What physical properties determine radio emission?

\[ f_{\text{plasma}}(\text{Hz}) = \sqrt{n_e (m^{-3})} \]

\[ f_{\text{gyro}}(\text{Hz}) = 28 \times 10^9 B(T) \]
What influences stellar activity?

Consistent with linear dynamo: \( \left\langle B_\nu \right\rangle \propto \Omega_* \propto P_{rot}^{-1} \)

TIME

Strong
Weak
Axisymmetric
Non-axisymmetric
Poloidal
Toroidal

See Gastine+12, Morin+12, Kochukhov+17
How do we observe the structure of stellar 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

• Only large-scale field detected
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

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

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

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

See also: Hussain+02, Folsom+15, Rosen+15, 16,
Zeeman-Doppler maps

Epsilon Eri - 2007

AD Leo - 2007

HD 189733 - 2008

Tau Boo - 2011
Do fully convective stars have a different dynamo?

\(<B_{tor}^2> [G^2]\)

\(<B_{pol}^2> [G^2]\)

\(<B_{tor}^2> \propto <B_{pol}^2>^{1.25 \pm 0.06}\)

\(<B_{tor}^2> \propto <B_{pol}^2>^{0.72 \pm 0.08}\)

See+15
Do fully convective stars have a different dynamo?

\[ \langle B_{\text{tor}}^2 \rangle \propto \langle B_{\text{pol}}^2 \rangle^{1.25 \pm 0.06} \]

\[ \langle B_{\text{tor}}^2 \rangle \propto \langle B_{\text{pol}}^2 \rangle^{0.72 \pm 0.08} \]

See+15
Low mass stars are activity over-achievers

\[ \dot{M} \propto \frac{F_X^{1.31 \pm 0.14}}{r_*^2} \]

See also Lammer+03, Cohen+15, Garrafo+16, Reville+16, Fichtinger+2017
Low mass stars spin down slowly and remain active for longer...

\[ J \propto R^{-2.95\pm0.29} \]

\[ 3D \text{ MHD models: Llama}+13, \text{Vidotto}+14,15, \text{do Nascimento}+16, \text{Nicholson}+16 \]
Modelling exoplanetary environments

1. Map the star’s magnetic field

2. Extrapolate magnetic field and solve for wind

3. Determine local conditions at exoplanetary orbit

See+2015
Large pressure scale height of low mass stars
-> slow fall-off in plasma frequency

\[ f_{gyro}(\text{Hz}) = 28 \times 10^9 B(T) \]

\[ f_{\text{plasma}}(\text{Hz}) = \sqrt{n_e (m^{-3})} \]
Magnetic fields of planet hosts

Vidotto+2015
3D MHD wind models

Some exoplanetary orbits are inside the Alfven radius
Exoplanets experience varying environments as they orbit

See also: Cohen+10, Strugarek+15, Vernisse+17a,b; Pinto+17

Vidotto+2015
Radio emission modulated on synodic period (and cycle period)

HD 189733

2007 June

2008 July

See +2015
Intermittent mass ejections in stellar winds

M dwarfs exoplanets in close orbits:

Continuous impact with stellar mass ejections if ejection rate \( \sim 6 \) solar (Khodachenko+07).

- **What determines the ejection rate?**
- Flux emergence rate
- Differential rotation (rate of shear)
Differential rotation decreases with mass

Marsden et al 2005, 2006; Jeffers et al 2011

Low mass, deep convective zone

Higher mass, shallow convective zone

Low mass, deep convective zone
Is the ejection rate a function of stellar mass?

Pilot study (Gibb+14):

• Emerge a simple bipole through stellar surface

• Evolve coronal magnetic field with magnetofrictional approach (Yang 86)

• Track formation and evolution of flux ropes (blue) that are precursors to coronal mass ejections.
Lower mass \text{ } \rightarrow \text{ lower surface shear} \rightarrow \text{ slowly-evolving coronae}

\[ d\Omega = 3.03\frac{T_{\text{eff}}}{5130 \text{ K}}^{8.6} \text{ deg/day} \text{ (Collier Cameron 07)} \]
Full-star, long term evolution

25 models, each evolved for 1 year:
• (1-5) x solar flux emergence rate
• (1-5) x solar differential rotation

Resolution:
• Spatial: $1^\circ$ at equator, less at poles
• Temporal: 1 day

Boundary conditions:
• open at $2.5R_*$, $B_r$ at surface

Gibb+16
The Sun on steroids...

Frequency and location of coronal ejections depends on:

- stellar rotation rate (magnetic flux emergence rate) and
- stellar mass (surface differential rotation)

(Gibb+14,16)
Full-star, long term evolution also shows that hotter stars have more dynamic coronae.

\[ \Omega = 3.03 \left( \frac{T_{\text{eff}}}{5130 \text{ K}} \right)^{8.6} \text{ deg/day} \] (Collier Cameron 07)

Overlying coronal field confines flux ropes and slows formation and ejection.
Increased shear confines flux ropes to active belts

* Histogram of emergence latitudes
Exoplanet environments vary with stellar mass and rotation rate (age)

- Low mass stars:
  - remain magnetically very active over long timescales
  - have low differential rotation (and slowly-evolving coronae?)
  - Implications for mass ejection rates?

- Exoplanet environments vary on synodic and stellar cycle timescales

NASA: STEREO