The Sun at the Source

COLLAGE 2023
ASEN-5519:
Space Weather Overview

Lecture #1
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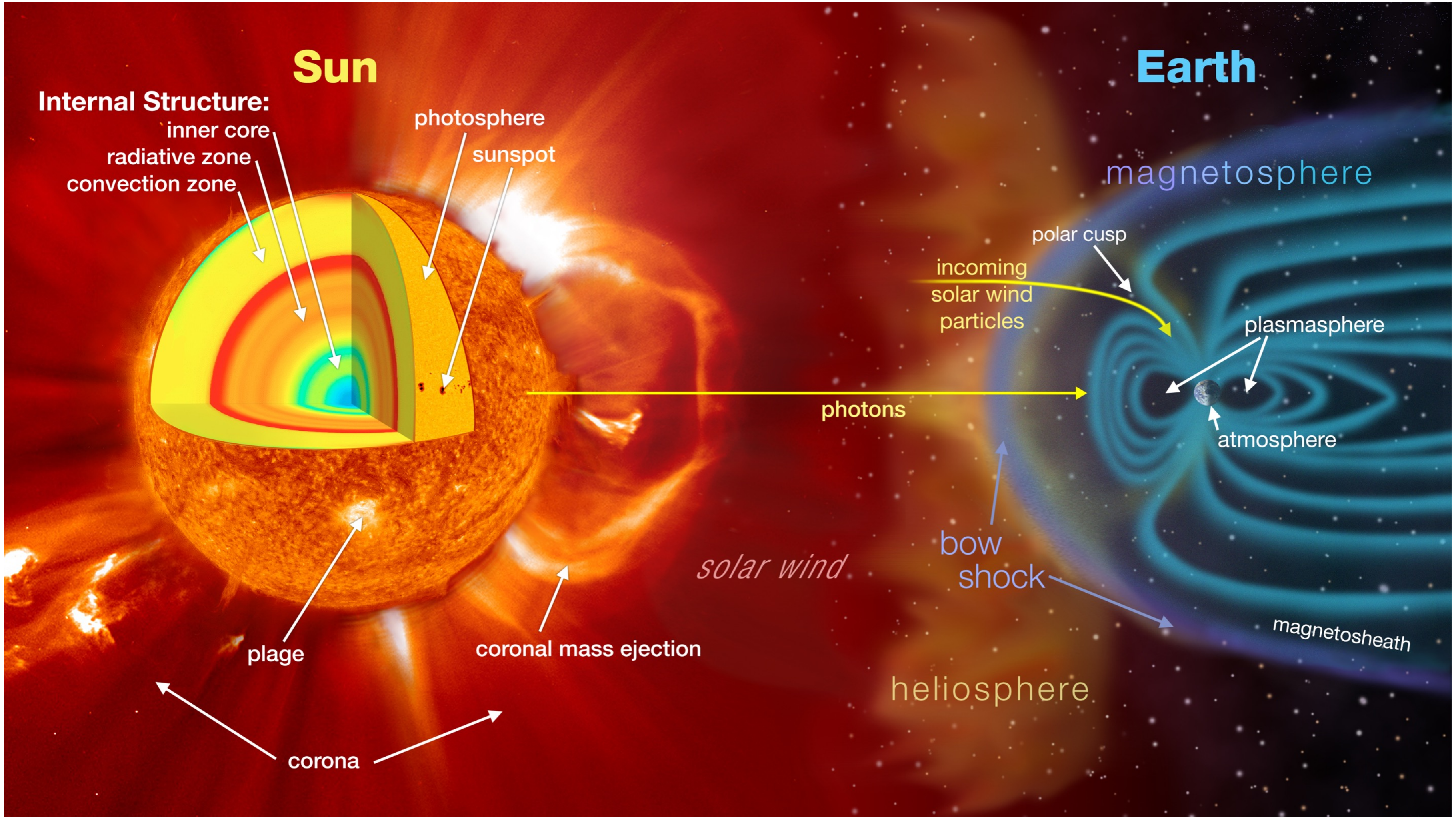


Key Concept: Energy Conversion

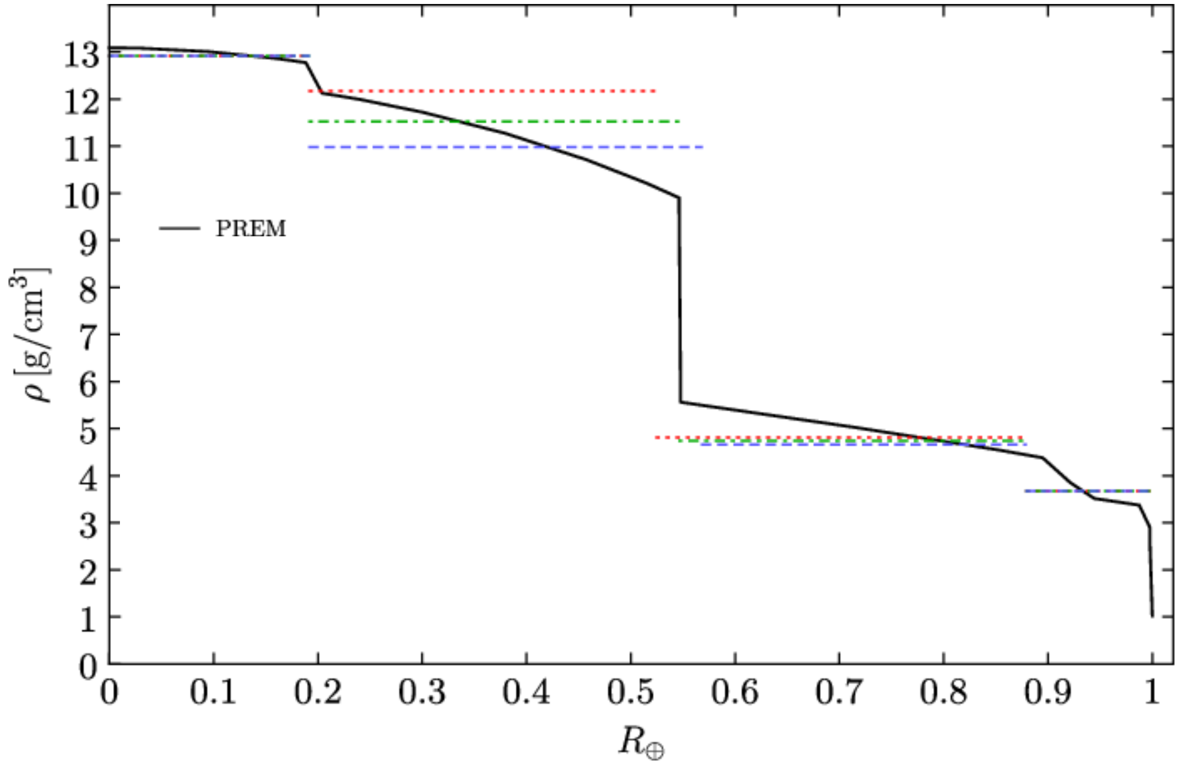
The Sun is an enormous cascade of processes converting different types of energy:

- Gravitational (Potential) – collapse of interstellar cloud
- Thermal – heating of plasma
- Nuclear – fusion in core
- Kinetic – convective flows, waves
- Electromagnetic – magnetic energy, waves
- Atomic – energy level transition, ionization

Key Concept: Density

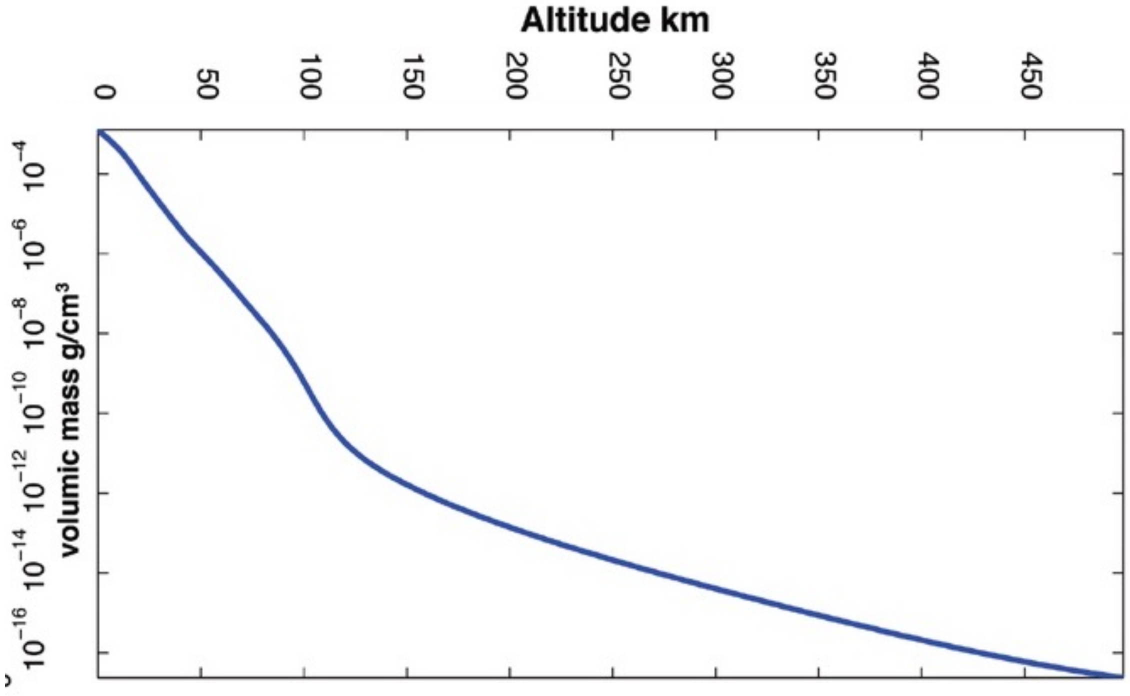
There is a continuous outward density gradient in the Sun.

For reference, compare the density profile of the Earth.



Density of Earth's Interior
with radius
Note linear scale
1 order of magnitude change

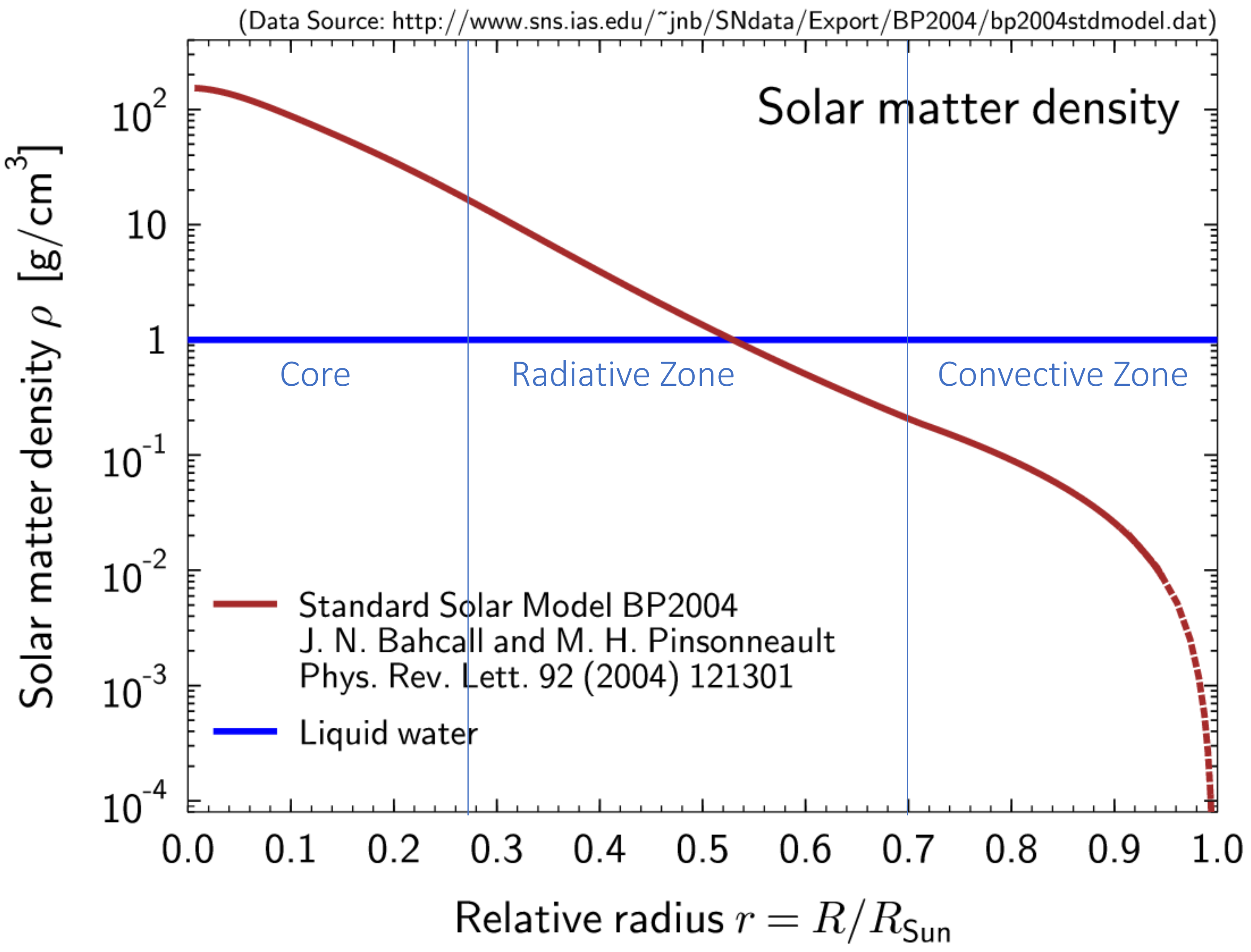
Density of Earth's Atmosphere
with height
Note logarithmic scale
12 orders of magnitude change



https://www.researchgate.net/publication/346576248_Earth_tomography_with_atmospheric_neutrino_oscillations

https://www.researchgate.net/publication/248866118_Vita_brevis_of_antibubbles

Solar Interior



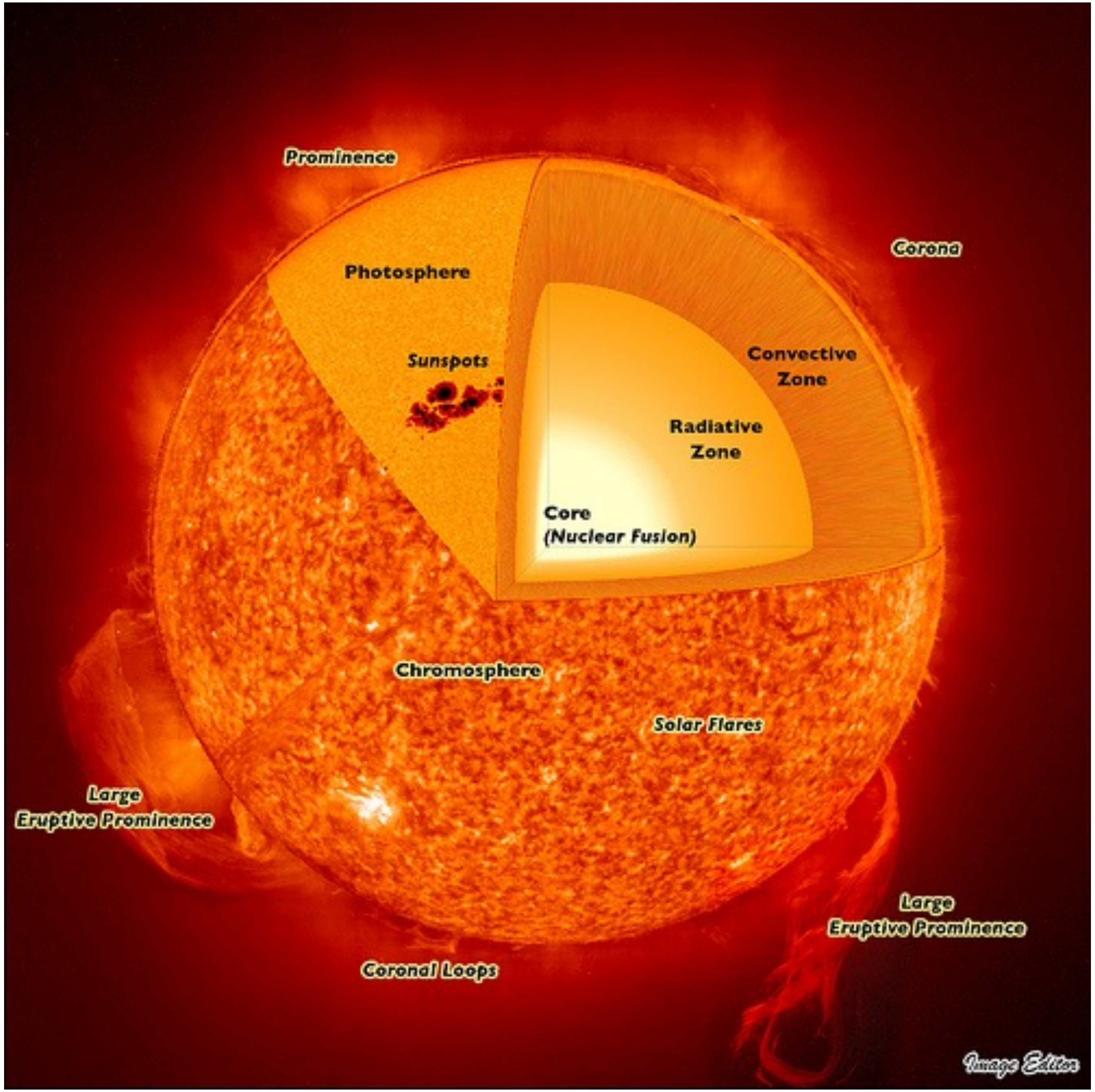
This instead is the density gradient in the Sun.

6 order of magnitude decrease from core to surface

Outer half of Sun (85% of volume) is less dense than water.

Solar Structure

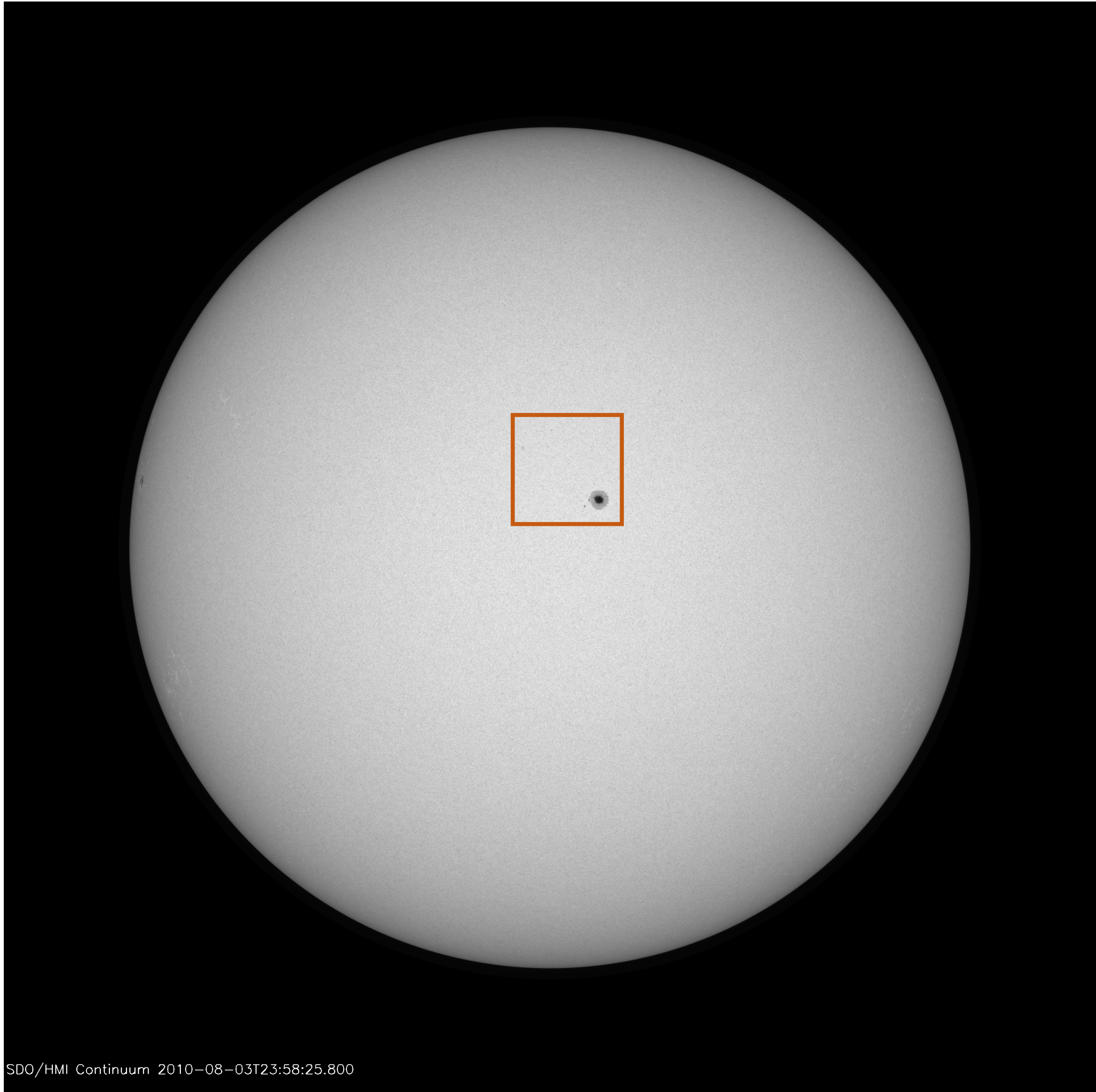
Different energy transport mechanisms at work as energy moves outward



Solar "Surface"

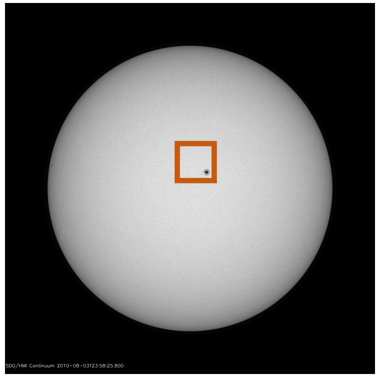
Called **Photosphere**

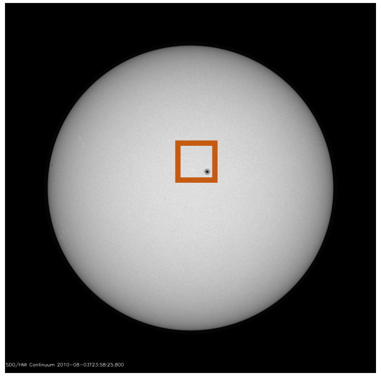
Radiative escape carries away most of solar energy as electromagnetic waves

