ASTR-6000 Seminar
COLLAGE: Coronal Heating, Solar Wind, & Space Weather

March 3, 2022

Solar wind evolution: from the rotating Sun to the heliopause

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Outline

1. Wrapping up ideas about how "flux-tube geometry is destiny" for fast & slow solar wind streams

2. Effects of solar rotation

   - The "Parker spiral" and corotating streams

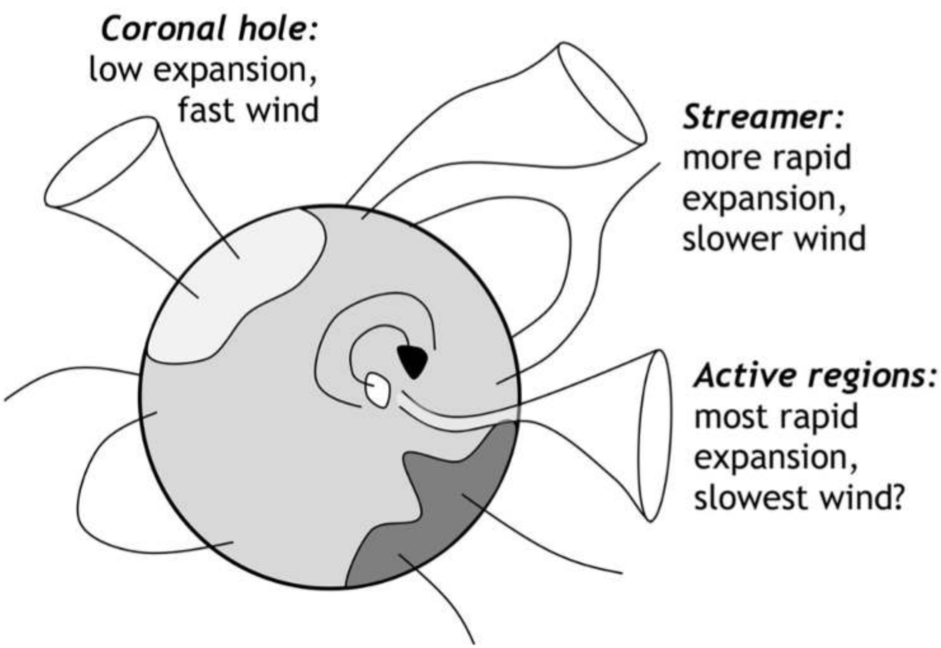
   - Corotating interaction regions (CIRs)

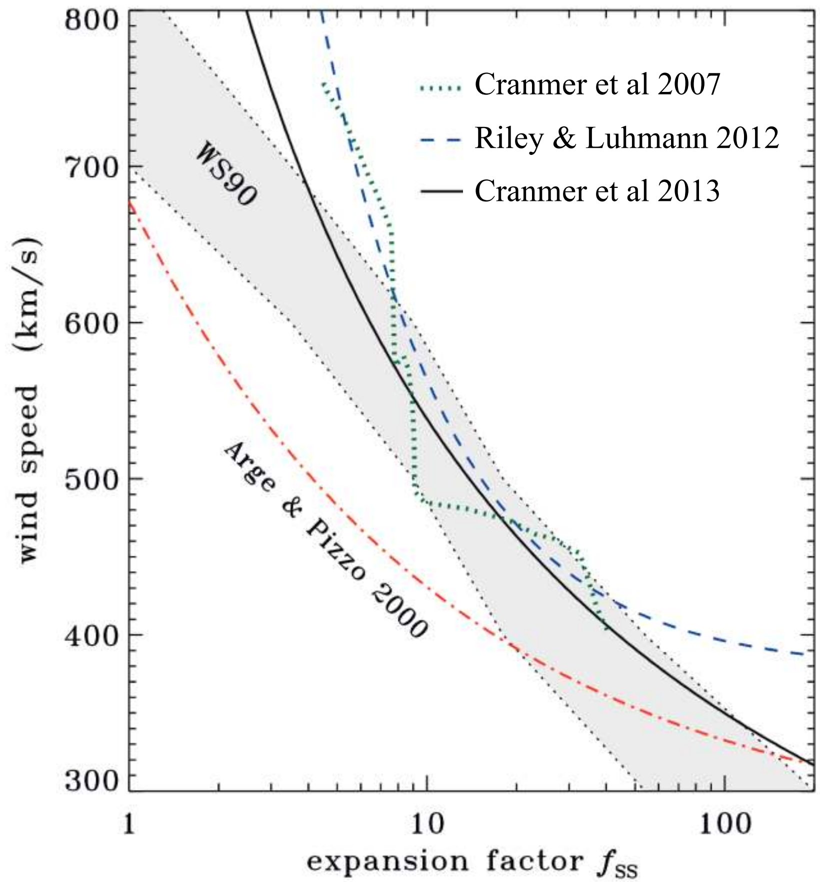
3. Evolution of turbulent fluctuations (corona to heliosphere)

4. The outer heliosphere

(1) *Solar wind flux-tube geometry*

We've seen how Yi-Ming **W**ang, Neil **S**heeley, & Nick **A**rge began to make use of a noticeable anti-correlation between wind speed at 1 AU and the superradial expansion factor f_{SS} at the PFSS source surface.

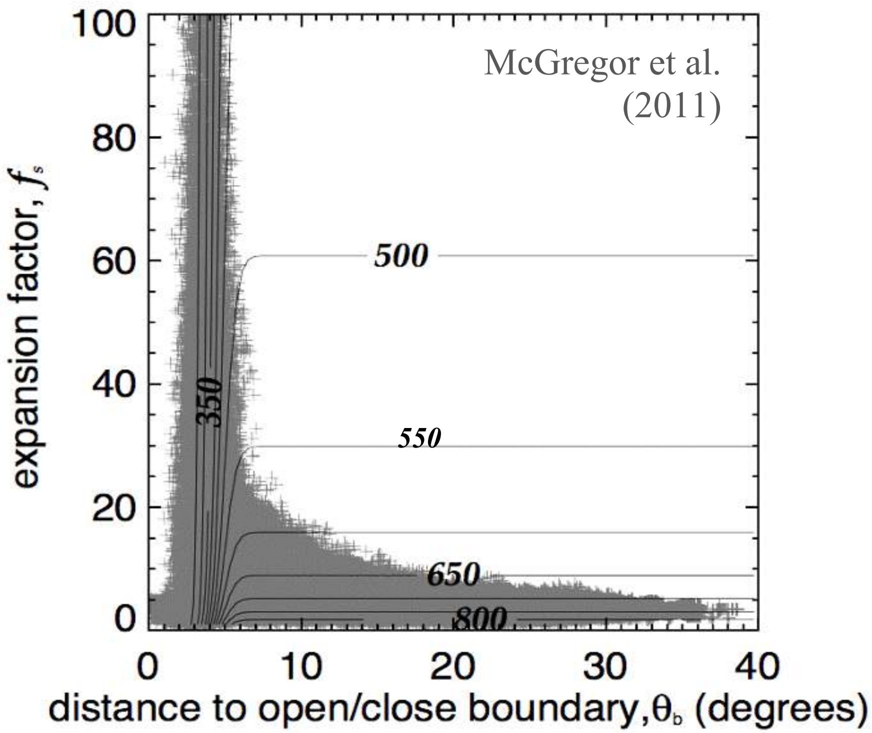




(1) *Solar wind flux-tube geometry*

- The original Wang & Sheeley (1990) anti-correlation can be improved a lot by adding a **second parameter…** but *which* second parameter works best?

Arge et al. (2000) proposed θ_b, the angular distance to the nearest coronal hole boundary:



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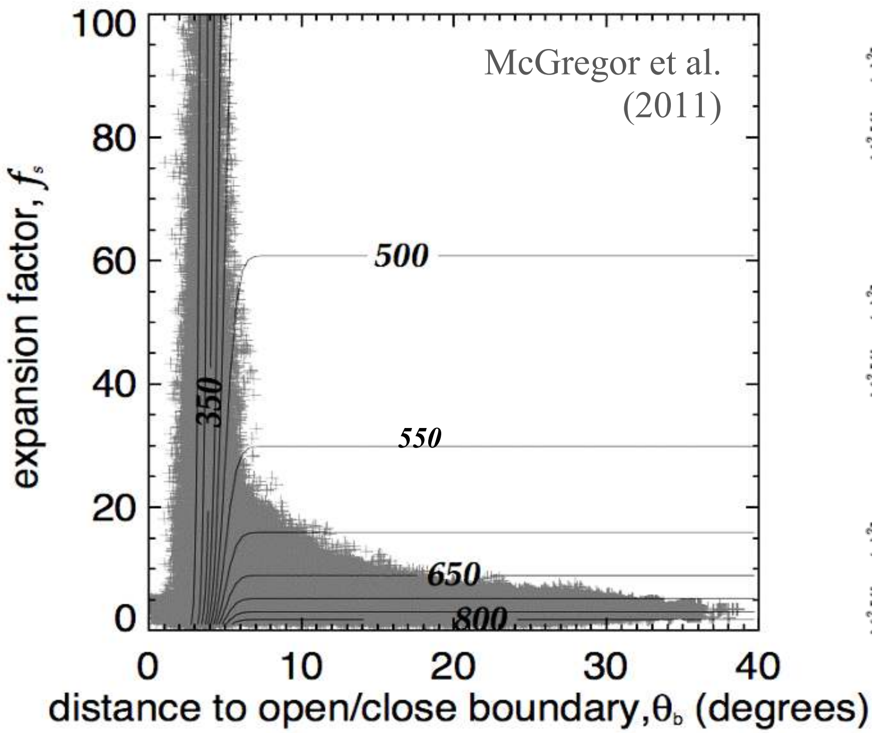
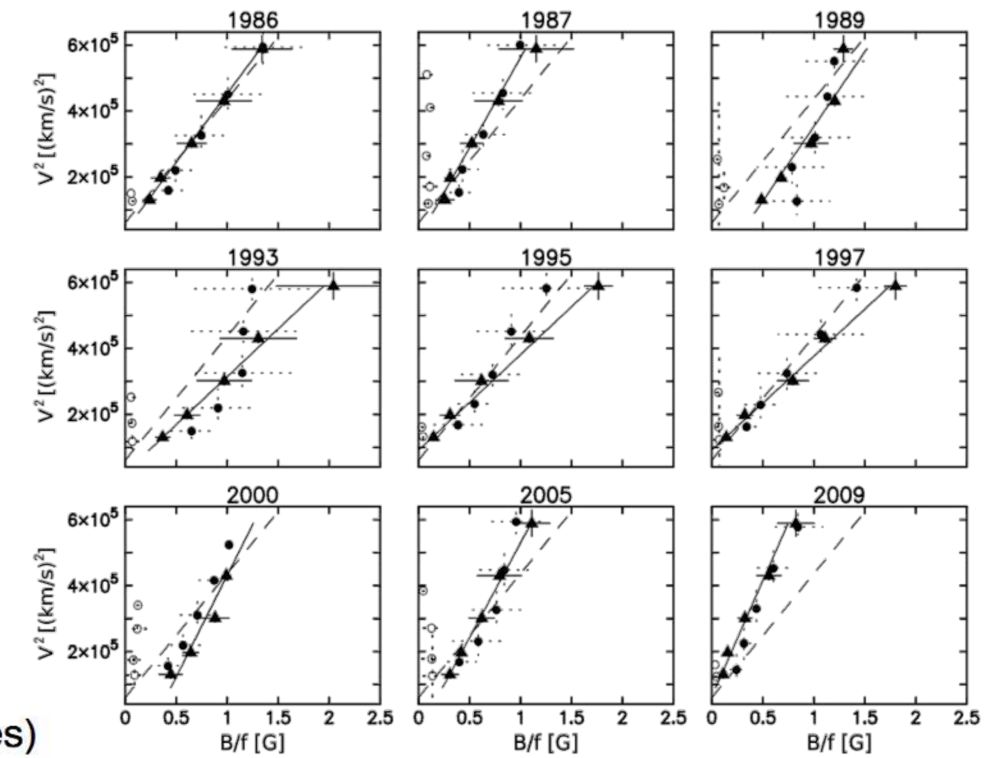
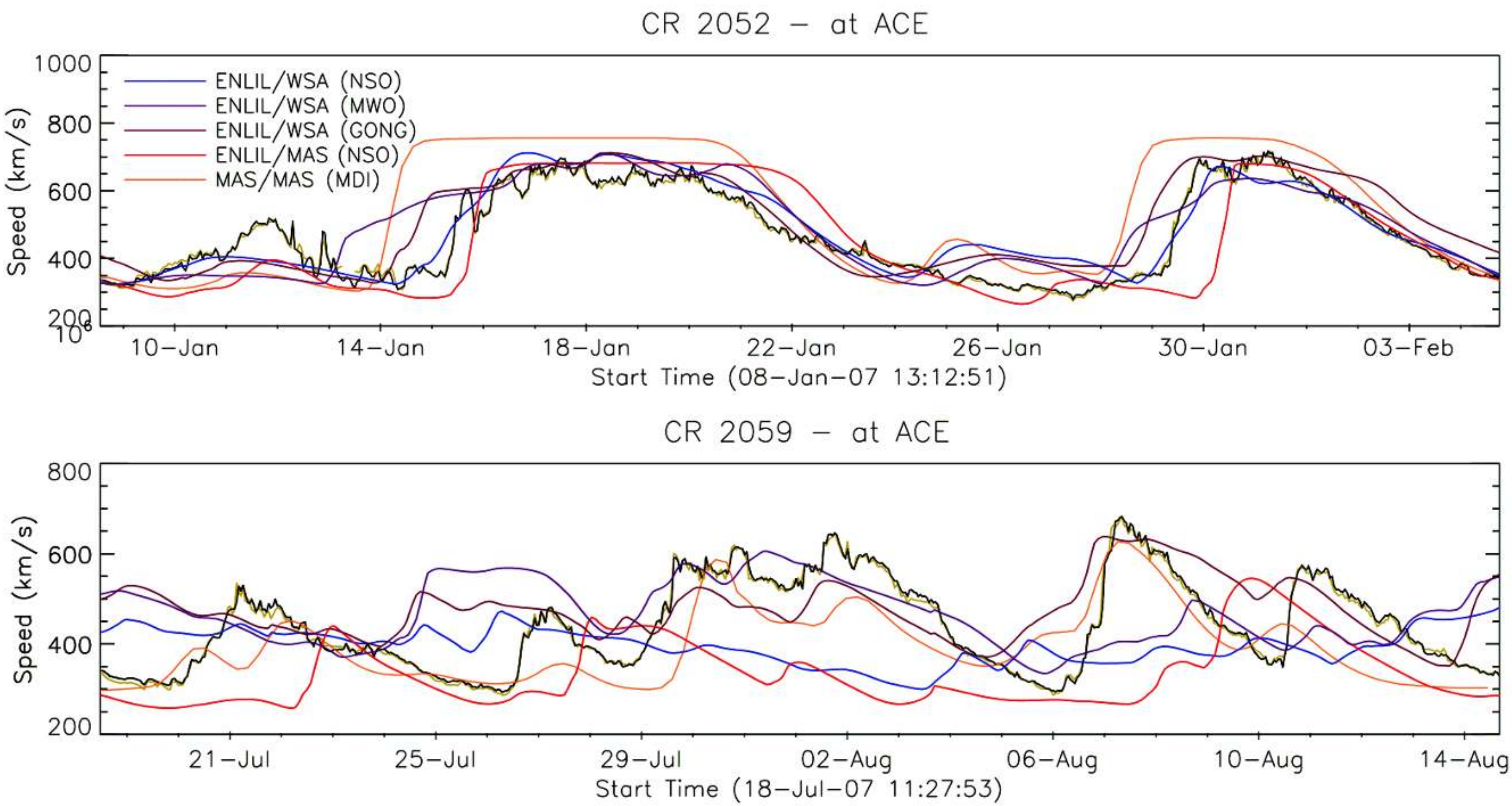


