

Measuring stellar magnetic fields



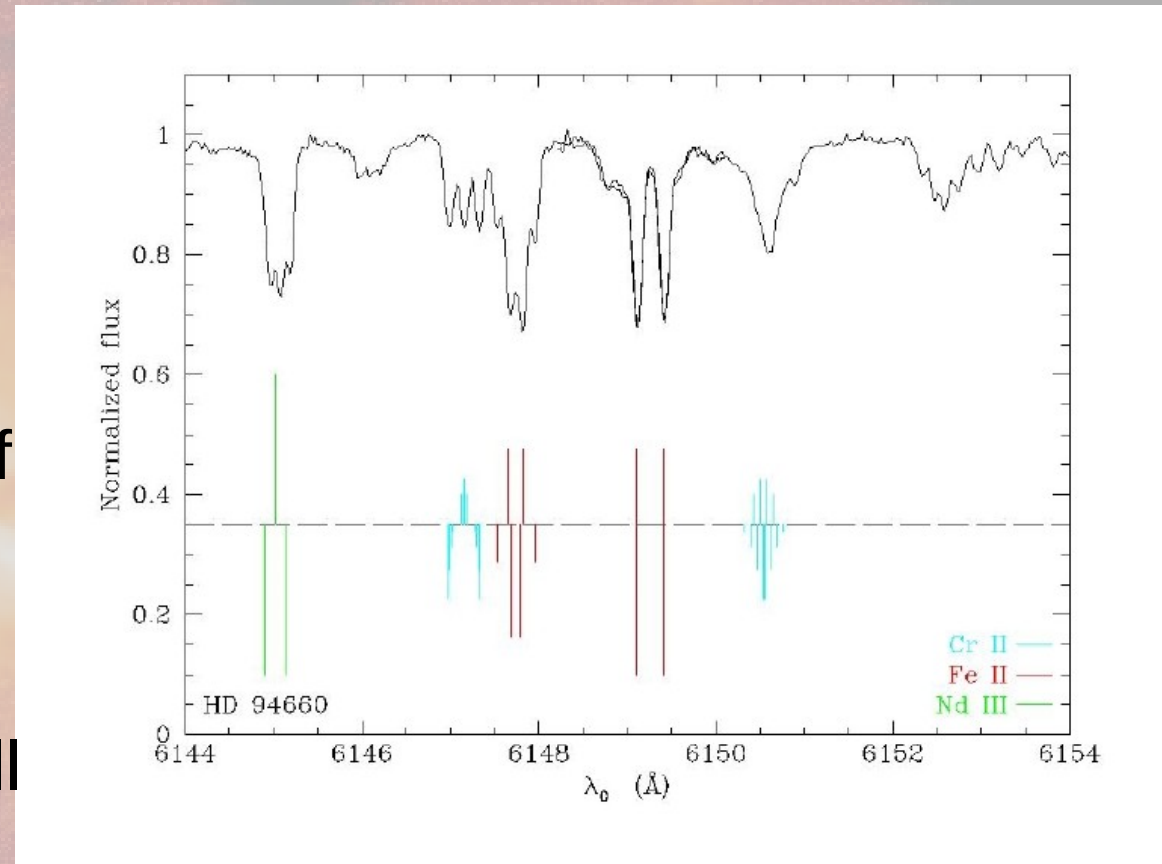
JDL

Outline

- We have now looked at atomic physics needed to detect magnetic fields in non-degenerate stars -- but this does not completely solve our problem
- How does this microphysics allow us to actually measure fields in stars, and what exactly do we measure?
- What kind of instrumentation is needed for magnetic field measurements?
- How are the polarimetric and intensity measurements that we actually make described?

