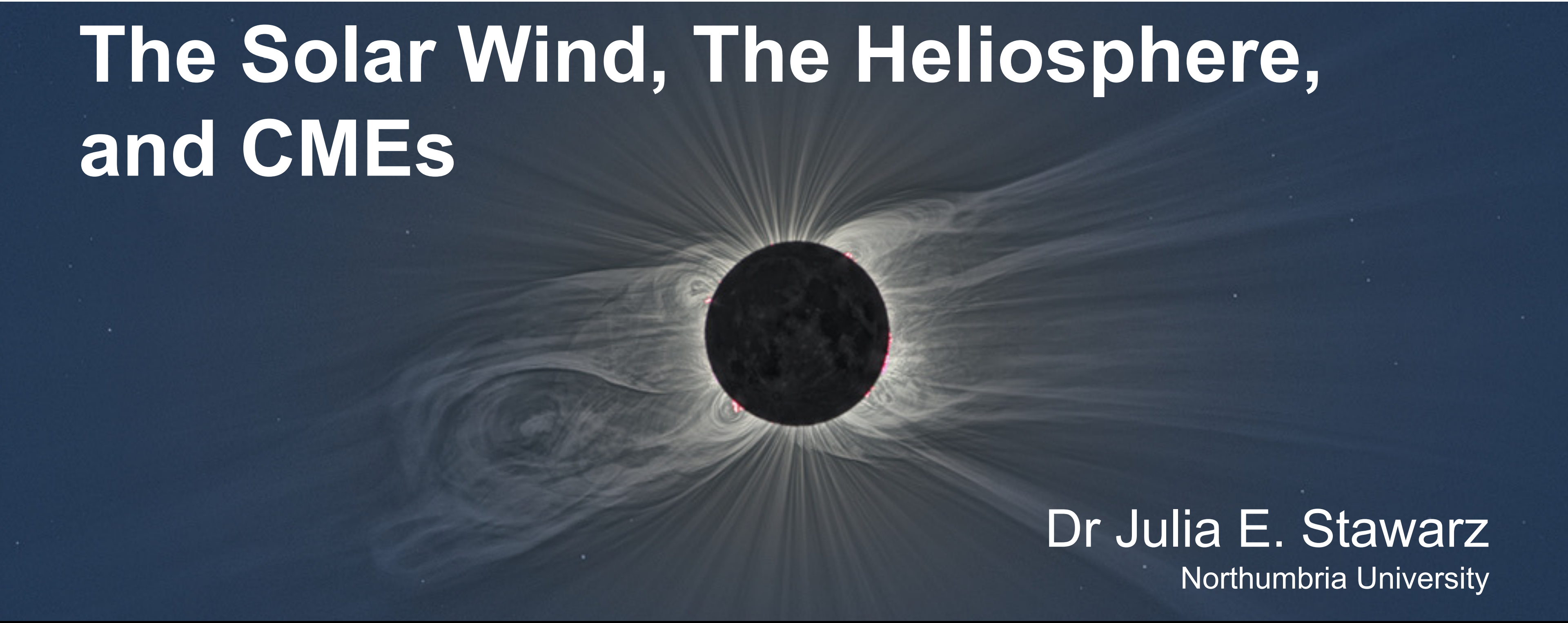

The Solar Wind, The Heliosphere, and CMEs

Dr Julia E. Stawarz
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Outline

Parker’s Solar Wind Model

→ Exospheric Solar Wind Models

→ The Solar Wind Magnetic Field

→ Early & Recent Observations of the Solar Wind

Complex/Transient Structure of the Solar Wind

→ Fast & Slow Solar Wind

→ Corotating Interaction Regions

→ Coronal Mass Ejections

→ Waves & Turbulence

The Boundary of the Heliosphere

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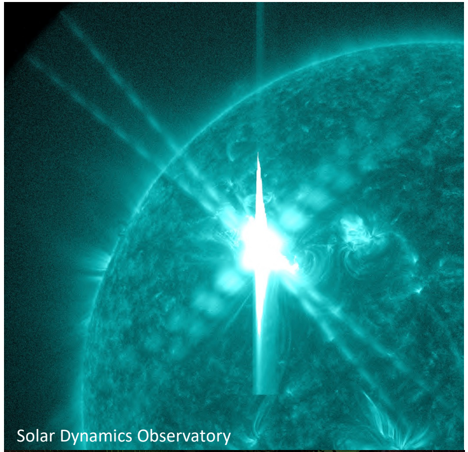
What is the Solar Wind?

The solar wind is a fast continuous flow of plasma emanating from the Sun → Sun's extended atmosphere



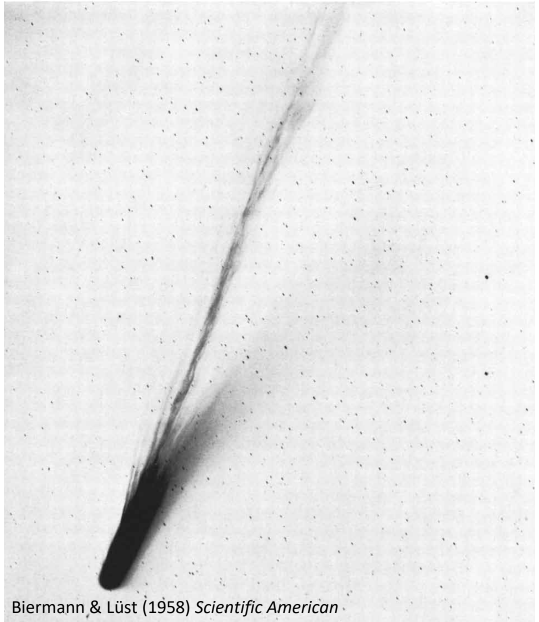
Solar Dynamics Observatory

earthobservatory.nasa.gov

What did we know before the space age?

Solar flares often followed several days later by geomagnetic storms
→ Sun at least intermittently ejecting material

Comet tails are always directed away from the Sun
→ Radiation pressure? ❌
→ Particle flow? → requires several 100 km/s flows



Biermann & Lüst (1958) *Scientific American*

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The Parker Solar Wind

Hydrodynamic Momentum Equation

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho\boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\nabla P - \frac{GM_{\odot}\rho}{r^2}\hat{\boldsymbol{r}}$$

Additional Assumptions

- **Steady State** $\frac{\partial}{\partial t} \to 0$
- **Spherically Symmetric** $\nabla \to \frac{\partial}{\partial r},\ \ \boldsymbol{u} \to u_r$
- **Isothermal Temperature Closure** $P = \frac{k_B T}{m}\rho(r)$
- **Constant Mass Flux** $4\pi r^2 \rho u_r = constant$

$$\to \frac{1}{\rho}\frac{\partial \rho}{\partial r} = -\frac{1}{u_r}\frac{\partial u_r}{\partial r} - \frac{2}{r}$$

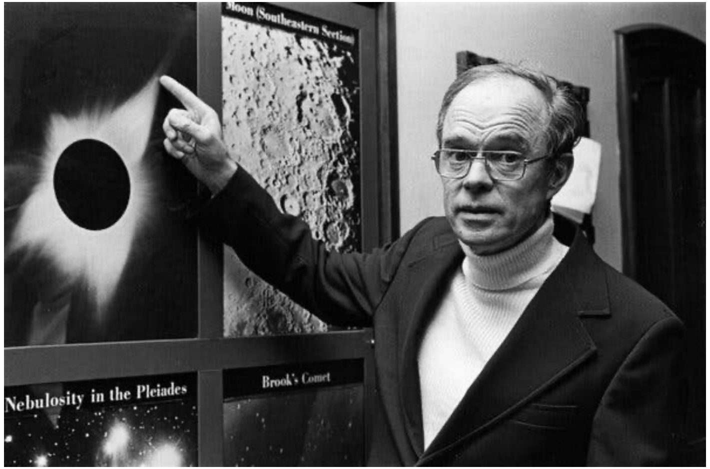
DYNAMICS OF THE INTERPLANETARY GAS AND MAGNETIC FIELDS*

E. N. Parker
Enrico Fermi Institute for Nuclear Studies, University of Chicago

Received January 2, 1958

ABSTRACT

We consider the dynamical consequences of Biermann's suggestion that gas is often streaming outward in all directions from the sun with velocities of the order of 500–1500 km/sec. These velocities of 500 km/sec and more and the interplanetary densities of 500 ions/cm^3 (10^{14} gm/sec mass loss from the sun) follow from the hydrodynamic equations for a 3×10^6 °K solar corona. It is suggested that the outward-streaming gas draws out the lines of force of the solar magnetic fields so that near the sun the field is very nearly in a radial direction. Plasma instabilities are expected to result in the thick shell of disordered field (10^{-5} gauss) inclosing the inner solar system, whose presence has already been inferred from cosmic-ray observations.



