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

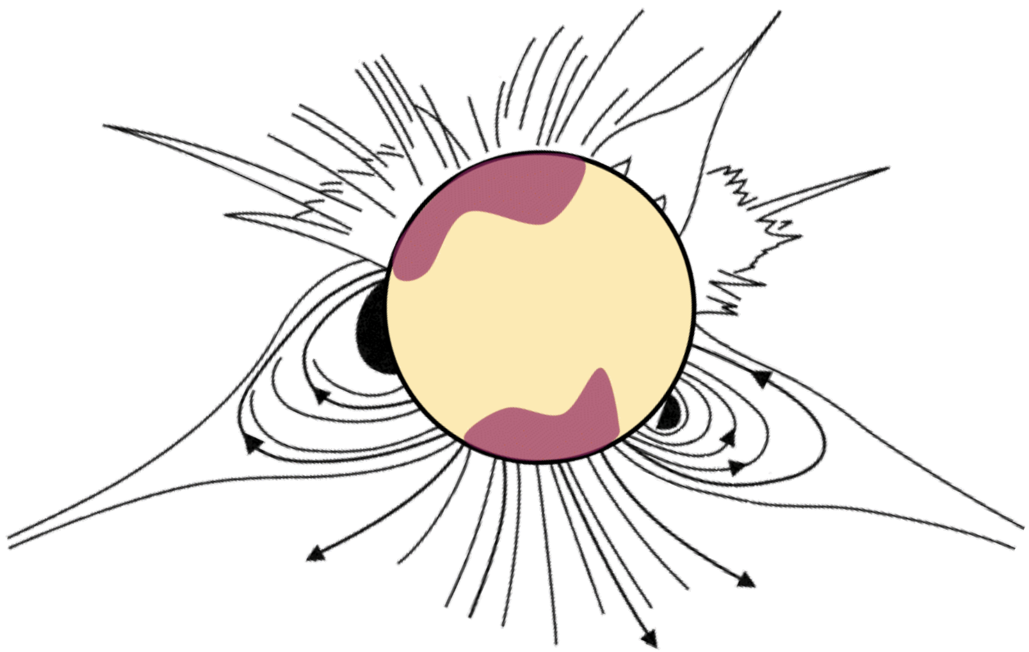
February 17, 2022

The open-field corona & the discovery of the solar wind

Dr. Steven R. Cranmer
Dr. Thomas E. Berger

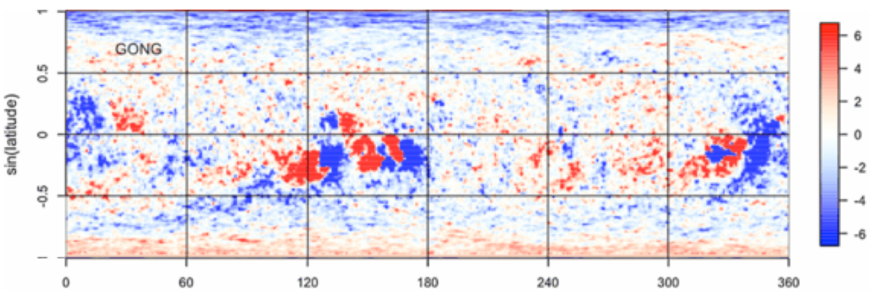
Outline

1. How does the Sun's magnetic field connect to the heliosphere?

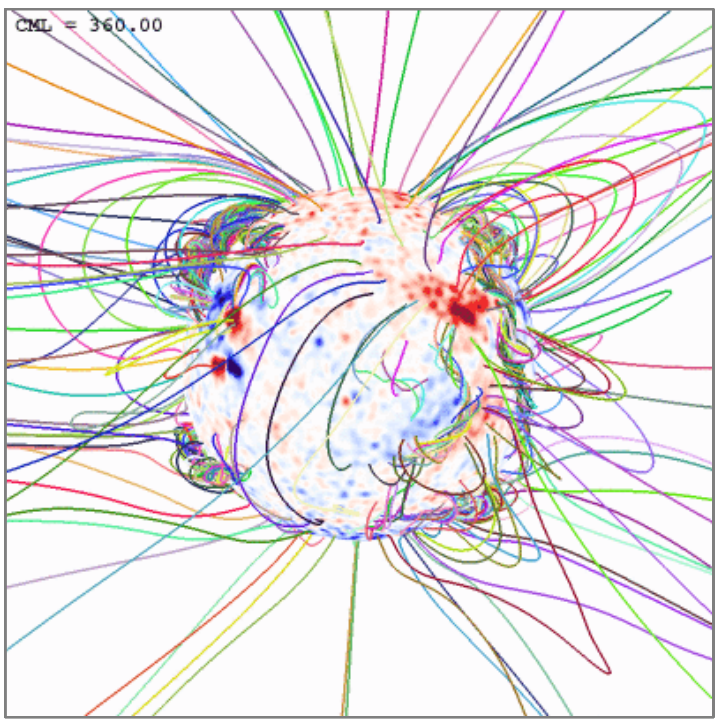


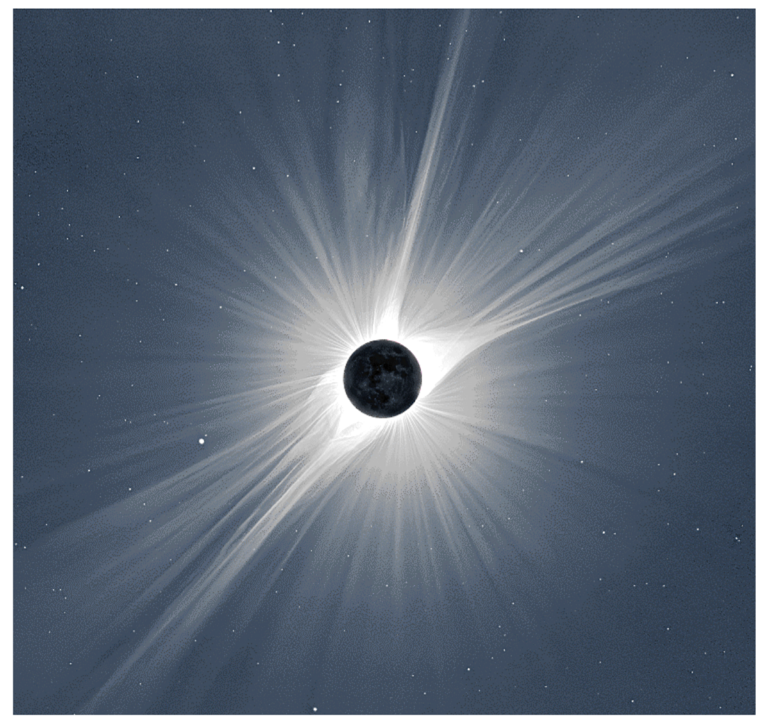
2. The solar wind: history & its physical necessity

(1) *The heliospheric magnetic field*



- Measurement of **photospheric** **B**-field is useful as a lower boundary condition.
- **Coronal** **B**-field measurements are difficult, but DKIST pushes the envelope…
- ***In situ*** **B** data helps constrain the total magnetic flux throughout the heliosphere.

