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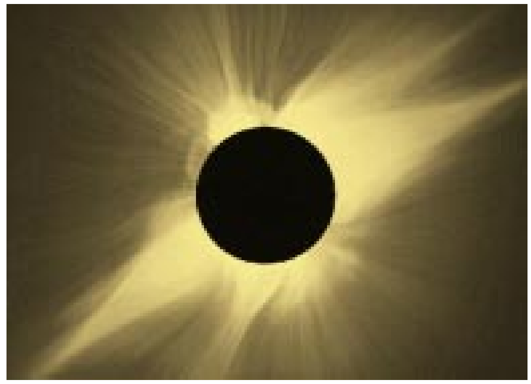
New Insights into Solar Wind Physics from SOHO

Steven R. Cranmer
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

- **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**

Discovery of the Solar Wind

The solar corona:

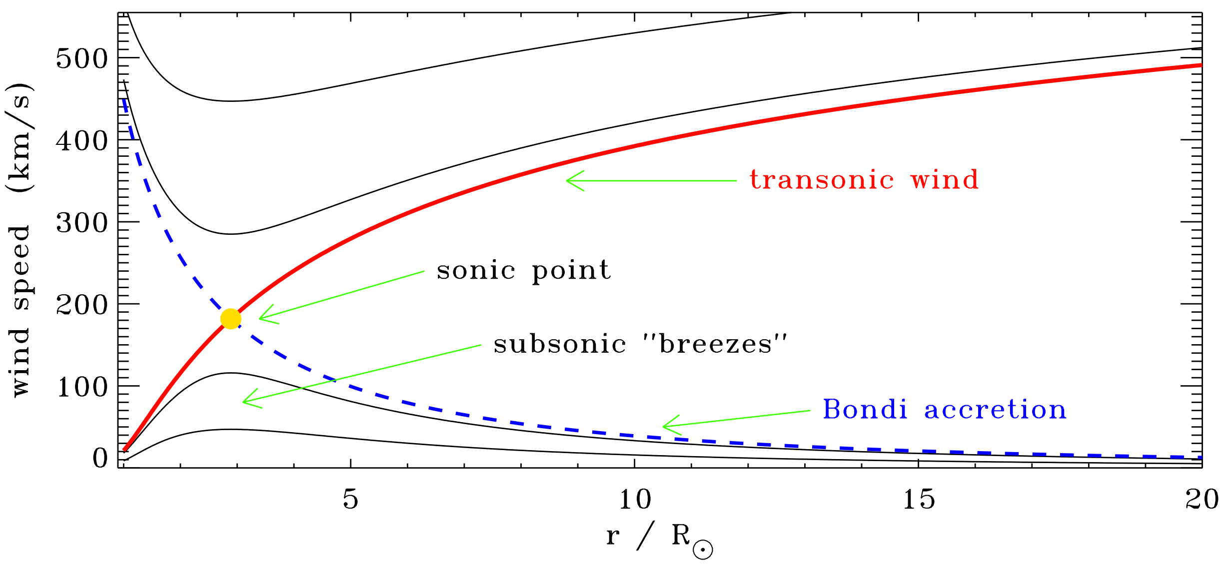


- ⋆ 1870s: unknown emission lines; a new element called *"coronium?"*
- ⋆ 1930s: Lines were identified as highly ionized ions: Ca^{12+}, Fe^{9+} to Fe^{13+}

$T > 1$ million K

The solar wind:

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



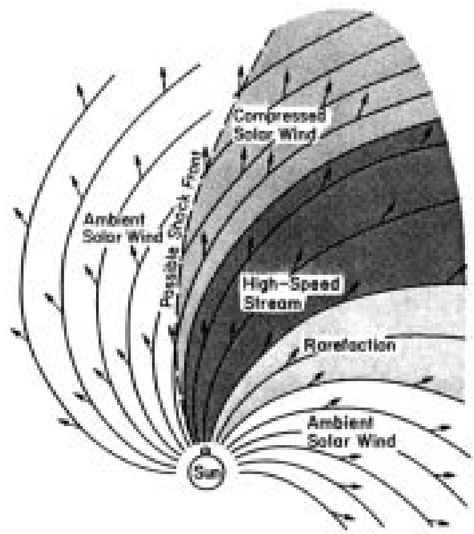
- ⋆ 1962: *Mariner 2* provided first direct confirmation of the continuous, supersonic solar wind.

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

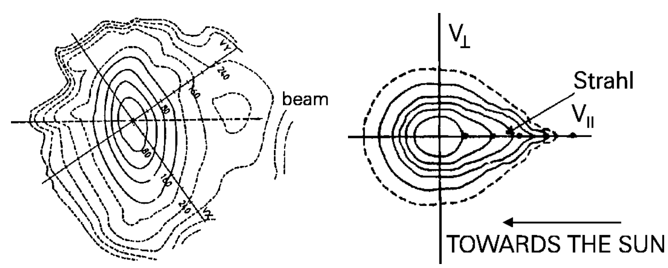
★ Neighboring wind streams with different speeds form Corotating Interaction Regions (CIRs):



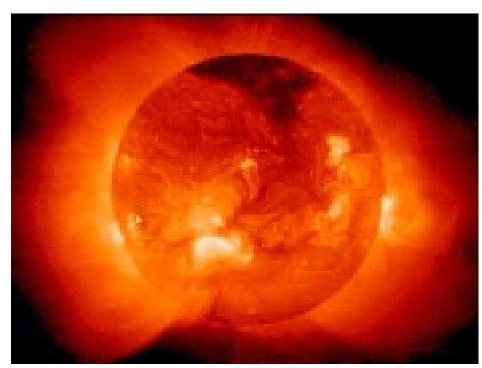
★ Uncertainties about which type is “ambient” persisted because measurements were limited to the ecliptic plane . . .