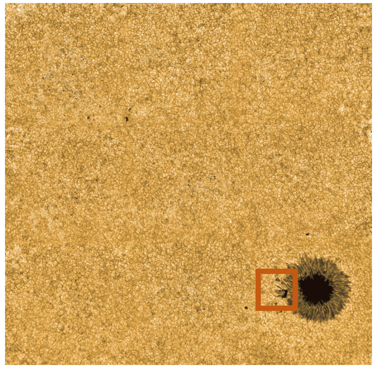


240 arcseconds = 170 Mm = $1/8^{th}$ solar diameter

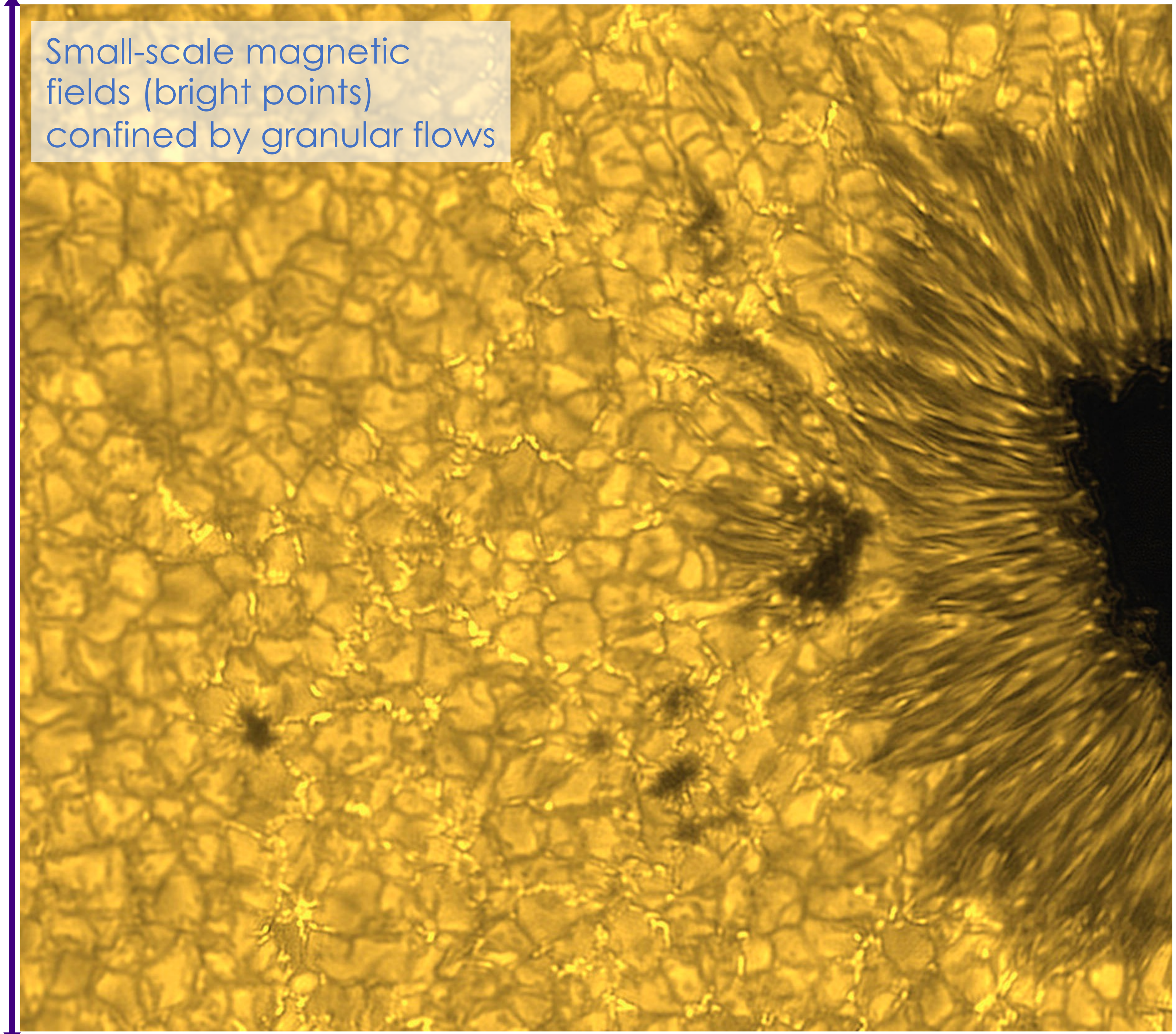
IBIS Mosaic – 03 August, 2010
Continuum







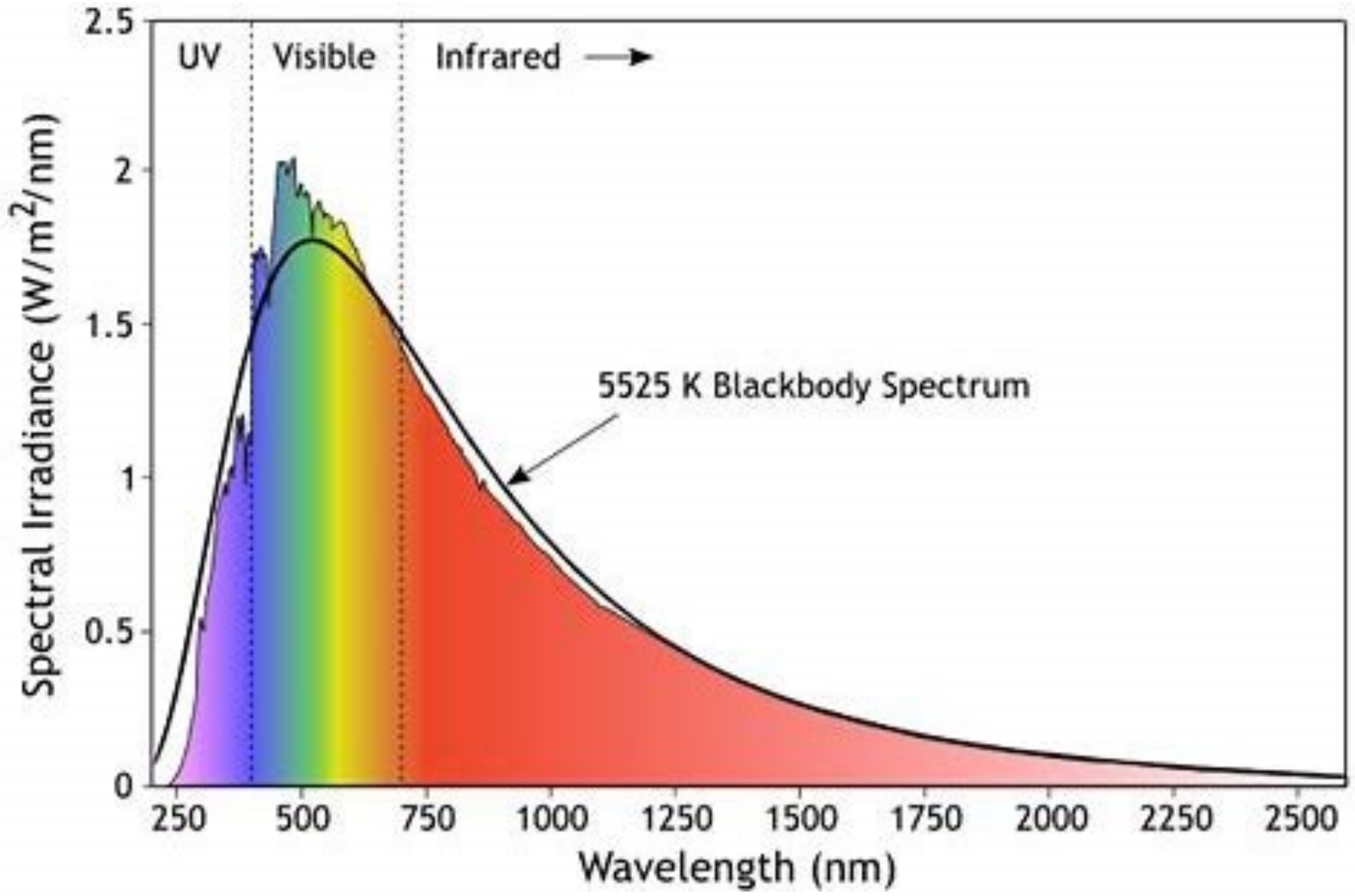
44 arcseconds = 32 Mm = 1/44th solar diameter



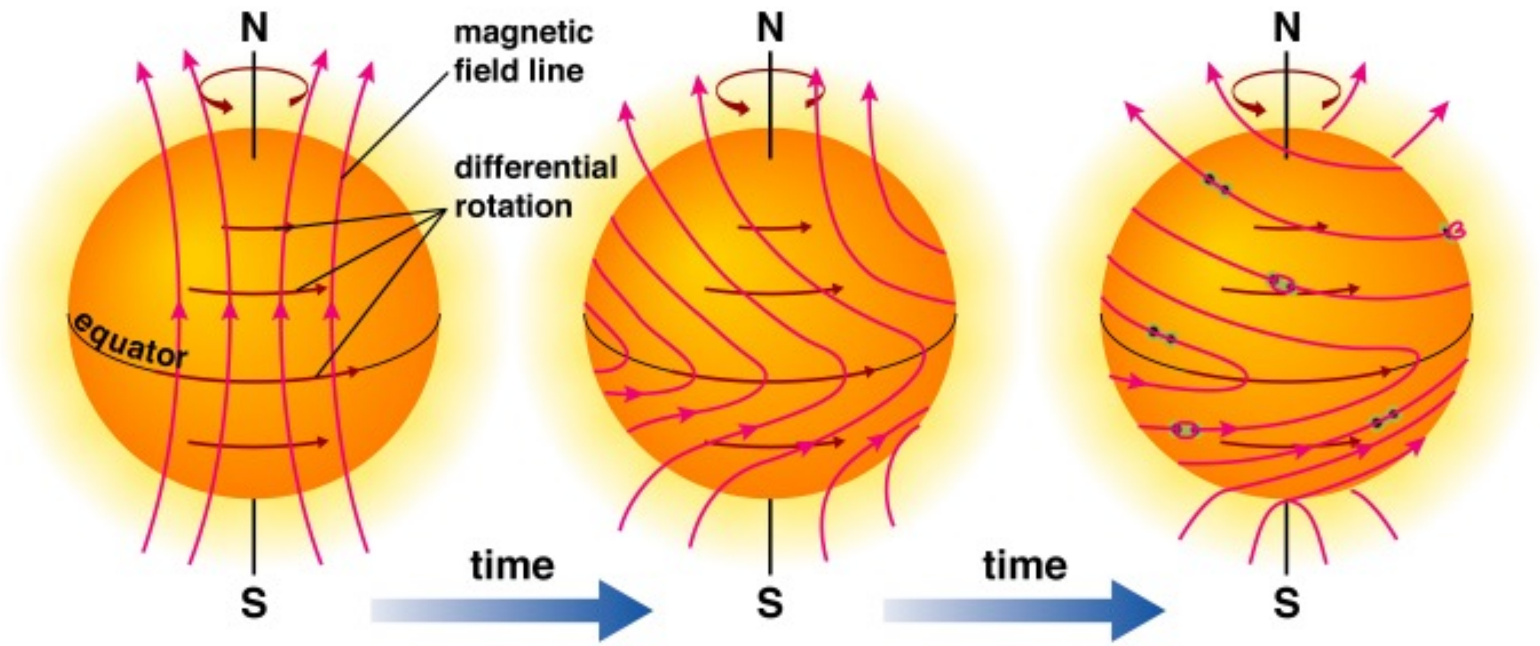
IBIS Mosaic – 03 August, 2010
G-band

Black Body

Continuum spectrum of Sun is an approximate blackbody spectrum

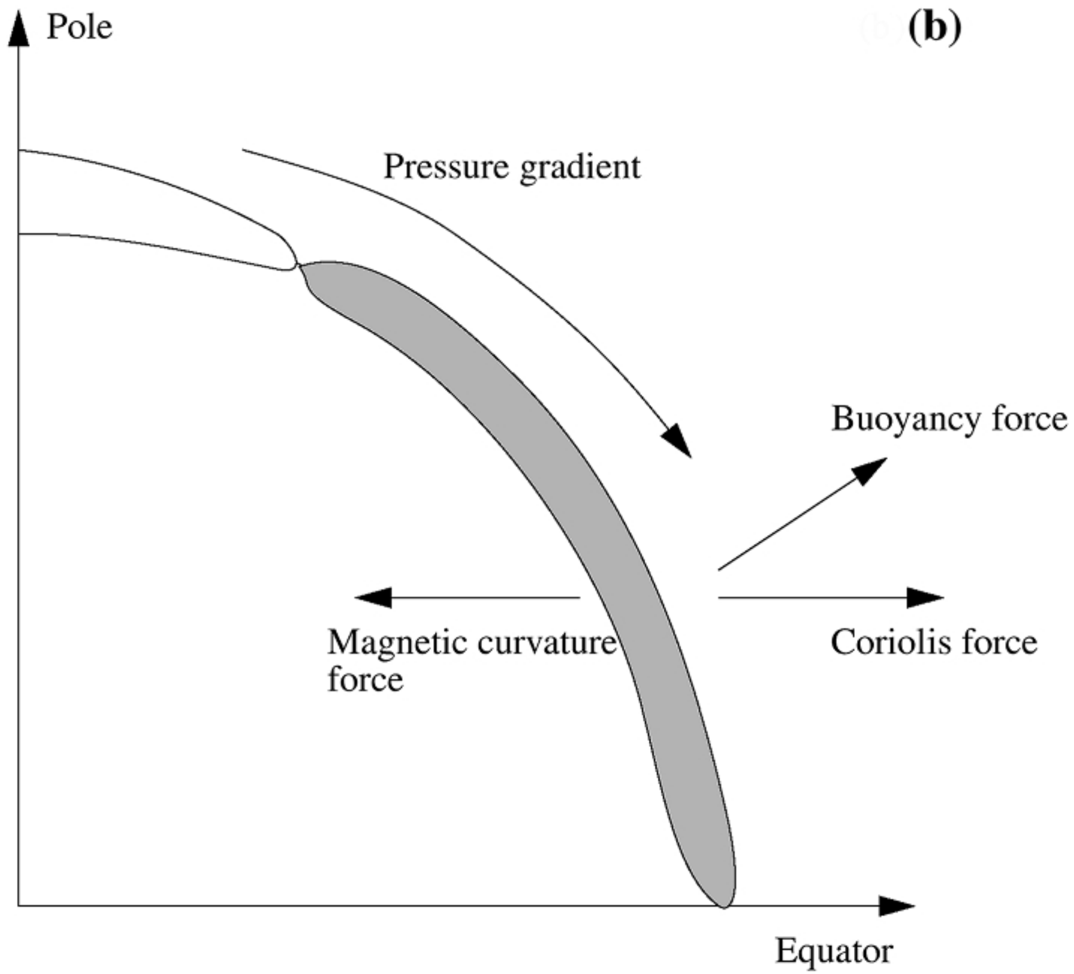


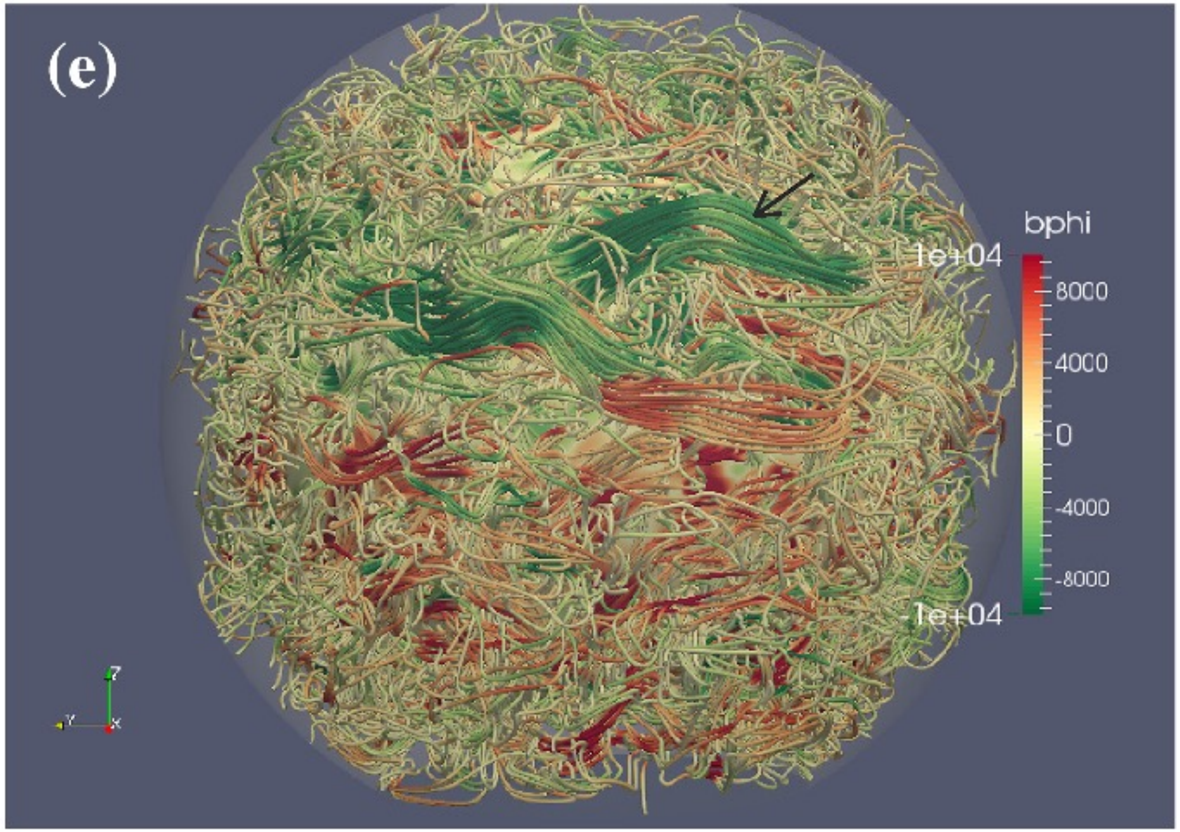
Magnetic Field Generation



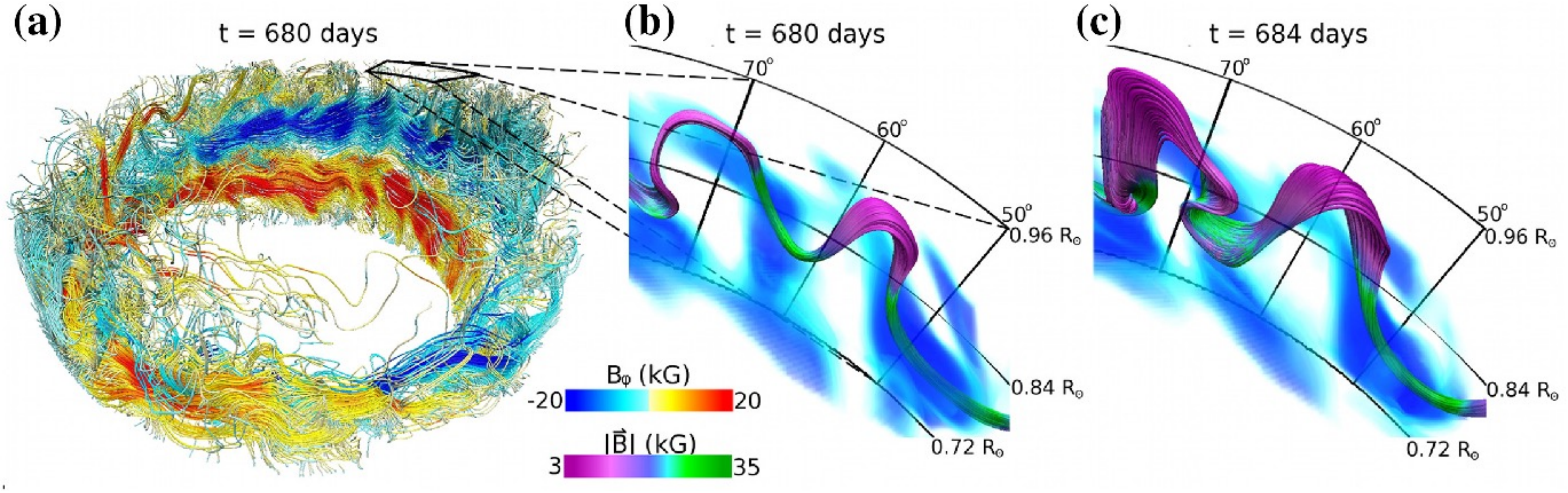
Differential rotation of Sun (higher latitudes rotate more slowly) twists up poloidal magnetic field.

Magnetic Field Generation





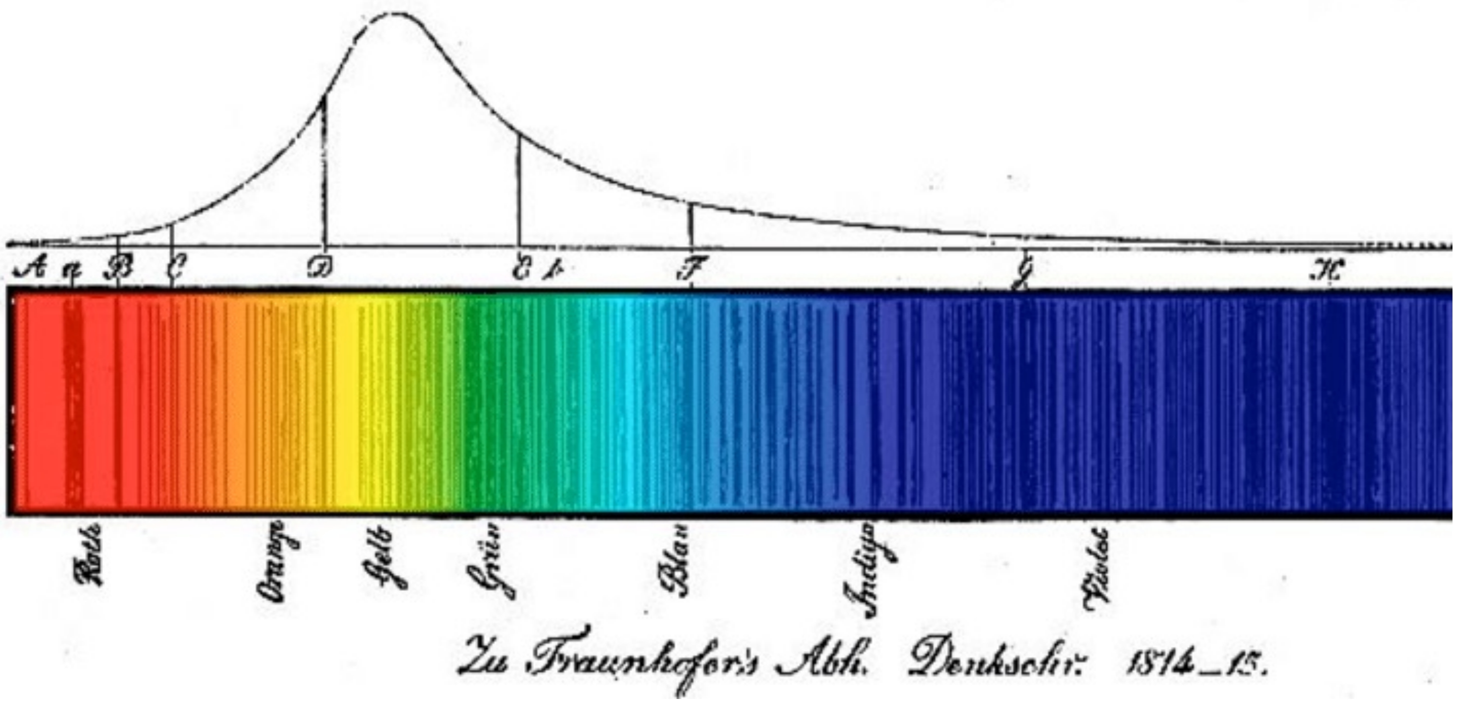
Magnetic Field Emergence

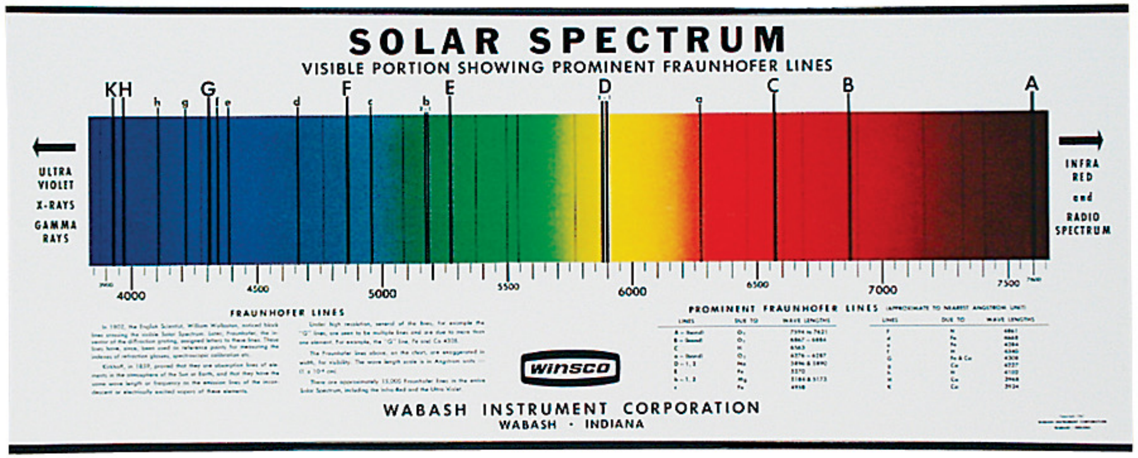


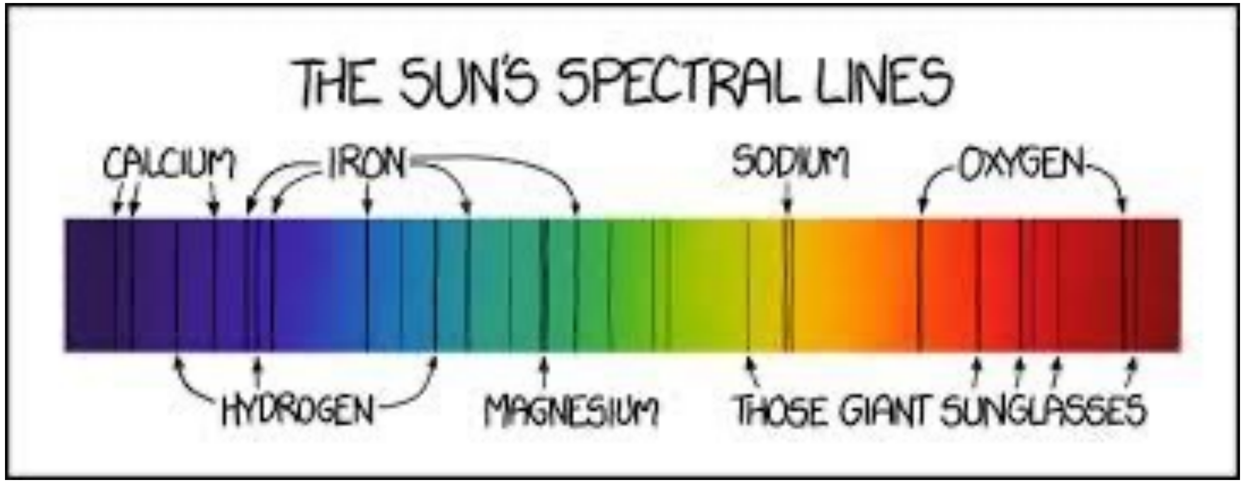
Nelson, *et al.*, 2013, https://arxiv.org/abs/1211.3129

Solar spectrum through the years

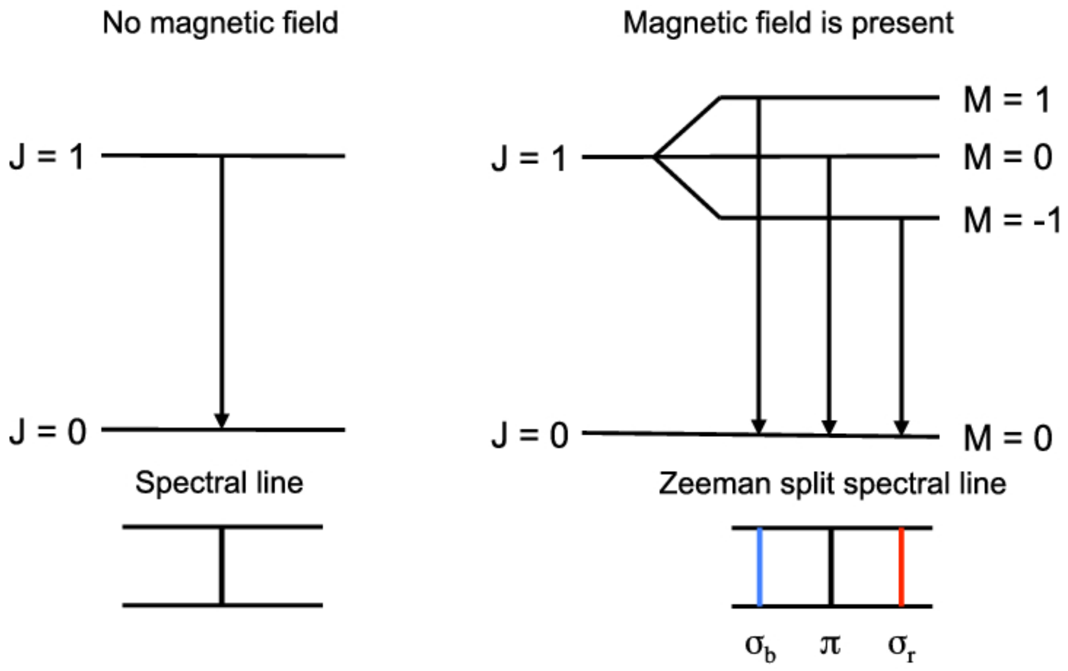
In addition to the blackbody spectrum, many dark spectral lines



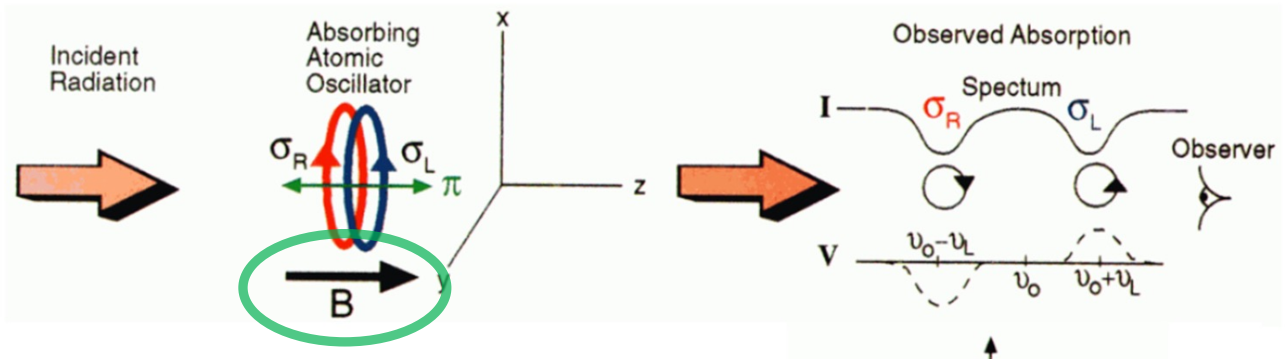




Magnetic Field Measurements (Zeeman)

