The Sun’s Magnetic Field and Upper Limits to the 14 keV X-ray line

Kenneth J. H. Phillips

Mullard Space Science Laboratory

University College London

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Solar Interior

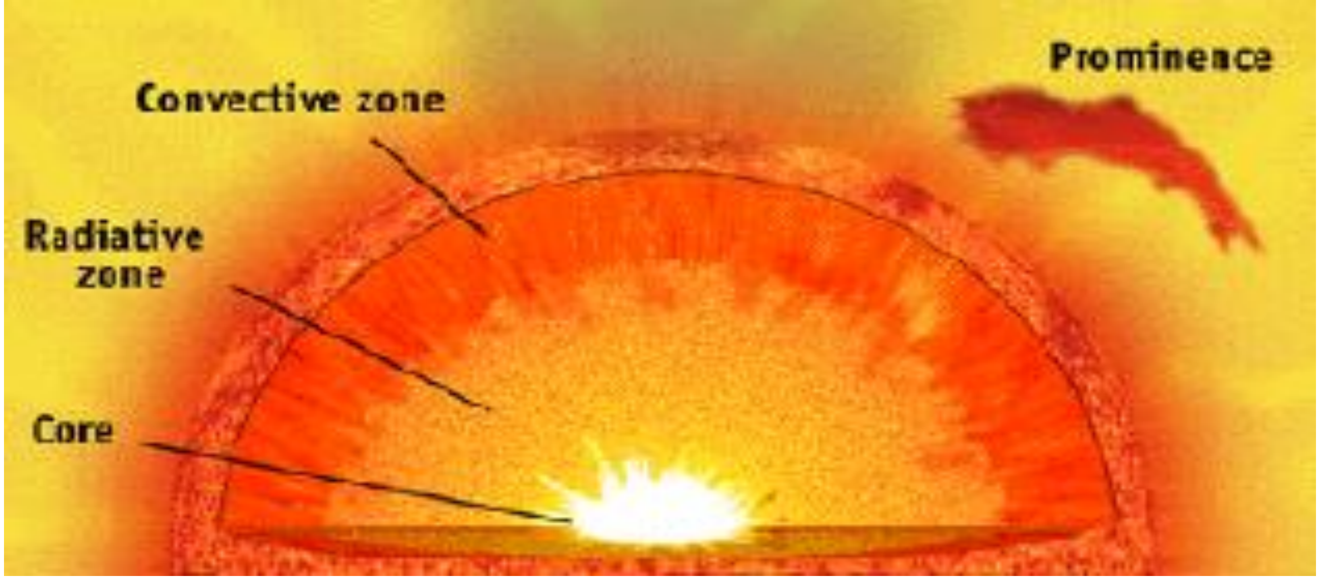
Energy generation in solar core (T~15 MK) by fusion reactions ($4p \rightarrow {}^4He$) is transferred to Sun's surface by radiation over inner part of interior, up to 0.7 R_Θ.

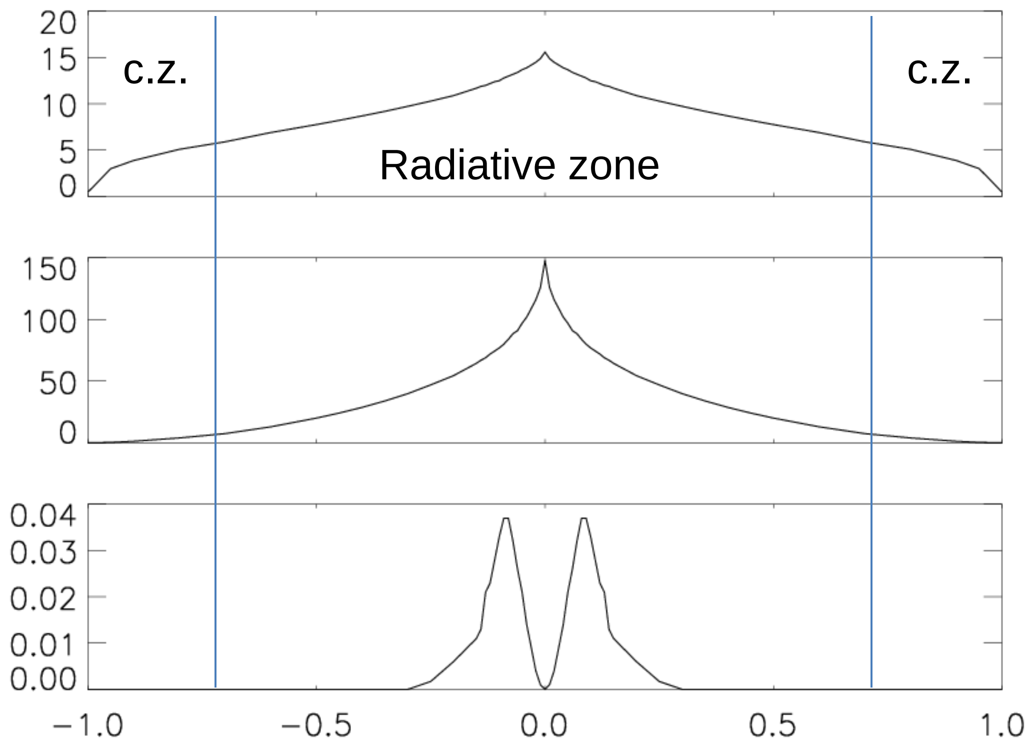
Here, the temperature has fallen to T~5 MK. Sudden **increase of opacity** (due to recombination of Fe ions).

From r= 0.7 R_Θ to the surface (photosphere), energy transfer is by **convection**.

This is described by the Standard Solar Model (SSM) containing all necessary physics and boundary conditions (observed solar radius, mass, luminosity etc.). See Bahcall (1989: *Neutrino Astrophysics*).

