# Observing and modelling stellar magnetic fields. 3. Stucture & Evolution

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# In the previous episode ...

- We looked at the problems of
  - computing synthetic spectra of magnetic (Ap) stars,
  - obtaining observations (high-resolution, four-Stokes parameters spectropolarimetry) that would realise the full value of such synthetic spectra
  - and comparing computations to observations to derive detailed magnetic (and abundance) maps
- Now we return to a few observational issues we have not yet discussed, and finish with a survey of what is known and what is still (very) unclear about stars with fossil fields

# Back to field detections

- We return to methods of detecting and measuring magnetic fields.
- First consider the problem of detecting weak magnetic fields in the chromosphere of Sun using the Hanle Effect.
- The Hanle effect is usually discussed in the context of the "second solar spectrum", the (mostly linear) polarisation of the Sun that is observed strongly near the solar limb
- It is called the second solar spectrum because it has almost as much structure as the solar intensity spectrum

J.O. Stenflo & C.U. Keller: The second solar spectrum. A new window for diagnostics of the Sun 933

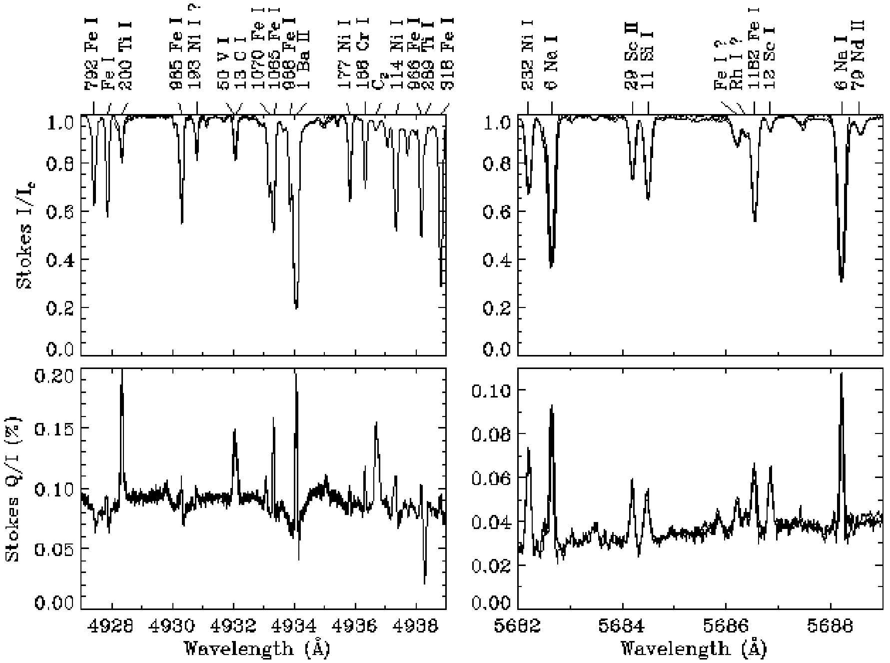



**Fig. 5.** Examples of the rich structuring and many unexpected atomic contributions to the second solar spectrum. Superposition of recordings made on different days shows that even the smallest polarization features are reproduced.

