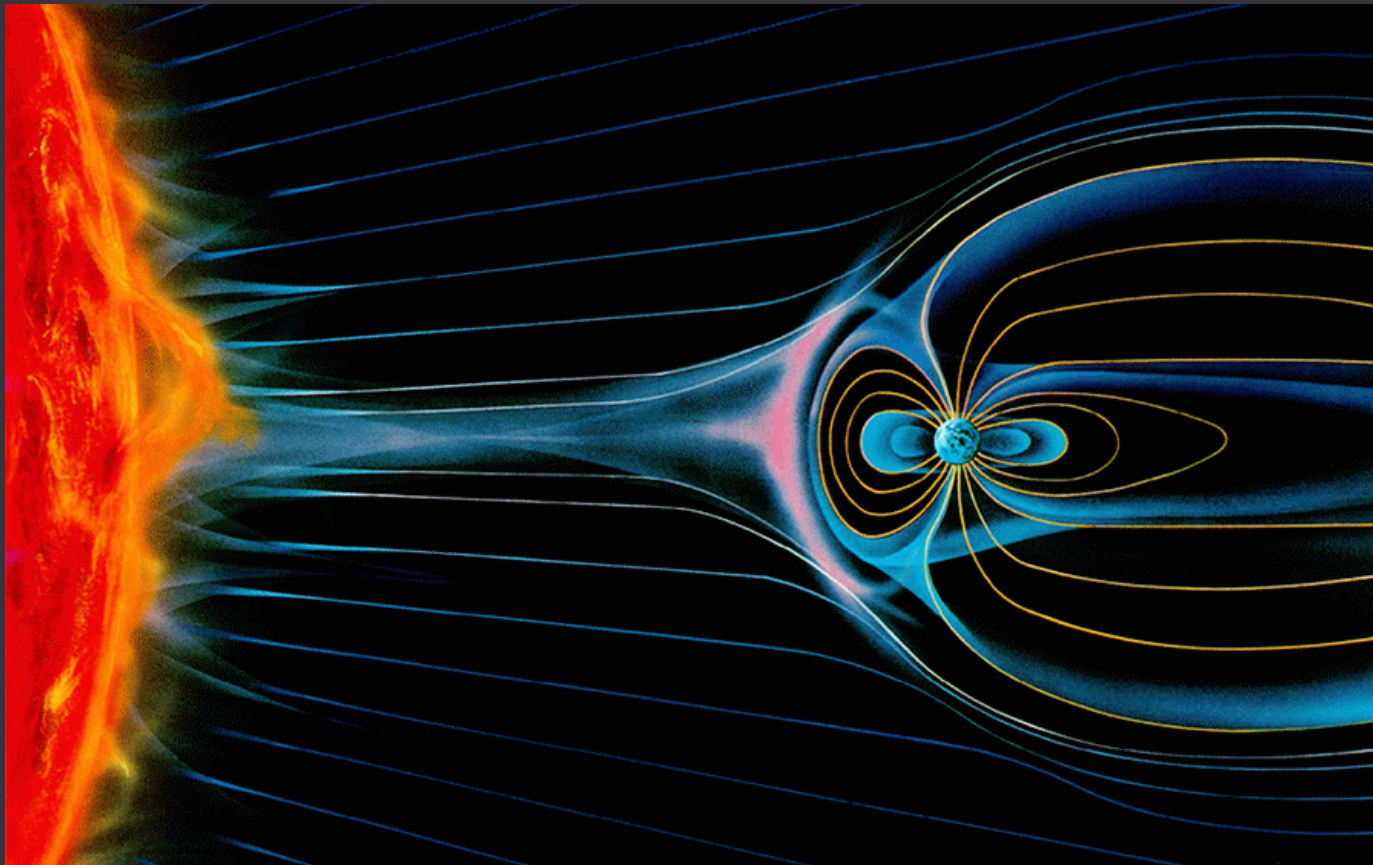


Exploring the Solar Wind with Ultraviolet Light



Steven R. Cranmer and the UVCS/SOHO Team

Harvard-Smithsonian Center for Astrophysics

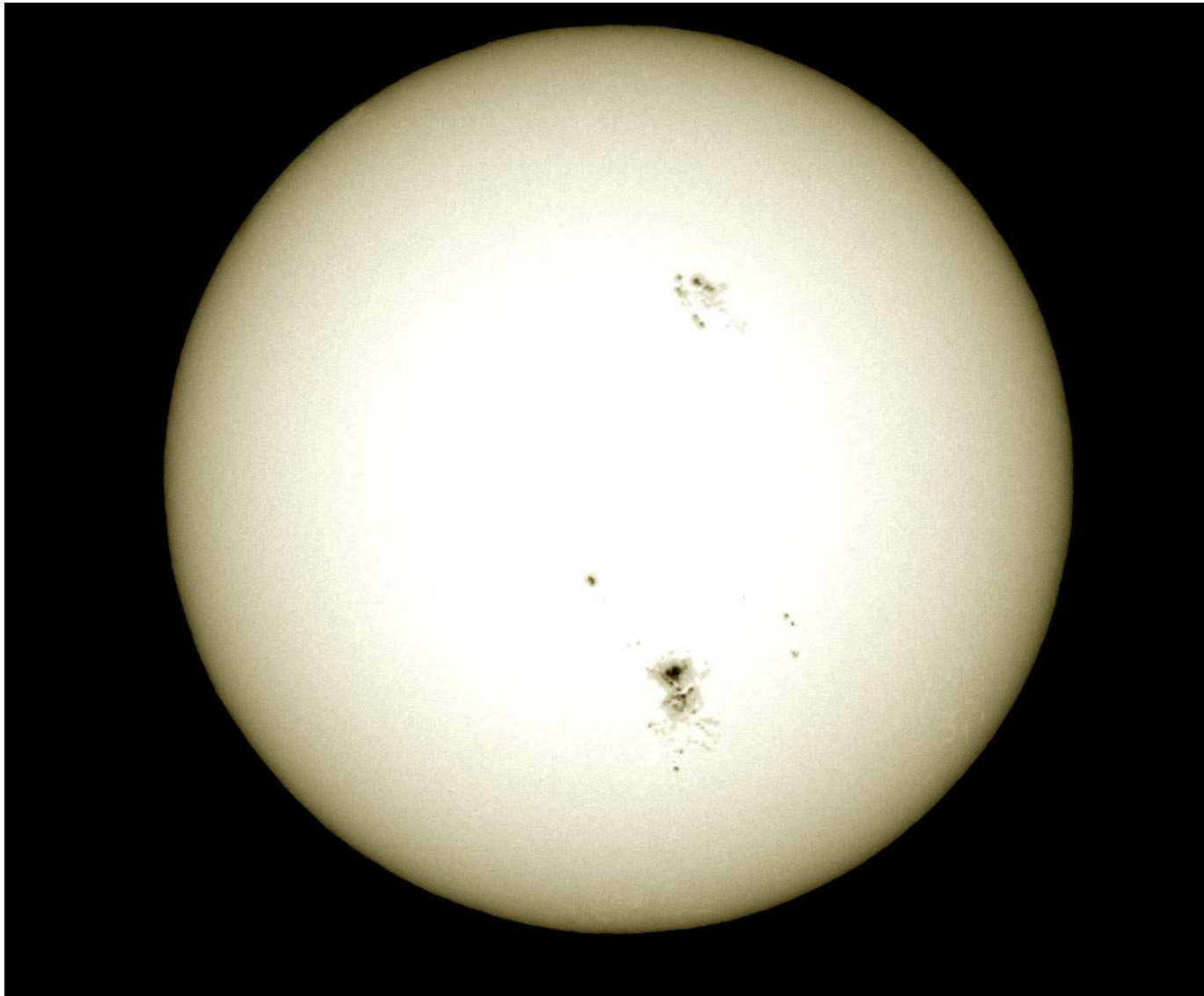


Outline:

- Motivation & history
- How does the Sun “expel” the hot solar wind?
- Modern space-based observations:
 - SOHO (Solar and Heliospheric Observatory)
 - UVCS (Ultraviolet Coronagraph Spectrometer)



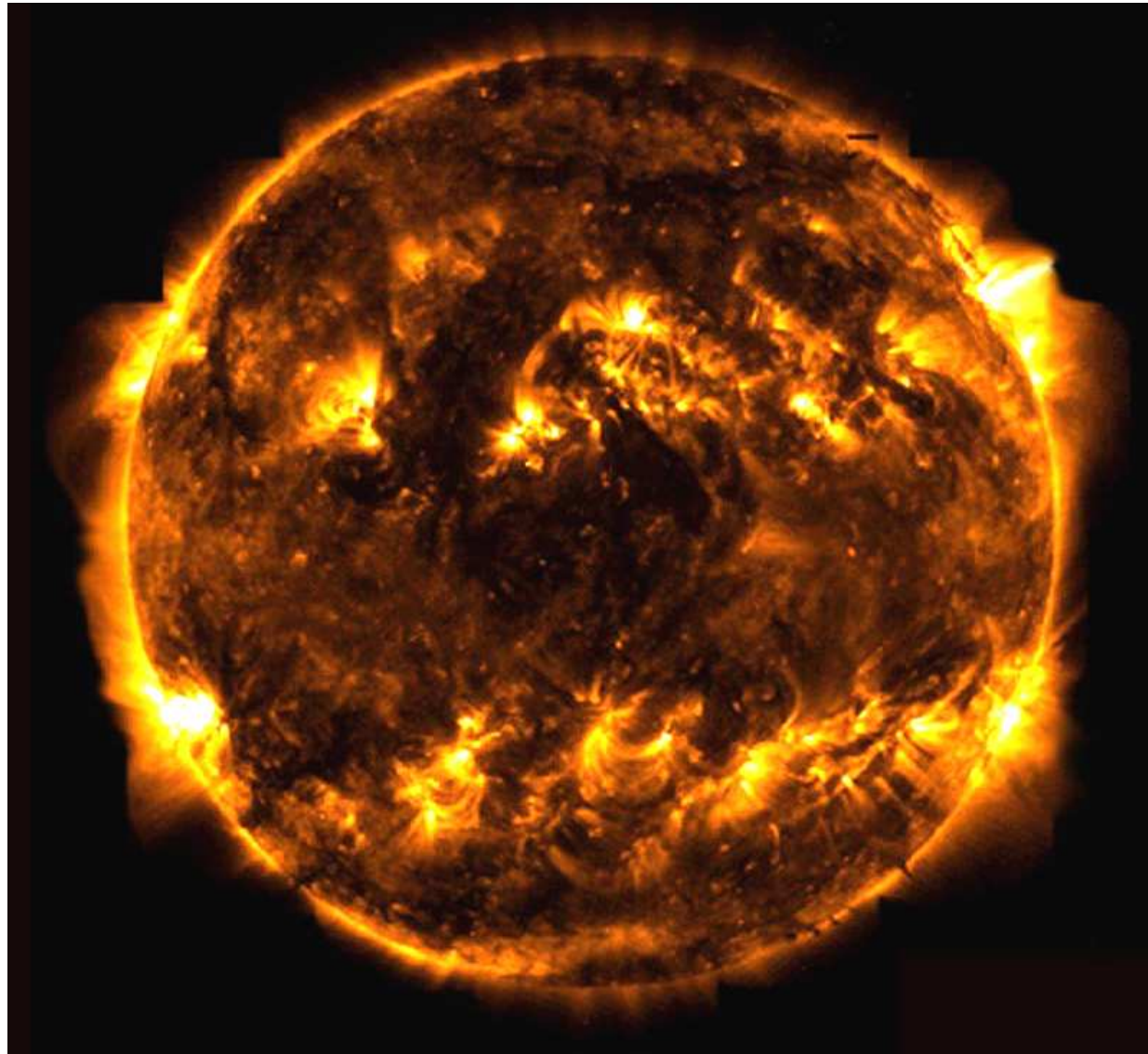
In visible light . . .



