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Exploring the Solar Wind with Ultraviolet Light

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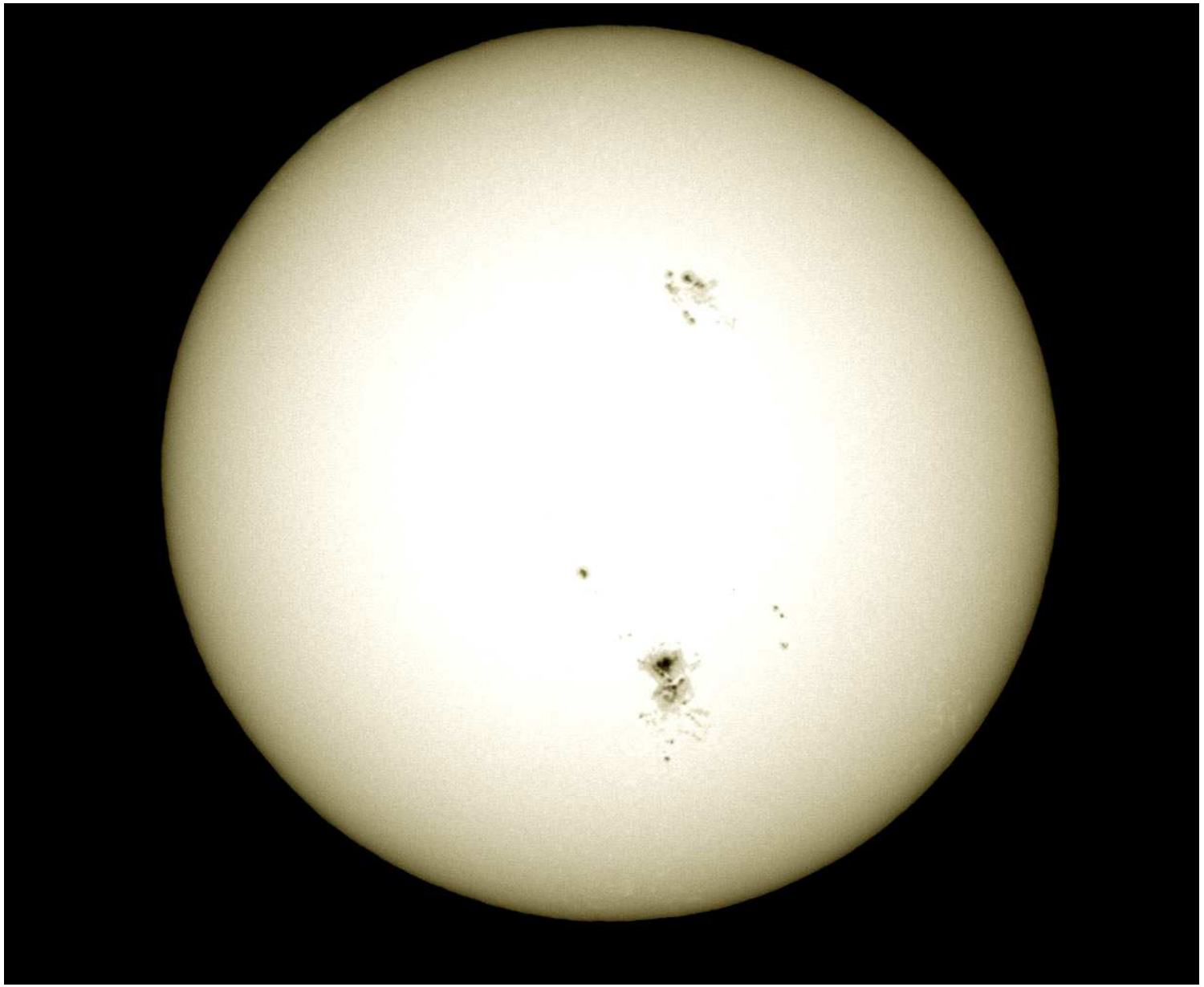
Background

- ⟶ Motivation and history
- ⟶ The “problem” of coronal heating

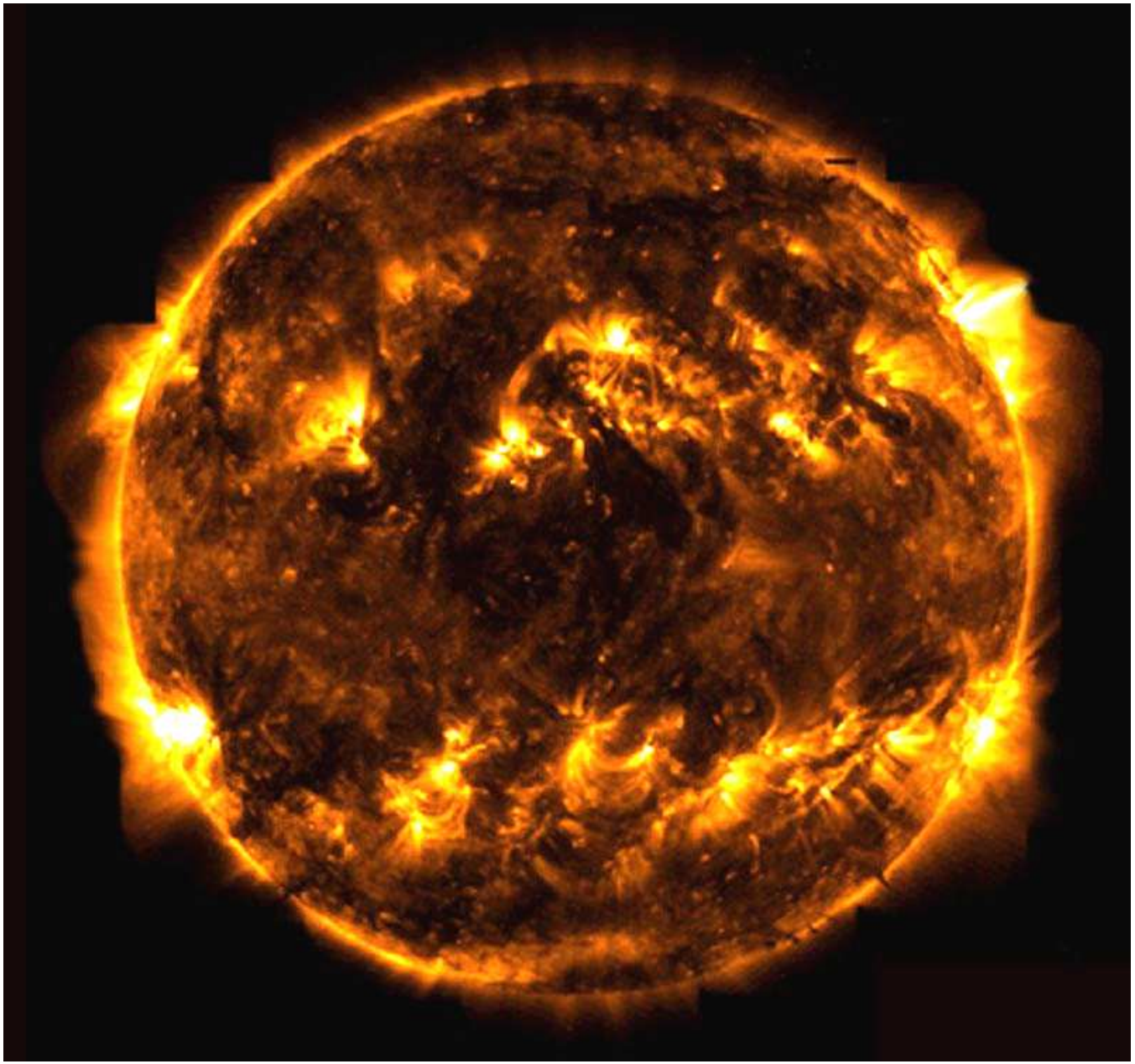
Modern Space-based Observations

- ⟶ SOHO (the Solar and Heliospheric Observatory)
- ⟶ UVCS (the Ultraviolet Coronagraph Spectrometer)
- ⟶ Ongoing results (1996–2003)

In visible light, the Sun appears calm and placid . . .



However, in ultraviolet light, the Sun is a much more chaotic place!

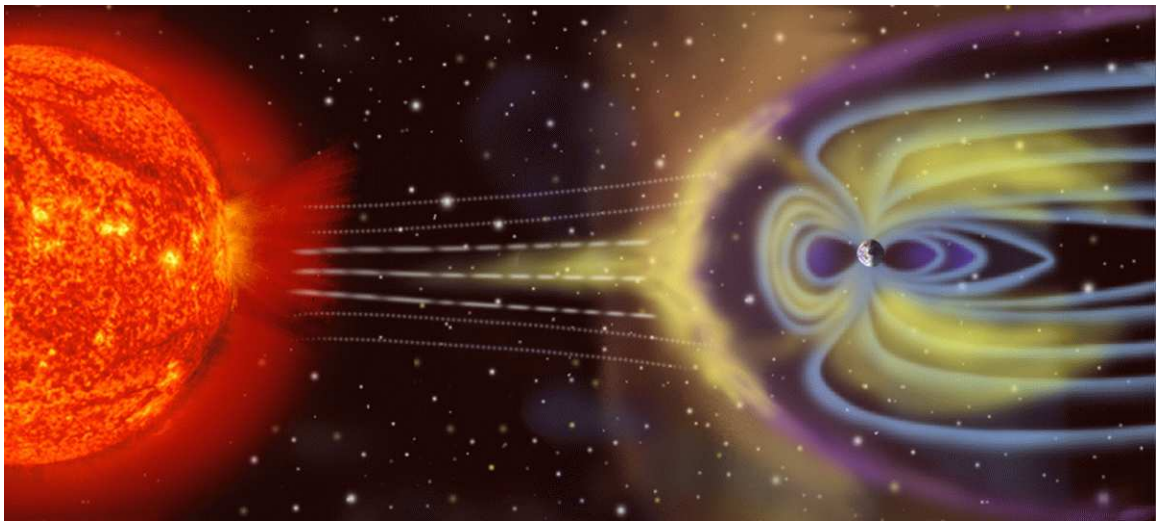


Solar Physics: A wide-angle view

- The Sun is the source of energy for life on Earth.
- The Sun is the closest example of a star.
- The Sun is a "laboratory without walls" for many basic processes in physics, at regimes (ρ, T, P) inaccessible on Earth!

