The Atmosphere of the Sun and What Happens in It

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Current Solar Spacecraft

NASA - ***The Solar Dynamics Observatory*** **(*SDO*)**

NASA/ESA - ***Solar TErrestrial Relations Observatory*** **(*STEREO*)**

Japan/NASA/UK - ***Hinode***

The Helioseismic and Magnetic Imager (HMI) on the *Solar Dynamics Observatory (SDO)* - Overview

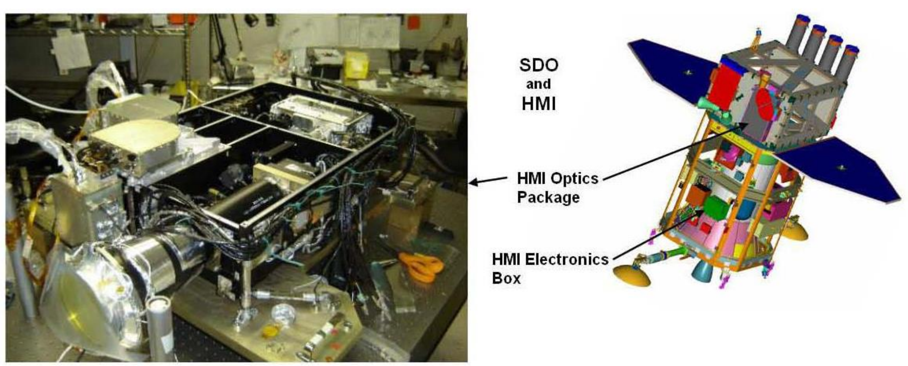
The HMI instrument design and observing strategy are based on the highly successful MDI instrument on *SOHO*, with several important improvements. HMI observes the full solar disk in the Fe I absorption line at 6173Å with a resolution of 1 arc-second. HMI consists of a refracting telescope, a polarization selector, an image stabilization system, a narrow band tunable filter and two 4096 pixel CCD cameras with mechanical shutters and control electronics. The continuous data rate is 55Mbits/s.

Images are made in a sequence of tuning and polarizations at a 4-second cadence for each camera. One camera is dedicated to a 45s Doppler and line-of-sight field sequence while the other to a 90s vector field sequence. All of the images are downlinked for processing at the HMI/AIA Joint Science Operations Center at Stanford University.

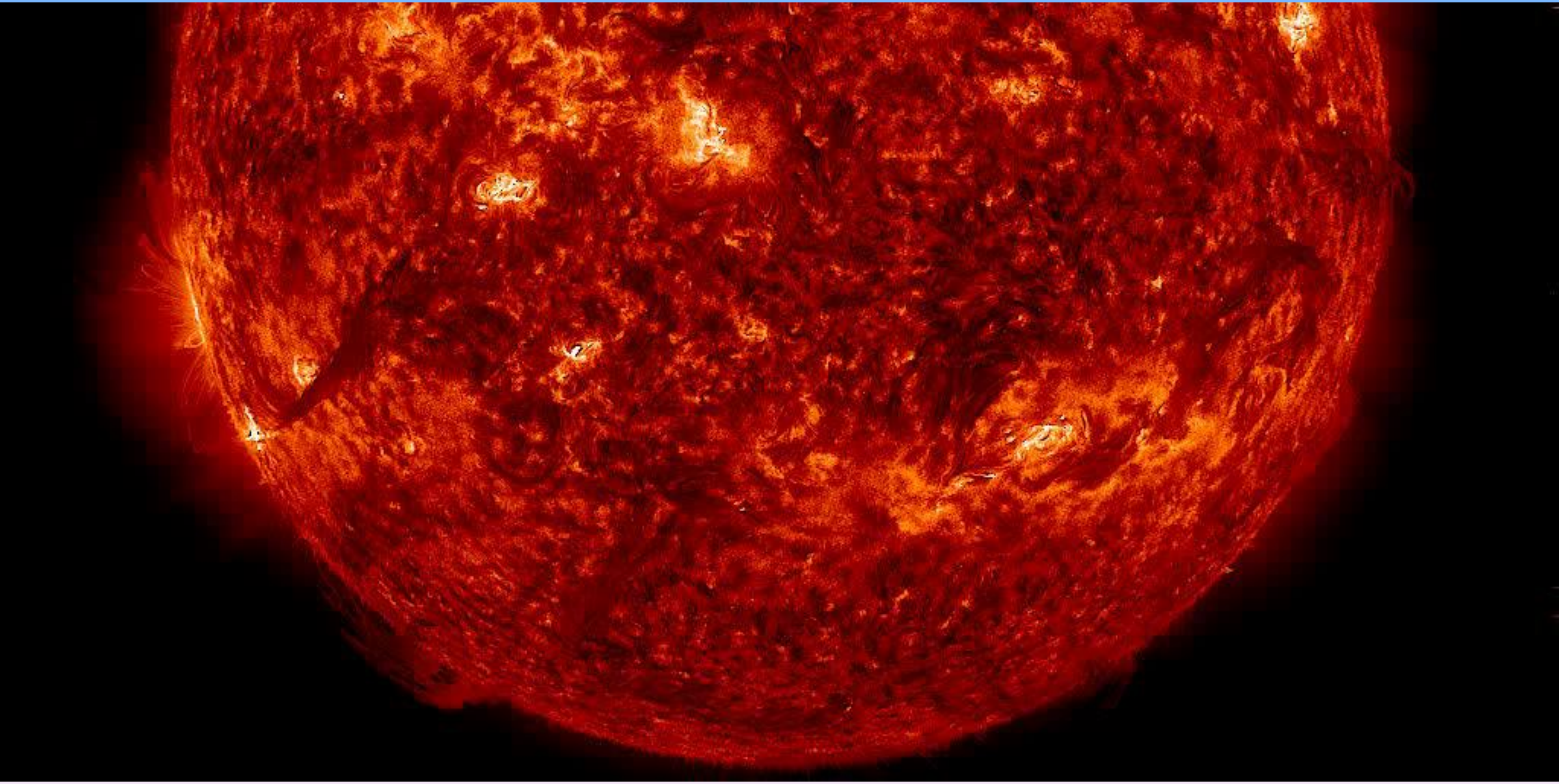
SDO was launched on 11 February 2010 into a geostationary orbit and is currently providing about 1.5 terabytes of data per day.

SDO has three instruments: HMI built by Stanford University (better than 1.5" angular resolution), the Atmospheric Imaging Assembly (AIA) EUV telescopes built by Lockheed Martin Solar & Astrophysics Laboratory (10 full-Sun images every 10s at 1.2" angular resolution), and the Extreme-ultraviolet Variability Experiment (EVE) built by the University of Colorado's Laboratory for Atmospheric and Space Physics

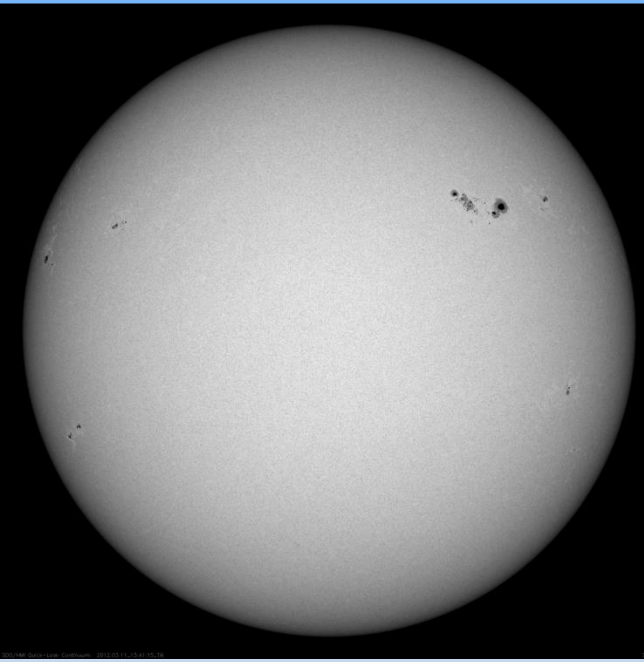
All data are in the public domain and accessible via several websites.



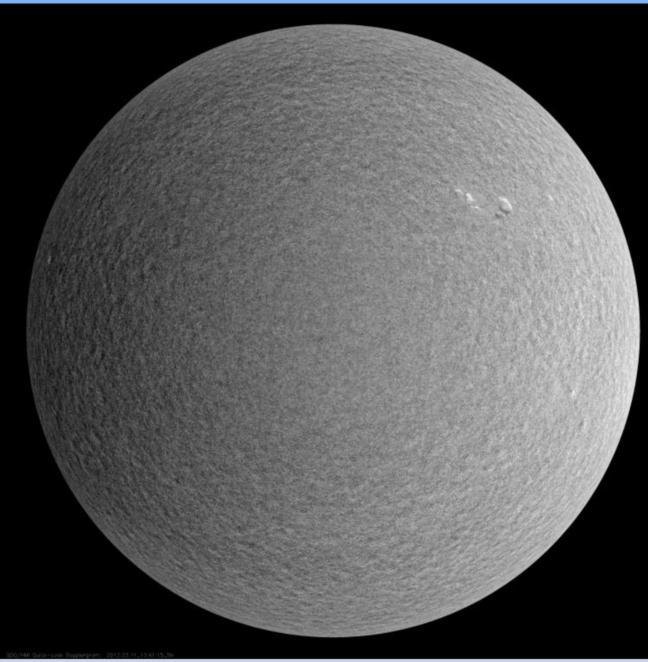
Atmospheric Imaging Assembly on *SDO*



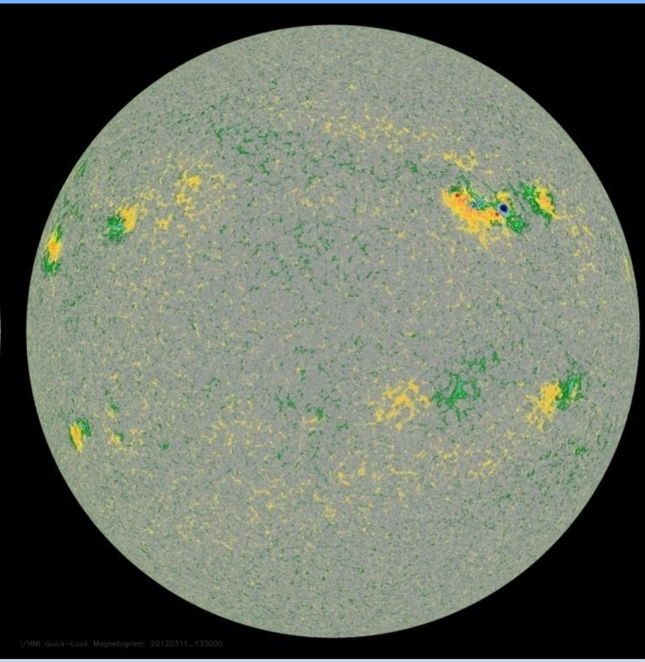
HMI/*SDO* Data Products



Visible light images



Dopplergrams



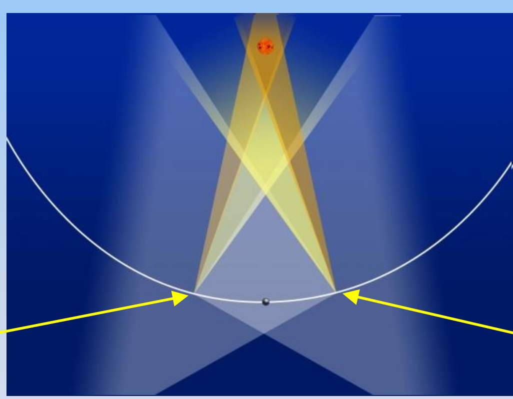
Surface magnetic fields

NRL Sun Earth Connection Coronal & Heliospheric Investigation (*STEREO*/SECCHI)

SECCHI/*STEREO*

- Full sun-earth view
- Side viewing (from ecliptic plane)
- Stereographic image pair

Sun

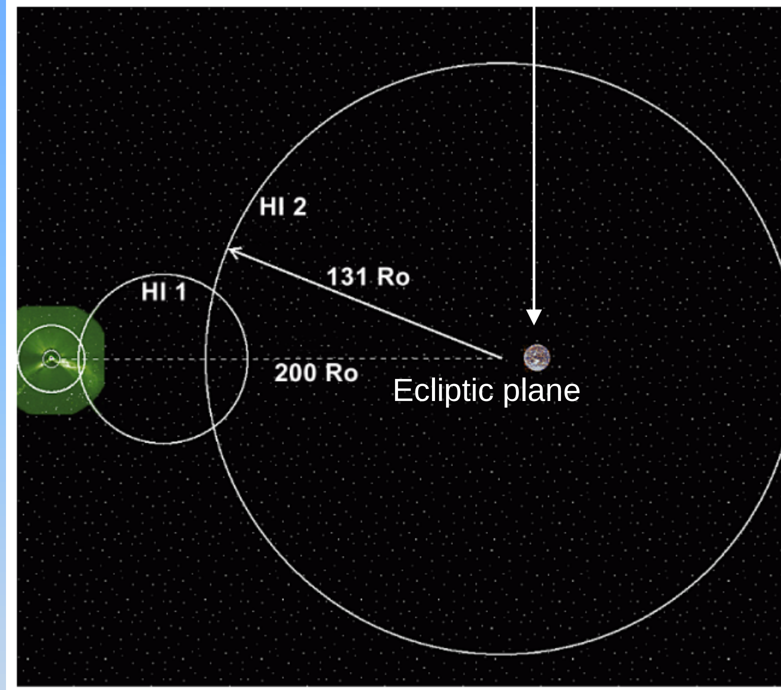


Earth

Field of view of SECCHI coronagraphs-1, -2; HI-1, HI-2 (viewed above ecliptic plane)

Earth

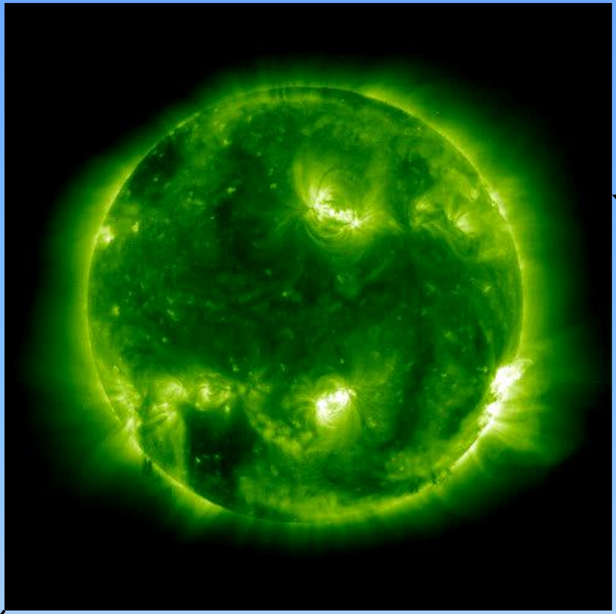
Sun



<u>Five progressive SECCHI fields of view</u>
EUV solar disk, Coronagraph-1, Coronagraph-2, Heliospheric Imager-1 (HI 1), Heliospheric Imager-2 (HI 2) shown as white circles.
LASCO comparison field in green
(viewed in ecliptic plane)

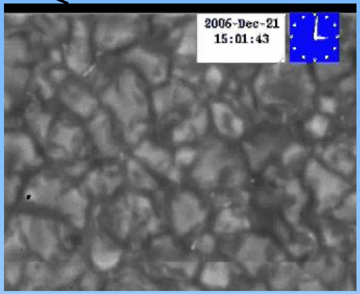
Solar Physics & Space Weather

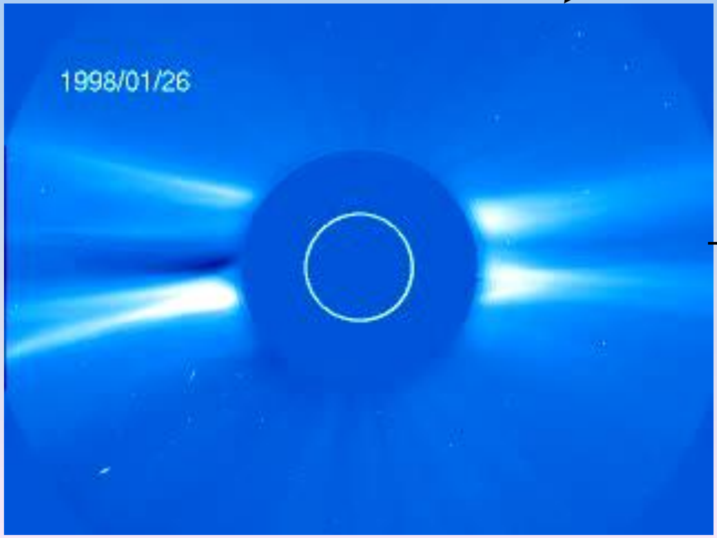
- Understanding the physical processes that produce the solar atmosphere, determine its morphology and evolution, and generate transient events such as the solar wind, solar flares, and coronal mass ejections
- Developing prediction algorithms for solar activity based on an understanding of the physical mechanisms
- Facilitating transitions (via agencies such as NOAA) of prediction algorithms into operational programs