Exploring the Solar Wind with Ultraviolet Light

DS-3 Science Lecture Series
U.S. Coast Guard Academy, Jan. 18, 2006

In ultraviolet light . . .

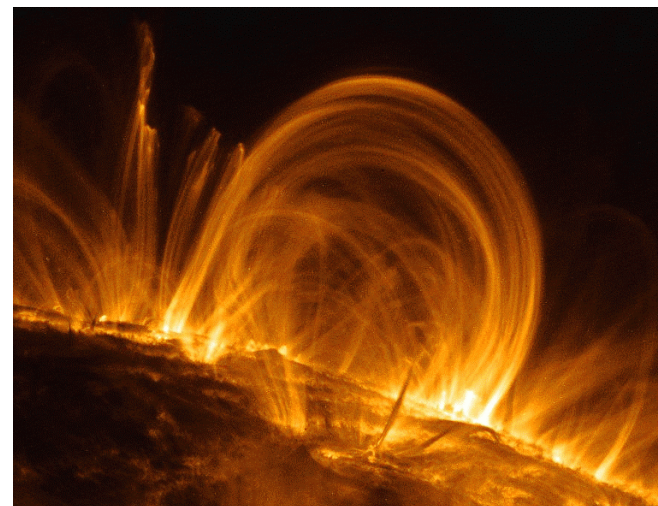
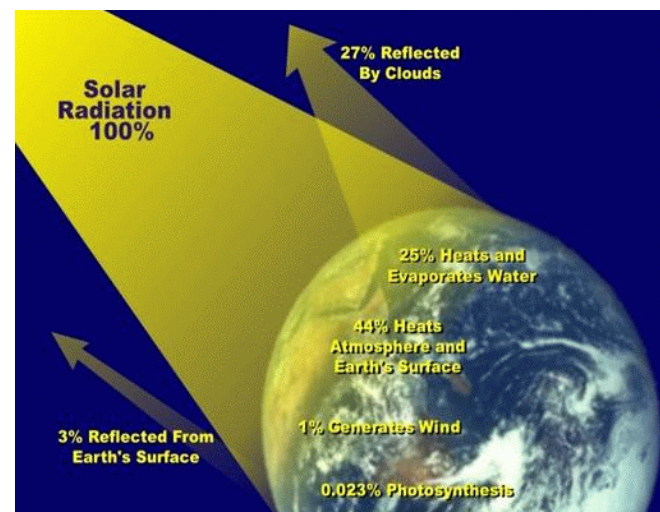


Exploring the Solar Wind with Ultraviolet Light

DS-3 Science Lecture Series
U.S. Coast Guard Academy, Jan. 18, 2006

Solar Physics: A wide-angle view

- The Sun is the source of energy for life on Earth, as well as weather & climate.
- The Sun is the closest example of a star.
- The Sun is a “laboratory without walls” for many basic processes in physics, at regimes (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 fuse hydrogen atoms into helium.

Radiation Zone:

- Photons bounce around in the dense plasma, taking millions of years to escape the Sun.

Convection Zone:

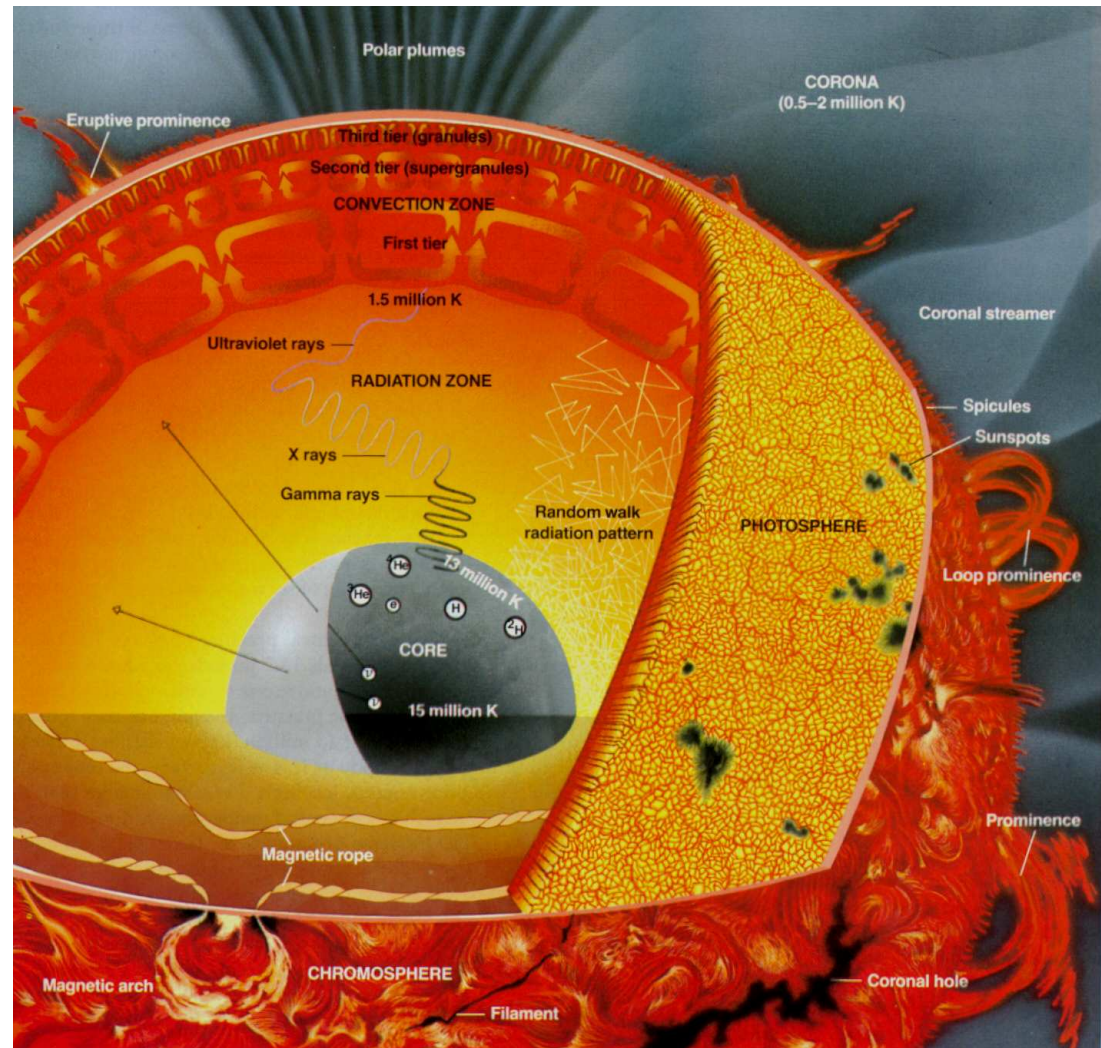
- Energy is transported by boiling, convective motions.

Photosphere:

- Photons stop bouncing, and start escaping freely.

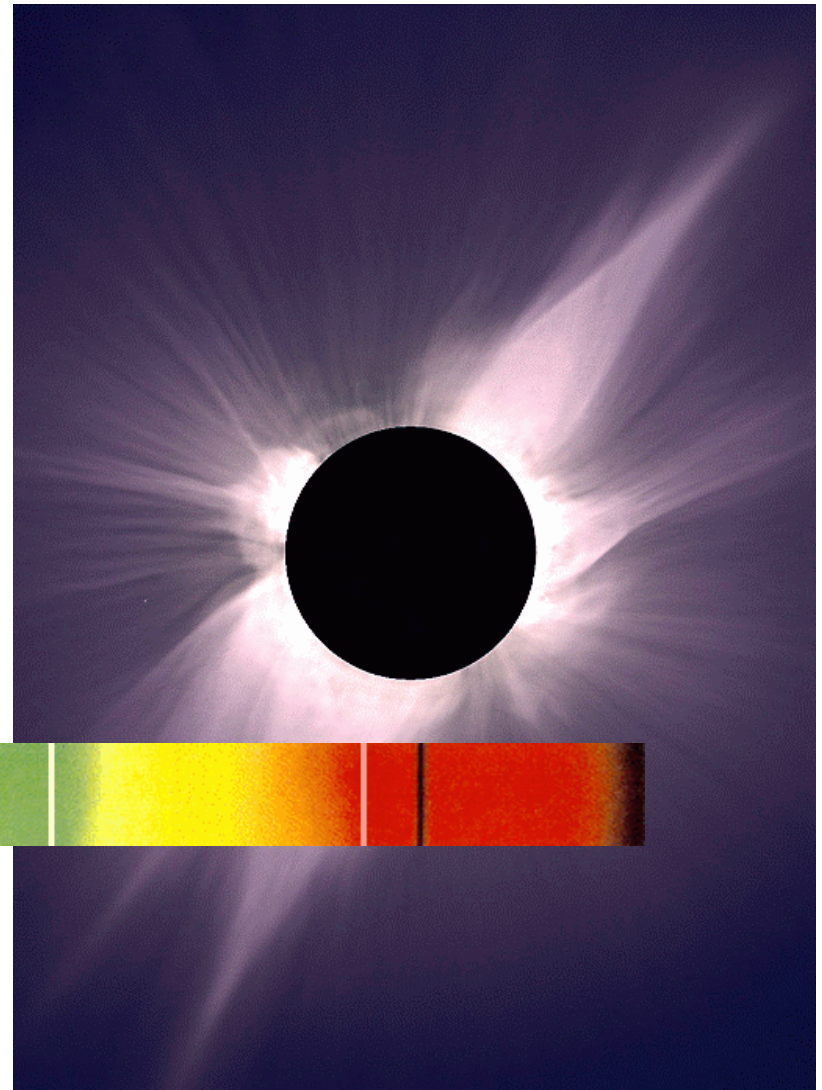
Corona:

- Outer atmosphere where gas is heated from ~5800 K to several **million** degrees!