SSM of Bahcall (1989): run of T, ρ, d(energy)





Temperature(MK)

Density (g cm^{-3})

d(energy generation)

Radial distance (unit = solar radius)

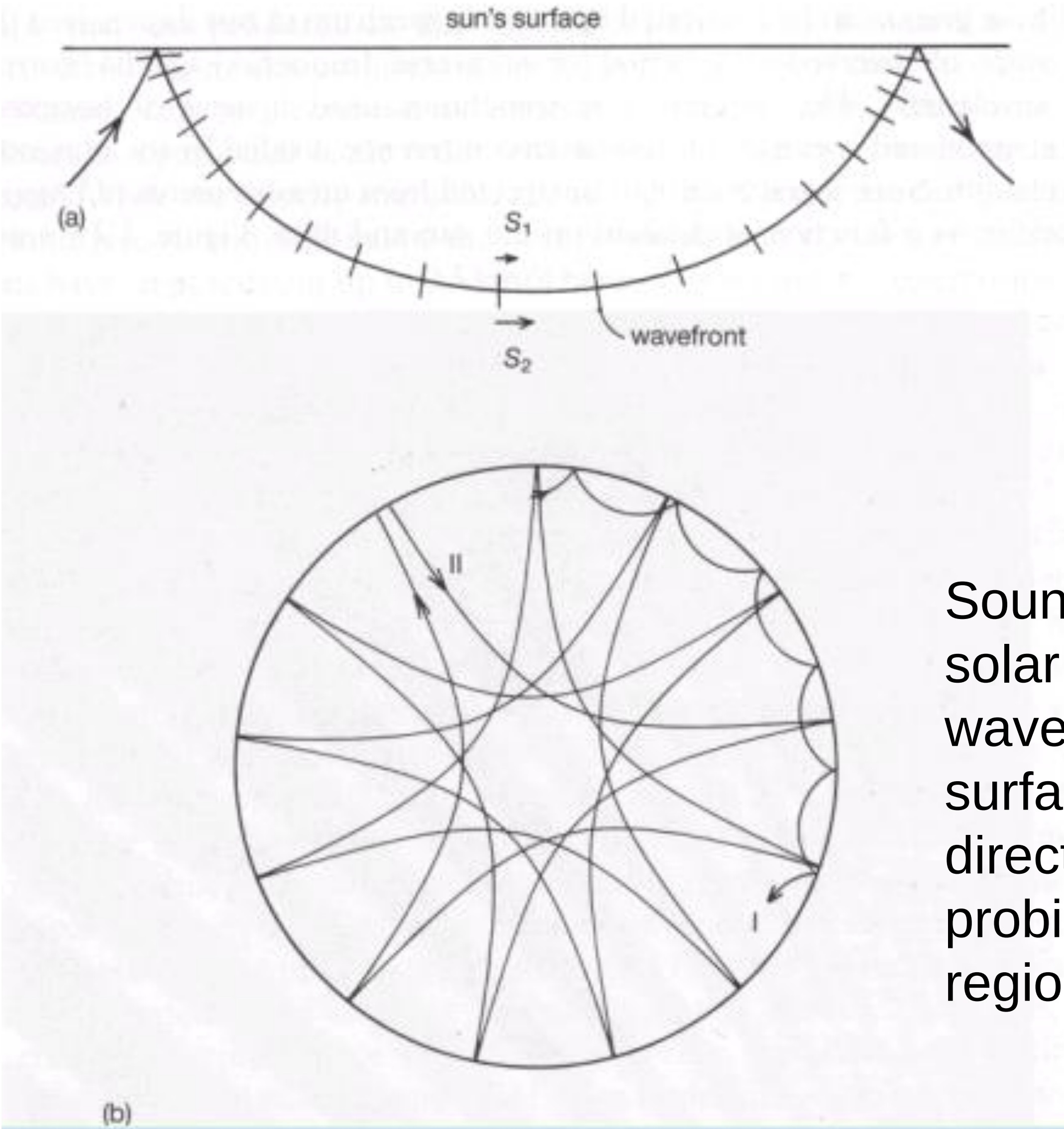
Testing the Solar Standard Model

Nothing can be "seen" below the photosphere of the Sun since the opacity is so large.

But we can probe the interior and test the SSM, through (a) flux of **neutrinos** at Earth resulting from fusion reactions; (b) **helioseismology** (oscillations produced by sound waves). There is (or used to be!) very good agreement between observations and the SSM.

Asplund et al.'s (2005) revised C and O abundances spoils things, but possibly this can be "mended" with slightly revised abundances of He, Ne, or Ar.

