Saas Fee 39

Magnetic Fields in the Atmospheres of the Sun and Stars

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Before starting...

Concentrate on observations: only few equations
Will use cgs units

Many people have contributed tremendously with material, advice etc. Without their help this lecture would never have been possible. Only some are named here:

Svetlana Berdyugina, Juan-Manuel Borrero, Paul Charbonneau, Stefan Dreizler, Mark Giampapa, Andreas Lagg, John Landstreet, Theresa Luftinger, Coralie Neiner, Hardi Peter, Ansgar Reiners, Manfred Schüssler, Greg Wade

Thank you!

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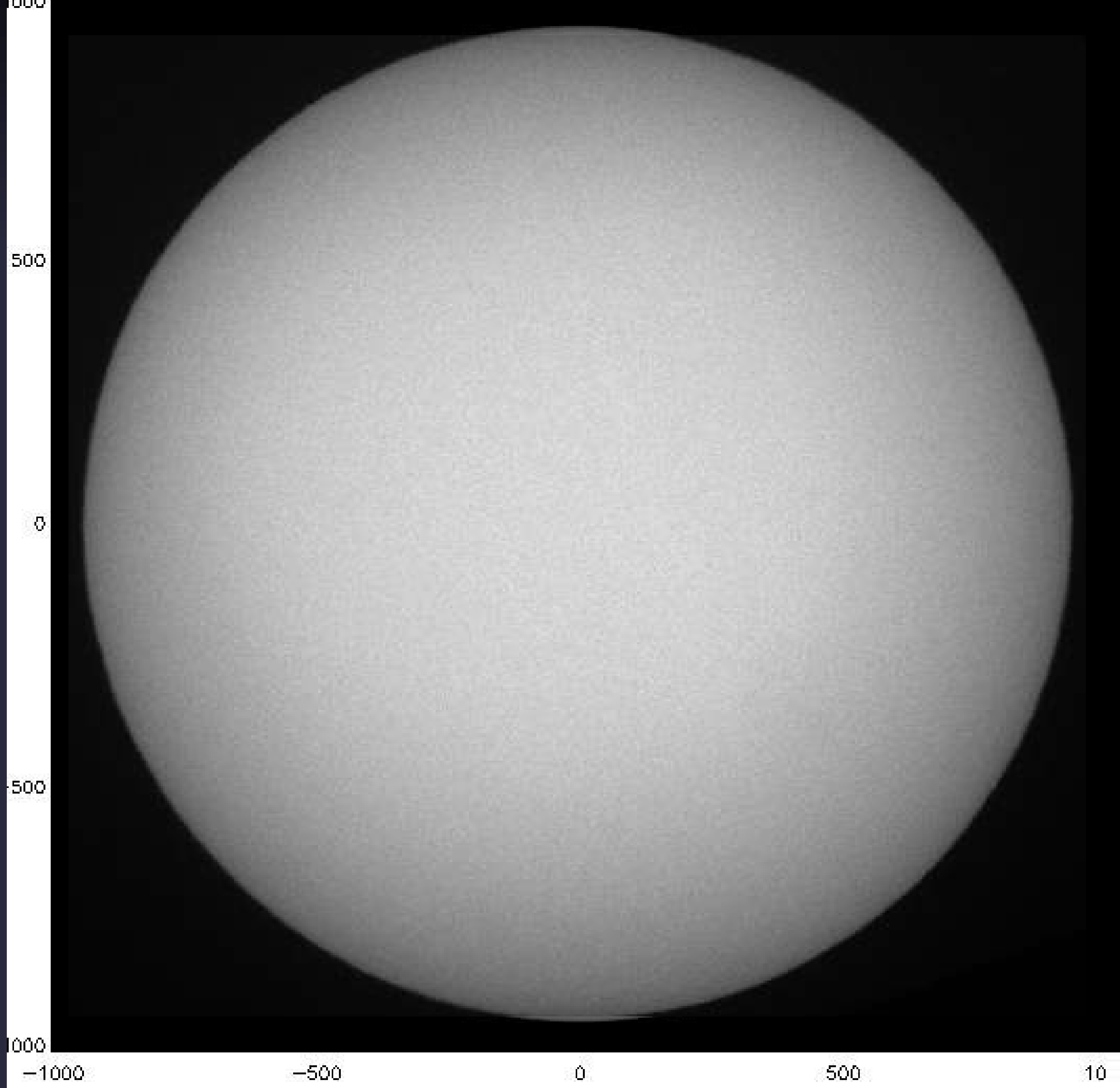
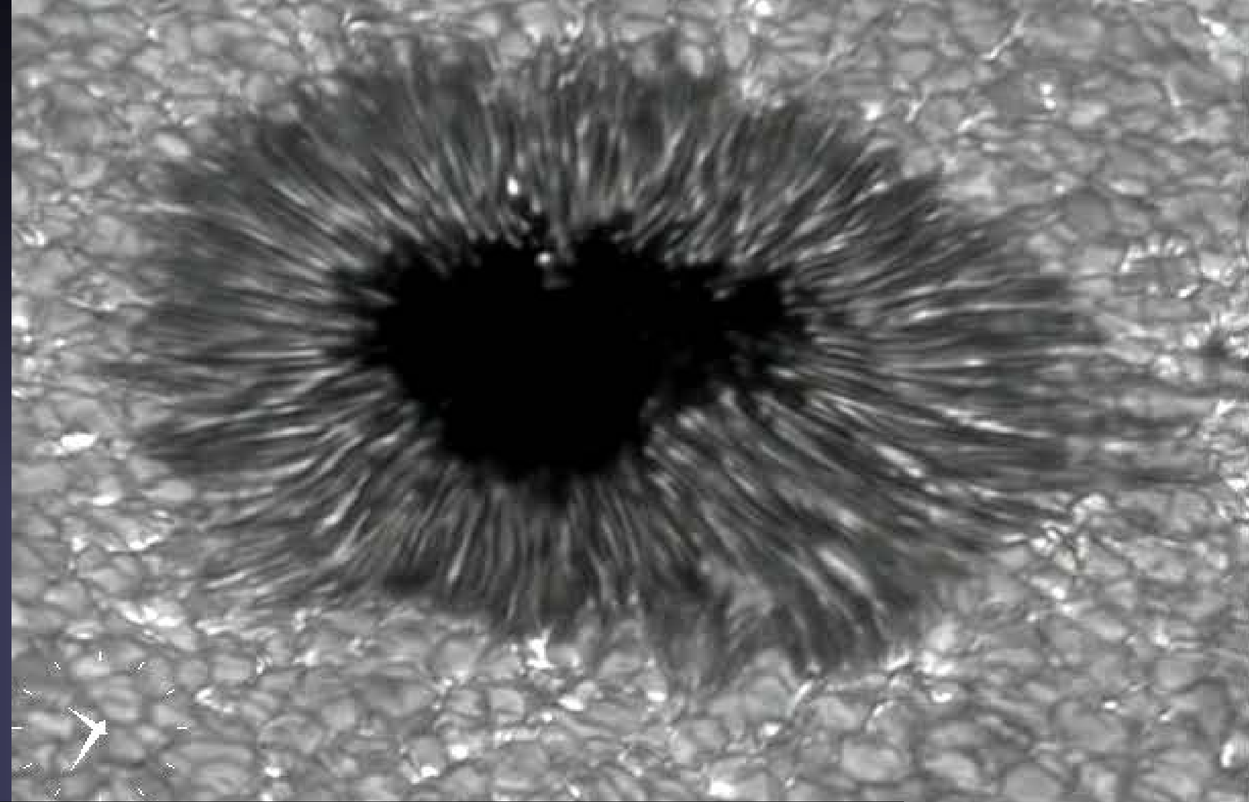
Introduction