Fujiki et al. (2015) proposed B_0, the photospheric magnetic field strength:



(1) *Solar wind flux-tube geometry*

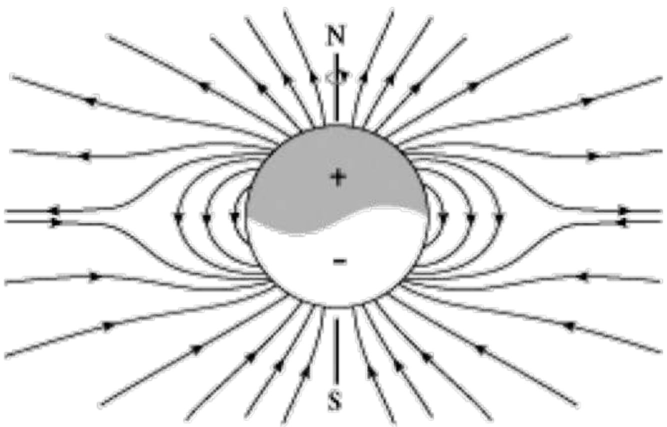
- **Validation** with real solar wind at 1 AU: sometimes WSA works great, sometimes it doesn't. Magnetogram source matters!

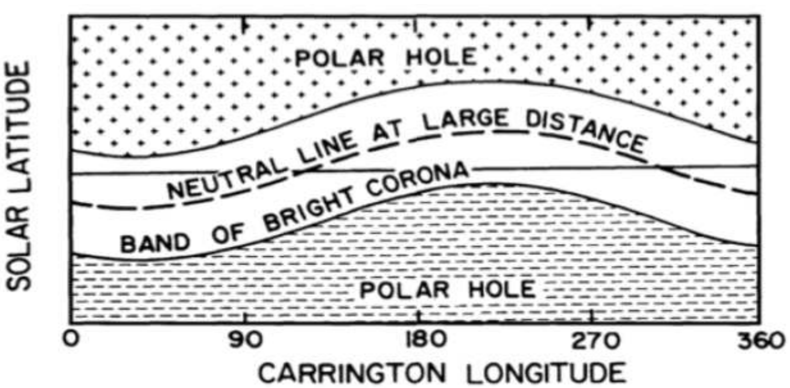


Gressl et al. (2014): over long times, correlation coefficients ≈ 0.50.

(1) *Solar wind flux-tube geometry*

- The global field can be mapped out using more sophisticated measures of flux-tube topology.
- A classical approach mainly considered the **heliospheric current sheet (HCS)** between opposing coronal-hole polarities:





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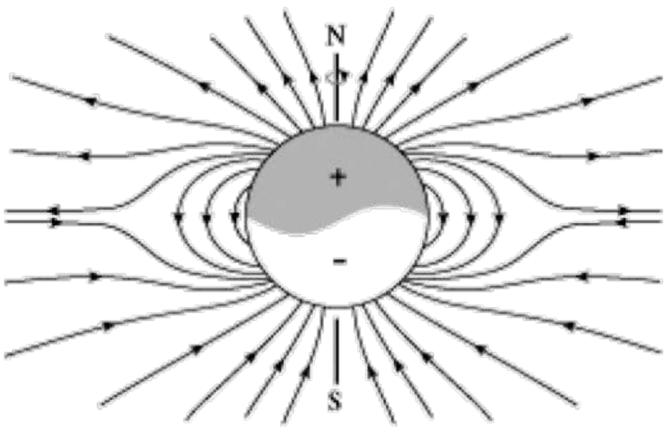
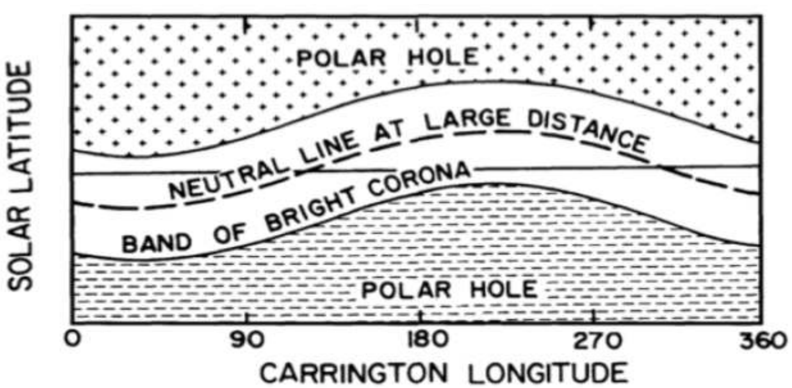
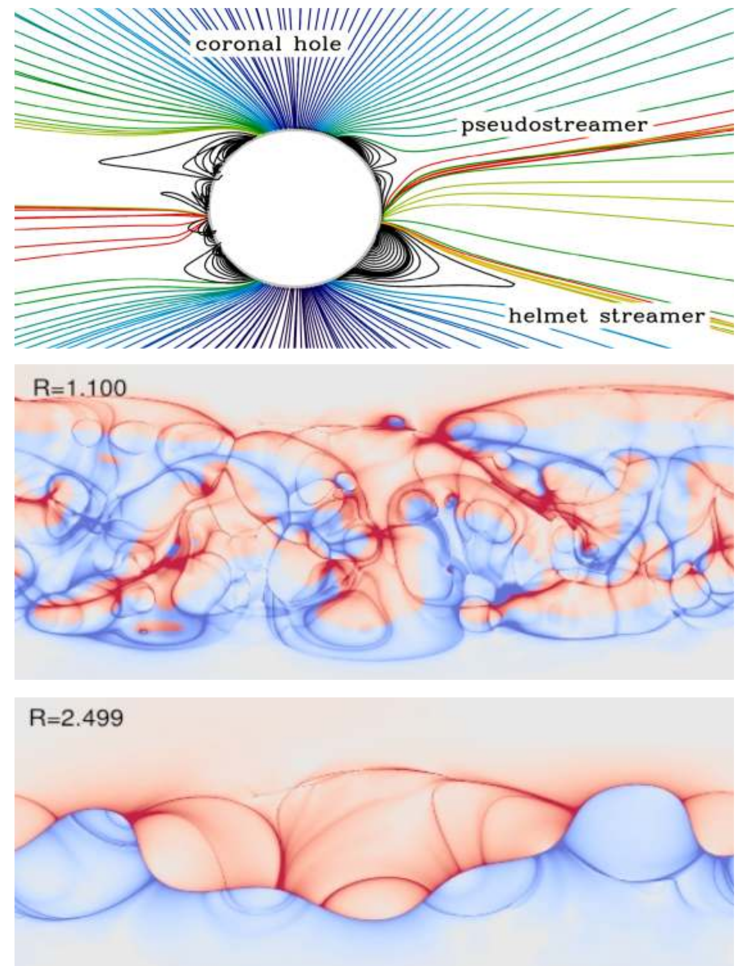




- Antiochos et al. (2011) kicked off a revolution in considering a web of topological separatrix surfaces, measured by "squashing factors:"