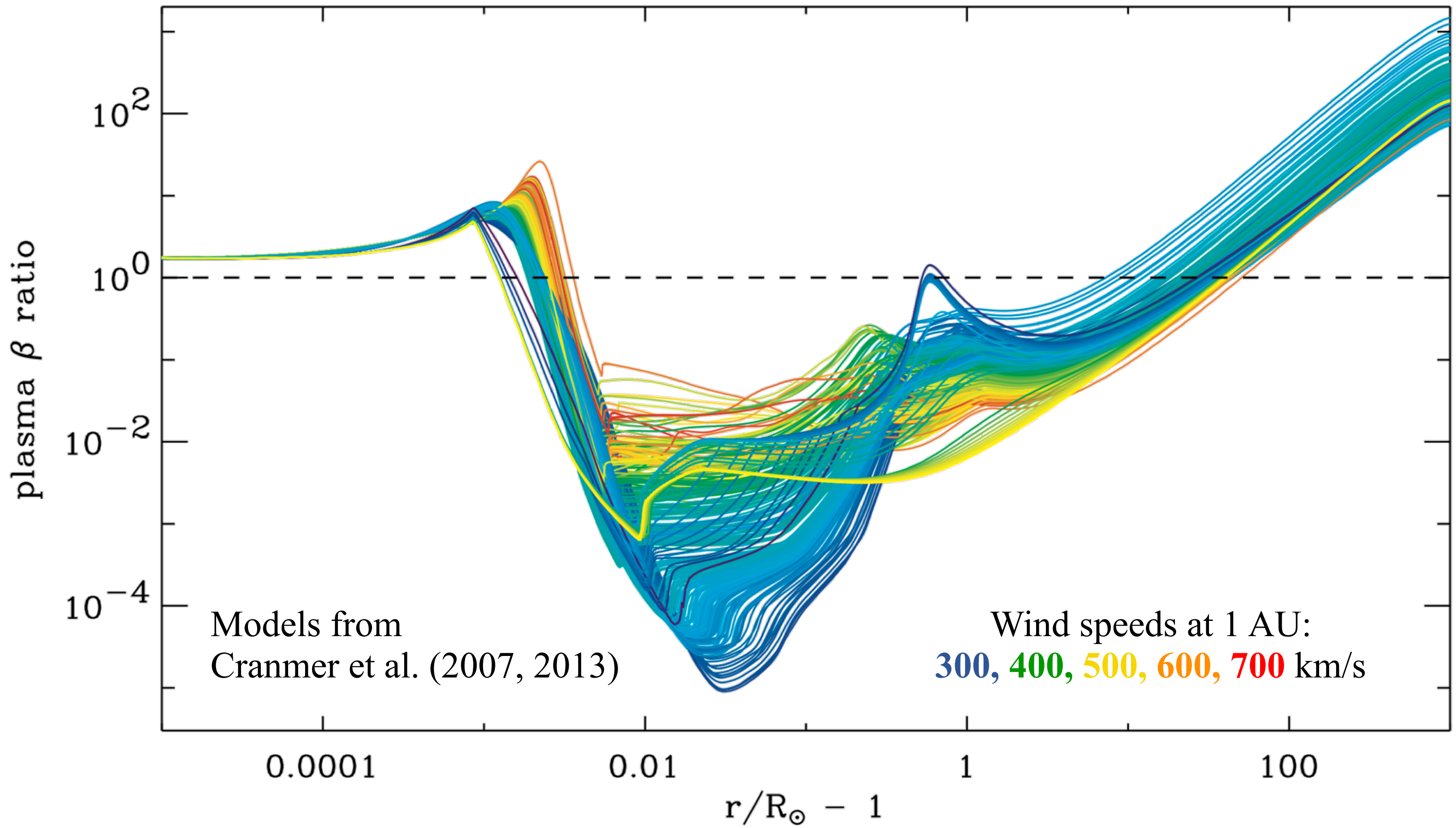




(1) *The heliospheric magnetic field*

- There are multiple techniques for extrapolating the **B** field.
- All methods must deal with the fact that the corona is magnetically dominated, while the outer parts of the heliosphere are gas-pressure dominated…

$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}} \approx \left(\frac{c_s}{V_{\rm A}}\right)^2$$



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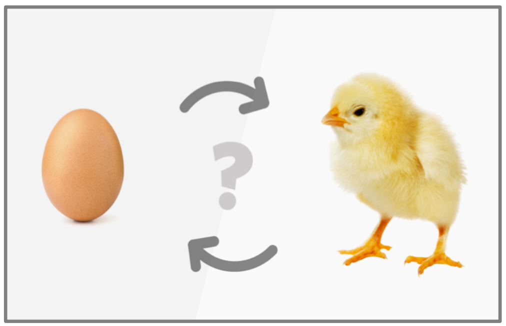

(solar wind not taken into account)

- Potential-field solutions
- PFSS: Potential Field with Source Surface
- PFSS + current sheets
- Linear force-free fields
- Nonlinear force-free fields
  (e.g., magnetofrictional relaxation)
- Full solutions to 3D MHD equations

(fully self-consistent with the solar wind)

(1) *Simplified MHD in the corona*

- Momentum equation: $$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla P_{\mathrm{gas}} + \mathbf{J}\times\mathbf{B} + \rho\mathbf{g}$$

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- Two ways to make that true: $\mathbf{J} = 0$, or $\mathbf{J}$ parallel to **B**. Usually the former.
- Recall Ampere's law: $\mathbf{J} = \frac{1}{\mu_0}\nabla\times\mathbf{B}$ Thus, both div & curl of **B** $\approx$ 0.

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- Recall Ampere's law: $\mathbf{J} = \frac{1}{\mu_0}\nabla\times\mathbf{B}$ Thus, both div & curl of **B** ≈ 0.
- Remember that $\nabla\times\nabla\psi = 0$ so we can express $\mathbf{B} = -\nabla\psi$
- "Potential fields" obey Laplace's equation… $\nabla\cdot\nabla\psi = \nabla^2\psi = 0$

(1) *The heliospheric magnetic field*

- Given a boundary condition on the sphere, the classical **potential field** is

$$\psi(r,\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} \left[a_{\ell m} \left(\frac{r}{R_\odot} \right)^{\ell} + b_{\ell m} \left(\frac{R_\odot}{r} \right)^{\ell+1} \right] Y_{\ell m}(\theta,\phi) \qquad \mathbf{B} = -\nabla\psi$$

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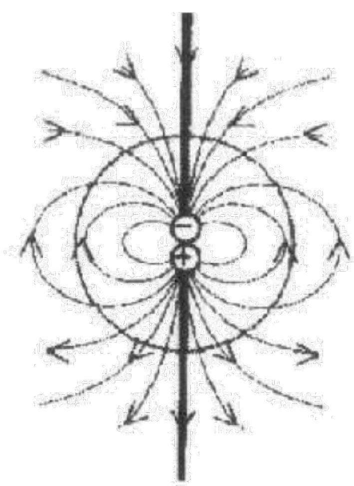
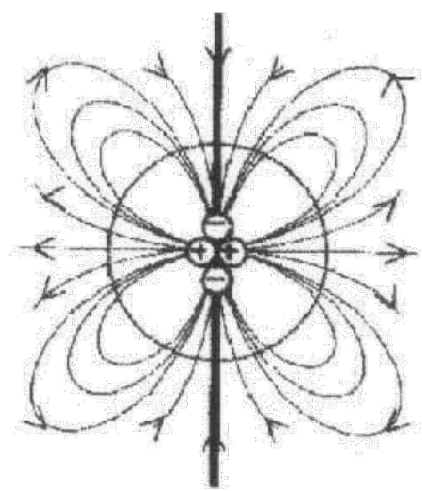
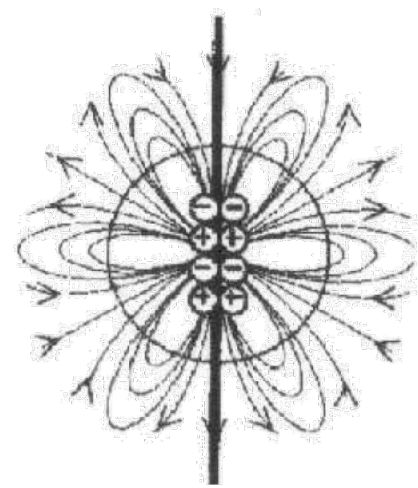
$\ell = 0$	**monopole** field	$\psi \propto r^{-1}$	$\mathbf{B}$ drops off as $1/r^2$
$\ell = 1$	**dipole** field	$\psi \propto r^{-2}$	$\mathbf{B}$ drops off as $1/r^3$
$\ell = 2$	**quadrupole** field	$\psi \propto r^{-3}$	$\mathbf{B}$ drops off as $1/r^4$
$\ell = 3$	**octupole** field	$\psi \propto r^{-4}$	$\mathbf{B}$ drops off as $1/r^5$


dipole


quadrupole


octupole

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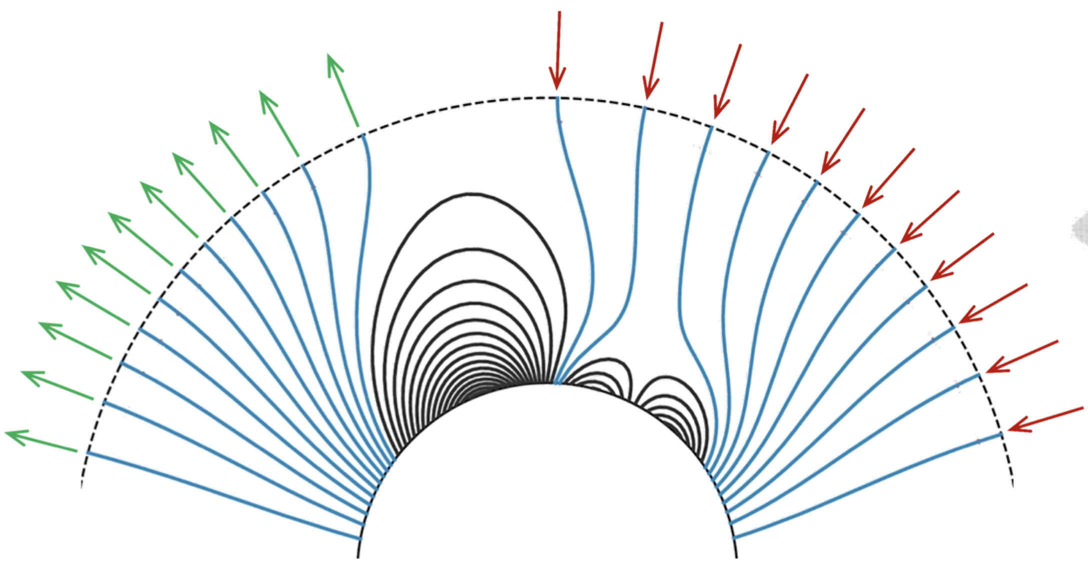
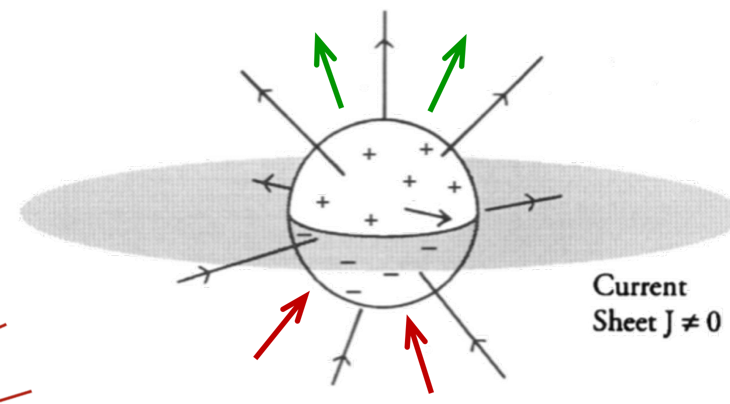
- If ψ = constant on the "source surface" ($r = R_{SS}$), then **B** is purely radial at & above it.