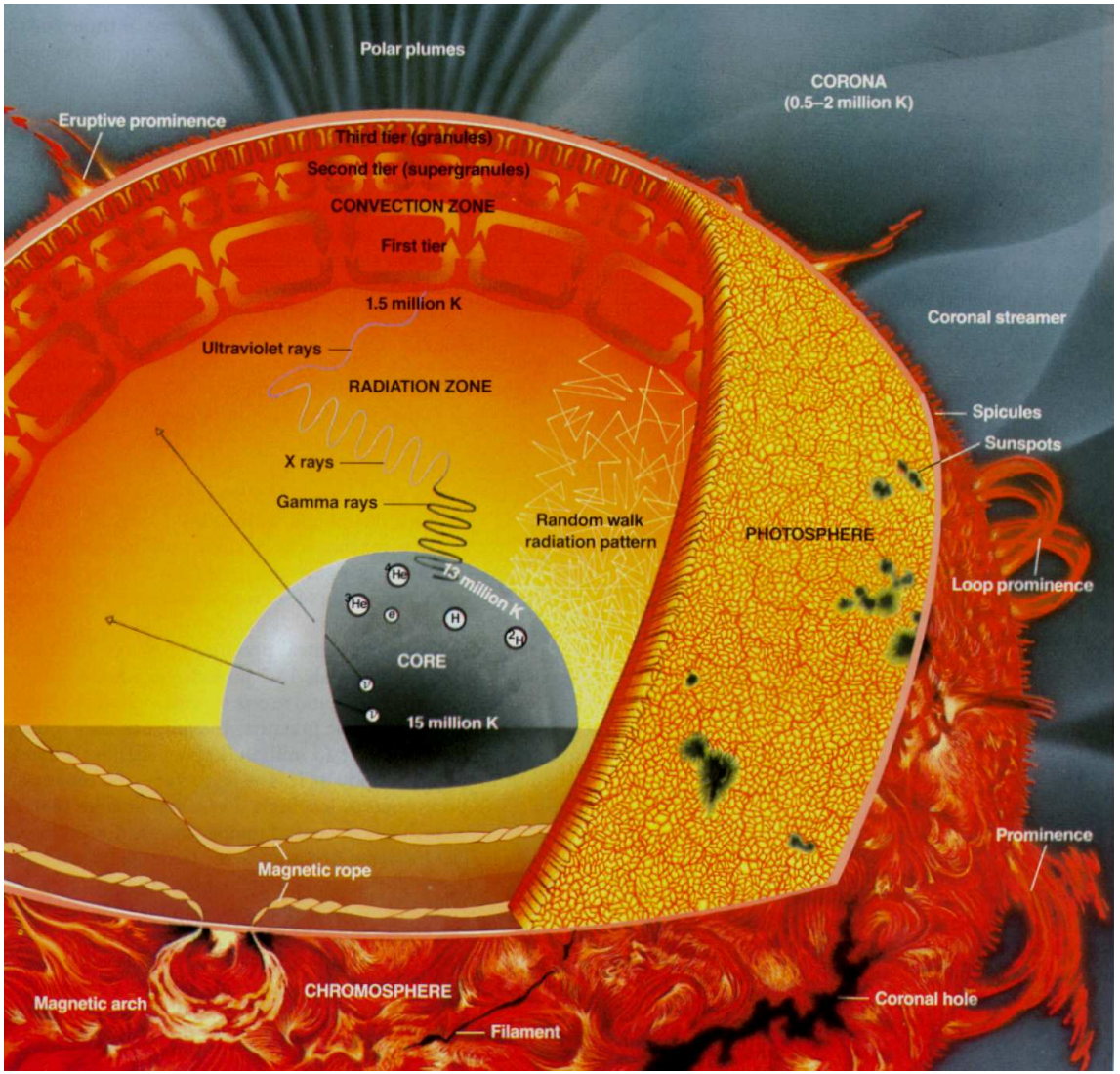
- **plasma physics**
- **nuclear physics**
- **non-equilibrium thermodynamics**
- **electromagnetic theory**

- **Space weather** can affect satellites, power grids, and the safety of orbiting astronauts . . . .



The Sun's Structure

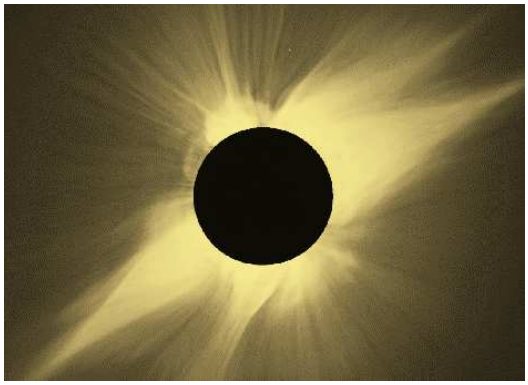
- **Core**
  - Nuclear reactions burn every second ~700 million tons of hydrogen into helium.
- **Radiation Zone**
  - Photons bounce around in the dense plasma, taking millions of years to escape the Sun.
- **Convection Zone**
  - Energy is transported by boiling, convective motions.
- **Photosphere**
  - Photons stop bouncing, and start escaping freely.
- **Corona**
  - Outer atmosphere where the gas is heated from ~5800 K to ***several million K!***



The Sun's Outer Atmosphere

The solar photosphere exhibits a ~blackbody temperature of 5800 K.

The solar corona:

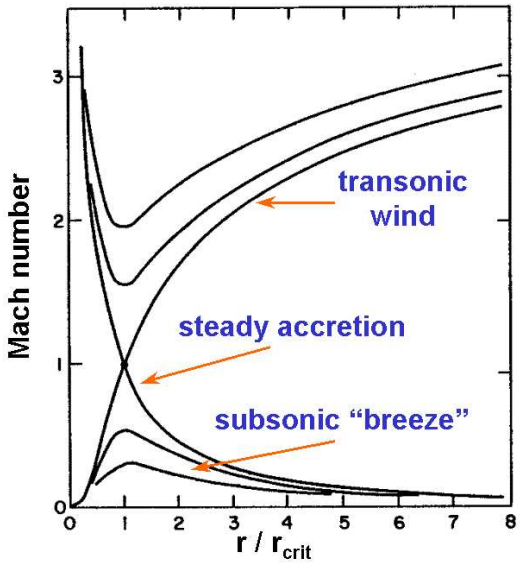


- 1870s: unknown emission lines; a new element called "*coronium?*"
- 1930s: Lines were identified as highly ionized ions: Ca^{12+}, Fe^{9+} to Fe^{13+}

$T > 1$ million K

The solar wind:

- 1860s to 1950s: evidence builds for outflowing plasma in the solar system (geomagnetic storms, comet tails)
- 1958: E. N. Parker proposed that the hot corona provides enough gas pressure to counteract gravity!
- 1962: *Mariner 2* provided first direct confirmation of the supersonic solar wind.

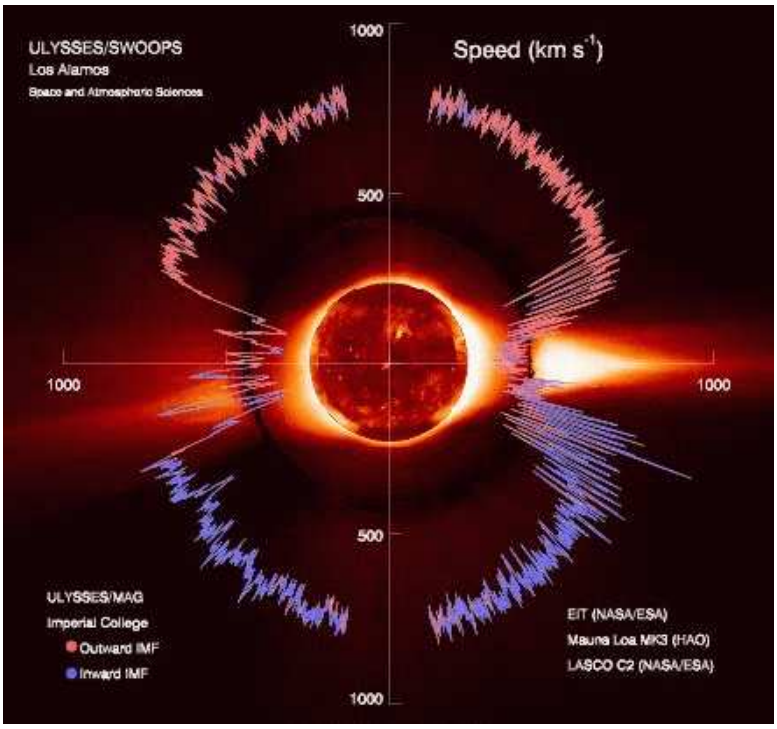


We still have not uniquely identified the physical processes that heat the corona and accelerate the solar wind . . . .

