Modelling complex magnetic fields in stars with radiative envelopes

James Silvester

Wednesday 30th August 2017, Brno
Magnetic Fields of Ap and Bp Stars

• These early-type stars have globally ordered strong magnetic fields usually accompanied by surface abundance anomalies.

• They offer a unique insight into the magnetic fields of stars with radiative envelopes, helping providing powerful constraints to:
  • Magnetic field formation and evolution.
  • The interplay between the magnetic field and atmospheric processes in these stars.
Magnetic Fields of Ap and Bp Stars

In Ap/Bp stars the magnetic field:

- Is globally ordered and has a relatively high strength, allowing for direct observation.

HD 125248 Babcock (1951)
Magnetic Fields of Ap and Bp Stars

In Ap/Bp stars the magnetic field:

- Is stable on time-scales of at least decades.

Phased longitudinal field measurements for HD 32633

- ESPaDOnS/NARVAL - 2010 (filled circles)
- MuSiCoS - 2000 (filled diamonds)
- Measurements by Borra & Landstreet - 1980 (triangles)
Initially the magnetic geometry was thought to be a simple pure dipole. This was later shown not to be the case (e.g Preston 1969).
Magnetic Fields of Ap and Bp Stars

53 Cam

a) Landstreet (1988)
b) Bagnulo et al. (2001)
c) Kochukhov et al. (2004)

Kochukhov et al. (2004)
Some Questions Surrounding the Magnetic Fields of Ap and Bp Stars

- With recent advances in spectropolarimetric instrumentation and techniques have we have started to probe the magnetic field structure in more detail.

Key Questions:

- What is the detailed geometry and magnetic configuration of Ap/Bp stars?
- How do the magnetic fields evolve?
- Do other stellar fundamental parameters affect the magnetic field evolution?
- How do magnetic fields contribute to the formation of abundance spots/structures?
<table>
<thead>
<tr>
<th>Star</th>
<th>Authors</th>
<th>Year</th>
<th>Resolution</th>
<th>Technique</th>
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<td>53 Cam</td>
<td>Kochukhov et al.</td>
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<td>α² CVn</td>
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<td>σ Ori E</td>
<td>Oksala et al.</td>
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<td>HD 32633</td>
<td>Silvester et al.</td>
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<td>HD 125248</td>
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<td>36 Lyn</td>
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<td>a Cen</td>
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<td>IQ Aur</td>
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MDI Mapping Data

Data for recent MDI mapping has been obtained using one (or more) of the following spectropolarimeters:
- ESPaDOnS at CFHT (Mauna Kea)
- Narval at TBL (Pic du Midi)
- HARPSpol on the ESO 3.6m (La Silla)

These instruments have proven performance/stability over multiple observing semesters.
The Spectropolarimeters

All 3 instruments are optical bench-mounted cross-dispersed echelle spectrographs, fibre-fed from a Cassegrain-mounted polarimeter units.

**ESPaDOnS & Narval**
- **Resolution:** \( R \approx 65000 \)
- **Throughput:** 15–20 %
- **Wavelength coverage:** 3690 to 10480 Å

**HARPSpol**
- **Resolution:** \( R \approx 110000 \)
- **Wavelength coverage:** 3780–6910 Å (with a 80 Å gap at \( \lambda = 5290 \) Å)
The Spectropolarimetric Data

HARPSpol four Stokes parameter spectra of HD 24712, Rusomarov et al. 2013
The Spectropolarimetric Data

Current Generation

MuSiCoS
Magnetic Map of $\alpha^2$ CVn

Modulus

Radial

Stokes IQUV Inversions derived simultaneously with abundance maps

Teff = 11,600 K
Magnetic field Map from Iron Lines from MuSiCoS Data vs ESPaDOnS/Narval Data for $\alpha^2$ CVn

This result shows:  

a) Reproducibility of the maps / reliability of the inversion code

b) The stability of the magnetic field over a decade timescale
Magnetic Field Map from various line sets using ESPaDOnS / Narval data for α² CVn

Strong Fe Lines

Weak Fe Lines

Combined Fe Lines

Cr Lines

Cr and Fe Lines

This result shows that very similar magnetic structure is derived from differing line sets
Mapping of HD 32633

Early observations of the Ap star HD 32633 indicated that the magnetic field was complex in nature (e.g., Babcock 1958, Borra and Landstreet 1980).

