University of Glasgow | School of Physics & Astronomy

SUPA course: The Sun's Atmosphere

Session 2021-22

Lecture 10 on "Observing and interpreting solar magnetism"

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The course thus far :

10/01/2022	Lecture 1: Introduction (Labrosse)
11/01/2022	Lecture 2: Solar atmosphere (Labrosse)
17/01/2022	Lecture 3: Plasma physics 1 (Kontar)
17/01/2022	Lecture 4: Plasma physics 3 (Kontar)
24/01/2022	Lecture 5: MHD 1 (MacTaggart)
25/01/2022	Lecture 6: MHD 2 (MacTaggart)
01/02/2022	Lecture 8: Radiation transport (Labrosse)
07/02/2022	Lecture 9: The solar photosphere (Hudson)
08/02/2022	Lecture 10: Solar magnetism (Hudson)

Useful homework questions based on this material

- Can one detect an oscillating coronal loop by Doppler shifts?
- For what value of B can a flux tube escape from the tachocline and emerge in one cycle?
- What is the electrical potential at the photosphere?
- At what stereoscopic angle can Stokes (I,V) do better than Stokes (I,Q,U,V)?

These are questions to be answered by rough approximation, and the necessary facts should be here on the slides. I will post discussion of these items on Files and at

http://www.ssl.berkeley.edu/~hhudson/presentations/supa.220207/

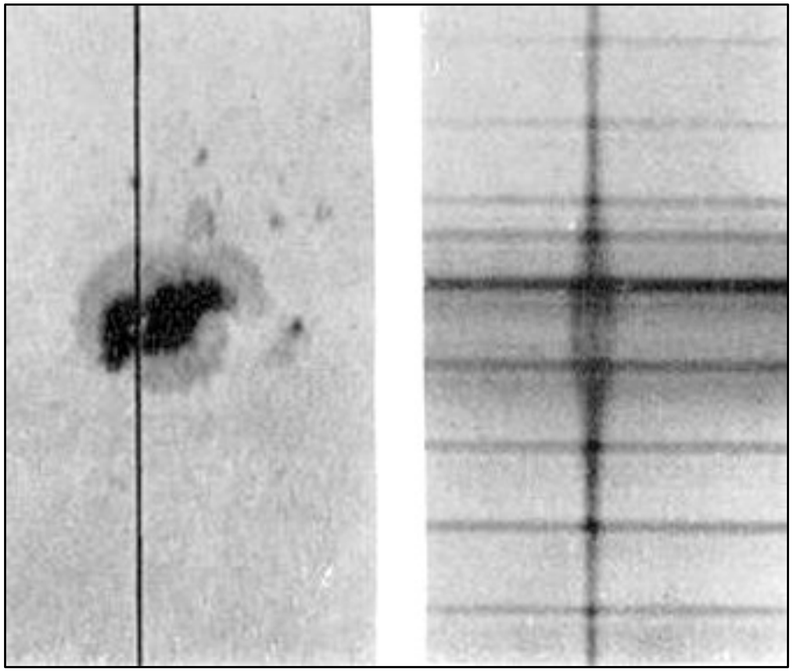
Sunspots and faculae are magnetic in nature

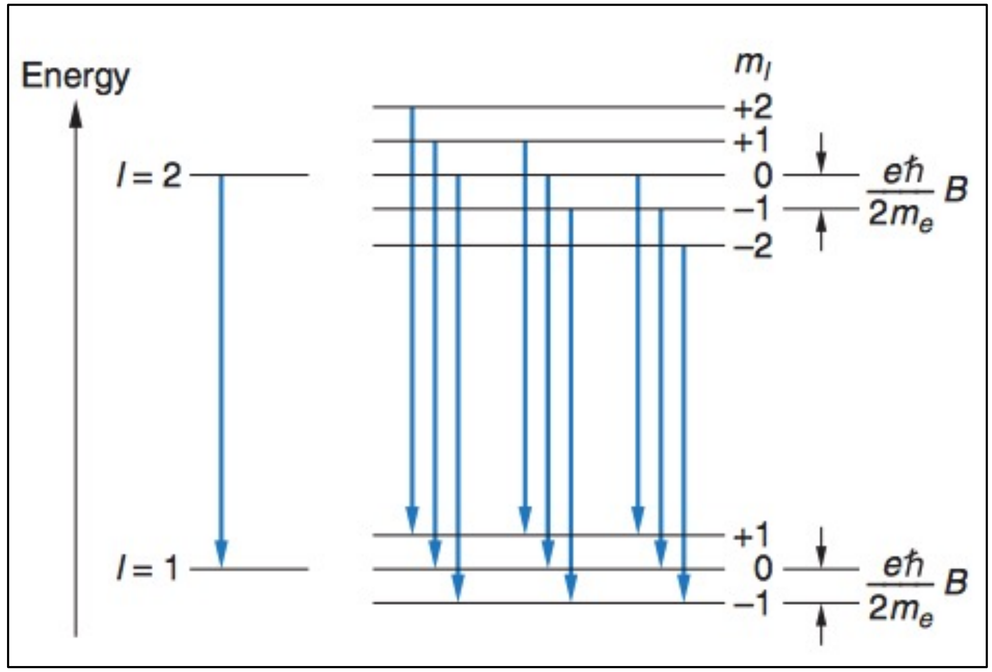
• The *spectroheliosope*, invented in the 19th century, enabled monochromatic views, for example in $H\alpha$.

• The measurement of circular polarization enabled Hale to recognize Zeeman splitting in sunspot umbrae, confirming the hint given by vortex-like patterns of $H\alpha$ fibrils.

• As reported by Jurčák et al. (2018) an umbra forms wherever $B_z > 0.14$ T (a fridge magnet!)

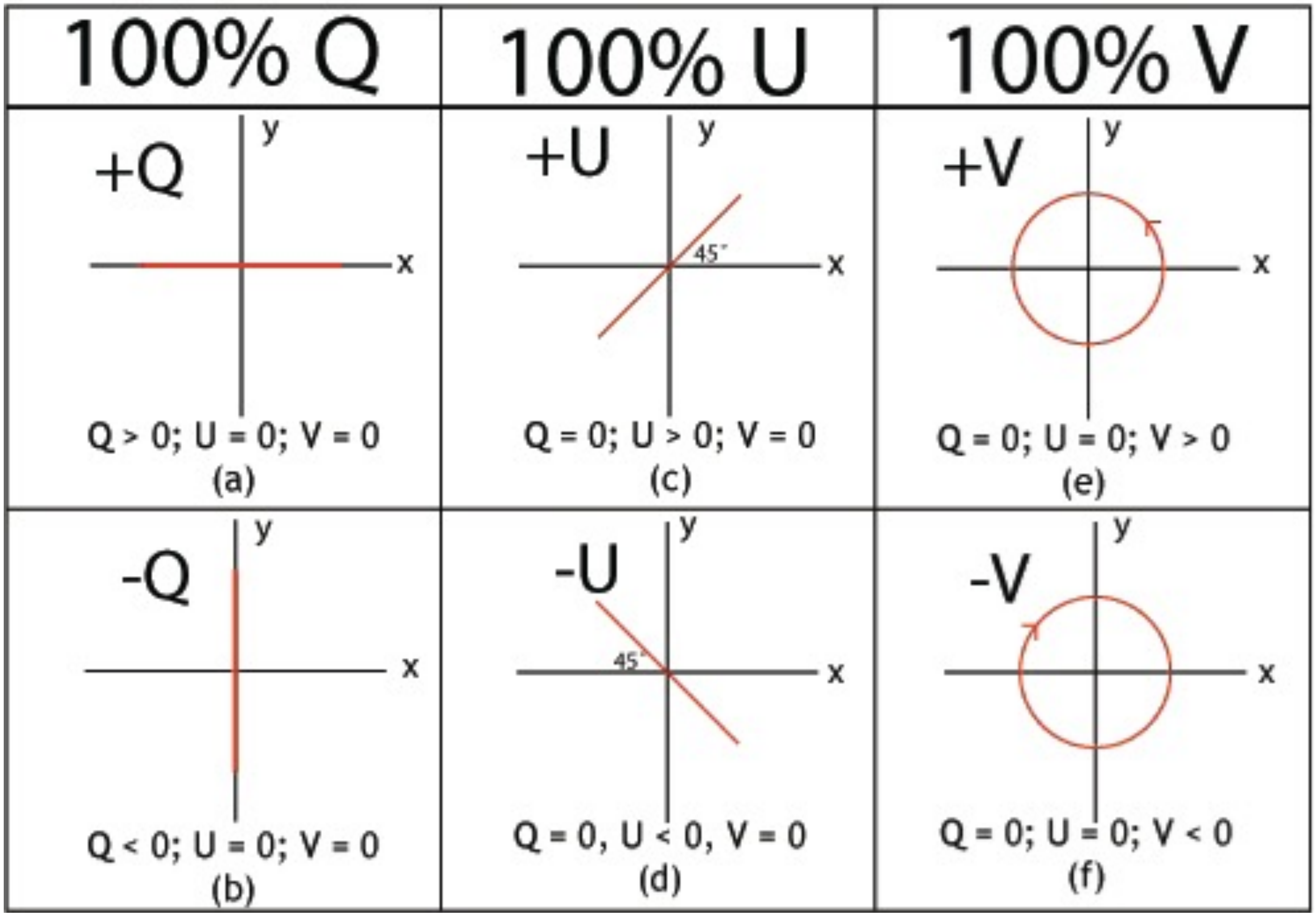
The Zeeman effect





- Magnetic fields distort atomic energy levels in a polarized manner.
- For sunspot 0.1 T fields, the splitting is visible to the naked eye in a spectroscope. The “Bohr Magneton” is 5.788 x 10^{-5} ev/T.
- The splitting depends upon the angle <B, eye>: the σ components (linear polarization) reflect the perpendicular field, whereas the π components (circular) reflect the line-of-sight field.

