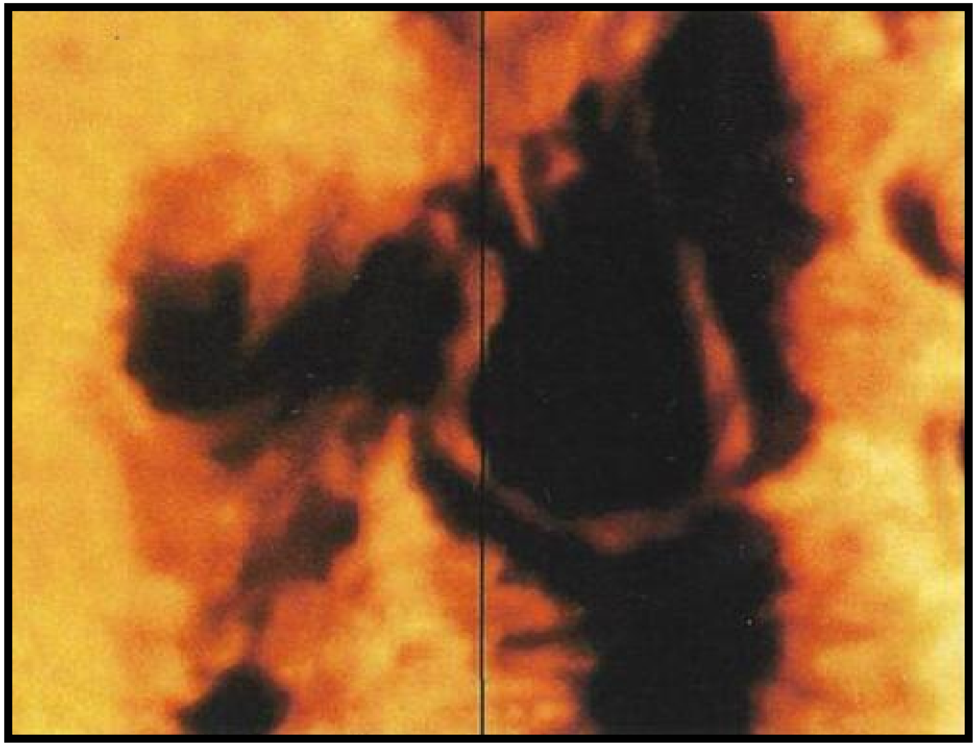
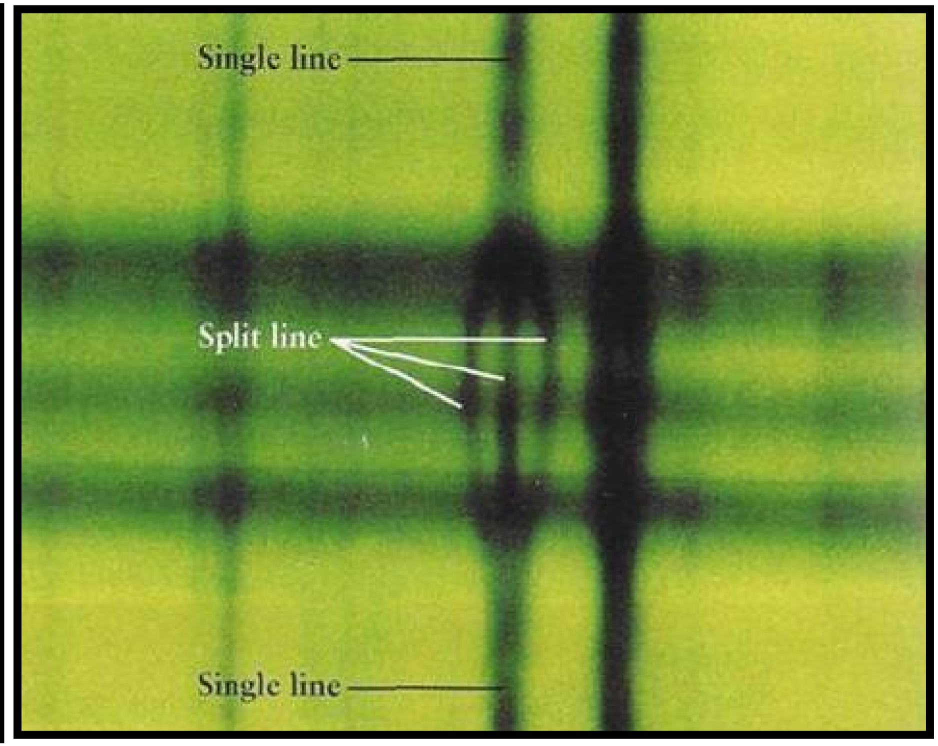
Measurement Methods of Chromospheric and Coronal Magnetic Fields

N.-E. Raouafi

Solar Magnetism





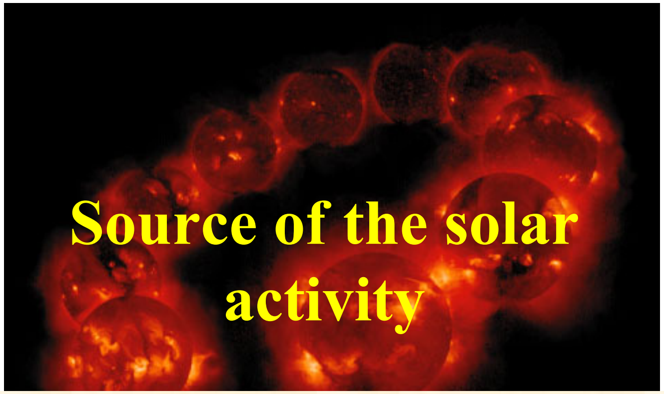
George Hale (1908)

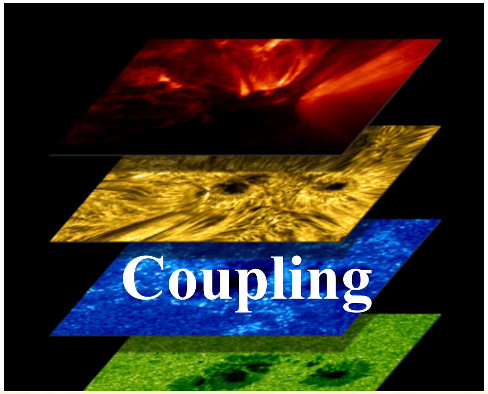
Observation of spectral line splitting in sunspots

Zeeman Effect →

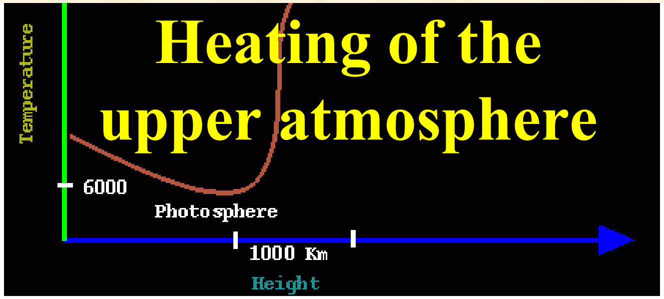
Start of the solar magnetism era

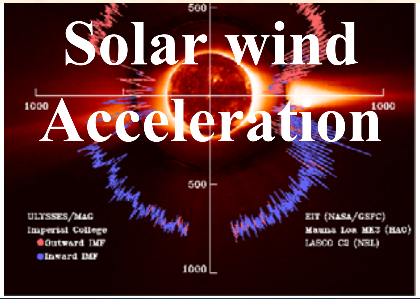
Effects of Magnetic Field in the Solar Atmosphere *(examples)*