SOHO/EIT
195 Å images

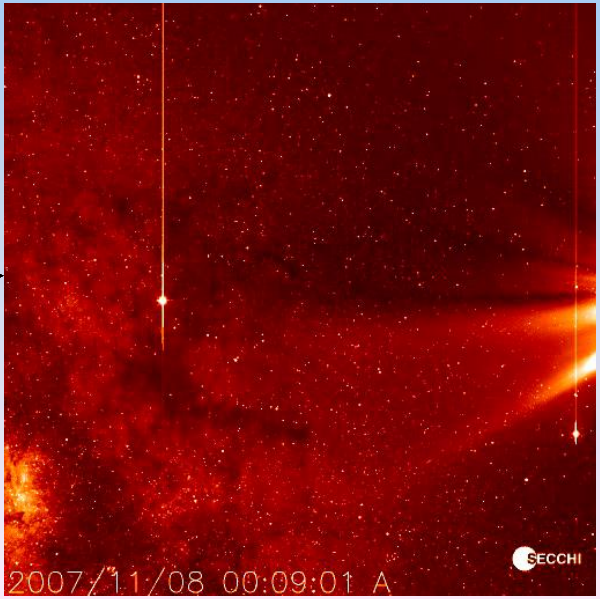
Hinode/SOT



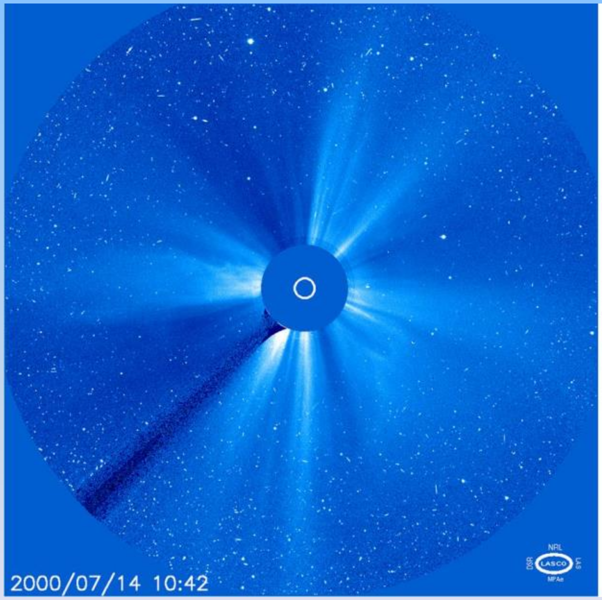


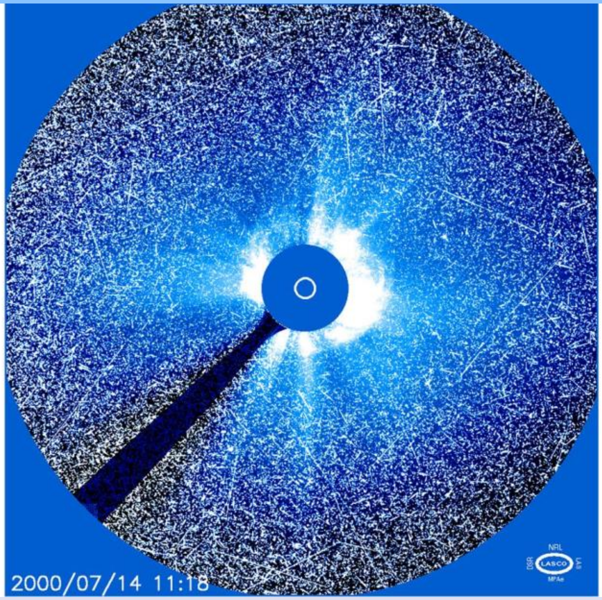
SOHO/LASCO
images: 4 weeks

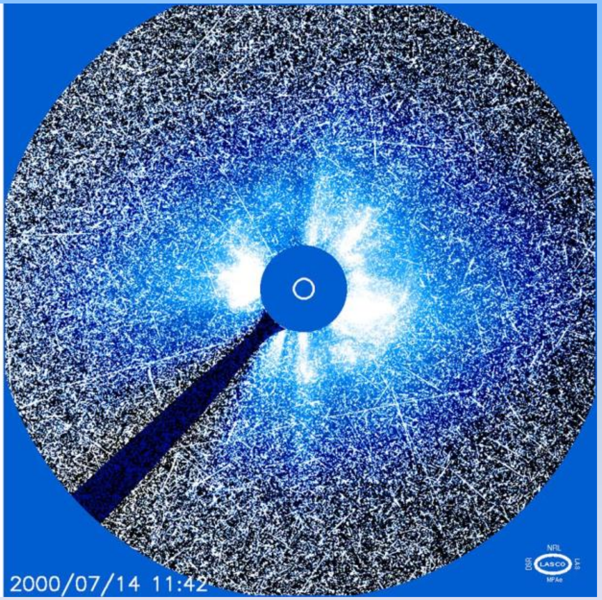
STEREO/HI



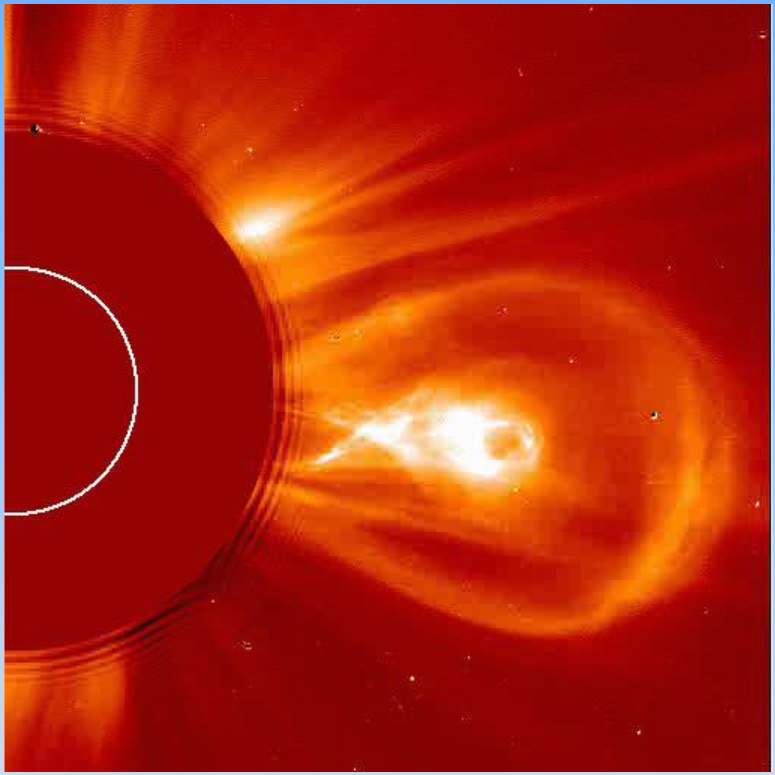
Solar Flare and Coronal Mass Ejection - LASCO C3 on *SOHO*



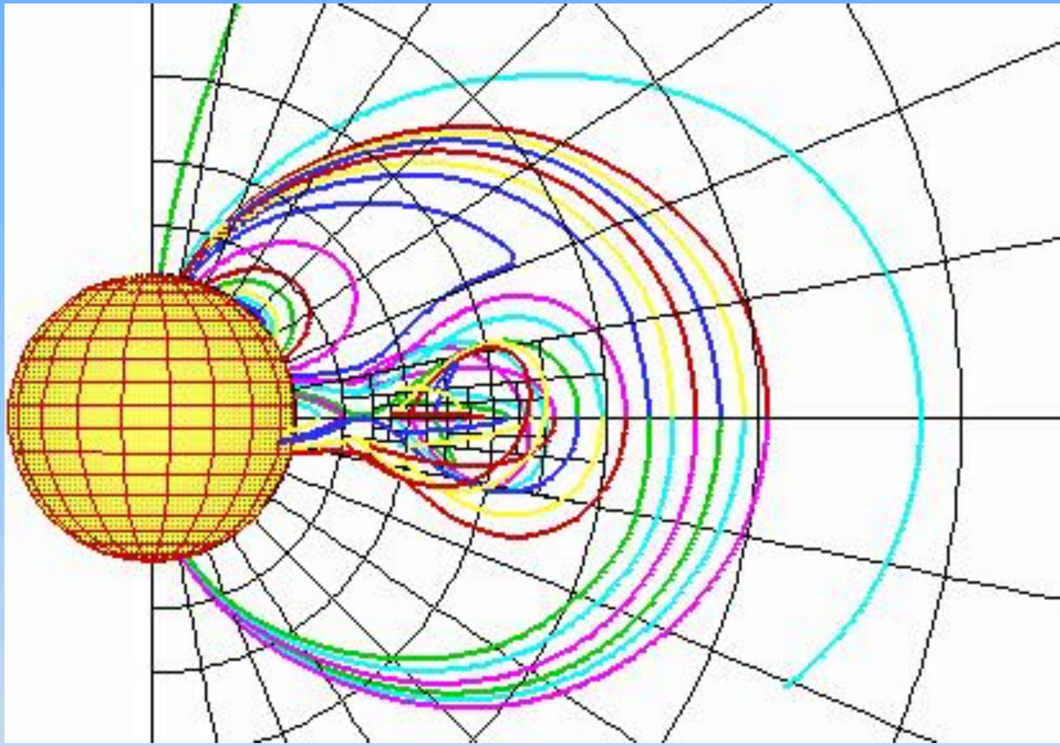




Breakout Model for Coronal Mass Ejections/Eruptive Flares



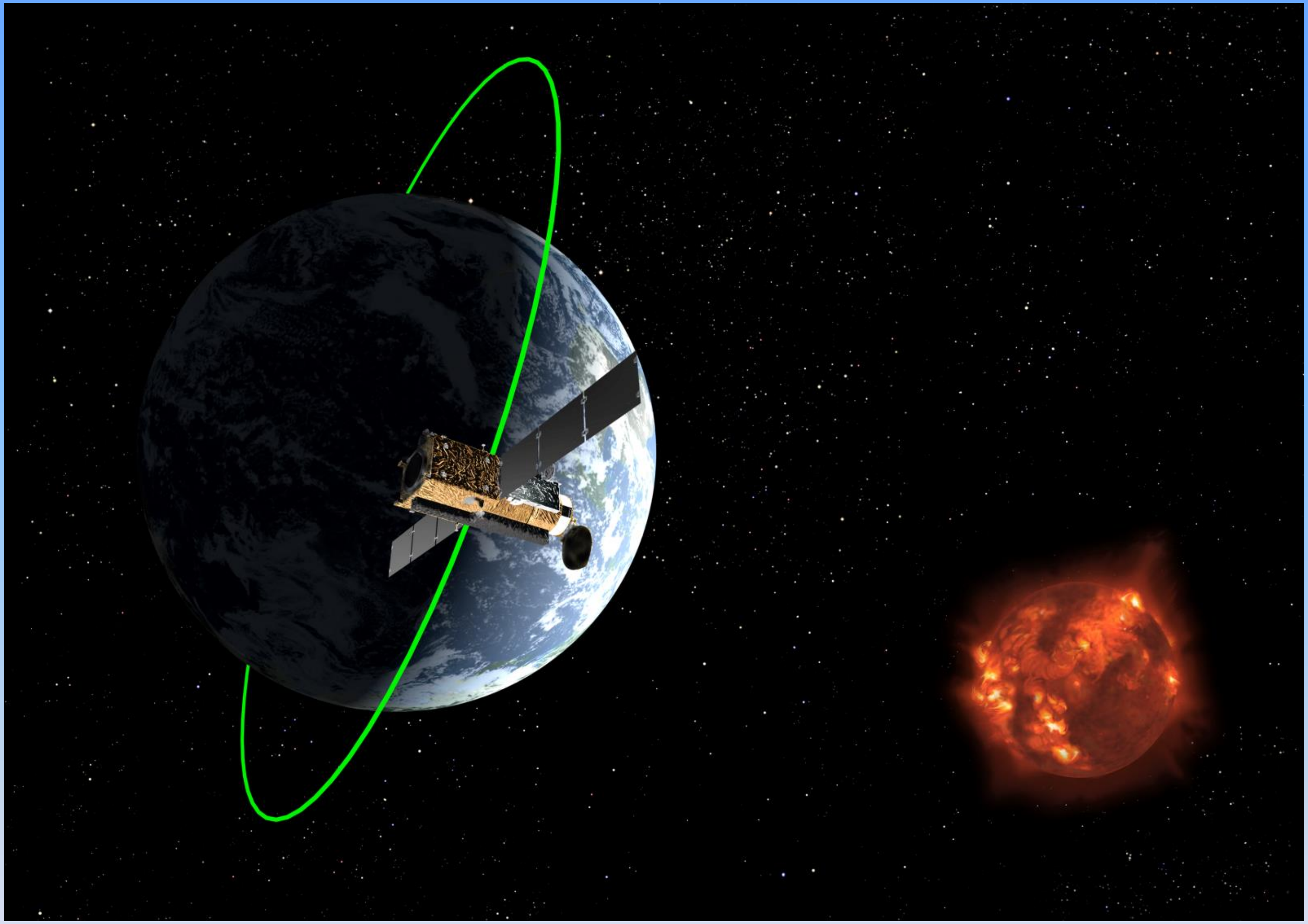
LASCO observation of coronal mass ejection (CME) on 02/05/99



Simulation of NRL's breakout model for CMEs using adaptive mesh refinement code

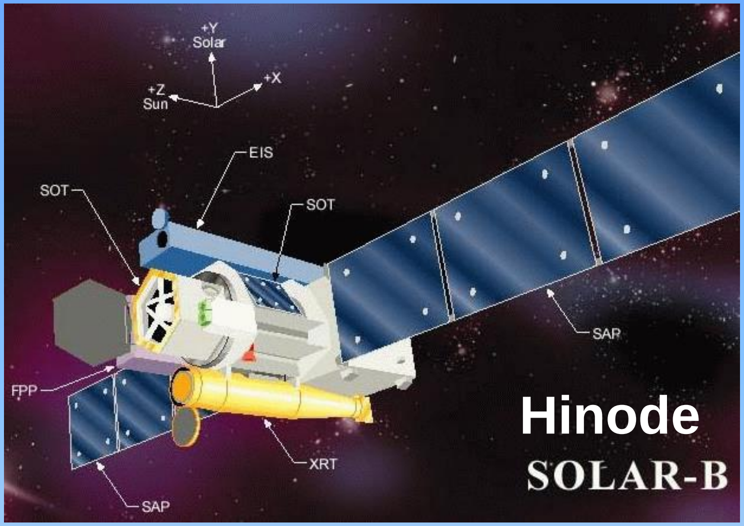
The *Hinode* Spacecraft

The Hinode Mission



Launch date: 23 Sept. 2006;Launch vehicle: ISAS MV; Mission lifetime: 3 years
Orbit: Polar, sun synchronous; Inclination: 97.9 degrees; Altitude: 600 km
Mass: 900 kg

The Extreme-ultraviolet Imaging Spectrometer (EIS) on *Hinode* - Overview



EIS is an international collaboration between Mullard Space Science Laboratory (MSSL), the Naval Research Laboratory (through NASA), and the National Astronomical Observatory of Japan. Geo. Doschek is the PI to NASA.

NRL provided/provides hardware, software, electronics, science design, data analysis, and operations support to EIS.

Hinode was launched on 23 Sept. 2006 and EIS has performed flawlessly since first light.

