Magnetic fields

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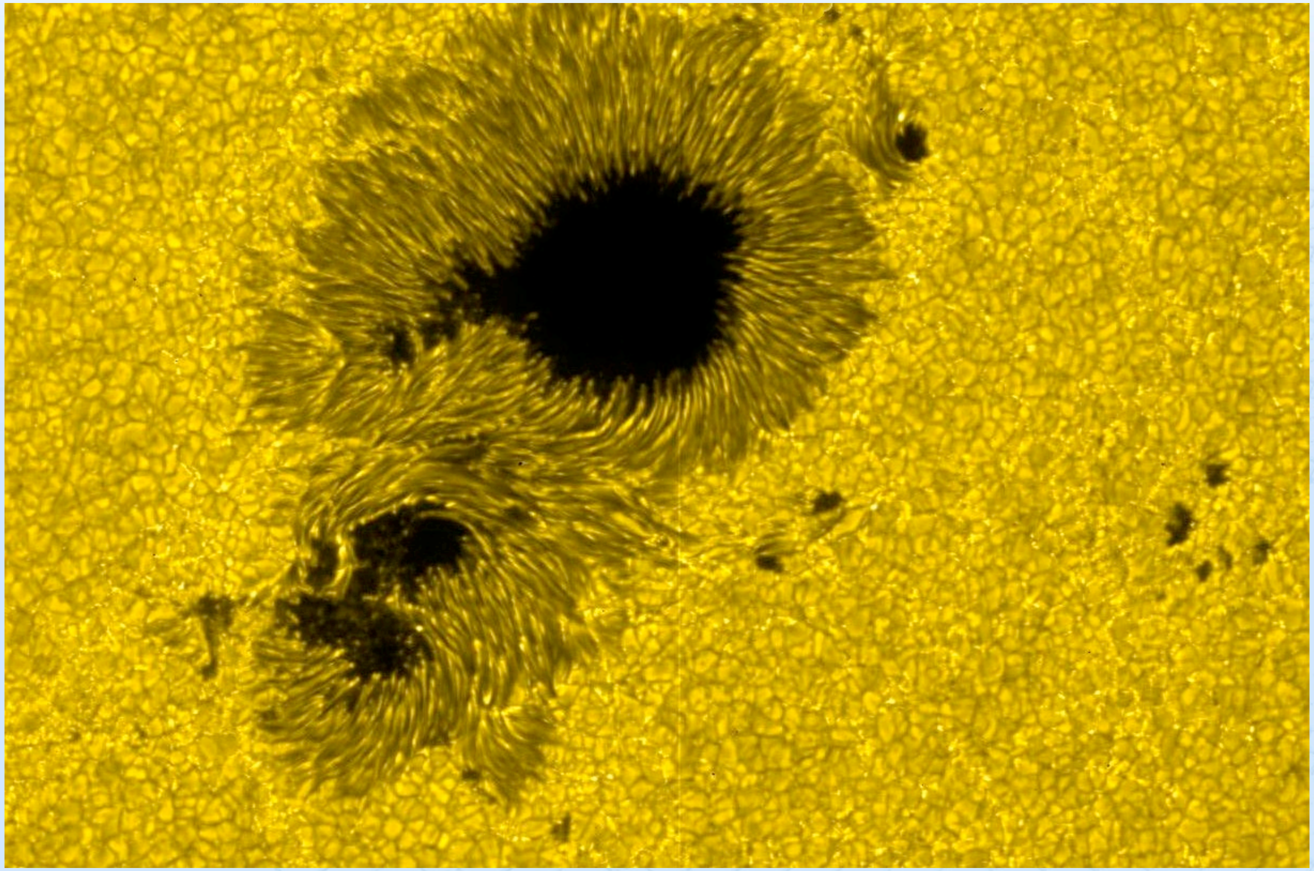
Magnetic fields …

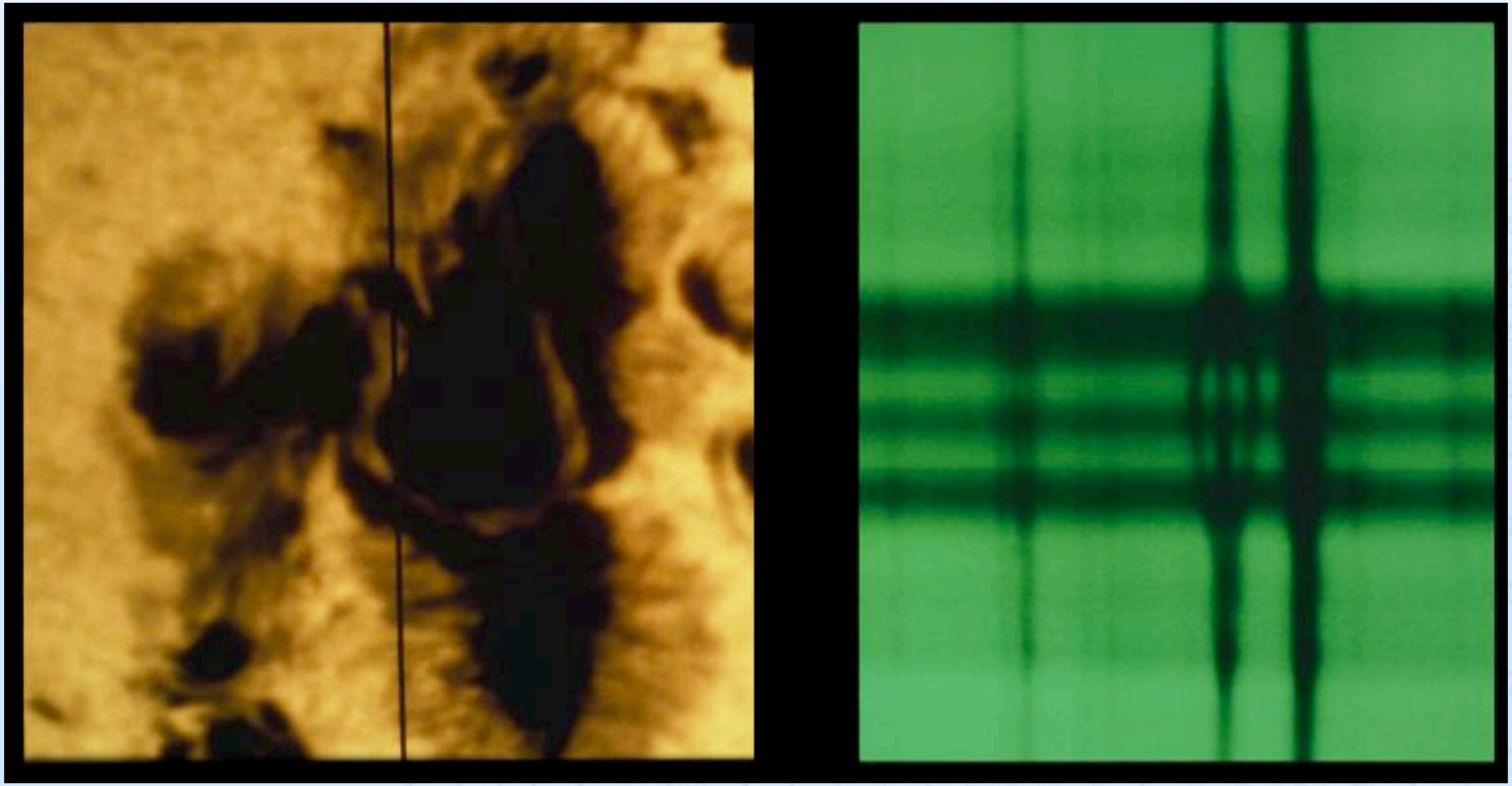
- are hated, since they make everything so complicated, including breaking your symmetries
- are loved, because they can explain every discrepancy of your favorite theory
- or: the larger the error, the larger the magnetic field

