Leverhulme lectures on stellar magnetism. 1. Overview

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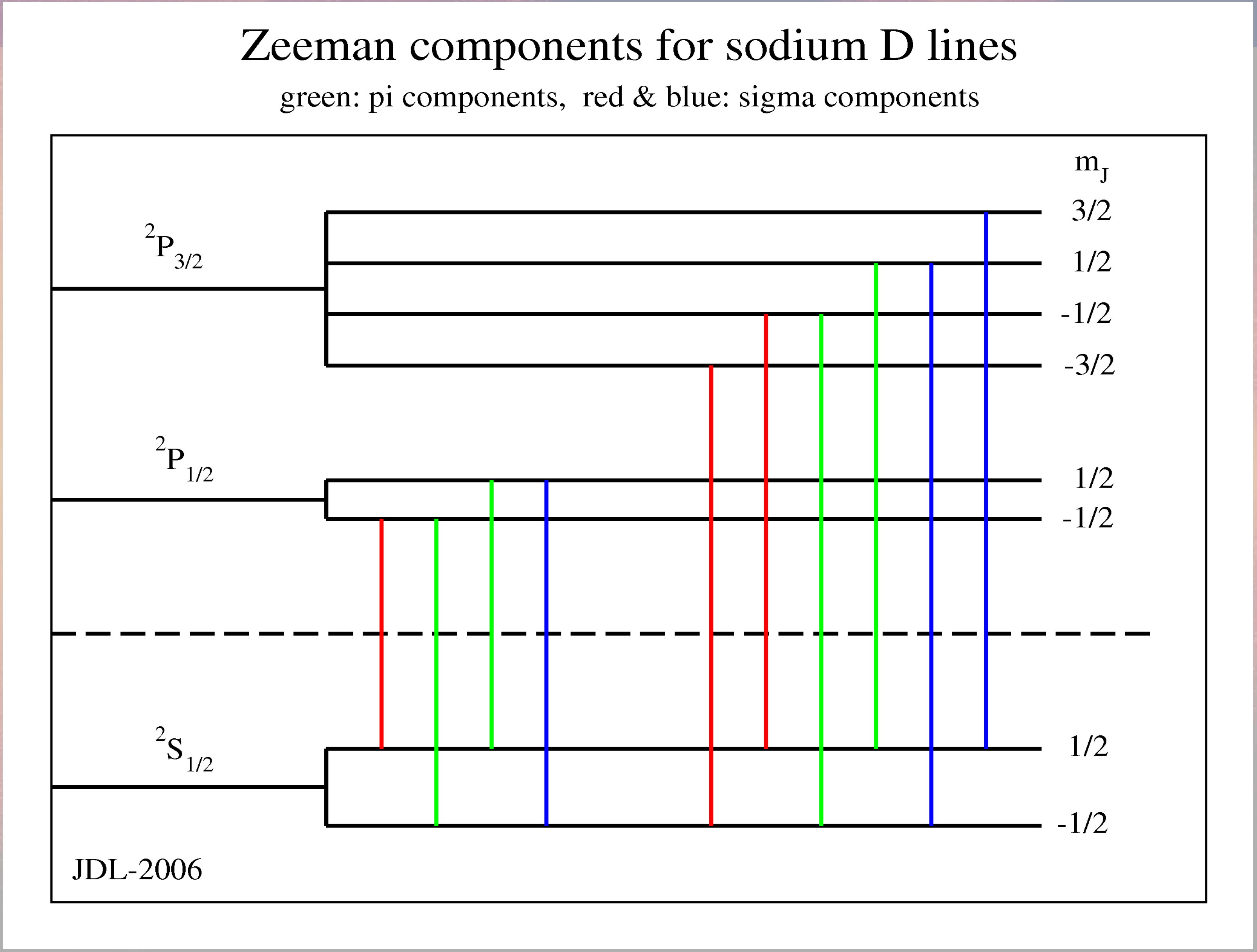
Stellar Magnetic Fields Introduction

- We study stellar *physics* to understand
  - How to get information about distant objects from observations
  - How to understand stellar structure, evolution, and observed phenomena such as X-ray emission or explosions
- Stellar physics employs mechanics, thermodynamics, electricity & magnetism, quantum and nuclear physics, etc
- One category of phenomena that might be present in stars, and might be important for understanding stellar structure or evolution, and for interpretation of spectra, is presence of a magnetic field **B**
- Can we detect magnetic fields? How? What can we learn about their possible importance?

Detection of magnetic fields: the Zeeman effect and its relatives

- For detailed study of stars, *spectra* are particularly powerful data because of rich information content of lines
- Spectral *lines* arise from atomic transitions between two energy states or levels
- Detection of magnetic field is possible because energy levels of atoms and ions are *perturbed* by a field, hence spectral lines are altered
- Perturbation occurs because atoms are little bar magnets μ due to electron orbits and intrinsic spin, so energy of a state depends on *orientation* of atom in magnetic field as $\mu \circ \mathbf{B}$
- Since different orientations are possible, single energy levels split in **B** field into multiple levels
- Hence single spectral lines also split into multiple lines

