Stellar spots and magnetism

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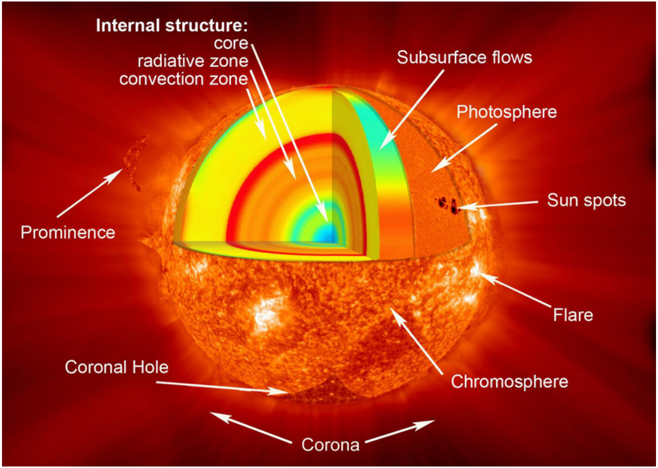
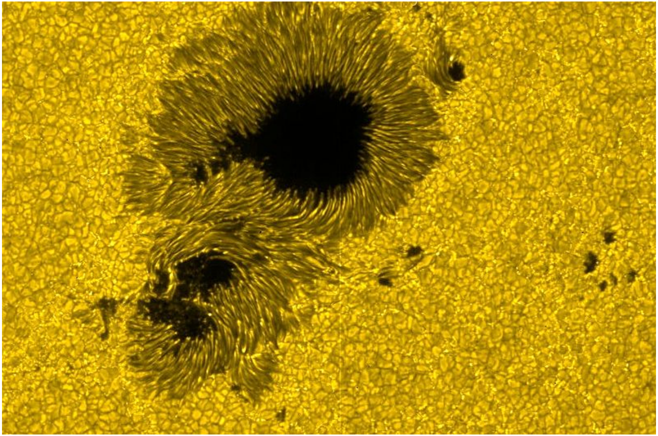
Barcelonnette, France

The Sun

The only star where active regions can be resolved in high spatial and temporal detail



Sunspots



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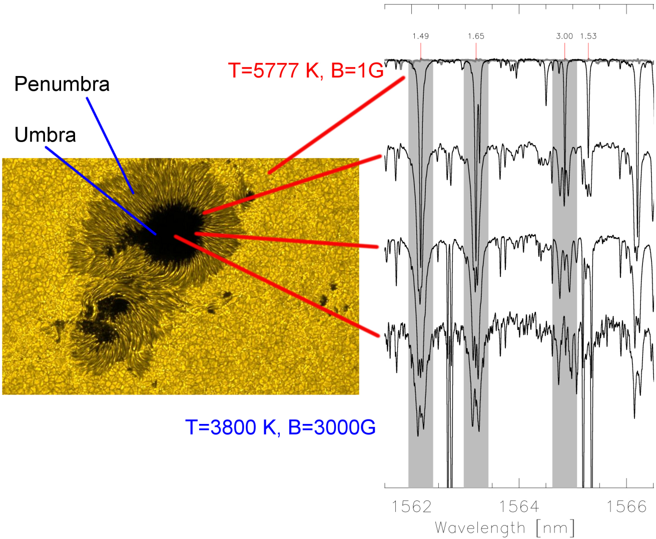
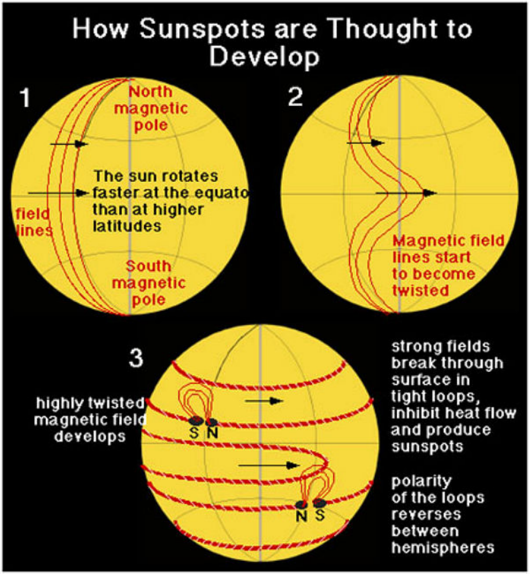
Sunspots


Penumbra
Umbra
T=5777 K, B=1G
T=3800 K, B=3000G
1.49
1.65
3.00
1.53
1562
1564
1566
Wavelength [nm]

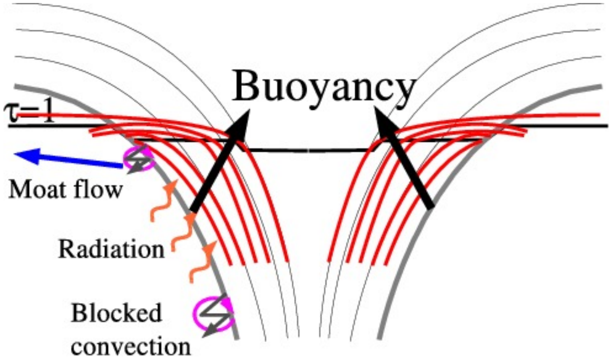
Sunspot: formation



Sunspot: structure

Magnetic field inhibits convection ⇒ decrease energy flux ⇒ temperature drops

Wilson depression: radiation from sunspot emerges from a deeper layer compared to a quiet photosphere



