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and the Sun, Hamburg, Germany, July 5–9, 2004*



## **New Insights into Solar Wind Physics from SOHO**

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**Background and brief history**



**The Solar and Heliospheric Observatory (SOHO)**

- Instrument overview
- “Launching” of the solar wind from the surface
- Coronal holes and the fast solar wind
- Streamers and the slow solar wind
- *Why is the fast/slow wind fast/slow?* —→ (space weather)



**Conclusions and future prospects**

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# Discovery of the Solar Wind

## The solar corona:

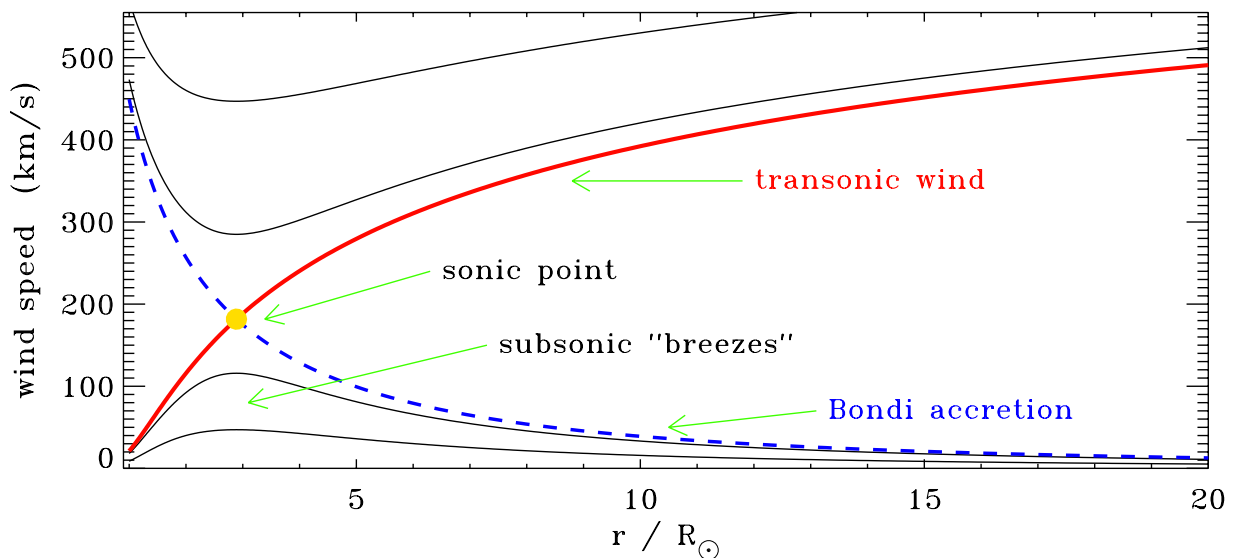
- ★ 1870s: unknown emission lines; a new element called “*coronium?*”
- ★ 1930s: Lines were identified as highly ionized ions:  $\text{Ca}^{12+}$ ,  $\text{Fe}^{9+}$  to  $\text{Fe}^{13+}$

$$T > 1 \text{ million K}$$



## The solar wind:

- ★ 1860s to 1950s: evidence builds for outflowing plasma in the solar system (flares → geomagnetic storms; anti-sunward comet tails)
- ★ 1958: Eugene Parker proposed that the hot corona provides enough **gas pressure** to counteract gravity!



- ★ 1962: *Mariner 2* provided first direct confirmation of the continuous, supersonic solar wind.

# Exploring the Solar Wind (1970s to present)

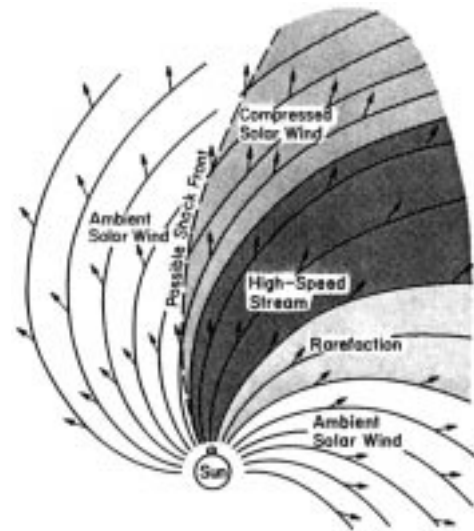
★ Two relatively distinct types of solar wind flow were found:

{	high-speed (500–800 km/s)	low density	~laminar flow
	low-speed (300–500 km/s)	high density	variable, filamentary

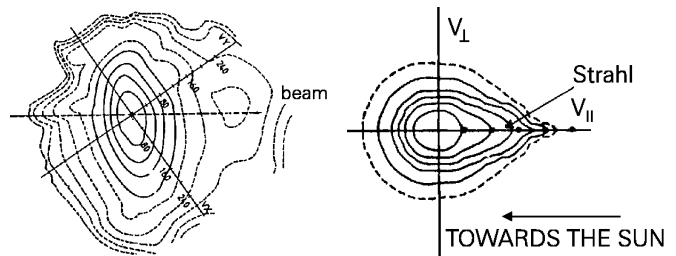
★ Neighboring wind streams with different speeds form Corotating Interaction Regions (CIRs):

★ Uncertainties about which type is “ambient” persisted because measurements were limited to the ecliptic plane . . .

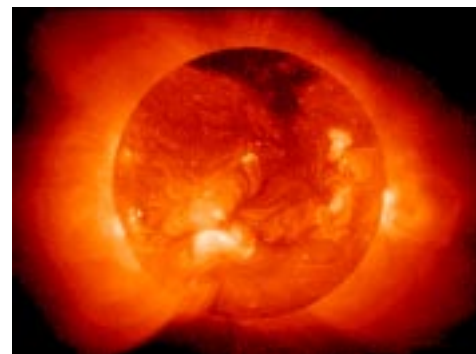
★ **Ulysses** left the ecliptic; provided 3D view of wind’s **source regions**.



