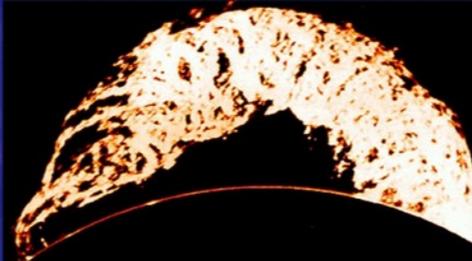
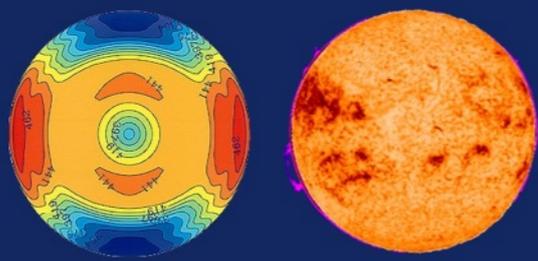


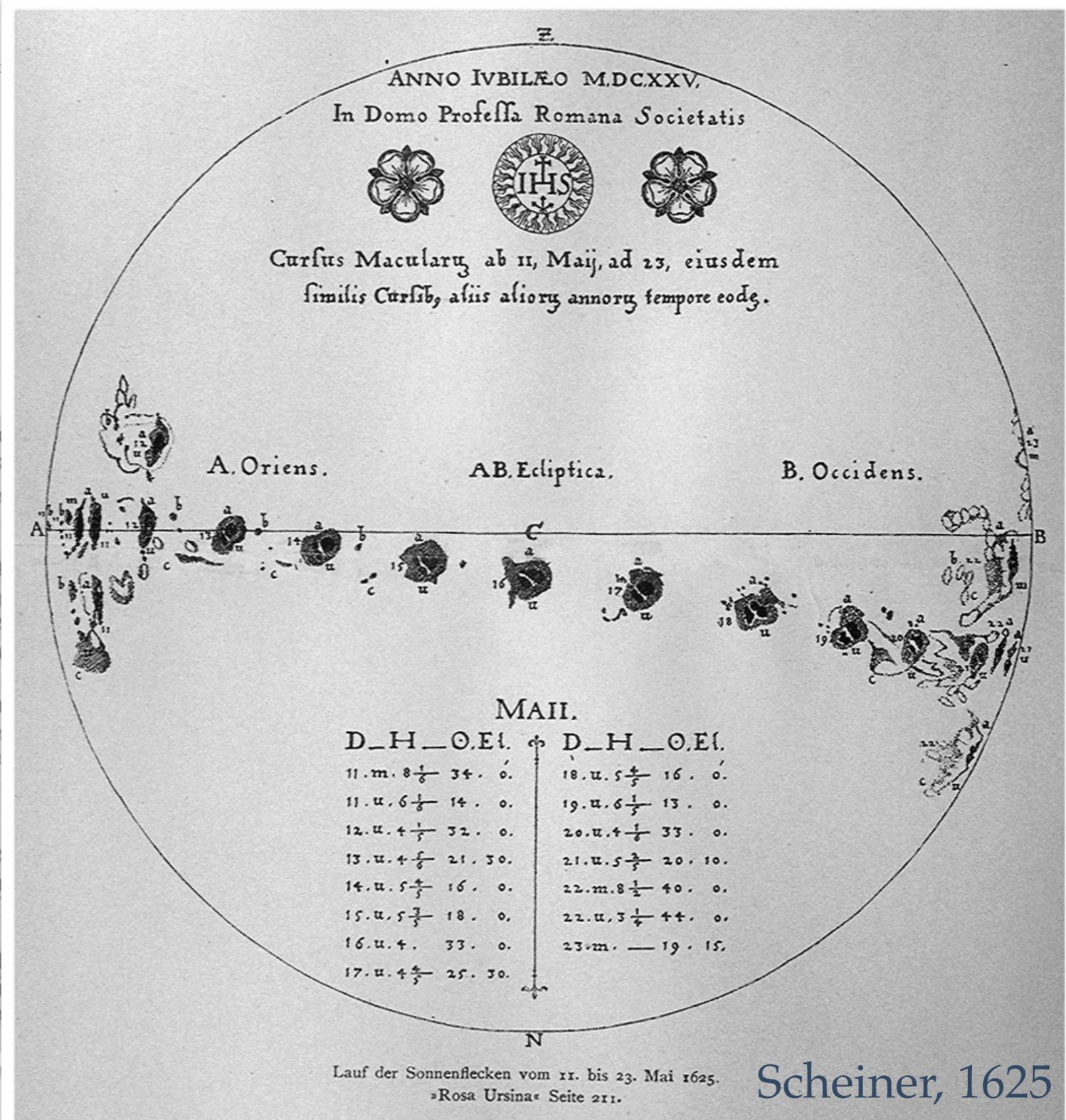
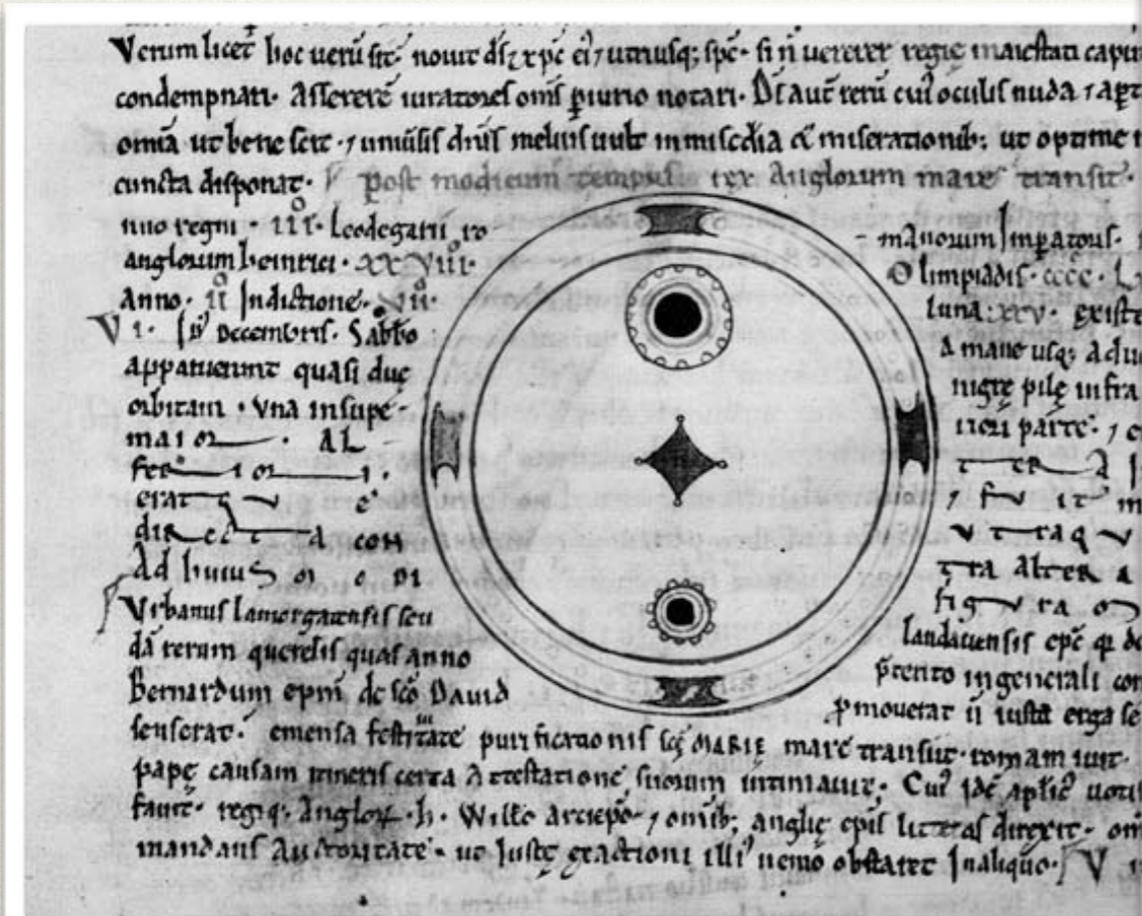
# Spectroscopy: The art and science of capturing magnetism

Rebecca Centeno (High Altitude Observatory)

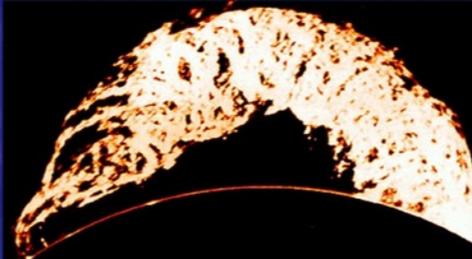
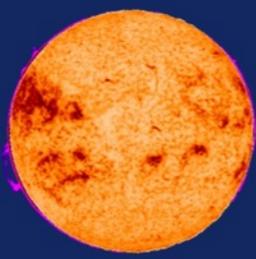
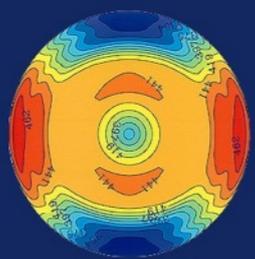


# Sunspots

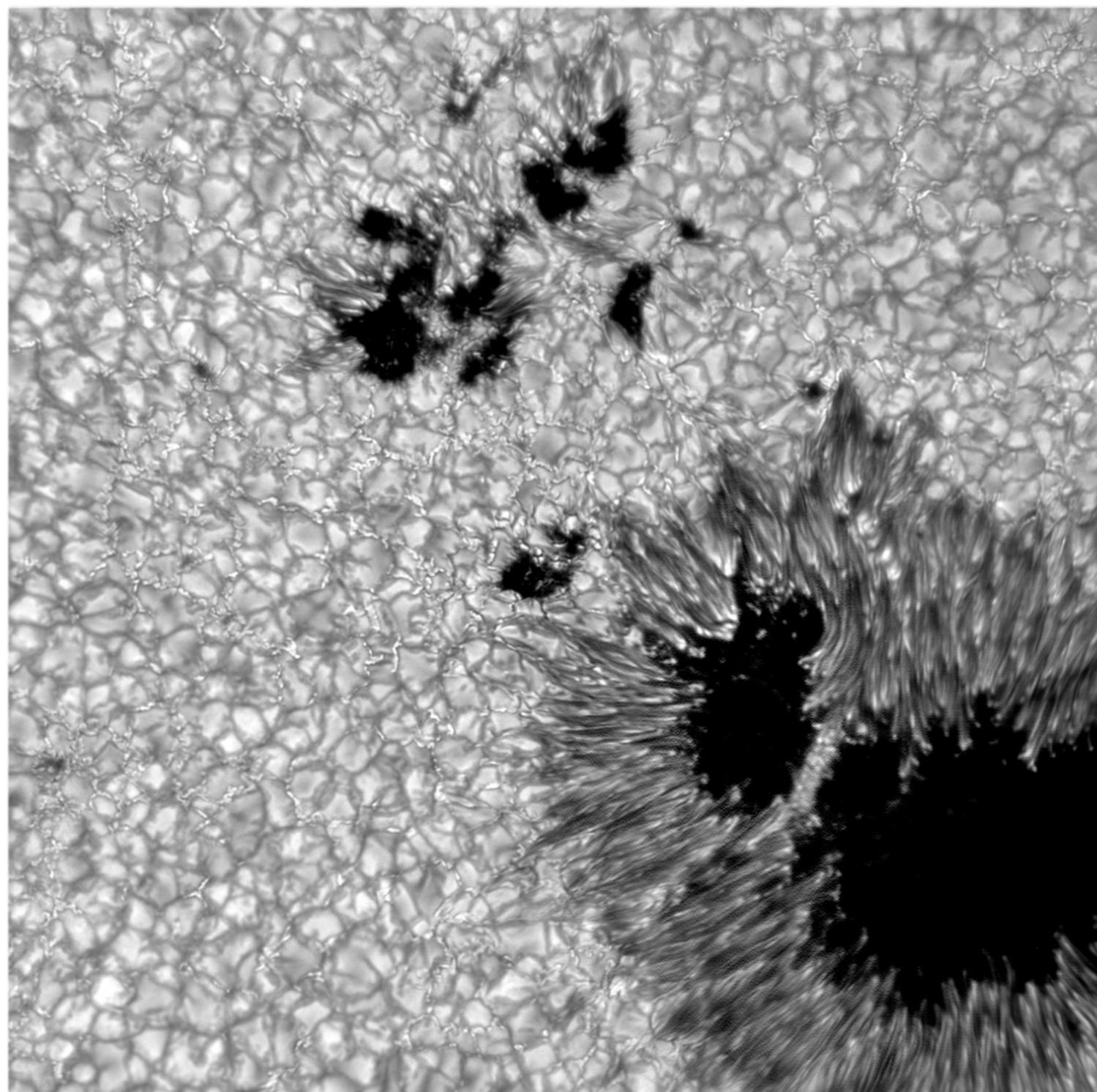
John Worcester, 1128



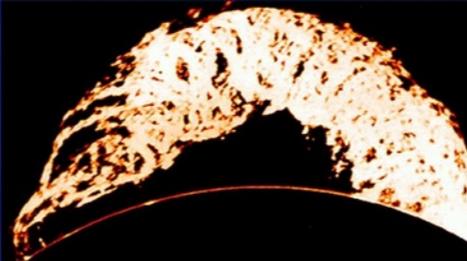
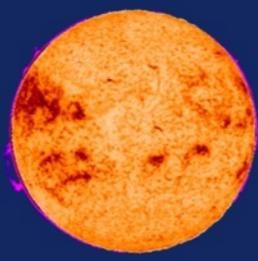
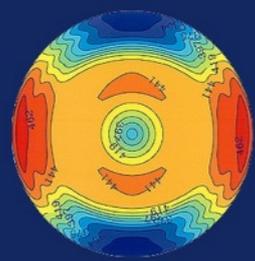
HAO