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The Parker Solar Wind

Hydrodynamic Momentum Equation

$$\rho \cancel{\frac{\partial \mathbf{u}}{\partial t}} + \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P - \frac{GM_\odot \rho}{r^2}\hat{\mathbf{r}}$$

$$\Downarrow$$

$$u_r \frac{\partial u_r}{\partial r} = \frac{k_B T}{m}\left(\frac{1}{u_r}\frac{\partial u_r}{\partial r} - \frac{2}{r}\right) - \frac{GM_\odot}{r^2}$$

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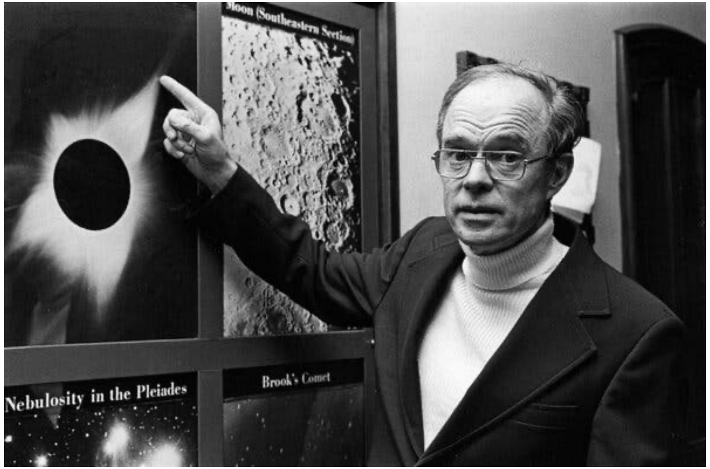

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The Parker Solar Wind

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$$\Downarrow$$

$$u_r \frac{\partial u_r}{\partial r} = \frac{k_B T}{m} \left(\frac{1}{u_r} \frac{\partial u_r}{\partial r} - \frac{2}{r} \right) - \frac{G M_\odot}{r^2}$$

$$\left(u_r^2 - \frac{k_B T}{m} \right) \frac{1}{u_r} \frac{\partial u_r}{\partial r} = 2 \frac{k_B T}{m} \frac{1}{r^2} \left(r - \frac{G M_\odot m}{2 k_B T} \right)$$

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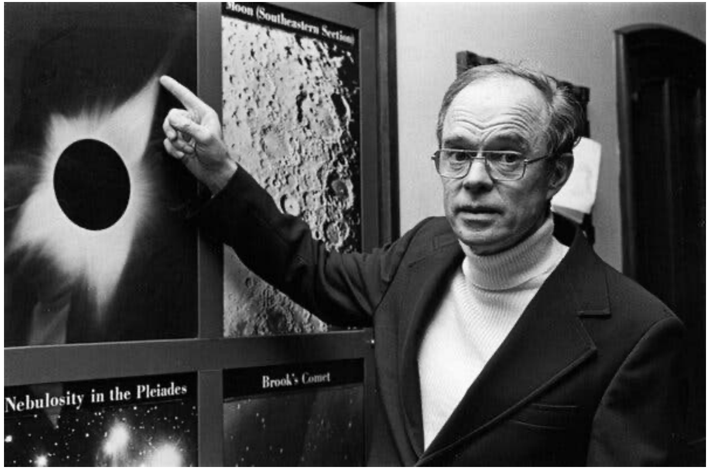

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The Parker Solar Wind

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$$u_r \frac{\partial u_r}{\partial r} = \frac{k_B T}{m} \left(\frac{1}{u_r} \frac{\partial u_r}{\partial r} - \frac{2}{r} \right) - \frac{G M_{\odot}}{r^2}$$

$$(u_r^2 - c_s^2) \frac{1}{u_r} \frac{\partial u_r}{\partial r} = 2 c_s^2 \frac{1}{r^2} (r - r_c)$$

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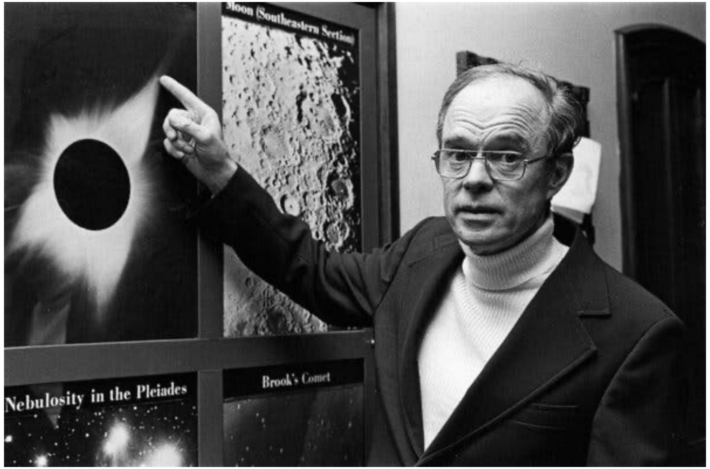

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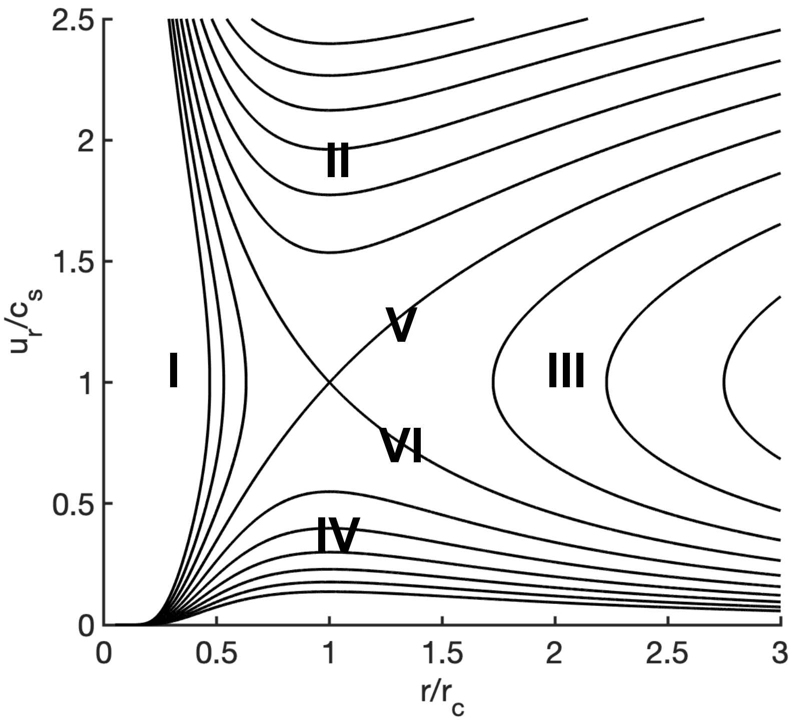
The Parker Solar Wind



Directly integrating differential equation gives:

$$\left(\frac{u_r}{c_s}\right)^2 - \ln\left(\frac{u_r}{c_s}\right)^2 = 4\ln\left(\frac{r}{r_c}\right) + 4\frac{r_c}{r} + C$$

Different families of solutions depending on constant

Which solutions are physically plausible?