The Sun in White Light

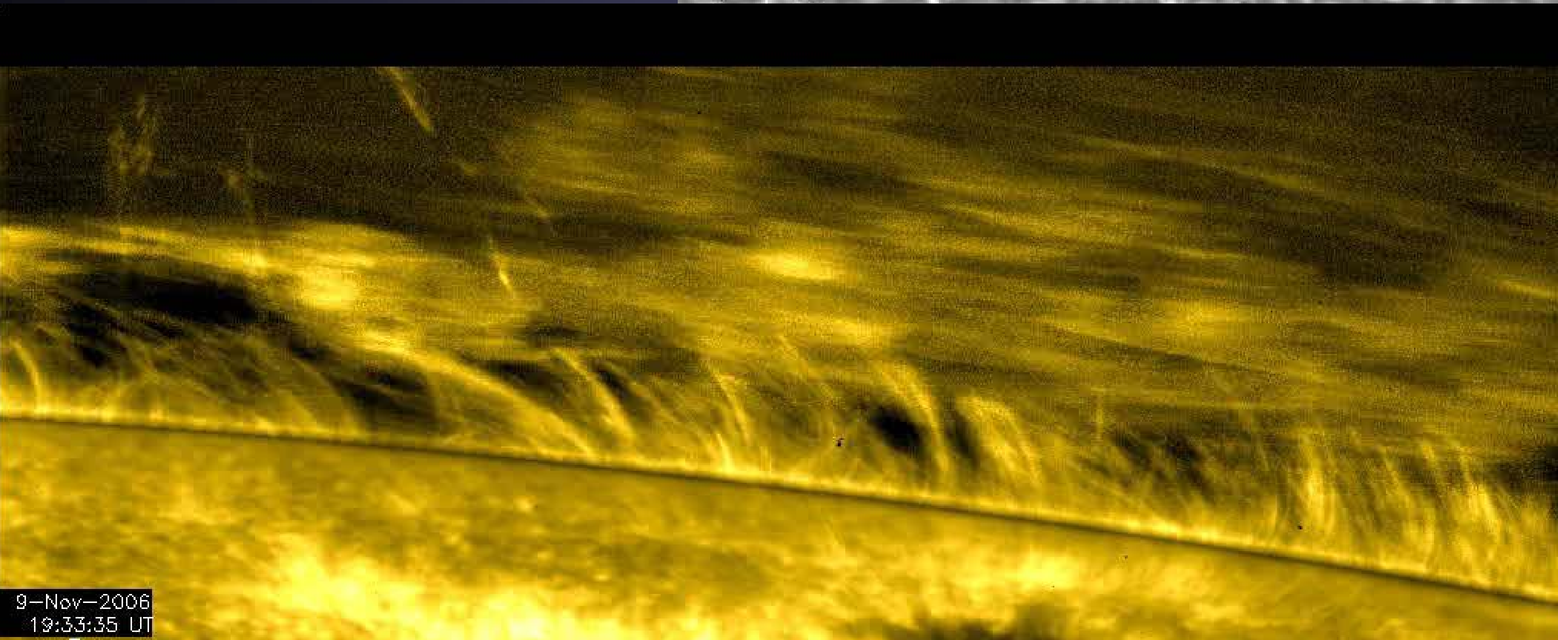
Gas at 5800 K



The Dynamic Sun

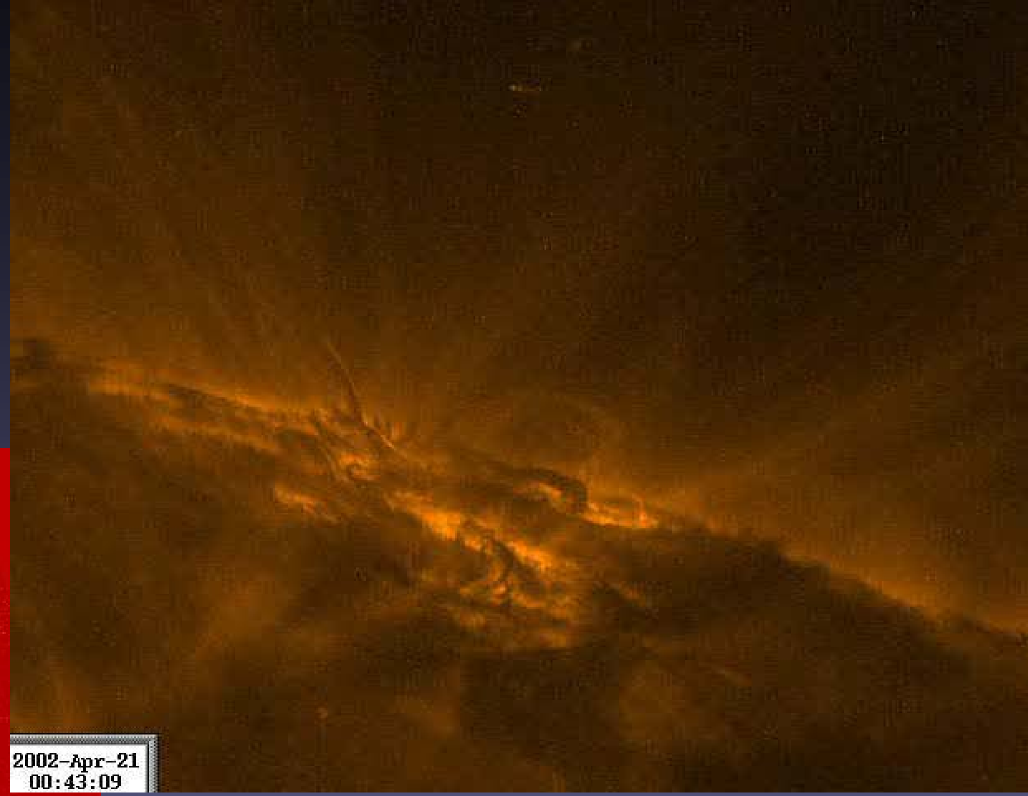


Prominence

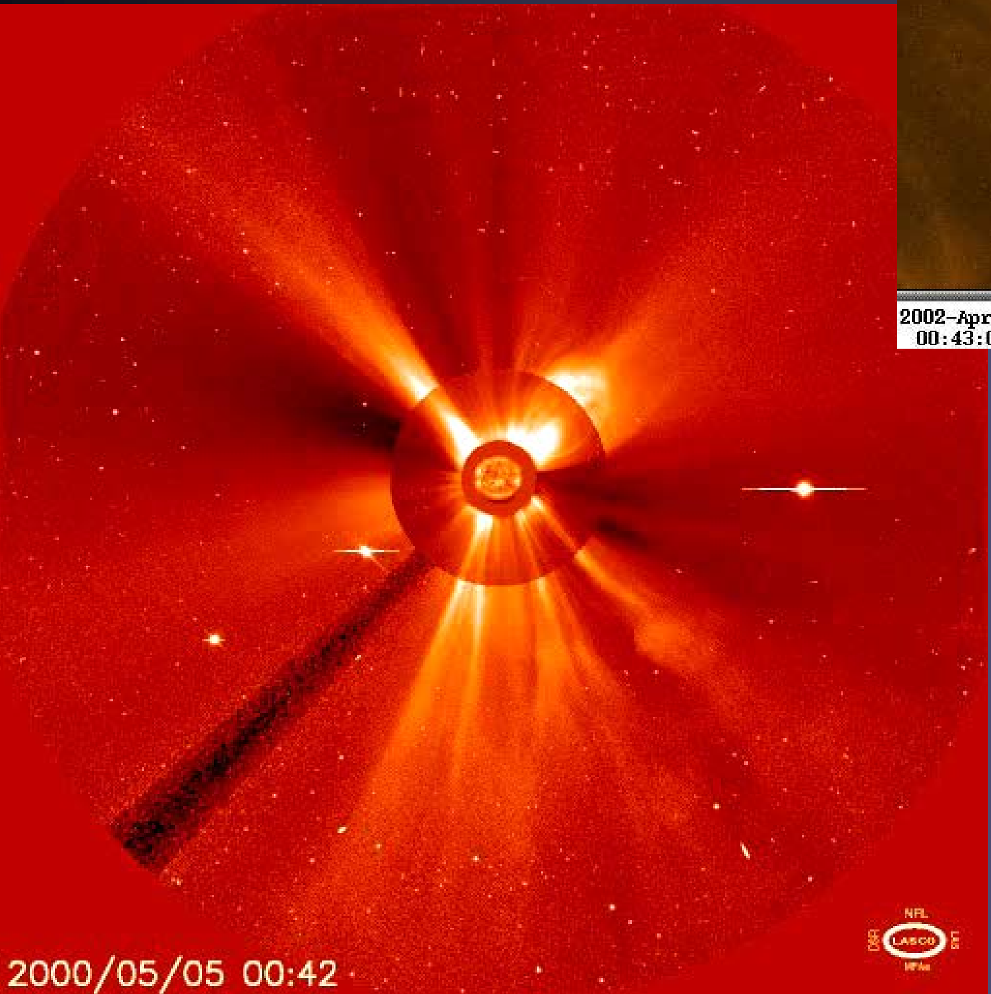


Sunspot

The Violent Sun

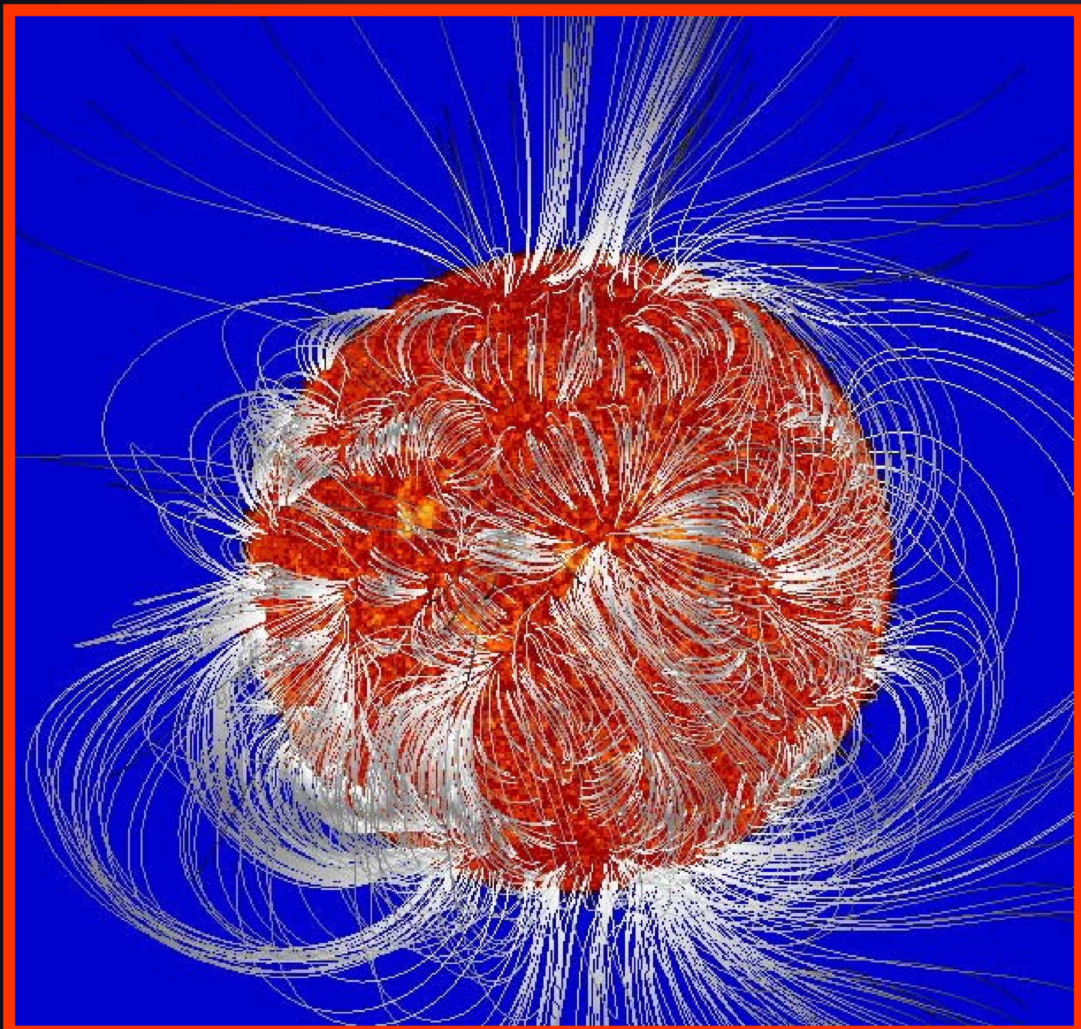


Flare



Solar wind and coronal mass ejections

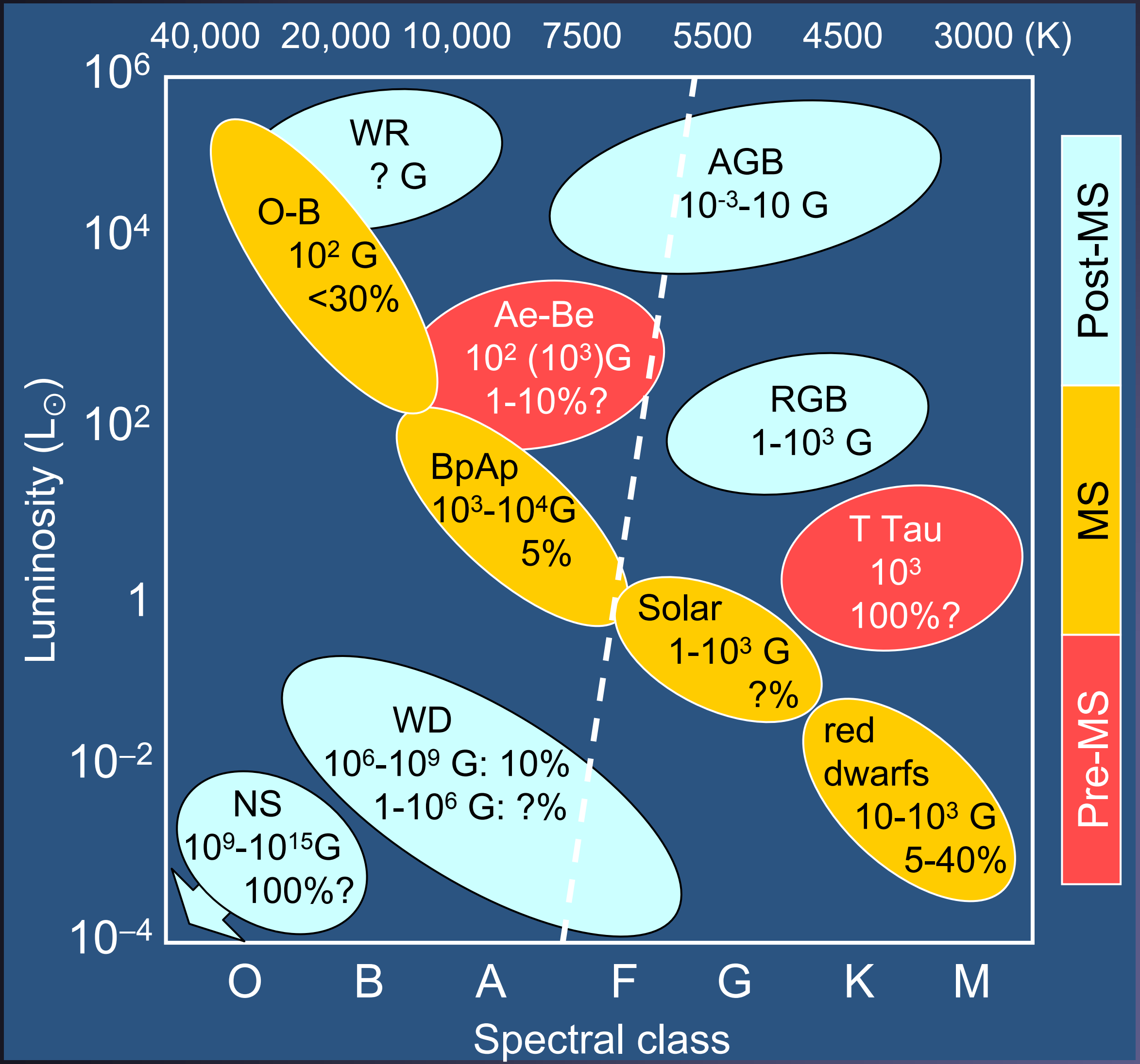
The source of the Sun's activity is the magnetic field



Wiegelmann 2004

➔ In order to understand the dynamics and activity of the Sun we need to know and understand the magnetic field

Stellar magnetic fields



Magnetic fields are found on stars throughout the HR-diagram

Often they produce activity on the star or influence its evolution (e.g. of stellar rotation)

Berdyugina 2008

Basics of polarimetry and the measurement of solar magnetic fields

Methods of solar magnetic field measurement

- Direct methods:
  - Zeeman effect → polarized radiation
  - Hanle effect → polarized radiation
  - Gyroresonance and Bremsstrahlung → polarized radiation (in radio range)
- Indirect methods: Proxies
  - Bright or dark features in photosphere (sunspots, G-band bright points)
  - Ca II H and K plage
  - Fibrils seen in chromospheric lines, e.g. Hα
  - Coronal loops seen in EUV or X-radiation

Atom in magnetic field

- Consider the Hamiltonian of an atom in a magnetic field (Gaussian cgs units; atom in L-S coupling)

$$H = -\frac{\hbar}{2m}\nabla^2 + V(r) + \xi(r)\mathbf{L}\cdot\mathbf{S} + \left(-\frac{e}{2mc}\mathbf{B}\cdot(\mathbf{L}+2\mathbf{S}) + \frac{e^2}{8mc^2}(Br\sin\theta)^2 \right)$$

- First 3 terms are kinetic energy, electronic potential, spin-orbit coupling with $\xi(r) = 1/(2m^2c^2r)(dV/dr)$
- Last two terms are magnetic energy terms derived from magnetic vector potential
- For fields up to B~10 MG (1 kT), magnetic terms are small compared to Coulomb potential. Fine structure and field treated by perturbation theory

Following J. Landstreet

Magnetic field regimes

$$H = -\frac{\hbar}{2m}\nabla^2 + V(r) + \xi(r)\mathbf{L}\cdot\mathbf{S} + \left(-\frac{e}{2mc}\mathbf{B}\cdot(\mathbf{L}+2\mathbf{S}) + \frac{e^2}{8mc^2}(Br\sin\theta)^2\right)$$

- Perturbation theory regimes:
  - Quadratic magnetic term << linear term << spin-orbit term: (linear) Zeeman effect
  - Quadratic magnetic term << spin-orbit term << linear term: Paschen-Back effect
  - Spin-orbit term << linear term << quadratic magnetic term: quadratic Zeeman effect