Sun with spots

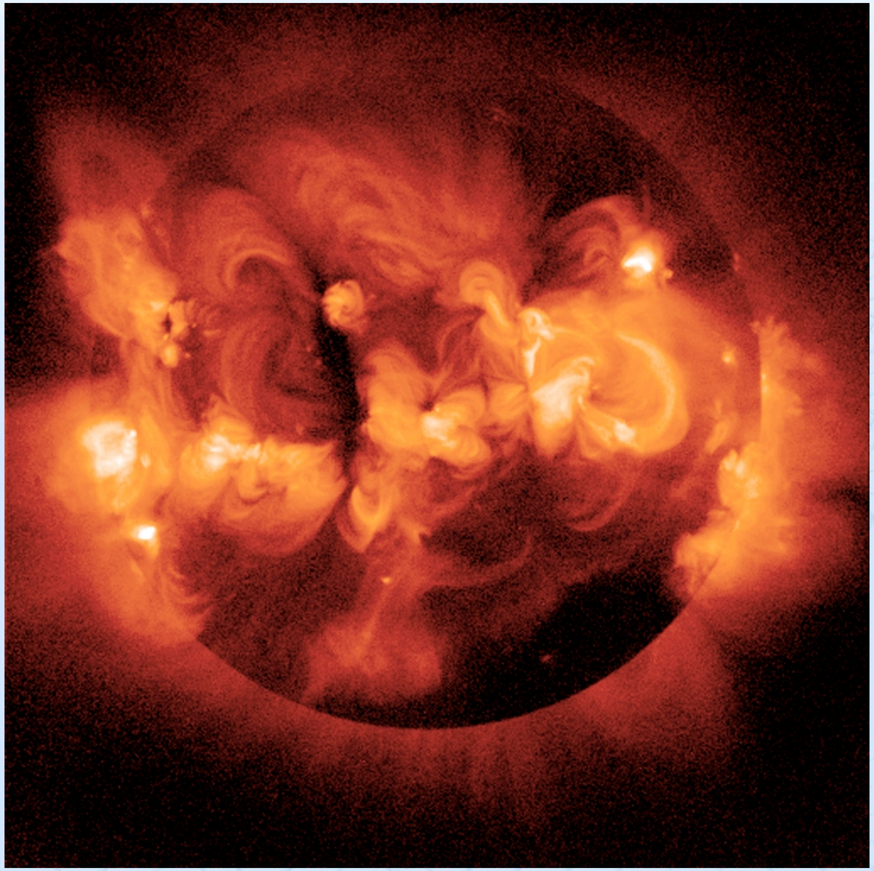
Sun spot



The Zeeman effect over a sun spot



The solar corona in X-rays



Stellar magnetic fields

- Are measured in Gauss:
  1G = 0.1 mT

- Sun: 0.5−4G, sunspots 2−5kG
- Vega: <1G
- Ap stars: Babcock's star 34kG
- White dwarfs: 10^3-10^9G
- Neutron stars: 10^9-10^{15}G

Where do they come from?

- Fossil fields:
  - – Magnetic flux BR^2 conversion from cloud collapse
  - – Efficient method needed to lose excessive magnetic flux
- Dynamo fields:
  - – Permanently regenerated in a dynamo process, using a seed field
  - – This leads to the solar cycle

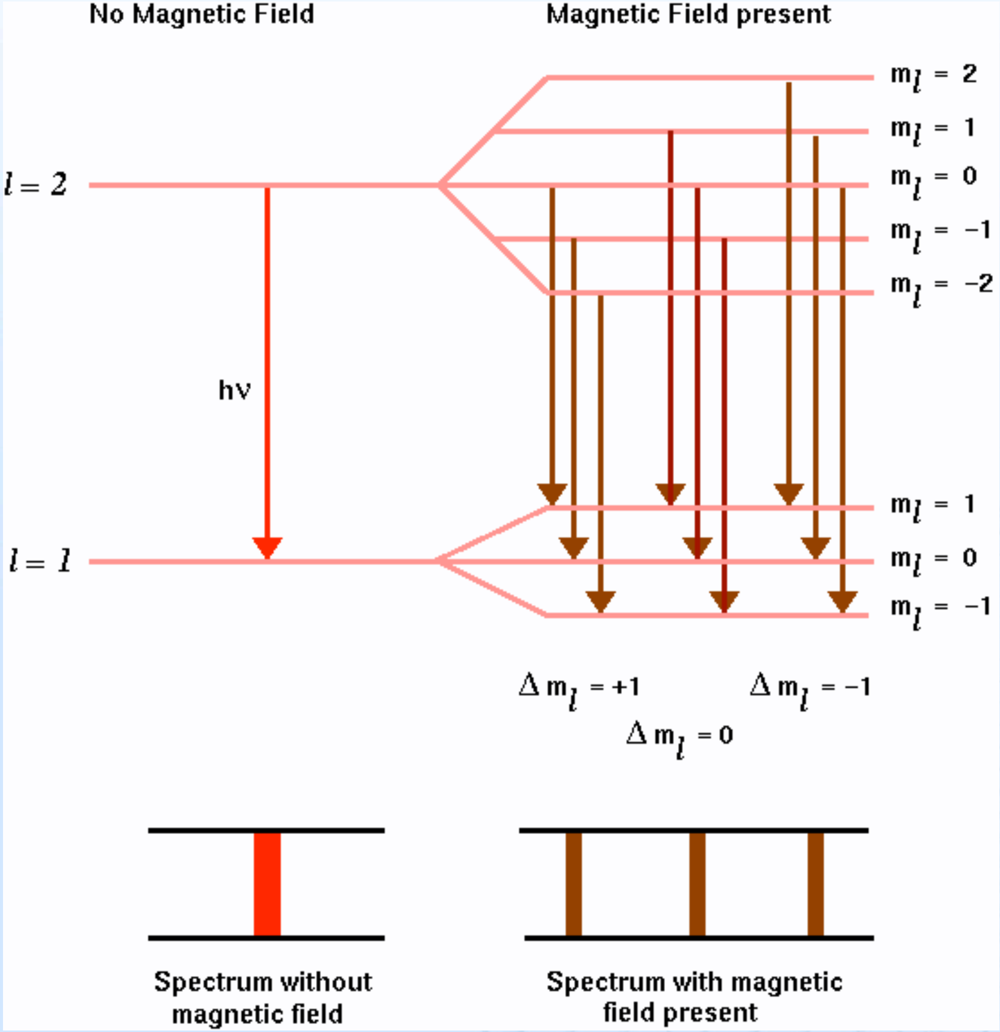
What do the magnetic fields do?