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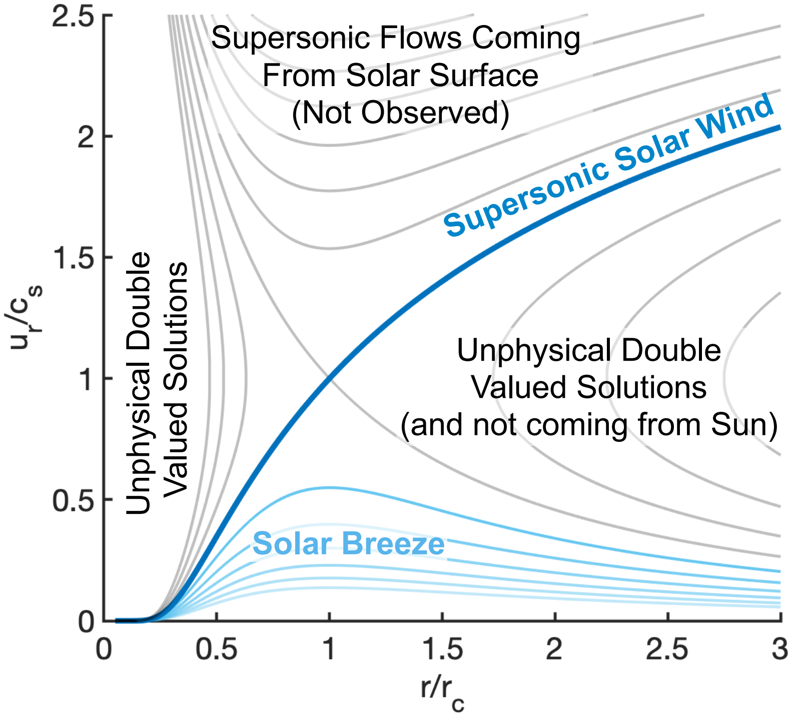
The Parker Solar Wind



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Which solutions are physically plausible?

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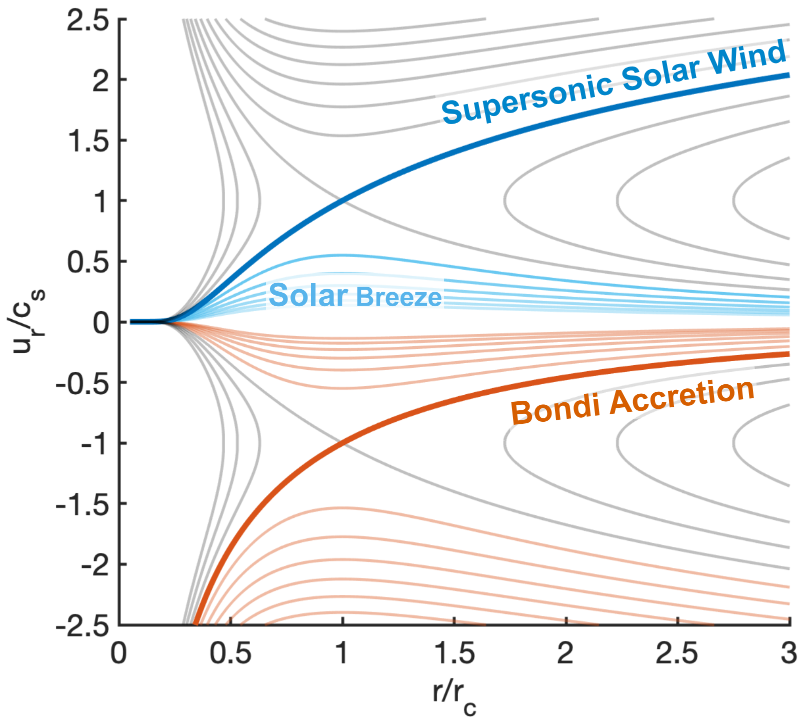
Connections with Astrophysics



Negative solutions describe spherically symmetric accretion

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Exospheric Solar Wind Model

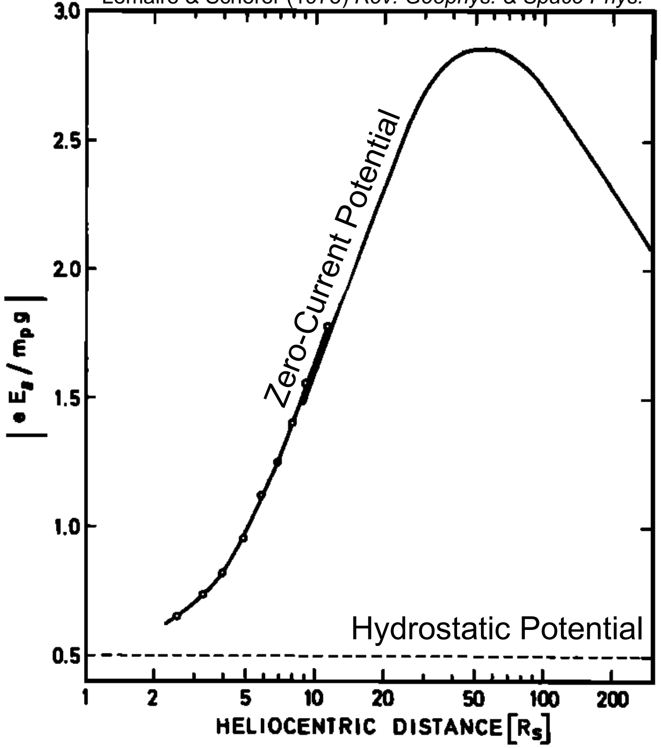
Collisionless *Kinetic* Model of the Solar Wind

- Lower mass of electrons means electrons are much more mobile than ions
  → more electrons have escape velocity from Sun
- To maintain quasi-neutrality, an *ambipolar* electric field is set up in the plasma accelerating the ions

$$E = -\frac{\nabla P_e}{ne}$$

- By requiring no net current, self-consistent solutions can be found resulting in a super-sonic solar wind
  → in limit of Maxwellian distributions and vanishing electron mass model is consistent with Parker solar wind

Lemaire & Scherer (1973) *Rev. Geophys. & Space Phys.*



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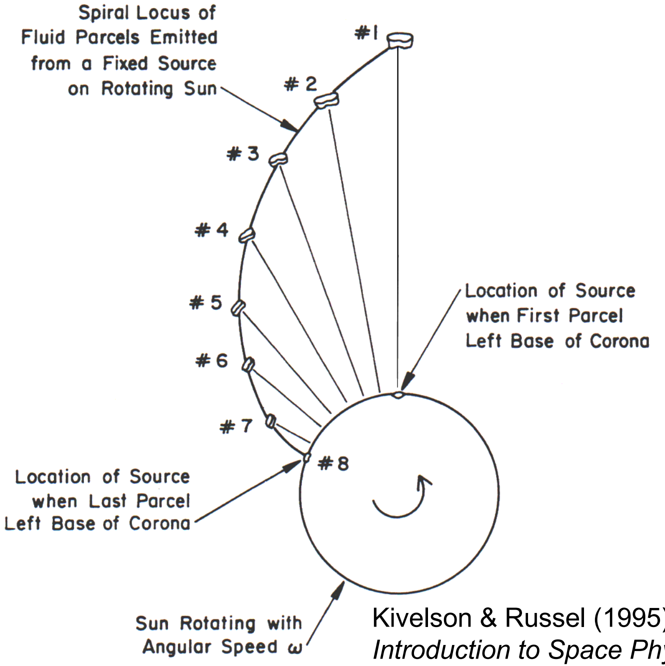
The Solar Wind Magnetic Field

What will the magnetic field lines embedded in the solar wind look like?