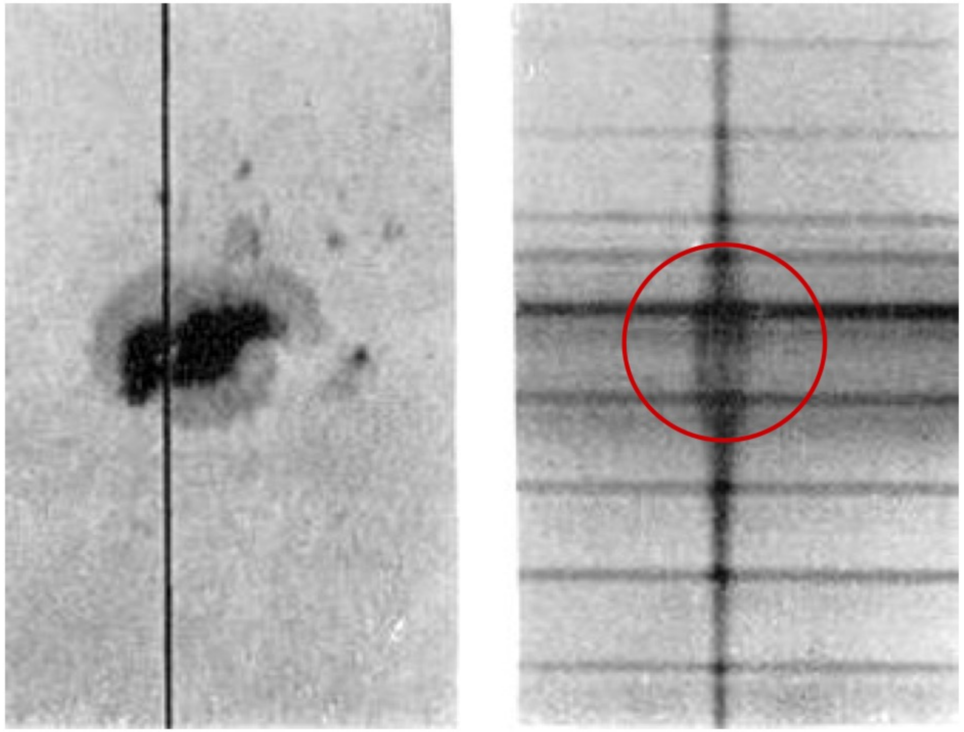


Longitudinal Zeeman Effect

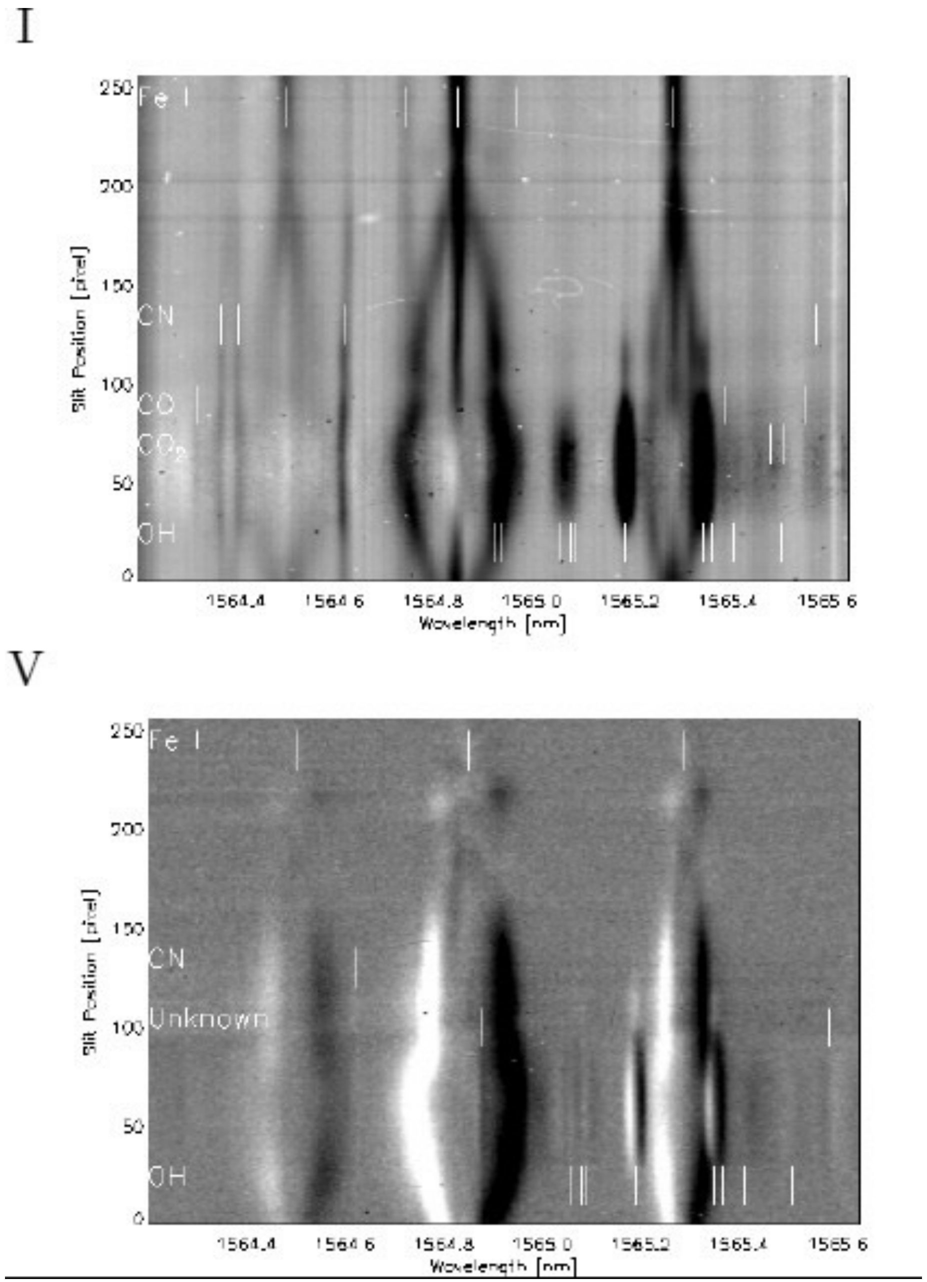


Properties of atomic transitions of certain spectral lines allow us to diagnose magnetic field in solar atmosphere (where line is formed)

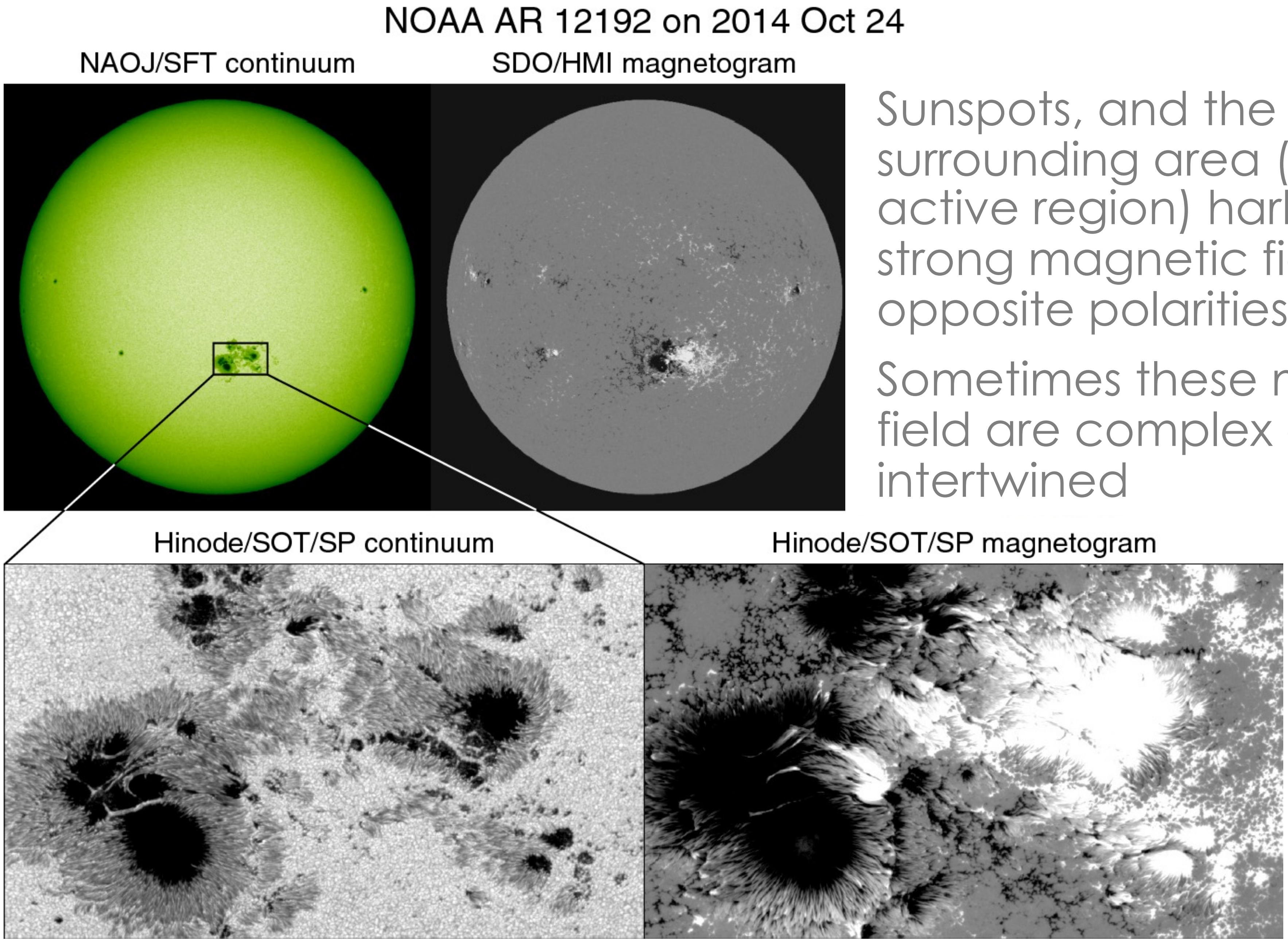
Easiest measurement is the field strength along the line of sight



G.E. Hale, F. Ellerman, S.B. Nicholson, and A.H. Joy (ApJ, 1919)



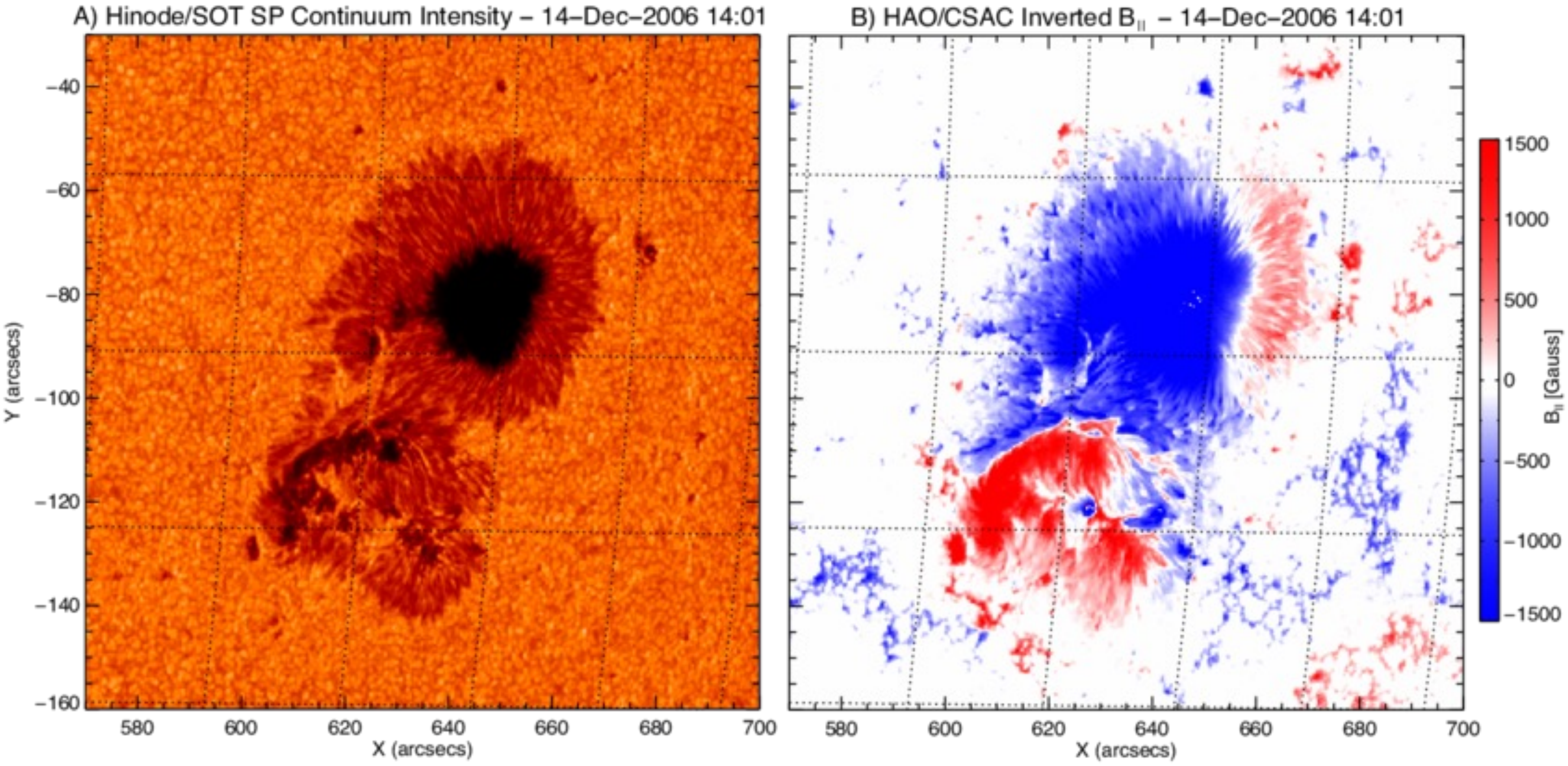
[Penn, 2014, Living Review Solar Physics](#)



Sunspots, and the surrounding area (the active region) harbor strong magnetic fields of opposite polarities.

Sometimes these magnetic field are complex and intertwined

Sunspots and Magnetic Fields

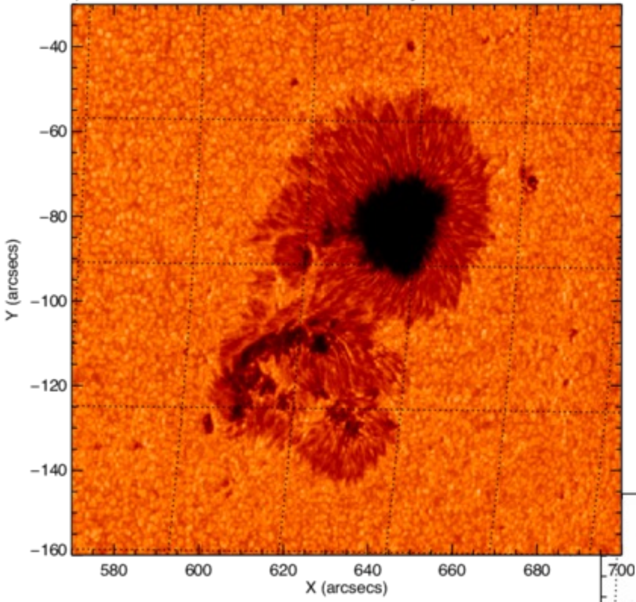


Another example, with magnetic field polarities shown as red and blue.

Notice sharp line between two polarities in some parts of the active region.

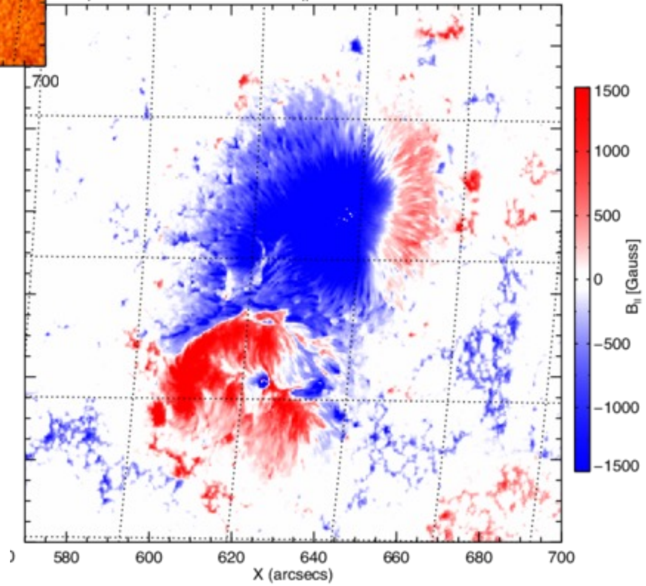
Polarity Inversion Lines (PIL) aka Neutral Lines

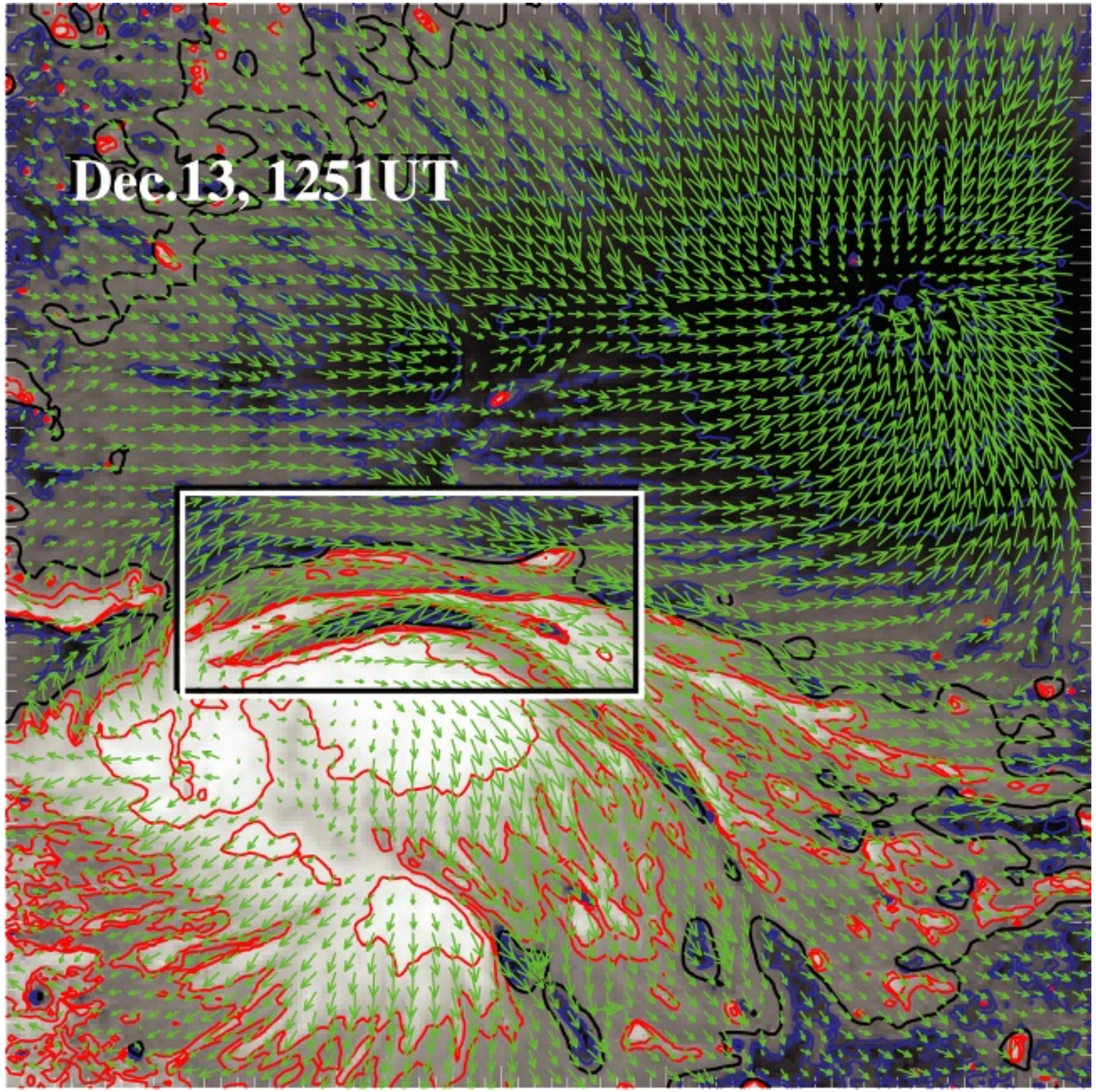
A) Hinode/SOT SP Continuum Intensity – 14–Dec–2006 14:01



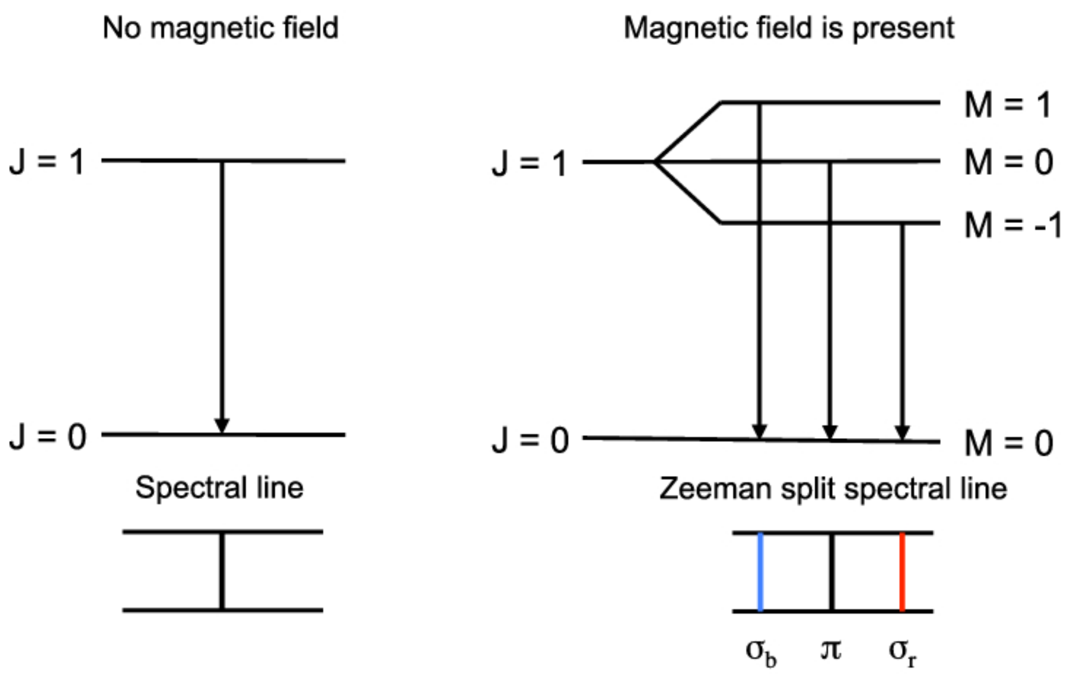
There can be strong, sheared horizontal magnetic fields at the locations where the polarity changes.