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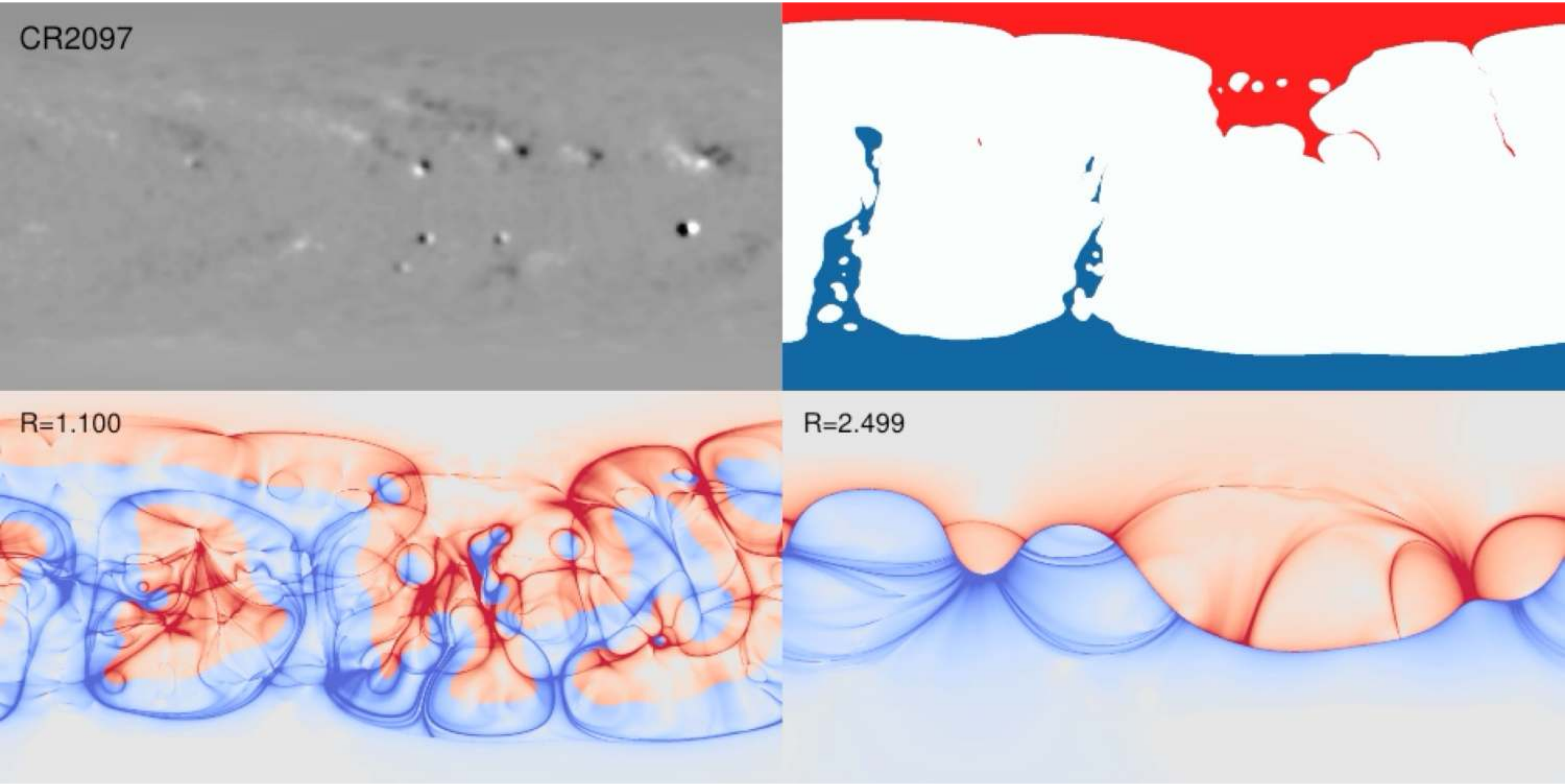
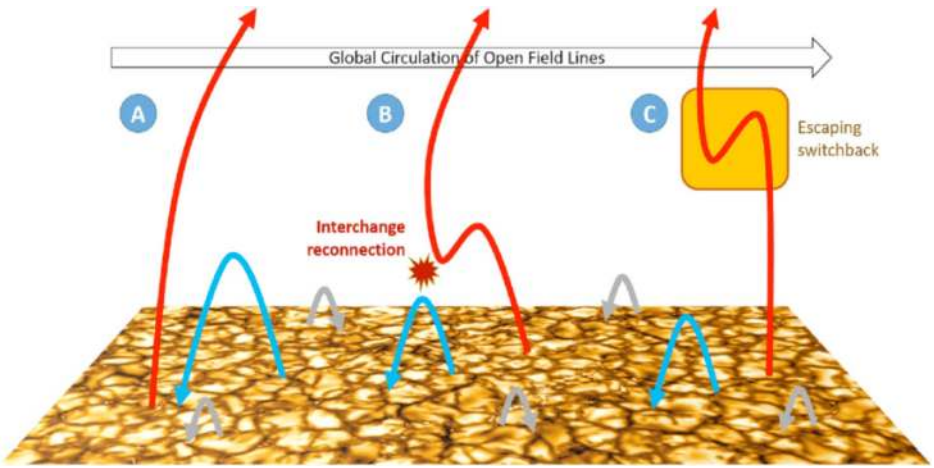
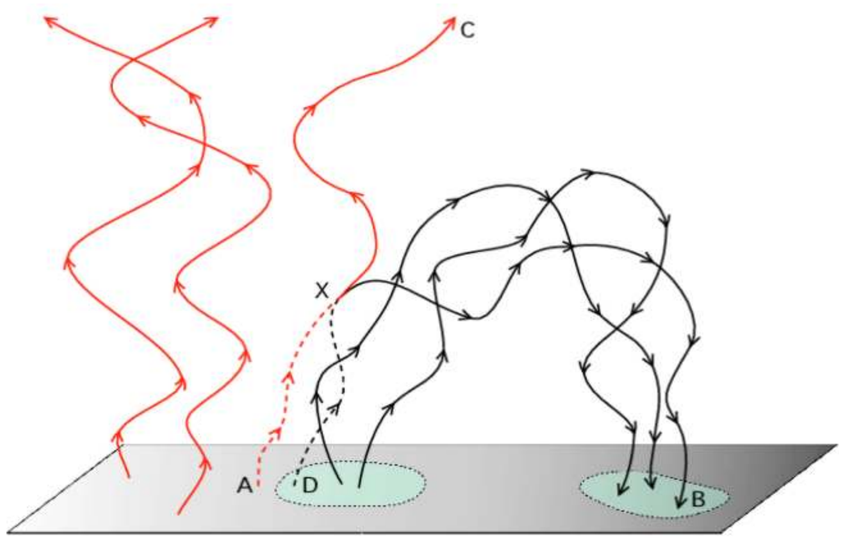


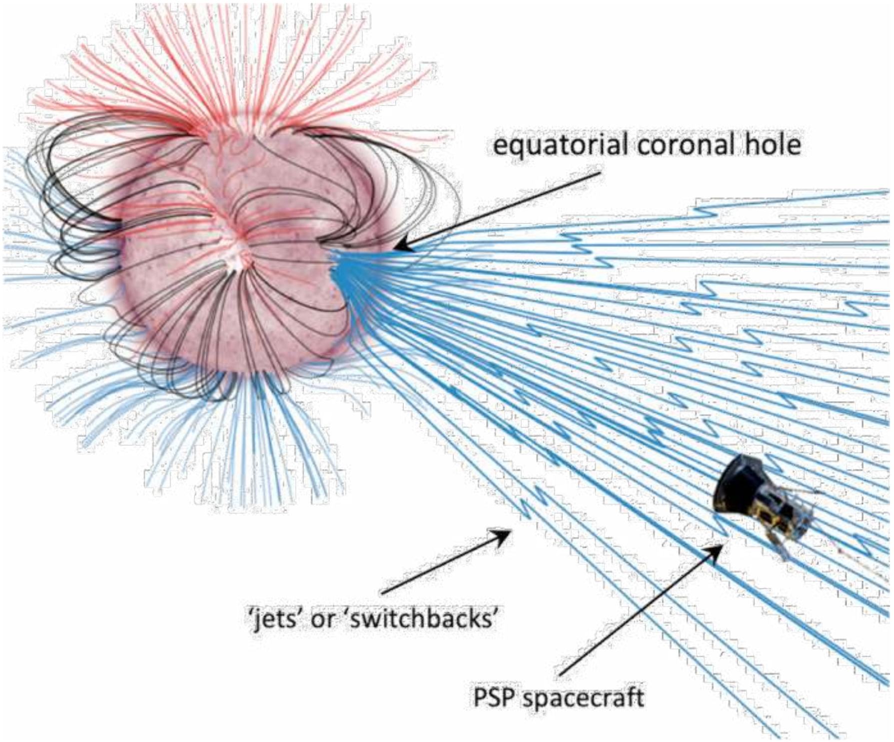
http://hmi.stanford.edu/QMap/

(1) *Solar wind flux-tube geometry*

"Squashed" field lines are likely to sit in the vicinity of rapidly evolving footpoints, which can produce **interchange reconnection** (e.g., jets, bursts of localized heating, "switchbacks").







(2) *Effects of solar rotation*

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Simulation credit: Predictive Science, Inc.

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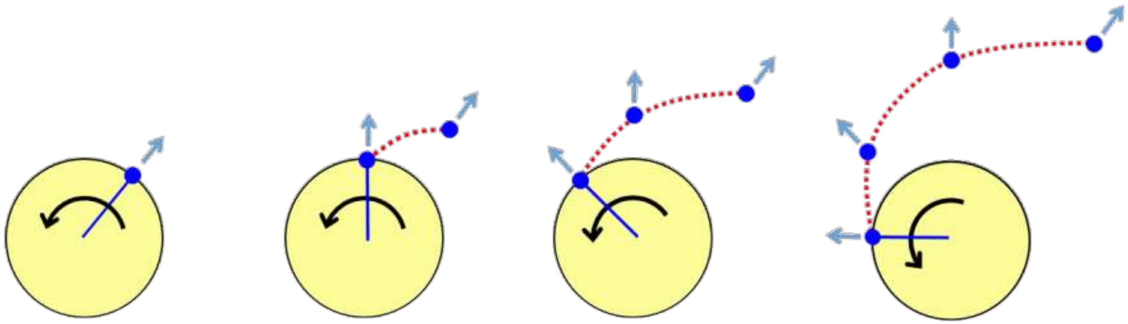
- The solar wind interacts with the Sun's **rotation** to form spiral-shaped streams.
- This was another of Parker's many discoveries in 1958.


(looking down from above)

- Each little "parcel" of the solar wind flows out **~radially** from where it was ejected.
- However, the place where it was ejected from keeps rotating.

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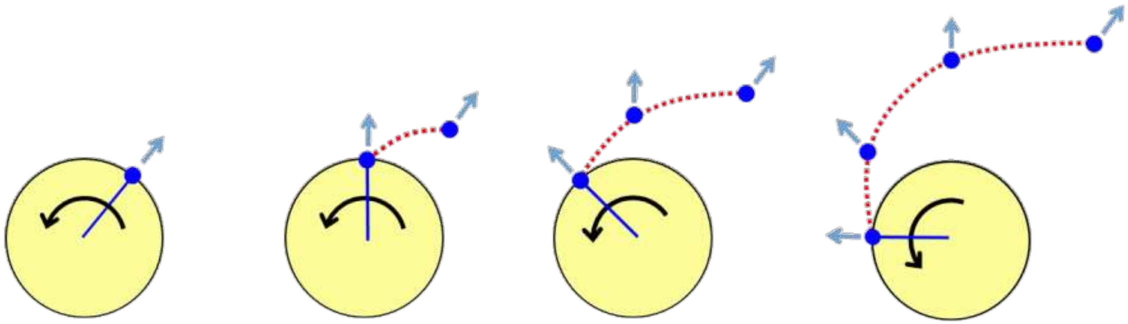

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- Each little "parcel" of the solar wind flows out **~radially** from where it was ejected.
- However, the place where it was ejected from keeps rotating.
- Similar to streams being shot out of a spinning garden sprinkler. The water droplets are shot out radially in that case, too.

(2) *Effects of solar rotation*

- A quantitative way of characterizing this effect can be found from the flux-freezing effect of the **ideal-MHD induction equation.**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

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- In the ecliptic, assume all θ-components are zero, and all is axisymmetric ($\partial/\partial\varphi = 0$)…

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(u_\phi B_r - u_r B_\phi\right)\right] = 0$$

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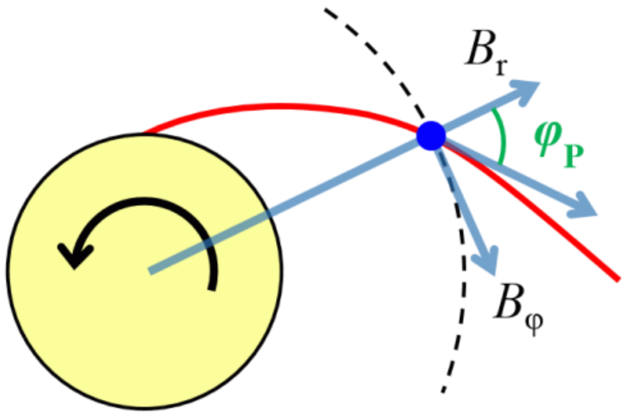
- Lastly, above the source surface, assume a "split monopole" radial field…

$$B_r \approx B_0\left(\frac{r_0}{r}\right)^2 \quad \Rightarrow \quad B_\phi \approx \left(\frac{u_\phi - \Omega r}{u_r}\right) B_r$$

- These are the field components that map out something close to an Archimedean spiral.