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

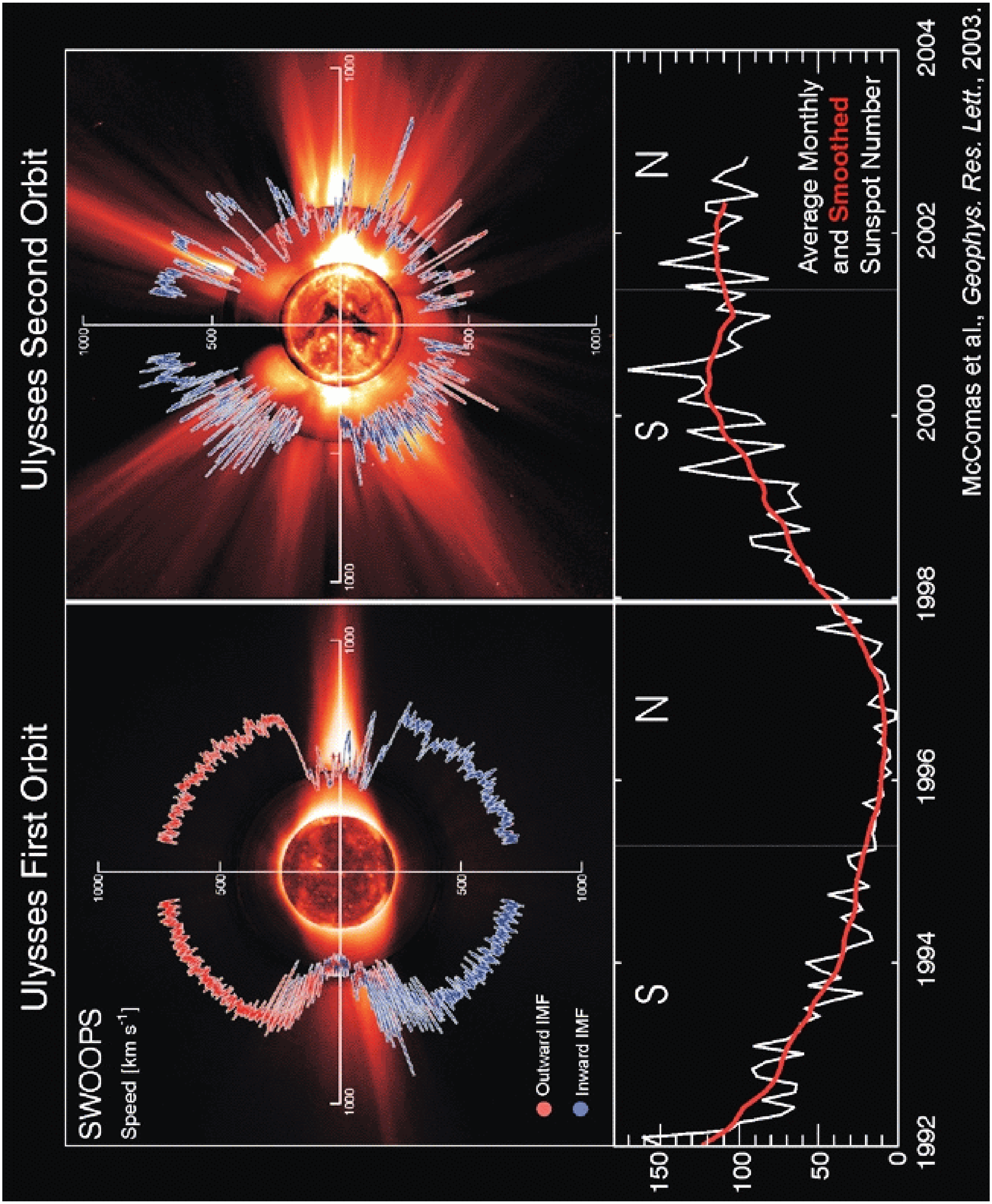
★ **Helios** explored the inner solar wind (0.3–1 AU); saw strong departures from **Maxwellian** velocity distributions:



★ **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 . . . .

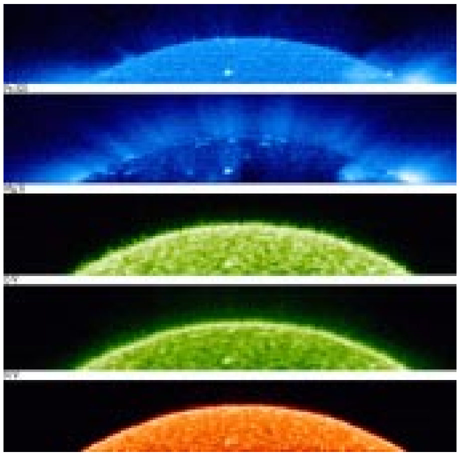


Ulysses First Orbit
Ulysses Second Orbit
SWOOPS
Speed [km s^-1]
Outward IMF
Inward IMF
1000
500
S
N
S
N
Average Monthly
and Smoothed
Sunspot Number
150
100
50
0
1992
1994
1996
1998
2000
2002
2004
McComas et al., Geophys. Res. Lett., 2003.

