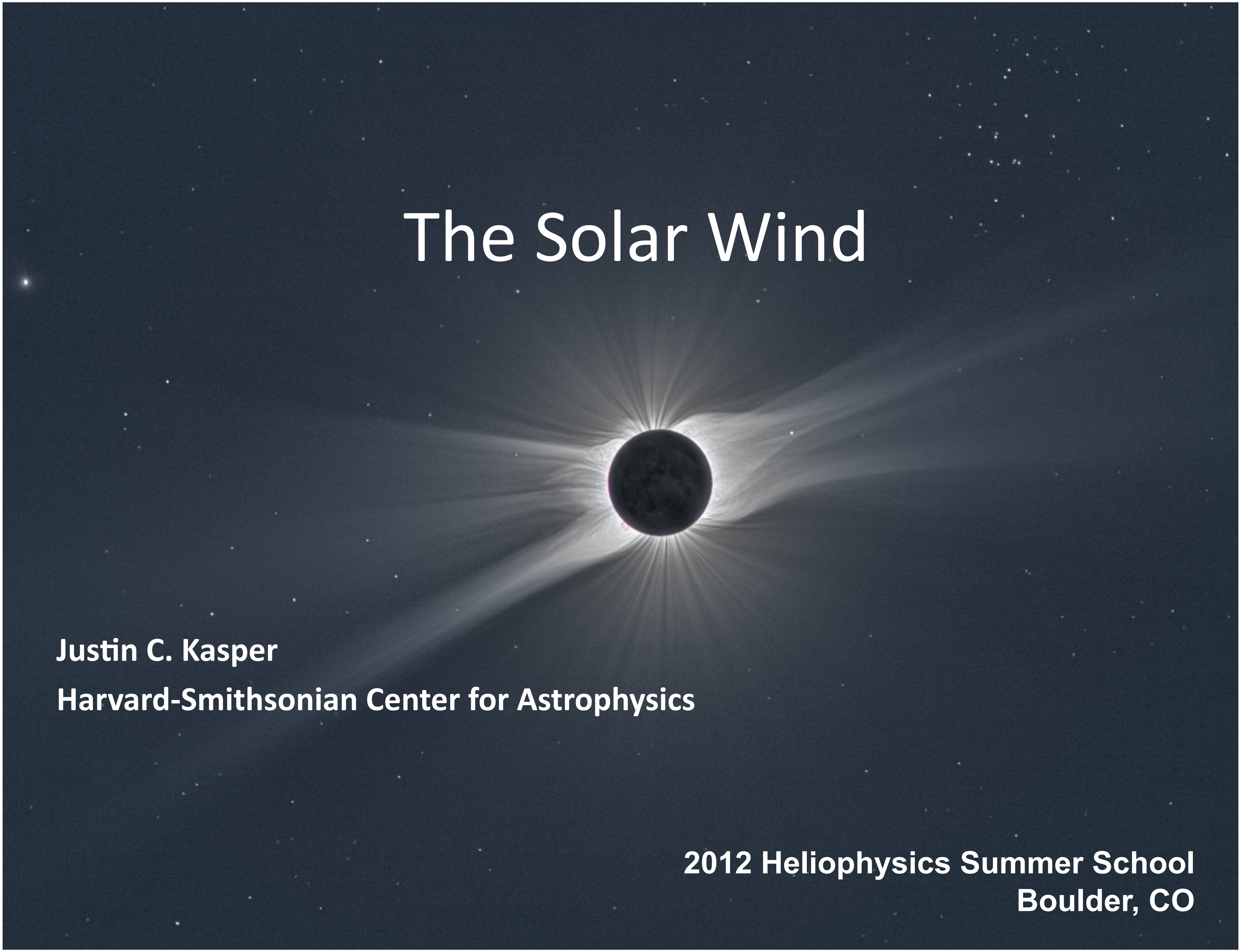
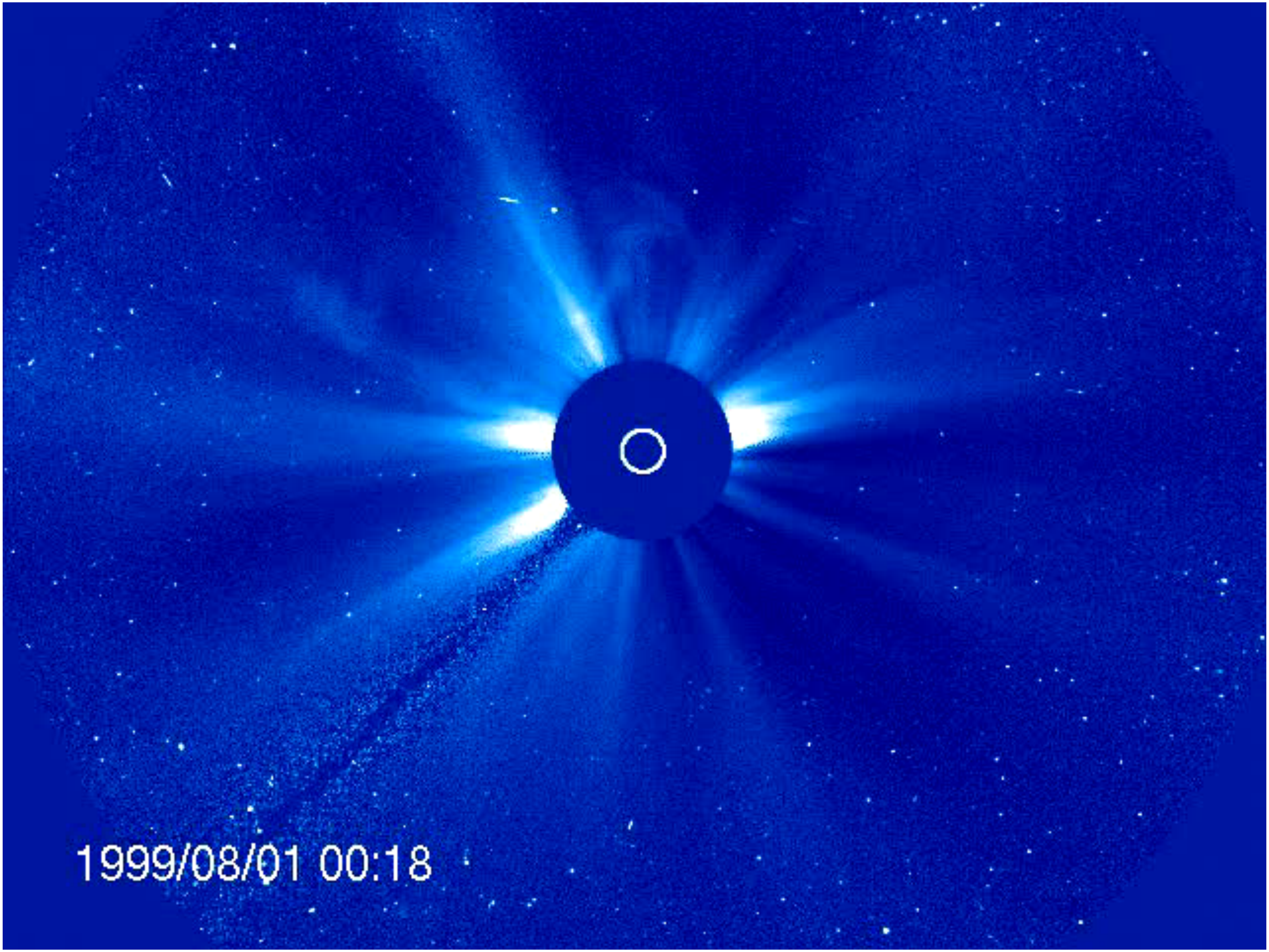


The Solar Wind

Justin C. Kasper

Harvard-Smithsonian Center for Astrophysics

2012 Heliophysics Summer School
Boulder, CO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Goals

- Historical progression of our observational and theoretical understanding of the solar wind
- A sense of why we study the solar wind
  - Connection between the Sun and interplanetary space
  - Heating and escape from the corona
  - Fundamental plasma physics
- Three-dimensional picture of the solar wind
- Highlight open questions and future opportunities

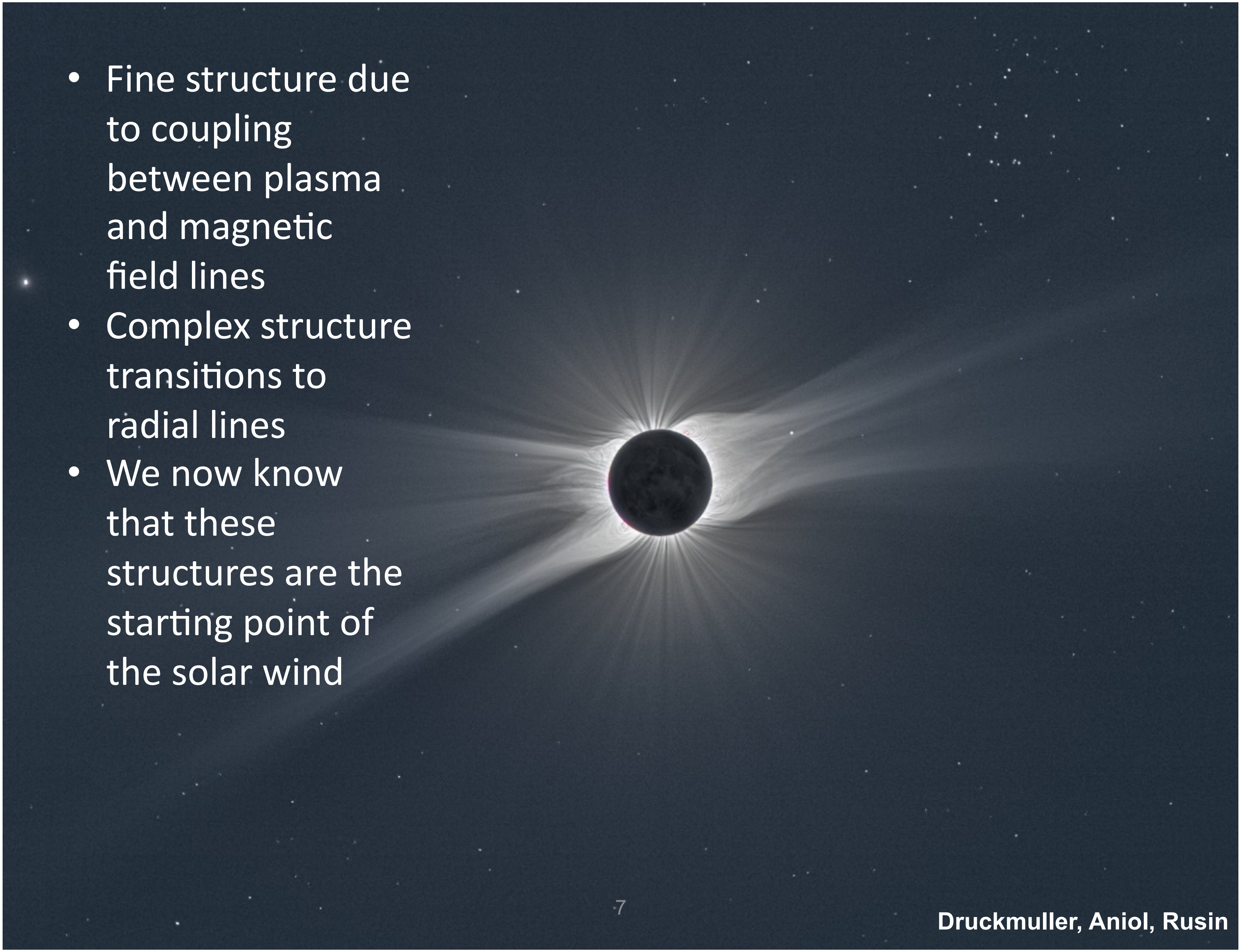
HOW DO WE EXPLORE THE SOLAR WIND?

Some observational techniques

- Eclipses
  - Thompson scattering
- Comets
  - Ionization, radiation pressure
- Early spacecraft
  - In situ instruments
- Current observational capability
- Future plans
  - Solar Probe Plus, Solar Orbiter

Earliest hints of a solar wind

- Astronomers have used solar eclipses to study the moon and the Sun for thousands of years
- Earliest recorded observations of eclipses date back to 6000BC
- "Astronomers Studying an Eclipse," a 1571 painting by Antoine Caron
- When direct sunlight is blocked, a corona (Latin for crown) of material surrounding the Sun can be seen

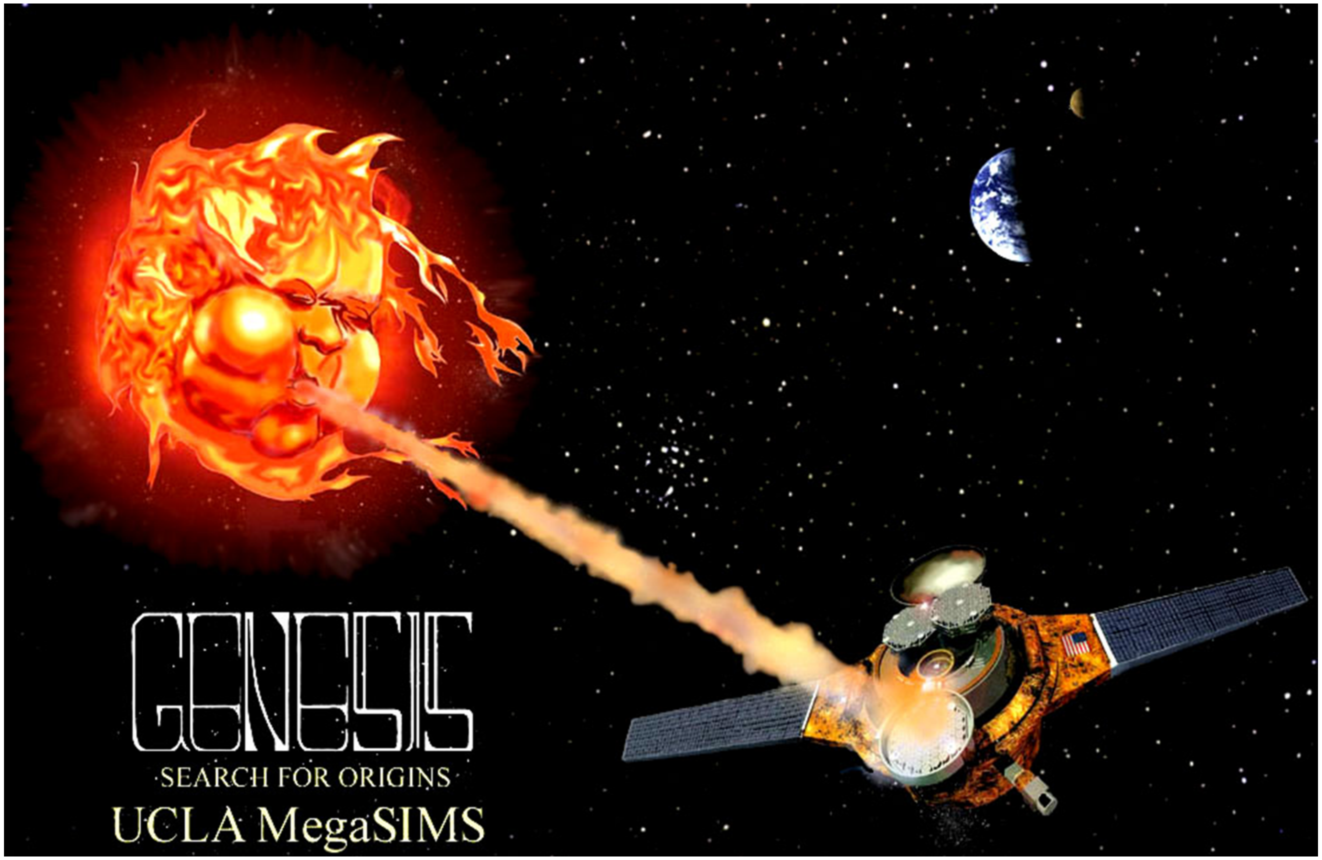


- Fine structure due to coupling between plasma and magnetic field lines
- Complex structure transitions to radial lines
- We now know that these structures are the starting point of the solar wind

Druckmuller, Aniol, Rusin

Early evidence for the solar wind

- 1859 Carrington event
  - Richard Carrington and Richard Hodgson each observe a solar flare in visible light
  - Severe geomagnetic disturbances observed the following day – how fast did the disturbance travel?
  - $1\ AU \sim 1.5 \times 10^8\ km$, $1\ day \sim 10^5 s$ so the transient travelled at $\sim 1500\ km\ s^{-1}$
  - Conjecture that Sun must, at least occasionally, release magnetized plasma at speeds of 1000-2000 km s^{-1}
- Comet Morehouse (1908)
  - Rapid variation in the tail, breaking up, flapping, and reforming
  - 1910 Arthur Eddington suggested variable tails required flow of particle radiation
  - 1916 Kristian Birkeland proposes comets and auroral activity imply continuous flow of ions and electrons from the Sun



PHYSICS OF SOLAR WIND ACCELERATION

Some facts established by the 1950s

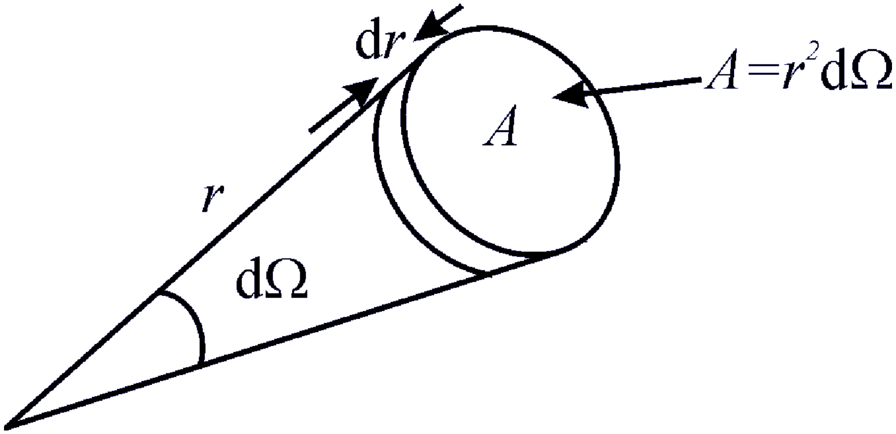
- Significant flux of ions and electrons in interplanetary space, likely continously
- Coronal temperatures of millions of degrees accepted
- Sydney Chapman determines that million degree corona is an excellent heat conductor and therefore may extend deep into space
- Ludwig Biermann predicts dense and fast flow of particles required to explain radial comet tails.
  - Suggests continuous speeds of 500-1500 km s^{-1}
  - densities of 500 p cm^{-3} at 1 AU (an overestimate)

We will consider three models

1. An extended atmosphere in hydrostatic equilibrium
2. A solar breeze due to evaporation of the corona into space
3. A supersonic solar wind

1. Extended hydrostatic atmosphere

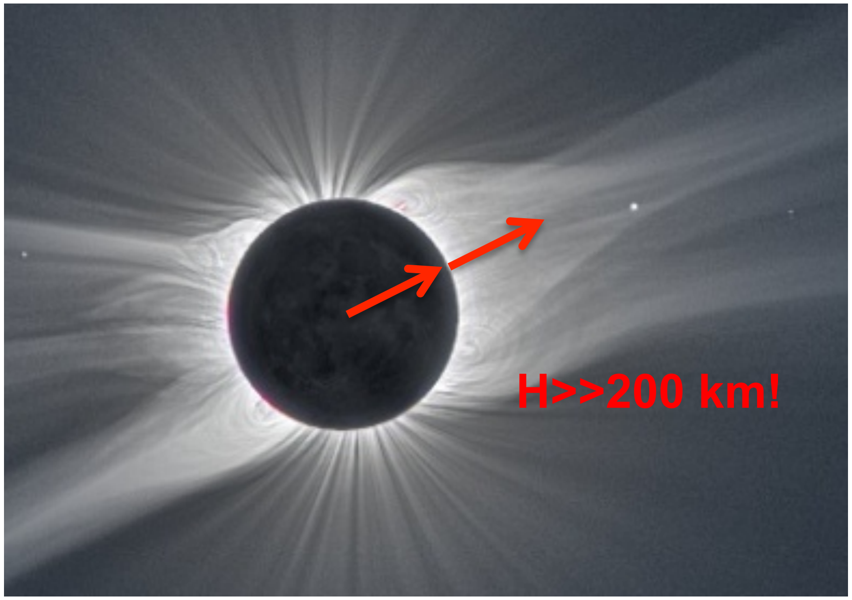
- Sydney Chapman, Notes on the Solar Corona and the Terrestrial Ionosphere, Smithsonian Contributions to Astrophysics, 1957
- Consider a patch in a spherically symmetric corona with area A and radial thickness dR a distance R from the Sun
  - Force due to pressure gradient $\mathrm{A}dp$
  - Force due to gravity $-\rho g A dR$, where $\rho(R)$ is the density of the plasma and $g(R)$ is local gravity



