

Modelling stellar magnetic fields using spectrum synthesis



JDL

Basic idea of spectrum synthesis

- We have a spectrum from a star, and we want to extract as much information as possible from it
- Basic strategy: starting from basic physics, compute the spectrum *expected* for this star if it conforms to our theories
- Expected spectrum may contain a number of adjustable parameters (abundance table, $v \sin i$, even T_{eff} or $\log g$)
- Compare computed spectrum with observed spectrum, fit adjustable parameters
- If fit is good, we have a plausible model (but it may not be unique – this is an ill-posed problem) & parameter values
- If not, we have left out some essential physics which we need to find

Computing an emergent spectrum: what is needed

- Starting with a suitable model atmosphere (T_{eff} , $\log g$, abundances), what do we have to do to compute the emergent polarised spectrum of a magnetic star (forward computation)?
 - Assume some magnetic field structure, and calculate the vector field at many (50+) grid points on the visible hemisphere
 - For each grid point compute detailed run of polarised opacities and retardances at all relevant depths (60+) at closely spaced frequencies or wavelengths (0.01 Å is barely adequate wavelength grid in visible). A window of 100 Å might be a useful size.
 - Then compute the emergent spectrum along the ray towards observer at each surface grid point, by solving the EOTs outward along the ray, for each wavelength in the window
- A lot of bookkeeping is required!

Details of local integration (basic idea)

- For unpolarised transfer $d\tau_\nu = \kappa_\nu dz$, where absorption coefficient includes atomic effects of both continuum and line absorption
- In “local thermodynamic equilibrium” (LTE), S_ν is simply the Planck function $S_\nu = B_\nu(T) = (2h\nu^3/c^2)/[\exp(h\nu/kT) - 1]$
- Unpolarised equation of transfer can be integrated using the integrating factor $\exp(-\tau_\nu/\mu)$, since S_ν is a *known* function of τ_ν

$$I_\nu(\tau_\nu) = e^{\tau_\nu/\mu} \int_{\tau_\nu}^{\infty} S_\nu(\tau_\nu') e^{-\tau_\nu'/\mu} d\tau_\nu'/\mu$$

- With lower limit 0, we get specific intensity emerging from surface
- Situation is closely analogous for polarised equations of transfer: we have four coupled, linear, first-order DEs, which we solve numerically starting from black-body conditions deep inside

Computing the emergent spectrum: techniques

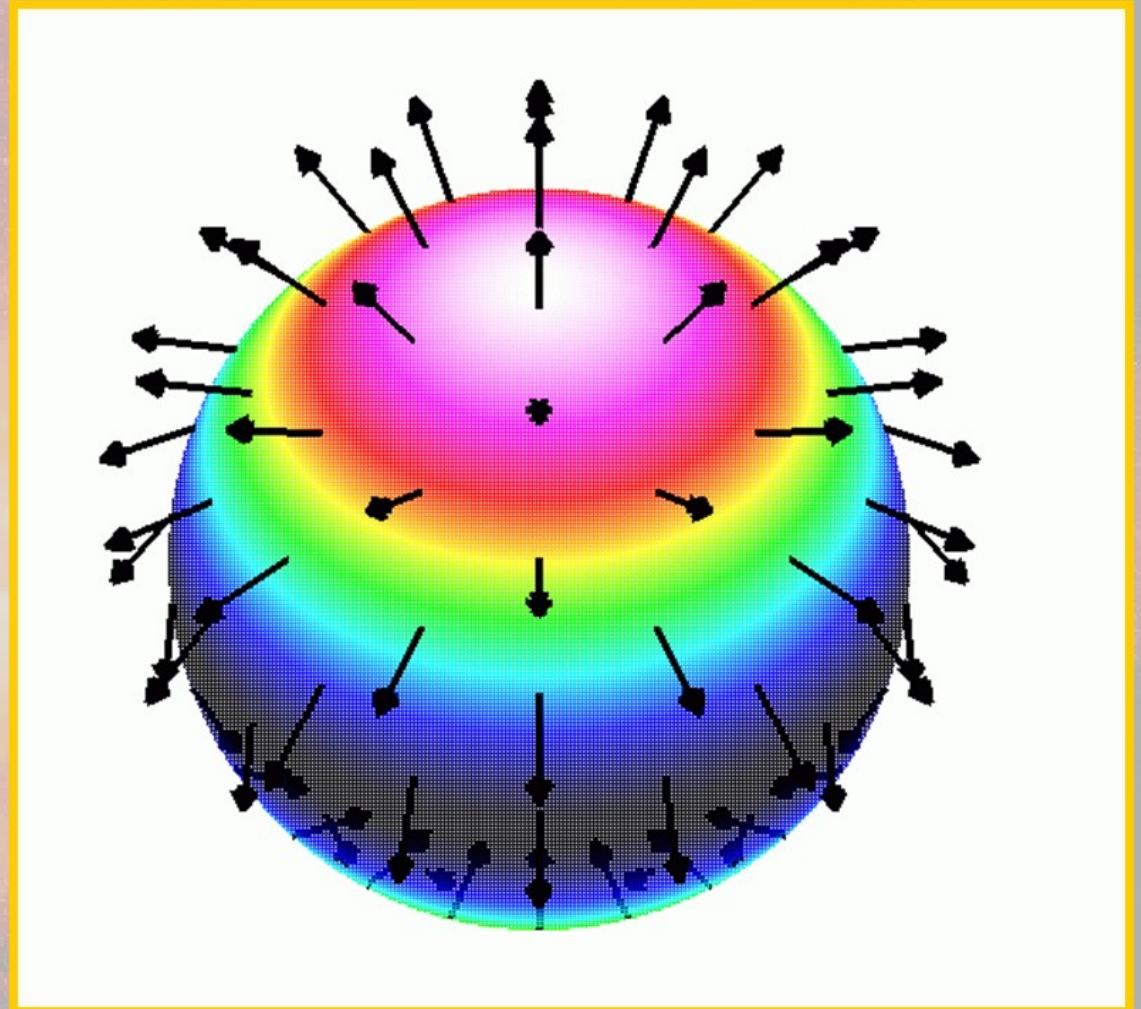
- Several aspects of this problem require special considerations
 - Need to have a suitable list of spectral lines, with gf values and Landé splitting factors. Usual source is VALD database at <http://ams.astro.univie.ac.at/vald/> which supplies both data from a variety of sources (some are better than others...)
 - Because one must compute the Voigt and Faraday-Voigt functions millions of times, an efficient algorithm is needed
 - Solving the equations of transfer numerically may be done with standard packages or methods (e.g. Runge-Kutta), but again this has to be done so many times that efficiency is essential, and you want a technique that does not require a very dense depth grid
- Descriptions of common codes discuss these points