Three of the Stokes parameters



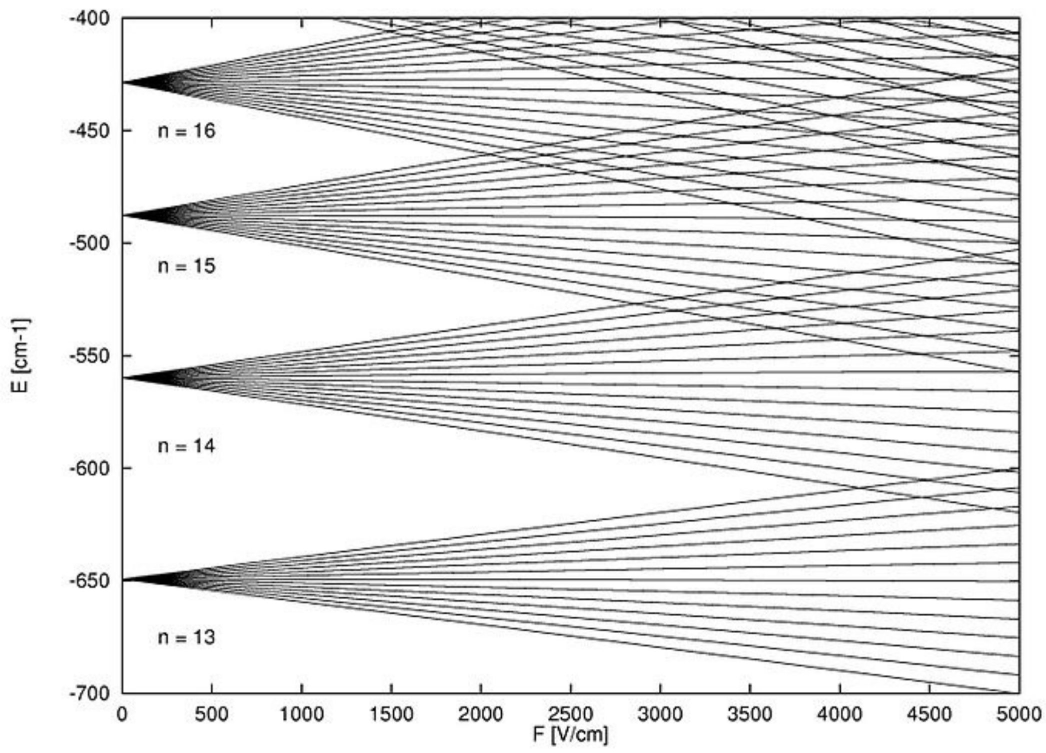
(the fourth Stokes parameter is just the intensity I)

Other observations of B

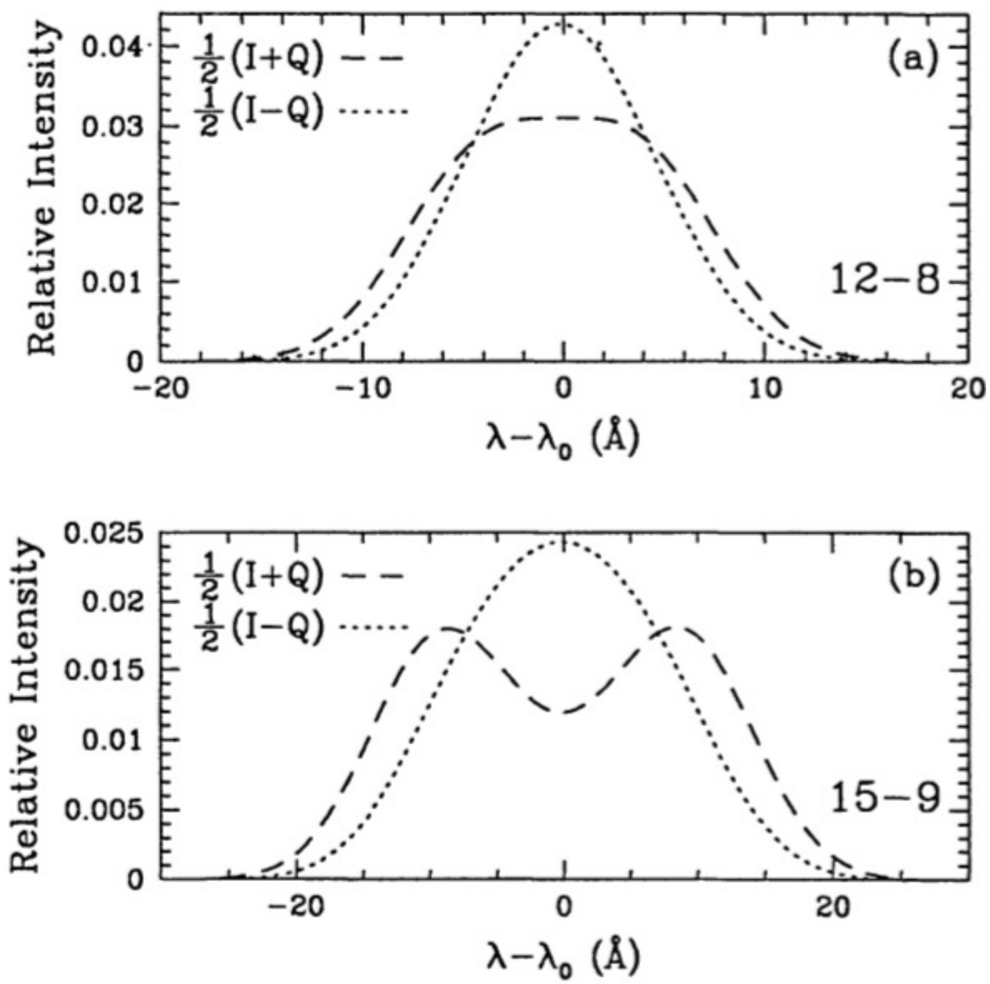
- The Hanle effect results from line depolarization when the collision frequency exceeds the Larmor frequency.
- Faraday rotation alters the polarization angle of a linearly polarized background source (e.g., a quasar).
- Image striations can be interpreted in terms of field direction: note that would be ~2/3 of the problem of measuring **B(r)**.
- Gyrosynchrotron radiation has natural circular polarization.
- Birefringence effects polarize even thermal emission from magnetized plasmas.

E observations

- The Stark effect results from level shifts due to the presence of an electric field (the generic term).
- Pressure broadening is the Stark effect at the atomic level in a dense plasma.



Stark Effect



Casini-Foukal 1996

- The effect is strongest for "Rydberg" states (e.g., n = 20), hence ALMA?
- Minimum detectable macroscopic fields may be of order 100 V/m.