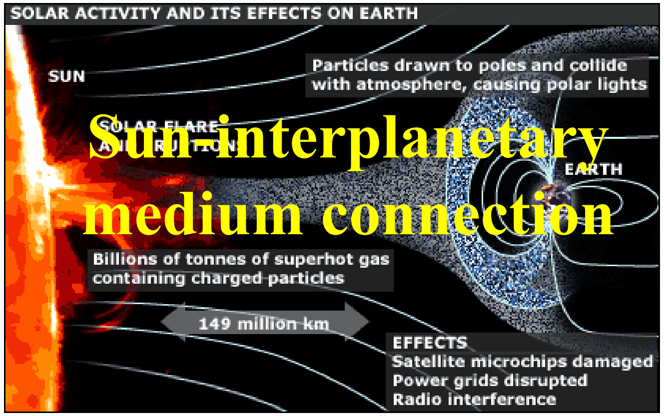


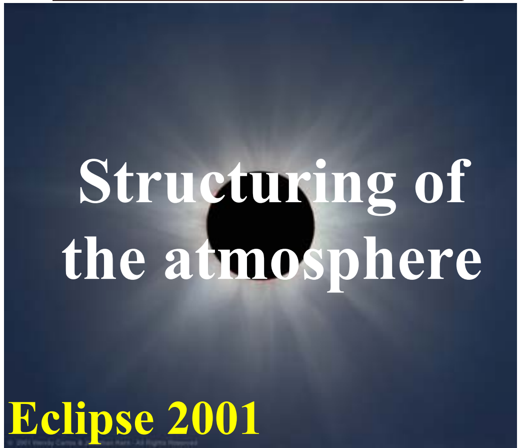


"If it were not for its magnetic field, the Sun would be as dull a star as most astronomers think it is" [R. Leighton 1965]









Solar magnetic field: Gross view

* **Closed component:**
  Most of the solar magnetic flux (> 90%);
  Closely correlated with sunspot activity;
  Strong fields (KG) occupy on average < 1% of the solar surface;
  Responsible for the total irradiance variations; …

* **Open component:**
  Small contribution to the solar magnetic flux;
  Poorly correlated with sunspot activity;
  Form the interplanetary field & solar wind; …

* The photosphere (chromosphere) is approximately a 2-D layer
  The magnetic field is 2-D vector field

* Any coronal remote measurement is affected by the line of sight
  The coronal field is 3-D and weak; More difficult to measure

[Stenflo 1982; Wang et al. 2005; …]

Qualitative measurements of the magnetic field
Field topology

Based on the emission properties of the plasma

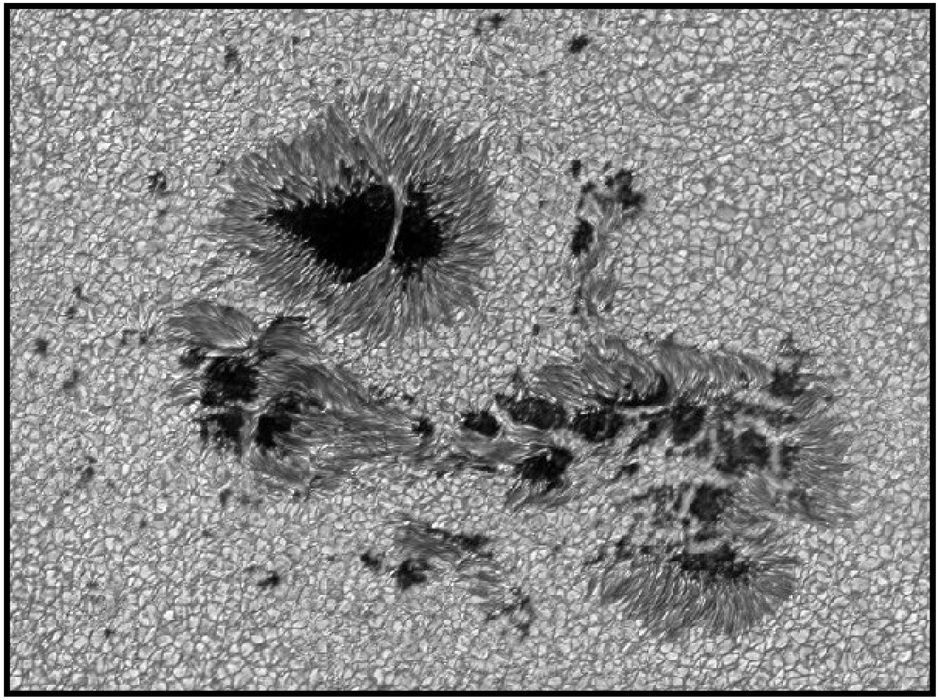
- **Contrast effect**
- **Temperature sensitivity of species emission**
- **Plasma trapping in the field lines**
  $\beta \ll 1$ in the solar atmosphere

No information on the field strength nor “orientation”

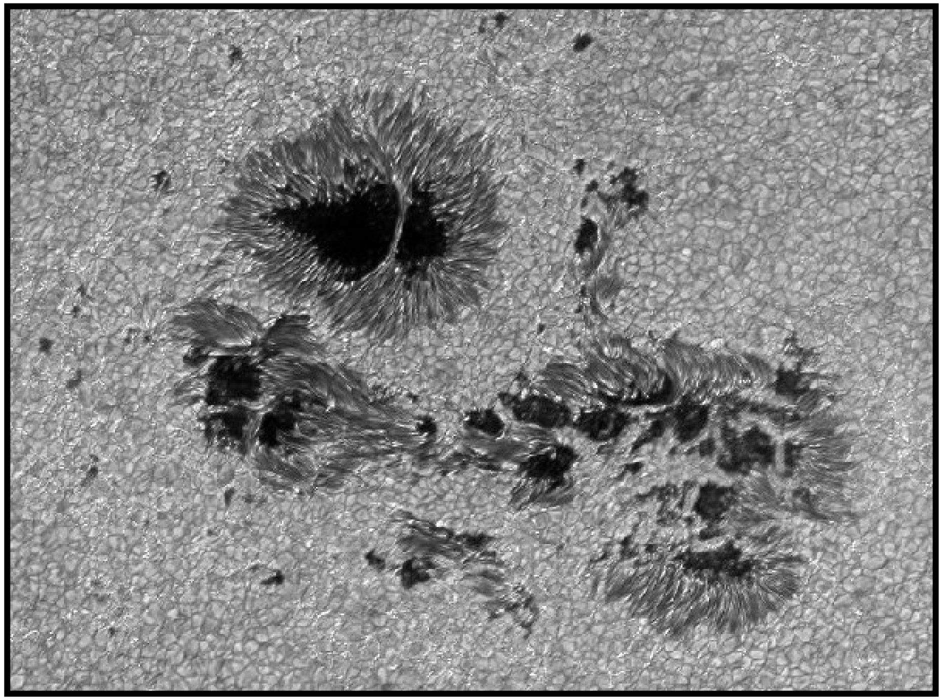
Observing different lines formed at different layers:
Topological evolution of the magnetic field through the solar atmosphere

Photosphere

Brightness contrast (Continuum 4320 Å)

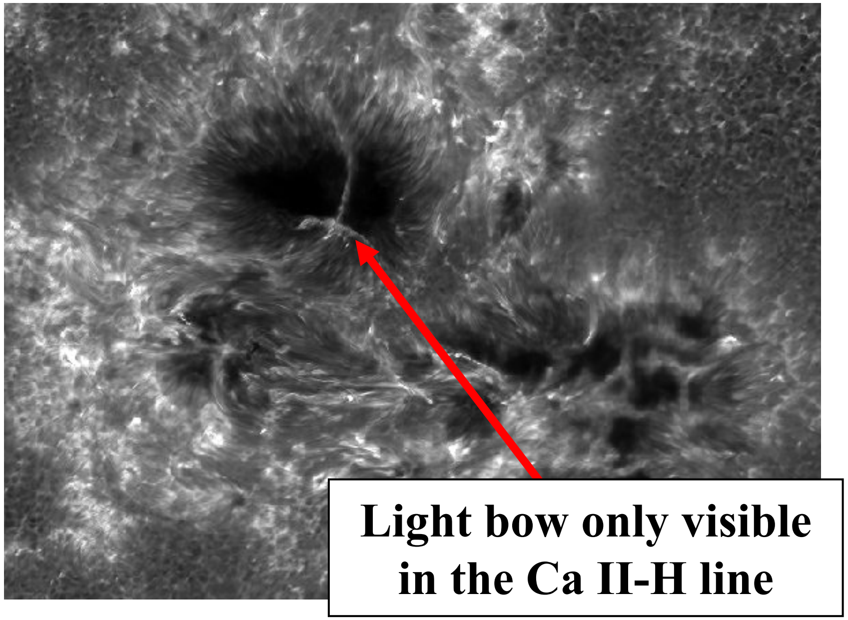


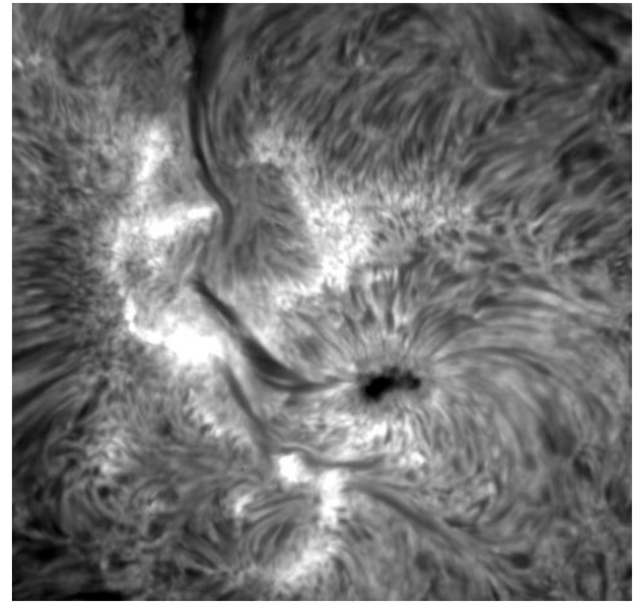
G-band: Better contrast



Sunspots Umbrae (**KG** vertical fields); **Penumbrae** (Flux tube threads at different inclinations); **Pores** (Emerging strong flux); **Light bridges**; **Granulations**; **Dark network lanes**; ...