# Hanle Effect

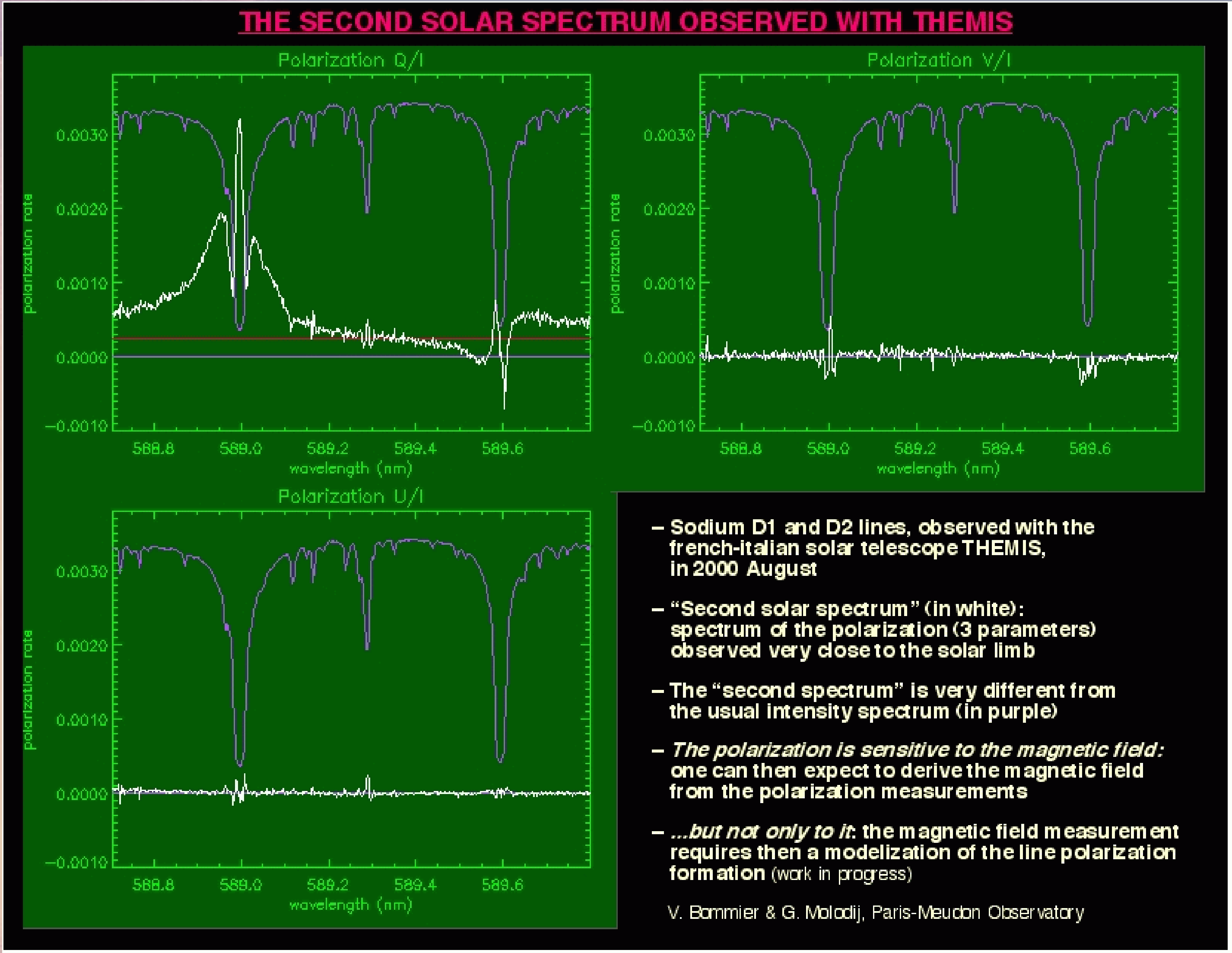
- The linear polarisation of the second solar spectrum is basically produced by resonance scattering.
- Consider an atom high in the Sun's atmosphere, near the limb of the Sun as seen by us. That atom is illuminated mainly from below.
- Suppose that a photon is absorbed by a particular transition, and then re-rediated by a transition back to the initial state (some absorptions will have this effect). If the re-radiated (or in fact, scattered) photon is sent towards us, it will be emitted in a direction at roughly $90^o$ to its initial motion, and it will be linearly polarised perpendicular to the plane containing the initial and final directions.
- Since the atom is mostly illuminated from below, the resulting (tiny) linear polarisation is parallel to the solar limb: the “second solar spectrum”

# Hanle effect (2)

- Now, if a weak magnetic field is present, during the brief period when the atom is in the excited state, its angular momentum vector precesses about the magnetic field with a period of ($4\pi mc/eB$). If this period is comparable to the lifetime of the upper atomic state, the precession will alter the plane of linear polarisation of the scattered photon.
- The real value of the Hanle effect is that with typical upper level lifetimes for scattering, rotation of the linear polarisation plane should be detectable for fields of a few tens of G
- This makes the effect potentailly very valuable for situations such as the solar chromosphere where the field expected is very small
- Hanle effect may also be visible in scattering disks around stars

# Hanle effect in Sun viewed with Themis

- All panels show *I* spectrum at top
- Shown: *Q/I*, *V/I*, *U/I*
- The Hanle effect would produce a very small signature as in the *U/I* plot at bottom



# Fields in Herbig Ae/Be stars (precursors of A and B stars)

- Herbig Ae/Be stars are very probably the pre-main sequence ancestors of main sequence A and B stars (they are found in regions of current or recent star formation; they are now visible, so they now have low accretion rates and will not grow much more; and they have masses in the right range to become A/B stars)
- Evelyne Alecian will talk about these stars in detail on Thursday
- I mention just one aspect of the subject that she will also discuss – fields of a few hundred G are now found in several Herbig AeBe stars.
- Since only a few of the HAeBe stars surveyed have detected fields, this result is consistent with the hypothesis that these magnetic pre-main sequence stars are the ancestors of main sequence magnetic stars

# Field measurement for huge fields

- Next we turn to methods of measuring magnetic fields in situations where they are really large (up to 1 GG, 100 kT)
- Such large fields are actually observed in a small fraction of white dwarf stars, which may be descendants of magnetic Ap stars
- Fields of white dwarfs are observed using several distinct detection methods which correspond to the behaviour of atoms in increasingly large fields
  - For fields below about 100 kG, the normal Zeeman effect (and perhaps the Paschen-Back effect in H) are used as in non-degenerate stars
  - From 100 kG to about 10 MG, the linear Zeeman effect is overtaken by the quadratic Zeeman effect
  - Above 10 MG, even the spectrum of H is no longer easily recognised. It is greatly distorted, and continuum polarisation (circular and then linear) becomes detectable

# Quadratic Zeeman effect

- Recall that the Hamiltonian of an atom in a magnetic field has a linear and a quadratic term in B.
- The effect of the quadratic term is to shift all spectral line components in H to shorter wavelengths by about

$$\Delta \lambda_Q \simeq \left(-e^2 a_0^2 / 8 m c^3 h\right) \lambda^2 n^4 \left(1 + m_L^2\right) B^2$$

  where wavelengths are in Å, $a_0$ is the Bohr radius, and $n$ and $m_L$ are the principal and magnetic quantum numbers of the upper level
- The quadratic effect dominates for hydrogen H10 for B > 10 kG
- At 1 MG, H8 would be shifted by about 350 km/s relative to Hα, an easily detectable effect (Preston 1970, ApJ 160, L143)
- Polarisation effects are similar to those of Zeeman effect, but components are not split symmetrically about unsplit line