For Sun

- Schiff 1955, Quantum Mechanics, Chapts. 23 & 39

Following J. Landstreet

(Linear) Zeeman effect

- In weak-field (Zeeman) limit, atomic energy level is only slightly perturbed by $(e/2mc)\mathbf{B}\cdot(\mathbf{L}+2\,\mathbf{S})$
- In L-S coupling (light atoms), J and M_J are good quantum numbers. Magnetic moment of atom is aligned with $\mathbf{J}$. Energy shift of level is proportional to $\mathbf{B}\cdot\mathbf{J}$, so there are $2J+1$ different magnetic sublevels

$$E_i = E_{i\,0} + g_i\,(e\hbar/2mc)\,B\,M_J = E_{i\,0} + \mu_0\,g_i\,M_J\,B$$

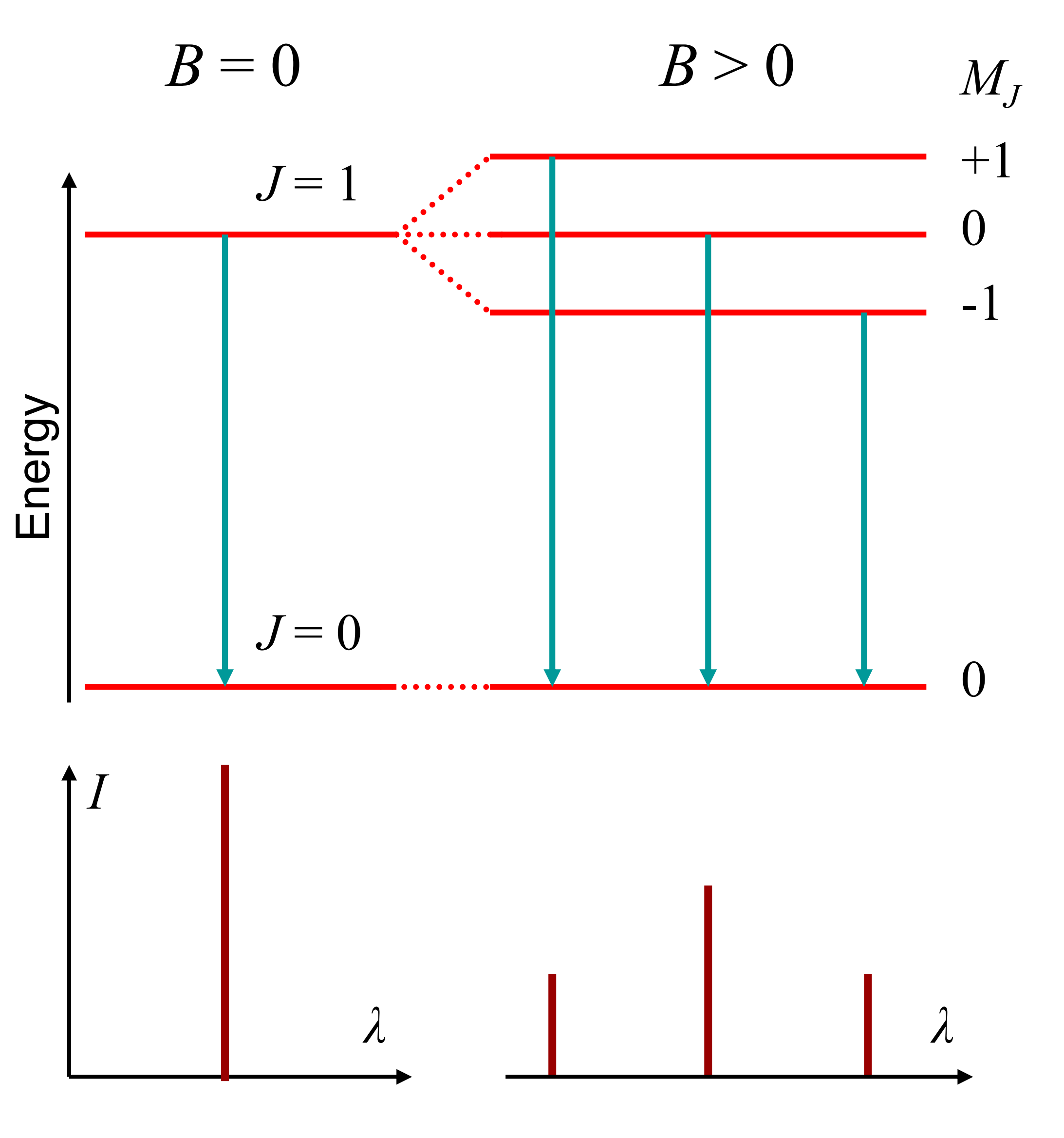
where

$$g_i = 1 + [\,J\,(\,J+1) + S\,(S+1) - L(\,L+1)]/\,[2\,J\,(\,J+1)\,]$$

is the (dimensionless) Landé factor (L-S coupling)

Zeeman splitting of atomic levels & lines

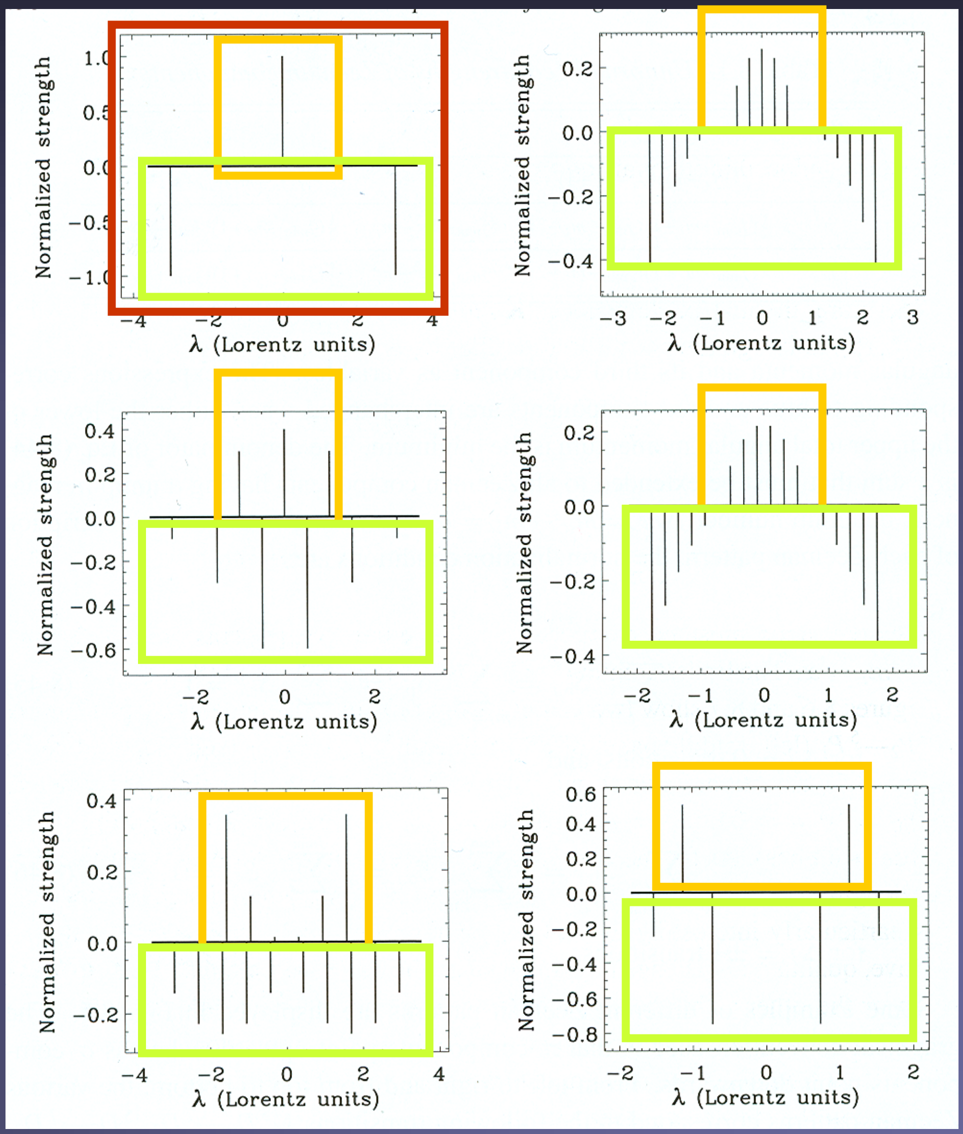
- Transitions between Zeeman split upper and lower atomic levels lead to spectral lines that are split in wavelength
- Transitions are allowed between levels with $\Delta J = 0, \pm 1$ & $\Delta M_J = 0\ (\pi), \pm 1\ (\sigma_b, \sigma_r)$ (for the most common types of transitions: electric dipole radiation)



Splitting patterns of lines

G. Mathys

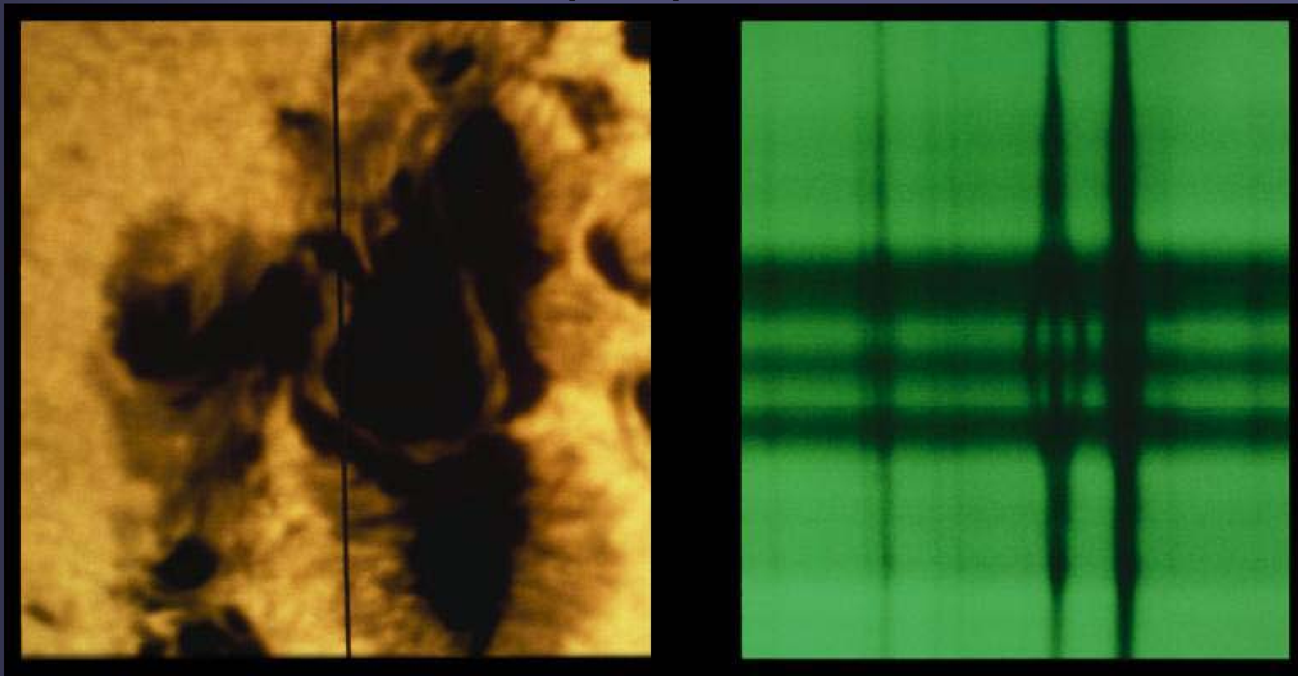
- Depending on g of the upper and lower levels, the spectral line shows different splitting patterns
- Positive: π components: $\Delta M_J = 0$
- Negative: σ components: $\Delta M_J = \pm 1$
- Top left: normal Zeeman effect (rare)
- Rest: anomalous Zeeman effect (usual)



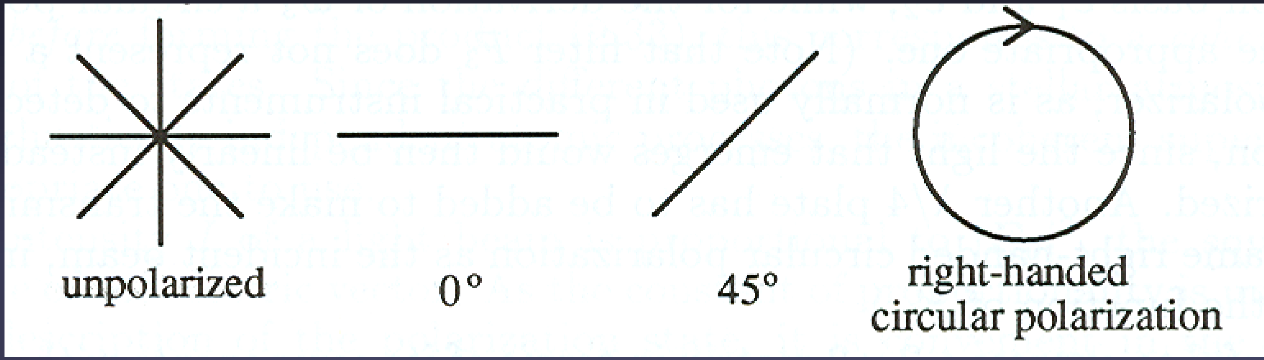
Zeeman effect observed

- First measurement of a cosmic magnetic field, in a sunspot, was carried out 1908 by G.E. Hale
- On Sun: Zeeman effect changes spectral shape of a spectral line (subtle in most lines outside sunspots)
- Zeeman effect also introduces a unique polarisation signature