Bright points (Concentration of tiny flux tubes; Resolution <100 Km) **[Muller & Roudier 1984; Rutten et al. 2001; Steiner et al. 2001; Berdyugina et al. 2003; Zakharov et al. 2005]**



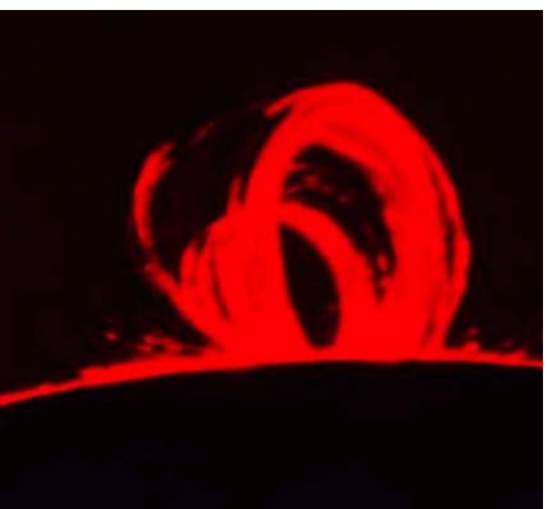


Lower Chromosphere **Ca II H & K**

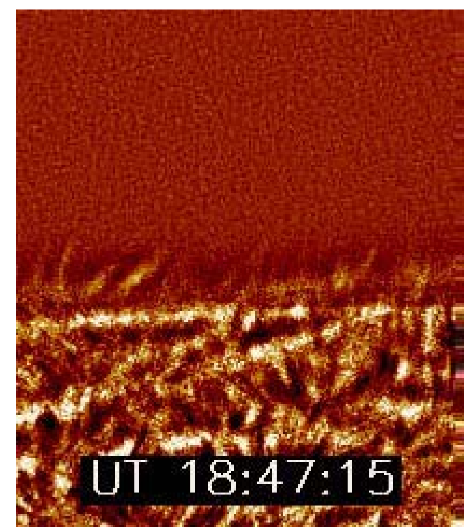
Umbrae; penumbrae; light Bridges; Granulation in negative; Bright plages

Upper Chromosphere **H-α**

Dark filaments; Homogeneous distribution of the field; **Canopy**

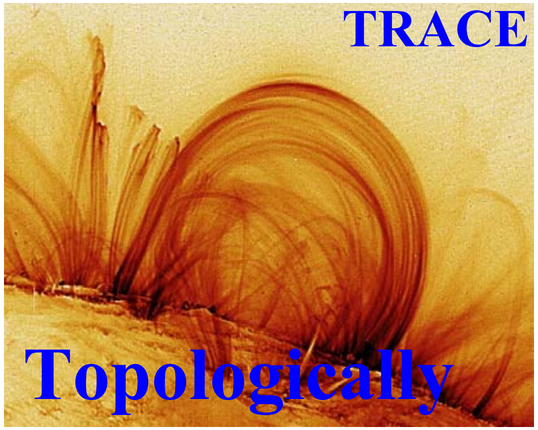


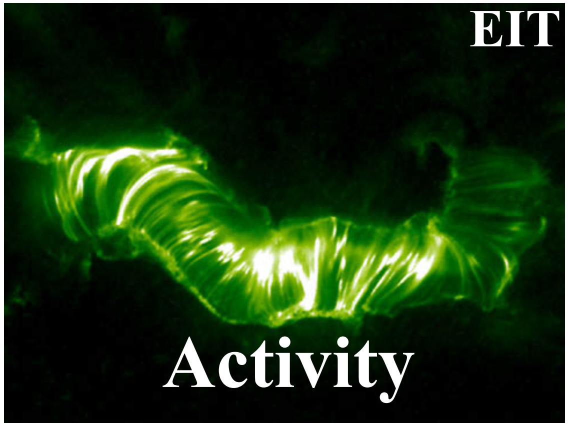
Cool material with coronal extension: Prominences; Spicules: Mass flow & shocks driving; Heating of the chromosphere; Relation to flux tubes [De Pontieu et al. 2004]



Corona UV & X-ray emissions

Good tracers of the magnetic field





(PEAs; Tripathi 2005)

Corona Density distribution

Streamers (closed field: Slow Wind);
Coronal holes (open field: Fast Wind);
Polar plumes & interplumes;
Superradial expansion; …

Quantitative measurements of the magnetic field

☞ Direct measurements: in situ

Available measurements are recorded faraway from the Sun

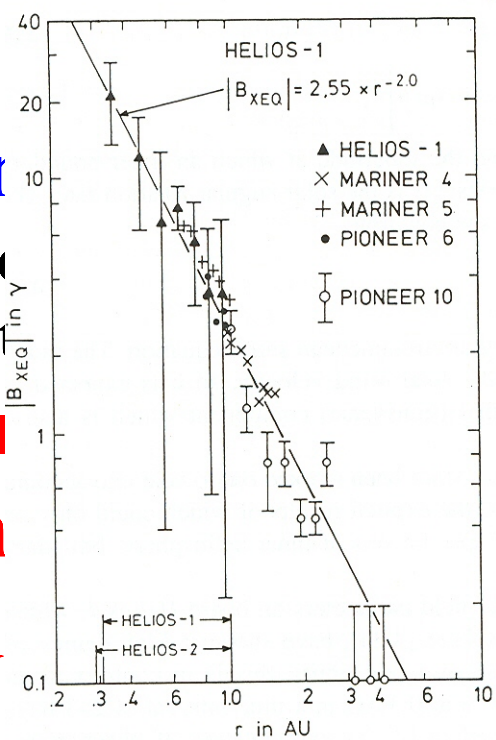
$0.3 \leq r \leq 1$ AU (*Pioneer* , *Mariner:* Behannon 1978; …;
***HELIOS:* Musmann et al. 1977; Mariani et al. 1978 & 1979; …)**