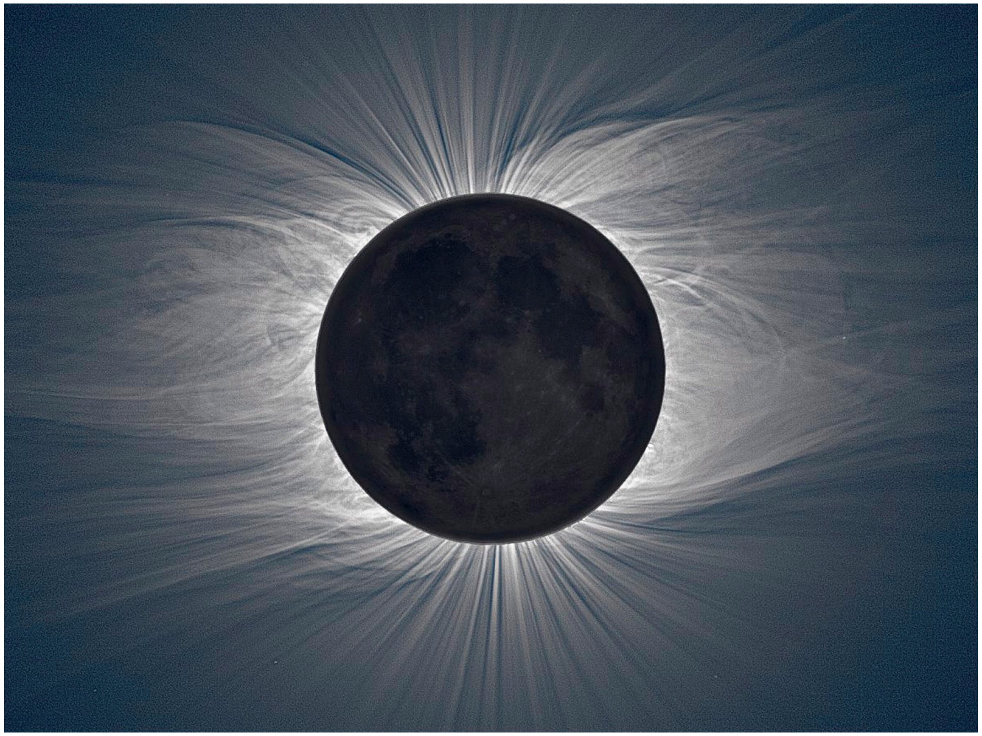
Data cubes

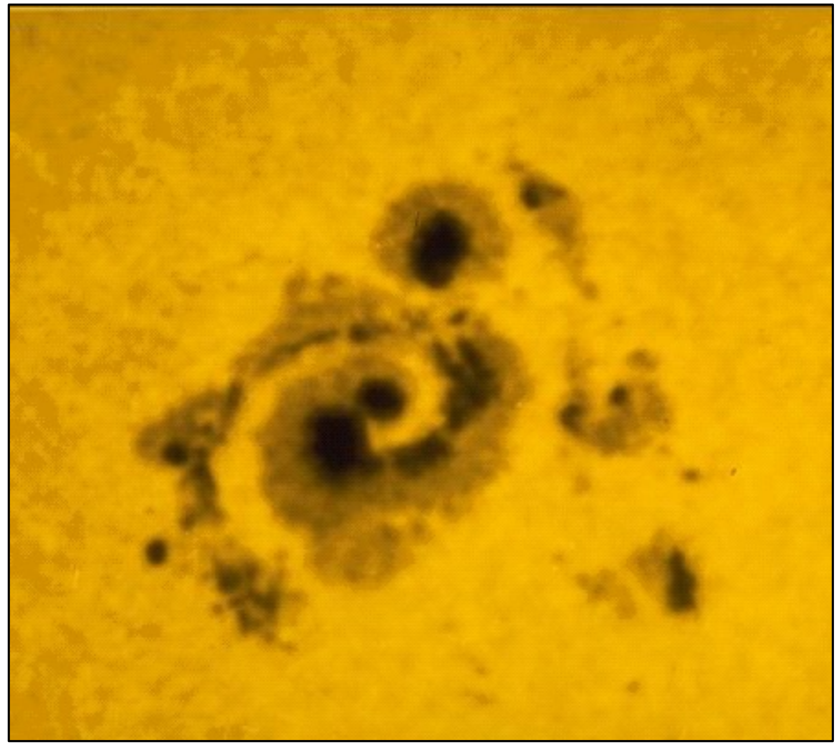
- The measurement process yields fluxes and errors: $f(x,y,\lambda,p,t)$ and $\delta f(x,y,\lambda,p,t)$.
- In principle the four Stokes parameters must be measured, with attendant problems in radiative-transfer theory; to get I, Q, U, V means four independent spectra are needed at each pixel and time: $f(\lambda,p)$ with p = [I,Q,U,V]

- Observational caveats: line-of-sight confusion and differing heights of formation of each parameter.

The bottom line might be (4096,4096,1e5,4,1e5) for one hour's data: 1 EB (exabyte).

Solar magnetism



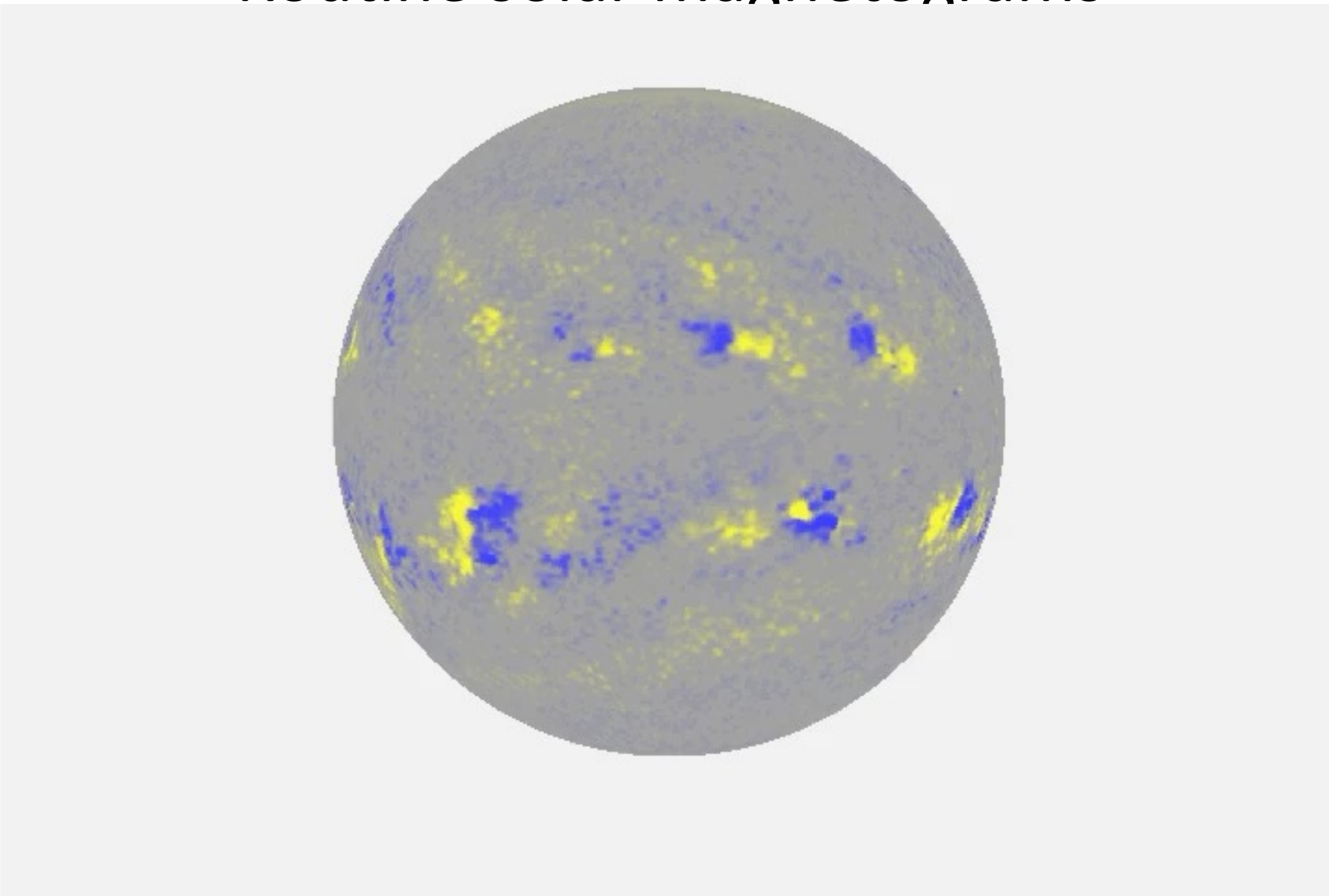


- The fine striations at the poles during an eclipse sure look like a dipole magnetic field.

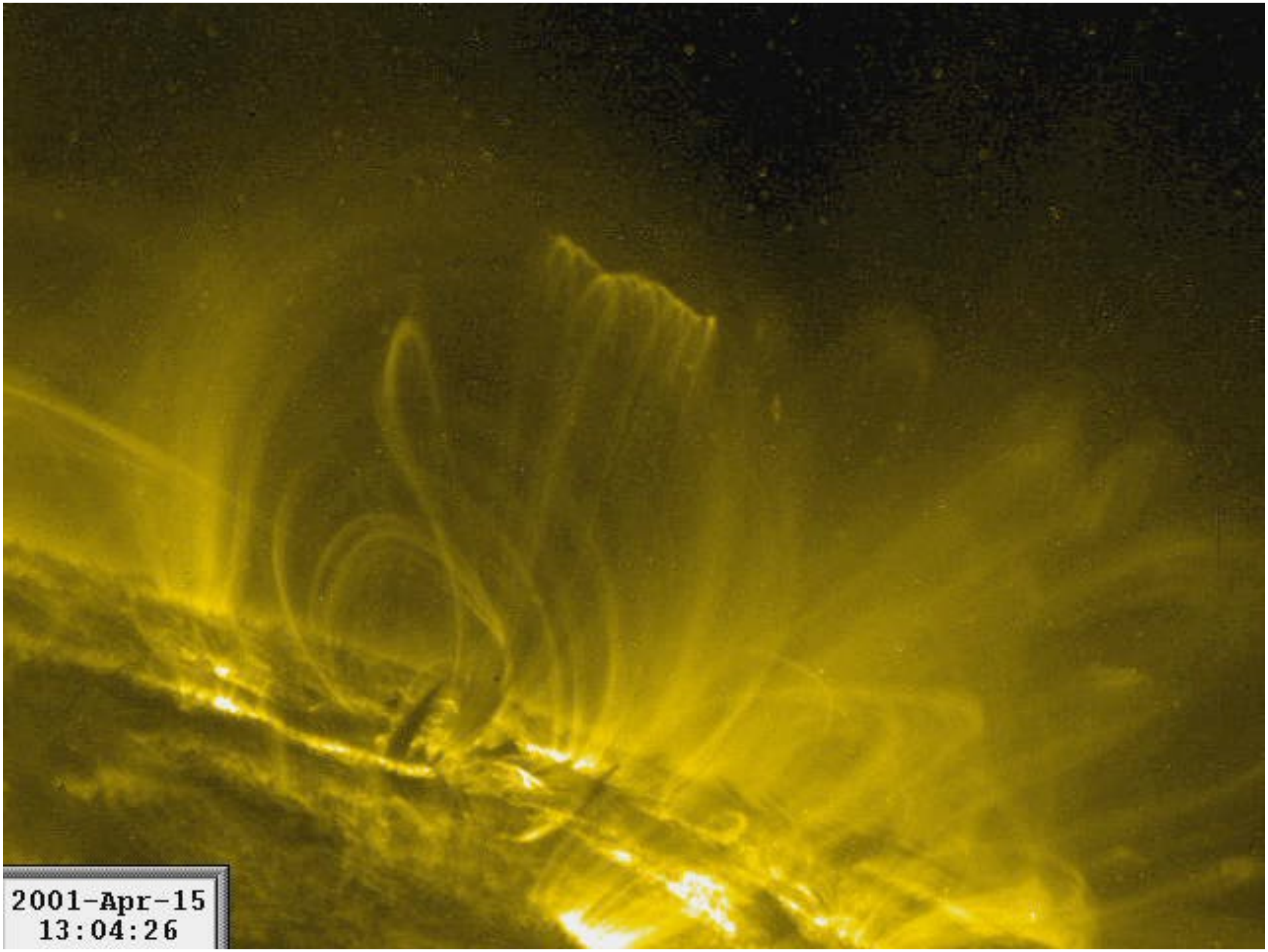
- Sometimes sunspots have spiral patterns.