★ **Helios** explored the inner solar wind (0.3–1 AU); saw strong departures from **Maxwellian** velocity distributions:

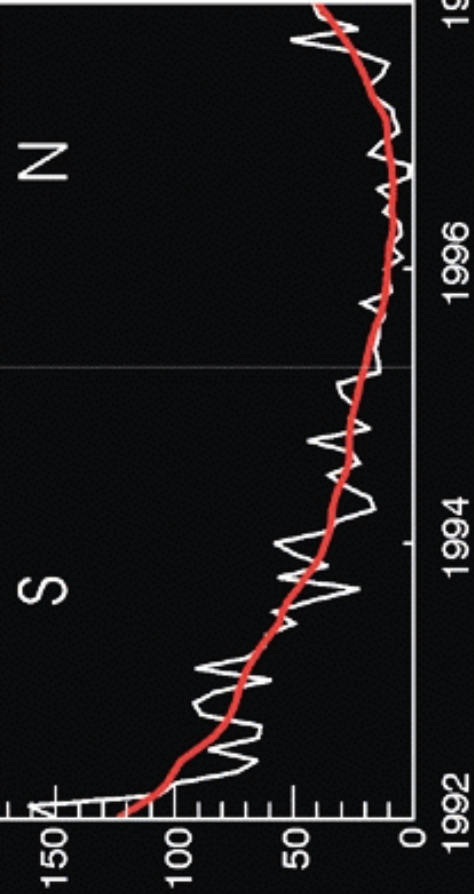
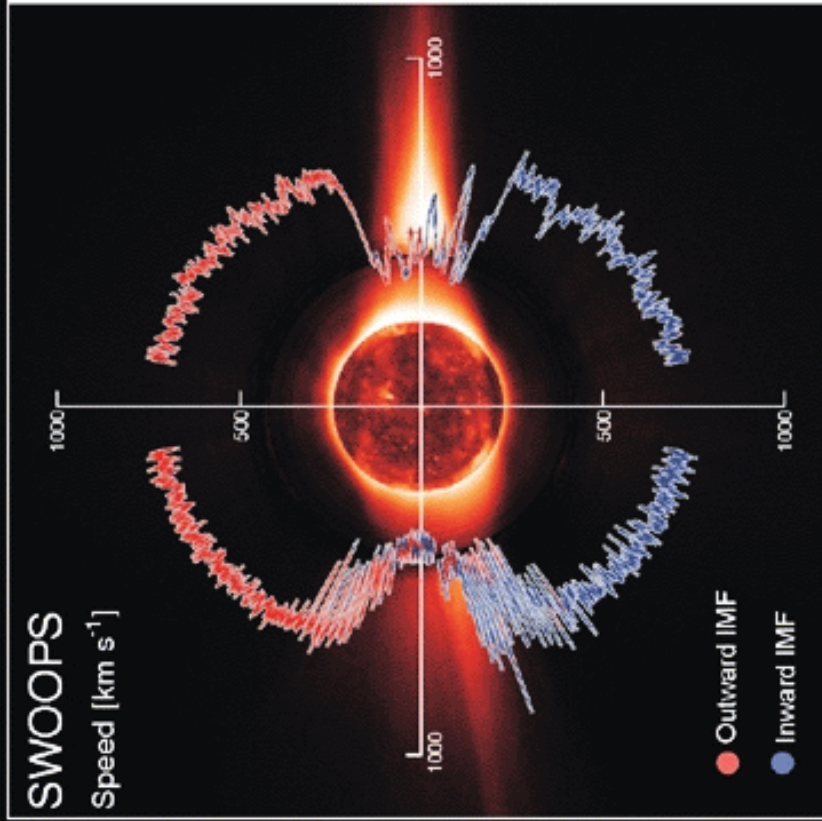


★ **Yohkoh** observed solar X-rays over a full solar cycle; discovered new transient phenomena; provided much more detail about how **coronal heating** depends on the **magnetic field**.

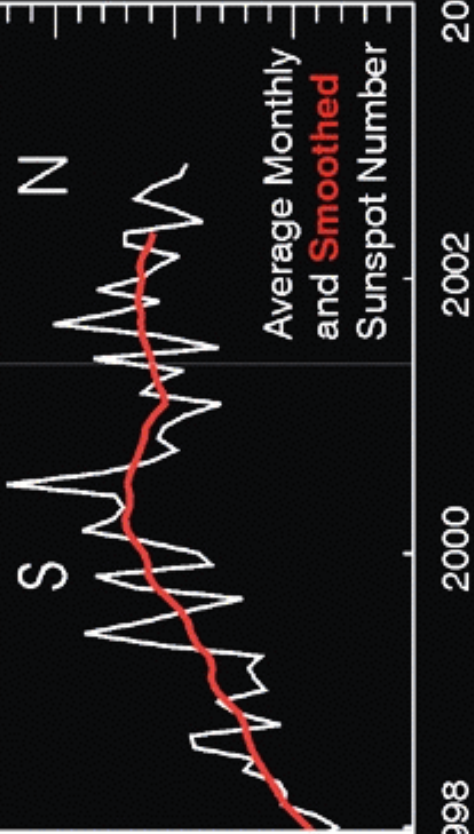
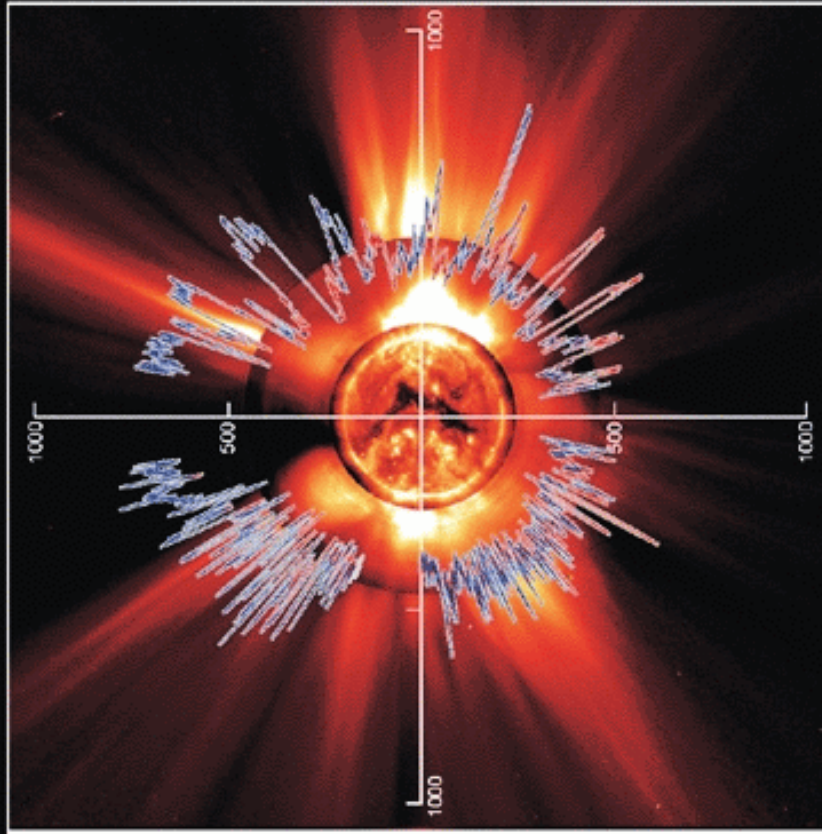