Example: Zeeman line components

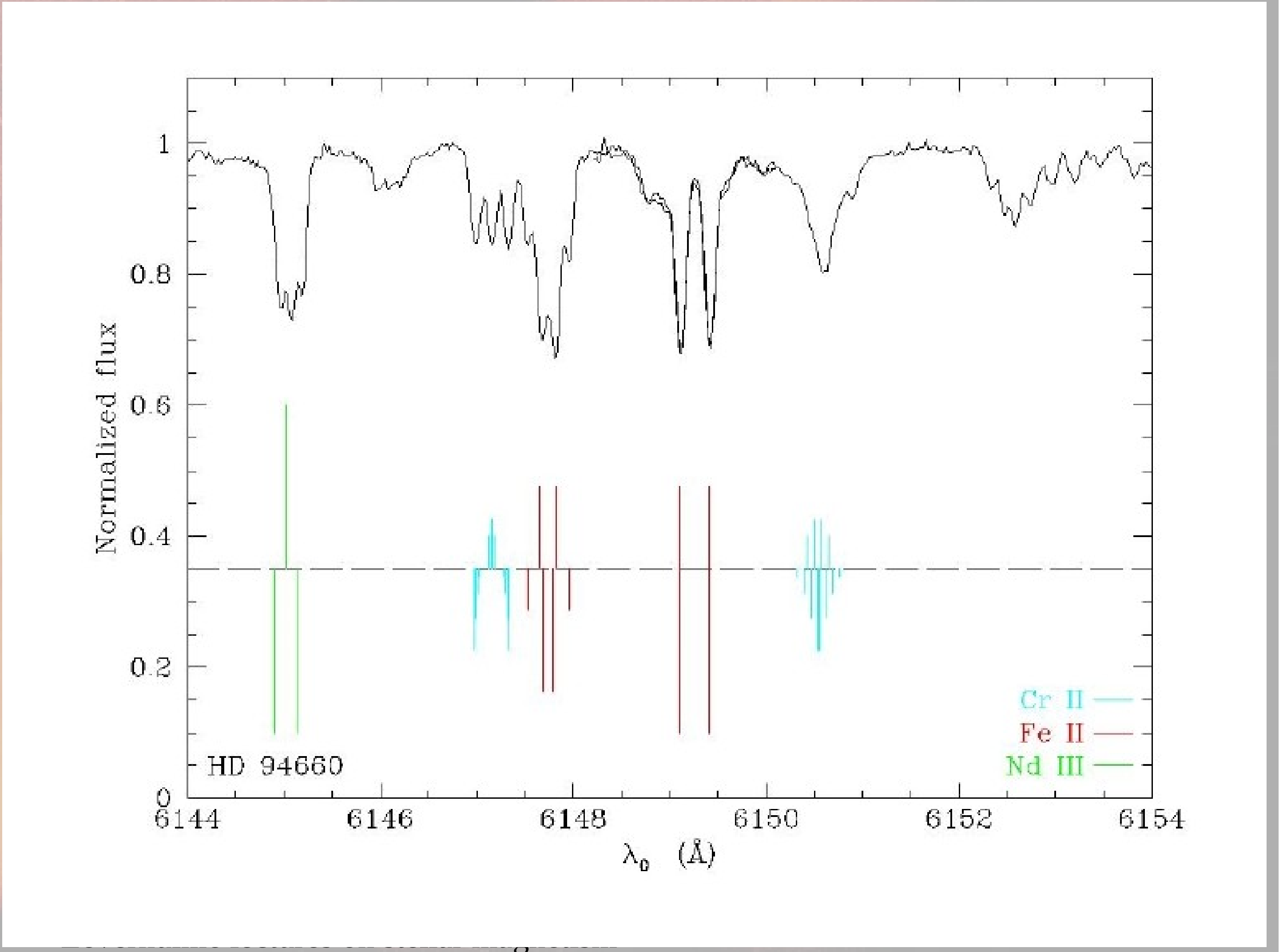


Observing the Zeeman effect

- Level splitting and hence line splitting increases with increasing **B** as $\Delta E \sim (eh/4\pi mc)B$
- To be visible, magnetic line splitting must compete with other line broadening mechanisms (thermal, rotational, etc)
- Splitting becomes detectable in (some) stellar spectra for **B** larger than a few kG (a fraction of 1 T)
- The different line components (π and σ) also have distinctive *polarisation* properties (e.g. in longitudinal field π components vanish and σ components on opposite sides of non-magnetic line wavelength have opposite circular polarisation)
- The polarisation properties make it possible to detect fields as small as a few G – if we have enough photons....