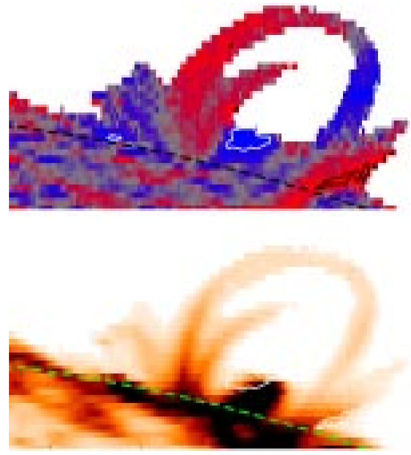

SOHO
The Solar and Heliospheric Observatory
New Views of the Sun

SOHO Instruments: Outer Solar Atmosphere

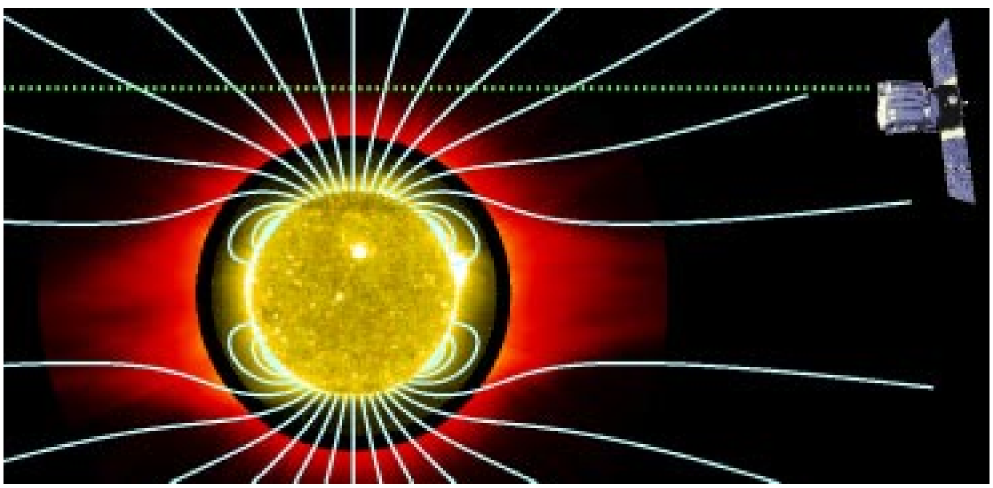
SUMER (UV spectrometer)



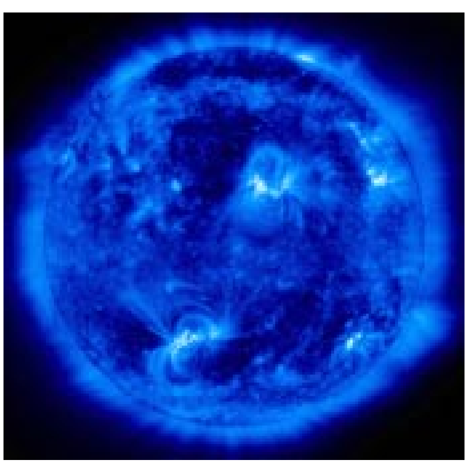
CDS (EUV spectrometer)



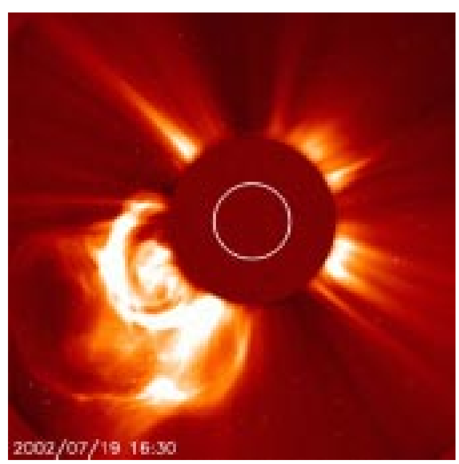
UVCS (UV coronagraph spectrometer)



EIT (EUV imager)

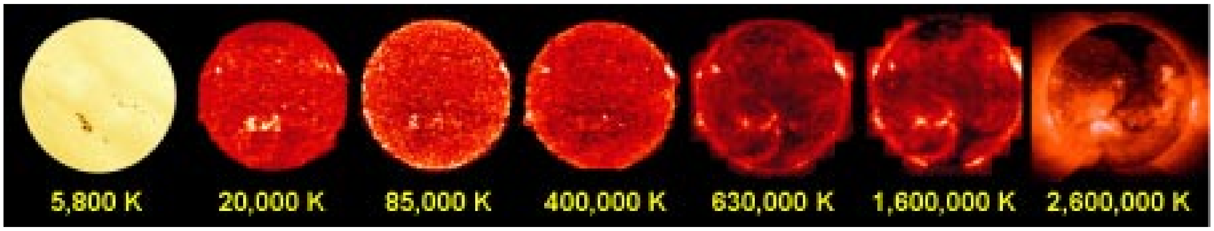


LASCO (visible coronagraph)