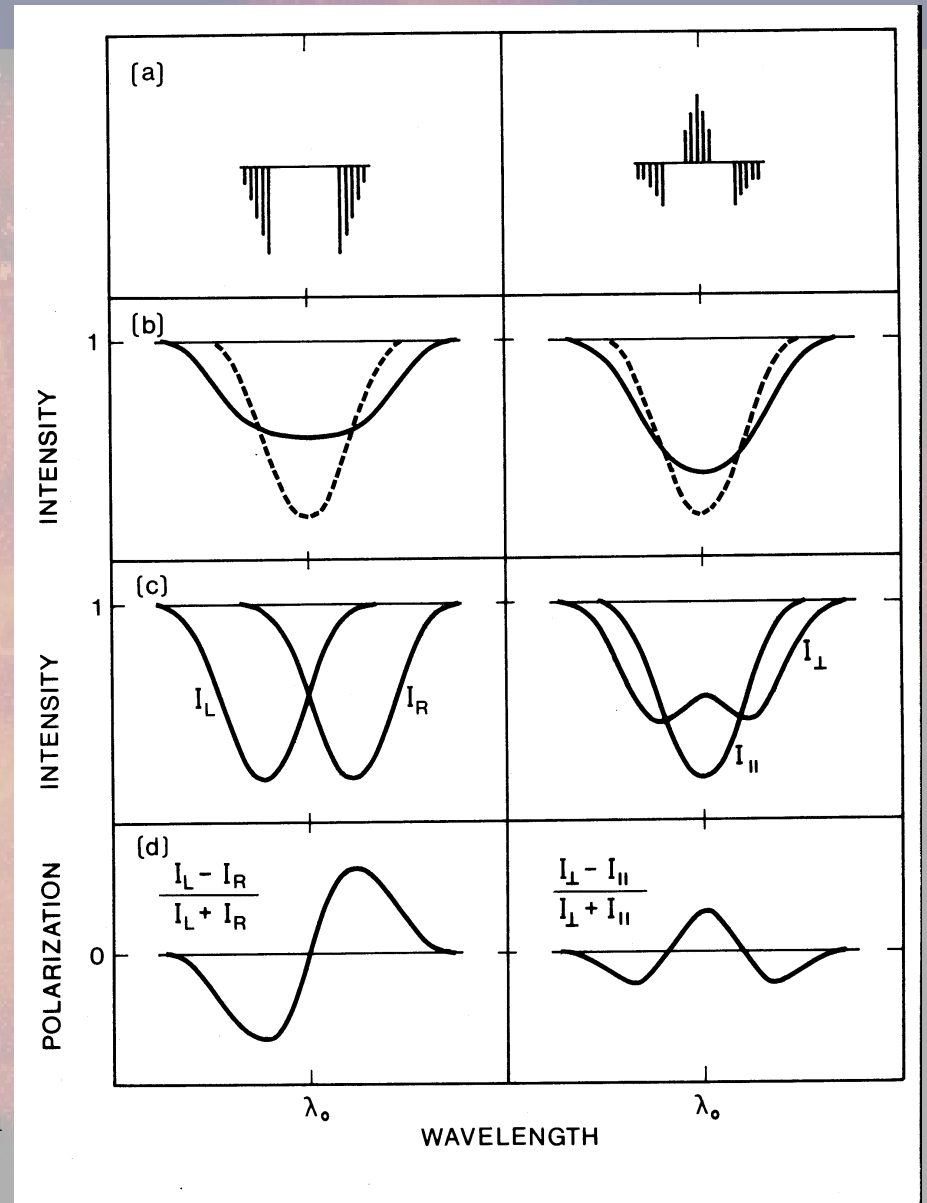
Zeeman splitting in HD 94660

- We have seen that a strong field ($> \sim 2$ kG) produces direct Zeeman splitting
- This leads to a simple measurement of $\langle B \rangle$
- Question: what kind of an average is $\langle B \rangle$??
- Question: what do we do if the field of interest is far too small to detect this way??



How to use Zeeman polarisation to get field measurement?

- Zeeman effect in spectral lines can alter stellar lines even if the stellar lines are not split-->
- For greatest detection sensitivity we need to obtain *polarised* spectra
- Need a combination of polarisation analyser (polarimeter) with spectrograph = *spectropolarimeter*



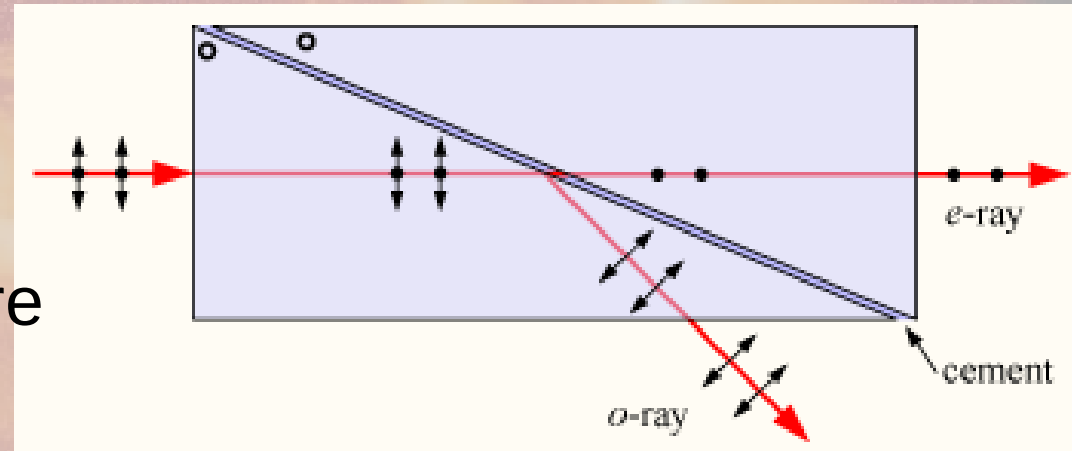
Polarimeters

- Simplest polarimeter is a device that rejects one sense of polarisation (circular, linear, etc) *or* separates two beams from the initial one, differing in polarisation state (e.g. Iceland spar) -->
- Iceland spar = crystalline calcite is *birefringent*: speed of light depends on polarisation state