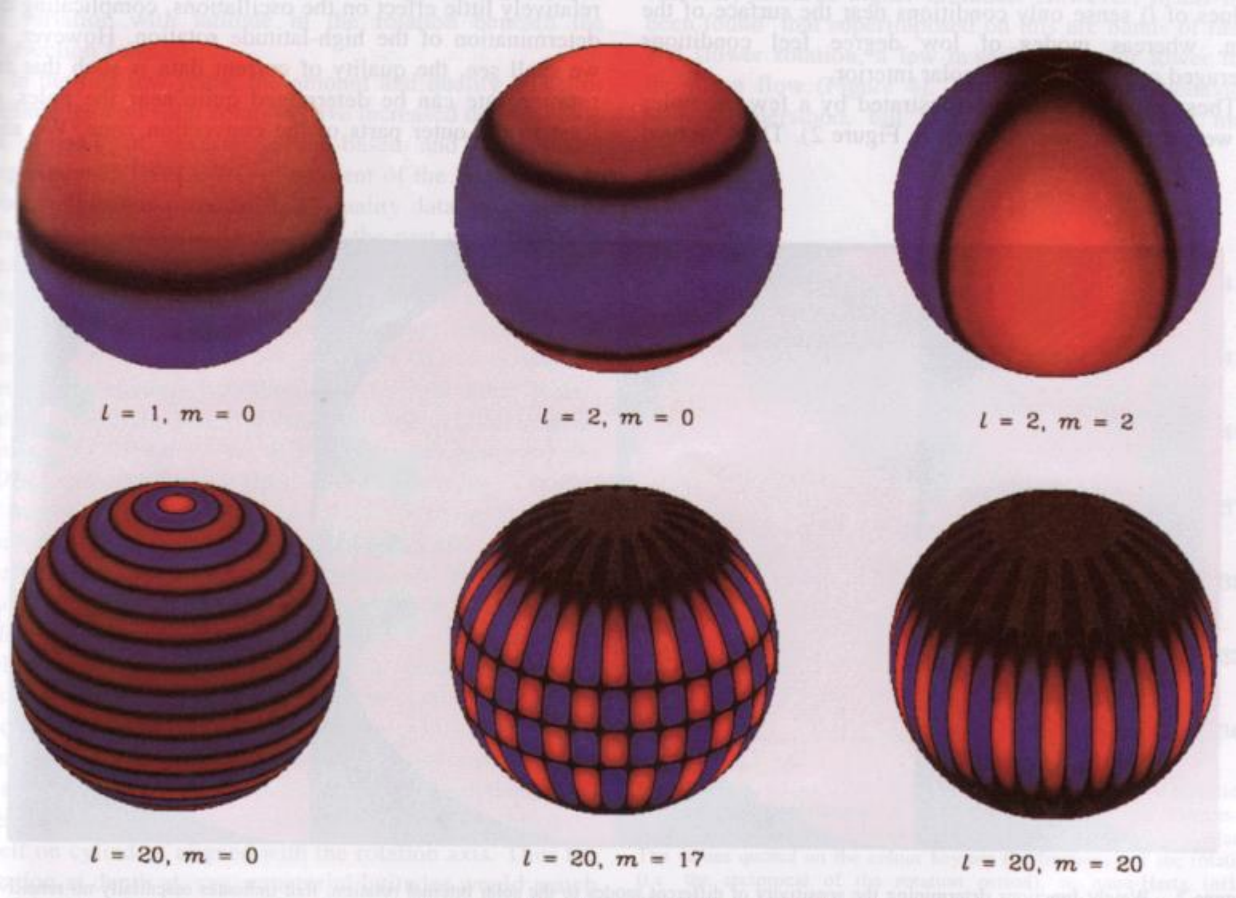
Helioseismology: Sound waves in solar interior



Sound wave near Sun's surface: wave front gets rotated. Observable oscillations at surface.

Sound wave paths in solar interior: some waves travel near surface, others may be directed much deeper,so probing the solar core regions.

Global resonant modes of Sun



Global oscillations observed by helioseismometers – sensitive spectrometers that can detect subtle oscillations.
Spectral line-like features correspond to each resonant mode described by *l* (order) and *m* (azimuthal order) .

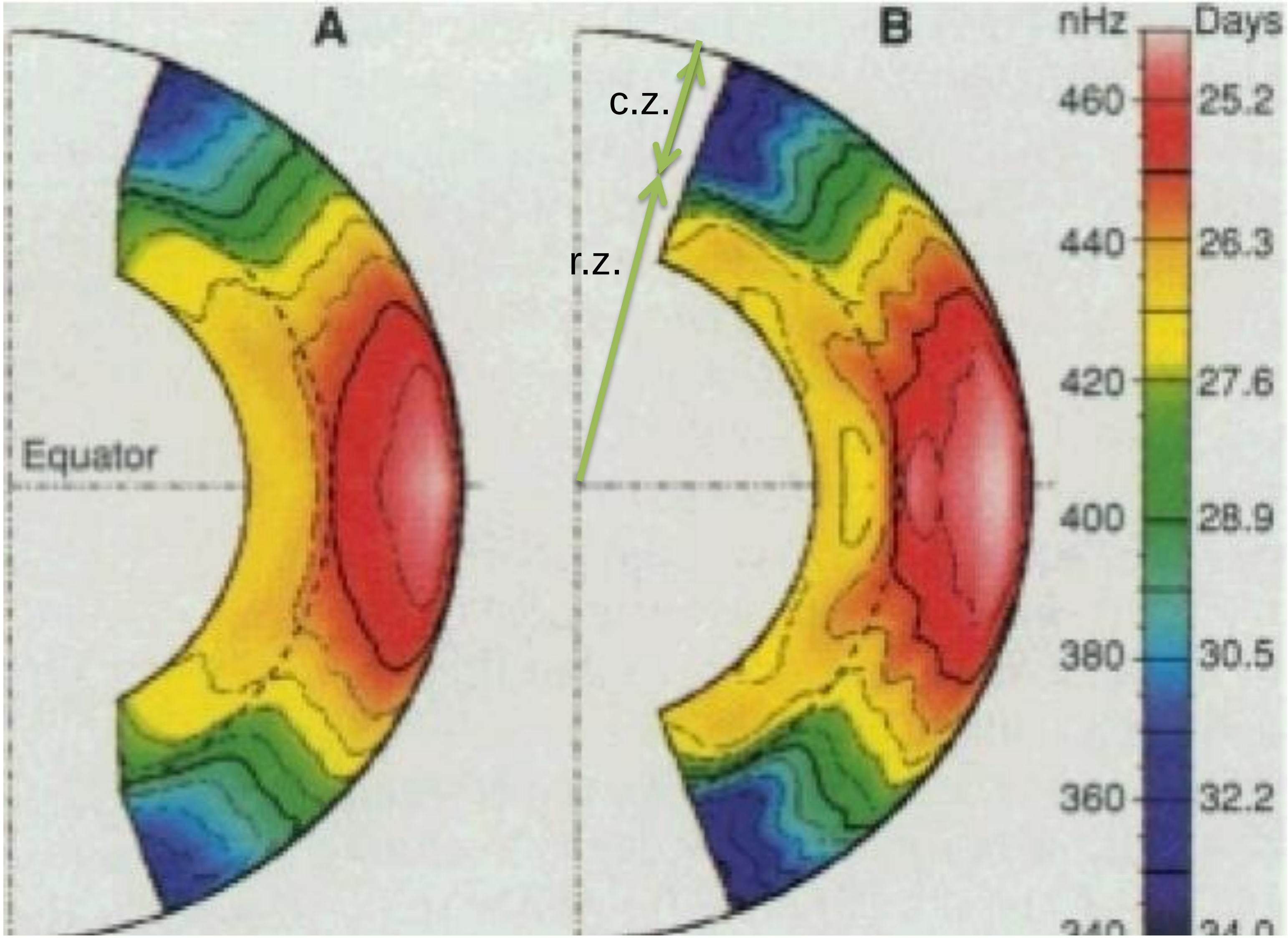
Rotational splitting of modes

The Sun **differentially rotates**: surface layers rotate with period 25 days (lat.=0^o) and 34 days (lat.=80^o).