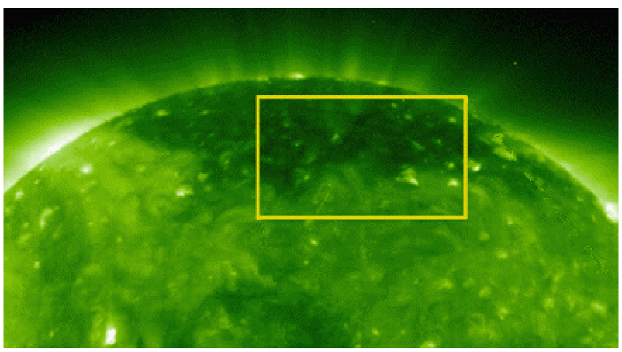


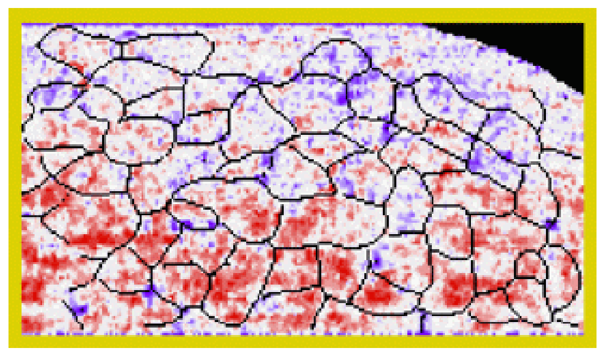
Wind Origins in Open Magnetic Regions

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

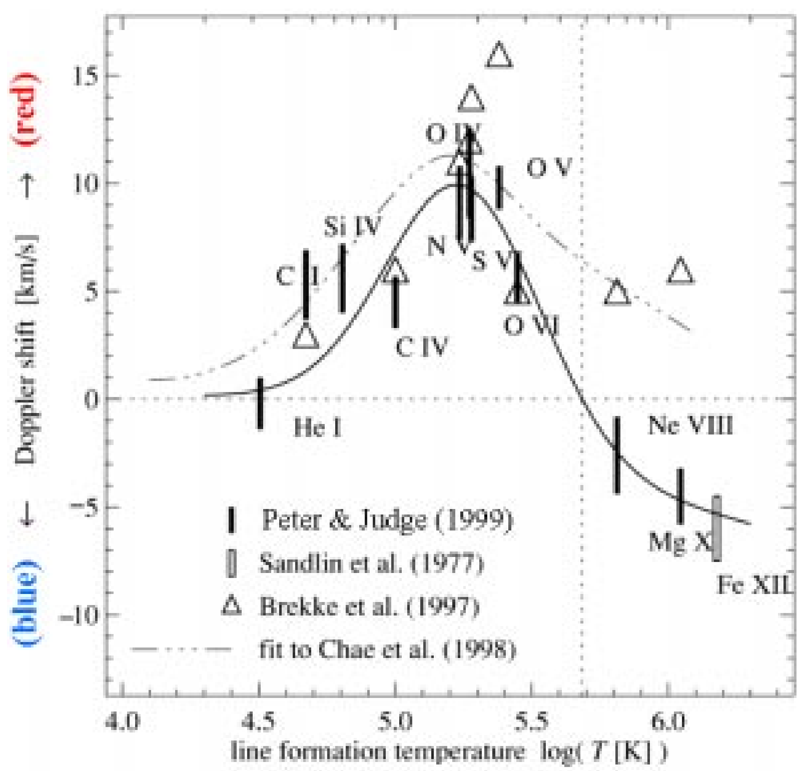


- SUMER spectroscopy shows blueshifts indicating outflow (or upward propagating waves?) in the low corona in the **supergranular network:**
- Coronal holes (e.g., Hassler et al. 1999)



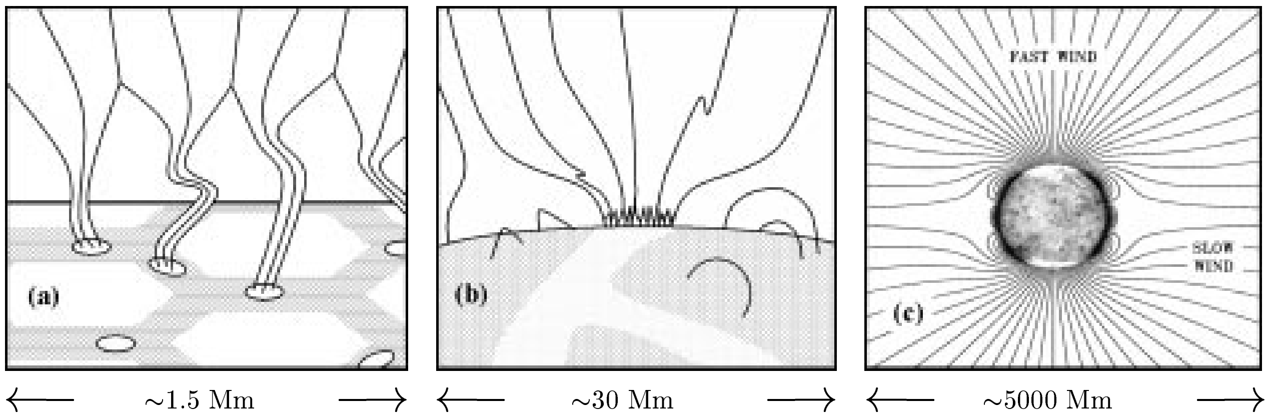


- “Quiet Sun”