Sunspot: sizes and lifetimes

Sunspots

Size: 1 000 – 100 000 km and more
Lifetime: from days to weeks

Granulation

Size: $\approx$ 1 000 km
Lifetime: 8 – 20 min

Starspot: definition

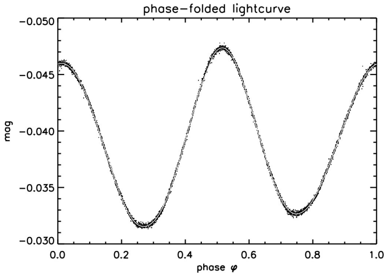
Definition:

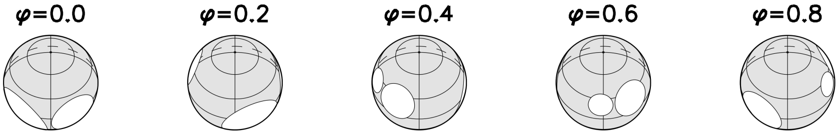
Starspot is a local inhomogeneity in the stellar atmosphere which is stable on time scales comparable to the dynamical times scale of the star $t_{\mathrm{spot}} > t_{\mathrm{dyn}}$

- Spots may be bright or dark compared to the surrounding (may depend upon wavelength)
- Have different physical nature

What about other stars?

Detection methods: photometry





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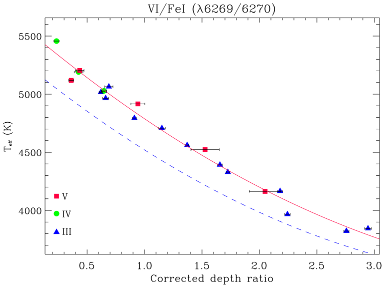
Detection methods: Line Depth Ratio (LDR)

Use lines with different temperature sensitivity to measure temperature contrast in spots



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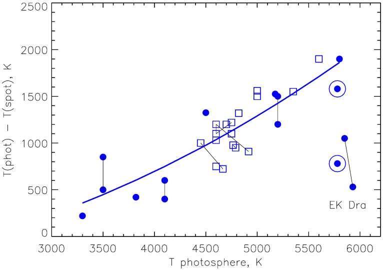

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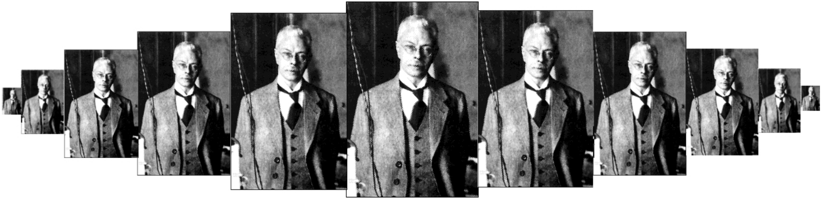
Detection methods: Zeeman splitting

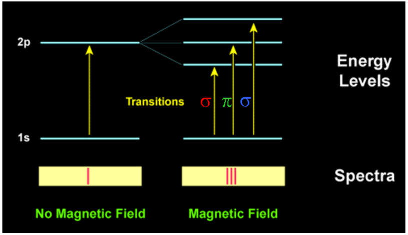
Pieter Zeeman

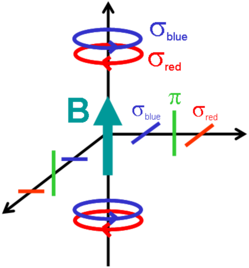
Detection methods: Zeeman splitting

Zeeman-σ^- Zeeman-π Zeeman-σ^+



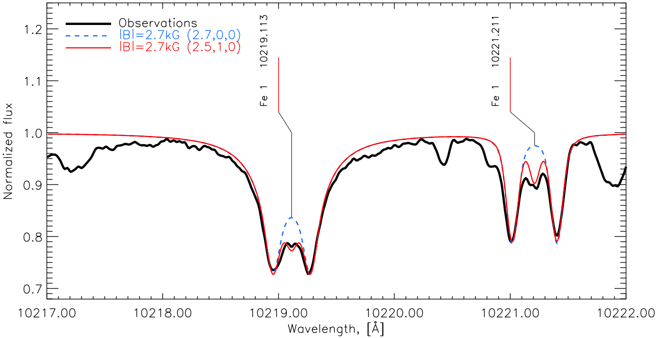
Detection methods: Zeeman splitting





Detection methods: Zeeman splitting

Strength and position of Zeeman π and $\sigma^{\pm}$ components contain information about surface magnetic field intensity and geometry



Detection methods: Zeeman Doppler Imaging (ZDI)

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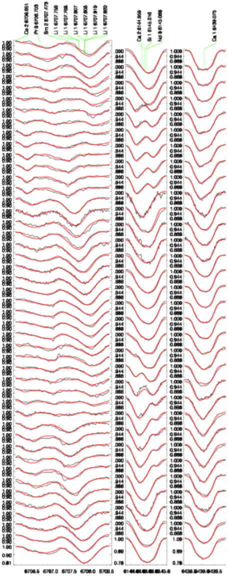