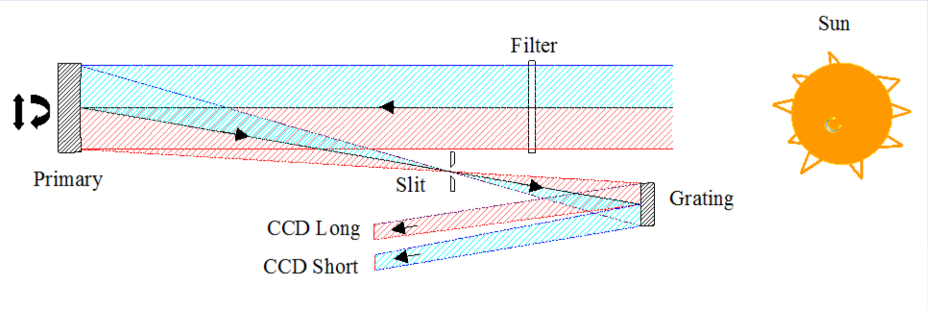
Hinode data are now in the public domain; a resource for research.

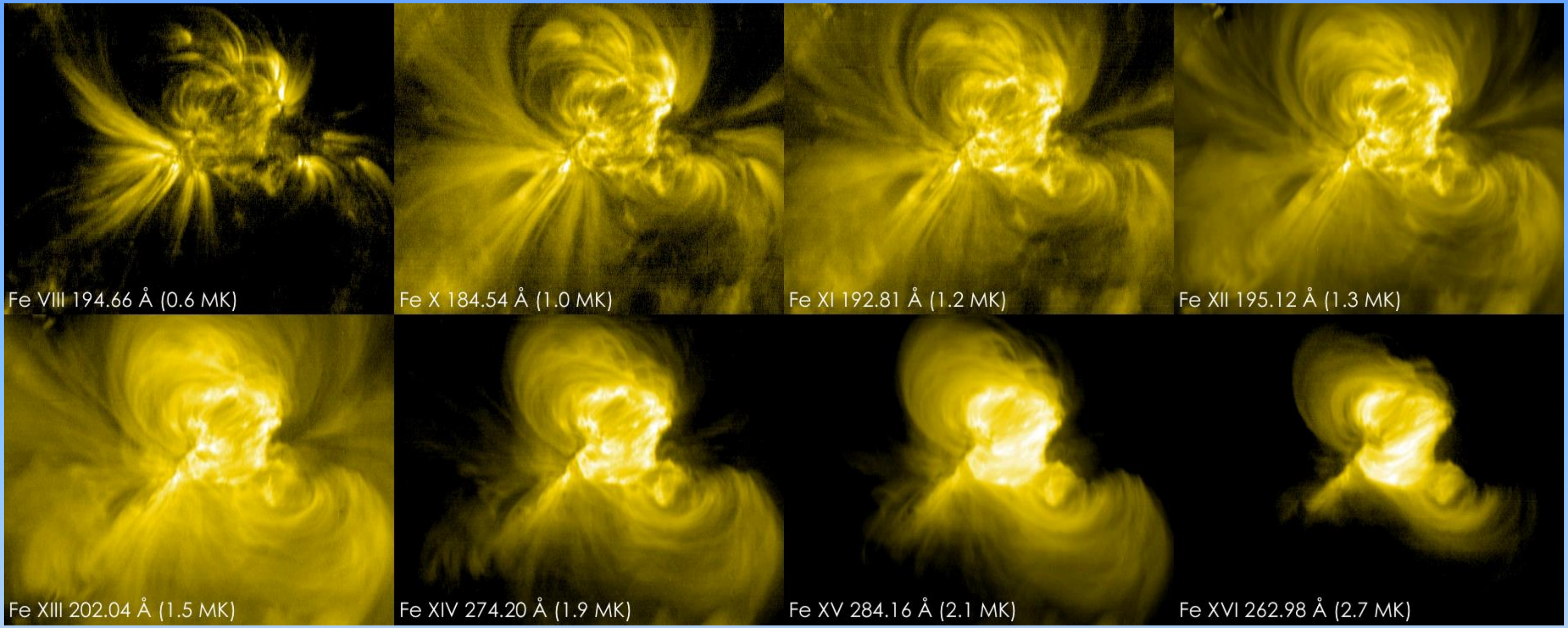
EIS obtains high resolution spectra in two EUV wavebands: 170-210 Å and 250-290 Å. High optical reflectivity for these wavebands is achieved using multilayer optics. Spectra can be obtained with narrow slits or with wider slots.

Sunlight passes through an Al filter and is imaged by an articulated primary mirror onto either a slit or slot. The light passes through the slit/slot and is diffracted by a grating and focused onto two CCD cameras. Below the green and pink refer to the two wavebands.

EIS can measure the electron temperature and density, turbulence, and plasma flows in solar plasmas with unprecedented precision.

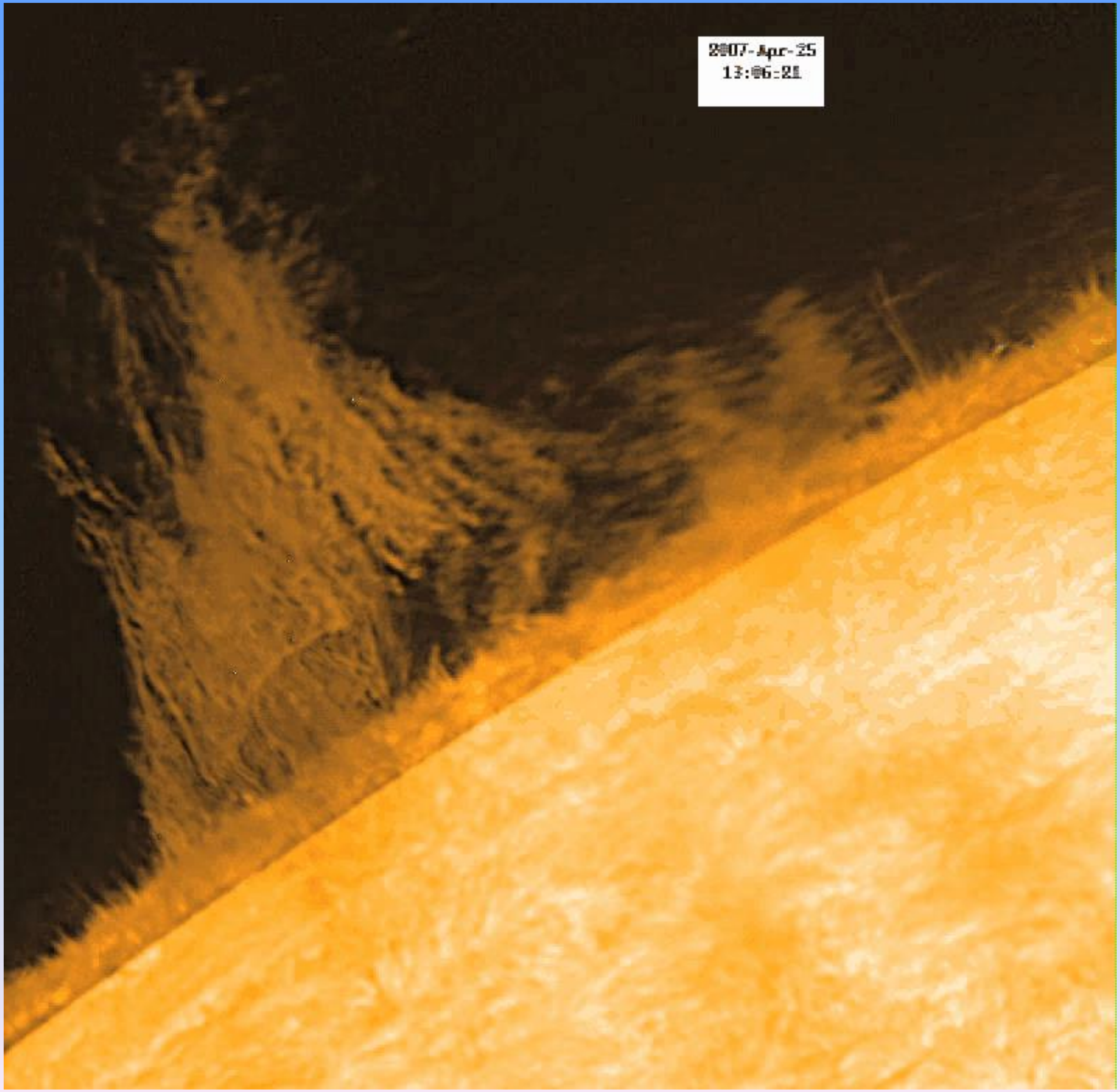
The spatial resolution of EIS is 2” (1400 km) and the spectral resolution is 0.0223 Å.



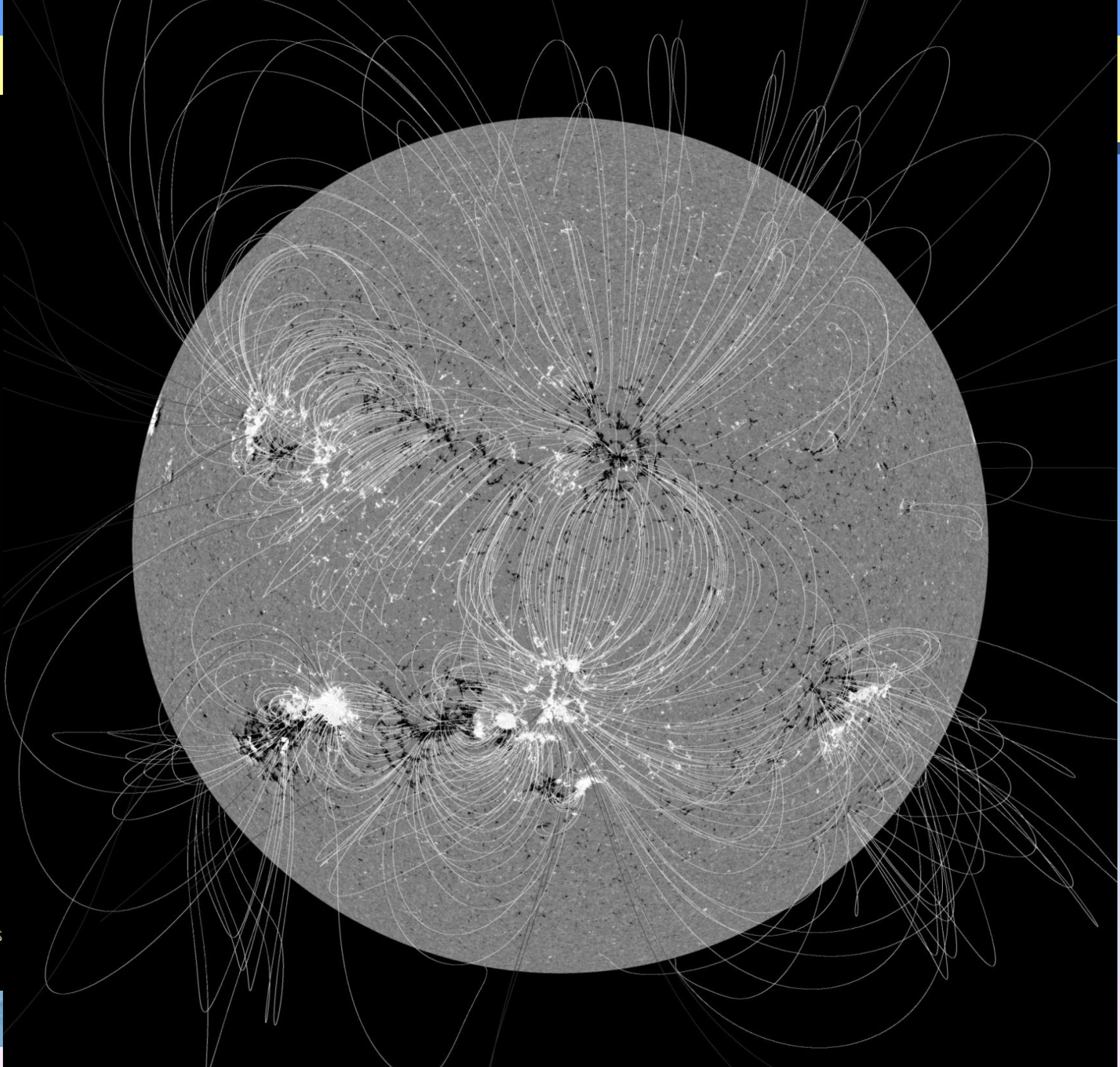


EIS 1" slit raster images of an active region. For the first time we have constructed images of active regions that allow us to trace in detail the active region structures from the chromosphere up into the corona.

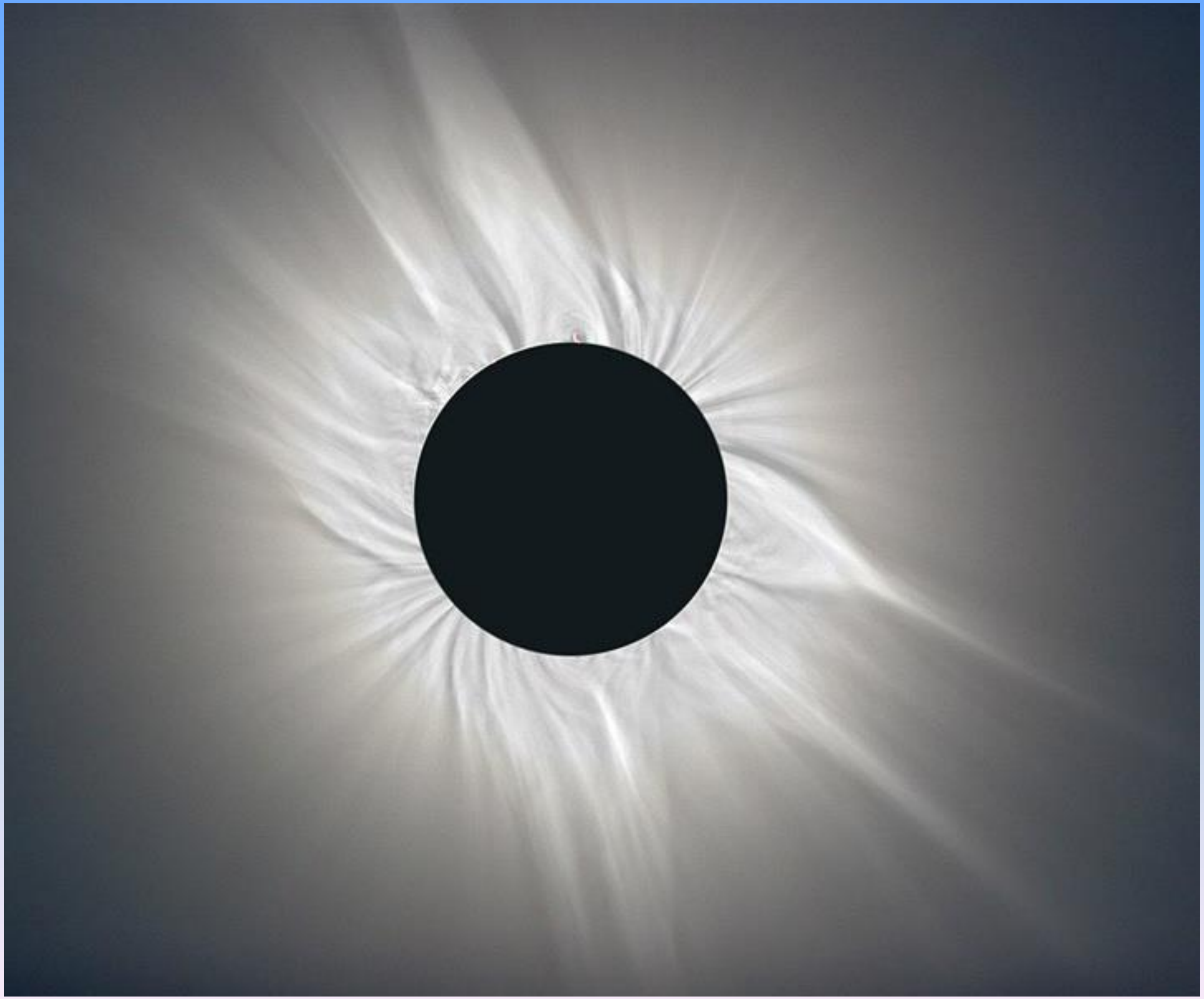
Hinode/SOT
limb prominence



The Structure of the Solar Atmosphere



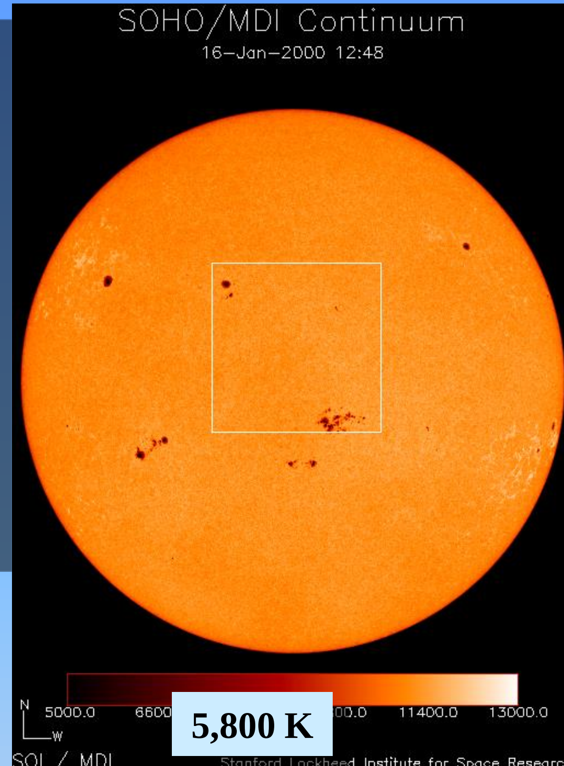
The Solar Atmosphere



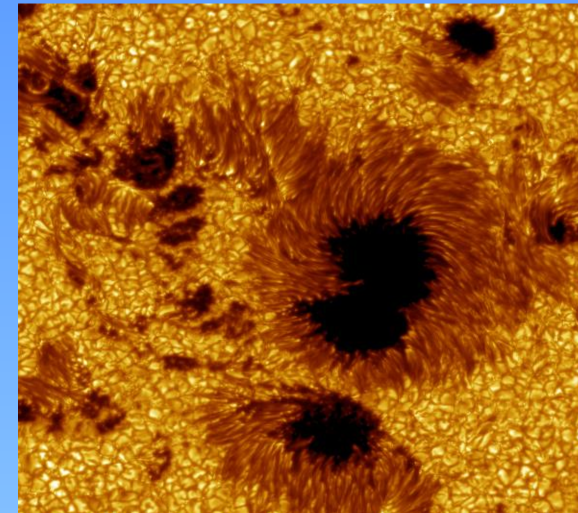
Solar Physics: Fundamental Questions

1- What drives solar explosions?
2- What structures and heats the solar atmosphere?
3- How does solar energy affect the heliosphere and the Earth's atmosphere?