(2) *Effects of solar rotation*



Weber & Davis (1967) worked out how u_φ depends on r, and once one gets well above the corona, $|u_\varphi| << |\Omega r|$. Thus,

$$\frac{B_\phi}{B_r} \approx -\frac{\Omega r}{u_r} = \tan \phi_{\rm p}$$

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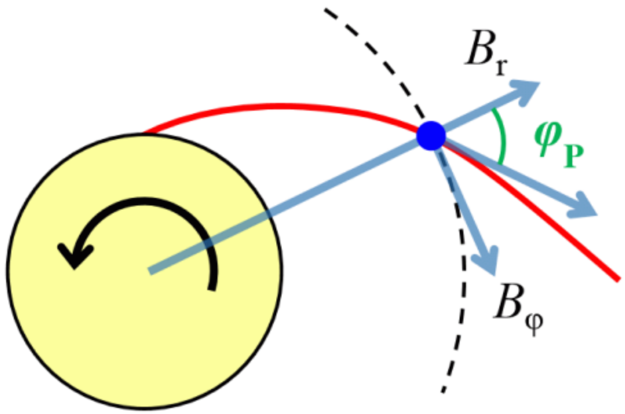

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Using the average $\langle u_r \rangle \approx 450$ km/s in the heliosphere,

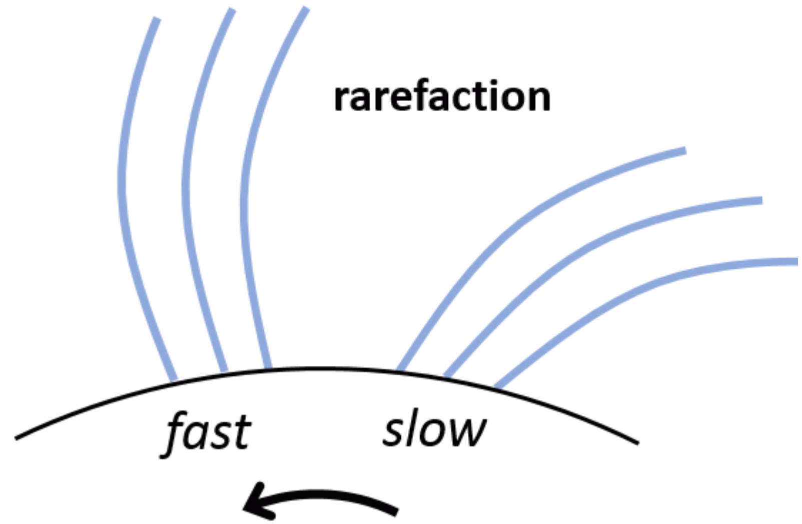
$$\begin{aligned}
\text{At } r = r_{ss} = 2.5\,R_\odot, &\quad \Omega r = 4.7 \text{ km/s} &\quad \phi_\mathrm{p} \approx -0.6^\circ \\
\text{At Mercury, } r = 70\,R_\odot, &\quad \Omega r = 130 \text{ km/s} &\quad \phi_\mathrm{p} \approx -16^\circ \\
\text{At Earth, } r = 215\,R_\odot, &\quad \Omega r = 400 \text{ km/s} &\quad \phi_\mathrm{p} \approx -42^\circ \\
\text{At Pluto, } r = 40 \times 215\,R_\odot, &\quad \Omega r = 16,000 \text{ km/s} &\quad \phi_\mathrm{p} \approx -88^\circ
\end{aligned}$$

At 1 AU, we're at the coincidental point where ϕ_p is always around -45°; i.e., $|B_\phi| \sim |B_r|$.

Of course, u_r can vary between about 250 and 800 km/s, so the Parker spiral angle at a given radial distance varies, too.

(2) *Effects of solar rotation*

- The tightness of the spiral angle depends on the wind speed.
- Fast wind streams out more radially...
- Slow wind curls around more...
- Now imagine 2 regions on the Sun, both at the equator, but at different longitudes.
- The wind streams may separate, leading to a low-density "near-vacuum."



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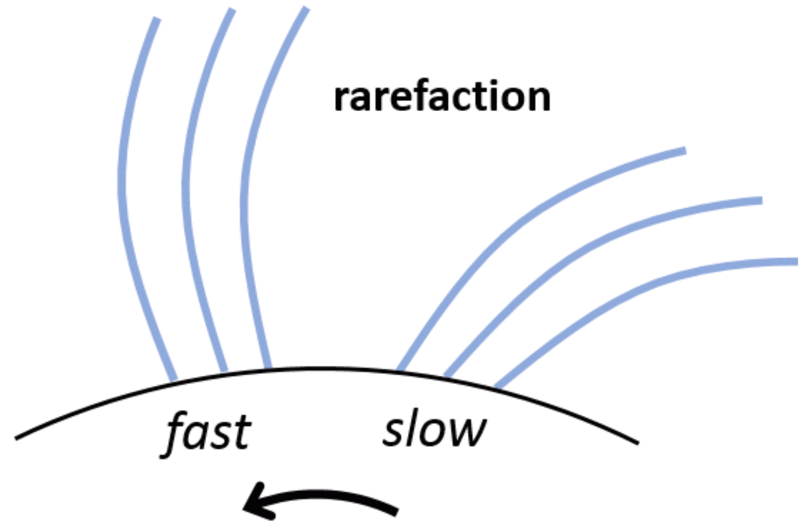
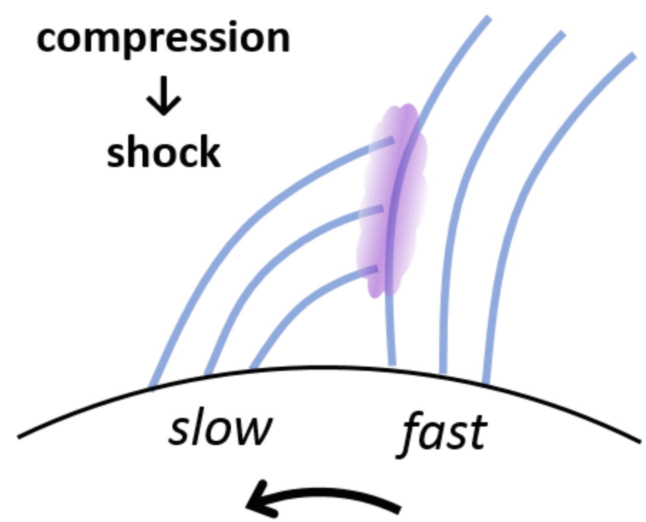
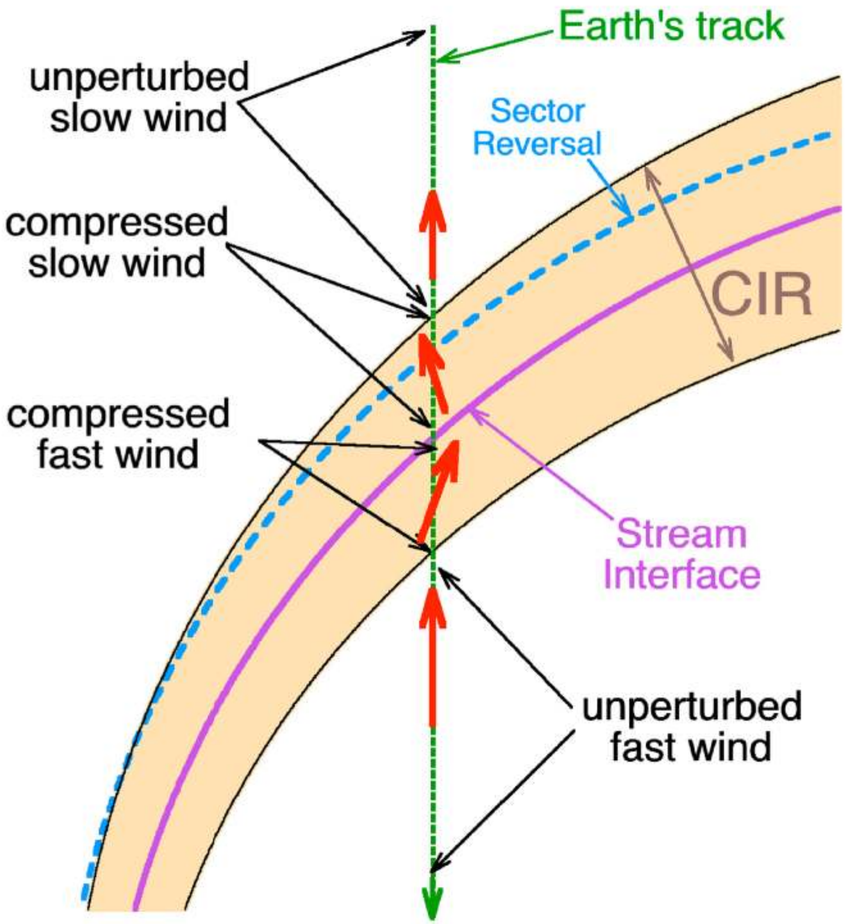
- Now imagine 2 regions on the Sun, both at the equator, but at different longitudes.
- The wind streams may separate, leading to a low-density "near-vacuum."
- Or they can collide, leading to a compressed high-density clump of plasma (a **corotating interaction region**) that grows nonlinearly into shocks with increasing distance…