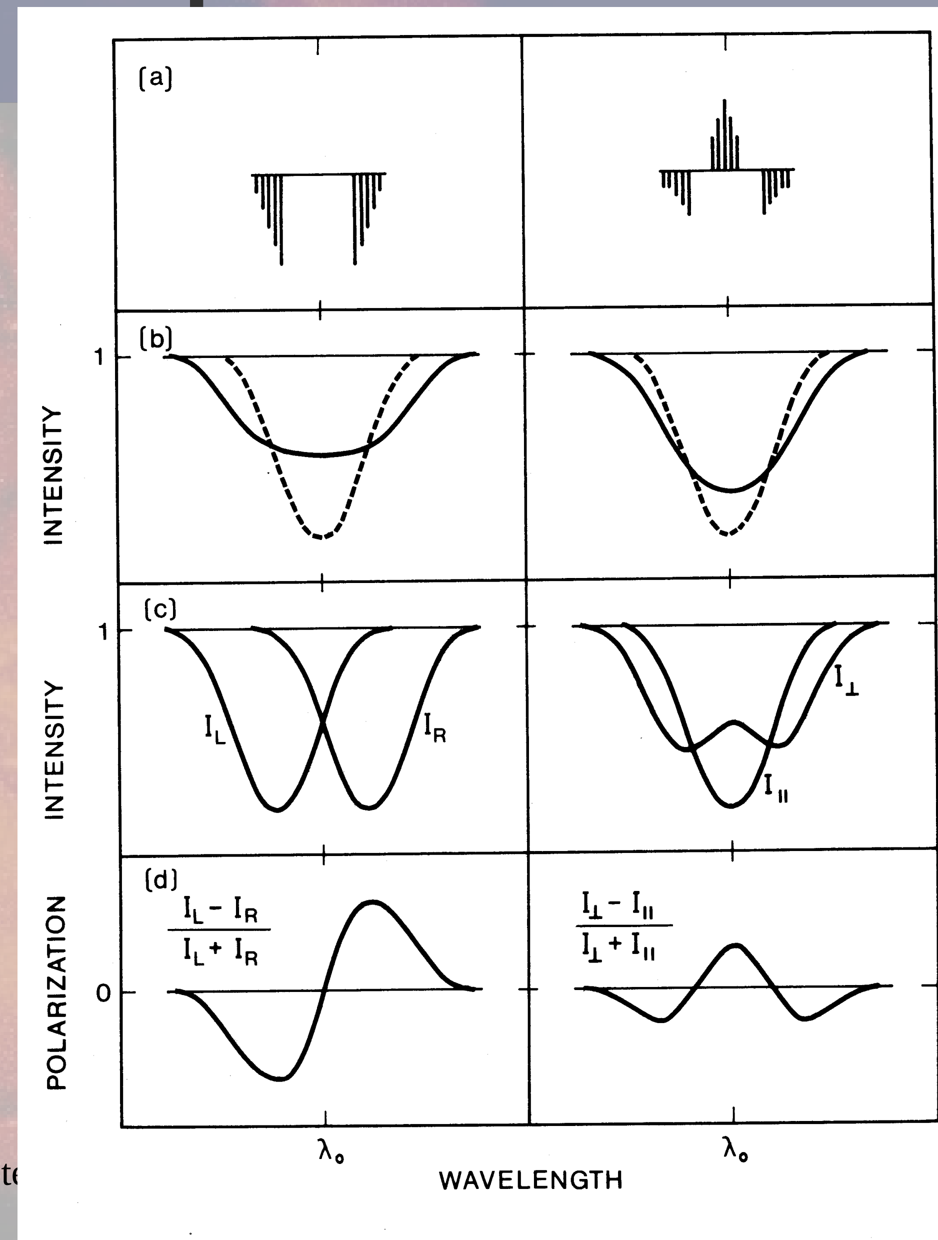
Zeeman splitting in HD 94660

- Upper: stellar spectrum showing Zeeman splitting of lines ~6 kG
- Lower: laboratory splitting of various lines in spectrum, π above and σ below line



Polarisation in stellar spectral lines

- In figure, left column is for field along line of sight, right is for field transverse to sight line
- Top row: splitting of some typical line in lab
- 2nd row: effects on unpolarised absorption line – little change in shape
- 3rd row: spectral line as seen in left & right or parallel & perpendicular polarisation
- Last row: net polarisations

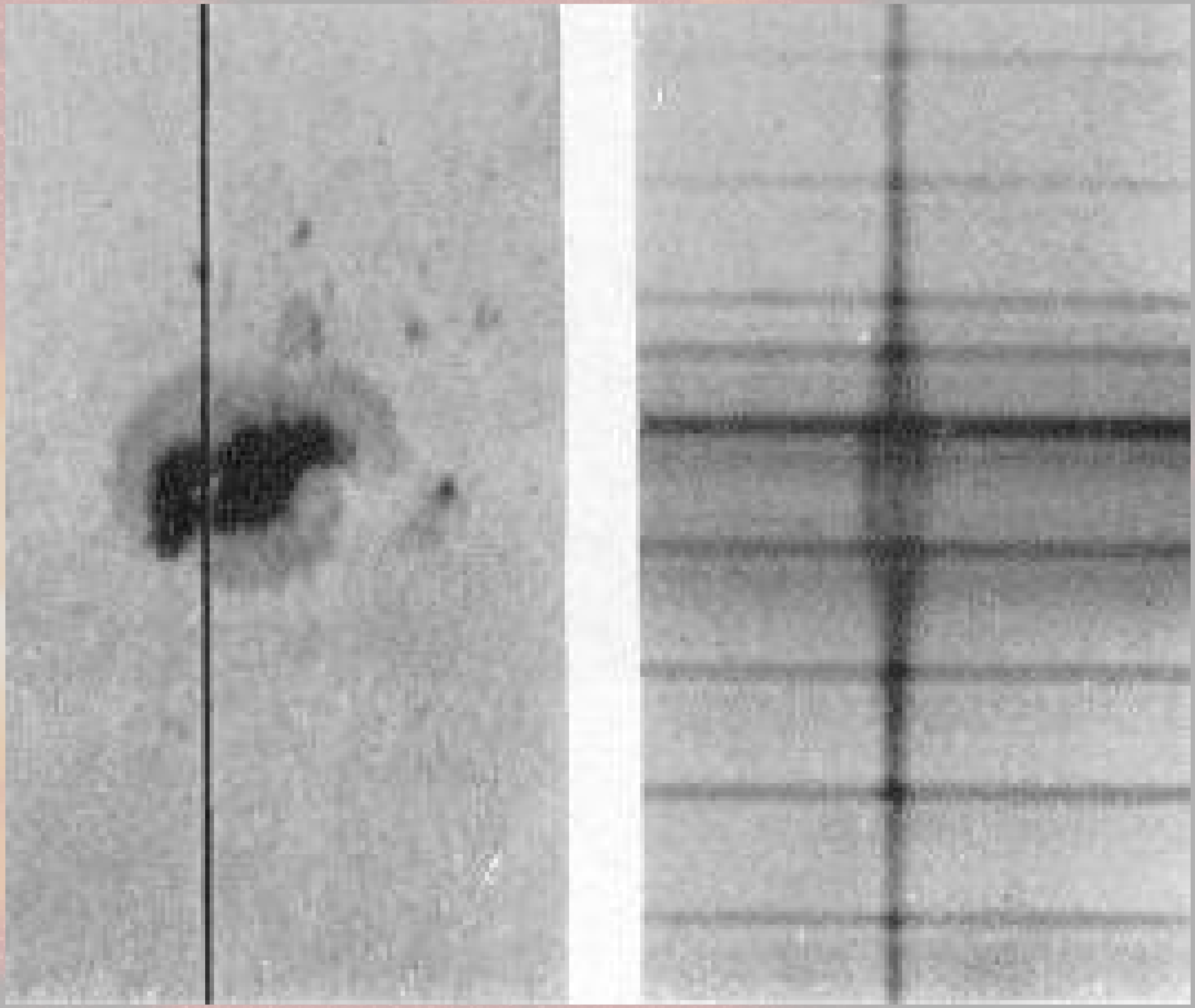


Can we detect & measure stellar fields with the physics discussed so far?