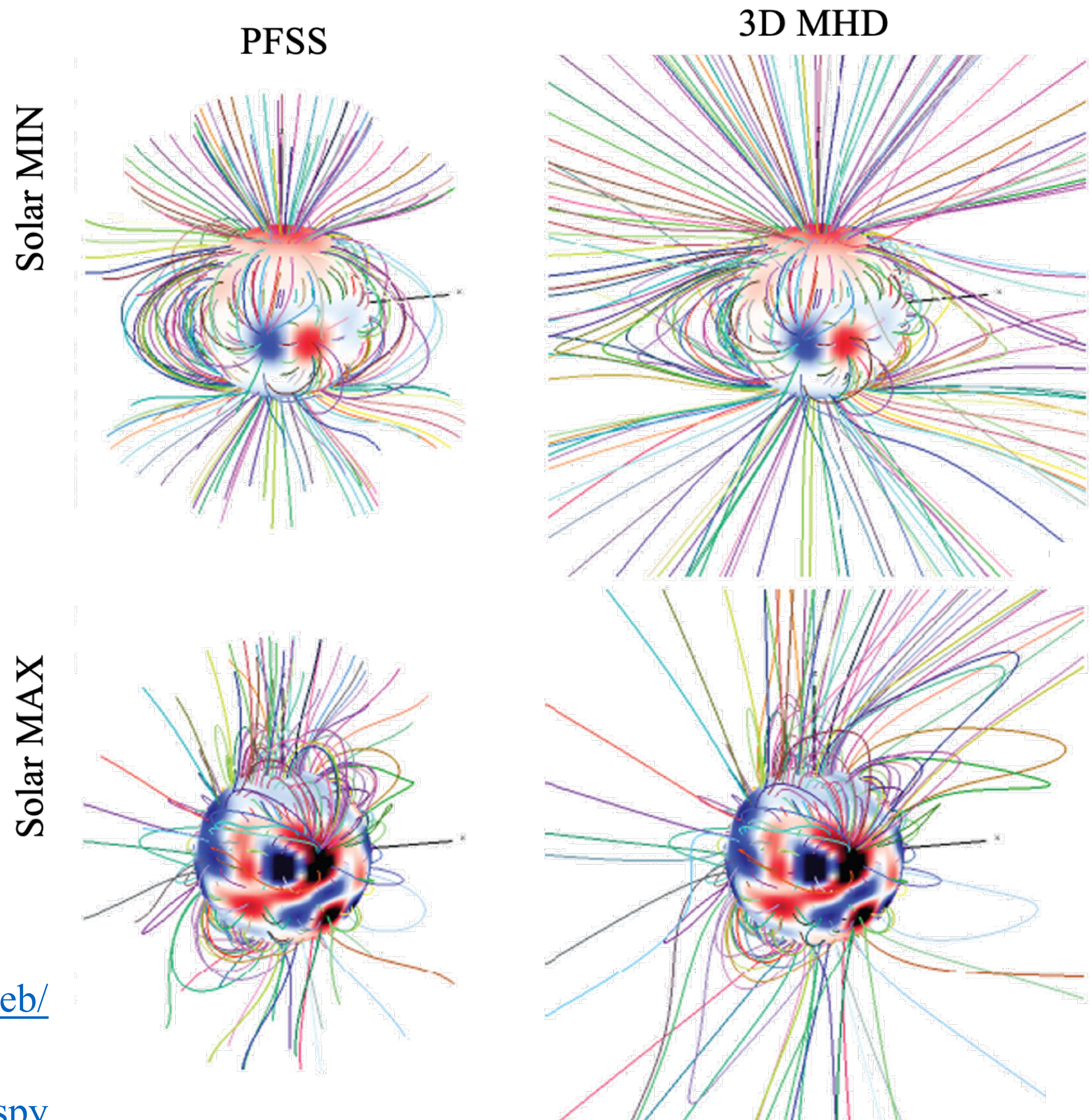




"split monopole"

(1) *The heliospheric magnetic field*

- PFSS is fast!
- A choice of $R_{SS} = 2.5\ R_{\odot}$ seems to capture many useful qualitative features of open/closed transitions in the outer corona, but no choice is perfect.
- Example comparisons from Riley et al. (2006) ⟶
- See a recent non-potential model that attempts to do better than PFSS while avoiding the computational demands of MHD:
  Rice & Yeates (2021, *ApJ,* 923, 57).



https://www.predsci.com/mhdweb/

https://ccmc.gsfc.nasa.gov/

https://github.com/dstansby/pfsspy

(2) *The solar wind*

- **Late 1800s → early 1900s:** evidence kept accumulating for *something* out there that connects the Sun and the Earth together.
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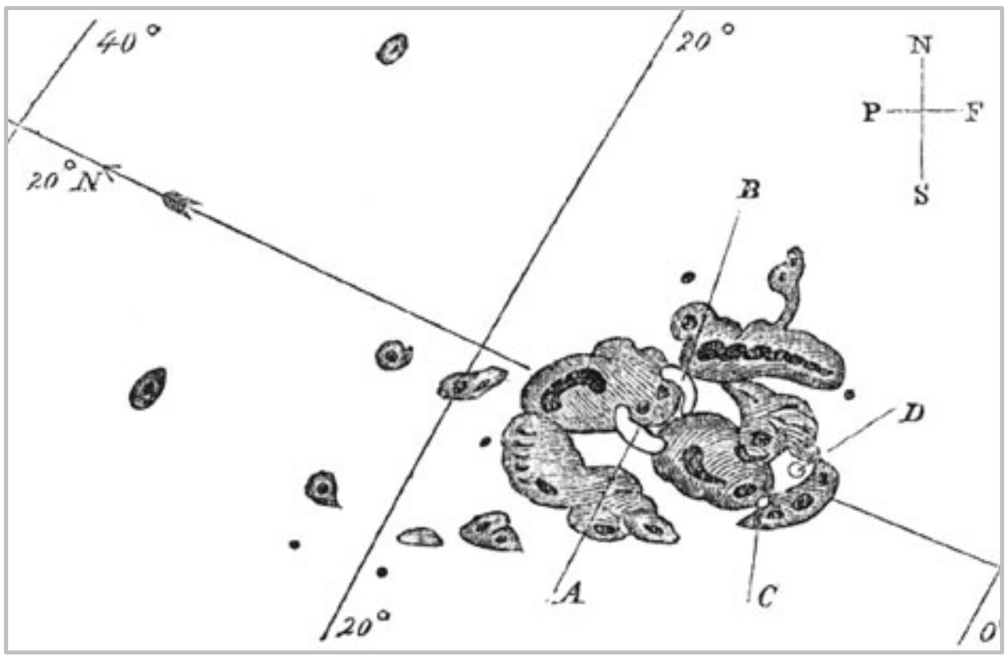
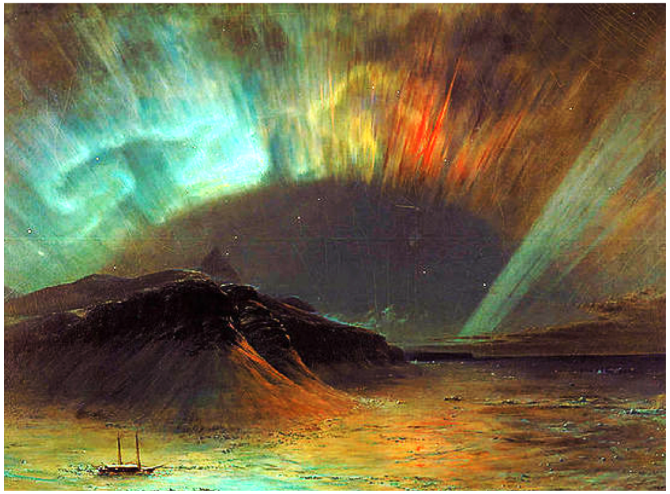
- I'll summarize 3 pieces of circumstantial evidence that Parker (1958) had in-hand…
- First, after the "Carrington event" (Sept. 1, 1859), there was increased awareness that there's some kind of cause-and-effect between events on the Sun & events on Earth.