Exploring the Solar Wind (1970s to present)

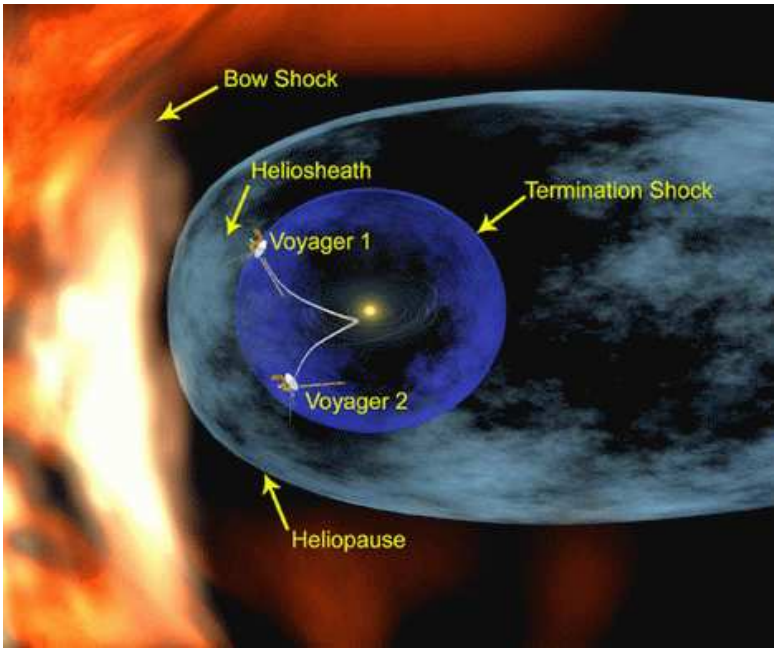
- Various space missions have pushed out the boundaries of the "known" solar wind. For example . . .
- **Helios 1 & 2** (probed between the orbits of Mercury → Earth)
- **Ulysses**
  1 to 5 AU,
  N to S poles

  (at sunspot min., *fast* wind over poles; *slow* wind over equator)



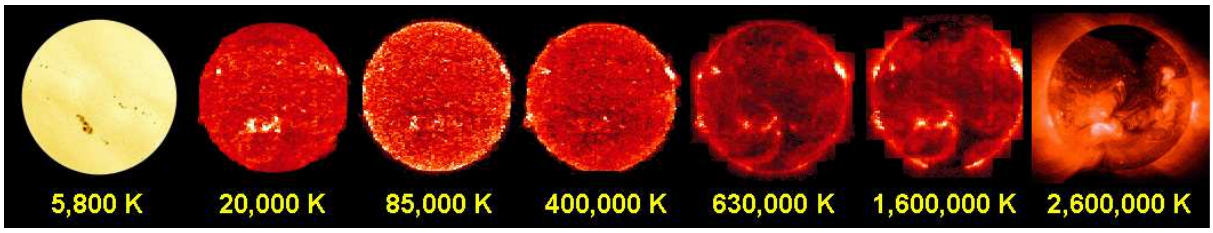
- **Voyager 1 & 2**
  1 to 90+ AU

  (recently found evidence for the "termination shock")



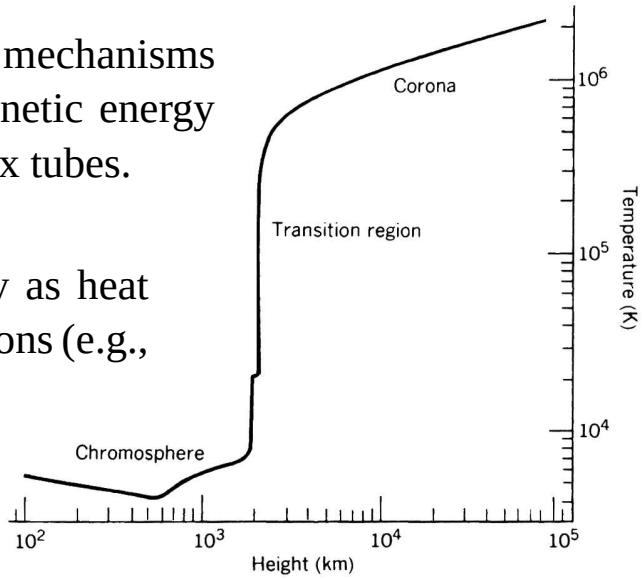
Coronal Heating Problems

- We still do not understand the physical processes responsible for heating the base of the corona ($10^4 \rightarrow 10^6$ K) . . .

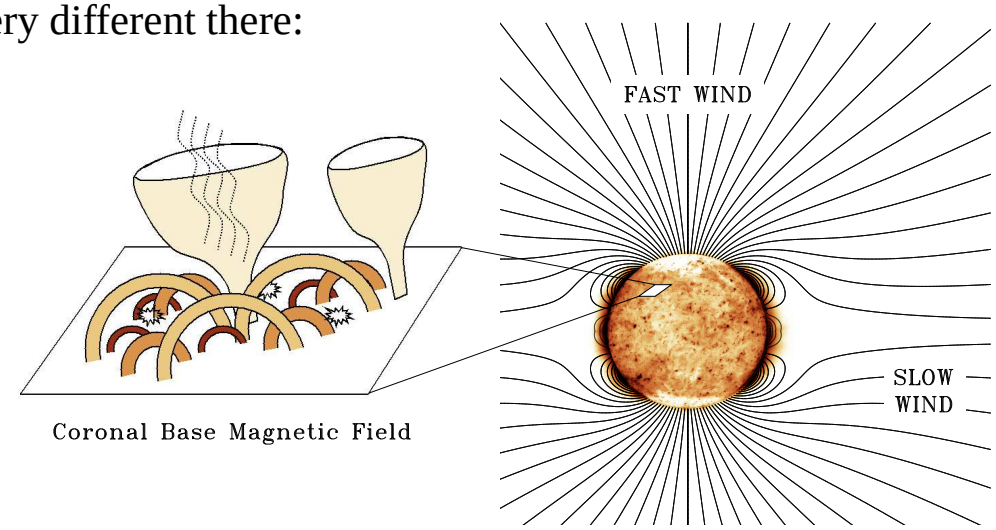


- Most suggested energy deposition mechanisms involve storage and release of magnetic energy in **small-scale** twisted or braided flux tubes.

  Dissipation of the magnetic energy as heat probably occurs via Coulomb collisions (e.g., viscosity, resistivity, conductivity).



- Additional energy deposition is required at larger distances, but the physics is very different there:

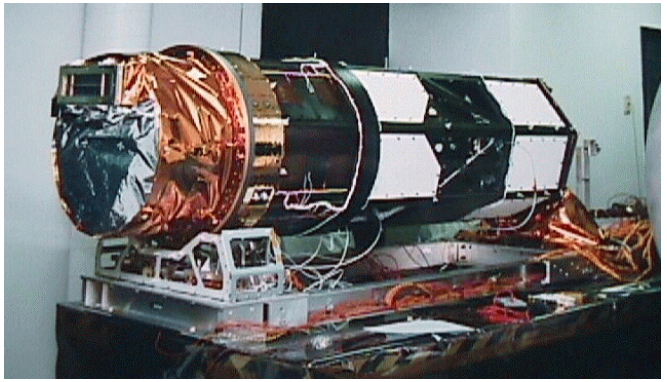


The SOHO Mission

SOHO (the Solar and Heliospheric Observatory) was launched in December 1995 with the goal of solving long-standing mysteries about the Sun:

- *Solar Interior: What are its structure and dynamics?*
- *Corona: Why does it exist and how is it heated?*
- *Solar Wind: Where is it accelerated and how?*

The Ultraviolet Coronagraph Spectrometer (UVCS), one of the 12 instruments on SOHO, studies the extended solar corona where the solar wind is formed.