**We still have not uniquely identified the physical processes that heat the corona and accelerate the solar wind . . . .**

# Ulysses First Orbit



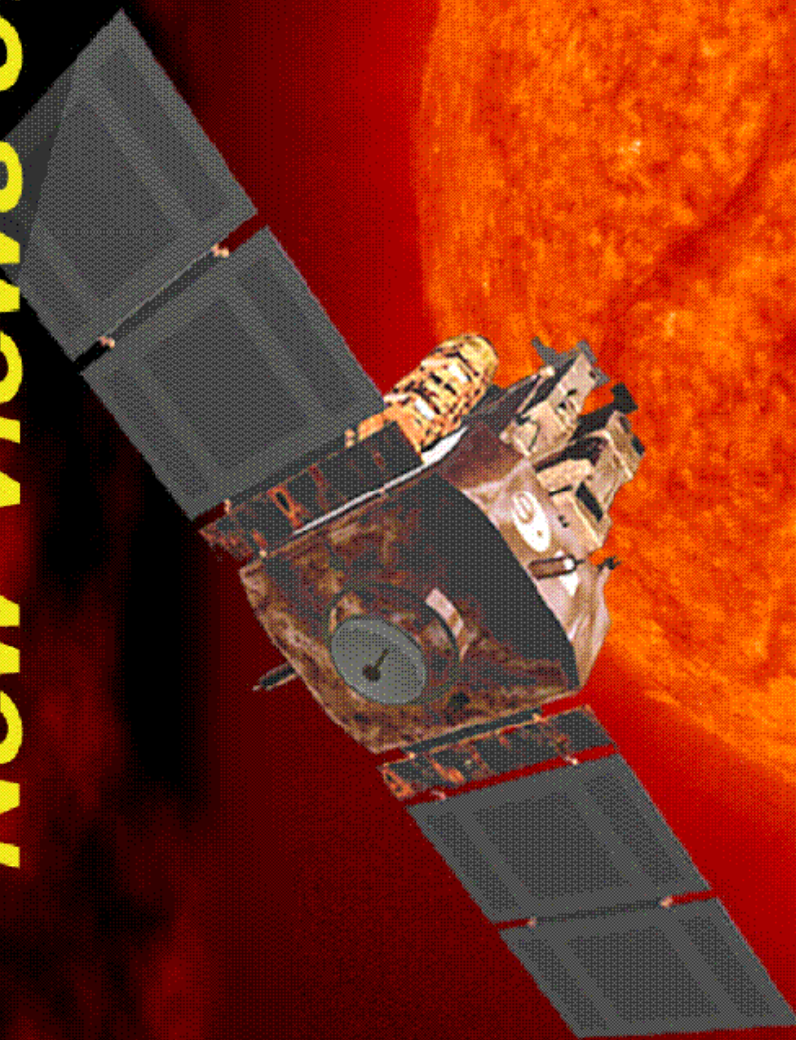
# Ulysses Second Orbit



# SOHO

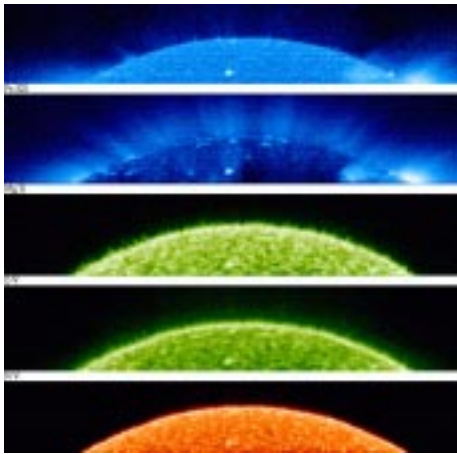
The Solar and Heliospheric  
Observatory

## New Views of the Sun

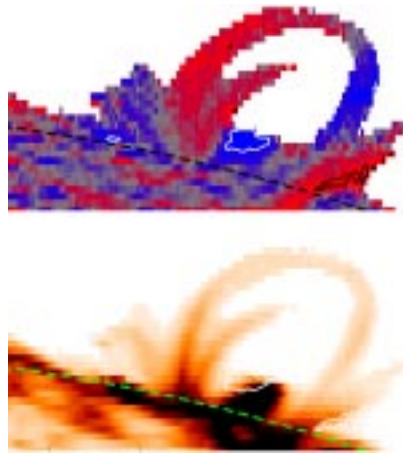


# SOHO Instruments: Outer Solar Atmosphere

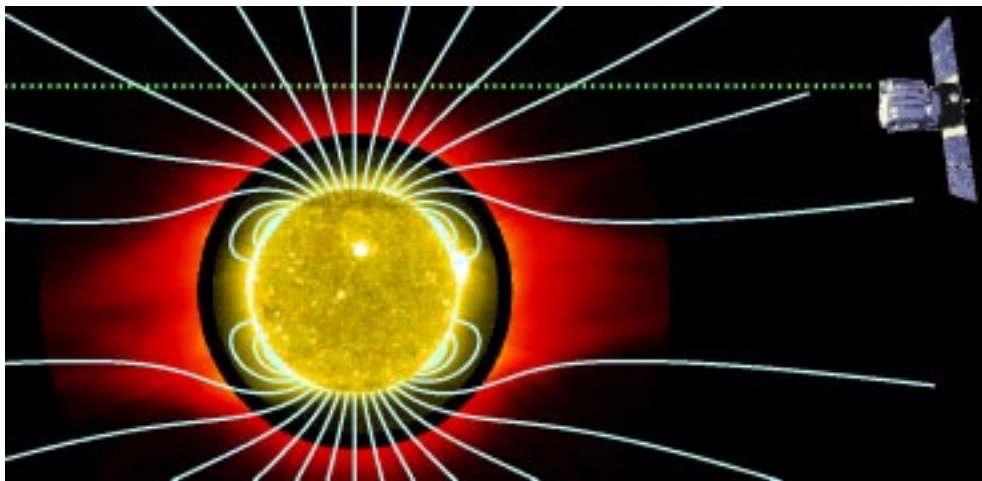
SUMER (UV spectrometer)