# Atomic structure in huge fields

- For fields above 10 MG, perturbation theory is no longer adequate. The magnetic terms in the Hamiltonian are **comparable to** the Coulomb terms, and the structure of the combined system must be solved numerically.
- This is actually a very difficult problem.However, it has been done for H, and to a large extent for He. (For references consult e.g. Becken & Schmelcher 2002, Phys Rev A, 65, 033416)
- Basically, each line component decouples from the others and moves about in a dramatic way.
- Absorption lines in stellar spectra for fields over about 50 MG are affected by fact that the line positions vary rapidly with B, and B is not constant over the stellar surface. Lines occur at wavelengths where for some range of B the absorption wavelength does *not* change rapidly.

# Precise calculations of hydrogen for large (~100 MG!) fields

- For large B values, the sigma components of spectral lines vary rapidly with wavelength. They are almost undetectable on stars where B varies by a factor of two.
- Some pi-like transitions have little variation over a range of field strength ("stationary components"). Such transitions can produce useful lines over a range of field strengths in the range of hundreds of MG (e.g. Wunner et al 1985, A&A 149, 102)

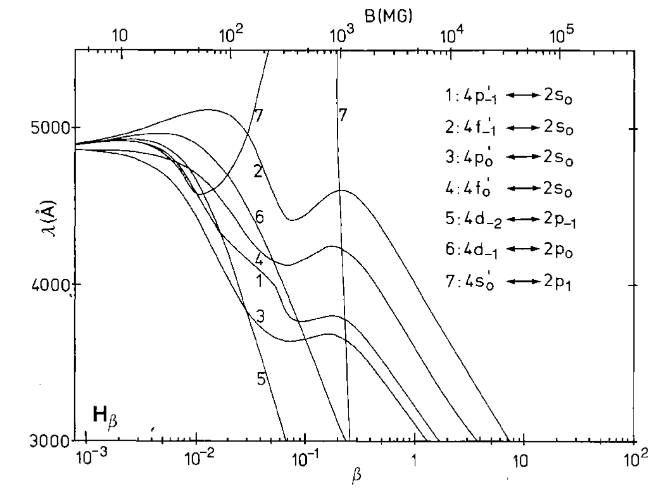



**Fig. 3.** The wavelengths of the 7 stationary H$\beta$ components as functions of the magnetic field

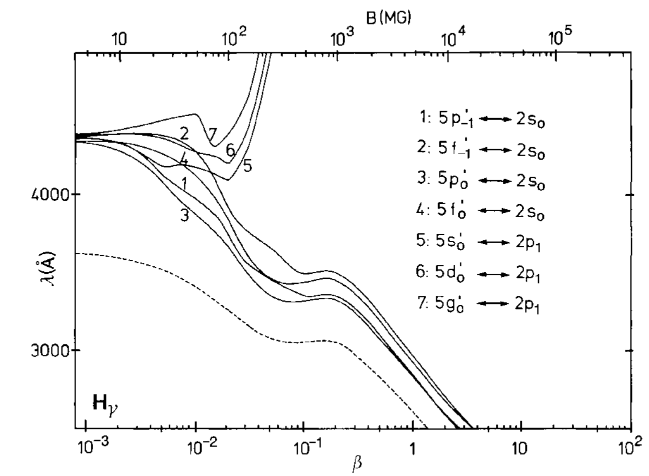



**Fig. 4.** The wavelengths of the 7 H$\gamma$ components stationary as functions of the magnetic field. Dashed curve: Balmer edge for transitions from $2s$ to the continuum

# Continuum polarisation of white dwarf radiation in MG fields

- Physically, the fact that free electrons spiral around magnetic field lines in a particular sense means that the continuum absorption is *dichroic*. Right and left circularly polarised light will be absorbed *differently*, and the continuum radiation will be circularly polarised by a field that has a big component along the line of sight.
- Significant continuum circular polarisation is found above about 10 MG.
- For still larger fields (above about 100 MG) a similar effect produces linear polarisation of continuum radiation.
- However, it has not so far been possible to calculate polarisation spectra of continuum radiation that resemble observed polarisation spectra (cf. Koester & Chanmugam 1990, Rep. Prog. Phys., 53, 837, Sec 8).