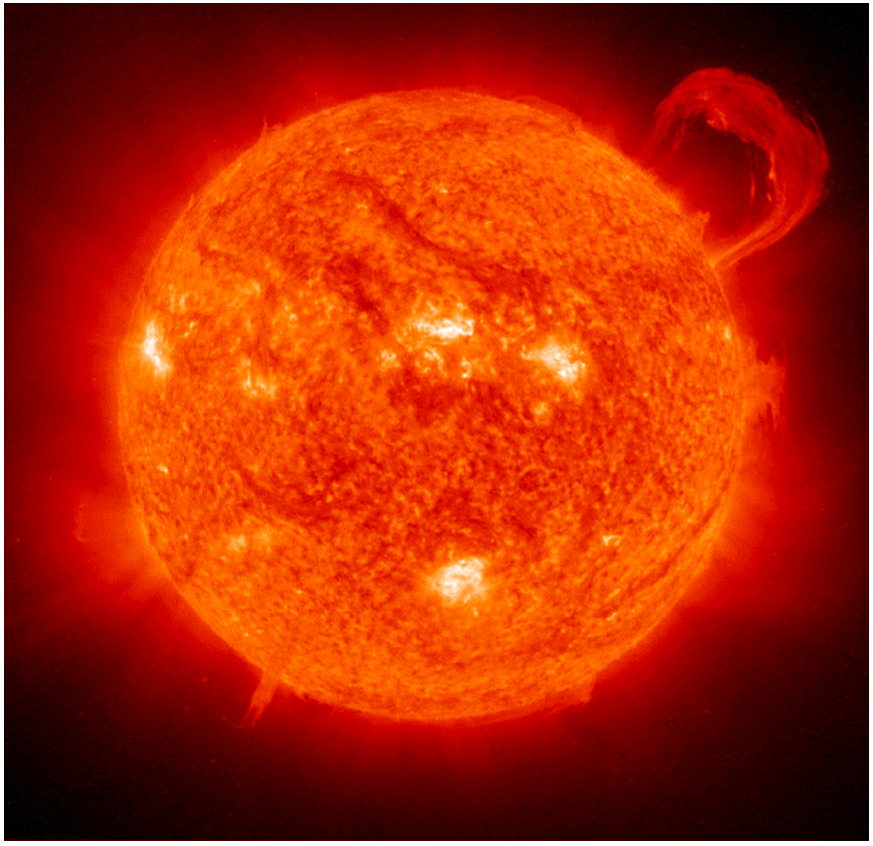


UVCS blocks out the bright disk of the Sun, in effect creating an "artificial eclipse," to be able to observe the much fainter ultraviolet light from the extended corona.

Example Images from SOHO . . .

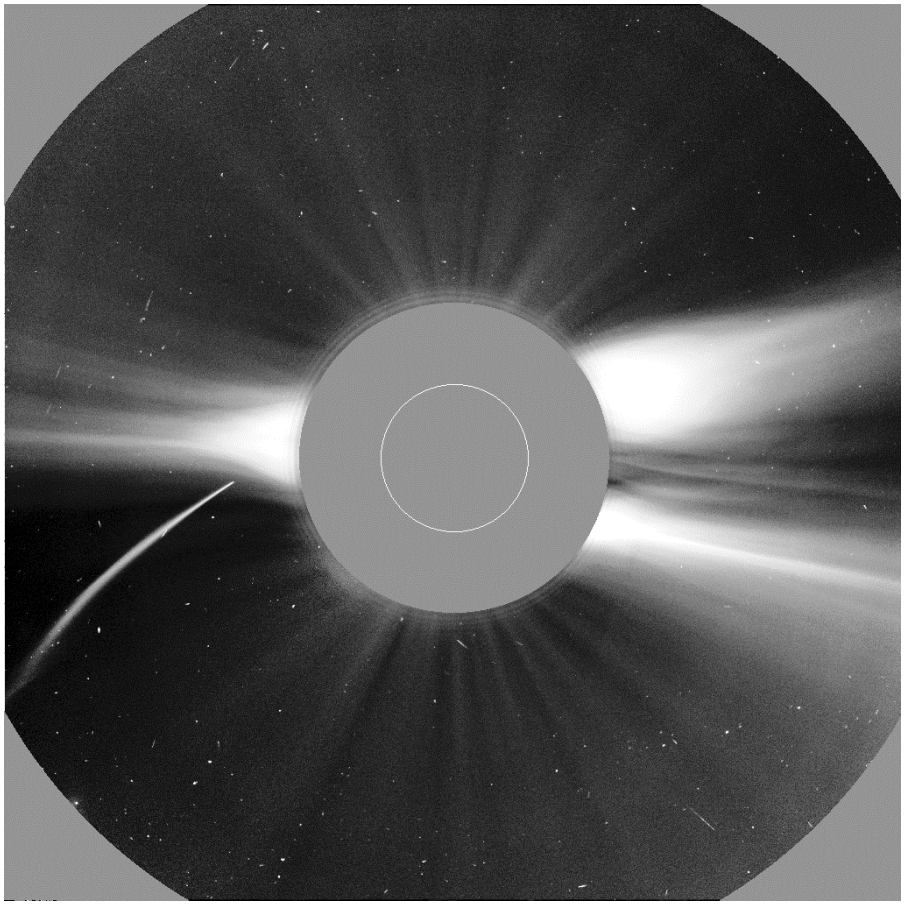
EIT

(Extreme-ultraviolet Imaging Telescope)



LASCO

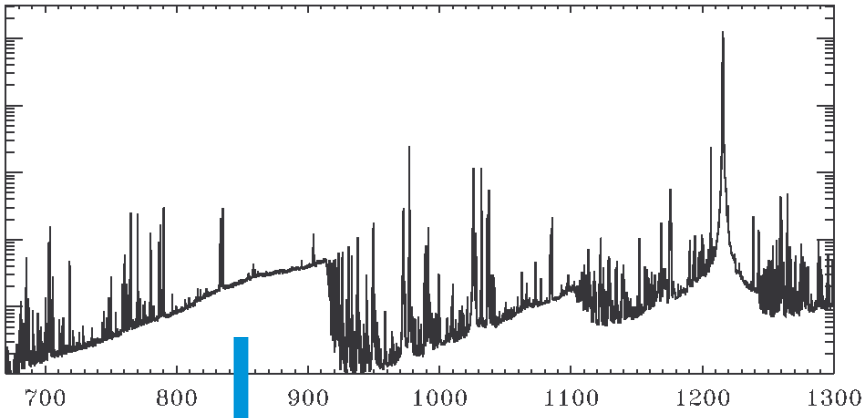
(Large-Angle Spectroscopic Coronagraph)

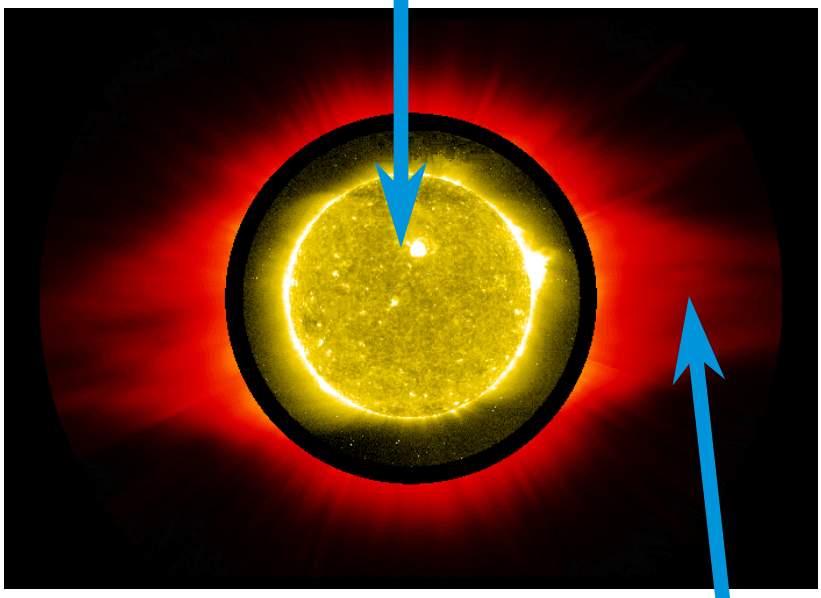


Example Spectroscopy from SOHO . . .

SUMER

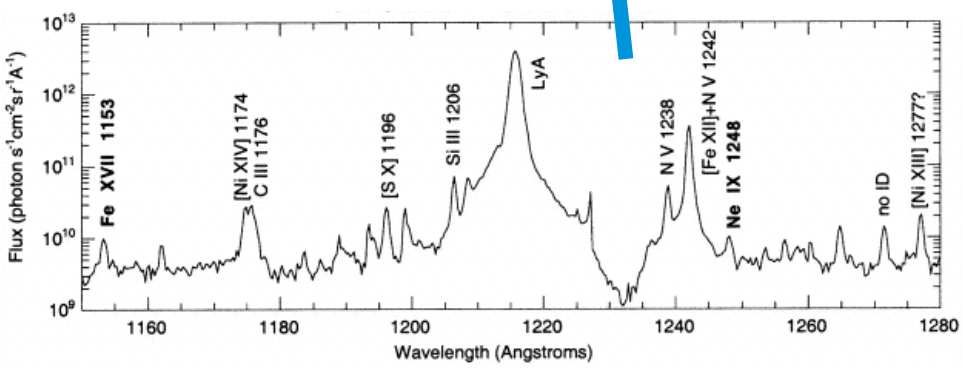
(Solar UV Measurements of Emitted Radiation)