Example of a spectrum synthesis code: Zeeman

- Zeeman (Landstreet 1988, ApJ 326, 967) is a simple magnetic line synthesis code available on course Web page
 - Contains simple parametrised field structures (colinear dipole, quadrupole, etc), also abundance tables specified on rings colinear with field axis (simple model of non-uniform abundances, needed for magnetic Ap stars)
 - Reads in fundamental parameters of star, assumed magnetic field parameters, spectral window to compute
 - Computes I , Q , U , V spectrum including line splitting and polarised transfer, using precomputed ATLAS atmosphere and VALD line list
 - Compares computed spectrum with an observed spectrum, selects best fit $v \sin i$, radial velocity, and χ^2 of fit
 - If desired, can iterate fit to optimise field or abundance parameters

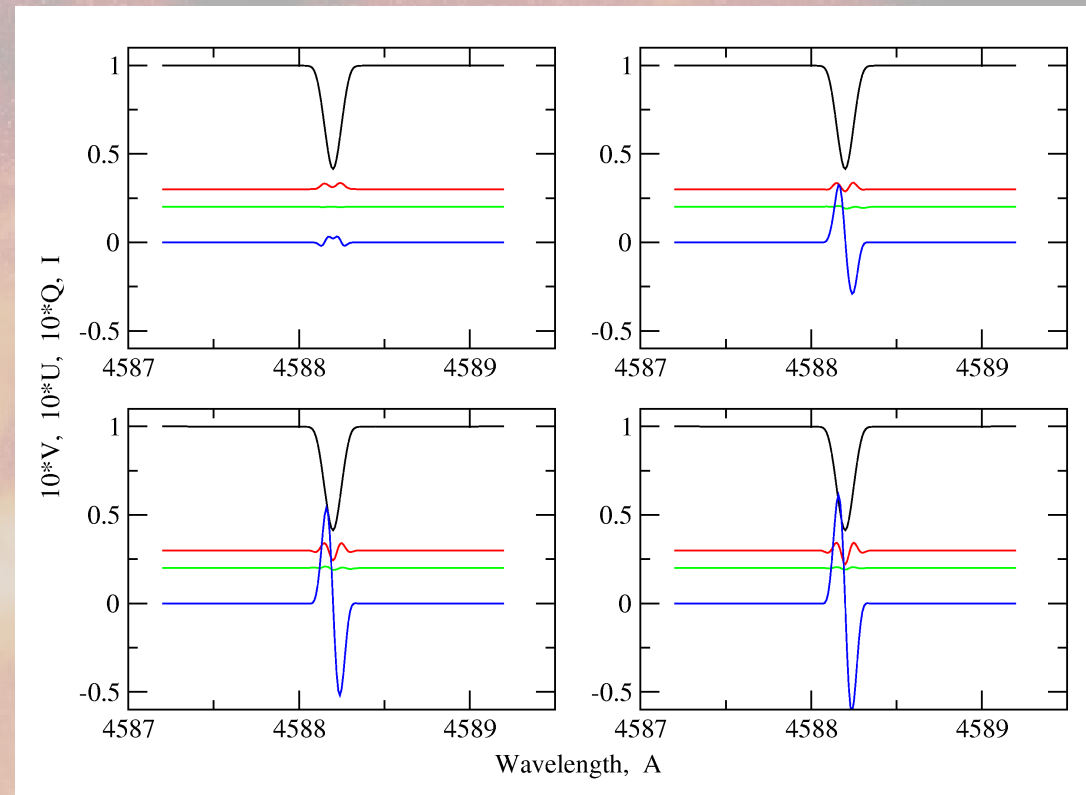
Simple model assumed by Zeeman

- Field is axisymmetric, a sum of low-order multipole components; parameters are orientations of rotation and magnetic axis, strengths of multipole components
- Abundance of elements to study is constant on rings symmetric about magnetic axis