NRL built hardware for *Yohkoh*, *SOHO*, *Solar-B*, and *STEREO*.

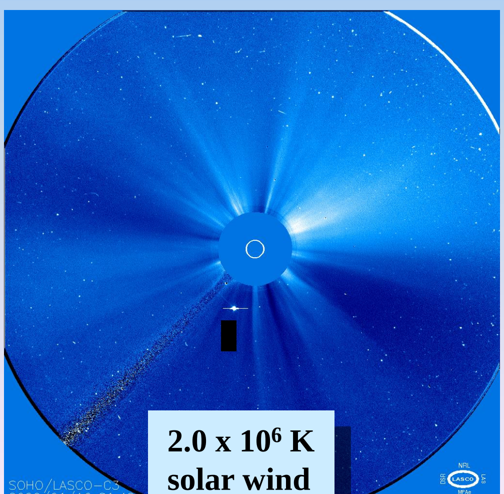


5,800 K

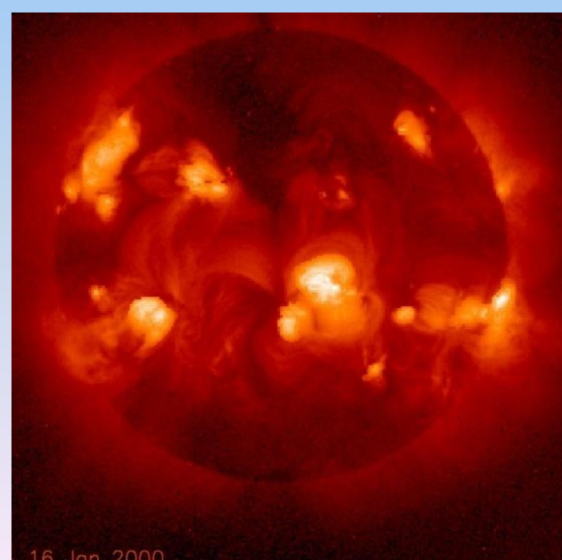


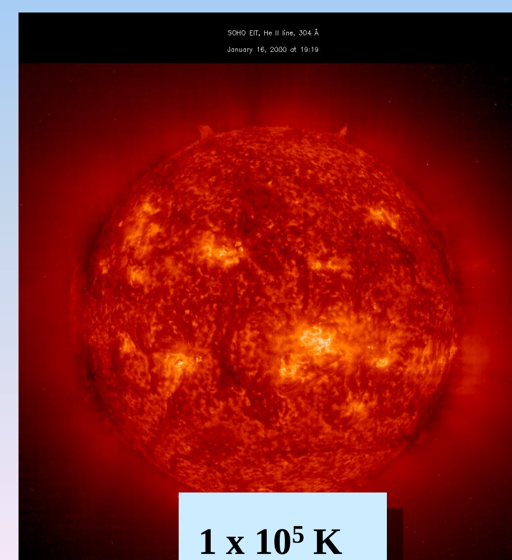
Solar "granules" or convection cells near sunspots in an active region. Granules are about 1000 km (~1.5") in size.

2.0×10^6 K inner corona



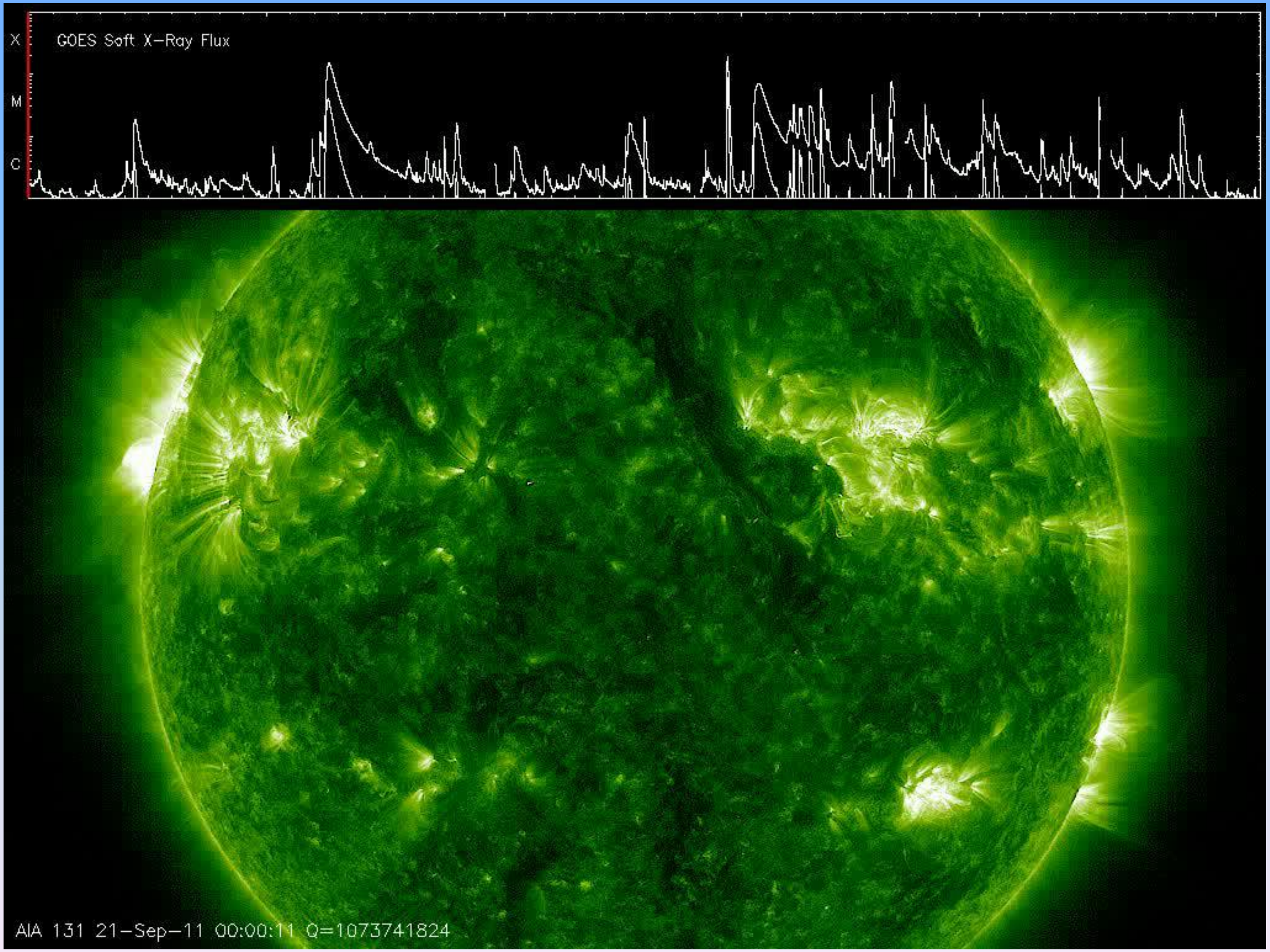
2.0×10^6 K solar wind



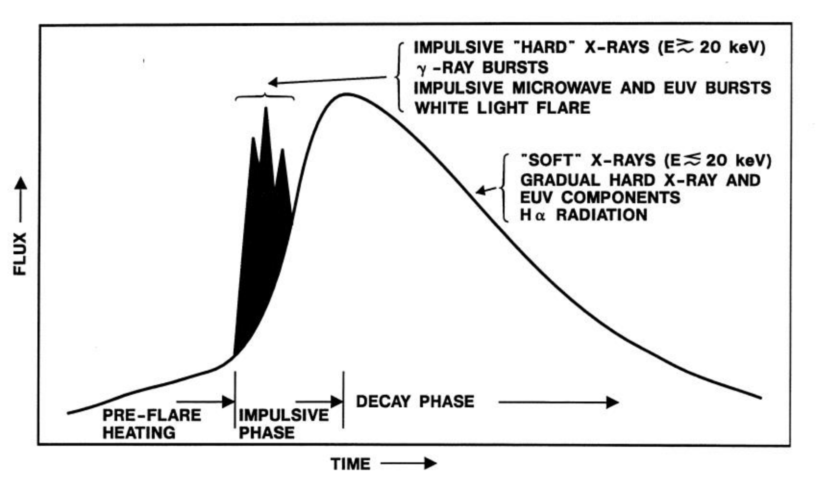


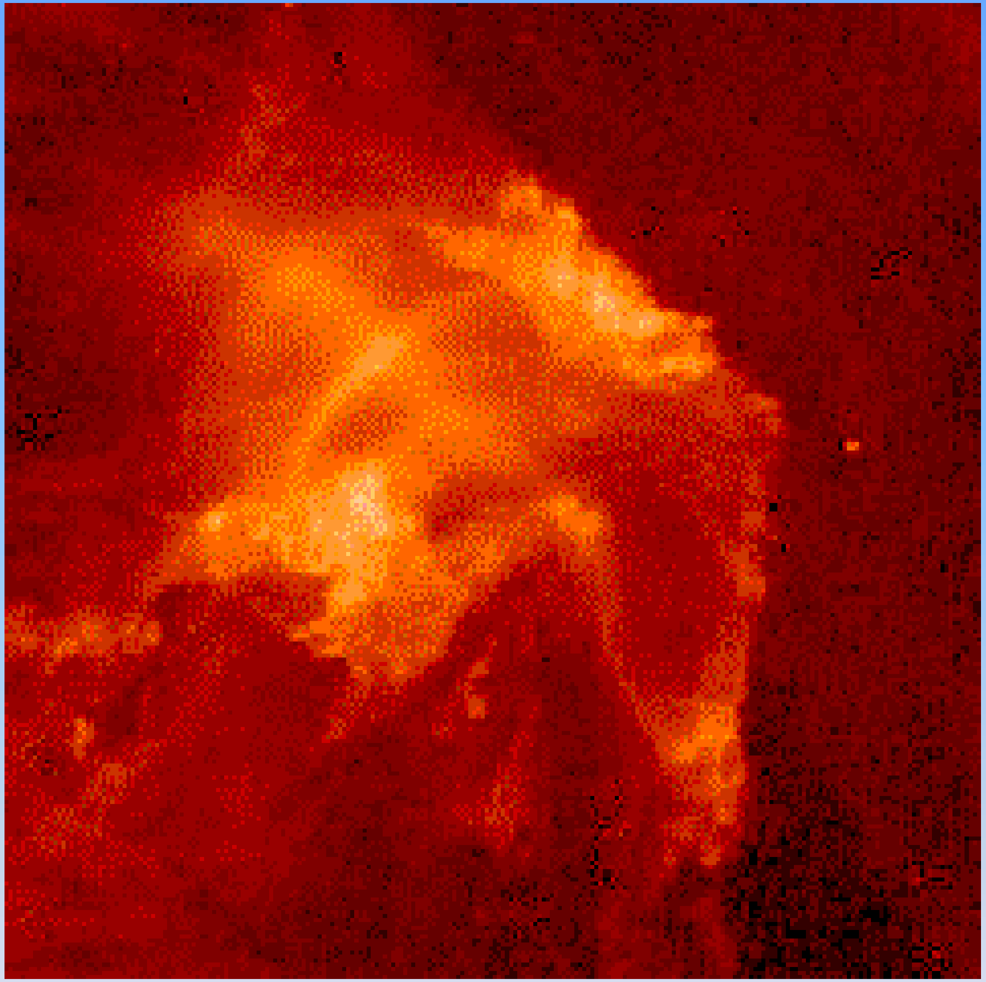
1×10^5 K

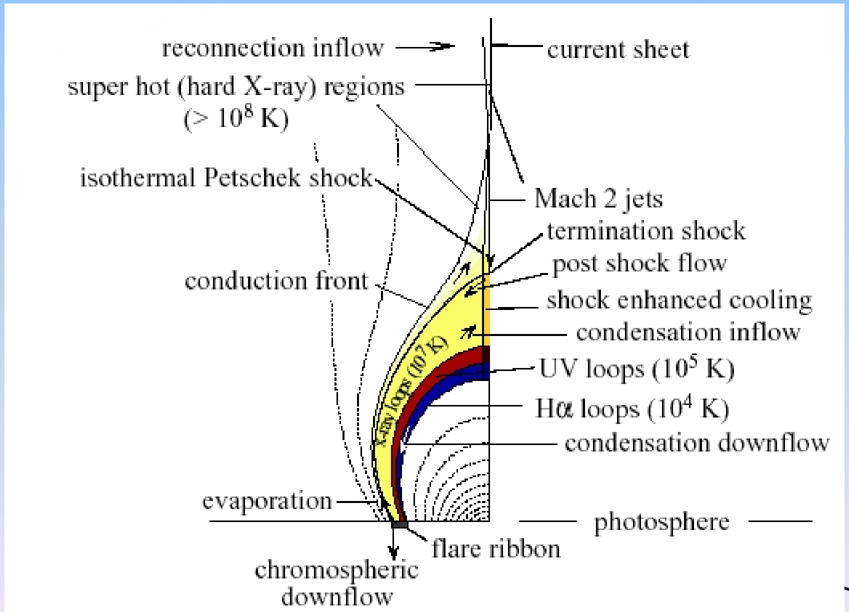
Solar Flares



Solar Flare Reconnection Model – The "Standard Model"