- In static equilibrium the forces balance, so $dp = -\rho g dR$
- Using $p = nkT$ and $\rho = Mn$, we find: $\boldsymbol{dn/n = -\frac{dR}{H}}$
  - $H(R) = kT/Mg$ is the scale height, and M is the mean molecular mass
  - For a proton-electron gas, $M \simeq 0.5 m_p$

1. Remarks on static equilibrium

- Assume close to the Sun g and T are constant, then $\ln n/n_o = -R/H$, and density falls off exponentially with R
  - If $T = 6000K$, $H \sim 200km$, 1000x smaller than observed in eclipses
  - Question: what can you do to make $H(R) = kT/Mg$ 1000x larger?
    - A) corona is 1000x hotter than photosphere
    - B) corona is made of a new form of matter 1000x lighter than proton



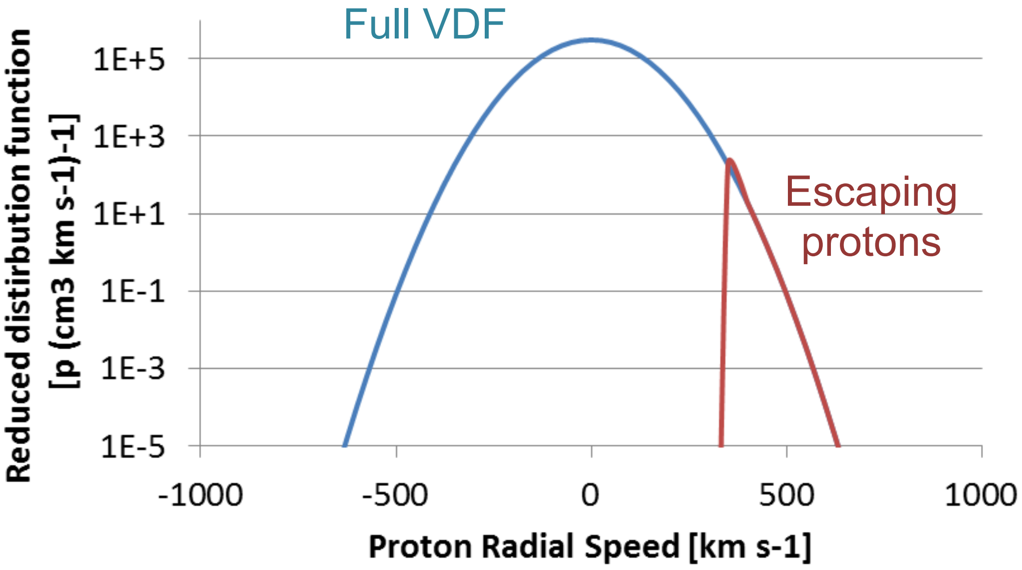
- In reality, $g \propto R^{-2}$, and T will fall off as the solar wind expands
  - Chapman realized that fully ionized corona is an excellent thermal conductor, so T may fall off slowly (see problem set question 3)
  - $H(R)$ will therefore be large and fall off slowly, permitting substantial densities in interplanetary space

1. Chapman's predictions

- Assume temperature T has maximum T_o at height $R = R_o$, which is slightly larger than $R_\odot$
- Use thermal conductivity K of a fully ionized proton-electron gas $K = K_o \left(\frac{T}{T_o}\right)^s$, with $s = \frac{5}{2}$
- Predictions
  - $T = T_o \left(\frac{R_O}{R}\right)^{1/(s+1)}$, or $T \propto R^{-2/7}$ weakly falling with distance
  - No net flows – plasma should be isotropic
  - Density drops to a minimum at about 0.8 AU, then asymptotically rises to finite value at infinity

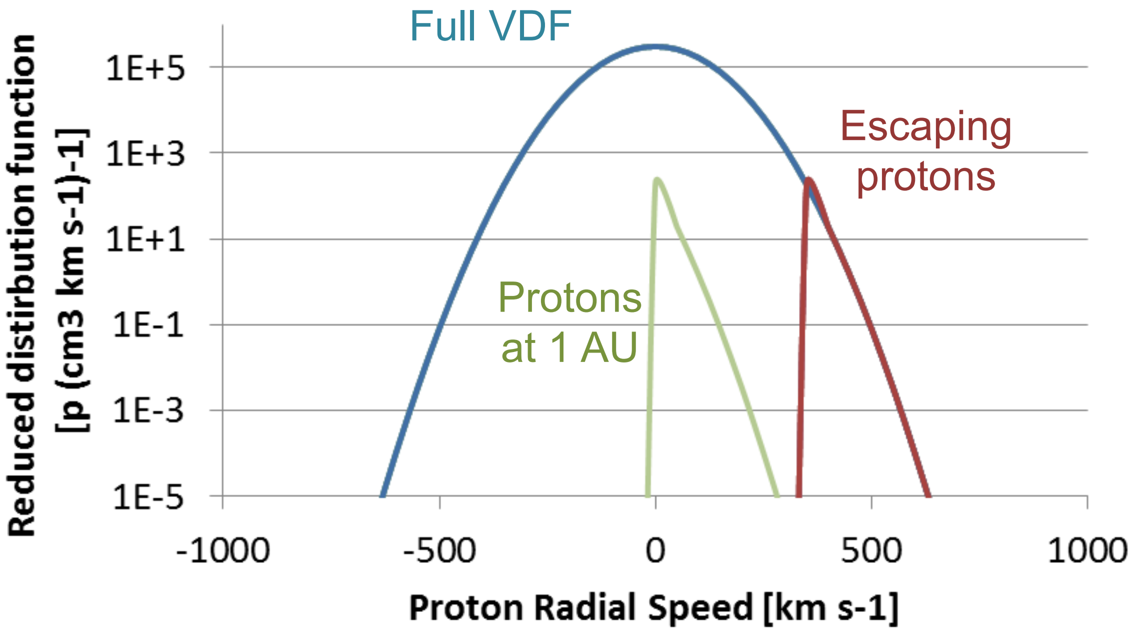
2. Evaporation of high energy tail

- Joseph Chamberlin, Expansion of a Model Solar Corona, ApJ, 1960
- Assume there is a surface about $3R_\odot$ above the surface of the Sun where ions and electrons become collisionless, but still can be described by a Maxwell-Boltzmann velocity distribution function
  - $f_j(\vec{v}) = n_j \pi^{-1.5} w_j^{-3} e^{-(\vec{v}-\vec{U}_j)^2/w_j^2}$, where $k_B T_j = \frac{1}{2} m_j w_j^2$,and set $\overrightarrow{U_j} = 0$
- All particles with speed v greater than escape speed $v_e = \left(\frac{2GM_\odot}{r}\right)^{1/2}$ will leave the corona and never return
- At $3R_\odot$, $v_e = 300\ km\ s^{-1}$
- Plot shows proton distribution with $T_p = 1MK$, with red region indicating protons with sufficient energy to escape



2. Chamberlin’s predictions

- The escaping distribution function will not look Maxwellian, but you can calculate an effective temperature. Predicts that $T \propto \left(\frac{R}{R_o}\right)^{-0.5}$, or 1/4th Chapman’s prediction at 1 AU
- $n_e \sim 370\ \mathrm{cm}^{-3}$
- Since most of the particles in the escaping tail just barely overcome the escape speed, the mean speed at Earth is low. $v \lesssim 20\ km\ s^{-1}$ at 1 AU
- Calls this a “solar breeze”

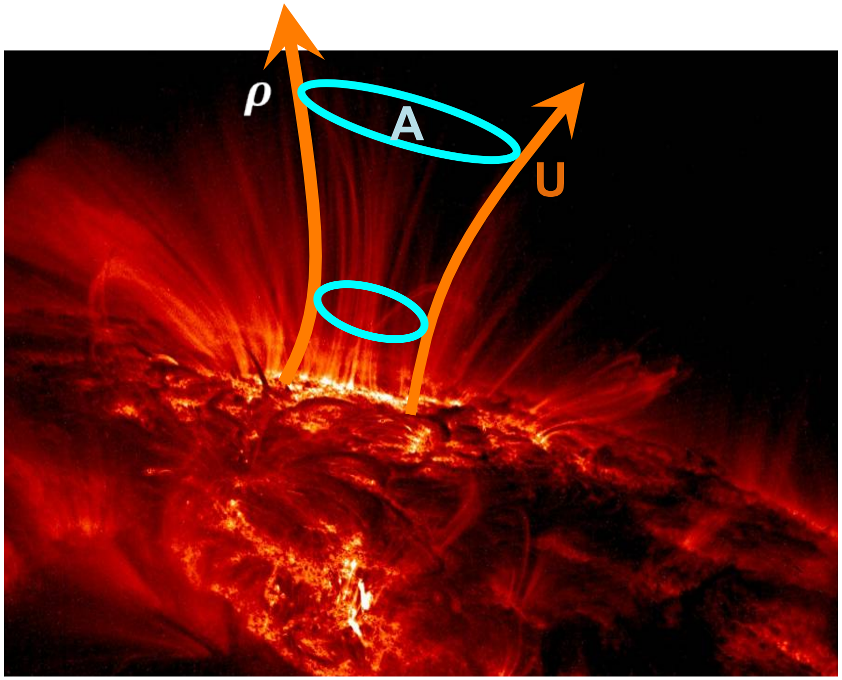


3. Continuous hydrodynamic expansion

- Eugene Parker, Dynamics of the interplanetary gas and magnetic fields, ApJ 1958
- Begins with several concerns about previous models
  - Predictions of speeds are way off
    - Zero net flow for the static atmosphere, ~ 20 km s^{-1} for the exospheric model. Instead should be at least 10x faster
    - Need a way to produce high speeds and sustain them as plasma expands away from the Sun
  - Chapman's model requires finite pressure at infinity that is many orders of magnitude smaller than estimated pressure of interstellar space
  - In fact, shows that static equilibrium is unstable, and therefore there will be a continuous outward hydrodynamic expansion of the corona
- So where does this expansion emerge from, and can it produce supersonic flows?

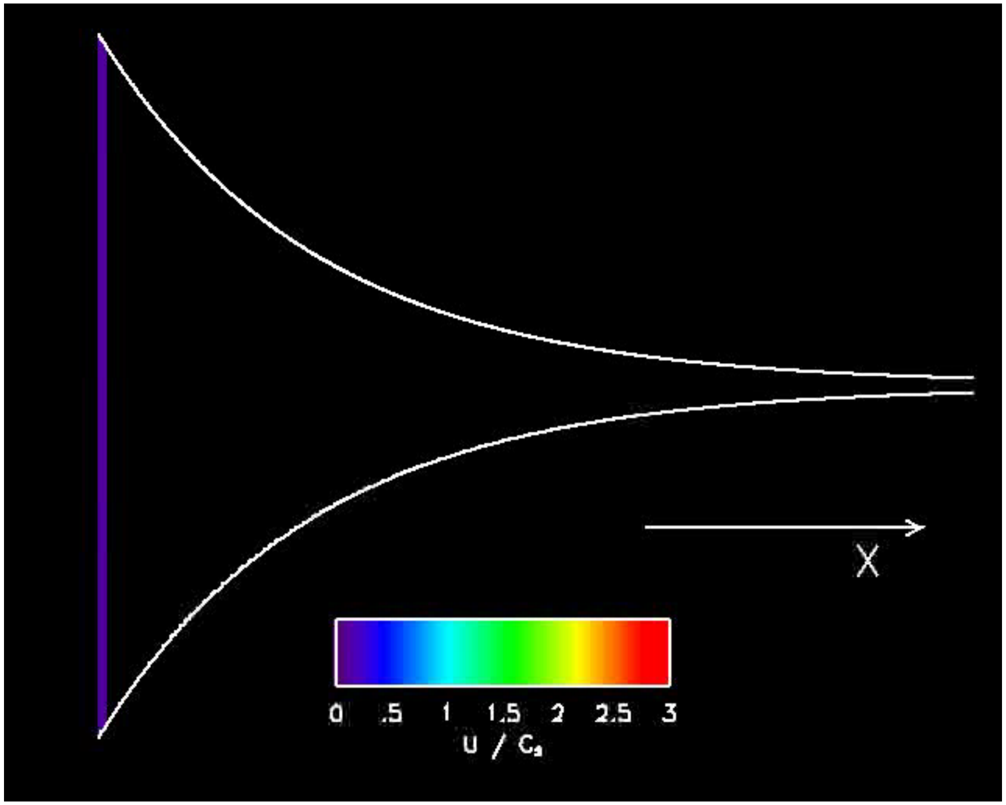
How hard is it to create supersonic flow?

- Consider an isothermal ideal gas of density ρ flowing through a tube with cross sectional area A at speed U
- Conserve flux $F = \rho A U$
  - so $\frac{dF}{dt} = 0$, or differentiating and dividing by F, $\frac{d\rho}{\rho} + \frac{dA}{A} + \frac{dU}{U} = 0$
- Aside: Since $C_s^2 = \gamma \frac{p}{\rho} = \frac{kT}{M} = const.$, $dp = C_s^2 d\rho$ (*)
- Momentum equation
  - In one dimension: $\rho U \frac{dU}{dx} = -\frac{dp}{dx}$
  - *Or* $\rho U \frac{dU}{dx} = -C_s^2 \frac{d\rho}{dx}$ *using (*)*
  - *Solve for* $d\rho = -\frac{\rho U}{C_s^2} dU$
- Finally: $\boldsymbol{\frac{dA}{A} = \left(\frac{U^2}{C_s^2} - 1\right) \frac{dU}{U}}$
- Let's consider the implications



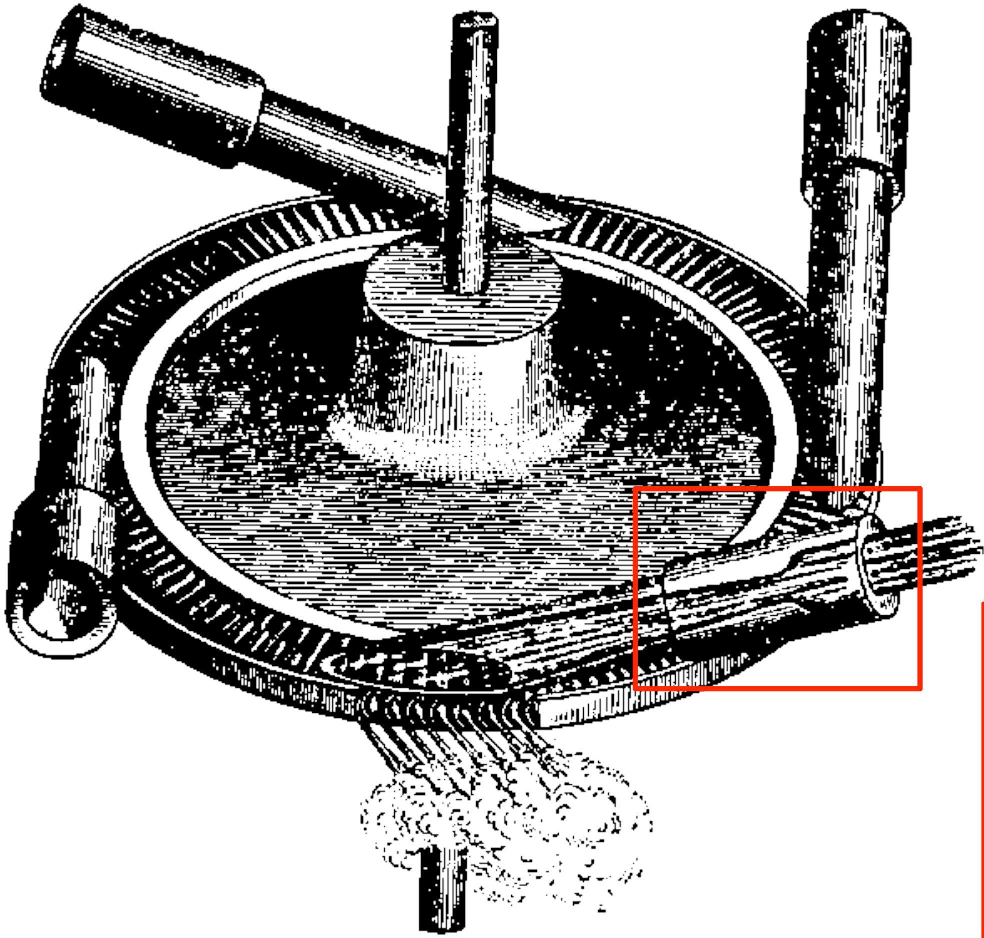
Acceleration in a Converging Tube

$$\frac{dA}{A} = \left(\frac{U^2}{{C_s}^2} - 1 \right) \frac{dU}{U}$$

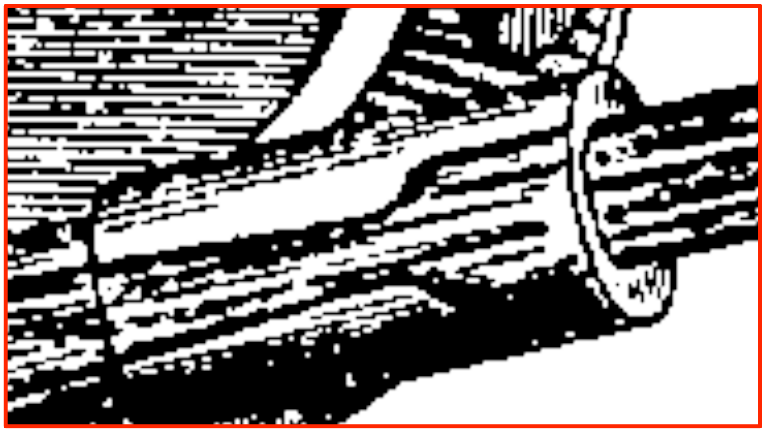


- Consider the initial acceleration of a fluid down a converging tube
- What is the sign of dA/A?
- When $U < C_s$, what is the sign of dU/U? What does that imply about the flow?
- What changes when $U > C_s$?
- The flow stagnates at $U = C_s$. We need to stop the flow from stalling

An inspiration from steam turbines



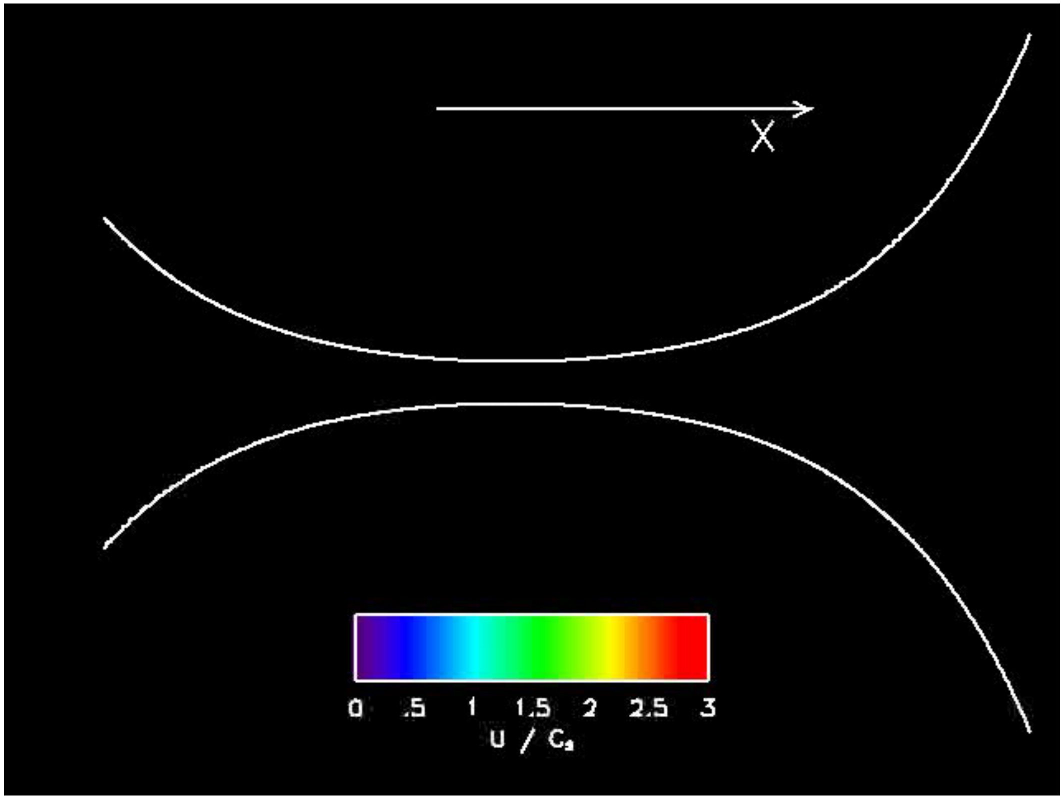
- deLaval nozzle developed to produce supersonic jets of steam within a turbine
- Trick is to allow the tube guiding the steam to diverge as the flow reaches the speed of sound



