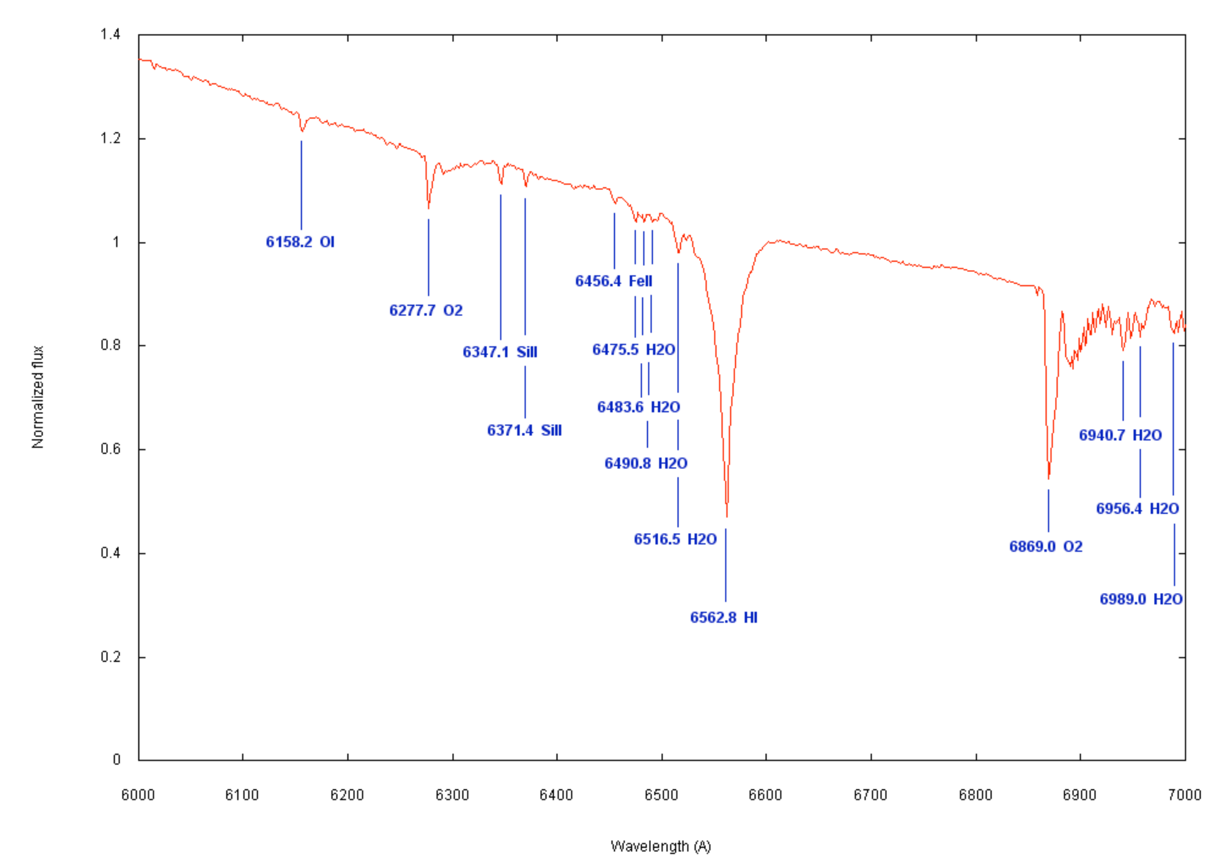
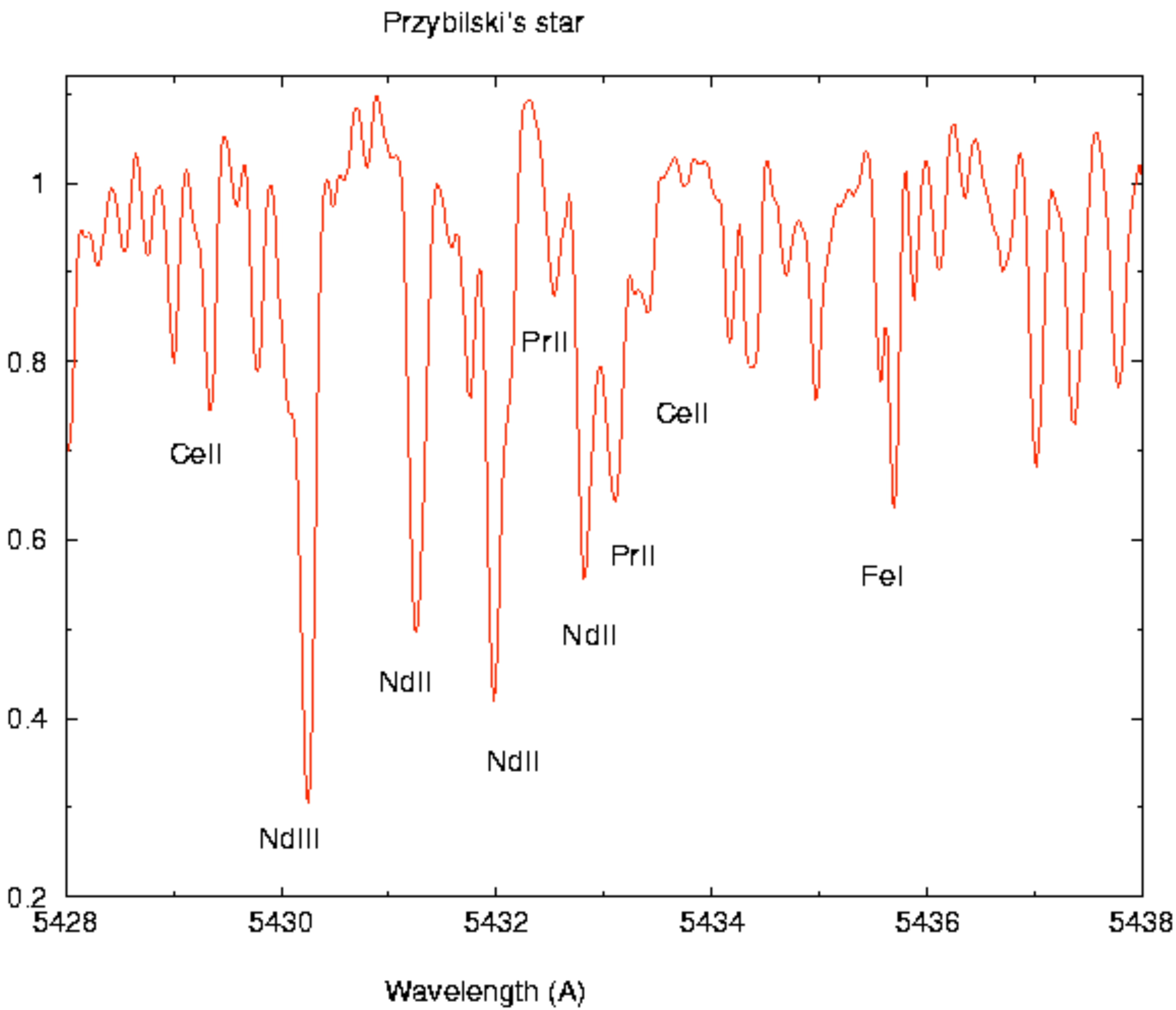
# Chemically peculiar stars