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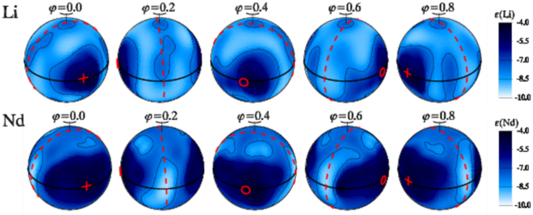
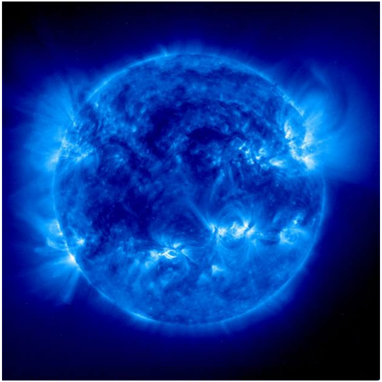
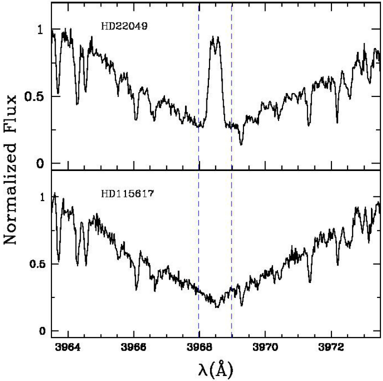


Solar-like activity indicators

Indirect diagnostics of inhomogeneous surface structures

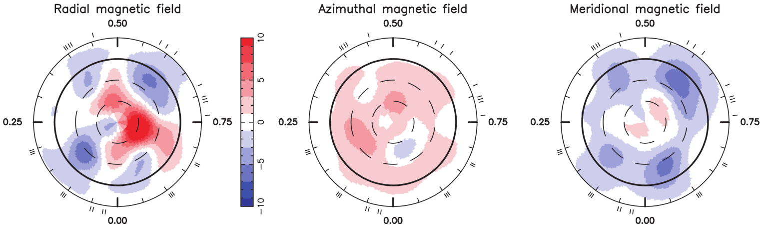
- Photometric variability (flaring events)
- Flux emissions: UV, X-ray $\mathrm{H}\alpha$, Ca II H & K



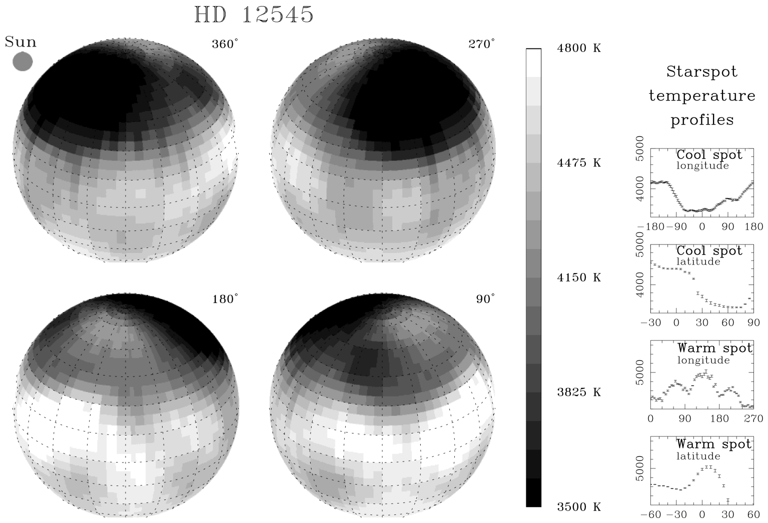


Sun-like stars: τ Boo

SpT: F7 V, $\langle B_s \rangle \approx 10$ G, differential rotation and activity cycle (2-3 year?) detected



Giant stars



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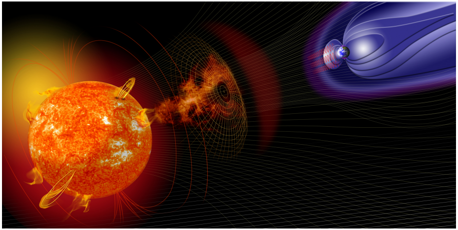
Giant stars

- Rapidly rotating giants show large spots with high temperature contrast, flares, activity cycles
- Typical magnetic fields of about few G
- Cool supergiants – local dynamo operating in the giant convection cells?

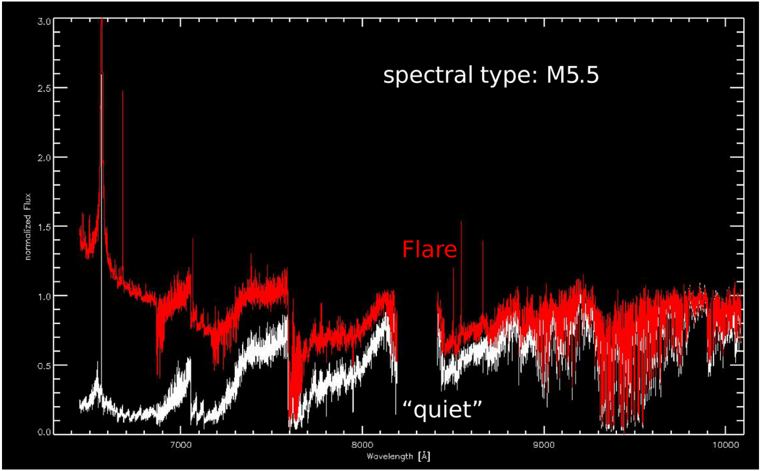
M-dwarfs

- Stars with $M < 0.35 M_{\odot}$ ($\sim$M3.5) are believed to become fully convective, (no tachocline layer similar to Sun-like stars; different dynamo's?)
- A typical kG magnetic fields (up to ≈ 4 kG) detected from integrated Stokes I spectra, i.e. average fields are of the order of that found in Sun-spots!