- Sure enough, these clues led Hale to the Zeeman effect.
- But note that there is both a global field, and a local one.

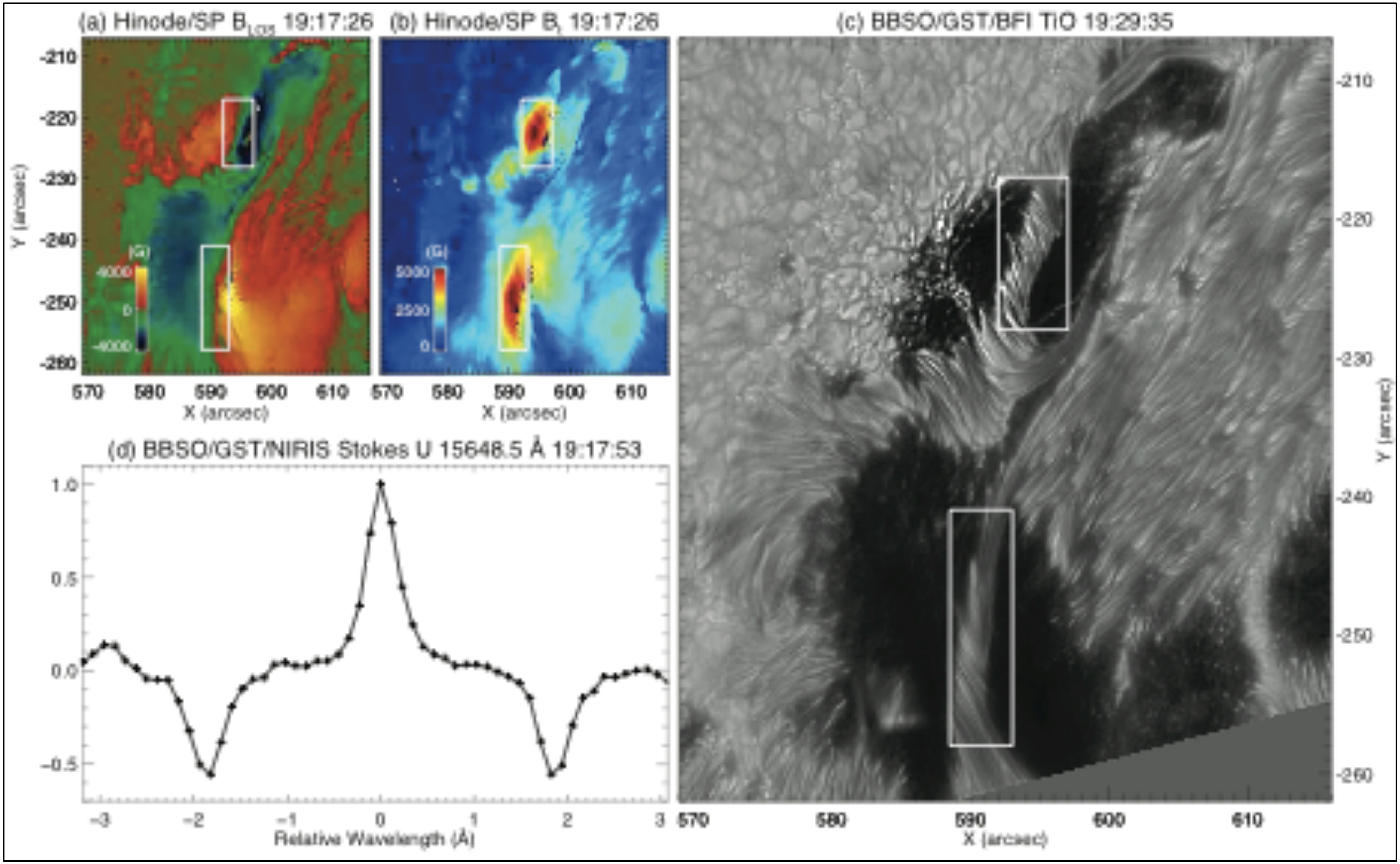
Routine solar magnetograms



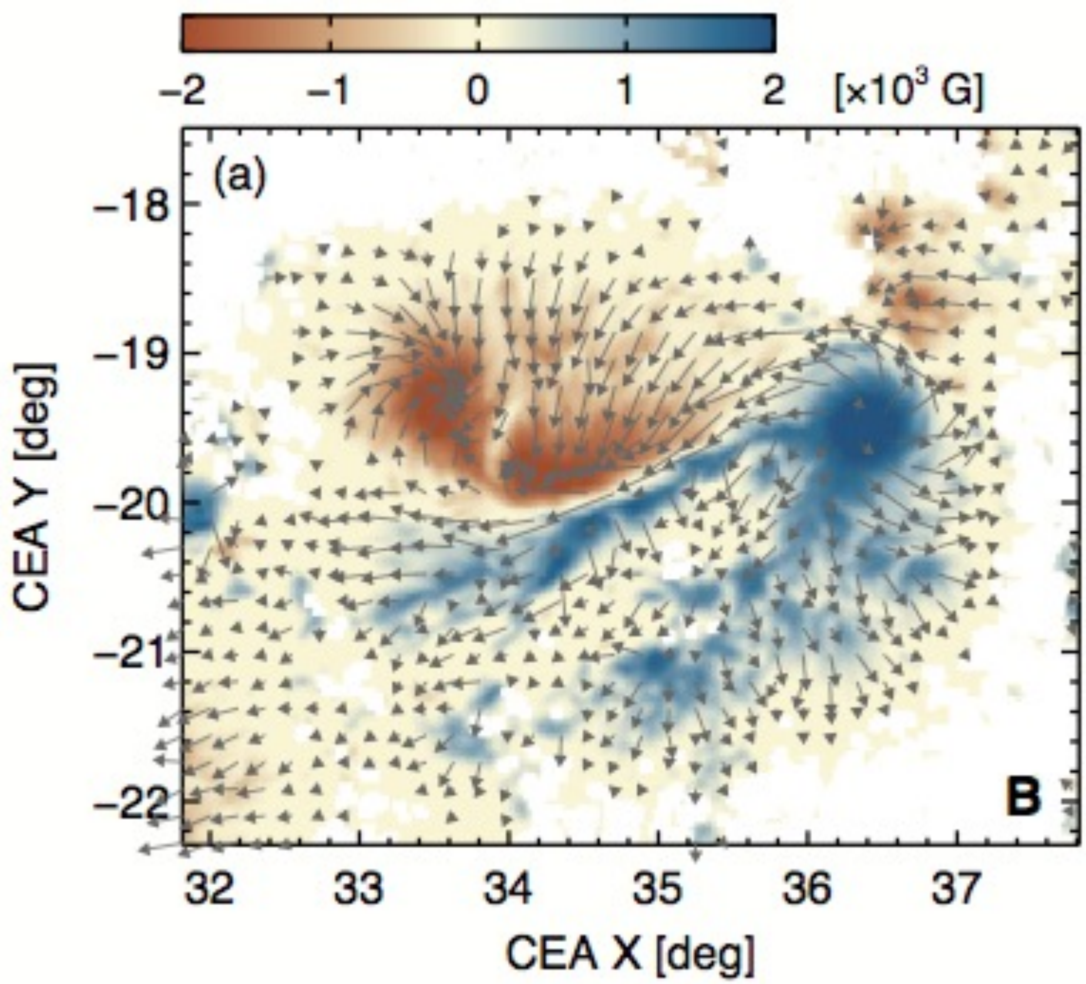
Magnetic transients II



Local: an extreme case

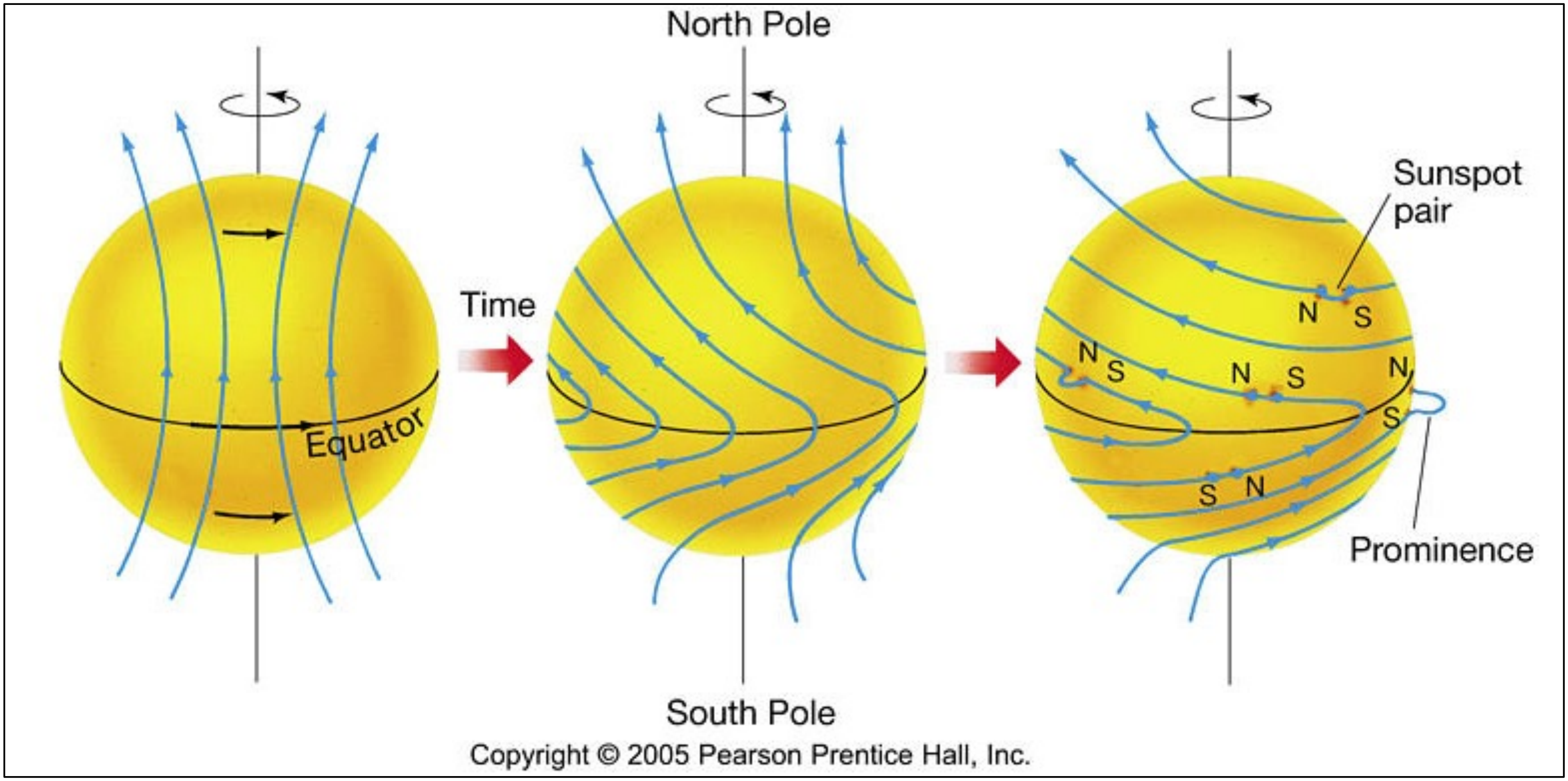


Vector field representation



With both parallel and perpendicular components, modulo a sign, one can infer the vector **B**.

Global: the Hale cycle



“Poloidal” fields amplify, due to differential rotation, and become “toroidal”

The problem of coronal magnetism

- We can use the Zeeman effect in the photosphere to determine the **B** (modulo symmetry-breaking) on a “surface,” but the 3D field is required to understand energetics.
- Unfortunately, the corona is optically thin – polarization signals are weak, and the structure is ill-defined because of the 3rd dimension.
- Can we just *extrapolate* from the photospheric boundary into the corona? With full Stokes info, we know the vector **B** in the “plane” of the photosphere.

Extrapolating the photospheric field