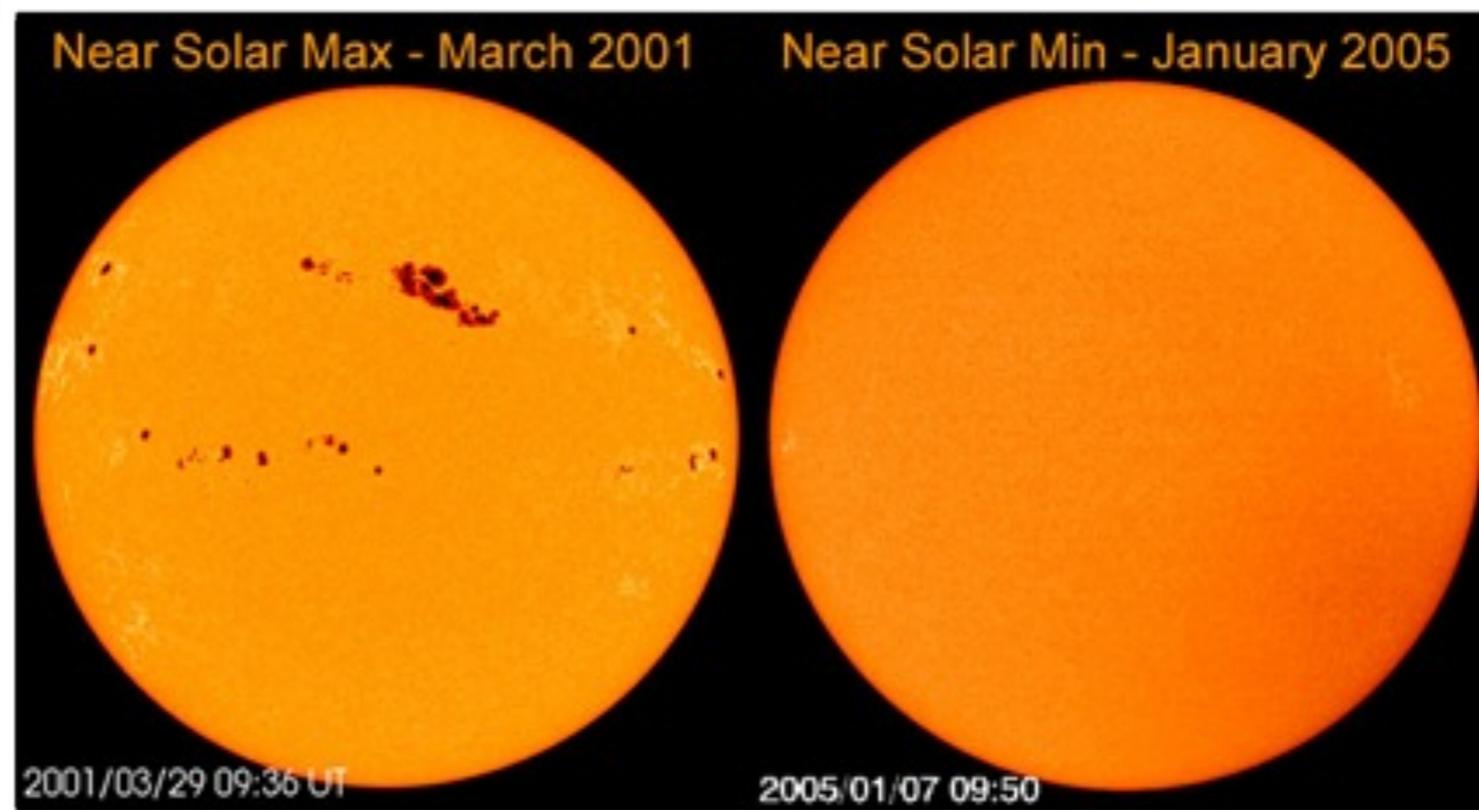
# Sunspots



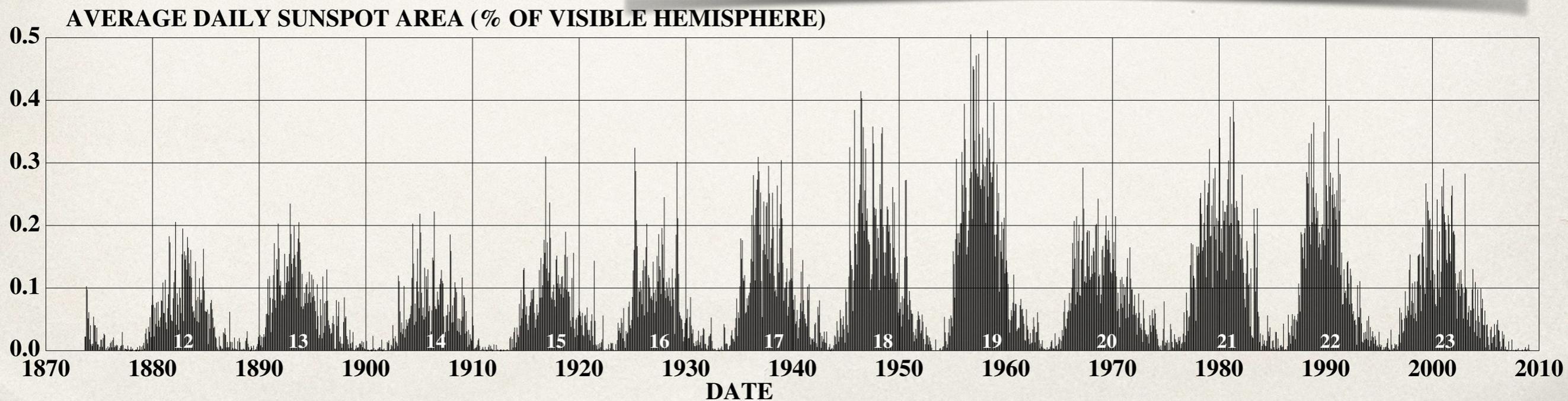
NST / BBSO

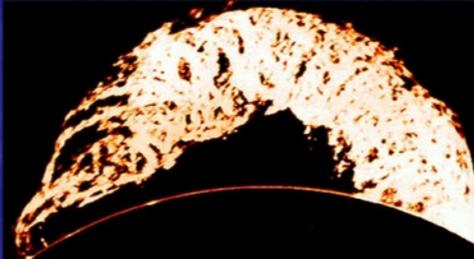
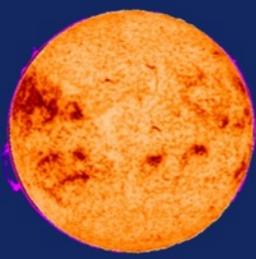
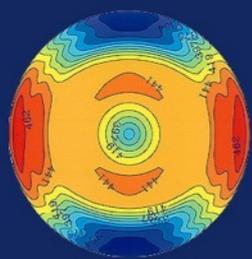


# Longer term: The Solar Cycle



Hathaway, 2010



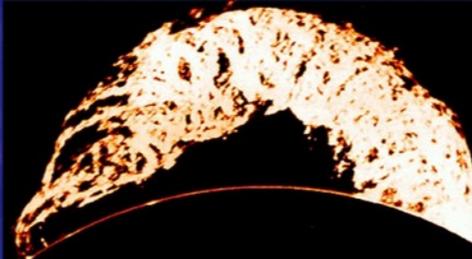
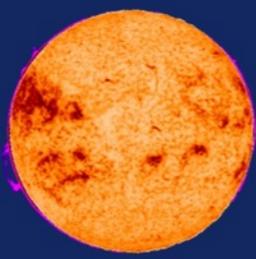
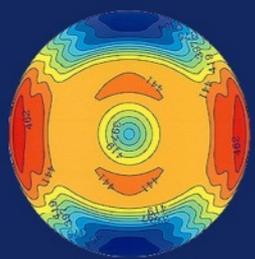


# Shorter term: Space Weather

"Space Weather" refers to the ever-changing solar-driven events and their interaction with the interplanetary medium

Solar Storms =  
Coronal Mass Ejections  
and Solar Flares,  
**originate from sunspots**

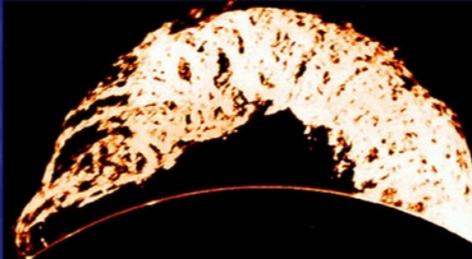
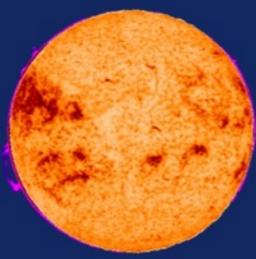
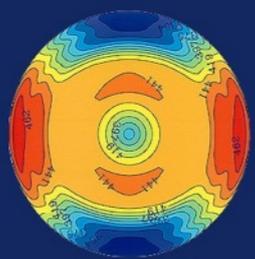
HAO



# Eruptive events



HAO

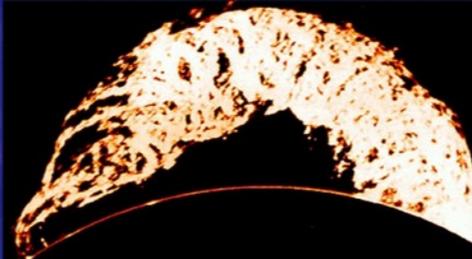
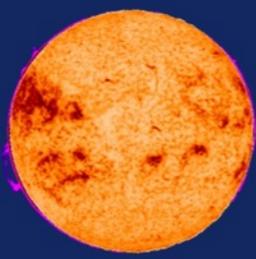
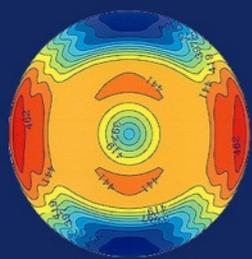