Stodola, Steam and Gas Turbine (1927)

The deLaval Nozzle

$$\frac{dA}{A} = \left(\frac{U^2}{C_s{}^2} - 1 \right) \frac{dU}{U}$$

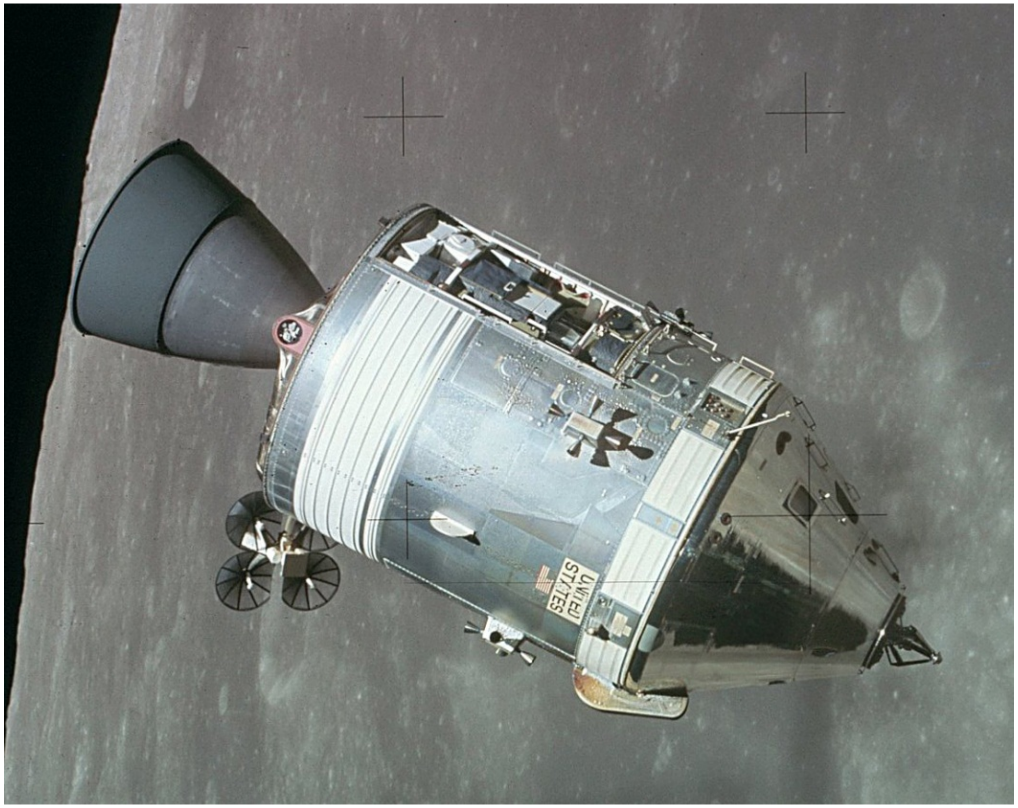


- When $U = C_s$, the tube stops converging and then begins to expand
- Now what happens to dU/U when $U > C_s$?
- If flow cannot become supersonic by the inflection in the tube then it slows down
- Otherwise the flow will become supersonic – this is always the case if the downstream end opens into a vacuum

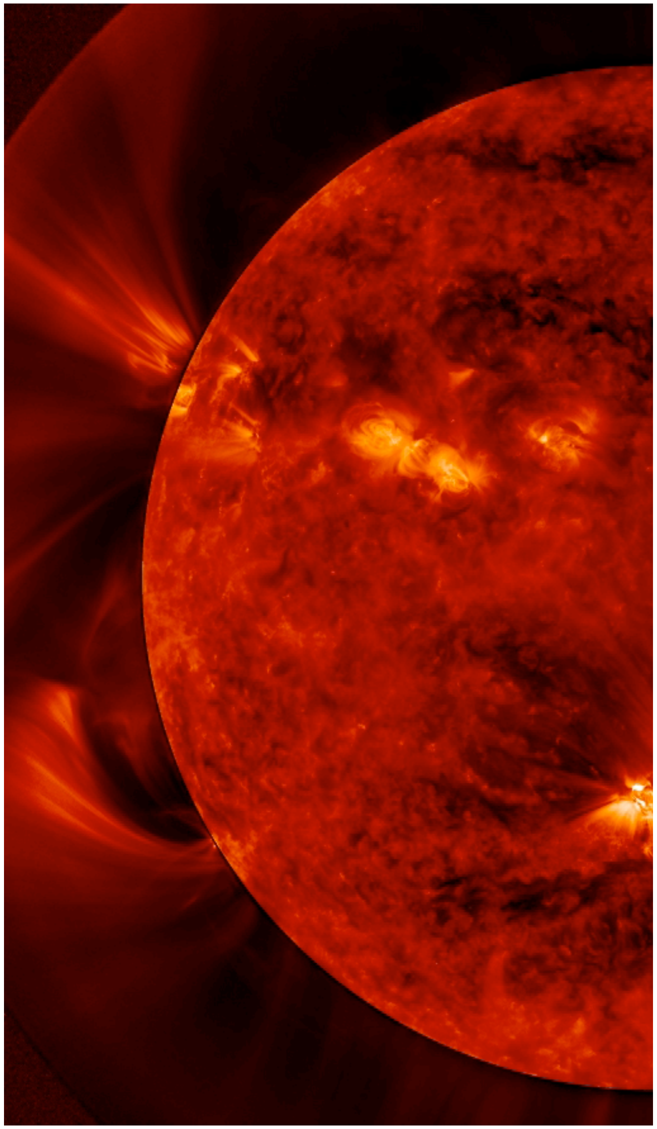
De Laval Nozzles and Space Exploration

Robert H. Goddard, Smithsonian National Air and Space Museum (1928)

Apollo Command/Service Module (1971)



Parker Model



- Eugene Parker (1958) realizes the that plasma in the solar corona may act like a De Laval nozzle
  - Converging tube → Density or pressure gradients
  - Diverging tube → Spherical expansion
- We'll consider a simple version where the corona is assumed to be isothermal at temperature T_o and that T is negligible far from the corona
  - Isothermal Parker model

Start with conservation and momentum eqns

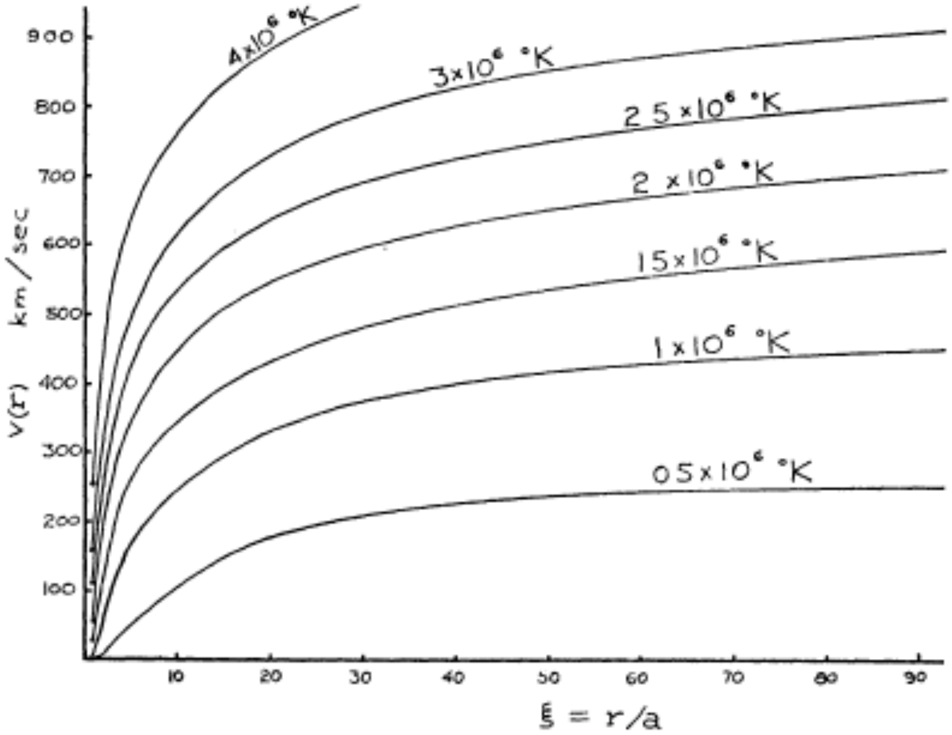
- Start with 3D (essential) MHD equations with spherical symmetry and time steady
  - Conservation of particles $\frac{d}{dr}(r^2\rho v) = 0$
  - Equation of motion $\rho v\frac{dv}{dr} = -\frac{dp}{dr} - \frac{GM_{\odot}\rho}{r^2}$
- Assuming ideal gas at single temperature T_o, we have a constant sound speed $C_s^2 = \frac{p}{\rho} = \frac{kT_o}{M}$
  - C_s is const. since T_o is fixed, so $\mathrm{d}\rho C_s^2 = dp$
- Remove pressure from the equation of motion: $v\frac{dv}{dr} = -C_s^2\,\frac{1}{\rho}\frac{d\rho}{dr} - \frac{GM_{\odot}}{r^2}$
- Next we use conservation equation to remove ρ

- Manipulating the conservation equation
  - $\frac{d}{dr}(r^2\rho v) = \rho\frac{d}{dr}(r^2 v) + r^2 v\frac{d\rho}{dr} = 0$
  - So $\frac{1}{\rho}\frac{d\rho}{dr} = -\frac{1}{r^2 v}\frac{d}{dr}(r^2 v)$
- This allows us to simplify the momentum equation
  - $v\frac{dv}{dr} = \frac{C_s^2}{r^2 v}\frac{d}{dr}(r^2 v) - \frac{GM_\odot}{r^2} \rightarrow \left(v - \frac{C_s^2}{v}\right)\frac{dv}{dr} = \frac{2C_s^2}{r} - \frac{GM_\odot}{r^2}$
  - Or $\left(v - \frac{C_s^2}{v}\right)\frac{dv}{dr} = \frac{2C_s^2}{r^2}(r - r_c)$, where $r_c = \frac{GM_\odot}{2C_s^2} = \frac{GM_\odot M}{2kT_\circ}$
- Note that the solar wind flow reaches the sound speed C_s when the plasma reaches the critical distance r_c

Parker's predictions

- This differential equation has five classes of solutions, which we will not delve into today. One solution passes through the critical point and produces a supersonic flow
- $\boldsymbol{\frac{v^2}{C_s^2} - \log\frac{v^2}{C_s^2} = 4\ln\frac{r}{r_c} + 4\frac{r_c}{r} - 3}$
- Some observations
  - Model easily produces high speeds at 1 AU with reasonable temperatures
  - For $r \gg r_c, v \gg C_s$ and $v \simeq 2C_s\sqrt{\ln r/r_c}$
  - Since $\rho \propto \frac{1}{r^2 v}$, $\rho \sim \frac{1}{r^2\sqrt{\ln r/r_c}}$ and the pressure at infinity is zero

Parker (1958)

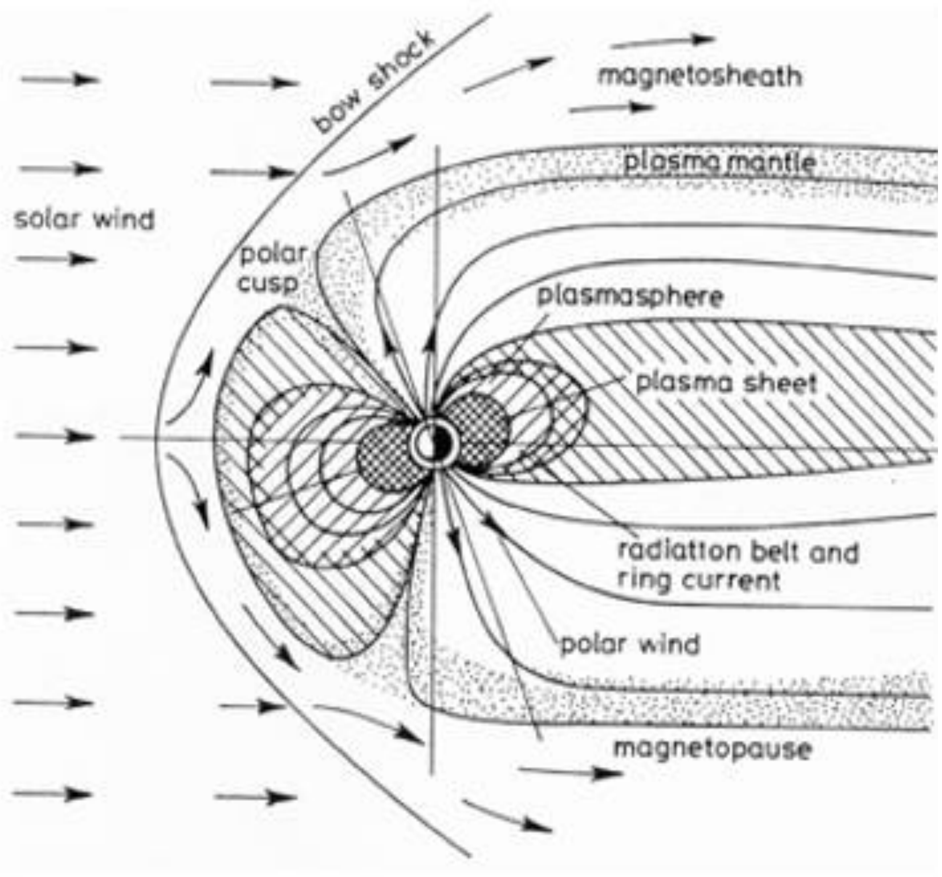


Many paths for improvement

- Remove assumption of isothermal corona
  - Ideally, develop self-consistent solution to coronal heating, coronal temperature, and solar wind acceleration
- Use a more realistic equation of state
  - Polytrope $p \sim \rho^{-\gamma}$
  - Unequal ion and electron temperatures, velocities
- Importance of magnetic field topology
  - Field overexpansion reduces efficiency of acceleration
  - (Directly related to coronal field expansion factors)
- Extended injection of energy into corona and solar wind from waves, reconnection

IN SITU MEASUREMENTS OF SOLAR WIND

Observational challenges: Location

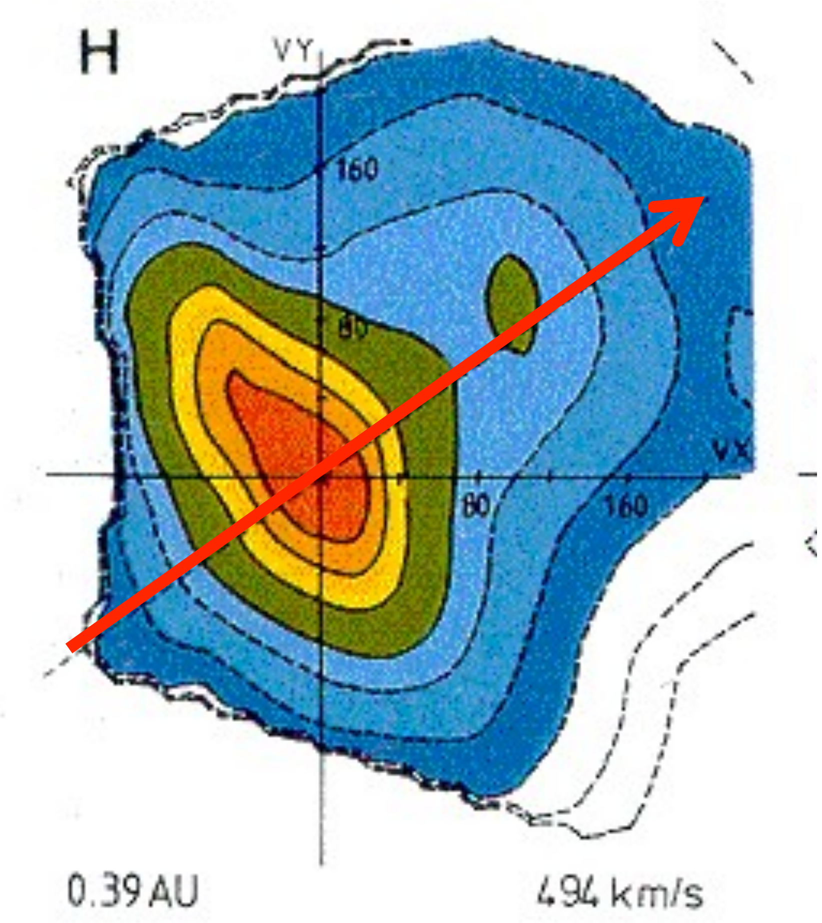


Davies (1990)

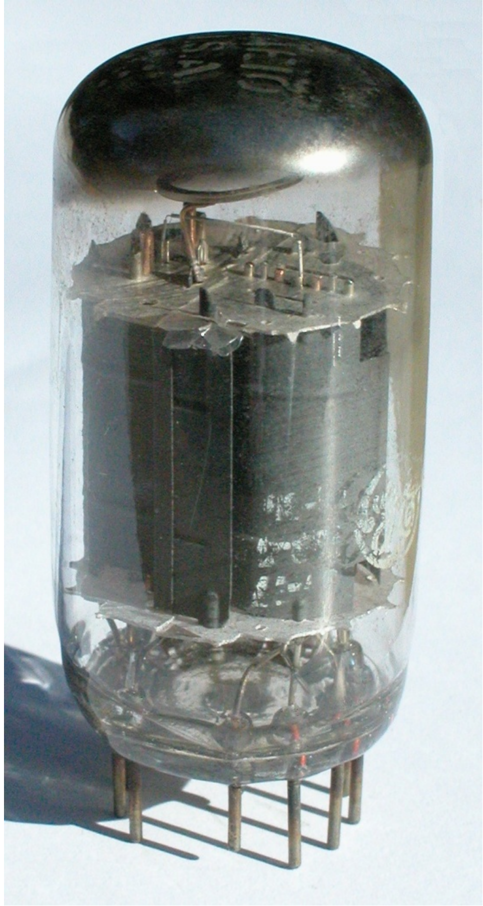
- Solar wind and magnetosphere are magnetized highly conductive plasmas and therefore cannot interpenetrate
- Solar wind flow exceeds fast mode wave speed, leading to strong bow shock as wind is heated, compressed, and diverted around Earth
- A spacecraft needs to get at least 30 RE from Earth to stand a chance of seeing the solar wind directly
- Today, ACE, Wind spacecraft examples of “L1 monitors” (use IMP-7, IMP-8, ISEE-3 for earlier periods)