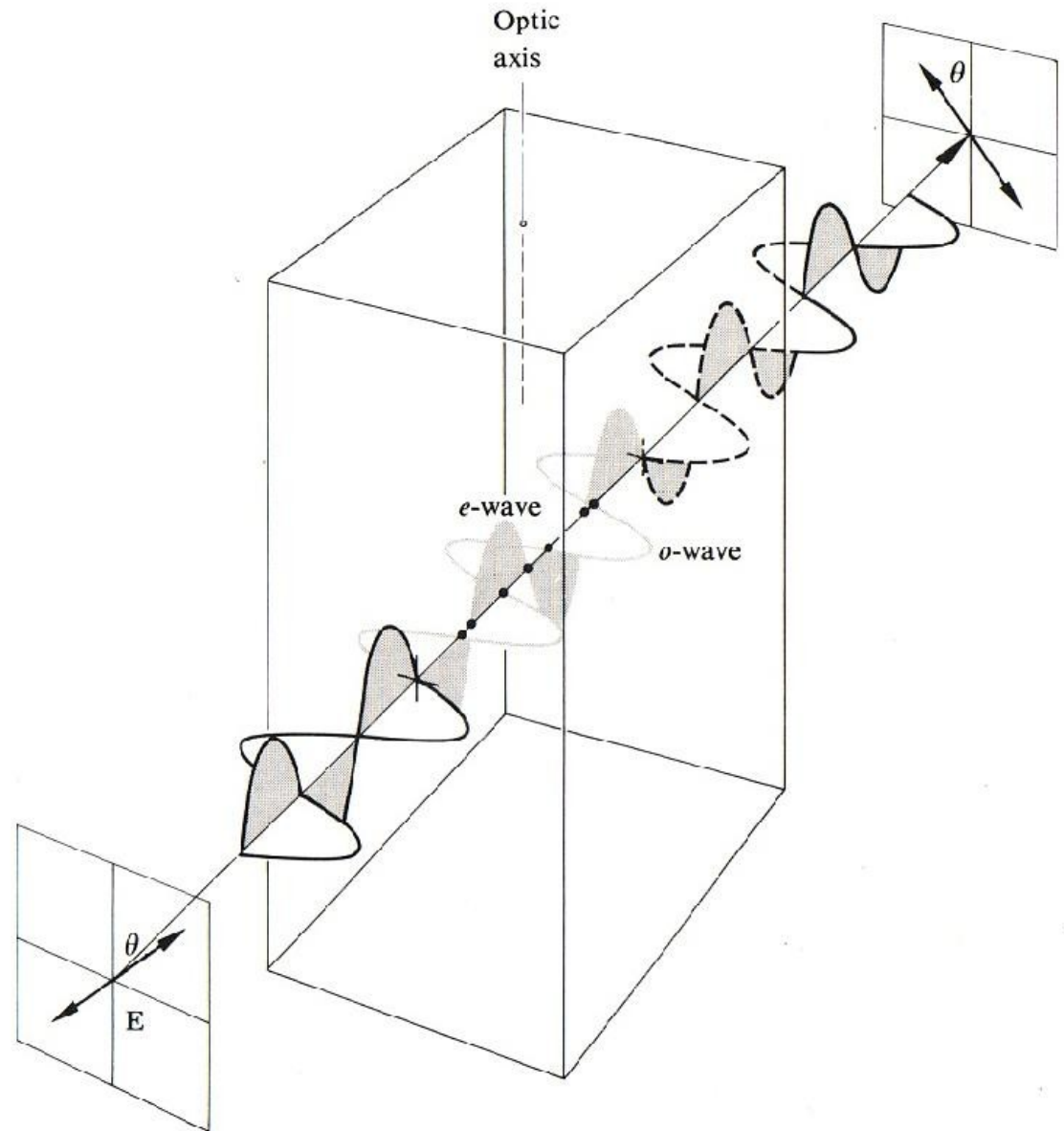
A (really) simple polarimeter

- Simple linear polarimeter is a polarisation analyser built from calcite wedges to transmit one polarisation state and reflect the other (Glan-Thompson prism)
- Get spectrum of star with polariser in front of entrance slit, rotate polariser 90° , then compare the two spectra
- Question: is this a *good* polarimeter??
- Question: what would improve it?
- Question: how to measure circular polarisation?