# Effects on the Earth

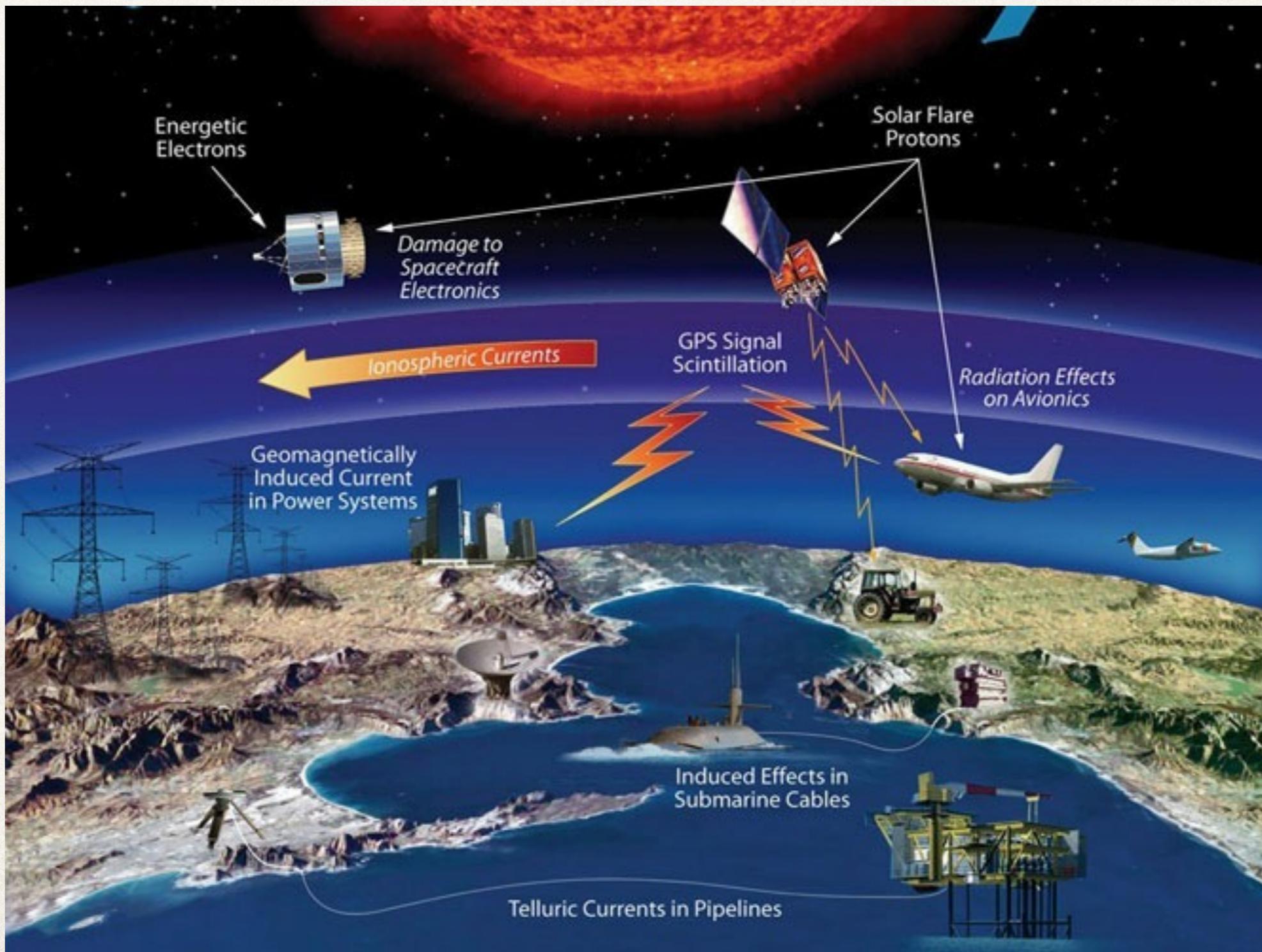
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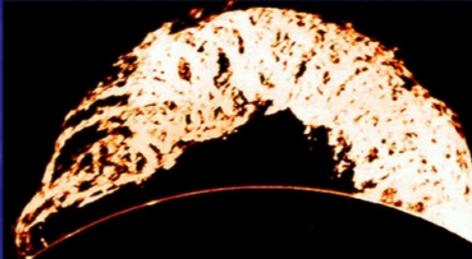
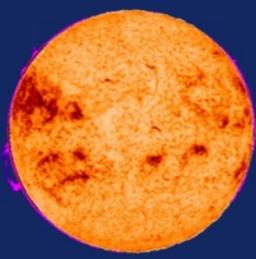
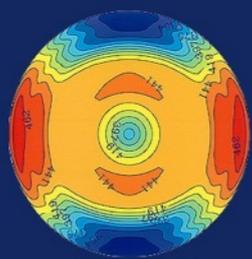


© David Cartier, Sr.



# Effects on the Earth

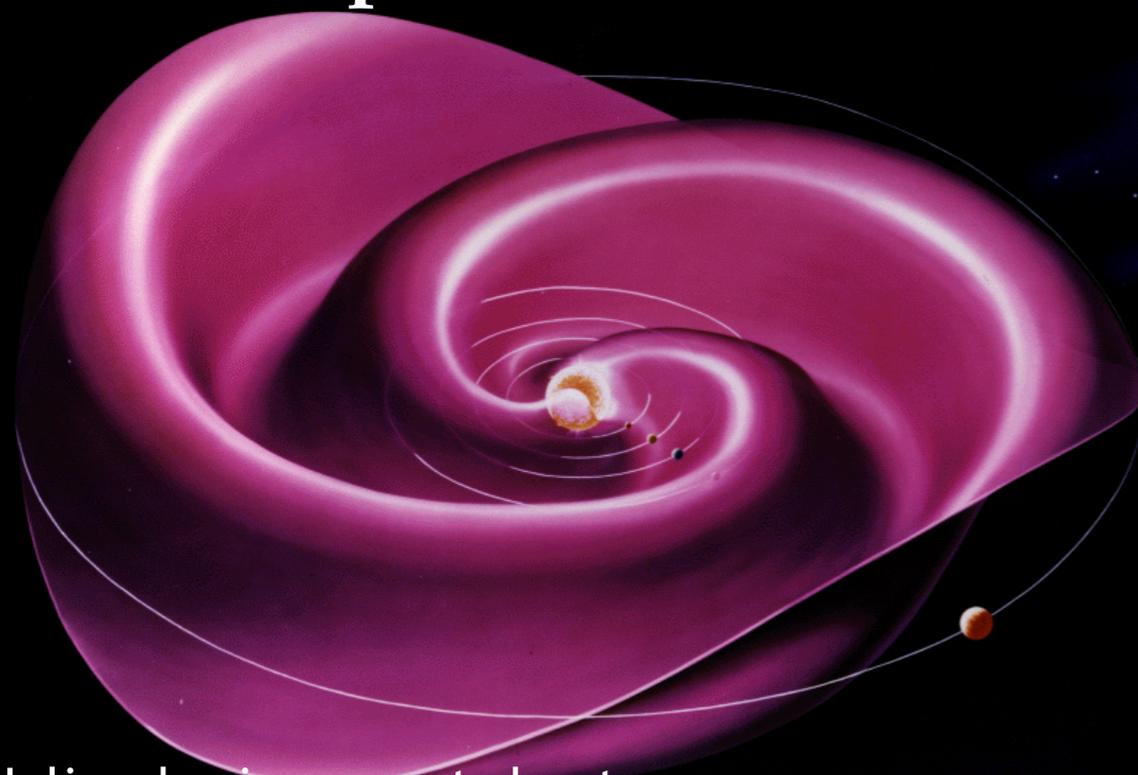




# The Sun's magnetism...

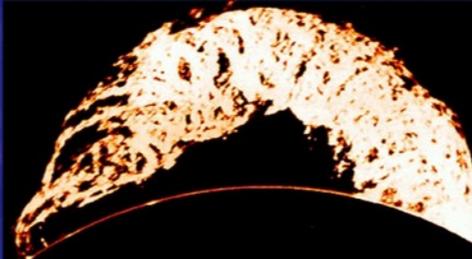
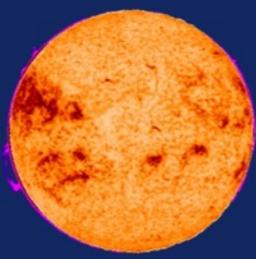
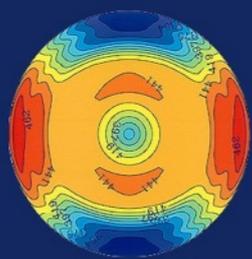
... extends out into space

"Parker Spiral"



Heliospheric current sheet  
(source: Lempfi, NASA)

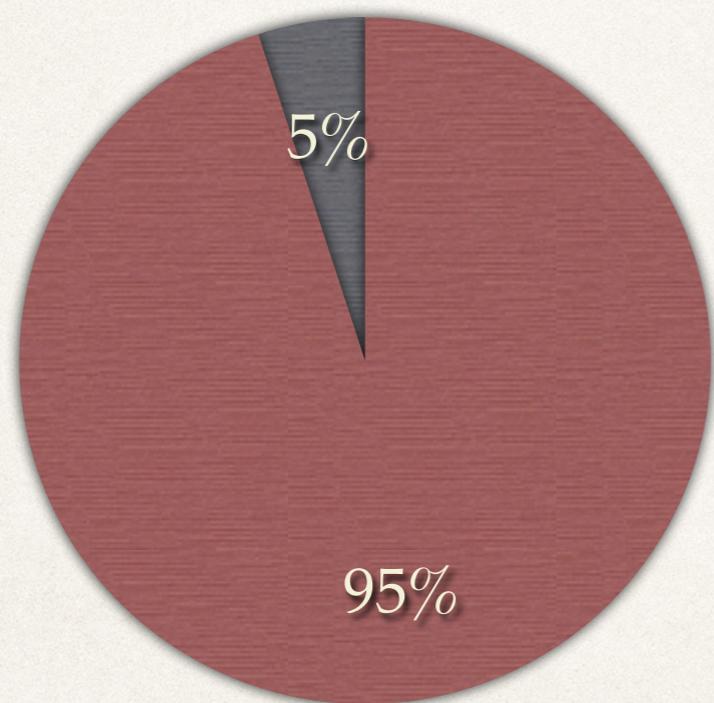




# Energy-wise

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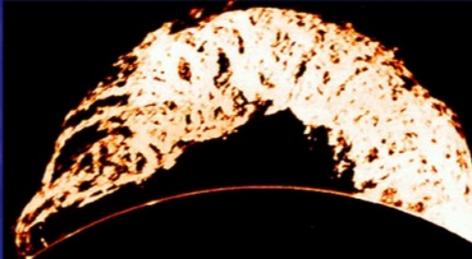
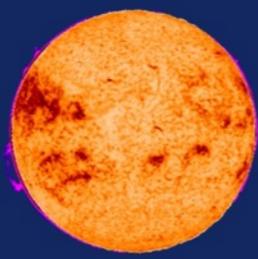
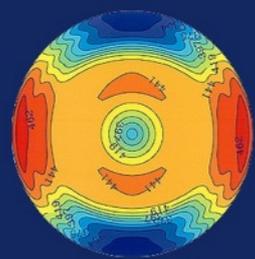
Percentage area of sunspots throughout the Solar Cycle



- Quiet Sun
- Active Regions

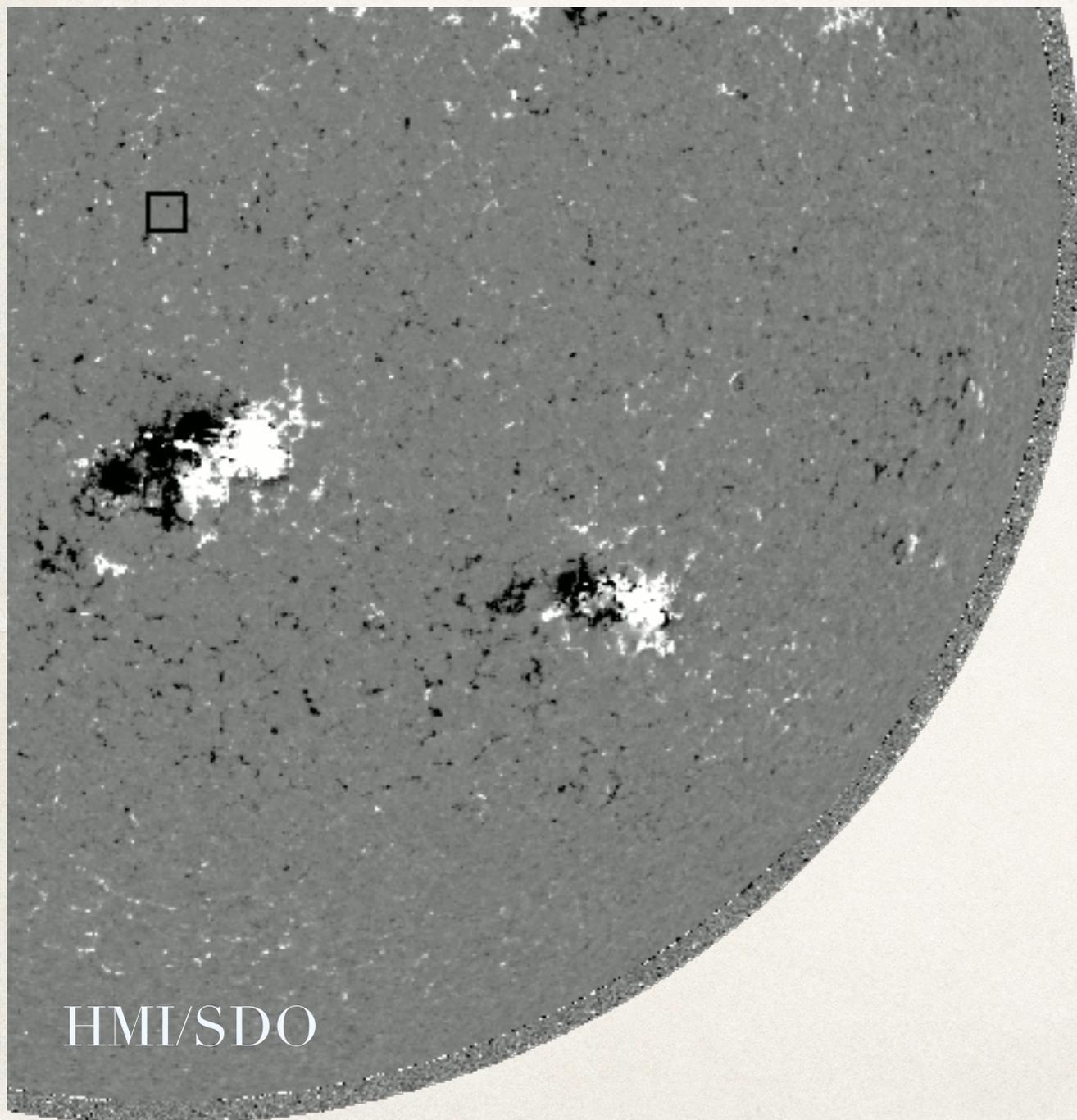
The energy harbored in the Quiet Sun fields is larger than that carried by sunspots throughout the Solar Cycle