The Sun's outer atmosphere

- **The solar photosphere** radiates like a “blackbody;” its spectrum gives T , and dark “Fraunhofer lines” reveal its chemical composition.
- Total eclipses let us see the vibrant outer **solar corona**: but what is it?
- 1870s: spectrographs pointed at corona:
 - Fraunhofer lines (not moon-related!)
 - unknown bright lines

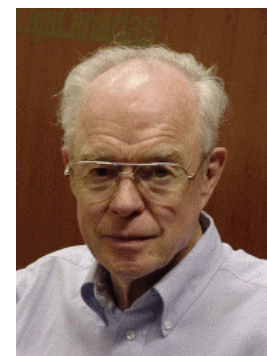
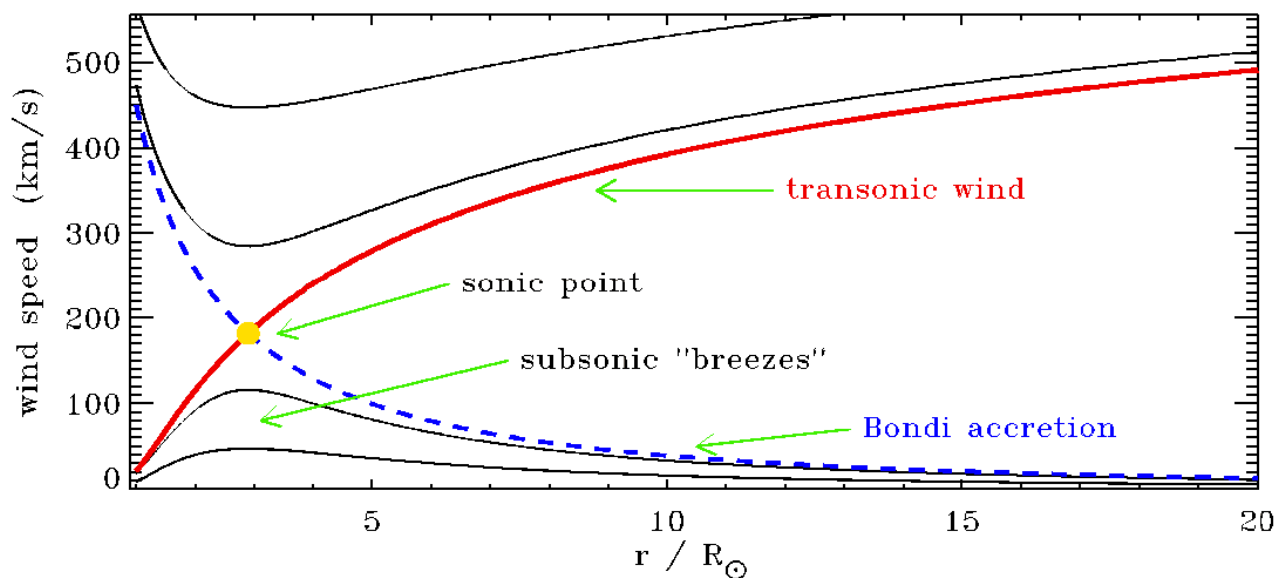


- Is there a new element (“**coronium?**”)
- 1930s: Lines identified as highly ionized ions: Ca^{+12} , Fe^{+9} to Fe^{+13} \longrightarrow *it's hot!*



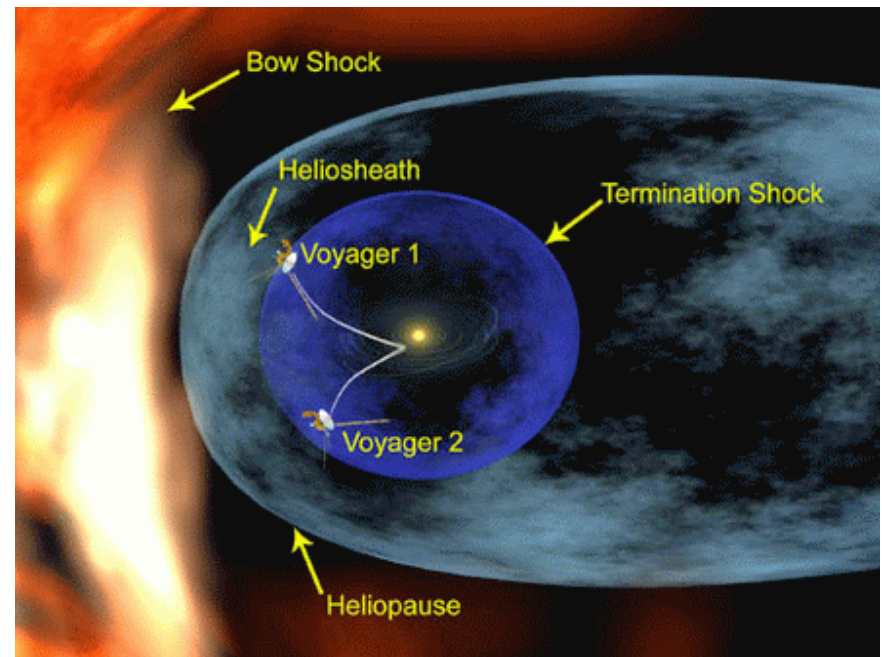
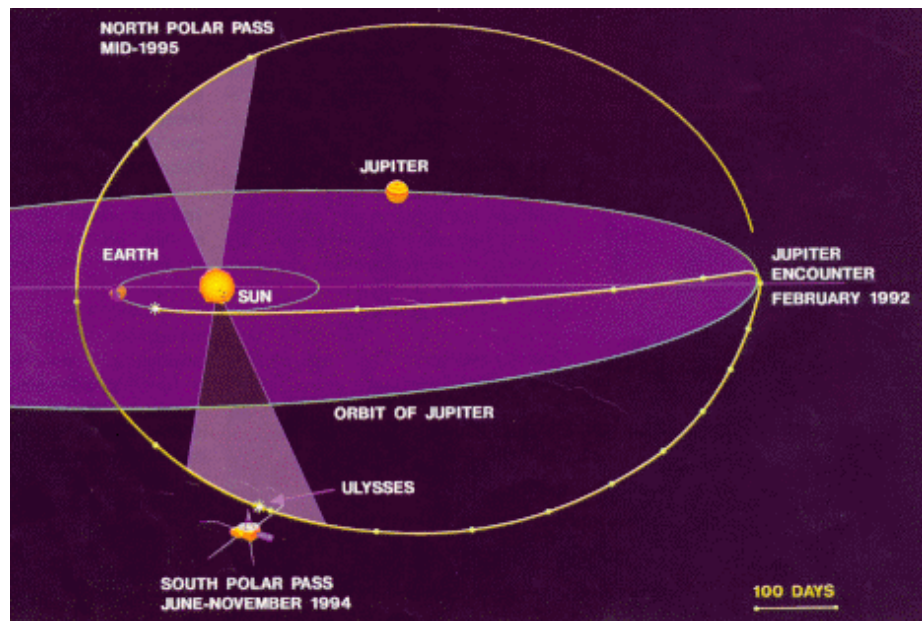
The solar wind

- 1860–1950: Evidence slowly builds for **outflowing magnetized plasma** in the solar system:
 - solar flares → aurora, telegraph snafus, geomagnetic “storms”
 - comet ion tails point anti-sunward (no matter comet’s motion)
- 1958: Eugene Parker proposed that the hot corona provides enough gas pressure to counteract gravity and accelerate a “solar wind.”
- 1962: **Mariner 2** provided direct confirmation!



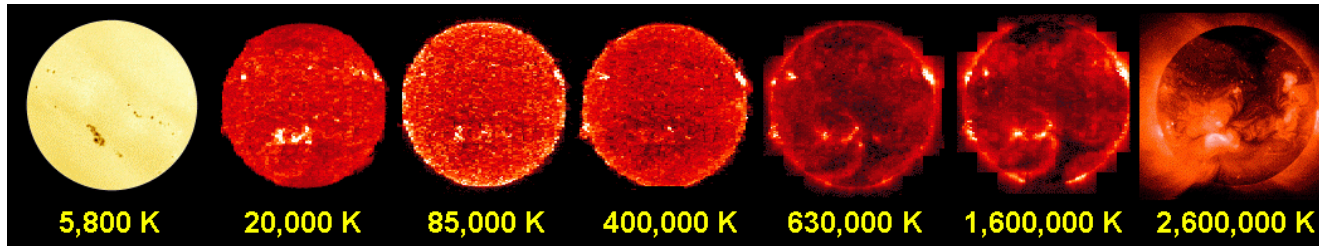
Exploring the solar wind (1970s to present)

- Space probes have pushed out the boundaries of the “known” solar wind . . .
- **Helios 1 & 2:** “inner” solar wind (Earth to Mercury)
- **Ulysses:** “outer” solar wind (Earth to Jupiter, also flew over N/S poles!)
- **Voyager 1 & 2:** far out past Pluto: recently passed the *boundary* between the solar wind and the interstellar medium



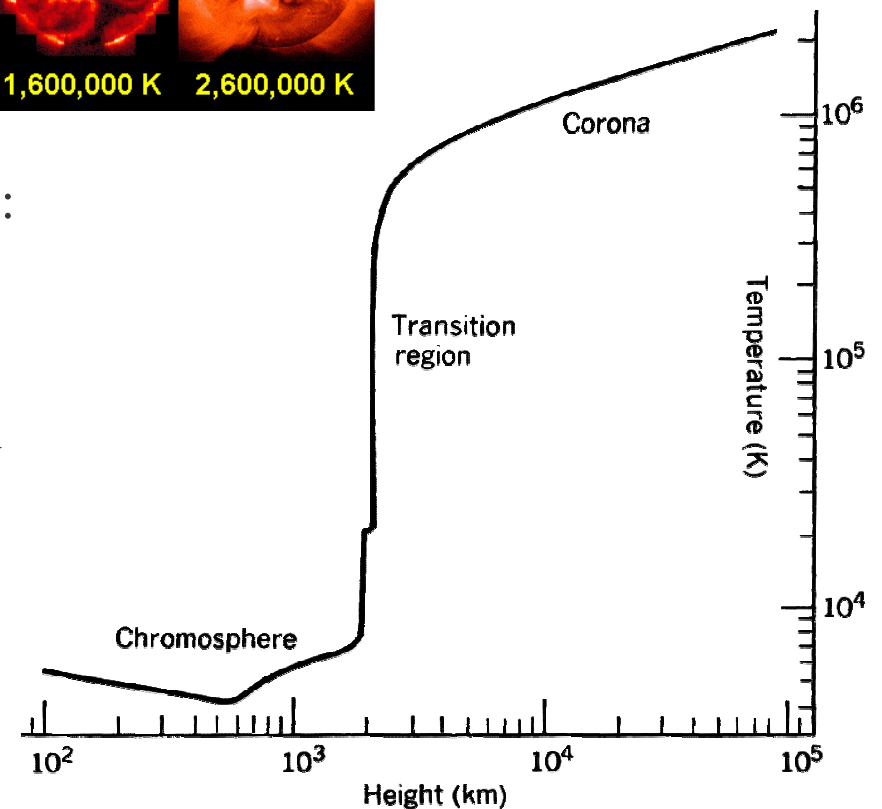
The “coronal heating problem”

- We still don’t understand the physical processes responsible for heating up the coronal plasma. A lot of the heating occurs in a narrow “shell!”



- Most suggested ideas involve 3 general steps:
 1. Churning convective motions that tangle up magnetic fields on the surface.
 2. Energy is stored in tiny twisted & braided “magnetic flux tubes.”
 3. Collisions between ions and electrons (i.e., friction?) release energy as heat.

Heating → Solar wind acceleration!