# White dwarf fields

- Magnetic fields have been found in over 50 isolated white dwarfs, and over 40 cataclysmic variable binaries
- These stars span a range in field strength from some kG to (probably) around 1000 MG
- They are either unvarying, or vary peridically with periods of hours or days.
- Weaker fields, below some 10s of MG, have familiar spectral lines
- Above this field they have very strange I, V, and sometimes Q, U spectra – see Grw +70 8247 -->

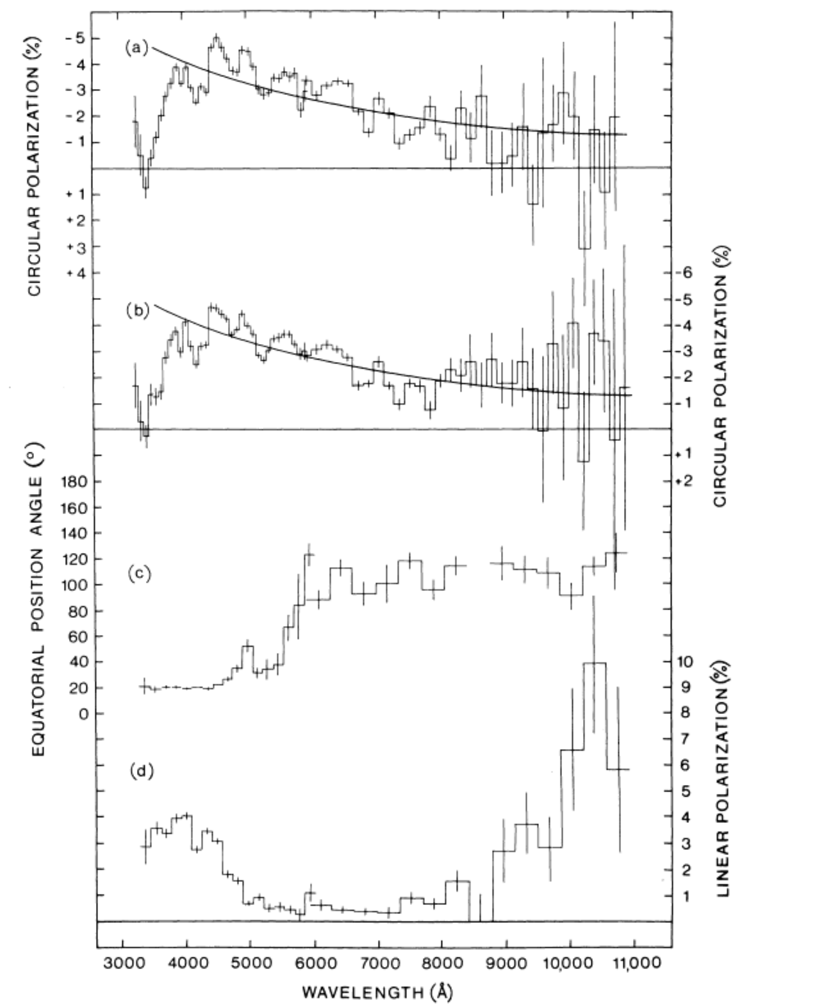



Fig. 1.—(*a*) Wavelength dependence of circular polarization of Grw+70°8247, 1972 August 3. (*b*) Wavelength dependence of circular polarization 1973 June 21. (*c*) and (*d*) Wavelength dependence of equatorial position angle and amplitude of linear polarization, 1972 August 2 and 3. Vertical error bars show ±1 standard error. The smooth curve in (*a*) and (*b*) is the theoretical wavelength dependence of circular polarization for $T_e = 10^4$ °K, $H_e = 3.7 \times 10^7$ gauss.

# Modelling of white dwarf fields

- Three areas of modelling have been explored
- Low field stars can be modelled successfully using high-field Zeeman splitting theory (full magnetic Hamiltonian). The observed spectra are best fit with roughly dipolar fields, typically with some decentring (i.e. one pole stronger than the other) See e.g. Putney & Jordan 1995, ApJ 449, 863.
- In high field white dwarfs, the absorption features in the I spectrum can sometimes be fit with “stationary components” found in the theoretical spectral line wavelength computations. These models reveal fields of 100s of MG, and again are consistent with simple field structure.
- Efforts have been made to model the polarisation spectra These have been only somewhat successful for circular polarisation, and generally unsuccessful for linear polarisation (cf Putney 1999, ASP Conf 169, 195)

# Modelling of WD KUV 813-14

- Putney & Jordan 1995 have modelled this star with a field of about 45 MG, $T_{eff}$ ~11000 K, and a variety of slightly different models
- I spectra at top, V spectra below; decentred dipole on left, dipole – quadrupole right