HAO

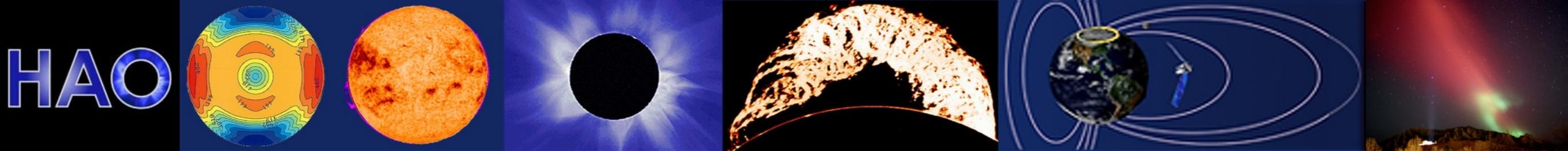


# The smaller scales

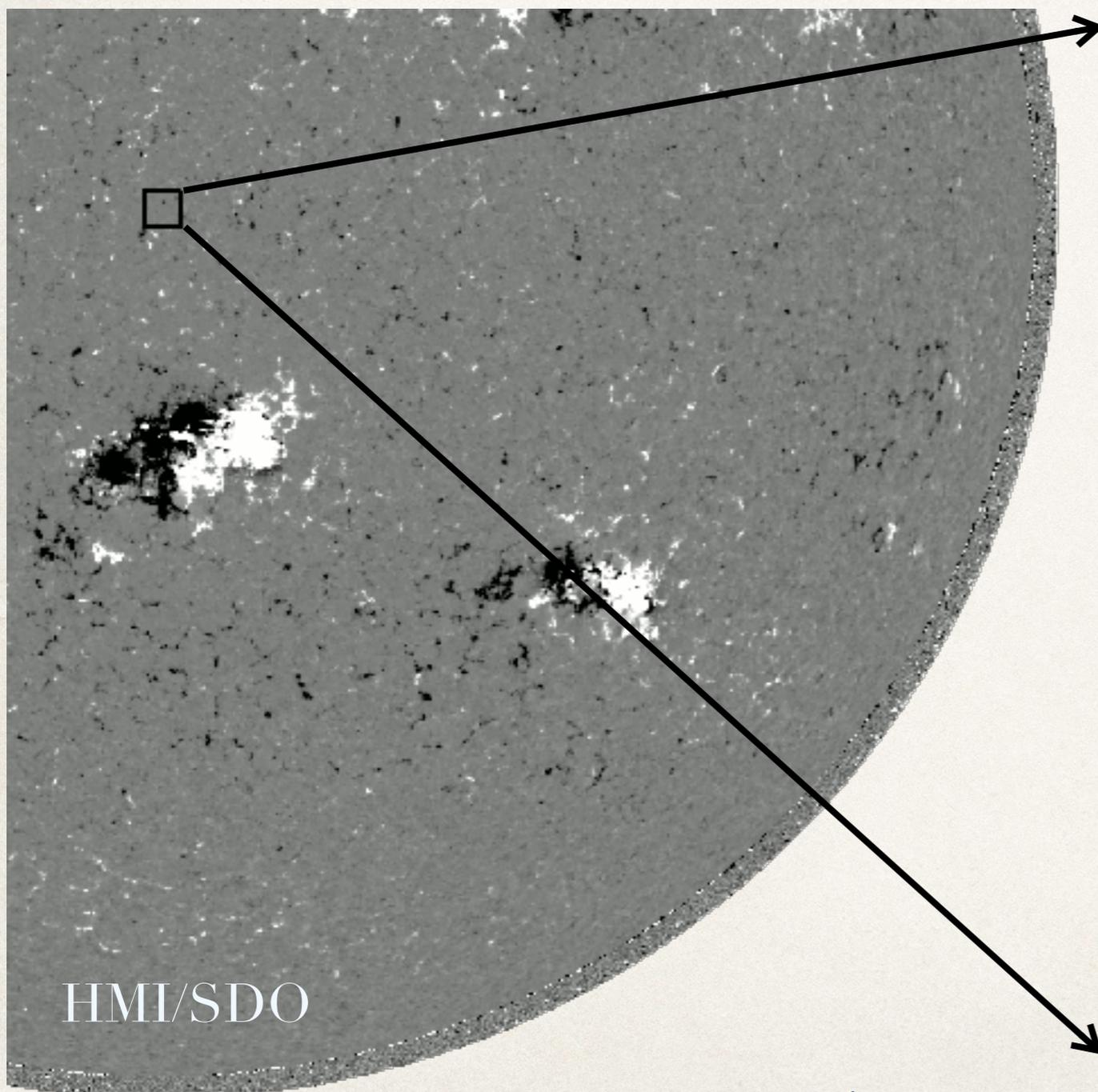
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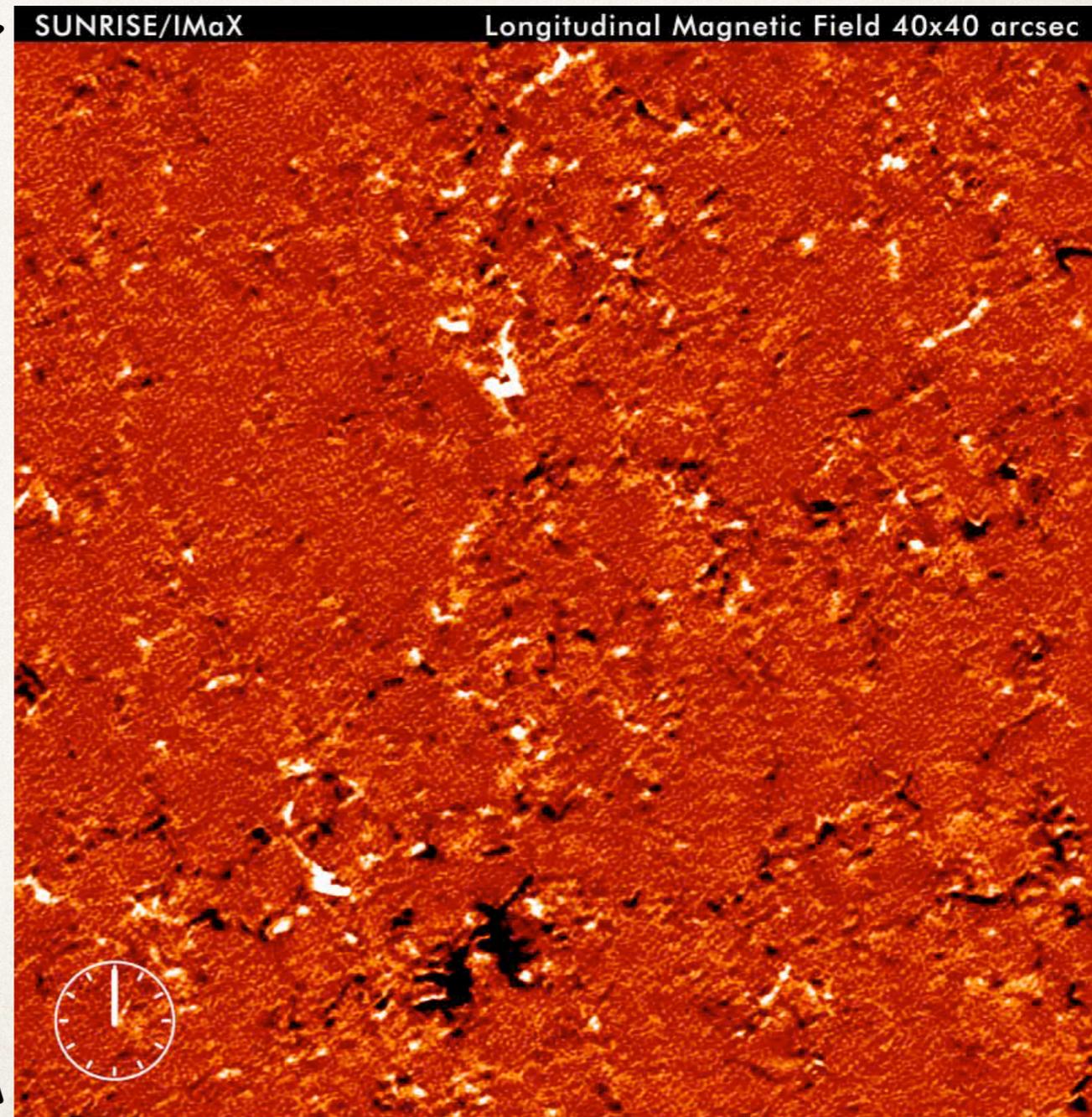
HMI/SDO



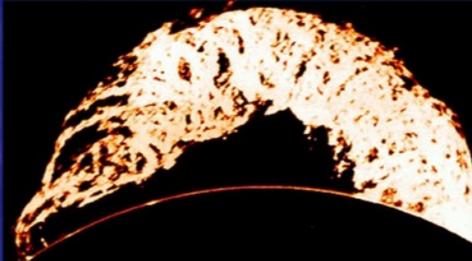
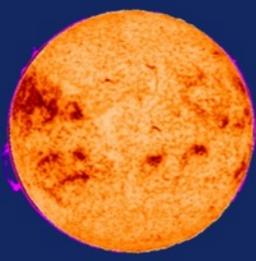
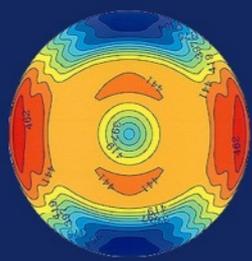
# The smaller scales



1 arcsec ~ 750 km



40 arcsec



# Why do we care?

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Structure, dynamics and energetics