- Can dominate the accretion processes in pre-main sequence stars
- Responsible for stellar activity (spots, flares, …)
- Heat the corona, which produces X-rays
- Brake stellar rotation, ie slowing stars down
- Accelerate cosmic ray particles in neutron stars, are responsible for the pulses in the pulsars (oblique rotator)

Zeeman effect

- Describes the splitting of a spectral line into several components in the presence of a static magnetic field
- distance between the Zeeman sub-levels is a function of the magnetic field, linear for weak fields; for strong fields see Paschen-Back effect
- Zeeman effect is proportial to the magnetic field B and to the square of the wavelength λ^2; ±0.012Å (π-σ separation) for 5000Å and 1kG
- can be used to measure the magnetic field in stars or laboratory plasmas
- Pieter Zeeman, Novel prize 1902

The Zeeman Effect

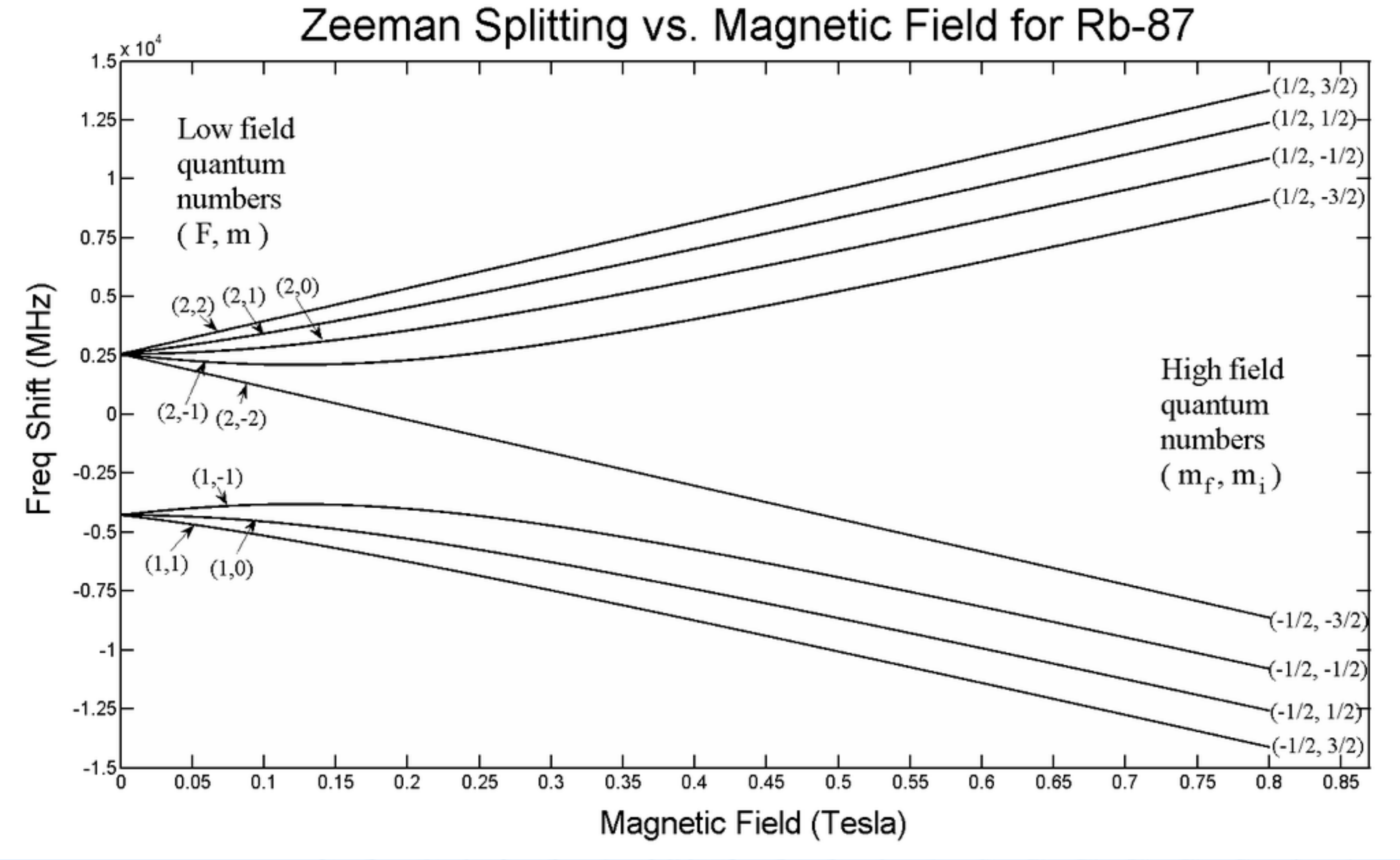


- In a magnetic field, energy levels in atoms split into several components. The larger the magnetic field, the larger the split.

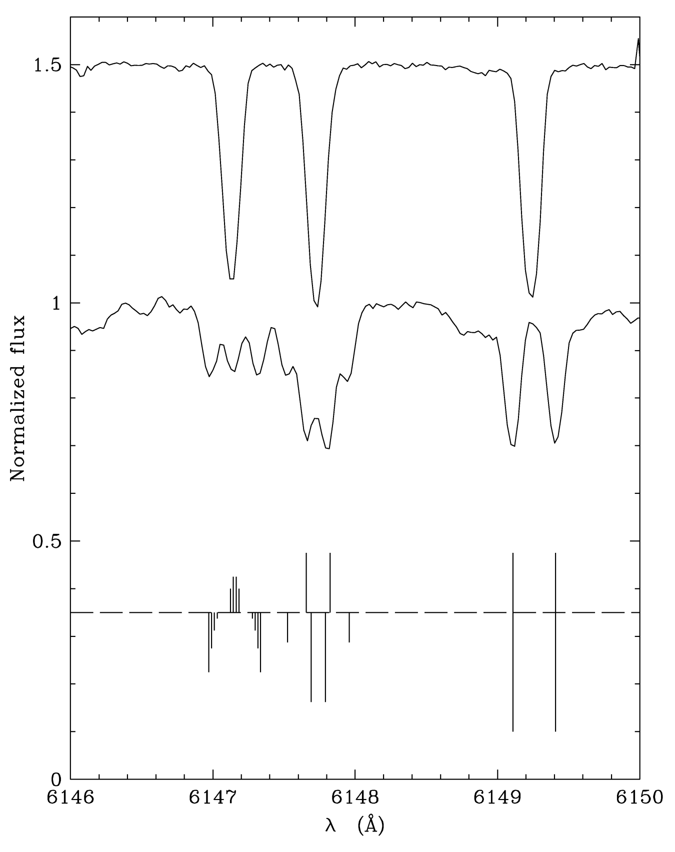
- Lines now form at every possible transition, in this case at three different wavelengths.

- The positions of the lines tell us about the strength of the magnetic field. The lines to the left and right are circularly polarized.

Zeeman Splitting



Magnetically resolved lines



Work horses for stellar magnetic field research

- Espadons@CFHT (Mauna Kea)
- FORS2@VLT (Paranal)
- HARPSpol@ESO3.6 (La Silla)
- NARVAL@BLT (Pic du Midi)

Magnetic field measures

The magnetic field is in every location a 3d-vector $B = (B_x, B_y, B_z)$.

We measure typically:

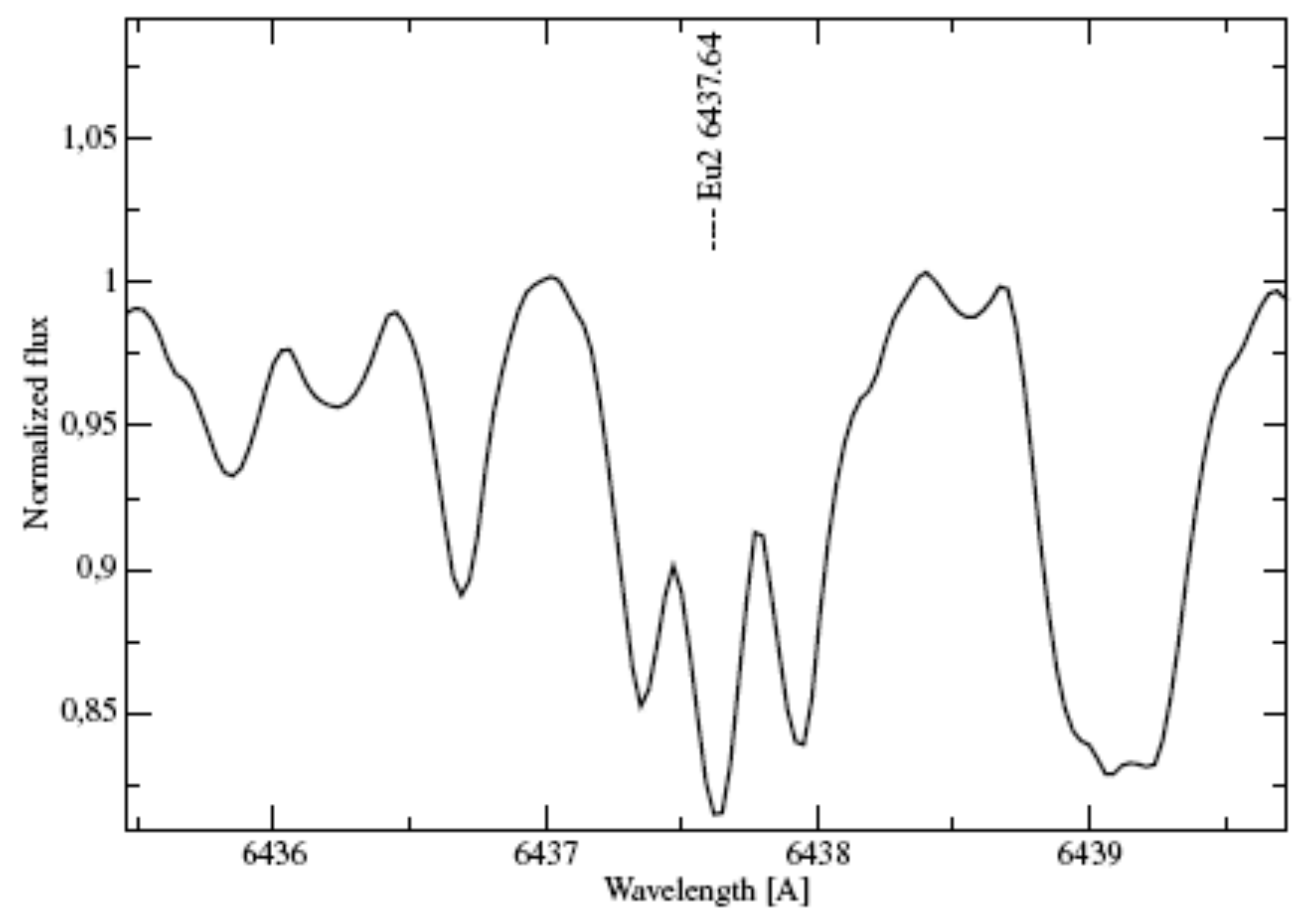
- the longitudinal magnetic field: $\langle B_z \rangle$
- the magnetic field modulus: $\langle |B| \rangle$
- the crossover effect: $v \sin i \langle x\, B_z \rangle$
- the mean quadratic magnetic field $(\langle B^2 + \langle B_z^2 \rangle)^{1/2}$

“averaged” over the stellar disk.

Magnetic field measurements

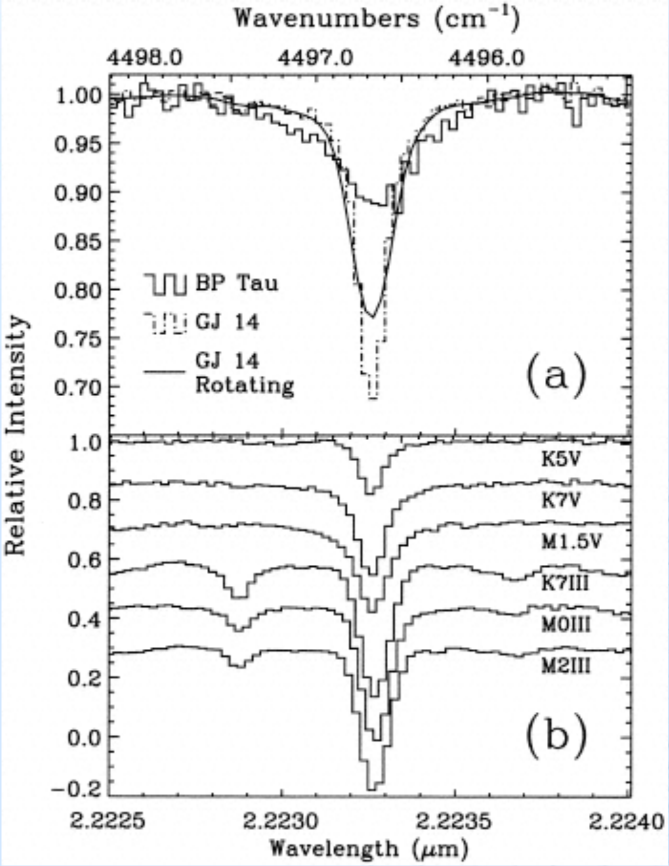
- Magnetic field studies are mainly based on one of the following quantities:
  - mean longitudinal magnetic field $\langle B_z \rangle$:
    - derived from measurements of wavelength shifts of spectral lines between right and left circular polarizations
  - crossover $v \sin i \langle x B_z \rangle$:
    - derived from measurements of the second-order moments of line profiles in Stokes *V* (difference of line width between opposite circular polarizations)
  - mean quadratic magnetic field $(\langle B^2 \rangle + \langle B_z^2 \rangle)^{1/2}$:
    - derived from measurements of the second-order moments of line profiles in Stokes *I* (total line widths in natural light)
  - mean magnetic field modulus $\langle B \rangle$:
    - derived from measurements of the wavelength separation of resolved magnetically split components of spectral lines in Stokes *I*
  - broad-band linear polarization (Q,U):
    - meaningful constraints on the magnetic field can be derived from consideration of the path followed by the star in the $(Q/I, U/I)$ plane

Zeeman splitting in unpolarized light for a strong magnetic field



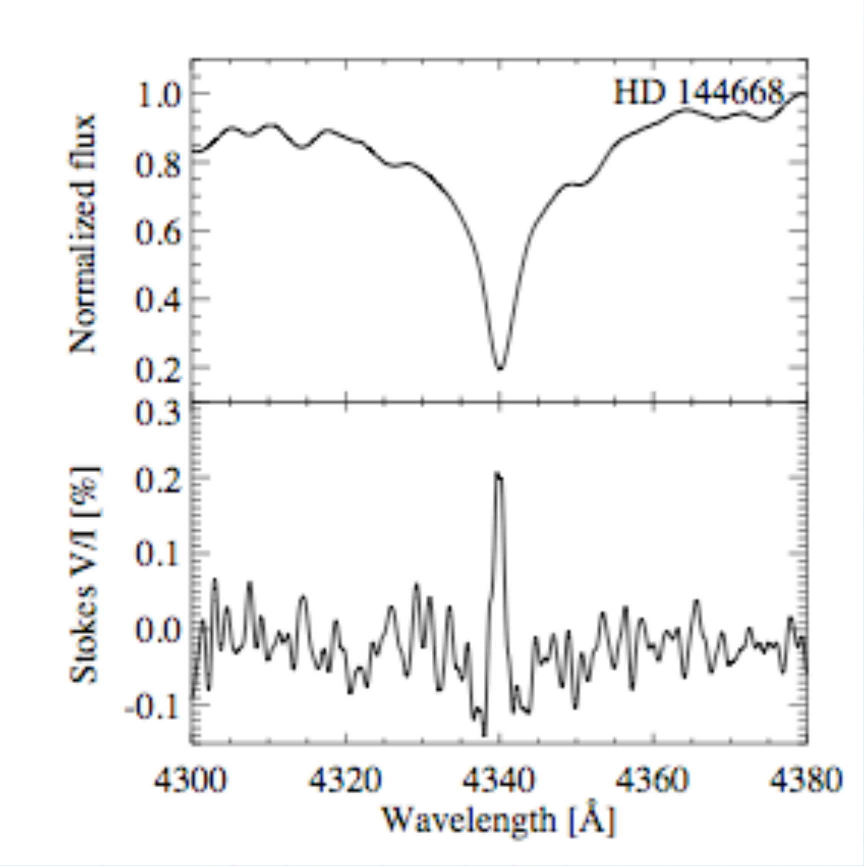
HD 924999 - 8.5kG (Hubrig & Nesvacil 2007)