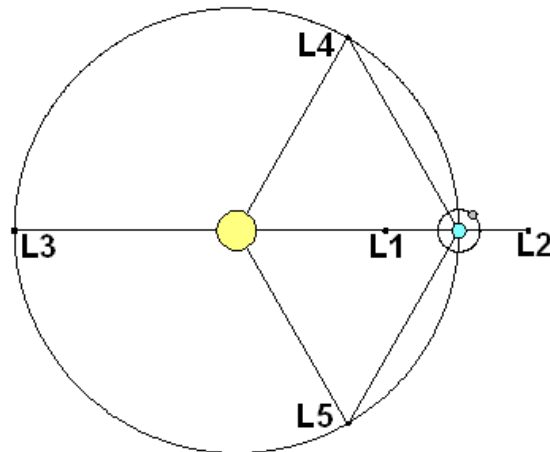


The SOHO mission

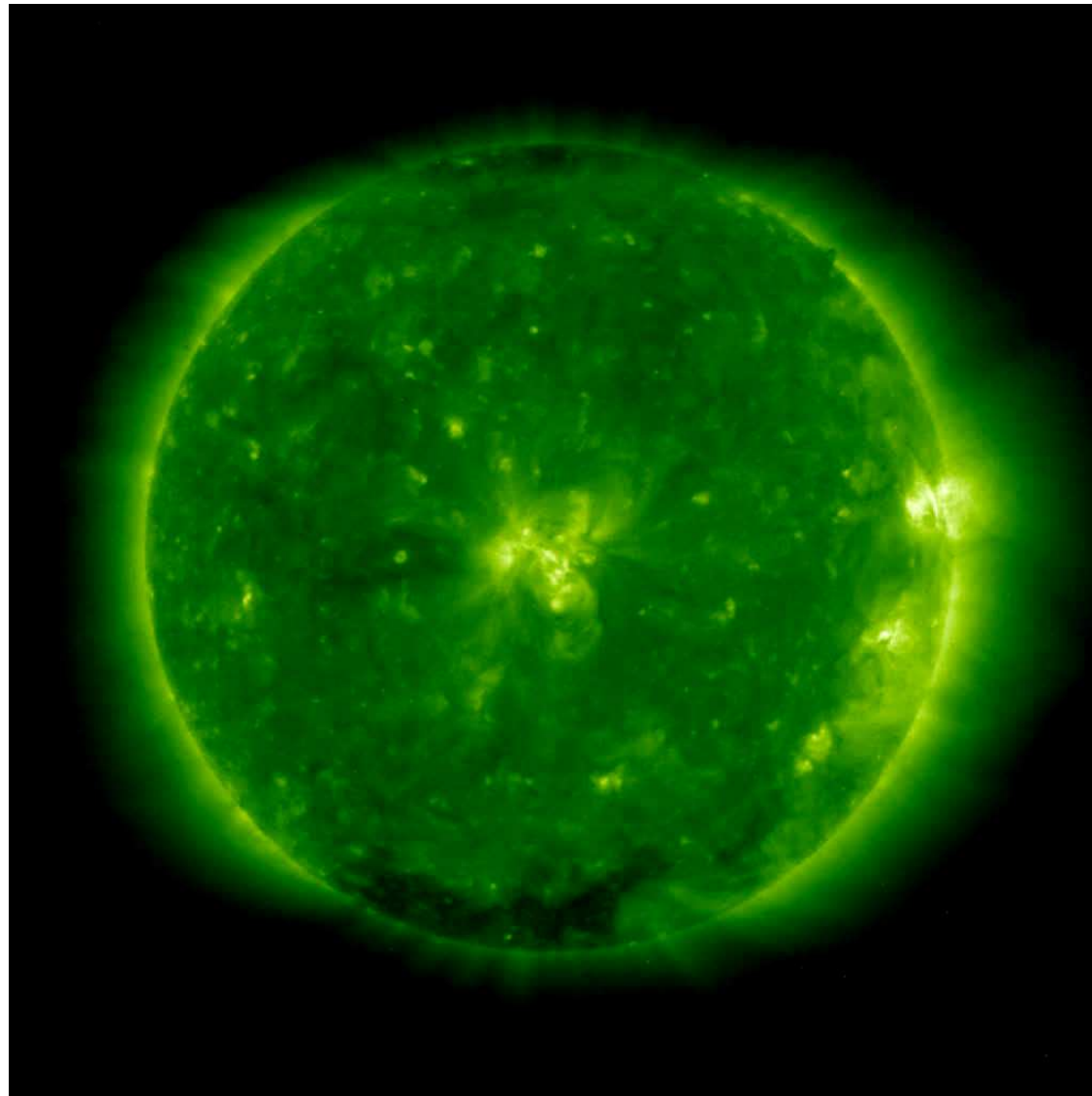
- **SOHO** (the Solar and Heliospheric Observatory) was launched in Dec. 1995 with the goal of solving long-standing mysteries about the Sun.
- 12 instruments on SOHO probe:
 - solar interior (via “seismology”)
 - solar atmosphere (images, movies, spectra)
 - solar wind (collect particles, measure fields)
 - interstellar gas (some light bounces back)



L1 orbit provides
24-hour viewing!

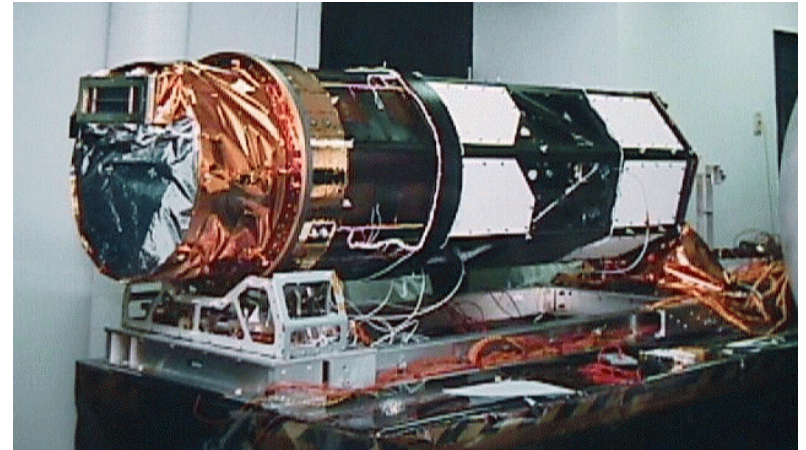


High-resolution UV images of the solar disk

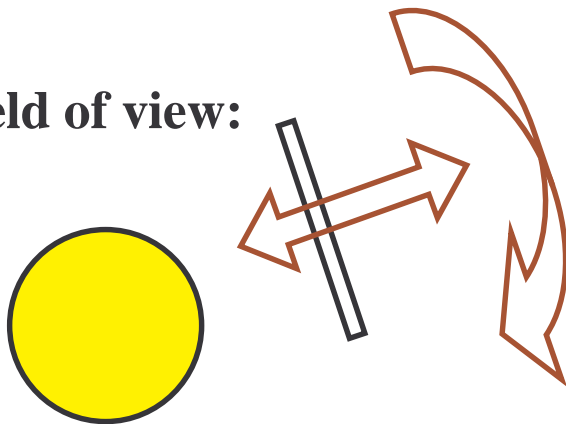


The UVCS instrument on SOHO

- **1979–1995:** Rocket flights and Shuttle-deployed *Spartan 201* laid groundwork.
- **1996–present:** The Ultraviolet Coronagraph Spectrometer (UVCS) measures plasma properties of coronal protons, ions, and electrons between 1.5 and 10 solar radii.
- Combines “occultation” with spectroscopy to reveal the solar wind **acceleration region!**



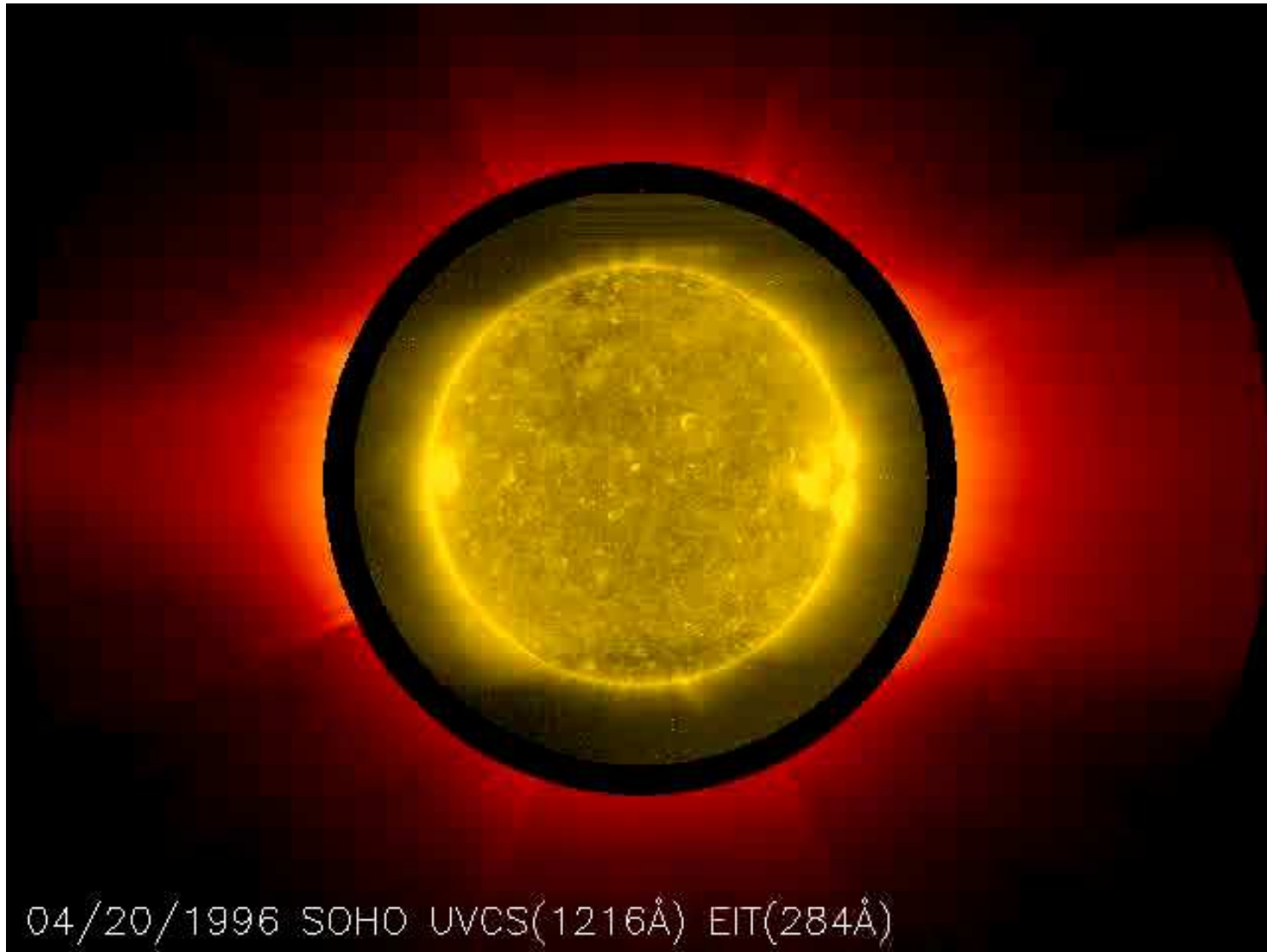
slit field of view:



- Mirror motions select height
- Instrument rolls indep. of spacecraft
- 2 UV channels: LYA & OVI
- 1 white-light polarimetry channel



Several rotations of UVCS + EIT

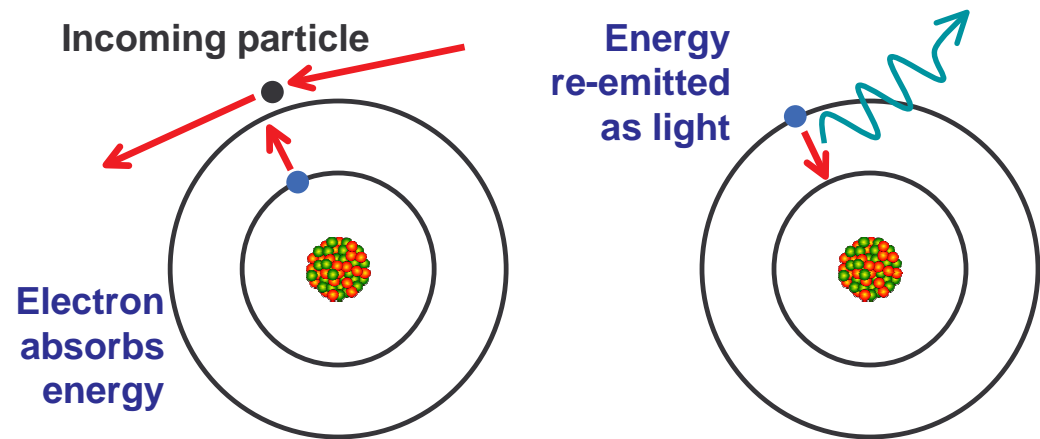


What produces “emission lines” in a spectrum?

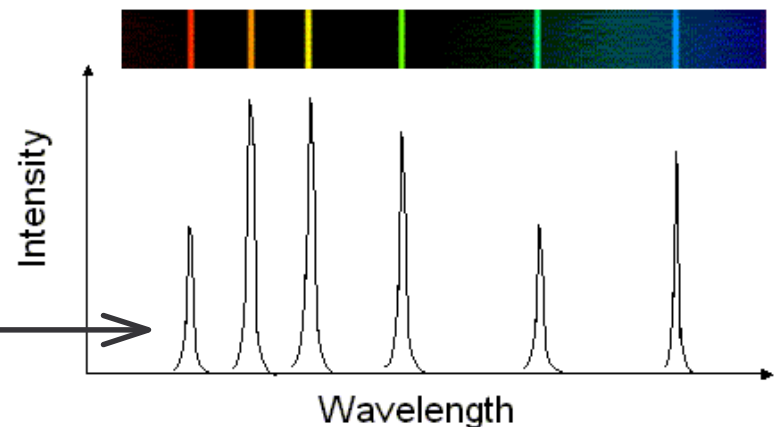
- There are 2 general ways of producing extra photons at a specific wavelength.

- Both mechanisms depend on the **quantum** nature of atoms: “bound” electrons have discrete energies . . .

- The incoming particle can be either:

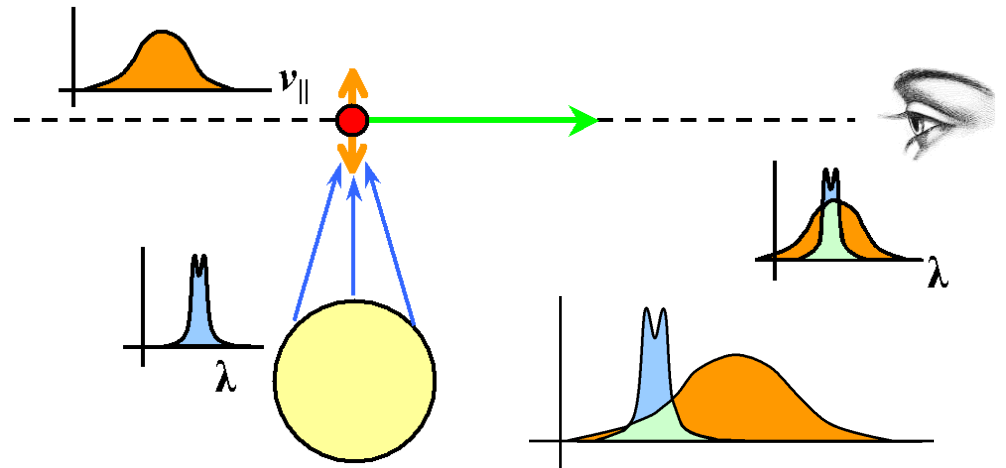
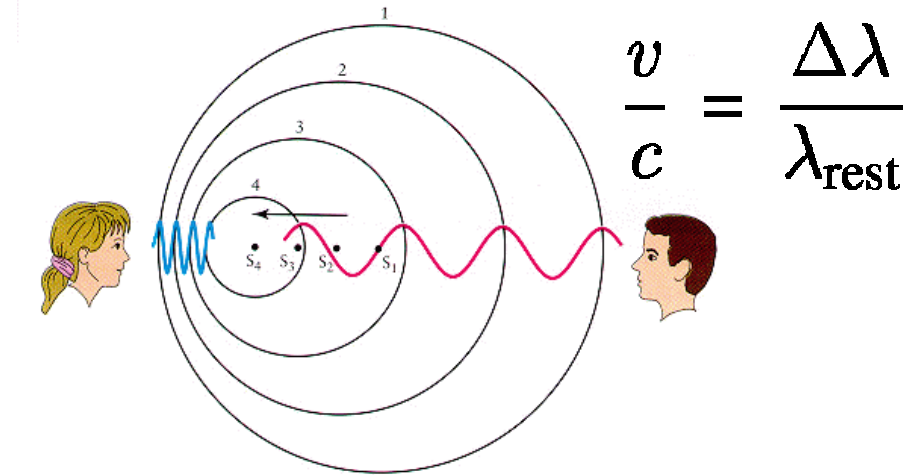


- A free electron from some other ionized atom (“**collisional excitation**”)
- A photon at the right wavelength from the bright solar disk (“**resonant scattering**”)
- There is some **spread** in wavelength



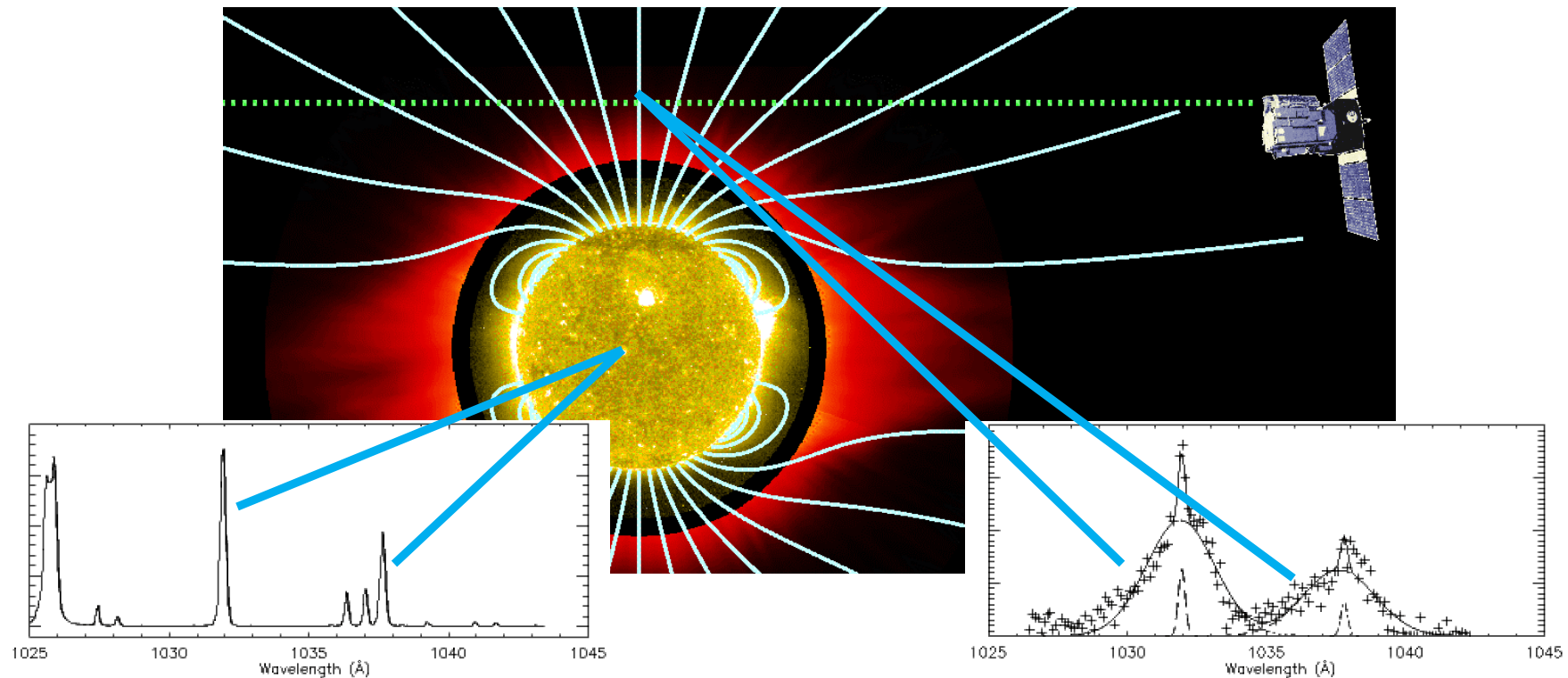
Using lines as plasma diagnostics

- The **Doppler effect** shifts photon wavelengths depending on **motions** of atoms:
- If profiles are shifted up or down in wavelength (from the known “rest wavelength”), this indicates the **bulk flow speed** *along* the line-of-sight.
- The widths of the profiles tell us about random motions along the line-of-sight (i.e., **temperature!**)
- The total intensity (i.e., number of photons) tells us mainly about the **density** of atoms, but for resonant scattering there’s also another “hidden” Doppler effect that tells us about the **flow speeds** *perpendicular* to the line-of-sight.



UVCS results: over the poles (1996-1997)

- The fastest solar wind flow is expected to come from dim “coronal holes.”
- In June 1996, the first measurements of heavy ion (e.g., O^{+5}) line emission in the extended corona revealed **surprisingly wide** line profiles . . .