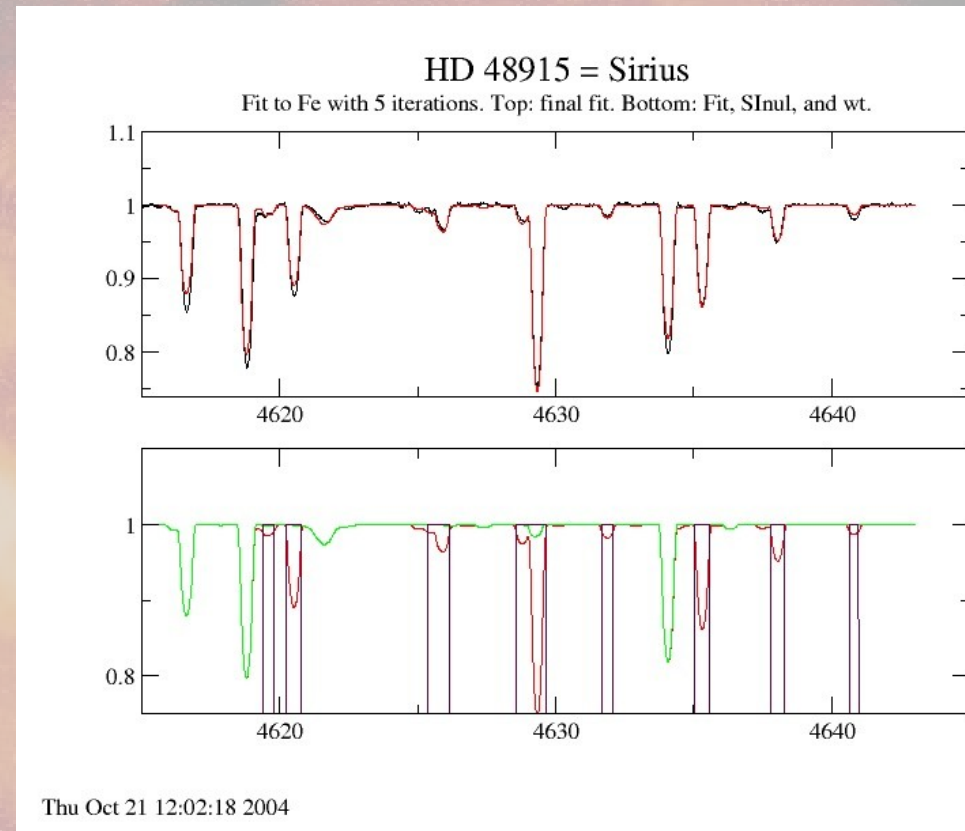
Examples of magnetic line profiles

- Example of line synthesis
 - Cr II 4588 in A0 star
 - Dipole field, polar field strength 1000 G (0.1 T)
 - Star not rotating
 - View from four inclinations from magnetic pole: 90, 60, 30, 0 degrees
 - Q , U , V all multiplied by 10; Q & U shifted up
- Note how much larger V is than Q or U



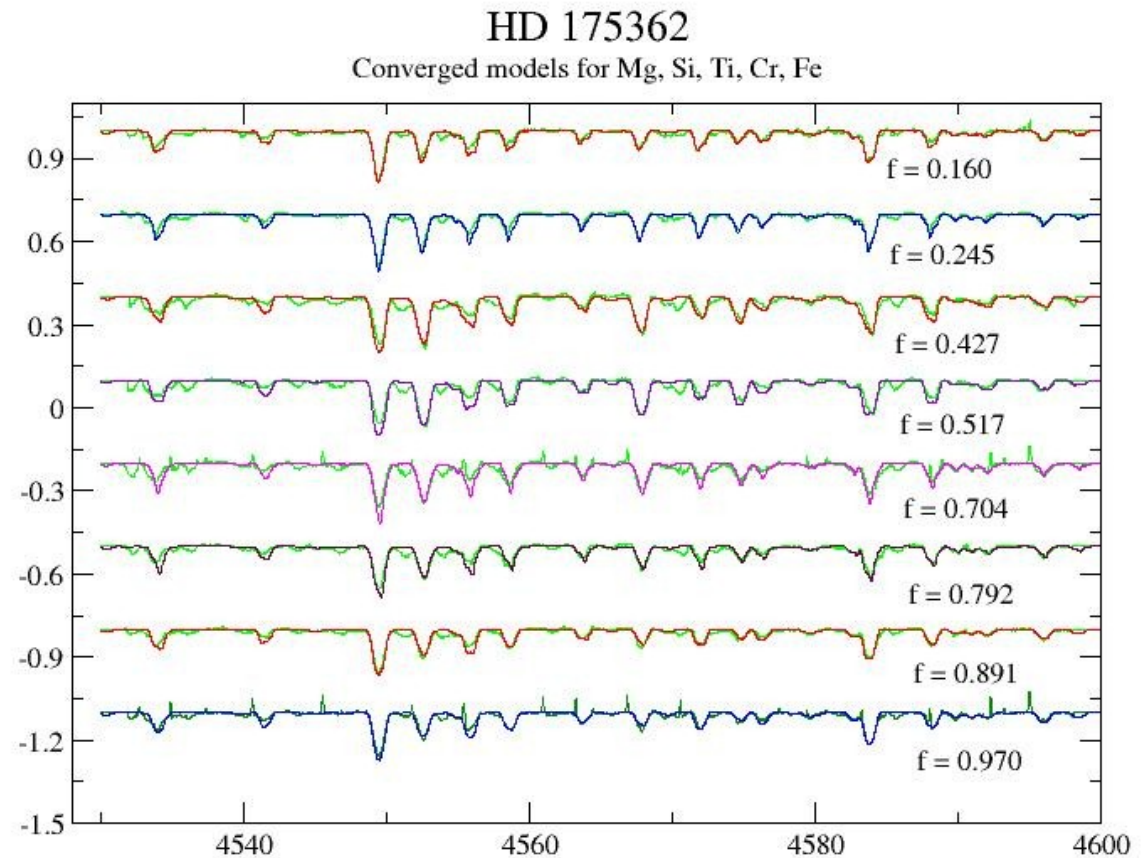
Modelling a normal star: Sirius as an example