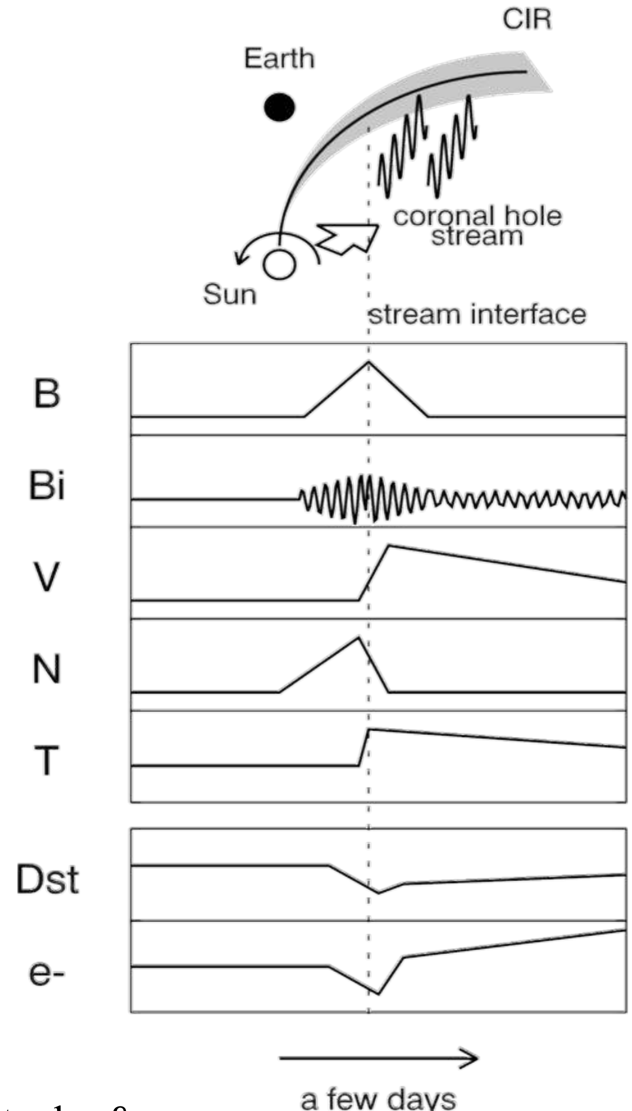


(2) *Effects of solar rotation*

- *In situ* consequences of flying through a corotating interaction region…



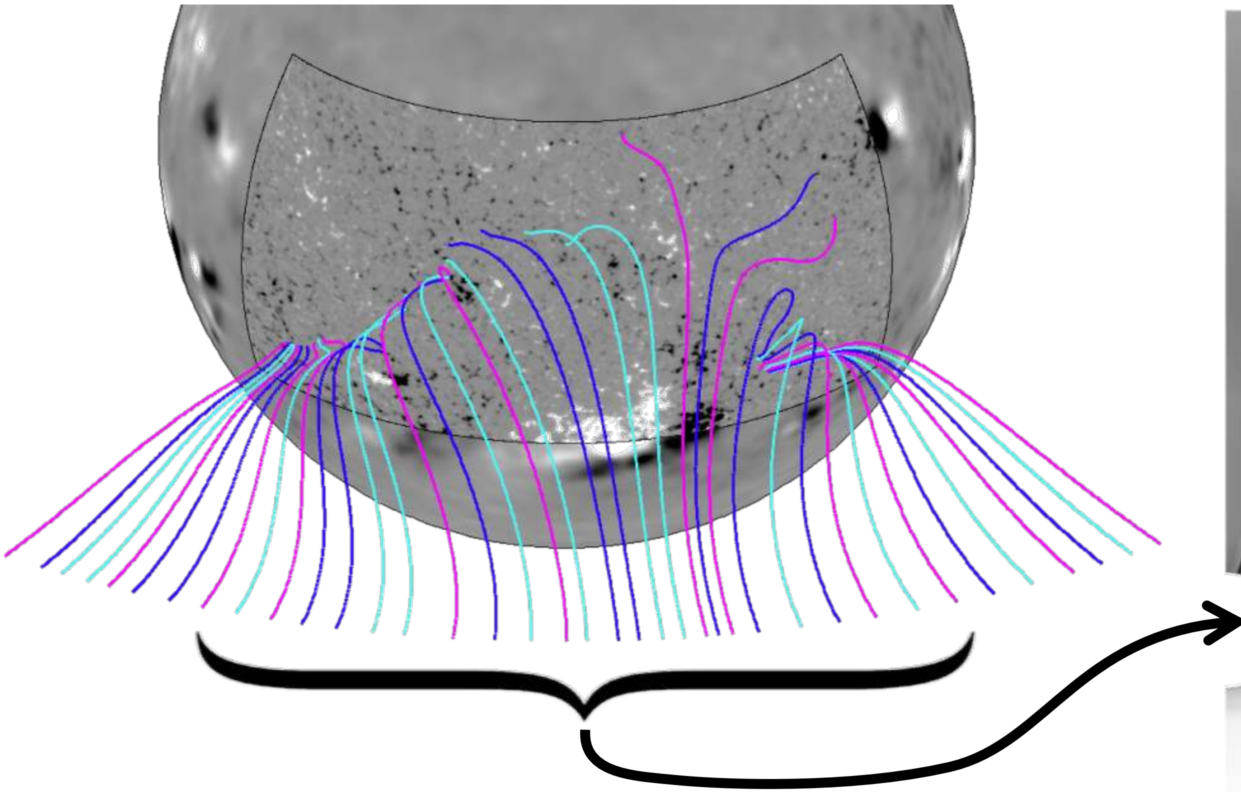
Borovsky (2020)

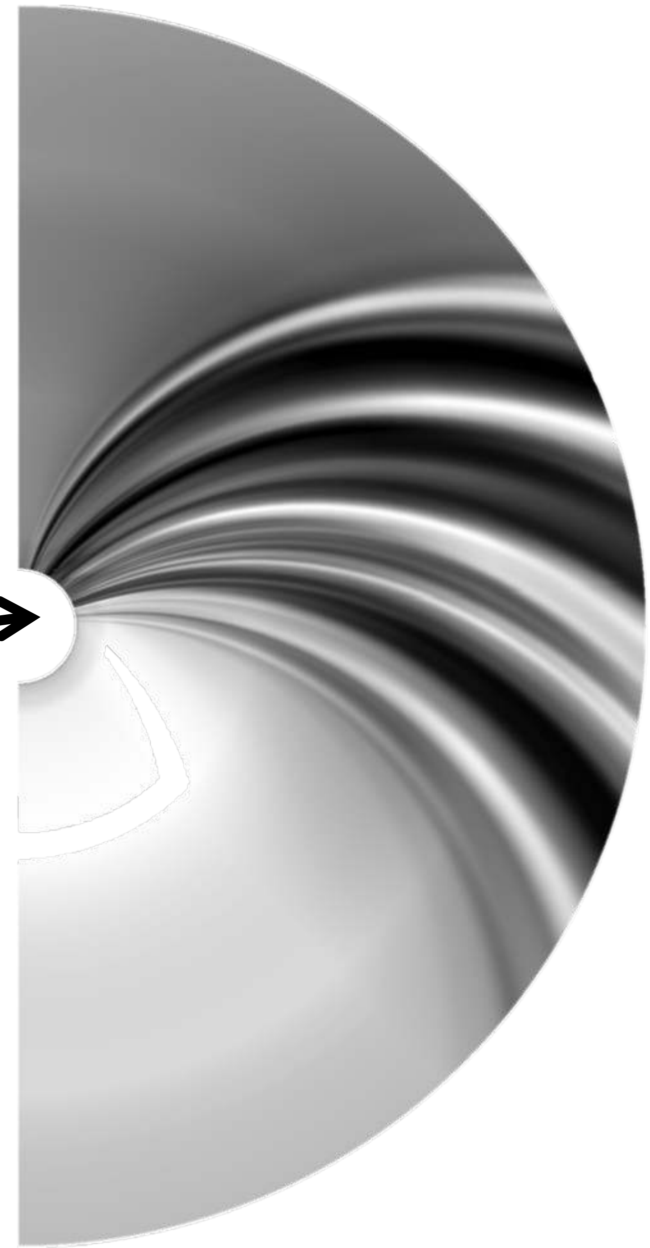


Kataoka & Miyoshi (2006)

Bi = any Cartesian component
e- = >2 MeV e- flux at GEO

(2) *Effects of solar rotation*

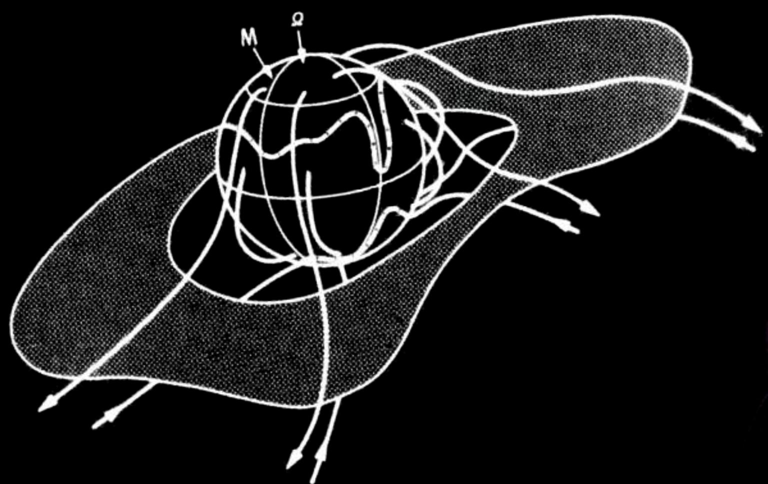


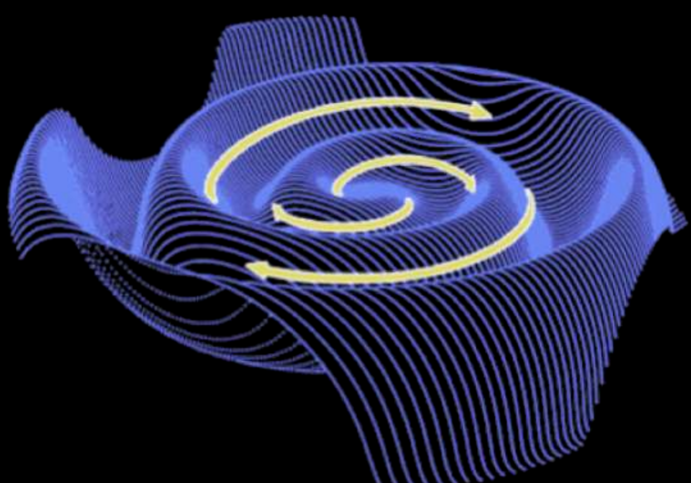


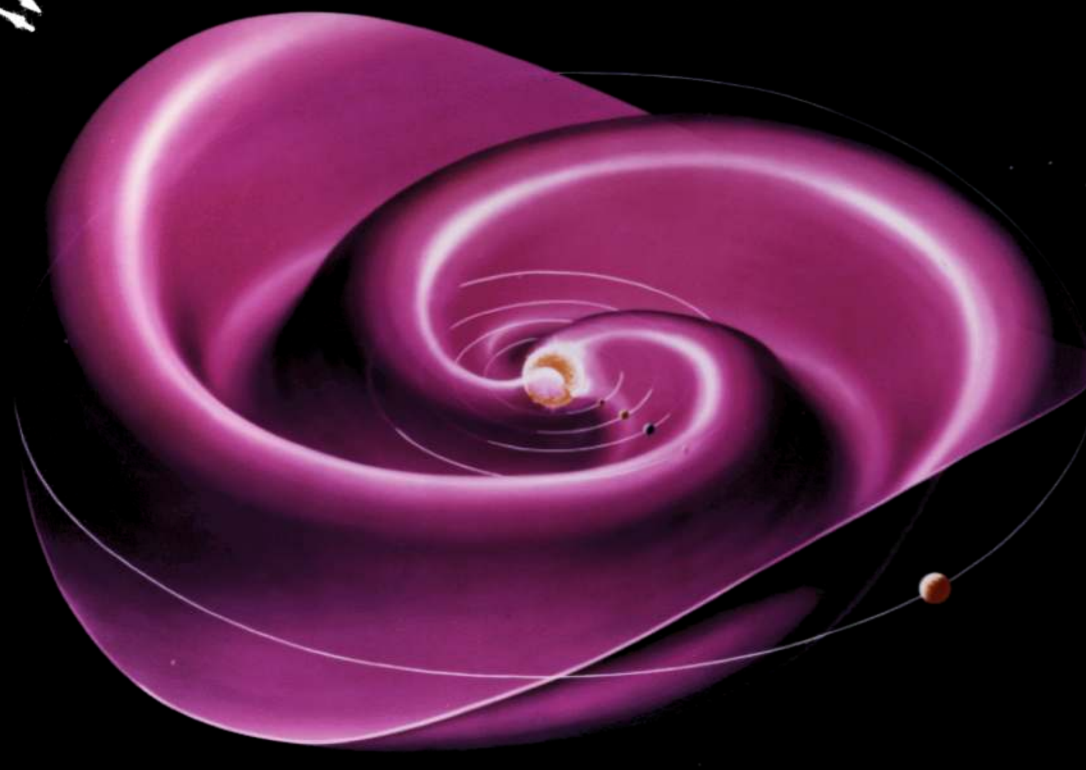
- High-resolution simulations (Cranmer et al. 2013) show fast/slow streams can neighbor one another on small (~supergranular) scales in the corona.
- CIRs act to **smear out** differences between fast & slow streams, thus making it difficult to track features all the way back to the corona. Only the big ones survive.

(2) *Effects of solar rotation*

- If the corona's magnetic field is a bit tilted with respect to the Sun's rotation...