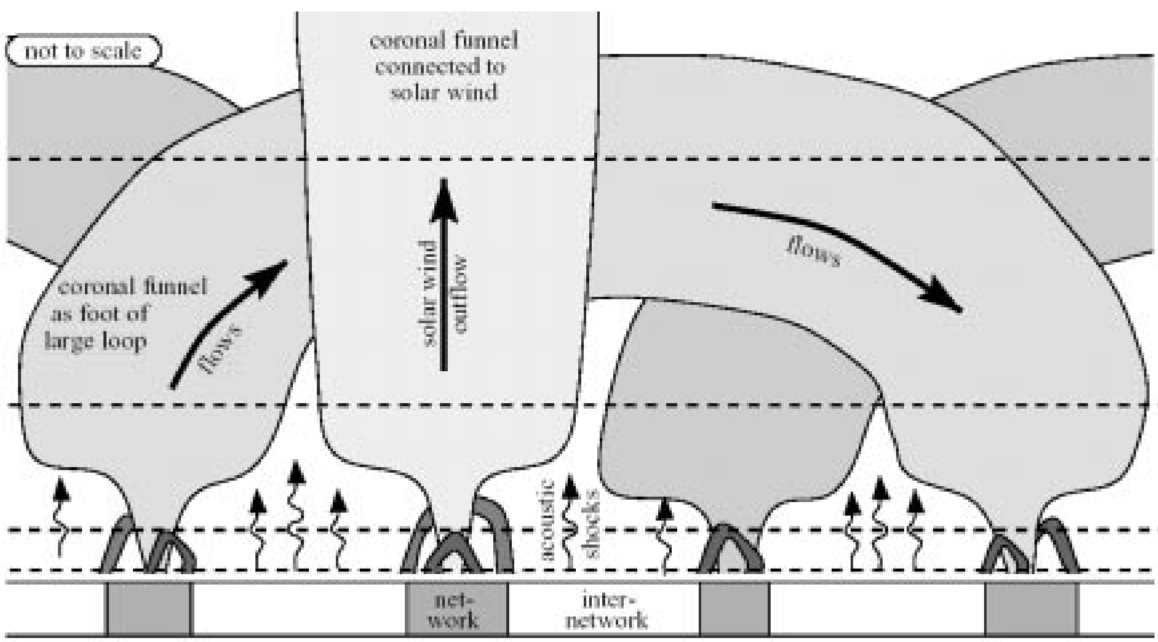
Wind Origins in Open Magnetic Regions

★ 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 Ballegooijen 2004)

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

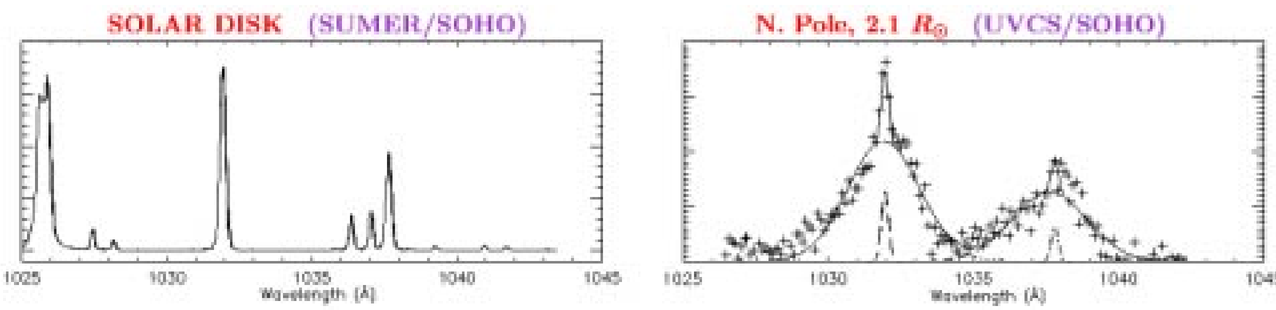


(Peter 2001)

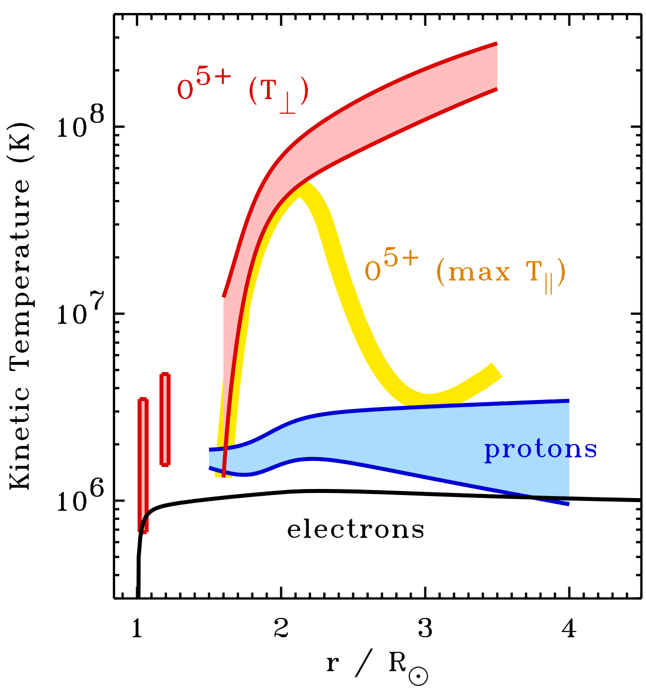
Fast Solar Wind: acceleration & heating

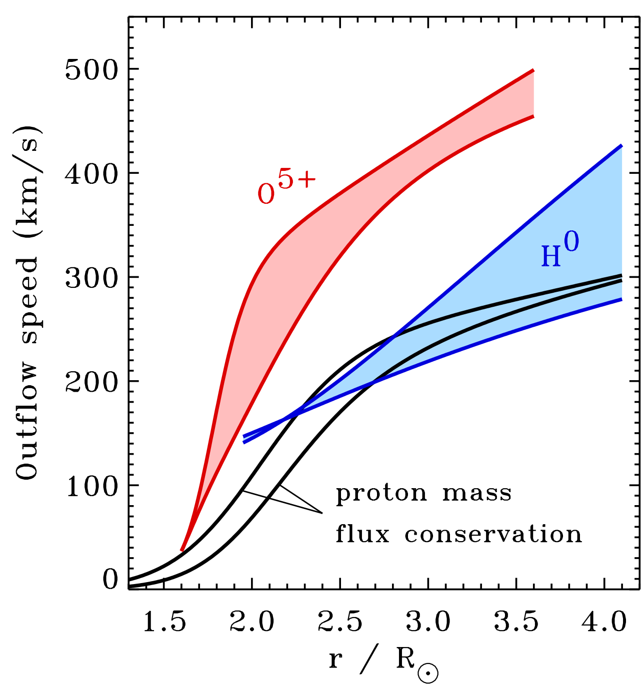
- ⋆ UVCS measured plasma properties of hot ($> 10^6$ K) protons and heavy ions in north/south **polar coronal holes** at solar minimum.