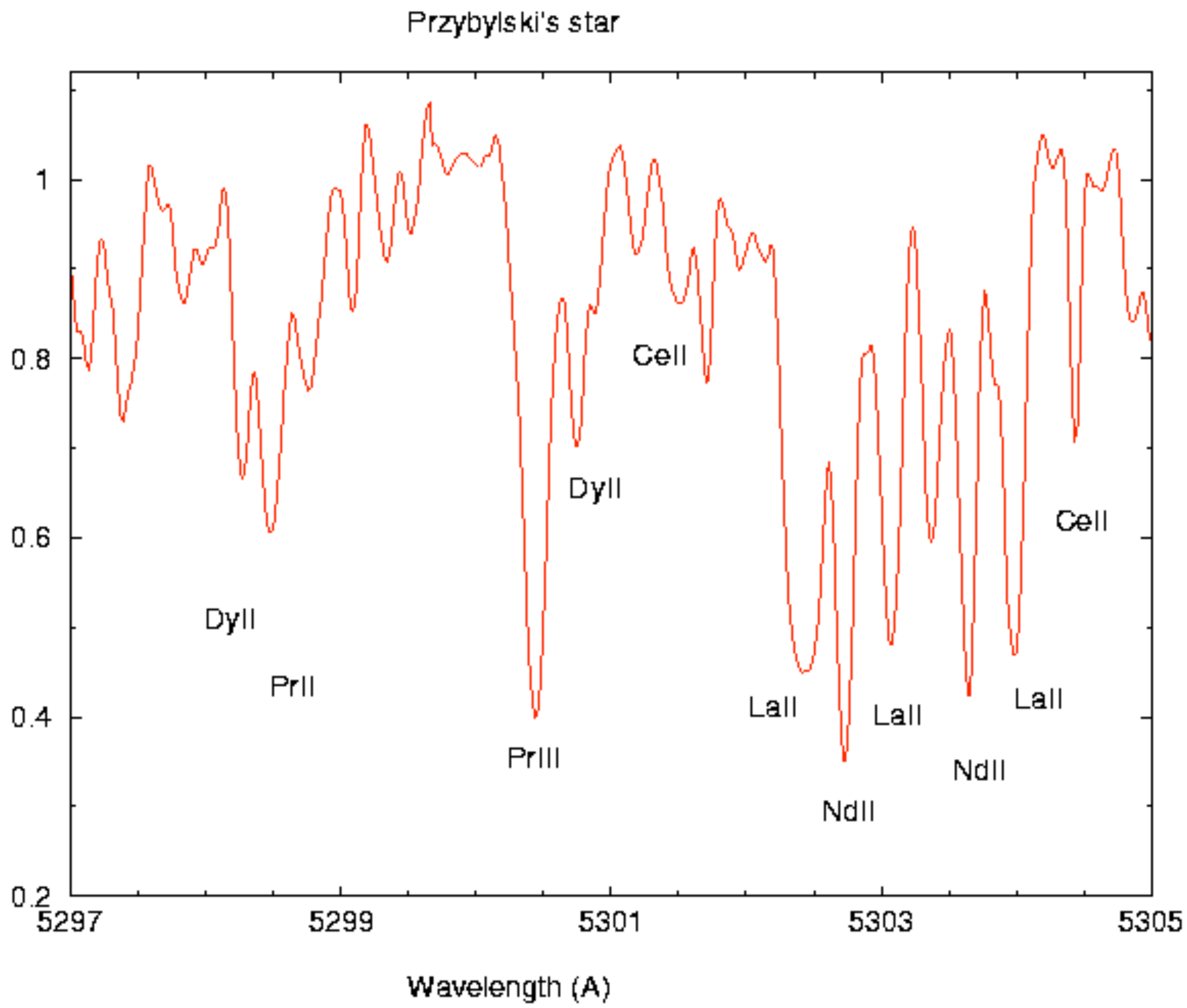
Markus Schöller

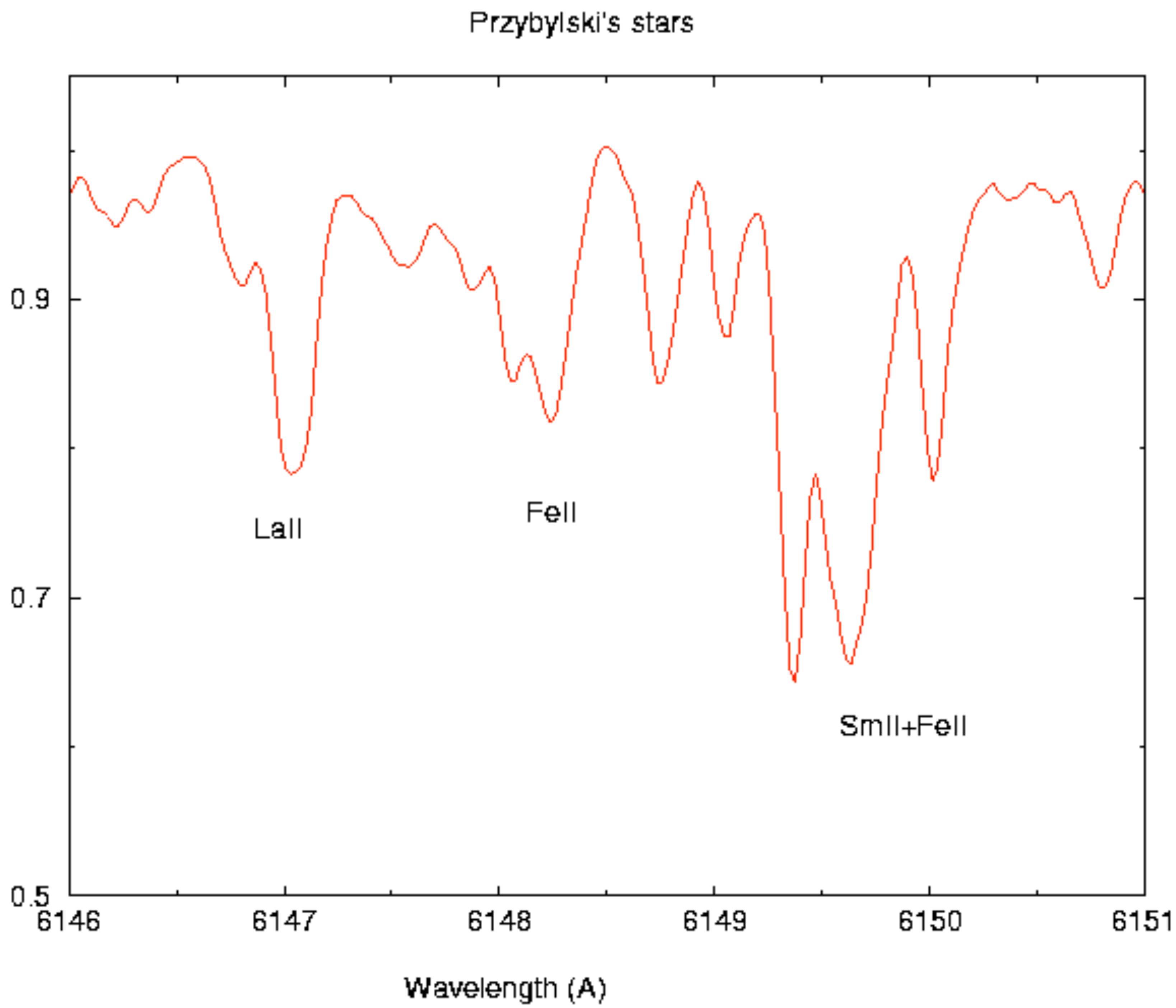
# Vega



1.4
1.2
1
0.8
0.6
0.4
0.2
0
Normalized flux
6000
6100
6200
6300
6400
6500
6600
6700
6800
6900
7000
Wavelength (A)
6158.2 OI
6277.7 O2
6347.1 SiII
6371.4 SiII
6456.4 FeII
6475.5 H2O
6483.6 H2O
6490.8 H2O
6516.5 H2O
6562.8 HI
6869.0 O2
6940.7 H2O
6956.4 H2O
6989.0 H2O


Przybilski's star
1
0.8
0.6
0.4
0.2
5428
5430
5432
5434
5436
5438
Wavelength (A)
CeII
NdIII
NdII
NdII
PrII
NdII
PrII
CeII
FeI


Przybylski's star
1
0.8
0.6
0.4
0.2
5297
5299
5301
5303
5305
Wavelength (A)
DyII
PrII
PrIII
DyII
CeII
LaII
NdII
LaII
NdII
LaII
CeII



Przybylski's stars
0.9
0.7
0.5
6146
6147
6148
6149
6150
6151
Wavelength (A)
LaII
FeII
SmII+FeII

# A wealth of information

- Castelli & Hubrig (2004) analyze a spectrum of the HgMn star HD175640 observed with UVES (*R*~90,000−100,000 and spectral coverage 3040−10,000Å) with SYNTHE (Kurucz 1993):
  - Abundances for 49 ions
  - 200/230/130 lines for abundances of light elements, ion group elements, elements with Z≥31
  - 80 Ti II emission lines, 40 Cr II emission lines
  - 100 lines for Mn II hfs, 140 lines for Ga II isotopic structure, 15 lines for Ba II hfs, 30 lines for Hg II isotopic/hf structure
  - 170 unidentified absorption lines, 30 unidentified emission lines

# Where do all these overabundances come from?

- Selective diffusion of different elements/ ions (see talk by T. Ryabchikova)

# Groups of CP stars

| Pec. type | Sp. type | $T_{eff}$ range | magnetic/spots |
|---|---|---|---|
| He-strong | B1-B4 | 17000-21000 | yes/yes |
| He-weak | B4-B8 | 13000-17000 | yes/yes |
| Si | B7-A0 | 9000-14000 | yes/yes |
| HgMn | B8-A0 | 10000-14000 | yes?/yes! |
| SrCrEu | A0-F0 | 7000-10000 | yes/yes |
| Am | A0-F0 | 7000-10000 | yes?/no |