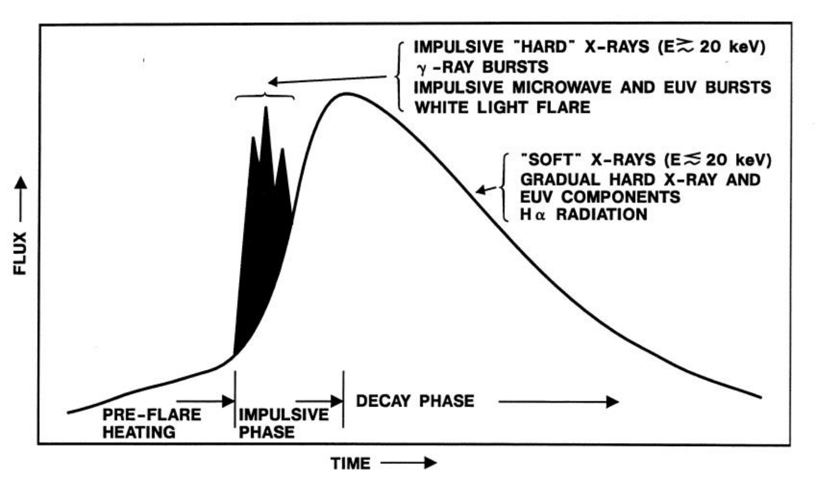


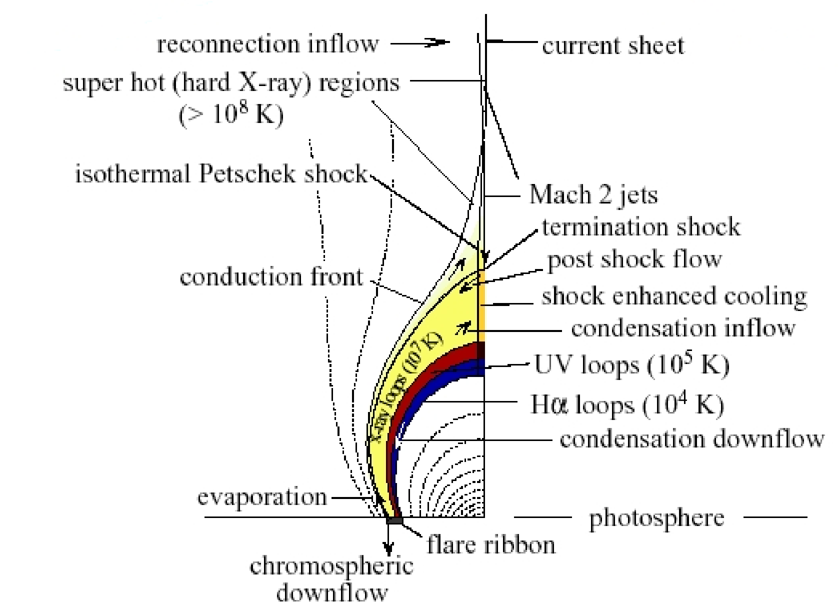


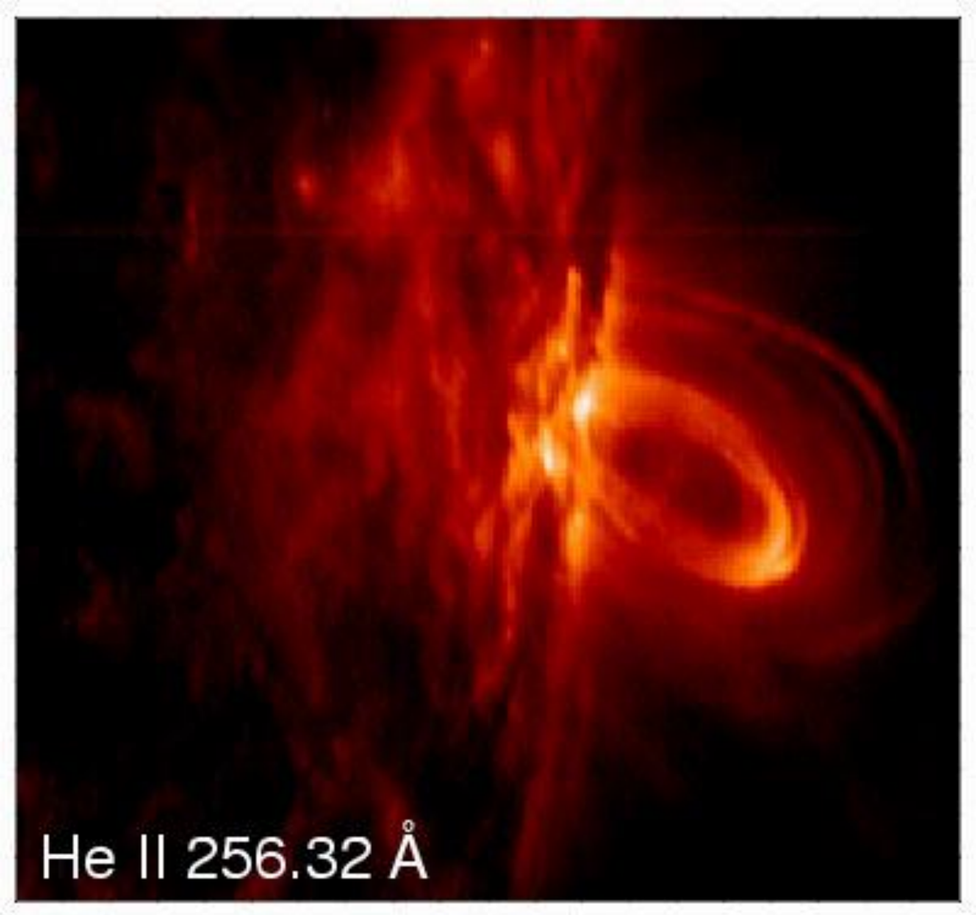


This schematic "Standard Flare Model" provides theoretical guidance for analyzing solar flare data.

Solar Flare Reconnection Model – The "Standard Model"

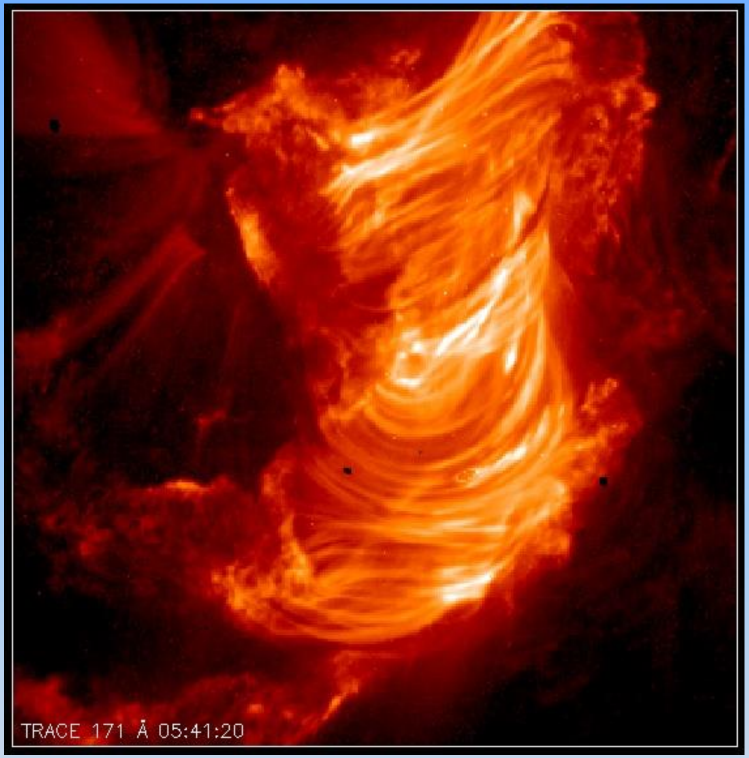


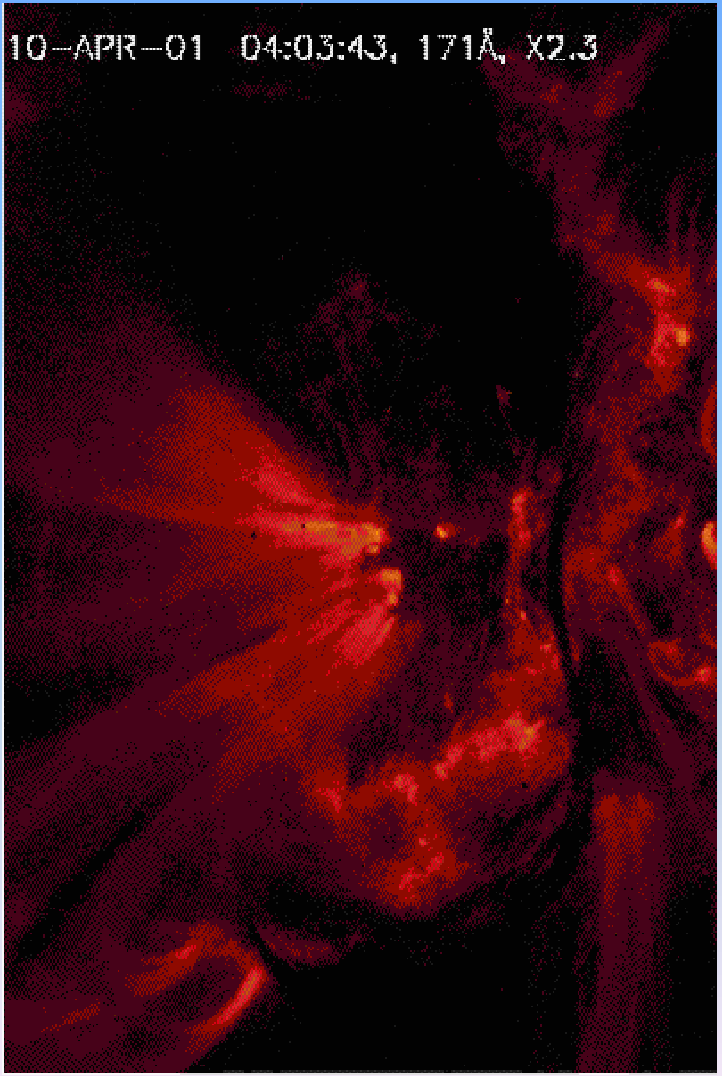




This schematic "Standard Flare Model" provides theoretical guidance for analyzing solar flare data.

Typical Large Flare Morphology and Evolution

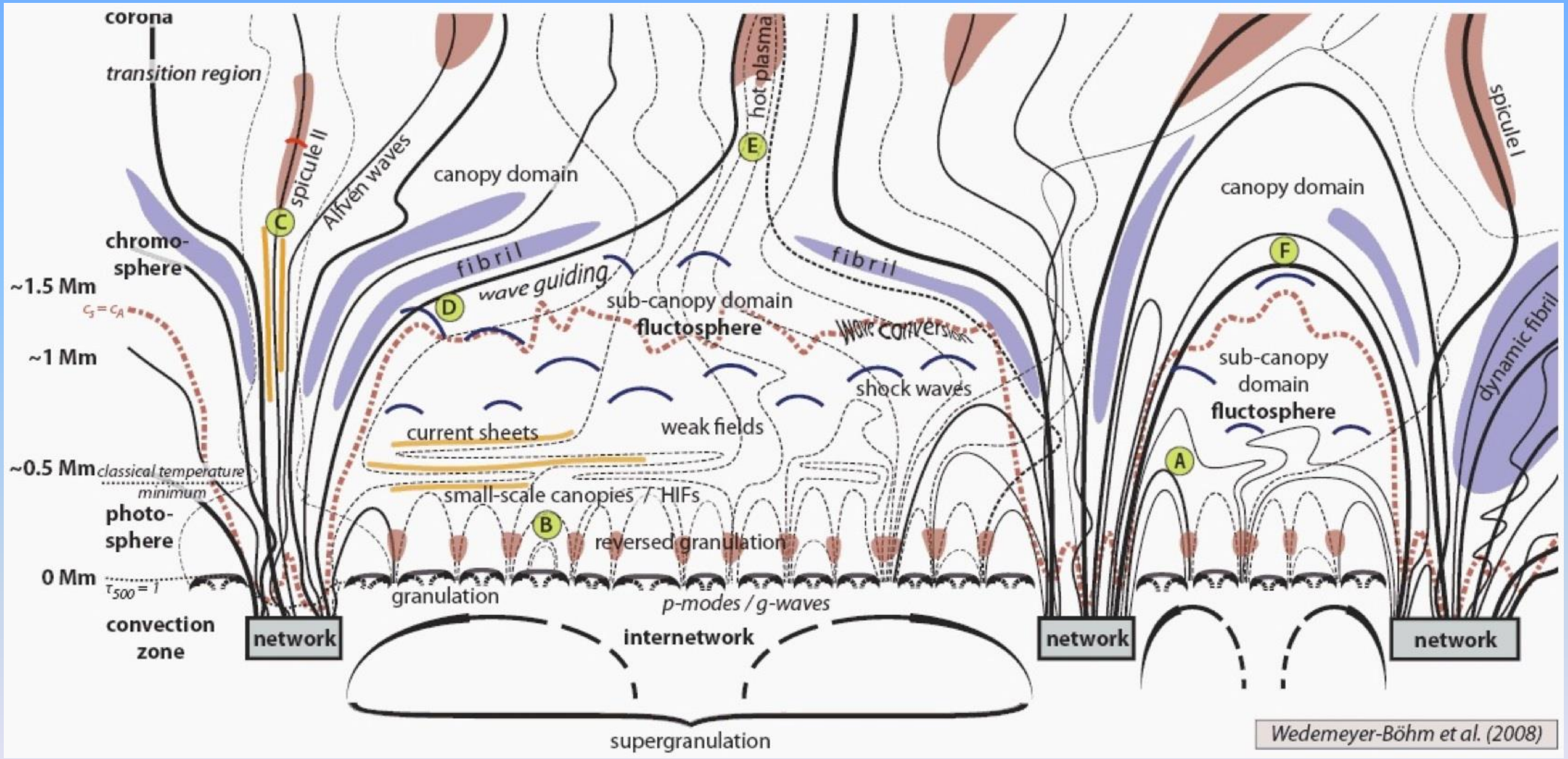


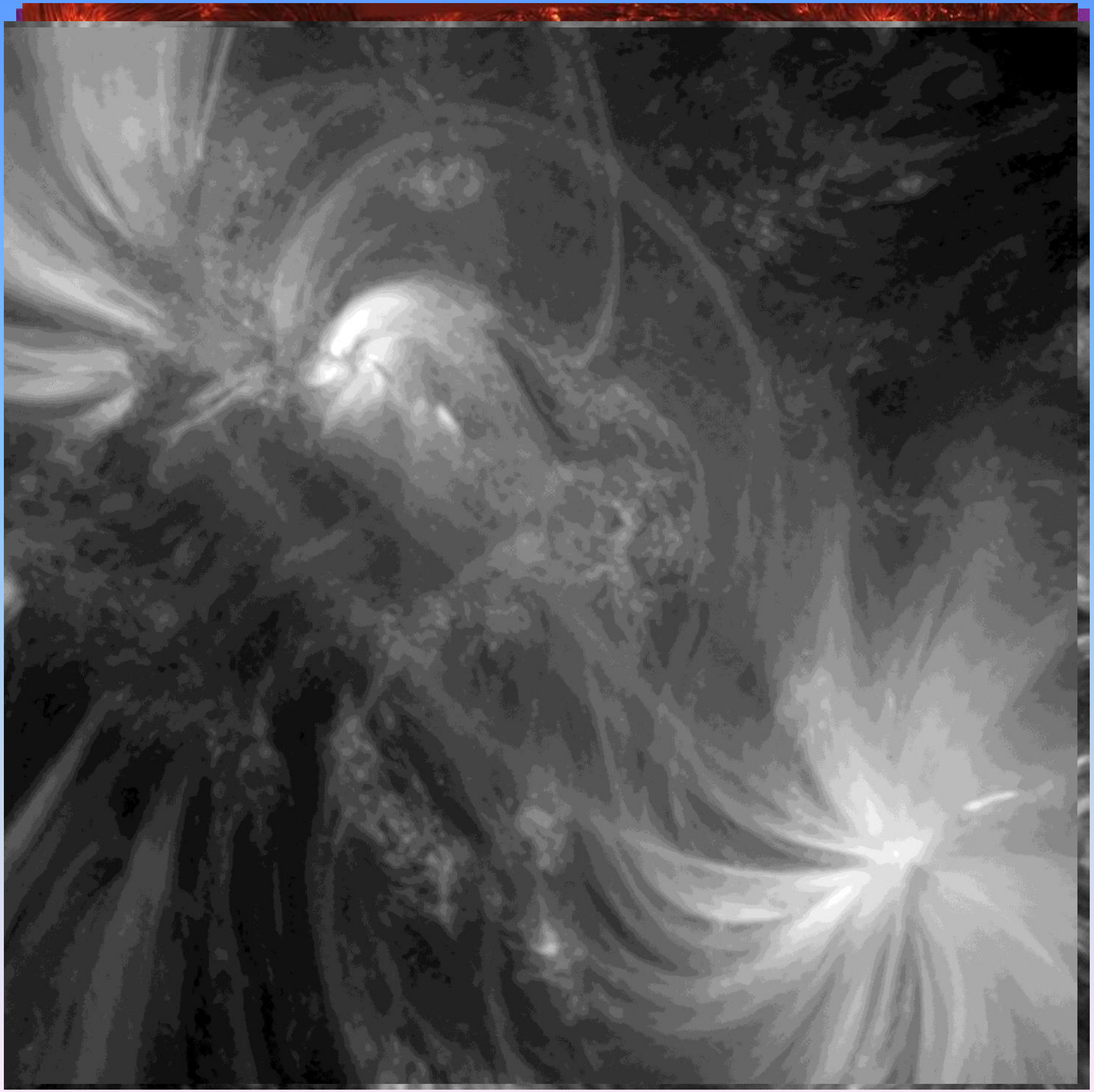


Flares show a rising arcade of soft X-ray emitting loops with a distribution of temperatures and continuous energy deposition.