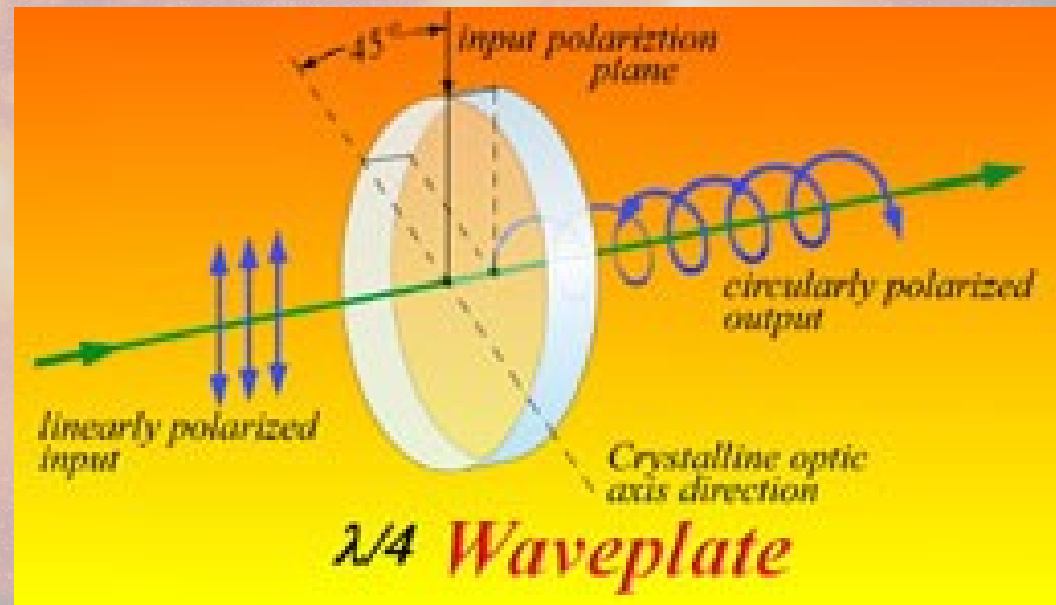
Second essential component of a polarimeter: a retarder

- A retarder has two axes such that e-wave has higher speed through substance than o-wave
- **E** is projected on these axes and each projected component travels separately
- When recombined at other side, polarisation state of wave is changed