- Hale (1908) observed splitting of spectral lines in spectra of Sun obtained with long slit covering a sunspot
- Verified that effect is magnetic by demonstrating (with circular polarisation analyser) that line components are circularly polarised
- From separation of line components, estimate that fields of sunspots are ~3000 G
- Sunspots and their fields come and go on time scales of *weeks*
- Now understood that *all* solar “activity” -- sunspots, flares, filaments and prominences, X-ray emission – is essentially magnetic in origin
- Other cool stars also show magnetic fields; strength depends strongly on rotation rate (faster rotation => larger **B**)

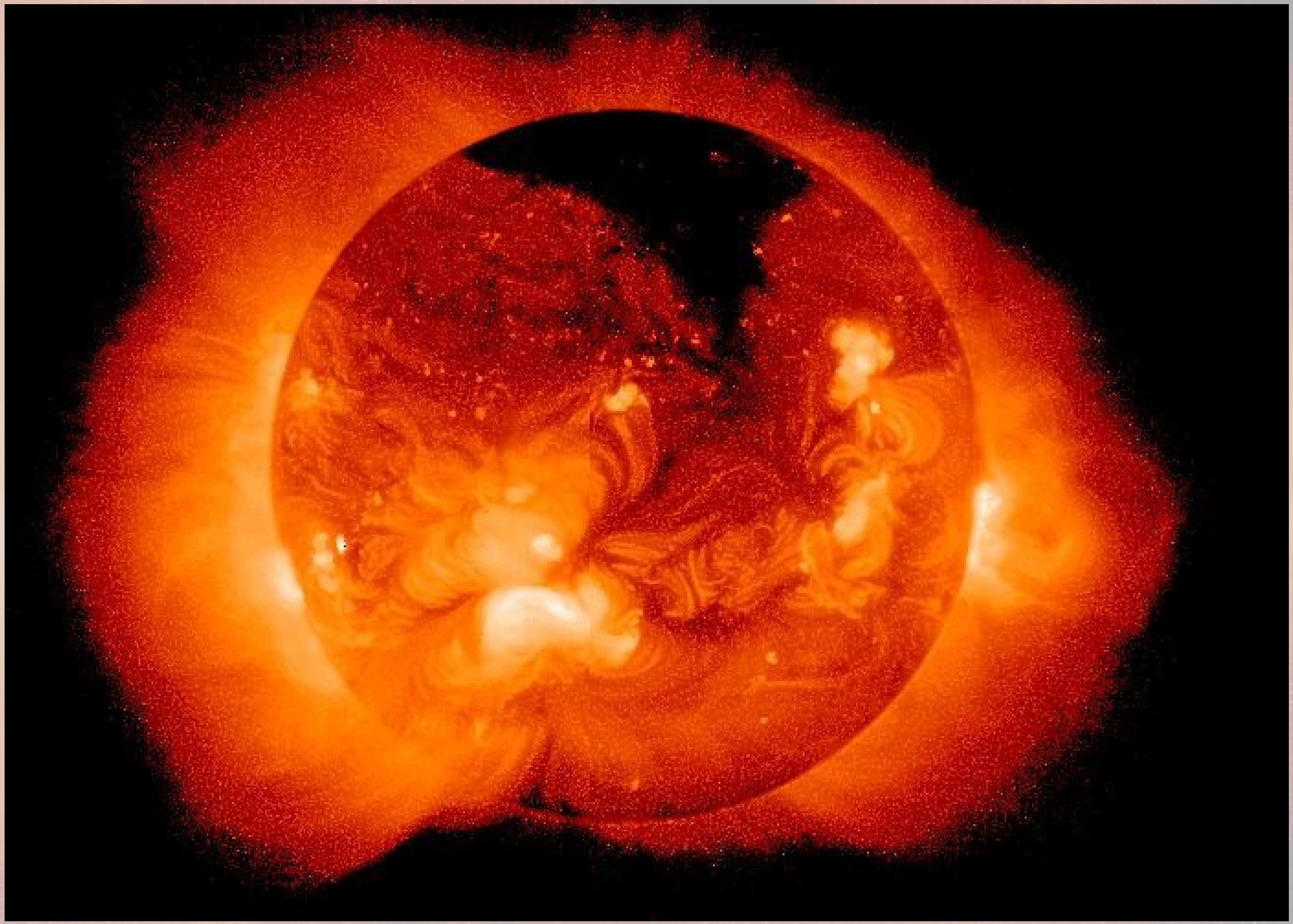
Hale's detection of sunspot field

- Left image: view of sunspot on slit plane (slit is vertical line)
- Right: spectrum (dispersed horizontally) with Zeeman splitting at location of spot