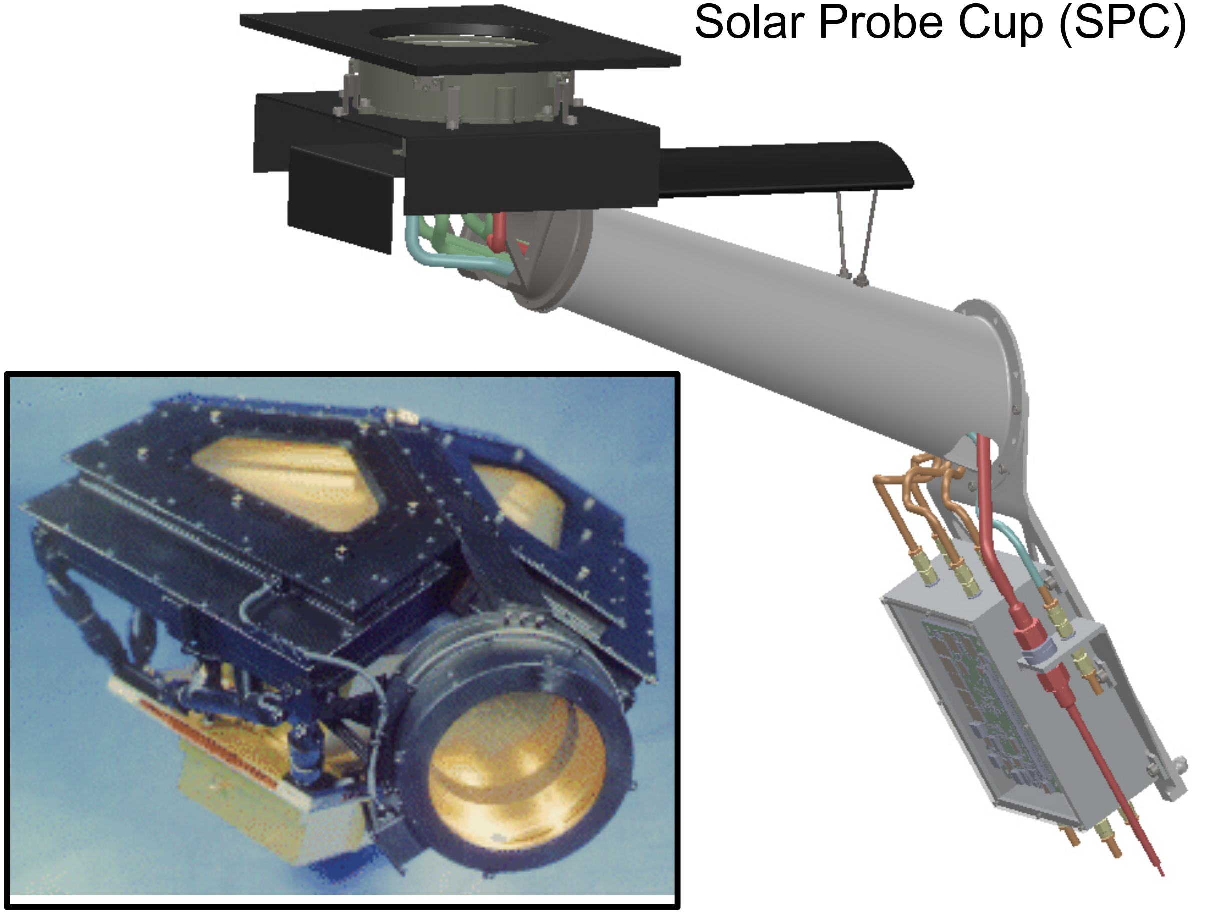
Observational challenges: Plasma

- Solar wind instruments need to measure velocity distribution functions
- Need to determine velocity (speed and direction), density, and temperature of the solar wind.
- Why not just fly an anemometer and a weather vane?
- Because the solar wind is not in equilibrium
  - Relative densities change
  - Species have different velocities
  - Species have different temperatures
  - Temperature can be hard to define
- Raw solar wind measurements are maps of the number of ions and electrons as a function of direction and energy



Example: Faraday Cup (aka Retarding Potential Analyzer)

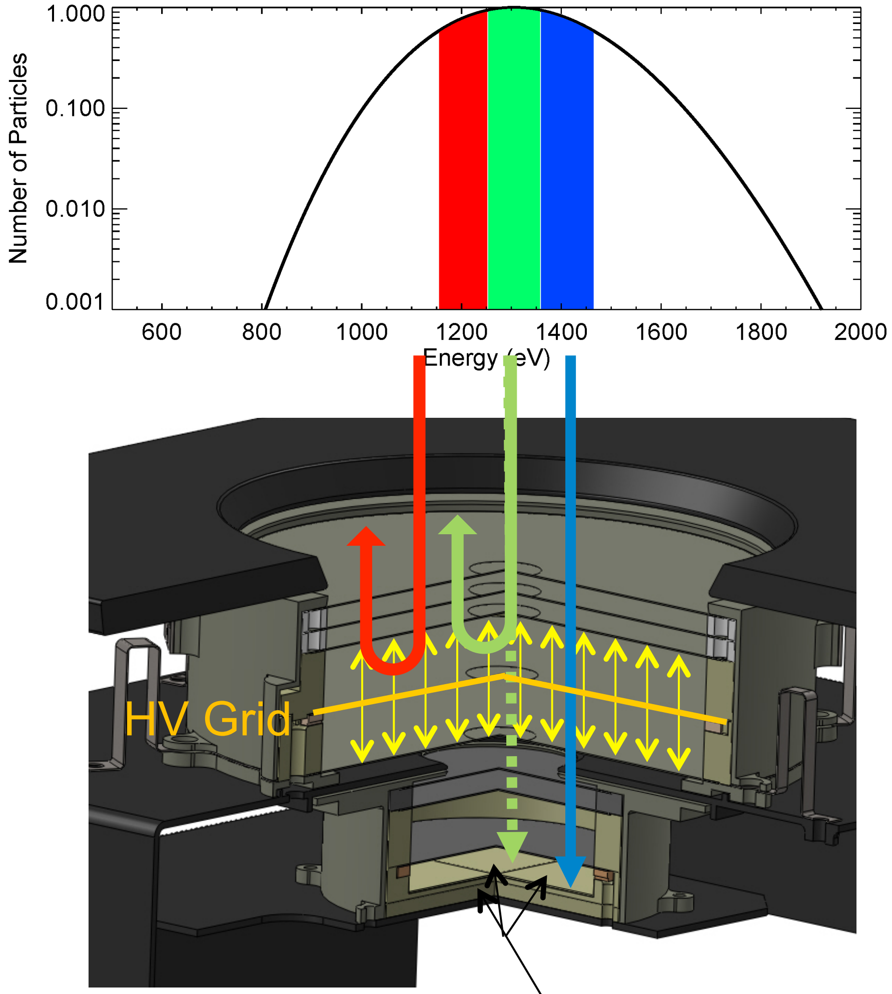




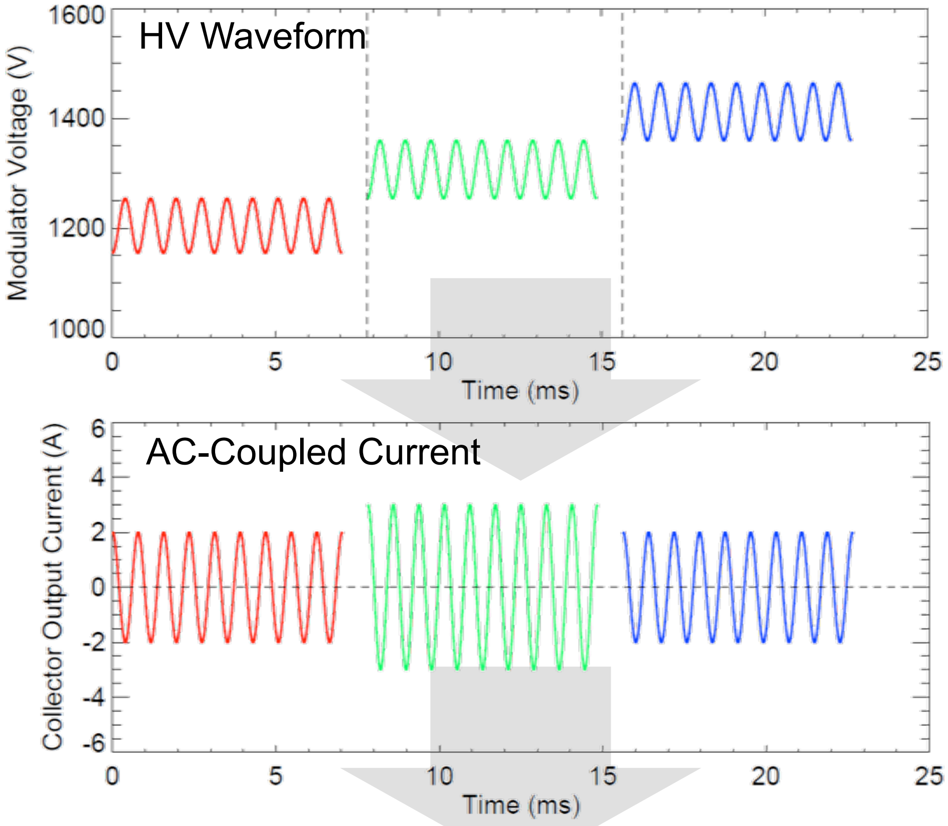
Solar Probe Cup (SPC)

Voyager PLS

Solar Probe Cup Operating Principle



Four collector plates

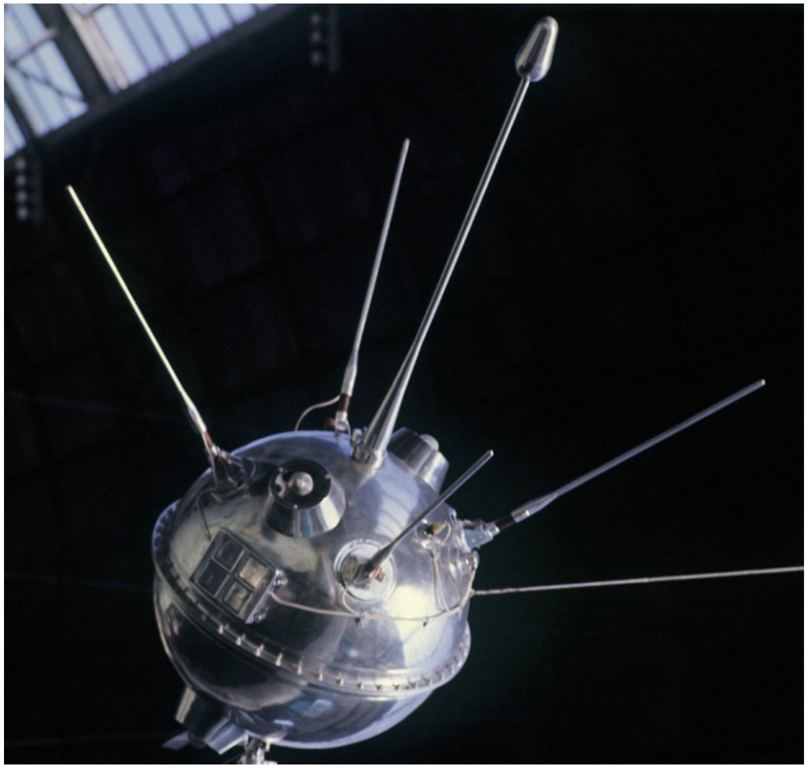


Convert signal to voltage and amplify
Measure amplitude with digital lock-in amplifier
Move on to next energy window

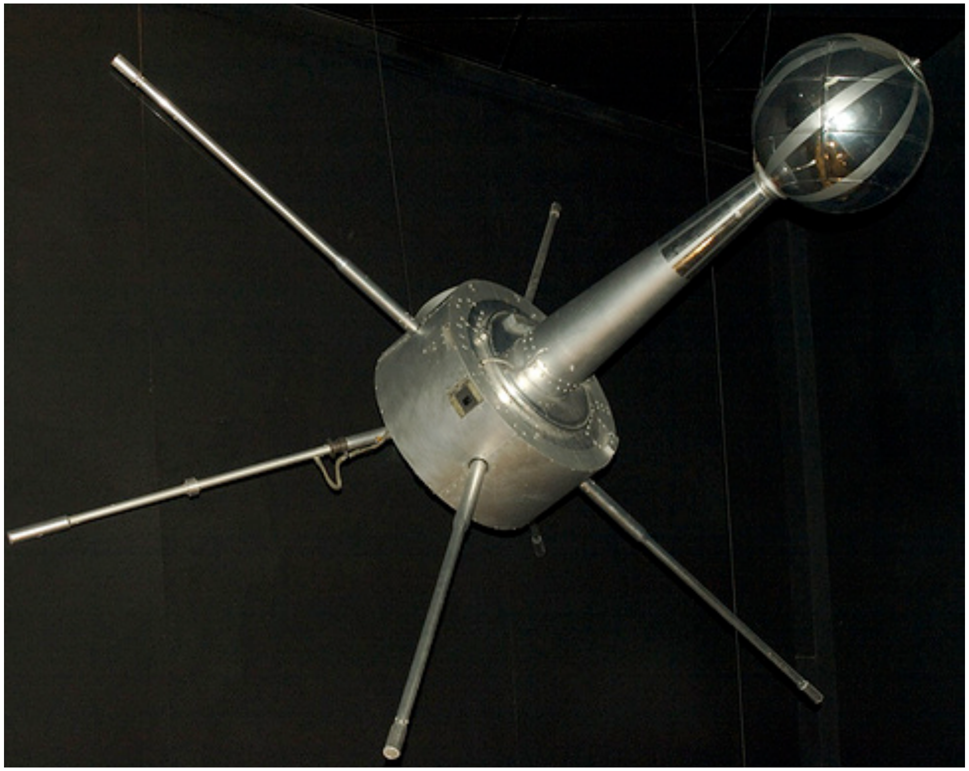
Reaching for solar wind

Luna 2 launched September 12, 1959; First artificial object to reach Earth escape speed; Ion flux of $2 \times 10^8 \text{cm}^{-2}\ \text{s}^{-1}$ Gringauz (1959)

Explorer 10 launched March 25, 1961; Measured n, V, and T of magnetospheric plasma. Large flow angles and temperatures implied deflection of solar wind by bow shock.



Interplanetary station Luna 1, Exhibition of Achievements of National Economy of the USSR (1965)

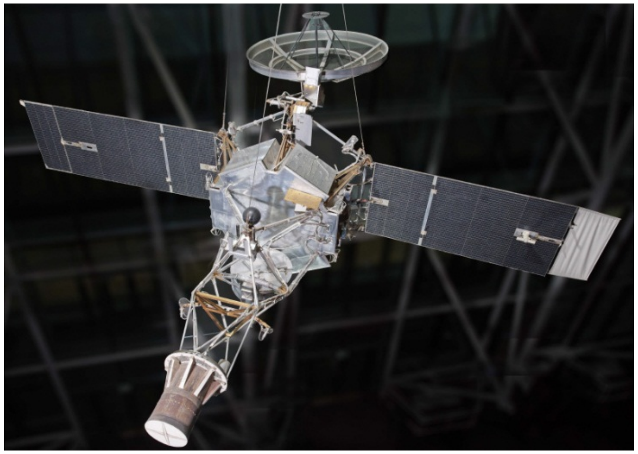


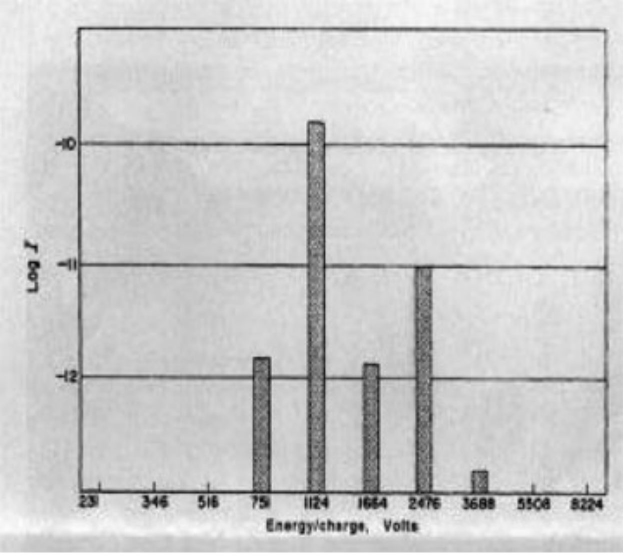
New Mexico Museum of Space History; Alamagordo, New Mexico, USA

Interplanetary Space with Mariner 2

- Launched August 1962
- First planetary encounter (Venus)
- 113 days of data
  - Confirm continuous radial flow of plasma
  - high, low speed streams ranging from 300-800 km s^{-1}
  - n, v, T relations
- Comparison of He and H
  - Similar velocities, but He often flowing faster along field direction
  - He/H highly variable, typically 4.5%
  - Ta up to 4x Tp

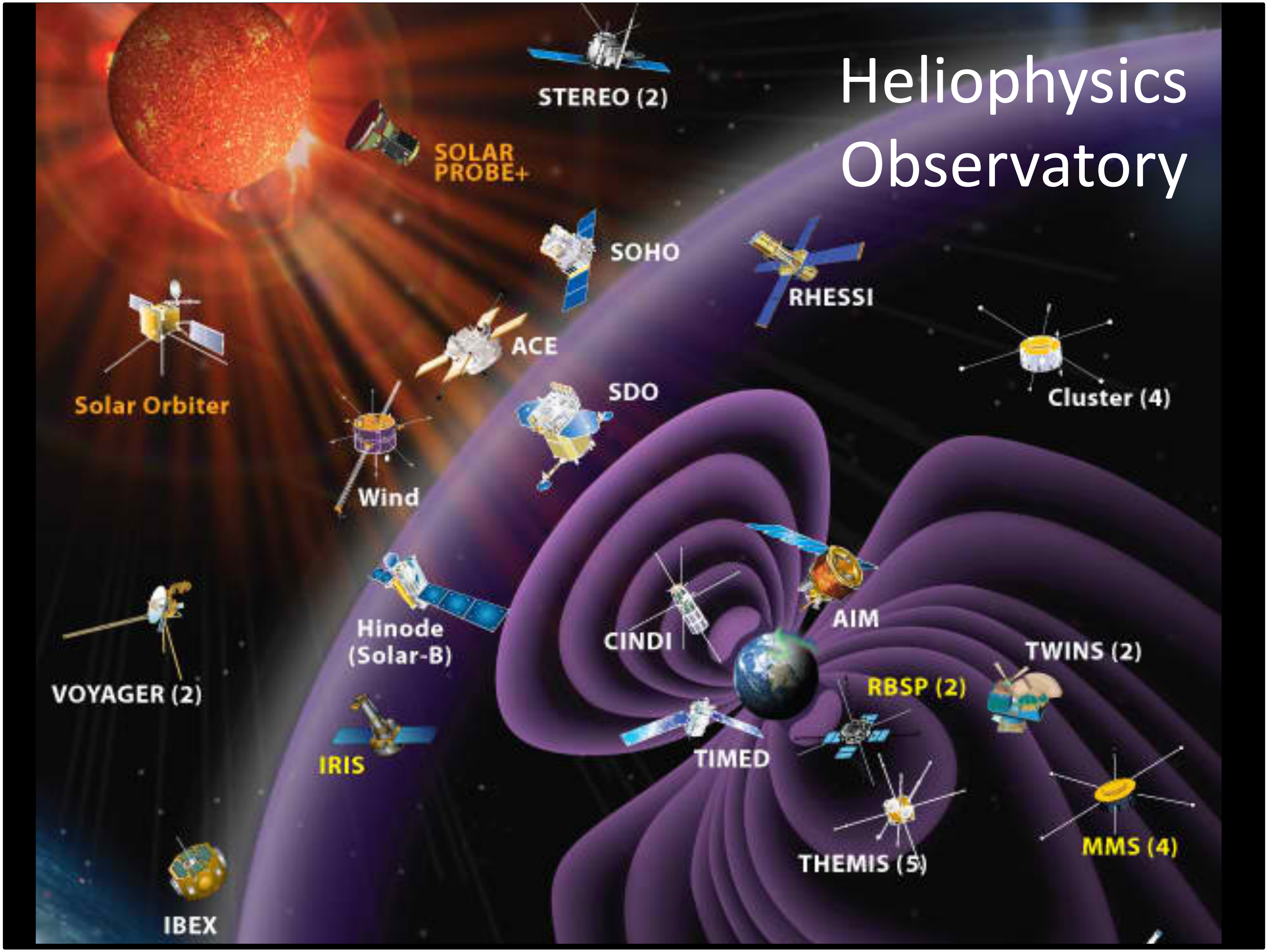
Smithsonian National Air and Space Museum