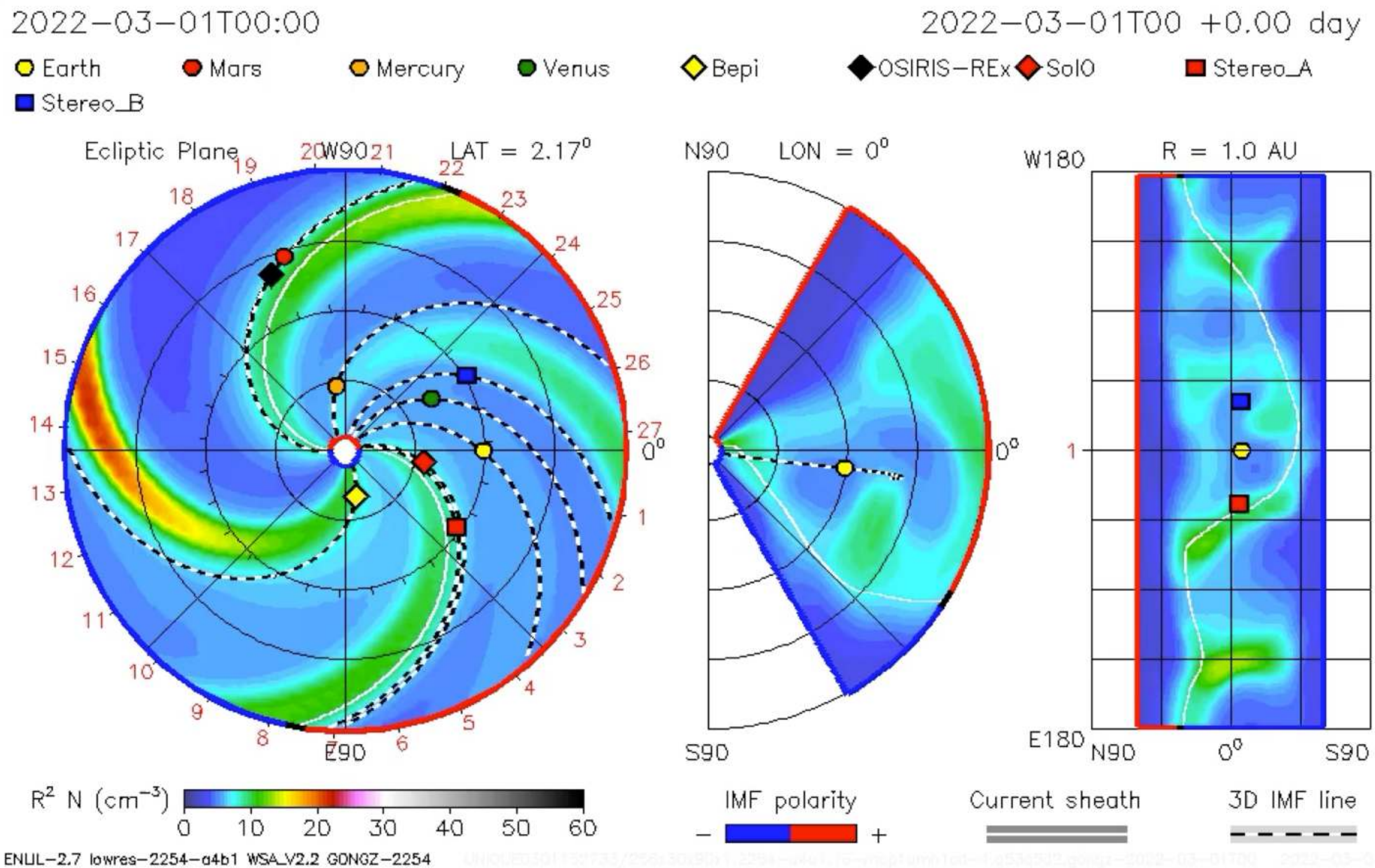






The HCS resembles a "ballerina skirt"

(2) *Effects of solar rotation*



(3) *Evolution of turbulent fluctuations*

From the thermodynamic state of the solar wind & its fluctuations, we deduce that there's still a lot of **damping → heating** going on in the heliosphere…

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Fits to data above ~0.2 AU:

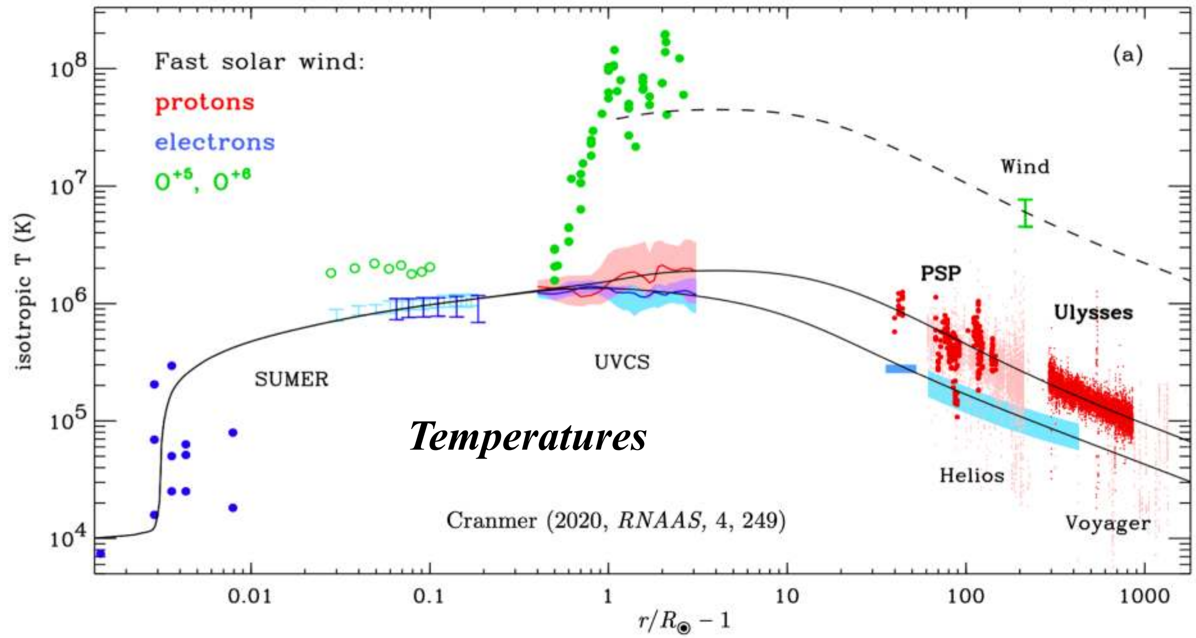
$$T_p \propto r^{-0.70}$$

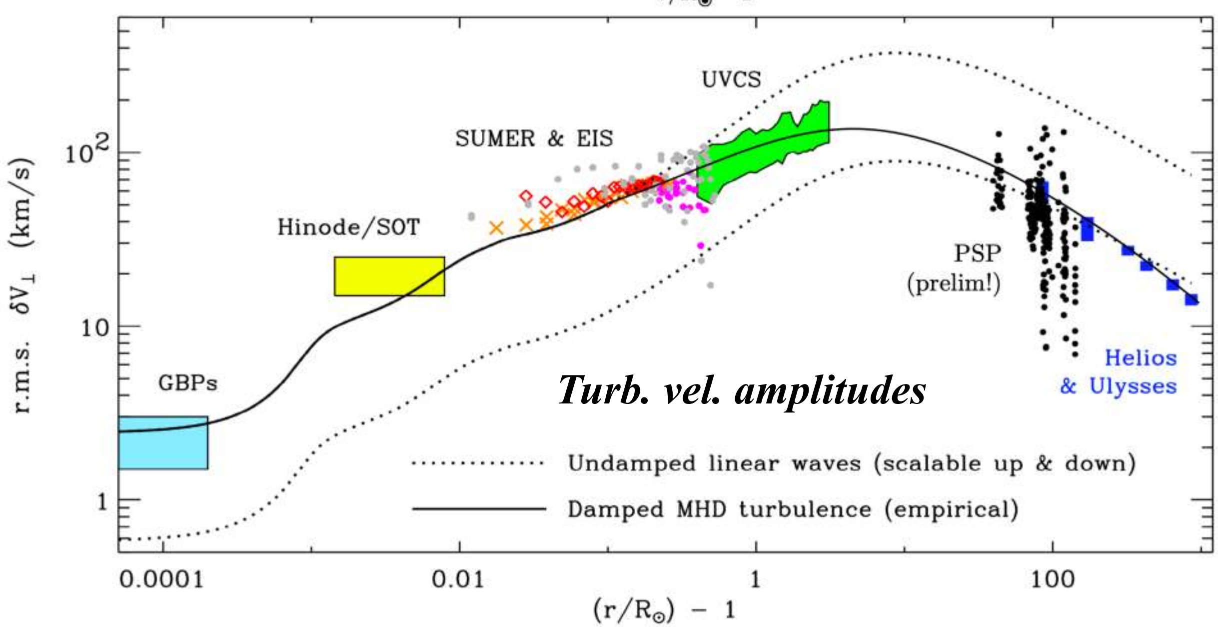
$$T_e \propto r^{-0.61}$$

$$\delta v_\perp \propto r^{-0.59}$$

$$\rho \propto r^{-2}$$

$$u \approx \text{constant}$$





(3) *Evolution of turbulent fluctuations*

- How can we understand these trends quantitatively? Thermal energy conservation:

$$\frac{\partial U_{\mathrm{th}}}{\partial t} = Q_{\mathrm{adv}} + Q_{\mathrm{rad}} + Q_{\mathrm{cond}} + Q_{\mathrm{heat}}$$

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- At large distances above the corona,

$$u \approx \text{constant} \quad , \qquad n \propto r^{-2} \quad , \qquad T \propto r^{-\delta}$$

- **Adiabatic** expansion (i.e., $Q_{\rm heat} = 0$) is satisfied when

$$T \propto n^{\gamma-1} \qquad \text{so, if} \quad \gamma = \frac{5}{3} \; , \qquad \text{then} \quad \delta = \frac{4}{3}$$

- The fact that the observed δ is < 4/3 implies there *is* continual heating in the solar wind.

(3) *Evolution of turbulent fluctuations*

- Using the power-law radial dependences (and continuing to ignore conduction),

$$\frac{3}{2} n u k_{\rm B} \frac{dT}{dr} - u k_{\rm B} T \frac{dn}{dr} = Q_{\rm heat} \quad \Longrightarrow \quad Q_{\rm heat} \propto r^{-(3+\delta)}$$

- Thus, from observations, $Q_{\rm heat}$ should drop off as r to the –3.6 to –3.7.

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- What about turbulence theory? $$Q_{\rm heat} \sim \rho (\delta v_\perp)^3 / \lambda_\perp$$

- The correlation length grows like $r^{+0.5}$ to r^{+1} (the latter when it expands like $A^{1/2}$)

- Alfvén wave velocity amplitude decreases as $r^{-0.50}$ (if no damping) to $r^{-0.59}$ (obs)

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- Thus, the turbulent heating rate drops as r to the –4.0 to –4.7.

