Magnetic fields in the upper solar atmosphere

Methods of determining the magnetic field above the solar photosphere

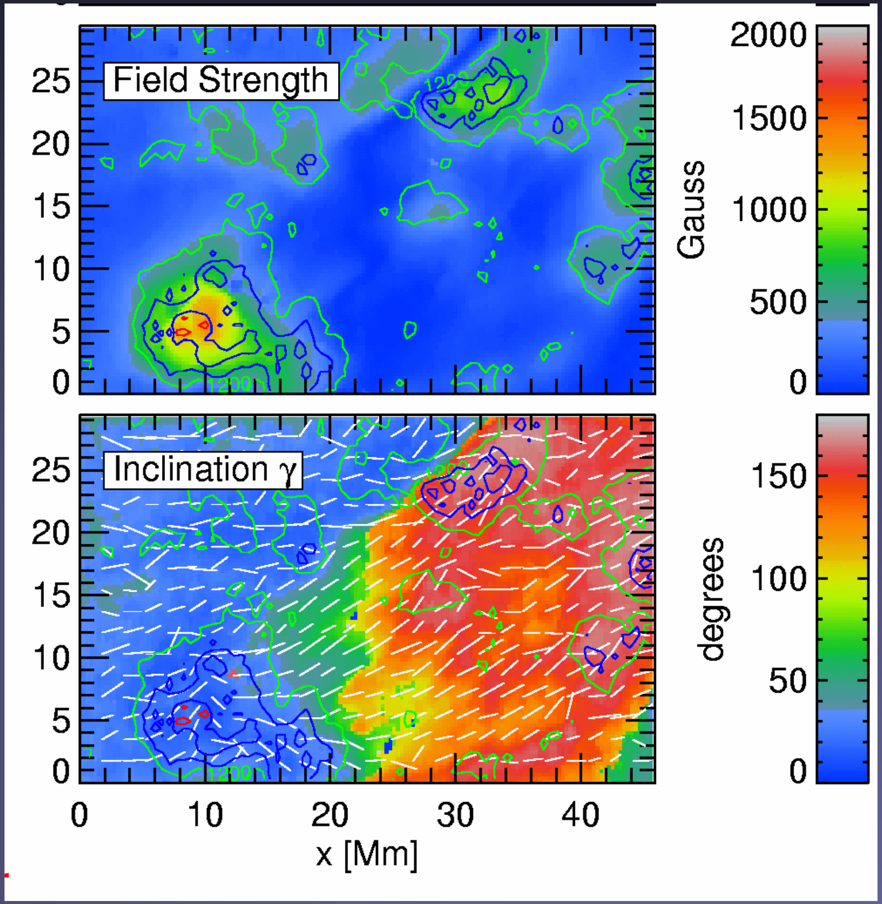
- Zeeman effect in chromospheric or coronal spectral lines (visible and IR)
- Hanle effect in chromospheric or coronal spectral lines (VUV, NUV, visible, IR)
- Gyroresonance emission at radio wavelengths
- Free-free emission at radio wavelengths
- Faraday rotation at radio wavelengths
- Coronal loop oscillations (EUV)
- In situ measurements in the heliosphere
- Extrapolation from photospheric magnetograms using potential or force-free fields

Problems with coronal field measurements

- In spite of this richness of techniques we know far less about the field in the corona than in the photosphere, where we can only employ 2 techniques
- Reasons:
  - Field in corona is much weaker than in photosphere: typically a few 10 G vs. 1000 G
  - S/N is much lower in corona than in photosphere (factor of $>10^3$)
  - corona is optically thin (for most techniques):
    - field can cancel even along line of sight!
    - we do not know where we are sampling the field

Zeeman effect: B near base of corona

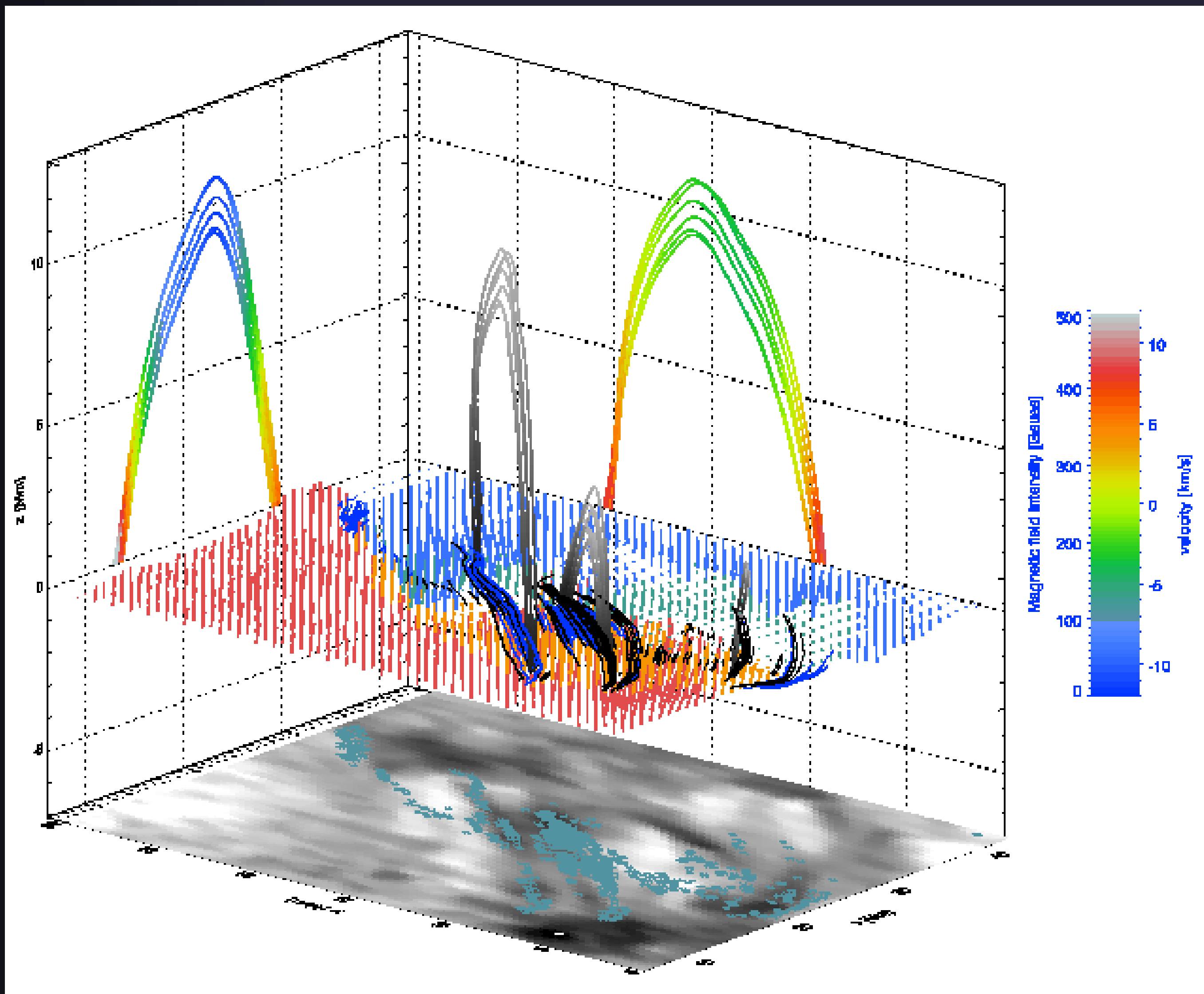
- Measurement of Zeeman effect (full Stokes vector) in He I 10830 Å
- Gives full magnetic vector at base of corona, in prominences & cool (freshly emerged) loops
- Advantages:
  - Optically thin: formation details not required
  - Allows high spatial resolution



Solanki et al. 2003, Lagg et al. 2004

Disadvantage: formation height?