Modes in the same direction of rotation have slightly higher frequency, those in the opposite direction slightly lower frequency.

Result is a **splitting of the azimuthal modes**, and hence a **powerful way of determining rotational speeds at different depths**.

Solar rotation as a function of depth



The Tachocline

Helioseismology shows that there is a **strong sheer layer**, with rigidly rotating material just below it and differentially rotating material just above.

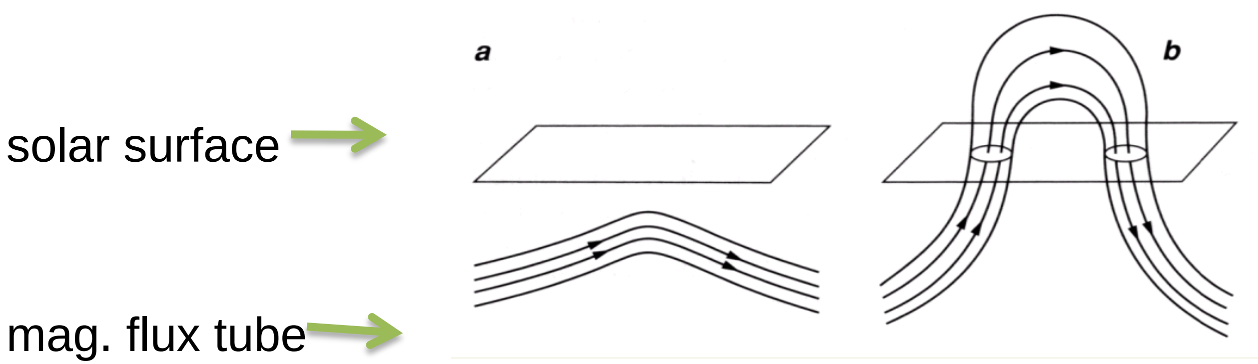
This is the **tachocline**, and corresponds to where cooler material sinking down in convective zone "overshoots".

It is only 0.02 $R_{\odot}$ thick (~15,000 km).

(Note: 1 solar radius = 1 $R_{\odot}$ = 700,000 km.)

Implications for the solar magnetic field

The dynamo cannot operate in the convective zone itself since any magnetic field, in the form of ropes, are liable to be buoyed up since density inside the rope < density outside the rope.



As the tachocline is almost convectively stable, it is the most likely **location for the solar dynamo**.

Magnetic field in the tachocline

With standard models for the convective zone, we can calculate the strength of the magnetic field assuming the dynamo is driven by turbulence:

$$B^2/2\mu_0 = \rho\, v_{turb}{}^2/2$$

The field is **toroidal** (lines parallel to latitude).

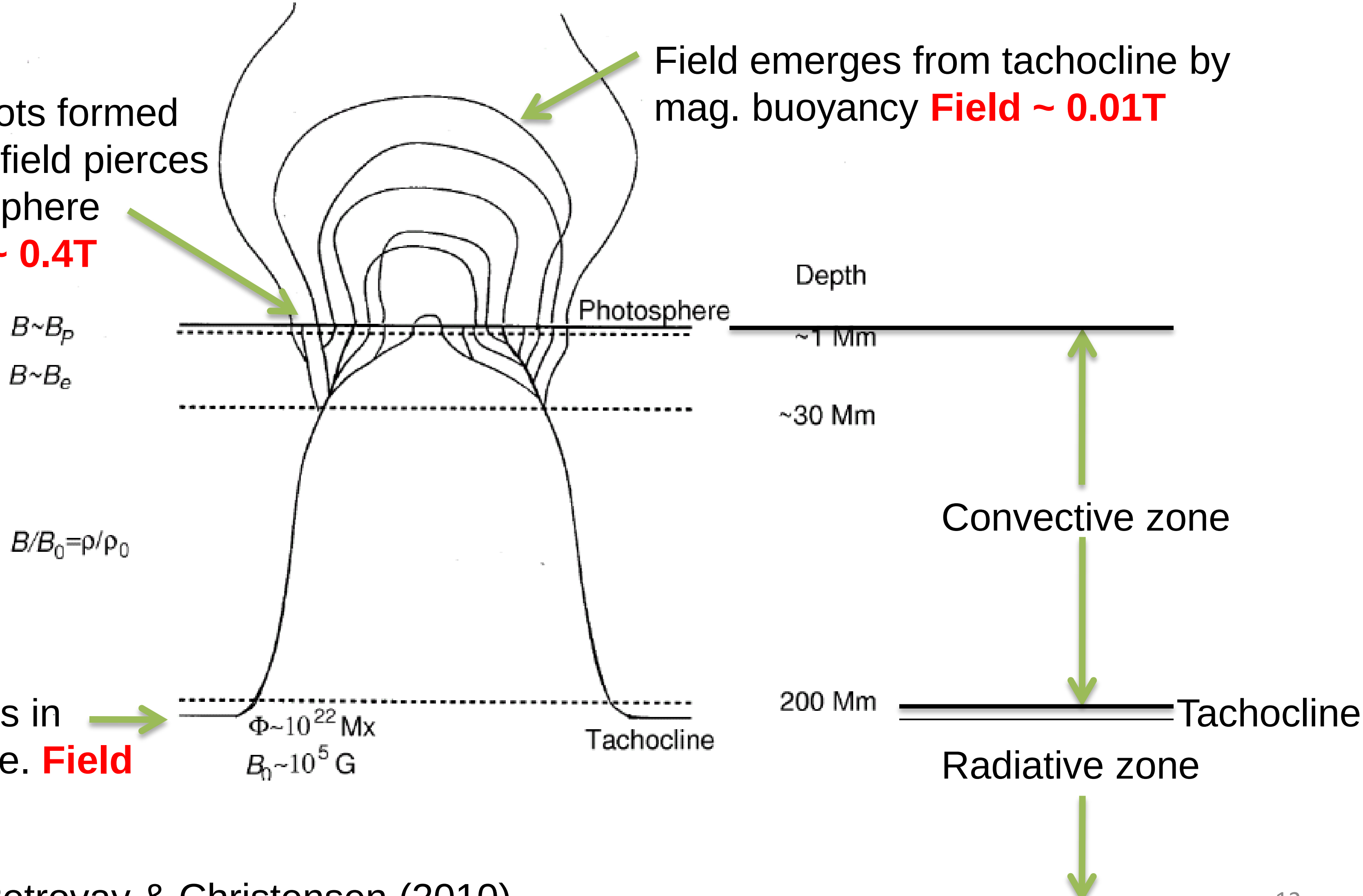
Pre-1989 calculations suggested B = 1 T, but Choudhuri et al. (Solar Phys. 1989) show that **B must be ~10T** for sunspot regions to be at observed latitude range.