UVCS

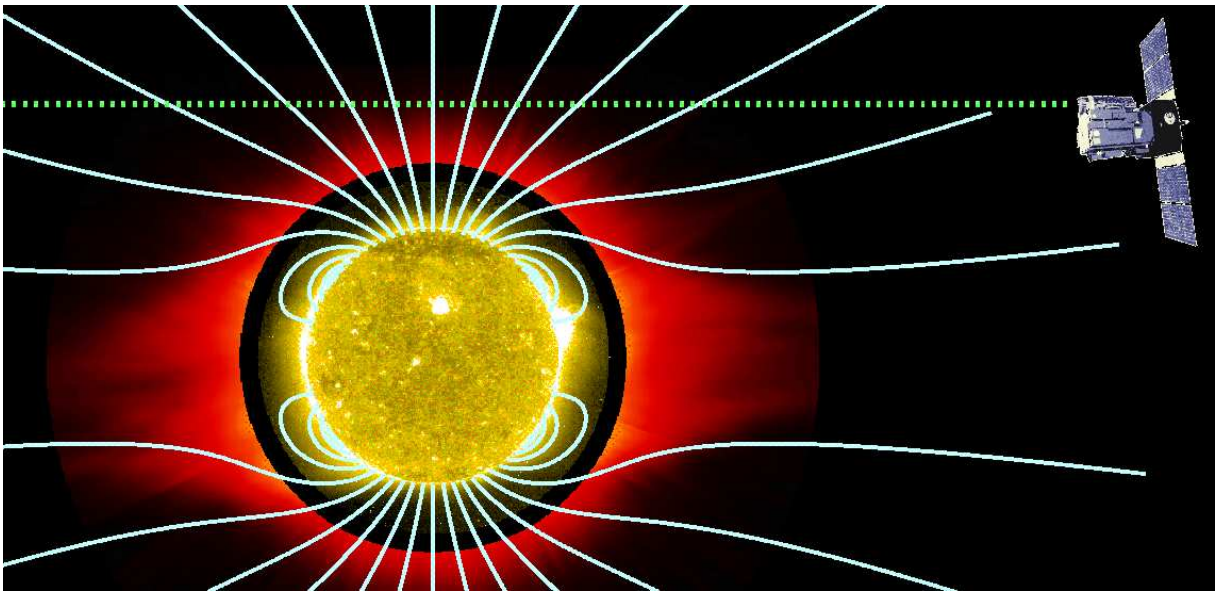
(Ultraviolet Coronagraph Spectrometer)



The UVCS Instrument and Mission

⋆ **Motivation:** measure plasma properties of hot ($> 10^6$ K) protons, electrons, and ions as they **accelerate.** (Too near Sun for *in situ*.)

1979–1995: H I Lyα measured with rockets, Spartan 201
1996–present: dozens of lines measured with UVCS/SOHO



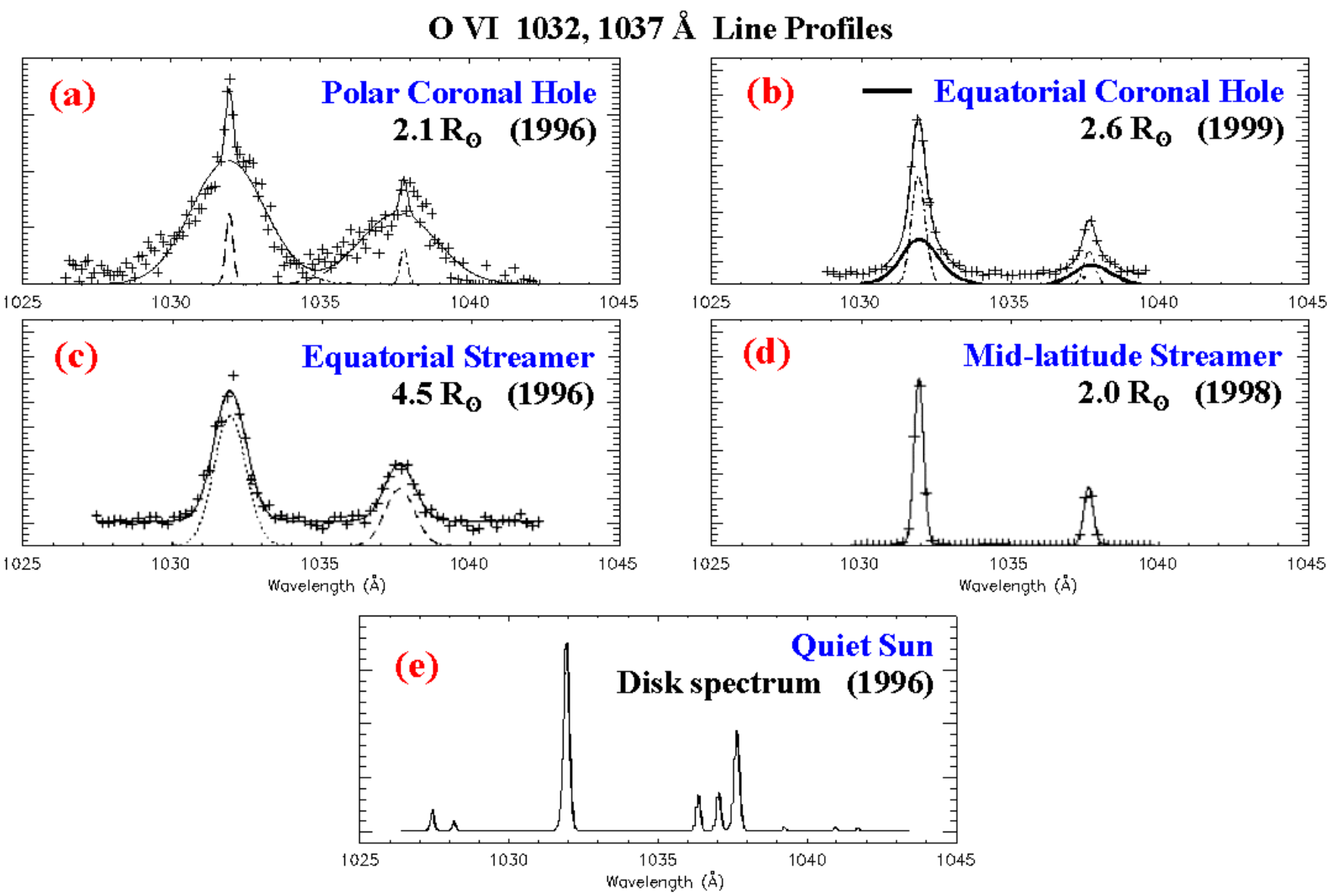
⋆ Occultation of the solar disk is required because the extended corona is **6** to **10** orders of magnitude less bright than the disk.

⋆ The scattered photon emission is usually **optically thin:** some degree of "deconvolution" is required to make sense of the data.

⋆ **Simplest diagnostics:**

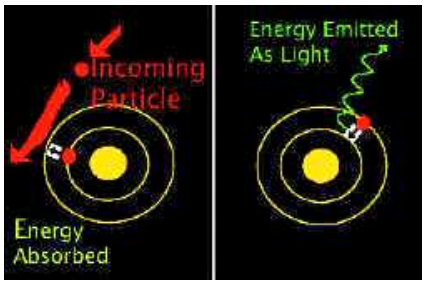
→ If lines are **Doppler shifted** with respect to their known (rest-frame) wavelengths, there is net motion **along** the line-of-sight.

→ The **widths** of the ∼Gaussian lines provide a near-direct measurement of the temperature of the plasma (more specifically: the projected velocity distribution along the line-of-sight).


O VI 1032, 1037 Å Line Profiles
(a)
Polar Coronal Hole
2.1 R⊙ (1996)
(b)
Equatorial Coronal Hole
2.6 R⊙ (1999)
(c)
Equatorial Streamer
4.5 R⊙ (1996)
(d)
Mid-latitude Streamer
2.0 R⊙ (1998)
(e)
Quiet Sun
Disk spectrum (1996)
1025
1030
1035
1040
1045
Wavelength (Å)

How are Emission Lines Produced?

There are two major ways of producing spectral line photons in the extended corona, but they share a general absorption/emission mechanism:



⋆ **Electron impact excitation → de-excitation**

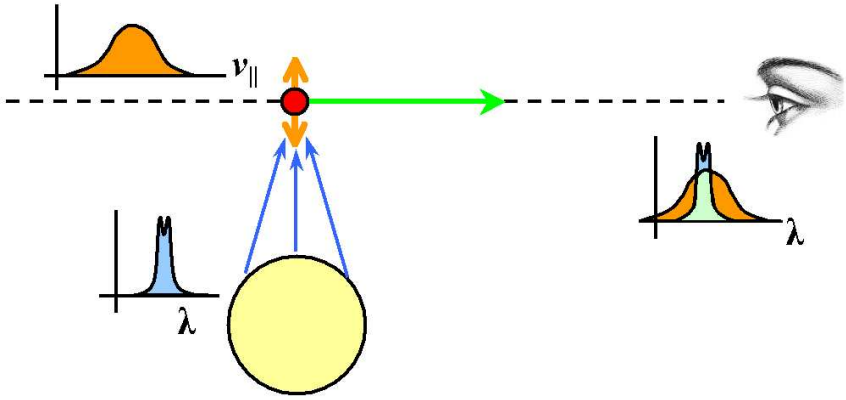
⇒ Profile width depends on line-of-sight velocity distribution

⇒ Total intensity $\propto n_e\, n_{atom}\, q(T_e)$

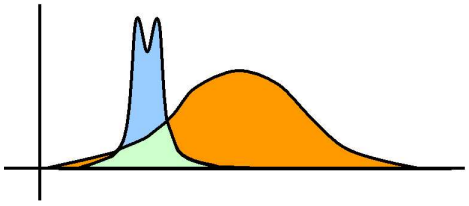
⋆ **Resonant scattering of photons from solar disk**

⇒ Profile width depends on line-of-sight velocity distribution

⇒ Total intensity depends on the **radial** component of the velocity distribution:



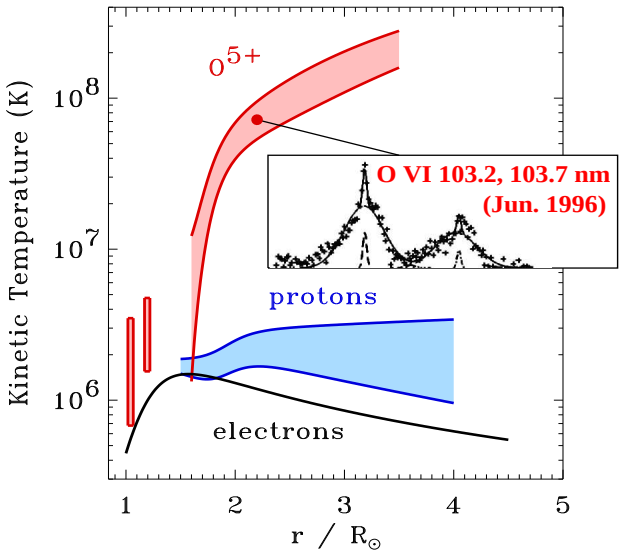
⇒ If atoms are **flowing** in the same direction as the incoming disk photons, the overlap is smaller and fewer photons get scattered **("Doppler dimming").**



UVCS results: fast solar wind (1996–1997)

- Detailed analysis of line profiles and intensities allows us to deduce that H^0 and O^{5+} have **anisotropic** velocity distributions between 1.5 and 4 $R_\odot$ in coronal holes. For O^{5+}, $T_\perp / T_\parallel \approx$ 10–100.

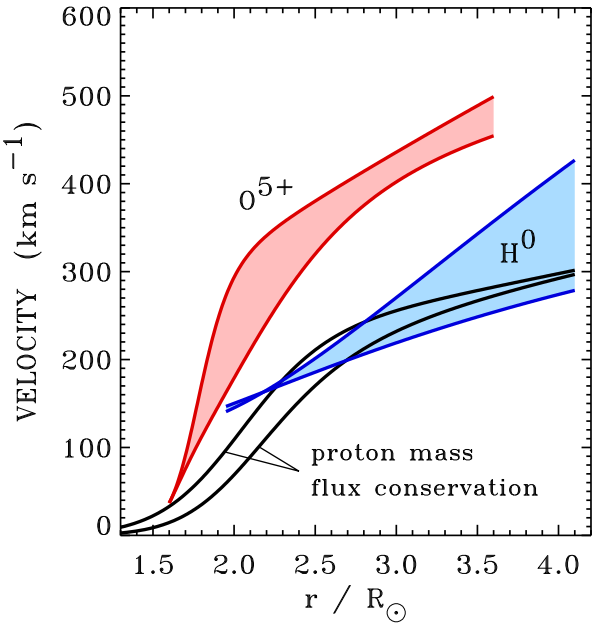
- For O^{5+}, $T_\perp$ approaches **200 million K** at 3 $R_\odot$. The kinetic temperatures of O^{5+} and Mg^{9+} are much greater than mass-proportional when compared with hydrogen.



- "Doppler-dimmed" line intensities are consistent with the **outflow speed** for O^{5+} being larger than the outflow speed for H^0 by as much as a factor of **two.**

(**Mass flux conservation** allows the bulk outflow speed to be predicted if we know the density, flux tube area, and total mass flux at 1 AU.)

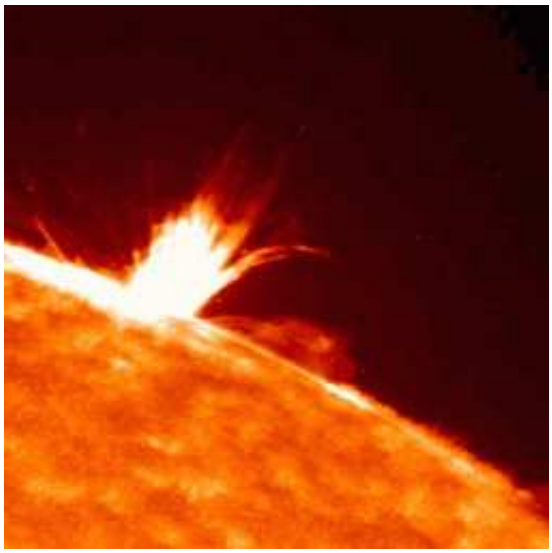
$$\left\{ \begin{array}{rcl} T_{\rm ion} & \gg & T_{\rm p} > T_{\rm e} \\ (T_{\rm ion}/T_p) & > & (m_{\rm ion}/m_p) \\ T_\perp & \gg & T_\parallel \\ u_{\rm ion} & > & u_p \end{array} \right\}$$



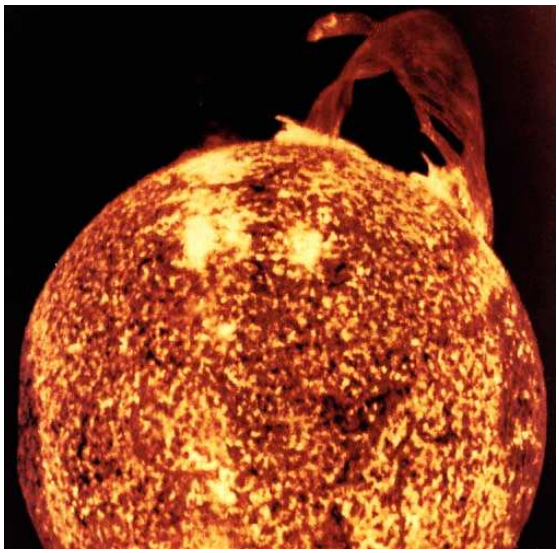
Coronal Mass Ejections (CMEs)

- CMEs are magnetically driven eruptions from the Sun that carry energetic, twisted strands of plasma out into the solar system. This plasma is the main source of **space weather.**
- CMEs occur about 3 times/day (solar max.), 0.3 times/day (solar min.)
- CMEs are related to other kinds of solar eruption:

solar flares

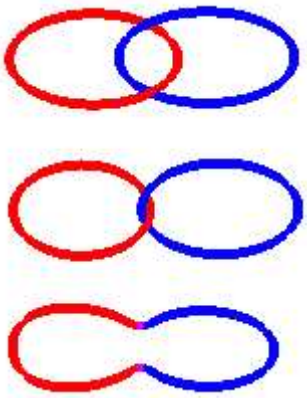


prominence eruptions

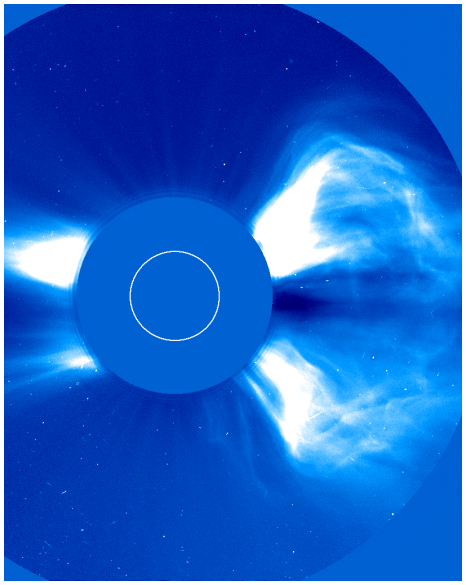


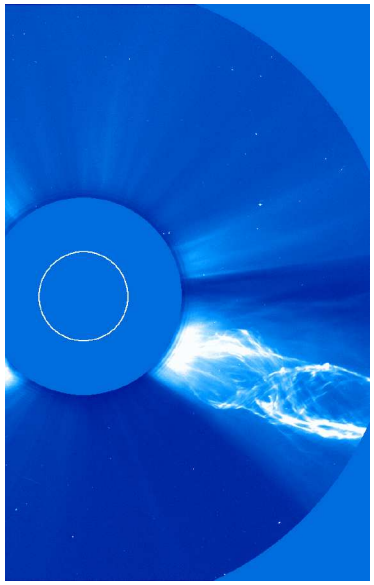
. . . but which is the "chicken;" which is the "egg?"

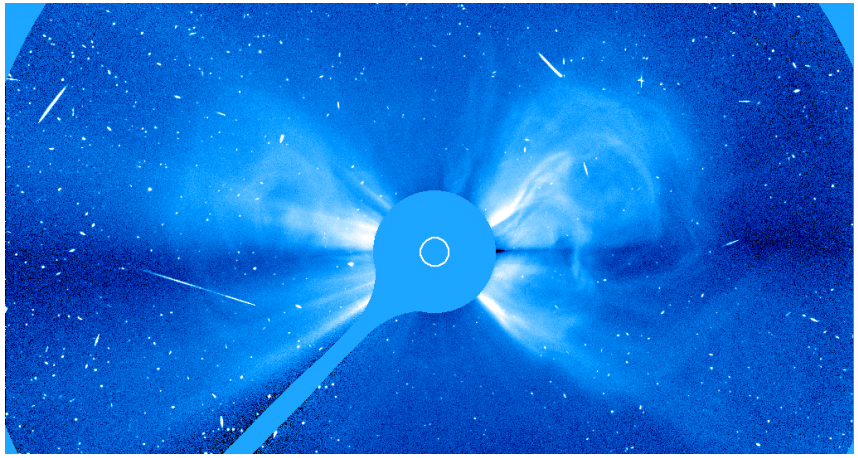
- CMEs are *probably* initiated and driven by **magnetic reconnection;** i.e., a process by which magnetic field lines lose their "identity" and switch to a new, usually lower-energy configuration.