# Ap and Bp stars

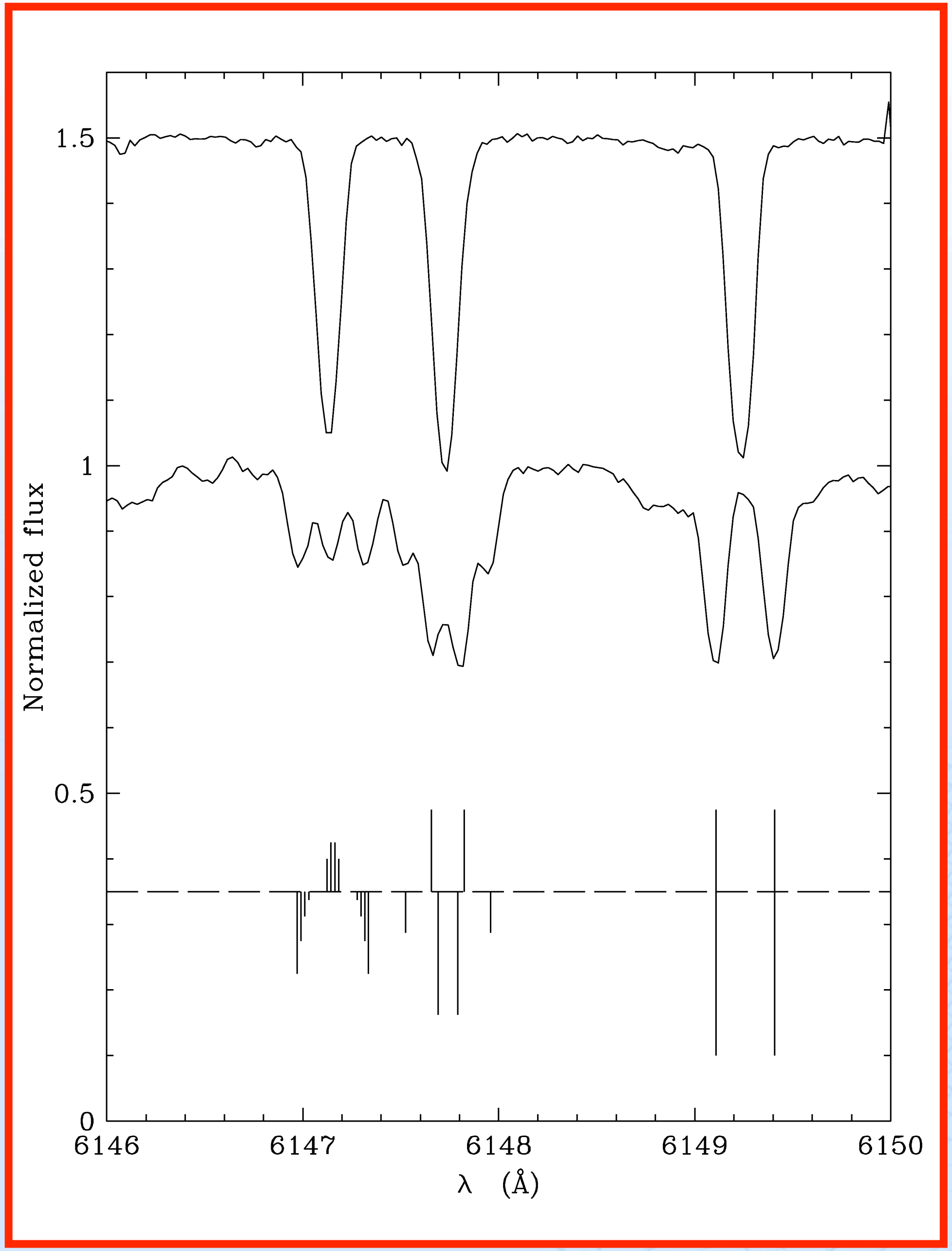
- Main sequence A and B stars in the spectra of which lines of some elements are abnormally strong or weak (e.g., Si, Sr, Cr, Eu, He…)
- They generally have magnetic fields that can be detected through observation of circular polarization in spectral lines
- All observables (magnitude in various photometric bands, spectral line equivalent widths, magnetic field) vary with the same period
- Periods range from half a day to several decades
- Abnormal line strengths correspond to non-solar element abundances (by up to 5−6 dex), confined to the stellar outer layers and interpreted as resulting from segregation processes

# Brief historical overview

- First detection of a magnetic field in a star other than the sun:
  - 1946: CS Vir (H.W. Babcock, 1947, ApJ 105, 105)
  - Essentially a determination of the longitudinal magnetic field
- Today, mean longitudinal magnetic field measurements throughout the variation period have been obtained for no more than 100 stars
- Crossover, mean quadratic magnetic field
  - First systematic determinations published in 1995 (G. Mathys, 1995, A&A 293, 733; A&A 293, 746)
  - Full phase coverage achieved for about two dozen stars
- Broad-band linear polarization (BBLP)
  - Bulk of published material gathered by J.-L. Leroy between 1990 and 1995 (J.-L. Leroy, 1995, A&AS 114, 79 and references therein)
  - Variations well studied for about 15 stars

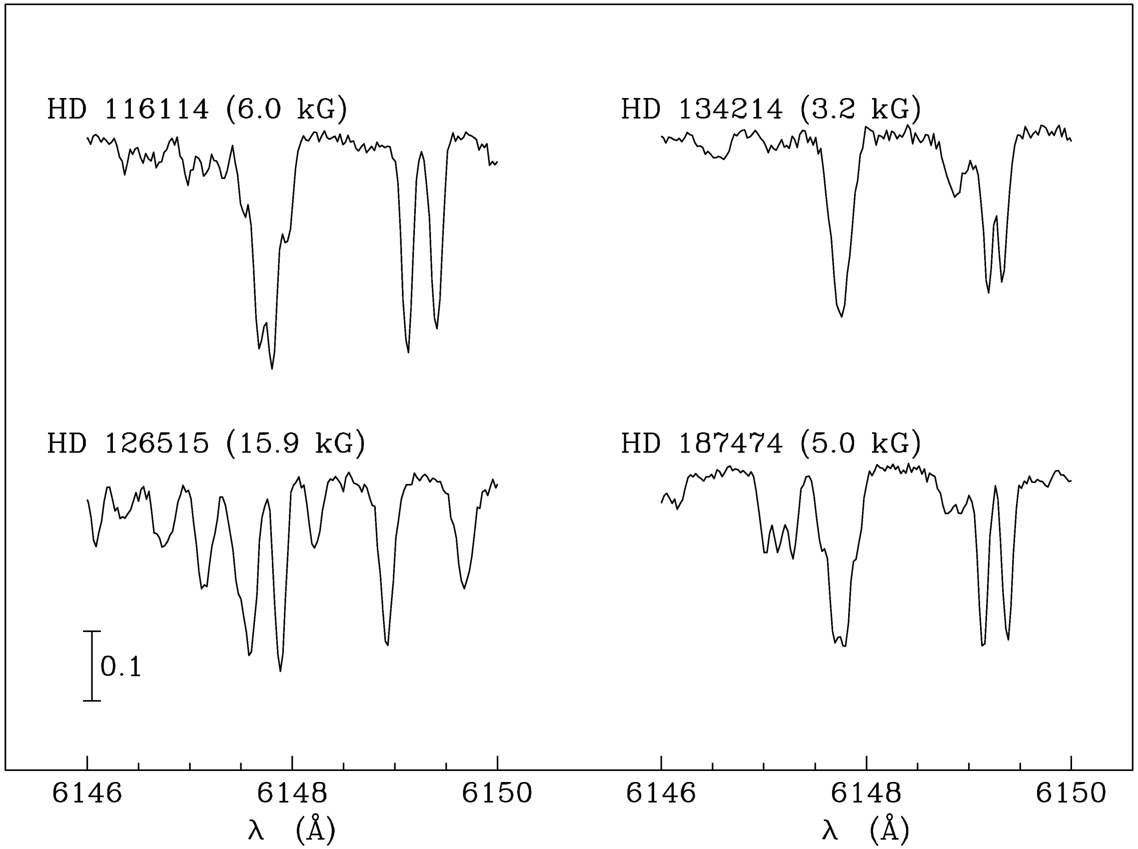
# Brief historical overview

- Ap stars with resolved magnetically split lines:
  - Resolution of magnetically split lines requires strong enough field, and sufficiently slow rotation
  - Resolved magnetically split lines first discovered in Babcock's star, HD 215441 (H.W. Babcock, 1960, ApJ 132, 521)
  - HD 215441: <*B*> ~ 34 kG (still the strongest field modulus measured)
  - 1987: 12 stars with magnetically resolved lines known, 4 studied throughout their variation period
  - 2001: 44 stars with magnetically resolved lines known, 24 studied throughout their variation period (G. Mathys *et al.*, 1997, A&AS 123, 353; G. Mathys, J. Manfroid & E. Wenderoth, in preparation)




# Ap stars with magnetically resolved lines: Fe II λ6149

# Some Ap stars with resolved magnetically split lines



# General trends and relations

1. Strongest fields tend to be found in more massive stars.
2. The strongest fields are found only in fast-rotating stars; all stars with rotation periods exceeding 1000 days have fields below 6.5 kG.
3. Slowly rotating magnetic stars generally have their magnetic and rotation axes aligned to within 20°, unlike the short period magnetic Ap stars, in which $\beta$ is usually large (Landstreet & Mathys 2000).