This field is in the form of toroidal field lines at latitudes < 30^o, wrapped in the form of ropes.

Field ascending to and above solar surface

Sunspots formed where field pierces photosphere **Field ~ 0.4T**

Field emerges from tachocline by mag. buoyancy **Field ~ 0.01T**



Field lines in tachocline. **Field = 10 T.**

After Petrovay & Christensen (2010)

Implications for solar Axions

Axions produced in the solar core may interact with the **solar magnetic field** by the inverse Primakoff effect:

The **10 T field in the tachocline**: there may be X-ray emission near the flux ropes which would be completely absorbed and so may **locally heat up** the interior & be observable with helioseismometers. Field is **perpendicular to the axion flow**.

The **0.4 T sunspot field** (but field parallel to axion flow).

The **0.01T field in localized coronal active regions**: field approx. perpendicular to axion flow.

General "quiet Sun" dipole-like magnetic field ~10^{-4} T: all-pervasive, mostly field perpendicular to axion flow.

X-ray/UV solar observations

Heating of the tachocline by axion-produced X-rays would be subtle and local, so **difficult to detect** with helioseismometers which generally observe global solar oscillations.

Observations proposed by Carlson & Tseng (1996) (i.e. observe X-ray emission in sunspots as they rotate across Sun) would be **extremely difficult.** (Sunspots evolve & are not strong X-ray emitters anyway.)

Coronal active regions are strong X-ray emitters, but emission is entirely due to hot plasma.

General quiet Sun field: Expect to see an X-ray “glow” at the apparent centre of the Sun.

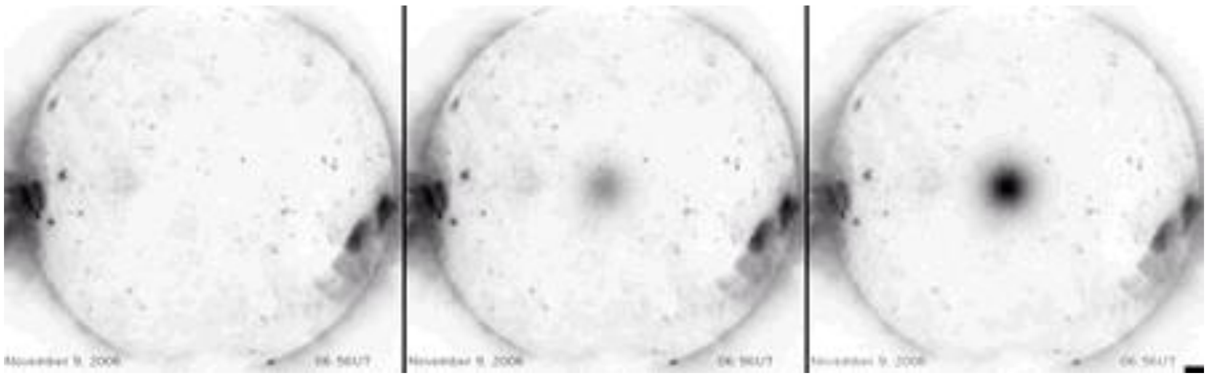
Quiet Sun corona & dipole field

Carlson & Tseng (1996) assumed coupling constant $g_{a\gamma\gamma}$ = 10^{-10} GeV^{-1} for light axions then calculated 3—6 keV X-ray emission from general corona to get 4.10^{-2} photons s^{-1} cm^{-2} keV^{-1} at Earth – **roughly what *RHESSI* saw** in 2005/2006! (See Hannah et al. 2007.)

Zioutas et al. (2004) used *RHESSI* X-ray emission to get a limit for $g_{a\gamma\gamma}$ for KK axions: this has been further constrained by observations of Hannah et al. to << 6.10^{-15} GeV^{-1}.

Since Hannah et al. (2007), we've had much weaker emission during the 2009 solar minimum (~10^{-2} smaller). So the constraint would be more severe.