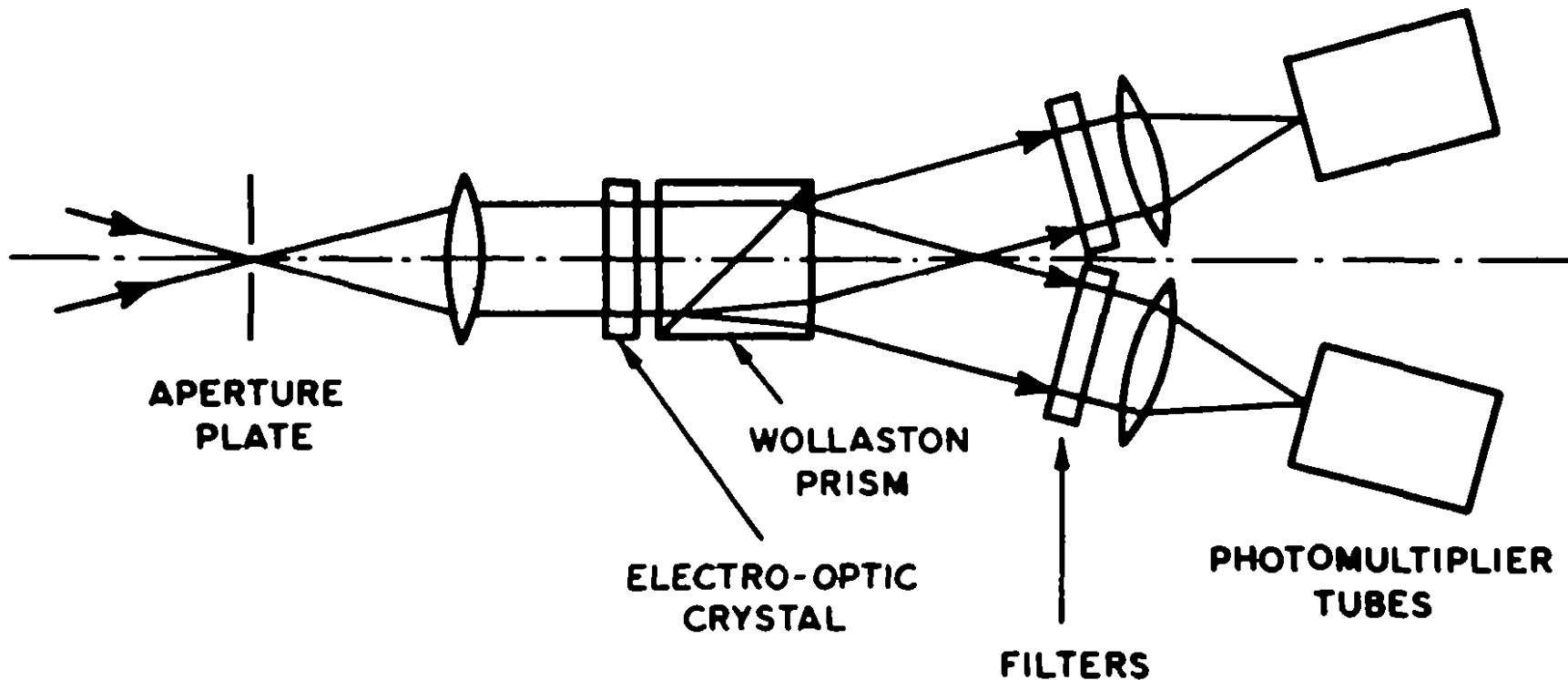
Circular polarimetry

- To do *circular* polarimetry we can convert circular polarisation into linear and then analyse the linear polarisation
- A quarter-wave plate resolves circular polarisation into two linear beams at right angles, 90° different in phase
- After the wave-plate, the two beams are in phase, converting a beam of circularly polarised light to linearly polarised light
- Also operates in reverse



A simple but real polarimeter

- First lens collimates beam – electro-optic crystal is a modulating quarter wave plate – Wollaston prism is linearly polarising beam splitter – filters define wavelengths – second lens focusses light on phototube cathodes