- Consider the magnetic field to be frozen-in to the hydrodynamic flow
- At solar surface, magnetic foot point rotates with Sun
- Once solar wind plasma leaves Sun, magnetic flux dragged radially outward

Produces Archimedean spiral magnetic
→ **Parker spiral** in solar wind context



Kivelson & Russel (1995)
Introduction to Space Physics

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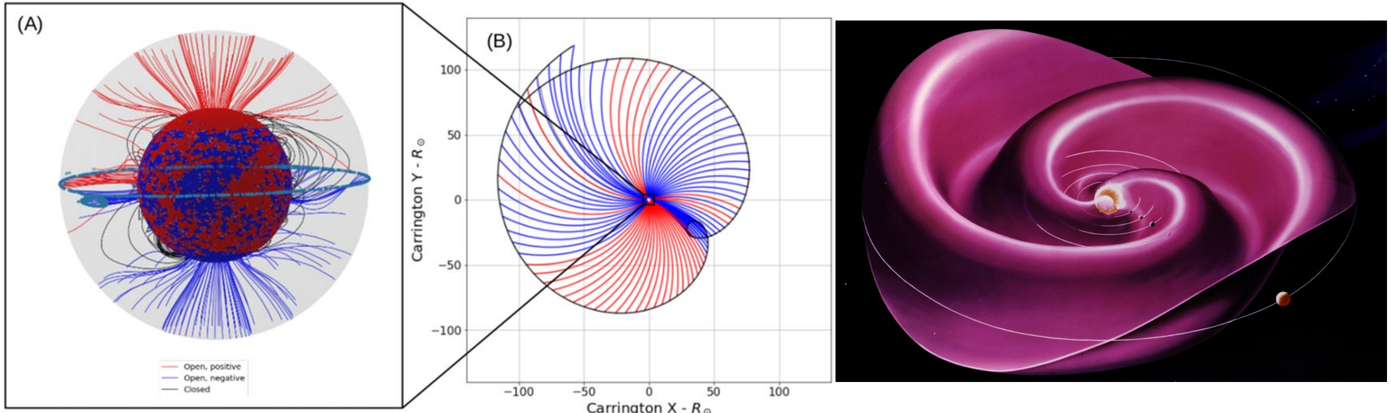
The Solar Wind Magnetic Field

What will the magnetic field lines embedded in the solar wind look like?

Sun has both inward and outward polarity magnetic fields that are dragged into solar wind

Current sheet present at interface of two polarities



Badman+ (2020) *ApJS*

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Solar Wind Observations

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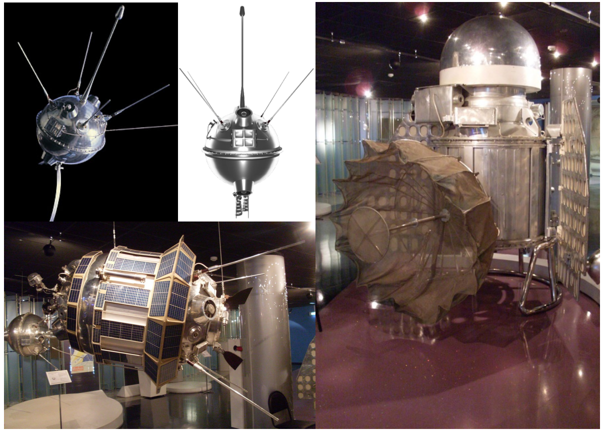
Early Solar Wind Observations

Soviet Luna 1-3 & Venera 1

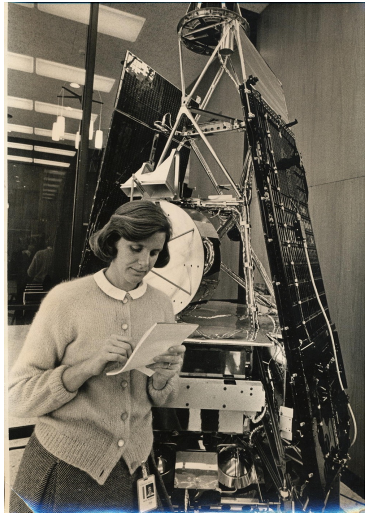
Made first measurements of solar wind between 1959 - 1961

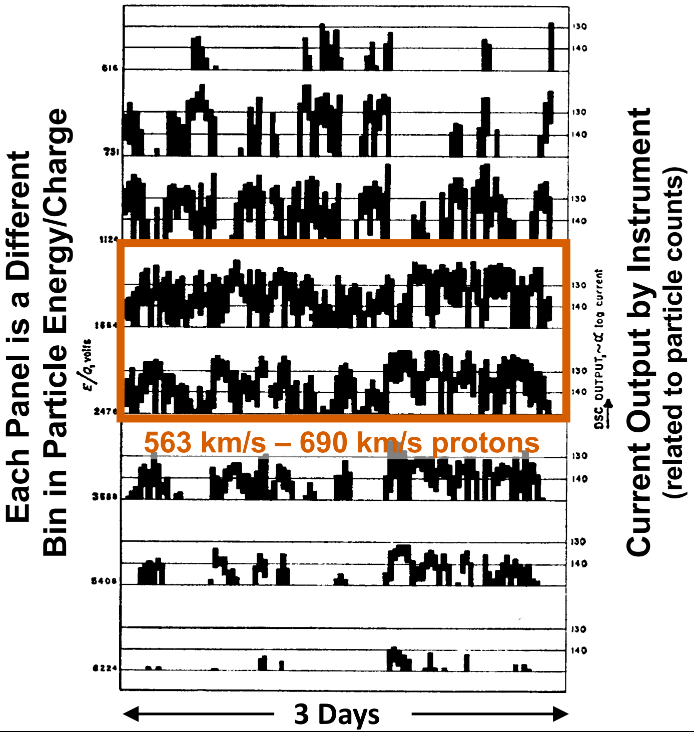


Science, **138**, 1905-1907 (1962)

The Mission of Mariner II: Preliminary Observations

MARCIA NEUGEBAUER
CONWAY W. SNYDER
Jet Propulsion Laboratory, California Institute of Technology, Pasadena





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New Solar Wind Observations

In-situ measurements at distances closer to sun than ever before

Both *in-situ* and remote sensing observations

Key Science Objectives

Parker Solar Probe [Fox+ (2016) *Space Sci. Rev.*]

- Trace the flow of energy that heats the solar corona and accelerates the solar wind
- Determine the structure and dynamics of the plasma and magnetic fields at the sources of the solar wind
- Explore mechanisms that accelerate and transport energetic particles

Solar Orbiter [Müller+ (2020) *A&A*]

- What drives the solar wind and where does the coronal magnetic field originate?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

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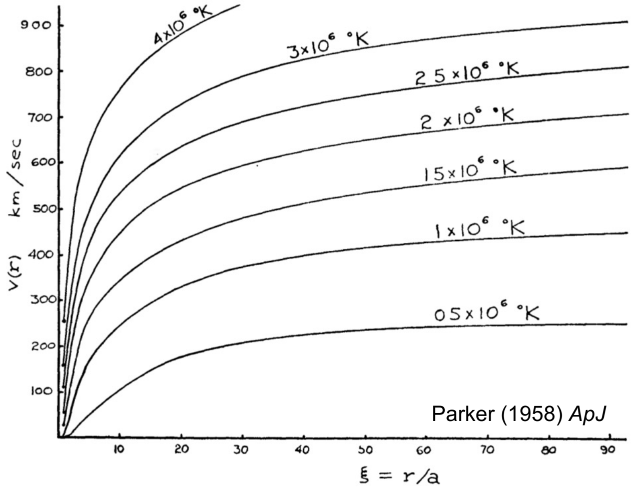
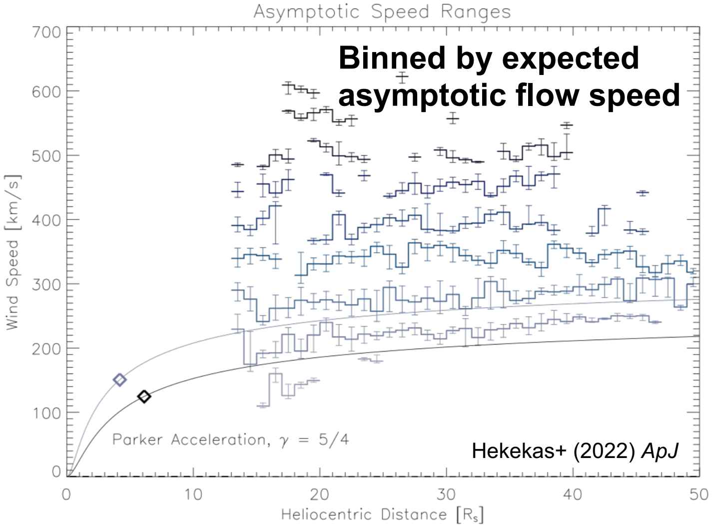
Solar Wind Acceleration

In the Parker (or exospheric) models, asymptotic solar wind speed depends on temperature in the corona