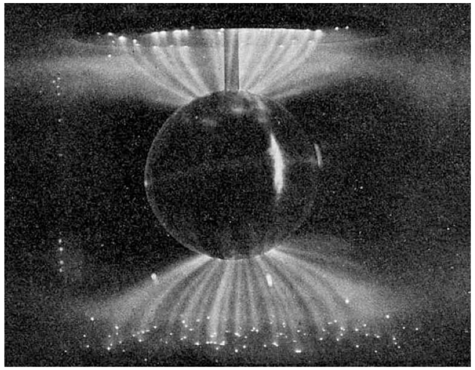
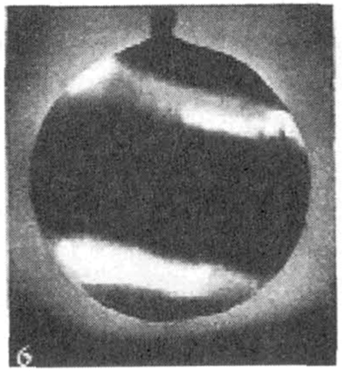
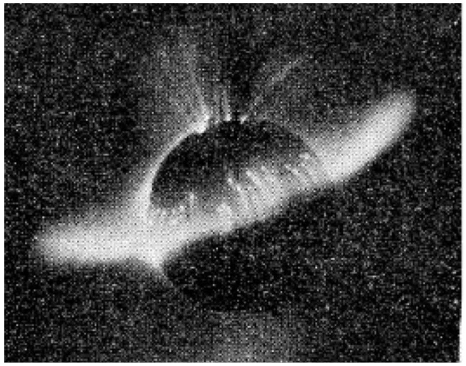
A STORM OF ELECTRICITY

TELEGRAPH WIRES USELESS FOR SEVERAL HOURS.

ONE OF THE MOST SEVERE DISTURBANCES FOR MANY YEARS, EXTENDING EVEN TO EUROPE—TELEPHONE WIRES ALSO OBSTRUCTED—BUSINESS DELAYED A GOOD PART OF THE DAY.

(2) *The solar wind*

- Ennis (1878): solar corona & terrestrial aurora were both the same kind of *"streaming forth of electricity."*
- Birkeland (1908): aurorae & geomagnetic storms *"...should be regarded as manifestations of an unknown cosmic agent of solar origin."*

(and he reproduced many auroral phenomena in the lab!)

- Serviss (1909): compared polar plumes to field lines traced by iron filings; hypothesized *"...there exists a direct solar influence not only upon the magnetism, but upon the weather of the earth."*
- Chapman (1918) proposed the Sun emits sporadic clouds of charged particles into the vacuum of space.

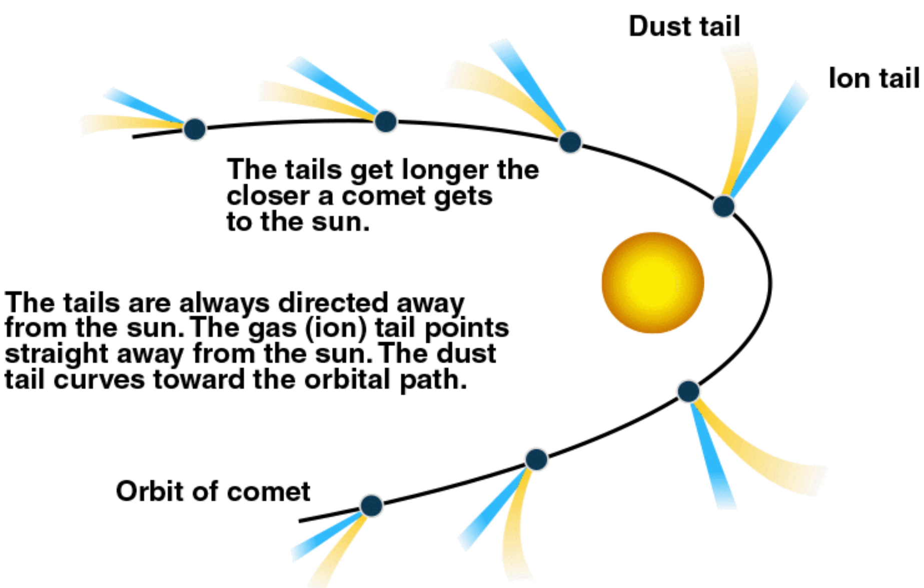
(for citations, see Cranmer 2019)

(2) *The solar wind*

- Second piece of evidence: many comets have **dust tails** (whose ejecta fall back along ballistic orbits) and **ion tails** (always oriented away from the Sun).
- Biermann (1951) also analyzed the kinematics of ion-tail inhomogeneities, which can be tracked to flow away from the Sun at speeds of a few × 100 km/s.

Kometenschweife und solare Korpuskularstrahlung

(Comet tails and solar corpuscular radiation)



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- Third piece of evidence: the existence of the hot (10^6 K) corona was well known, but if the corona was assumed to exist in a state of **hydrostatic equilibrium,** it gives a nonsensical answer for the gas pressure.

- For Chapman's (1957) heat conduction model,

$$T(r) = T_0 \left(\frac{r_0}{r}\right)^{2/7} \quad \text{and as } r \to \infty, \quad P \to P_0 \exp\left[-\left(\frac{V_{\text{esc},0}}{c_{s,0}}\right)^2\right] \approx 10^{-5} \text{ dynes/cm}^2$$

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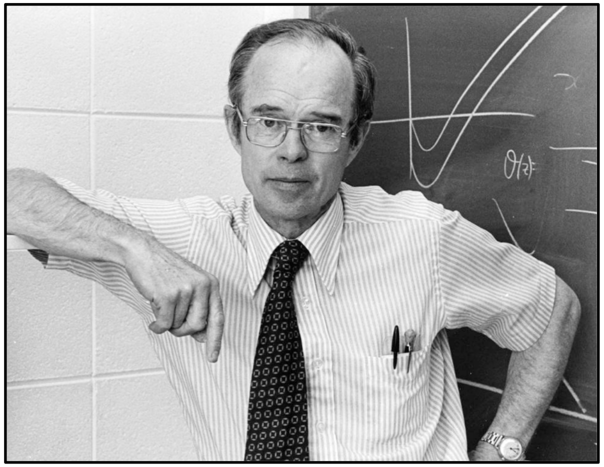
- However, by the 1950s, astronomers already knew typical gas pressures in the local **interstellar medium** were only 10^{-14} to 10^{-12} dynes/cm^2.
- If such a huge pressure difference were to exist, the pressure-gradient force would cause the corona to expand (explosively?) out to huge distances (parsecs?) before coming into equilibrium with the interstellar medium.
- If a new hydrostatic equilibrium was established, the near-Sun corona wouldn't look anything like it does now…
    - Something about this doesn't make sense.

(2) *The solar wind*

- Eugene Parker (1958a, *ApJ,* 128, 664) put the pieces together to conclude the gas in the outer corona must be in a continual state of acceleration & expansion.
- **2018:** first time NASA names a spacecraft after a living scientist: ***Parker Solar Probe!***
- https://www.youtube.com/watch?v=WH_TC9VzMUA



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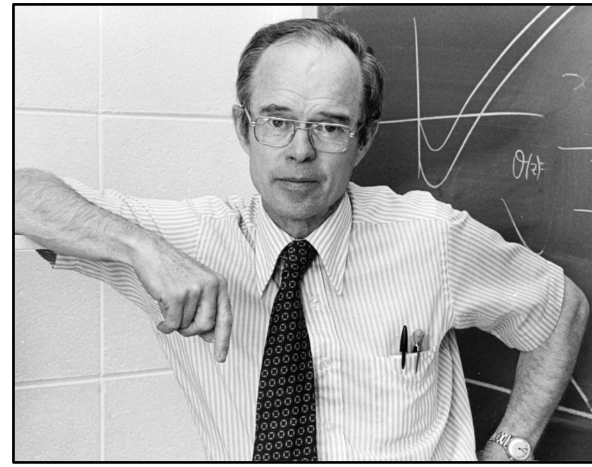

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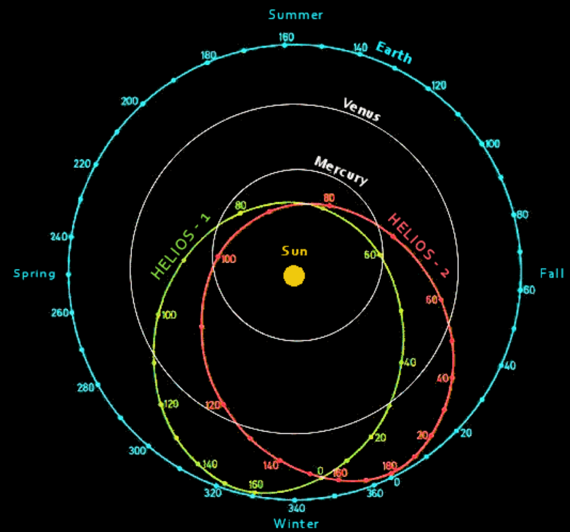
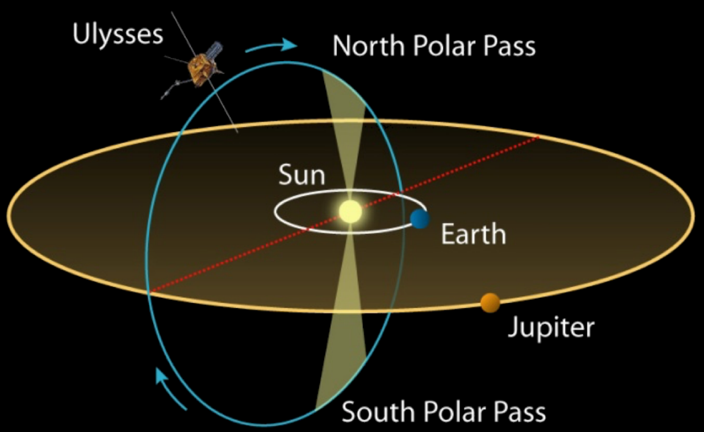
- **1959-1961:** Intermittent measurements on early probes that left Earth's magnetosphere: Russian *Lunik, Venera;* American *Explorer 10*
- **1962:** Marcia Neugebauer & colleagues got continuous data from ***Mariner 2*** on its way to Venus.
- The solar wind exists, and it behaves very much like Parker predicted.