# General properties of Ap star magnetic fields

- Mean-longitudinal magnetic field non-zero:
  - large-scale organization:
    - circular polarization from tangled (solar-like) fields mostly cancels out in disk integration
  - significant dipole-like component:
    - dipole: $\langle B_z \rangle / \langle B \rangle \sim 0.3$
    - quadrupole: $\langle B_z \rangle / \langle B \rangle \sim 0.05$
    - toroidal or higher-order multipolar components sufficient to account for the observed longitudinal field would induce strong distortions of spectral line profiles in Stokes *I*

# General properties of Ap star magnetic fields

- The magnetic field covers the whole stellar surface and the distribution of field strengths over the star is fairly narrow:
  - the magnetic field is observed at all phases
  - continuum is reached between split components of resolved lines
  - the resolved magnetically split components are rather narrow

# The oblique rotator

- Magnetic field is not symmetric about the stellar rotation axis
- Other surface features (e.g., abundance distribution) are determined by the magnetic field
- Observed variations result from changing aspect of the visible hemisphere as the star rotates
- Thus the variation period is the rotation period of the star
- No intrinsic variations of the magnetic fields have been observed

# Geometric structure

- Early models:
  - quasi-sinusoidal variations of the longitudinal field
  - simplest model: dipole with centre at the star's centre and axis inclined with respect to the stellar rotation axis
- Stars with magnetically resolved lines:
  - mean magnetic field modulus generally has one maximum and one minimum per rotation period (even for stars with reversing longitudinal field): centred dipole ruled out
  - alternative models:
    - dipole offset along its axis (parameters: $i$, $\beta$, $B_d$, $a$)
    - collinear dipole + quadrupole (parameters: $i$, $\beta$, $B_d$, $B_q$)
    - good match with 4 observables: maximum and minimum of longitudinal field and field modulus
    - to first order, both models are equivalent

# Geometric structure

- Additional constraints: crossover, mean quadratic field
  - collinear dipole + quadrupole + octupole give a pretty good first approximation in many cases (J.D. Landstreet & G. Mathys, 2000, A&A 359, 213):
    - dipole: primarily accounts for the longitudinal field
    - quadrupole: gives field strength contrast between poles
    - octupole: responsible for equator-to-pole field strength contrast
- Asymmetric variation curves of some field moments:
  - magnetic field is not symmetric about an axis passing through the centre of the star (G. Mathys, 1993, IAU Coll. 138, p. 232)
  - generalized multipolar model (S. Bagnulo et al., 1999, A&A 358, 929, and references therein):
    - observables: $\langle B_z \rangle$, $\langle x B_z \rangle$, $(\langle B^2 \rangle + \langle B_z^2 \rangle)^{1/2}$, $\langle B \rangle$, BBLP
    - $\chi^2$ minimization between predicted and observed values of the observables at phases distributed throughout the rotation period

# Geometric structure

- Ultimately, direct inversion of line profiles recorded in all 4 Stokes parameters will allow one to derive magnetic field maps without *a priori* assumptions(*):
  - demanding in terms of S/N, resolution, phase coverage
  - numerical instabilities
  - heavy computations
  - so far restricted to a few individual stars

(*) but with a regularization condition…

- Effect of abundance inhomogeneities must also be taken into account

# Field strength distribution

- Mean longitudinal magnetic field:
  - mean longitudinal magnetic field distribution extends all the way down to the detection limit, 100 G or less (J.D. Landstreet, 1982, A&AR 4, 35)
  - rms mean longitudinal magnetic field averaged over a stellar rotation period is of the order of 300 G for “classical” Ap stars, and larger (~ 1 kG?) for hotter He weak and He strong Bp stars (ibidem)

# Field strength distribution

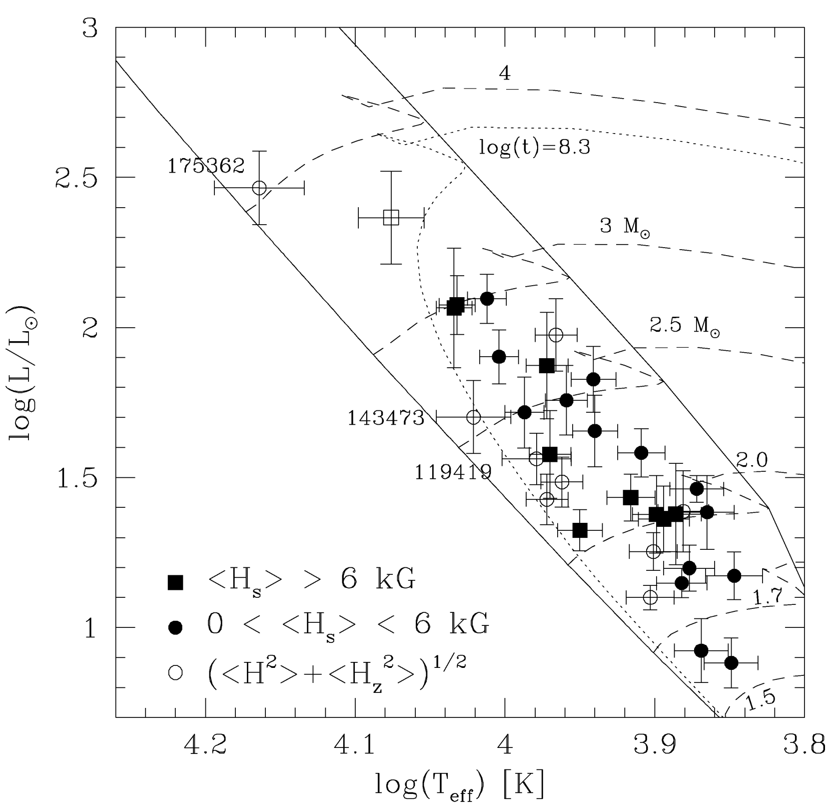
- Mean magnetic field modulus:
  - the mean field modulus characterized better the intrinsic stellar magnetic field than the mean longitudinal field, which is much more dependent of the geometry of the observation
  - most Ap stars with magnetically resolved lines have a mean magnetic field modulus (averaged over the stellar rotation period) comprised between 3 and 9 kG; but there is a lower cutoff of the distribution at 2.8 kG:
    - one expects to be able to resolve lines down to 1.7 kG or lower
    - at some rotation phases of some stars, resolution is observed at 2.2 kG
  - relation between field modulus and temperature:
    - lower limit of distribution roughly temperature independent
    - hotter stars may have stronger fields than cooler stars

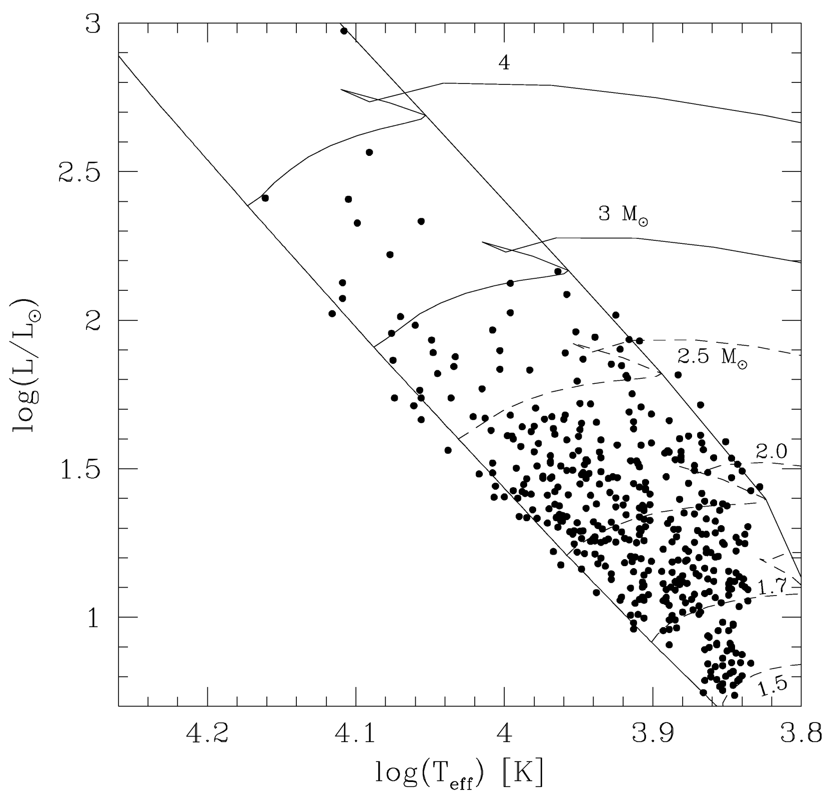
# Magnetic field and rotation

Ap star variation periods span 5 orders of magnitude:

- until recently, there seemed to be no systematic differences between short and long period stars
- confirmation that very long periods are indeed rotation periods has been brought by BBLP (Leroy *et al.*, 1994, A&A 284, 174)
- systematic study of Ap stars with resolved magnetically split lines has doubled the number of known stars with $P > 30$ days:
  - the distribution of the periods longer than 1 year is compatible with an equipartition on a logarithmic scale
  - no star with $P > 150$ d has a mean field modulus exceeding 7.5 kG; more than 50% of the resolved line stars with shorter periods have a field modulus above this value (Mathys et al., 1997, A&AS 123, 353)
  - in the collinear dipole + quadrupole + octupole model, the angle between the magnetic and rotation axis is generally smaller than 20º for stars with $P > 30$ d, unlike for short period magnetic Ap stars, for which this angle is usually large (Landstreet & Mathys, 2000, A&A 359, 213)