M-dwarfs

CN Leo – Flare star observed in a flare

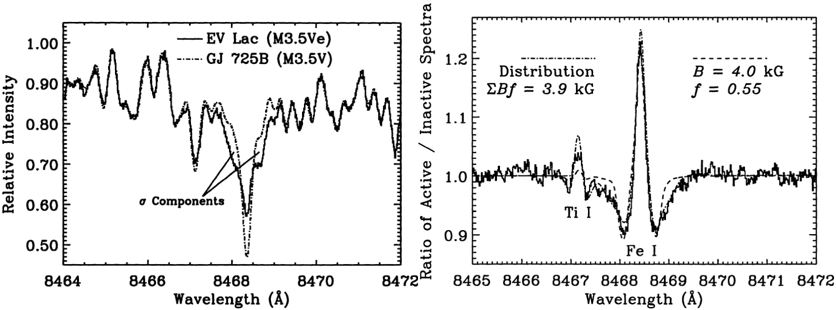


M-dwarfs

M-dwarfs

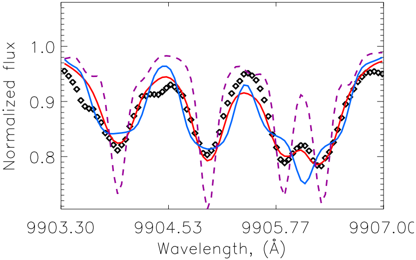
Detection of strong complex fields

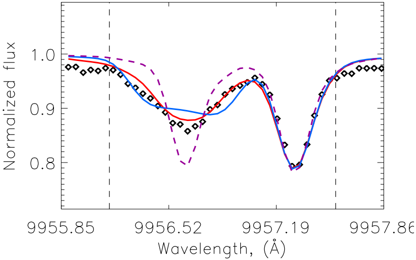
Johns-Krull & Valenti (1996, 2000), Fe I 8468.4 Å line



Magnetic Fields in M-dwarfs

Analysis of FeH lines, AD Leo, M3.5, $\langle B_s \rangle = \sum \langle B_s \rangle_i f_i = 2.9$ kG





Fit shown for:
red – multi-component $\langle B_s \rangle = \sum \langle B_s \rangle_i f_i$
blue – single-component $\langle B_s \rangle = |\mathbf{B}|$

See Johns-Krull & Valenti (1996, 2000), Reiners & Basri (2007), Shulyak et al. (2013) for magnetic field measurements

Magnetic Fields in M-dwarfs: geometries

Polarimetry: Morin et al. (2008, 2010), analysis of Stokes-V spectra (ZDI of LSD profiles)

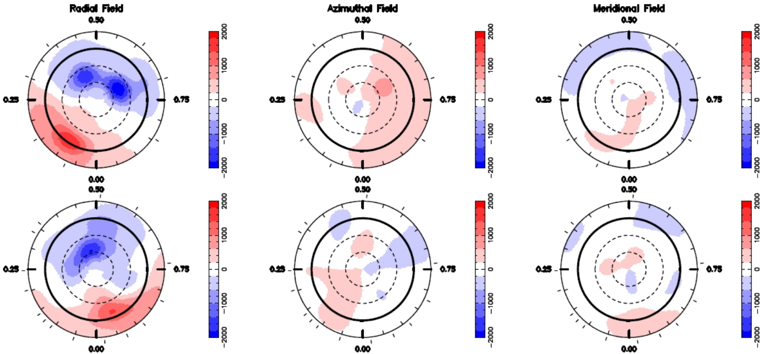


Figure 5. Same as Figure 2 for EV Lac, using data obtained in 2006 (upper row) and 2007 (lower row).

Magnetic Fields in M-dwarfs: geometries

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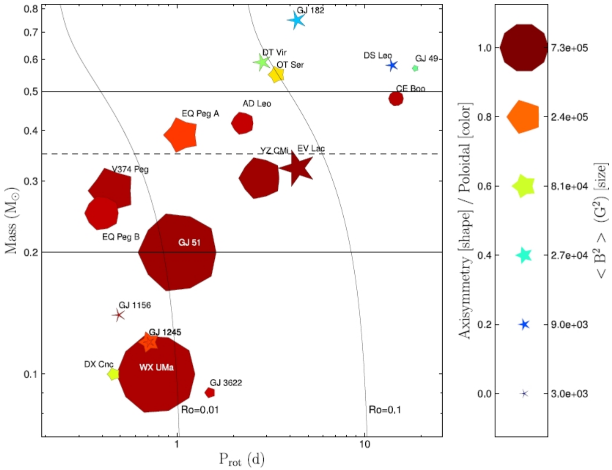
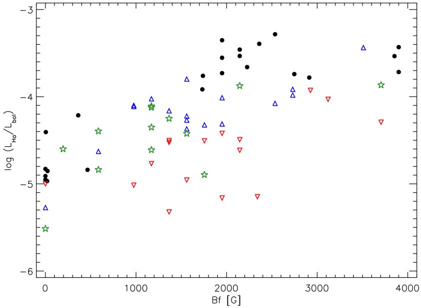


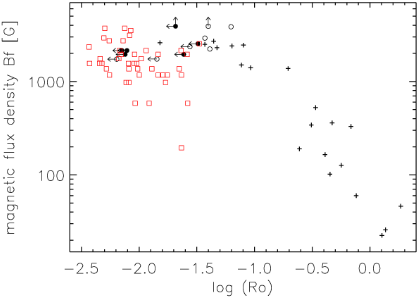
Magnetic Fields in M-dwarfs: geometries

Polarimetry: Morin et al. (2008, 2010), analysis of Stokes-V spectra (ZDI of LSD profiles)

- Find a clear transition between partly and fully convective stars
- Fully convective stars host strong axisymmetric fields
- Partly convective stars host weaker non-axisymmetric fields with dominated toroidal component
- Though some exceptions still exist...