(2) *The solar wind*

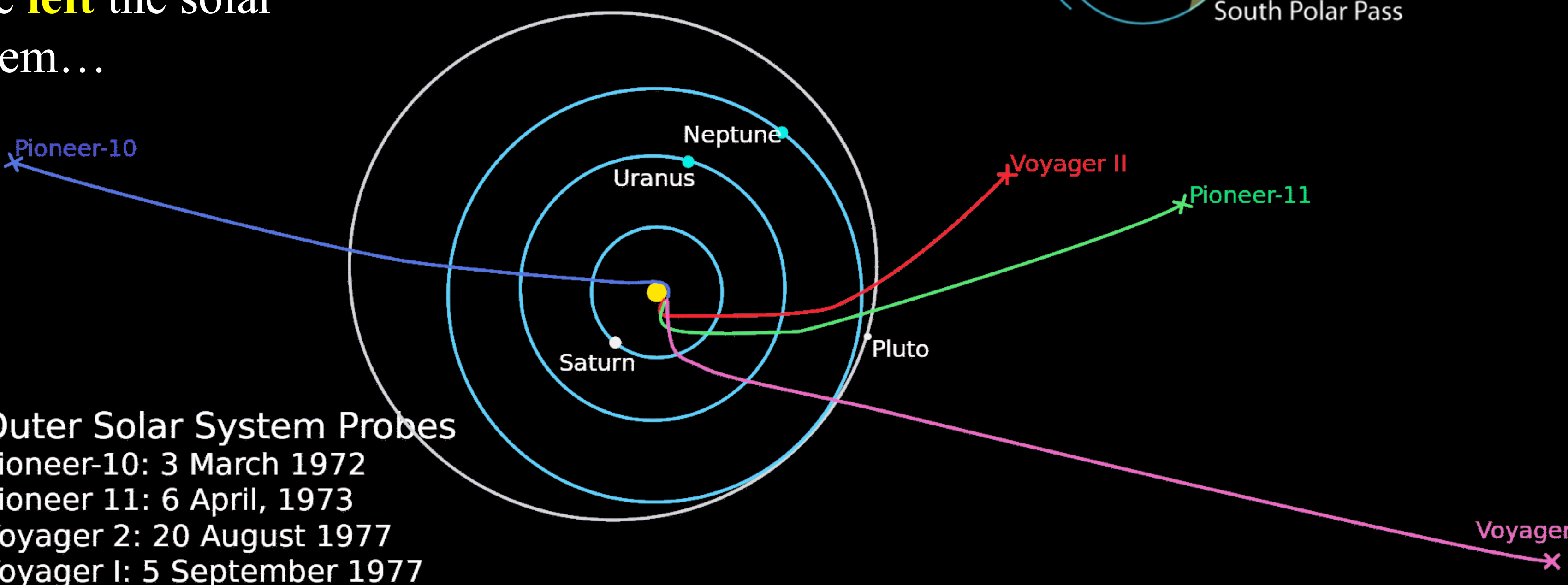
Helios & *PSP* went **in** past Mercury's orbit



Ulysses went **up & out** of the ecliptic plane



Voyagers & *Pioneers* have **left** the solar system…



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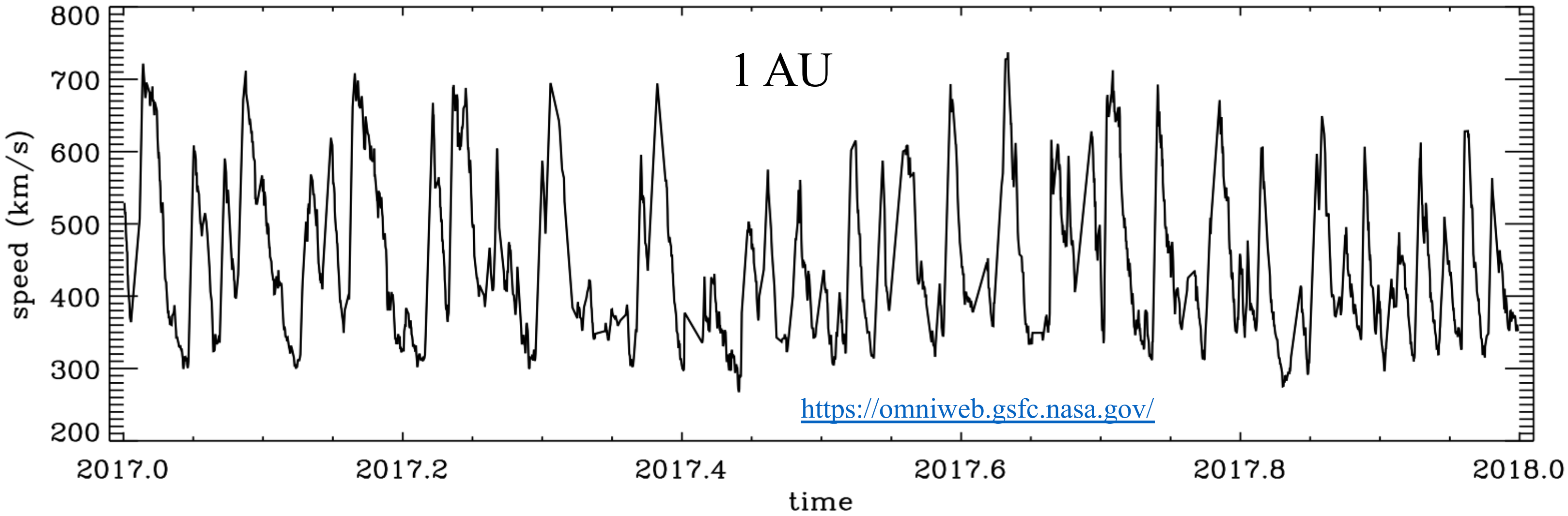