- ⋆ **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:**



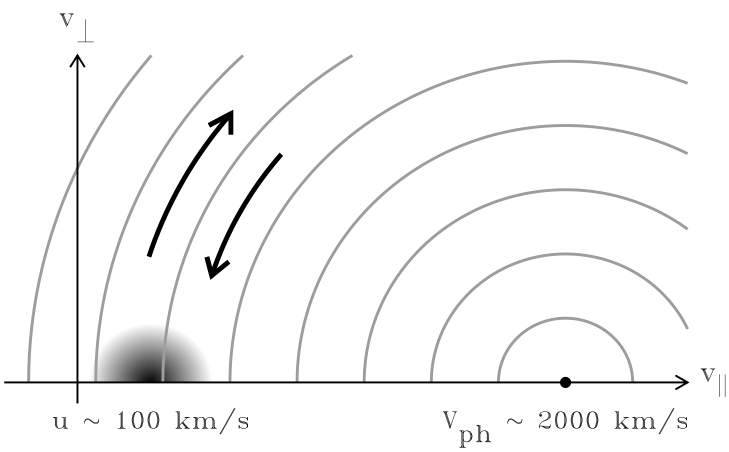


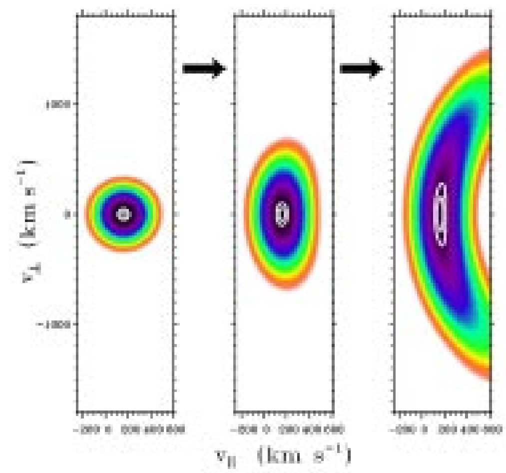
Fast Solar Wind: acceleration & heating

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

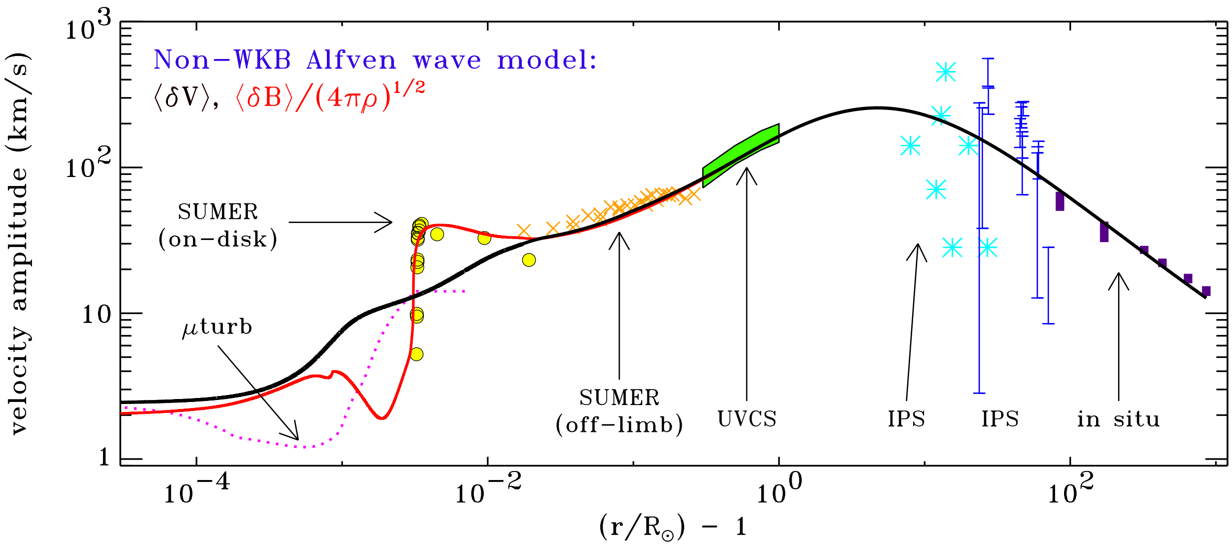
$$\left\{\begin{array}{c} T_{\rm ion} \gg T_{\rm p} > T_{\rm e} \\ (T_{\rm ion}/T_p) > (m_{\rm ion}/m_p) \\ T_\perp \gg T_\parallel \\ u_{\rm ion} > u_p \end{array}\right\}$$

- **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:





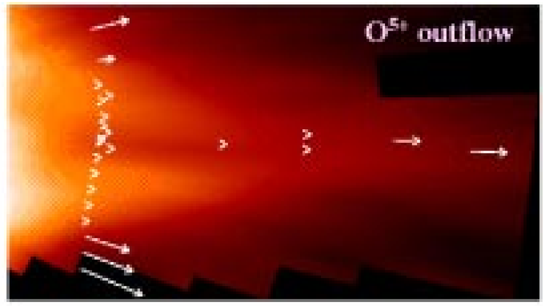
- MHD waves with frequencies > 10 Hz have not yet been observed in the corona or wind, but there is ample evidence for **lower-frequency Alfvén waves** (< 0.01 Hz) which may be converted into ion cyclotron waves gradually in the corona.