B) HAO/CSAC Inverted $B_{||}$ – 14–Dec–2006 14:01



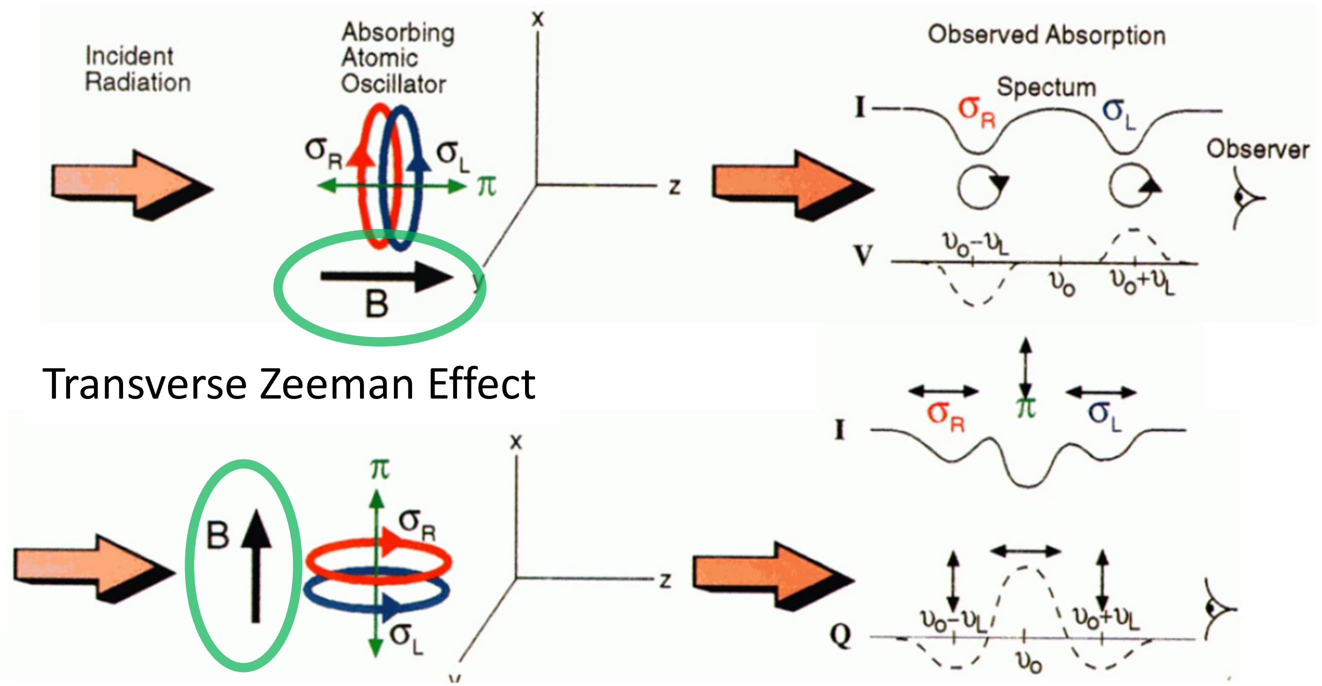


Magnetic Field Measurements (Transverse)



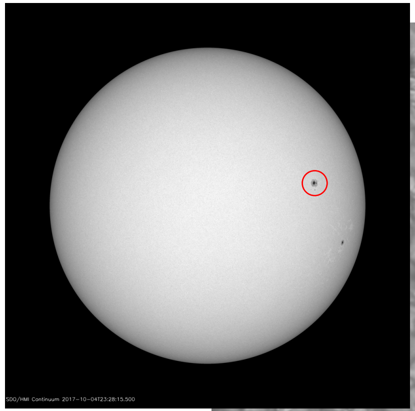
Longitudinal Zeeman Effect

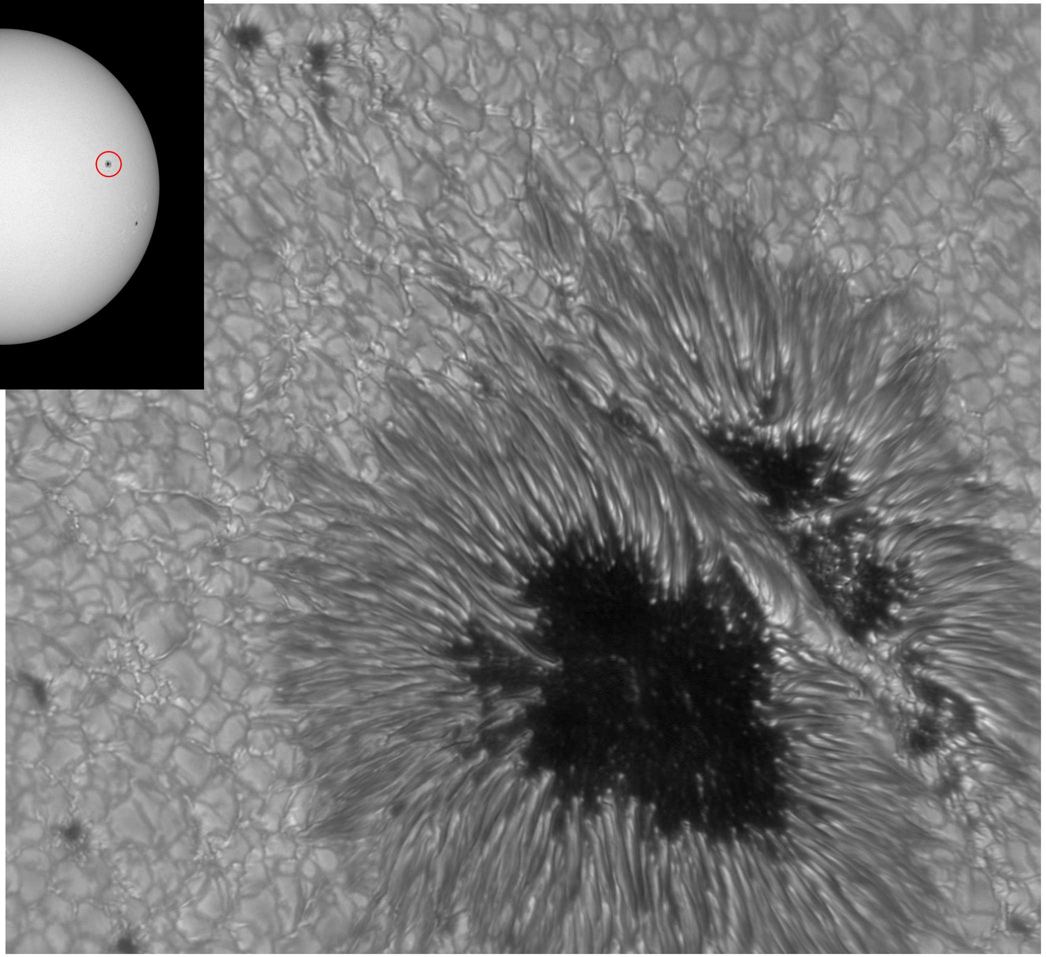
Transverse Zeeman Effect



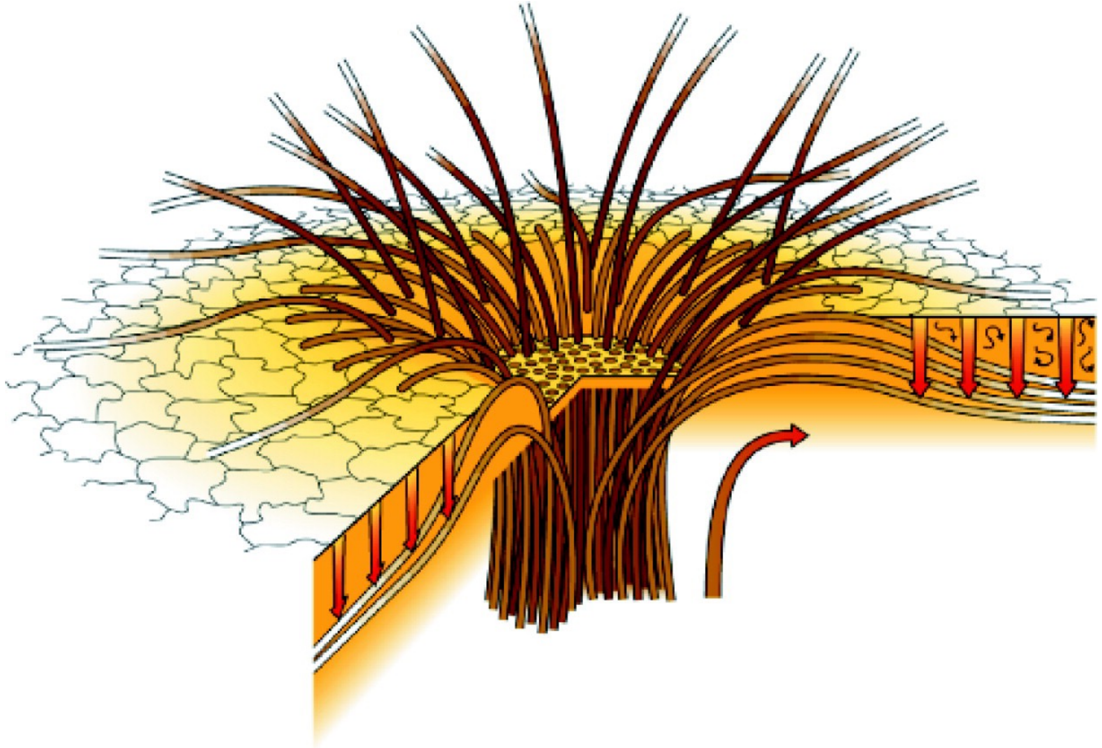
We can also measure the horizontal field with the Zeeman effect, but it is harder, noisier.

Sunspot Penumbra



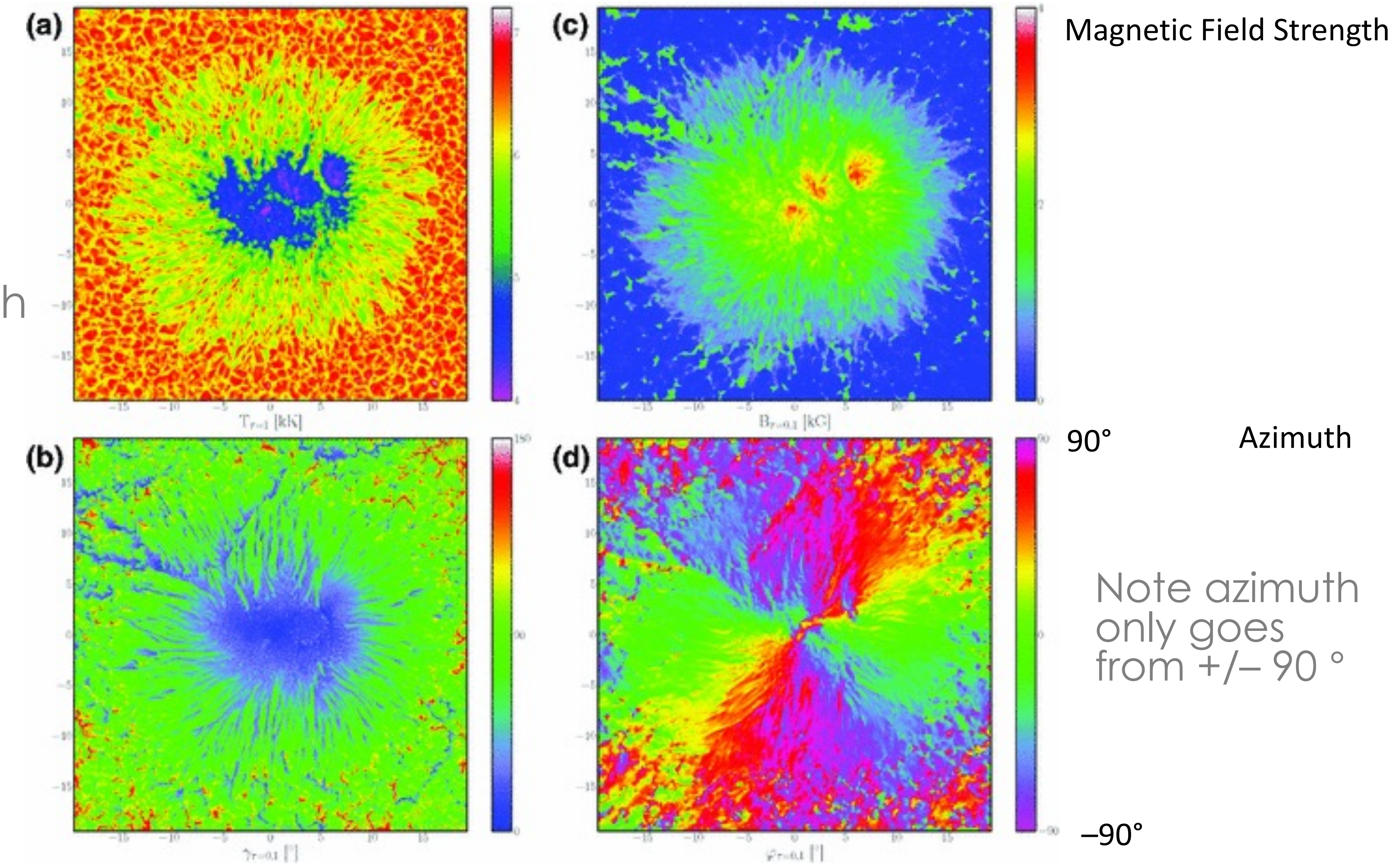


43'' = 31 Mm



Penumbra can be seen surrounding dark sunspot umbra – these are sites of complicated, predominantly horizontal fields

We can derive multiple parameters about the solar atmosphere with spectral lines.



Note azimuth only goes from +/– 90 °

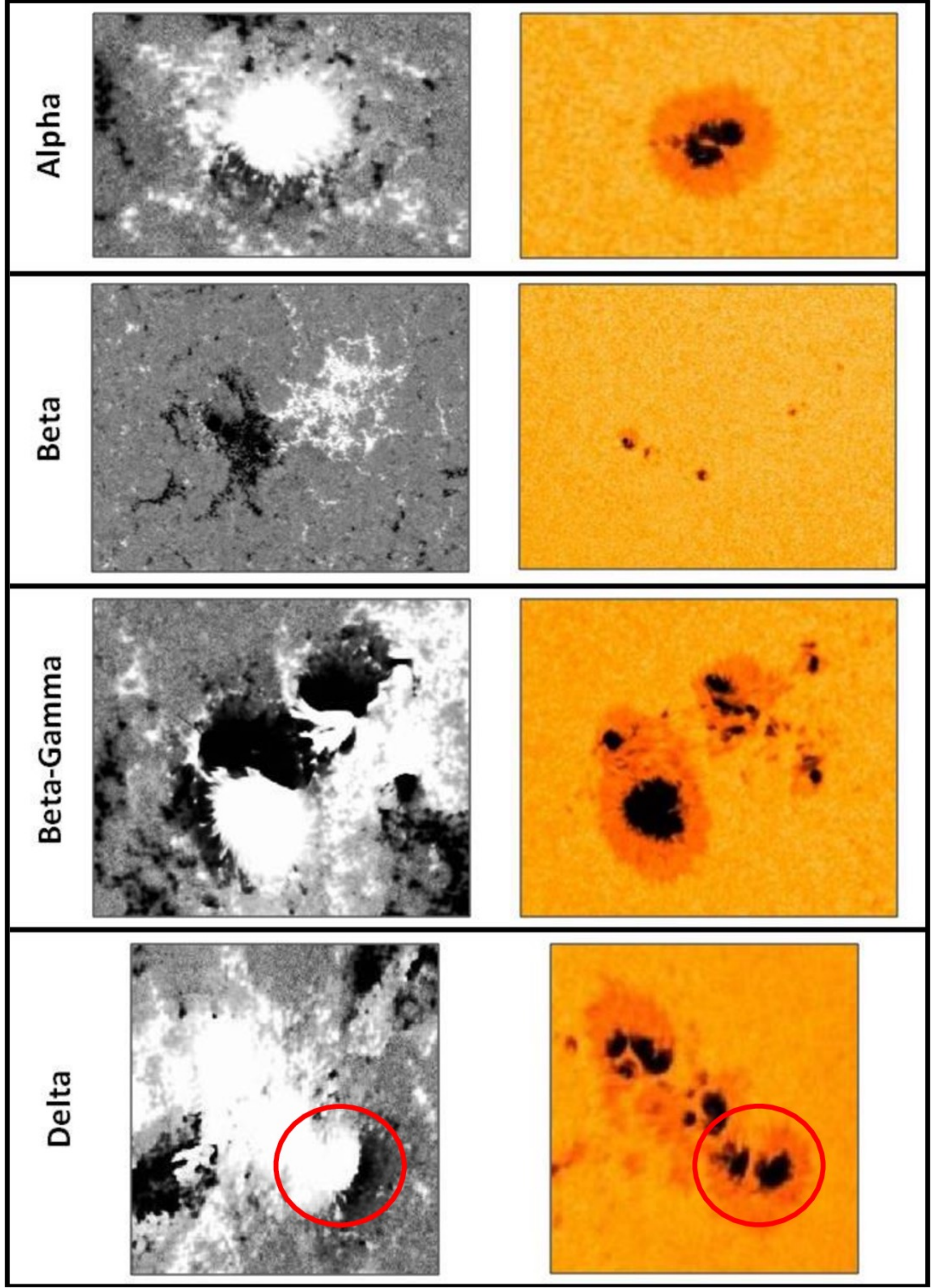
Mt. Wilson Classification

Flaring and CME activity may be related to complexity of magnetic field. How do we characterize different active regions?

Table 4. Mount Wilson Magnetic Classification Codes

Alpha	Unipolar (single magnetic pole) sunspot groups
Beta	Bipolar sunspot groups with a simple and distinct division between areas of opposite polarity
Beta-Gamma	Bipolar sunspot groups with no easily discernible dividing line separating areas of opposite polarity
Gamma	Complex sunspot groups with areas of opposite polarity completely intermixed, preventing classification as a bipolar group
*Delta	Denotes sunspot groups consisting of opposite polarity umbrae within the same penumbra

*Note that the classification code 'Delta' is not a standalone magnetic classification. It is simply a descriptor that can be affixed to the end of the 'Beta', 'Beta-Gamma', and 'Gamma' classification codes, allowing for a total of seven unique magnetic codes.



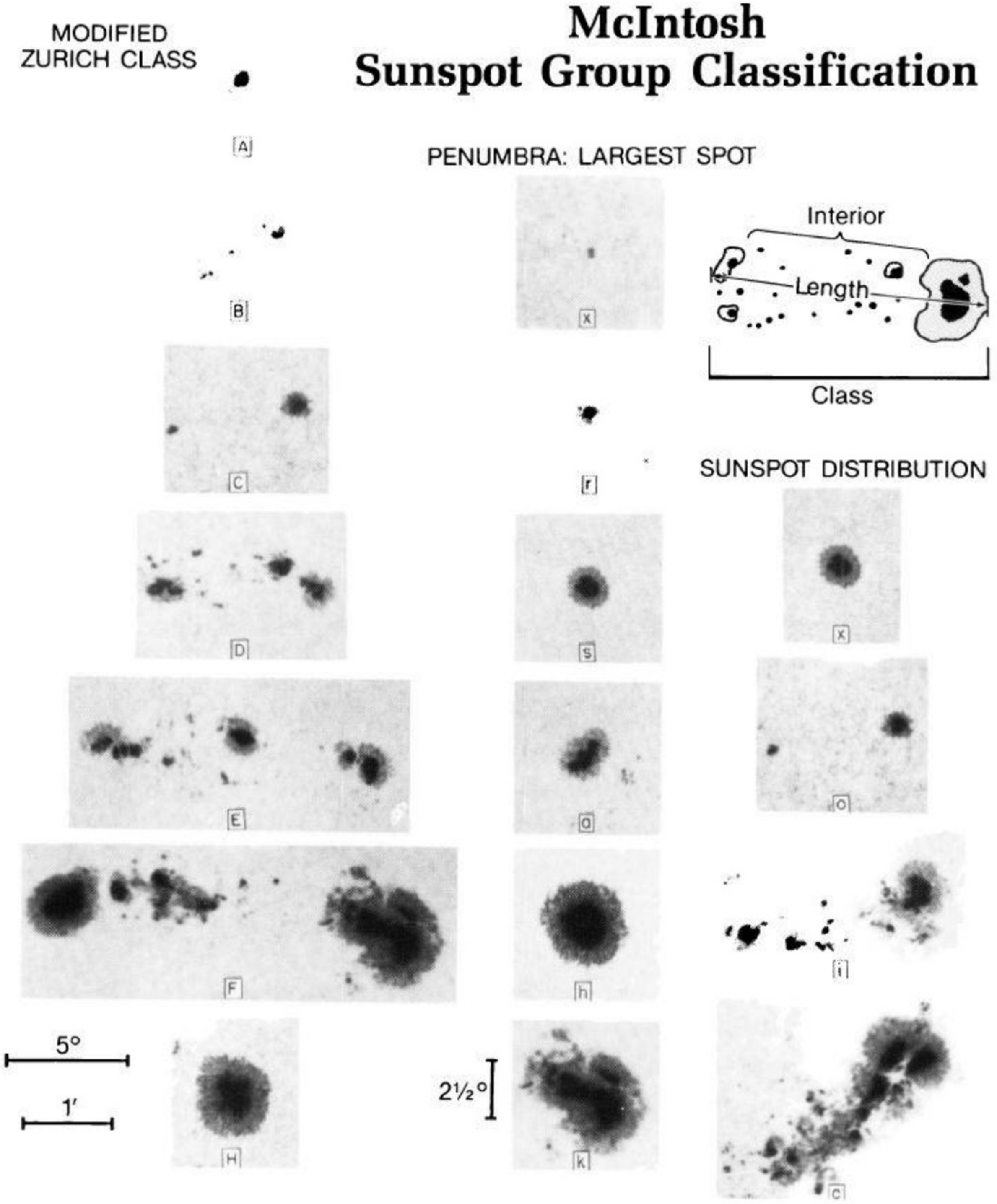
McIntosh Classifications

This classification scheme just uses distribution of sunspots, not magnetic field measurements.

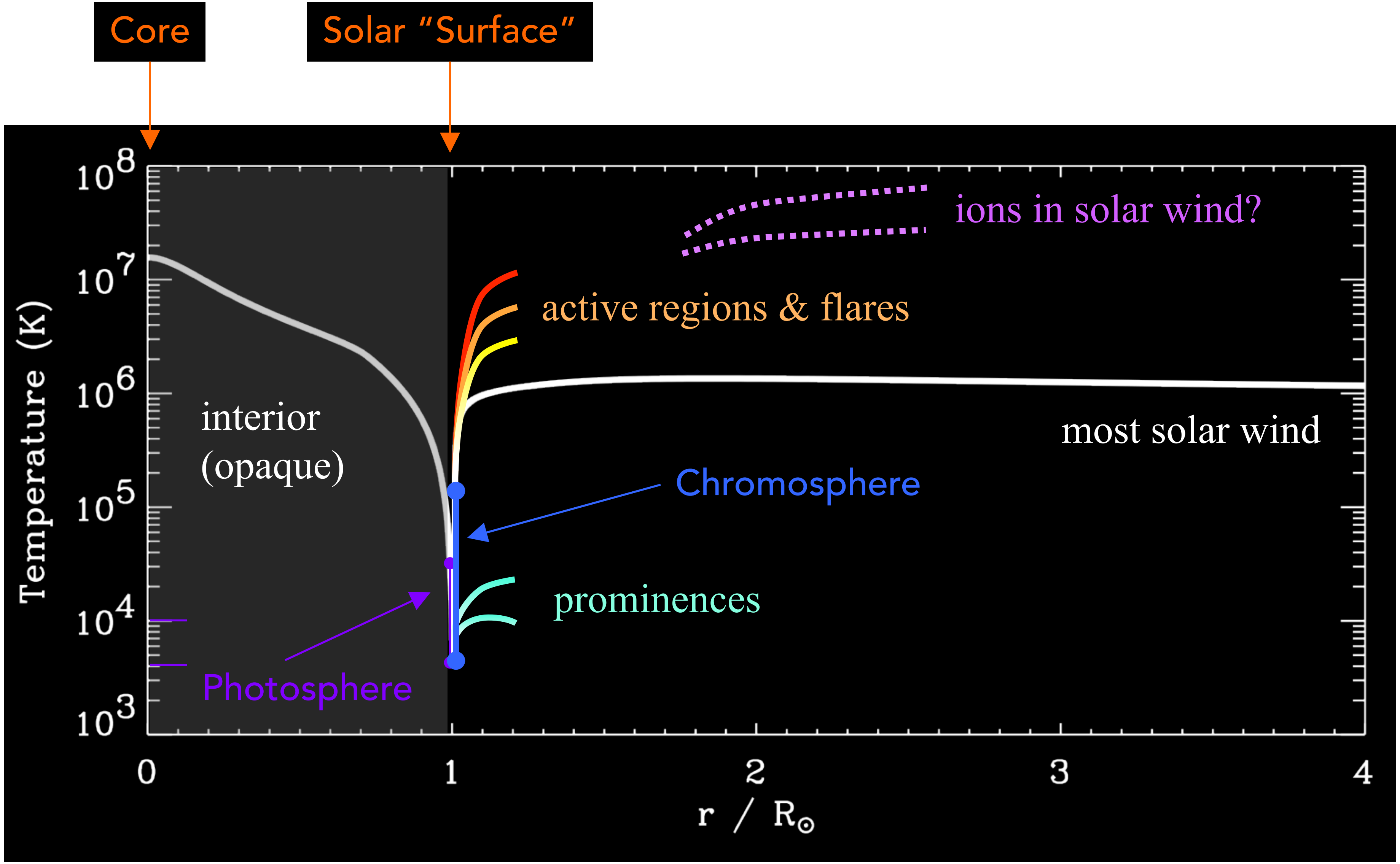
TABLE IV

Most flare-productive sunspot types 1969–1976 (from Kildahl, 1980)

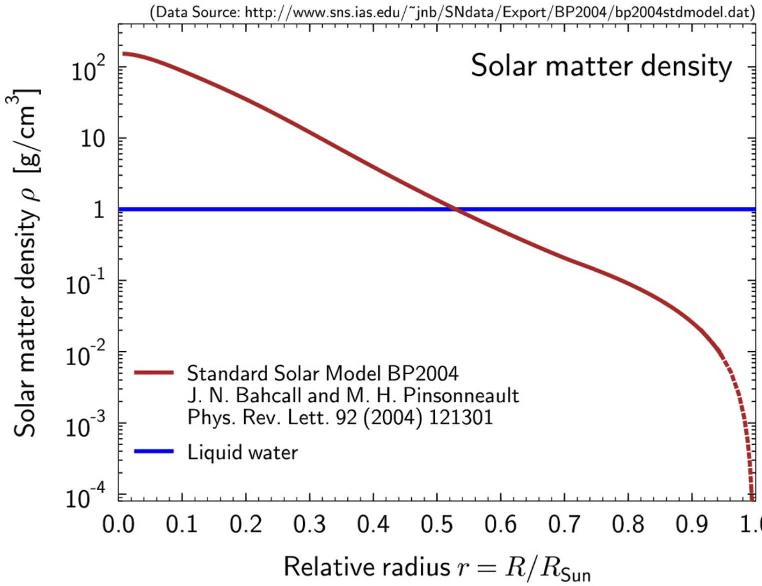
McIntosh type	Number of occurrences	Number of class M flares	Number of class X flares	Flares/occurrence per 24 hours	
				M	X
H*sx*	1963	99	6	0.05	0.003
D*so*	553	51	6	0.09	0.01
D*ai*	324	58	7	0.18	0.02
D*kc*	100	72	10	0.72	0.10
E*ki*	81	103	11	1.27	0.14
E*kc*	63	149	21	2.36	0.33
F*ki*	47	106	17	2.26	0.36
F*kc*	27	39	13	1.44	0.48



What happens higher in the solar atmosphere?



What happens higher in the solar atmosphere?