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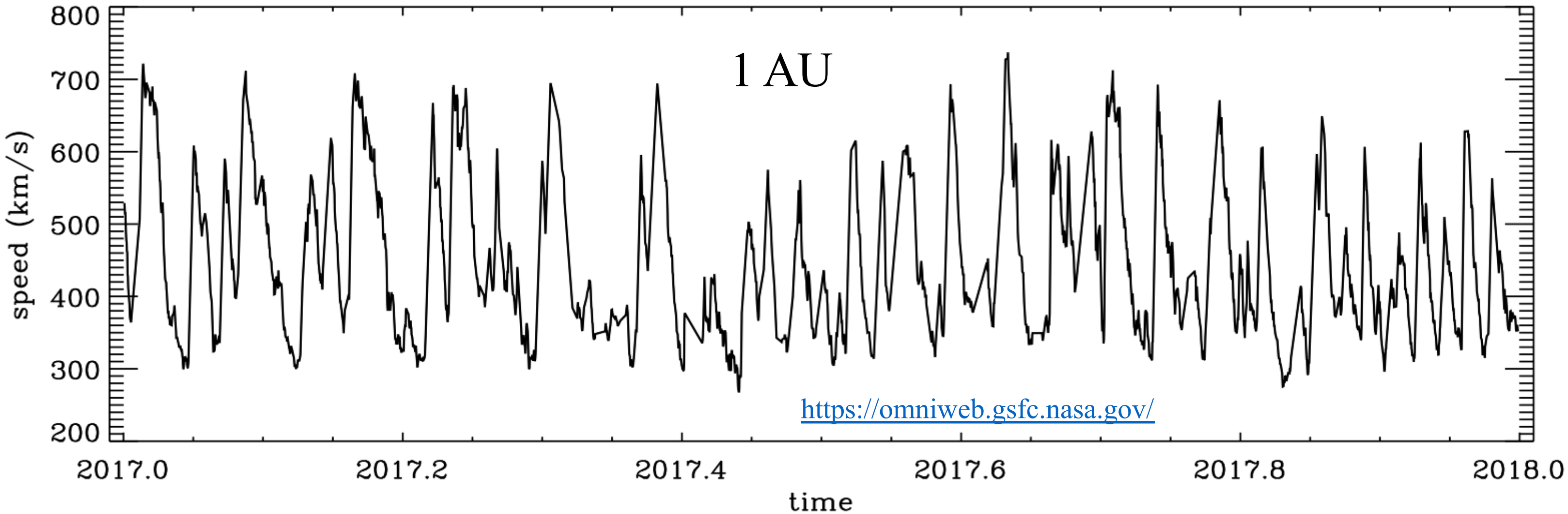
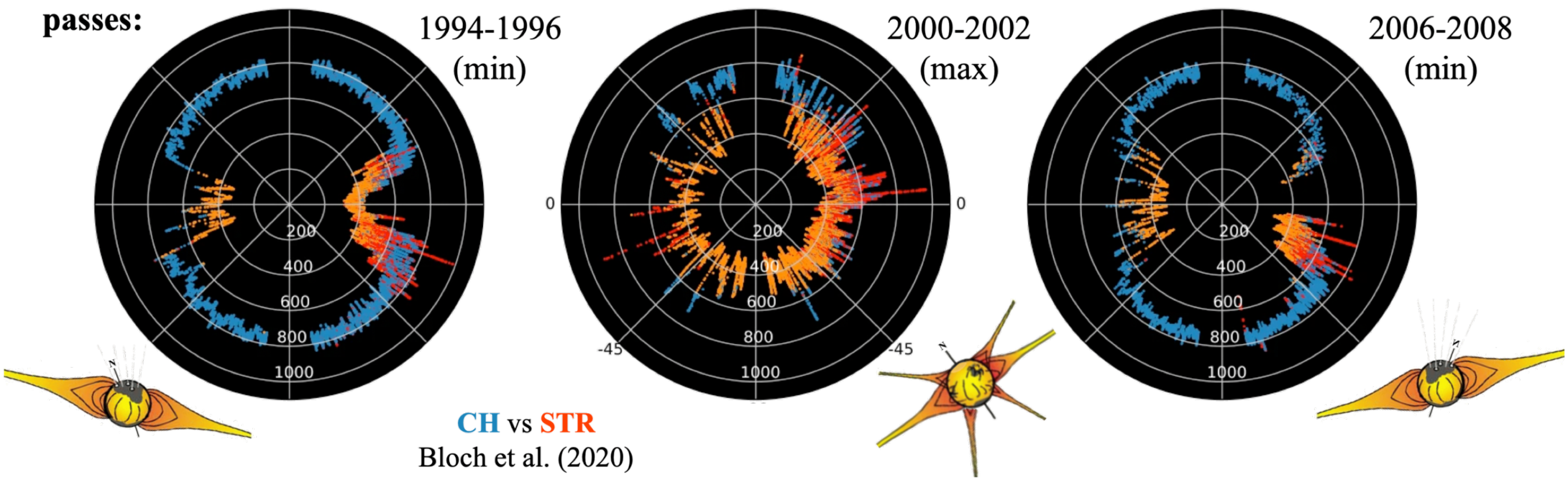


***Ulysses* polar passes:**



CH vs **STR**
Bloch et al. (2020)

(2) *The solar wind*

Parker's initial hydrodynamic solution:

- Time-steady (i.e., all time derivatives = 0), but still allowing $\mathbf{u} \neq 0$
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For a time-steady system, mass conservation is simple:

$r^2 \rho u = \text{constant}$. By convention, we define $$\boxed{\dot{M} = 4\pi \rho u r^2}$$

and $\dot{M}$ is the total **mass loss rate** of the wind (in kg/s), integrated around all 4π steradians of solid angle.

- **Note:** Parker (1958) doesn't predict $\dot{M}$. For that, we need the "base pressure" from a coronal heating model like RTV or Martens (2010)!

(2) *The solar wind*

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c_i = "isothermal" sound speed

(from mass conservation)

- The RHS is a sum of outward (pressure gradient) + inward (gravity) forces.
- The LHS can be counter-intuitive… does RHS > 0 produce radial acceleration or deceleration? Compressible "transonic" flows can be weird.

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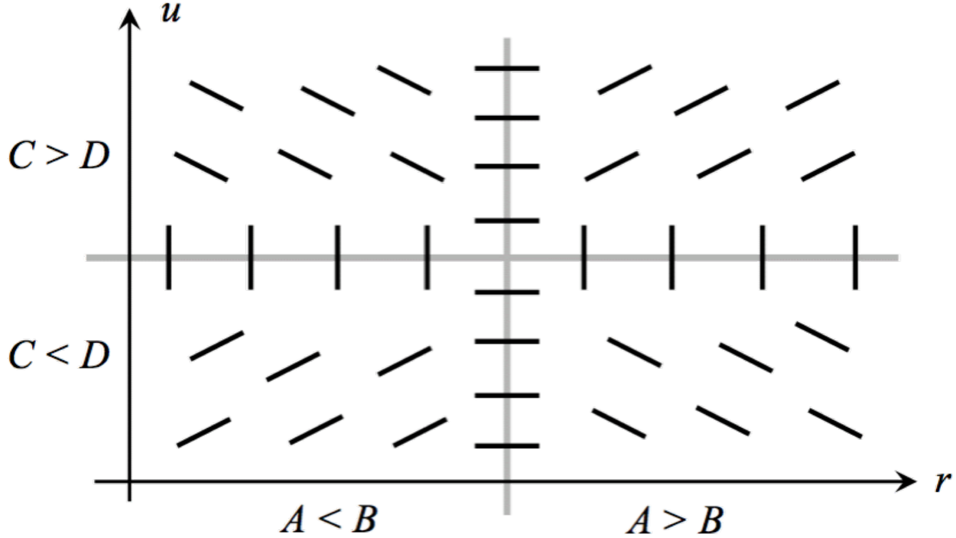
$$\left(u - \frac{c_i^2}{u}\right)\frac{du}{dr} = \left(\frac{2c_i^2}{r} - \frac{GM_\odot}{r^2}\right) \quad\Longrightarrow\quad \frac{du}{dr} = \frac{A(r) - B(r)}{C(u) - D(u)}$$

(2) *The solar wind*



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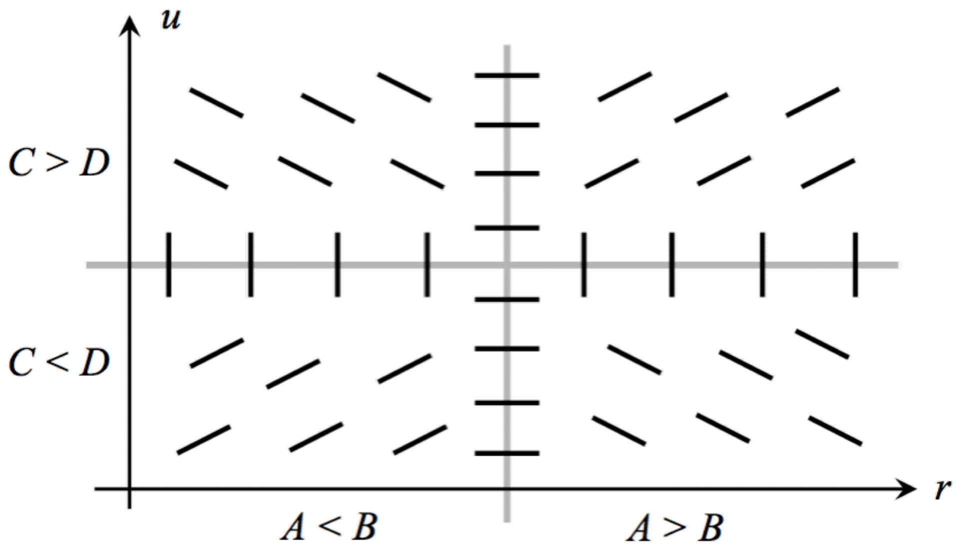
(2) *The solar wind*



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Note there are **singular points** when:

- $A = B$, but $C \neq D$ (flat)
- $A \neq B$, but $C = D$ (unphysical?)
- Both $A = B$ and $C = D$ (Parker's critical point)

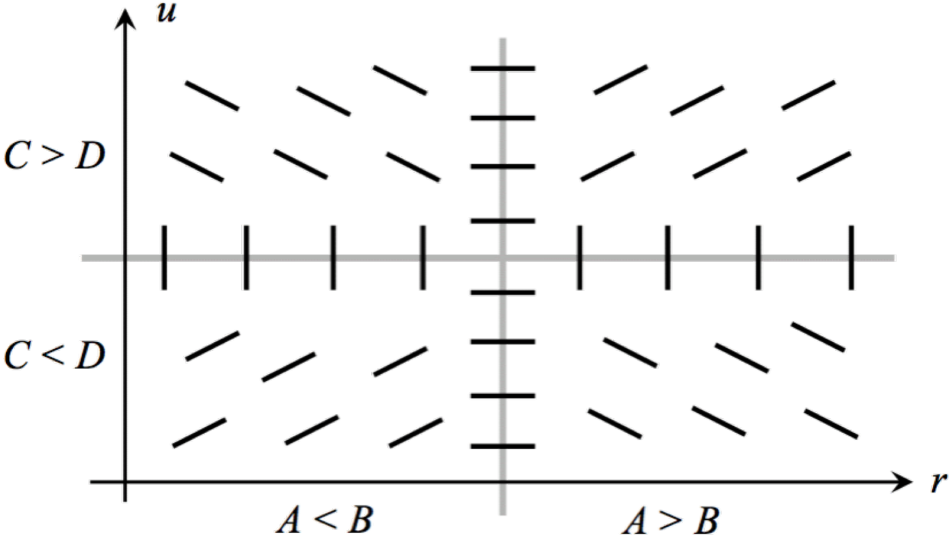
(0/0, so L'Hôpital's rule gives *du/dr*)