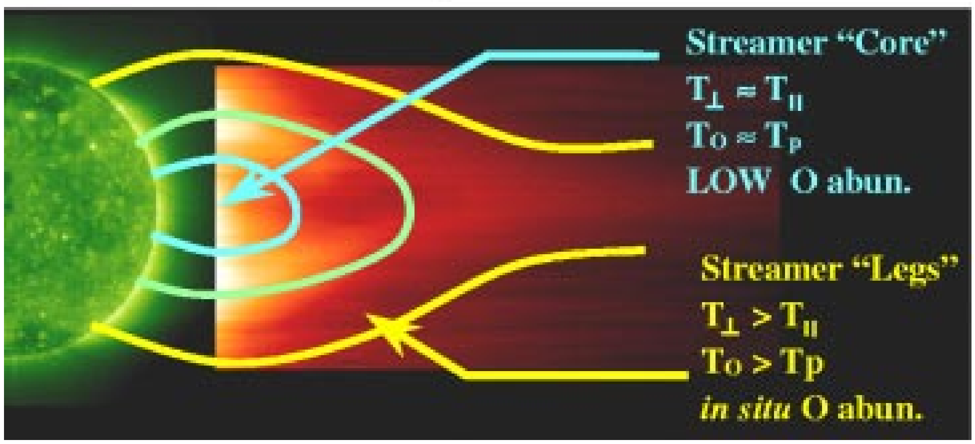


Slow Solar Wind: a coronal "census"

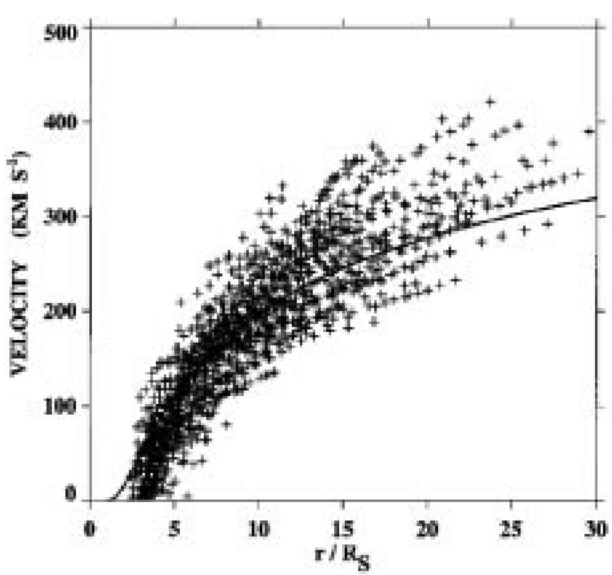
- The visible corona is dominated by bright, tapered **"helmet streamers"** known for decades to be associated with the slowest solar wind streams. But what is the **magnetic topology** of these regions?

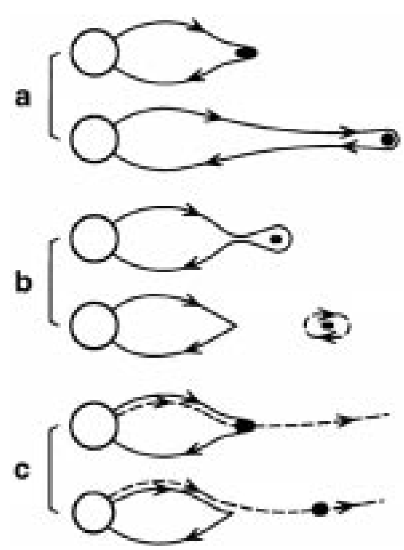
- **UVCS spectroscopy** found outflows consistent with slow wind only along the EDGES of streamers at solar minimum:





- **LASCO movies** spotlighted low-contrast "blobs" continually ejected from streamer CUSPS . . .





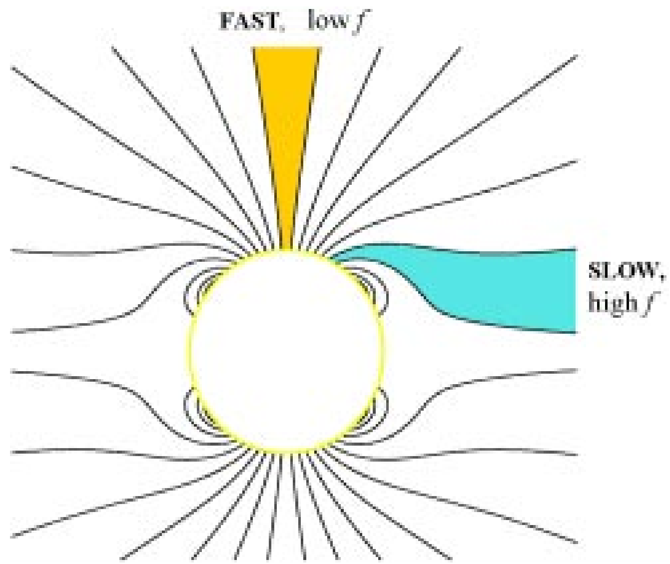
Why is the fast [slow] wind fast [slow]?