Average of the radial and azimuth components with high accuracy

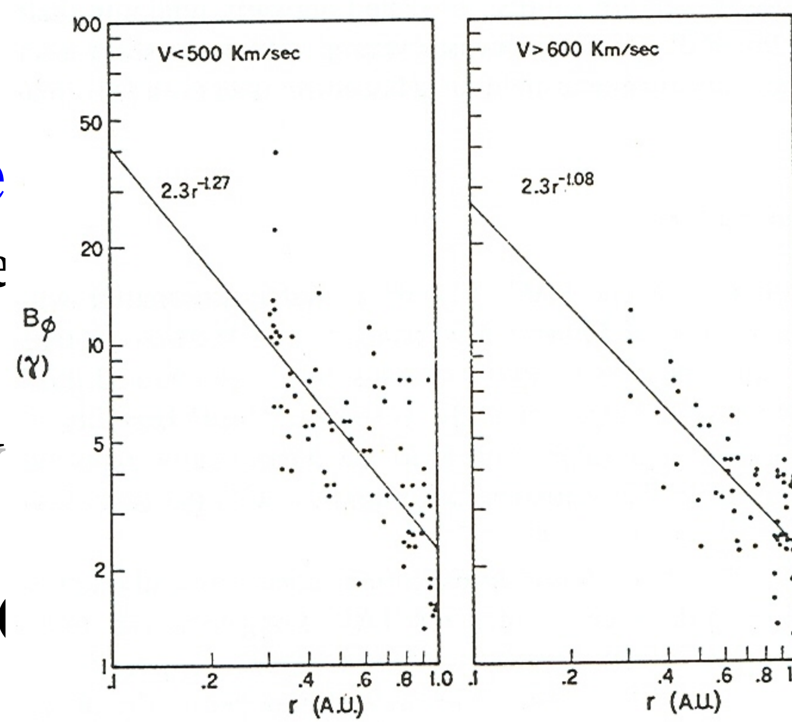
☞ Re… …ne

Based … …pe… …by
magne…

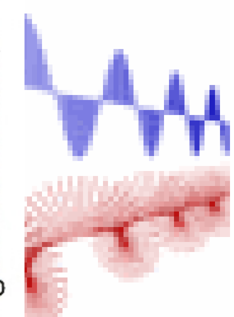
Zee… N…
Han… P…
Rad…



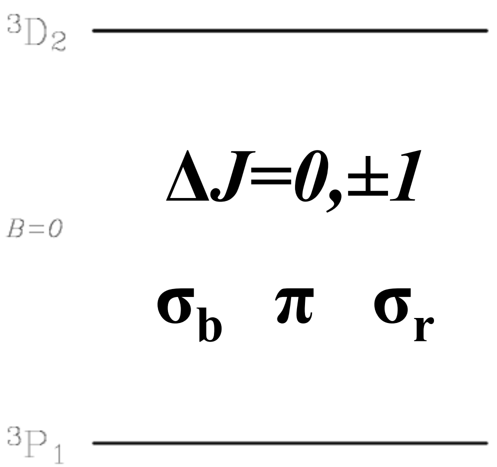
Daily averages of $|B_r|$



Daily averages of $|B_\varphi|$



Zeeman Effect

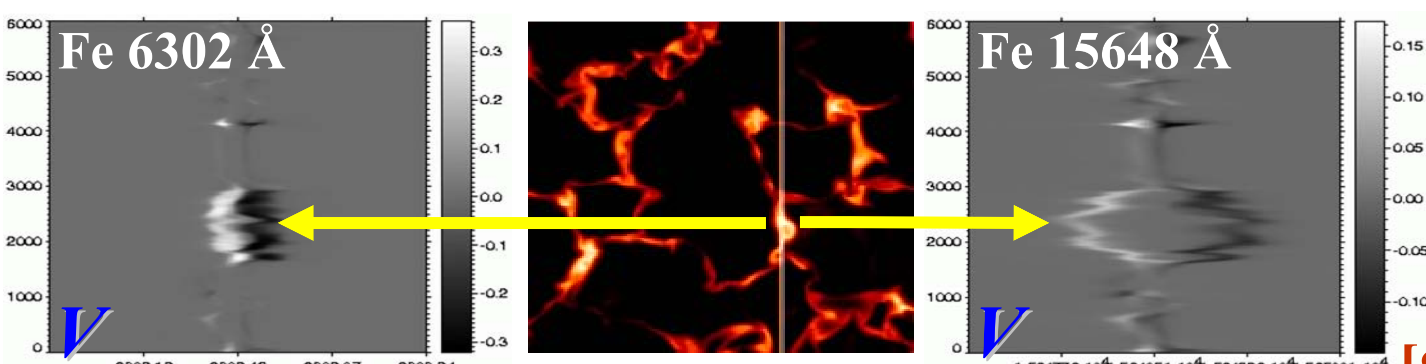


Magnetic field induces

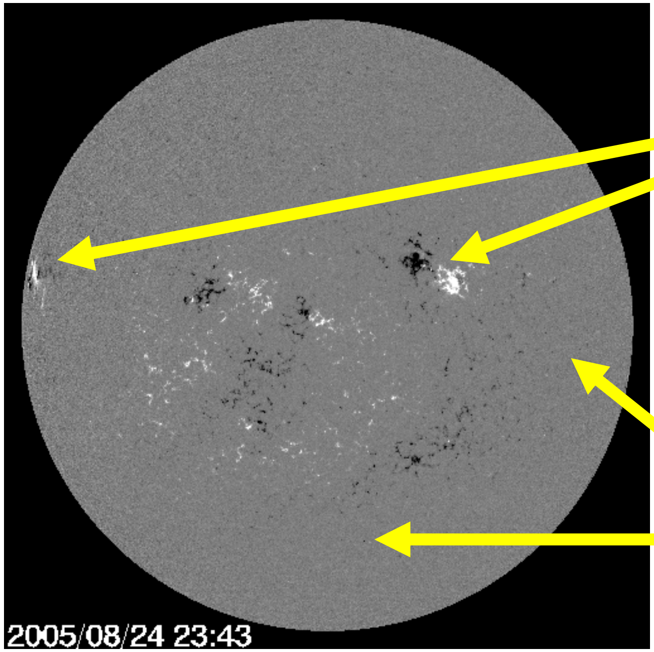
- **Splitting of atomic levels**
- **Change in spectral line profiles**
  (measurable if splitting ≥ Doppler width)
- **Polarization signature**

Zeeman λ-splitting: $\Delta\lambda \propto g_{\mathrm{eff}}\, B\, \lambda^2$

➡ **Chromosphere: Works better in the visible & infra-red**
Corona: Works better in the infra-red (weakness of the field)



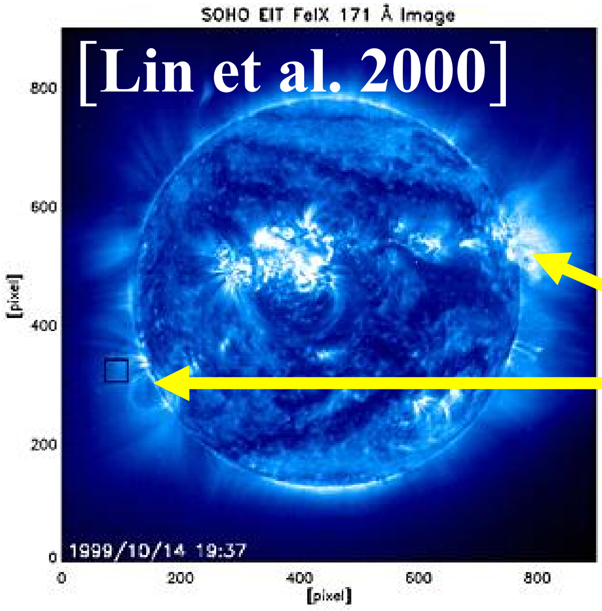
[Schüssler et al. 2003]



Zeeman effect works for:
Strong fields (100 < B < KG) with homogeneous polarities (sunspot, plages, pores, ...)
Small area of the solar surface

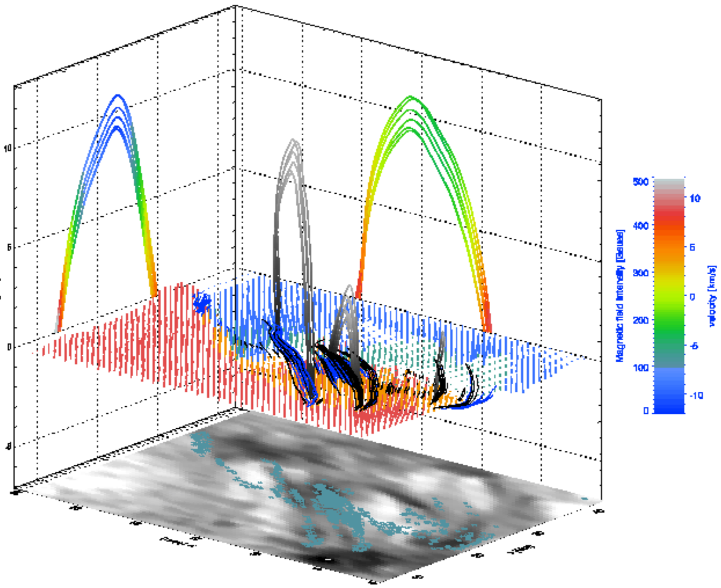
No Zeeman effect in mixed polarities regions: cancellation effect