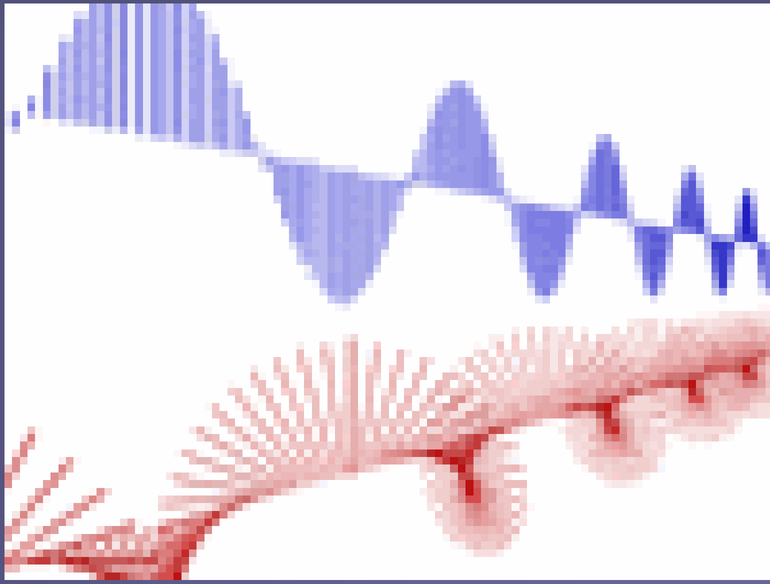
→ Measurement of polarization is central to measuring solar magnetic fields



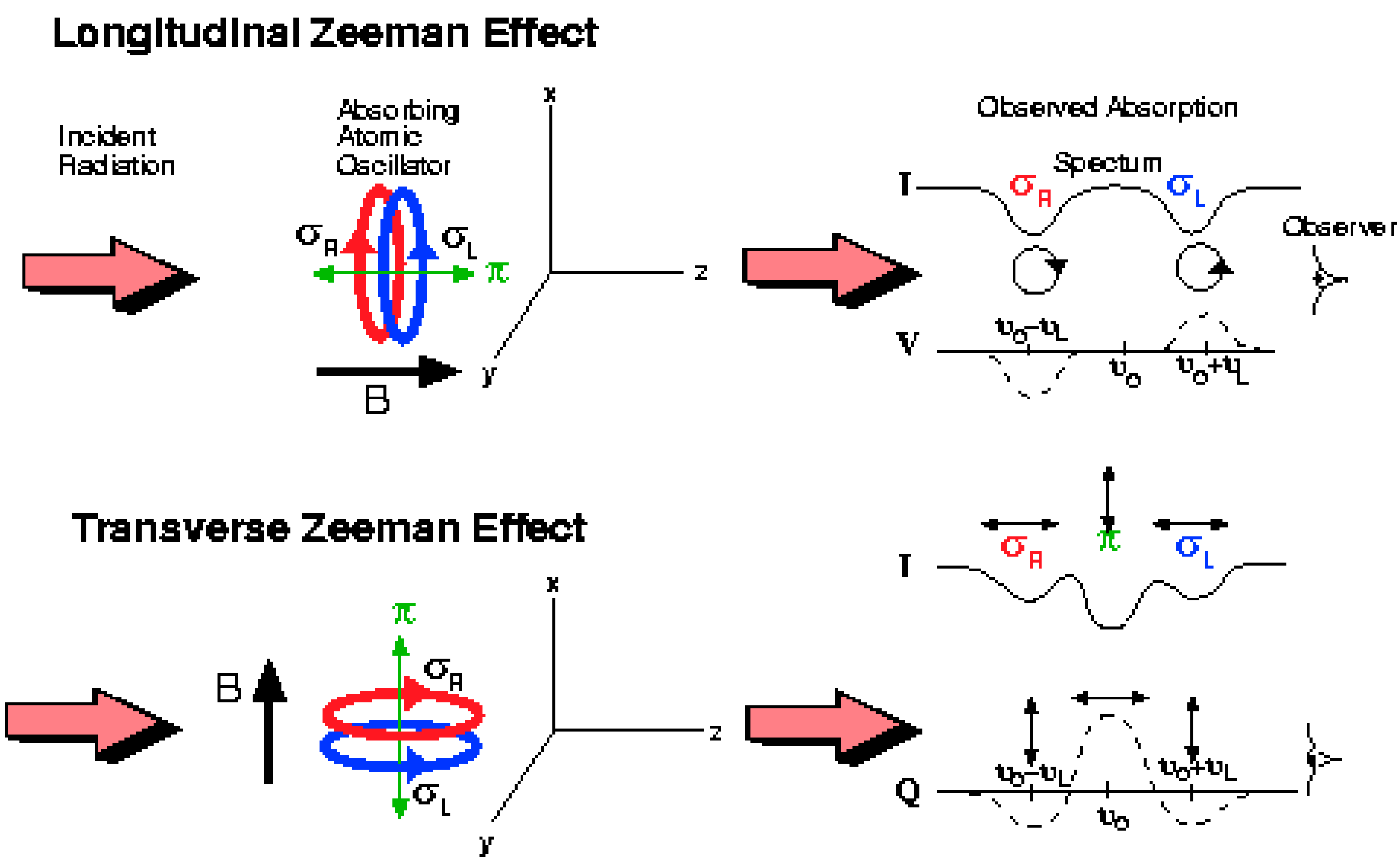
Polarized radiation



- Polarized radiation is described by the 4 Stokes parameters: I, Q, U and V
- I = total intensity $= I_{lin}(0^o) + I_{lin}(90^o) = I_{lin}(45^o) + I_{lin}(135^o) = I_{circ}(\text{right}) + I_{circ}(\text{left})$
- $Q = I_{lin}(0^o) - I_{lin}(90^o)$
- $U = I_{lin}(45^o) - I_{lin}(135^o)$
- $V = I_{circ}(\text{right}) - I_{circ}(\text{left})$
- Note: Stokes parameters are sums and differences of intensities, i.e. they are directly measurable

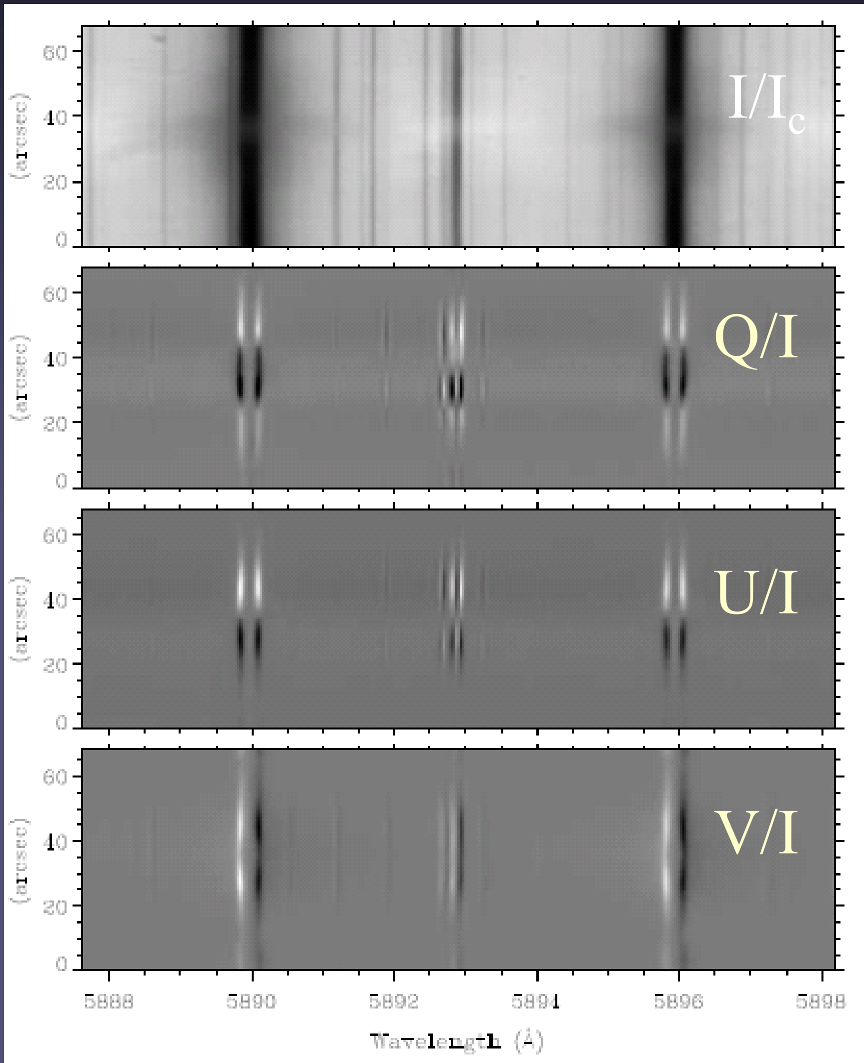


Polarization and Zeeman effect



Zeeman effect: information content

- Line splitting
  - Stokes $I \Rightarrow B$
- Line broadening
  - Stokes I : no info on $\mathbf{B}$
- Polarization
  - Stokes $V \Rightarrow <B_{long}>$
  - Stokes $Q, U, V \Rightarrow \mathbf{B}$
- Atomic diagnostics (hot gas)
  - Zeeman effect (except some Ap stars & WDs)
- Molecular diagnostics (cool)
  - Zeeman & Paschen Back



(ZIMPOL, J. Stenflo)

Effect of changing field strength

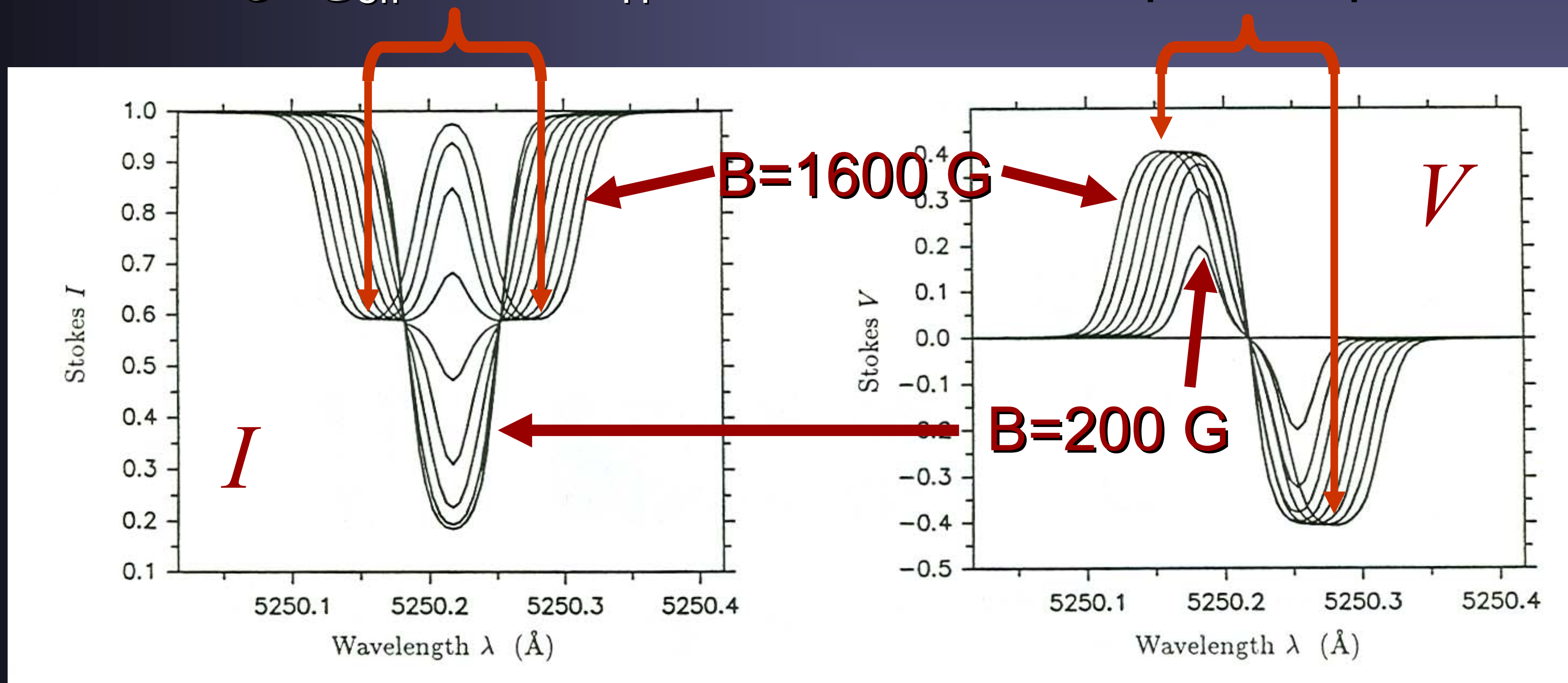
Formula for Zeeman splitting (for B in G, λ in Å):

$$\Delta\lambda_H = 4.67\ 10^{-13}\ g_{\text{eff}}\, B\, \lambda^2 \quad [\text{Å}]$$