The Solar Atmosphere is Highly Structured

How do mass and energy flow through the atmosphere?





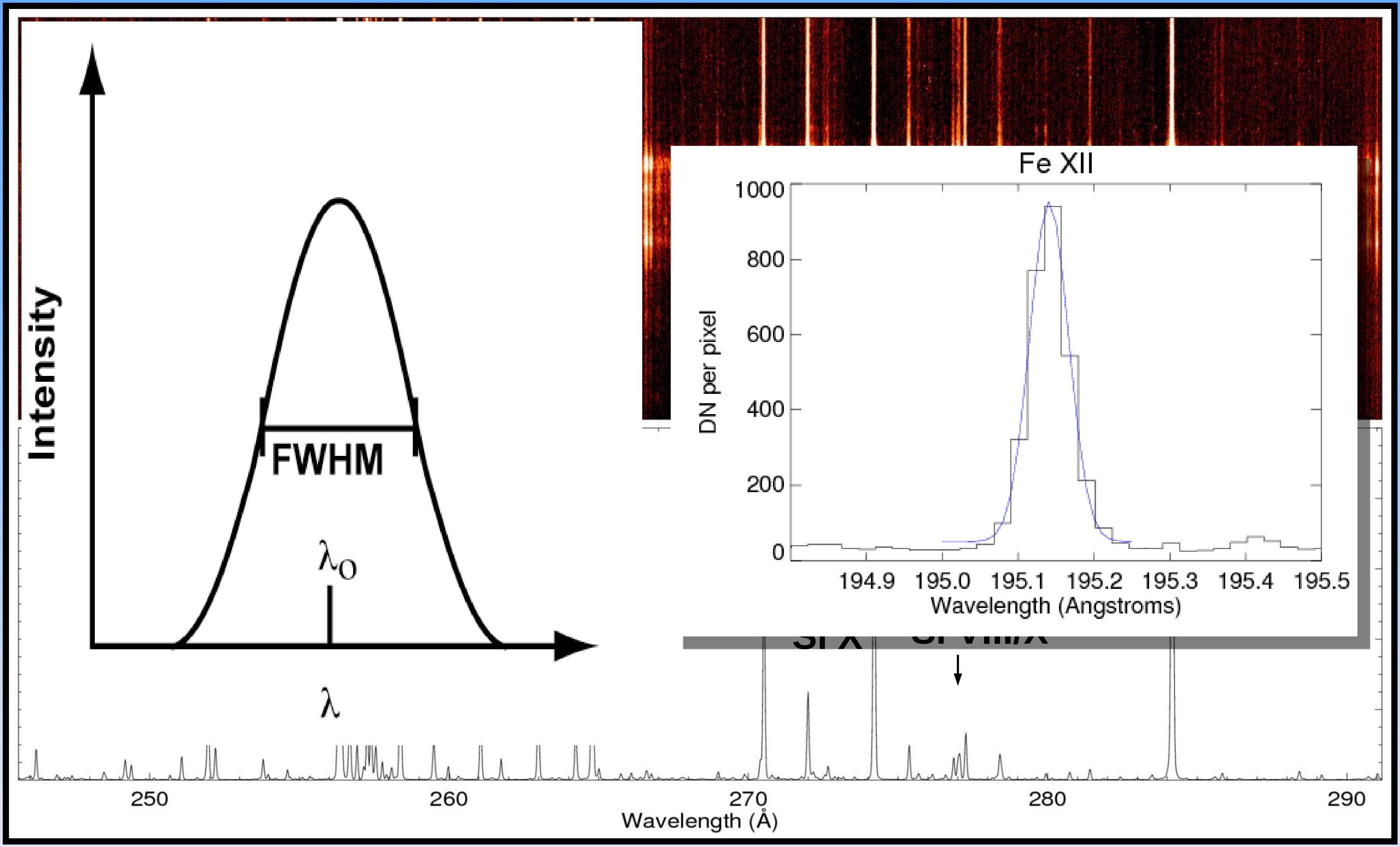
Matching spatial resolution from the photosphere into the corona allows us to determine energy deposition through-out the atmosphere.

IBIS Ca II 8542 Å (0.25”)
~5,500 K
IBIS Hα (0.25”)
~10,000 K
AIA 304 Å (1.2”)
~0.1 MK
AIA 171 Å (1.2”)
~1.0 MK

Images courtesy of Gianna Cauzzi

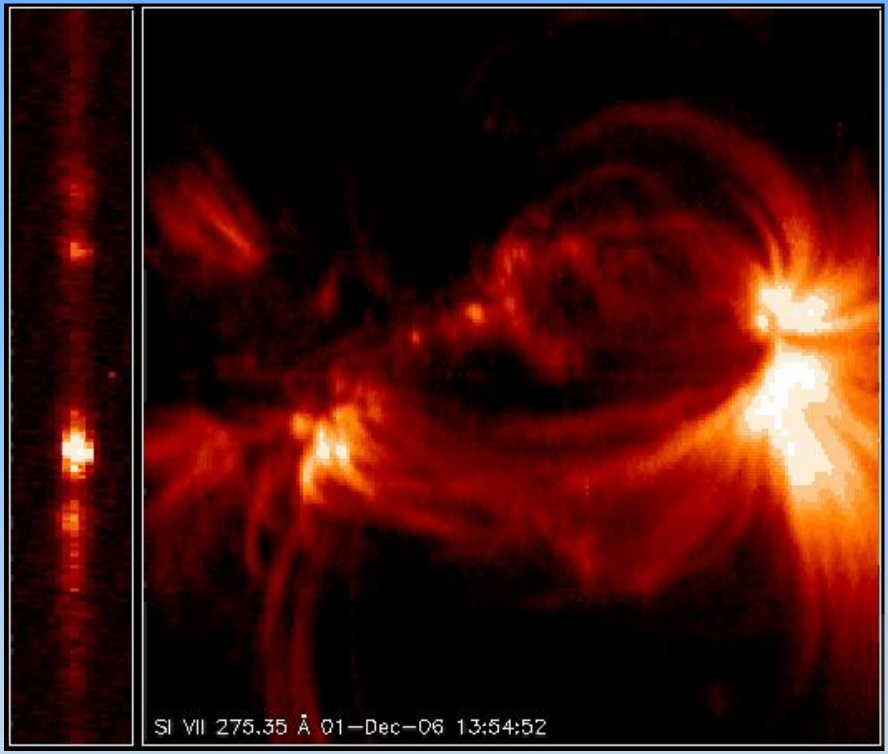
Extreme-ultraviolet Imaging Spectroscopy

Hinode/EIS Long Wavelength Band 1" Slit Spectrum

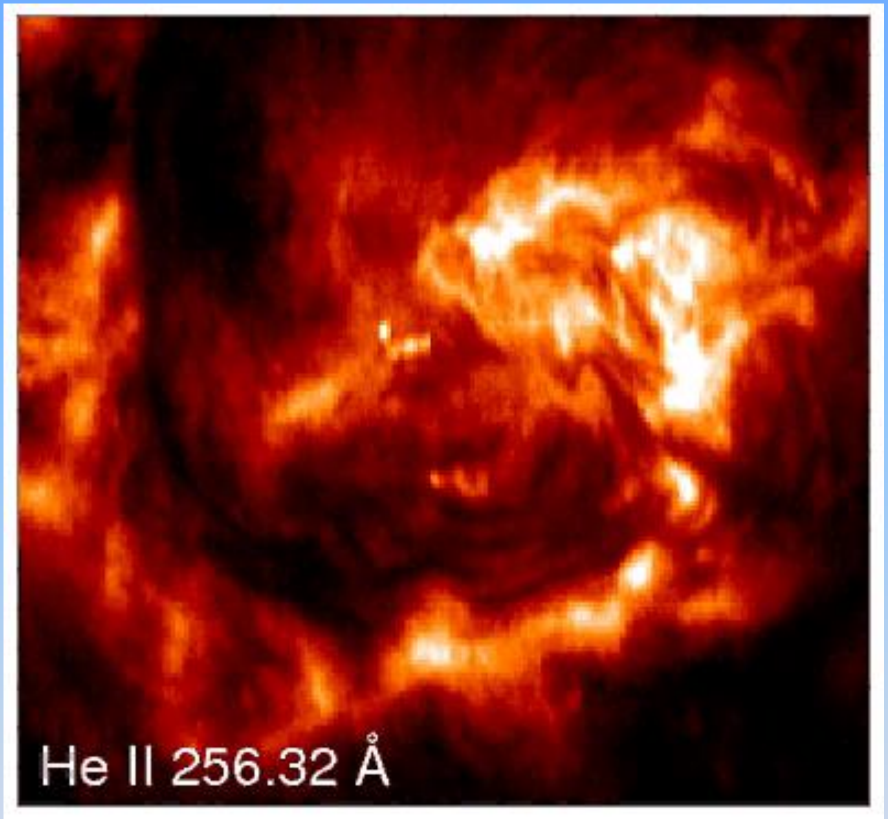


Hinode/EIS long wavelength band spectrum of an active region (center) flanked by quiet Sun regions. About 50% of the lines are new.

The Construction of an EIS Active Region Raster

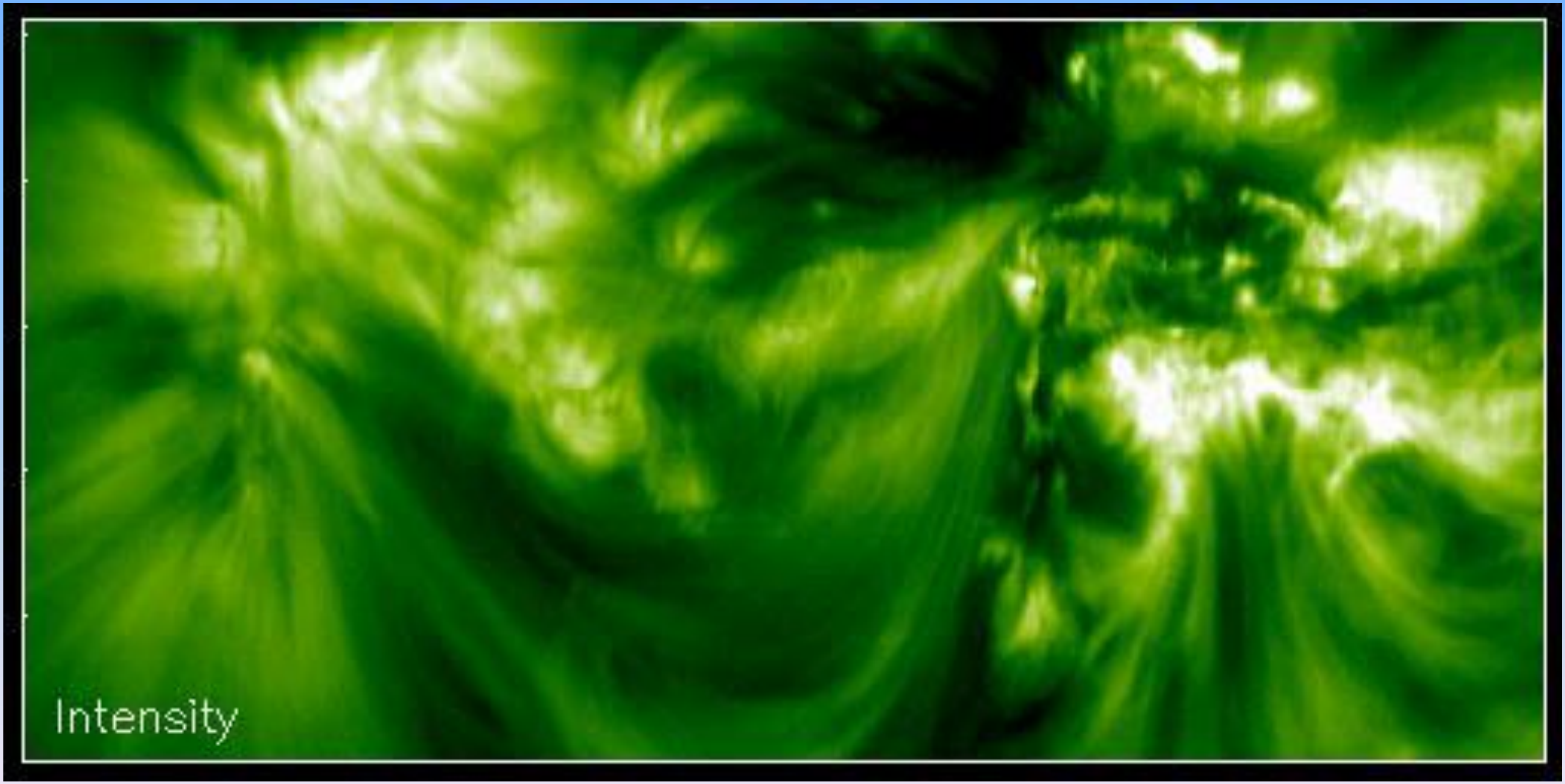


Movie showing motion of the EIS slit across a Si VII image of an active region. Non-thermal mass motions and bulk Doppler motions are being deduced from the slit images.



Movie showing an active region in intensities of spectral lines formed at different temperatures.

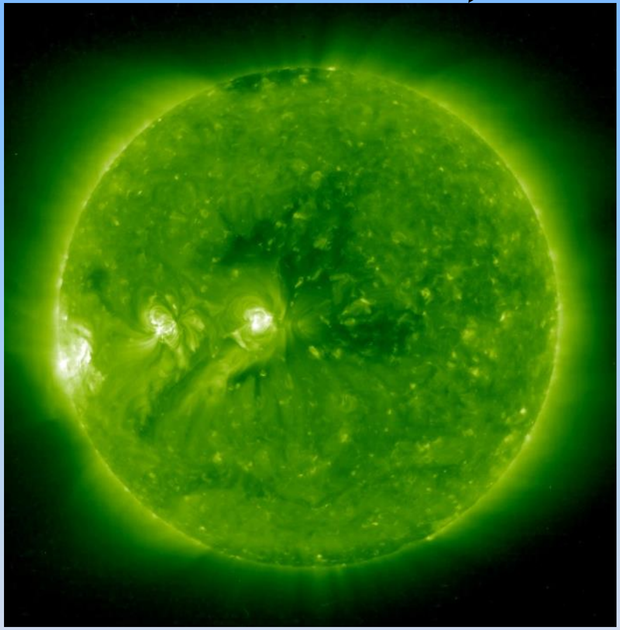
Active Region Dynamics with EIS Rasters



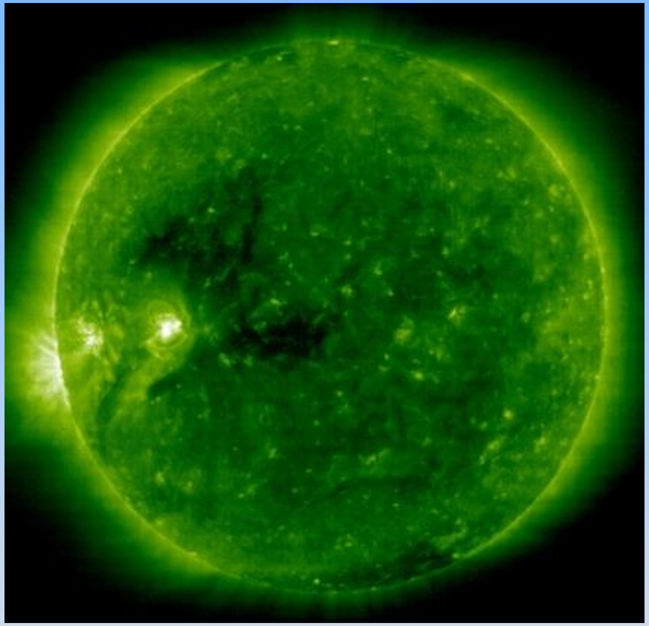
STEREO/SECCHI Extreme Ultraviolet Imager (EUVI)

In Space Weather, you get ahead by being behind.