Need high spatial resolution



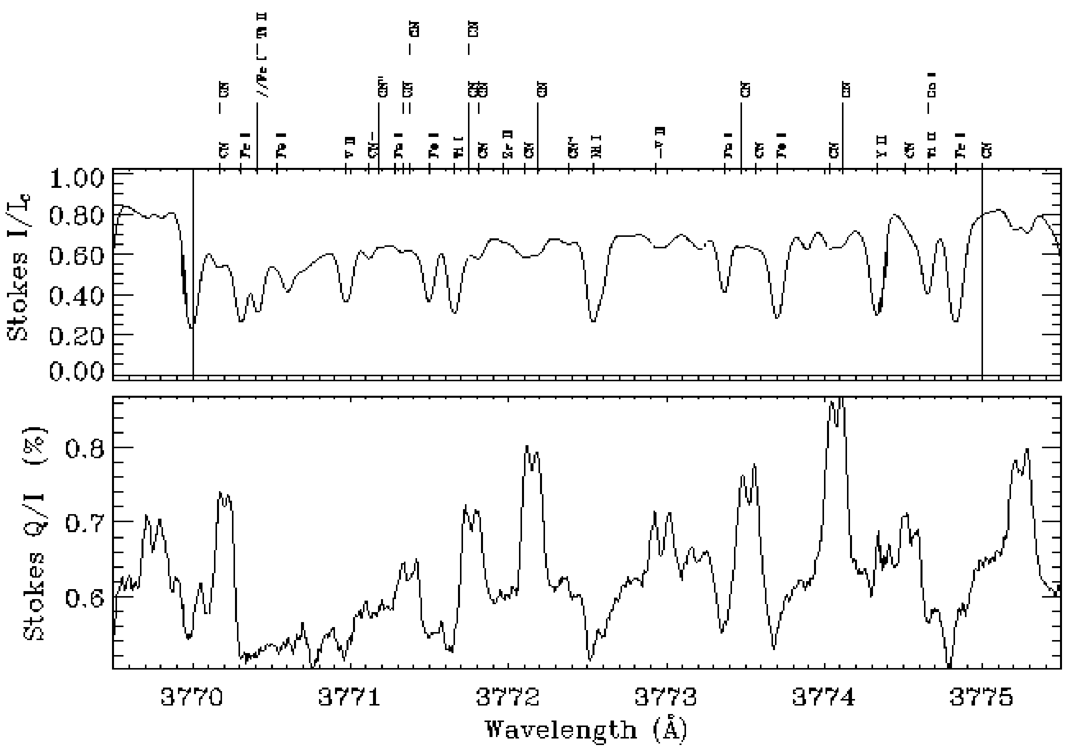
Corona: Not many applications due to field & emission weakness

Need active regions at the limb with strong coronal emission



[Solanki et al. 2003; Lagg et al. 2004]

Measurement of the 3-D magnetic vector (He I 10830 Å): identification of emerging loops & current sheet (*signature of heating*) high in the chromosphere



The Second Solar Spectrum

Volume I, II & III

Visible – UV Zeeman effect

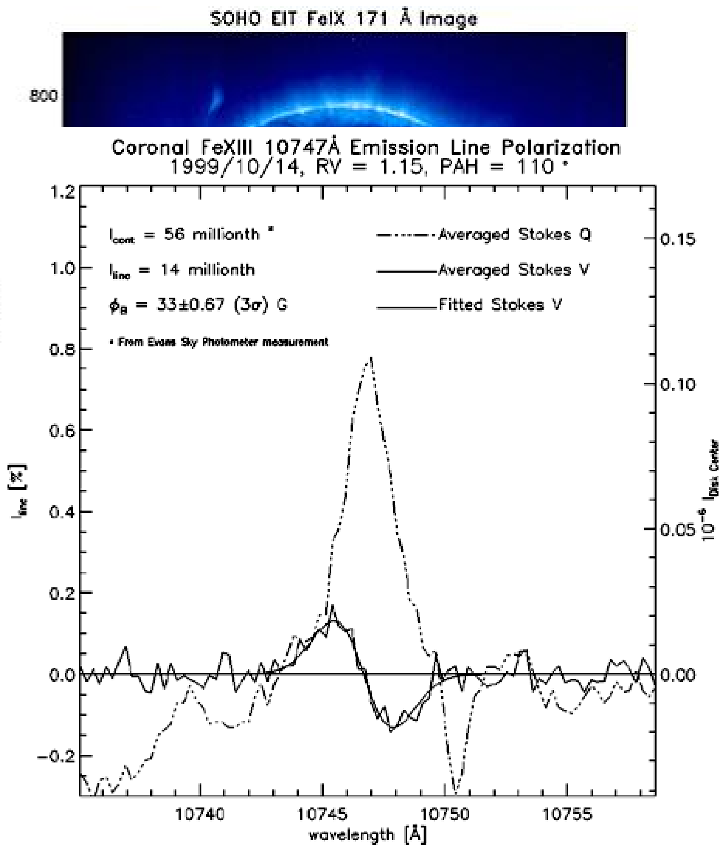
[Achim Gandorfer]

Coronal Zeeman effect

[Harvey 1969]
Fe XIV 5303 Å green line above active regions and in prominences
$B = 13 \pm 20$ G

[Kuhn 1995] **Fe XIII 10747 Å above active regions using Evans coronagraph:** Upper limit on B of 40 G

[Lin et al. 2000]
Fe XIII 10747 Å above active region
$B(1.12 - 1.15\ R_{\odot}) = 10 - 33$ G

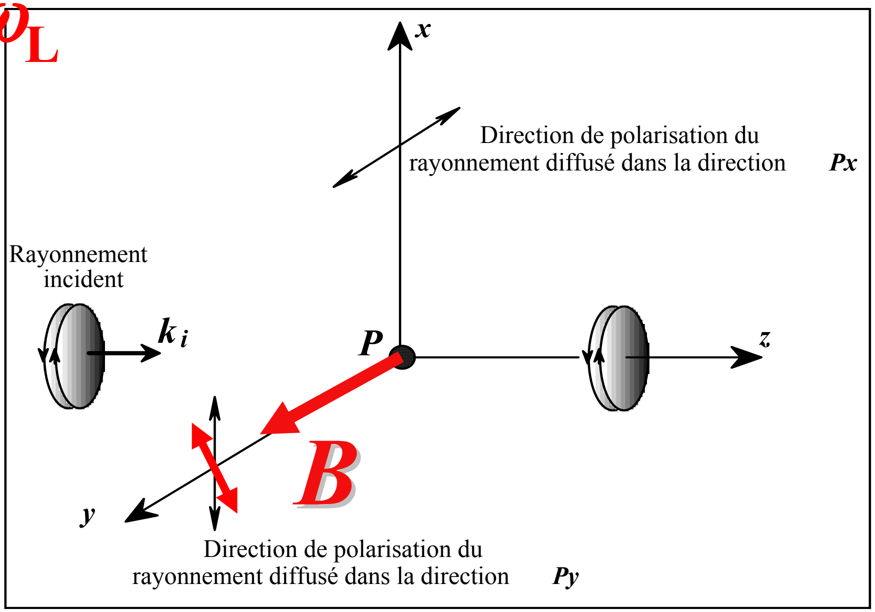


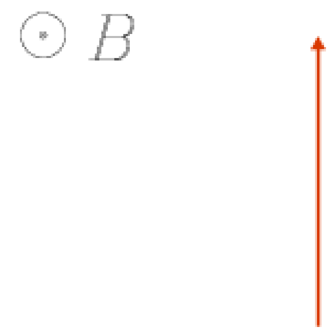
These measurements suffer poor spatial & temporal resolution

Hanle Effect: Modification of the linear polarization of resonant scattered radiation by a local magnetic field

Classical interpretation:

Excited atom ≡ damped ($\propto A_{ul}^{-1}$) oscillators precessing around ***B*** at ω_L





$$\omega\,\tau \approx 1$$
$$P \neq P_0\,;\varphi \neq 0$$

- ➢ ***P & φ are function of the three components of B***
- ➢ **Ideally Hanle effect provides non-ambiguous vector field**

The Hanle effect

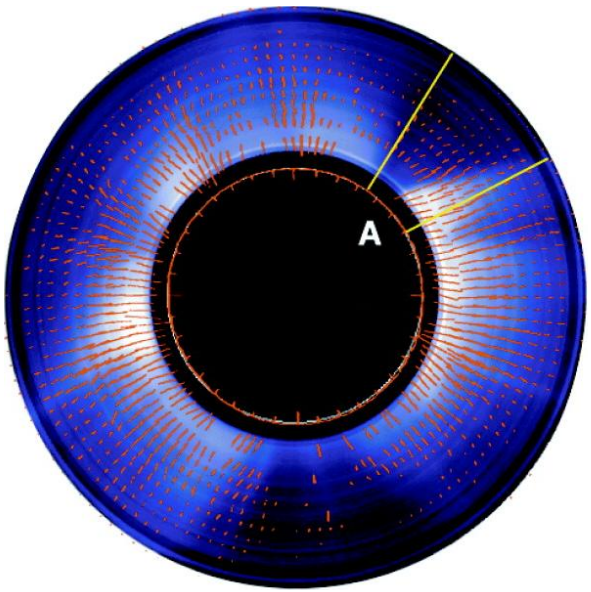
- * **Works for typical fields < 100 G (depends on the spectral line);**
- * **Needs high polarimetric sensitivity & moderate spatial resolution**
  (weakness of the Hanle signal)
- * **Needs resonance scattering:**
  Solar limb (Stenflo & Keller 1997; etc.; *Talk by J. Trujillo***);**
  Prominences (Sahal-Bréchot et al. (1977); etc.; *Talk by A. Lopez Ariste***)**