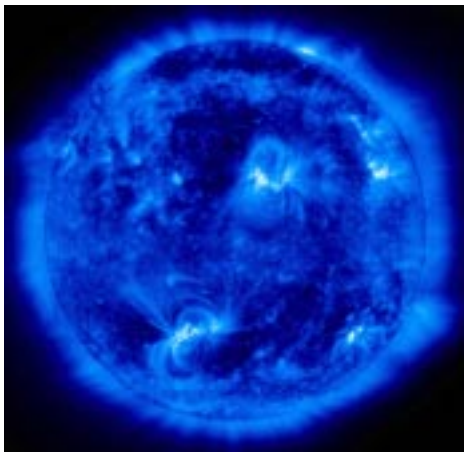
CDS (EUV spectrometer)



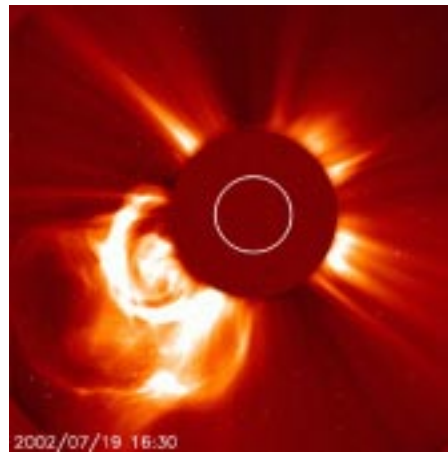
UVCS (UV coronagraph spectrometer)



EIT (EUV imager)

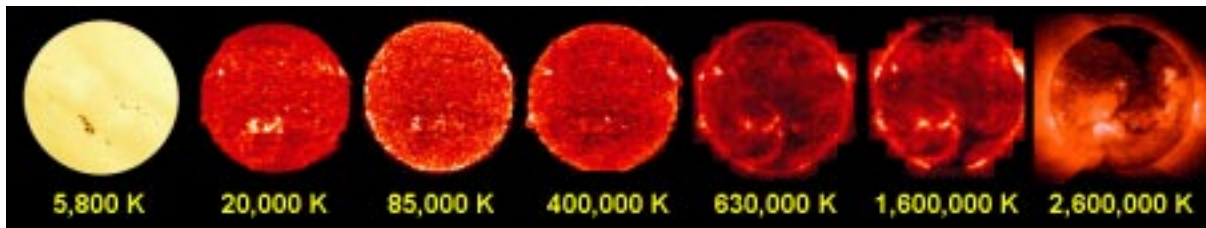


LASCO (visible coronagraph)

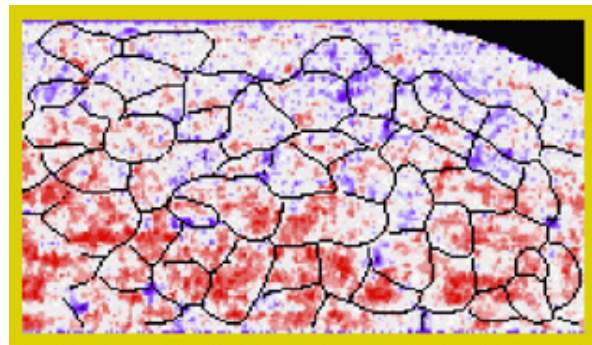
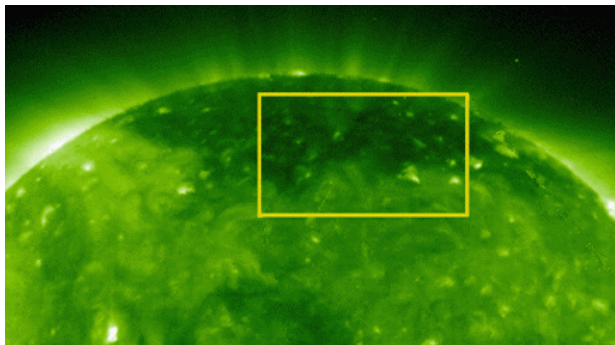


# Wind Origins in Open Magnetic Regions

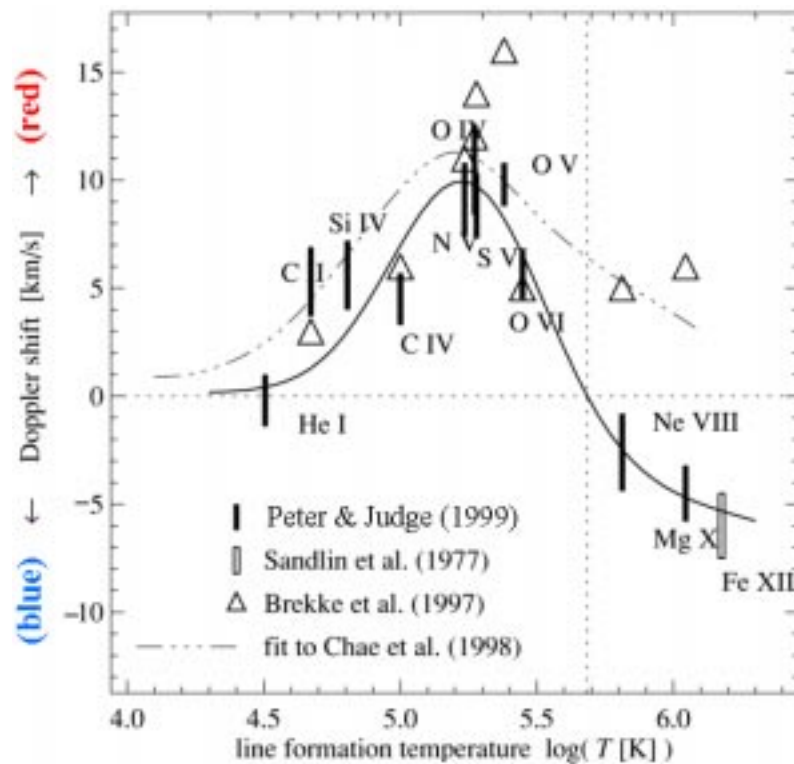
- ★ Sharpness of the transition region is evident from CDS spectroscopy:



- ★ SUMER spectroscopy shows blueshifts indicating outflow (or upward propagating waves?) in the low corona in the **supergranular network**:
- ★ Coronal holes (e.g., Hassler et al. 1999)