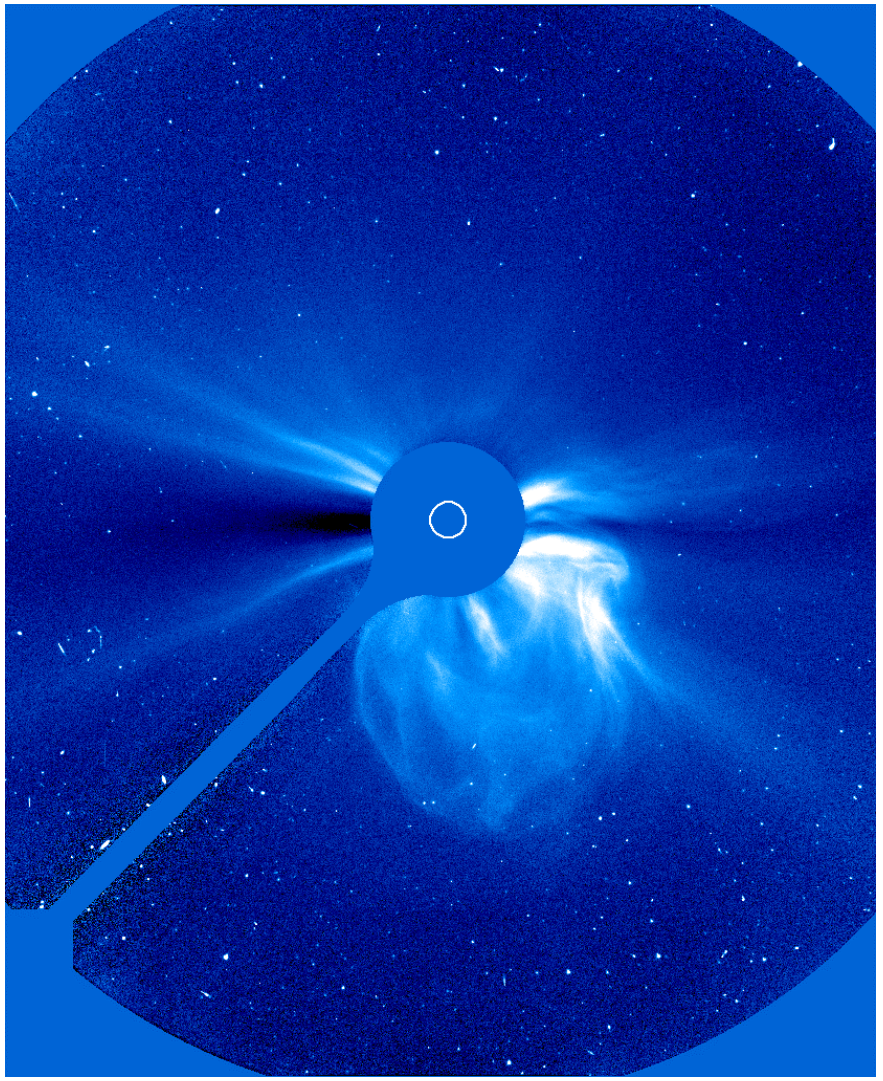


LASCO CME Gallery







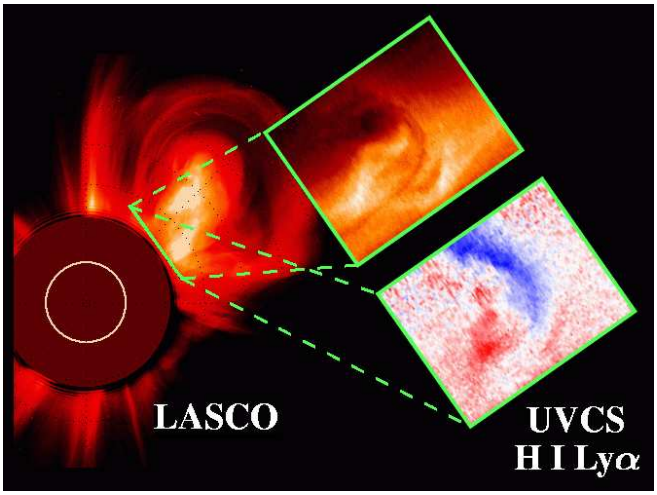


UVCS Observations of CMEs

- Spectroscopy in the acceleration region of CMEs opens up a new window on their physics . . .

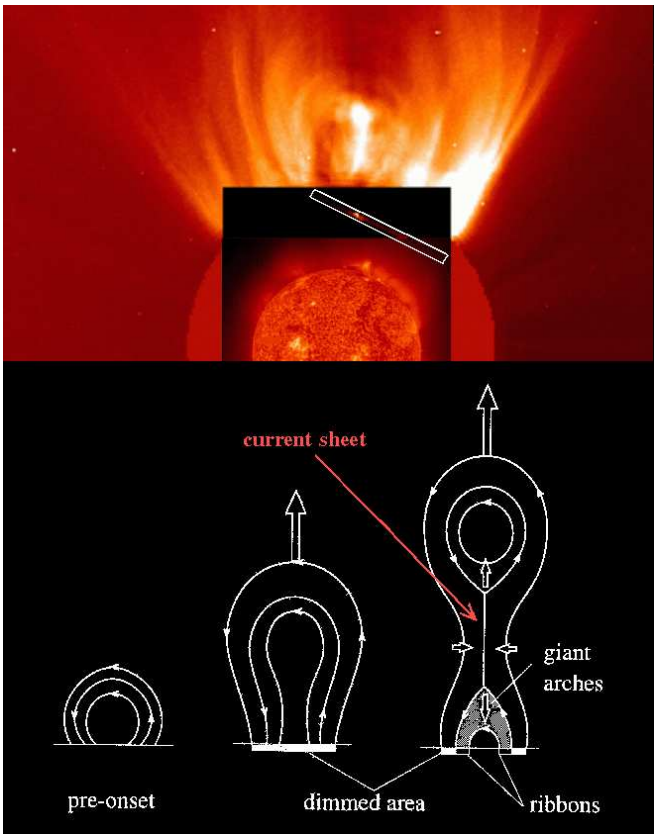
Examples:

- **Doppler shifts** of CME strands provide a measure of their "handedness" in a way images alone could not.



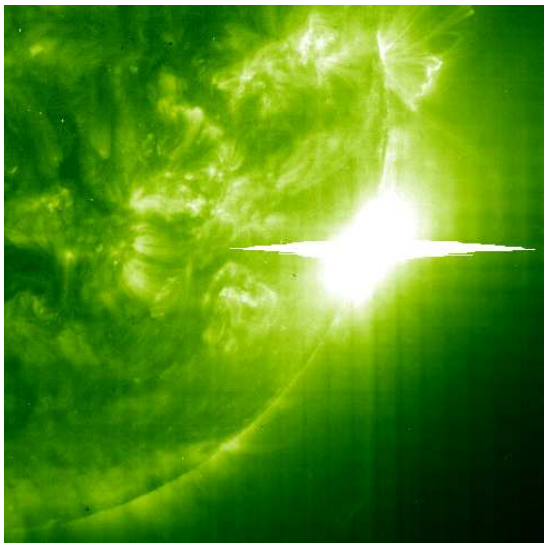
- Features that show up in some lines, but not in others, provide a "census" the plasma components (coexisting with different temperatures!) in a CME.

  (6 million K plasma in a thin **current sheet** stretching between the CME and the hot loops on the Sun) ⇒