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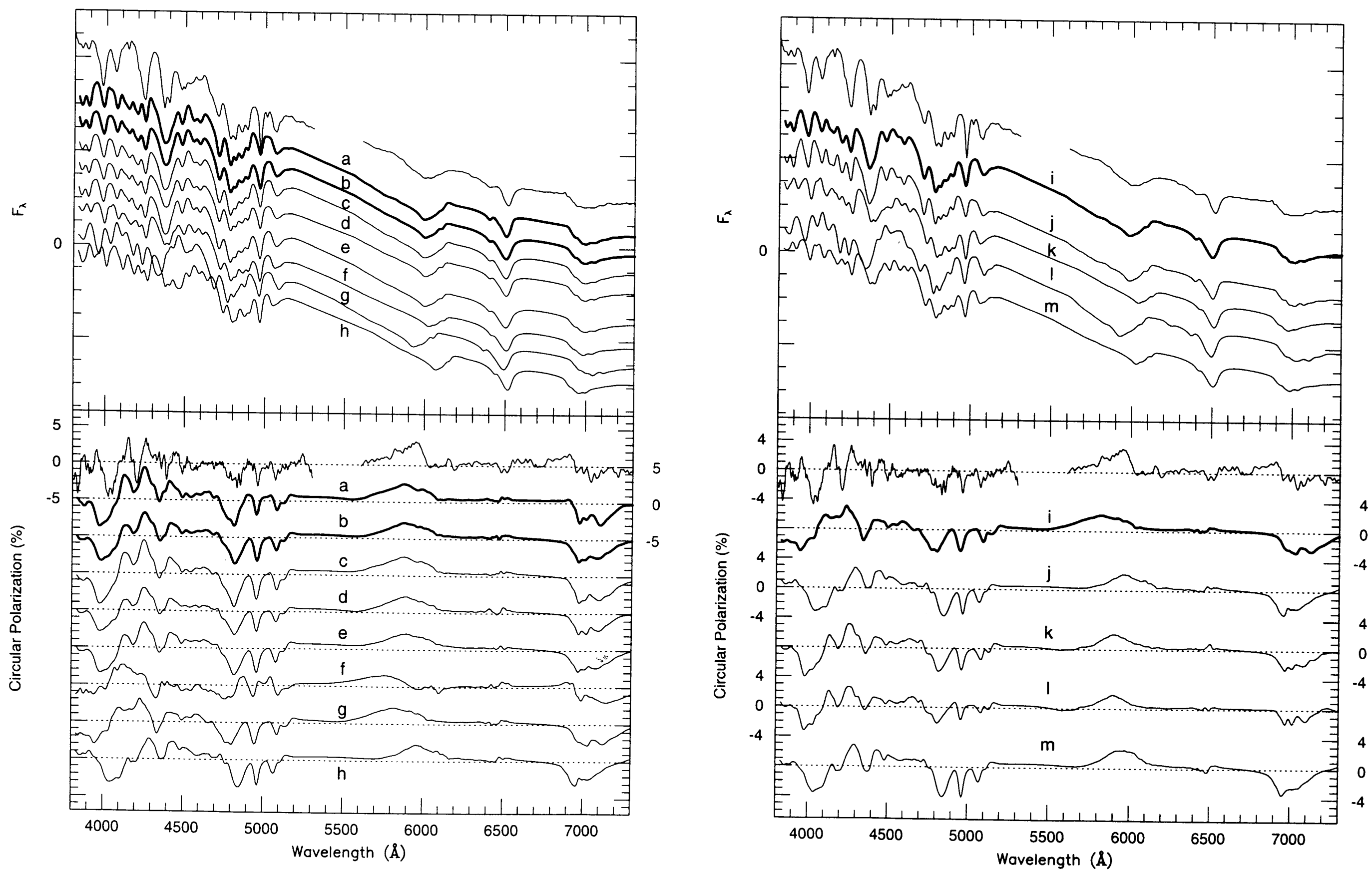



FIG. 3.—KUV 813–14. The top and bottom panels are similar to those in Fig. 2: the zero next to the upper panel marks the zero point of the observed flux and the models are shifted for clarity; the dotted lines in the lower panel mark $V/I = 0$ for each spectrum and each tick mark is 1% circular polarization (values are indicated for the observed and first model spectra). The observed data is an average of the 1992 data. Table 3 lists the different models for this figure. The models all have log $g = 8.0$ and are convective.

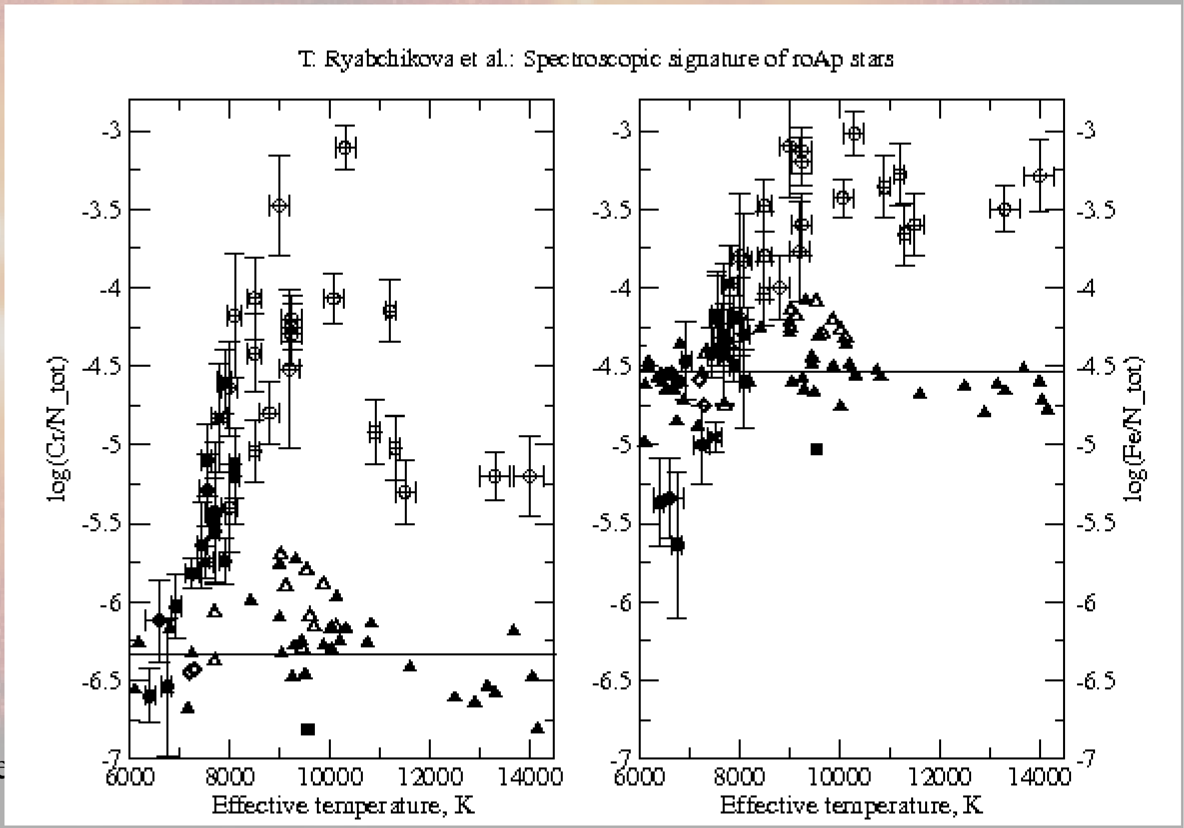
FIG. 4.—KUV 813–14. Similar to Fig. 3, except these models are dipole+quadrupole. Table 4 lists the different models for this figure. All models have an effective temperature of 11,000 K. $B_{quad}$ is the quadrupolar field strength and both the quadrupolar dipolar fields are centered on the star. The angle $\theta$ is the angle between the dipole and the quadrupole. The angle $\phi$ is the azimuthal angle of the quadrupole rotated about the dipole axis.