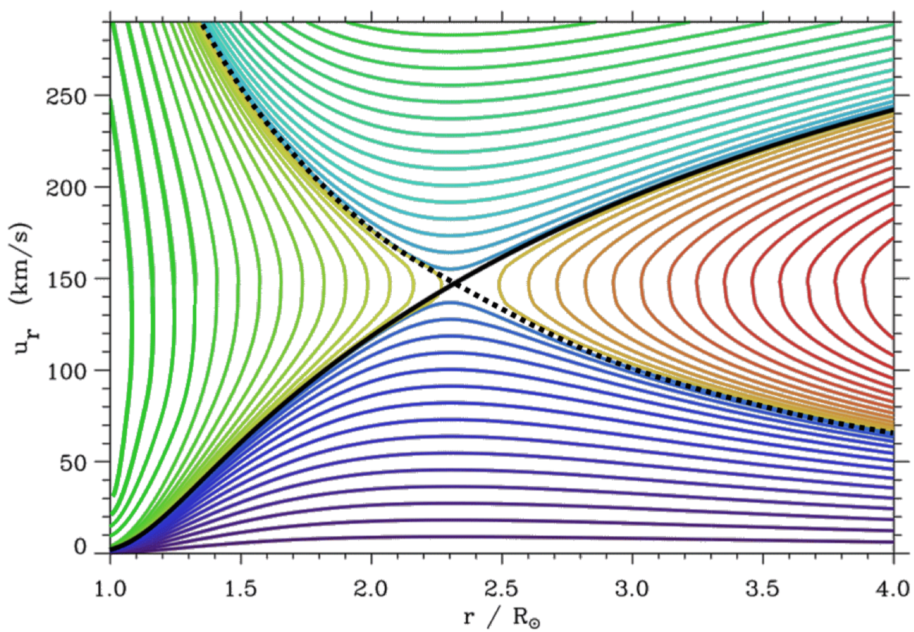
$$r_c = \frac{GM_\odot}{2\,c_i^2}$$

$$u_c = c_i$$

For a larger c_i, the critical point is closer to the Sun (∇P "beats" gravity sooner).

(2) *The solar wind*





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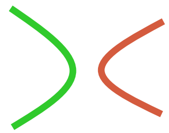
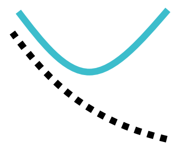
(2) *The solar wind*

Which solutions correspond to reality?

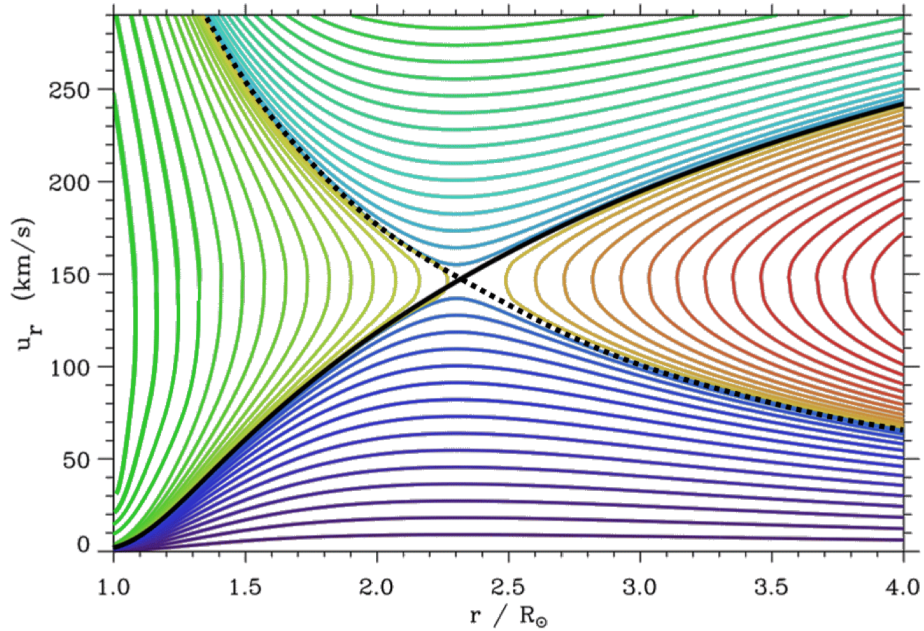
- Some are double-valued



- Some have fast outflows at the Sun's surface (where we don't really see outflows)



- What's left?



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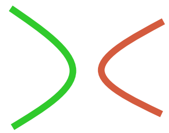

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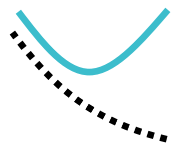

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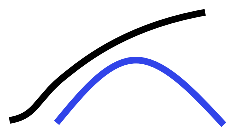
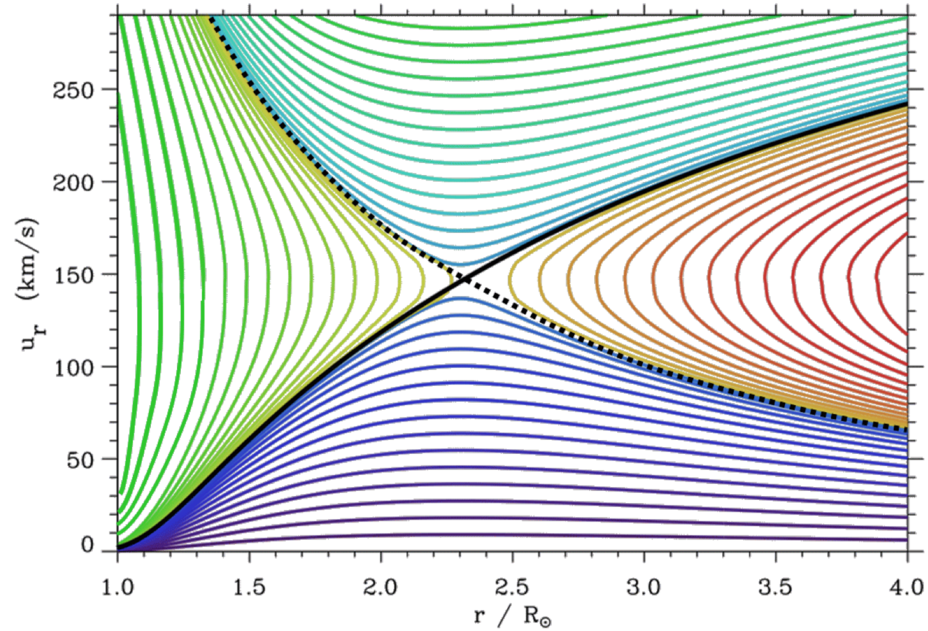




- **The subsonic solar breezes,** which have $u \to 0$ at infinity, so they suffer the same problems as the hydrostatic solutions.
- **The "transonic" solar wind,** which Parker suspected was the true steady-state "stable attractor" (proved by Velli 1994, *ApJL,* 432, L55)

$$(u^2 - c_i^2) - c_i^2 \ln\left(\frac{u^2}{c_i^2}\right) = 4c_i^2 \ln\left(\frac{r}{r_c}\right) + 2GM_\odot\left(\frac{1}{r} - \frac{1}{r_c}\right)$$