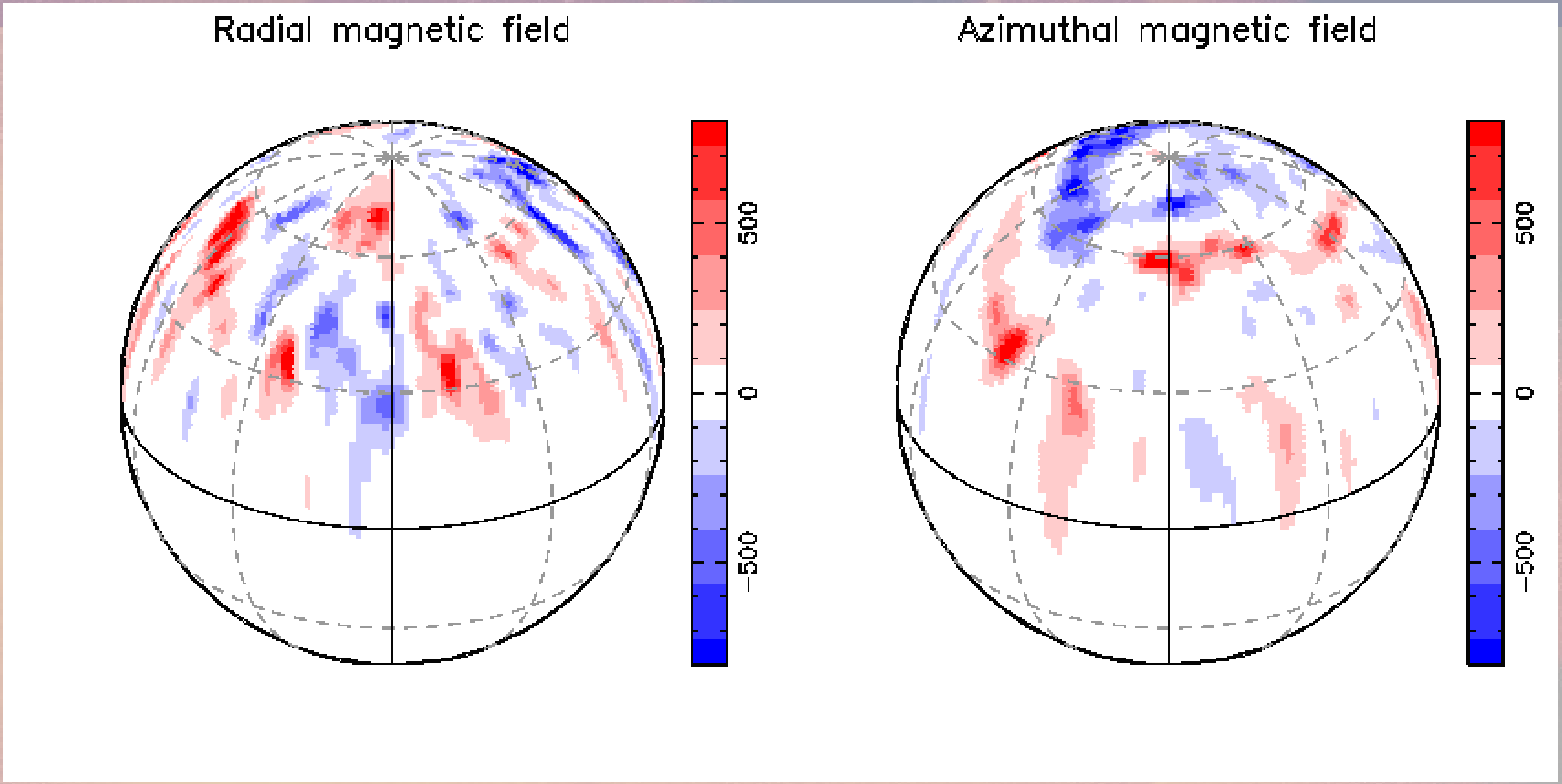


Solar photosphere is “simple”, (almost) dominated by gas energy

Solar corona in X-rays – solar activity is a completely magnetic phenomenon



Magnetic observations of AB Dor

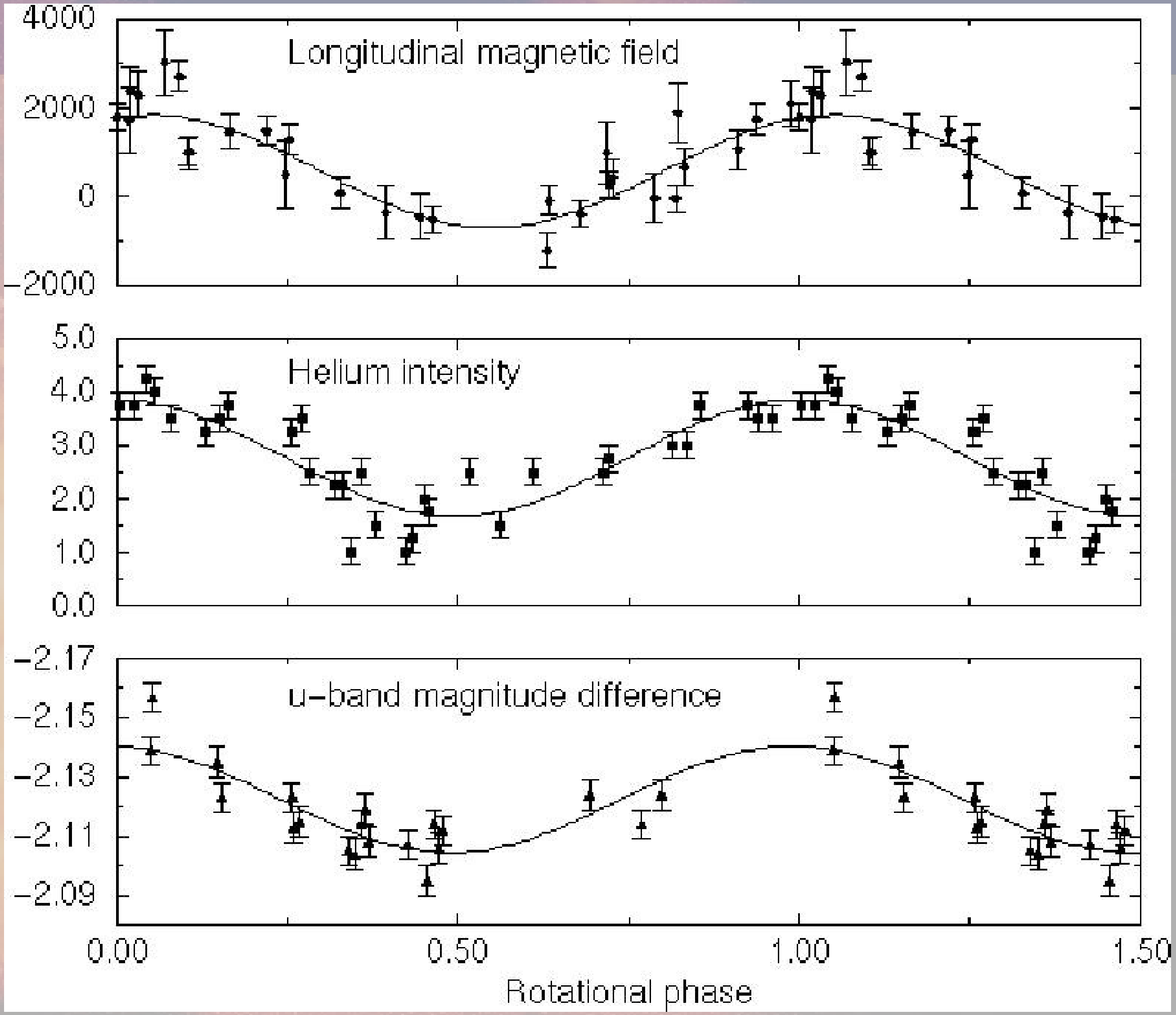


Fields of middle and upper main sequence stars

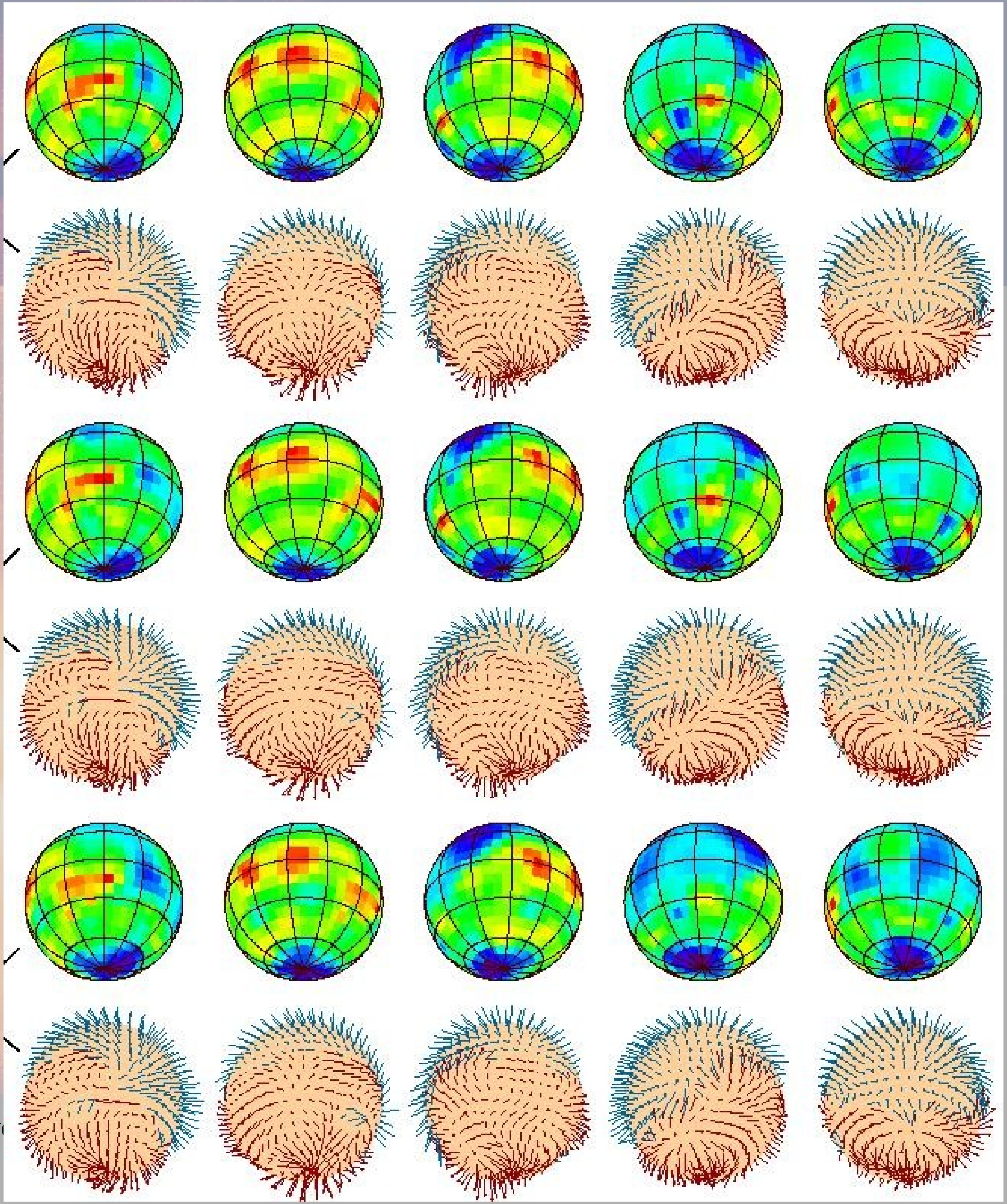
- A few % of stars above 2 M_o show magnetic fields
- Fields are usually detected by polarisation properties of Zeeman effect (measures $\langle B_z \rangle$ rather than $|B|$)
- These fields are intrinsically static, $\langle B_z \rangle$ changes only because star rotates and we see different sides
- Fields range from 300 to 30,000 G in different stars
- These magnetic stars ("magnetic Ap stars") show very unusual atmospheric chemistry – underabundant He, O; overabundant Si, Cr, Sr, rare earths....
- Surface abundances vary over surface and with height in atmosphere!
- Ap stars rotate unusually slowly, some with periods of many years