# Evolutionary status of magnetic Ap stars

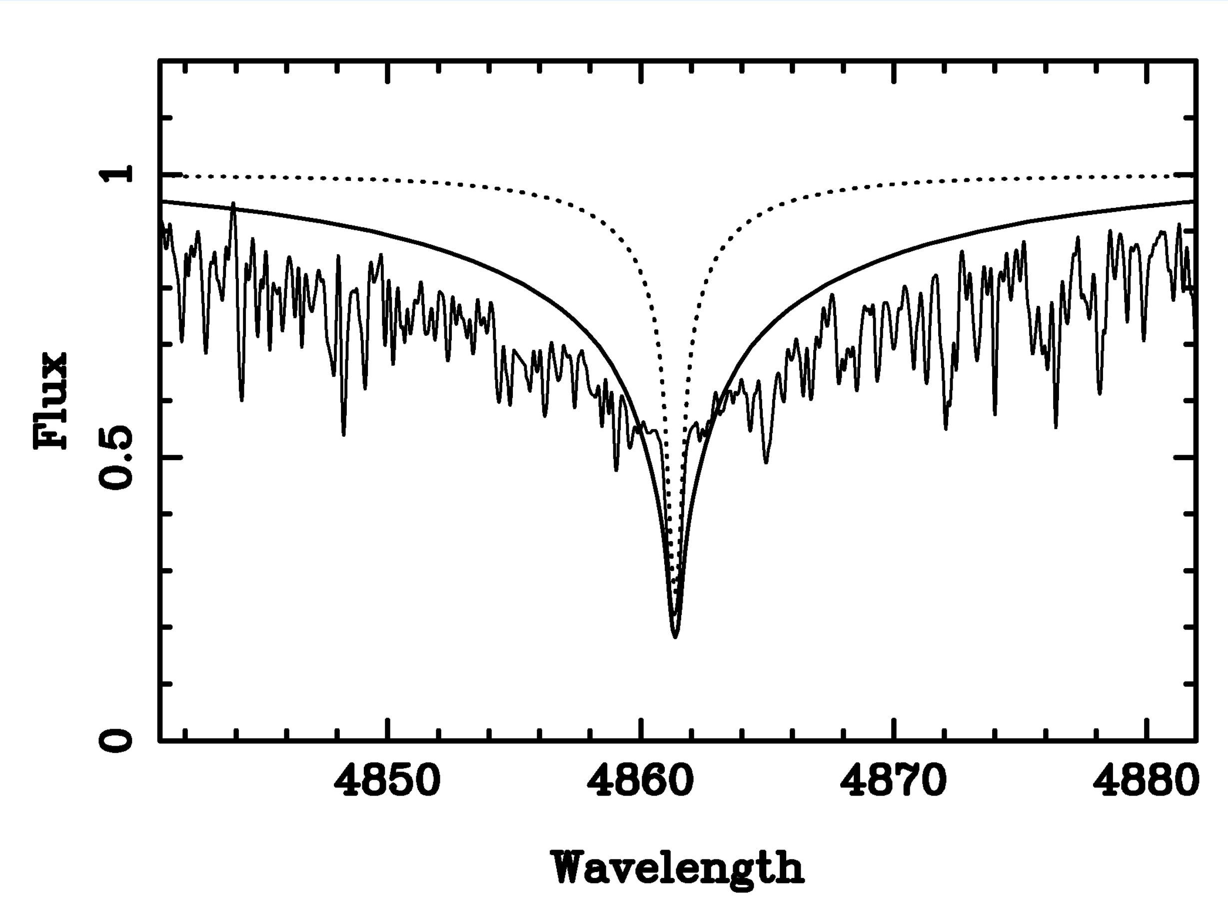


# Effect of magnetic fields on the structure of stellar outer layers

- Magnetically controlled winds
- Elemental abundance stratification
- Evidence for abnormal atmospheric structure:
  - Profiles of hydrogen Balmer lines in cool Ap stars cannot be fitted by conventional models
  - Possible impact on longitudinal field determination by Balmer line polarimetry

# Core-wing anomaly of hydrogen Balmer lines




HD 965

Theoretical curves:

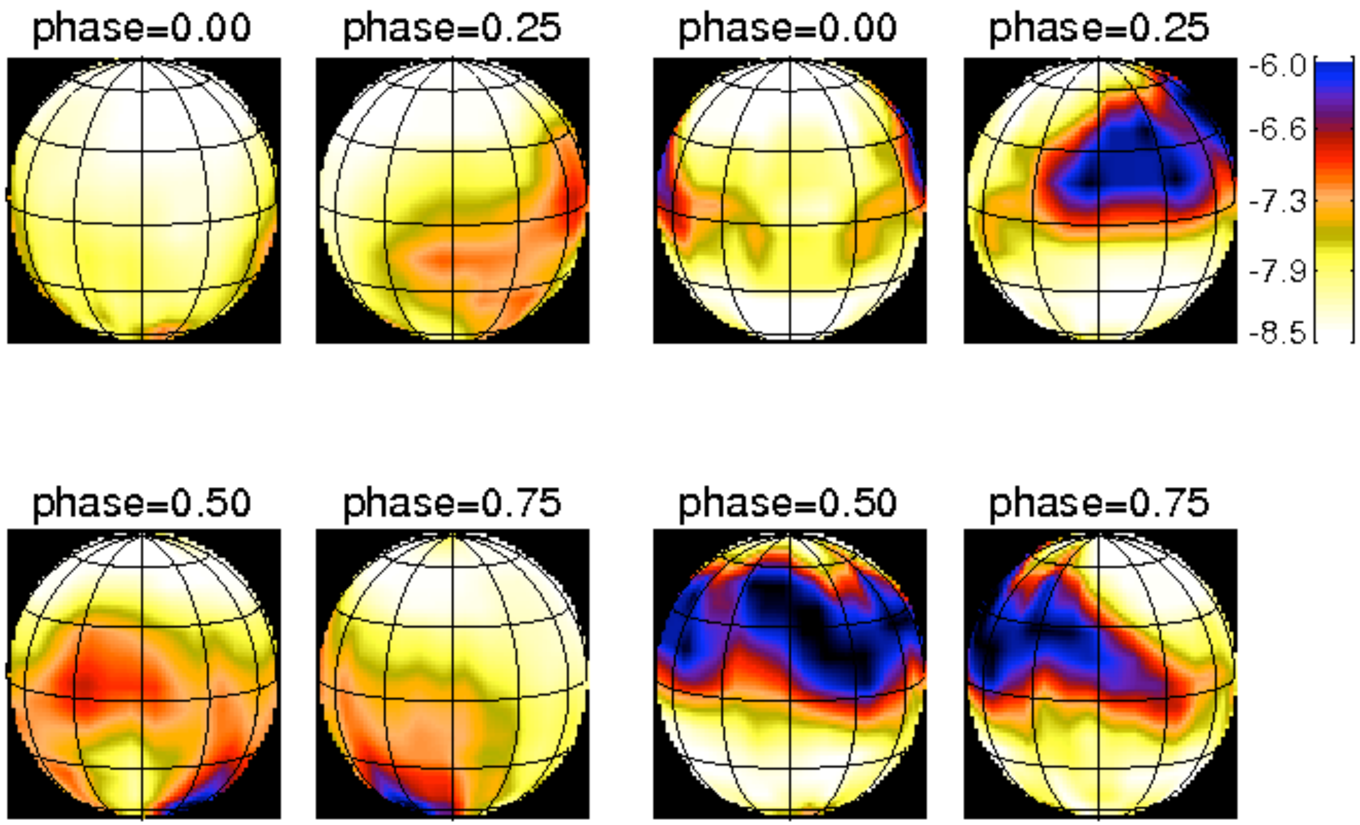
┈┈┈ $T_{eff}$ = 5500 K

—— $T_{eff}$ = 7000 K

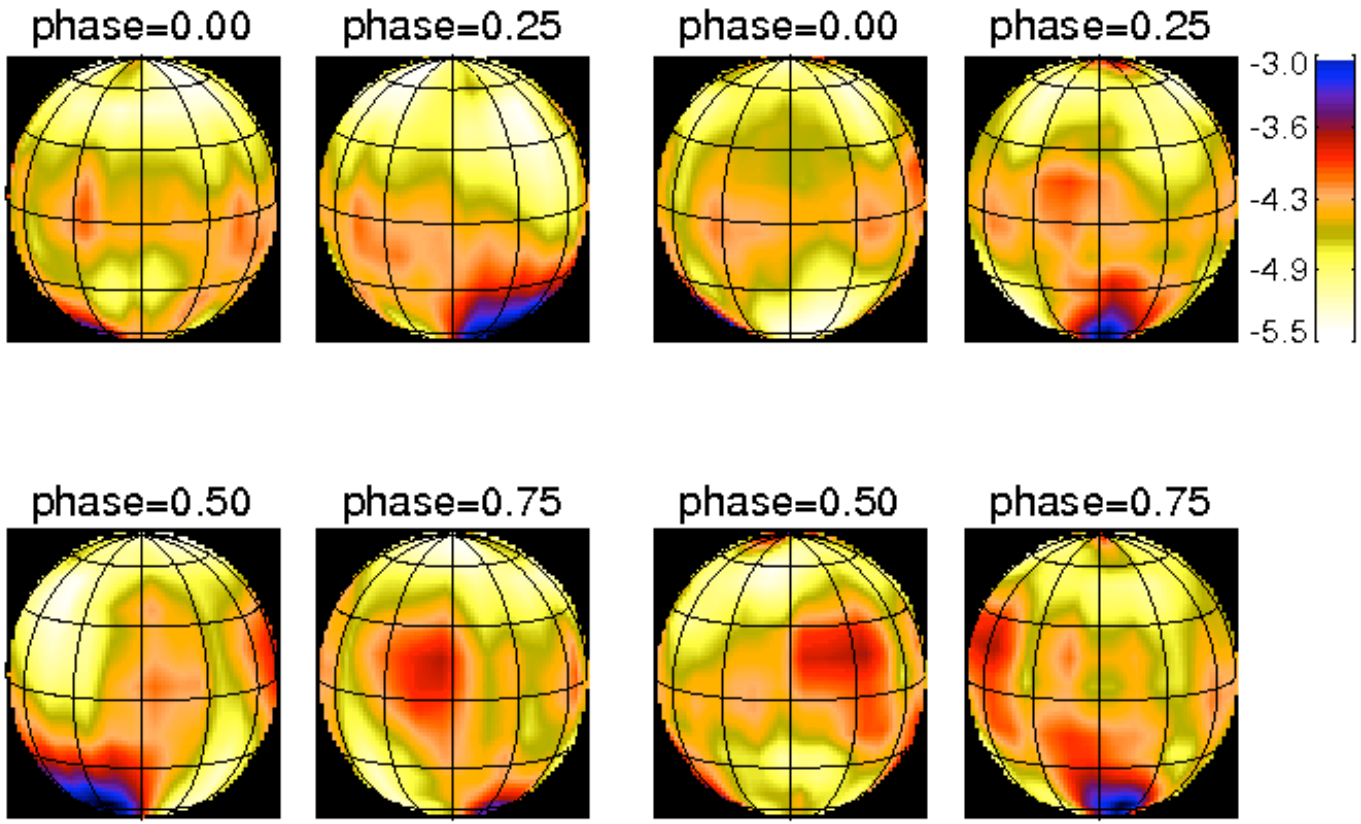
# HgMn stars

- Peculiar stars with B8-A0, $T_{eff}$=10,000–14,000K
- Extreme overabundance of Hg (up to 6 dex) and/or Mn (up to 3 dex). Show the most obvious departures from a nuclear abundance pattern.
- ~150 stars are known. Many stars are found in young associations (Sco-Cen, Orion OB1).
- Most slowly rotating stars on the upper main sequence – exceptionally stable atmospheres: <v sin i>=29 km/s, extremely sharp-lined spectra. Easy to study isotopic and hyperfine structure.
- More than 2/3 belong to SB systems with a prevalence of $P_{orb}$~3–20d**.** Many stars are in multiple systems.
- Spectrum variability is due to the presence of chemical spots.
- No strong large-scale organized magnetic fields, but tangled magnetic fields are possible.
- No enhanced strength of REE, but of heavy elements W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi – a natural laboratory for the study of heavy elements.
- Anomalous isotopic abundances of He, Hg, Pt, Tl, Pb, Ca.

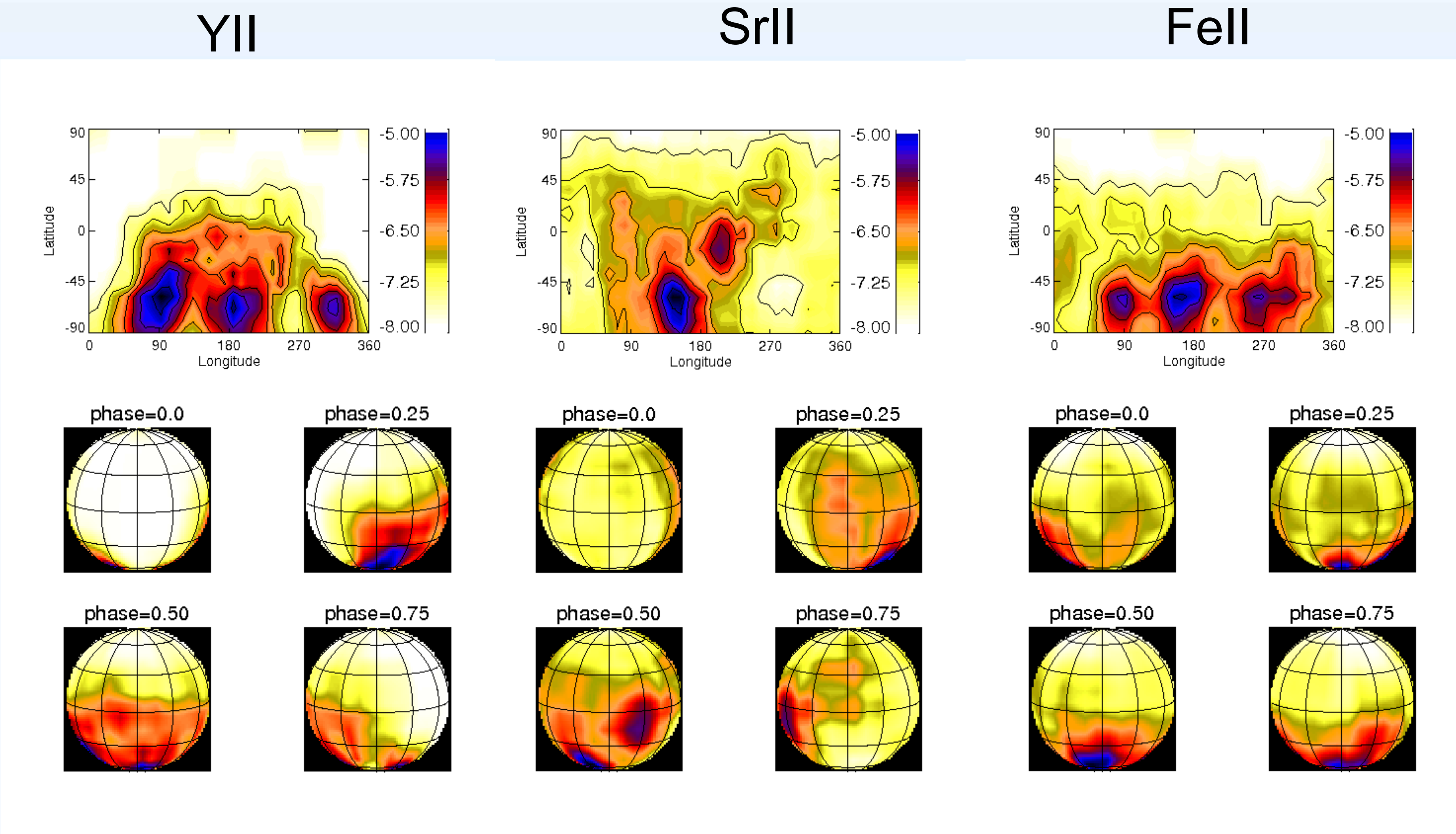
# Y maps using observations of AR Aur in 2005 and 2009/2010



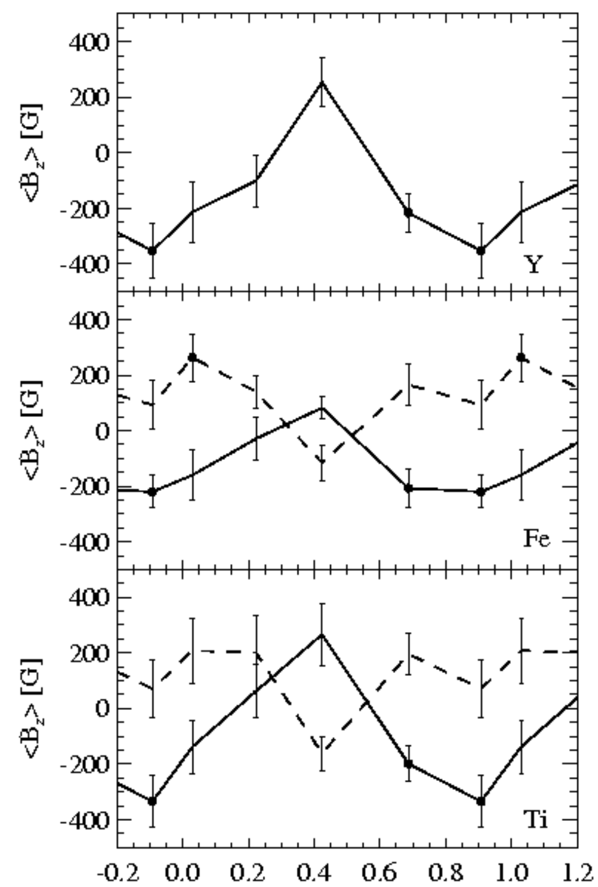
# Fe maps using observations of AR Aur in 2005 and 2009/2010