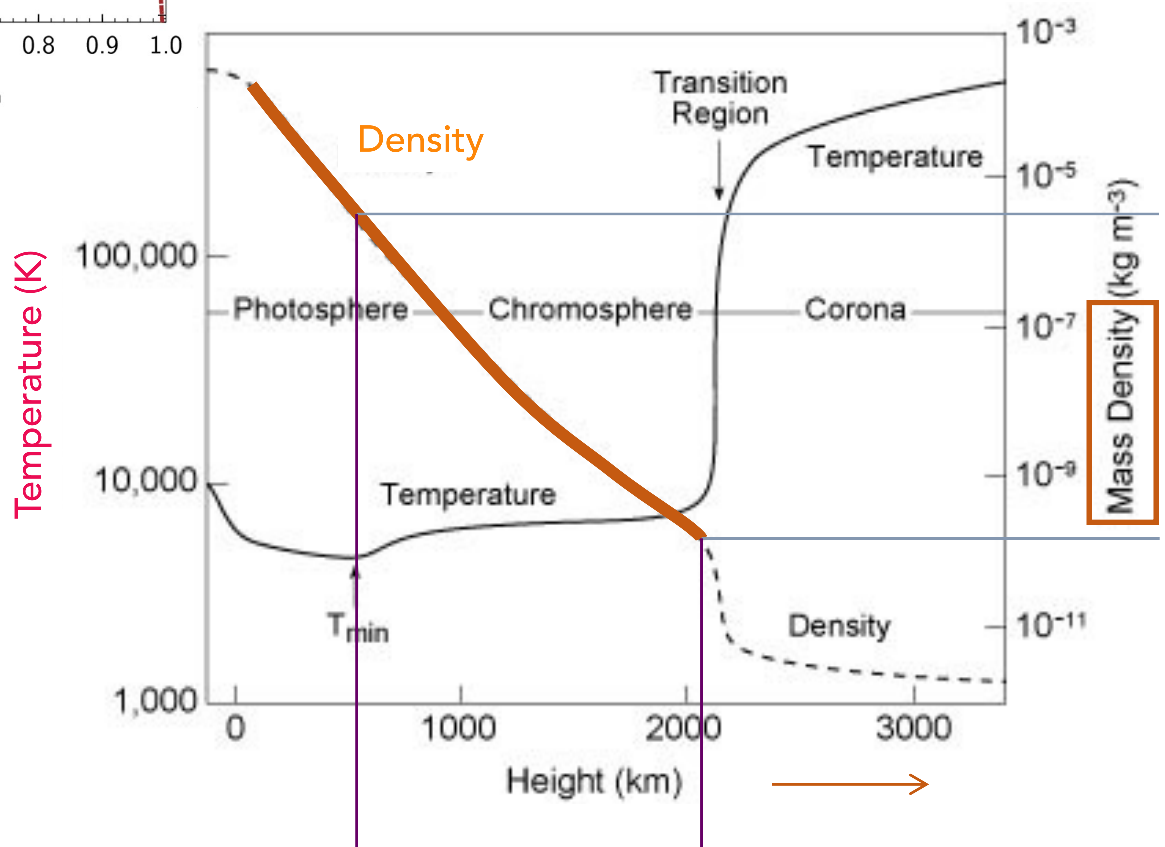


Terrestrial atmosphere

1.2×10^{-3} g / cm^3

Martian atmosphere

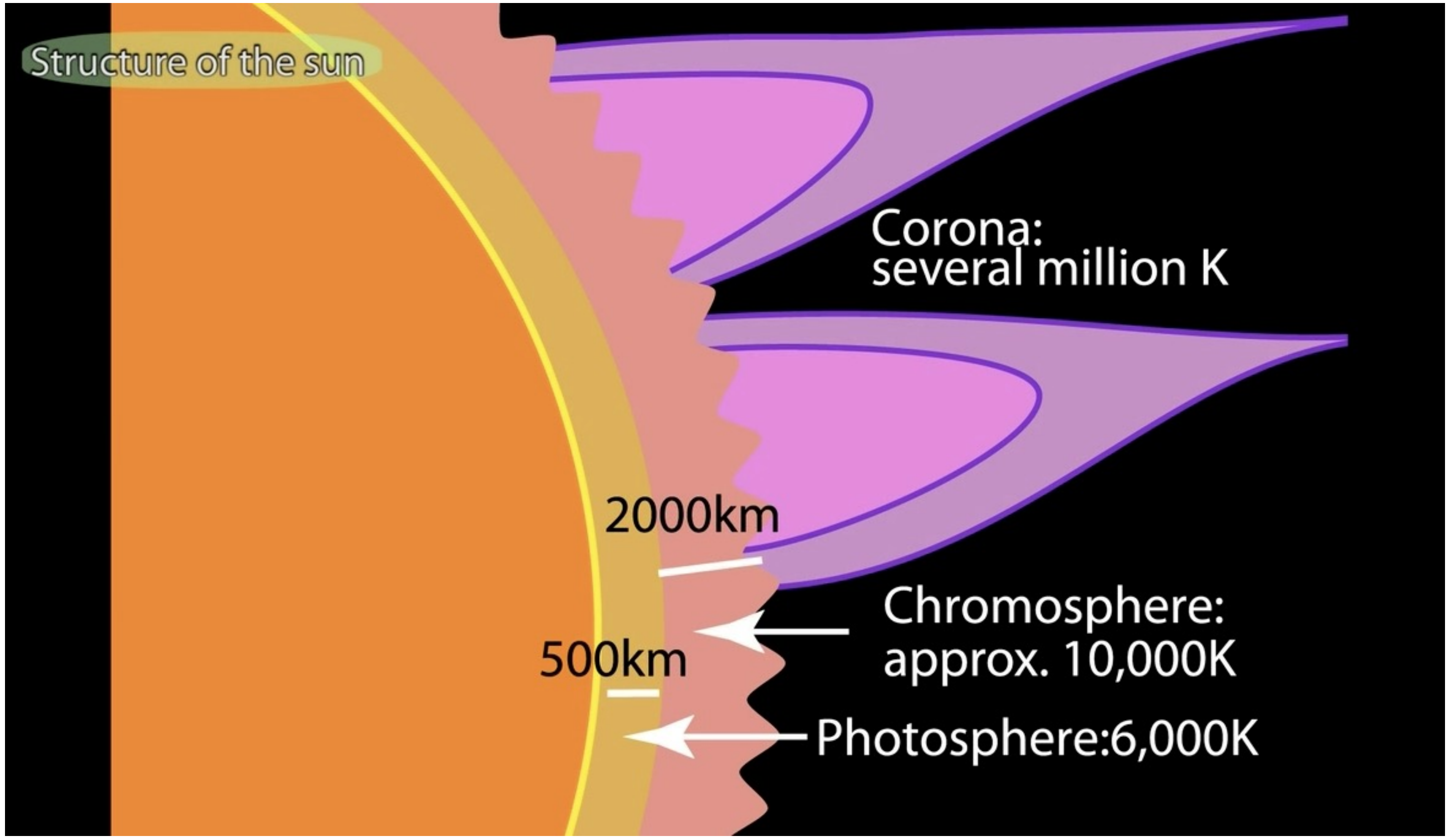
1.5×10^{-5} g / cm^3



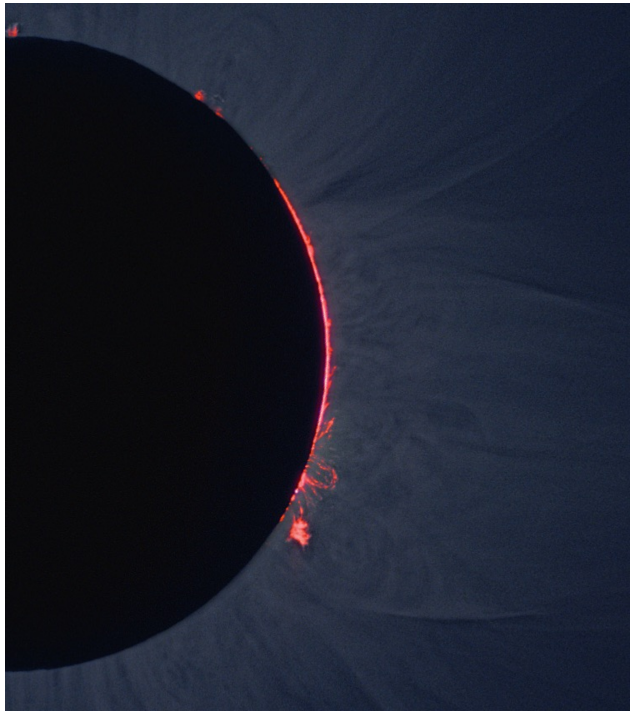
10^{-9} g / cm^3

10^{-13} g / cm^3

Solar (Stellar) Atmosphere

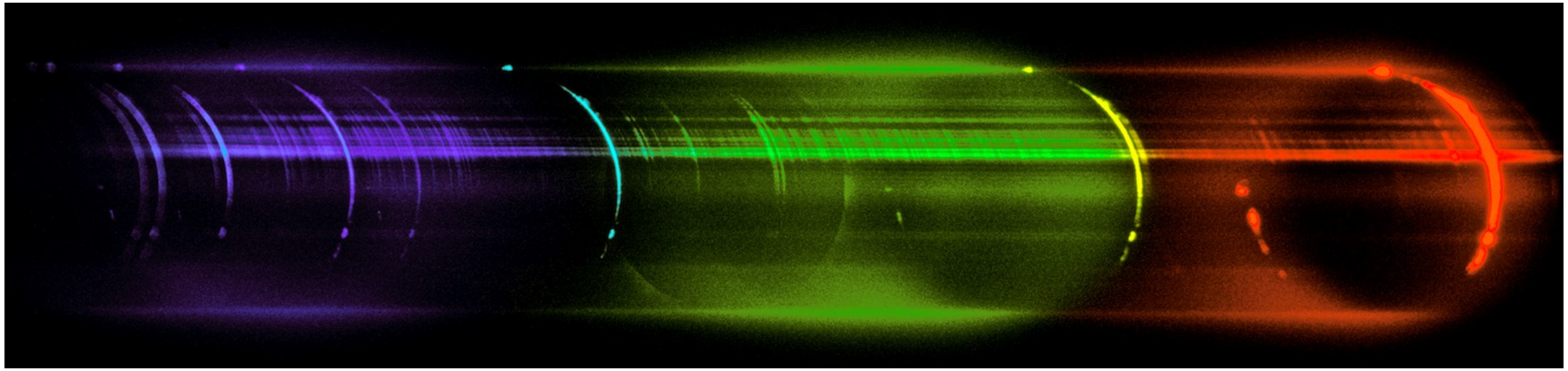


	Thickness	Density	Energy requirements	Mass
Photosphere	~500 km	$\rho_{ph} = 2x10^{-5}$ gr/cm^3	$F_{ph} = 6$ kW/cm^2	4 x 10^{20} kg
Chromosphere	~2000 km	10^{-3} – 10^{-6} x ρ_{ph}	10^{-4} x F_{ph}	2 x 10^{18} kg
Corona	> 10^6 km	10^{-8} x ρ_{ph}	< 10^{-5} x F_{ph}	6 x 10^{15} kg

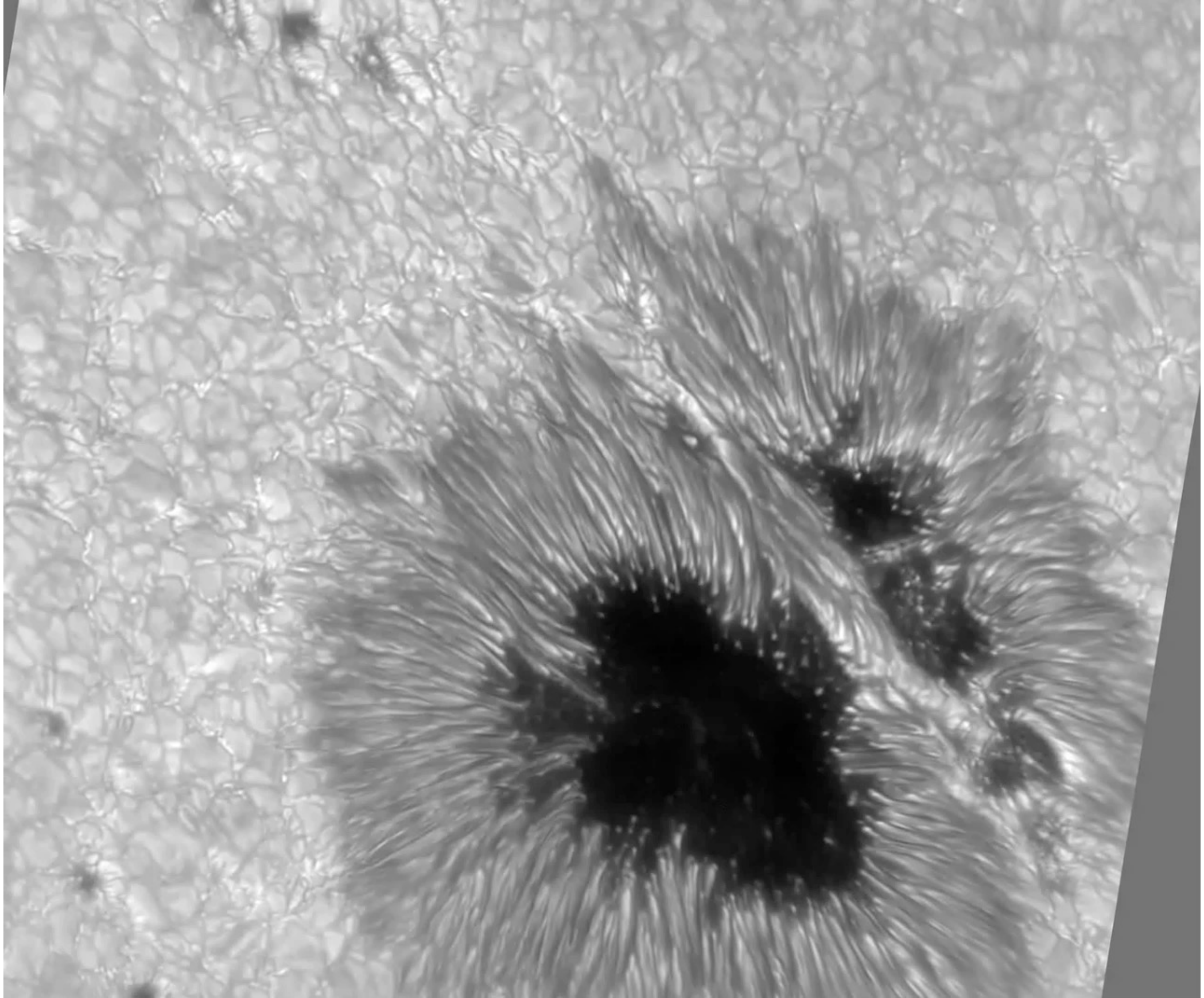


Chromospheric Radiation

Radiation from chromosphere comes in the form of continuum radiation (in the UV and millimeter wavelengths) and many emission lines in the visible and UV



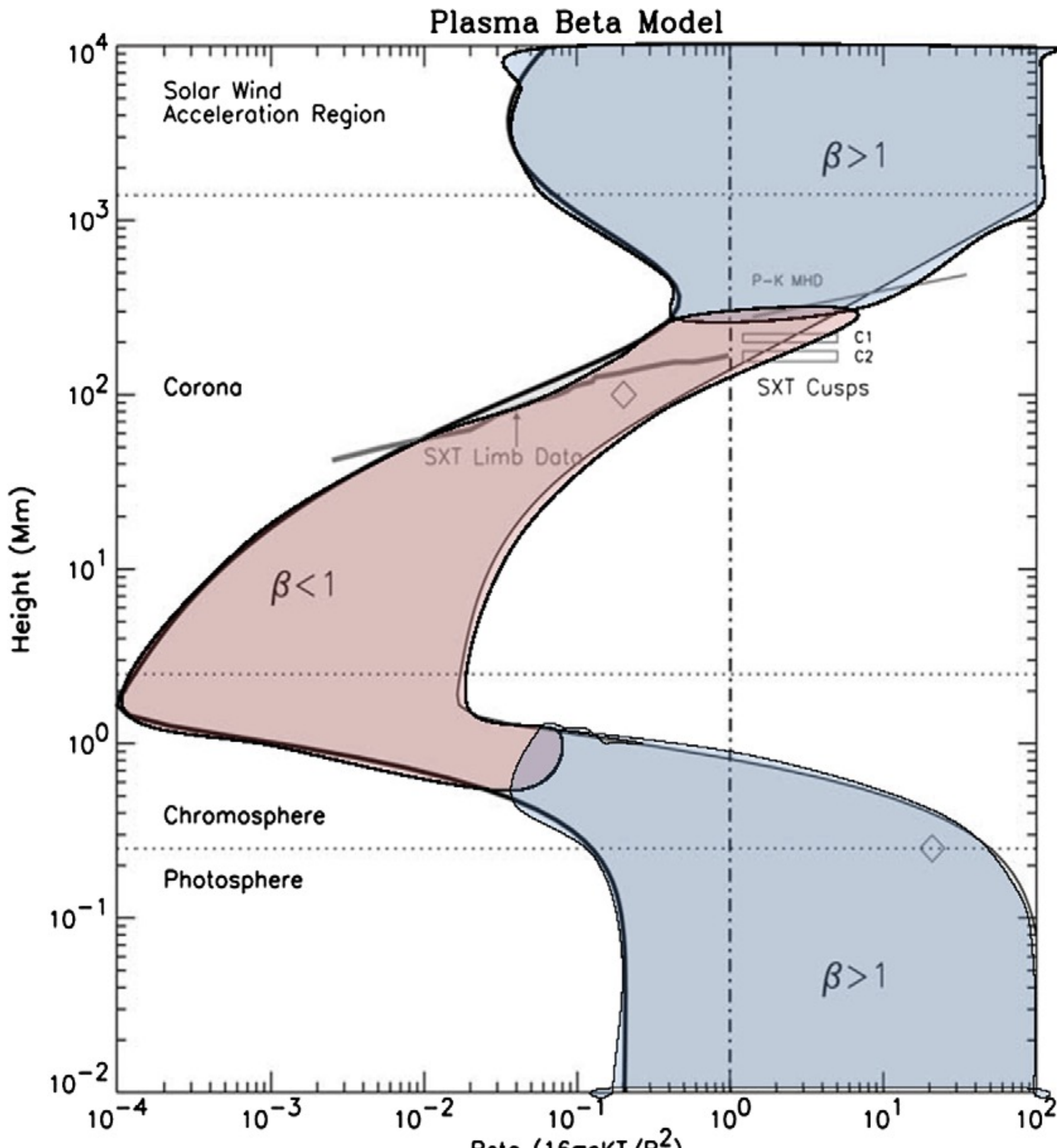
flash spectrum courtesy Dr. Manfred Rudolf



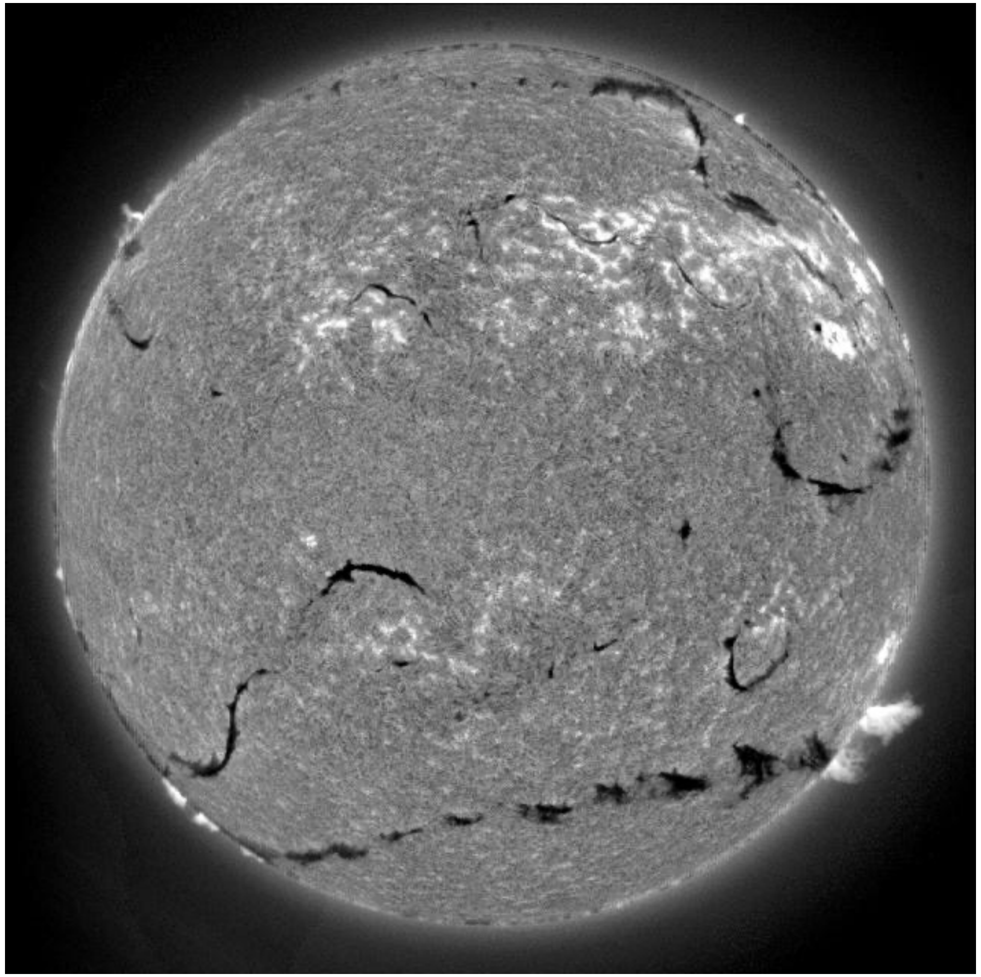
Magnetic Field Dominance

$$\text{plasma } \beta = \frac{\text{plasma pressure}}{\text{magnetic pressure}}$$

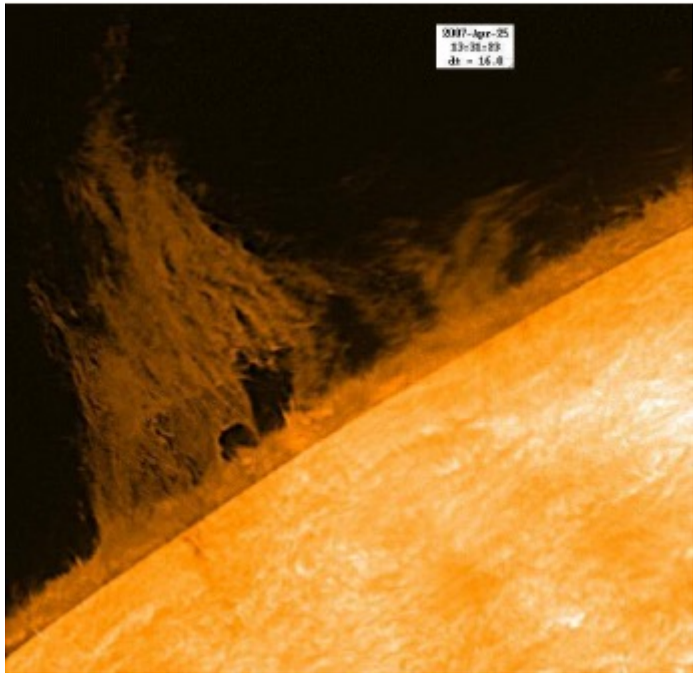
In the chromosphere and corona, because of the steep drop in density, the magnetic field begins to dominate the plasma motions.