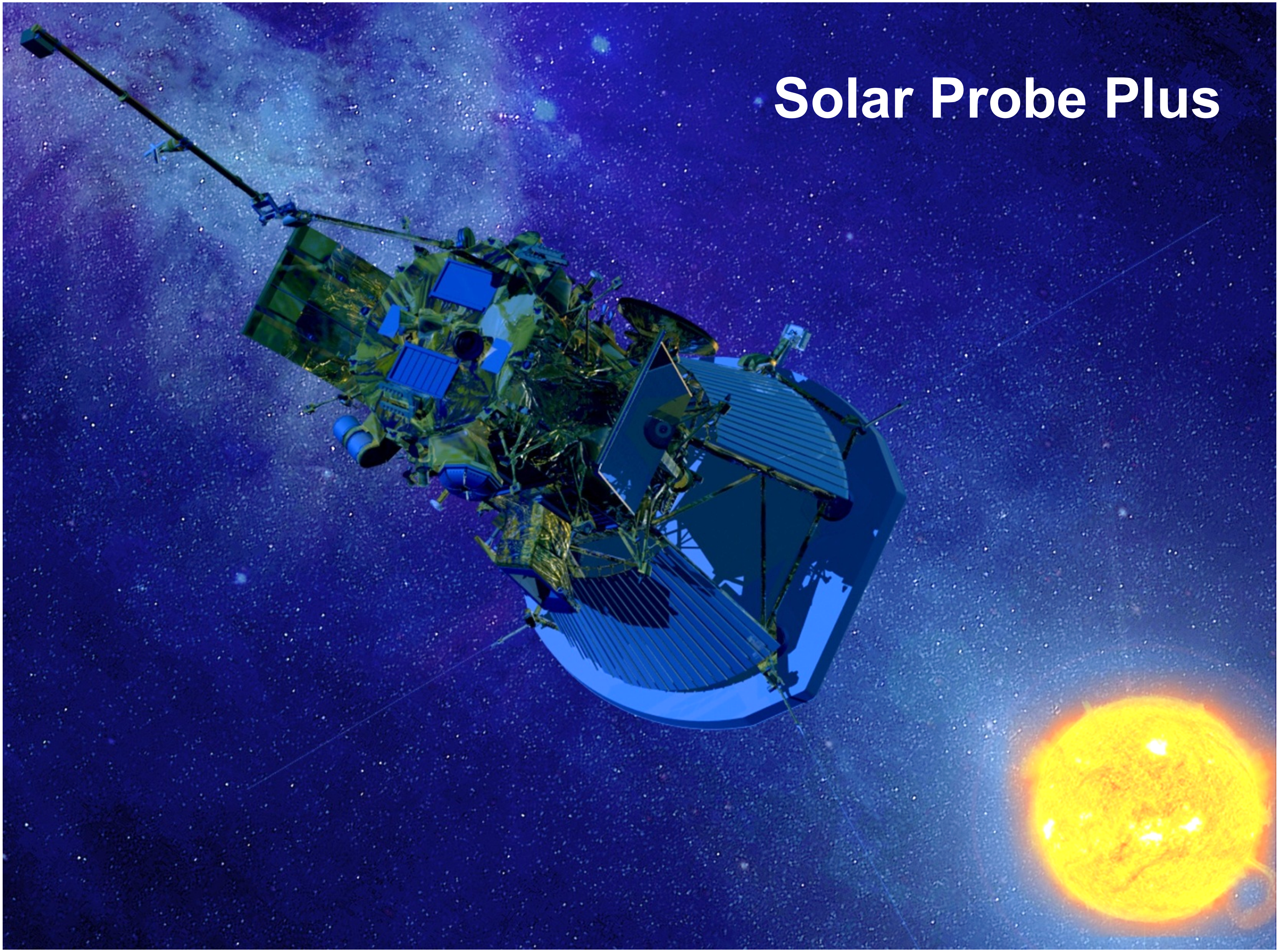




Energy/charge spectrum of solar wind ions

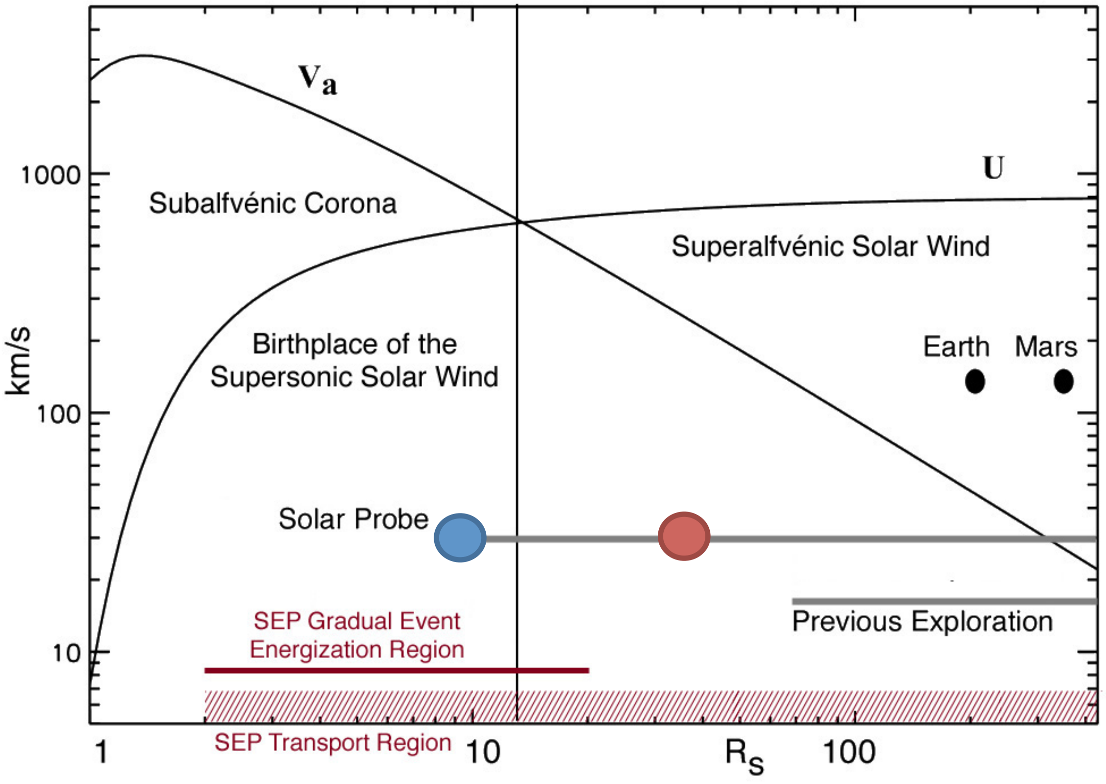
Heliophysics Observatory

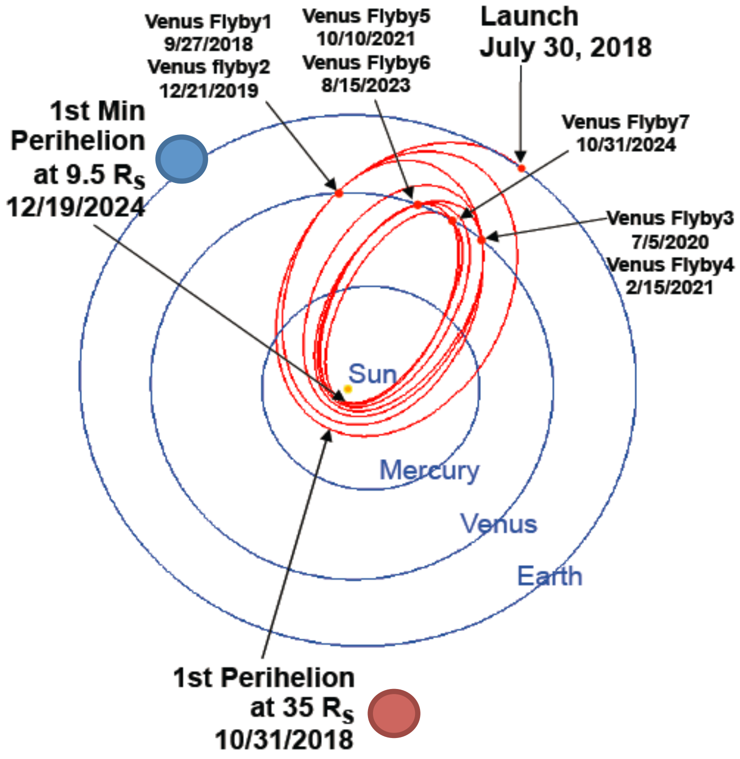


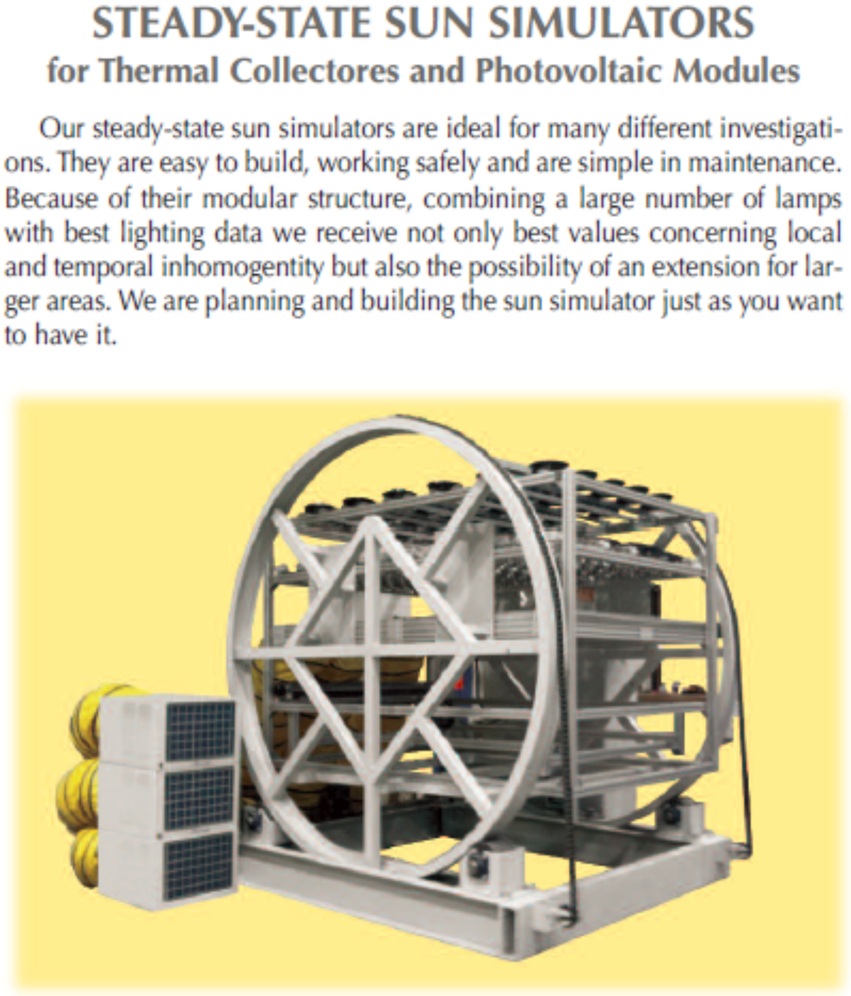


Solar Probe Plus

Solar Probe Plus orbit







STEADY-STATE SUN SIMULATORS

for Thermal Collectores and Photovoltaic Modules

Our steady-state sun simulators are ideal for many different investigations. They are easy to build, working safely and are simple in maintenance. Because of their modular structure, combining a large number of lamps with best lighting data we receive not only best values concerning local and temporal inhomogentity but also the possibility of an extension for larger areas. We are planning and building the sun simulator just as you want to have it.

THE “STEADY STATE” SOLAR WIND

Large Table of Numbers

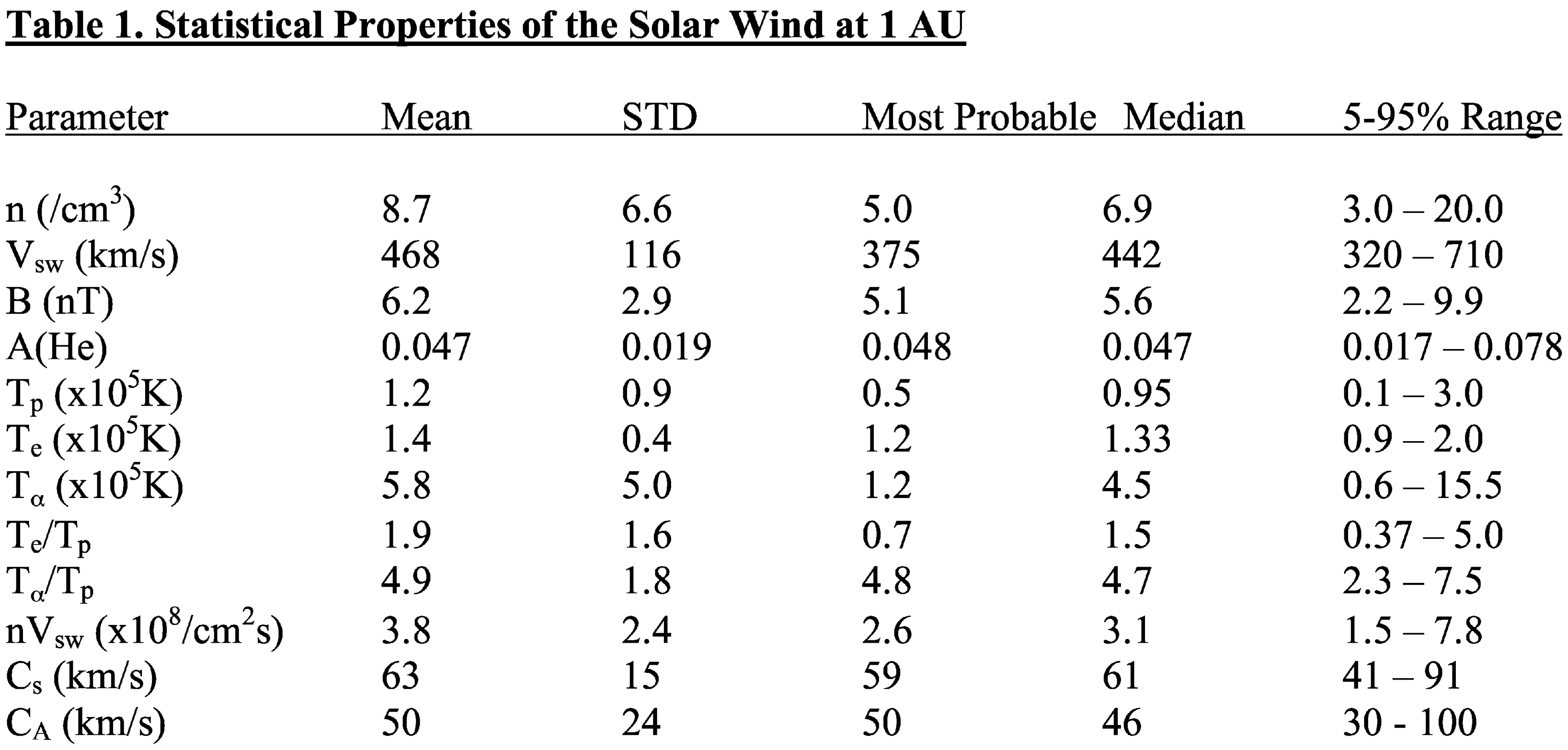


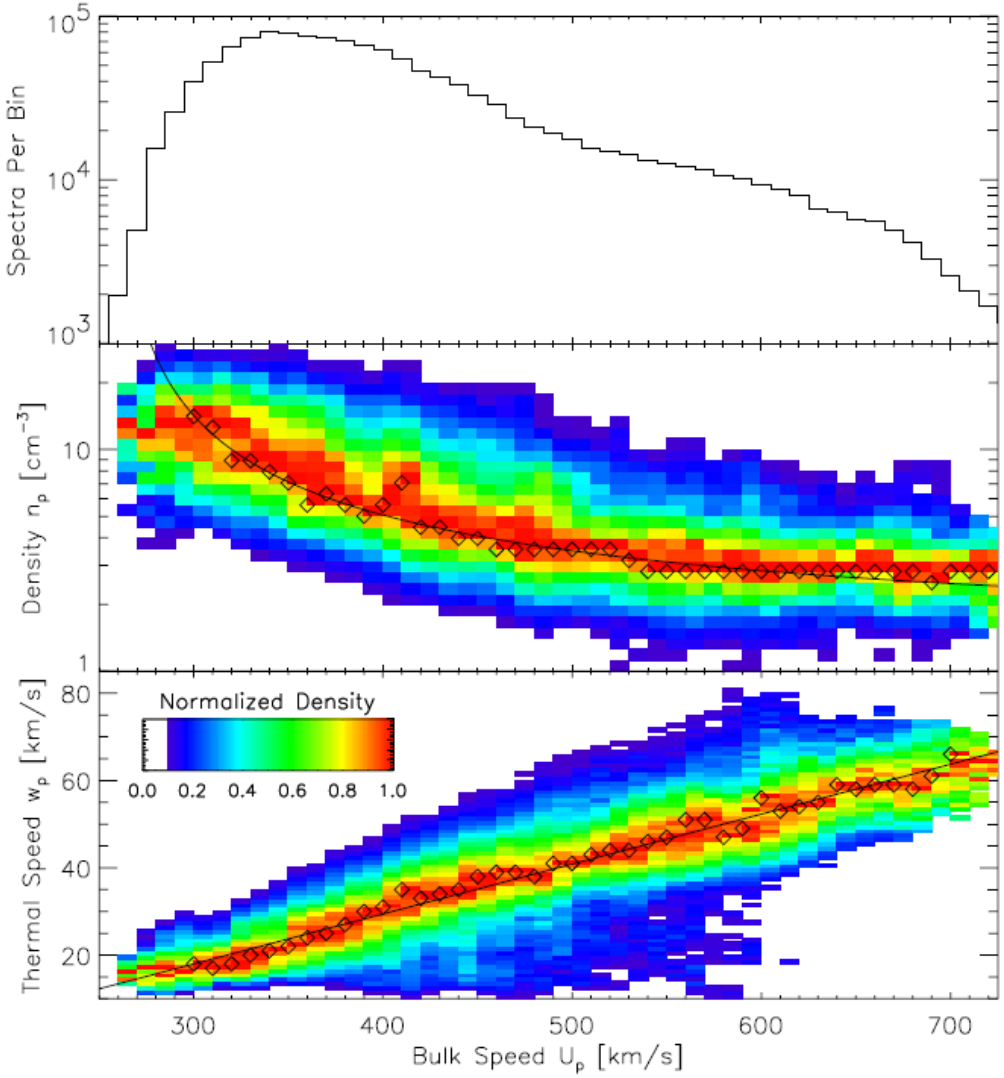
Table 1. Statistical Properties of the Solar Wind at 1 AU

Parameter	Mean	STD	Most Probable	Median	5-95% Range
n (/cm^3)	8.7	6.6	5.0	6.9	3.0 – 20.0
V_{sw} (km/s)	468	116	375	442	320 – 710
B (nT)	6.2	2.9	5.1	5.6	2.2 – 9.9
A(He)	0.047	0.019	0.048	0.047	0.017 – 0.078
T_p (x10^{5}K)	1.2	0.9	0.5	0.95	0.1 – 3.0
T_e (x10^{5}K)	1.4	0.4	1.2	1.33	0.9 – 2.0
T_α (x10^{5}K)	5.8	5.0	1.2	4.5	0.6 – 15.5
T_e/T_p	1.9	1.6	0.7	1.5	0.37 – 5.0
T_α/T_p	4.9	1.8	4.8	4.7	2.3 – 7.5
nV_{sw} (x10^8/cm^{2}s)	3.8	2.4	2.6	3.1	1.5 – 7.8
C_s (km/s)	63	15	59	61	41 – 91
C_A (km/s)	50	24	50	46	30 - 100

n is proton density, V_{sw} is solar wind speed, B is magnetic field strength, A(He) is He^{++}/H^+ ratio, T_p is proton temperature, T_e is electron temperature, T_α is alpha particle temperature, C_s is sound speed, C_A is Alfven speed.

