$
- Co-rotation radius=$7.4R_{\odot}$
- Accretion rate $3\times10^{-8} M_{\text{Sun}}/\text{yr}$
V2129 Oph

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

TWA6: Skelly et al 2008
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 H$_\alpha$
Does the stellar corona extend out to the prominence locations?

Extrapolate surface field

– Potential Field Source Surface model

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

Isothermal, hydrostatic corona

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

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)
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.

Where does the corona end?
Low mass stars have coronae that extend beyond the co-rotation radius

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

=> Coronal extent limited by pressure balance

Where does the corona end?
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
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?

- Convective shell (solar-like)
- Fully-convective
- Radiative interior
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

### Tau Boo: signed flux in northern hemisphere

**Fares et al 2009**
Note change of polarity over 1 year

June 2007

Jan 2008

July 2008
Questions?

Mass

Luminosity

convective shell (solar-like)

radiative interior

fully-convective