i) Field derived from a scalar potential (∇ **x B** = 0)
ii) Linear force-free models, LFF (∇ **x B** = α **B**)
iii) Non-linear force-free models, NLFF:
∇ **x B** = $\alpha(x,y)$ **B**

....

iv) MHD models: zero beta, "cold plasma"; $P_B >> P_g$

....

v) MHD models, multi-fluid MHD
vi) Non-MHD models: any dynamics, actually

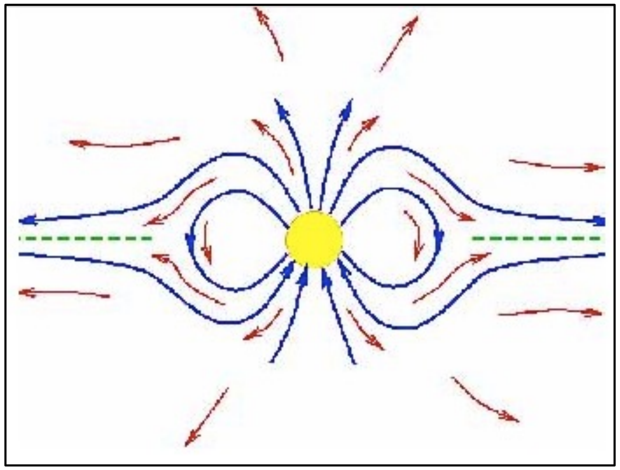
Potential fields

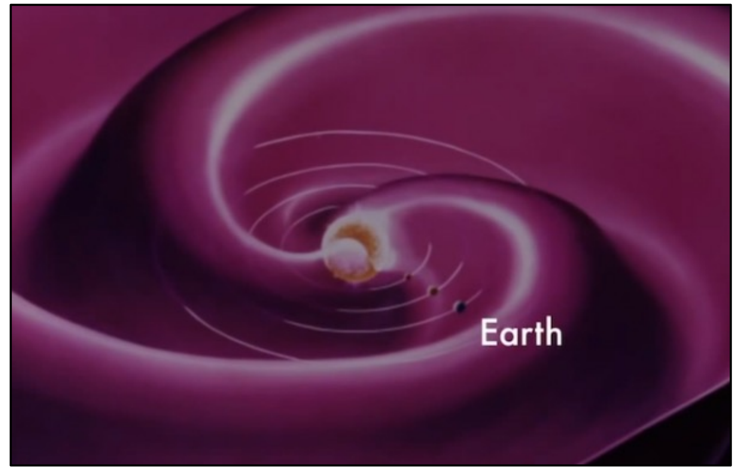
- Extrapolation would be OK if there were no plasma in the corona, but if that were the case we couldn't see it!
- We could in principle ignore this basic fact and just plow ahead.
- In the absence of currents (∇ **x B** = 0)*, one can uniquely extrapolate the coronal magnetic field via spherical harmonics.
- An example would be to represent the photospheric magnetic field as a set of *magnetic charges* from which a multipole expansion could determine the coronal field.
- In the popular "PFSS" model**, in which the Laplace's equation is solved inside a concentric spherical domain, outside of which the field is assumed to be radial.