Structure of Cool Magnetic Loops



Magnetic loops deduced from measurements of He I 10830 Å Stokes profiles in an emerging flux region.

Left projection: Field strength

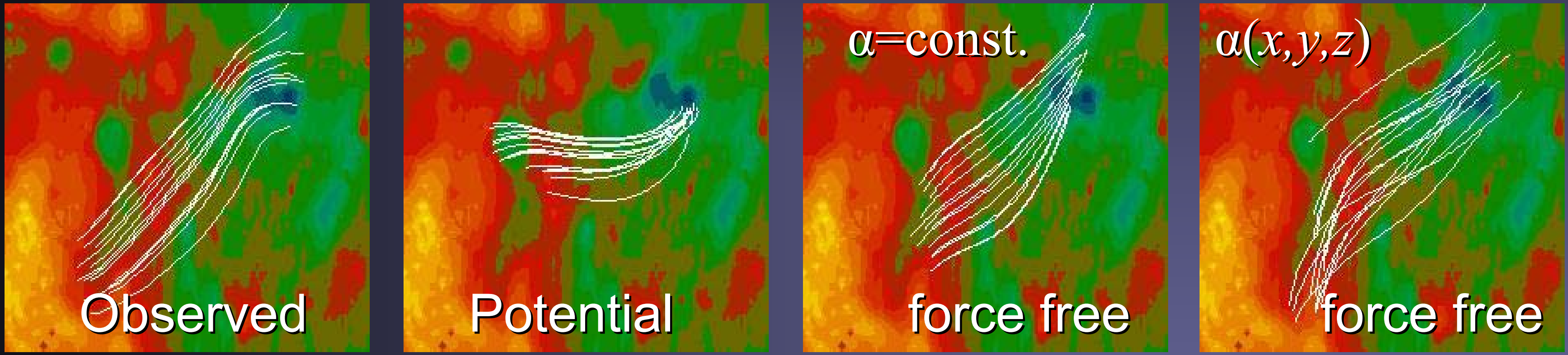
Right projection: Vertical velocity

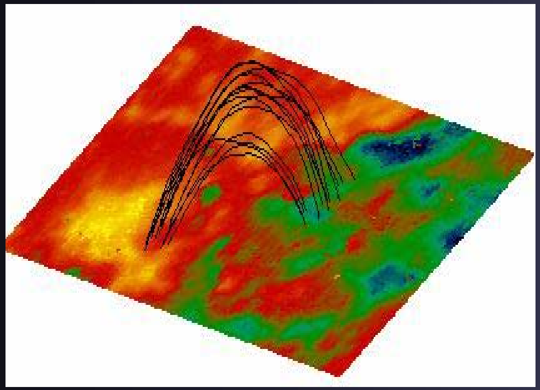
Solanki et al. 2003 (A. Lagg)

Testing Magnetic Extrapolations

- Force-free field with $\alpha(x,y,z)$ reproduces loops reconstructed from observations better than force-free field with α=const. and far better than a potential field extrapolation