- Synthesis fits to *non-magnetic* stars may be very accurate
- Require good choices of T_{eff} , $\log g$, abundances, radial velocity, $v \sin i$, and microturbulence parameter
- T_{eff} and $\log g$ often chosen from available Stromgren or Geneva photometry calibrations
- Automated iterative fitting of most remaining parameters works well for such stars



Modelling a magnetic star

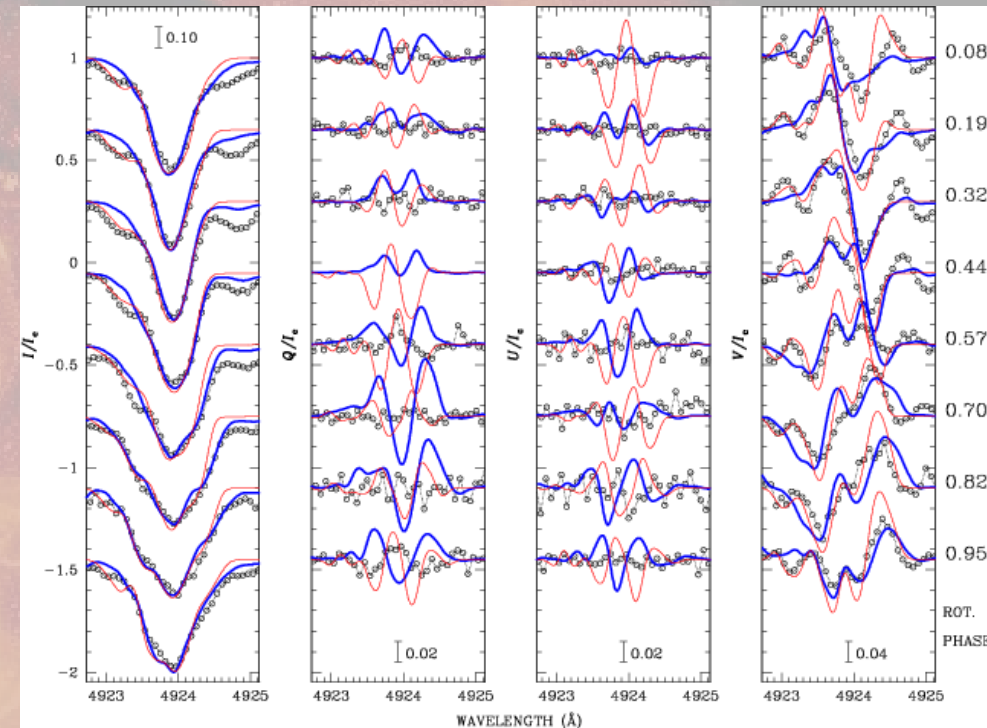
- Example of a fit to a series of spectra of a strongly magnetic B3 star, HD 175362
- Mg, Si, Ti, Cr all mildly variable over surface
- Spectral line strength strongly affected by presence of magnetic field which reaches $\langle B_z \rangle = +5$ and -7 kG as star rotates



Tue Jul 20 14:43:02 2004

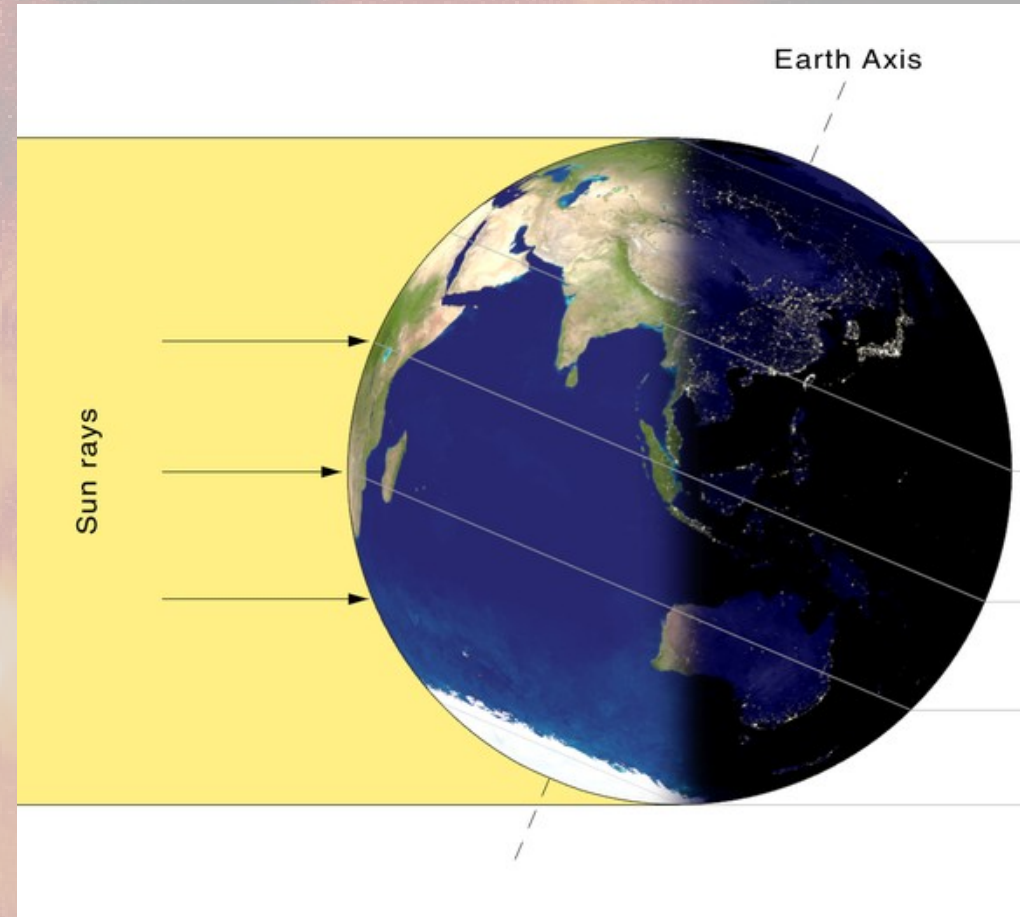
Modelling a magnetic star: tests of parametrised models