On-disk profiles: $T = 1\text{--}3$ million K

Off-limb profiles: **$T > 200$ million K !**

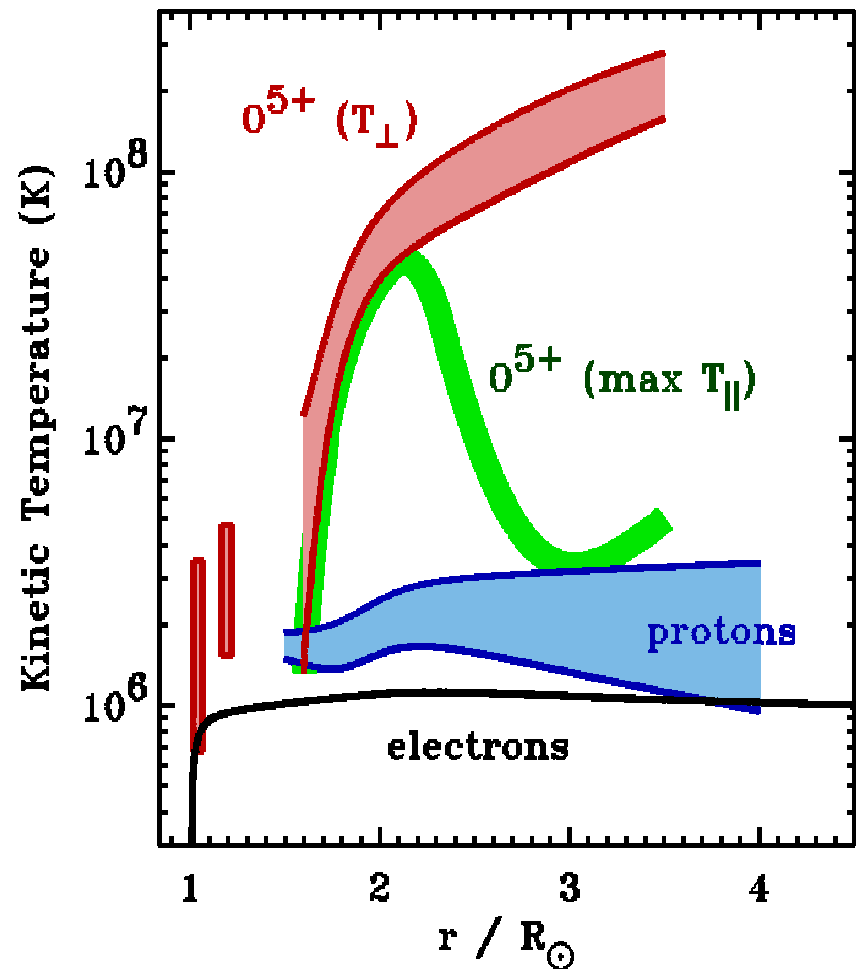


Coronal holes: the impact of UVCS

UVCS/SOHO has led to new views of the acceleration regions of the solar wind. Key results include:

- The fast solar wind becomes **supersonic** much closer to the Sun ($\sim 2 R_s$) than previously believed.
- In coronal holes, heavy ions (e.g., O^{5+}) both flow **faster** and are **heated** hundreds of times more strongly than protons and electrons, and have **anisotropic temperatures**. \longrightarrow **“Collisionless!”**

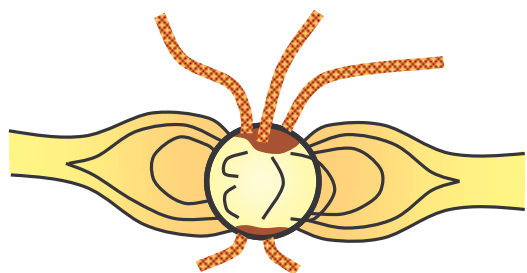
$$\left\{ \begin{array}{l} T_{\text{ion}} \gg T_p > T_e \\ (T_{\text{ion}}/T_p) > (m_{\text{ion}}/m_p) \\ T_{\perp} \gg T_{\parallel} \\ u_{\text{ion}} > u_p \end{array} \right\}$$



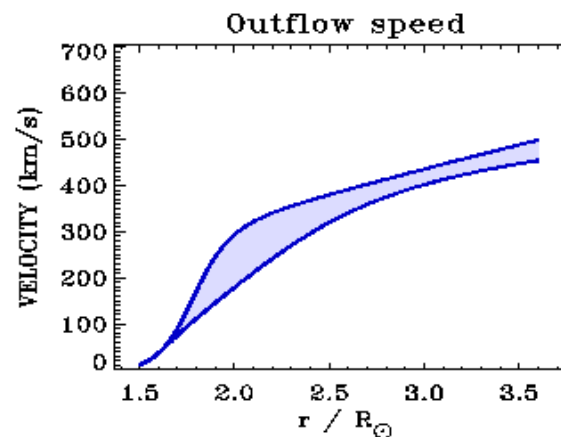
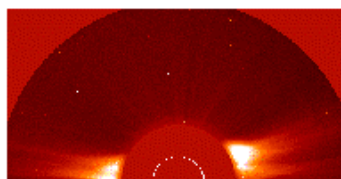
Coronal holes: over the 11-year solar cycle

- Even though large coronal holes have similar outflow speeds at 1 AU (>600 km/s), their **acceleration** (in O^{+5}) in the corona is different! (Miralles et al. 2001)

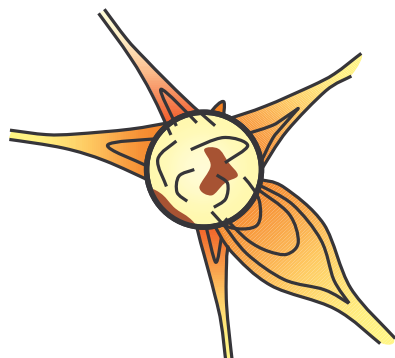
Solar minimum:



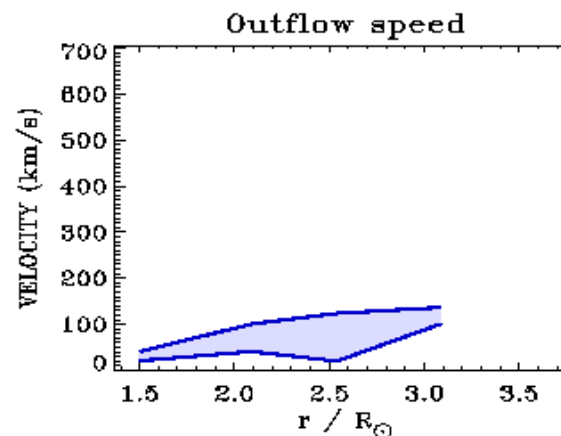
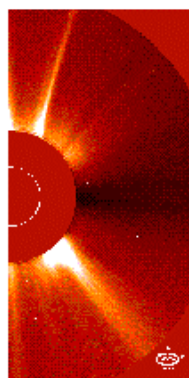
POLAR (1996)



Solar maximum:

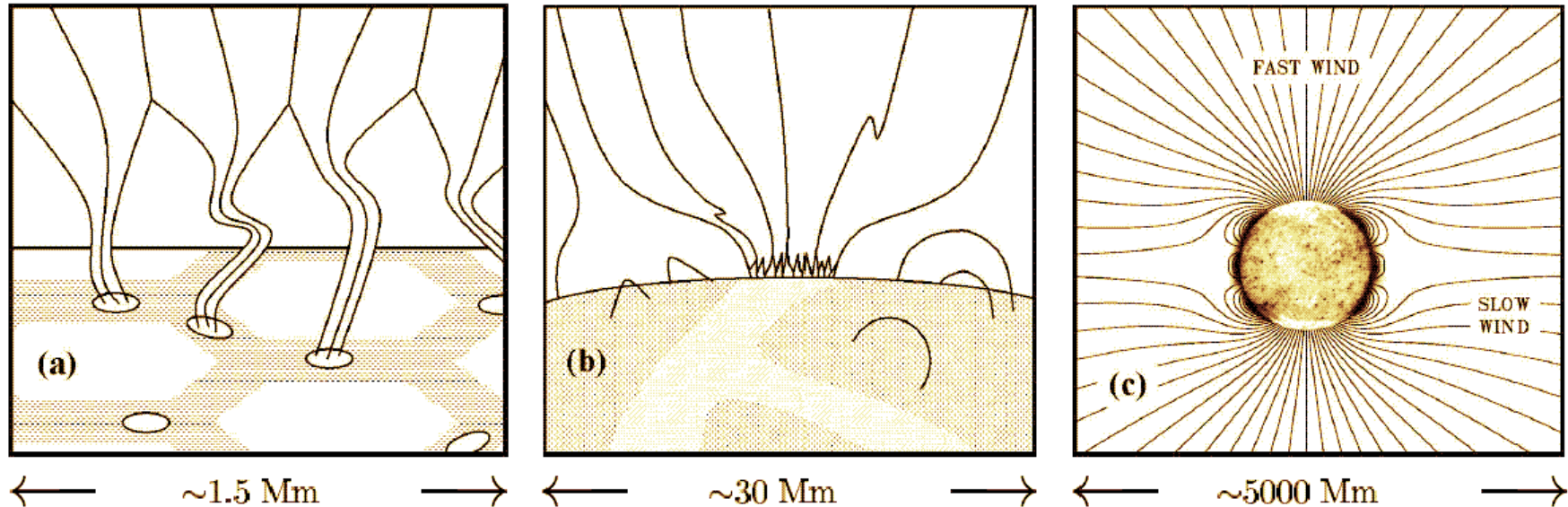


EQUATORIAL (1999)