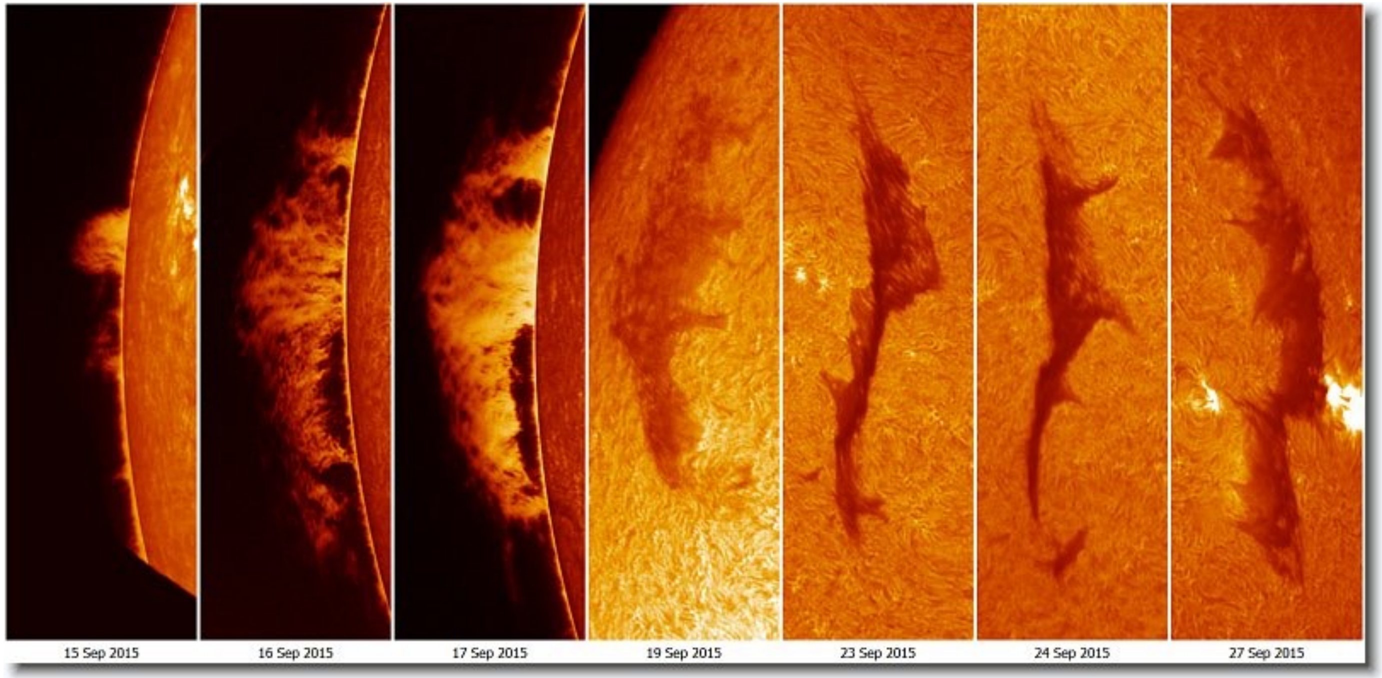


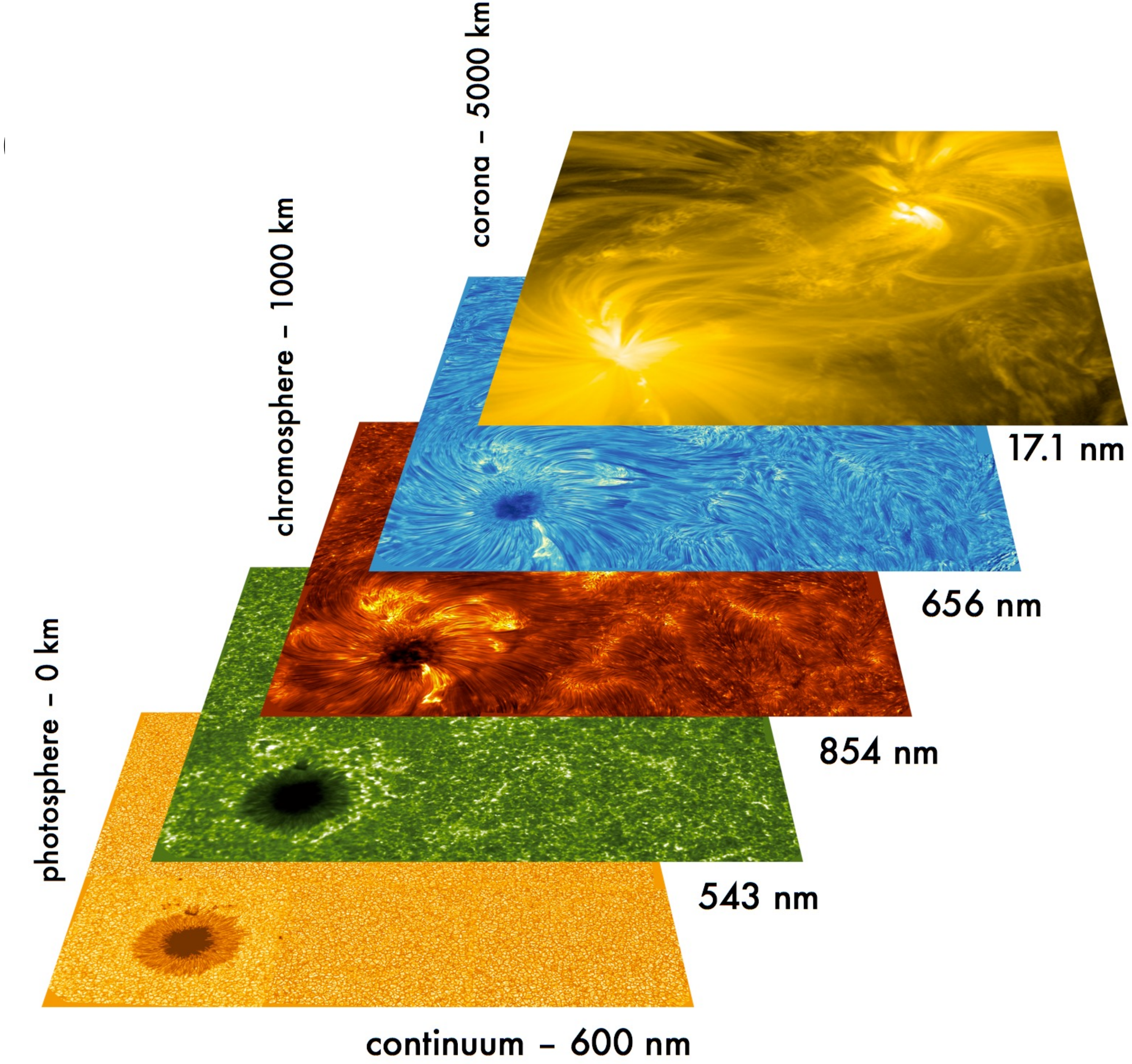
Filaments and Prominences



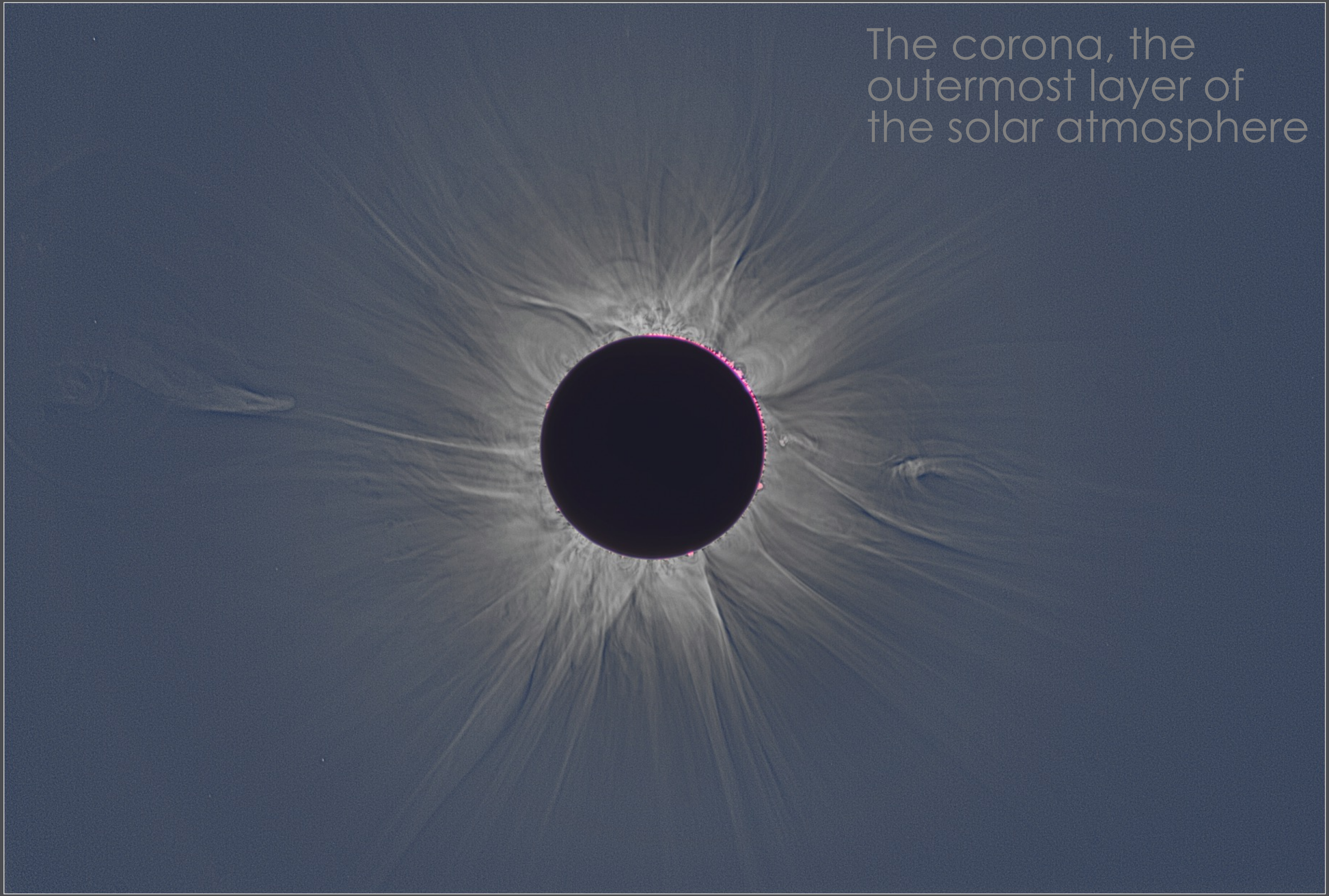
This creates neat things like prominences (seen at the limb) and filaments (same structures, but seen on the disk)



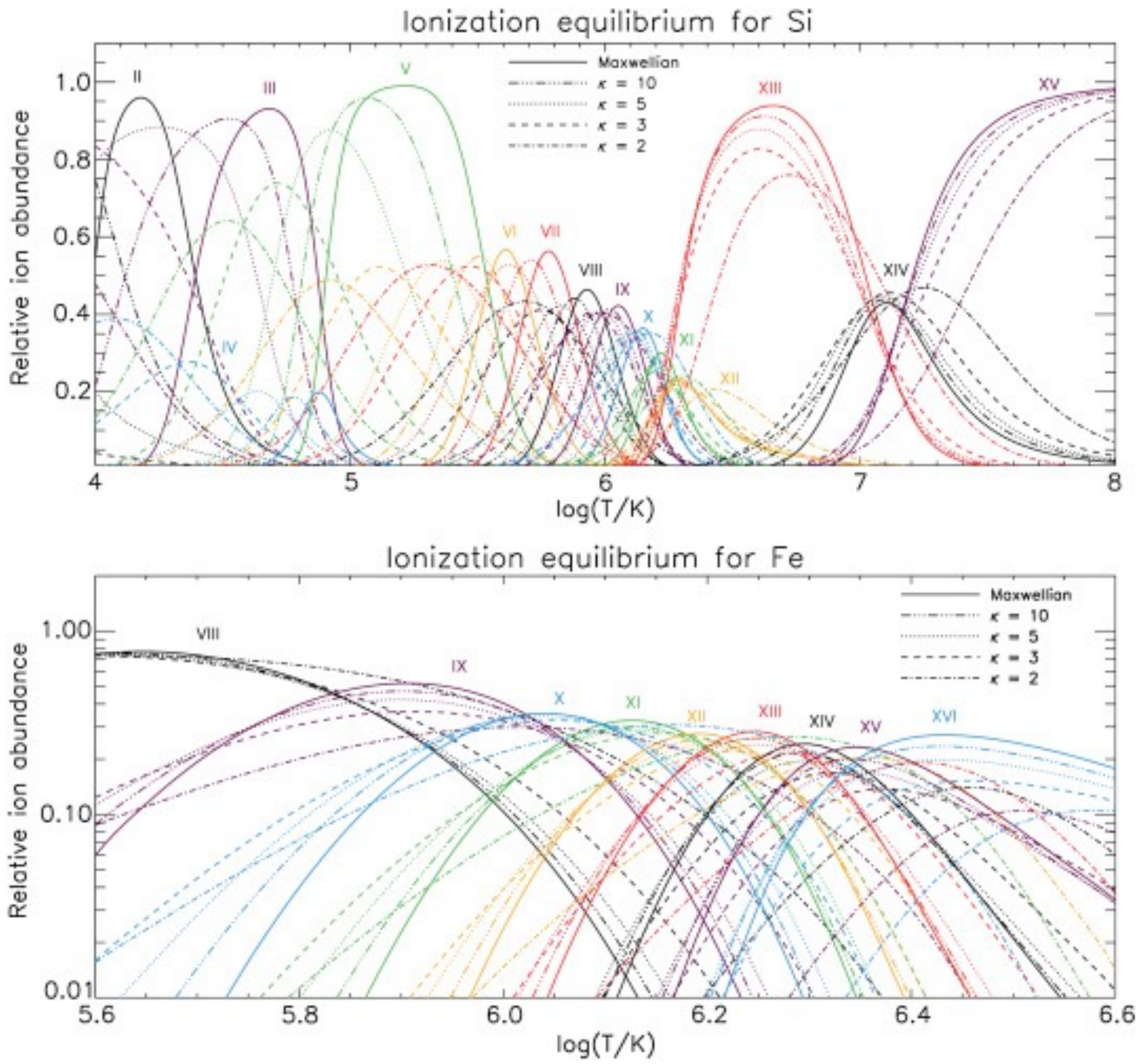




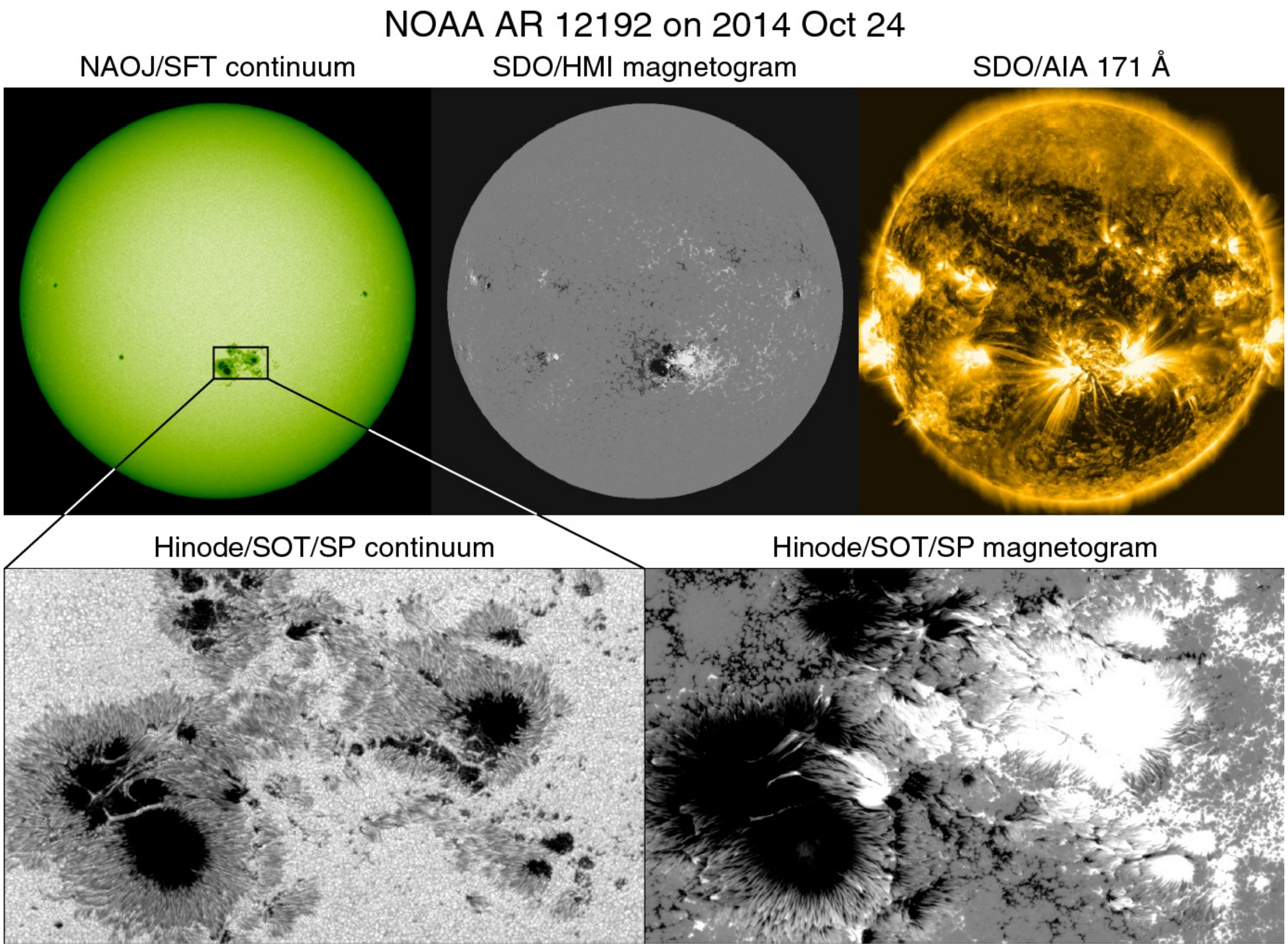
A view of how structures connect up through different regions of the atmosphere



Total Solar Eclipse 2013

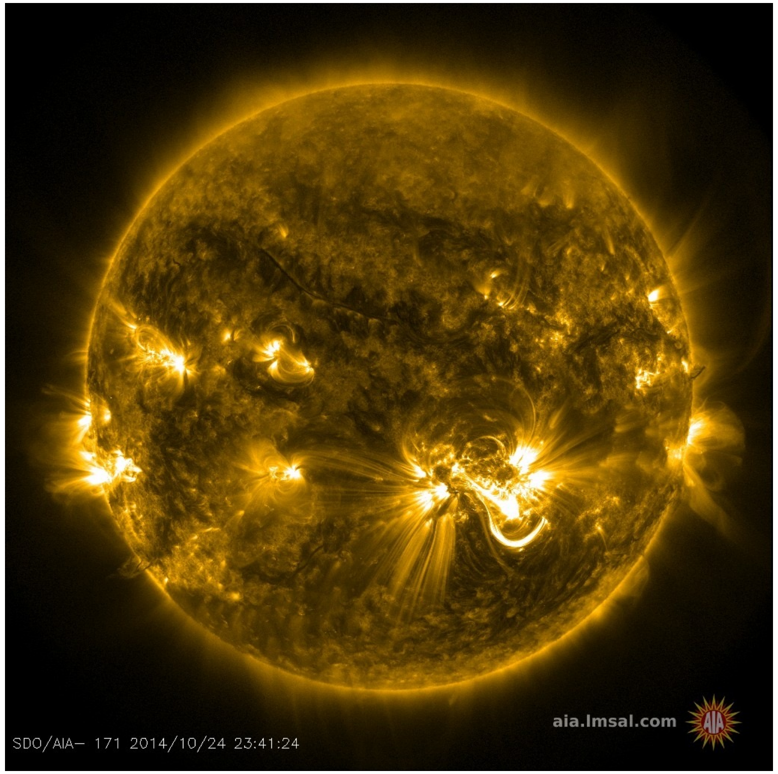


Again we also use spectral lines to diagnose the conditions in the corona – different ionization states indicate different ambient temperatures

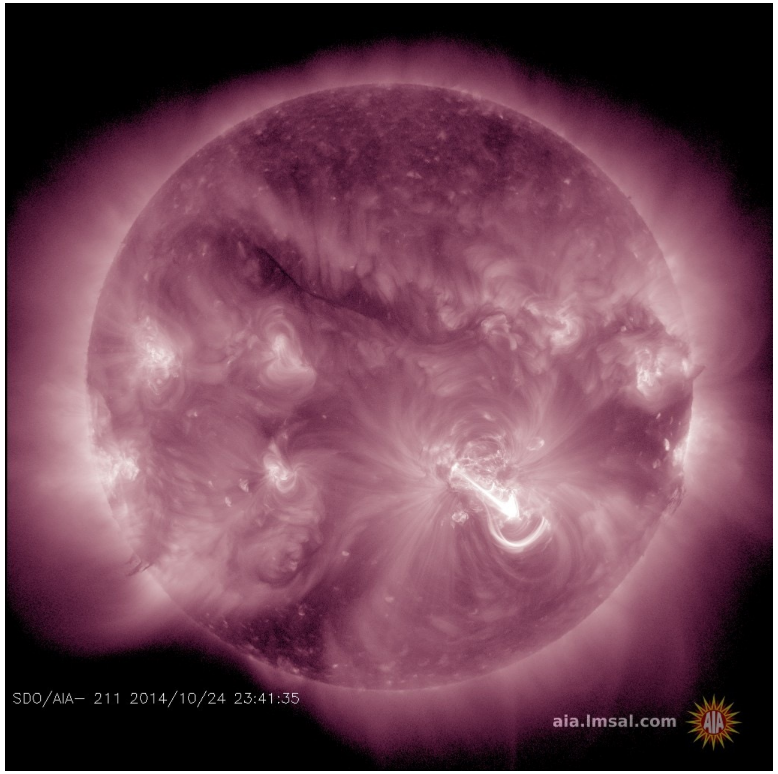

NOAA AR 12192 on 2014 Oct 24
NAOJ/SFT continuum
SDO/HMI magnetogram
SDO/AIA 171 Å
Hinode/SOT/SP continuum
Hinode/SOT/SP magnetogram