Prospects for Hinode X-ray Telescope

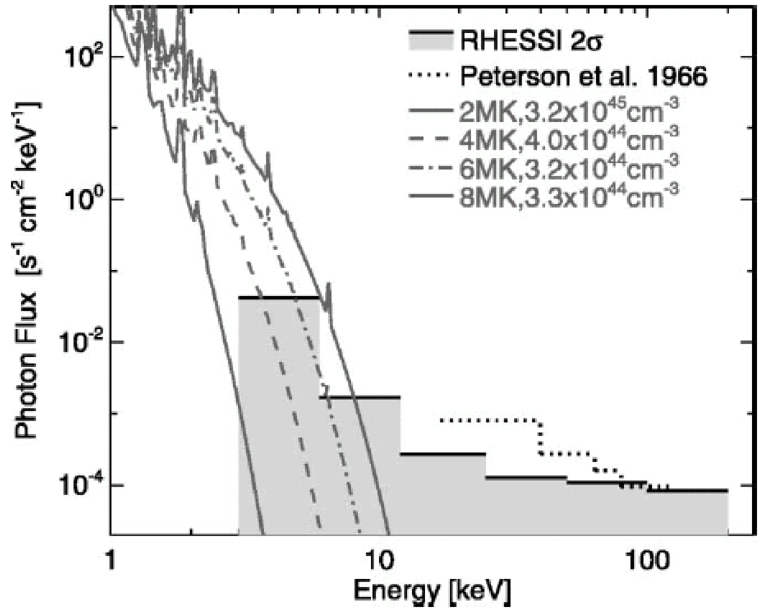


Simulations of Hugh Hudson, RHESSI nugget no. 50 (2007)
http://sprg.ssl.berkeley.edu/~tohban/nuggets/

The Sun is still (2010) only weakly active, so the Hinode XRT could look for dim X-ray spots at the centre of the X-ray Sun (if there are no active regions there).

This is probably being done right now, but I don't know progress.

RHESSI limits to the 14 keV Fe^{57} axion-induced X-ray line



RHESSI can only set upper limits to high-energy X-ray emission during quiet-Sun periods. (Res. ~ 1keV.)

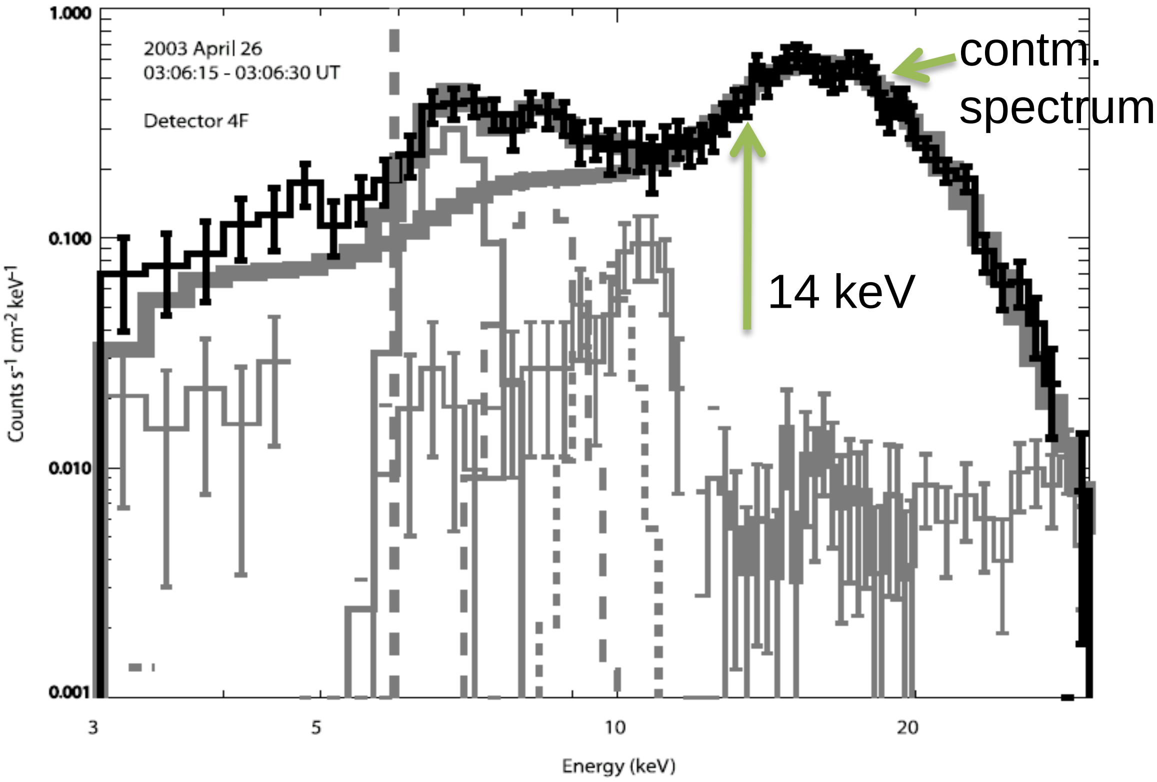
Hannah et al. got 2σ limits in 2005/2006 for > 3 keV X-rays which set limit on 14 keV line flux: maximum flux in 10—20 keV range is 3.10^{-3} photons cm^{-2} s^{-1}.

No evidence of 14 keV X-ray line in flare spectra

An example of a RHESSI solar flare spectrum.

In this count rate spectrum, nothing is seen at 14 keV.

(The 11 keV feature is due to a background feature because of the Ge crystal detectors.)



Concluding remarks

The Sun is a good testing ground for axion observations, providing some of the best constraints.

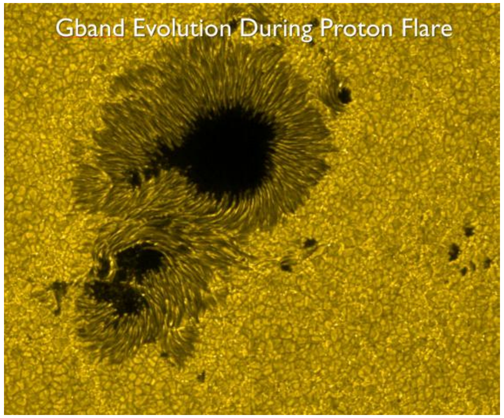
Maybe tachocline is heated by X-rays produced by axions: local departures from SSM?