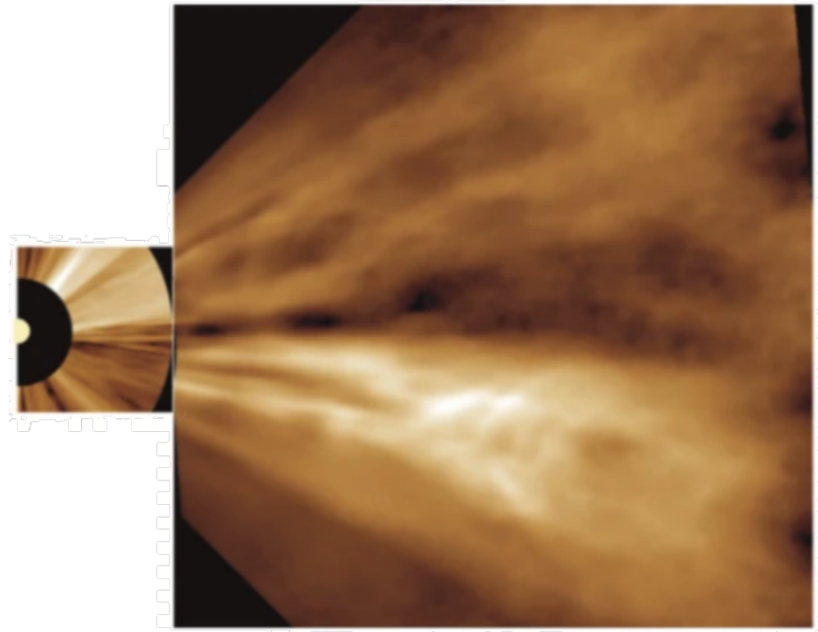
- Not *too* terrible for such a simplistic turbulence model.
  Better ones do better…

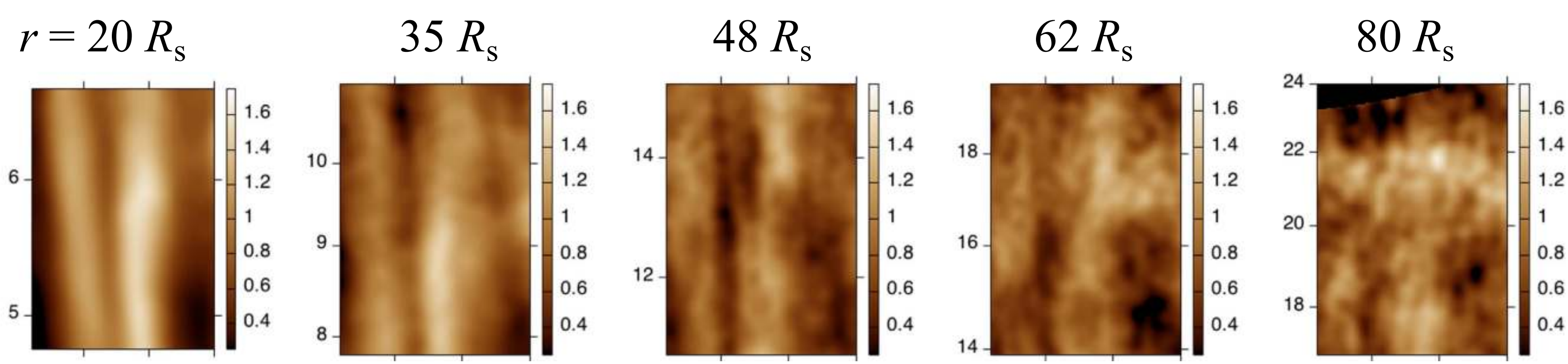
(3) *Evolution of turbulent fluctuations*

- Hints toward better (anistropic) turbulence models:

- DeForest et al. (2016) found that the aspect ratio of density fluctuations varies strongly from **“striated”** (i.e., field-aligned, near the Sun) to **“flocculated”** (isotropically fluffy, far from the Sun).

- The radius where the transition occurs seems to be close to where β exceeds 1.

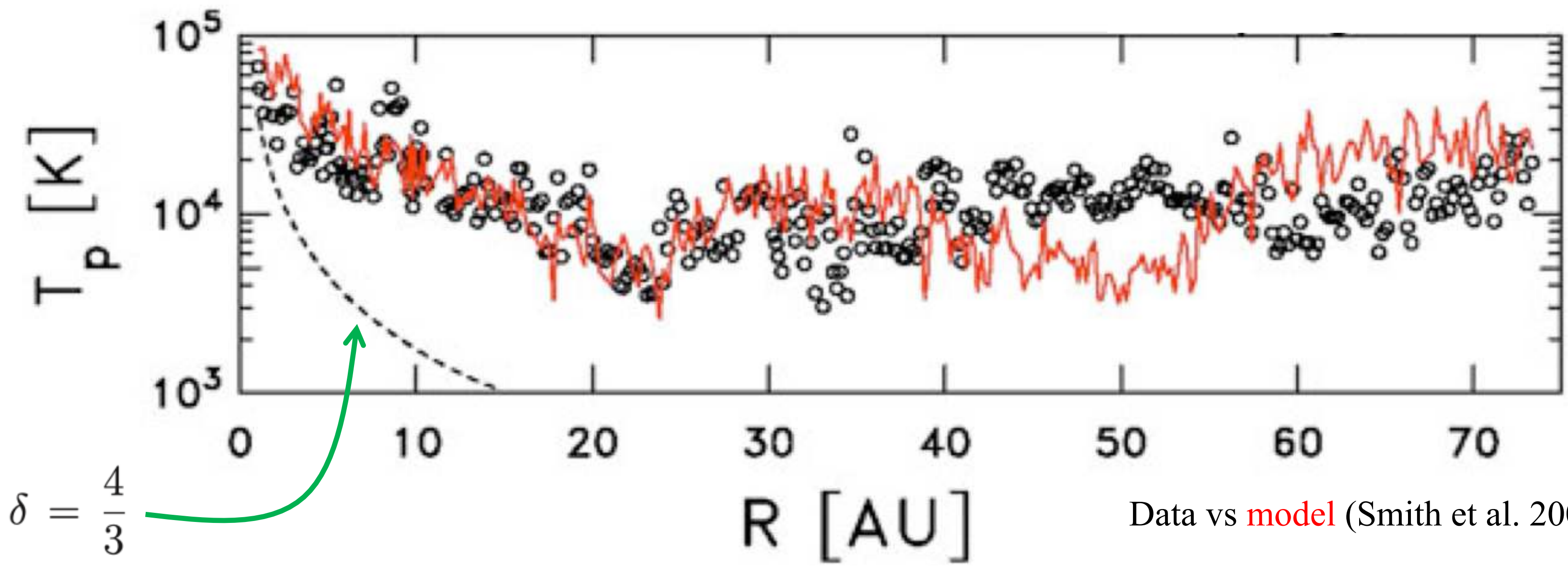




https://www.youtube.com/watch?v=rGMVTHqaG90

(3) *Evolution of turbulent fluctuations*

- In the outer heliosphere (i.e., $r > 20$ AU), Voyager 2 observed that $T(r)$ flattens out... and starts to rise…

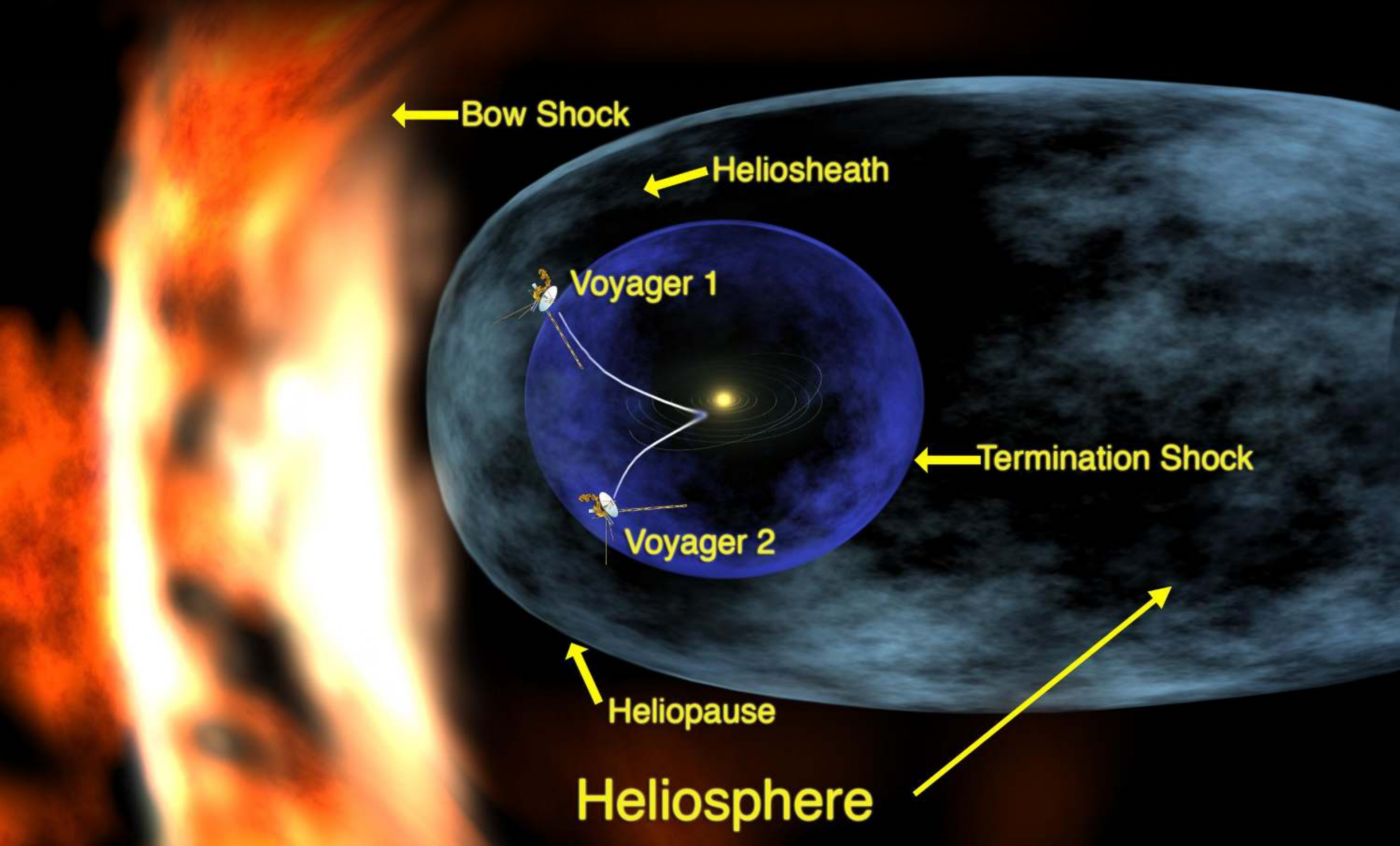


Data vs model (Smith et al. 2006)

- **Pickup ion heating:** interstellar neutral atoms flow into the heliosphere and occasionally undergo charge exchange with solar wind protons. Their velocity distribution is highly non-Maxwellian, and it is unstable to the growth of MHD waves… and those waves damp rapidly to heat the plasma.

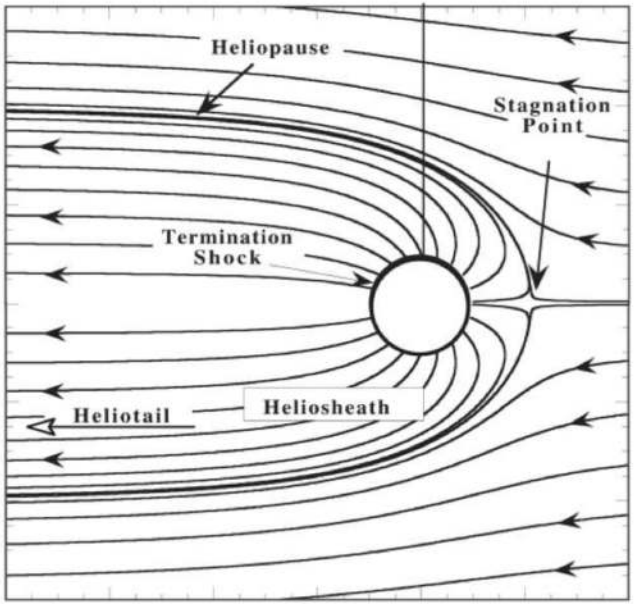
(4) *The outer heliosphere*

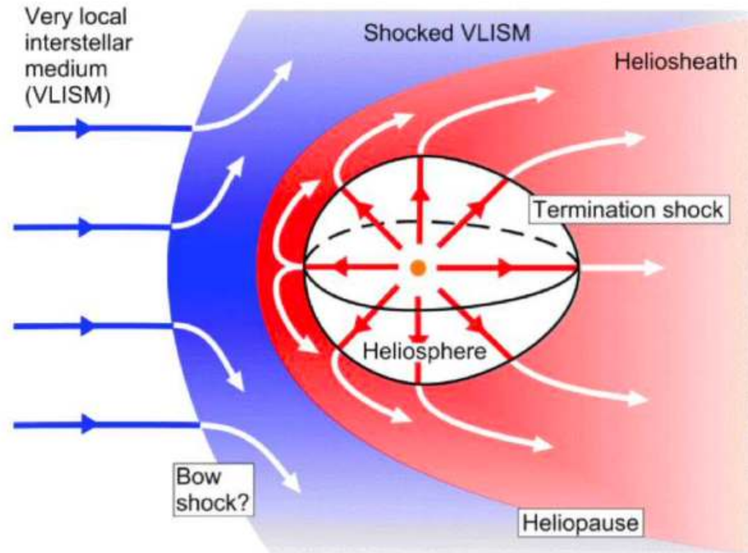
- The Sun, planets, and surrounding solar wind all make up a single system ("the heliosphere") that's hurtling through the galaxy at a speed of ~23 km/s.