Range of spatial and temporal scales

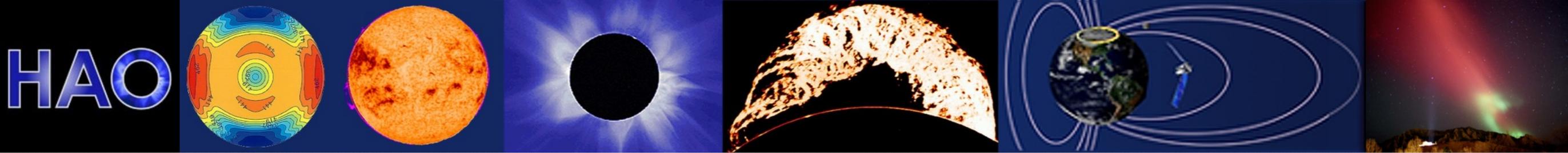
Connectivity among layers

Energy storage, transport, deposition

Pathways from Sun to Earth

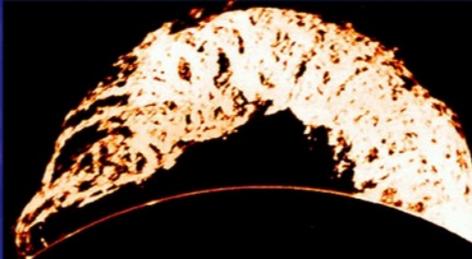
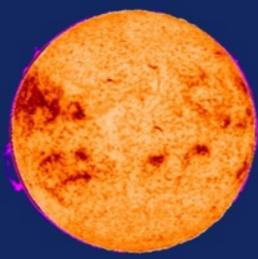
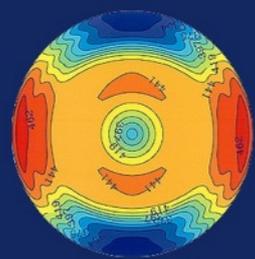
Solar Cycle

Space Weather



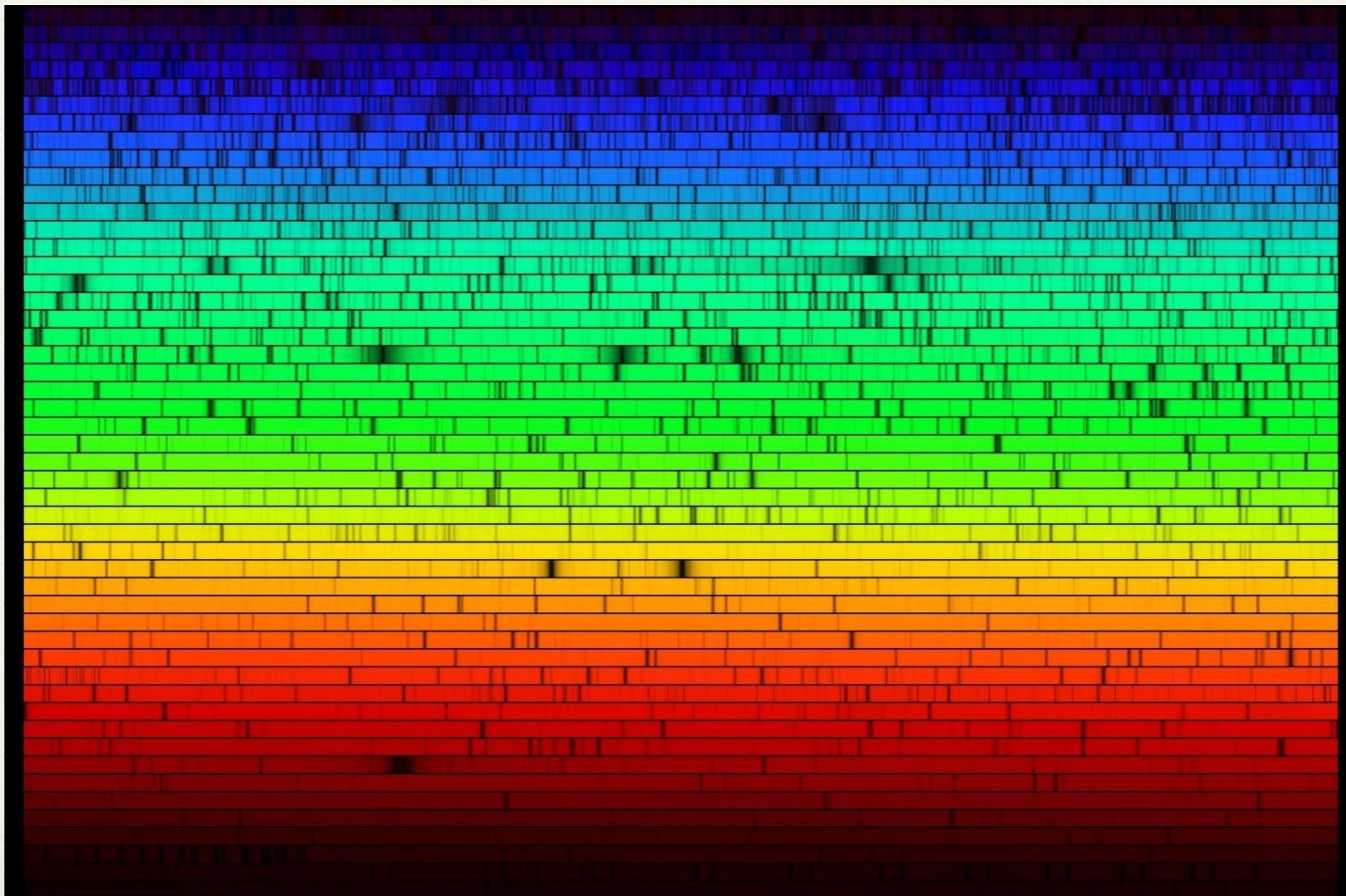
But... How do we go about measuring these magnetic fields?

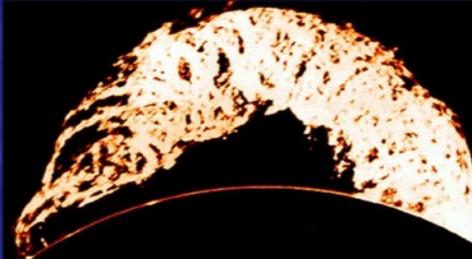
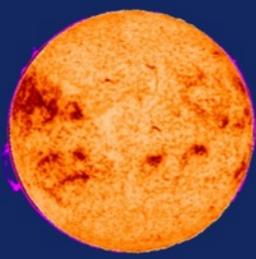
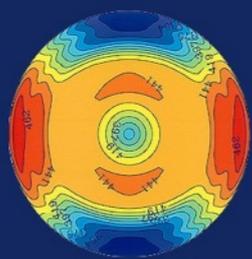
HAO



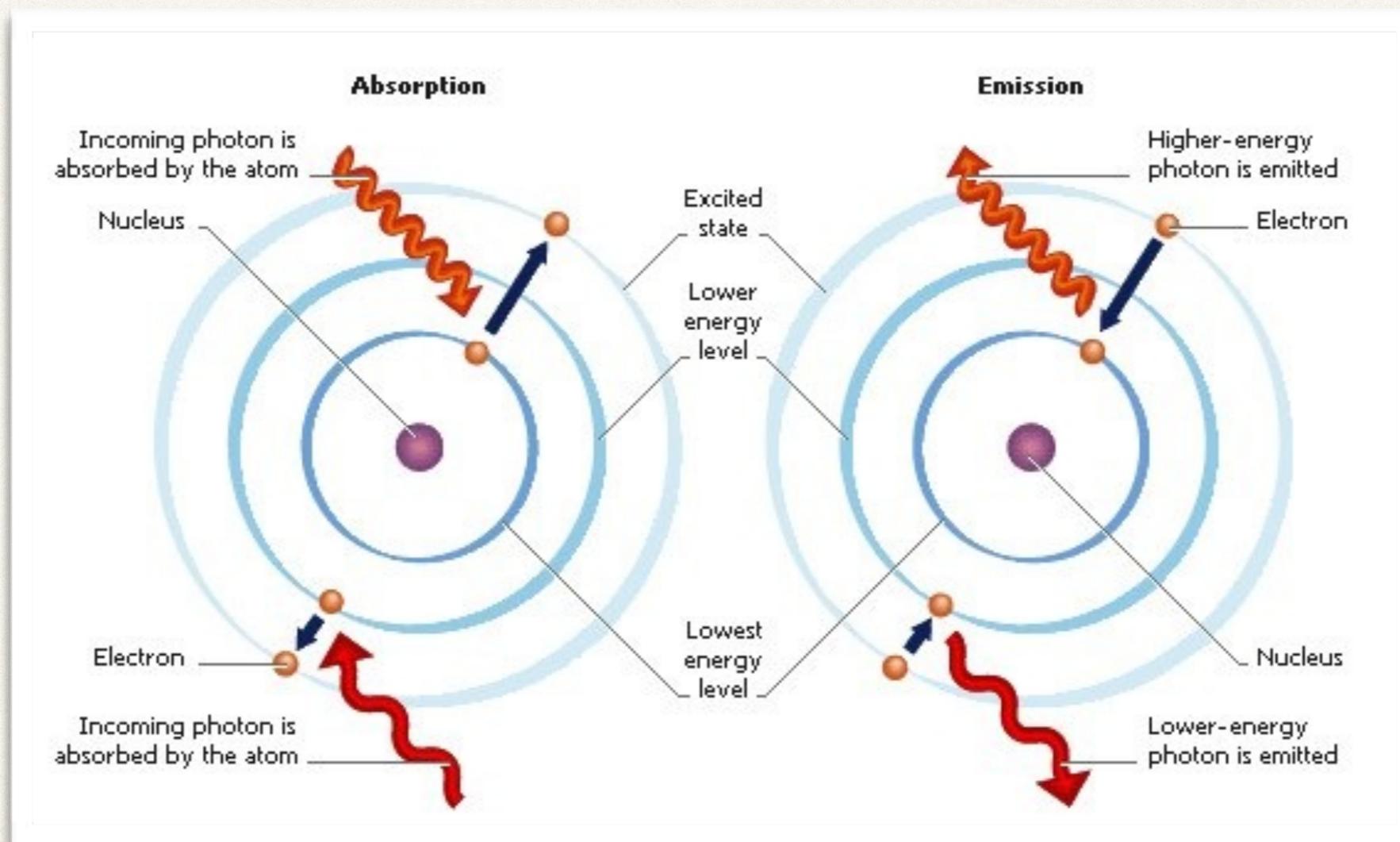
# The Sun's spectrum

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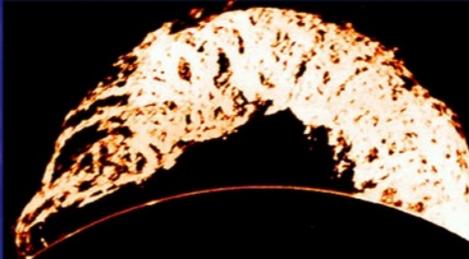
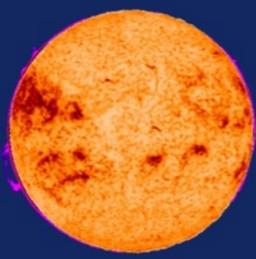
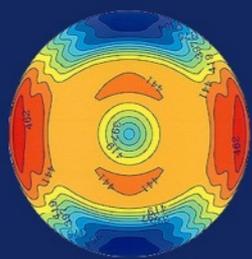




# Light and matter



Each energy configuration of each type of atom imprints a specific signature on the Sun's spectrum



# Radiative Transfer

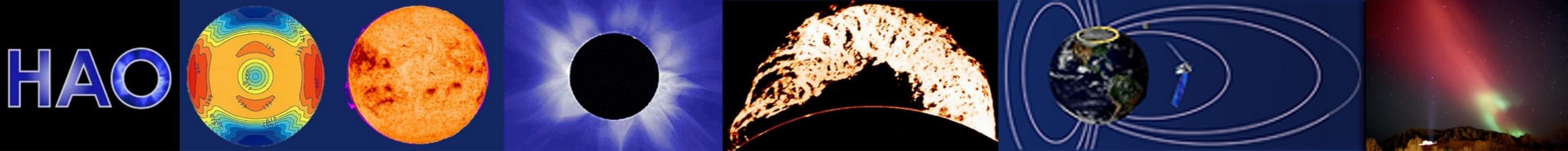
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## **Radiative Transfer Equation:**