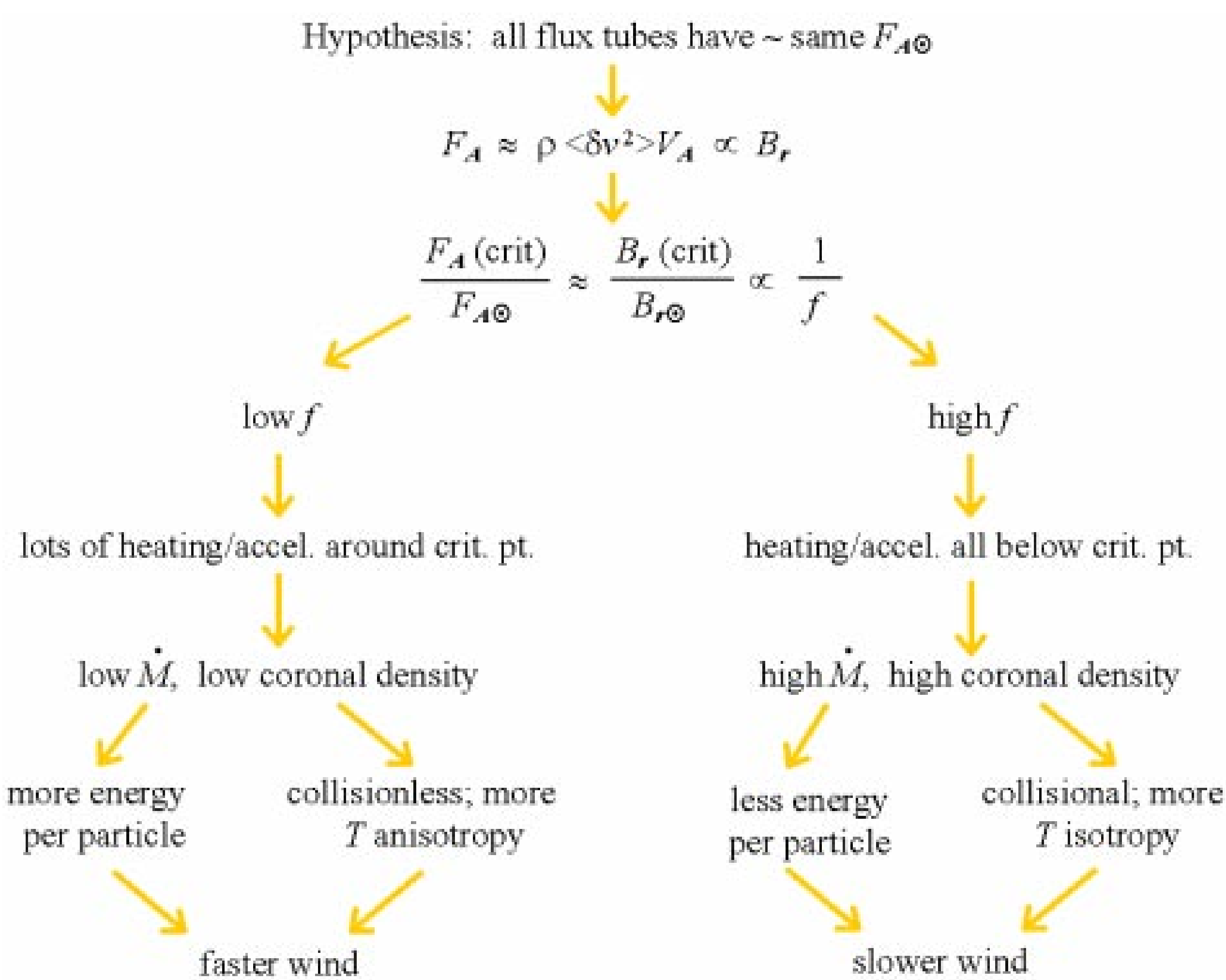
- ⋆ **Easy answer:** More heating in coronal holes? **(Probably not!)**

- ⋆ 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).

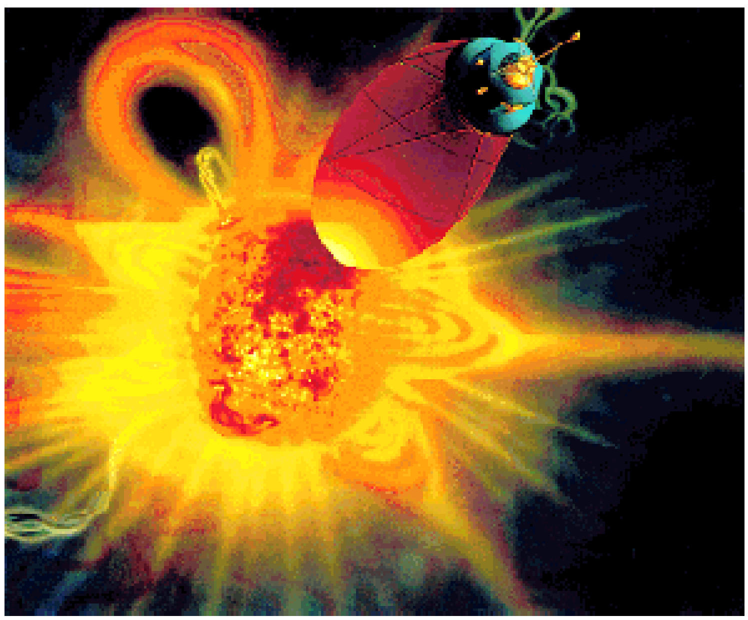




Conclusions

- ⋆ 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., $\boldsymbol{T}_{\mathrm{e}}$ and $\boldsymbol{T}_{\mathrm{p}}$) with sufficient accuracy, as a function of r, θ, 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/**