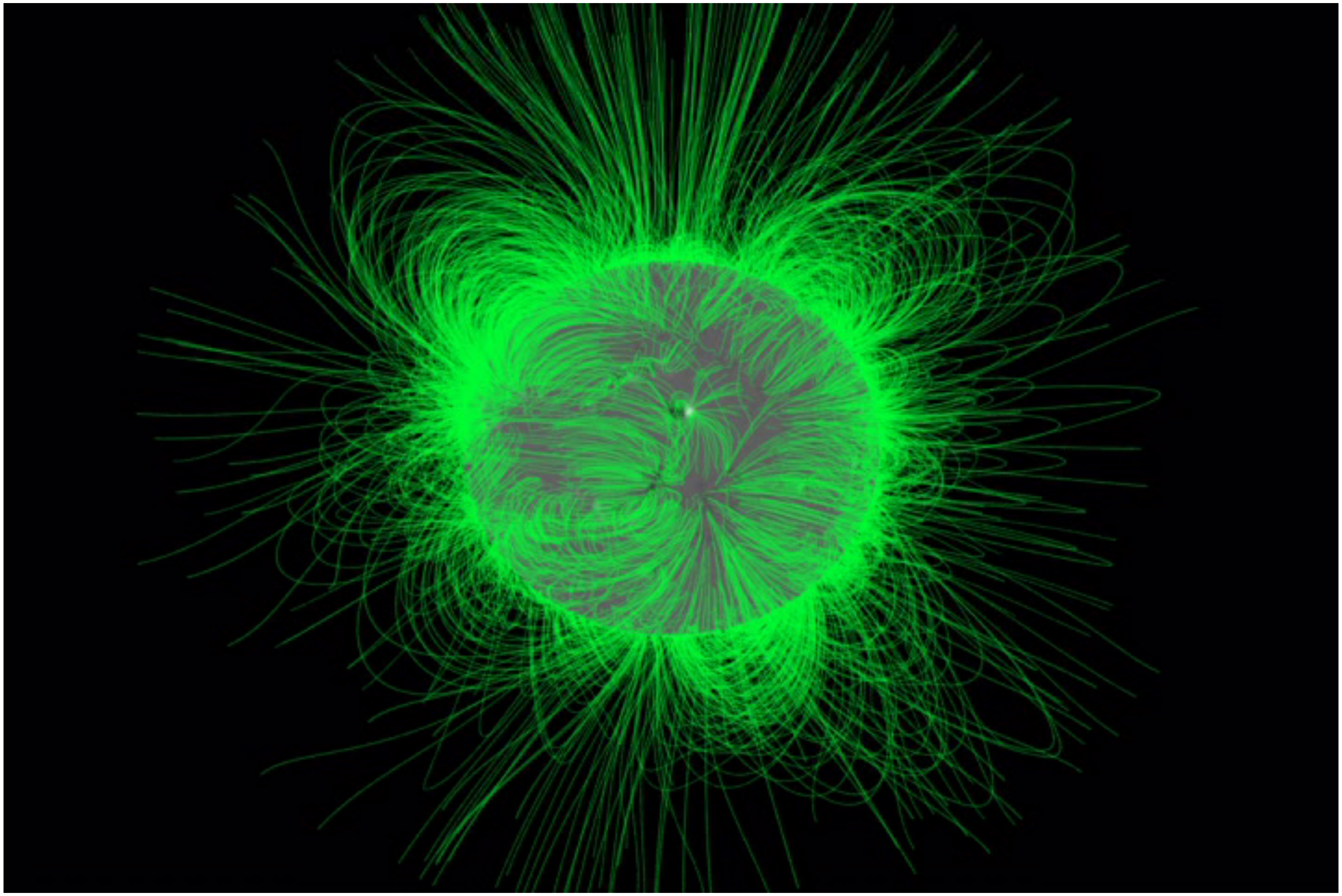
(Table provided by Jack Gosling)

Trends at 1 AU

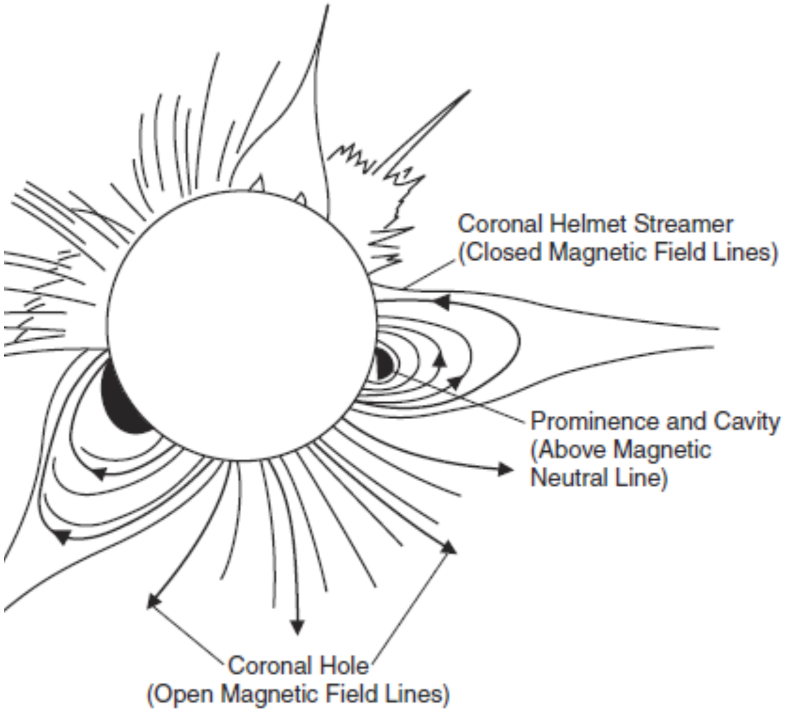


- 4.5 million measurements of the solar wind at 1 AU from 1995 through 2005
- Histogram of speeds
  - 260 – 700 km s^{-1}
- Distribution of density with speed
  - Mass flux roughly constant
- Distribution of thermal speed $1/2m_p w_p^2 = k_B T_p$ with speed
  - Tight relationship between bulk and thermal speeds ($\frac{U_p}{w_p} = 10$)
  - Expected temperature useful for identifying transients like coronal mass ejections

Solar wind sources



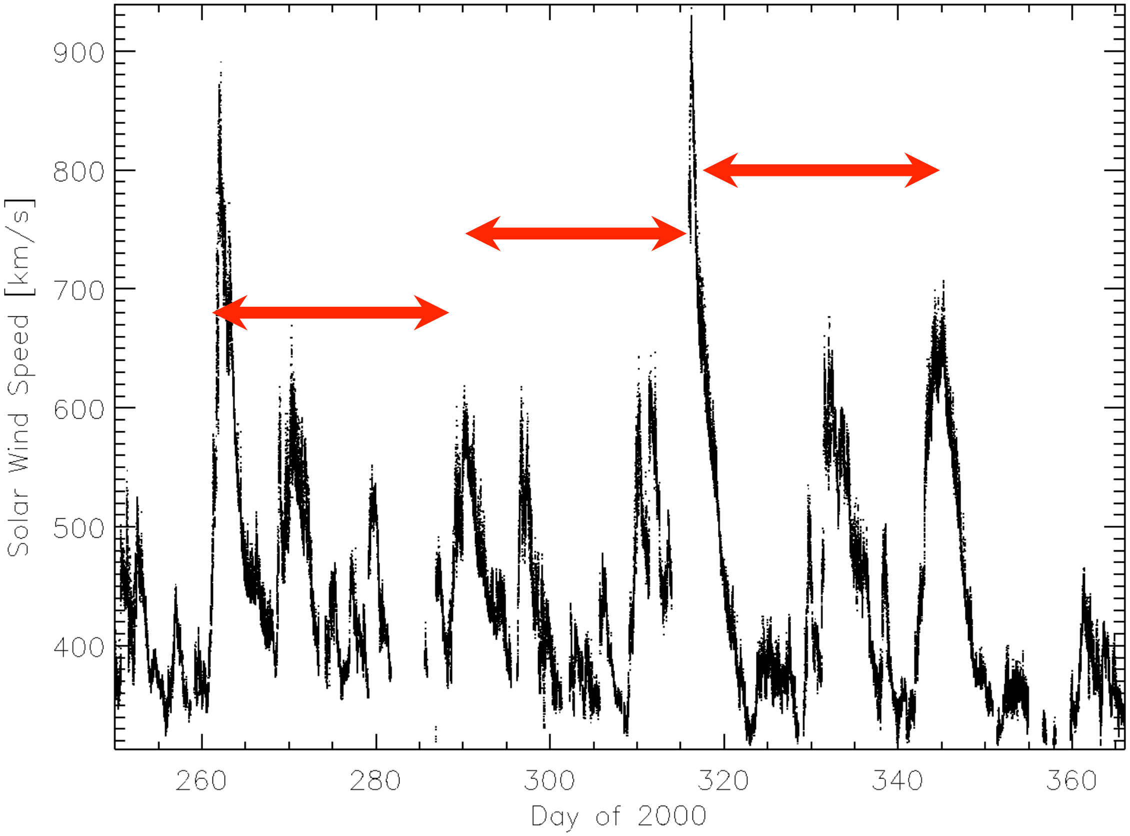
The Standard Paradigm



Hundhausen (1995)

- Fast solar wind
  - Emerges from open field lines associated with coronal holes
- Slow solar wind
  - Escapes intermittently from the streamer belt and near the heliospheric current sheet
- Other sources
  - Active regions
  - Coronal mass ejections (CMEs)

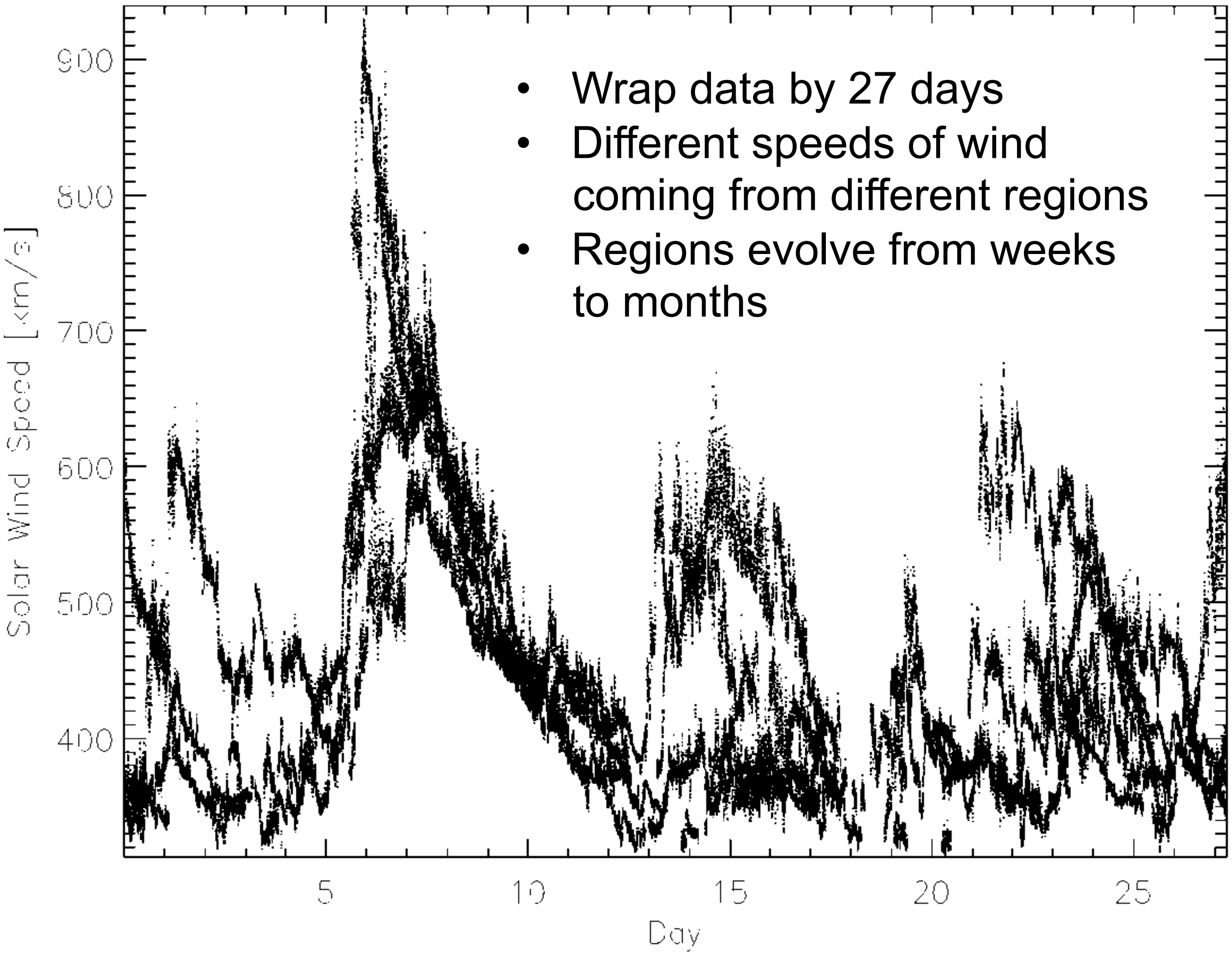
Several months at 1 AU



Wind/SWE

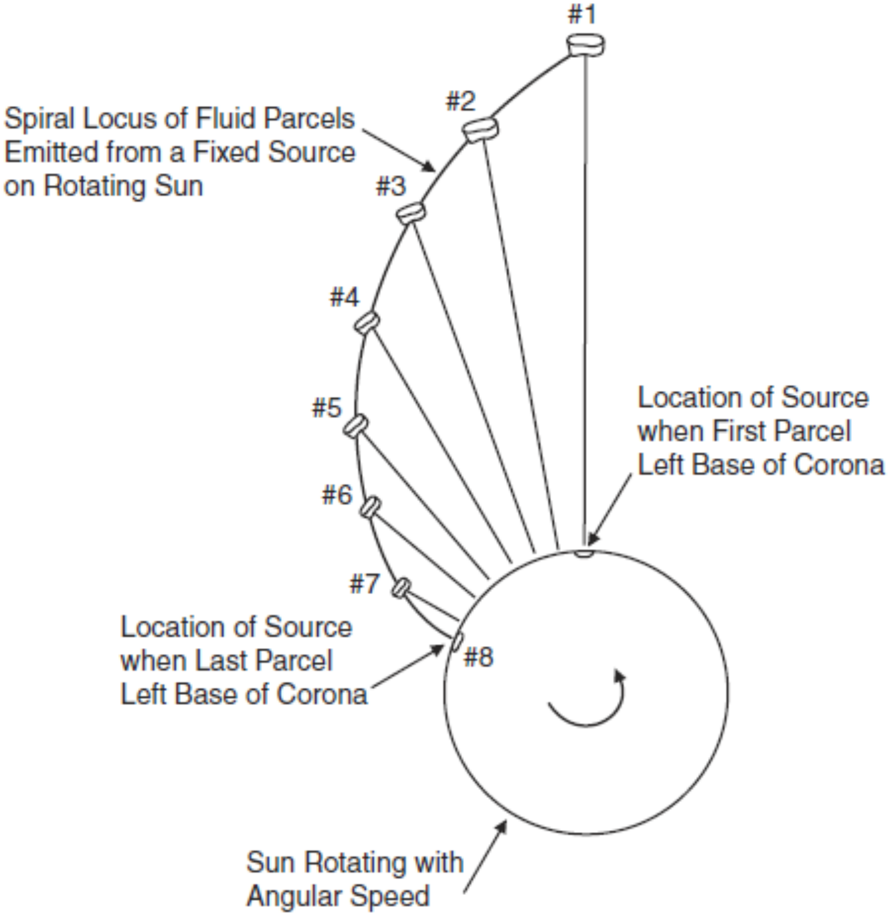
- ➢ Variable
- ➢ Structured
- ➢ Periodic? What period should we expect?

Repeating streams of wind



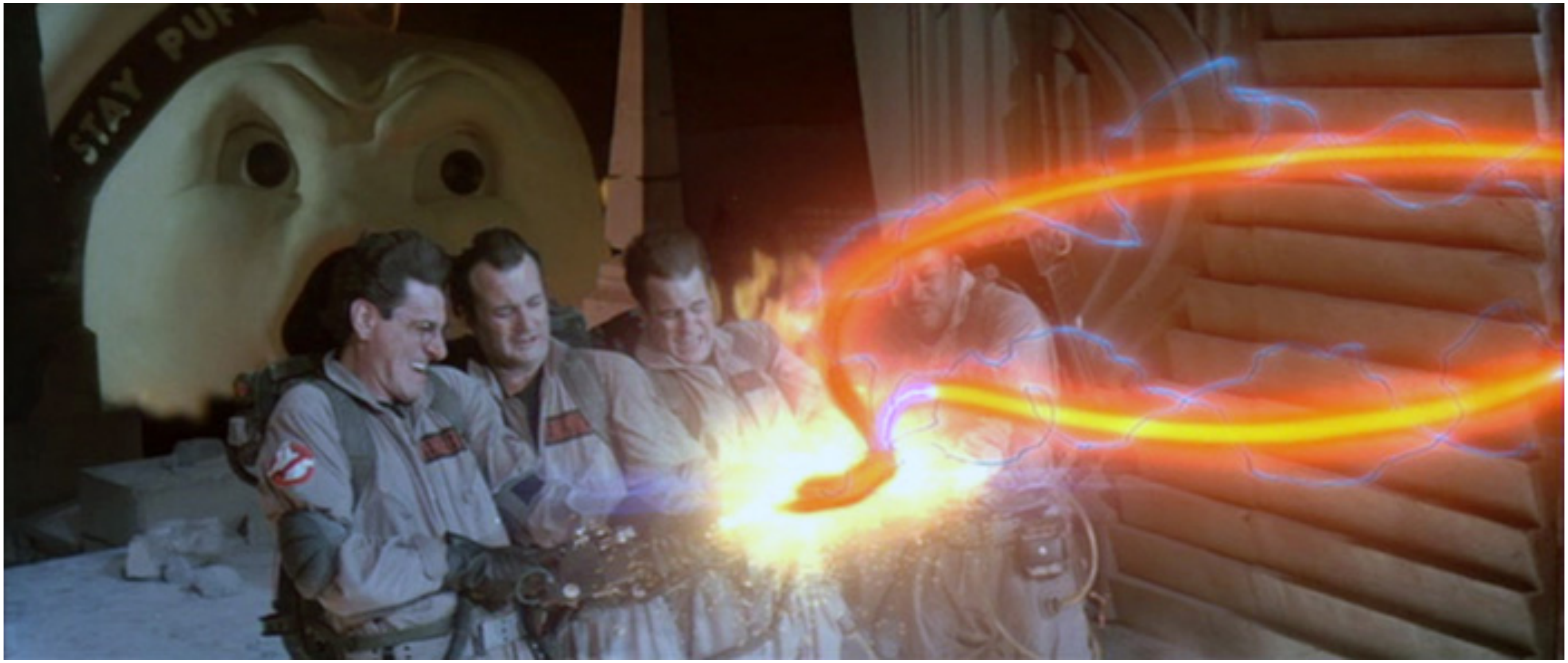
- Wrap data by 27 days
- Different speeds of wind coming from different regions
- Regions evolve from weeks to months

Evolution of a stream into space



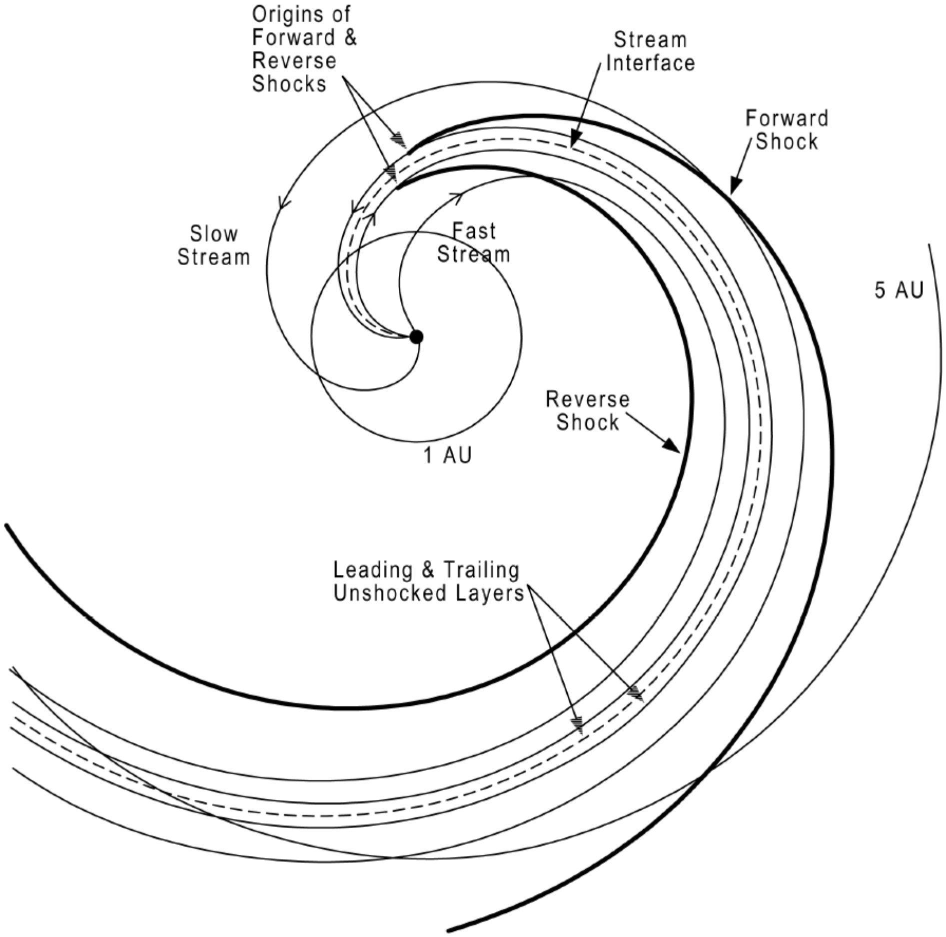
Hundhausen (1995)