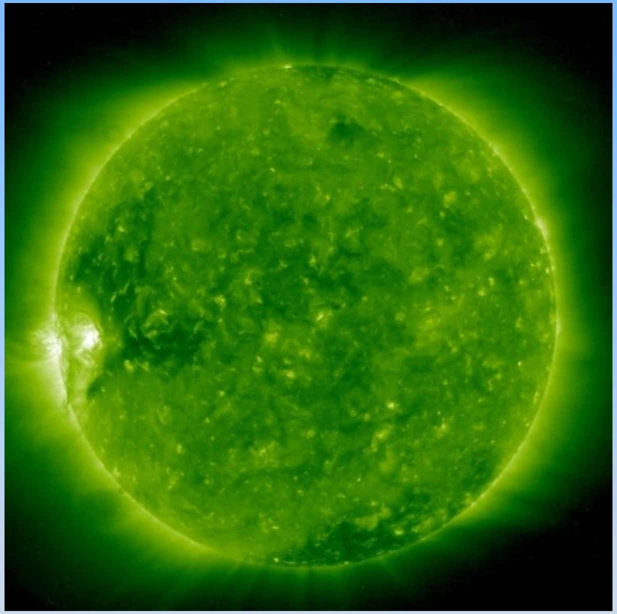
24 March 2008



195 Å image – behind

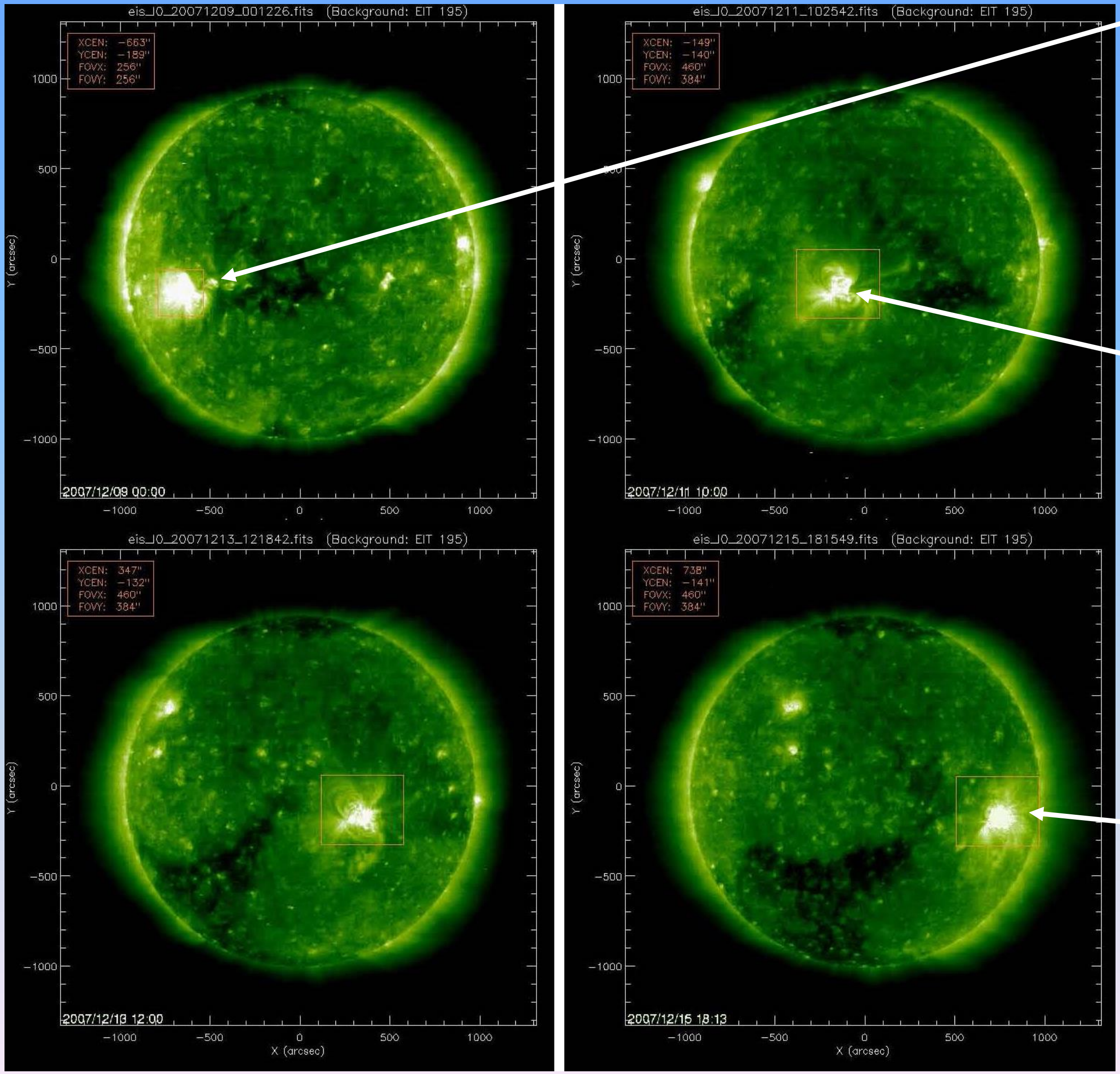


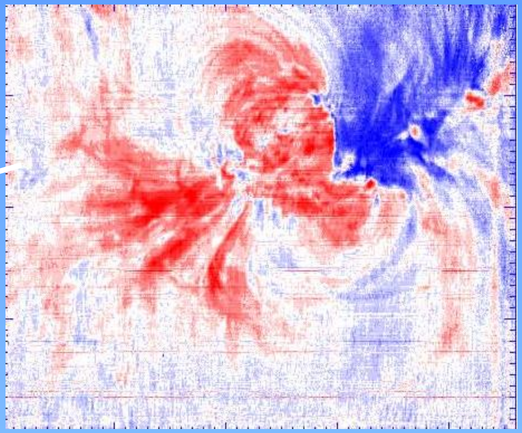
195 Å image – Sun-Earth line – *SOHO*/ EIT image

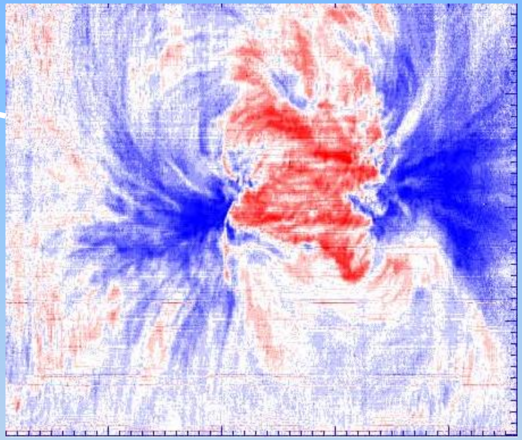


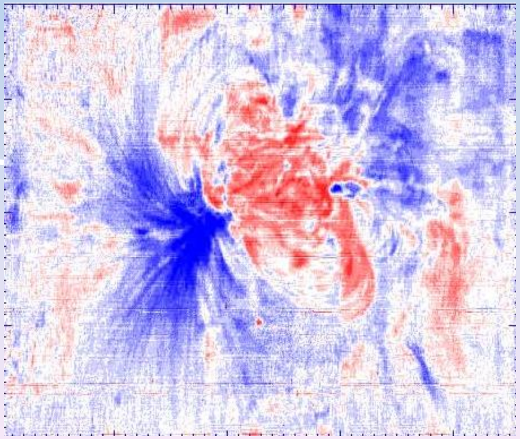
195 Å image – ahead

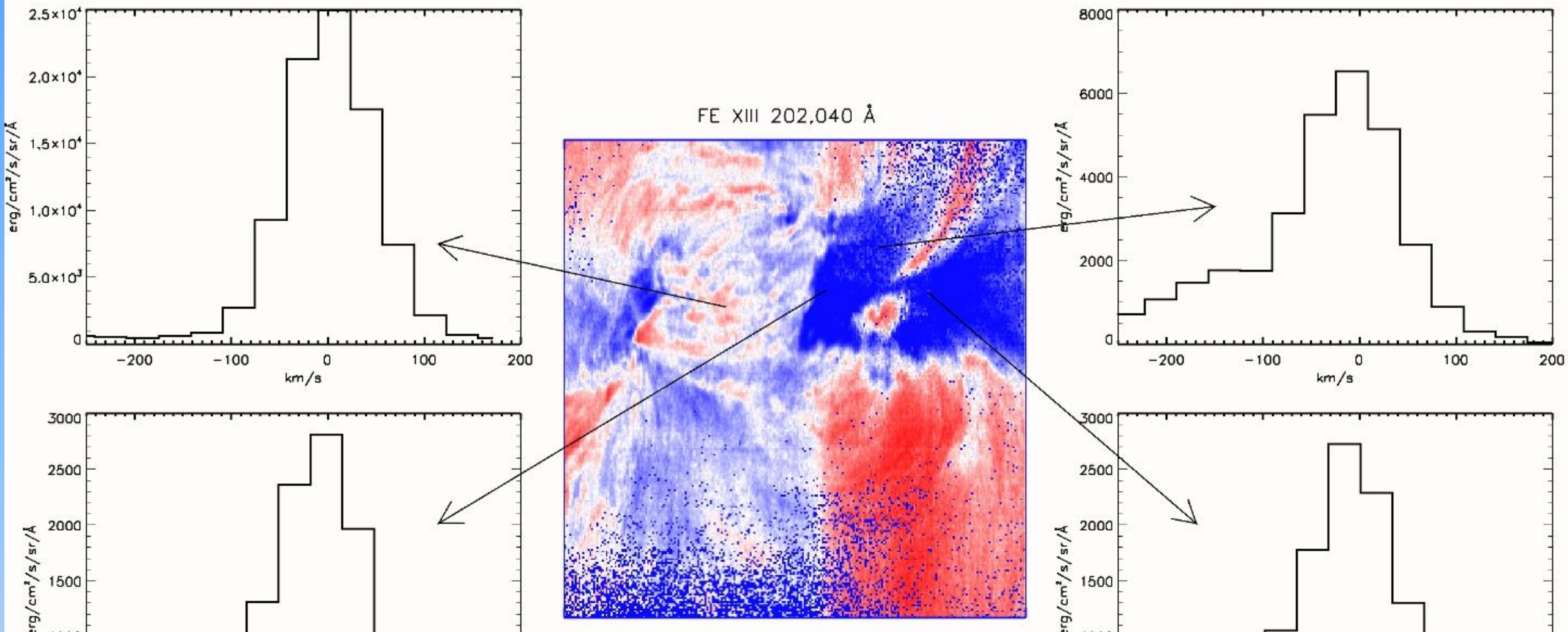
Active Region Flows – A Source of the Solar Wind?



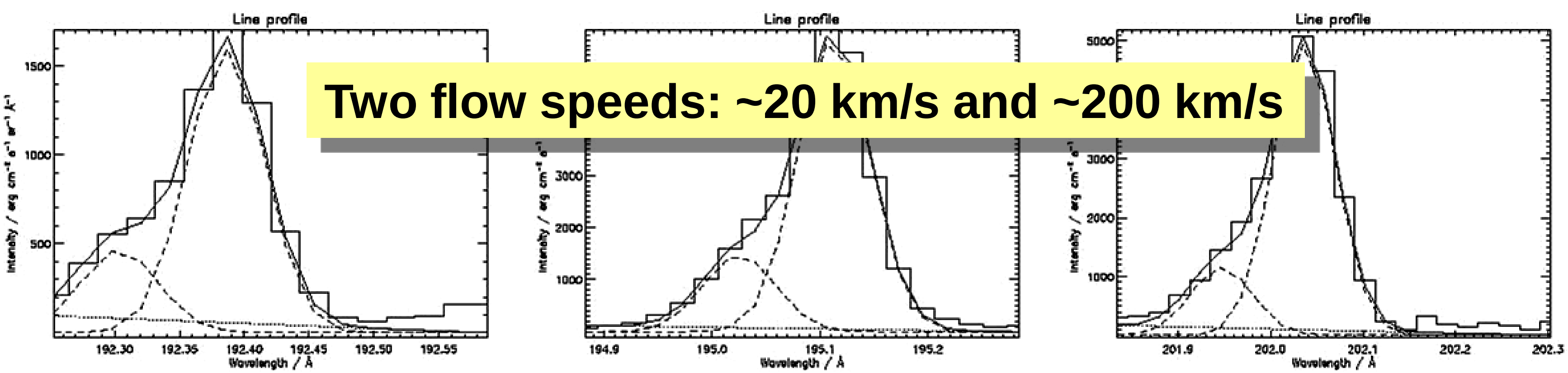








Two flow speeds: ~20 km/s and ~200 km/s

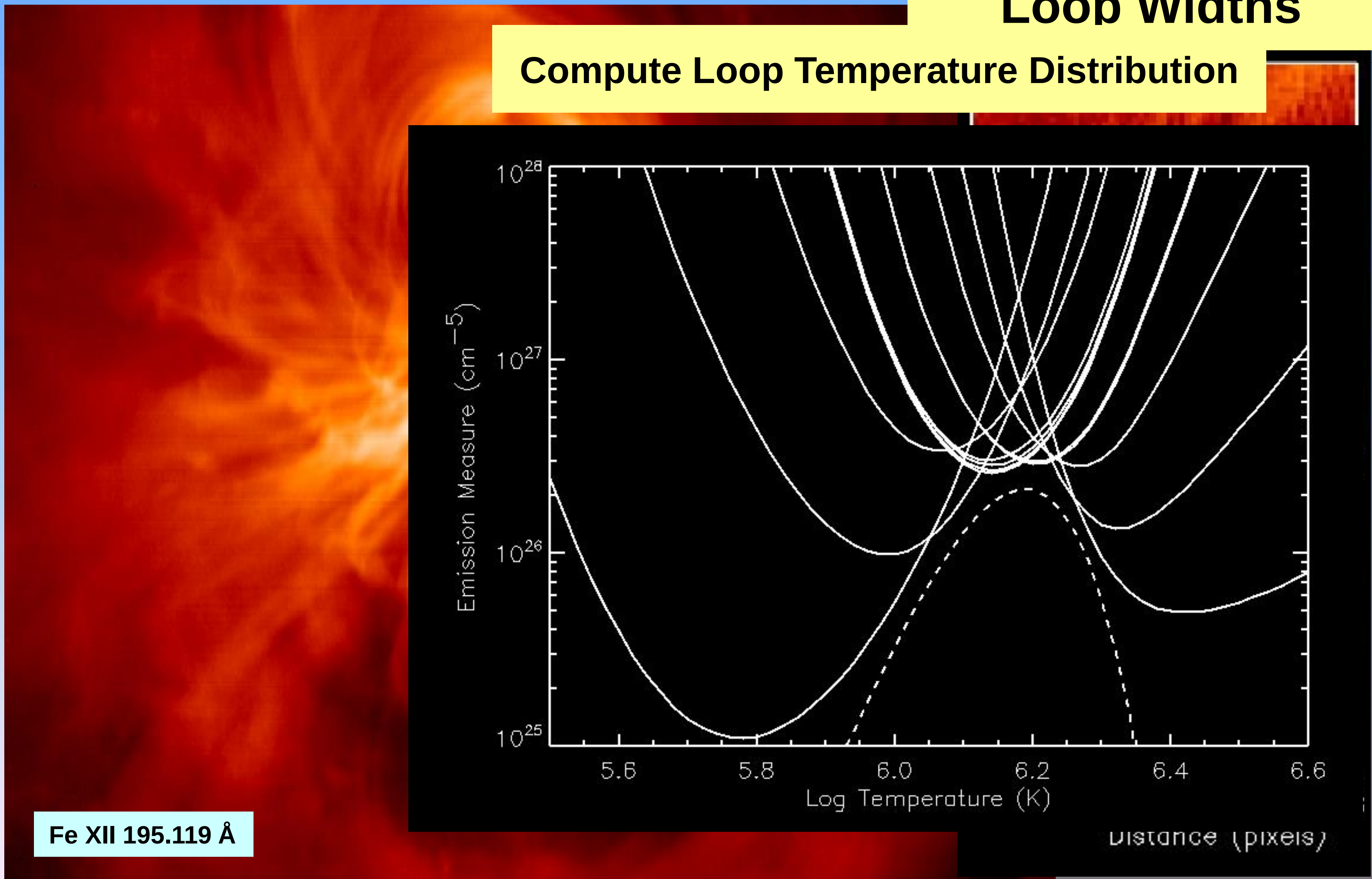


(a) Fe XII 192.39 Å (b) Fe XII 195.12 Å (c) Fe XIII 202.04 Å from Warren, Ugarte-Urra, Doschek, Brooks, & Williams 2008, 686, L131