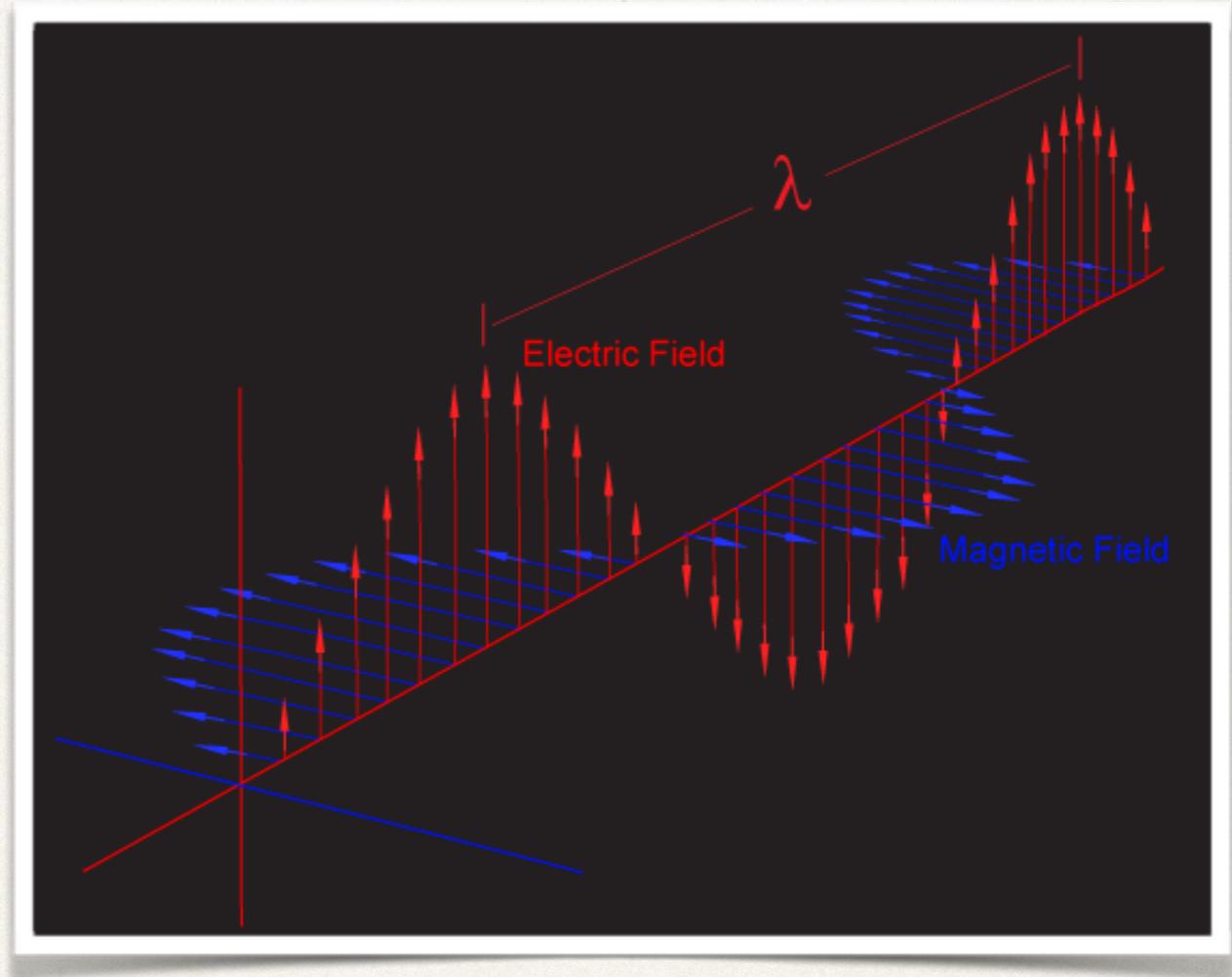
Describes how a beam of light loses energy by absorption, gains it by emission and redistributes it by scattering as it travels

## **Statistical Equilibrium Equations:**

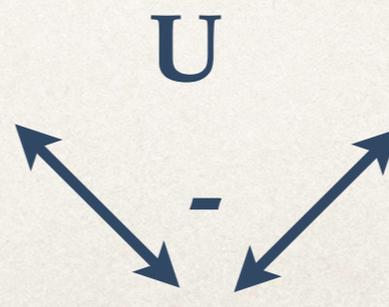
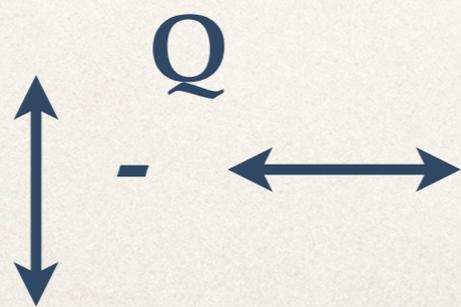
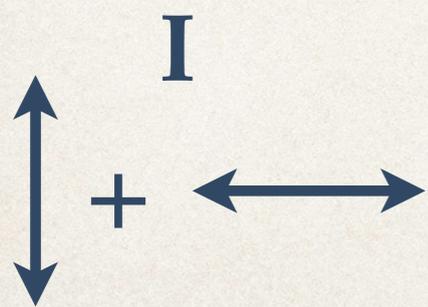
Tell us how many atoms there are in each possible energy configuration

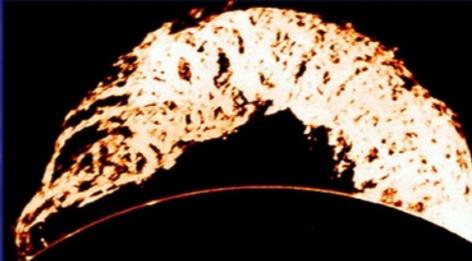
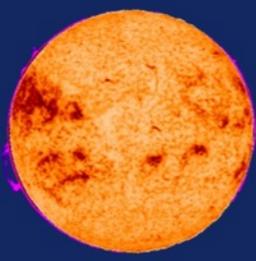
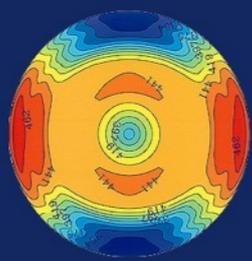


# Polarization of light



Stokes Parameters:



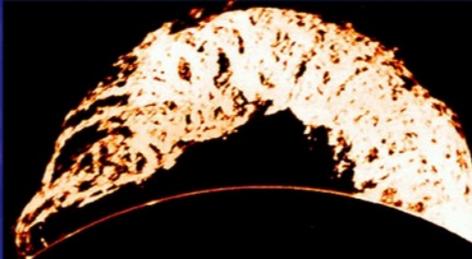
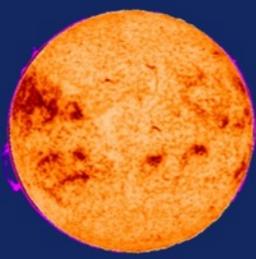
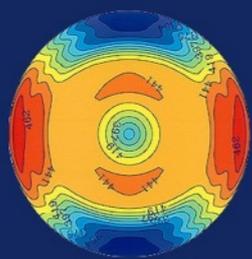


# Polarizing mechanisms

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Several mechanisms can produce polarization in spectral lines:

- Anisotropy in the excitation mechanism of the atom
  - Impact polarization
  - Optical pumping
- External field breaking the axis of symmetry
  - Electric field
  - Magnetic field

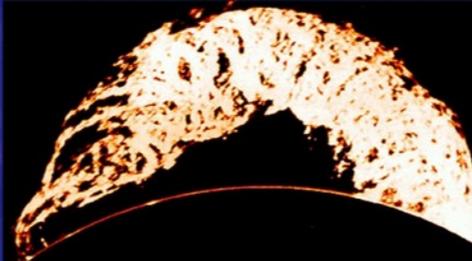
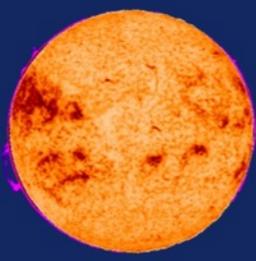
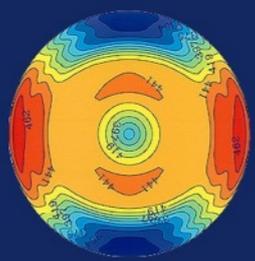


# Spectro-Polarimetry

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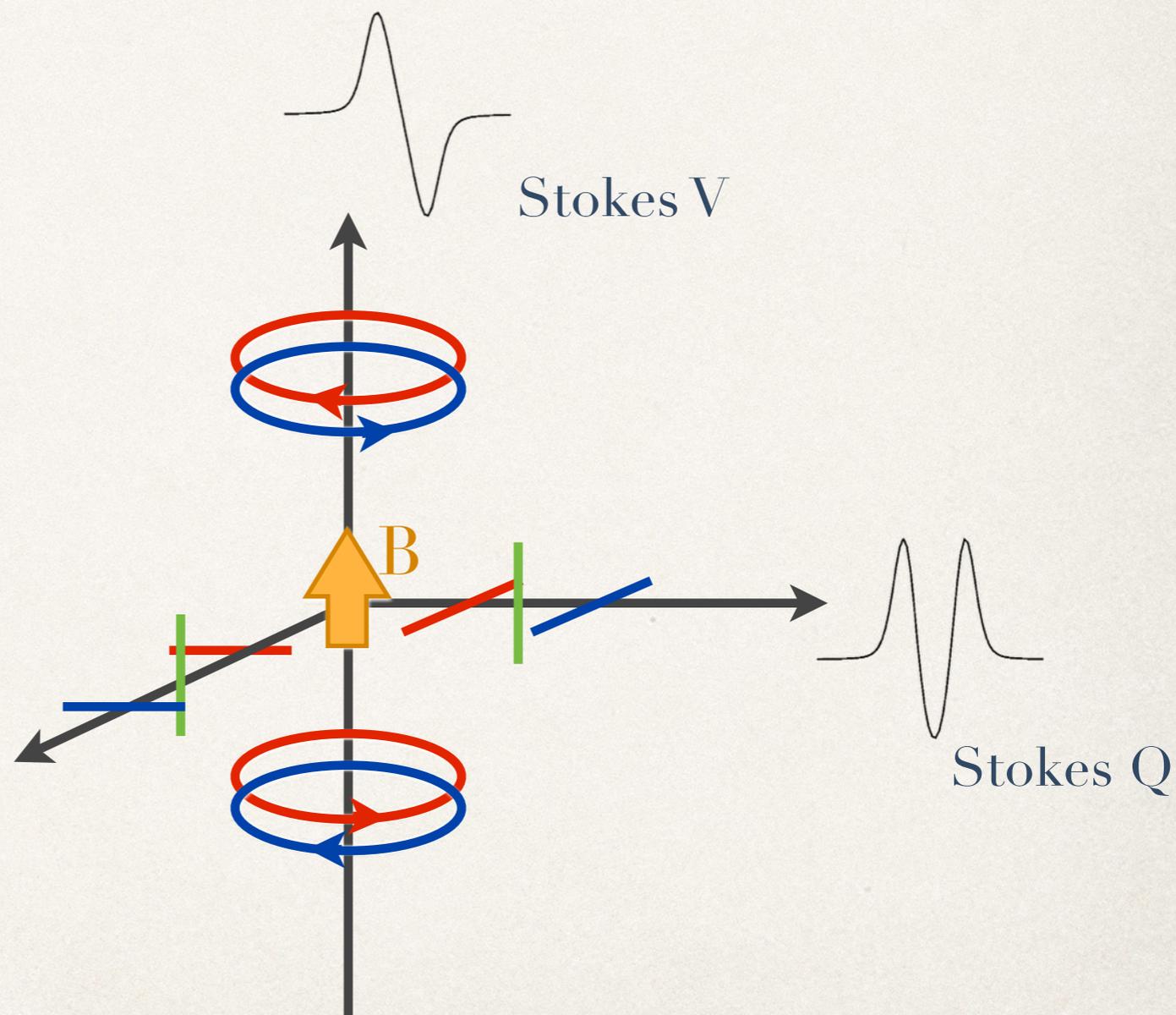
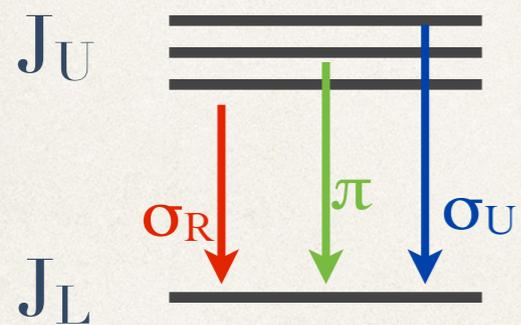
Spectropolarimetry is the measurement of the distribution of energy and polarization of light as a function of frequency