➔ Loops harbour strong currents while still emerging

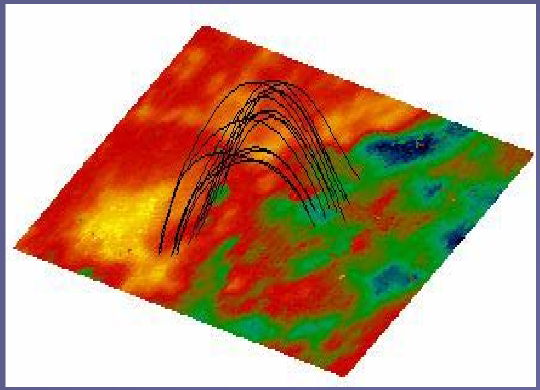




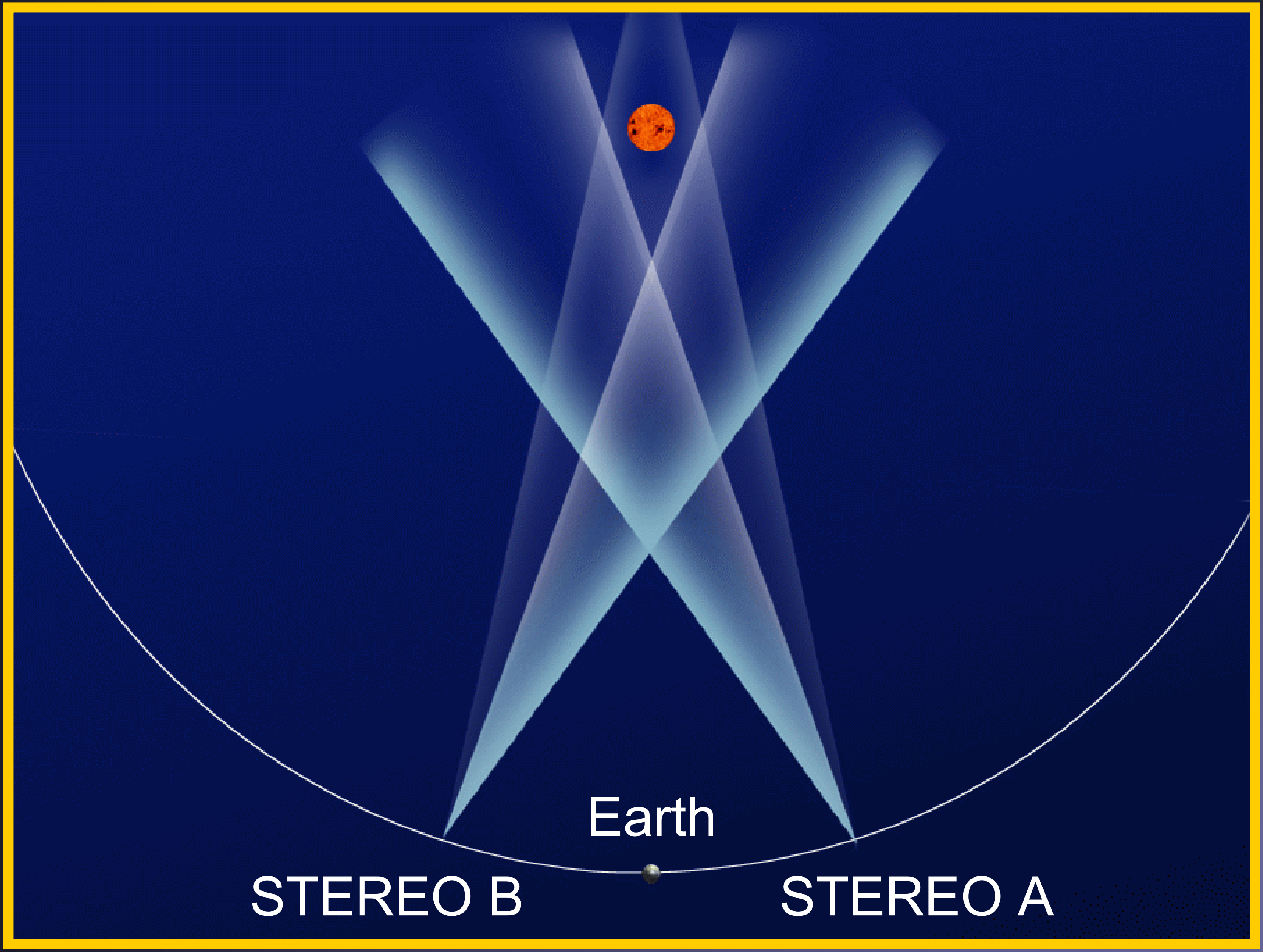
$$\nabla \times \mathbf{B} = 0$$

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$

Wiegelmann et al. 2005



STEREO: Solar-TErrestrial RElations Observatory

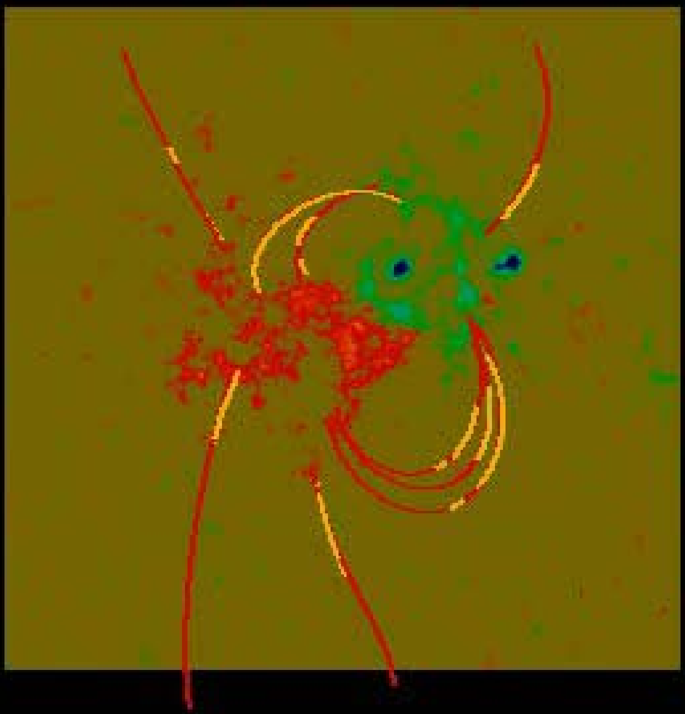


Coronal loops in 3-D

Yellow lines: First stereoscopic reconstruction of coronal loops observed by the two STEREO spacecraft looking at the Sun from different directions.

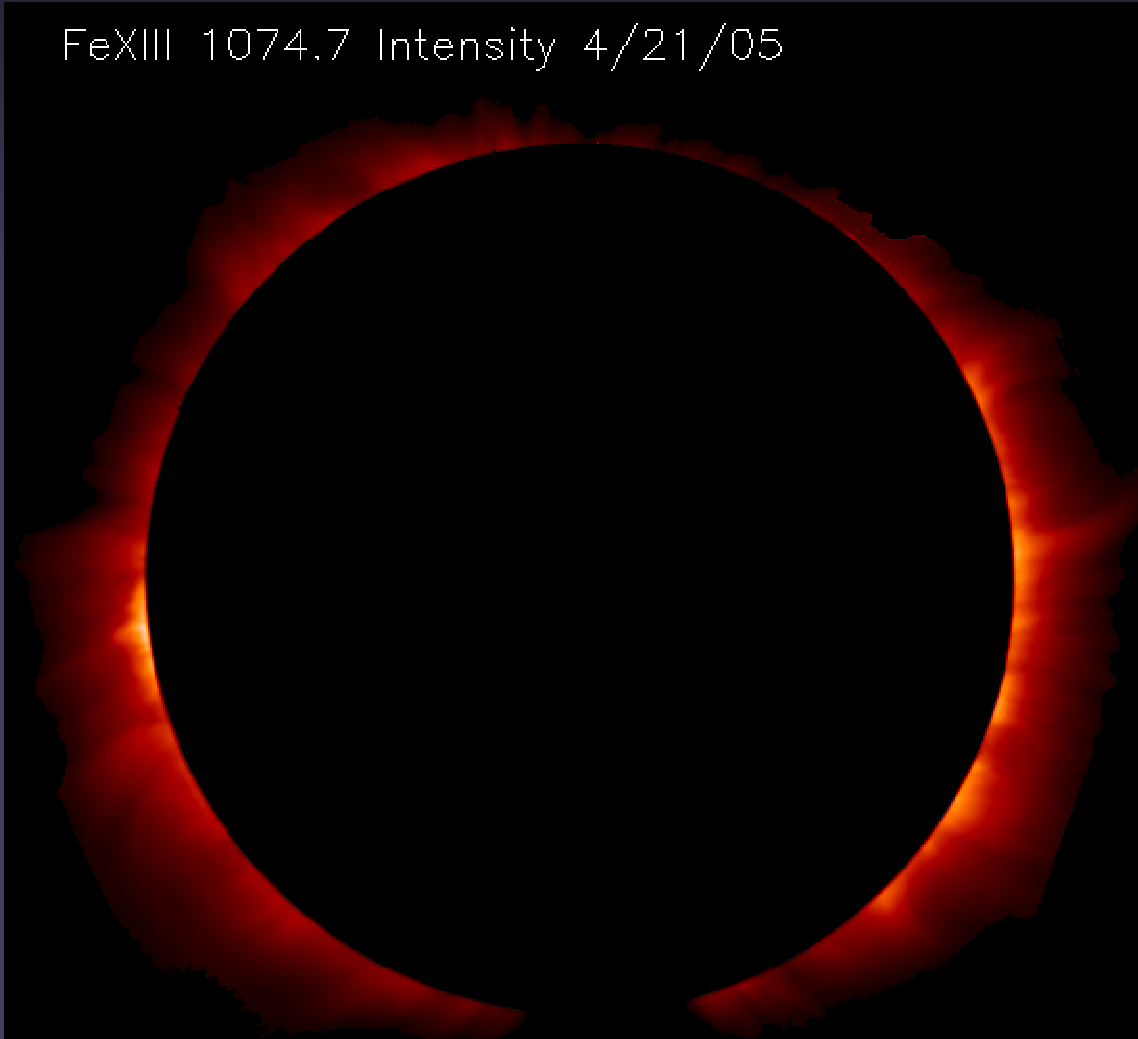
Red lines: magnetic field extrapolations starting from magnetogram on solar surface

Feng et al. 2007



Coronal Zeeman & Hanle effect

- Coronagraphic obs. of Fe XIII 1074.4 & 1079.8 Å lines give B_z and azimuthal direction
- Integration through corona: limited spatial information
- Instrument: Coronal Multi-channel Polarimeter (CoMP): full Stokes