While the slow solar wind can be reasonably accounted for by observed temperatures, the fast solar wind is not



Parker (1958) *ApJ*



Hekekas+ (2022) *ApJ*

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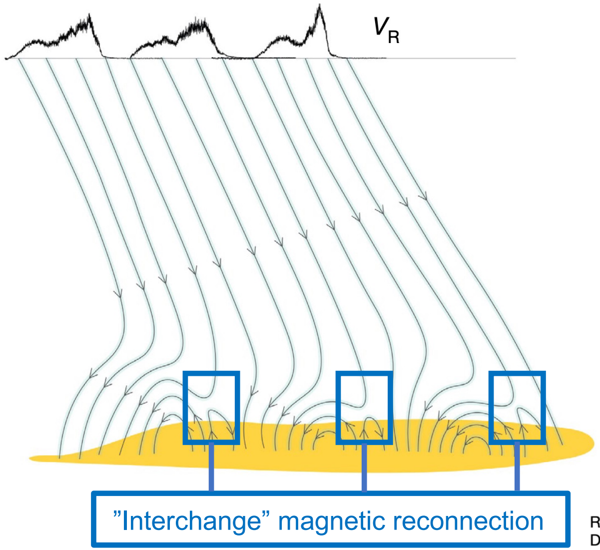
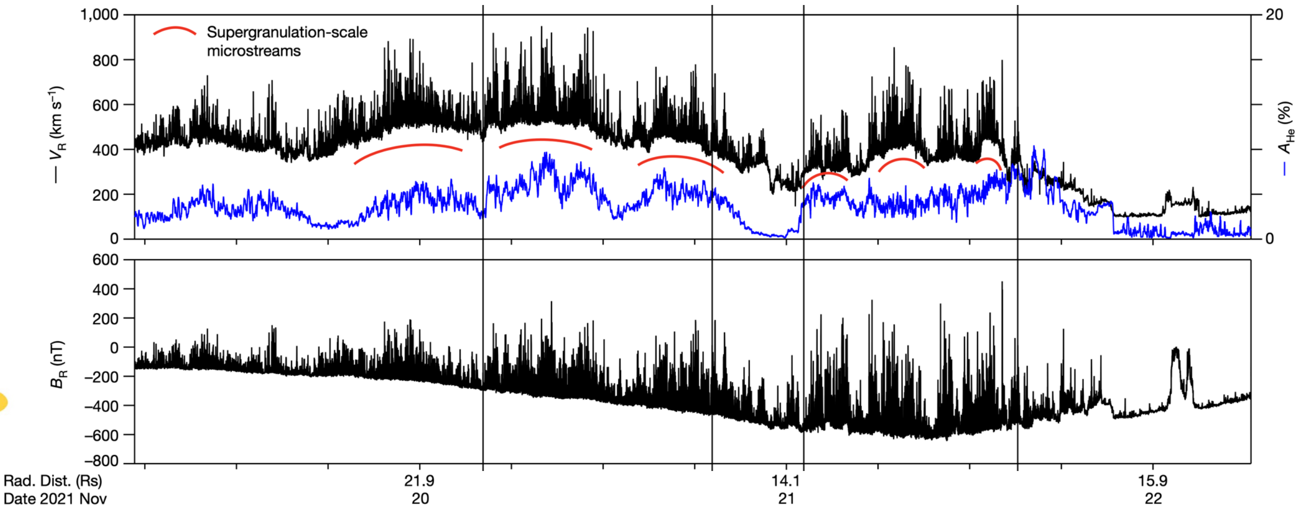
Solar Wind Acceleration

Recent observations from Parker Solar Probe near the Sun, have suggested that *interchange reconnection* on top of a Parker-like slow solar wind background may account for fast solar wind streams





Bale+ (2023) *Nature*

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Multi-Spacecraft Conjunctions

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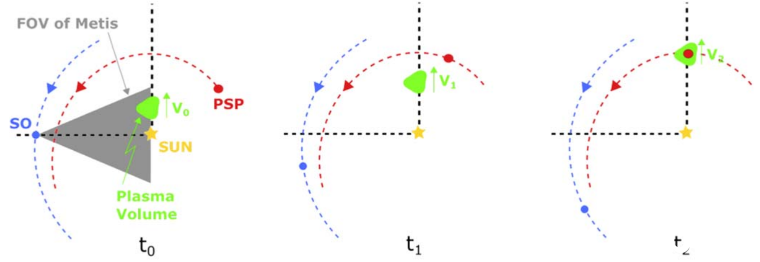
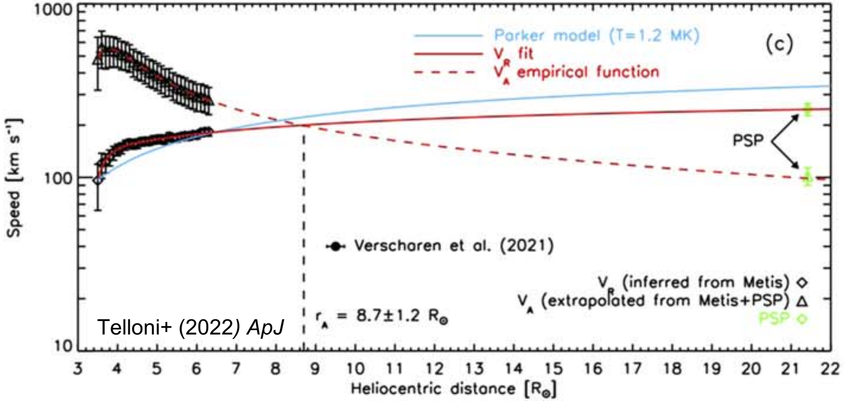
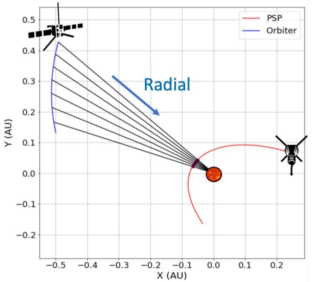
Combined PSP-Solar Orbiter In-Situ & Remote Sensing Measurements



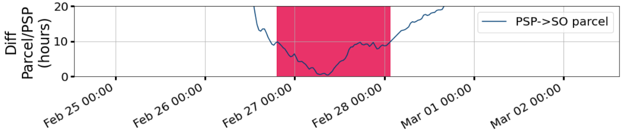


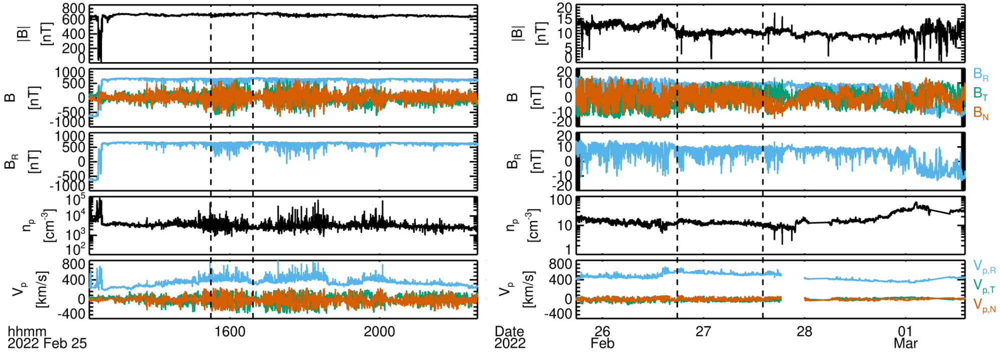
Telloni+ (2022) *ApJ*

Radial Alignments Between PSP & Solar Orbiter



Both spacecraft see nearly the same parcel of plasma when accounting for propagation of the plasma!