A real spectropolarimeter: polarisation module followed by spectrograph

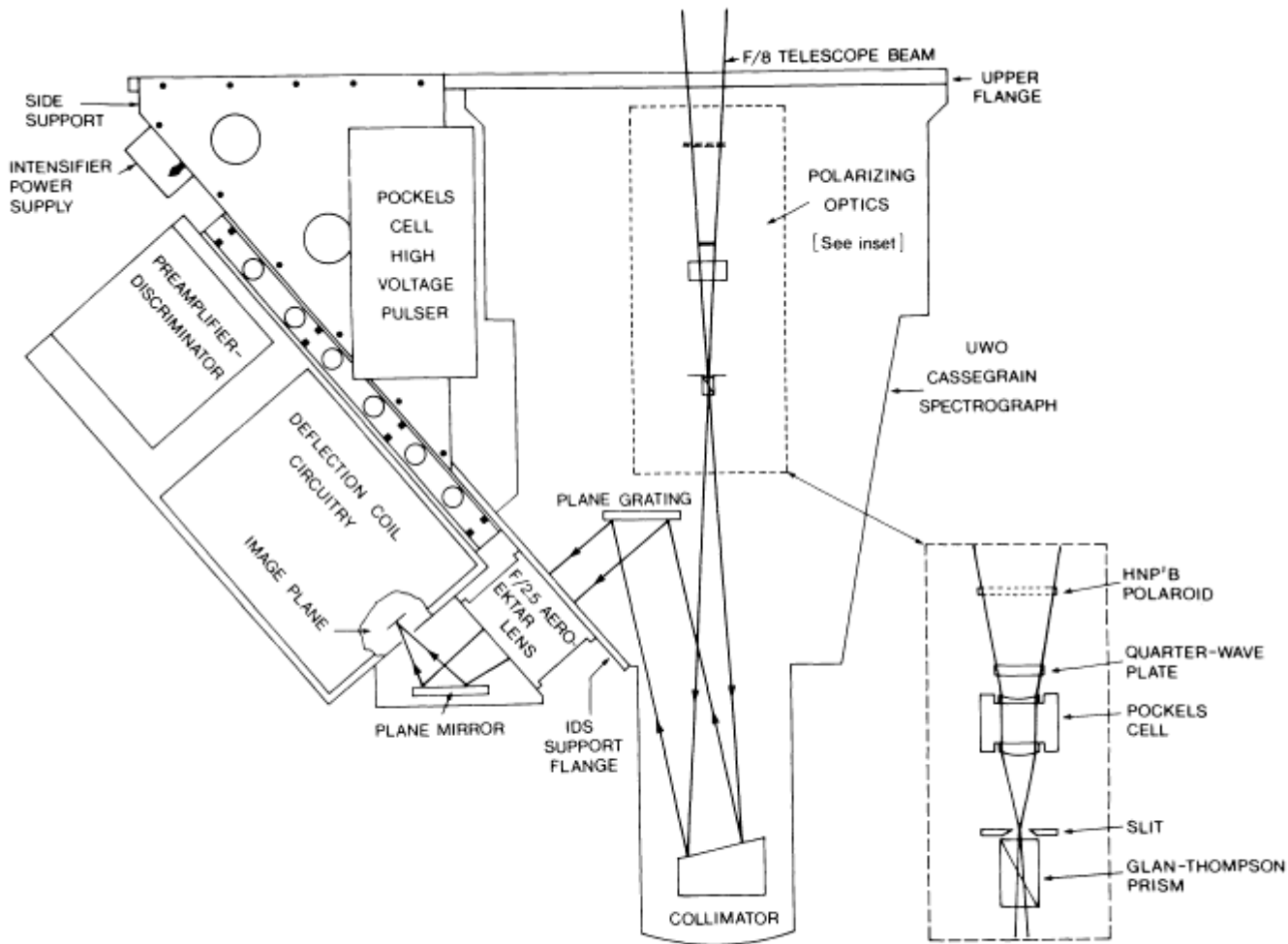
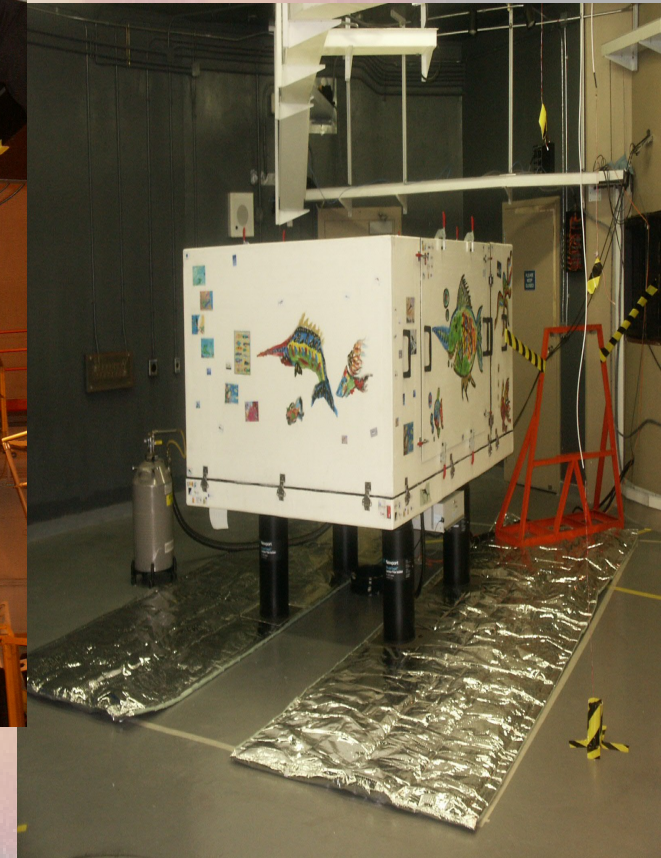
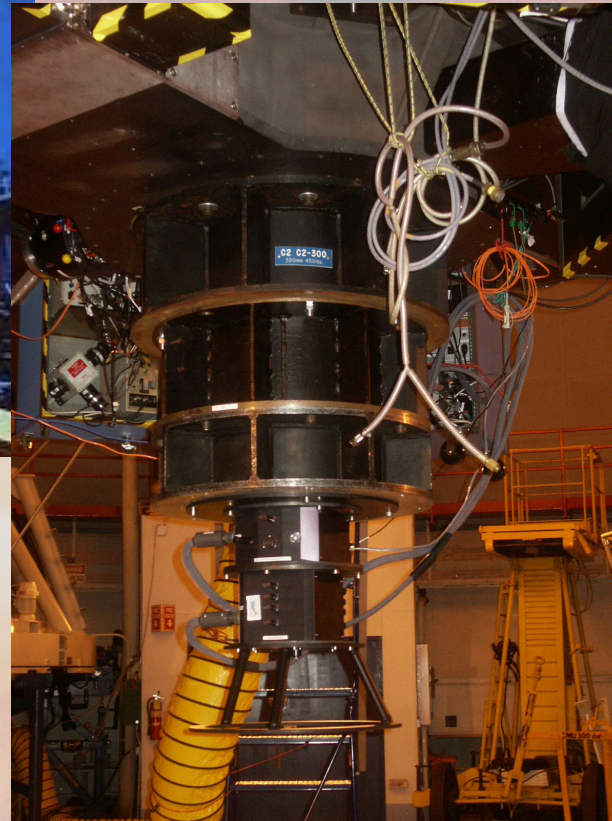


FIG. 3—Schematic drawing of the IDS-spectropolarimeter from the same view as Figure 2. The light path is also presented as a general guide to the optical layout of the system. The drawing is not to scale.