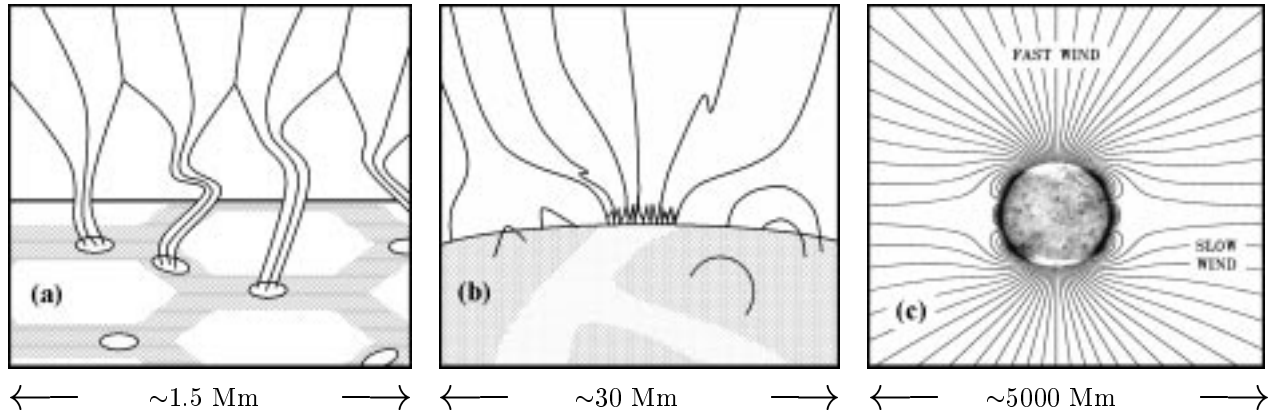


- ★ “Quiet Sun”



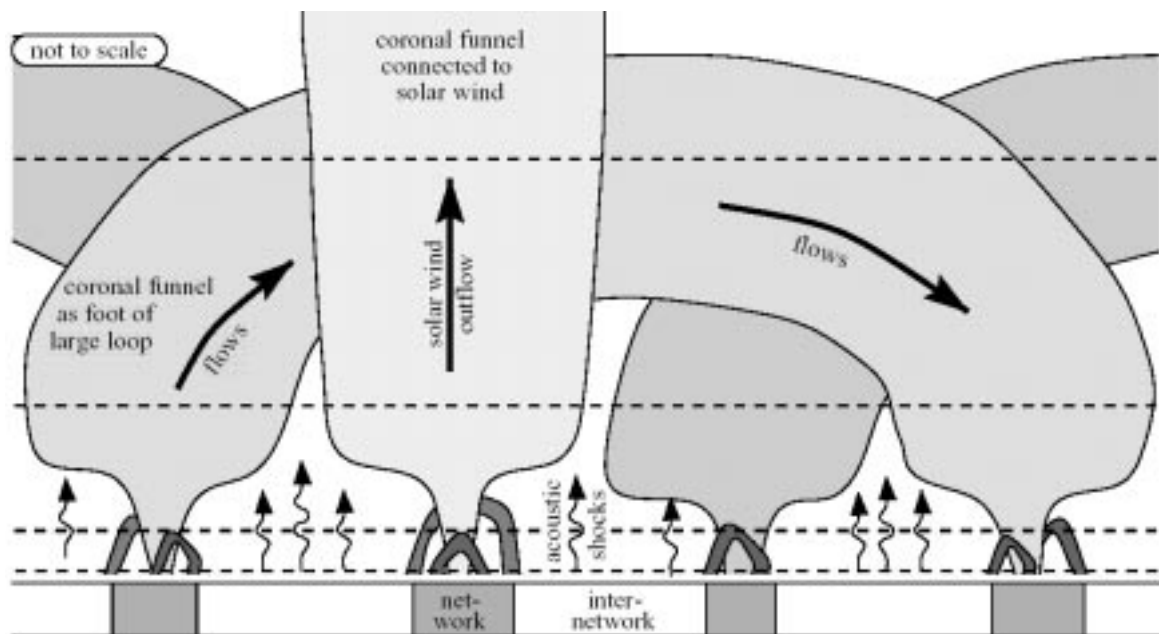
## Wind Origins in Open Magnetic Regions

- ★ These cartoons illustrate the basic **magnetic-field geometry** for flux tubes that feed the solar wind. Note the successive merging of flux tubes on granular and supergranular scales . . .



(Cranmer & van Ballegoijen 2004)

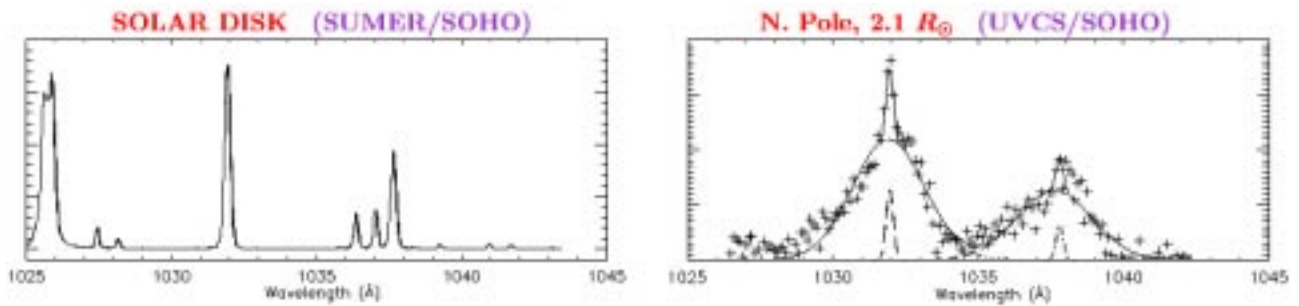
- ★ Interpreting observations of chromospheric and transition-region lines can be complicated . . .