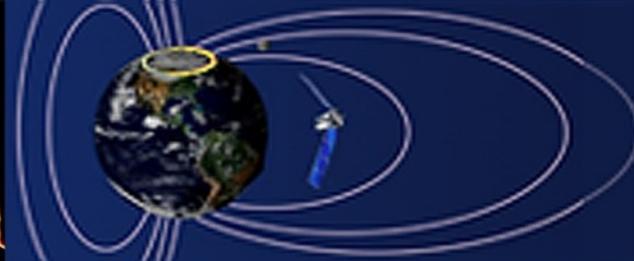
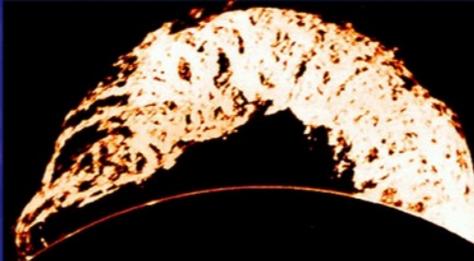
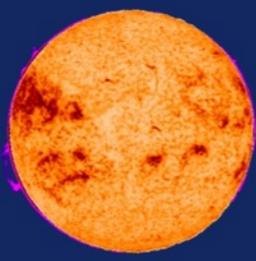
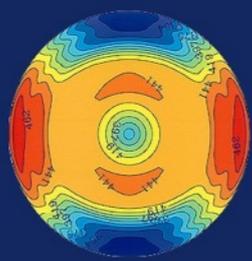
It is an incredibly powerful tool for remote sensing of magnetic fields in the Sun's atmosphere



# The Zeeman effect

Splitting of the energy levels of an atom:

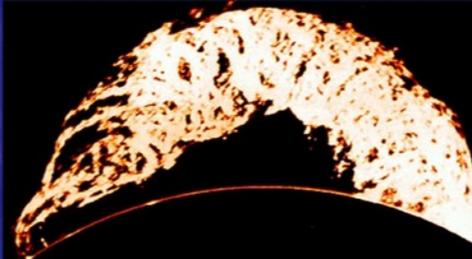
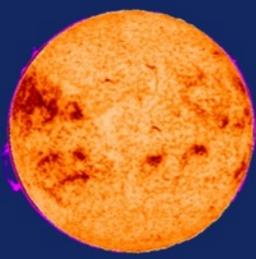
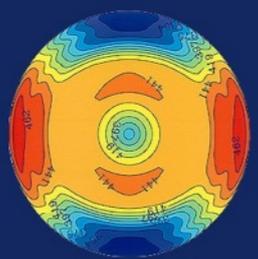




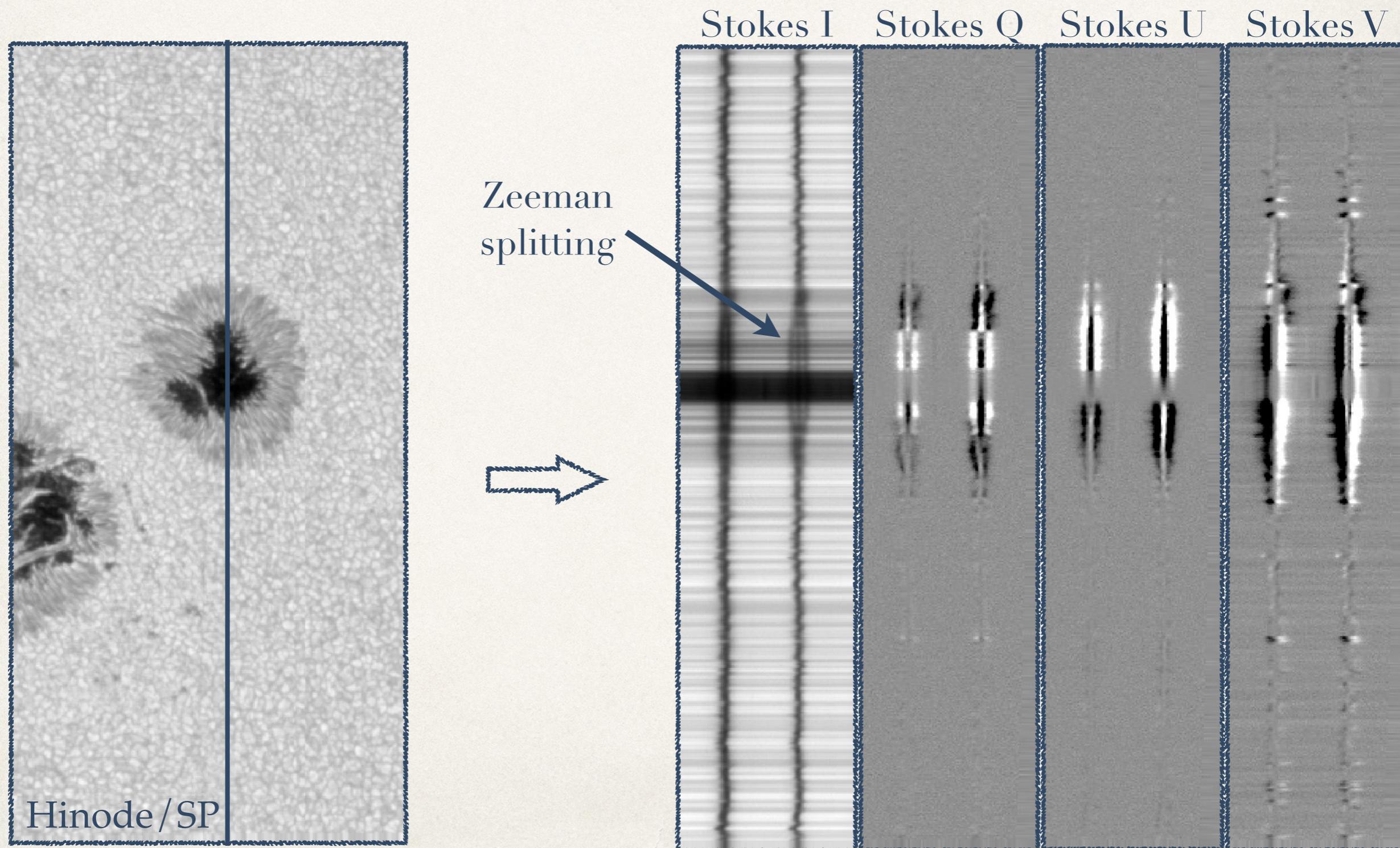
# Very generally...

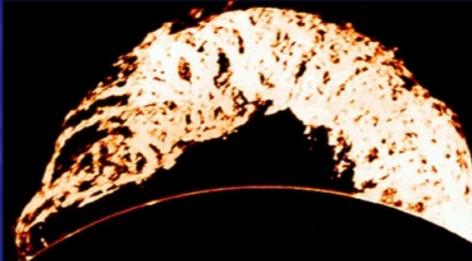
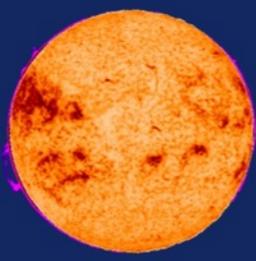
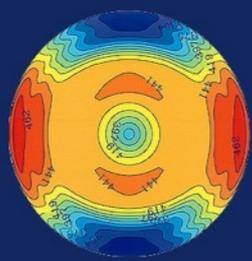
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- ✻ Zeeman splitting - FIELD STRENGTH
- ✻ Circular polarization - LONGITUDINAL
- ✻ Linear polarization - TRANSVERSE
- ✻ Intensity - magnetic vs. non-magnetic



# The Zeeman effect





# Inversions

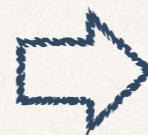
## Forward problem: Radiative Transfer

Physical conditions

(temperature, pressure..)

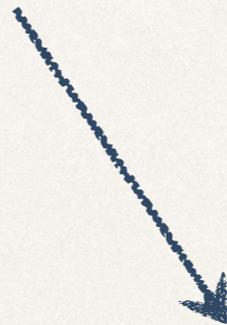
Reasonable assumptions

Solve Radiative Transfer



Emergent spectra

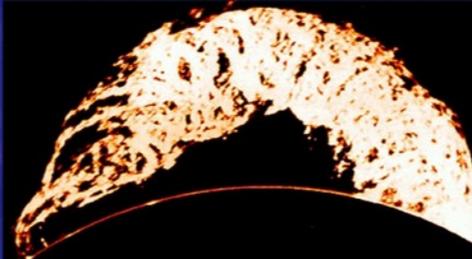
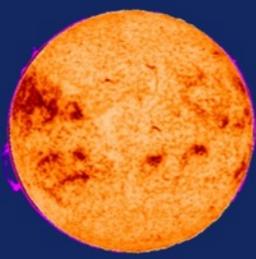
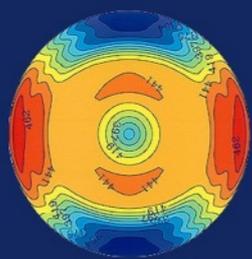
(I, Q, U, V)



Inverse problem:

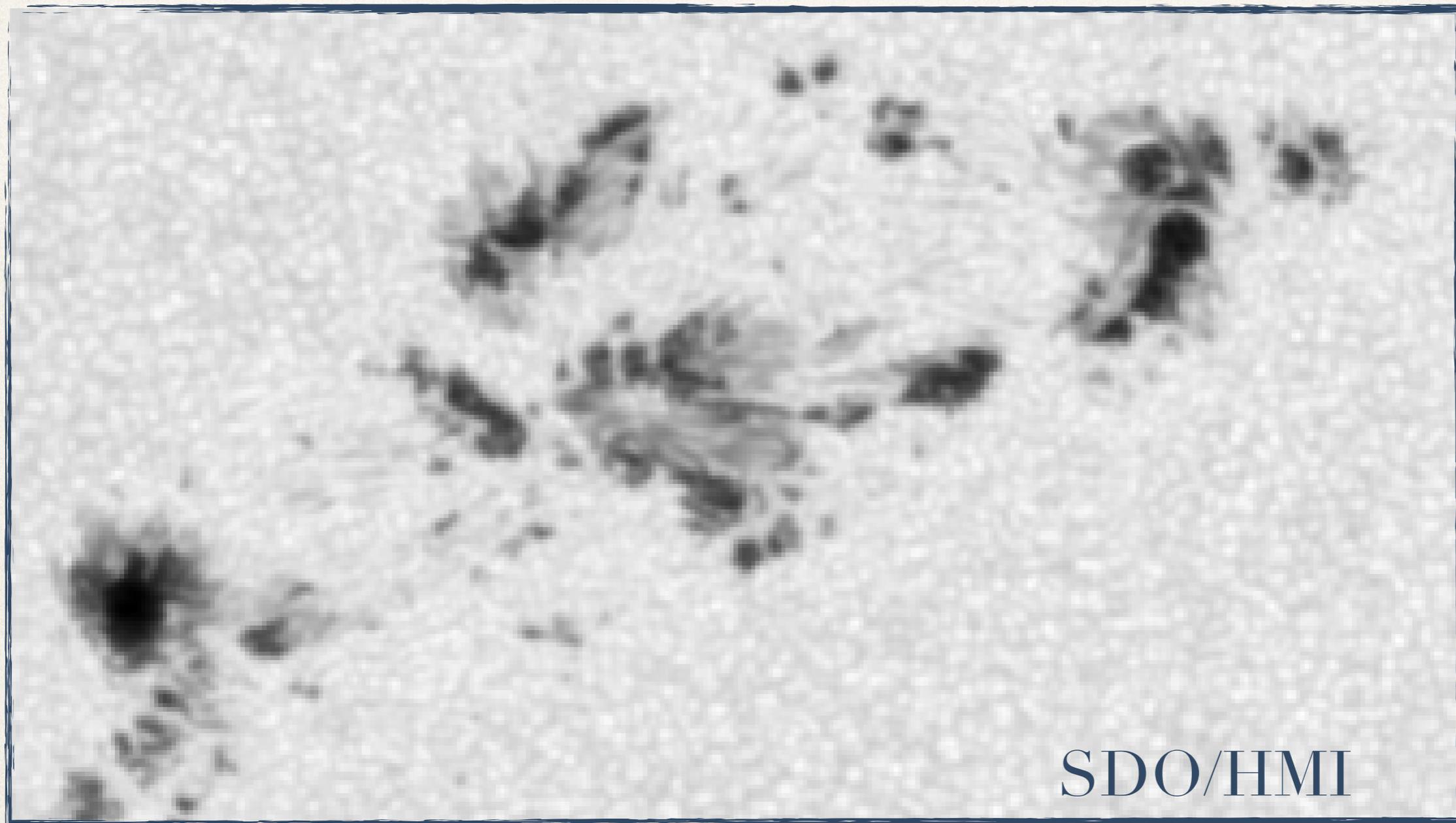
Given the observations, what are the physical conditions in the Sun's atmosphere?