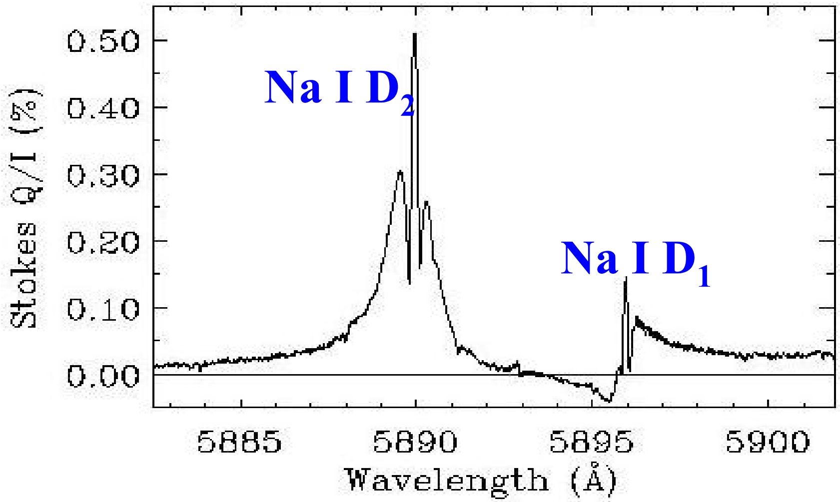
- * **Unlike Zeeman effect: Field strength from depolarization by turbulent fields [Stenflo 1982]**

- * **Hanle strong-field regime** ($\omega_\mathrm{L} >> A_{ul}$)
  Direction of the field [Charvin 1965]

[Querfeld 1974, 1977; Arnaud & Newkirk 1987; …]

Mainly radial field *(Fe green & IR lines)*





[Stenflo & Keller 1997] Polarization picks in the corps of Na I D-lines Enigma!!!

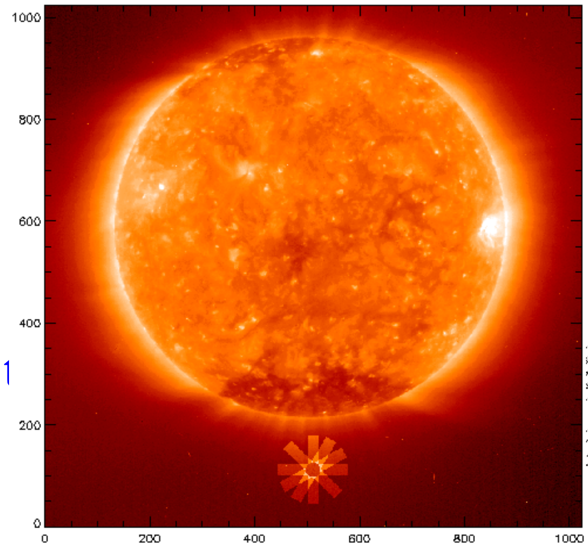
- **[Landi Degl'Innocenti 1998] Polarization in the ground level: "Evidence against turbulent and canopy-like magnetic fields in the solar chromosphere" or milligauss field**

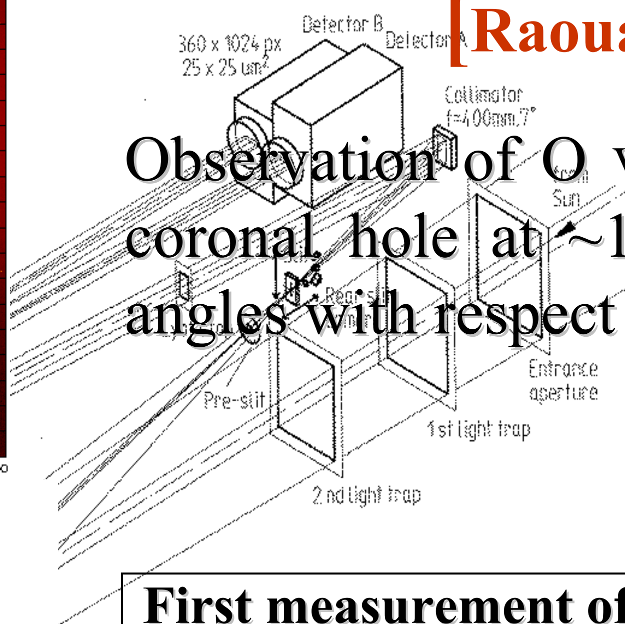
- **[Bianda, Stenflo & Solanki 1999] Hanle depolarization of lines with unpolarized lower level: evidence forturbulent and/or canopy-like fields**

- **[Schrijver & Zwaan 2000] Na I D-lines are formed below the canopy & above the turbulent photospheric fields of few Gauss strength that drop off very fast**

- **[Trujillo Bueno et al. 2003]**
  Multilevel radiative transfer modeling + Optical pumping:
  New insight into chromospheric fields

Hanle effect works better in the UV





[Raouafi et al. 1999 & 2002a,b]

Observation of O VI 1032 Å in the polar coronal hole at ~1.3 $R_\odot$ under different angles with respect to the polar axis

First measurement of the polarization of a UV line in the corona

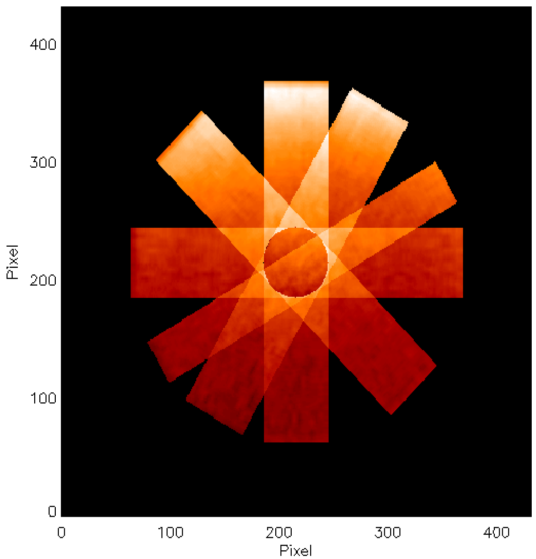
Capability of rastering

$p = 9 \pm 2$ % ; $\varphi = 9 \pm 6°$; $r = 2.88 \pm 0.05$

Constraints on the magnetic field in the polar coronal holes: B ~ 3 G

on of SUMER's polarization sensitivity

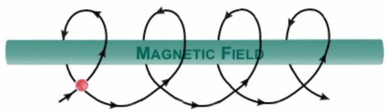
[Hassler et al. 1997]



$\varphi \neq 0$: Evidence of Hanle effect signature in the polar coronal holes

⇨ Possibility of measuring the magnetic field in the corona using UV lines

Gyroresonance emission



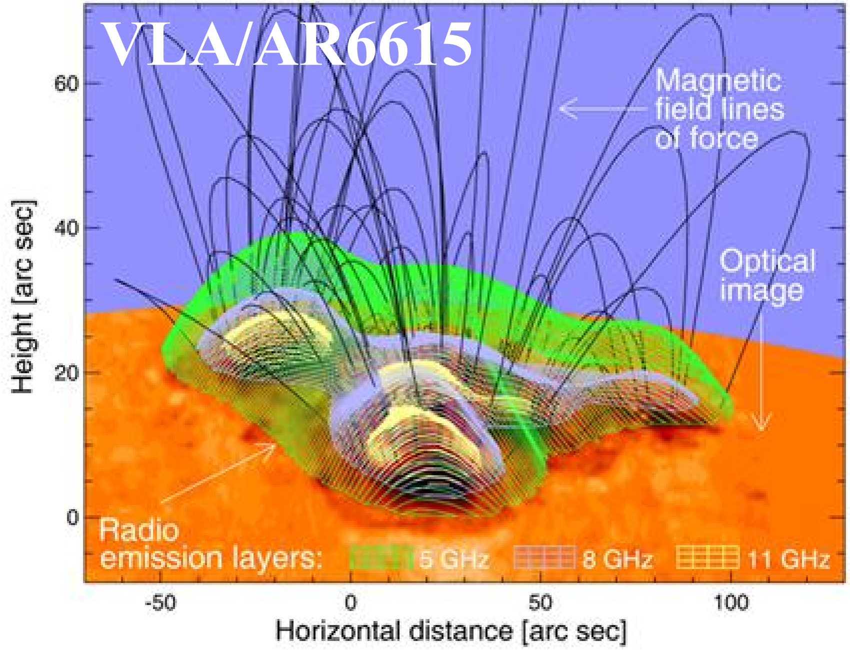
☞ **Interaction of the circular polarized electromagnetic modes (*x* & *o*) with the electrons yield a strong circular polarization signal**