S. Tomczyk, 2004

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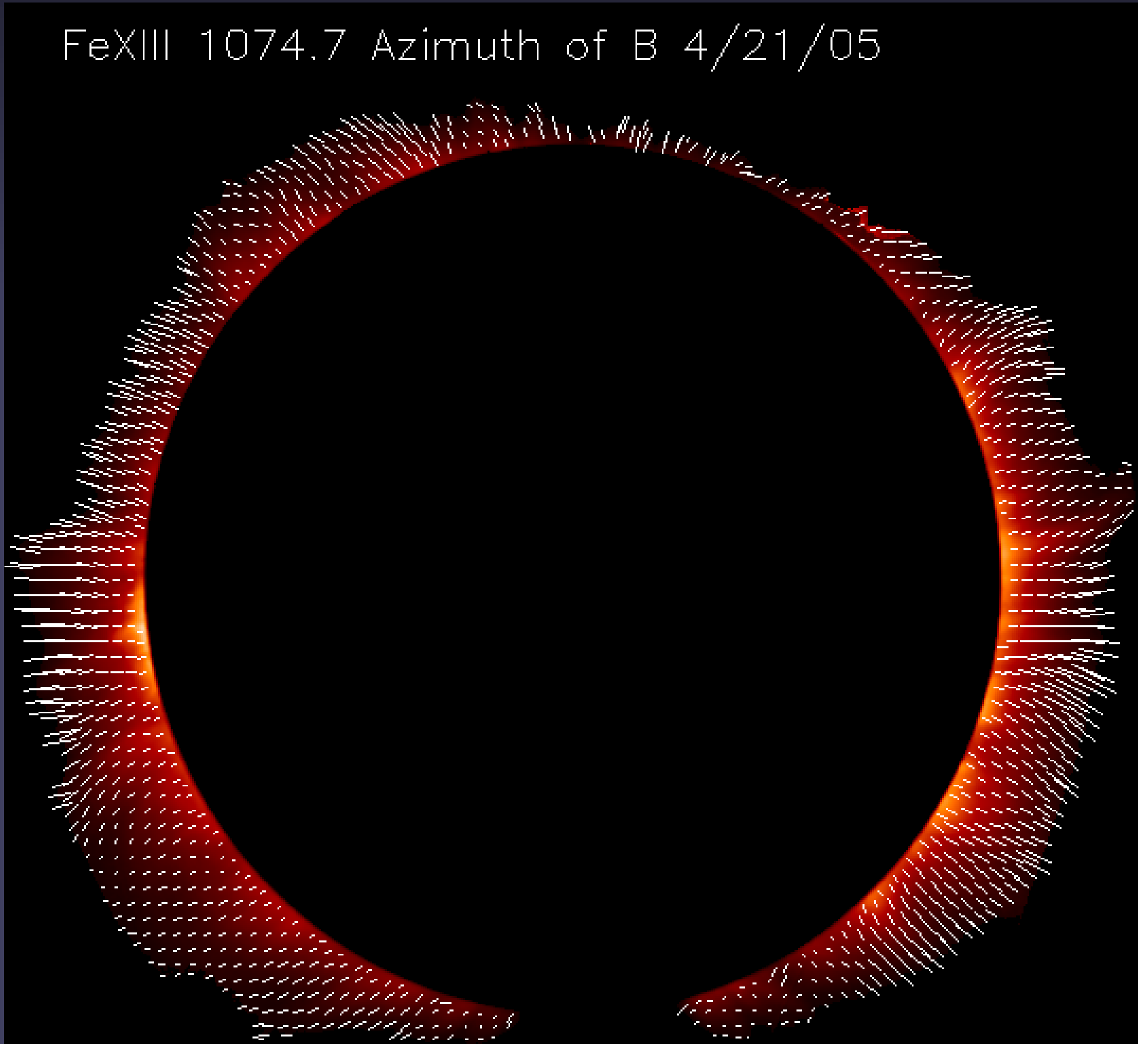

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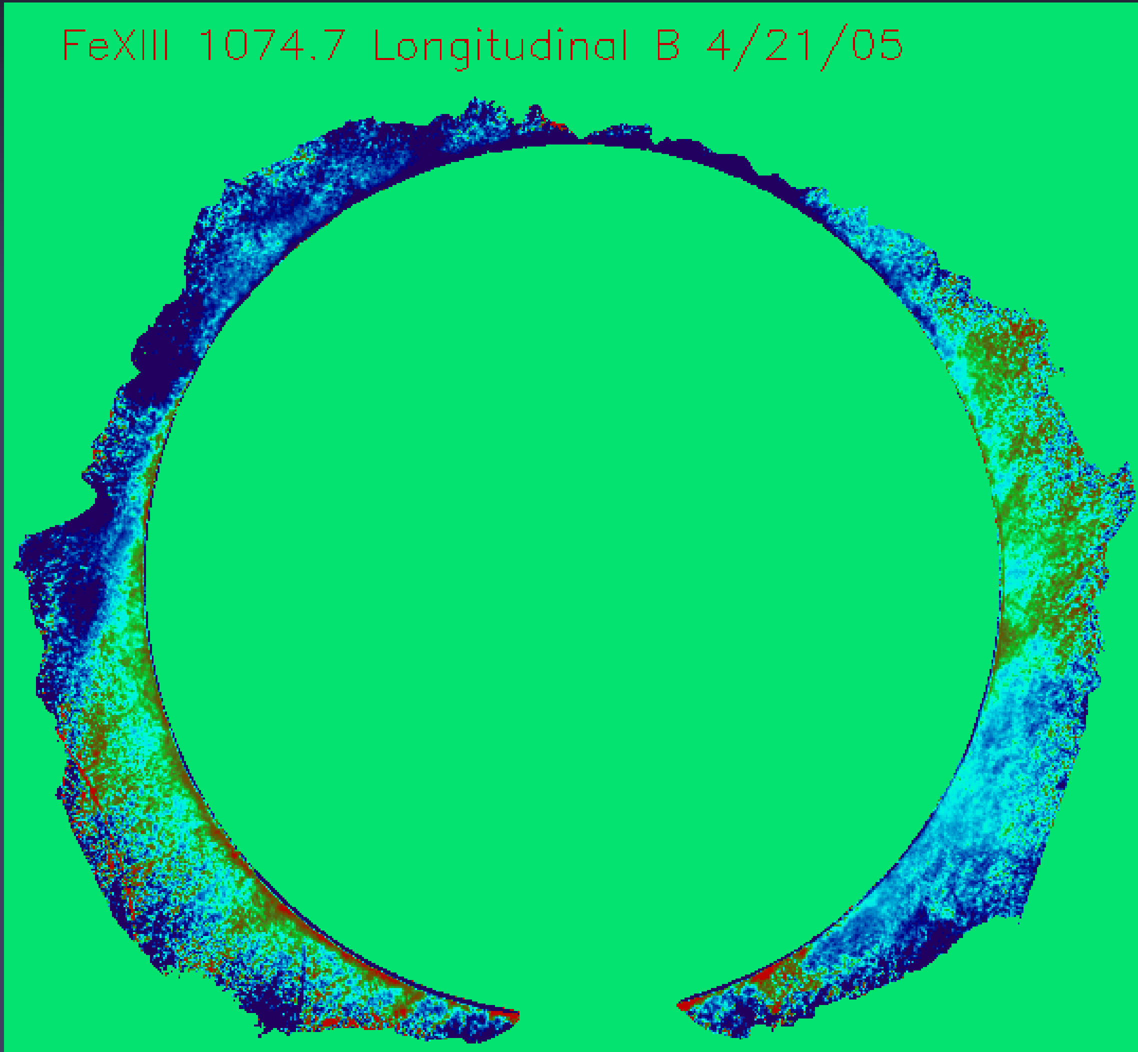
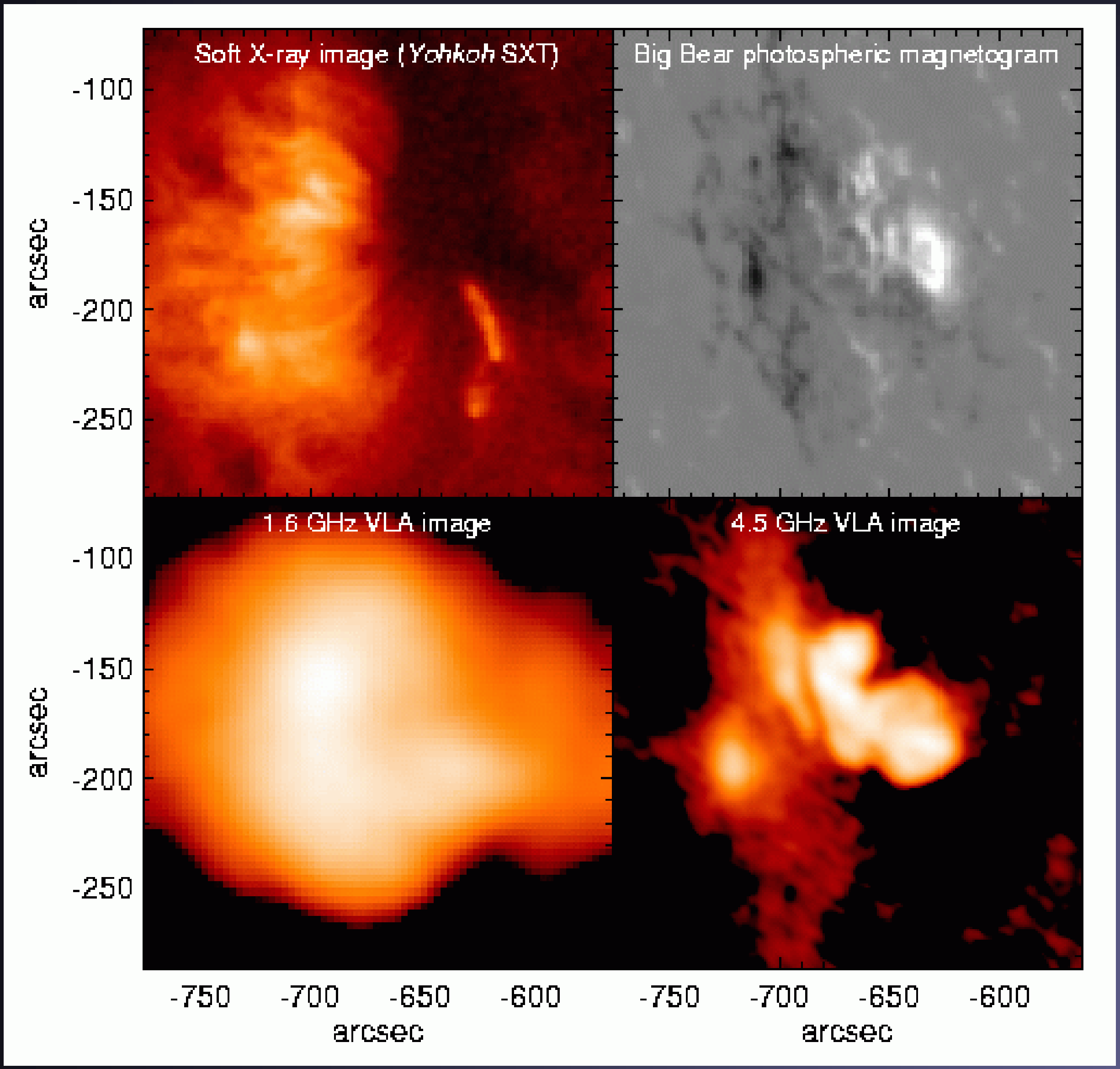