EIS: Computing Loop Physical Parameters

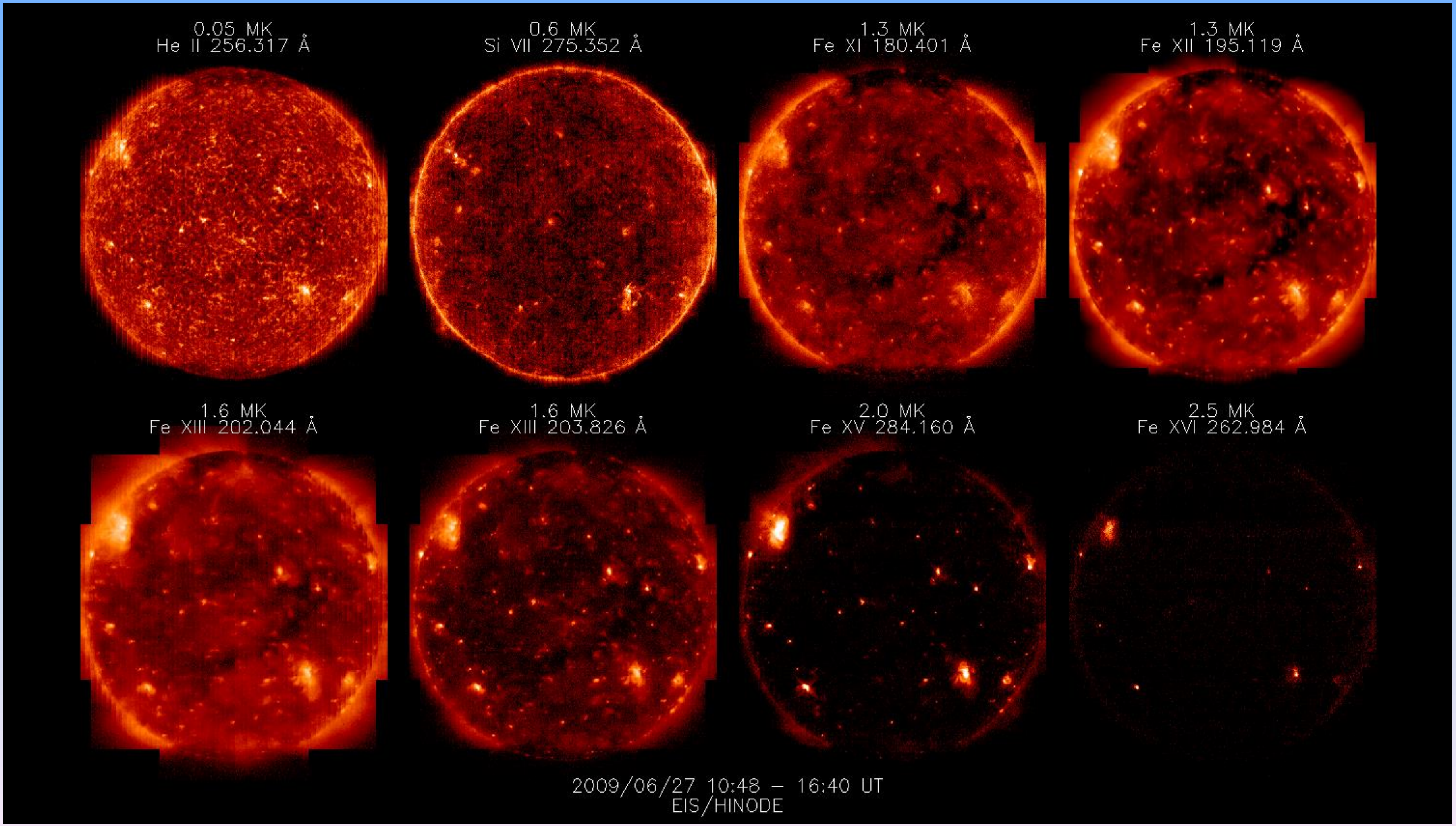
Compute Line Intensities and Loop Widths

Compute Loop Temperature Distribution



The Total Solar EUV/X-ray Irradiance

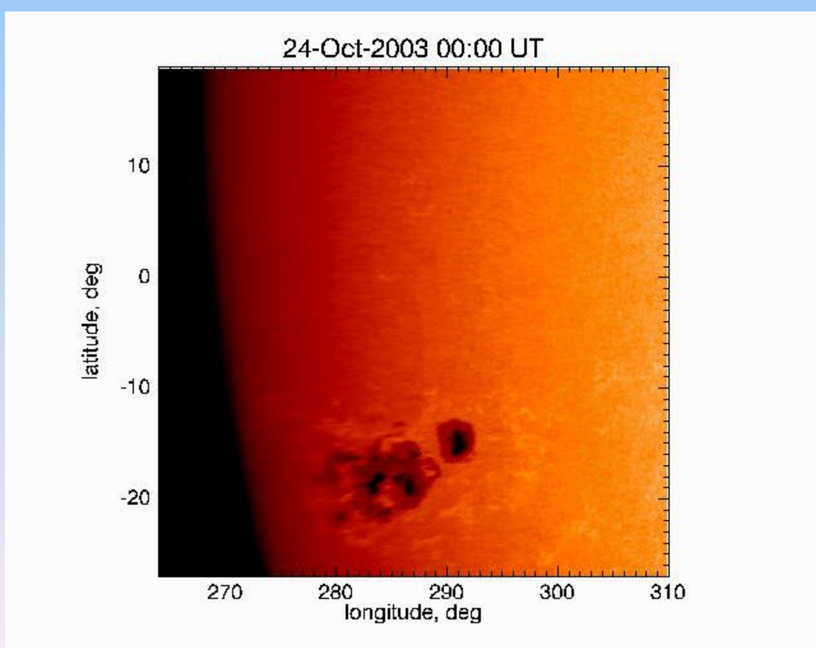
EIS Full Sun Slot Images for Solar Irradiance Measurements

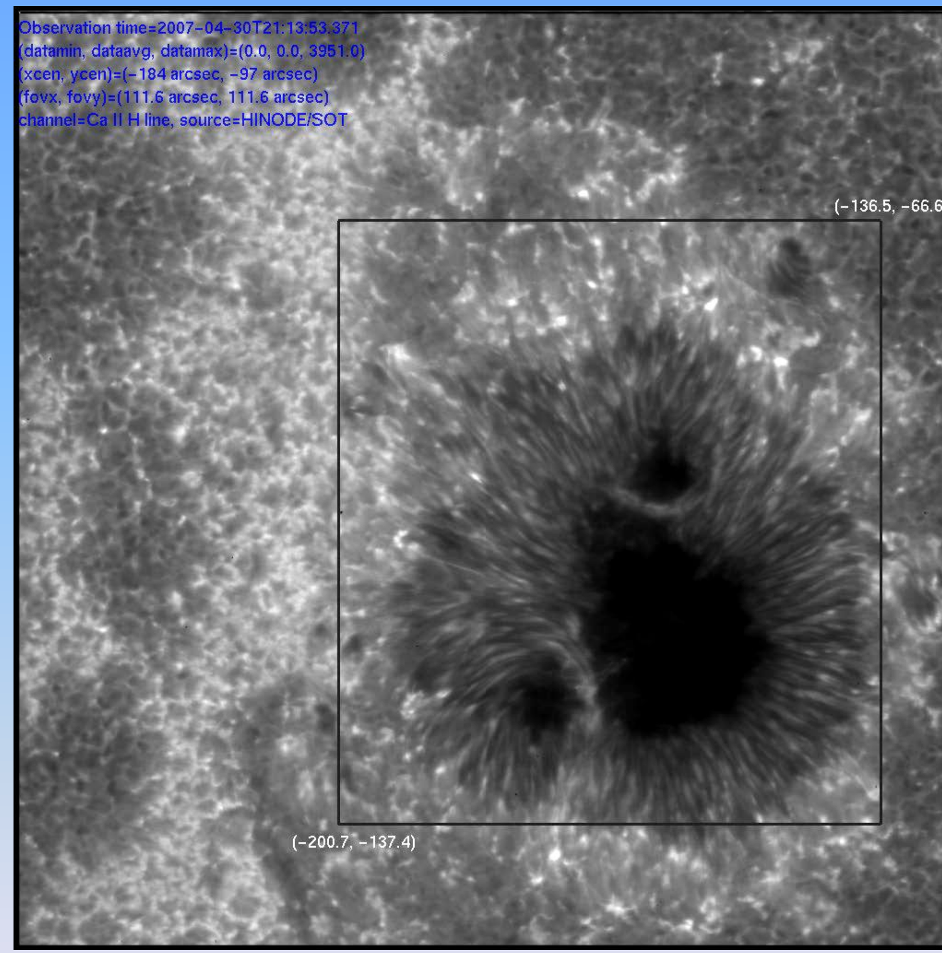


Ugarte-Urra & Warren 2009, private communication

What are sunspots? Can we predict when they will emerge from below the solar surface? And how would we do this?

- ***Sunspots***
  - **Formed by strong magnetic fields (a few thousand Gauss) that inhibit heating within them**
  - **Cooler than the surface by about 2000 K**
  - **Formed below the Sun's surface**
- ***The emergence of many sunspots produces an active region***
  - **Source of flares, coronal mass ejections**
  - **Modify solar irradiance**
- ***Acoustic waves are key for prediction***



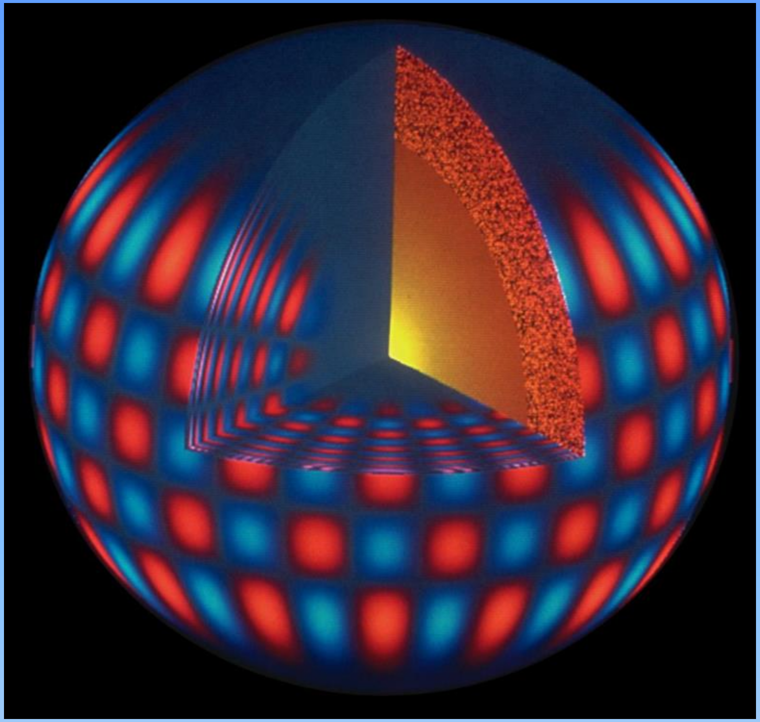


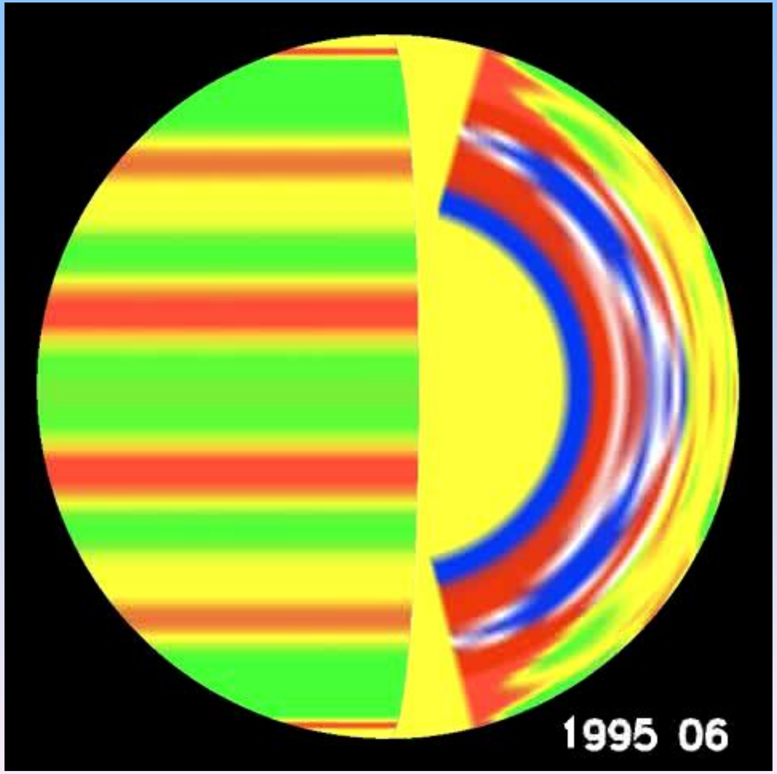
The main objective is to predict the emergence of strong magnetic flux.

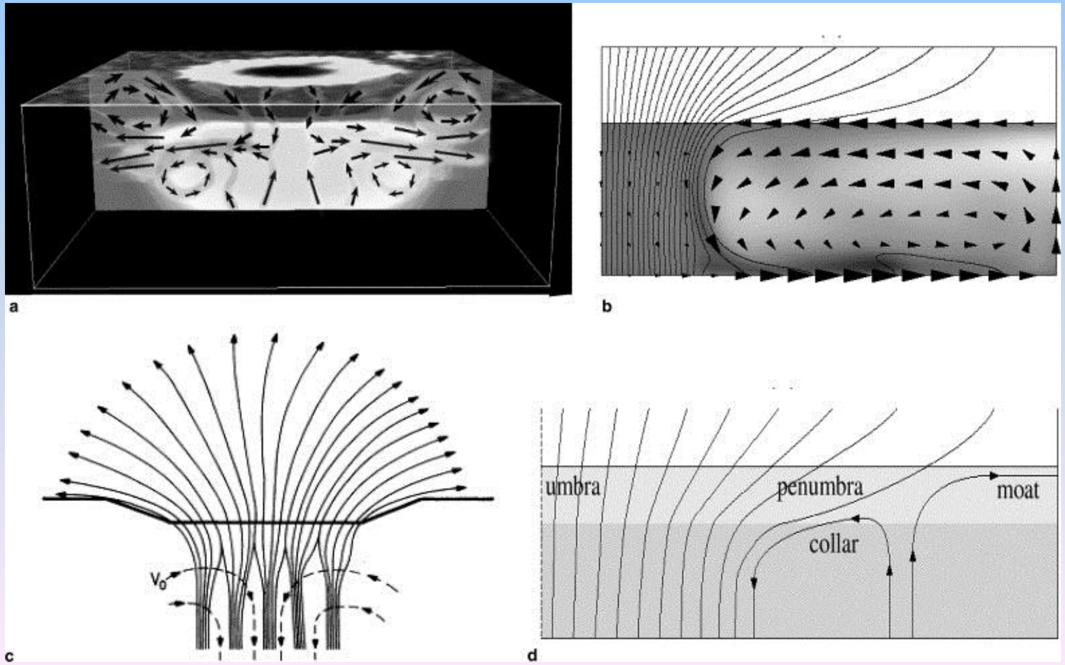
Helioseismology and its Potential

***Global Helioseismology*: study of acoustic standing waves that propagate throughout the Sun. Highly successful in understanding the solar interior.**

***Local Helioseismology*: study of acoustic traveling waves over a local solar area to predict flux emergence. A work in progress with limited success so far.**







Conclusions

- Since the beginnings of space research around 1960 our knowledge of the solar atmosphere has increased enormously.
  - X-ray to UV imaging techniques (multi-layer optics in particular)
  - Solar spectroscopy, particularly imaging spectroscopy
  - *In situ* measurements
- Theoretical research, e.g., numerical simulations (3D MHD, particle codes) have become more and more sophisticated, but the basic solar atmosphere heating mechanisms are still not conclusively known, although there is no lack of ideas and work on the subject!