SDO EUV Images

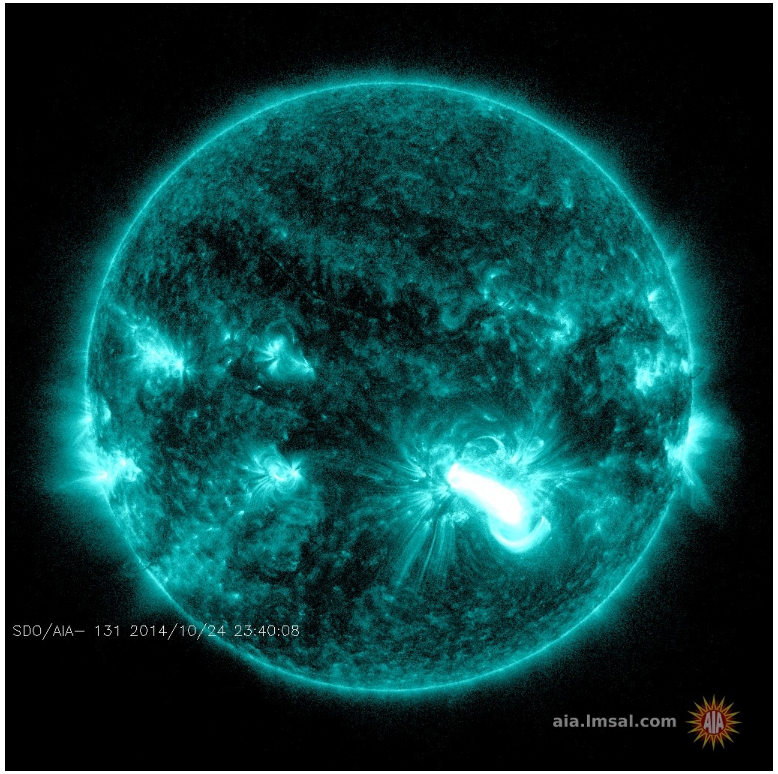
171 Å
Fe IX
$10^{5.8}$ K



171 Å
Fe XIV
$10^{6.3}$ K

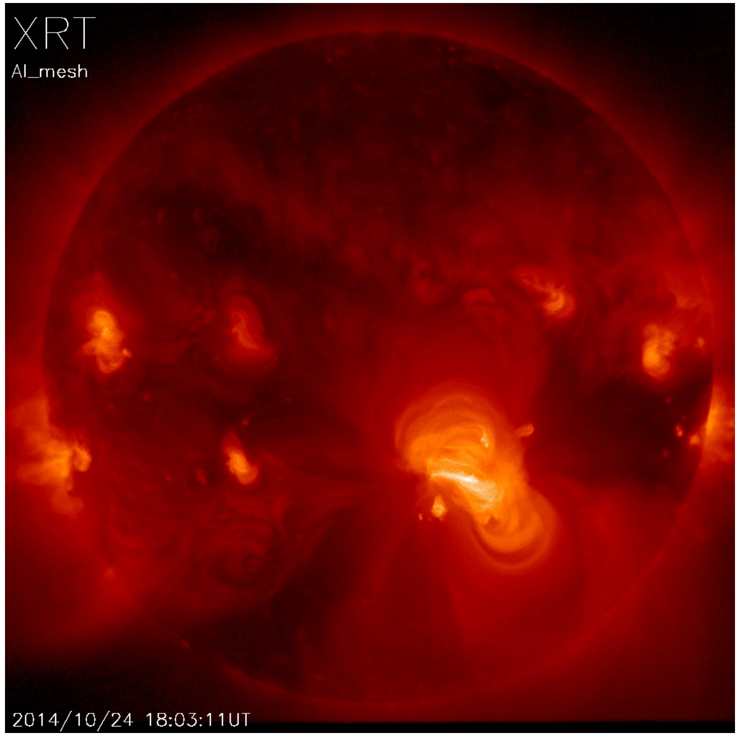


171 Å
Fe XX, XXIII
10^{7} K

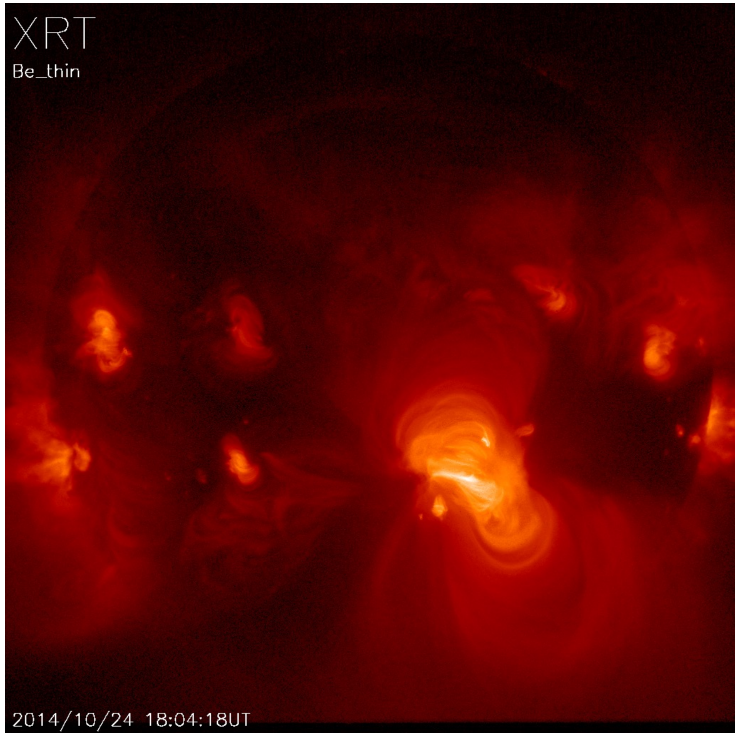


XRT X-ray Images

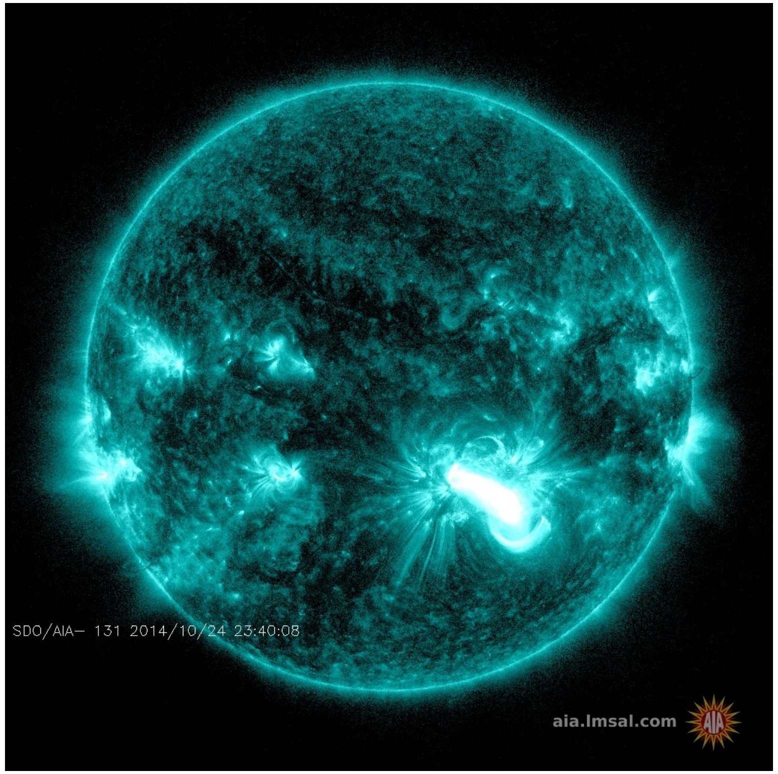
Al-Mesh
$10^{6.9}$ K



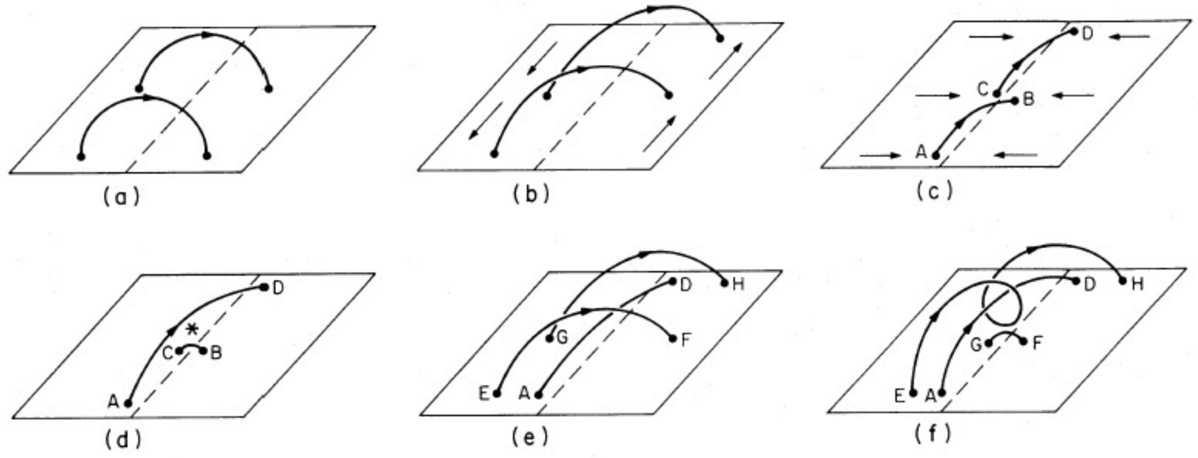
Be-Thin
$10^{7.1}$ K

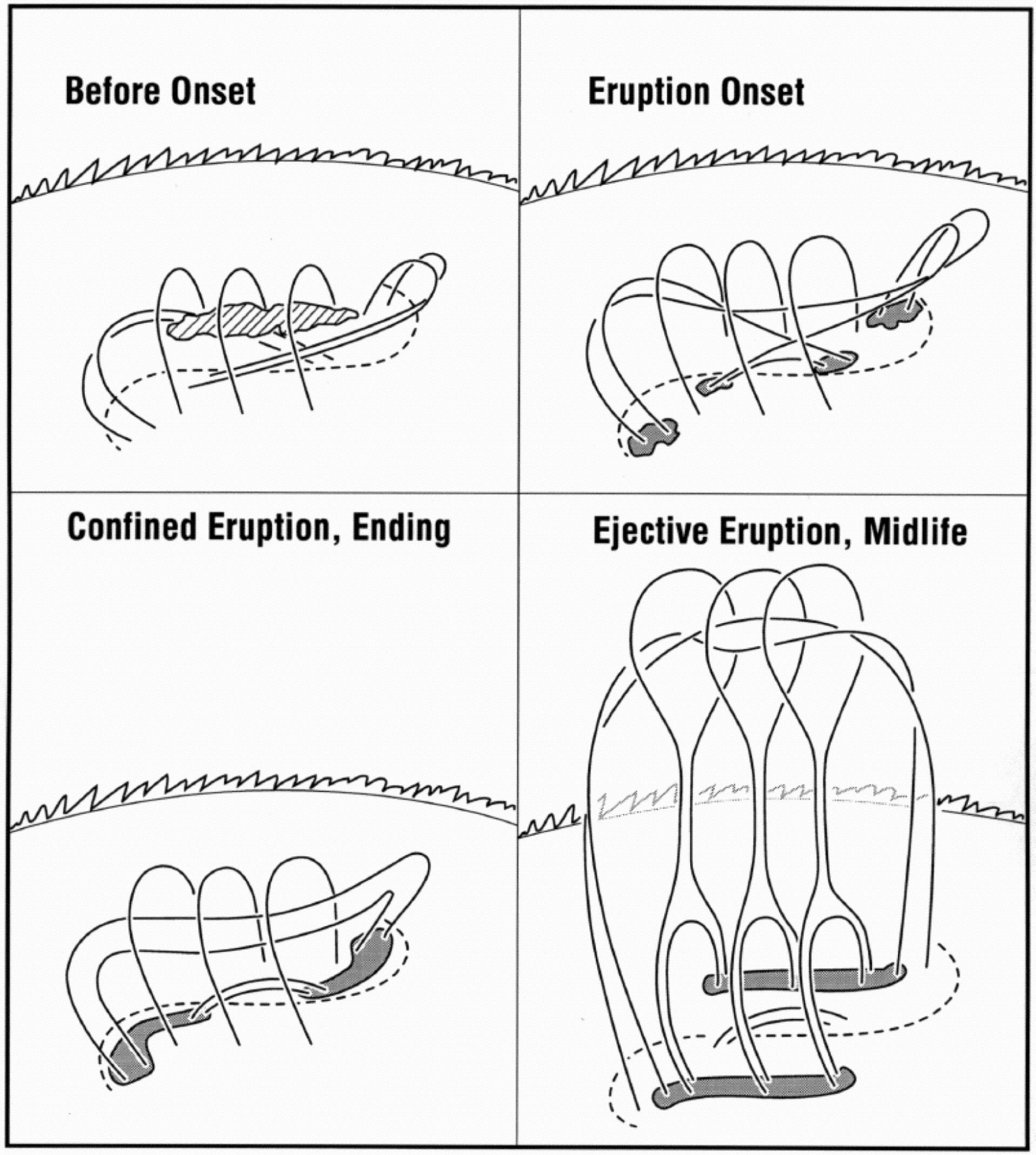


171 Å
Fe XX, XXIII
10^7 K



Magnetic Energy Storage

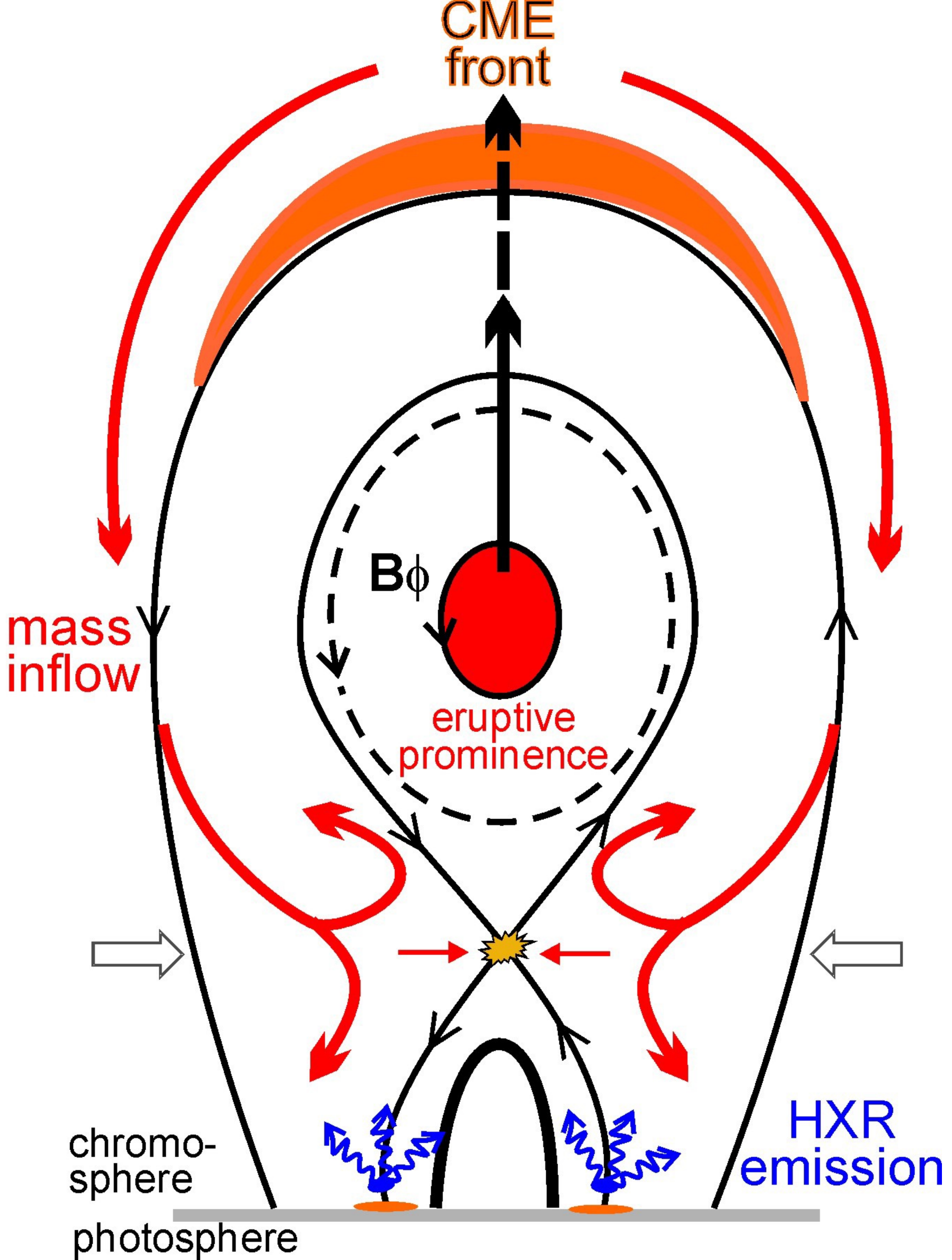




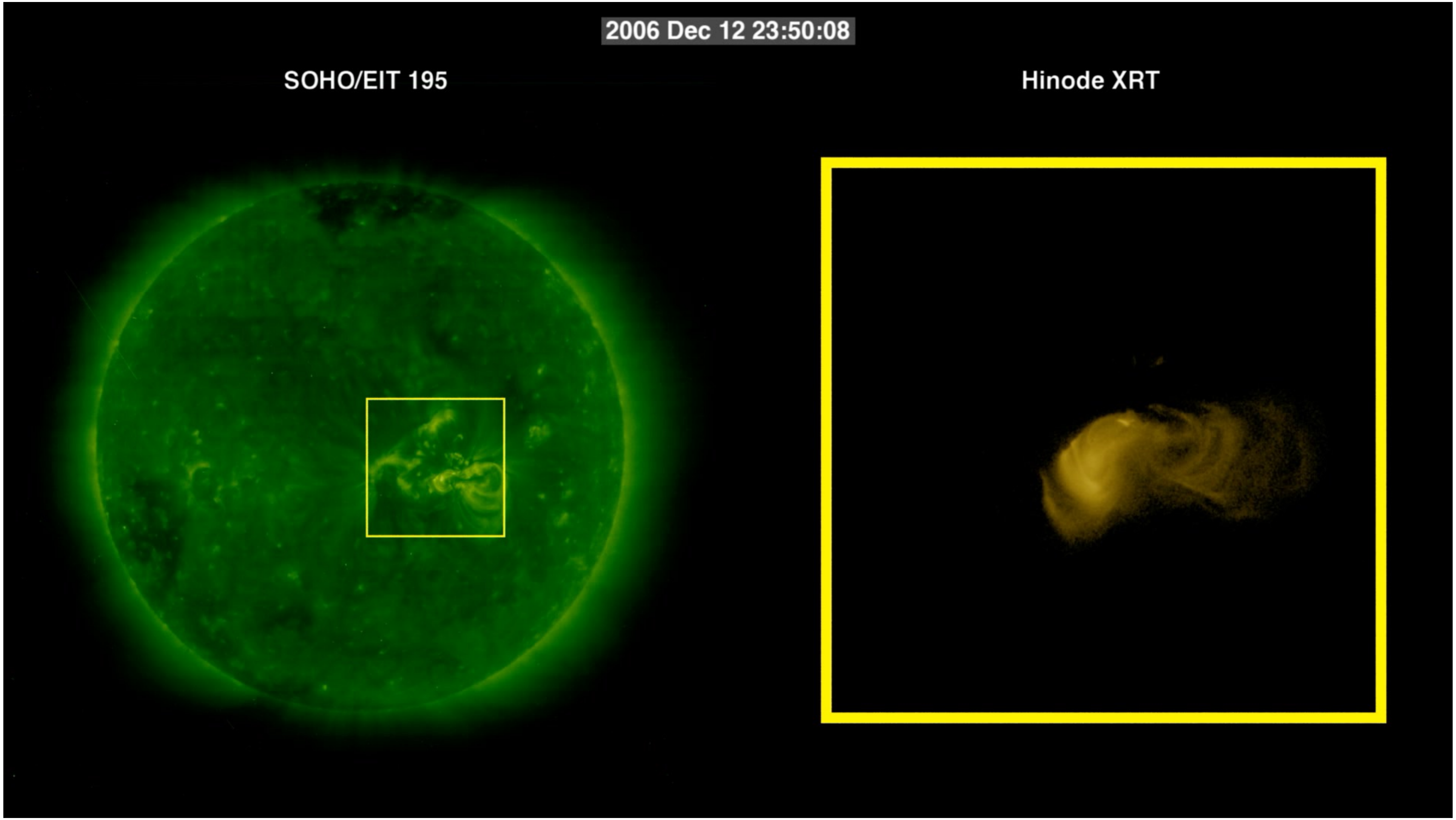
Driven by the plasma motions in the photosphere, the magnetic field in the photosphere can become intertwined and store energy in an unstable state

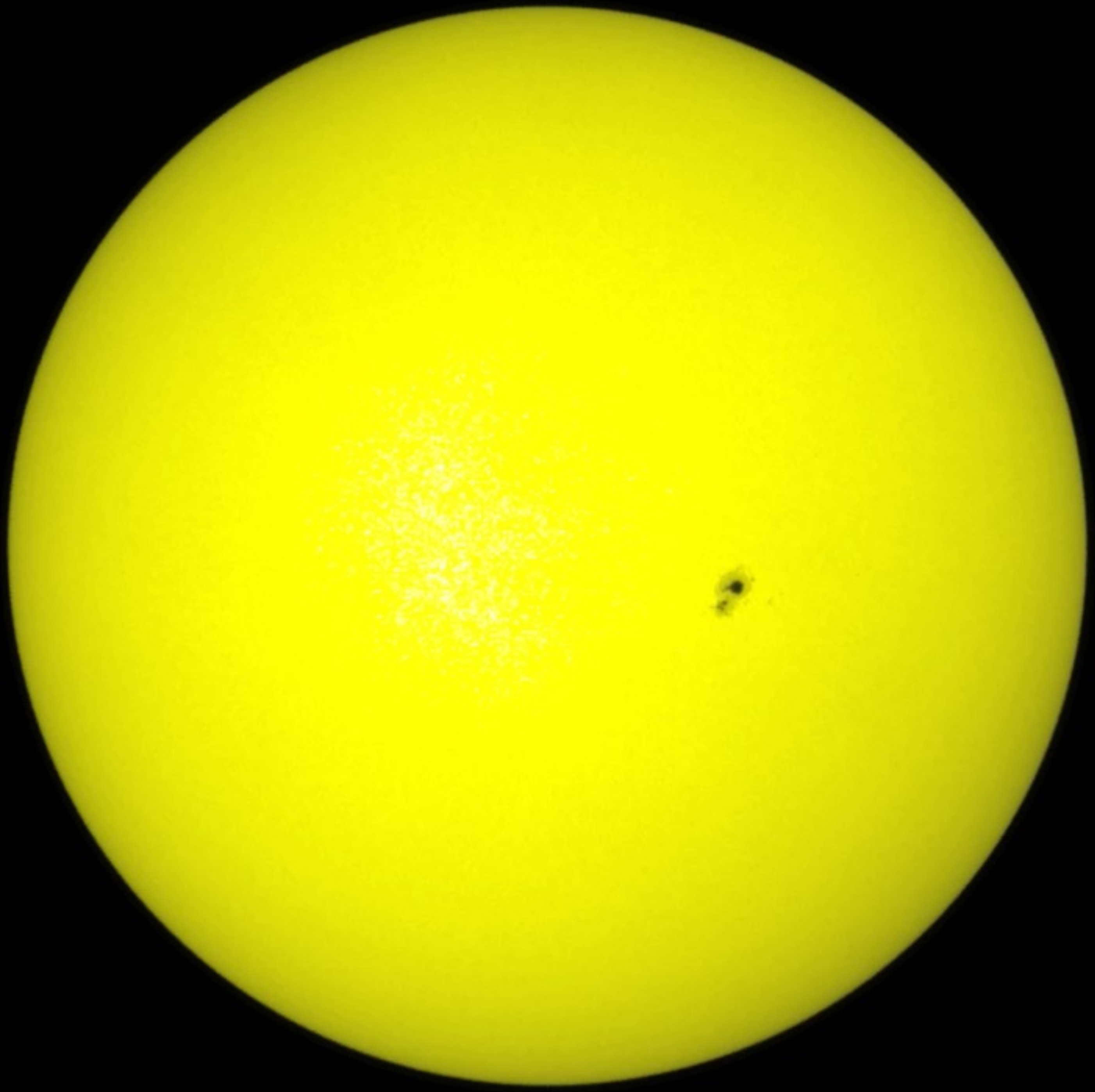
Magnetic Energy Release

The magnetic energy can then be impulsively released, resulting in the release of high-energy photons, heating of the solar chromosphere, and outward flux of high-energy particle and mass ejections (CME).

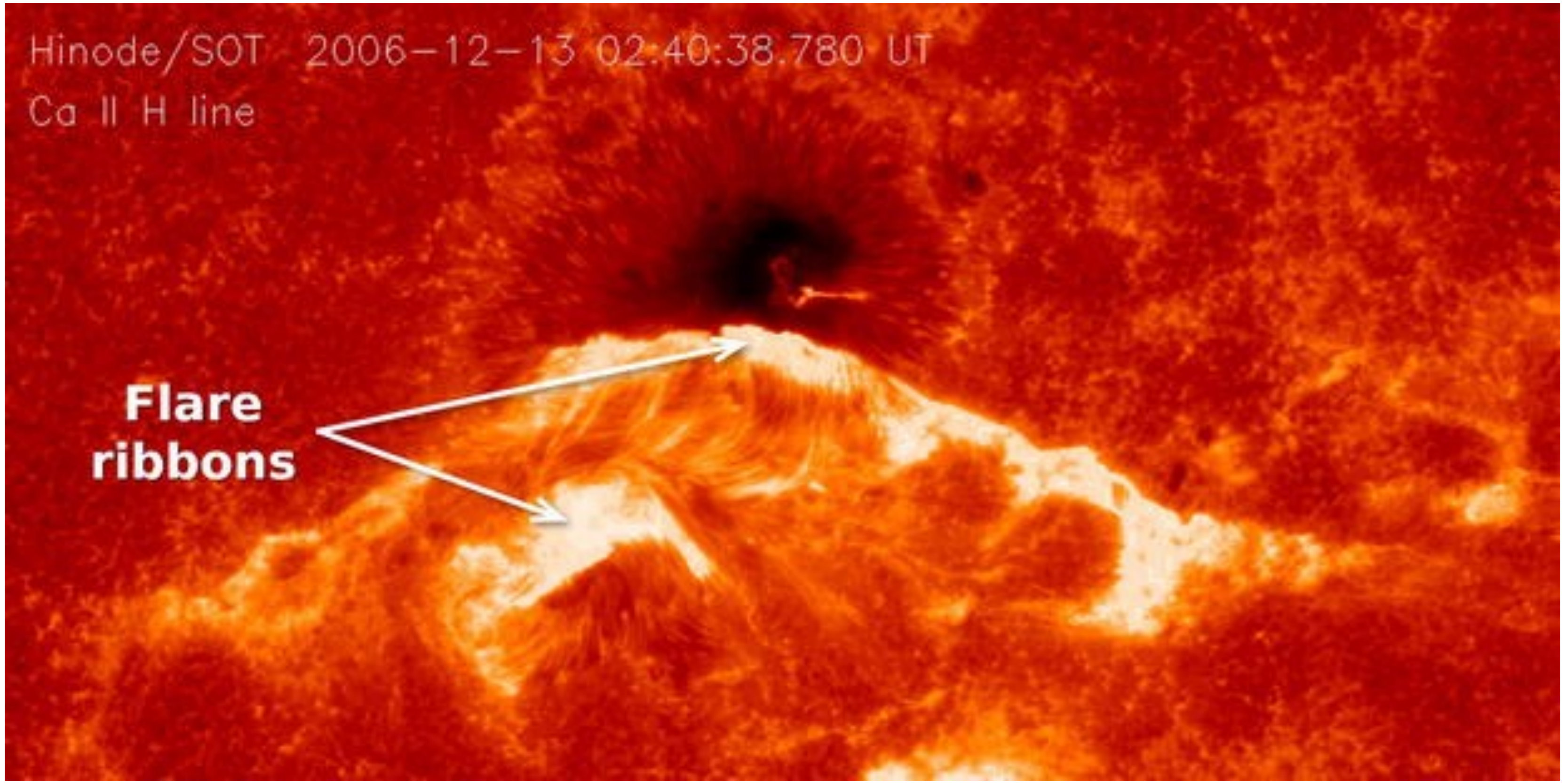


Example Flare (movie)





Chromospheric Response

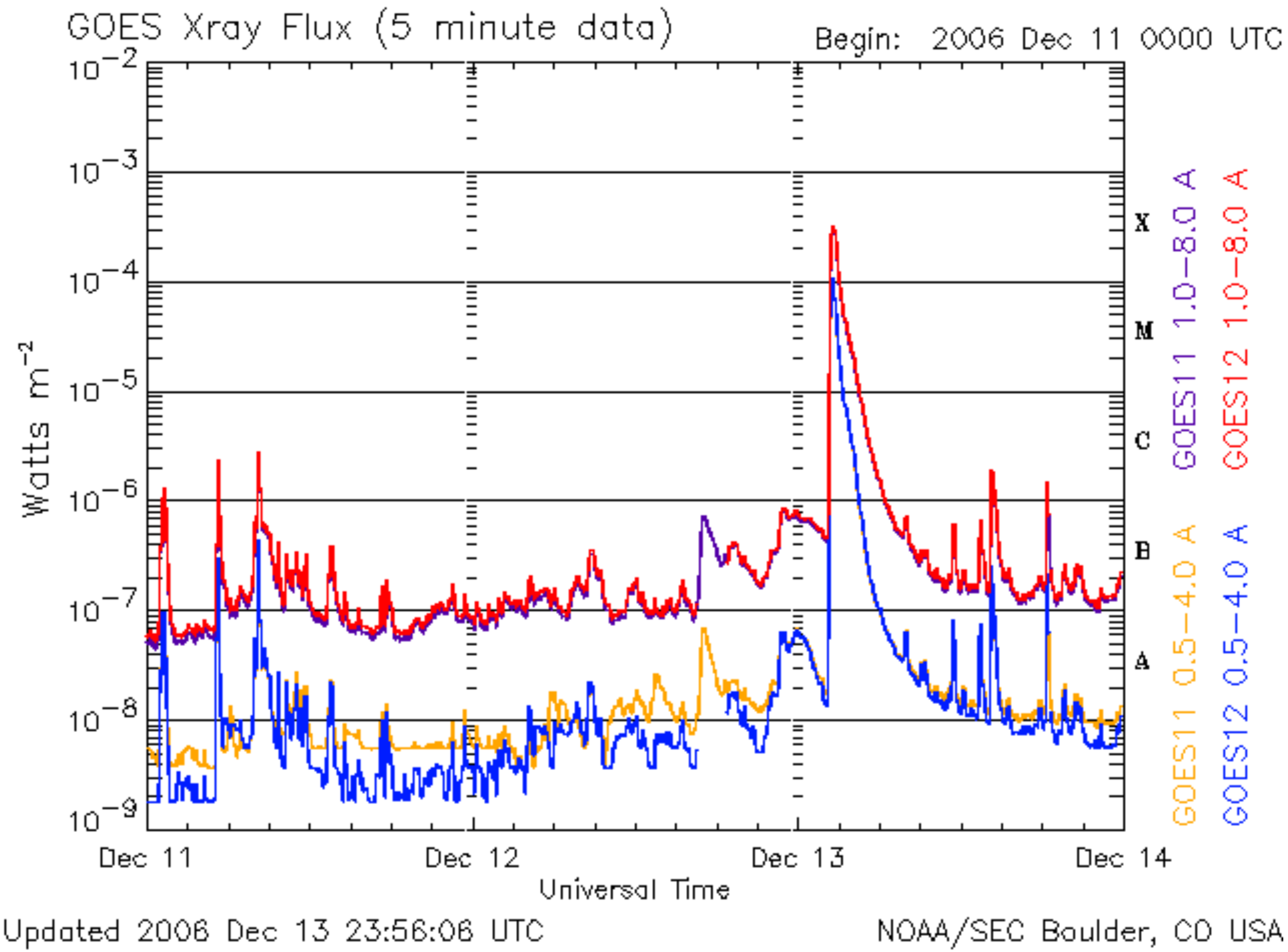


Flares generate energy propagation down to loops of magnetic loops, heating their footpoints in the chromosphere, which tend to fall on either side of the polarity inversion line

Activity Indicators

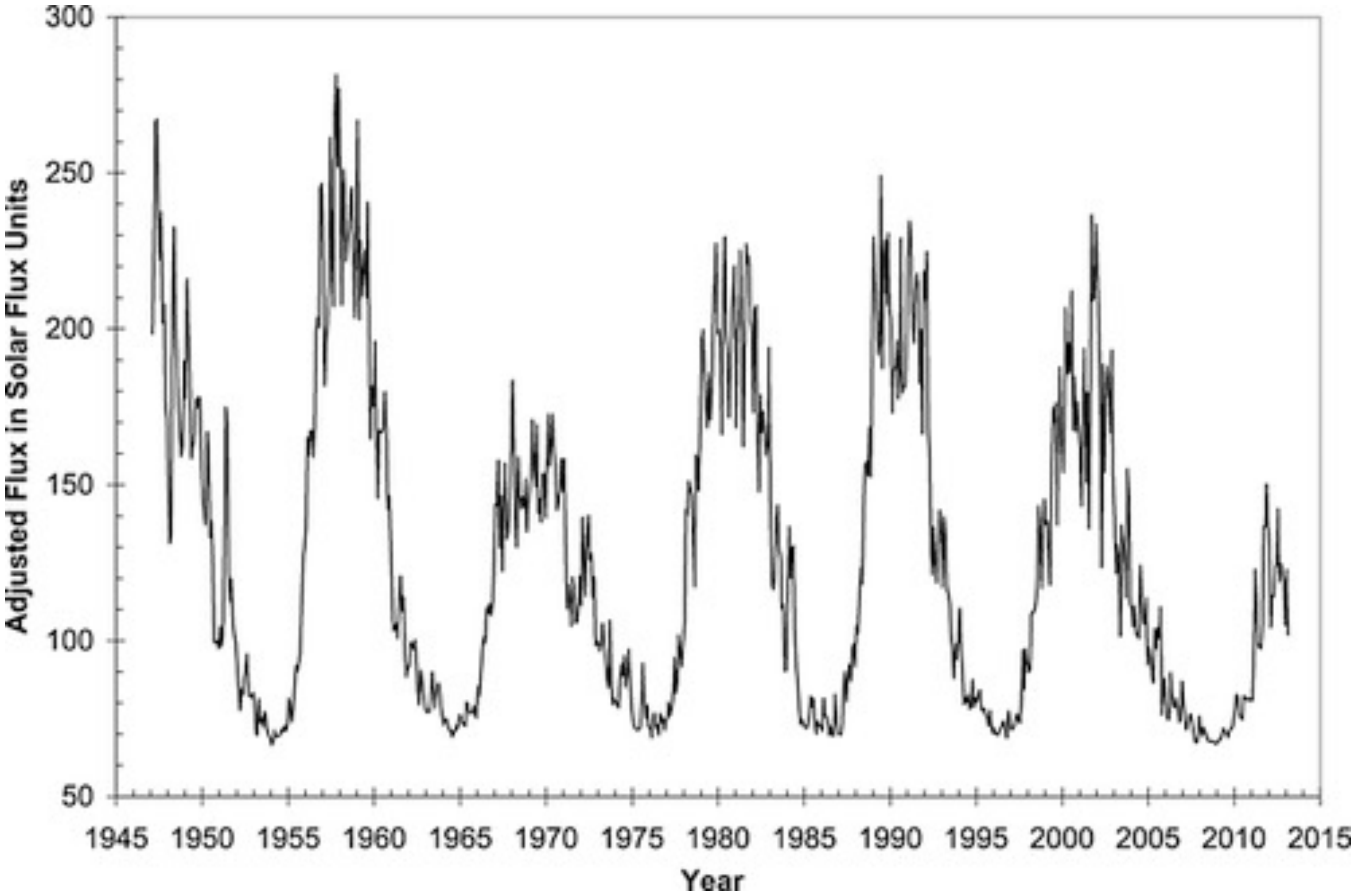
Integrated, full-sun X-ray flux shows solar flare activity, with the flares showing up as sharp rises and slower decays.