S. Tomczyk, 2004

Radio measurements of coronal field

- Two main emission mechanisms compete in the solar corona at microwave frequencies:
  - free-free emission or bremsstrahlung: produced by collisional energy loss of non-thermal e^-. Present everywhere in corona. Dominates in regions of weaker field, e.g. active region plage, and at low frequencies ($\nu < 2$ GHz)
  - Gyroresonance emission or cyclotron emission or magneto-bremsstrahlung: produced by the gyration of e^- around magnetic field lines (Larmor orbit) due to Lorentz force. Sun: dominant in strong-field regions above sunspots, and generally at frequencies above a few GHz.
- Both mechanisms produce circular polarisation.

Active region at different radio frequencies



At low frequencies (lower left) bremsstrahlung (f-f) dominates radio emission. Maps resembles soft X-rays (upper left)

Above 2-3 GHz, gyro emission dominates radio maps. They resemble magnetograms (right)

Gyroresonance

- Produces emission peaks at multiples s of e^- gyrofrequency

$$\nu_B = \left(\frac{e\ B}{2\pi\ m_e c} \right) = 2.80 \times 10^6 B \qquad \text{[cgs units]}$$

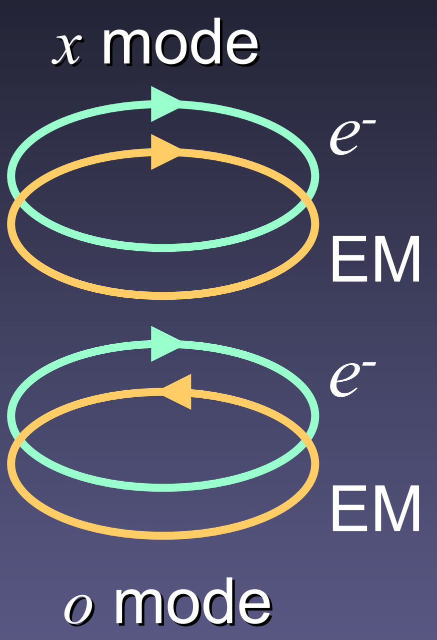
- Gyrofrequency scales linearly with B
- Note: For strong fields of 10 MG, as found in magnetic WDs, the gyrofrequency reaches optical wavelengths; for $B > 10^{10}$ G (e.g. pulsars) it reaches X-ray & γ-ray wavelengths
- Opacity of gyroresonance emission for Maxwellian distribution of e^- velocities:

$$\propto \quad n_e B/(\partial B/\partial l)\ (\ T \sin^2\theta / mc^2\ )^{s\text{-}1}$$

where $s = 1, 2, 3, \ldots$ is the harmonic, θ is angle between $\mathbf{B}$ and line of sight (brighest for perpendicular fields)