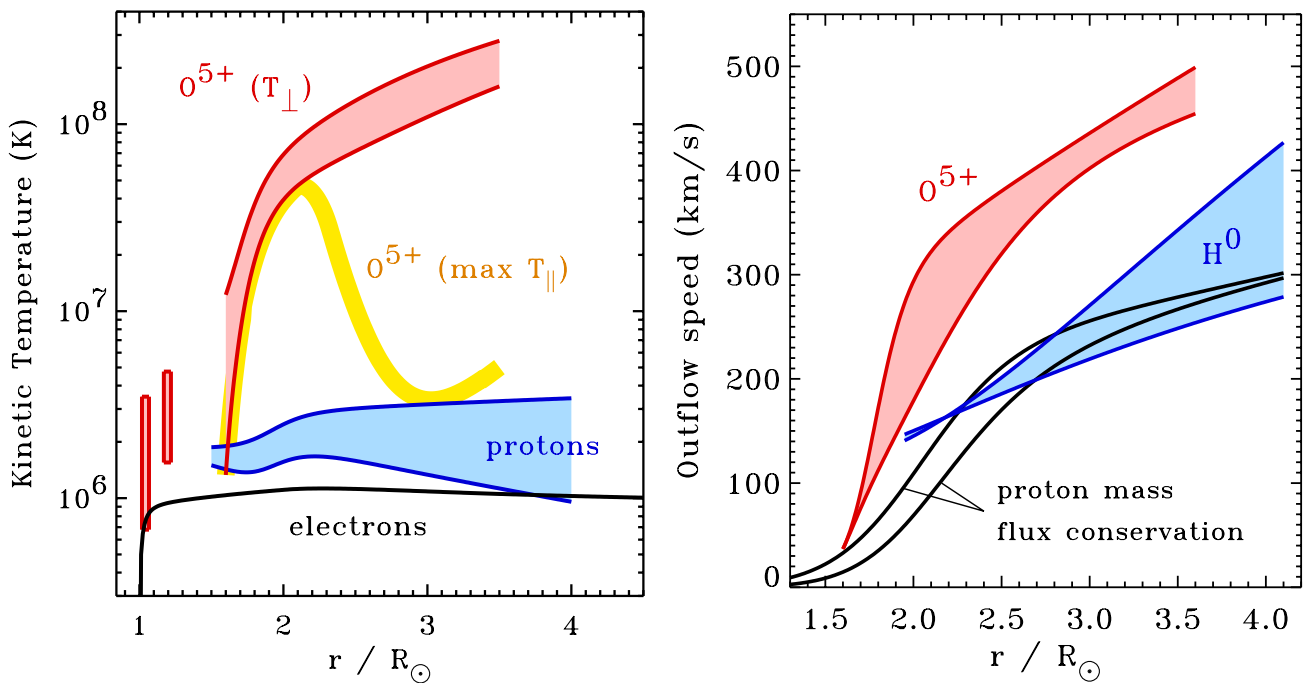
(Peter 2001)

# Fast Solar Wind: acceleration & heating

- ★ UVCS measured plasma properties of hot ( $> 10^6$  K) protons and heavy ions in north/south **polar coronal holes** at solar minimum.
- ★ **Simplest diagnostic:** WIDTHS of emission lines provide a near-direct measurement of the velocity distribution projected along the line of sight (Doppler broadening): i.e.,  $\sim T_{\perp}$  **in coronal holes**. O VI 1032, 1037:



- ★ Lines are formed via resonant scattering (of disk photons). The total intensity depends on the radial component of ion's velocity distribution (Doppler dimming/pumping); i.e.,  $\sim u_{\parallel}$  &  $T_{\parallel}$  **in coronal holes:**

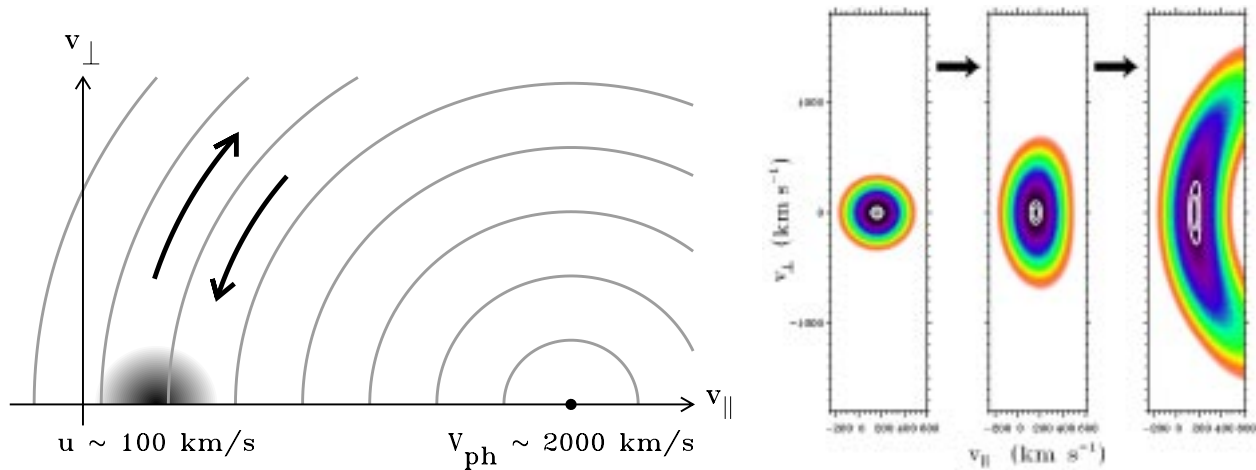


# Fast Solar Wind: acceleration & heating

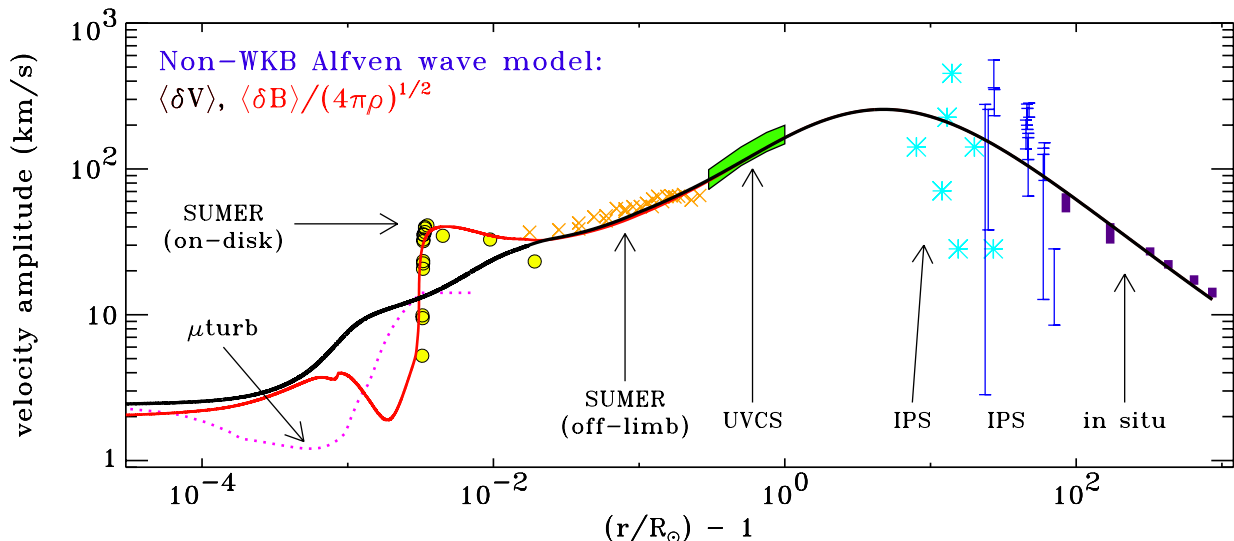
- ★ In the extended corona, energy must propagate up from the Sun and ultimately dissipate **collisionlessly** to heat the particles as observed:

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

- ★ **Ion cyclotron waves** ( $10^2$ – $10^4$  Hz) have been suggested as a natural energy source that can be tapped to preferentially heat/accelerate ions:



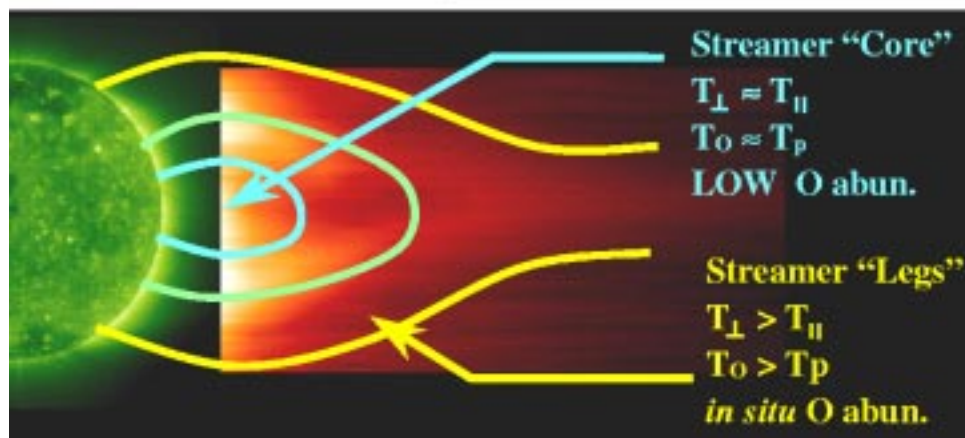
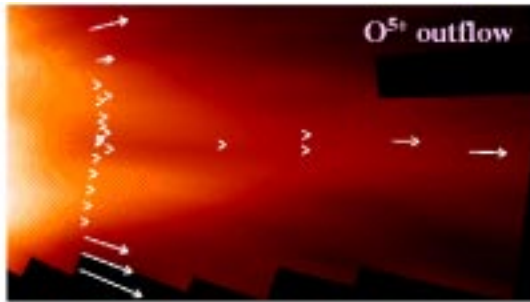
- ★ MHD waves with frequencies  $> 10$  Hz have not yet been observed in the corona or wind, but there is ample evidence for **lower-frequency Alfvén waves** ( $< 0.01$  Hz) which may be converted into ion cyclotron waves gradually in the corona.



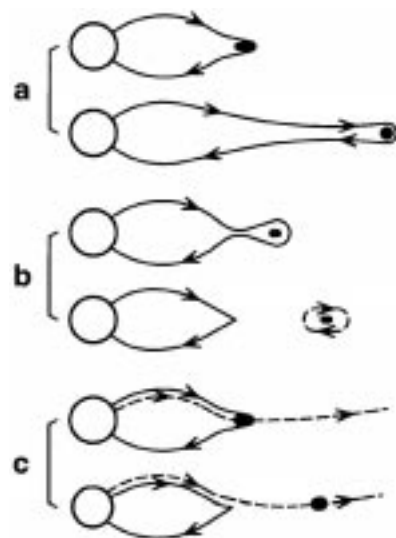
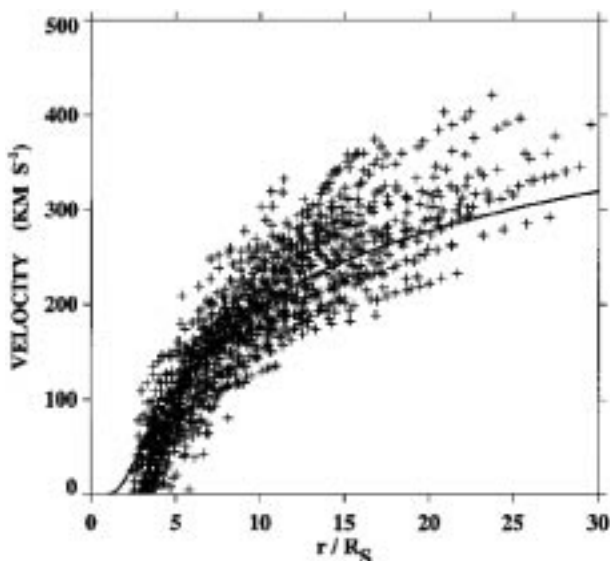
## Slow Solar Wind: a coronal “census”

- ★ The visible corona is dominated by bright, tapered “**helmet streamers**” known for decades to be associated with the slowest solar wind streams. But what is the **magnetic topology** of these regions?

- ★ **UVCS spectroscopy** found outflows consistent with slow wind only along the **EDGES** of streamers at solar minimum:



- ★ **LASCO movies** spotlighted low-contrast “blobs” continually ejected from streamer CUSPS . . .