Rotation-Activity-Magnetic Field





● M0-M6 △ M7 ⋆ M8 ▽ M9

+ sun-like stars ● M6 and early
□ M7-M9

Summary

Spots in low-mass stars with outer convective envelope:

- generated but a dynamo action: interaction of the convection and magnetic field;
- have temperature contrast from $\approx$ 2000 K in G to a few hundred K's in M stars;
- the spot's lifetimes are proportional to their sizes and vary from days to years.

Magnetic fields are:

- dynamo generated ($\alpha\Omega$-mechanism involving differential rotation);
- have complex structures very different from, e.g., simple dipole;
- change on time scales of years or less.

Early-type stars

- Have weak or no convection in subphotospheric layers
- Silent in X-ray and radio (although hot O-type stars known to show emission lines and produce hard X-rays, these are connected with strong stellar wind, not with flaring events)
- Yet, some of B-F stars are known to have spots

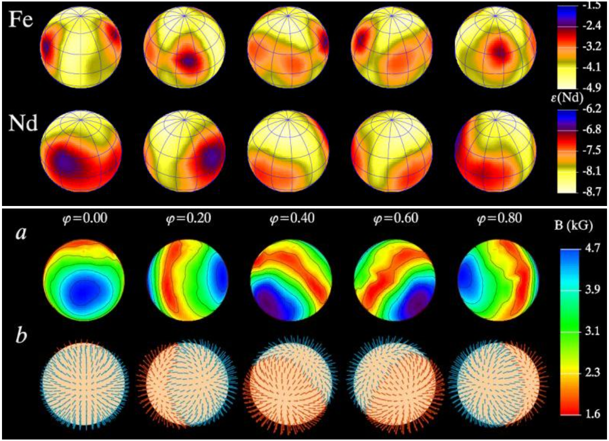
CP stars

Chemically Peculiar (CP) stars:

- Non-solar chemical abundances in general; vertical and horizontal abundance inhomogeneities (called “stratification”)
- Many host global magnetic fields of the order of a few kG
- Some have fields up to $\approx$ 30 kG (strongest fields among MS stars!)

Abundance spots: α^2 CVn

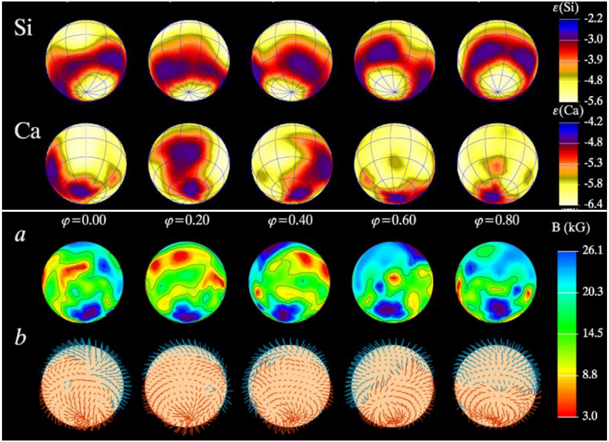
Inversions of Stokes I, V



©http://www.astro.uu.se/∼oleg

Abundance spots: 53 Cam

Inversions of Stokes I, Q, U, V: more details recovered



Abundance spots: physics

- strong magnetic fields partly or fully suppress plasma mixing processes;
- perfect condition for developing microscopic particle diffusion;
- this diffusion is maintained by the interplay between two main forces:
  1. gravitational settling
  2. radiative levitation
- these forces act differently on different ions, leading to accumulation of chemical elements at different atmospheric depths

Diffusion Velocity

The diffusion velocity V_{D_i} of an ion in a binary mixture (protons, electrons, and trace ions), without magnetic field (see Aller & Chapman 1960; Michaud 1970):

$$V_{D_i} \approx D_i \left[-\frac{\partial \ln c_i}{\partial z} + \frac{Am_p}{kT}(g_{rad} - g) + \frac{(Z_i + 1)m_p}{2kT} \right]$$

D_i – diffusion coefficient

c_i – is the ion concentration (the ratio of the ion partial pressure over the total gas pressure)

Z_i – charge ($Z_i = 0$ for neutrals)

Third term – correction for the microscopic electric field

If thermal diffusion is present then respective term should be added (however, in most cases thermal diffusion in unimportant)

Radiative Acceleration

Radiative acceleration of a given ion *i*:

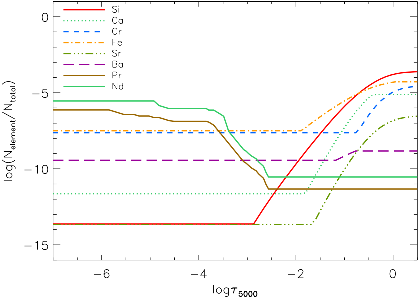
$$g_{rad}^{(i)} = \frac{4\pi}{c}\frac{\rho}{m_i N_i}\int_0^\infty (\kappa_c + \kappa_l) H_\nu d\nu$$

g_{rad} due to lines absorption can be much larger than those of continuum

Diffusion operates even in the Sun: He sinks downwards and change the size of the convection zone (confirmed by helioseismology)