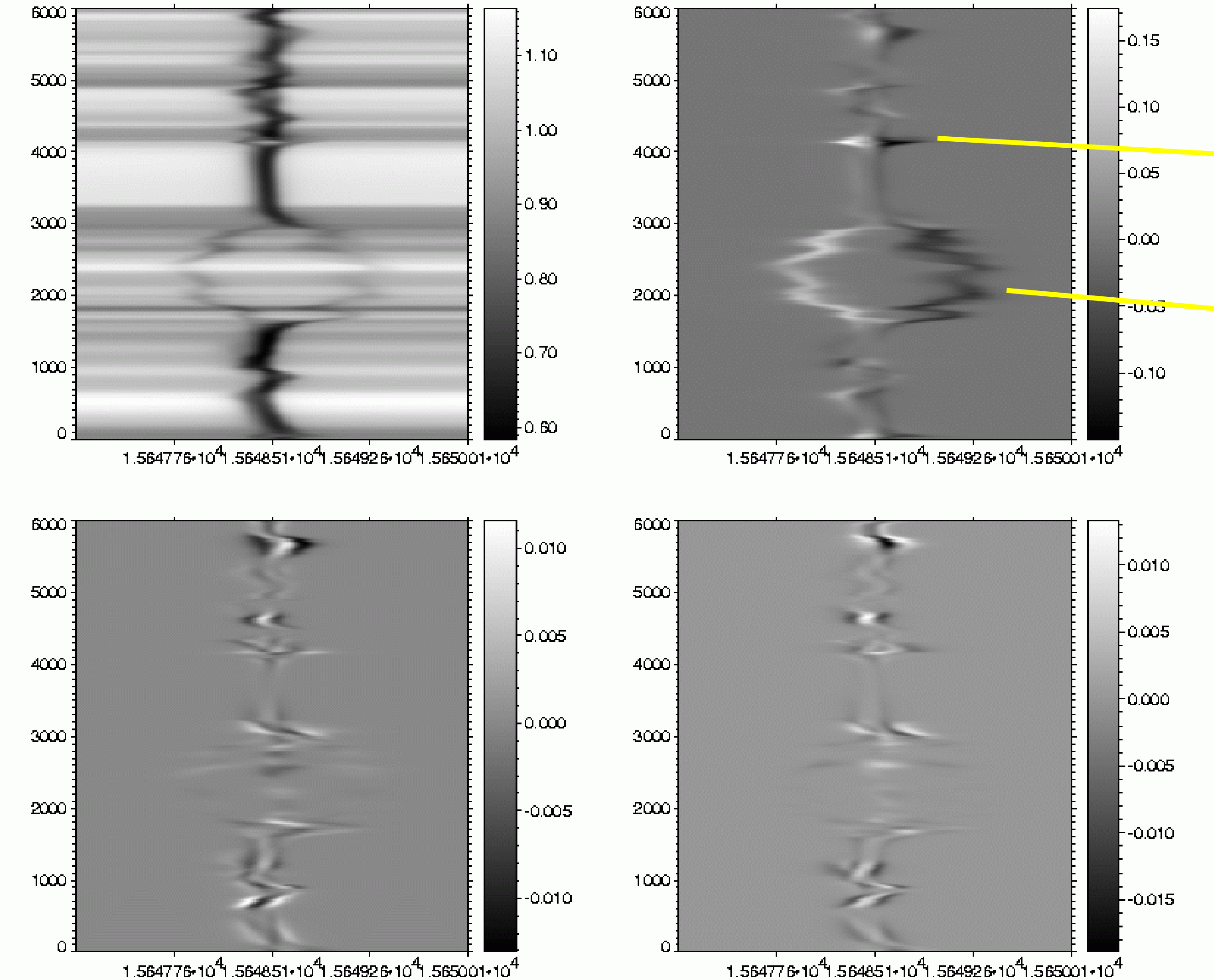
$$g_{\text{eff}} = \frac{1}{2}(g_l + g_u) + \frac{1}{4}(g_l + g_u)(J_l(J_l+1) - J_u(J_u+1))$$

g_{eff} is the effective Landé factor of line

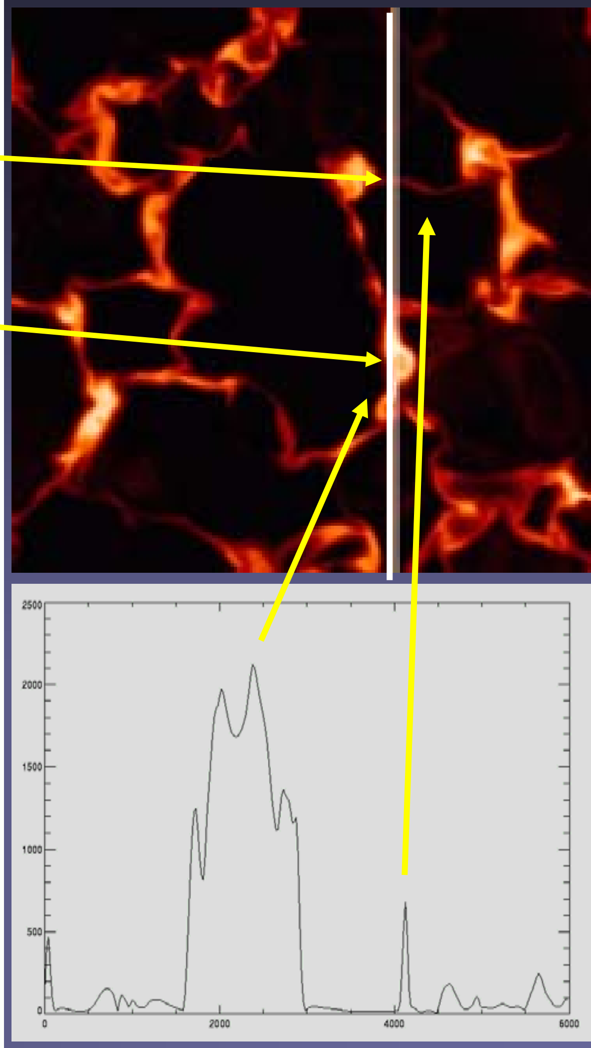
For large $g_{\text{eff}} B\lambda^2$: $\Delta\lambda_H = \Delta\lambda$ betw. σ-component peaks



Zeeman splitting ~ λ^2

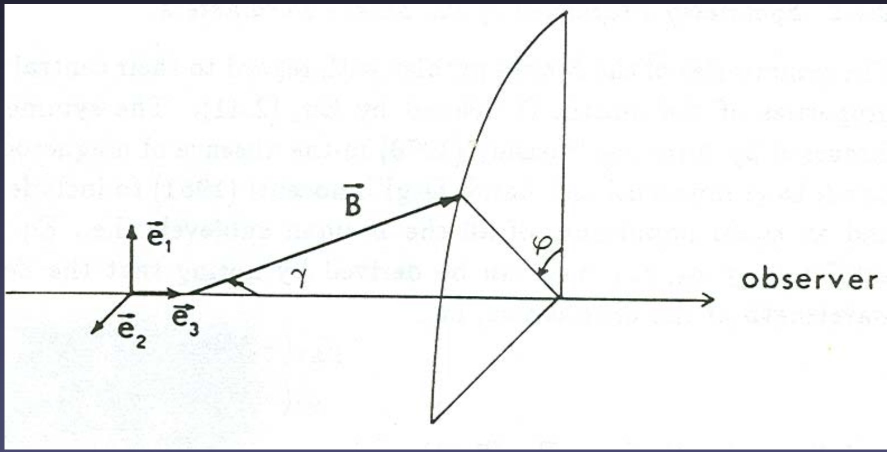


Fe I 1564.8nm



Dependence on B, γ, and φ

- $I \sim \kappa_\sigma (1+\cos^2\gamma)/4 + \kappa_\pi \sin^2\gamma/2$
- $Q \sim B^2 \sin^2\gamma \cos 2\varphi$
- $U \sim B^2 \sin^2\gamma \sin 2\varphi$
- $V \sim B \cos \gamma$

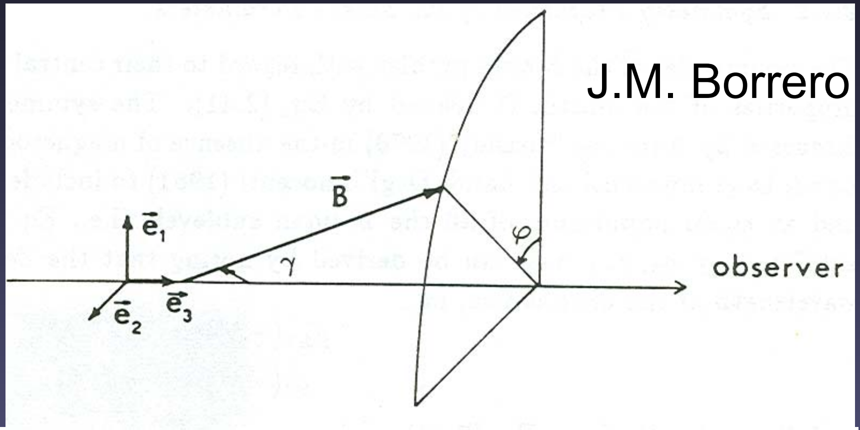


J.M. Borrero

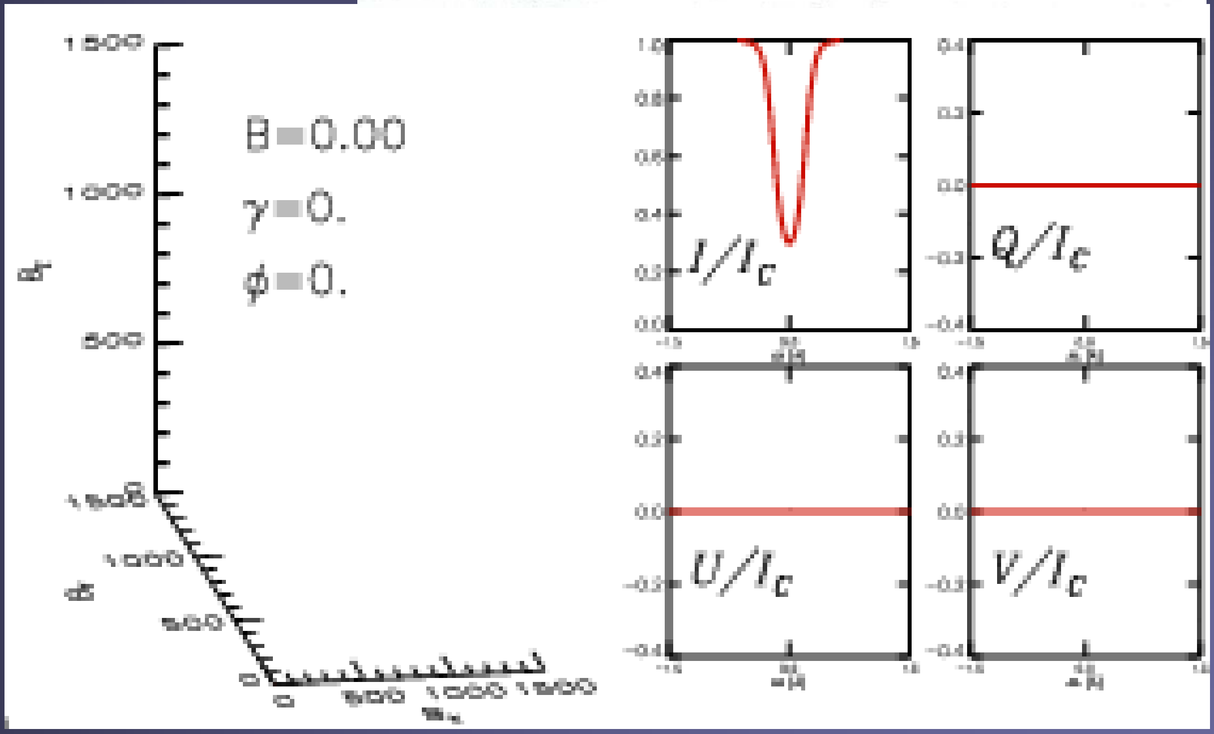
- V: longitudinal component of B
- Q, U: transverse component of B
- Above formulae for Q,U,V refer to relatively weak fields (e.g. B and B^2 dependence of field)
- Zeeman splitting etc. is hidden in κ_σ and κ_π. For Q, U, V these dependences have not been given for simplicity.