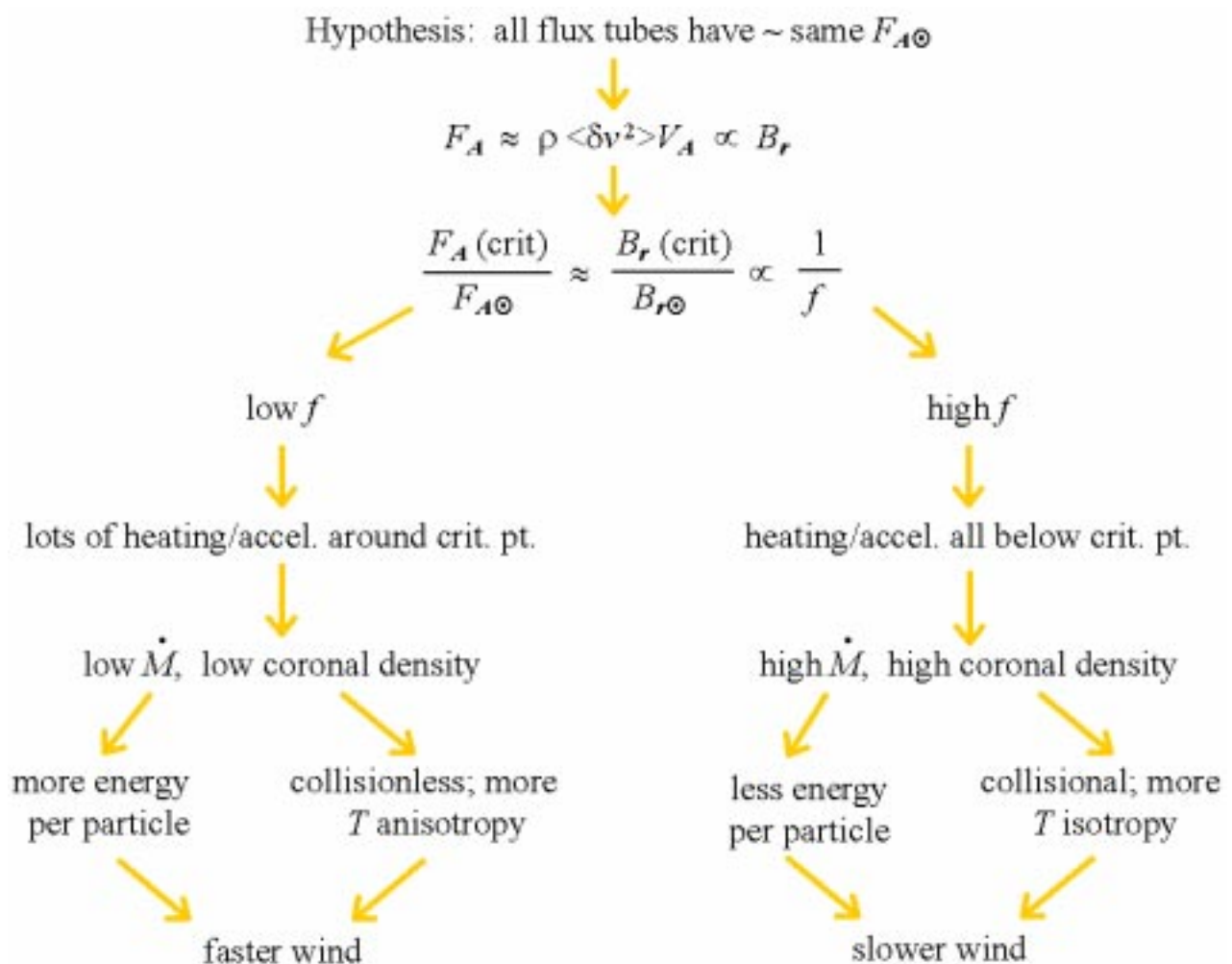
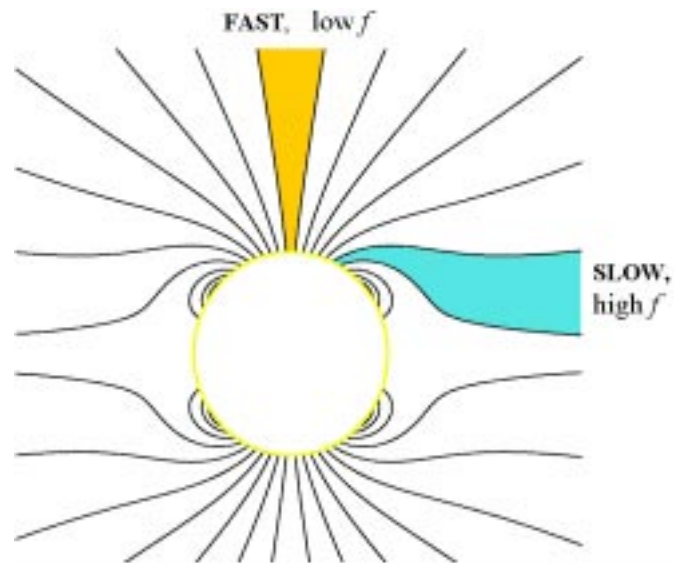
# Why is the fast [slow] wind fast [slow]?

★ **Easy answer:** More heating in coronal holes? (Probably not!)

★ Comparison of coronal magnetic field models with *in situ* solar wind speeds gives a useful **empirical law:**

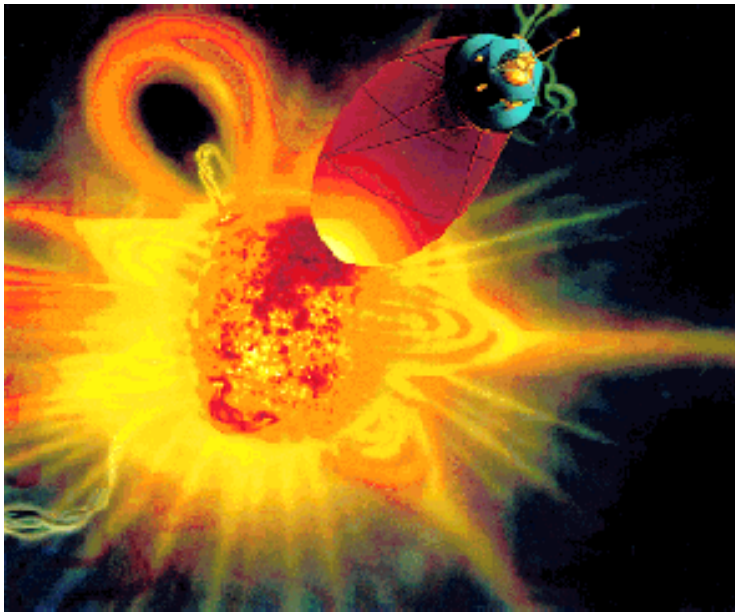
$$u_{\infty} \sim f^{-2/5}$$

(e.g., Wang & Sheeley 1990).



## Conclusions

- ★ Our understanding of the dominant physics in the acceleration region of the solar wind is increasing rapidly . . . but so is the complexity!
- ★ We still don't know several key plasma parameters (e.g.,  $T_e$  and  $T_p$ ) with sufficient accuracy, as a function of  $r$ ,  $\theta$ , and solar cycle.
  - ⇒ SDO, STEREO, & Solar-B will launch in a few years.  
We really need *Solar Probe* and a next-generation UVCS !



- ★ Future models must predict the properties of **many minor ion species**, because these may be the only means of distinguishing between competing models that, e.g., predict the *same* bulk plasma heating rates.
- ★ The lines of communication between { solar, stellar, plasma } physicists must be kept open.
- ★ *See also:* <http://cfa-www.harvard.edu/~scranmer/>