# Interesting issues for magnetic white dwarfs

- The fields of white dwarfs appear to be relatively simple in structure, and to have long-term stability in time. This suggests that they are similar in nature to those of magnetic Ap stars, and probably fossil fields.
- If a magnetic Ap star is compressed in radius by a factor of about 100 (the ratio of main sequence radii to white dwarf radii), while approximately conserving its magnetic flux, the field strength is expected to increase roughly as $B \sim (R_{init}/R_{final})^2$, so a field of 1 kG on the main sequence will rise to roughly 10 MG, which is a typical white dwarf field.
- This suggests that magnetic white dwarfs may be the evolutionary descendants of Ap stars. The numbers of each are roughly consistent with this hypothesis.
- The magnetic white dwarfs have remarkably low specific angular momentum. The reason for this is very unclear.

# Recent advances in study of magnetic Ap/Bp stars

- We come back to the magnetic Ap/Bp stars. Some valuable new information about these stars has come to light in recent years.
- Systematic one-shot abundance studies of abundances of specific elements in a large sample of stars reveal systematic patterns in the abundance variations, as seen in the figure.
- Note that these specific abundance patterns are *very* different from what is seen in other A stars (triangles in figure)

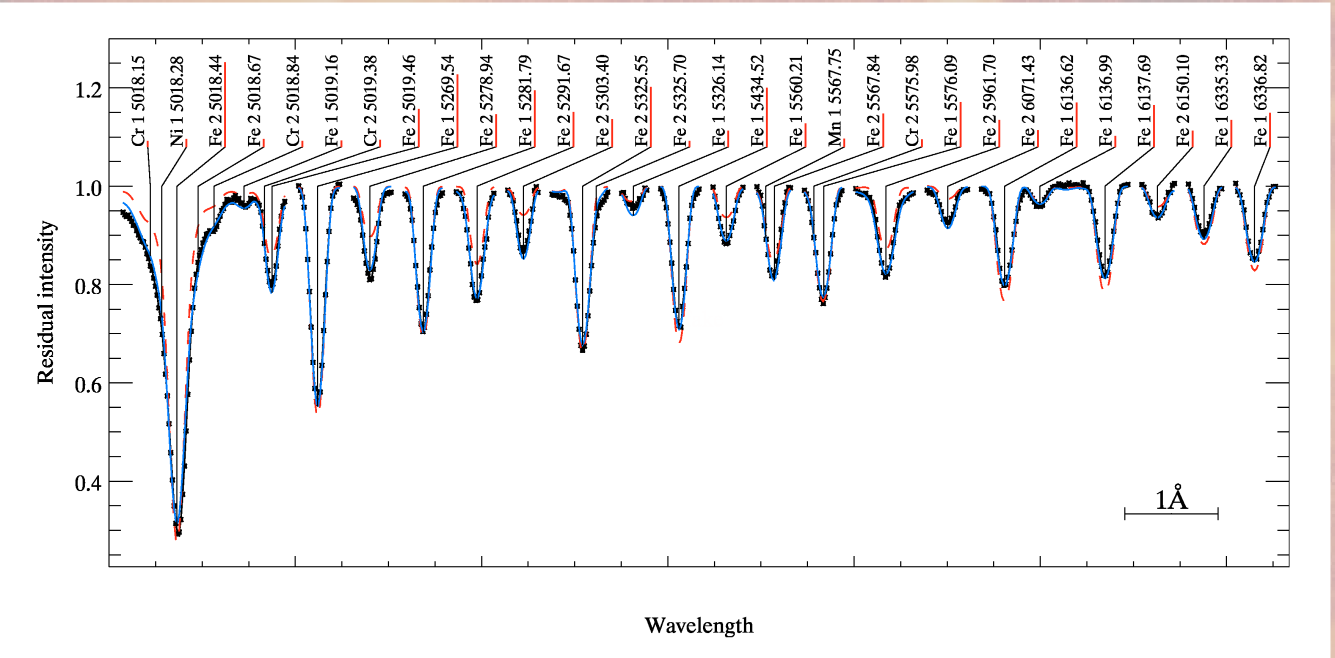


# Magnetic Ap/Bp stars (2)

- Another area of interesting results has come from the study of *vertical stratification* in these stars.