Properties of gyroresonance emission

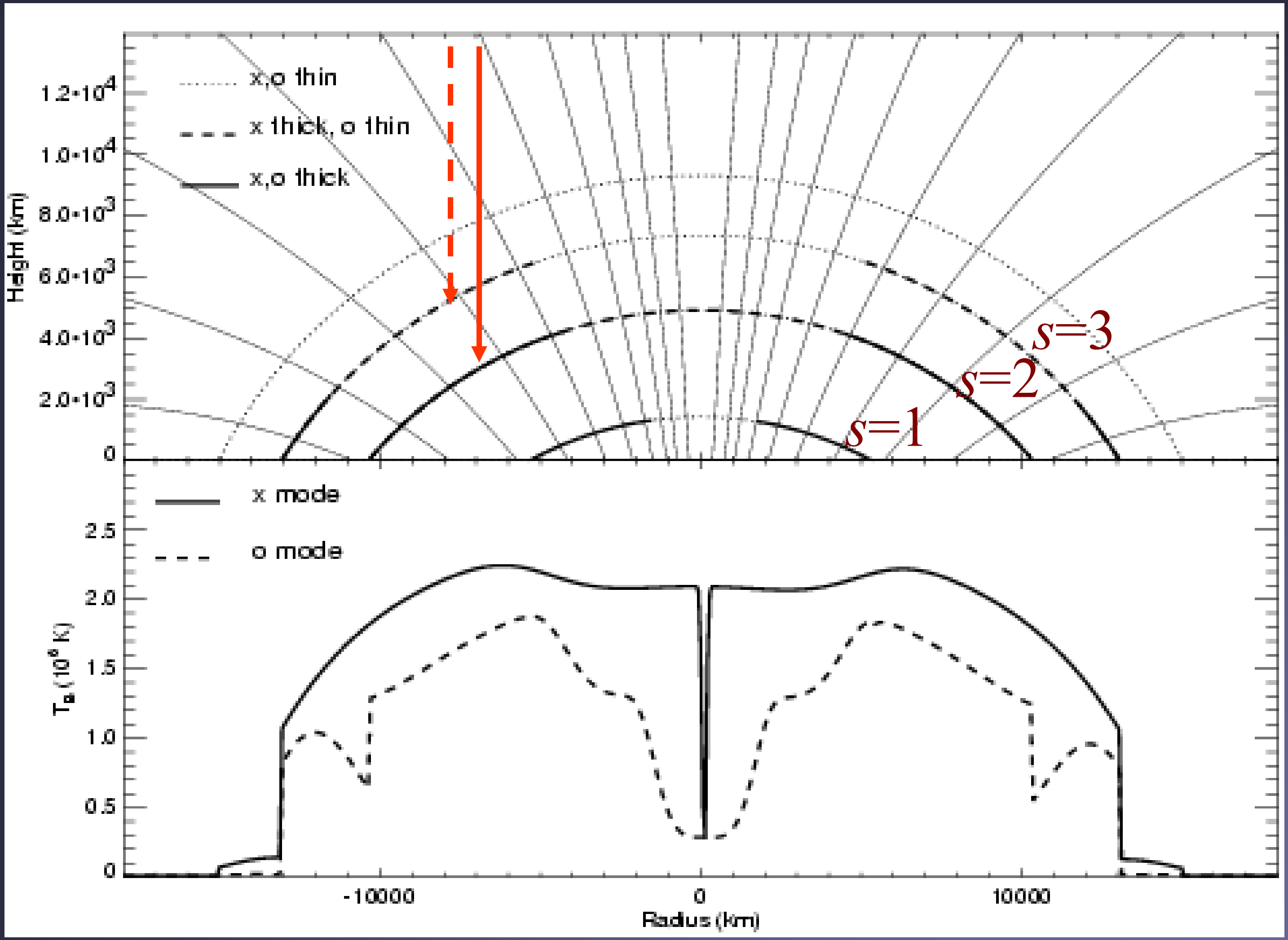
- Big difference in opacity of two polarizations of EM waves: extraordinary (x) mode interacts more with e^- than ordinary (o) mode
- x and o modes → opposite circular polarizations (key to unlocking B)
- Looking on solar atmosphere from above, we only see down to highest optically thick layer at a given frequency and polarization, typically $s=3$ for x-mode, $s=2$ for o-mode



Calculated model sunspot gyroresonance layers

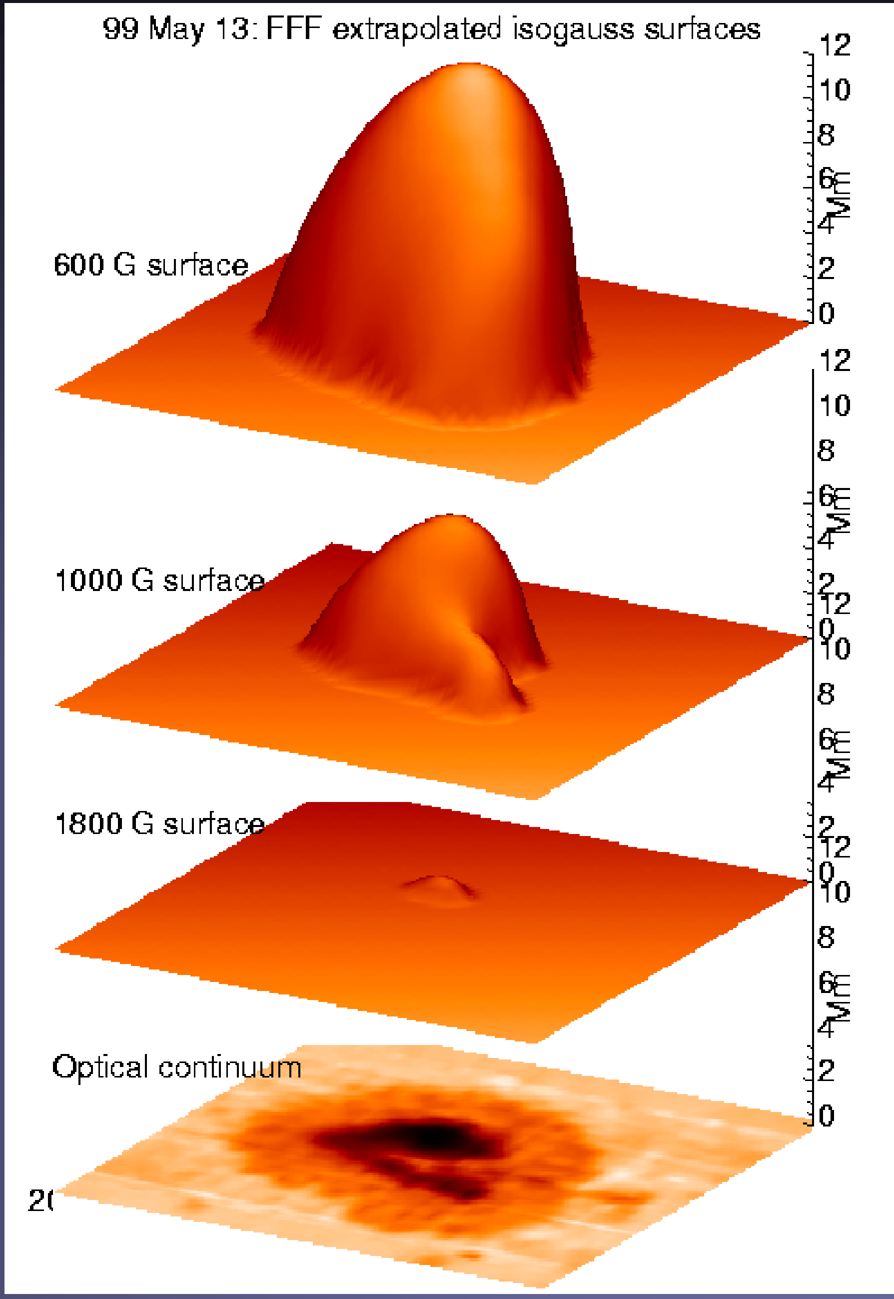
Gyro-resonance provides field strength B, but also gives some limited information on direction of field