Typical Ap stars variations (HD 184927)

- Top: <B_z> variations
- Middle: He line strength (equivalent width)
- Bottom: brightness variations in Stromgren *u* band



- Variation of **B** over surface of 53 Cam deduced from polarised spectra
- Columns show star with steps of 0.2 in rotational phase
- Three pairs of rows are maps from three lines of Fe II
- Colourful balls are maps of |**B**|, hairy balls show vector **B**



Measurement of huge magnetic fields of white dwarf stars

- In fields of more than ~100 MG, magnetic energy in atom is comparable to Coulomb energy, and computation of atomic absorption (line and continuum) becomes really difficult
- The fact that free electrons spiral around magnetic field lines in a particular sense means that 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 large component along the line of sight.
- Observable 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.

White dwarf fields

- Magnetic fields found in 50+ isolated white dwarfs, and 40+ cataclysmic variable binaries
- Field strength range from some kG to (probably) around 1000 MG
- Fields are either unvarying, or vary periodically with periods of hours or days (like magnetic Ap stars)
- 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 – e.g. Grw +70 8247 --->

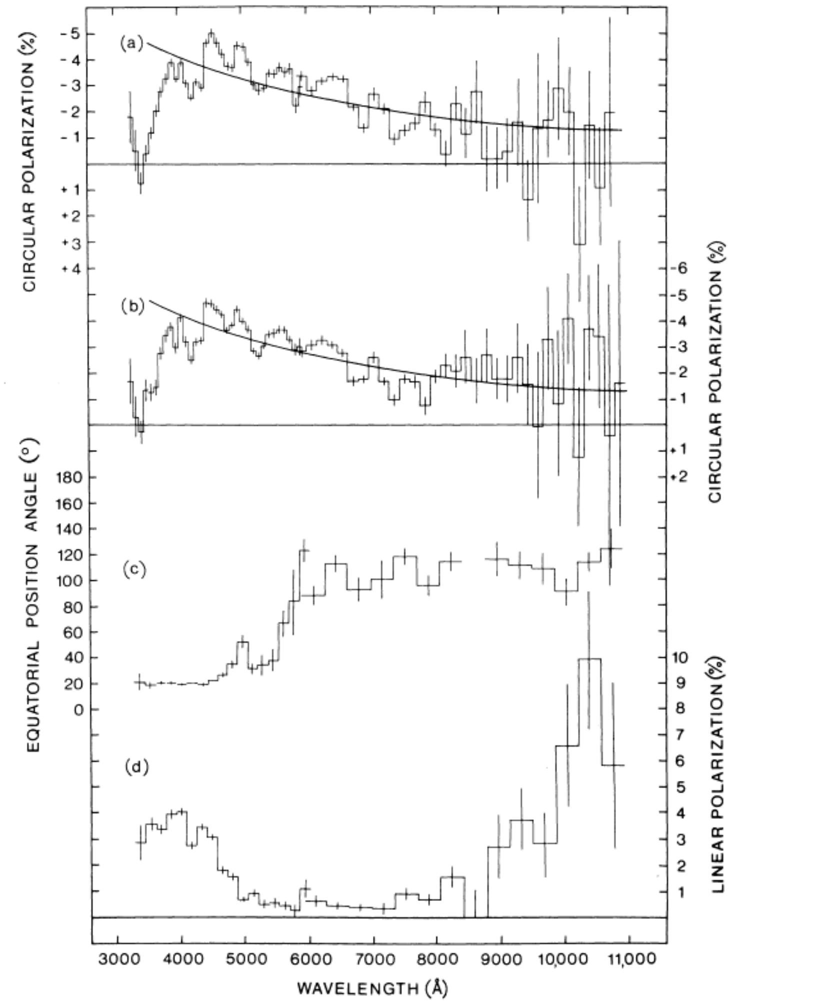
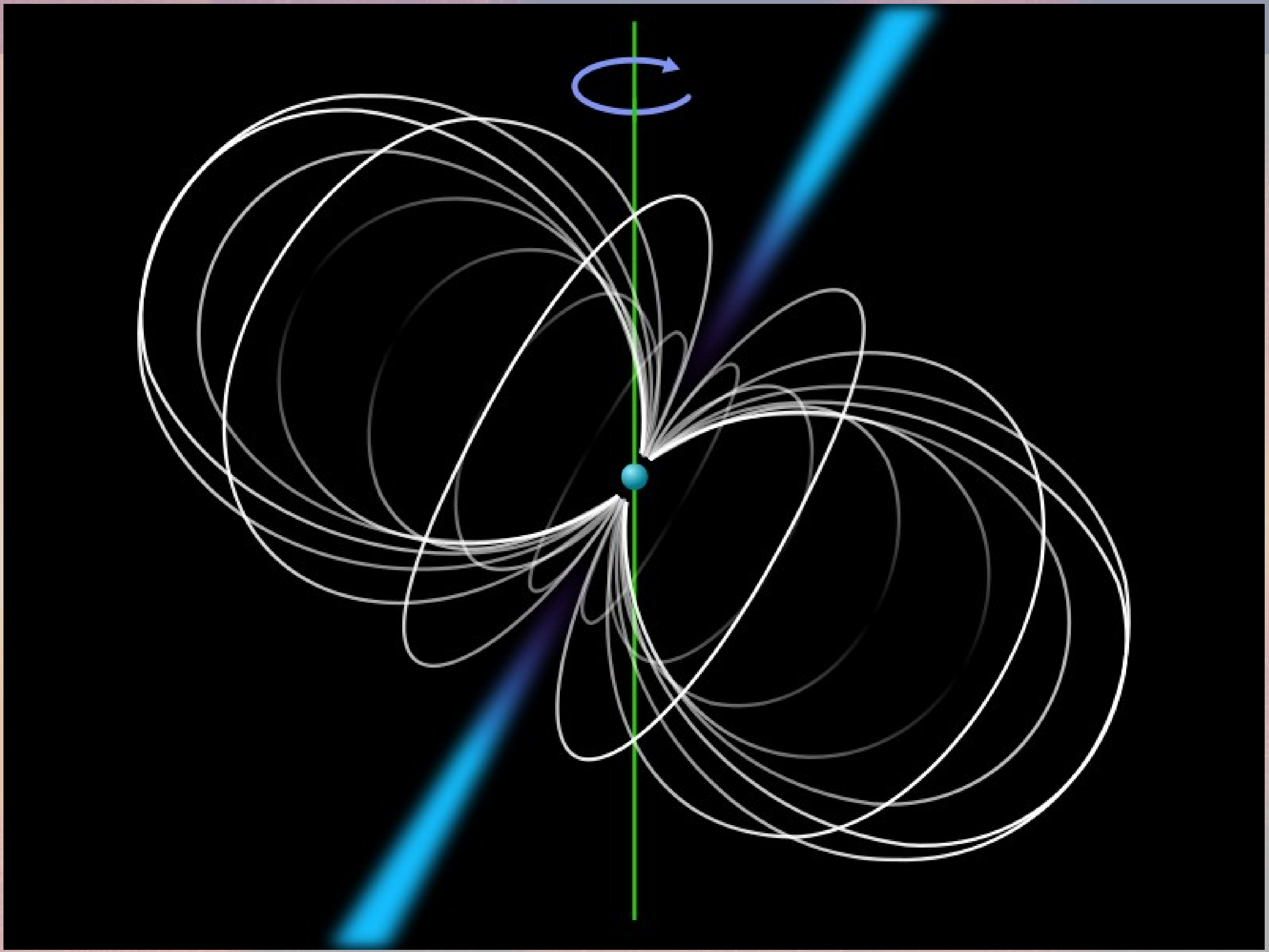