⇒ Powerful diagnostic of $100 \leq B \leq 2000$ Gauss

☞ **Opacity is significant only at the first discrete harmonics of ω_B:**

$$B_{max} = \frac{\nu_{\tau=1}}{2.8\,10^6\, s} \left(s = 2 \text{ or } 3\right)$$

Observing at the different harmonic frequencies yield isogauss surfaces of the magnetic field at different coronal heights ⇔



[Lee et al. 1998]

Limitation: **No information on the Gyroresonance emission height**

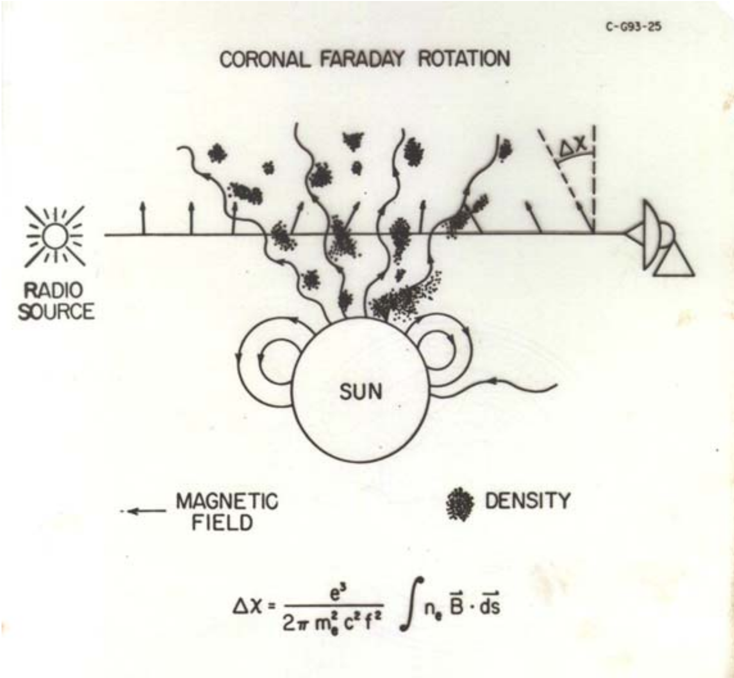
Compensation:

Stereoscopic observations [Aschwanden & Bastian 1994]

Extrapolations [Lee et al. 1998]

…

Faraday rotation: Rotation of the plane of linear polarization of radio radiation propagating through a magnetized plasma with density n_e



Radio refractive index

$$n^2 \approx 1 - \frac{\omega_p^2}{\omega^2}\left(1 \mp \frac{\Omega_e}{\omega}\right) \quad \begin{cases} \omega : & \text{wave frequency} \\ \omega_p : & \text{plasma frequency} \\ \Omega_e : & e^- \text{ gyrofrequency} \end{cases}$$

$$v_p = c \mp \frac{c\,\omega_p^3}{2\,\omega^3}\,\Omega_e \quad \begin{cases} - \text{ RH circular polarization} \\ + \text{ LH circular polarization} \end{cases}$$

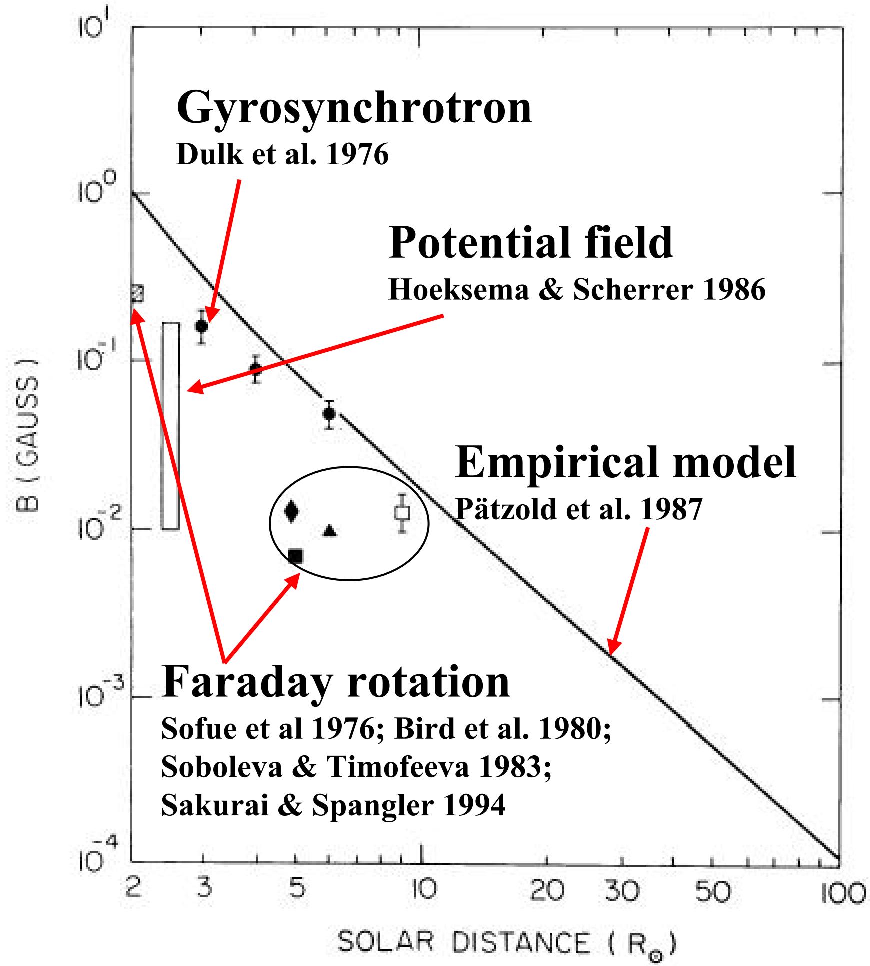
Rotation of the plane of linear polarization by

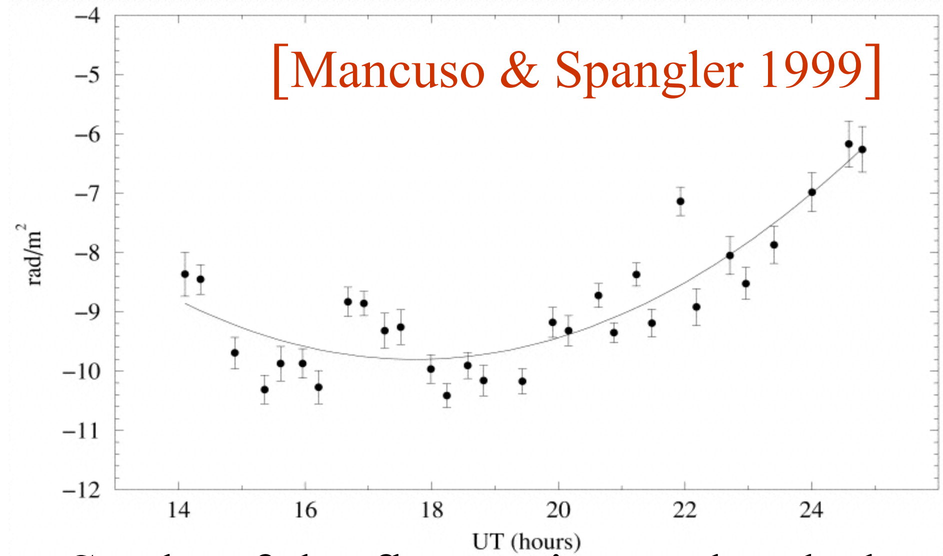
$$\Delta\chi \propto \int_{\mathrm{LOS}} n_e\, \vec{B} \cdot \vec{\mathrm{ds}}$$