x o modes



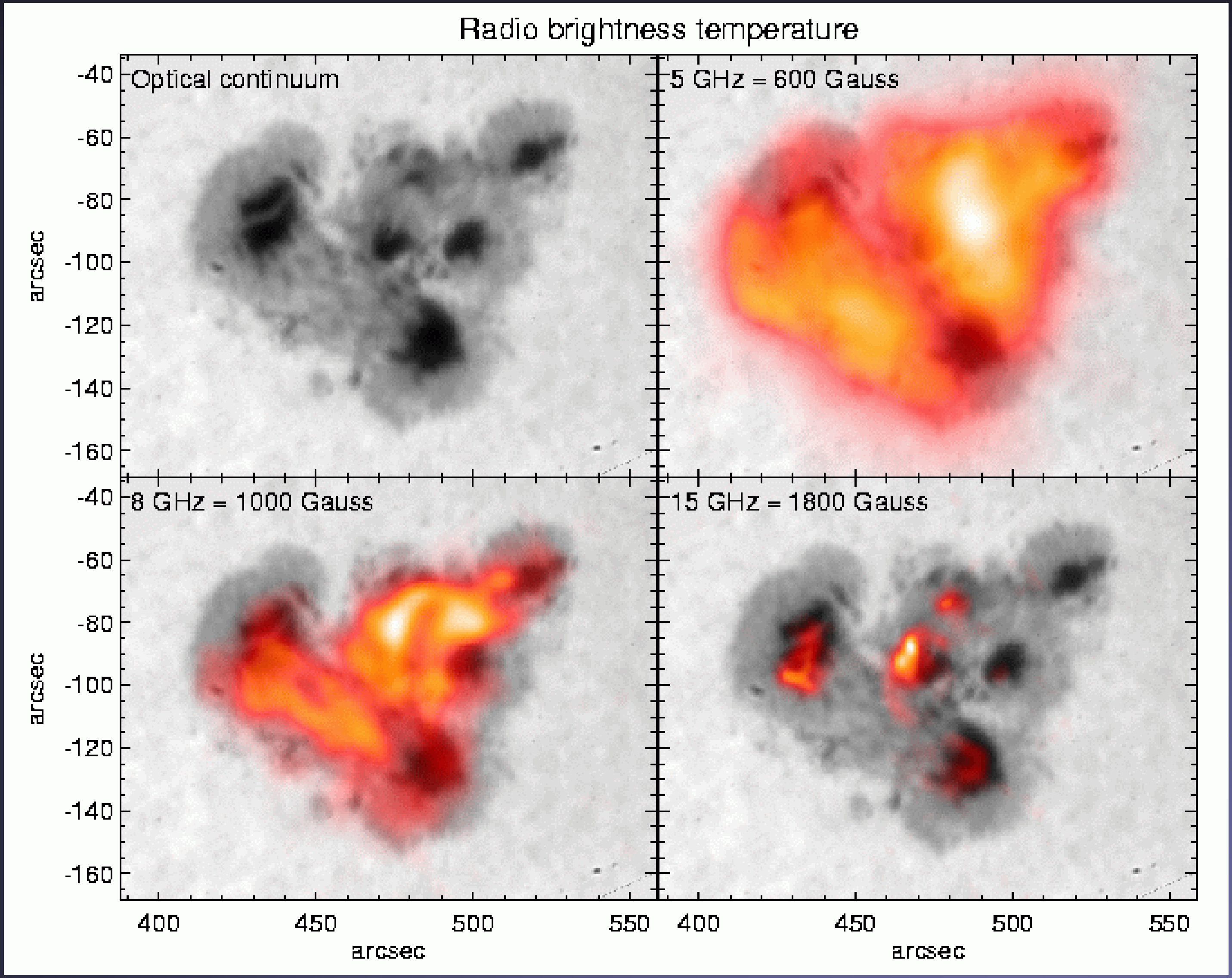
Gyroresonance layers

- Gyroresonance opacity is the only mechanism that makes corona optically thick at frequencies > 4 GHz
- Emission comes from a surface of constant B
- Microwaves are sensitive to fields in range 200–3000 G
- High levels of circular polarization also indicate presence of strong B and can be used to measure temperature gradients



Radio Emission from Coronal Magnetic Fields

Region showing strong shear: radio images show high B and very high temperatures exactly where the magnetic field is non-potential

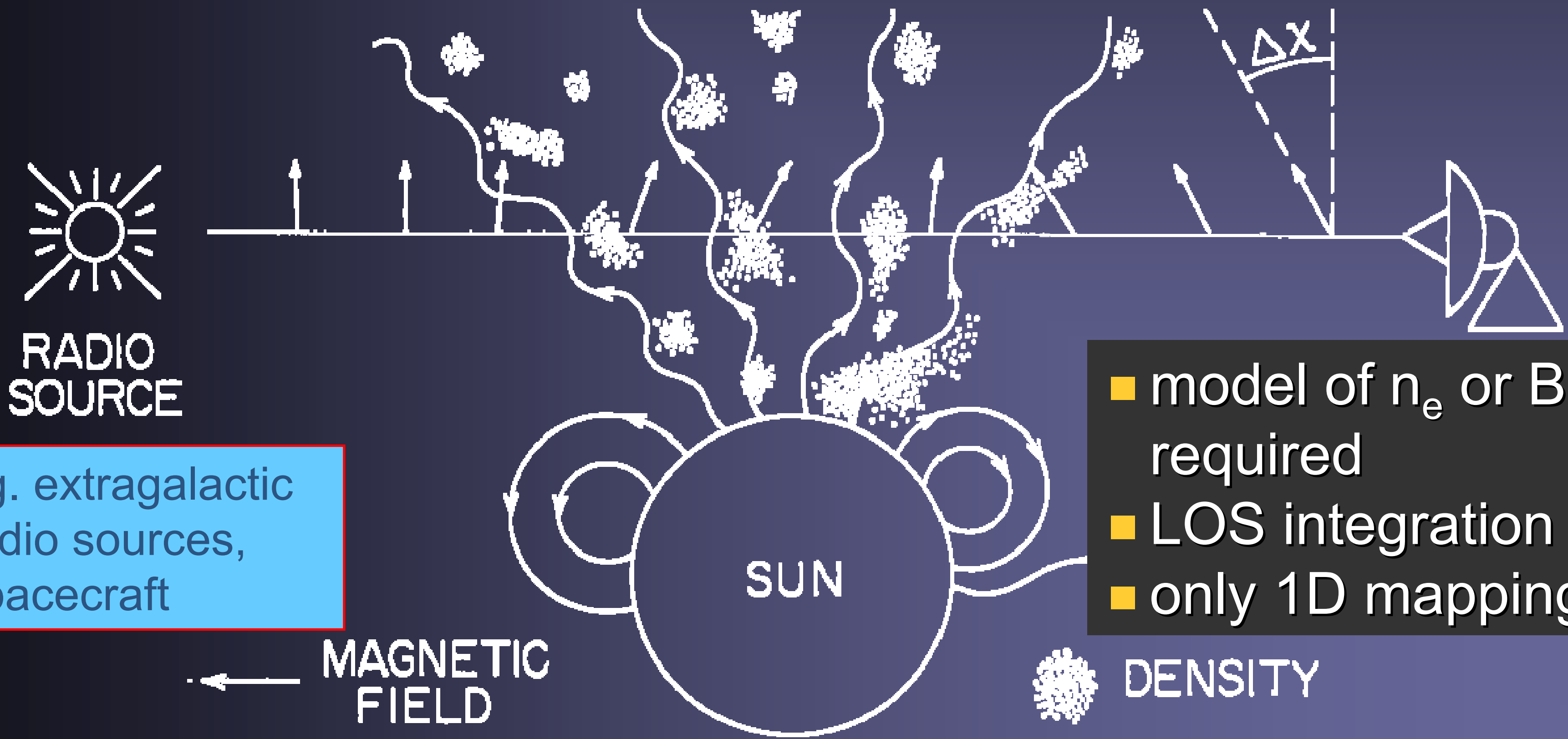


Radio Measurements: Faraday Rotation

- plane of linear polarization is rotated by magnetized plasma with density n_e (Nicholson 1983) :