* Thus, solutions of Laplace's equation: $\nabla^2 \mathbf{B} = 0$

** "Potential Field Source Surface"

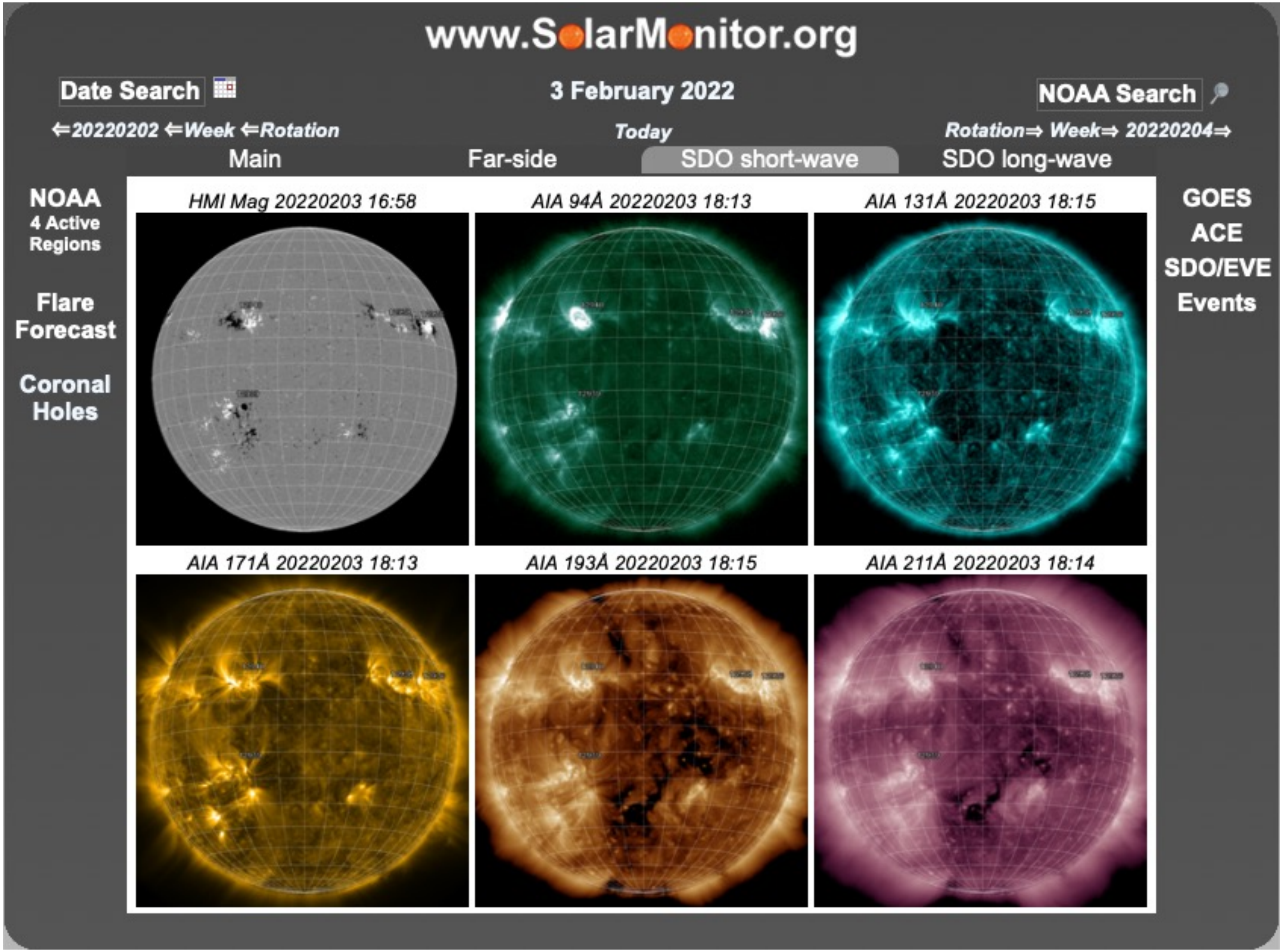
Heliospheric current sheet



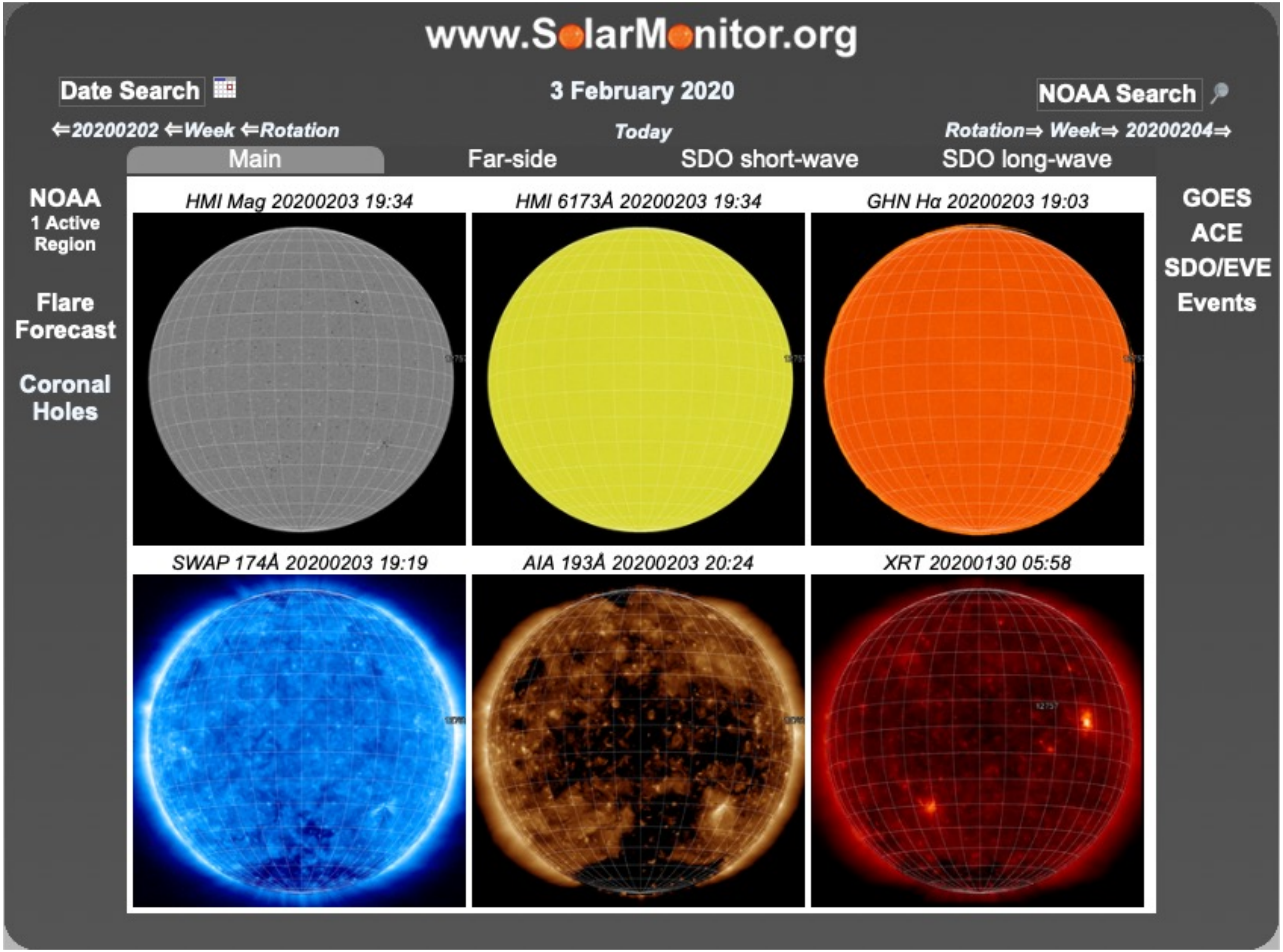


- A solar wind, with radial field, violates the potential-field concept of zero current.
- The rotation of the Sun induces a spiral pattern in the heliosphere due to the solar wind.
- Field asymmetry introduces warps ("sectors" at 1 AU) in the structure.

The Sun last week



Two years ago



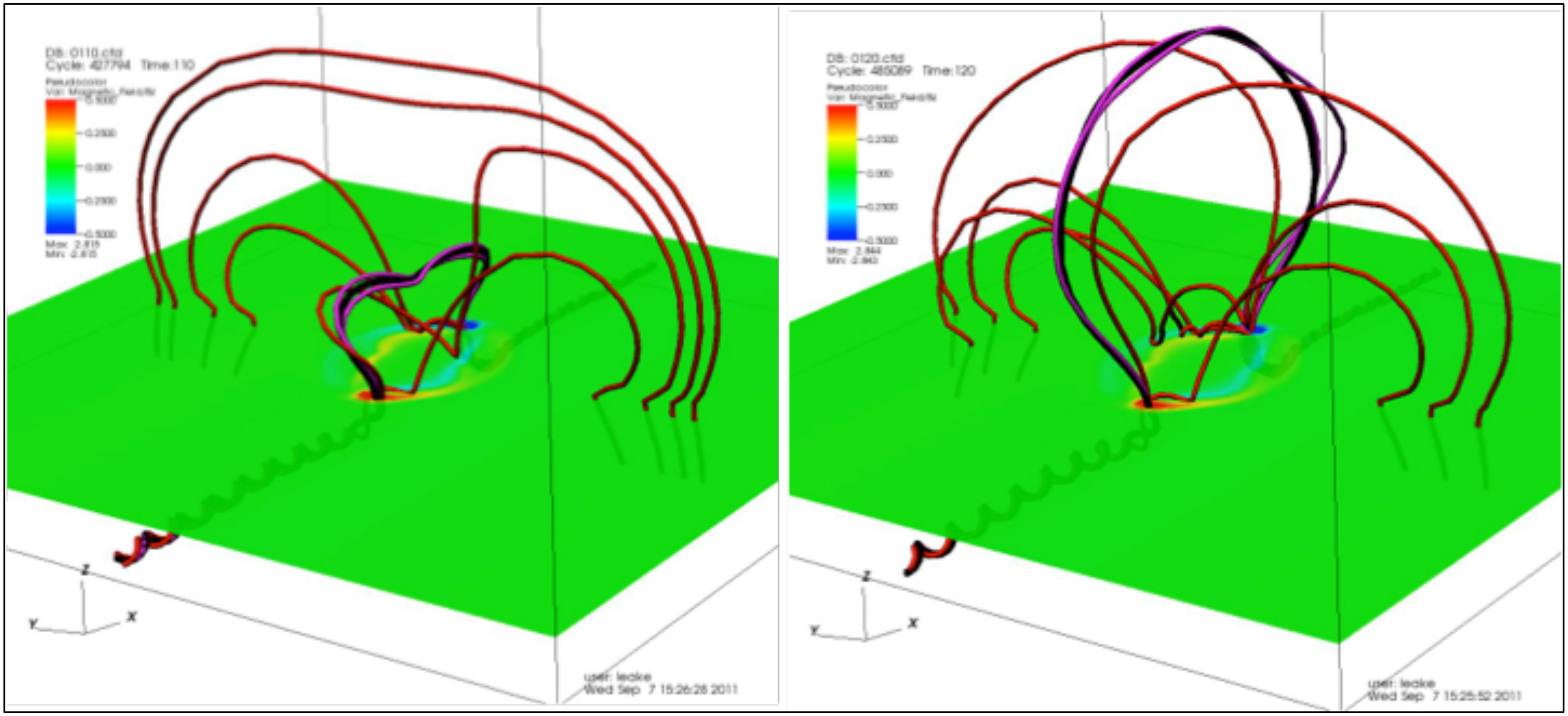
The stability of the coronal field

• A solar magnetic transient (flare or CME; coronal mass ejection) derives energy from the magnetic field: $\mathbf{B}^2/8\pi$ (in CGS units). It must become more potential-like as this happens.

• Identifying the plasma instabilities that do this is an open problem now, and of course very important for flare prediction ("space weather")

- Ideal MHD instability (no magnetic reconnection), such as the kink instability
- Resistive instabilities, such as the torus instability or the "tether-cutting" cartoon

The “torus instability”



• A *flux rope* forms above a *photospheric inversion line.*
• This structure is held in place by overlying field.
• Torok & Kliem (2005) suggest that if this overlying field decreases in strength with height, the structure may blow.

The "tail wags the dog?"