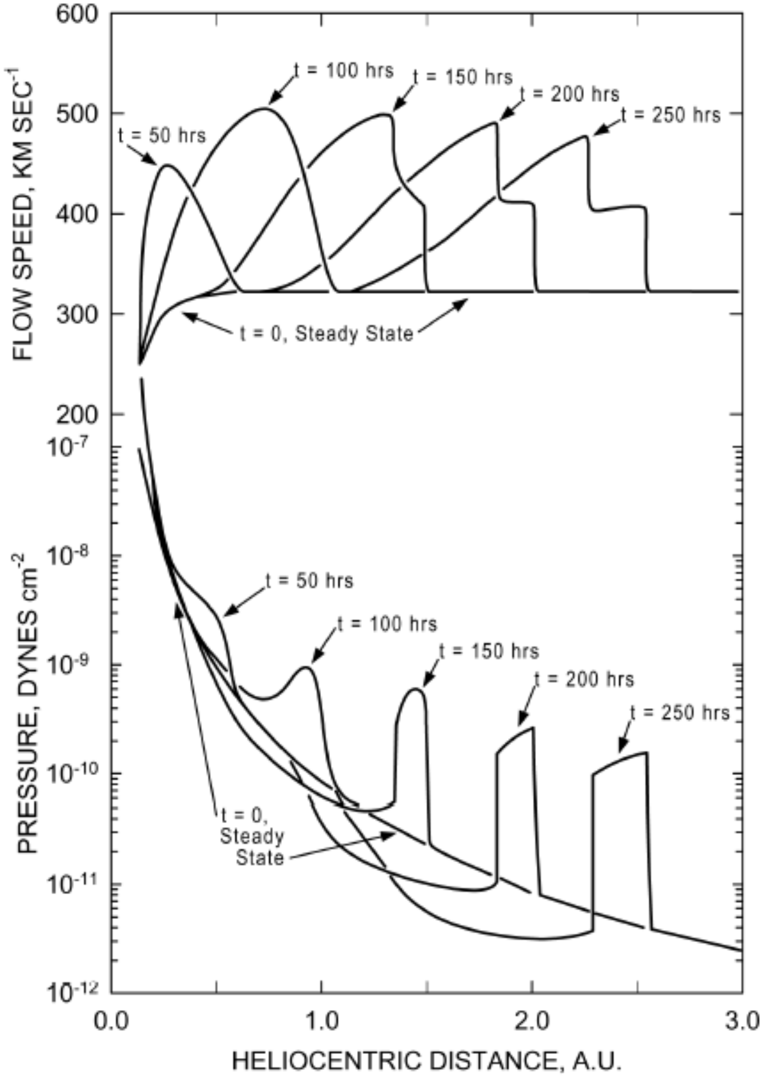
- The Parker Spiral
- Beyond some distance r_o plasma streams radially away from Sun at steady speed v_o
- Since Sun rotates at angular frequency Ω, streamlines take the form
- $\frac{r}{r_o} - 1 - \ln\left(\frac{r}{r_o}\right) = \frac{v_o}{r_o \Omega}(\phi - \phi_o)$
- In steady state, with $\vec{\nabla} \cdot \vec{B} = 0$, and $\vec{B}_o$ at r_o in the radial direction
  - $B_r = B_o \left(\frac{r_o}{r}\right)^2$
  - $B_\theta = 0$
  - $B_\phi = B_o \frac{\Omega}{v_o}(r - r_o)\left(\frac{r_o}{r}\right)^2 \sin\theta$



STREAM INTERACTIONS

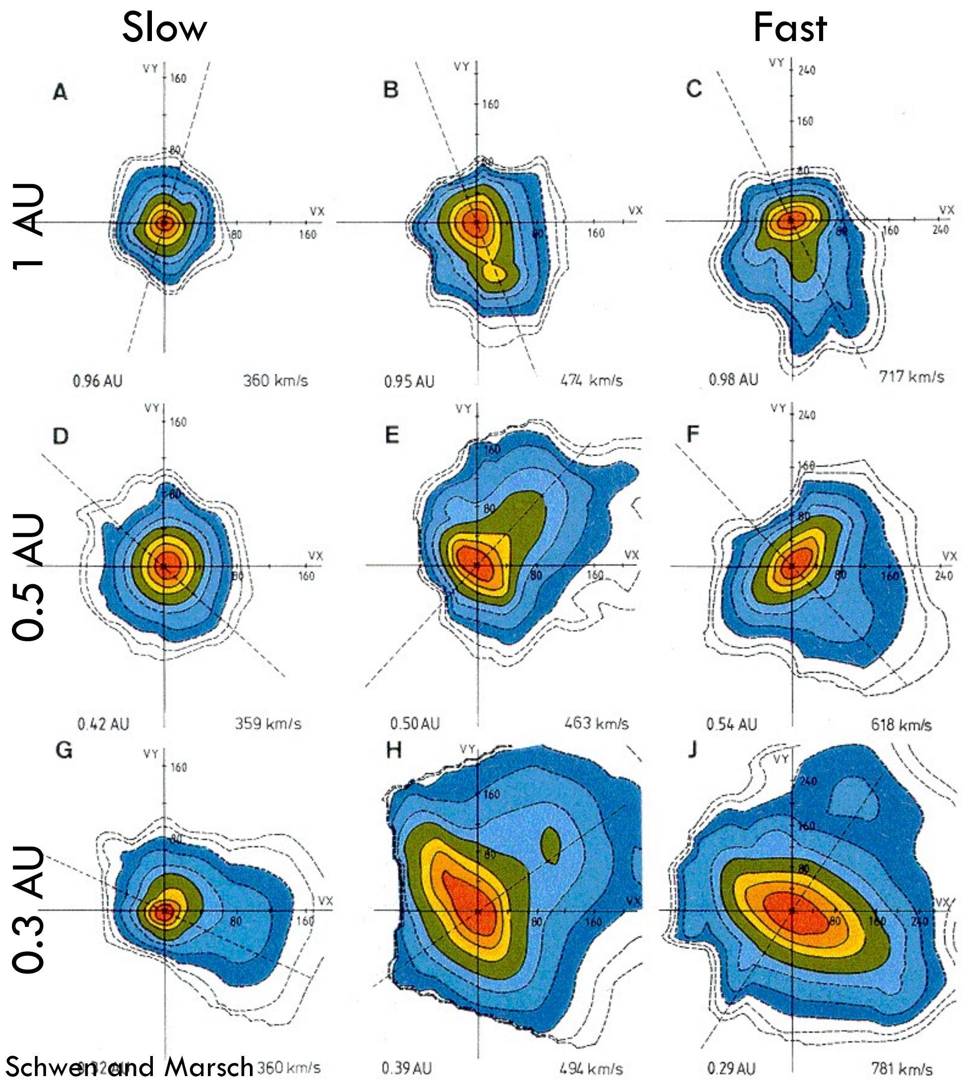
Fast wind overtakes slow wind





THREE-DIMENSIONAL STRUCTURE

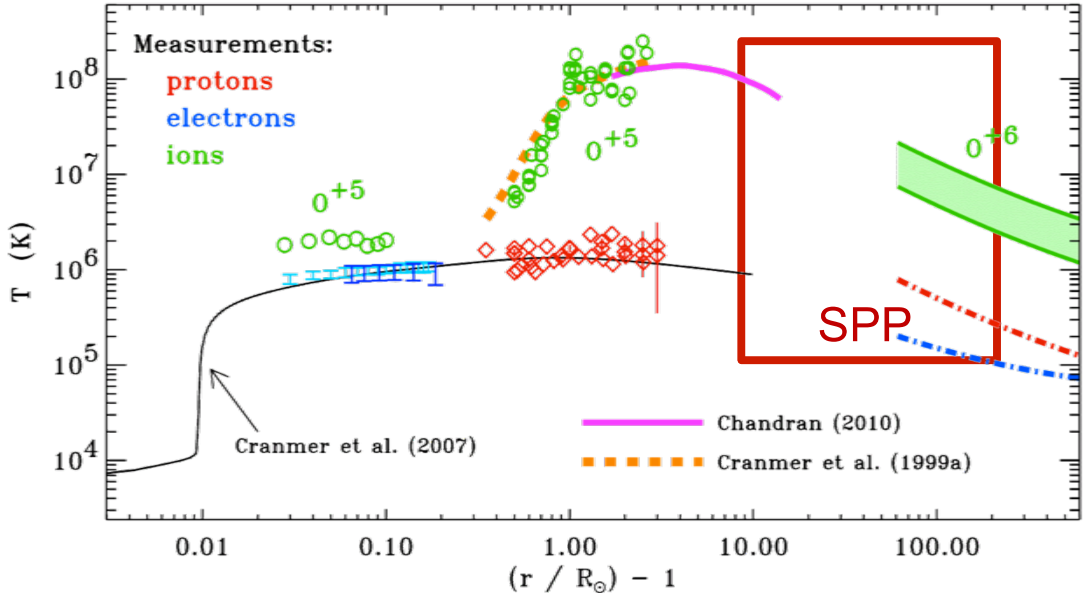
Kinetic properties of the solar wind

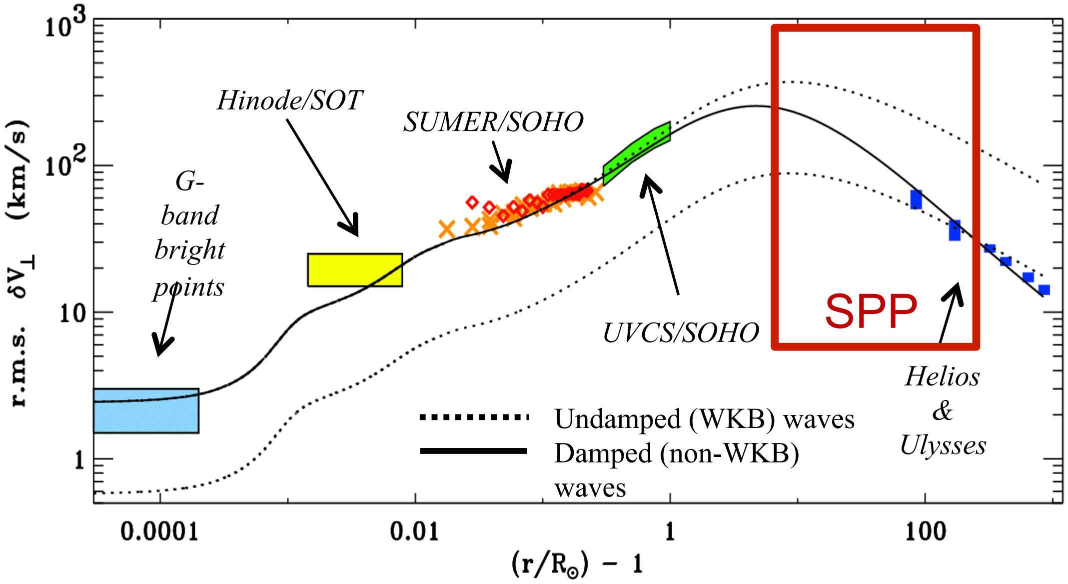


Schwenn and Marsch

- Kinetic or non-thermal features
  - Field-aligned anisotropies
  - Beams
  - Different temperatures
- Radial evolution
  - Stronger closer to Sun
  - Stronger in fast wind
- Paradigm
  - Slow wind is Maxwellian and behaves as single fluid
  - Fast wind has strong non-thermal aspects
  - Slow/fluid, Fast/kinetic
- Word of caution: collisional relaxation plays a role

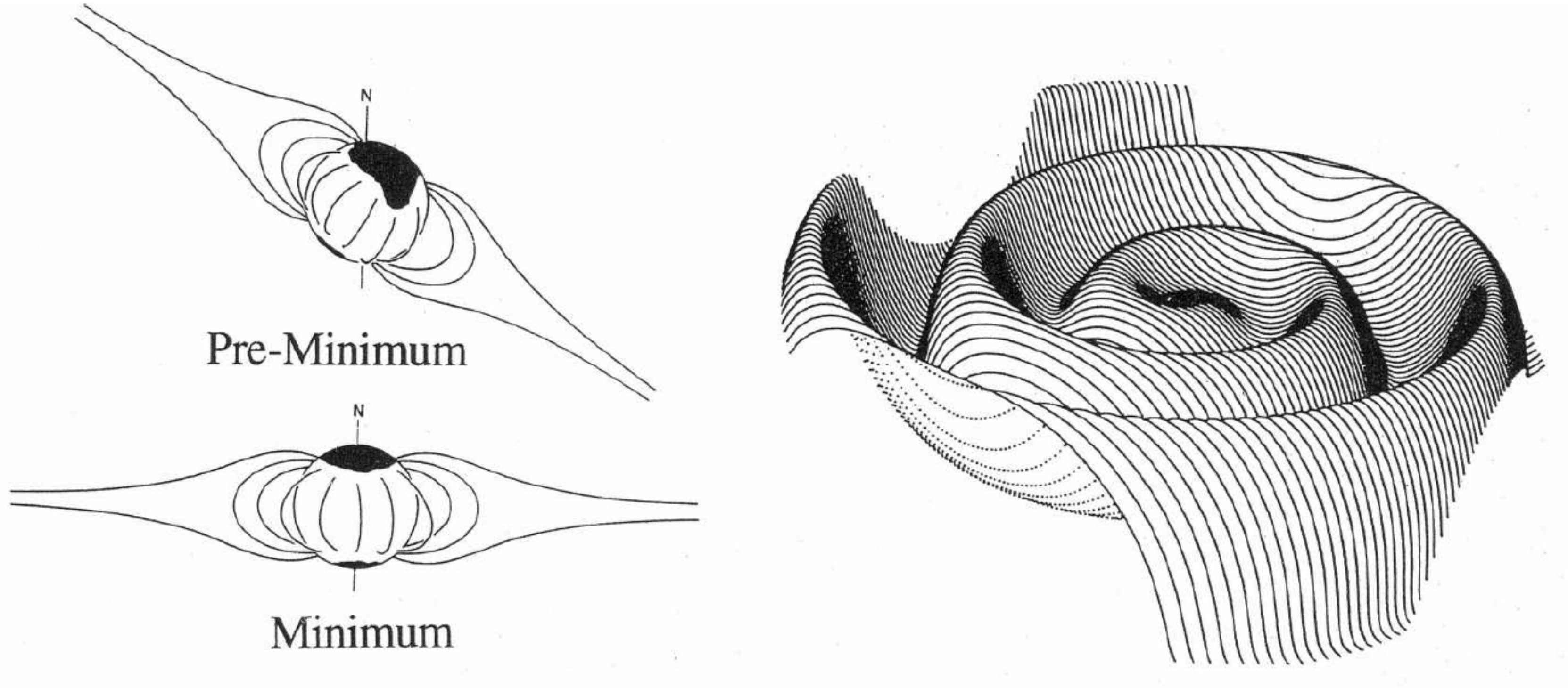
Evolution of energy with distance



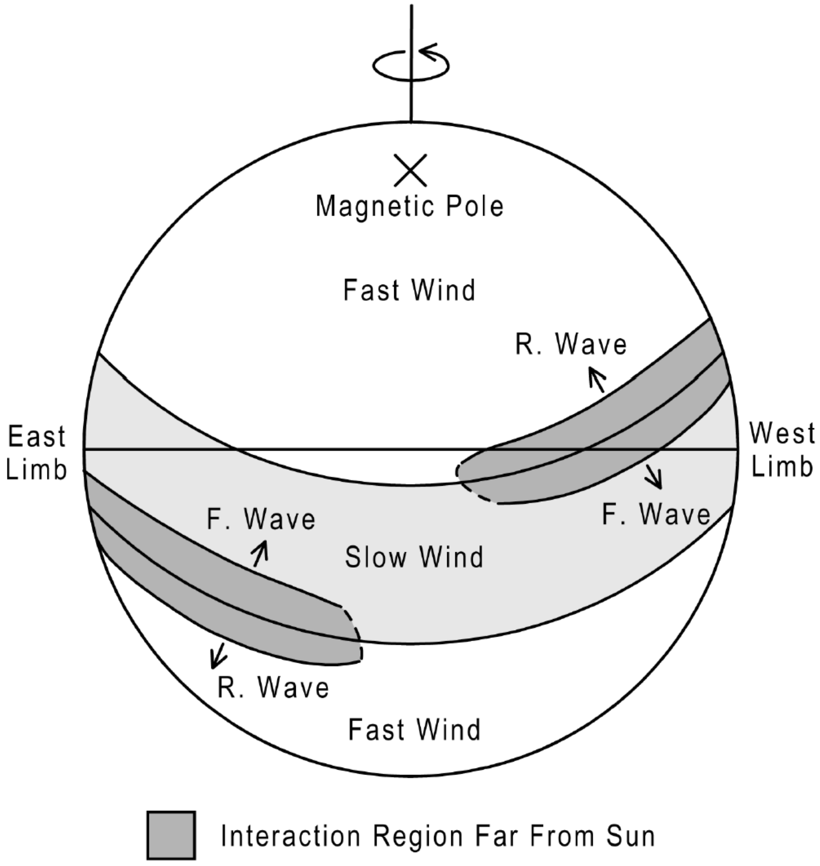


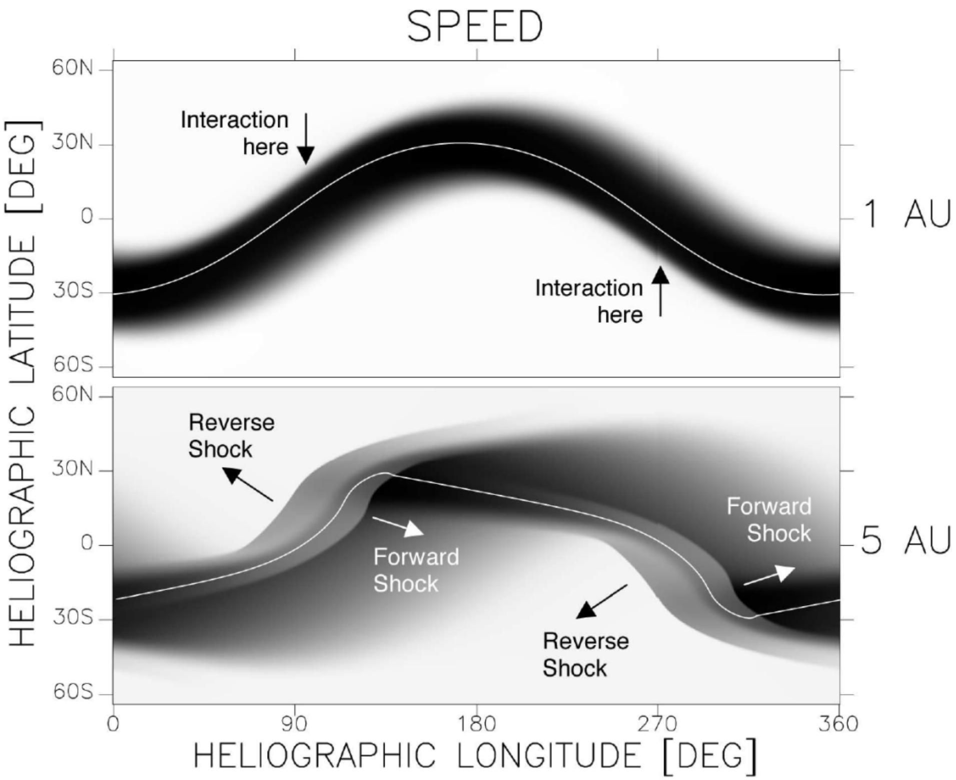
- Why are temperatures so large in corona?
- Why do temperatures not fall off adiabatically with distance?
- What are the energy sources and how are they dissipated?
  - Turbulence
  - Magnetic reconnection
  - Waves