Dependence on B, γ, and φ

- $I \sim \kappa_\sigma(1+\cos^2\gamma)/4 + \kappa_\pi \sin^2\gamma/2$
- $Q \sim B^2 \sin^2\gamma \cos 2\varphi$
- $U \sim B^2 \sin^2\gamma \sin 2\varphi$
- $V \sim B \cos \gamma$

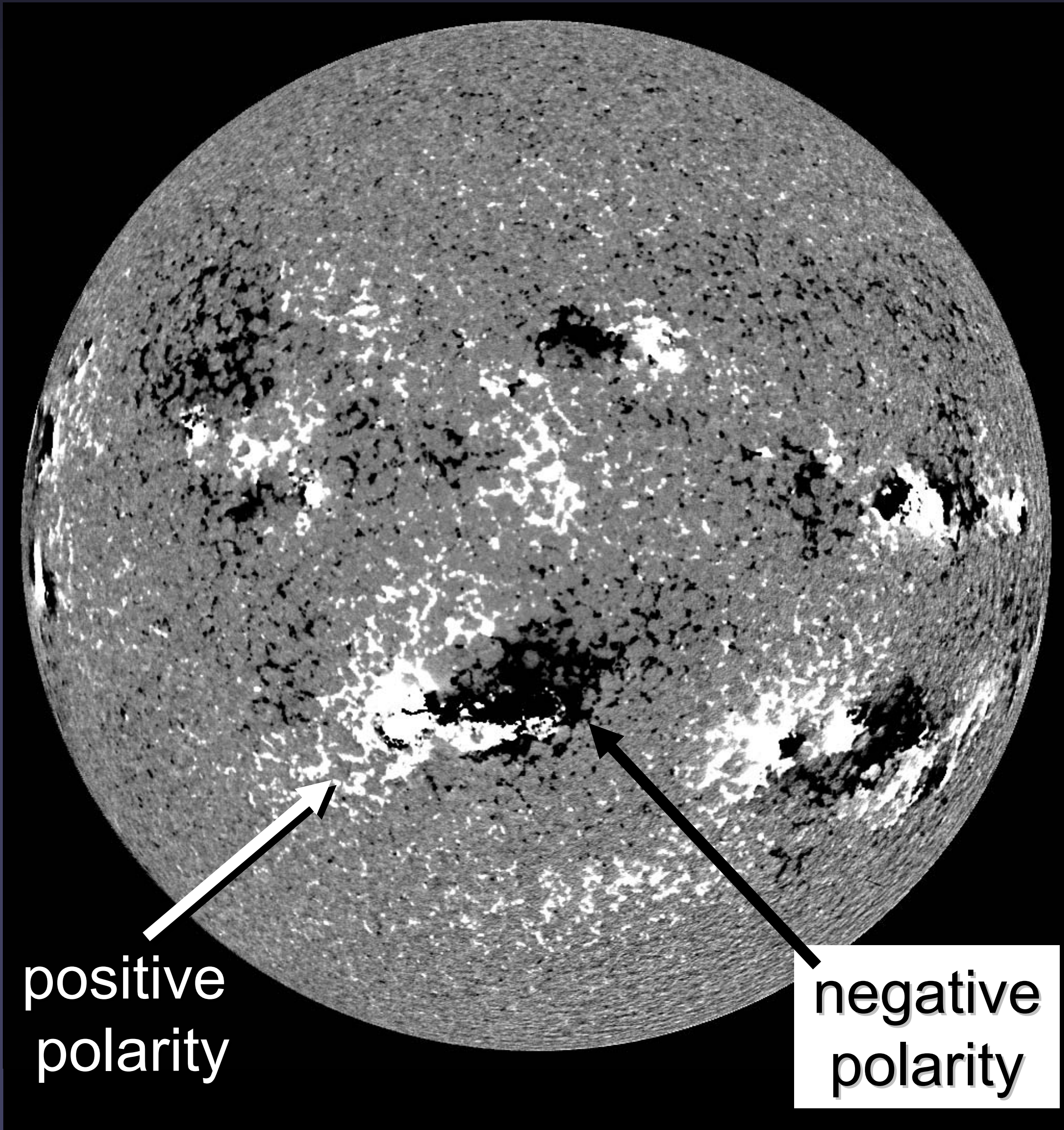


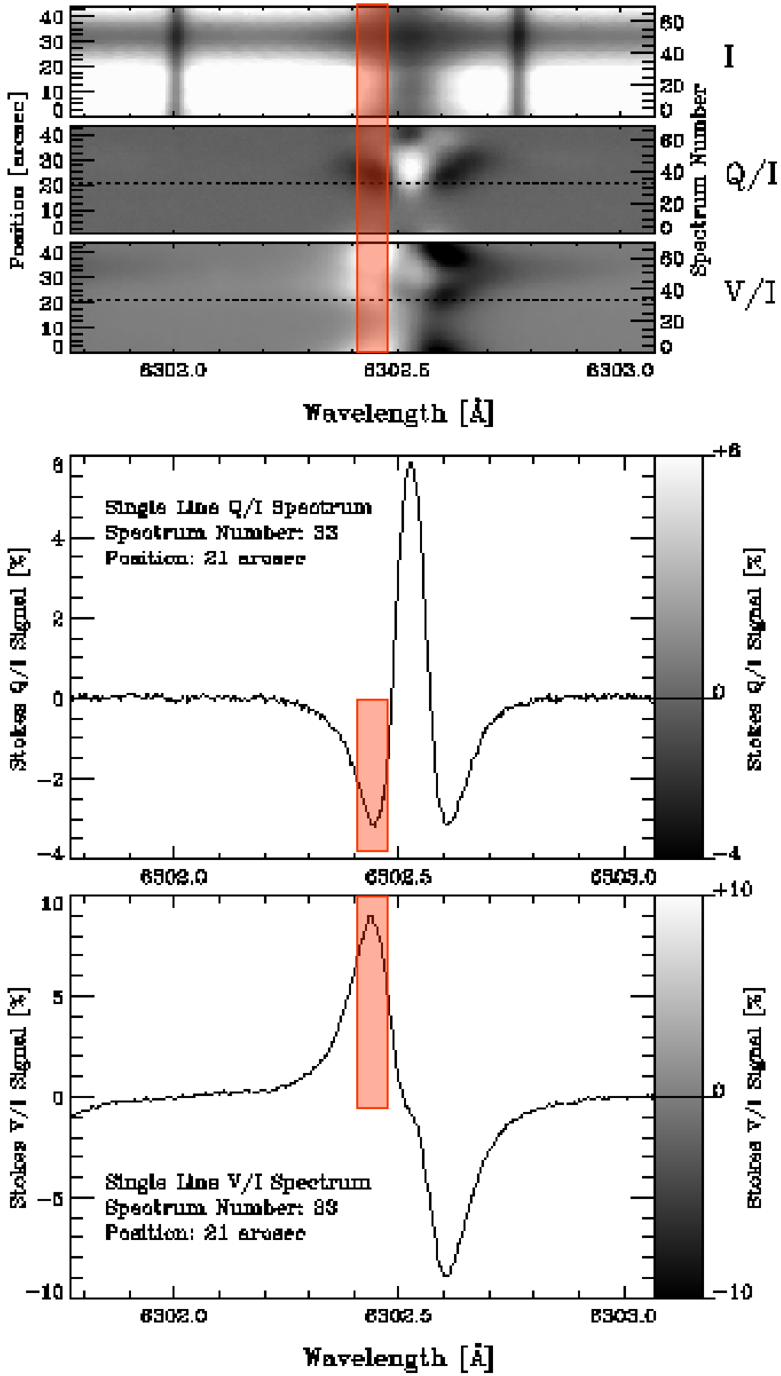
- Q, U: transverse component of B
- V: longitudinal component of B
- Formulae for Q,U,V refer to weak fields
- κ_σ and κ_π (splitting etc.) not given for Q,U,V for simplicity



Magnetograms

- Magnetograph: Instrument to make maps of (net circular) polarization in wing of Zeeman sensitive line
- Useful when star can be resolved, e.g. Sun
- Image: Example of magnetogram obtained by MDI
- Conversion of polarization into magnetic field requires a careful calibration.

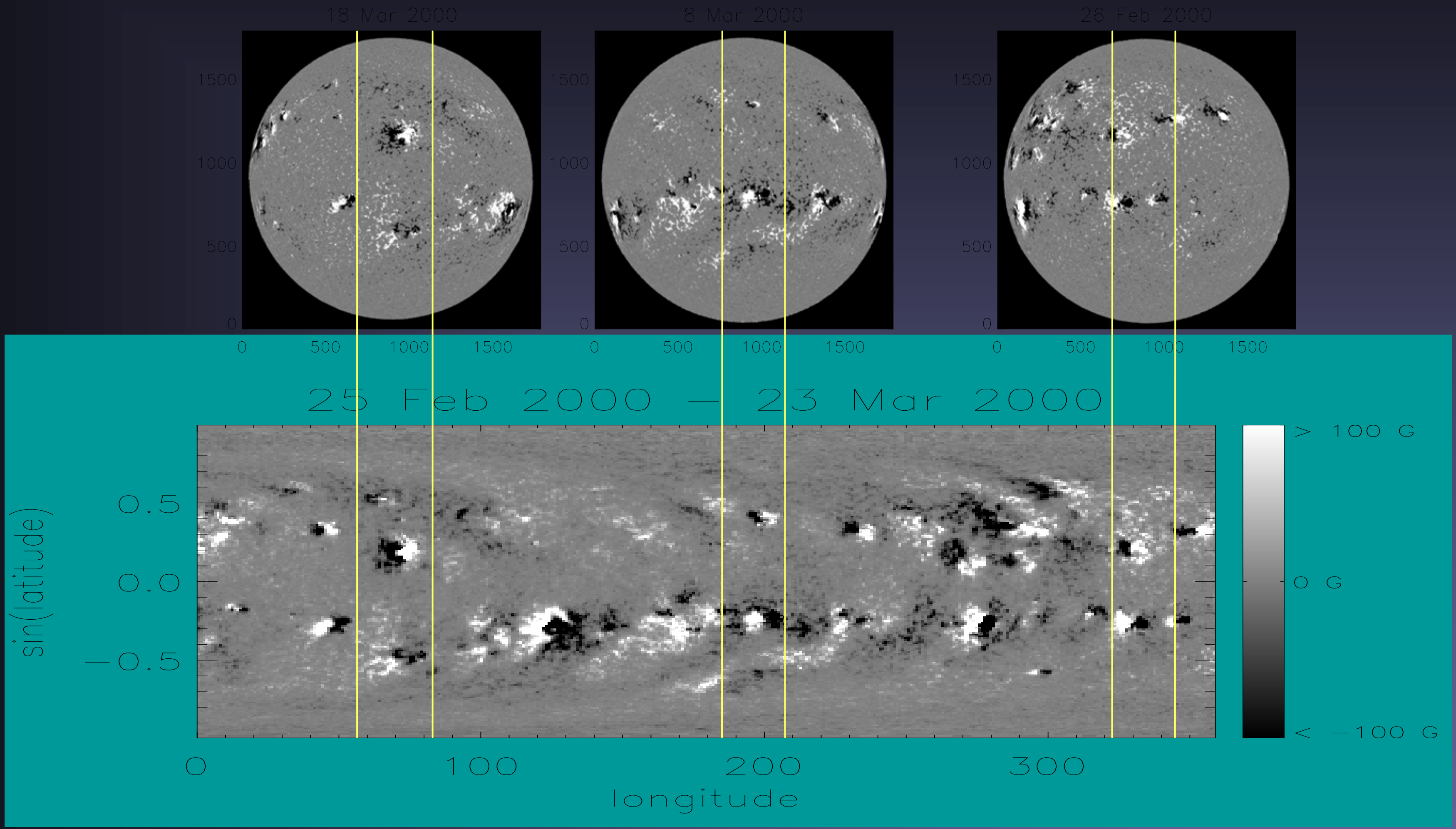




What does a magnetogram show?

- Plotted at left:
  - Top: Stokes *I*, *Q* and *V* along a spectrograph slit
  - Middle: Sample Stokes *Q* profile
  - Bottom: Sample Stokes *V* profile
  - Red bars: example of a spectral range used to make a magnetogram. Often only Stokes *V* is used (simplest to measure), gives longitudinal component of *B*.

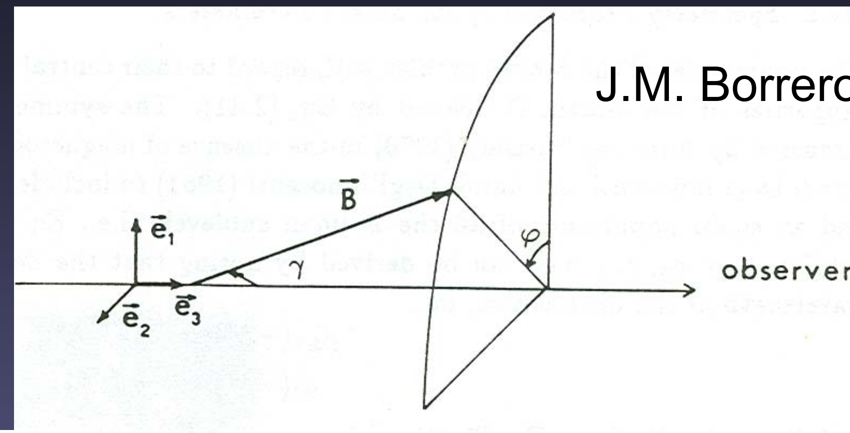
Synoptic charts



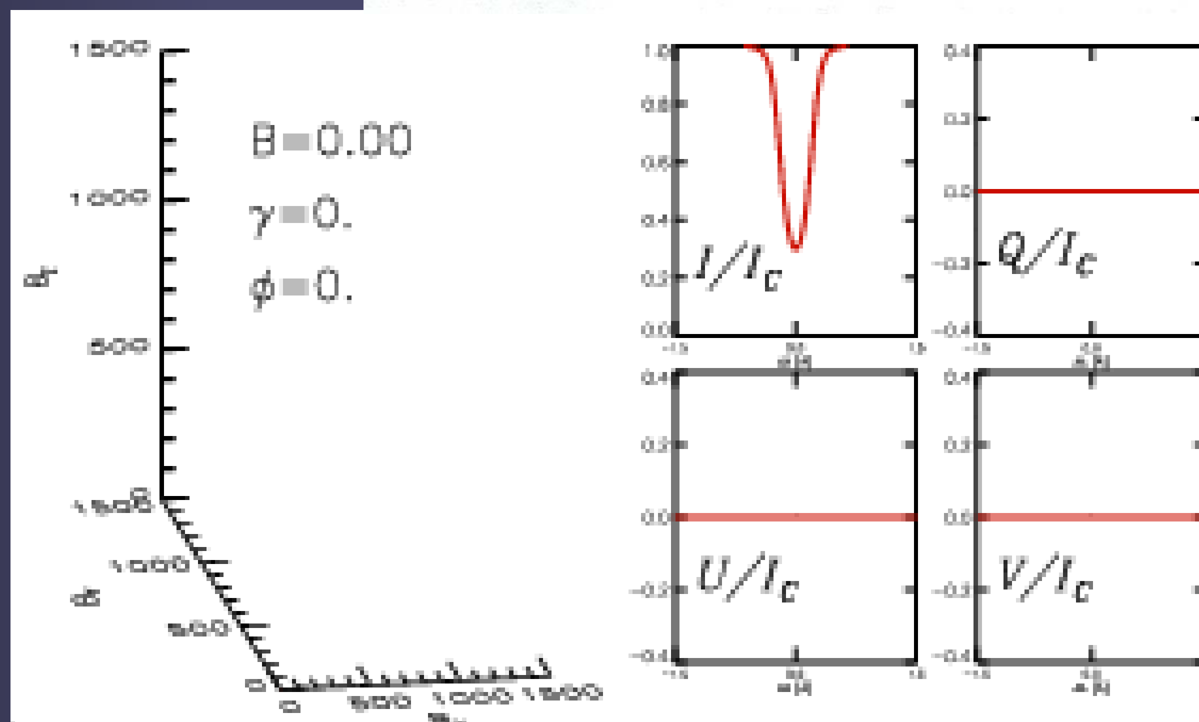
Synoptic maps approximate the radial magnetic flux observed near the central meridian over a period of 27.27 days (= 1 Carrington rotation)