Line broadening



- Johns-Krull et al. (1999) find a magnetic field of 2.6±0.3 kG in BP Tau from the broadening of the Ti I line at 2.2233μm

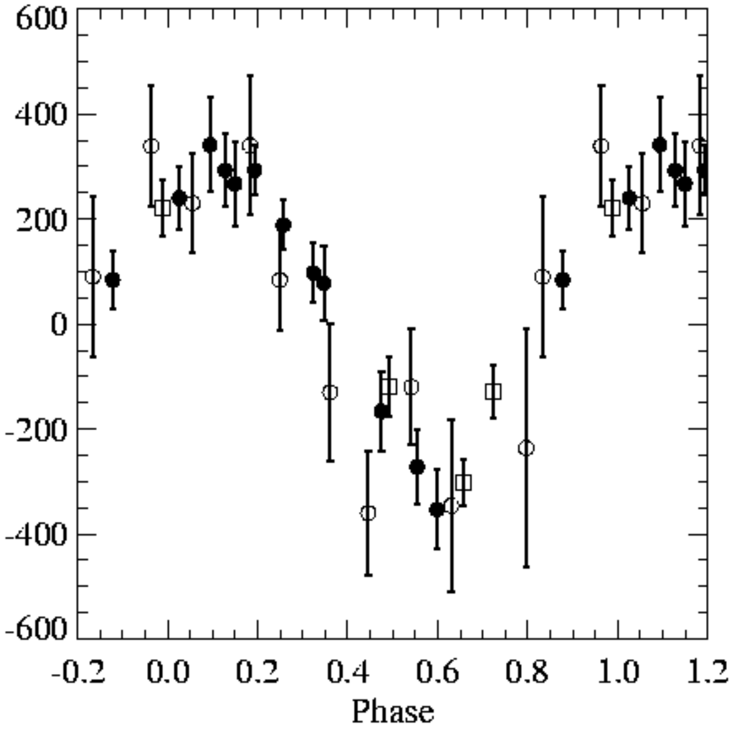
The crossover effect



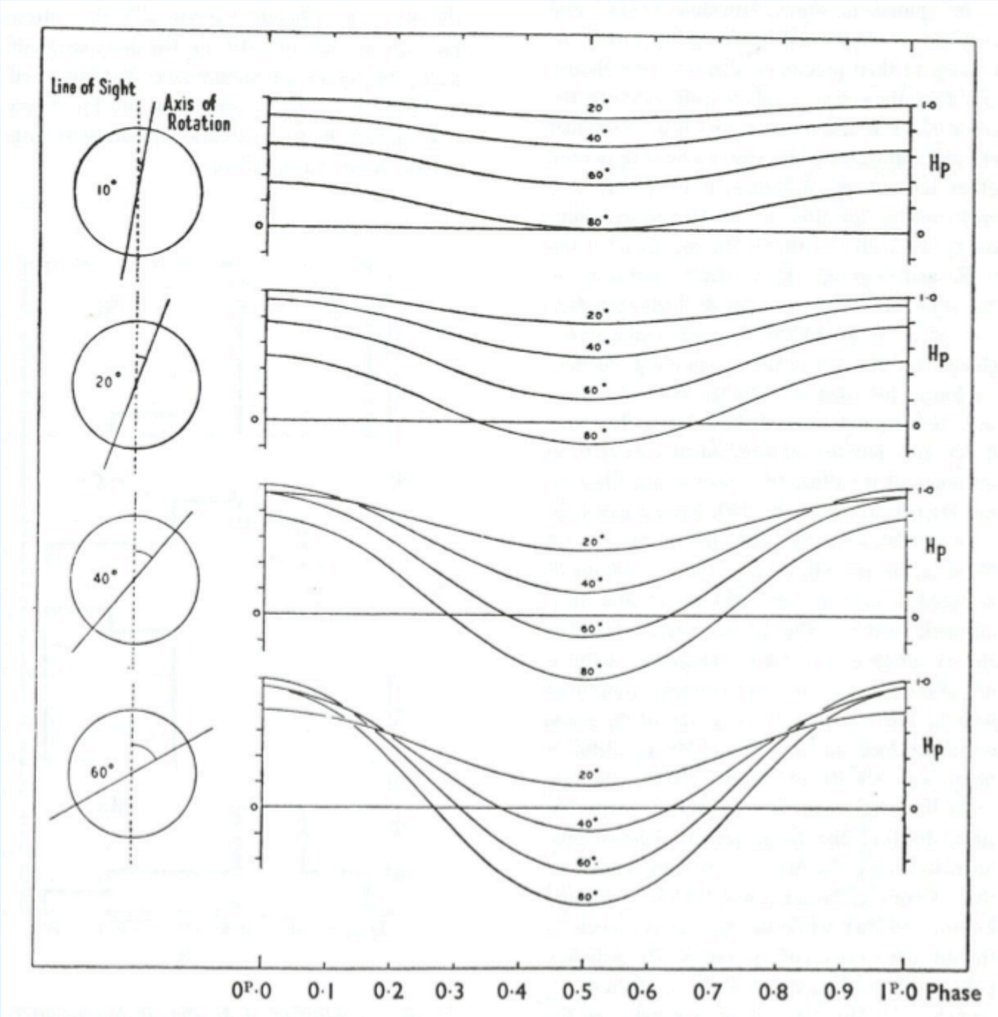
Mean longitudinal magnetic field - $\langle B_z \rangle$

- The mean longitudinal magnetic field is the component of the magnetic field parallel to the line of sight averaged over the stellar hemisphere visible at the time of observation and weighted by the local emergent spectral line intensity.
- It depends strongly on the angles between line of sight, rotation axis, magnetic axis, as well as rotation phase.
- Thus, it is very useful to follow stellar rotation, but limited in (non-)detection of magnetic fields with single observations.