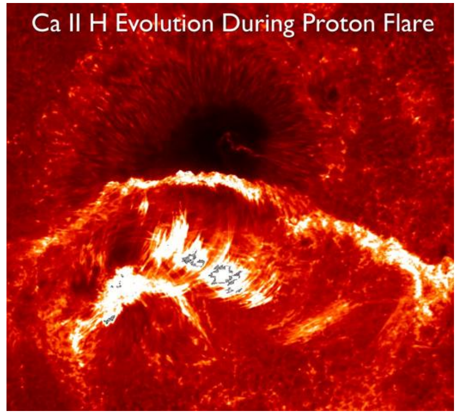
X-ray emission from sunspots may vary as they rotate across Sun: problem is that sunspots evolve.

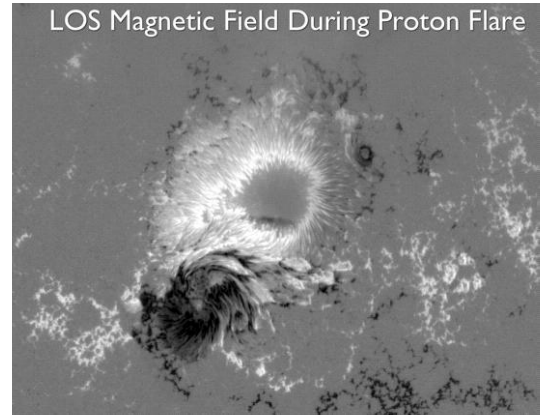
Quiet Sun X-ray emission might show regions of enhanced intensity near Sun centre.

Maybe best chance of detecting/imposing useful limits on axion flux would be through 14 keV Fe^{57} M1 nuclear line or M1 atomic transitions (e.g. the Fe^{+16} 1.7096nm X-ray line in coronal spectra).

Hinode images of solar active regions

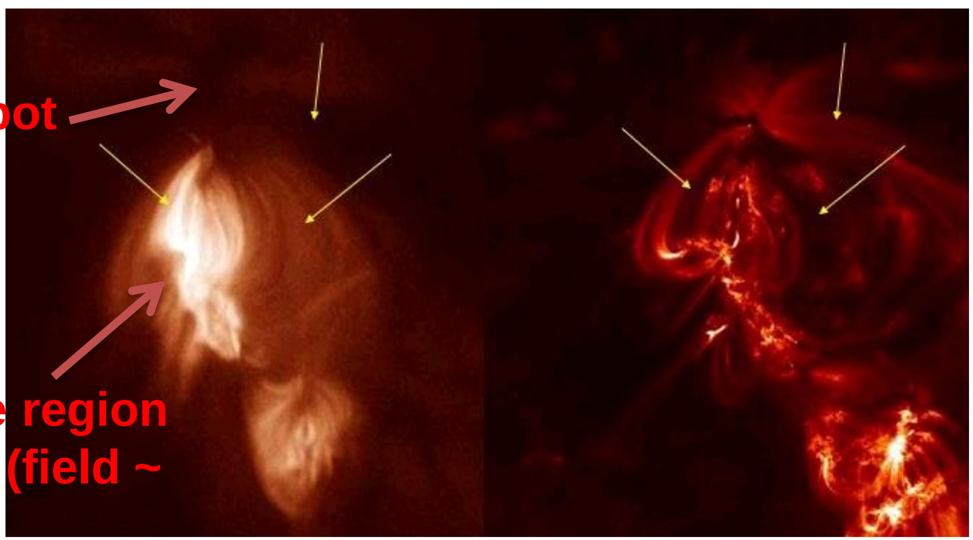






Large sunspot (field ~ 0.4T)

Sunspot



Active region loops (field ~ .01T)

Soft X-rays   Extreme ultraviolet (TRACE)

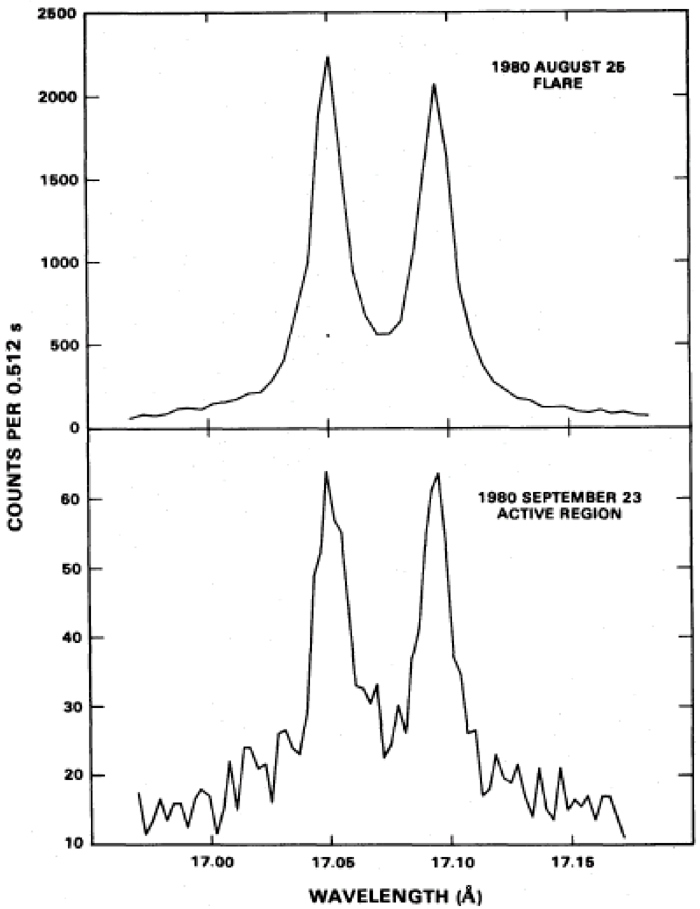
Active region with sunspot (top of image) in X-rays & EUV: NO emission in SXR, only loops emerging from spot.

M2 atomic transitions in solar corona

Fe XVII lines (emitted by Fe^{+16} ions) occur in X-ray region at 1.5 nm and 1.7 nm.

Fe XVII 1.7096 nm line due to an M1 transition: $2p^6\ {}^1S_0 - 2p^6\,3s\ {}^3P_2$ (i.e. $\Delta J=2$). Right next to it (1.7051 nm) is an E2 transition.