- Using MuSiCoS (or ESPaDOnS) data we can now return to problem of modelling magnetic stars
- We can test models derived from simple field measurements ($\langle B_z \rangle$, B , or other field moments) by observing $[I, Q, U, V]$ spectra as a function of rotational phase and then computing predicted line profiles using the model derived from moments (example: 53 Cam)
- Result: poor fits, especially to Q, U Simple field models from field average measurements are only first approximations to real structure



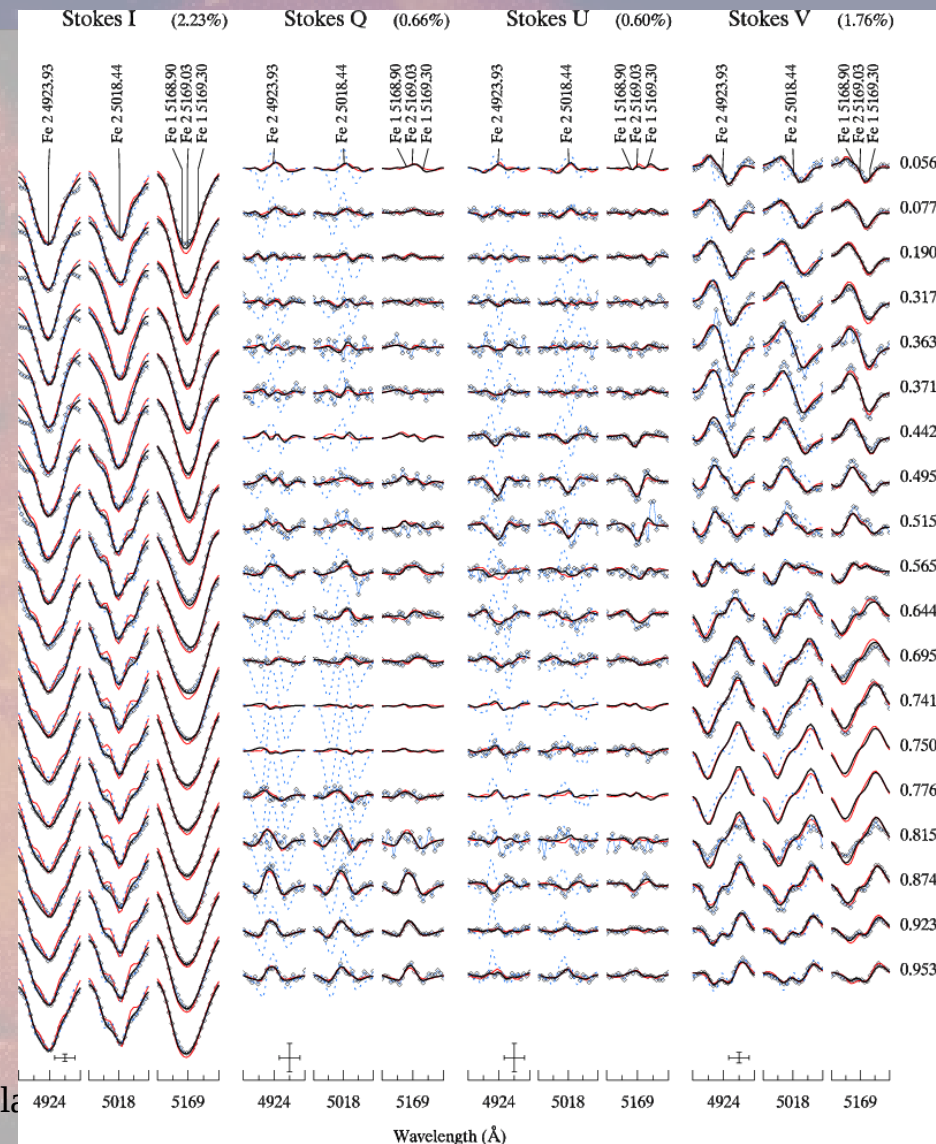
Basic idea of 2D mapping

- How is it possible to deduce 2D map using only integrated light??
- Basic idea: longitude of a feature derived from when it is most visible in spectrum
- Latitude derived from length of time feature is visible, and from extreme Doppler shifts
- Could use this idea to “map” Earth with only point source observations