Stawarz+ (*in prep*)

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Complex Solar Wind Structure

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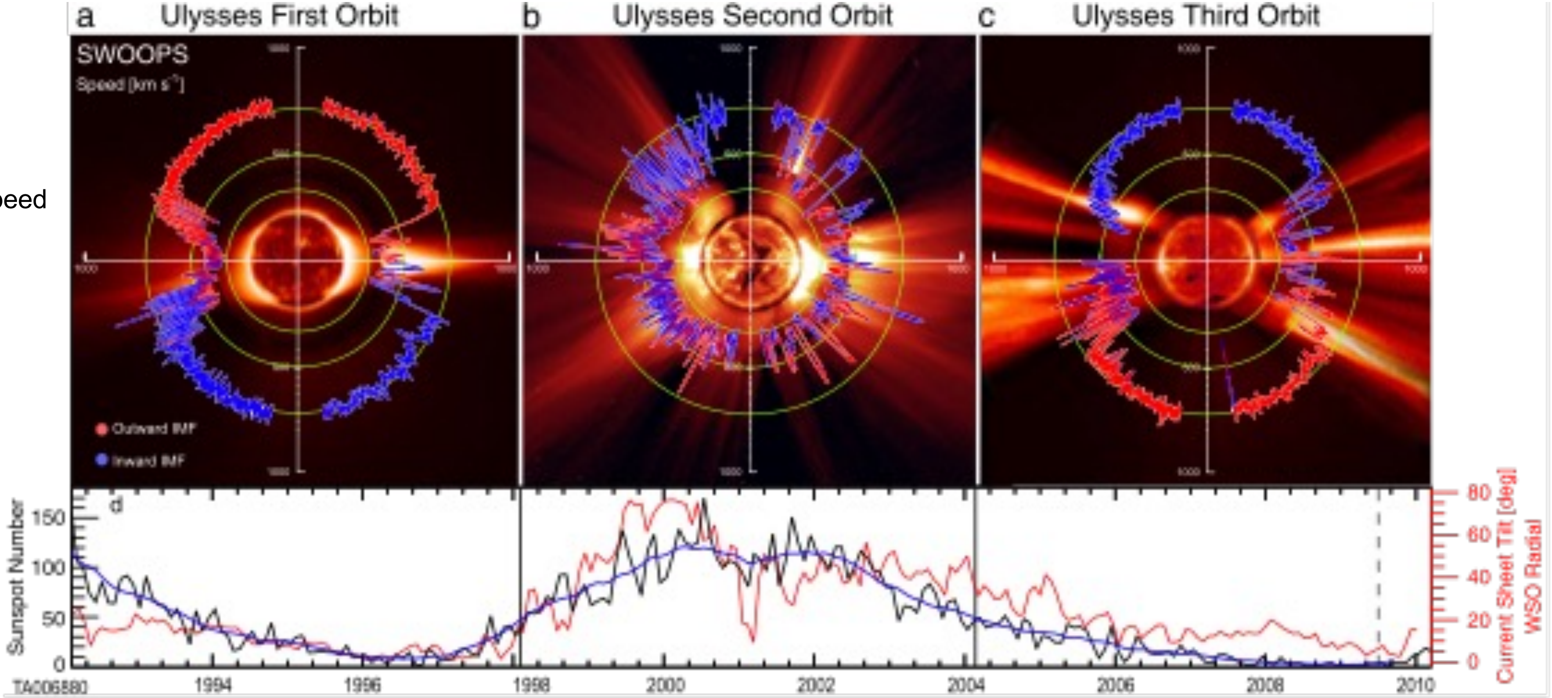
Fast & Slow Solar Wind Structure

Radial distance
→ Solar Wind Speed

Polar Angle
→ Solar Latitude



Fox+ (2016) *Space Sci Rev.*

Location in Solar Cycle

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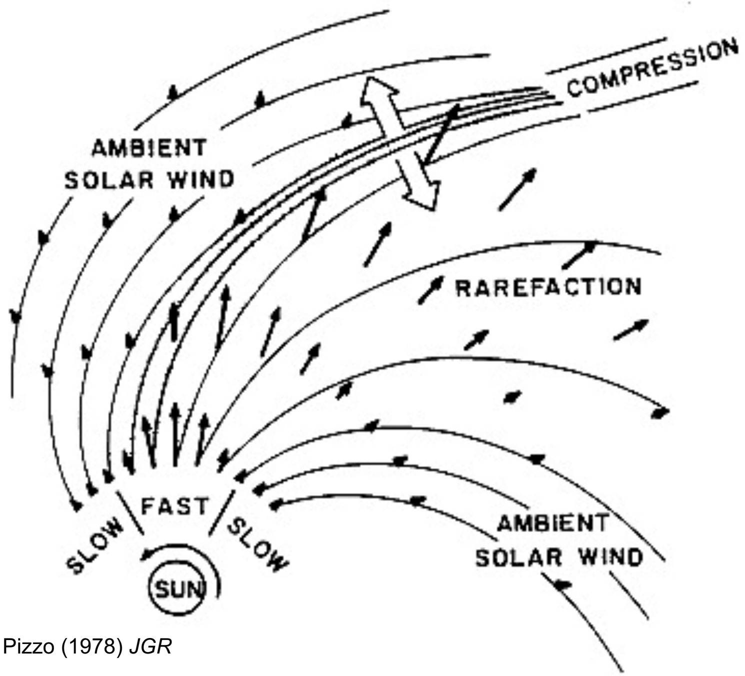
Corotating Interaction Regions



Pizzo (1978) *JGR*

As Sun rotates faster and slower wind can end up ahead or behind each other

Slow ahead of Fast (Corotating Interaction Region)

Solar wind compressed between regions of slower and faster wind

→ can develop into pair of shocks

Fast ahead of Slow (Rarefaction)

Faster wind pulls away from slower wind creating region of depleted particle density

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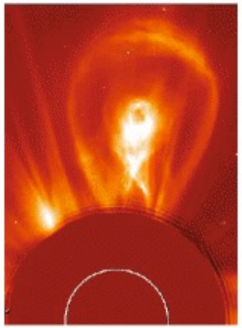
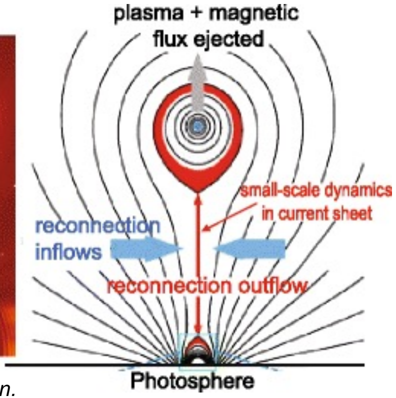
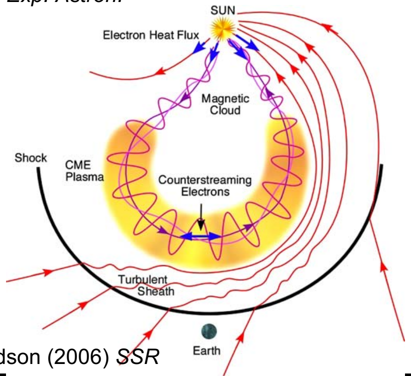
Coronal Mass Ejections





Teriaca+ (2012) *Exp. Astron.*



Zurbuchen & Richardson (2006) *SSR*

Magnetic reconnection at Sun release loops of twisted magnetic field that expand into solar wind

<u>Structure</u>

Shock – generated as CME pushes its way through the ambient solar wind

Sheath – region of shocked solar wind, which often contain strong fluctuations and complex structure generated by the shock

Magnetic Cloud – region of intense twisted magnetic field released from the Sun (flux rope)

Force Free Field

$$\cancel{\rho\frac{\partial \boldsymbol{u}}{\partial t}} + \cancel{\rho\boldsymbol{u}\cdot\nabla\boldsymbol{u}} = \cancel{-\nabla P} + \boldsymbol{j}\times\boldsymbol{B} \quad \rightarrow \quad \boxed{\boldsymbol{j}\times\boldsymbol{B} \sim 0}$$

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Example Coronal Mass Ejection from the Sun to the Earth