The Flare/CME Activity of Oct–Nov 2003

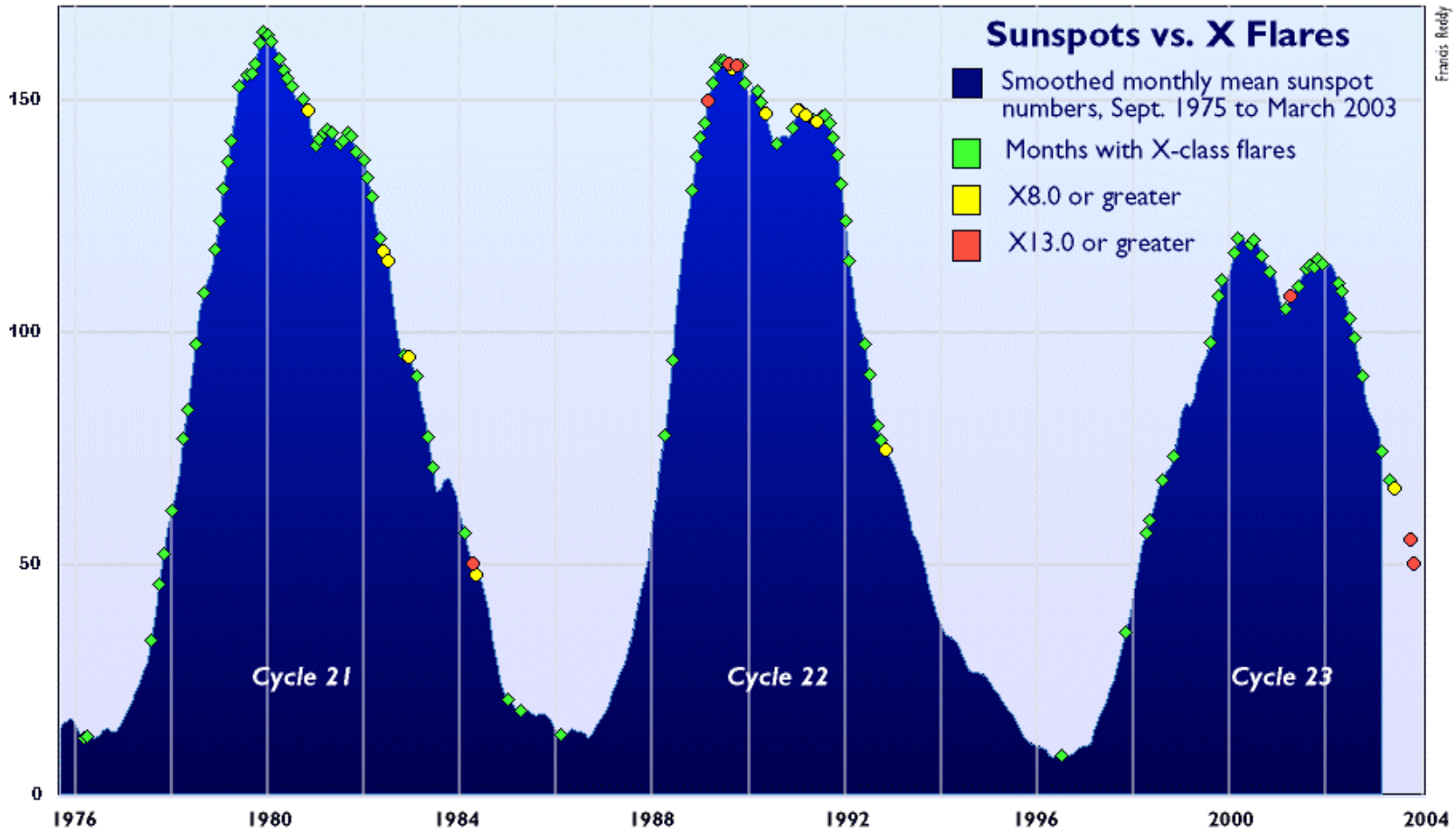
- Over 2 weeks, 11 "X-class" solar flares occurred (equal to the same number observed in the past year!), including the **most energetic flare** ever measured in X-rays, on November 4.



- Many "halo" CMEs were directed towards Earth, with unprecedented speeds ($>$ 2000 km/s).
- A Japanese communications satellite was damaged; many others were put into "safe mode."
- The FAA altered flight paths of some planes to avoid radiation dosage (equal to 1 to a few chest X-rays).
- Space Station crew took shelter in Zvezda module (most shielding) at least 6 times to avoid high radiation.
- Aurora Borealis observed down to Texas and Florida (Louisiana?)
- Analysis of UVCS data is proceeding rapidly, because the active regions responsible for these flares are rotating around again **this week!**

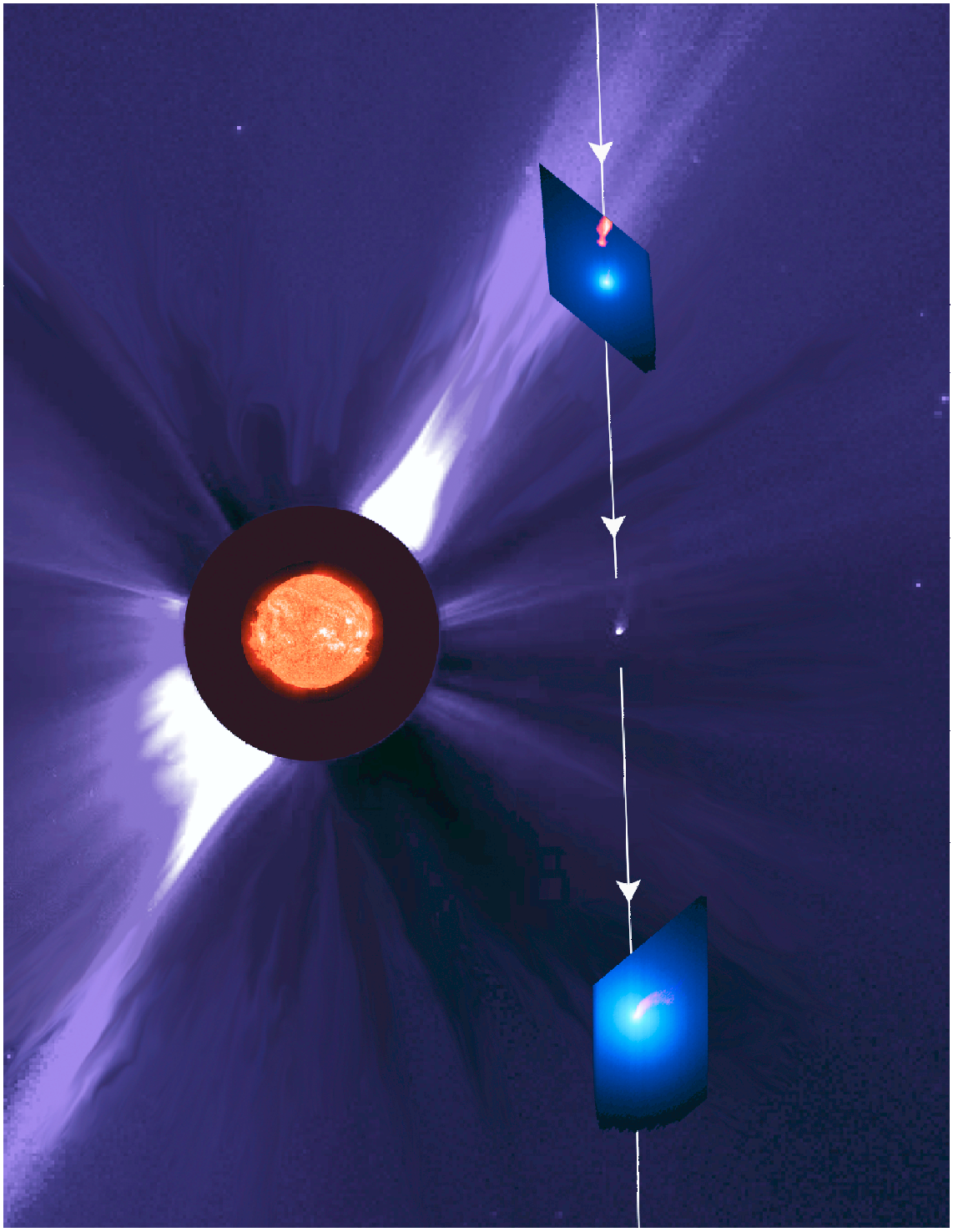
Sunspots and X-class Flares

- We're in the "declining" phase of the 11-year solar cycle
- **X-class** is defined as an X-ray flux (at Earth) $>10^{-4}$ W/m^2; "Xn" = flux of n $\times 10^{-4}$



SOHO Observations of a Comet

- In January 2003, UVCS observed doubly-ionized carbon for the first time in any comet (Comet Kudo-Fujikawa); *Science,* in press.

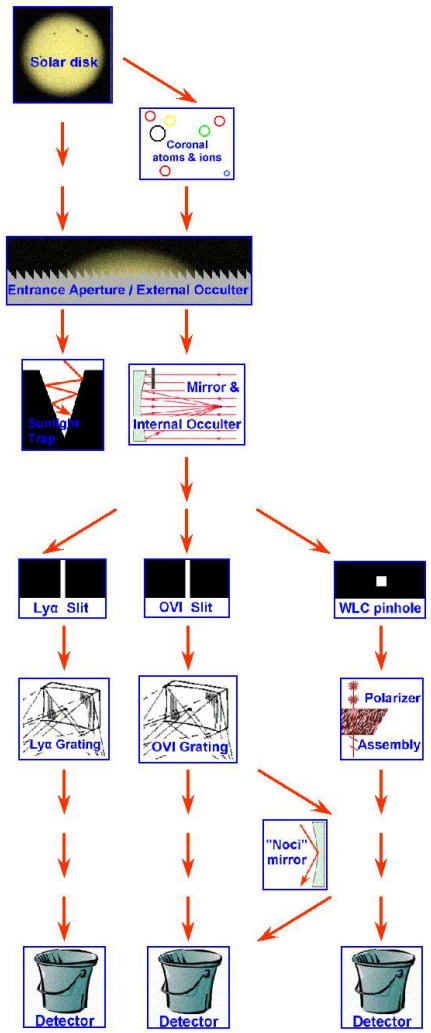


Conclusions

- SOHO and UVCS have gathered data for almost 8 years, and (cross your fi ngers) for more to come.
- UVCS results have led to new views of the acceleration regions of the solar wind and CMEs, and demonstrated the power of spectroscopy to learn things that cannot be gleaned from images alone!

Get Involved!

- So much data has been collected that a large fraction still remains to be analyzed.
- Many web tools and tutorials have been developed, and more are being written as more students become involved. ⟹
- We welcome more participation and collaboration with students!



http://cfa–www.harvard.edu/uvcs/SUBR/
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