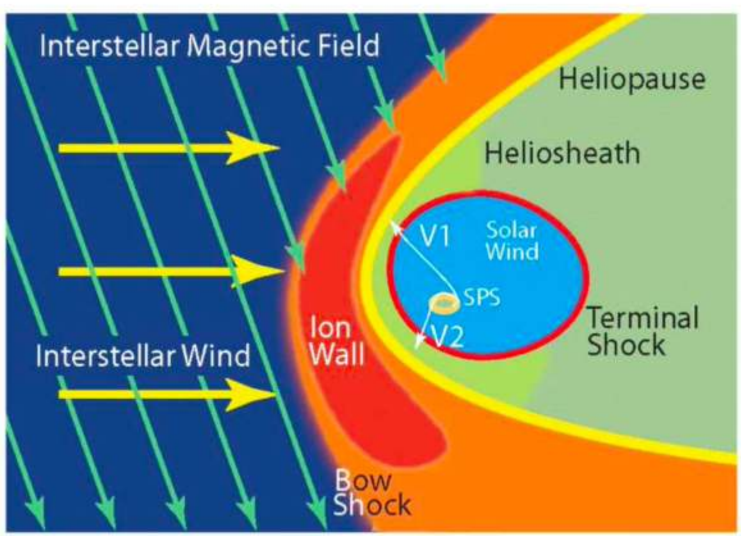


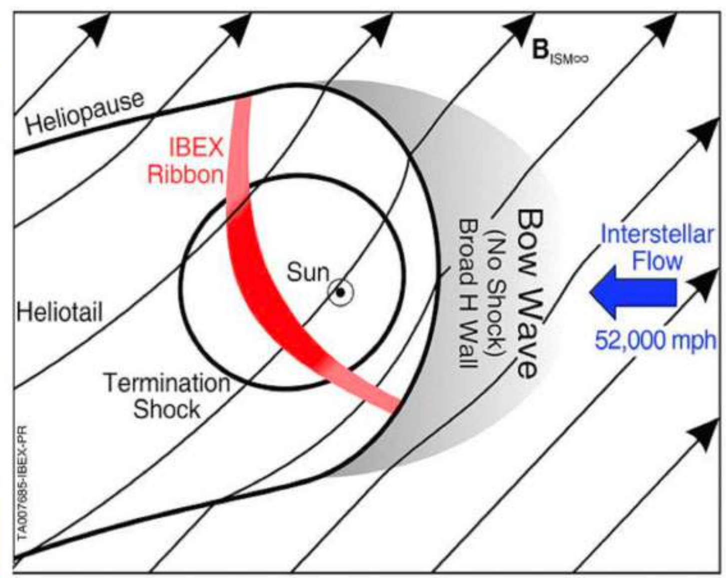
(4) *The outer heliosphere*

Plasma parcels in relative *supersonic* motion will establish multiple discontinuities…



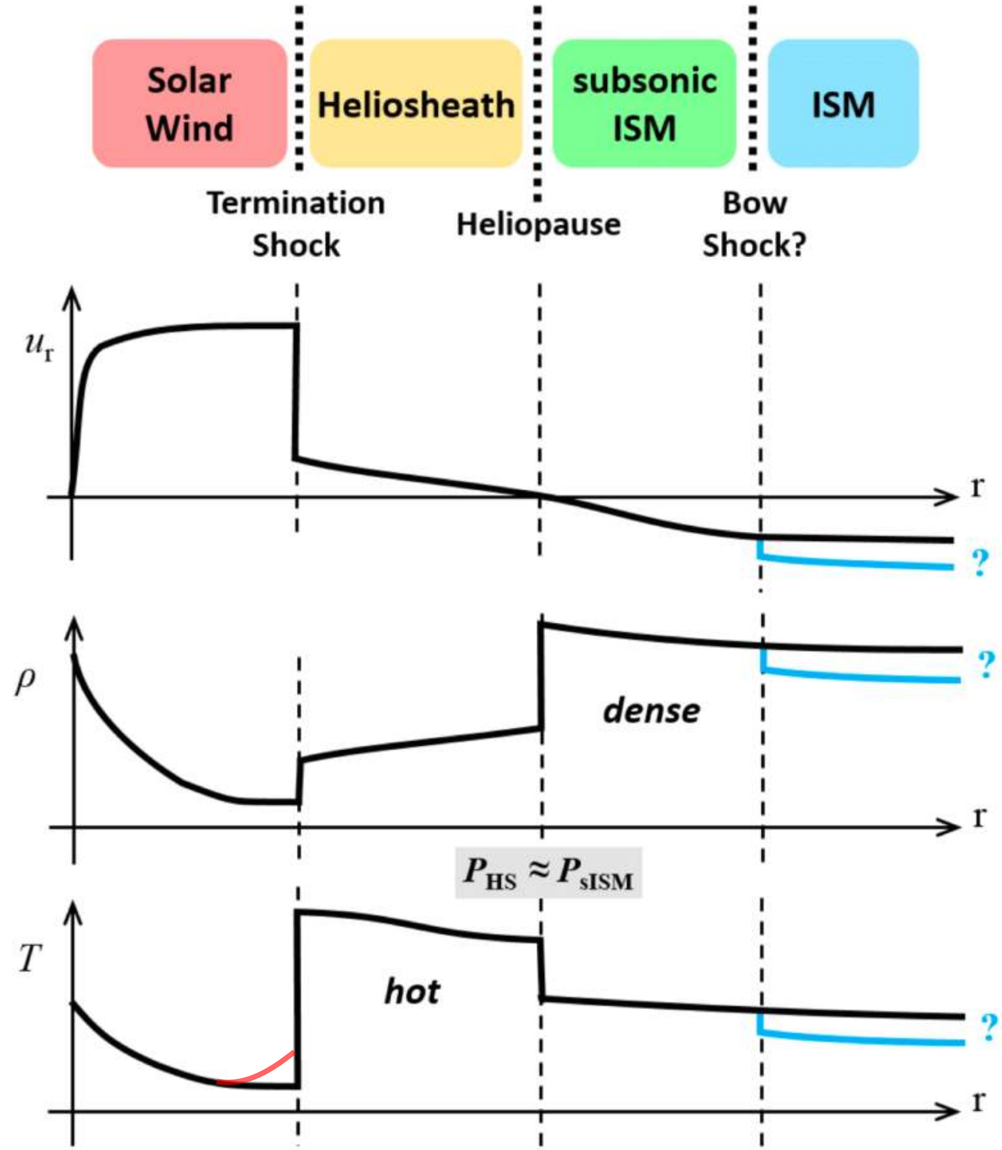






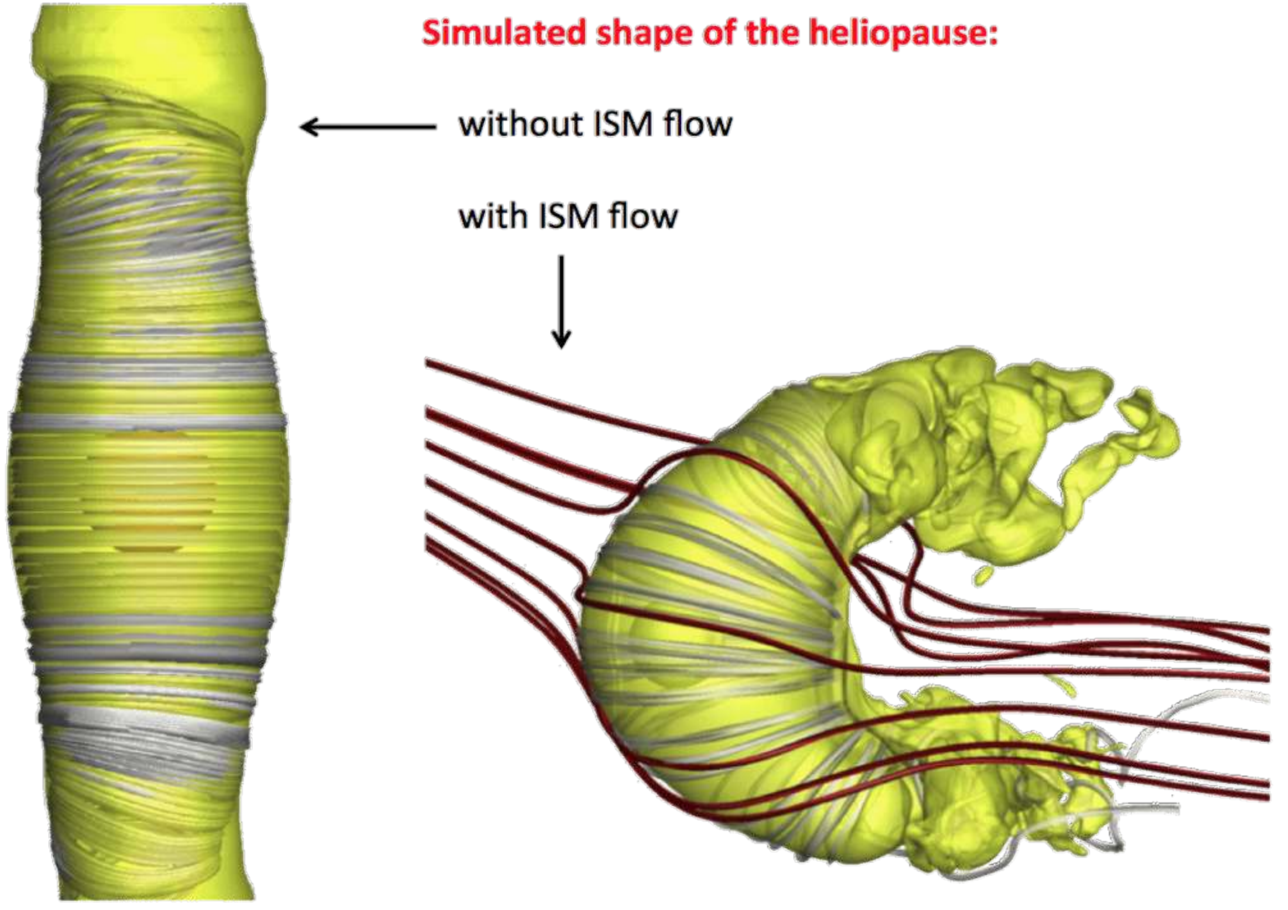
(4) *The outer heliosphere*

- The heliosphere and ISM adjust themselves so they are in rough **pressure equilibrium** with one another.
- However, the solar wind is (locally) supersonic, so there must be at least 1 shock that decelerates it to a subsonic flow (the heliosheath) that is "allowed" to come into pressure equilibrium with the ISM.
- If the ISM flow (23 km/s) was also locally supersonic, it would have to be shocked, too. Most recent info from IBEX says that it's probably *not*.



(4) *The outer heliosphere*

- Do those cartoons really tell the whole story? Don't forget the **Parker spiral** magnetic field! It gets everything twisted up, and exerts strong "hoop forces" (i.e., magnetic tension) on the local plasma.
- Opher et al. (2015, *ApJL,* 800, L28) proposed that the outer magnetic field looks more like a croissant...



For next week

- Continue tinkering with the hands-on computation exercise; due next week (Thursday, March 10, 2022).

- Participate in the #hands-on-2-discussion channel on Slack, even if just to vent about python…