Vertical stratification examples

Backwarming effect in upper layers due to REE cloud (Shulyak et al., 2009, A&A, 499, 879)



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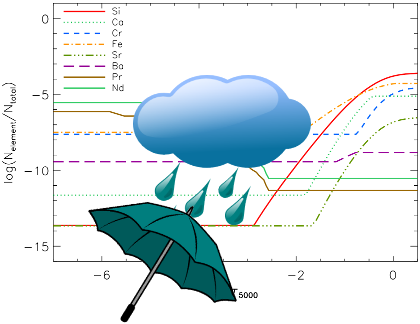

Vertical stratification examples

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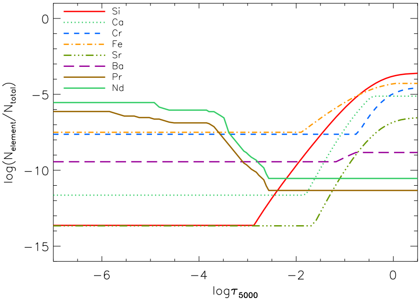
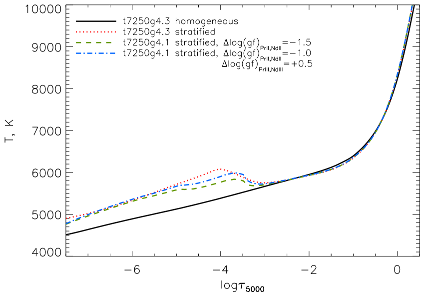
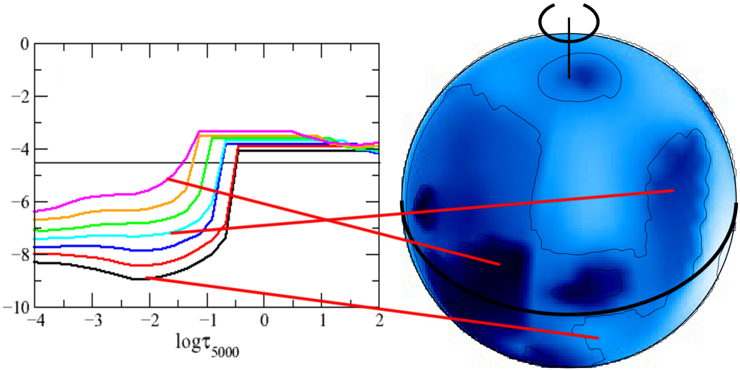




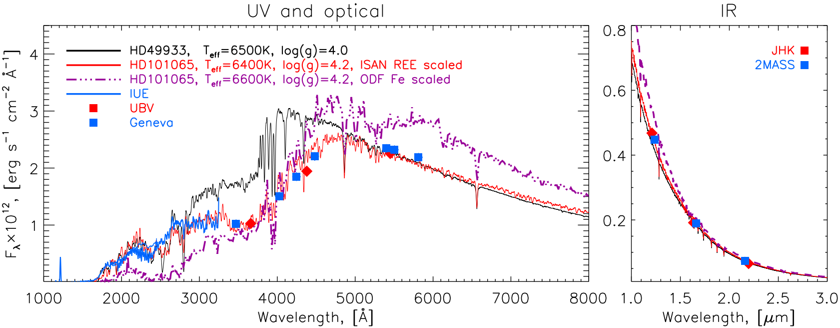
Link between vertical stratification and spots

Spots is the vertical stratification modulated by the strength and orientation of local magnetic field and/or other processes

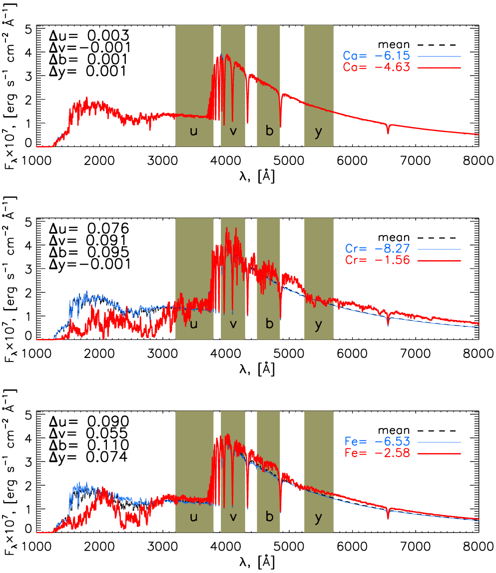


Impact of peculiar abundances

Peculiar abundances lead to the energy redistribution so that stars at the same $T_{\rm eff}$ may look dramatically different



Nature of the light variability in CP stars



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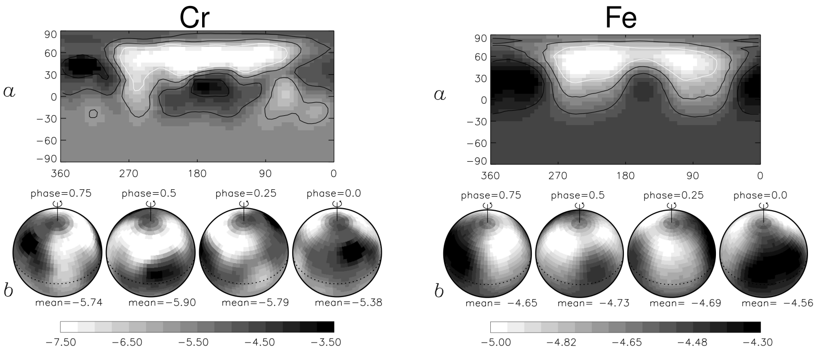