The corona is orders of magnitude less energetic than the photosphere, and yet…

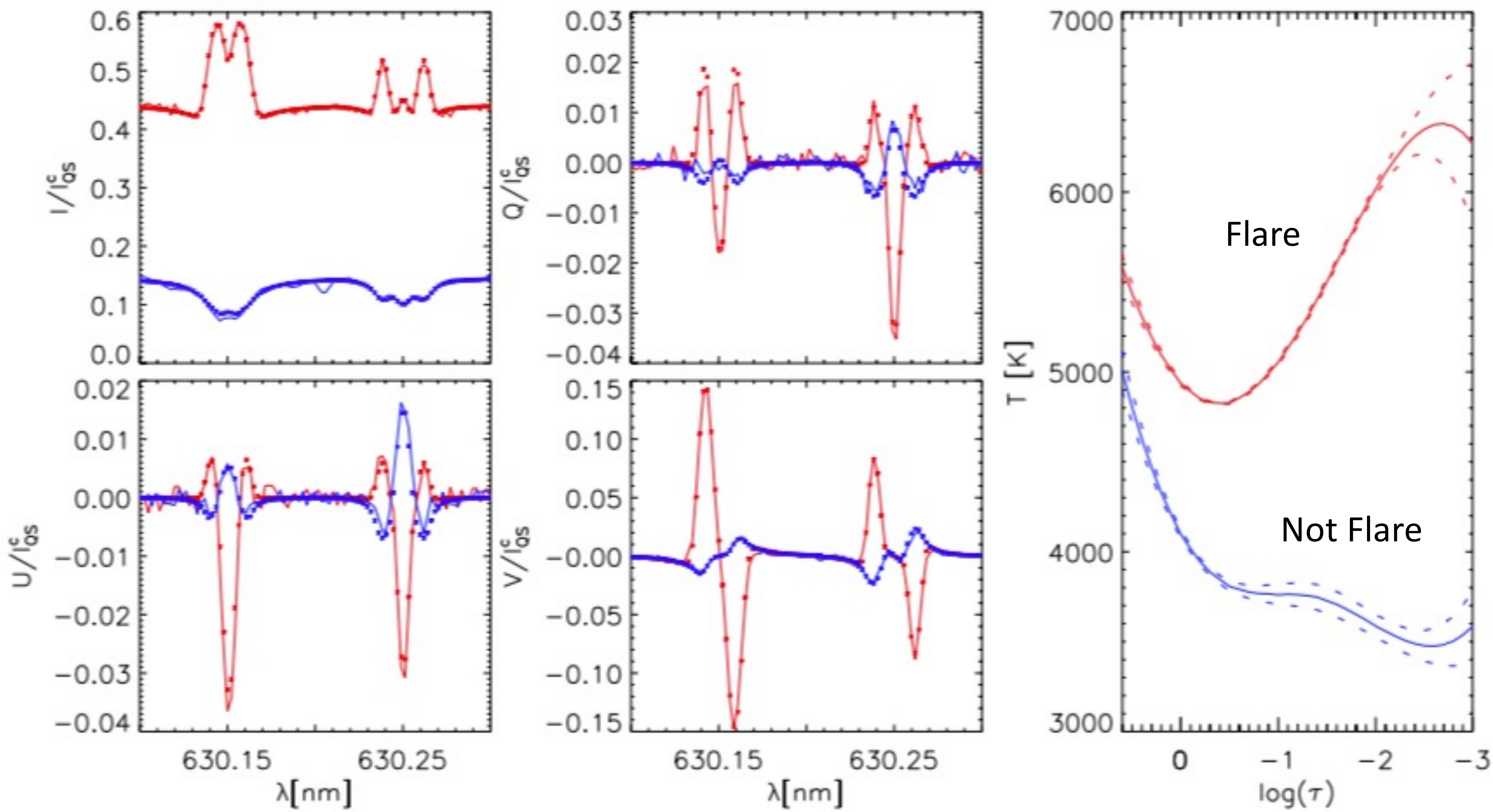
- We see "sunquakes," acoustic disturbances within the solar interior, following powerful flares.
- Flares may cause sunspots to rotate.

These and other effects have no established theoretical explanation.

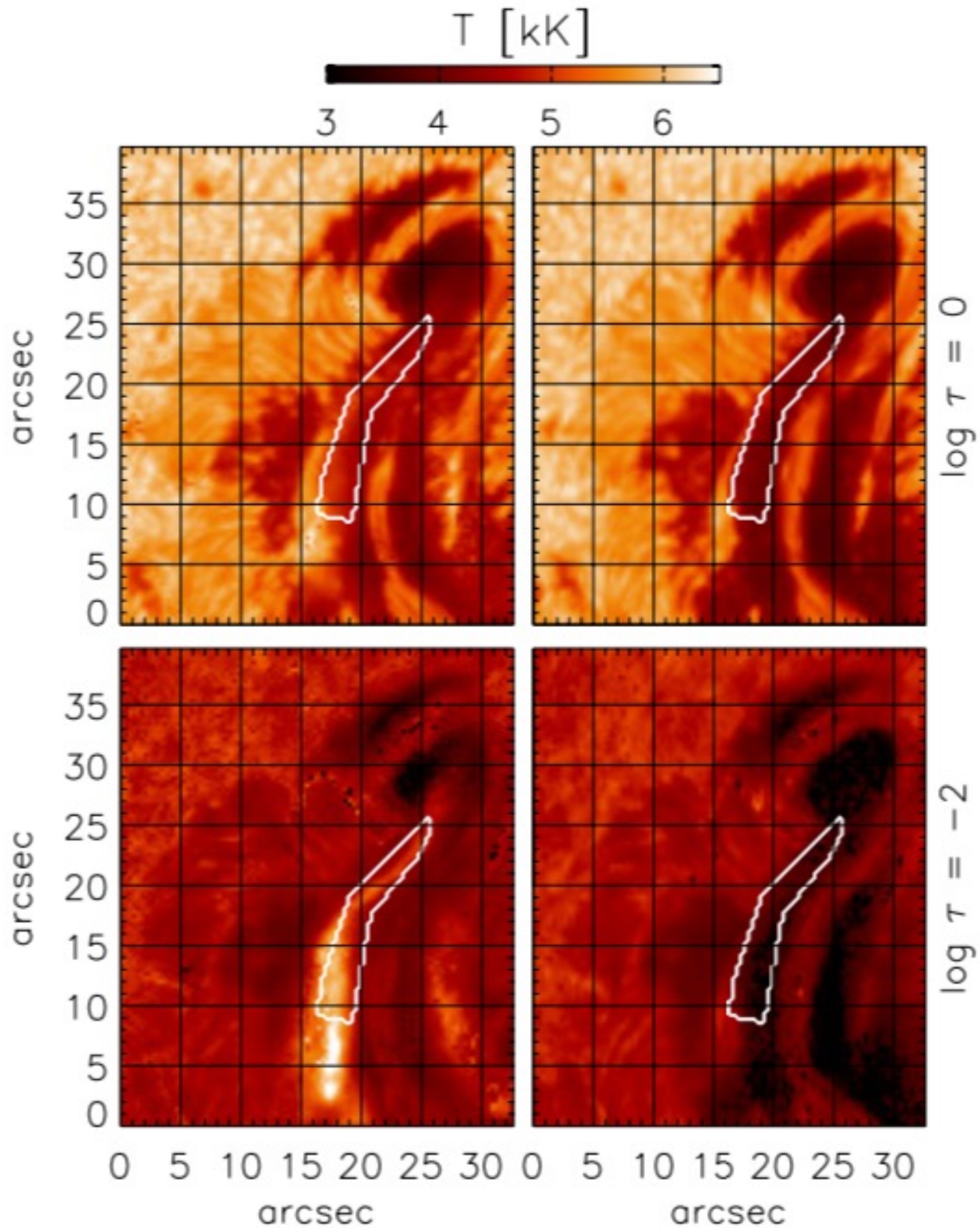
An exemple research paper

- Jurčák *et al.* 2018, “Heating of the solar photosphere during a white-light flare”
  - The behavior of an actual photospheric spectral line
  - “Line inversions” to obtain quasi-3D structure
  - What the Stokes parameters can tell you
  - How flares might work
- The ”SIR” Stoke Inversion code translates line profiles, “forward fitting” T to a coarse 1D map at 5 points over a four-decade range of optical depths: many, many assumptions!