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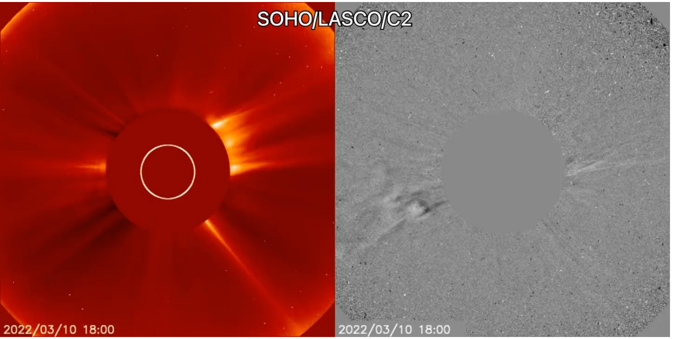
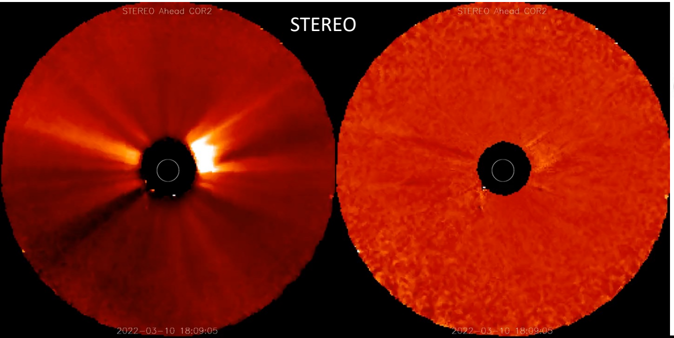
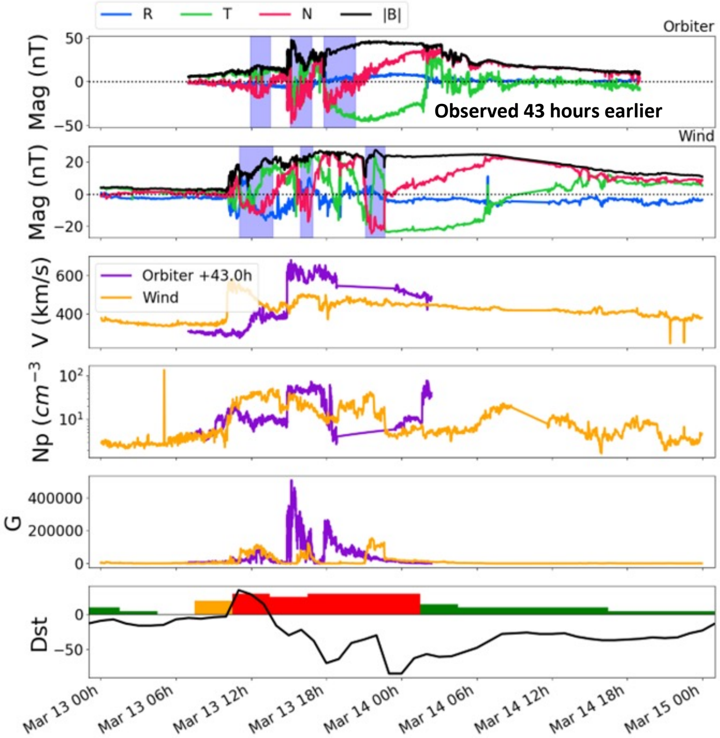
Coronagraph Images observed on March 10







Courtesy of Ronan Laker

Solar Orbiter at ~0.5AU observed on March 12

Wind at L1 point (~1AU) observed on March 13

Aurora Borealis could return to North East skies tonight

TYNE TEES | WEATHER | NEWCASTLE | NORTHERN LIGHTS | Monday 14 March 2022, 5:00pm

Ross Hutchinson
Weather Presenter, ITV Tyne Tees and Border

Taken just after midnight on 14 March in Northumberland.
Credit: Connor Madden

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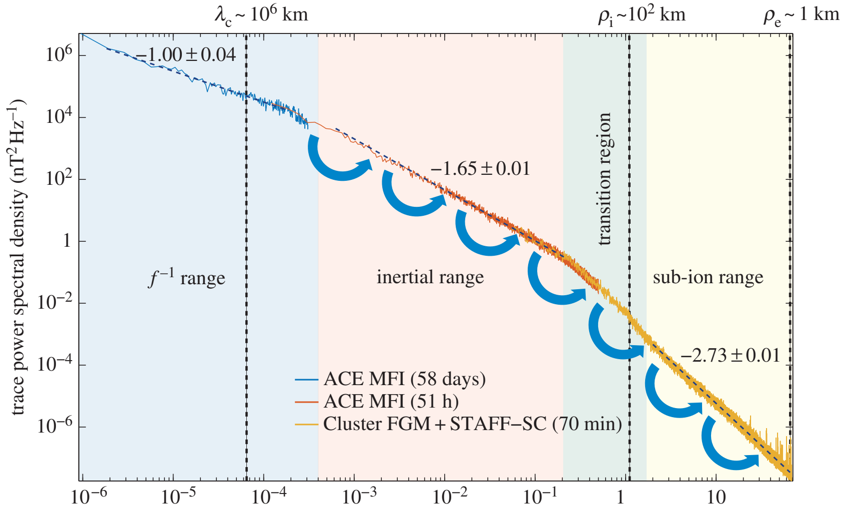
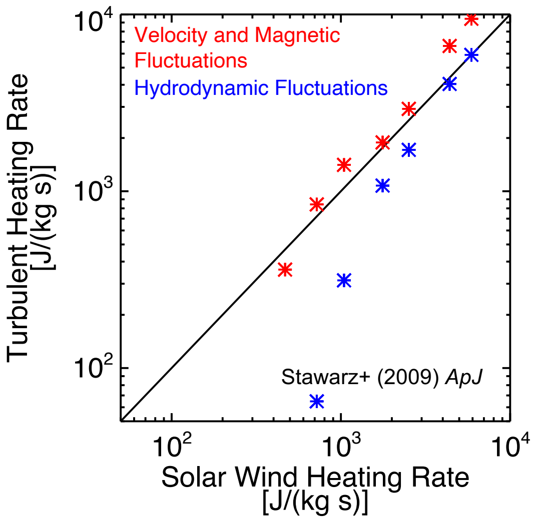
Small Scale Solar Wind Structure: Turbulence & Waves

The solar wind is filled with complex multi-scale fluctuations at smaller-scales that are thought to be associated with nonlinear turbulent dynamics

Solar Wind Power Spectrum



Kiyani+ (2015) *Phil. Trans. A*



Turbulence transfers fluctuation energy to progressively smaller scales where it can be dissipated

Dissipation of solar wind turbulence thought to play a role in coronal and solar wind heating

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The Boundary of the Heliosphere