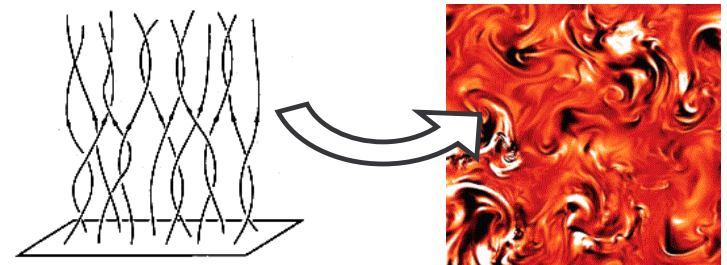


Turbulent heating of the ions

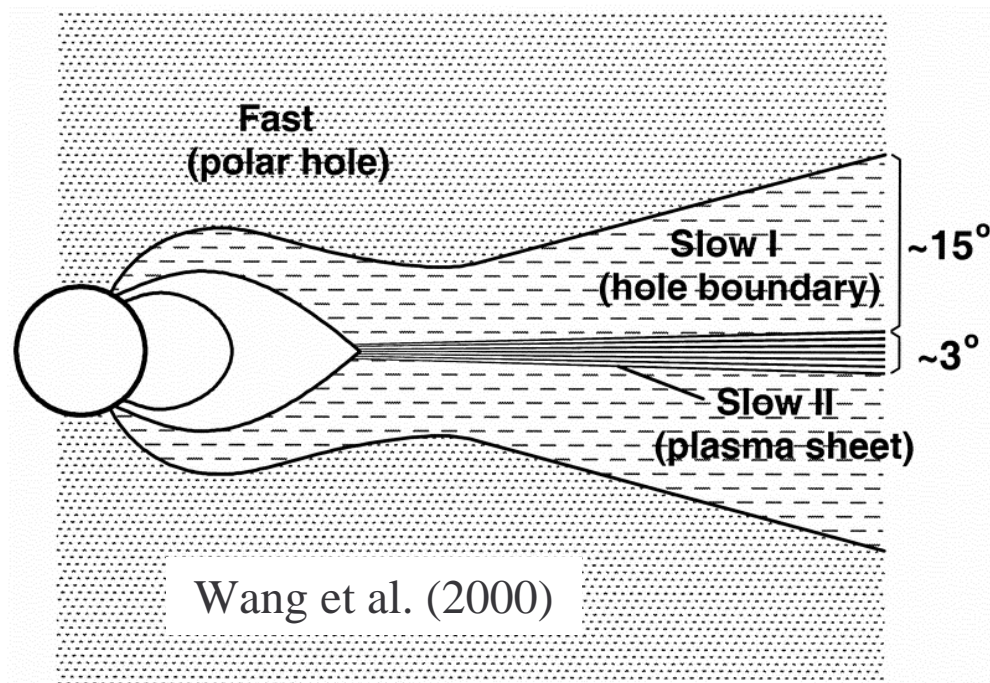
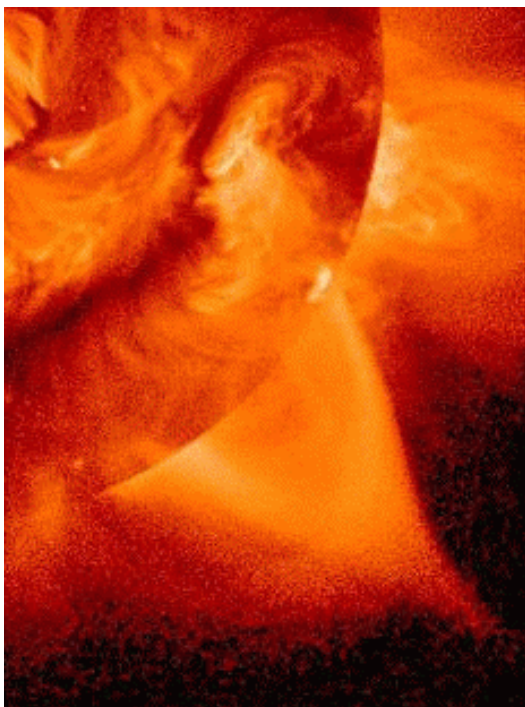
- UVCS observations have **rekindled theoretical efforts** to understand heating and acceleration of the plasma in the (collisionless?) acceleration region of the wind.



- Shaking a magnetic field back and forth creates “Alfven waves” that become **turbulent** and can damp out . . . heating some particles more than others.



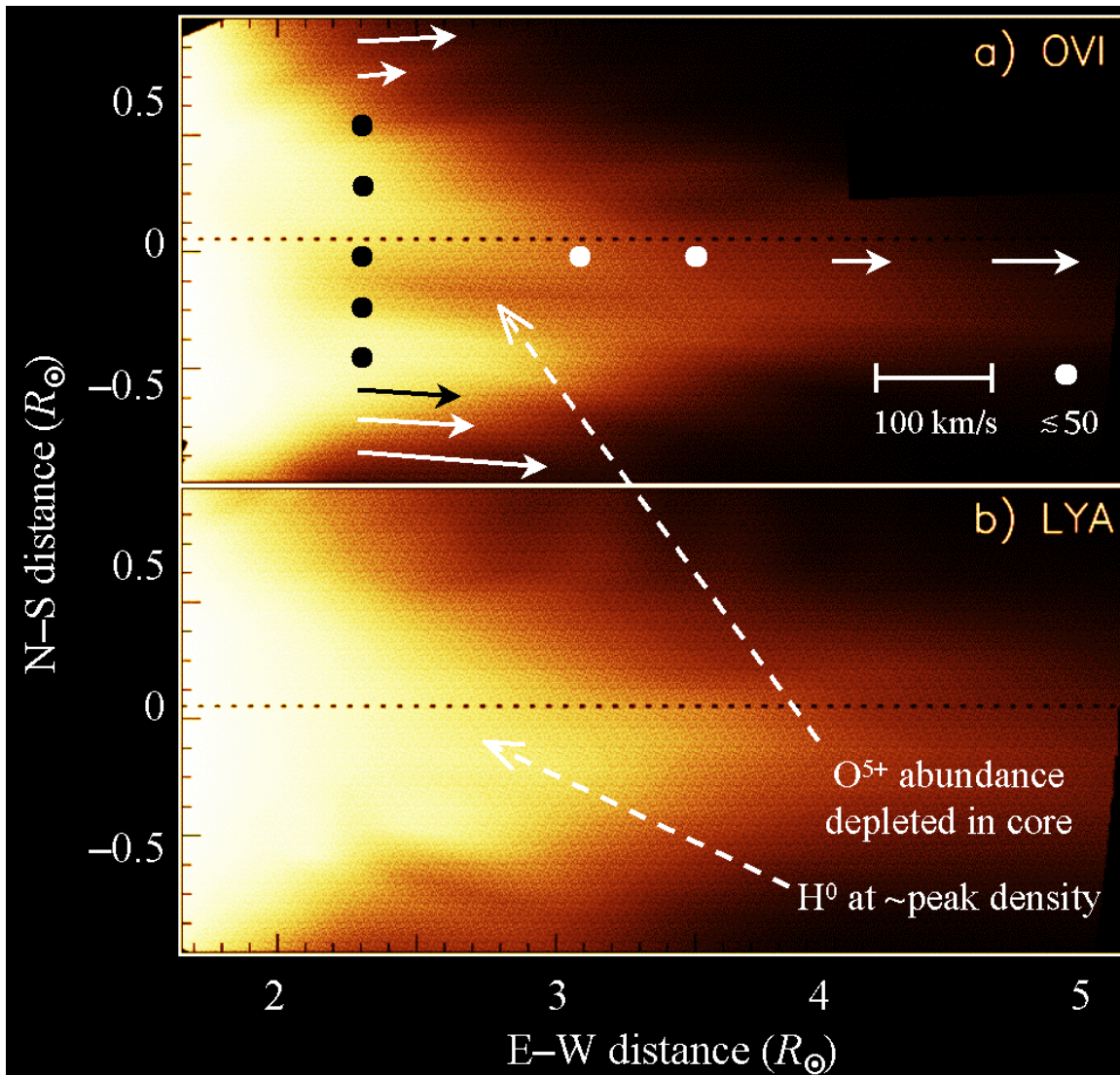
Streamers: open or closed?



- **High-speed wind:** strong connections to the largest coronal holes
- **Low-speed wind:** still no agreement on the full range of coronal sources:
 - hole/**streamer** boundary (streamer “edge”)
 - streamer** plasma sheet (“cusp/stalk”)
 - small coronal holes
 - active regions (some with **streamer** cusps)



Streamers with UVCS

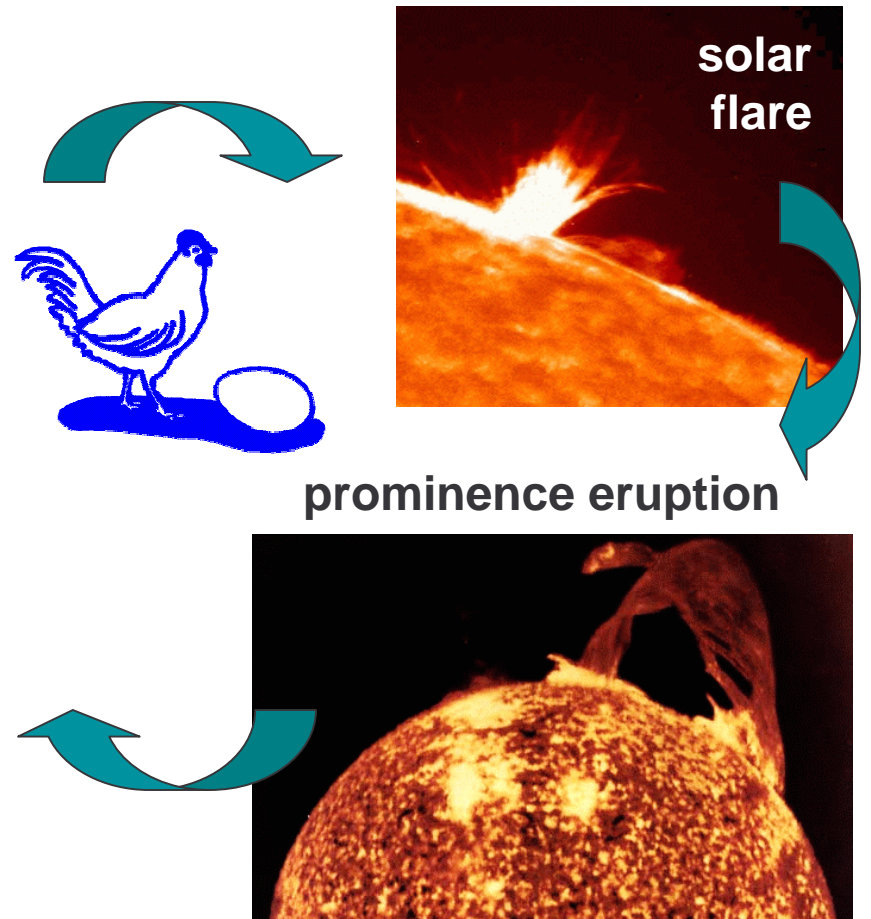
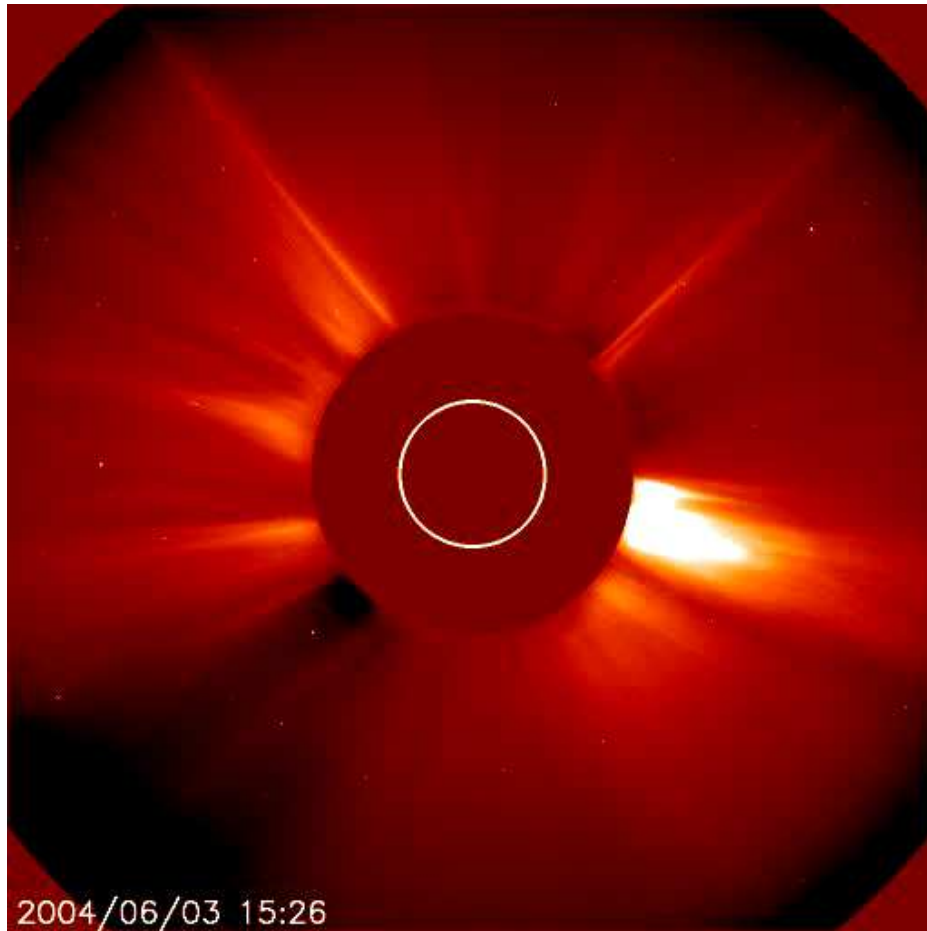