Dependence on B, γ, and φ

- $I \sim \kappa_\sigma(1+\cos^2\gamma)/4 + \kappa_\pi \sin^2\gamma/2$
- $Q \sim B^2 \sin^2\gamma \cos 2\varphi$
- $U \sim B^2 \sin^2\gamma \sin 2\varphi$
- $V \sim B \cos\gamma$



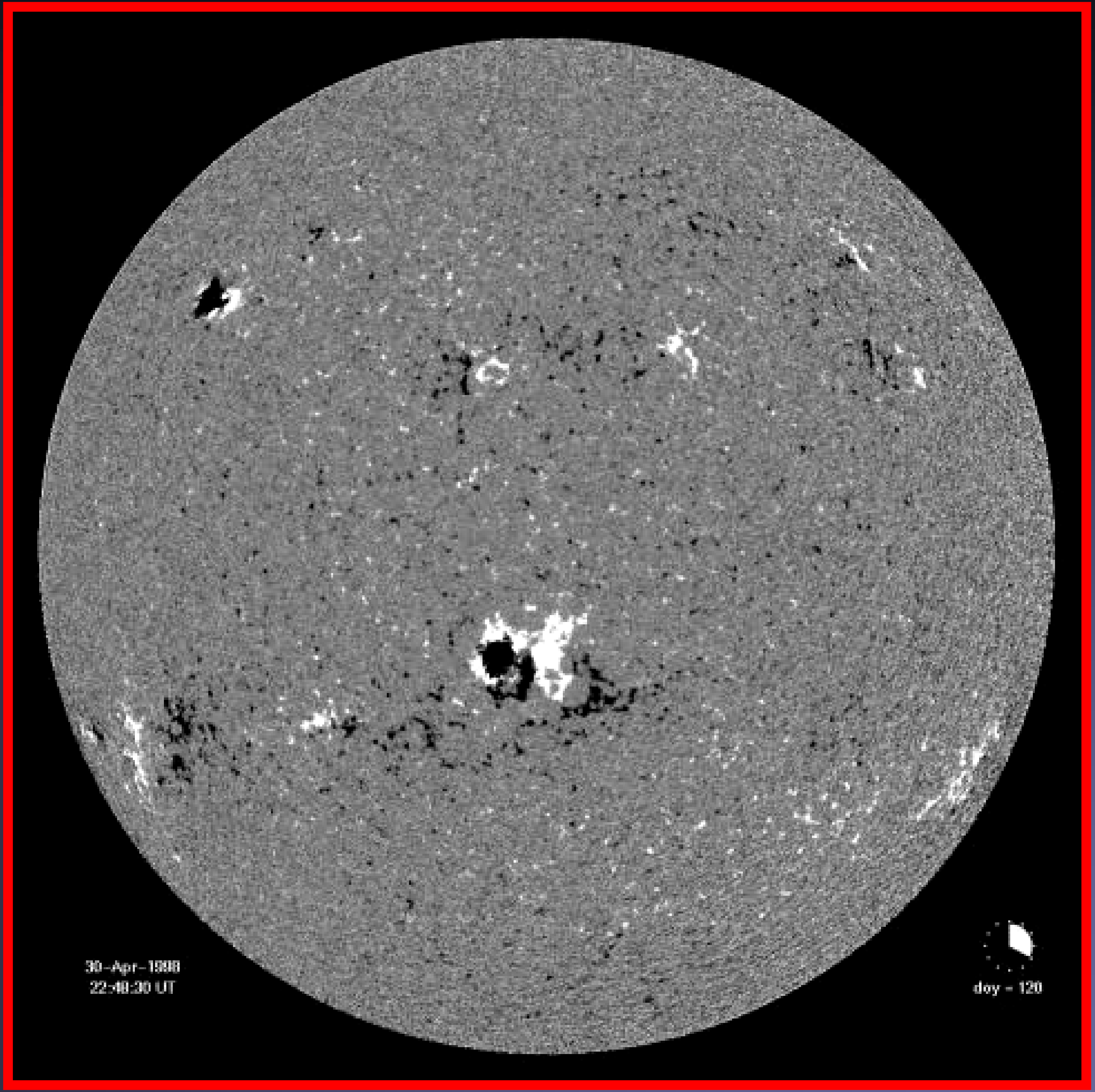
- Q, U: transverse component of B
- V: longitudinal component of B
- Formulae for Q, U, V refer to weak fields
- κ_σ and κ_π (splitting etc.) not given for Q, U, V for simplicity



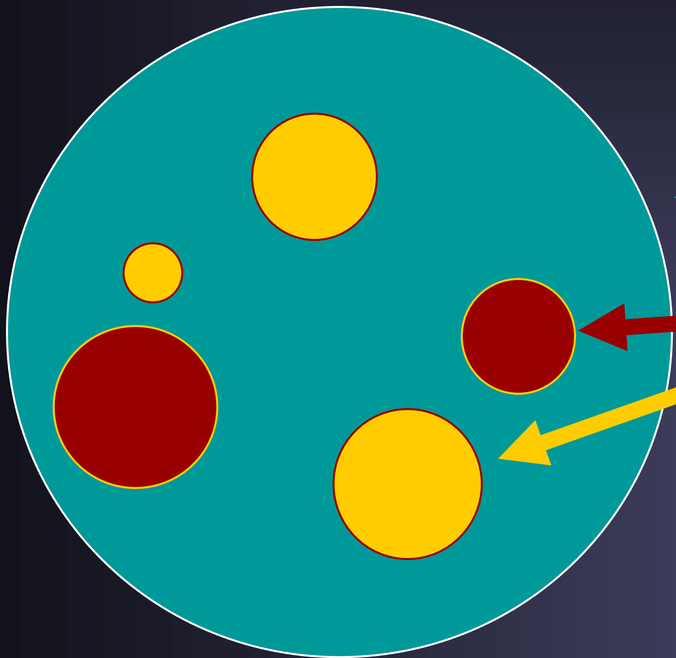
Measured Magnetic Field at Sun’s Surface

Month long sequence of magnetograms (approx. one solar rotation)

MDI/SOHO
May 1998



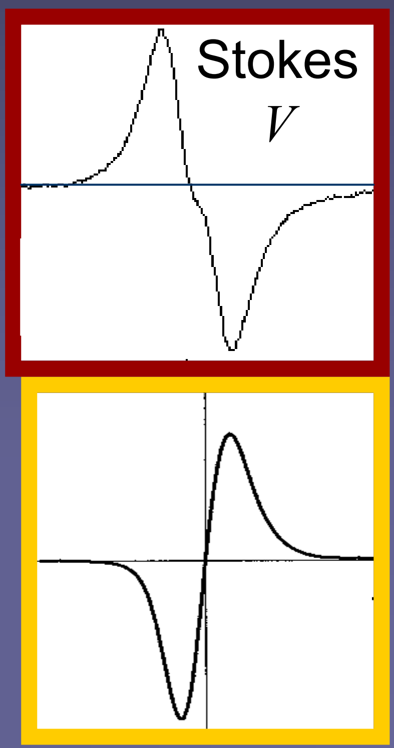
Cancellation of magnetic polarity

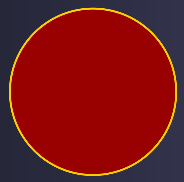


Spatial resolution element

Unresolved magnetic features with field strength B and filling factor

$$f = \sum_i A_i / A_{\mathrm{tot}}$$





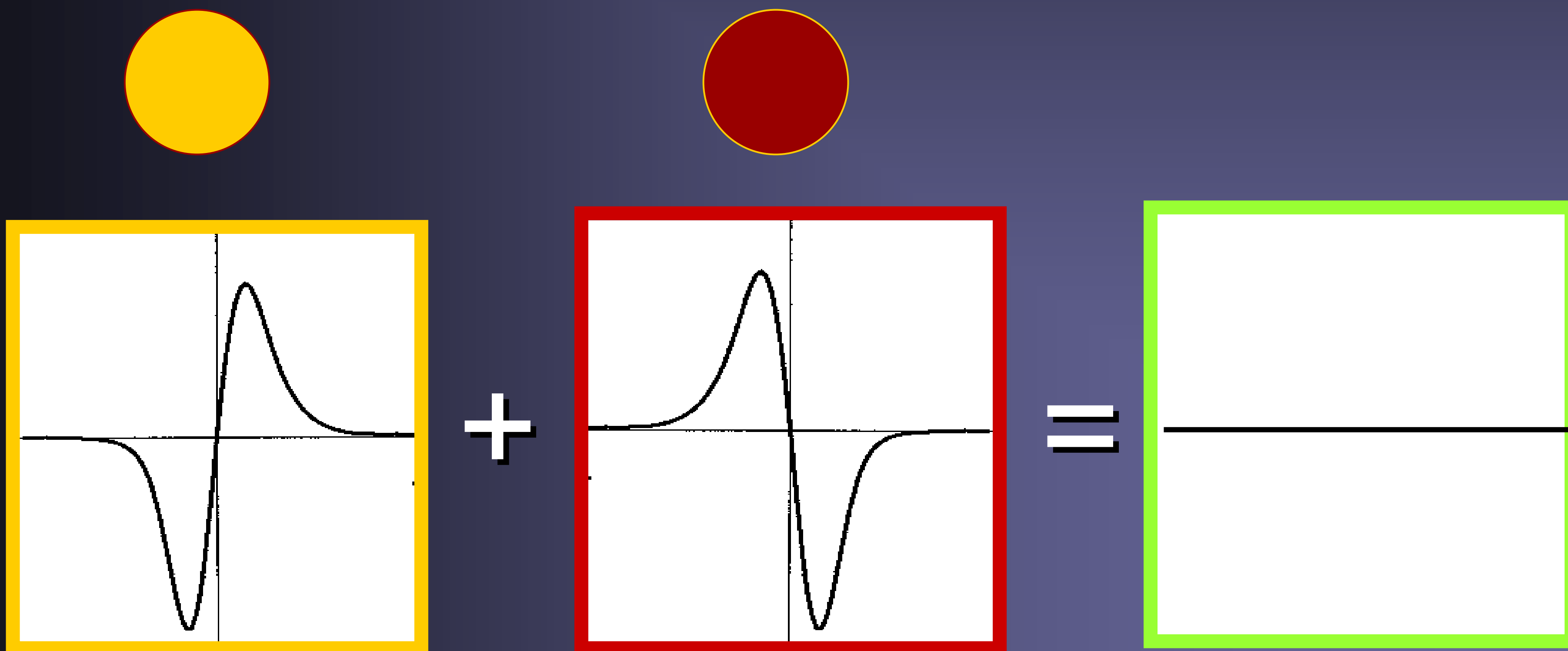
= positive polarity magnetic field

= negative polarity magnetic field

Stokes *V* signal cancellation

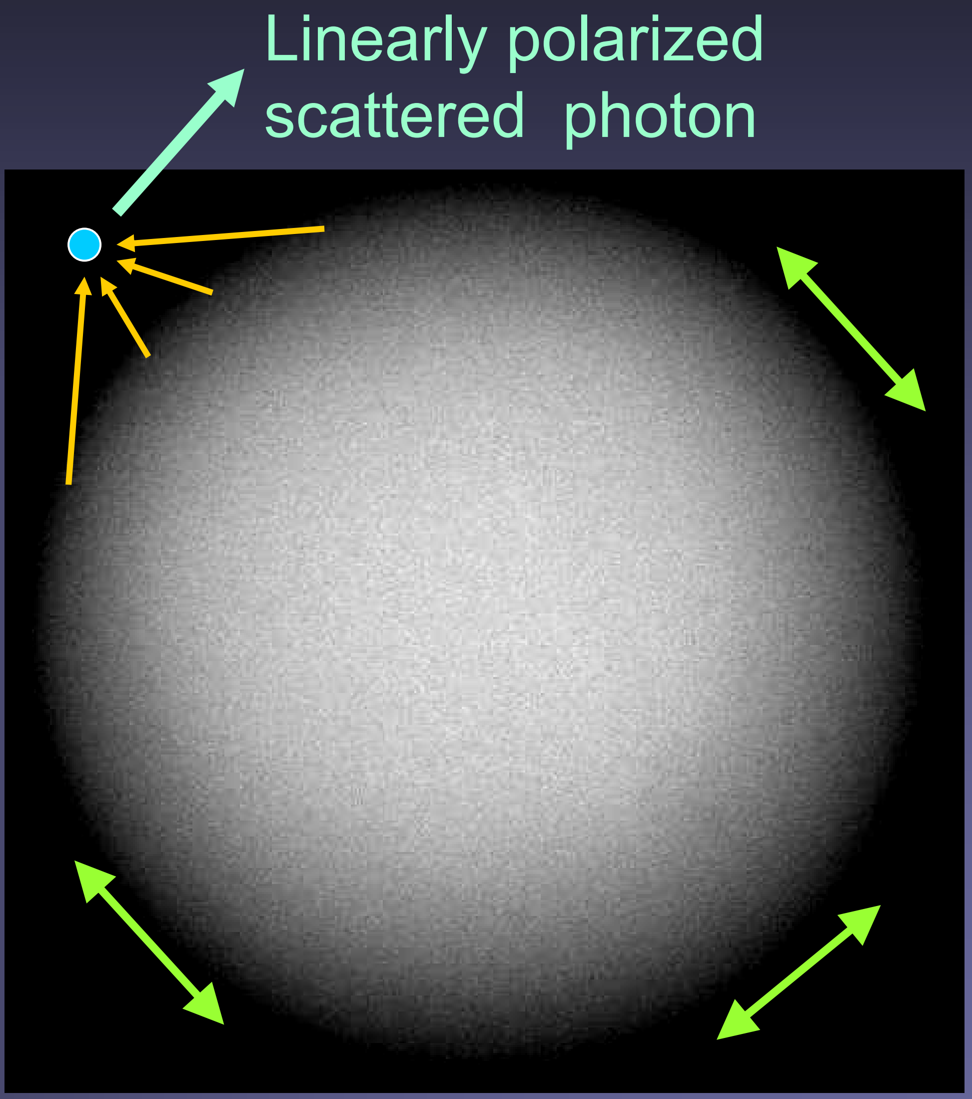
Stokes V signal only samples the net magnetic flux.
Extreme case:

negative polarity magnetic flux = positive polarity magnetic flux



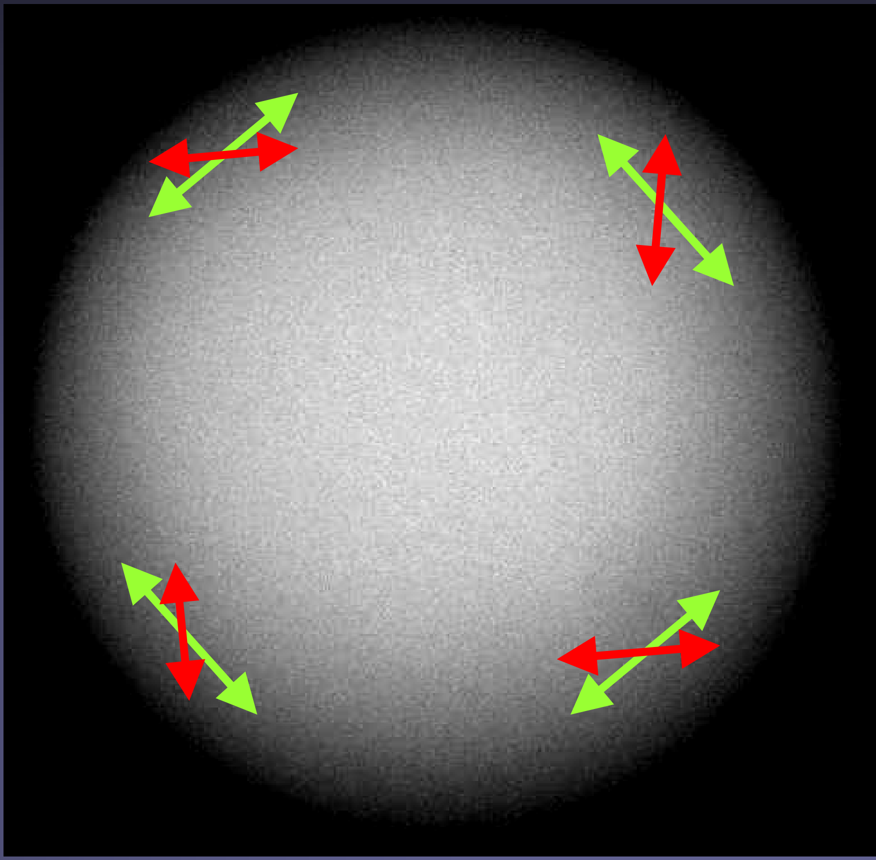
Scattering polarisation at Sun's limb

- If collisions are rare, light is scattered
- Illumination of atoms is anisotropic due to:
  - Limb darkening ($dT/dz < 0$, where T = temp.)
  - atom high in atmosph.
- Scattering + anisotropy → linear polarisation parallel to limb



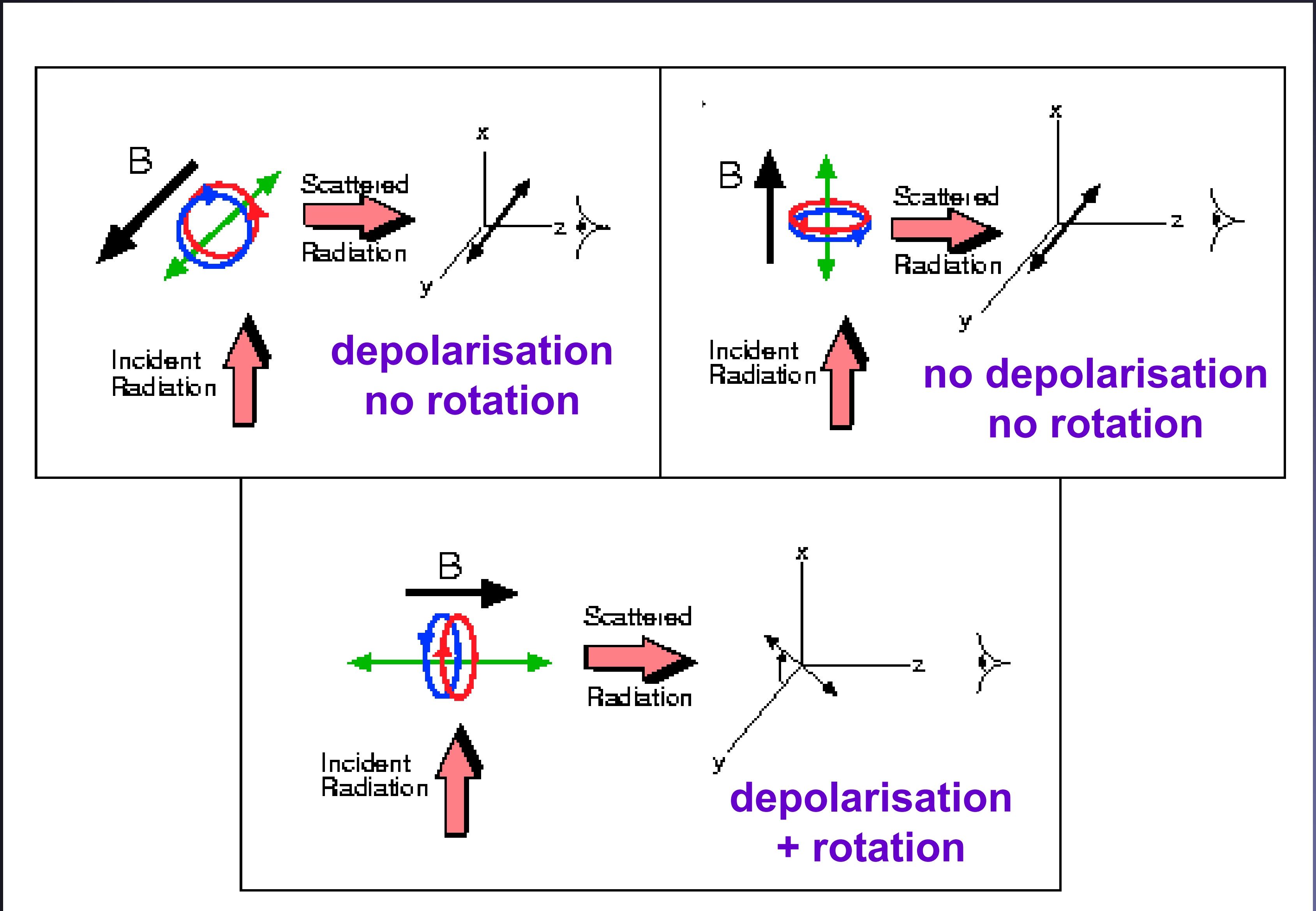
Hanle effect

- Hanle effect: Modification of scattering polarisation by magnetic field. 2 effects:
- Depolarisation
  - depends on field orientation
  - depends on B (it is complete if $\Delta\lambda_H$ >> natural line width, i.e. for $B > 0.1\text{-}100$ G)
  - also present for unresolved mixed polarity fields
- Rotation of polarisation plane
  - depends on B, γ, χ
  - only if field is spatially resolved



Signature of Hanle effect for spatially resolved field

Hanle diagnostics: simple examples



Example of Hanle rotation & depolarisation

- More complex to describe Hanle than Zeeman effect
- Hanle parameters:
  - Depolarization factor p/p_{max} where p is polarization degree for $B \neq 0$, p_{max} is p for $B=0$
  - Angle of rotation β, with $\tan 2\beta = U/Q$ ($\beta=0$ for $B=0$)
- Atmospheric parameters
  - Field strength parameter Ω, with $\Omega = 2 g_u \omega_L / \gamma_N \sim B$, where γ_N is natural damping constant, ω_L is Larmor frequency, g_u is Landé factor of upper level,

$$\gamma_N = \frac{\mu_0 e^2 \omega^2}{6\pi\, m_e c} \qquad \omega_L = \frac{e}{2m_e} B$$

  - Field azimuth χ, with $\chi=0$ for $B \parallel$ LOS

Hanle effect example (contd.)

- Hanle depolarisation in general changes between $0.2B_0$ and $5B_0$

$$B_0 = \frac{2m\gamma_N}{eg_u}$$

- Expression for B_0 is equivalent to saying that for $B=B_0$ we have $\omega_L = \gamma_N$

Stenflo 1994

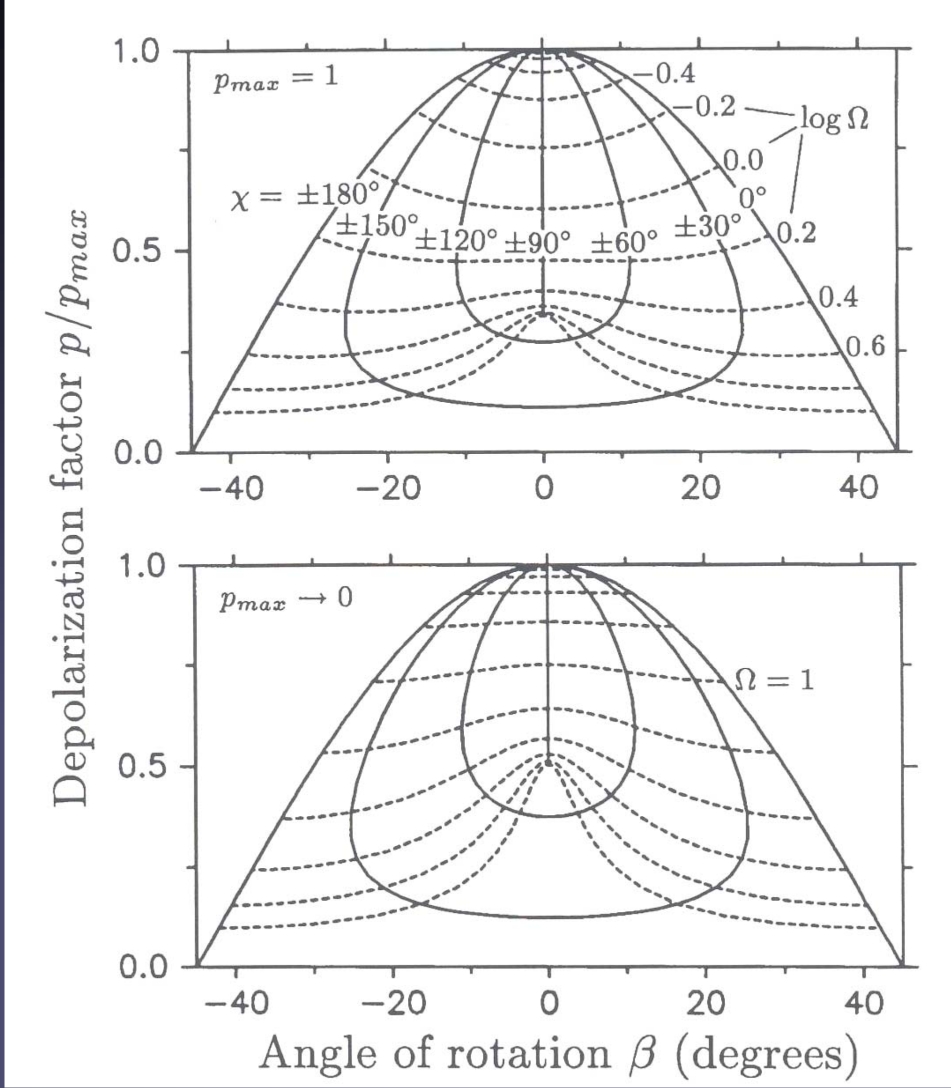


Illustration for horizontal field seen exactly at limb, scattering radiation coming exactly from below