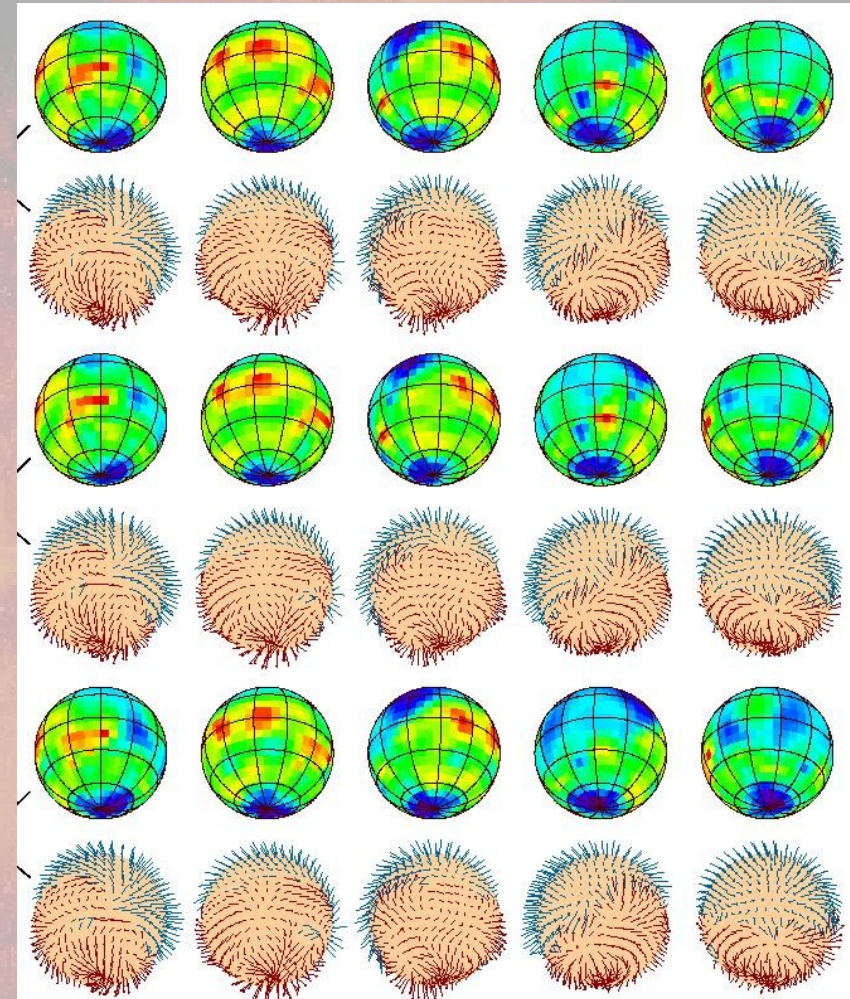
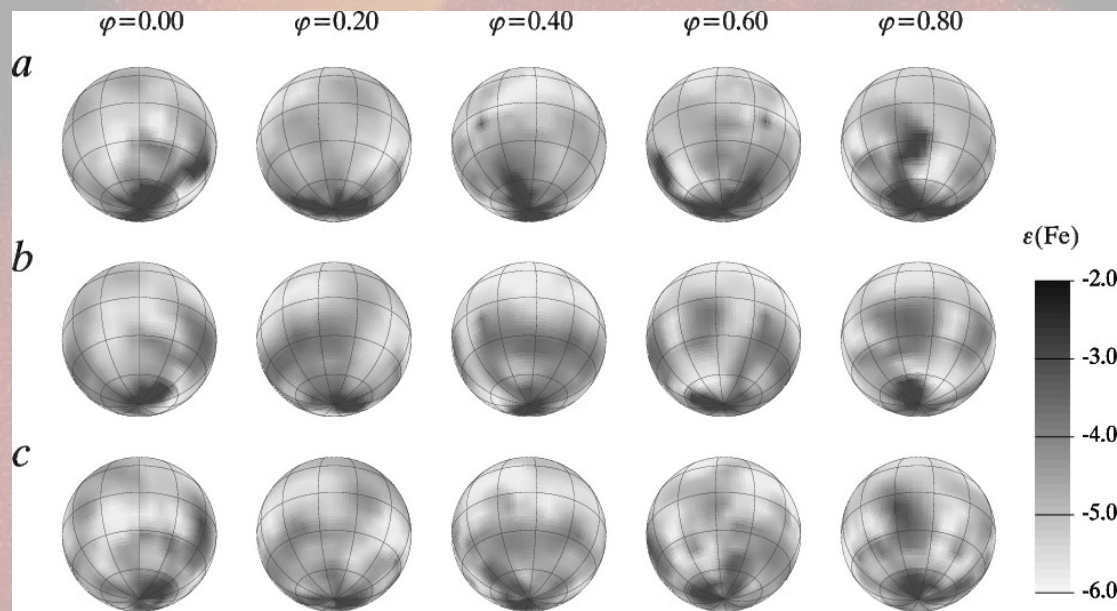


Mapping a magnetic star: detailed surface maps

- To *map* surface structure of star, create mapping code that can fit spectra of all 4 Stokes parameters at many rotational phases by iterative adjustment of abundance and field maps
- Requires many cycles of forward computation, comparison, backwards feedback to improve maps, then through cycle again (Kochukhov et al 2004, A&A 414, 613)