FIG. 1.—(a) Wavelength dependence of circular polarization of Grw+70°8247, 1972 August 3. (b) Wavelength dependence of circular polarization 1973 June 21. (c) and (d) Wavelength dependence of equatorial position angle and amplitude of linear polarization, 1972 August 2 and 3. Vertical error bars show ±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.

Neutron star fields

- Discovery of pulsed radio sources with periods of a few sec – pulsars -- revealed (1) existence of neutron stars, and (2) that they are strongly magnetic
- Neutron star fields can almost never be measured “directly” (from spectra). Field inferred from rate of period increase, due to EM radiation carrying off angular momentum
- Deduced fields range from about 10^9 to 10^{15} G, typical about 10^{12} G. Pulsing occurs because field axis is not parallel to rotation axis
- Nature of pulsed radio radiation is still not very clear, but seems to involve acceleration of electrons from surface which then spiral in strong circumstellar field lines. Energy comes from neutron star rotational energy
- Short-period (ms) pulsars are “powered” by accretion

Sketch of pulsar beams



Do magnetic fields matter?

- Fields in stars do *not* seem to affect basic structure or evolution – usually ignored in courses on this topic
- In cool (Sun-like) stars, fields *are* responsible for essentially all “activity”: flares, X-rays, chromospheric emission lines
- Fields in more massive stars do affect spectra of stars through surface phenomena associated with fields – anomalous chemistry, surface inhomogeneity, etc. Need to be aware of this to correctly interpret observed spectra
- Fields capable of coupling star to surrounding material (local ISM, mass loss, accretion disk) with potentially very important effects on transfer of mass and angular momentum during star formation, with stellar mass loss, and in close binary systems

Origin and evolution of fields

- Weak magnetic fields are present in ISM – few µG to mG
- Fields probably partly retained by collapsing gas cloud as star forms, due to high conductivity of gas => field lines are (partly) frozen in and compressed, and field is *amplified*
- Such retained fields may be origin of “static” fields of MS stars – if flux is left in star, ohmic decay is very slow (~10^{10} yr in MS star!) so observed fields of Aps may be fossils
- If magnetic Ap star is compressed in radius by factor of ~100 (ratio of main sequence radii to white dwarf radii), conserving magnetic flux, field strength increases roughly as $B \sim (R_{init}/R_{final})^2$, so a field of 1 kG on the main sequence will rise to ~10 MG, a typical white dwarf field. Magnetic white dwarfs may descend from Aps

Origin & evolution (cont.)

- Similarly, typical fields of neutron stars are about right for flux conservation from kG MS fields. Are these fields also fossil remmnants? Not yet known
- *However,* the fields of Sun-like stars are clearly not static, and not fossils. Observed field strength rises rapidly as rotation period grows shorter => these are *dynamo* fields, currently generated in host stars, perhaps from fossil “seed”
- Dynamos are not surprising in cool stars, which have deep outer convection zones and wide range of rotation
- Slow rotation of most low-mass MS stars probably due to magnetic coupling of star to stellar winds
- Relationship of dynamo fields to fossil fields presently unclear

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- This material will be expanded as a post-graduate course in next seven weeks, Mondays at 12 at Queen's and Tuesdays at 11:30 at Armagh (1 week behind)
- If you want to know more, please consult class web site at http://www.arm.ac.uk/lectures/landstreet (not yet linked directly to Armagh Observatory home page, I think, but it will be soon)
- This web site will have slides from these lectures, a short “textbook” (from a previous version of this course), and a large number of fairly easy exercises – if you want to really benefit from this (or any other) astrophysics lecture, do the exercises!