(2) *The solar wind*

- Parker (1958): higher temperature, faster wind…

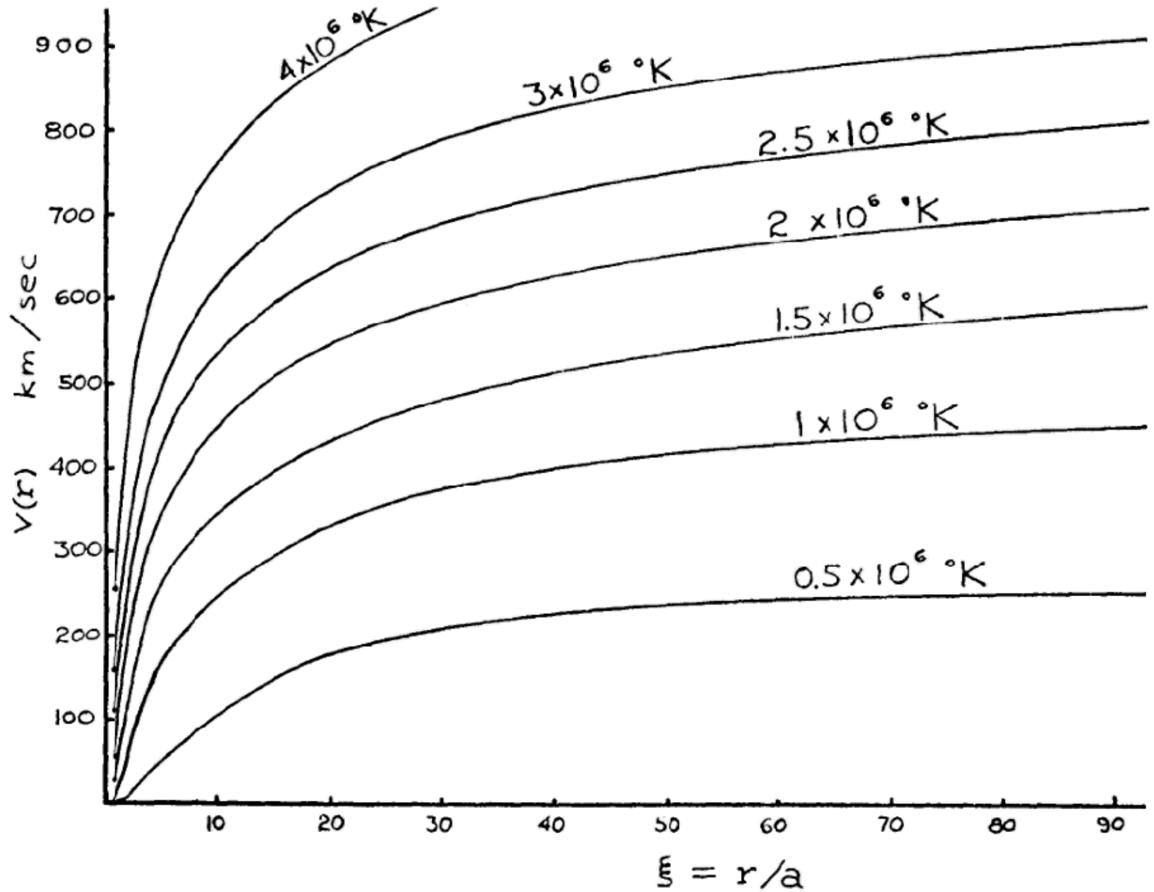


FIG. 1 —Spherically symmetric hydrodynamic expansion velocity $v(r)$ of an isothermal solar corona with temperature T_0 plotted as a function of r/a, where a is the radius of the corona and has been taken to be 10^{11} cm

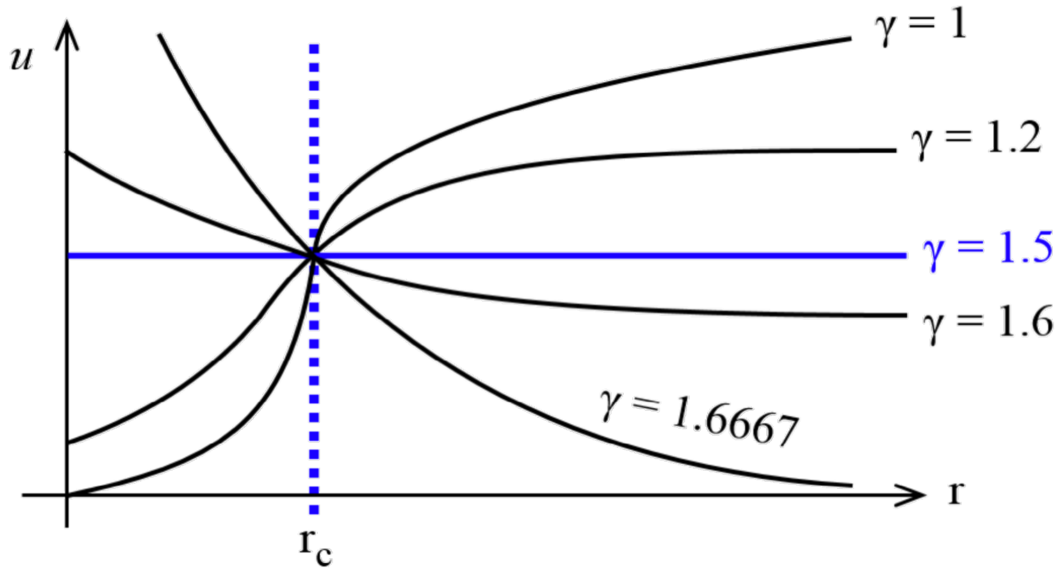
(2) *The solar wind*

- Owocki (2004) outlined another way to solve for $u(r)$ via Bernoulli's equation…

$$\mathcal{E} = \frac{u^2}{2} - \frac{GM_\odot}{r} + \left(\frac{\gamma}{\gamma-1}\right) c_i^2 = \text{constant} .$$

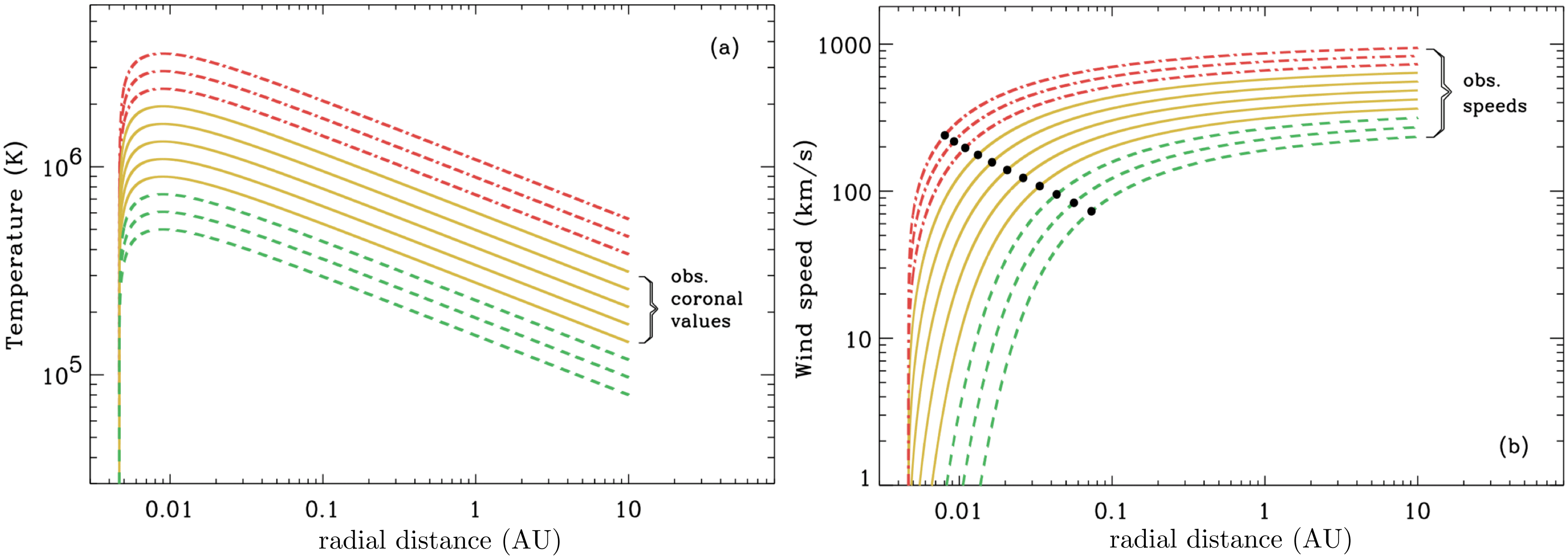
$$\mathcal{E}_c = \frac{u_c^2}{2}\left(\frac{5-3\gamma}{\gamma-1}\right) \qquad \mathcal{E}_\infty = \frac{u_\infty^2}{2} \qquad \text{i.e.,} \qquad \boxed{u_\infty = u_c\sqrt{\frac{5-3\gamma}{\gamma-1}}}$$

- Accelerating solutions with a constant "terminal speed" require $1 < \gamma < 1.5$.
- As $r \rightarrow \infty$, adiabatic expansion has $T \propto r^{2-2\gamma}$, *in situ* data constrains $1.15 < \gamma < 1.35$.



(2) *The solar wind*

- If we have an observationally-constrained numerical tabulation for $T(r)$, we can just integrate the momentum equation numerically…



- **Problem:** the full range of observed temperatures (yellow) reproduces only *some* of the observed speeds at 1 AU.
- Other physics is needed to explain slowest ($u < 300$ km/s) & fastest ($u > 600$ km/s) solar wind streams.

For next week

Read (parts of) two complementary papers:

- Paper 4a: Wang & Sheeley (1990, *ApJ,* 355, 726, 8 pages),
  "Solar wind speed and coronal flux-tube expansion"
  [okay to skip: section **IV**] [ADS]

- Paper 4b: Cranmer (2005, arXiv:astro-ph/0506508, 6 pages),
  "Why is the fast solar wind fast & the slow solar wind slow?"
  [okay to skip: sections **5, 6, and 7**] [ADS]

- Participate in the #paper-4-discussion channel on Slack for next week (February 24, 2022)