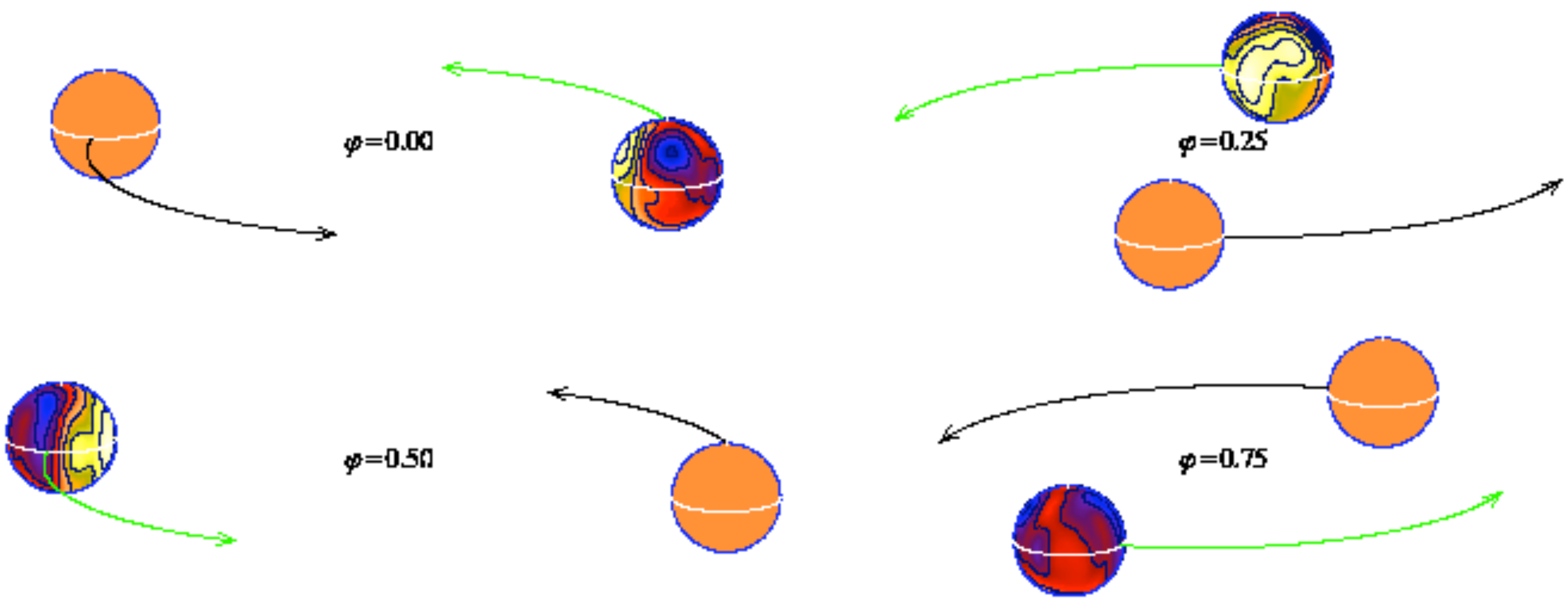
# AR Aur: SOFIN observations in Dec. 2010 (5 phases only)