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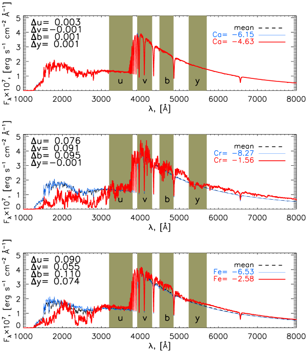
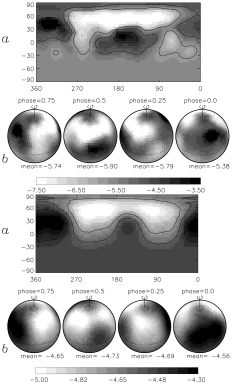
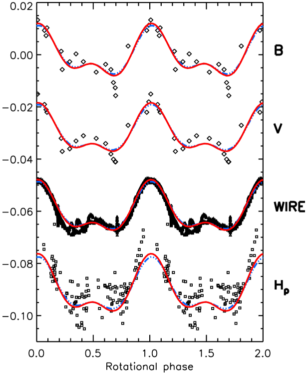
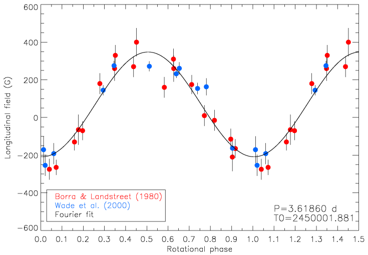


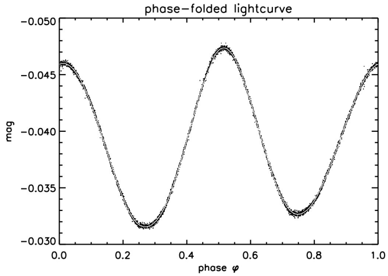




Spots and magnetic field

Magnetic and light curves are stable over at least ≈ 100 years

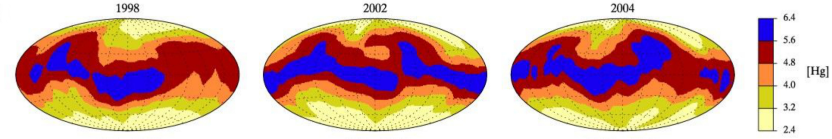




HgMn stars

Abundance spots are found also in hot HgMn stars for which no magnetic fields were reported suggesting that the magnetic field is not the only process supporting element separation...

Abundance spot evolution in α And



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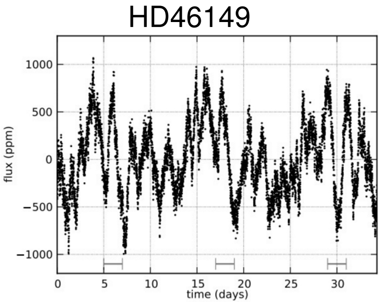
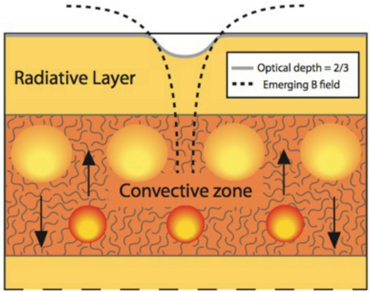
Spots in hot O-stars

Subsurface convection can lead to bright temperature spots in hot stars(?)





ⓒDegroote et al., 2010 ⓒCantiello & Braithwaite, 2011

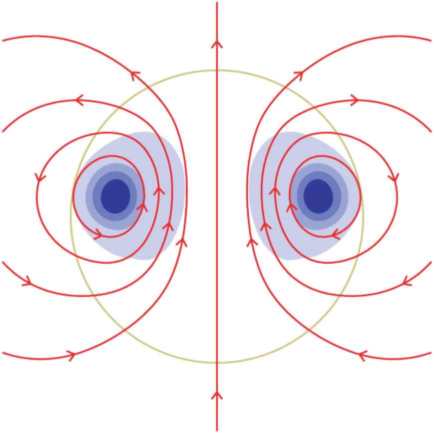
Origin of the magnetic field in early-type stars

- CP stars of types B-F have likely fossil fields
- Normal B-F stars have no or very weak fields on the order of 1 G or less. Two cases reported
  1. Vega (B=0.6 G), Ligniéres et al 2009
  2. Sirius (B=0.2 G), Petit et al 2010, 2011

  No clear explanation for magnetism in these stars (failed fossil, see Braithwait & Cantielo 2013)
- O stars can host subsurface convection due to ionization of He and Fe

Fossil field stability proven

Braithwaite & Spruit, 2004
Stable configuration of magnetic field is obtained as a combination of toroidal and poloidal components



Summary

Spots in early-type stars with radiative envelope:

- have chemical nature and caused by diffusion processes;
- can be bright or dark depending upon wavelength;
- stable on time scales of decades (except HgMn stars which demonstrate spot evolution).

Magnetic fields:

- have fossil origin;
- have simple geometry and are organized at large scales;
- do not change on time scales of many decades.