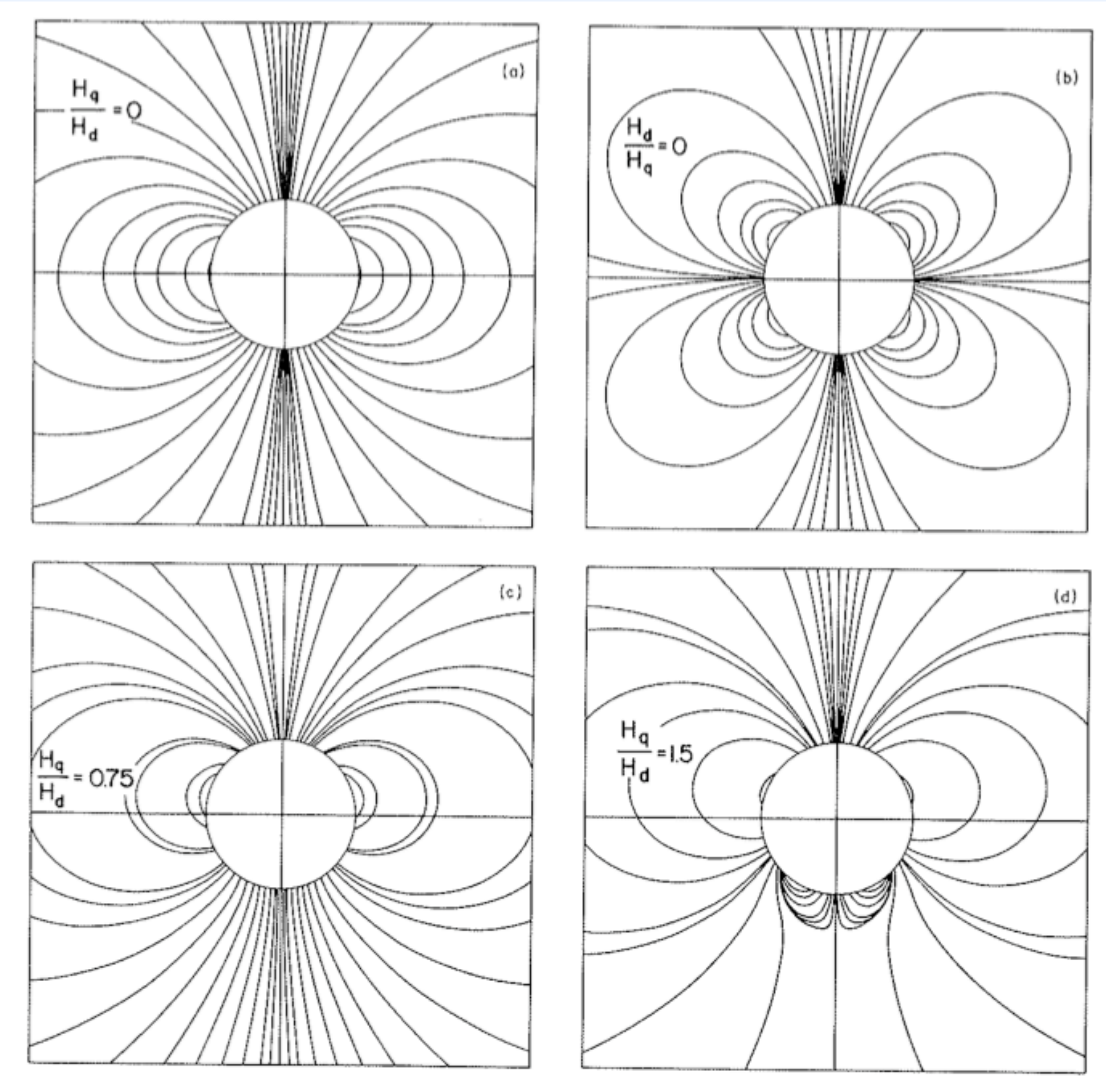
Variation of the longitudinal magnetic field with rotation in the case of θ^1 Ori C



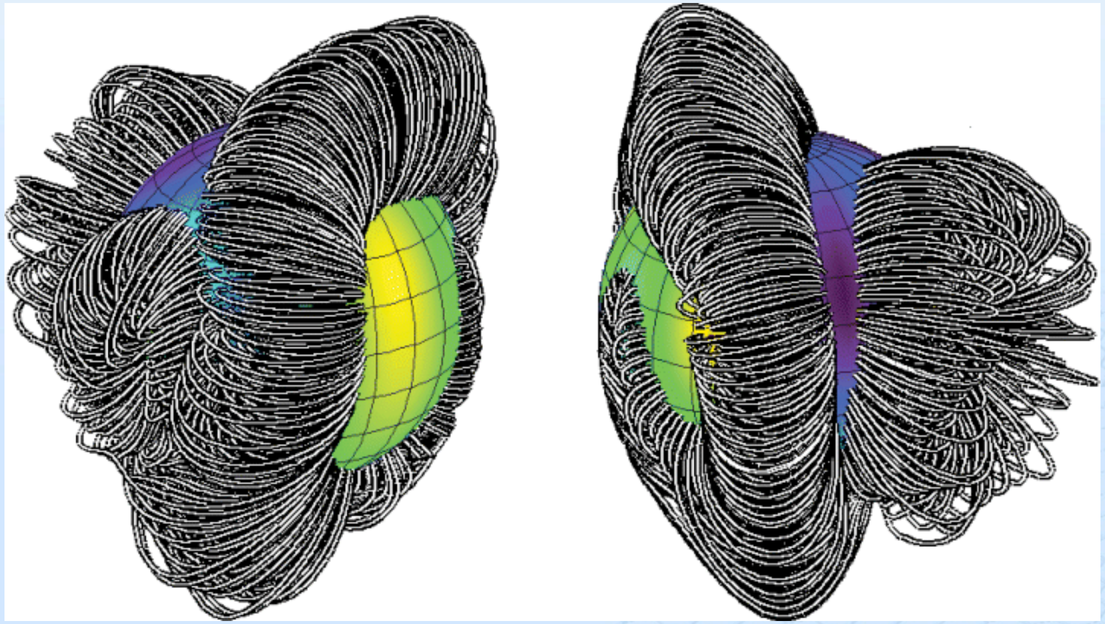
Viewing the oblique rotator from different angles



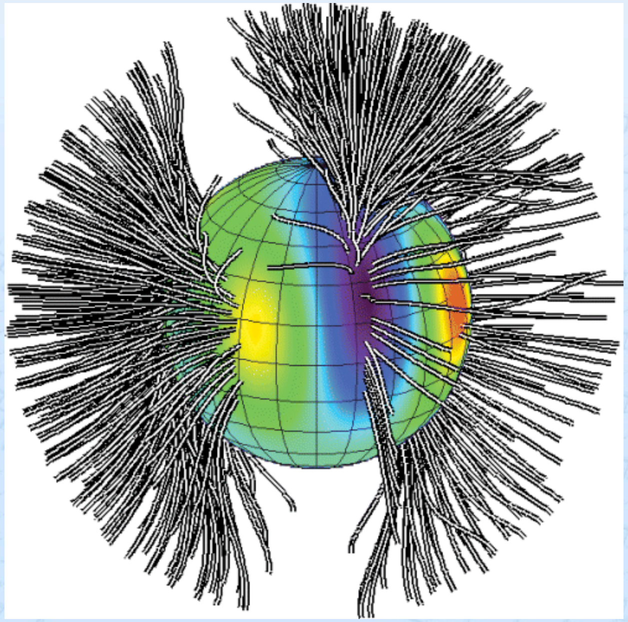
Dipole and quadrupole



Not all stars are dipoles!



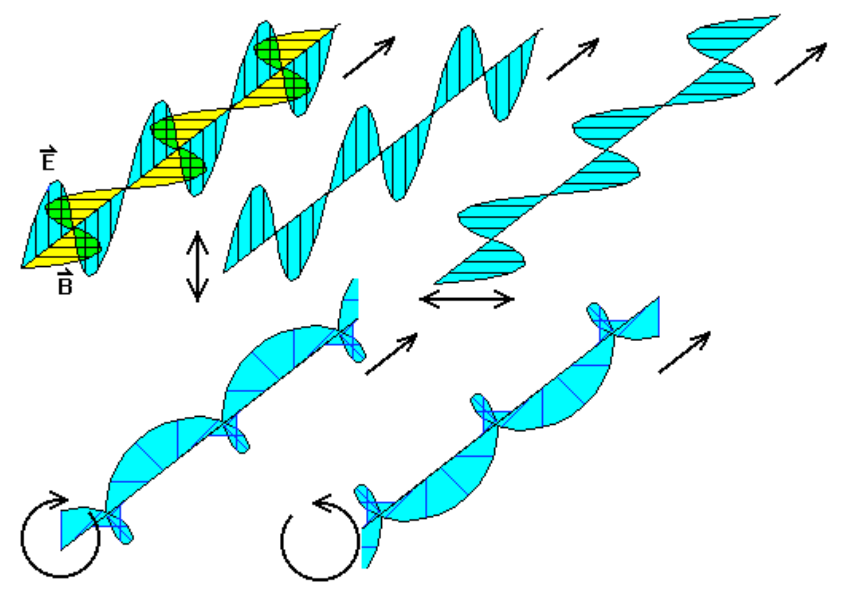
Closed lines



Open lines

τ Sco - Donati et al. (2006)