- This can occur in the (magnetically stabilised) atmospheres of Ap stars if the supporting force of upward radiative acceleration (driven by photons) varies strongly through the atmosphere (for example by a change in ionisation state of the supported element)
- Calculations of the competition between gravity and radiative levitation suggest that stratification should occur in the visible photosphere for some elements.
- This can be detected observationally by modelling a variety of weak and strong lines. Several recent projects have clearly revealed this phenomenon

# Observations of Ap abundance stratification

- Fit to many lines of Fe with uniform abundance model (red) and with stratified model (blue); deduced abundance stratifications. From Ryabchikova et al 2005, A&A 438, 973



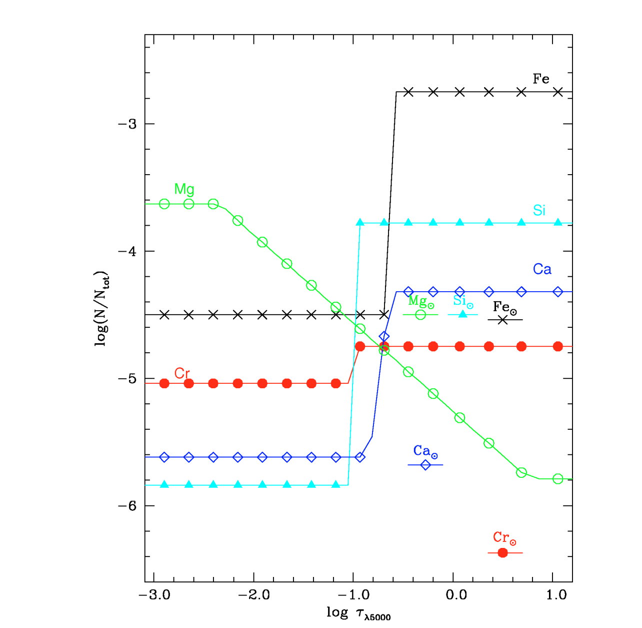



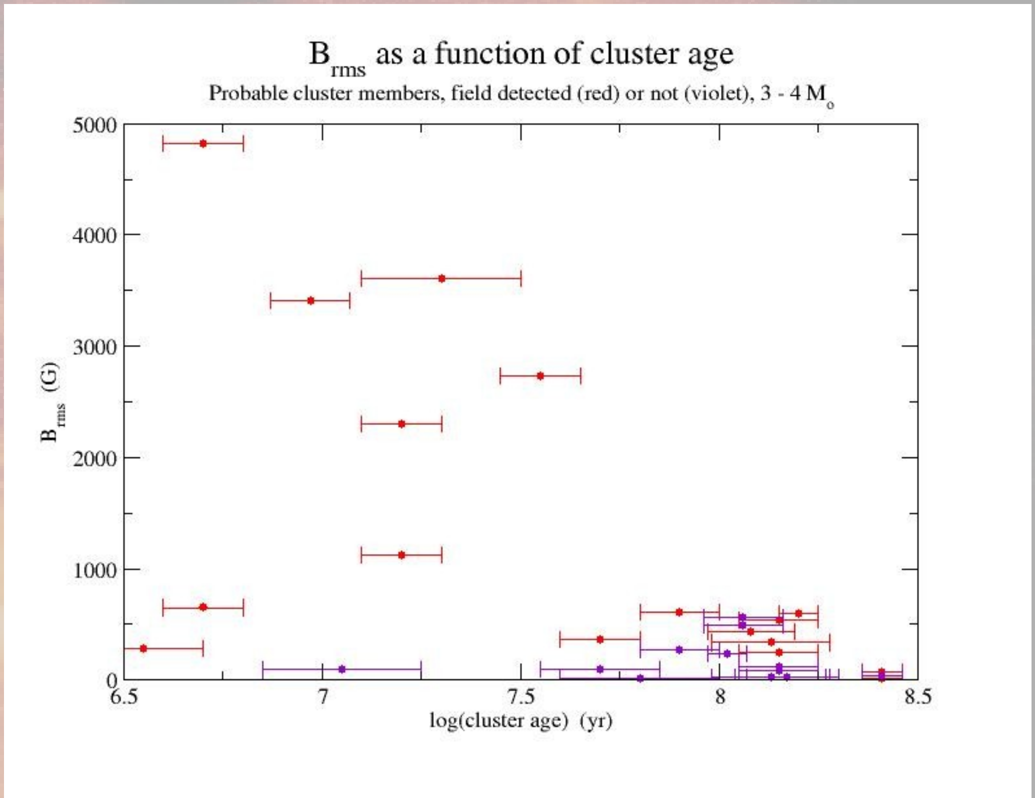

**Fig. 7.** Abundance stratification in the atmosphere of HD 204411.

# Minimum field strength for Ap chemistry

- Michel Auriere (and a cast of thousands of helpful MuSiCoS observers) have recently demonstrated conclusively the initmate connection between the observed chemical peculiarities of Ap stars and the presence of a magnetic field.
- They selected a sample of 28 well-known Ap stars in which fields had never been detected (most have been observed for fields before). Using the MuSiCoS spectropolarimeter, they showed that every star has a field.
- They established a lower limit of about 300 G for the minimum field necessary for field stability and Ap peculiar chemistry in the magnetic Ap star regime (paper recently accepted by A&A).
- Previous studies have show that other categories of A/B stars have no fields at a level an order of magnitude smaller.