Recent advances in observational capabilities

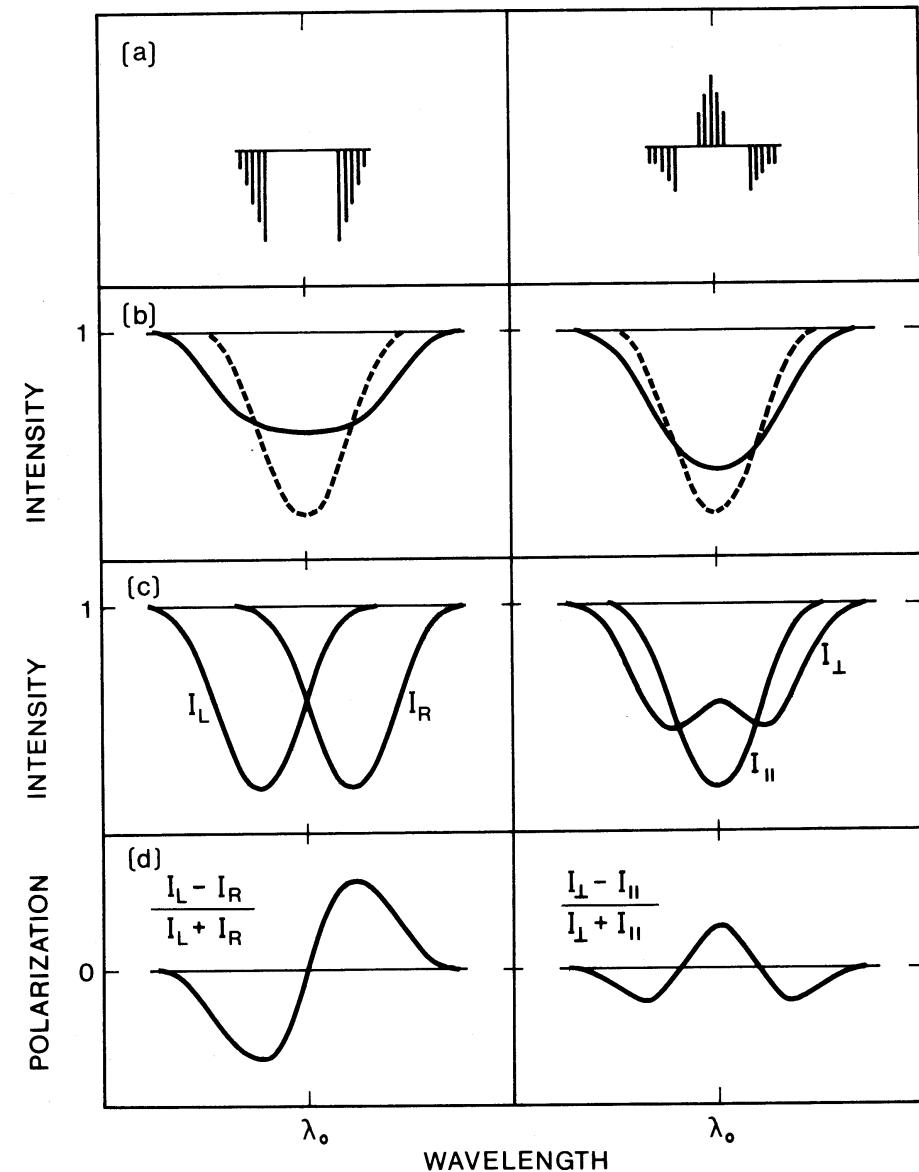
- Major advance during past 10 years has been development of facility instruments capable of high resolution stellar spectropolarimetry in all four Stokes parameters
- Most important: MuSiCoS spectropolarimeter and its successors, ESPaDOnS and Narval, all due to J-F Donati.
- MuSiCoS provided spectra with $R = 35000$ for window 4600 – 6600 Å. Main limit was low efficiency, but provided wholly new types of data, provoked several major break-throughs.
- ESPaDOnS and Narval observe region 3700 to 10400 Å with $R = 68000$ and far higher efficiency.

ESPaDOnS: a spectropolarimeter at Canada France Hawaii Telescope



Degree of polarisation

- It is very convenient to work with idea of “fractional polarisation” rather than with spectra in right & left polarised light
- Last row shows how polarised spectra may be combined to describe degree of polarisation of light in spectrum
- Define this polarisation for linear & circular polarisation