HAO



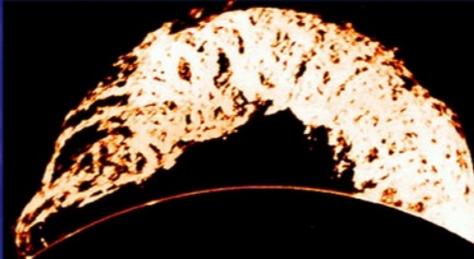
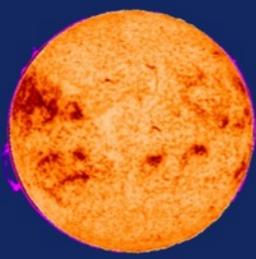
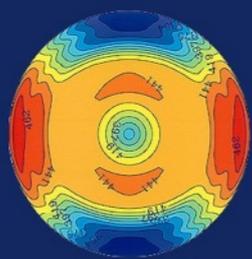
One example:

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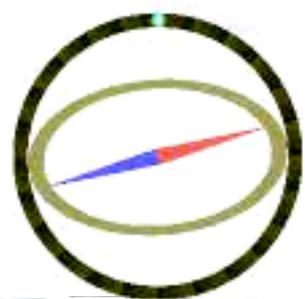
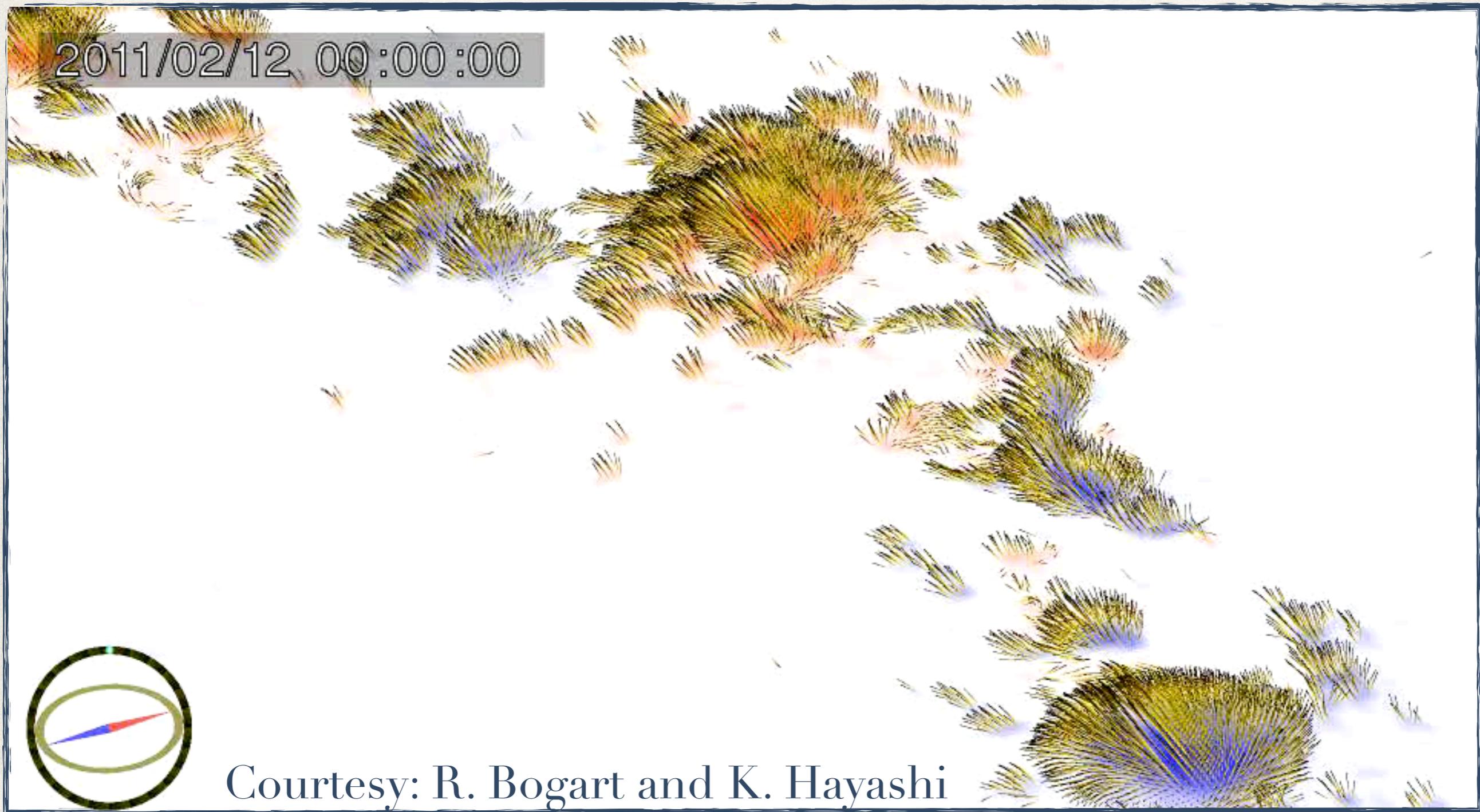
SDO/HMI

HAO

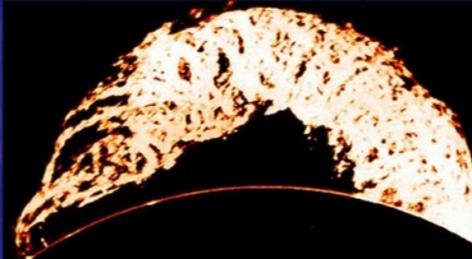
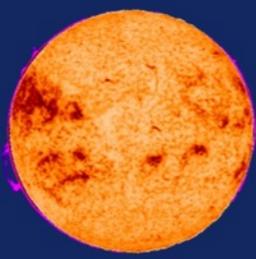
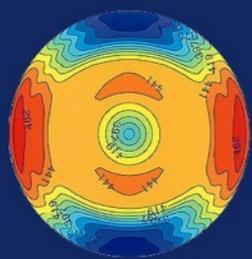


# And the inversion results...

2011/02/12 00:00:00



Courtesy: R. Bogart and K. Hayashi



# The Sun in different lights

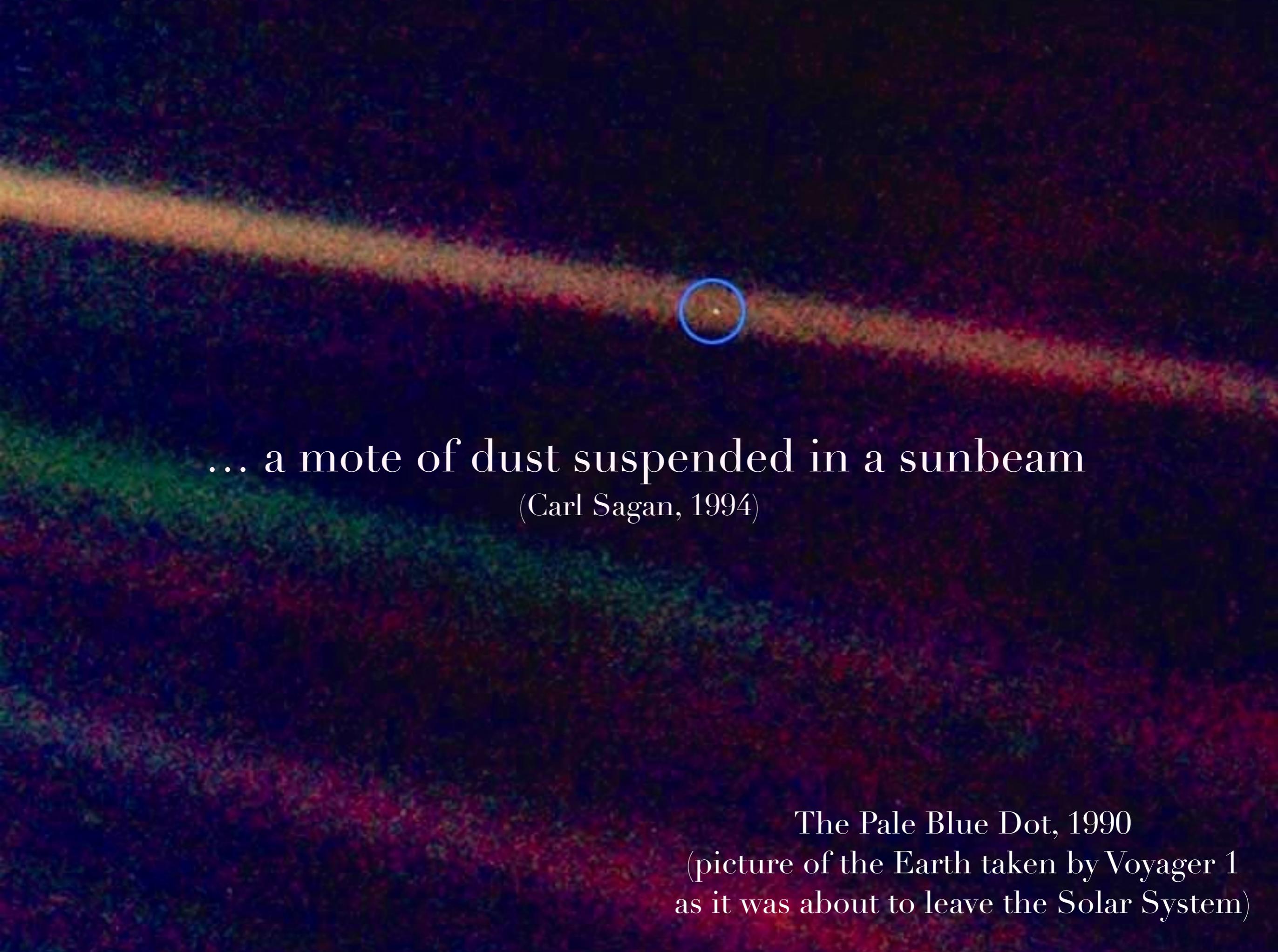
**Corona**

Different physical regimes reign in different layers of the Sun's atmosphere...

**Chromosphere**

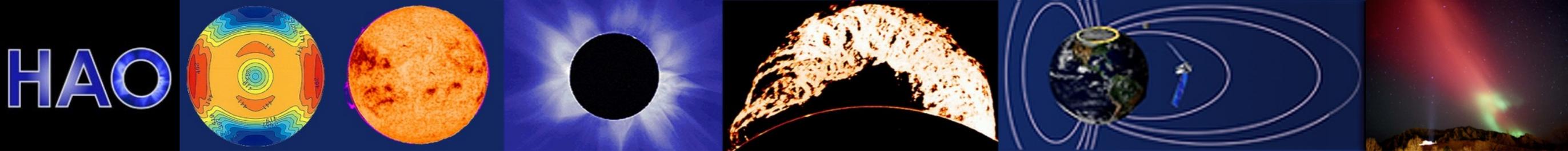
...and different lights allow us to probe them

**Photosphere**

A colorful, grainy image of a sunbeam, likely from a film. The beam is a horizontal band of light, transitioning from yellow and orange on the left to red and purple on the right. A small, bright yellow dot is circled in blue in the center of the beam.

... a mote of dust suspended in a sunbeam  
(Carl Sagan, 1994)

The Pale Blue Dot, 1990  
(picture of the Earth taken by Voyager 1  
as it was about to leave the Solar System)



# The pale blue dot...

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From this distant vantage point, the Earth might not seem of any particular interest. But for us, it's different. Consider again that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there – on a mote of dust suspended in a sunbeam.

The Earth is a very small stage in a vast cosmic arena. Think of the rivers of blood spilled by all those generals and emperors so that in glory and triumph they could become the momentary masters of a fraction of a dot. Think of the endless cruelties visited by the inhabitants of one corner of this pixel on the scarcely distinguishable inhabitants of some other corner. How frequent their misunderstandings, how eager they are to kill one another, how fervent their hatreds. Our posturings, our imagined self-importance, the delusion that we have some privileged position in the universe, are challenged by this point of pale light. Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity – in all this vastness – there is no hint that help will come from elsewhere to save us from ourselves.

The Earth is the only world known, so far, to harbor life. There is nowhere else, at least in the near future, to which our species could migrate. Visit, yes. Settle, not yet. Like it or not, for the moment, the Earth is where we make our stand. It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another and to preserve and cherish the pale blue dot, the only home we've ever known.