Open questions:

- temperature spots in O-stars
- weak fields in “normal” A-F stars

CP stars: spot detection with interferometry

- Interferometry is a new independent method to study spotted surfaces of CP stars (spot location, brightness contrast, etc.)
- Interferometry is the only method to resolve spots in slowly rotating CP stars for which no Doppler Imaging possible

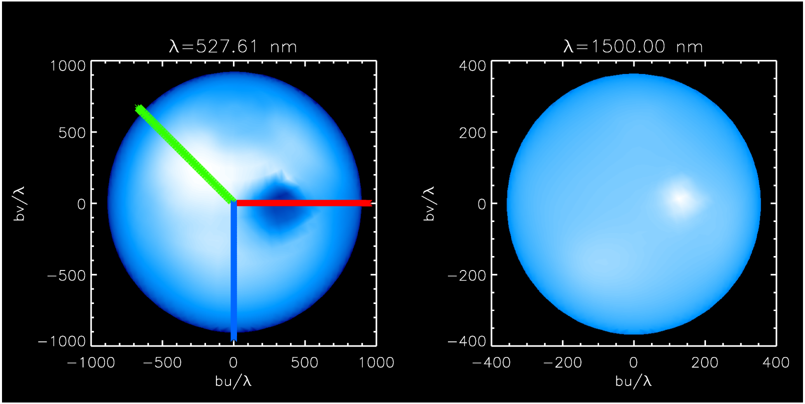
Case study: ϵ UMa

ϵ UMa, CP stars of A0-type with pronounced photometric variability and DI maps available. It has radii $R = 4R_{\odot}$ and $V = 1.76$, therefore a good candidate for modern interferometric facilities:

- CHARA/VEGA (visual domain)
- VLTI/AMBER (IR domain)

Some pretty images of the star

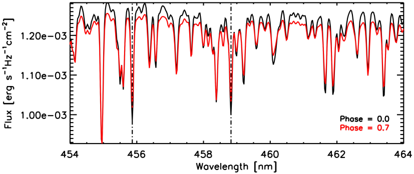
Intensity images of ϵ UMa at two wavelengths and $\phi = 0$.
Three projected baselines are shown on the left plot.

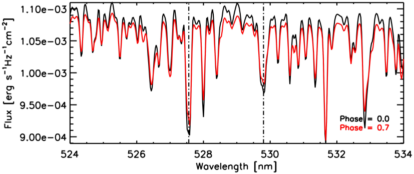


Visual domain

Spectral features with pronounced variability due to spots

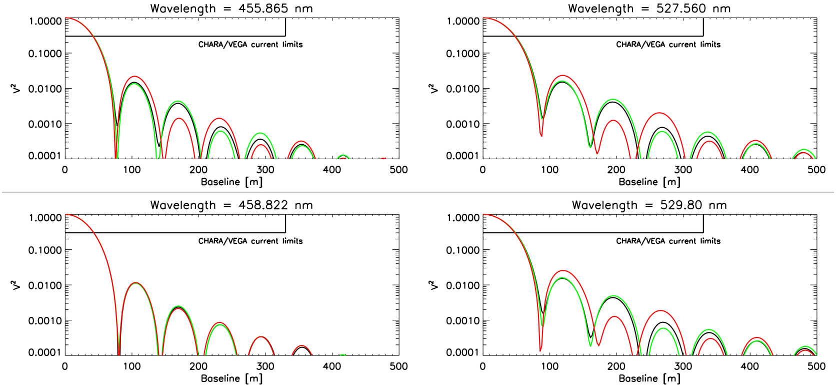
Cr II 455.86 nm, 458.82 nm, Fe I+Cr II 527.6 nm, and Cr I 529.8 nm)





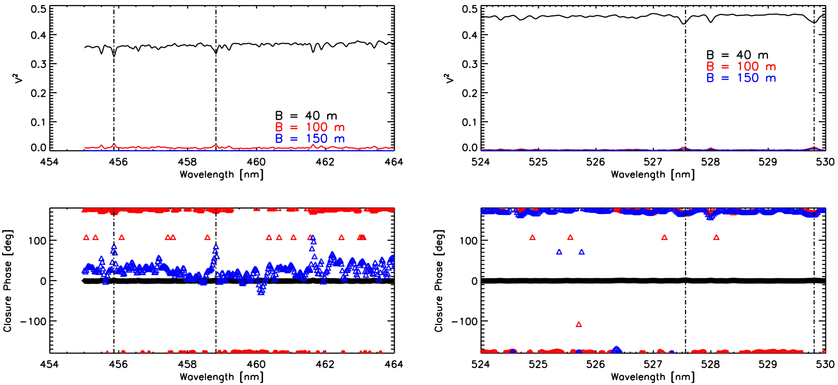
Visual domain

The effect of abundance spots on the visibility curve at different wavelengths at $\phi = 0$



Visual domain

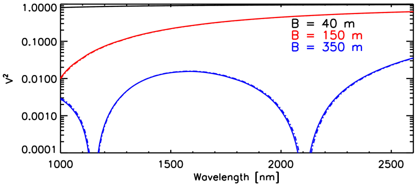
Visibilities and closure phases

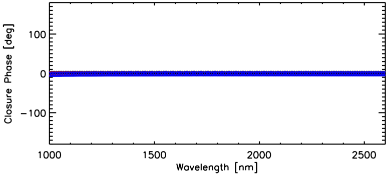


IR domain

Visibilities and closure phases

Predictions for homogeneous (full line) and spotted (dash-dotted line) models are shown.





Summary

- The detection of the position of spots in the absolute visibility is beyond the capabilities of CHARA/VEGA: the baseline have the right length but the dynamic range of the instrument is not enough.
- The spots are not detected in the near-IR, at least at low resolution.
- Comparing visibilities with synthetic observables allow one to constrain the models.
- Improved interferometric facilities will provide a unique possibility to study spots on slowly rotating CP stars for which no Doppler Imaging possible.