The Stokes vector

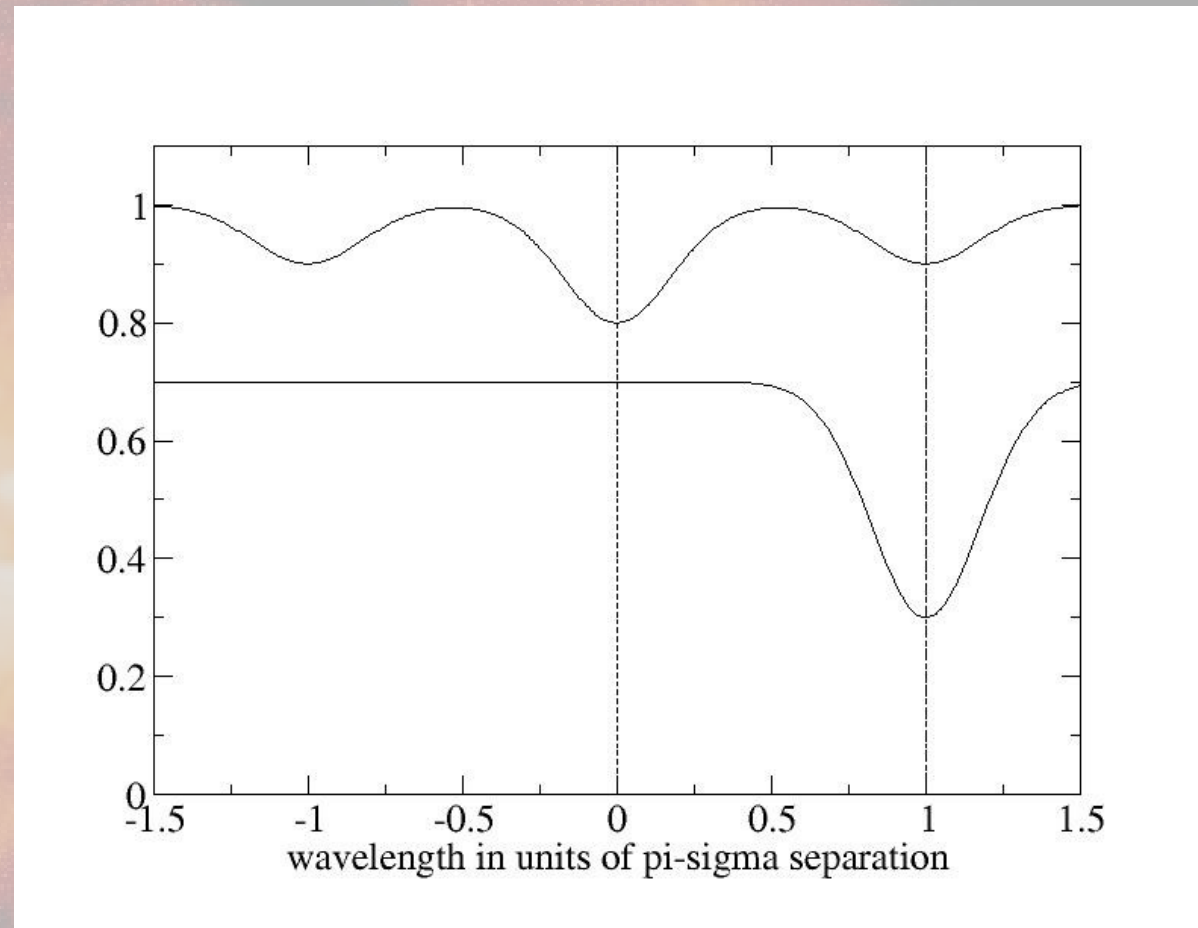
- Specifically, to describe *polarised* light mathematically we use the Stokes parameter description: $[I, Q, U, V]$
- I is the total intensity of light in the beam
- For Q and U , measure the intensity of the beam through perfect linear polarisers (polarising analysers) orientated at 0, 45, 90, and 135 degrees. $Q = I_0 - I_{90}$, $U = I_{45} - I_{135}$
- Measure the intensity of the beam through two perfect circular polarisers. $V = I_{right} - I_{left}$
- $[I, Q, U, V]$ describe the polarisation state of a light beam adequately for modelling its interactions with matter
- $[I, Q, U, V]$ are functions of frequency and direction
- Q, U, V are sometimes normalised to I ($Q \rightarrow Q/I$, etc).

Field measurements in stars: a simple approximation

- How can we use spectral observations of (usually circular) polarisation to deduce some value of magnetic field strength in the observed star?
- Since circular polarisation is produced by *line-of-sight* field component, we expect that the measurement deduced from circular polarisation will describe a mean of this field component over surface of star: $\langle B_z \rangle$ (mean longitudinal field)
- Question: what kind of average is $\langle B_z \rangle$?
- Question: what should we measure to determine longitudinal field strength?

Zeeman pattern in one sense of circularly polarised light

- Figure shows Zeeman pattern seen in *one* sense of circularly polarised light, in transverse (upper) & longitudinal (lower) field
- As direction of field shifts from transverse to longitudinal, mean position of observed line moves away from non-magnetic position



Deducing field strength from polarimetry

- Objective is to use circular polarisation observations to derive a mean line-of-sight field strength for observed star
- From previous figure, one can accept that the separation between the position of the spectral line as seen in right and in left circularly polarised light is given by the mean separation of the sigma components multiplied by the cosine of the angle θ between the field and the line of sight
- This leads directly to the formula
$$\Delta\lambda = 2 \times 4.67 \times 10^{-13} z \lambda^2 B \cos \theta$$
where λ is in Å units, and z is a suitable average Lande factor
- Assume that this is approximately correct for spectral lines even if they are strong enough to be saturated

Field measurement in Ap stars weak field limit

- If the field is very weak, so splitting is small compared to (local) line width, the separation of the two circularly analysed components is as shown below. A measurement of net circular polarisation V in the line wing yields a field estimate through

$$V(\lambda) \approx 9.34 \cdot 10^{-13} z \lambda^2 (dI/d\lambda) \langle B_z \rangle$$

where all wavelengths are measured in Å.

(cf Landstreet 1982, ApJ 258, 639; Bagnulo et al 2002, A&A 389, 191)