Ratio varies with time. The reason is unclear...



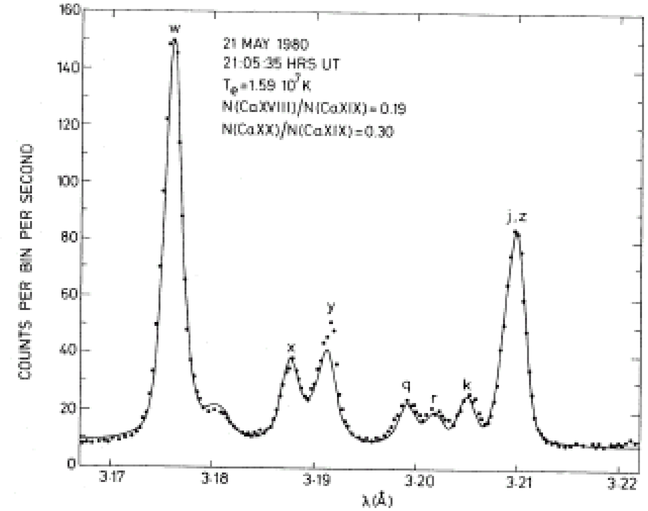
Something odd about He-like ion spectra

$x = 1s^2\ {}^1S_0 - 1s2p\ {}^3P_2$ M1

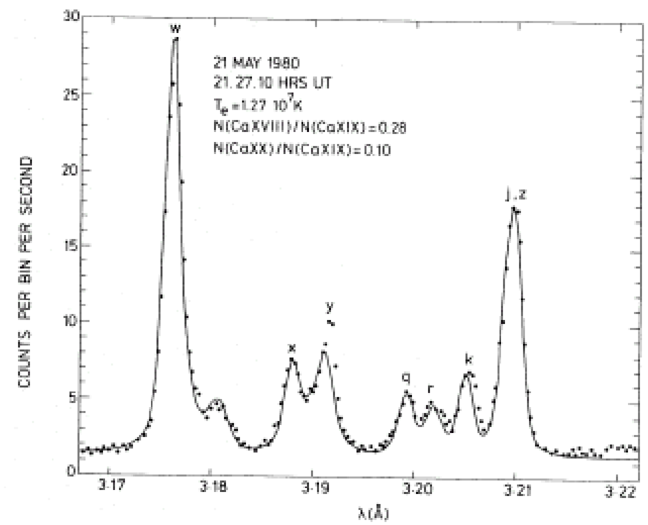
$y = 1s^2\ {}^1S_0 - 1s2p\ {}^3P_1$ E2

y never seems to agree with theory, but x does.

But this might be because of peculiar excitation from the 1s2s ${}^3S_1$ level.



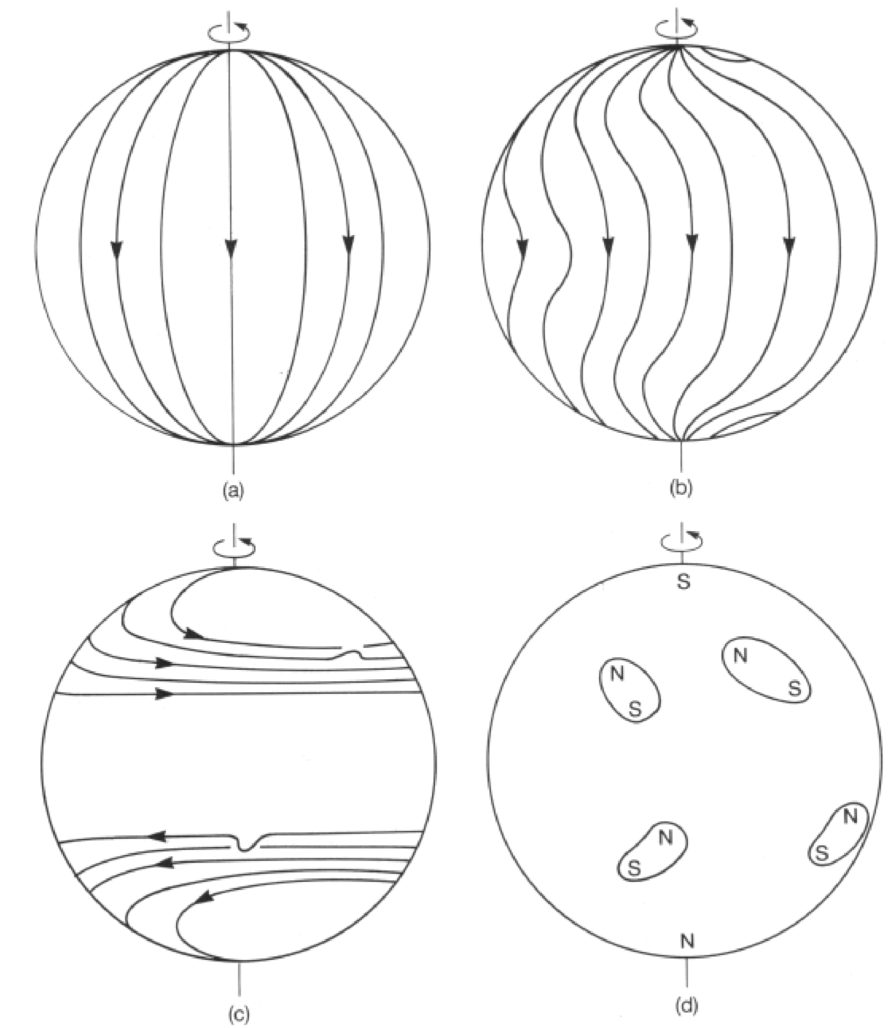
(a)



(b)

Examples of He-like Ca (Ca XIX) spectra during flares.

Field lines over a sunspot cycle



Sound speeds in Sun

Near photosphere 10 km/s (travel time ~days)

Near tachocline 250 km/s (travel time ~5 hr).