Twenty phase resolved observations of HD 32633 were obtained in Stokes IQUV with ESPaDOnS and Narval.

Babcock 1958

Teff = 12,800 K
Magnetic Map Diagnosis Comparisons

Spherical Harmonics Inversion (used for final map)

Surface Elements Inversion

Stokes IV only inversion

Stokes IQUV from dipolar + quadrupolar structure
HD 32633

Stokes IQUV Inversions derived *simultaneously with abundance maps*

Teff = 12,800 K
HD 32633 fits to Stokes Q and U
Spherical Harmonic Energies for HD 32633

![Graph and Table]

<table>
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<tr>
<th>$l$</th>
<th>$E_{\text{Pol}}$ (%)</th>
<th>$E_{\text{Tor}}$ (%)</th>
<th>$E_{\text{tot}}$ (%)</th>
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<td>83.5</td>
<td>16.5</td>
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Very Latest Results
Fig. 2.—Spectroscopic variations of 49 Cam. (a) the variation in the magnetic field; (b) and (c) the variations in line depth for Fe + Cr and for the rare earths; (d) the variations in line-blocking in the v filter band. In the top panel, filled circles and crosses represent observations made at Mauna Kea and by van den Heuvel (1971), respectively. Probable errors for the plotted points are given in table 2.
Very Early Results: HD 62140 (49 Cam)
Very Early Results: HD 62140 (49 Cam)

<table>
<thead>
<tr>
<th>Stokes I</th>
<th>Stokes Q</th>
<th>Stokes U</th>
<th>Stokes V</th>
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</table>

CP Workshop, Vienna - 13th September 07

WORKSHOP
10. - 14.09.07
49 Cam

Stokes IQUV Inversions derived simultaneously with abundance maps

Teff = 7,700 K
49 Cam

Stokes Q

Teff = 7,700 K
49 Cam

Stokes IV Inversions derived *simultaneously with abundance maps*

Teff = 7,700 K
49 Cam

Stokes IV
36 Lyncis

Modulus

Horizontal

Radial

Averaged Line Stokes IV Inversions

Oksala et al. Submitted

Teff = 13,000 K
36 Lyncis

![Graph showing Poloidal and Toroidal Field strengths]

![Graph showing LSD Stokes V vs. V (km/s)]
A Cen - He Peculiar Star

Work in collaboration with Laurie Huang, Gregg Wade, Jiří Krčička and Ewa Niemczura.

Averaged Line Stokes IV Inversions

Teff = 19,000 K
IQ Aur

Modulus

Horizontal

Radial

Averaged Line Stokes IV Inversions

Work in collaboration with Ilya Yakunin

Teff = 14,000 K
How do the Spherical Harmonic Energies compare?

HD 32633

CU Virginis
Kochukhov et al. (2014)

Stokes IV

36 Lyn
Temp > 12,000 K

Alpha² CVn

HD 125248
Rusomarov et al. (2016)

Stokes IV

HD 75049
Kochukhov et al. (2015)

Temp 12,000 to 9500 K

49 Cam

HD 24712
Rusomarov et al. (2015)

Temp < 9500 K
If a star is member of open cluster, we can use the age of cluster to get accurate stellar age.

By using cluster Ap/Bp stars we probe of magnetic field complexity as a function of age.

The aim is to produce a set of Stokes IV magnetic maps for the target stars.
In Summary

• Through recent mapping we have shown the reliability of our inversion procedure.

• We have shown that the magnetic fields of Ap/Bp stars can be varied even within the same temperature/mass range.

• With the increasing the number of Ap/Bp stars mapped using using MDI:
  • We can now further investigate how other stellar parameters correlate with magnetic field complexity.
  • HARPSpol Open Cluster Project in particular will allow us to probe age vs magnetic field complexity.
Thank You!  Děkuji!