The “size” of a flare is defined by the maximum value of the emission, and labeled by letters (B, C, X, M) indicating order of magnitude changes in flare emission.



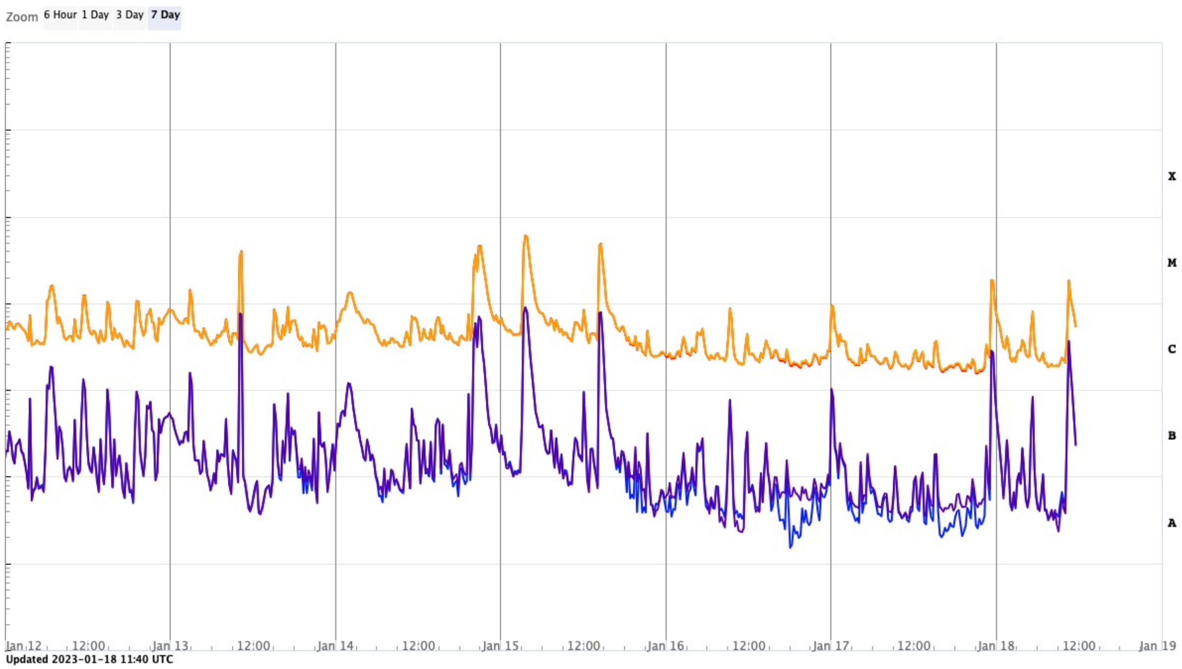
Radio 10.7 cm flux

Radio flux (10.7 cm wavelength) provides a good proxy for solar activity, and can be obtained from the ground, resulting in a long, continuous series of observations

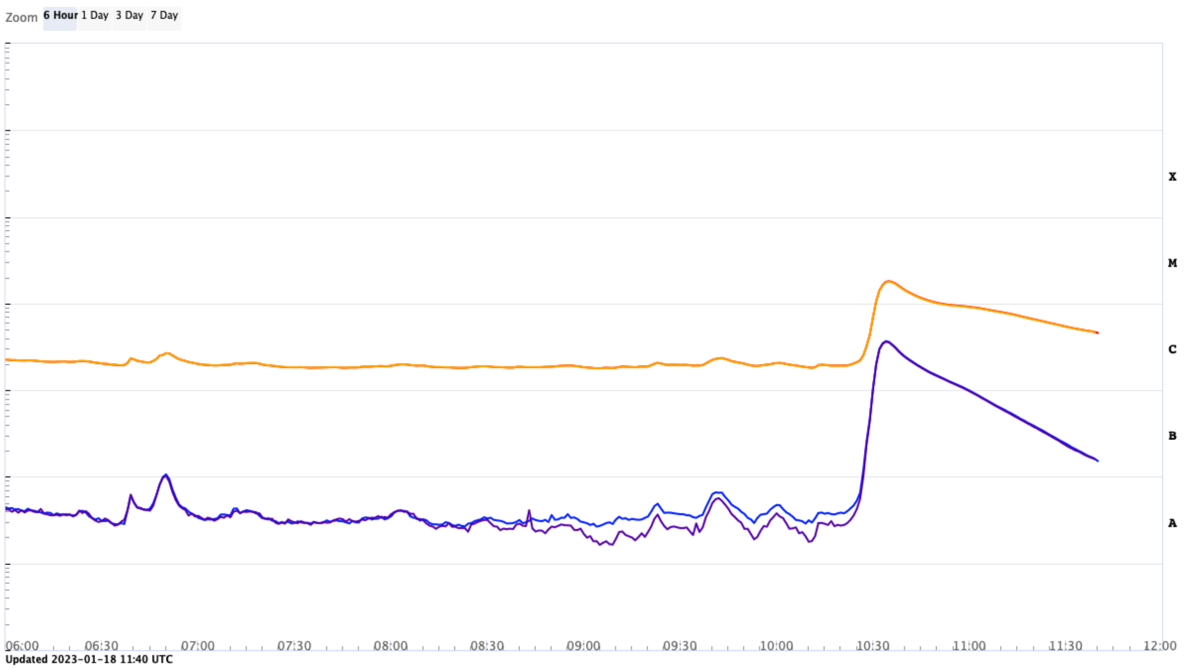


NOAA Web Pages

7-day X-ray Flux

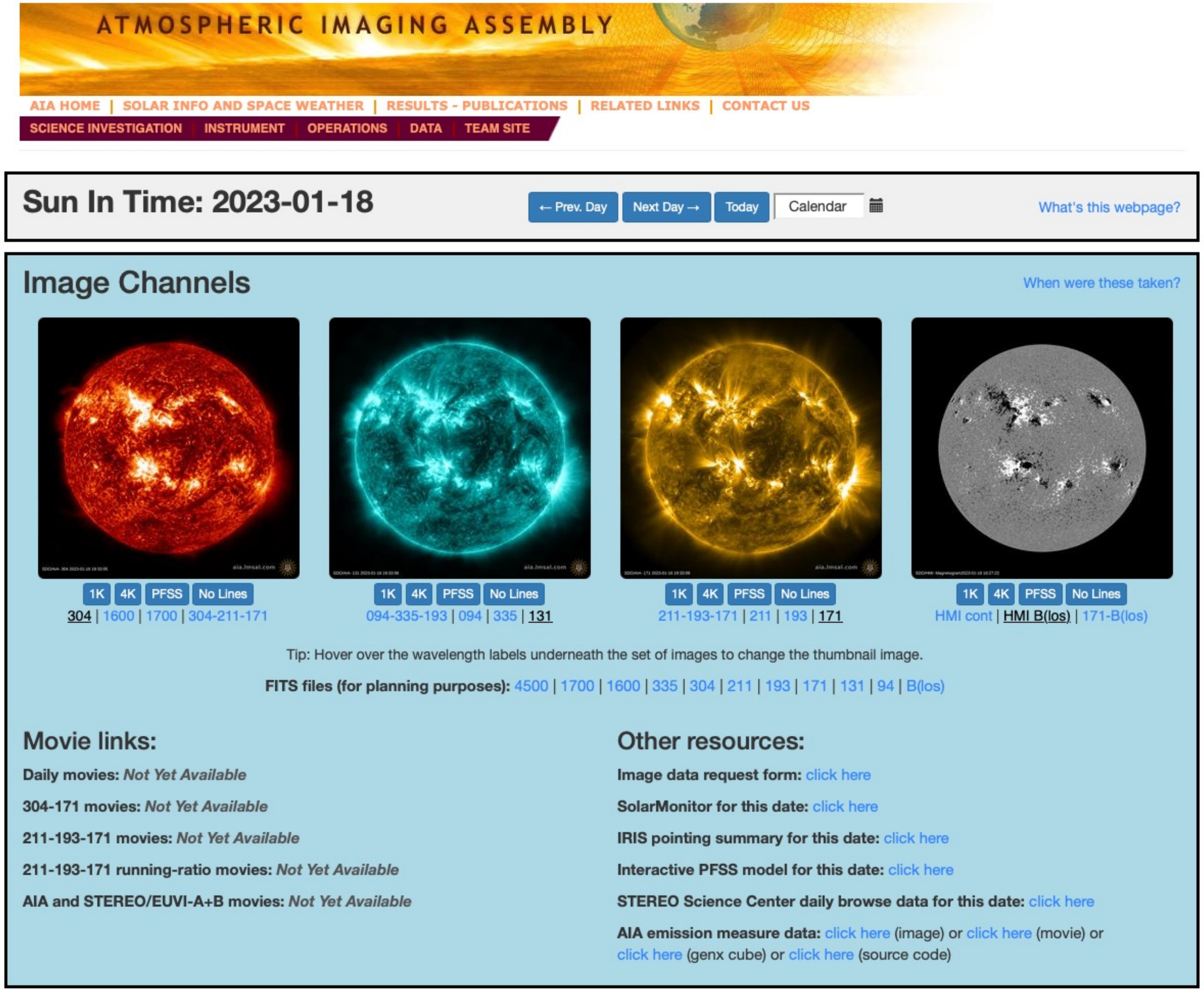


6-hour X-ray Flux

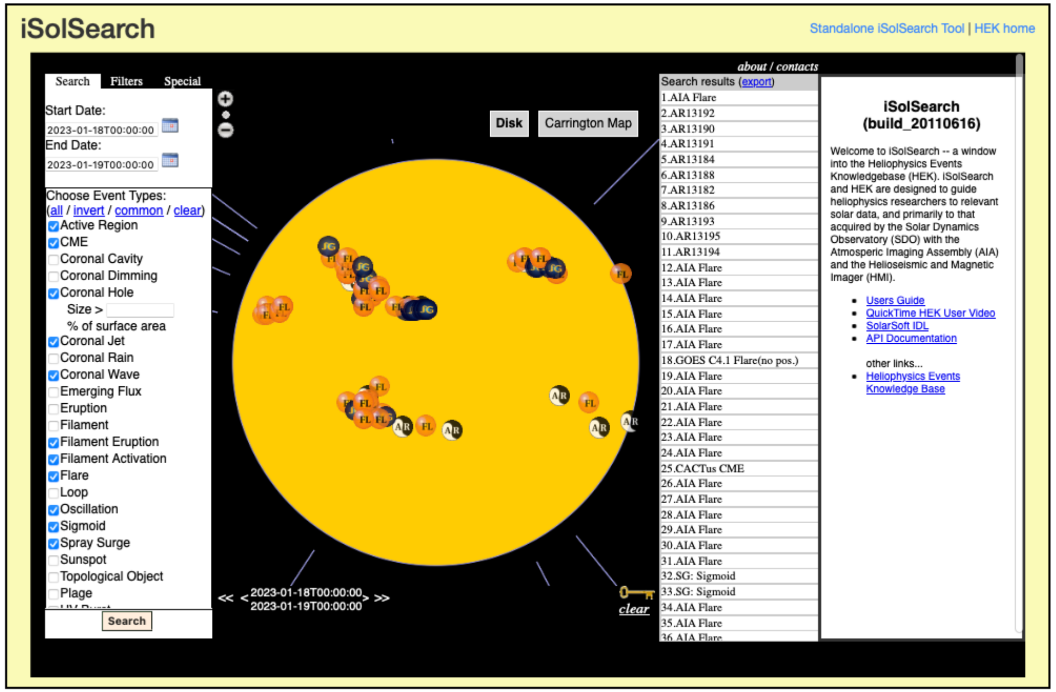


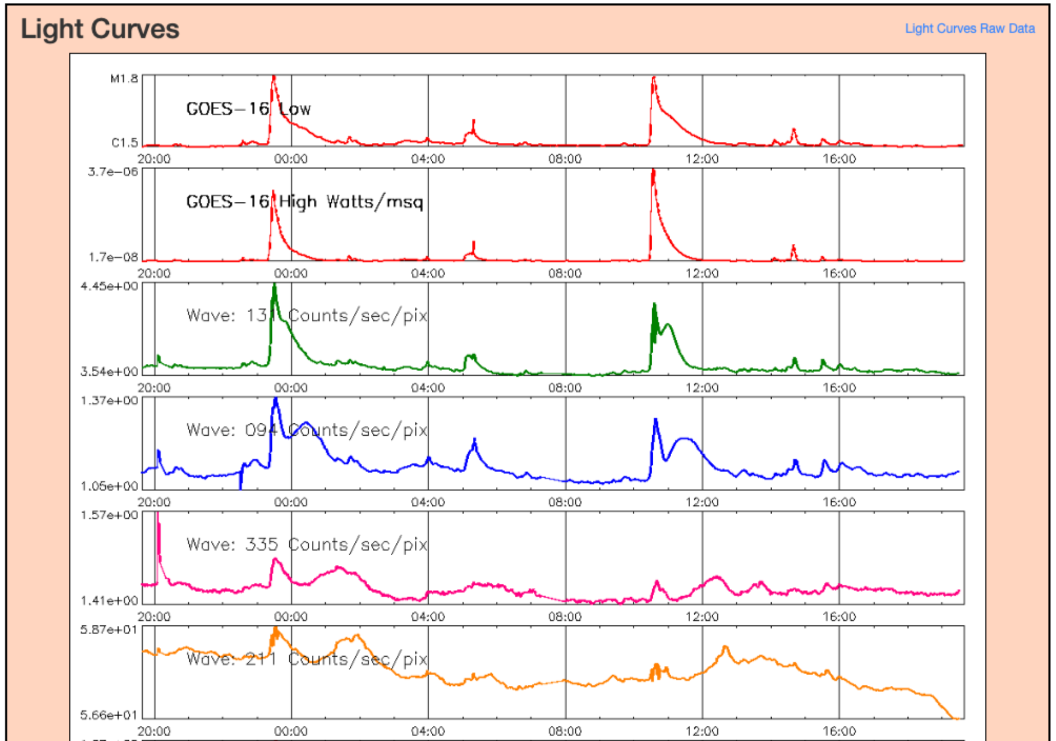
https://www.swpc.noaa.gov/products/goes-x-ray-flux

sdowww.lmsal.com

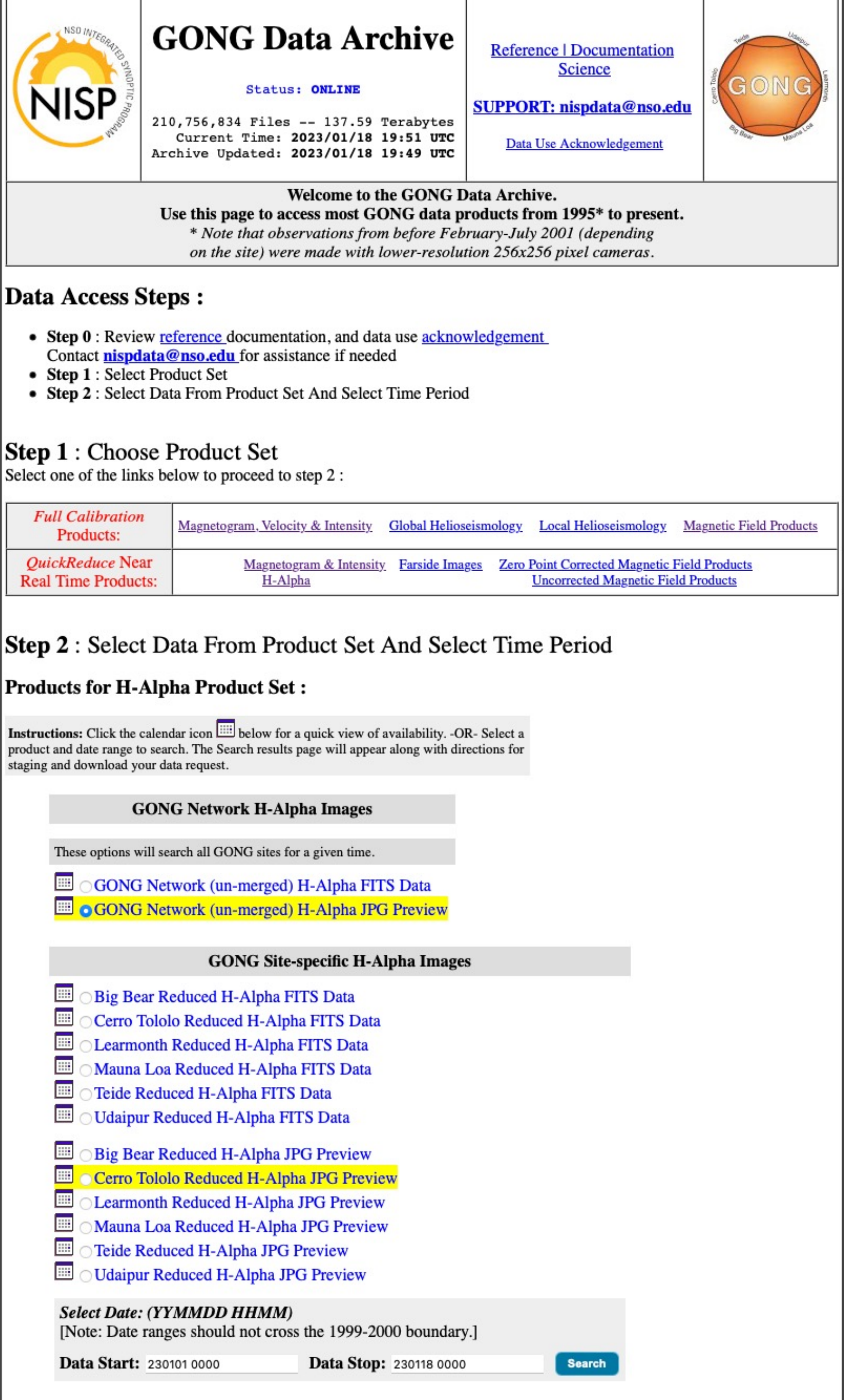


sdowww.lmsal.com

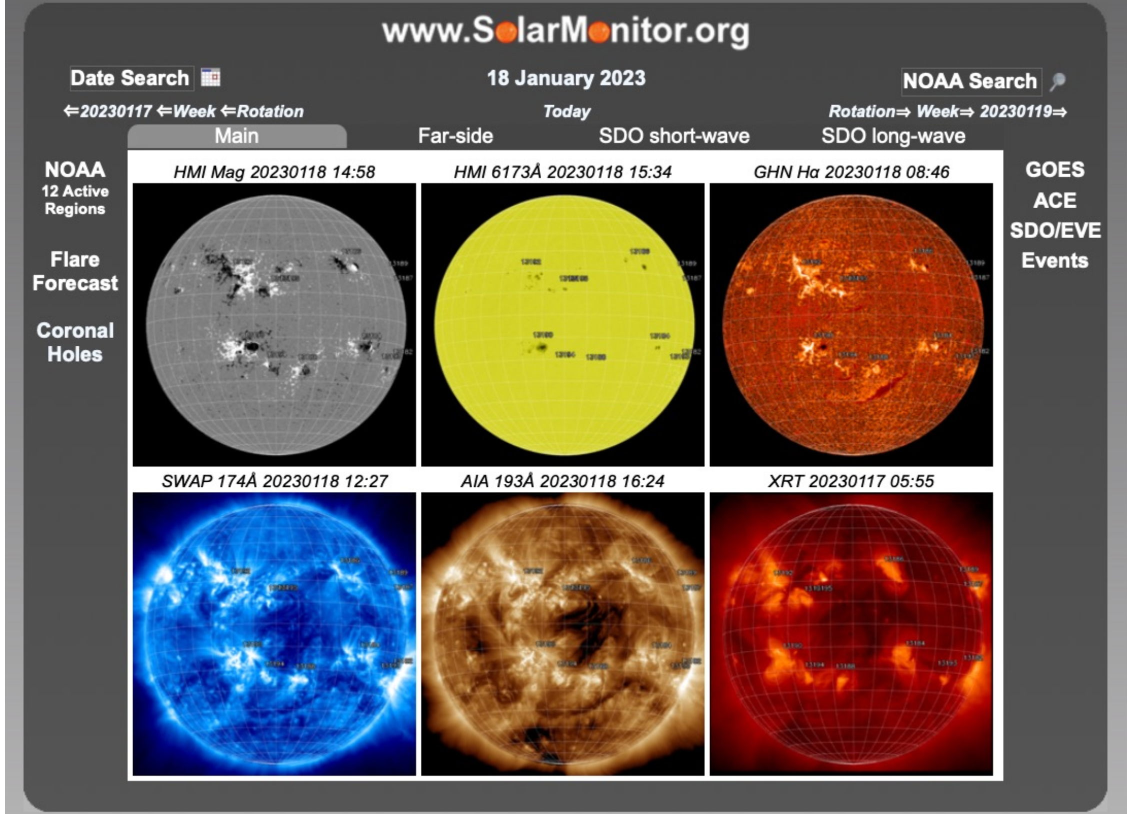




gong2.nso.edu



solarMonitor.org

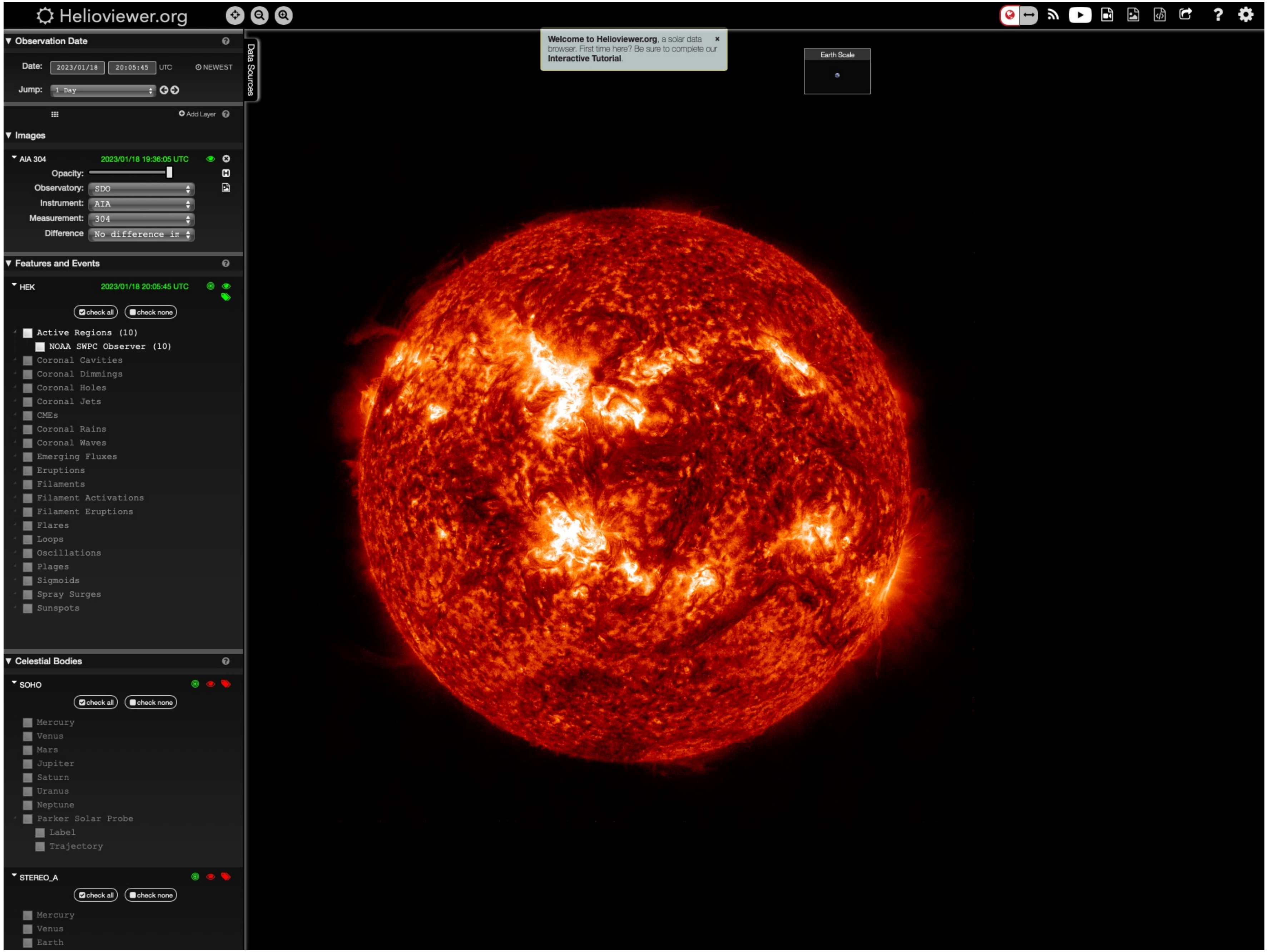


Today's/Yesterday's NOAA Active Regions

NOAA Number	Latest Position	Hale Class	McIntosh Class	Sunspot Area [millionths]	Number of Spots	Recent Flares
13182	S17W91 (931",-285")	α/β	Axx/Cro	0000/0020	01/05	-
13184	S13W48 (708",-165")	α/β	Hsx/Cso	0190/0210	05/07	-
13186	N25W39 (557",470")	β/βγ	Eho/Eho	0430/0440	11/14	-
13188	S24W15 (231",-323")	β/β	Bxo/Dro	0010/0030	07/10	- / C3.2(22:29)
13190	S14E10 (-164",-156")	βγ/βγδ	Eki/Ehi	0900/0880	20/21	-
13191	N11W02 (33",267")	β/β	Dsi/Dkc	0320/0360	13/13	-
13192	N19E16 (-255",392")	β/βγ	Fki/Fki	0380/0400	13/13	-
13193	S21W69 (850",-320")	β/β	Cro/Dso	0030/0060	03/06	-
13194	S23W00 (0",-304")	β/β	Bxo/Bxo	0000/0010	04/07	-
13195	N11W06 (100",267")	β/-	Dro/---	0030/----	08/--	-
13187	N16W90 (936",267")	/	/	/	/	-
13189	N23W91 (896",378")	/	/	/	/	-

Class (HH:MM) -Today
Class (HH:MM) -Yesterday

helioviewer.org



Virtual Solar Observatory

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  Derive time intervals from event catalogs
- [ ] **Observable**
  Search based on physical observables ⓘ
- [ ] **Instrument / Source / Provider**
  Search based on instruments ⓘ or data archives ⓘ
  - [ ] Compact listing
  - [ ] Instrument / Source (not provider dependent)
  - [ ] Instrument Only (not source or provider dependent)
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  - [ ] Show Nickname Definitions

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VSO Documentation

Documentation for Scientists, Programmers and Data Providers, including Changes, FAQs, and contact info.

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