Polarization of light

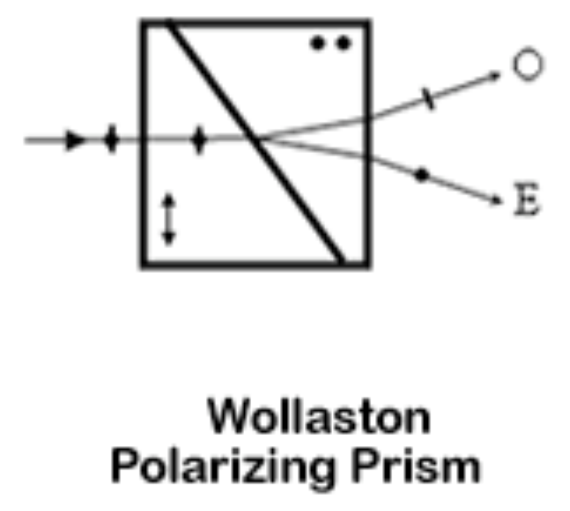


- Polarized light comes in two flavors:

- Linear and circular polarized light.

- For the magnetic field detection, we are only interested in the left and right circular polarized light.

Optical components needed

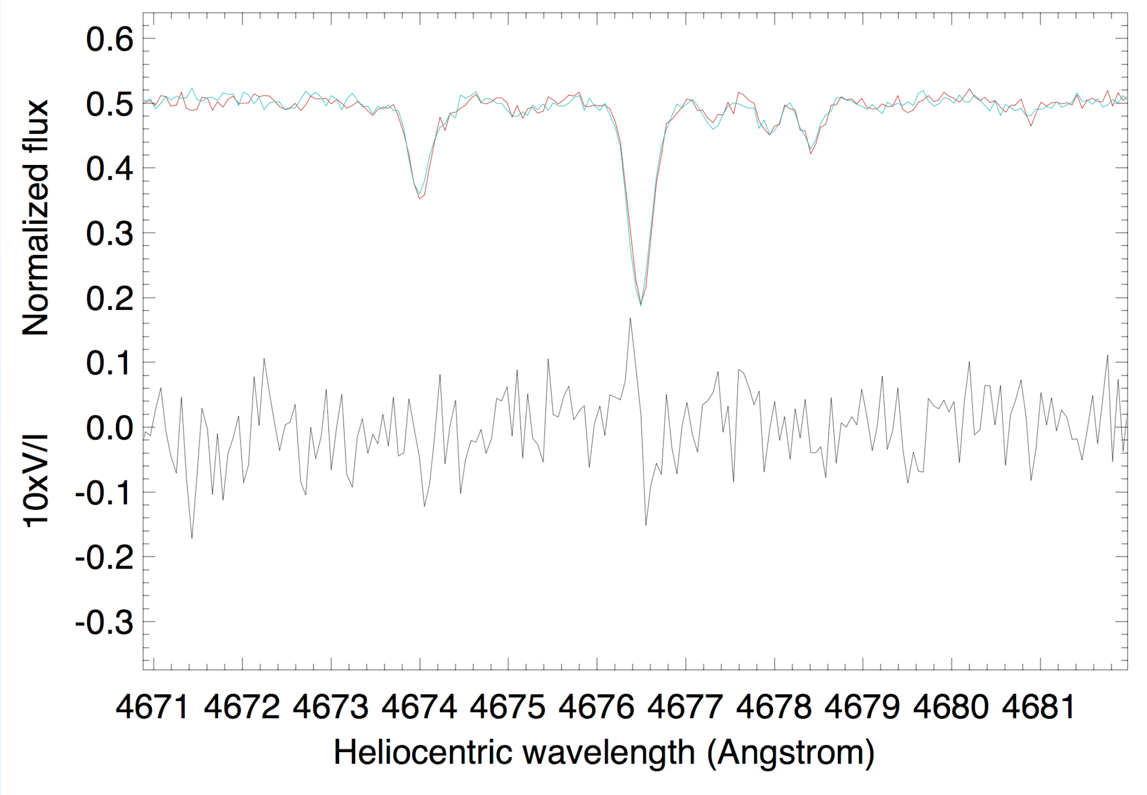


Wollaston Polarizing Prism

- A Wollaston prism splits the linearly polarized light into the ordinary and the extraordinary beams.
- A quarter wave plate changes linearly polarized light into circularly polarized light and circularly polarized light into linearly polarized light.
- A half wave plate changes polarization axes.

For FORS2: quarter wave plate to go from circular polarization to linear polarization, half wave plate to swap O and E beams, Wollaston to split the light (22” beam divergence), R~2000-4000.