$$\Delta\chi \propto \lambda^2 \int_{LOS} n_e \vec{B} \cdot d\vec{s}$$

➔ measures product of n_e and B_{LOS}

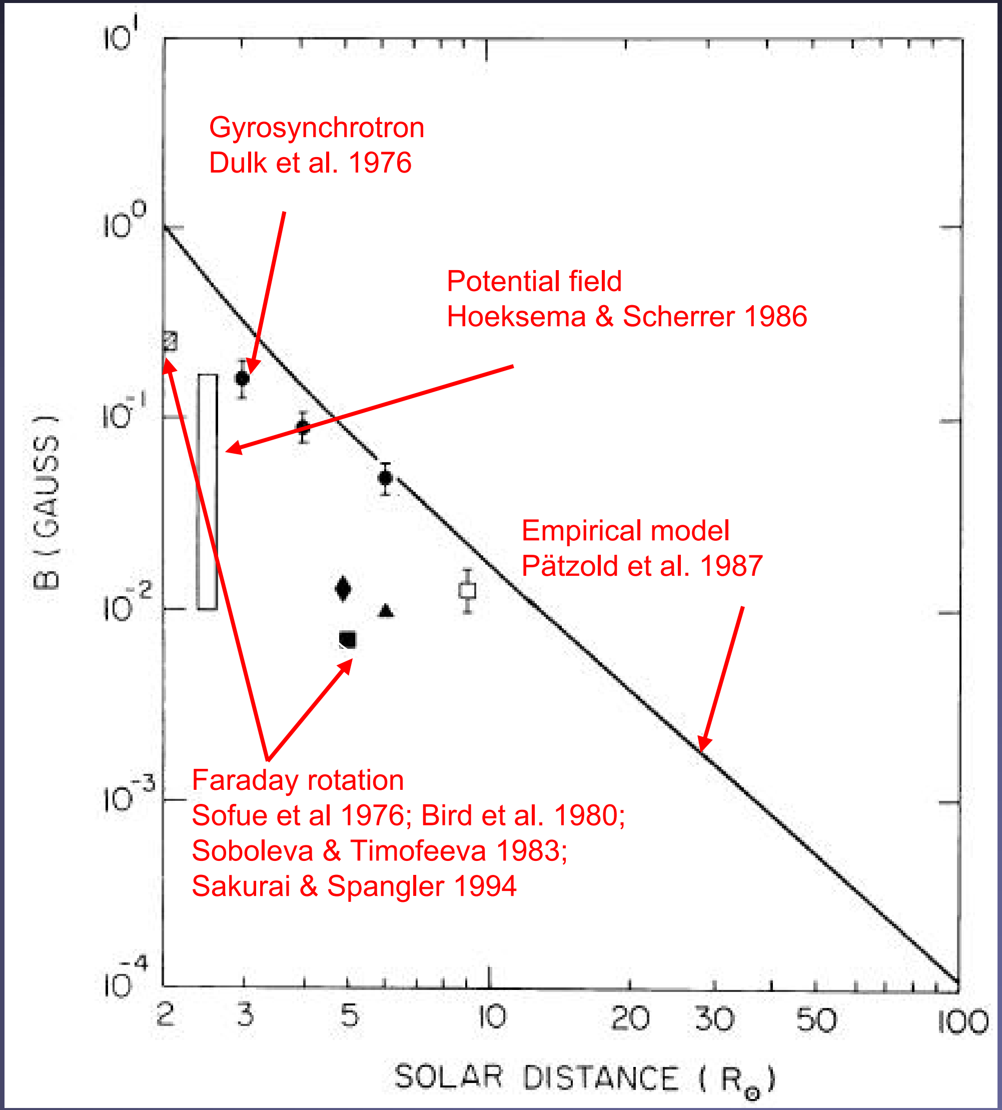


eg. extragalactic radio sources, spacecraft

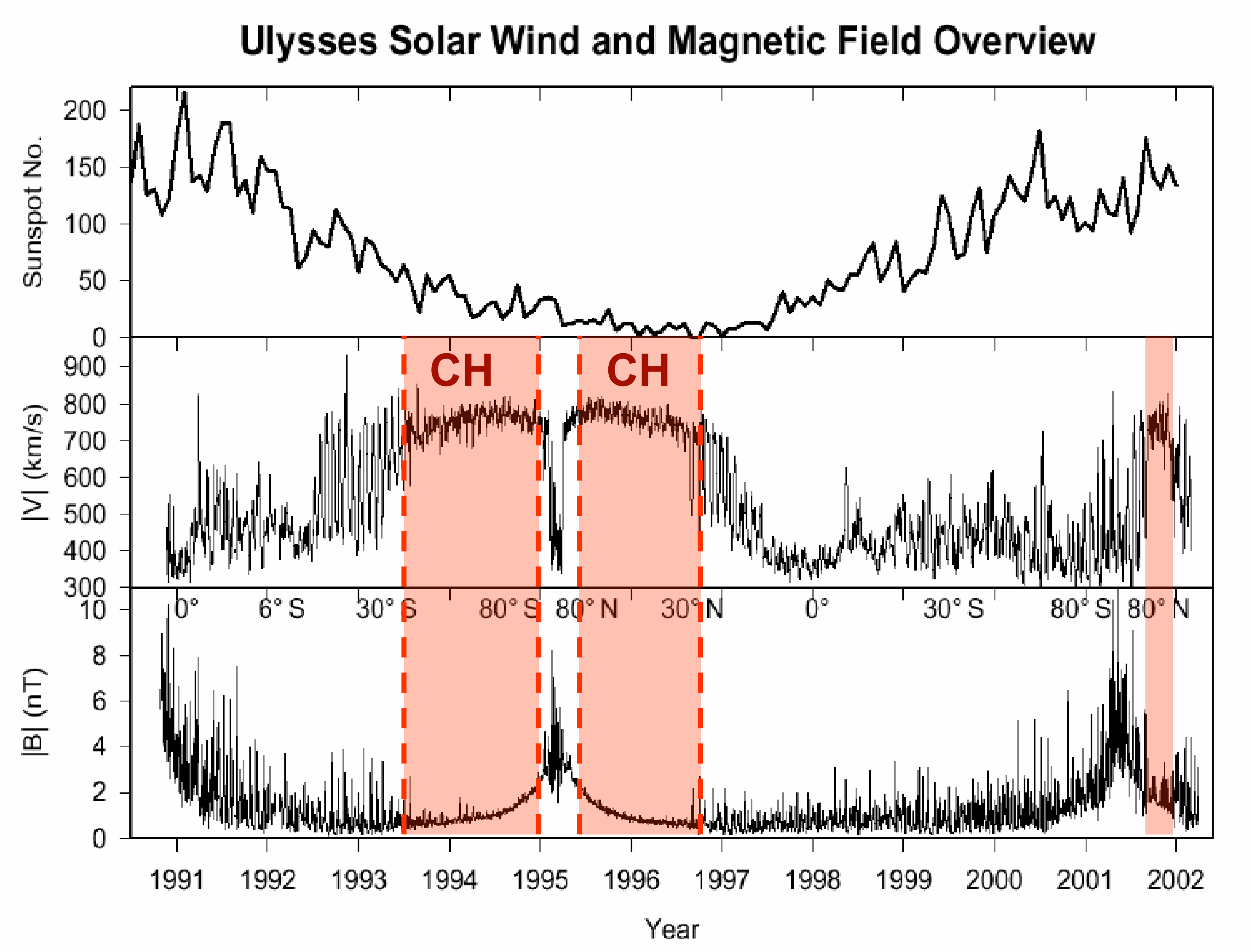
- model of n_e or B required
- LOS integration
- only 1D mapping

Faraday rotation: results

- Measurements at 2 or more λ allow Δχ to be deduced without knowledge of initial polarisation angle
- Most Faraday rotation results refer to the outer corona, where the field is weaker & density is lower
- Easier for weak fields & low-density plasma: avoids multiple rotations



Heliospheric magnetic field from Ulysses



Making the Parker spiral visible

- Ulysses followed electron streams ejected from Sun on 25 & 30.10.1994 from above the south solar pole, with the help of the clouds' radio emission (dots)
- The e^- streams follow the Parker spiral as expected