Hinode line profiles and inversion for T



Hinode line profiles and inversion

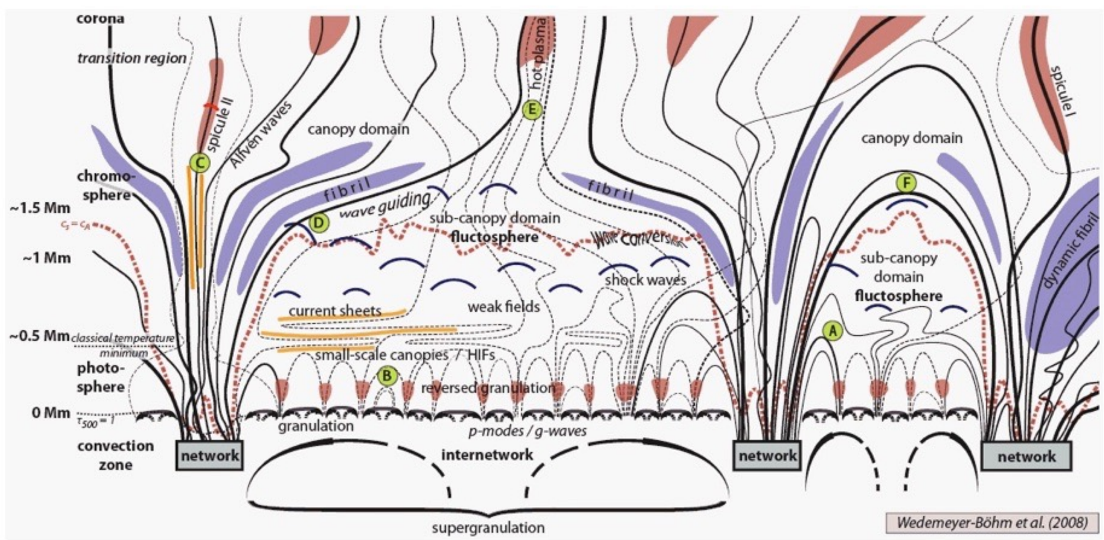


Photospheric level

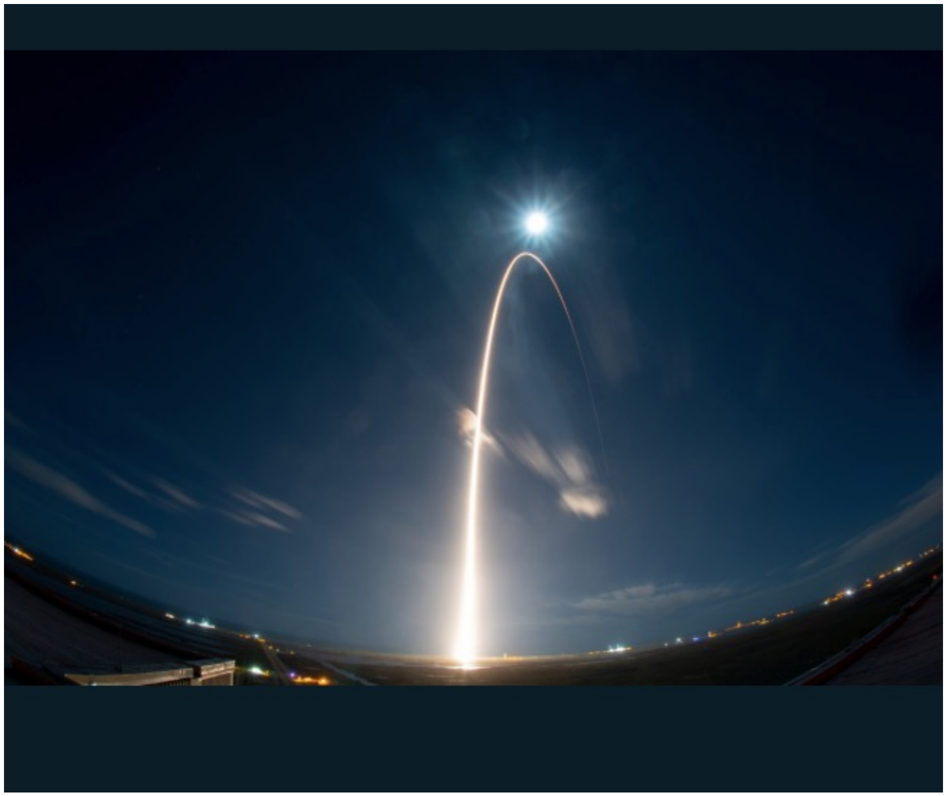
~300 km higher

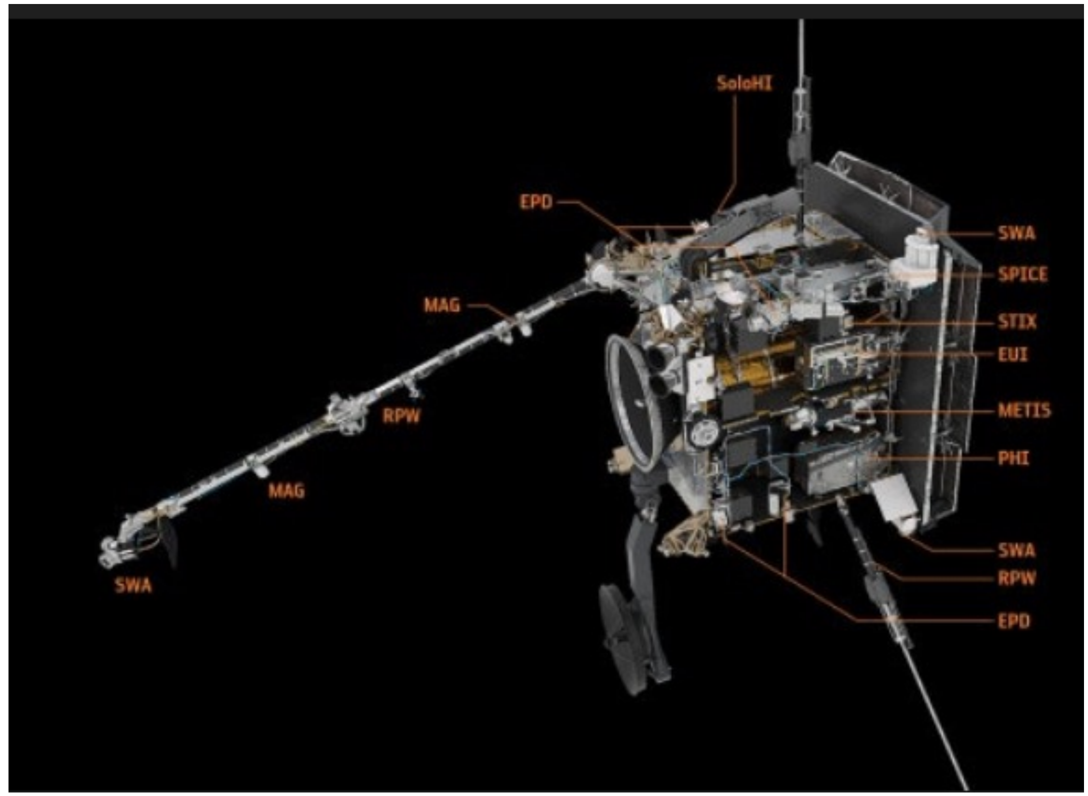
Conclusions

- Magnetism makes the solar atmosphere interesting from the point of view of plasma physics.
- ALMA (now), DKIST (“first light” already), and Orbiter (just launched) offer wonderful new observational opportunities.



A new space observatory!





Solar Orbiter launch anniversary Feb. 10!

Useful homework questions based on this material

- What is the minimum Earth detectable by photometry of a Sun-like star?
- How round is the Sun?
- How big does a solar optical telescope need to be?
- How deep can a Wilson depression be?

These are questions to be answered by rough approximation, and the necessary facts should be here on the slides. I will post discussion of these items on Files and at

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If there's time

- Helio- and Asteroseismology

p-modes, g-modes, and ripples

1941MNRAS.101..367C

THE NON-RADIAL OSCILLATIONS OF POLYTROPIC STARS

T. G. Cowling, M.A., D.Phil.

(Received 1941 November 6)

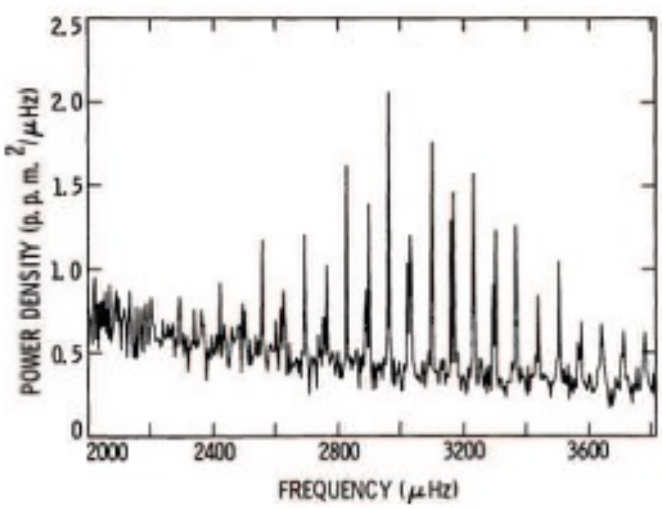
1. The problem of the non-radial oscillations of a fluid globe is of interest in the theory of the tidal distortion of binary stars. If the periods of rotation of the components

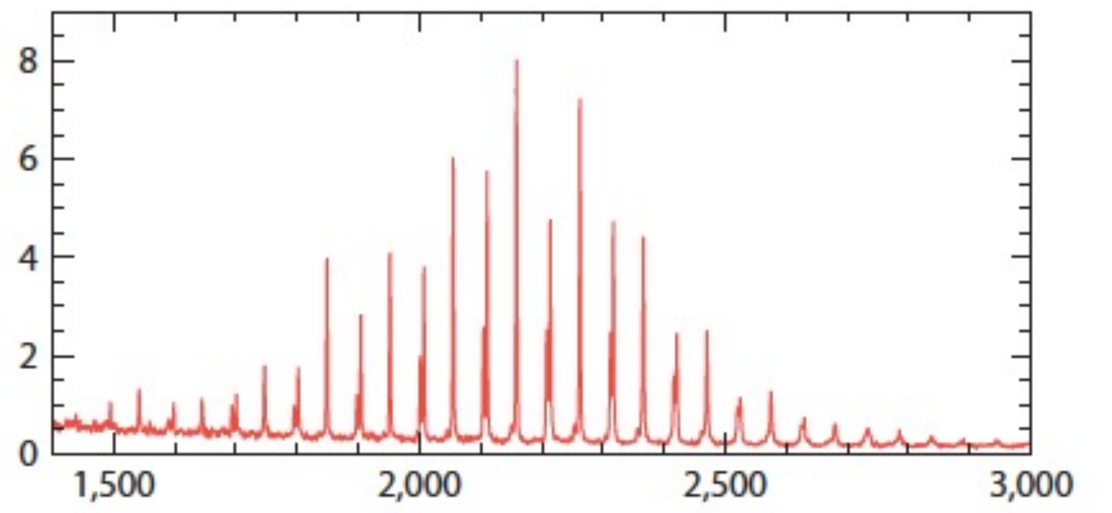
Classification of modes in the Cowling approximation

- p-modes: mainly acoustic standing waves, global
- g-modes: internal gravity waves, evanescent in the convection zone
- f-modes: surface waves

The solar interior also supports acoustic waves excited by flares

Solar and stellar p-modes





The Sun (Woodard, 1987)

- solar-type
- period ~27 d
- 4.85 x 10^{-6} pc
- m ~ -27

16 Cyg A (Chaplin & Miglio, 2013)

- solar-type
- period ~27 d
- 21 pc
- m ~ 6