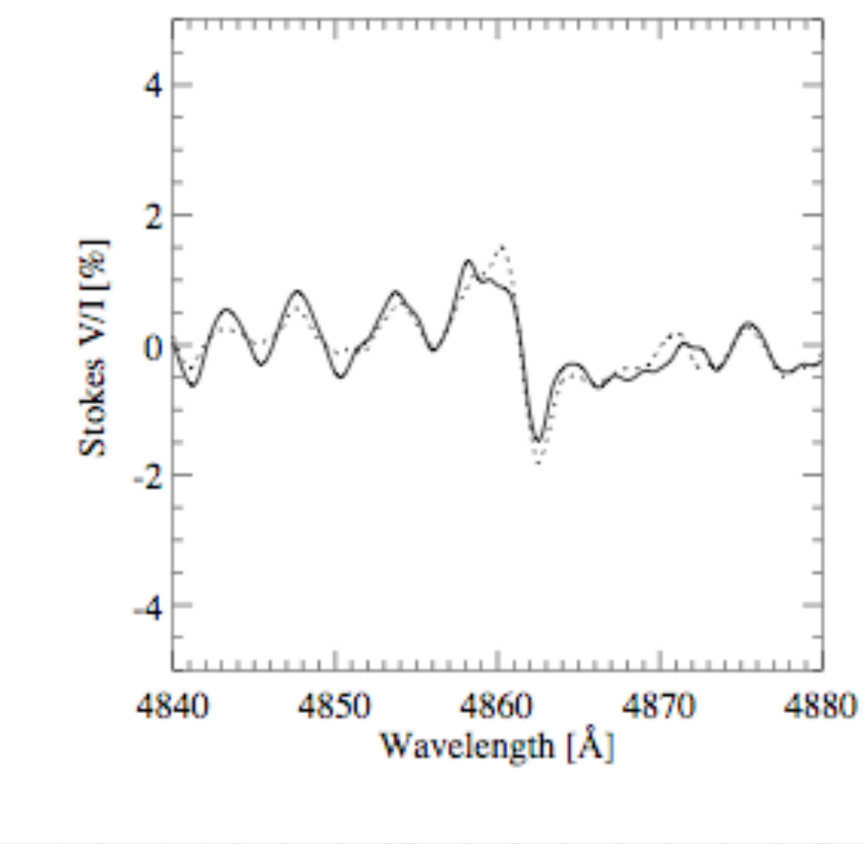
Polarization spectra from SOFIN@NOT



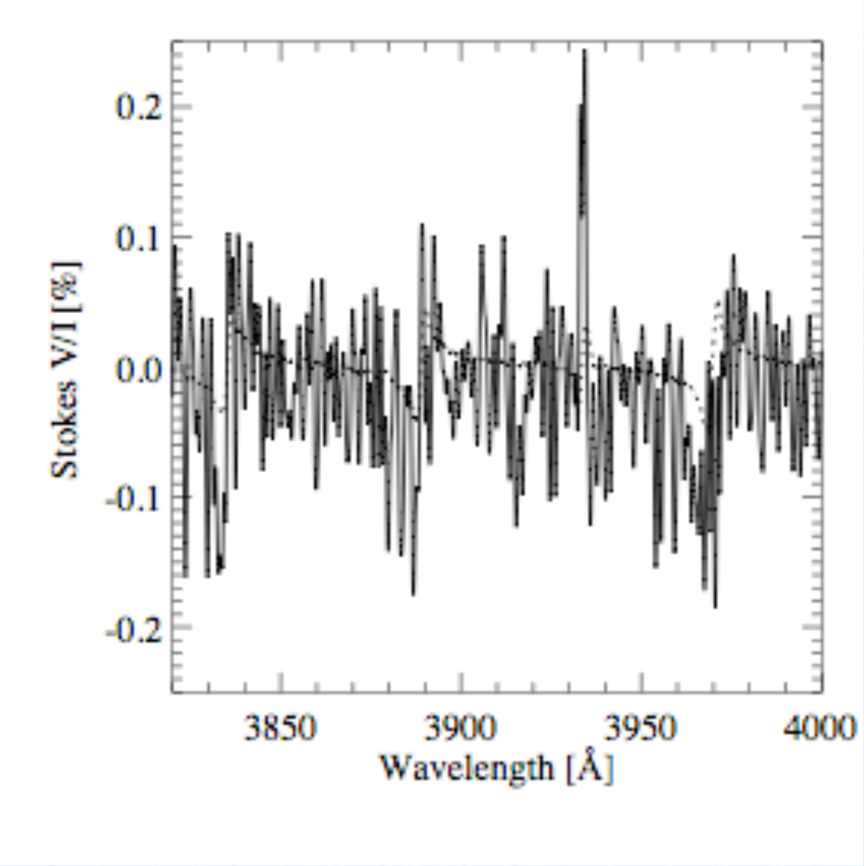
300G signal

$$\frac{V}{I} = \frac{1}{2}\left\{\left(\frac{f^{\mathrm{o}} - f^{\mathrm{e}}}{f^{\mathrm{o}} + f^{\mathrm{e}}}\right)_{\alpha=-45^\circ} - \left(\frac{f^{\mathrm{o}} - f^{\mathrm{e}}}{f^{\mathrm{o}} + f^{\mathrm{e}}}\right)_{\alpha=+45^\circ}\right\}$$

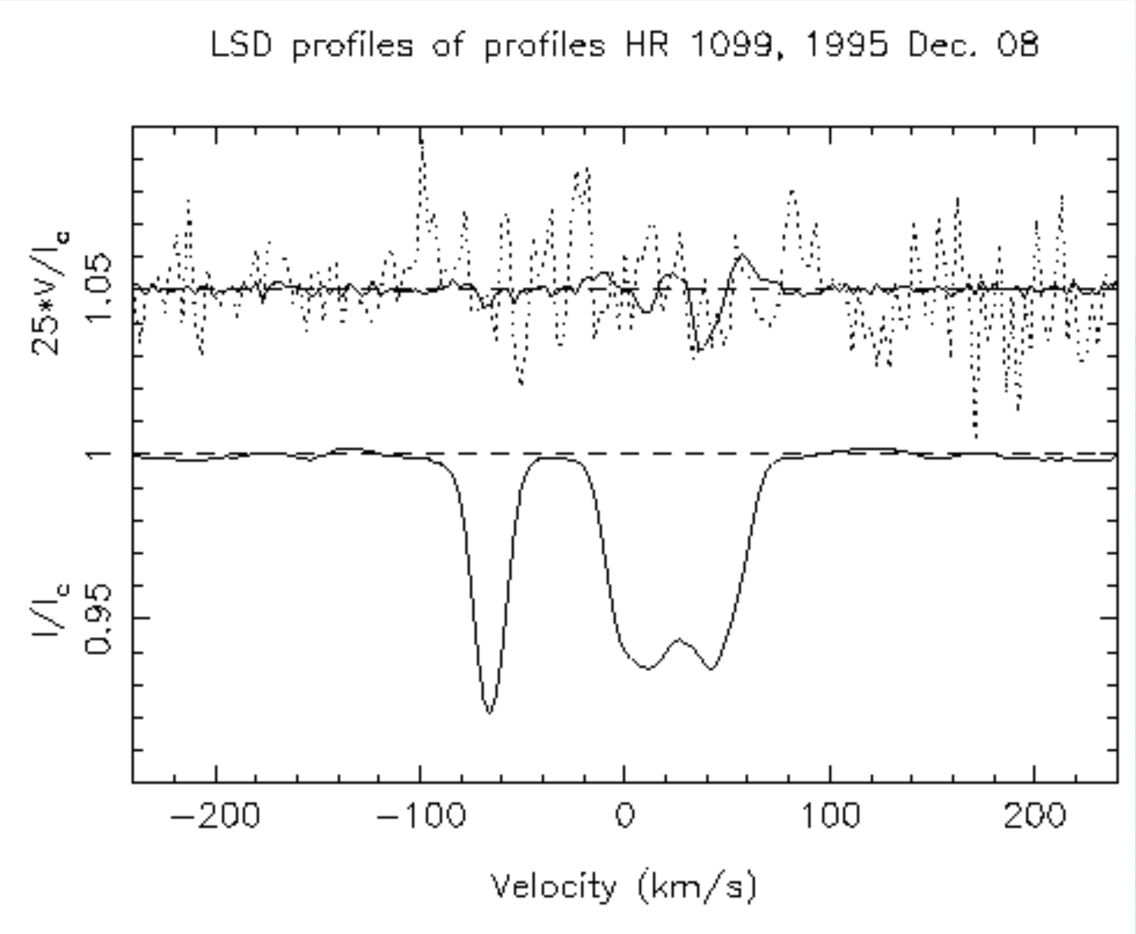
“Fitting” lines - strong field



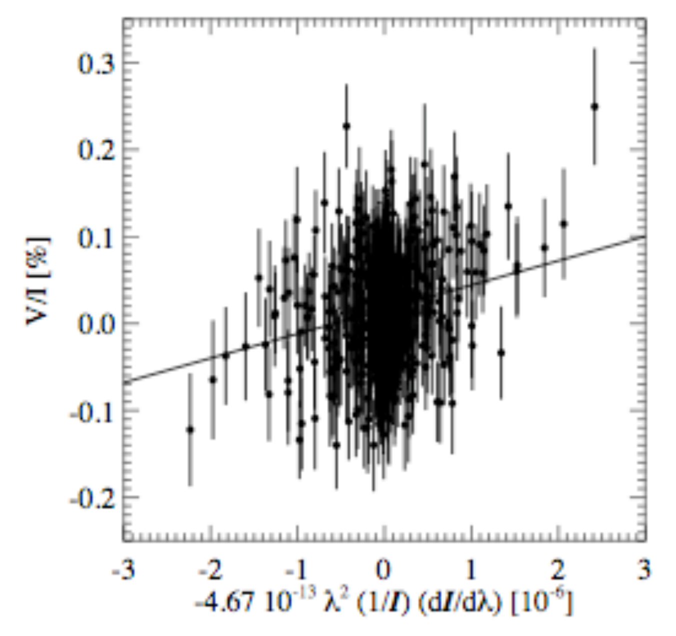
“Fitting” lines - weak field



Least Square Deconvolution



Fitting the magnetic field



$$\frac{V}{I} = -\frac{g_{\mathrm{eff}} e \lambda^2}{4\pi m_{\mathrm{e}} c^2} \frac{1}{I} \frac{\mathrm{d}I}{\mathrm{d}\lambda} \langle \mathcal{B}_z \rangle$$