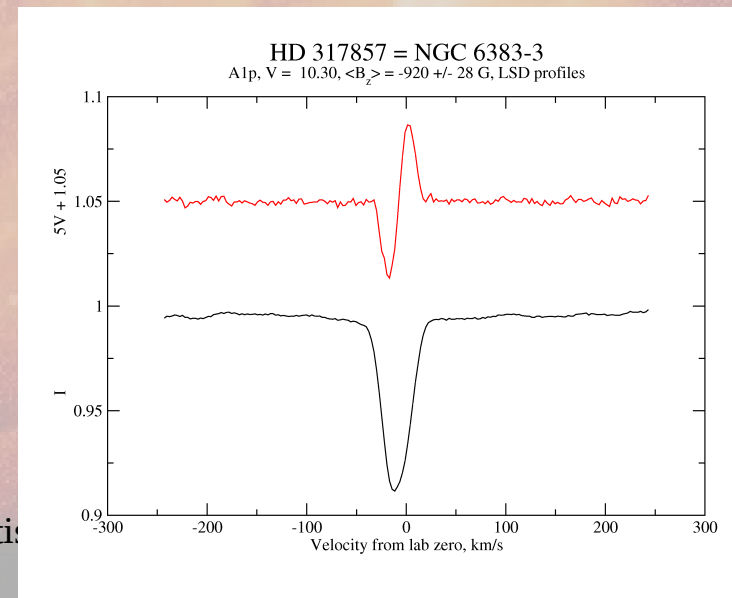
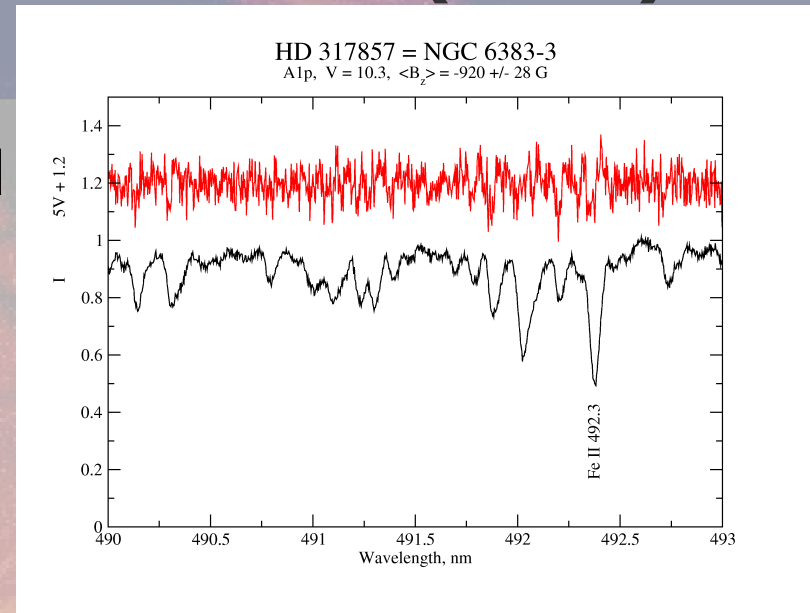
Further results for 53 Cam



- Above: Fe distribution from 3 lines of multiplet 42 as function of rotational phase
- Right: magnetic field strength and orientation from same three lines

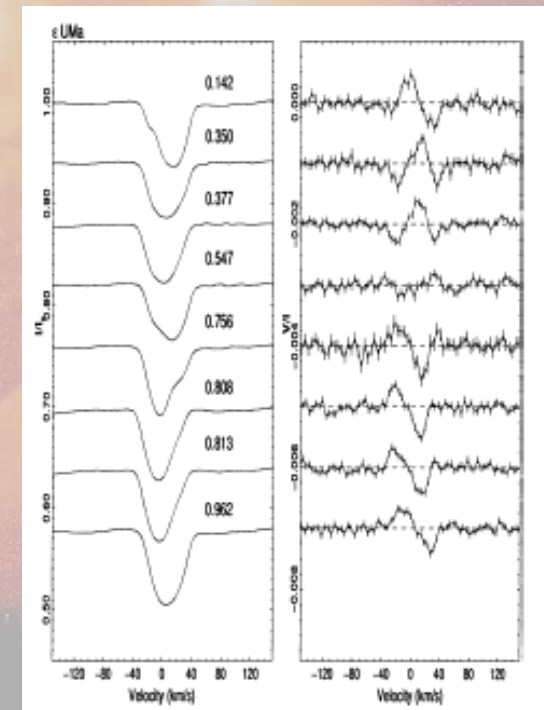
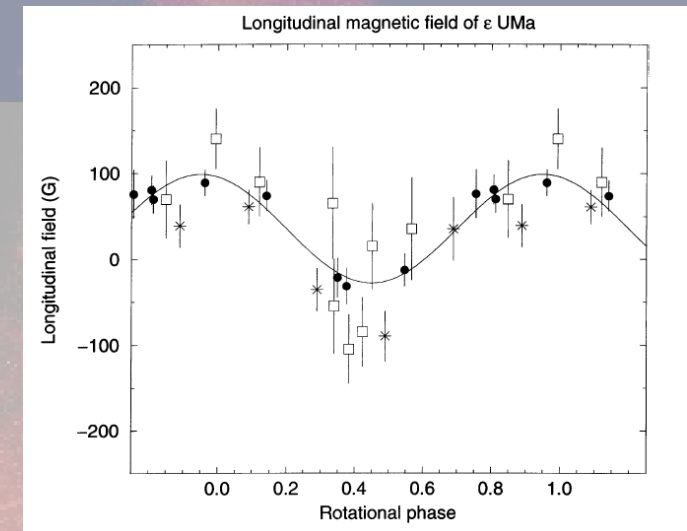
Least squares deconvolution (LSD)