# AR Aur: SOFIN magnetic field observations

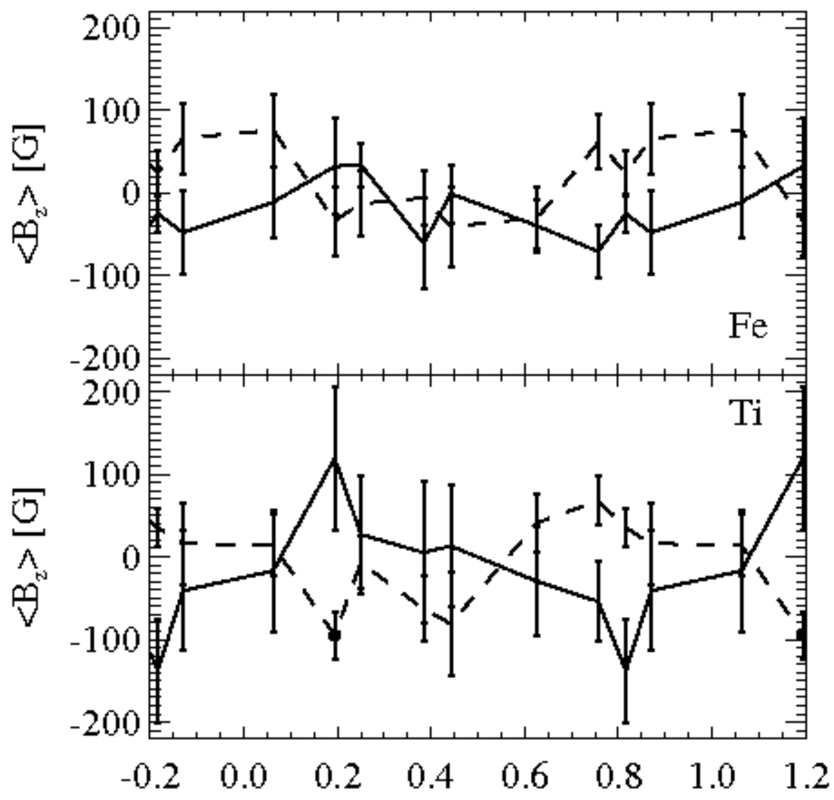


# Orbital motion and rotation of components in SB2 systems with a HgMn primary

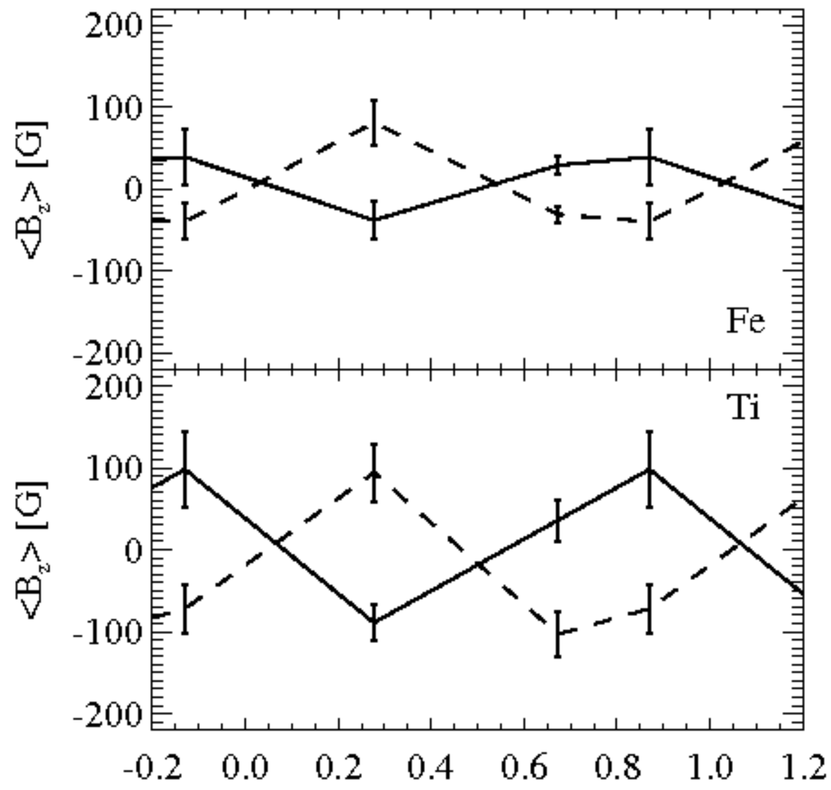



66 Eri (Makaganiuk et al. 2011)

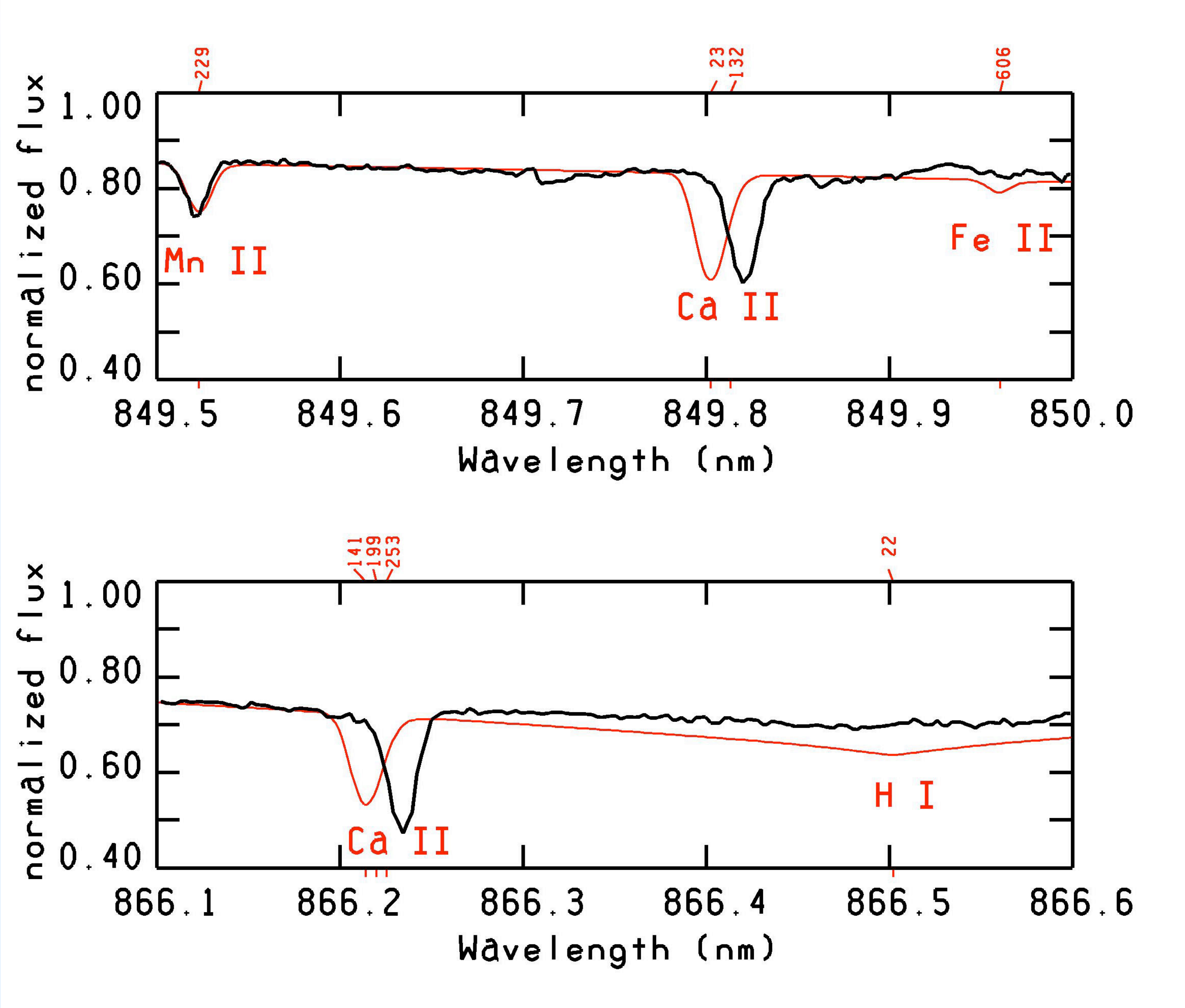
# Magnetic field measurements in the HARPS spectra of 66 Eri using lines of different elements



# Magnetic field measurements in both components of 41 Eri



# Ca-48 shift in the HgMn star HD 175640 (HR 7143)




Castelli & Hubrig 2004

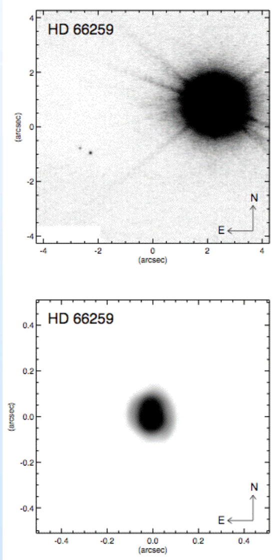
# Multiplicity of late-type B stars with HgMn peculiarity*

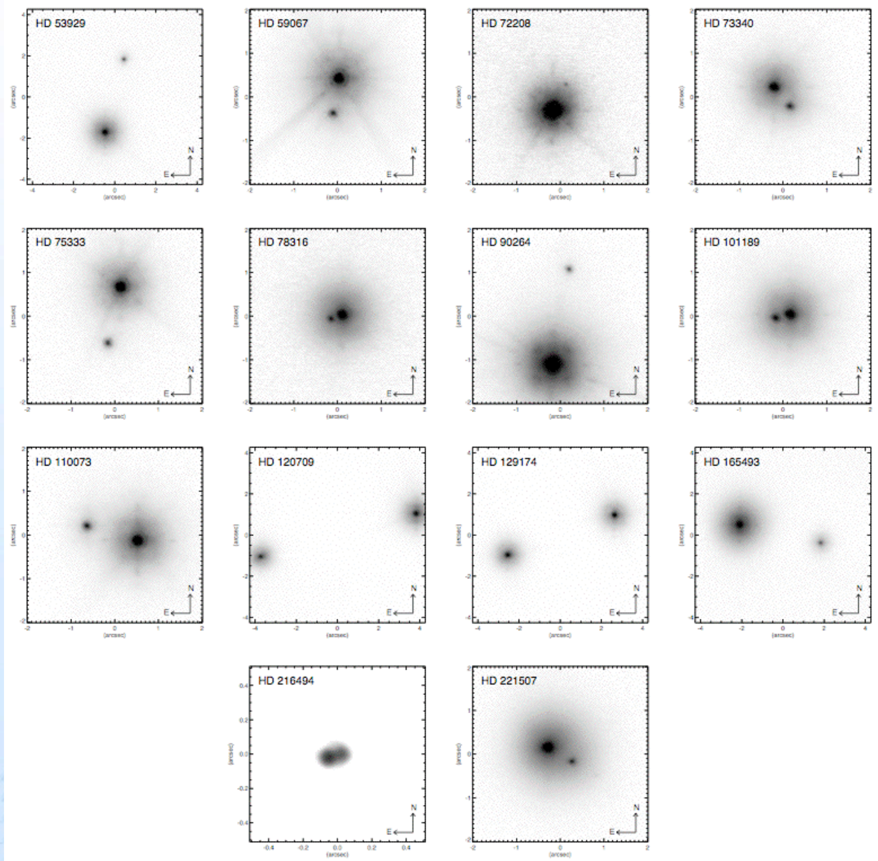
M. Schöller[1], S. Correia[2], S. Hubrig[2], and N. Ageorges[3]

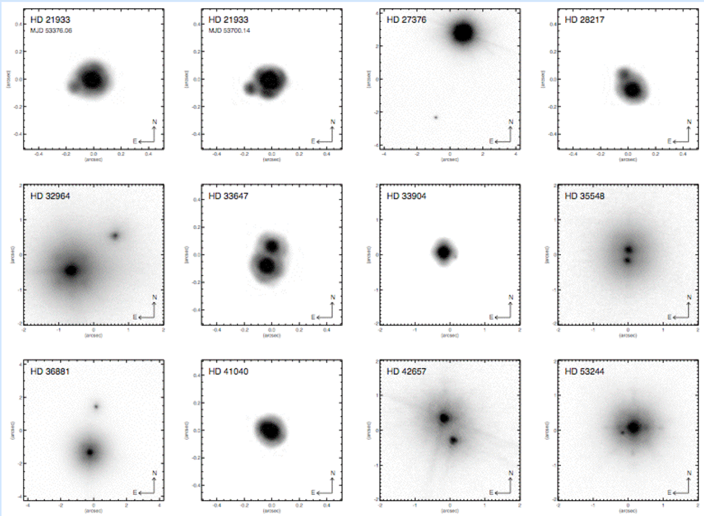
Observations of 57 HgMn stars with NACO (Ks/S13 camera):

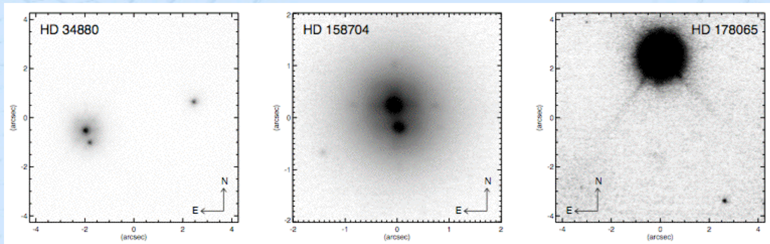
•34 companion candidates in 25 binaries, three triples, and one quadruple
•Nine companion candidates found for the first time
•Five objects are very likely chance projections
•Only five stars in the sample show no indication of multiplicity, taking into account that 44 systems are confirmed or suspected spectroscopic binaries

# Companion Zoo



# Binarity for different stellar types

| Type | Percentage | Reference | SB |
|---|---|---|---|
| A | ~35% | Kouwenhoven et al. 2005 | |
| B | ~30% | Kouwenhoven et al. 2005 | |
| Magnetic Ap | 43% | Carrier et al. 2002 | Very few SB2 |
| Magnetic Bp | ~20% | Renson & Manfroid 2009 | Very few SB2 |
| HgMn | >90% | Schöller et al. 2010 | 2/3 |
| Am | >90% | Renson & Manfroid 2009 | >90% |
| roAp | 24% | Schöller et al. 2012 | 2 out of ~45 |

# Summary

- Chemically peculiar stars are probably the most challenging main sequence stars to model due to magnetic fields, element segragation, stratification, …
- They are the atomic physics laboratory
- They are the best objects to learn about magnetic field models, to be applied to other classes of stars
- Binarity for different classes is different, potentially leading to insights into star formation mechanisms