[Nicholson 1983]

Coronal Faraday effect is effective from ~ 4 to ~ 15 $R_\odot$ & during occultation of

* **Natural sources** (*Galactic or extragalactic:* **Sofue et al. 1976; Bird et al. 1980; Mancuso & Spangler 1999; ...**): Advantage is the existence of these sources around the Sun & their spatial extend
* **Interplanetary space probes** (*PIONEER:* **Stelzried et al. 1970**; *HELIOS:* **Bird 1982, Pätzold et al.1987; ...**): Observations are only possible close to the ecliptic & rare



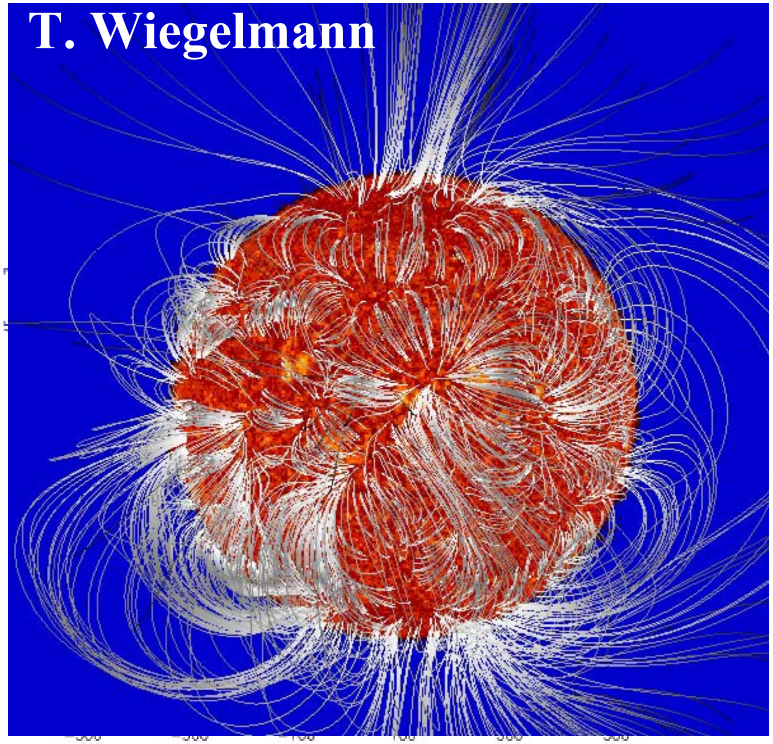


Study of the fluctuating and turbulent component of the coronal plasma (***B, n_e, waves***) through time variations of rotation measures (RM) [Hollweg et al. 1982; *HELIOS*]

Magnetic field in CMEs B(7.5 $R_\odot$) = 10 - 20 mG [Bird et al. 1985; *HELIOS*]

Limitations of the method: Occultation occurs infrequently; 2-D mapping is not possible; Model dependence of Faraday rotation (Needs density model n_e to diagnose **B** and visa versa)

Extrapolation of the magnetic field



Potential fields (*J*=0: simple topologies);
Linear & Non-linear force-free field
(*J*//*B*: complex topologies)

Powerful tools for evaluating

- **The energitics and activity of coronal magnetic structures (active regions, filaments, loops, etc.)**
  [Heyvaerts & Hagyard 1991; Amari et al. 1999; ...]
- **Coronal flows [Marsch et al. 2004]**
- **Large scale coronal field [Wiegelmann et al.]**
- **...**

Need accurate photospheric fields: errors may affect the reconstruction of the coronal field [klimchuk & canfield 1994]

Force-freeness of photospheric fields? Values of α may not be appropriate in the corona since the photosphere is not force-free [Metcalf et al. 1995]

Need chromospheric & coronal measurements to constraint extrapolation models + Proxies (loops, ...) for comparison

Other methods

Bremsstrahlung emission

LOS averaged field strengths from circular polarization signal from actives regions (accuracy as low as 1-6 Gauss with RATAN-600 & VLA radio telescopes)

[Brosius et al. 1997; Bogod & Gelfreikh 1980; Gelfreikh 1994; …]

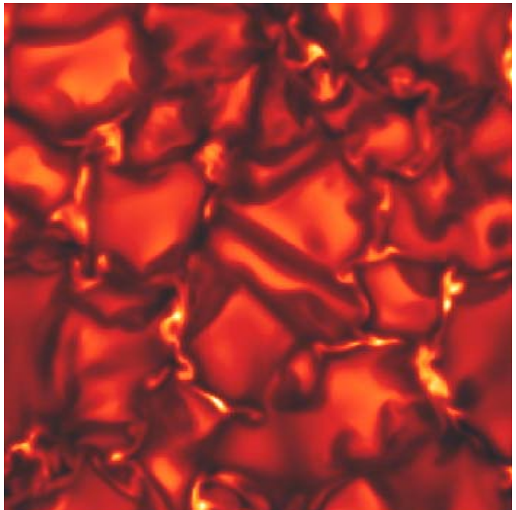
Talk By S. White

Coronal loop oscillations

Flare-generated oscillations of coronal loops:

Absolute value of the magnetic field strength [Nakariakov & Ofman 2001]

Simulations

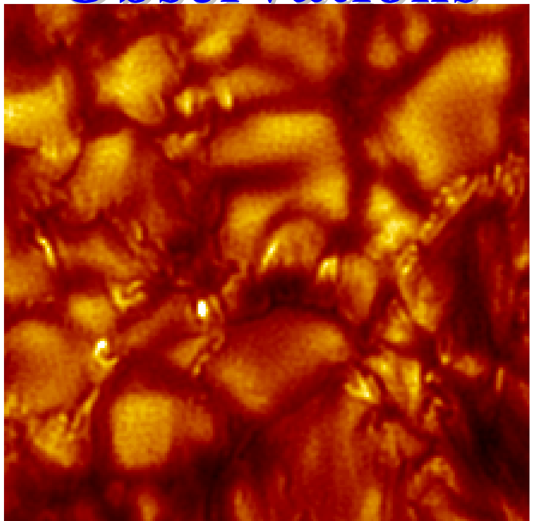


G-Band

20 km resolution
[Schüssler et al. 2003]

SST ~100 km resolution
[Scharmer et al. 2002]

Observations



Magnetometry (*future projects*)

Coronal field:

Advanced Technology Solar Telescope (**4 m; 2012; Polarization in the infra-red);**

Solar Probe (2013) **Two solar polar passes at ~4 $R_\odot$: Golden opportunity for in-situ measurements of the coronal field close to the Sun**

Chromospheric field:

GREGOR Tenerife **1.5 m**; wind flushing; λ= 0.39 nm – 2.5 μm; FOV 300″; Spatial resolution **70 km**; Adaptive optics

Beat the Seeing

DOT++ La Palma **1.4 m;** wind flushing; Adaptive optics (speckle reconstruction); Spatial resolution 0.07″

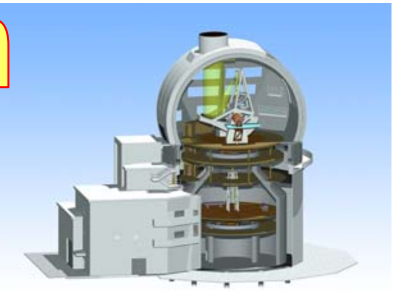
Towards the Building Block

New Solar Telescope BBSO (2006) **1.6 m**; high-order Adaptive Optics; Real-time speckle image reconstruction; Visible & infrared (IR) polarimetry; λ = 0.39 - 1.6 μm; Spatial Resolution: **0.07″ at 500 nm & 0.11″ at 1.56 μm**

of Stellar Magnetism

Advanced Technology Solar Telescope (Haleakala, Hawaii) **4 m**

Polarization sensitivity **10^{-4}**; λ = 0.3 - 35 mm (UV – IR);
Spatial resolution < **0.1″**; High-order adaptive optics



Conclusions

What is needed is complete picture for the solar atmosphere

- **Combine the different techniques: Proxies; Zeeman & Hanle effects; radio observations; Simulations, ...**
- **Simultaneous multi-line observations: field at different layers**
- **Combine ground and space observations**
- **Improve measurements of the other plasma parameters (densities, temperatures, flows, …)**
- **…**

Future of the solar magnetic field

- **Promising future for strong fields**
- **More work has to be done for weak fields**
- **Much more work is to be done for the coronal field**