- Donati et al (1997) have developed a very powerful tool for using spectropolarimetric data to detect weak fields even when polarisation signal is hardly visible: LSD
- Example of weak signal in faint cluster Ap star
 - Even in very strong Fe II line at 4923, V hardly detectable
 - When signals from thousands of lines are averaged, field signature easily visible
- Found that LSD V signal (but not Q , U) may be modelled like single line



Measurement of really weak fields

- The bright Ap star ϵ Uma shows power of LSD
- Although it is extremely bright ($m_V = 1.85$) it was really difficult to detect with single- or few-line techniques (large error bars on $\langle B_z \rangle$ curve at right)
- With LSD data from Musicos, the field is very obvious and the uncertainty in $\langle B_z \rangle$ decreases by about one order of magnitude (small error bars on $\langle B_z \rangle$ curve)



Modelling of cool stars

- A code for mapping magnetic fields from LSD spectropolarimetry of cool stars has been developed by Donati
- This has been used to map I and V LSD spectra of active cool stars, as in the map of HR 1099 to right (Petit et al 2004, MNRAS 348, 1175), where the observations at the bottom are the thin lines and the fitted model gives the bold lines

186 *P. Petit et al.*

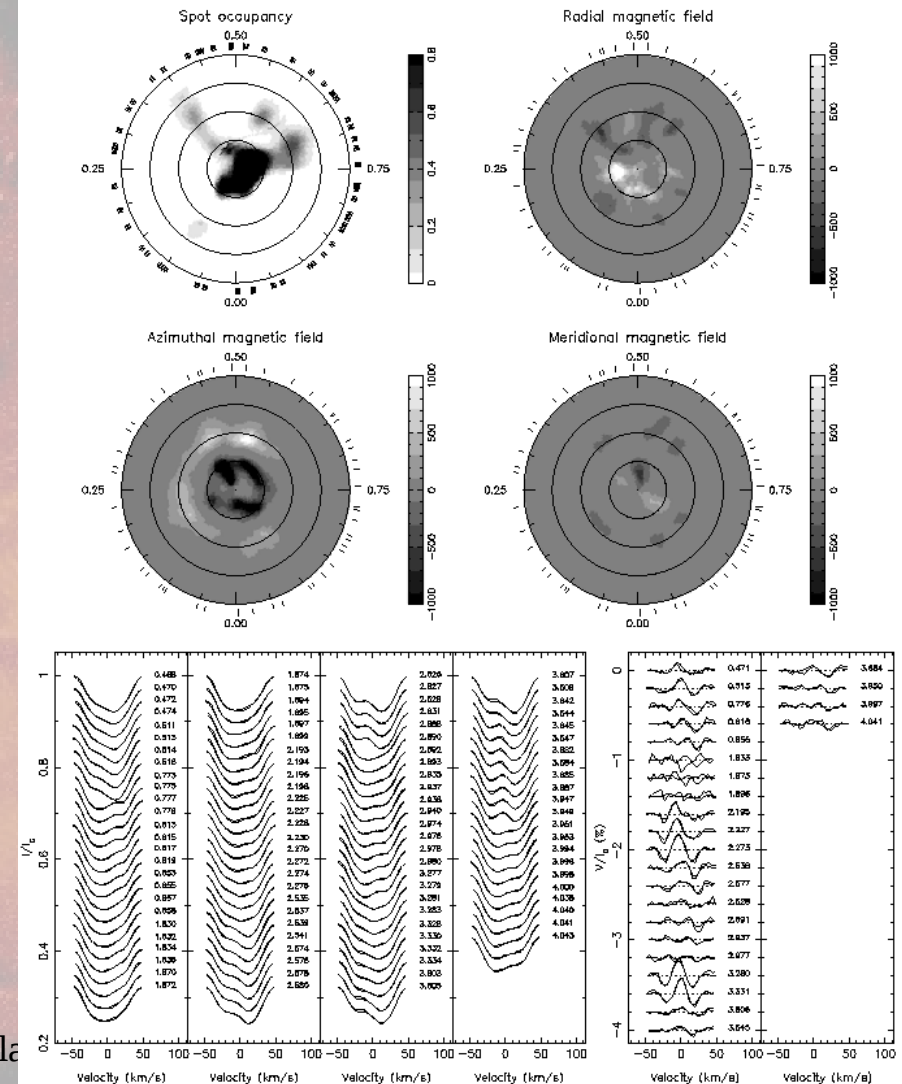


Figure 6. Same as Fig. 2 for the 2001.96 dataset.

Summary

- The point of this lecture is that computation of spectra of magnetic stars using a good underlying physical model is quite practical, and with sophisticated mapping techniques is beginning to yield detailed maps of both hot (well, tepid) and cool magnetic stars
- The first such maps reinforce the conclusion that magnetic Ap stars have topologically simple fields that are really very different from the complex fields of cool, solar-like stars.
- *But*: recall that this is an ill-posed problem, and maps do not provide unique solutions to data, particularly at level of fine detail. In practice maps have limited spatial resolution – the finer the detail, the less certain it is.