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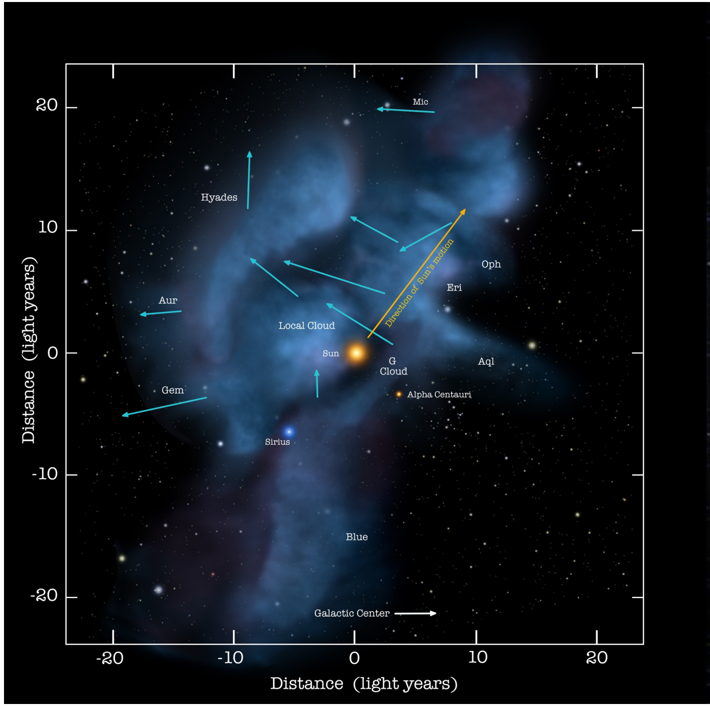
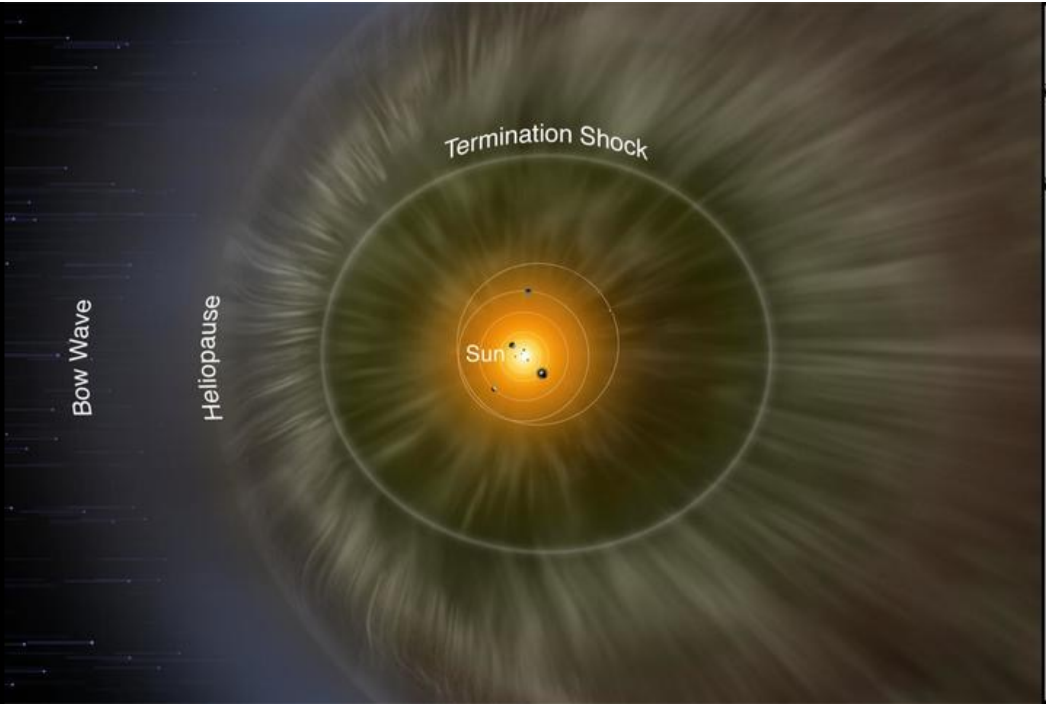
Interaction with Interstellar Medium





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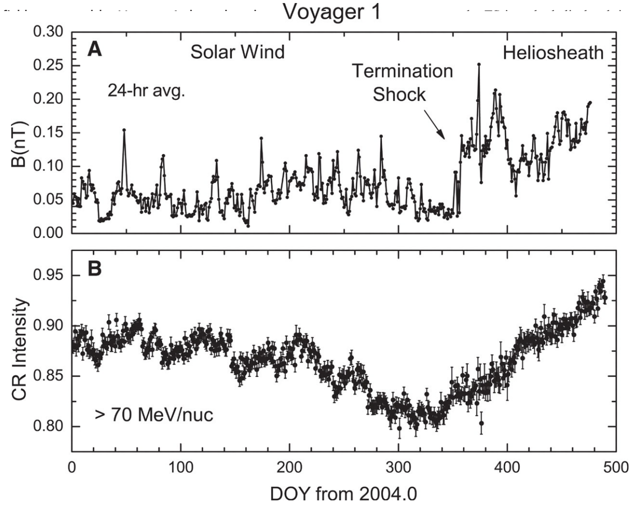
Studying the Interaction with the Interstellar Medium

Both Voyager 1 and Voyager 2 have crossed the termination shock and heliopause

Science, **309**, 2027–2029 (2005)

Crossing the Termination Shock into the Heliosheath: Magnetic Fields

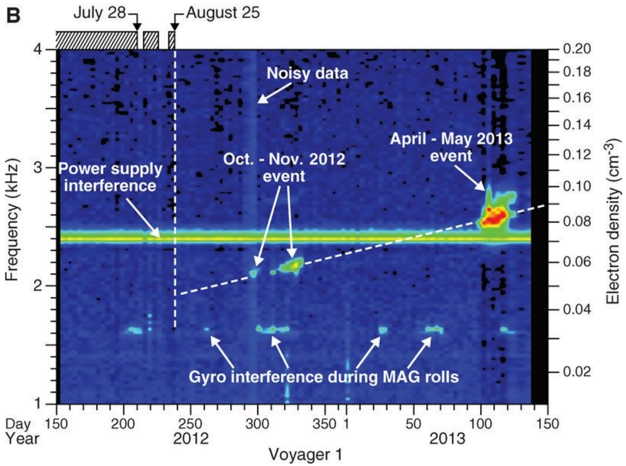
L. F. Burlaga,[1*] N. F. Ness,[2] M. H. Acuña,[1] R. P. Lepping,[1] J. E. P. Connerney,[1] E. C. Stone,[3] F. B. McDonald[4]



Science, **341**, 1489–1492 (2013)

In Situ Observations of Interstellar Plasma with Voyager 1

D. A. Gurnett,[1*] W. S Kurth,[1] L. F. Burlaga,[2] N. F. Ness[3]



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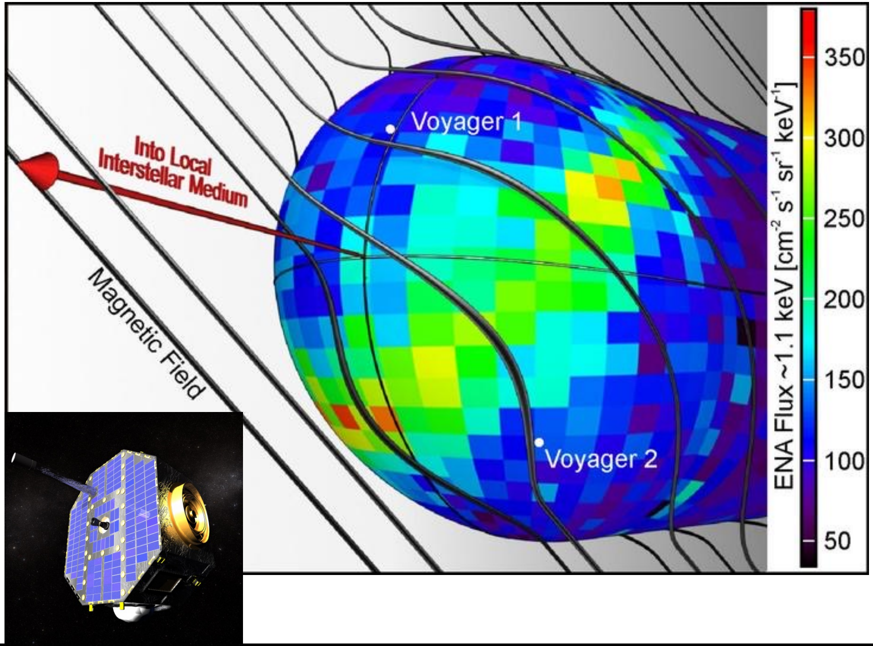
Studying the Interaction with the Interstellar Medium

IBEX mission has measured the heliospheric boundary using energetic neutral atoms



Measures the energy and direction of neutral particles created through charge exchange in the heliosheath

Next generation version of this mission (**IMAP**) is currently being developed by NASA with a UK contribution

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Summary

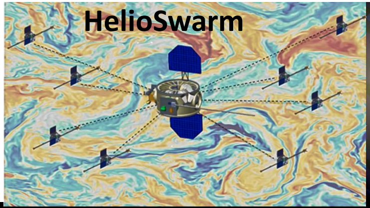
Interplanetary space is filled with a fast flow of plasma emanating from the Sun

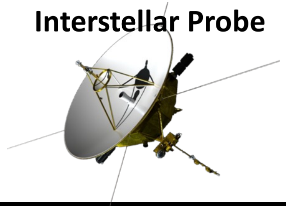
Global structure broadly understood using relatively simple Parker Model along with intuition about MHD

A variety of more complex structure is present beyond the pure Parker solar wind, which motivate much of the ongoing research in the solar wind

→ Important for Sun-Earth interaction

→ "Laboratory" for studying fundamental plasma processes





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