- Streamers viewed “edge-on” look different in H^0 and O^{5+}
- Ion abundance depletion in “**core**” due to grav. settling?
- Brightest “**legs**” show negligible outflow, but abundances consistent with *in situ* slow wind.
- Higher latitudes and upper “**stalk**” show definite flows (Strachan et al. 2002).
- Stalk also has **preferential ion heating & anisotropy**, like coronal holes! (Frazin et al. 2003)



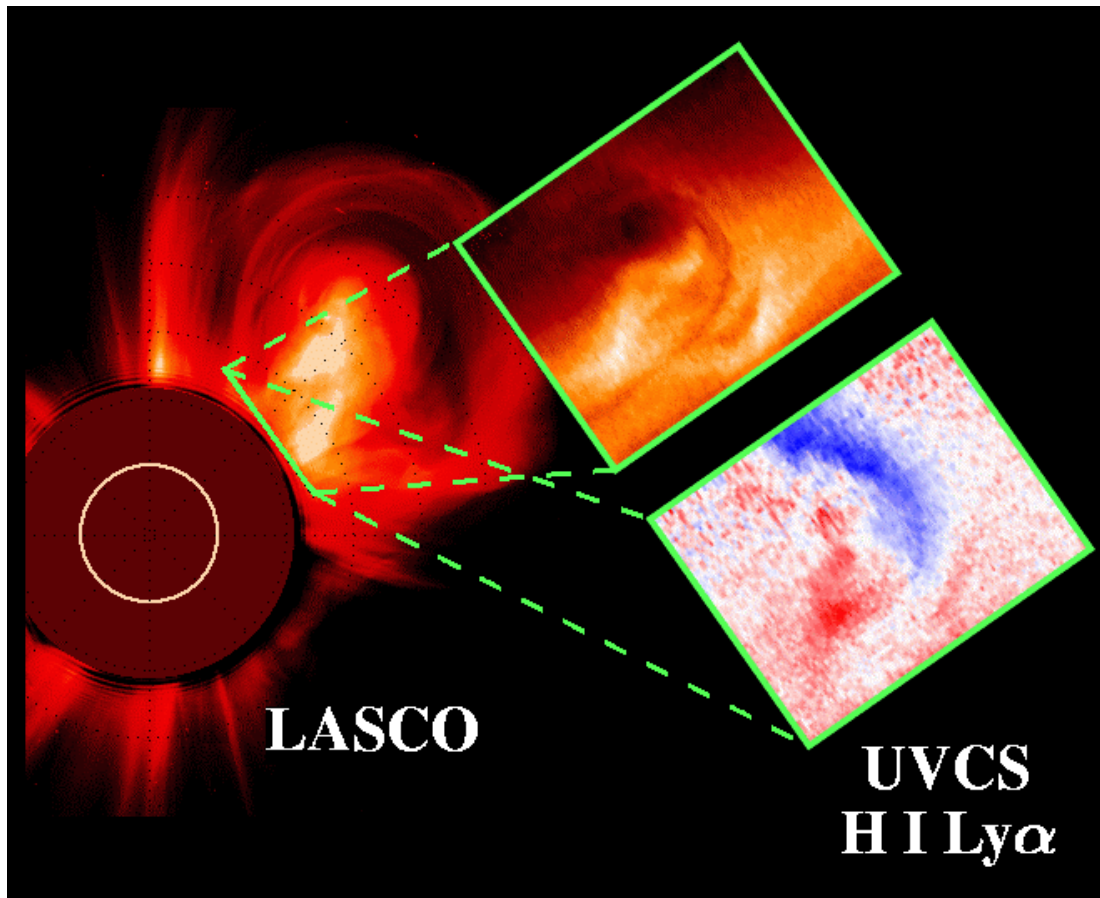
CMEs

- Coronal mass ejections (CMEs) are magnetically driven eruptions from the Sun that carry energetic, twisted strands of plasma into the solar system . . .

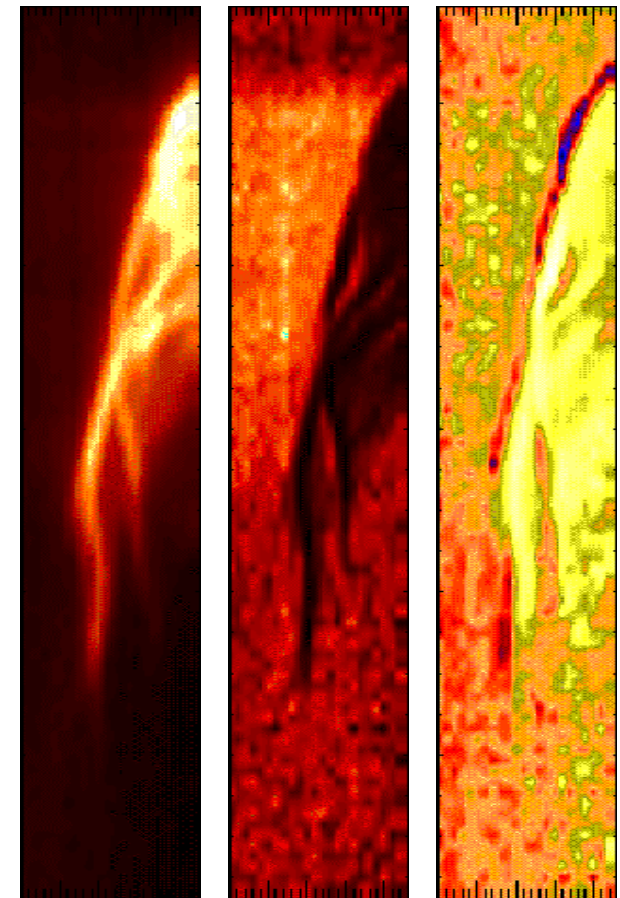


UVCS CME results: Doppler shifts

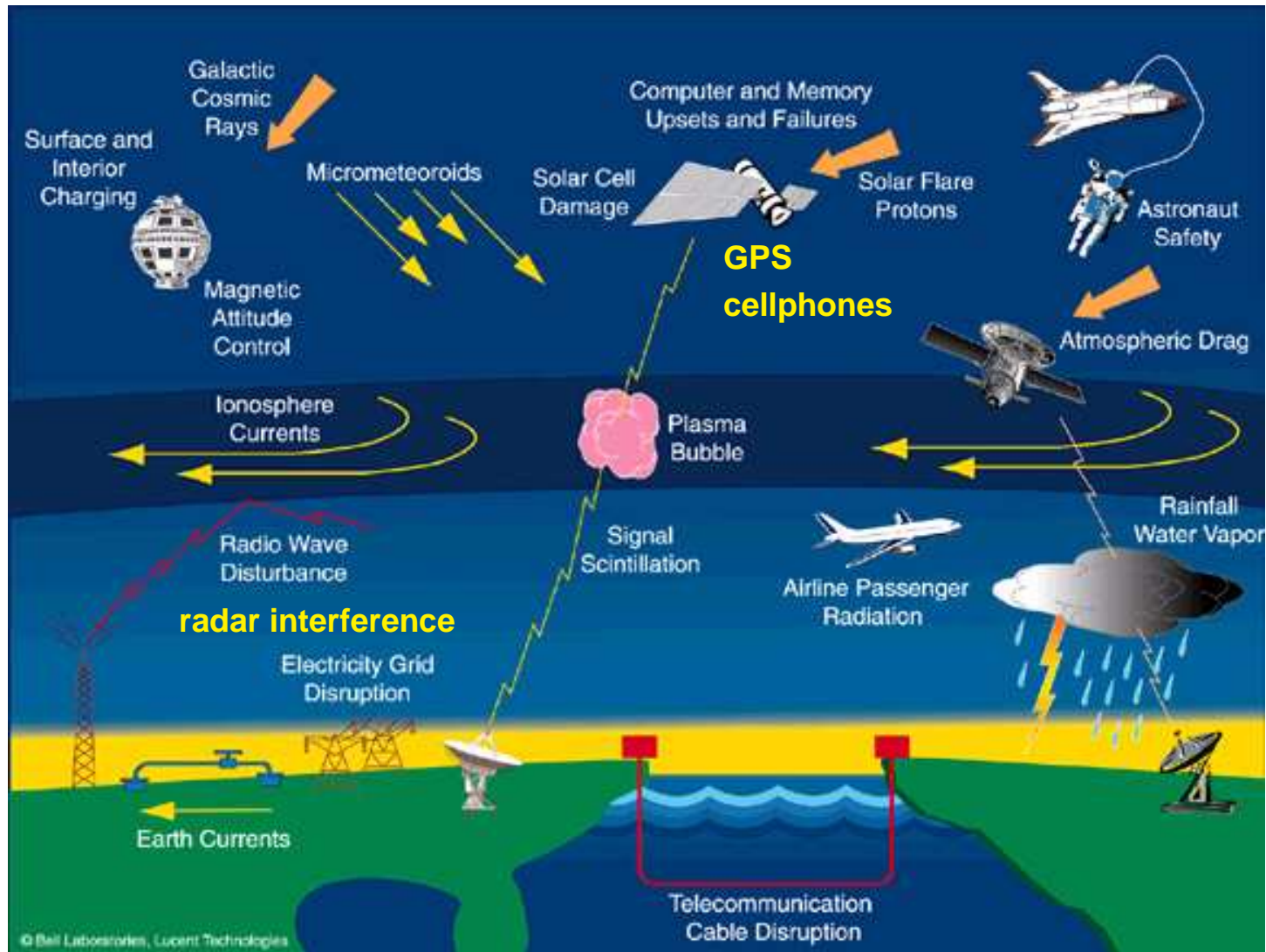
- Images and movies contain much information, but **spectroscopy** provides more!



Feb. 12, 2000



Practical application: space weather prediction?



Conclusions

- SOHO and UVCS results have led to new understanding of the acceleration of the solar wind, and demonstrated the power of spectroscopy to learn things that cannot be gleaned from images alone!

Get involved?

- We welcome more participation and collaboration with students!
- 10 years of data is only beginning to be fully analyzed.
- Many web tools and tutorials have been developed, with more coming online all the time. →
- *For more info:* <http://cfa-www.harvard.edu/~scranmer/>