# Evolution of field strength in Ap stars

- I and several collaborators have obtained the first sample of magnetic stars of known ages spanning the full main sequence lifetime by observing Aps in associations and clusters
- A typical result is at right, where we see that all ages from ZAMS to TAMS are found, and that field strengths in this mass range seem to decline after an age of about 40 Myr



# How are stellar fields produced?

- Two main mechanisms have been proposed to explain the presence of magnetic fields in stars:
- The *fossil field* hypothesis argues that since the ISM is permeated by magnetic fields, contraction of clouds from this medium to form stars could sweep up magnetic flux lines (which would be attached to the collapsing cloud because it is a good electrical conductor), leading eventually to fields in main sequence stars. Such fields might be quite passive at present, explaining the stble fields of Ap stars.
- The rapidly varying field of the Sun suggests that its field is not produced in this way, but that it arises from active hydrodynamical motions inside the Sun which entrain small magnetic fields and twist them into stronger fields which emerge from the surface. This is the *dynamo field* theory, already discussed in this course.

# Fossil fields: tepid stars, white dwarfs

- Fossil fields are expected to have strengths which are not closely related to current rotation rates; in fact, because a long-lived field may help a star to lose angular momentum, strong fields might particularly occur in slowly rotating stars. This seems to be true of both magnetic Aps and white dwarfs.
- Such fields are also likely to change structure only on rather long time-scales. The lack of intrinsic variability (other than rotation of the host star) is an important argument that Ap and white dwarf fields are probably fossil fields.
- Fossil fields, almost by definition, are produced during a previous phase of a star's life. This could be as recent as the pre-main sequence if a strong dynamo operated then, or could even be traced back to the field of the interstellar gas.

# Fossil field evolution: theoretical ideas

- It may seem amazing that fossil fields do not die out due to ohmic decay. In fact we can estimate the deacy time directly from Maxwell's equations if the conductivity is known.

$$\nabla \times E = \frac{1}{c}\frac{\partial B}{\partial t} \rightarrow E/L \sim B/ct$$

$$\nabla \times B = \left(\frac{4\pi}{c}\right) j \rightarrow B/L \sim 4\pi\sigma E/c$$

Here we are ignoring displacement current, and using the Maxwell equations as order of magnitude relations. σ is the conductivity. Combining the equations we find

$$t \sim 4\pi\sigma L^2/c^2$$

where L is the scale of the system and everything is in cgs Gaussian units (of course). This gives a time of order $10^{10}$ yrs for field decay in a main sequence star!

# Fossil field evolution

- We are thus led to the view that the large-scale fields of Herbig Ae/Be stars, the magnetic Ap/Bp main sequence stars, and the magnetic white dwarfs may form an evolutionary sequence of stars that have fossil fields.
- These fields may even originate in the field of the ISM. Since the ISM undergoes a contraction by a scale factor of order 10 million to form a star, potentially field amplification from ISM fields of 1 µG could reach 100 MG in main sequence stars.
- The total absence of such fields at the surfaces of main sequence stars shows that much flux must be lost!
- However, we have no obvious answer to key questions
  - Why do strong fossil fields occur only in stars above 1.5 $M_0$
  - Why do only a few % of A/B stars have strong fossil fields
  - How do these fields survive the very convective giant stage

# Angular momentum evolution of magnetic stars

- Angular momentum presents us with another challenge
- Magnetic Ap/Bp stars typically have only about 0.1 times the specific angular momentum as normal A/B stars. This seems to be true even of very young magnetic stars.
- The angular momentum probably was lost during the star formation process, possibly early in the pre-main sequence phase when the field would allow angular momentum to be transferred to a stellar wind (Stepien 2000, A&A 353, 227)
- A small fraction of magnetic Ap stars have angular momentum even another factor of 10 or 100 smaller. What factor allowed these stars to lose almost all their rotation?
- Finally, the rotating magnetic white dwarfs have still smaller specific angular momentum, about $10^4$ times less even than the magnetic Ap stars. And some magnetic white dwarfs appear not to rotate “at all”. Why?

# Executive summary

- Strong, global magnetic fields are found in some (but not most) middle and upper main sequence stars by observing the Zeeman effect in polarised spectra
- Much valuable information about these stars can now be obtained by modelling the exciting new spectropolarimetric data obtained from MuSiCoS, ESPaDOnS, and Narval.
- Strong global fields are also found some (but not most) white dwarfs.
- Plausibly, the fields found in Herbig AeBe stars, those of magnetic Ap/Bp stars, and those of magnetic white dwarfs may form an evolutionary sequence of fossil fields (assuming rough flux conservation), but many questions remain.
- The evolution of angular momentum of this sequence of objects also presents many interesting puzzles.