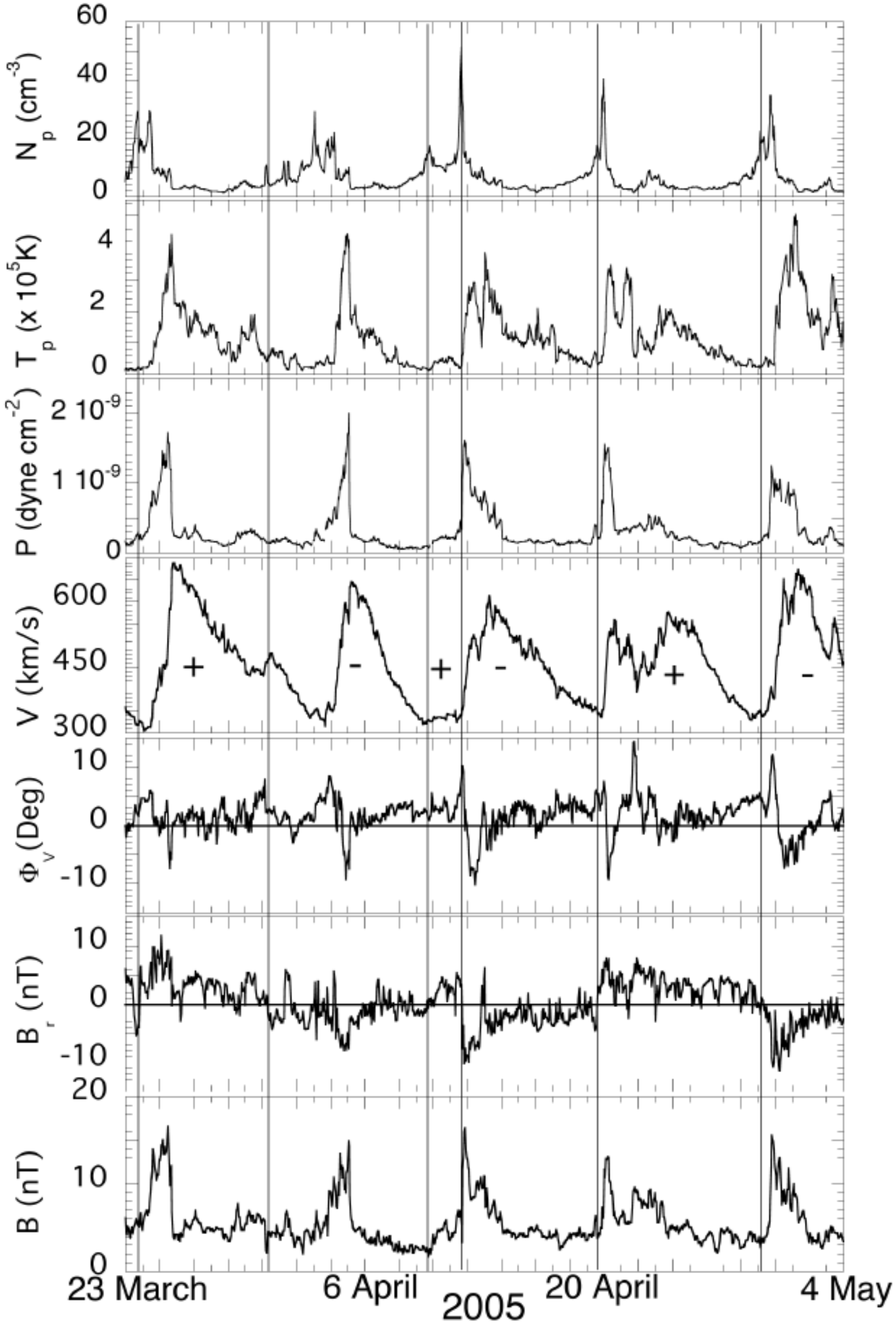
Effects of a tilted current sheet



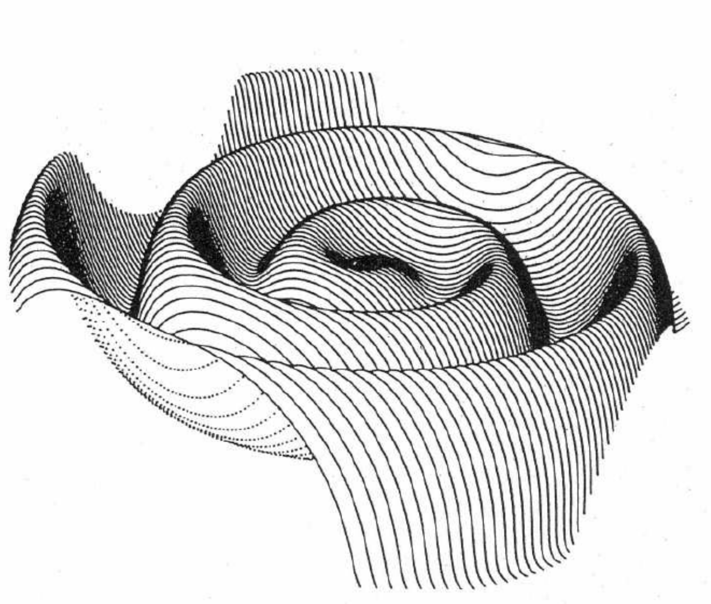
Stream Interactions in 3D



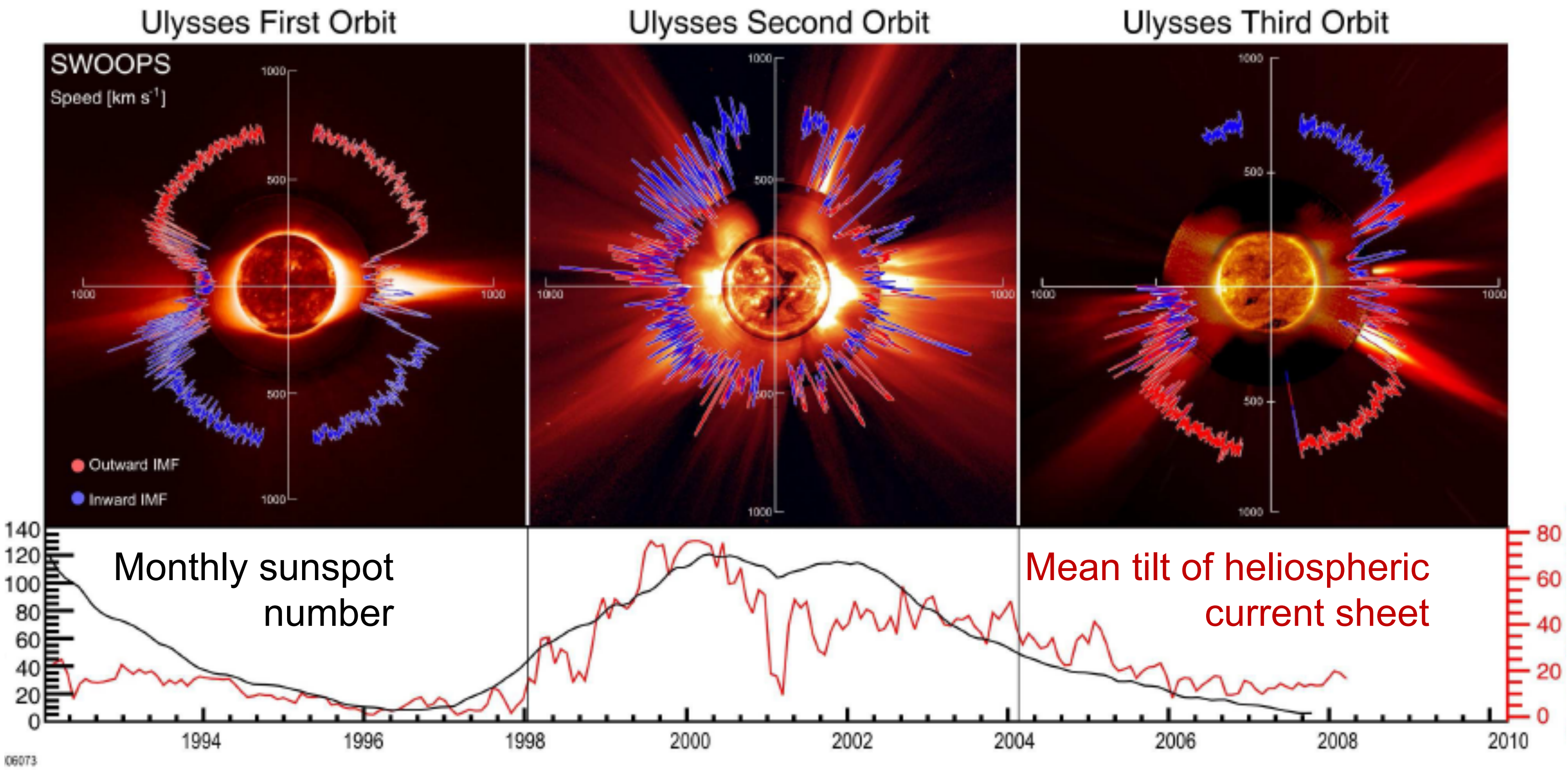




N_p (cm^-3)
0
20
40
60
T_p (x 10^5 K)
0
2
4
P (dyne cm^-2)
0
1 10^-9
2 10^-9
V (km/s)
300
450
600
+
-
+
-
+
-
Φ_V (Deg)
-10
0
10
B_r (nT)
-10
0
10
20
B (nT)
0
10
23 March
6 April
20 April
4 May
2005

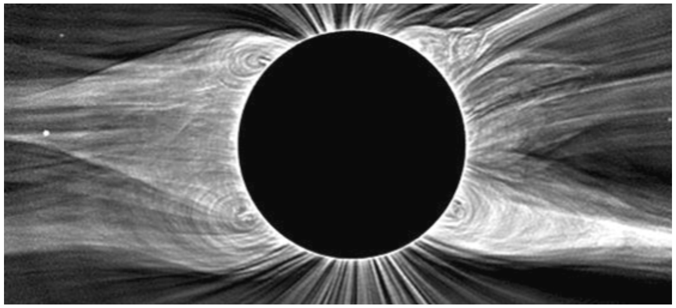


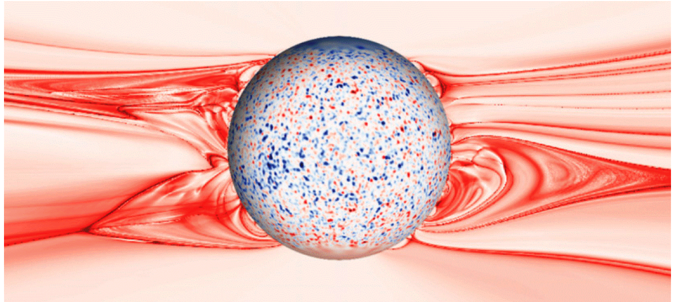
Three dimensional heliosphere



Monthly sunspot number

Mean tilt of heliospheric current sheet

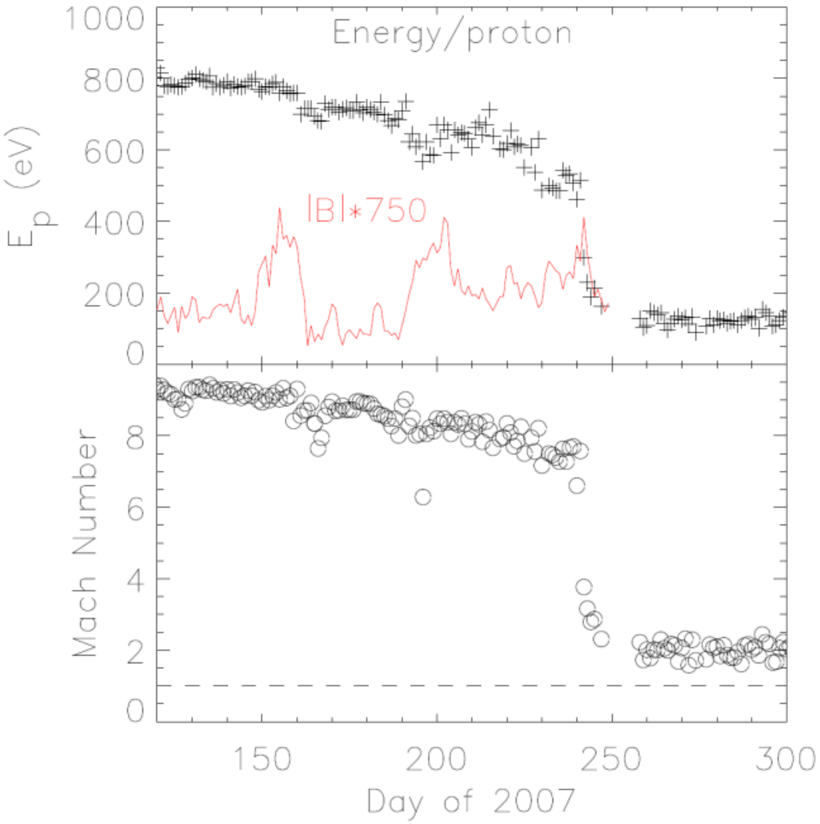


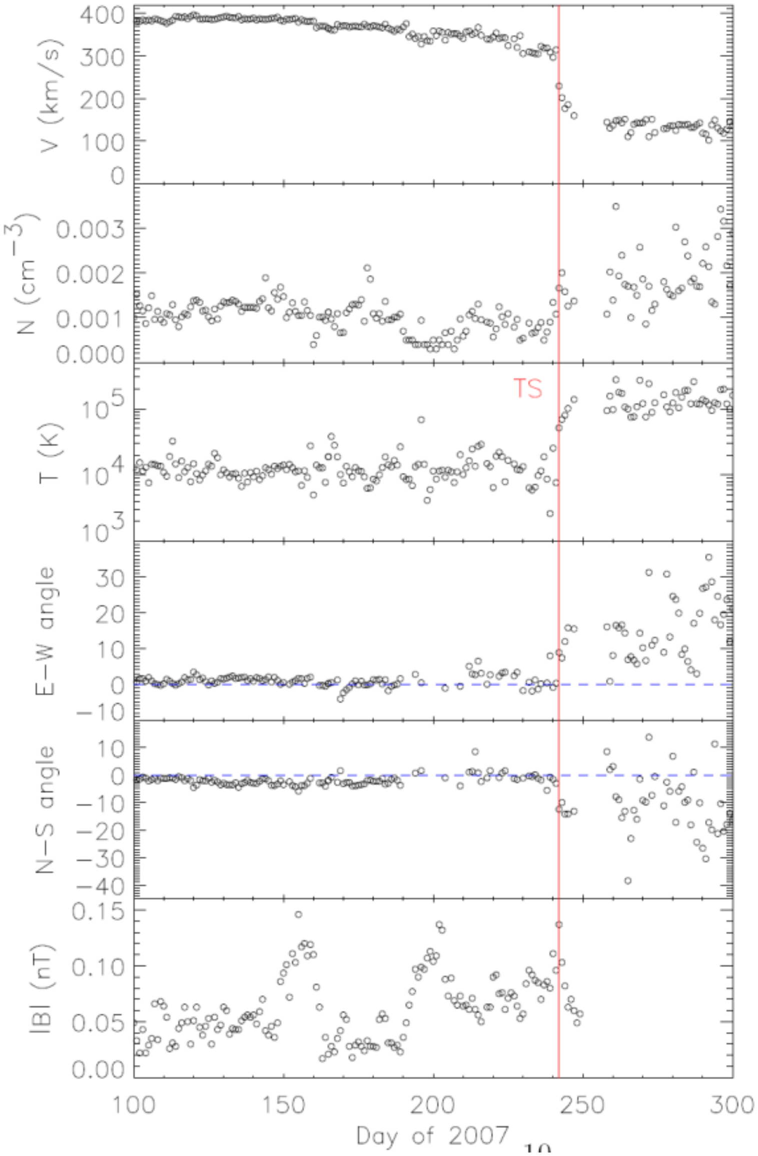


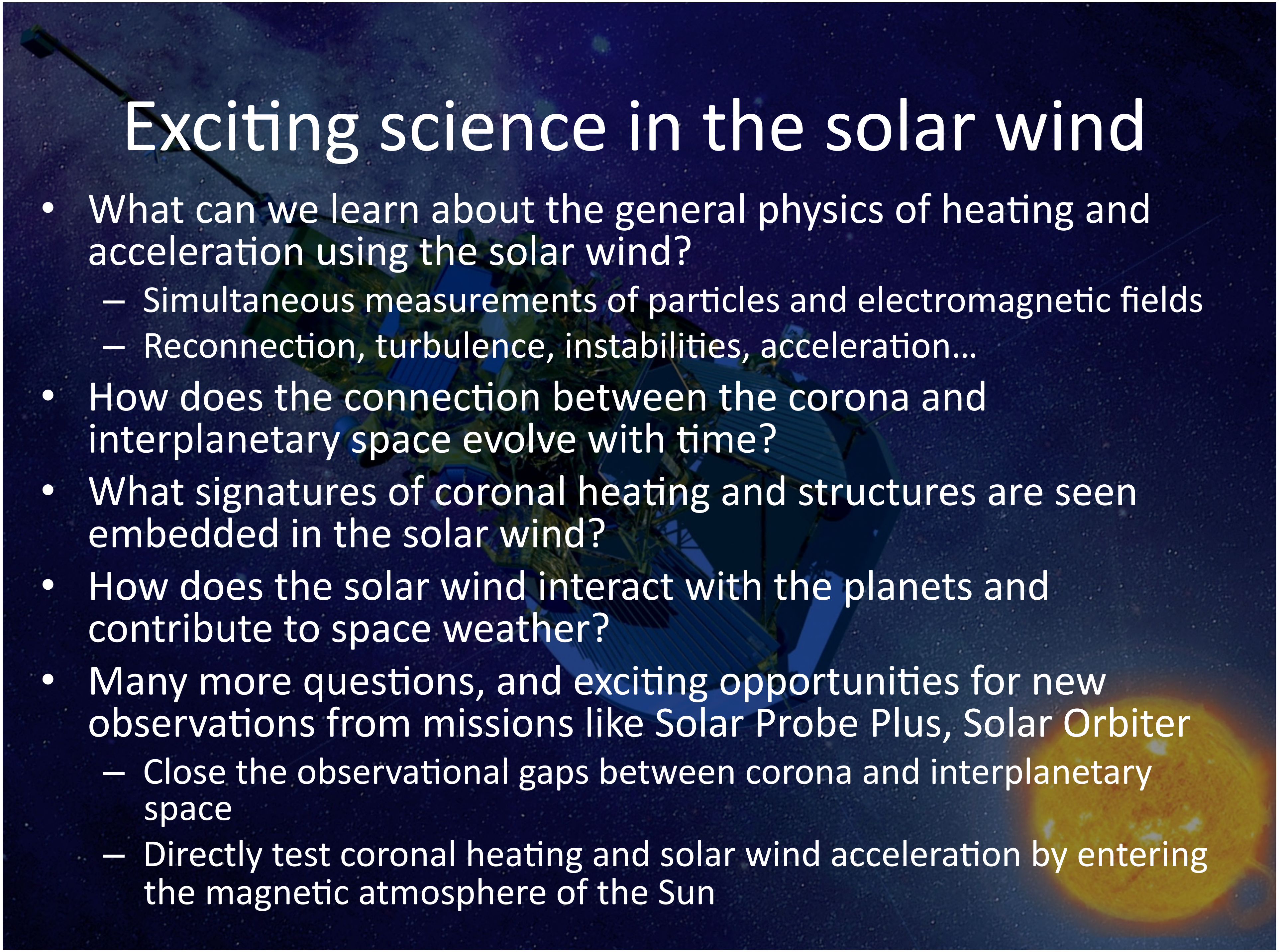
McComas et al. (2008)

The Outer Limits

- Voyager 1 crossed termination shock in December 2006
- Voyager 2 crossed in August 2008
-







Exciting science in the solar wind

- What can we learn about the general physics of heating and acceleration using the solar wind?
  - Simultaneous measurements of particles and electromagnetic fields
  - Reconnection, turbulence, instabilities, acceleration…
- How does the connection between the corona and interplanetary space evolve with time?
- What signatures of coronal heating and structures are seen embedded in the solar wind?
- How does the solar wind interact with the planets and contribute to space weather?
- Many more questions, and exciting opportunities for new observations from missions like Solar Probe Plus, Solar Orbiter
  - Close the observational gaps between corona and interplanetary space
  - Directly test coronal heating and solar wind acceleration by entering the magnetic atmosphere of the Sun

ADDITIONAL MATERIAL

SHORT TERM VARIATION

Trends continued

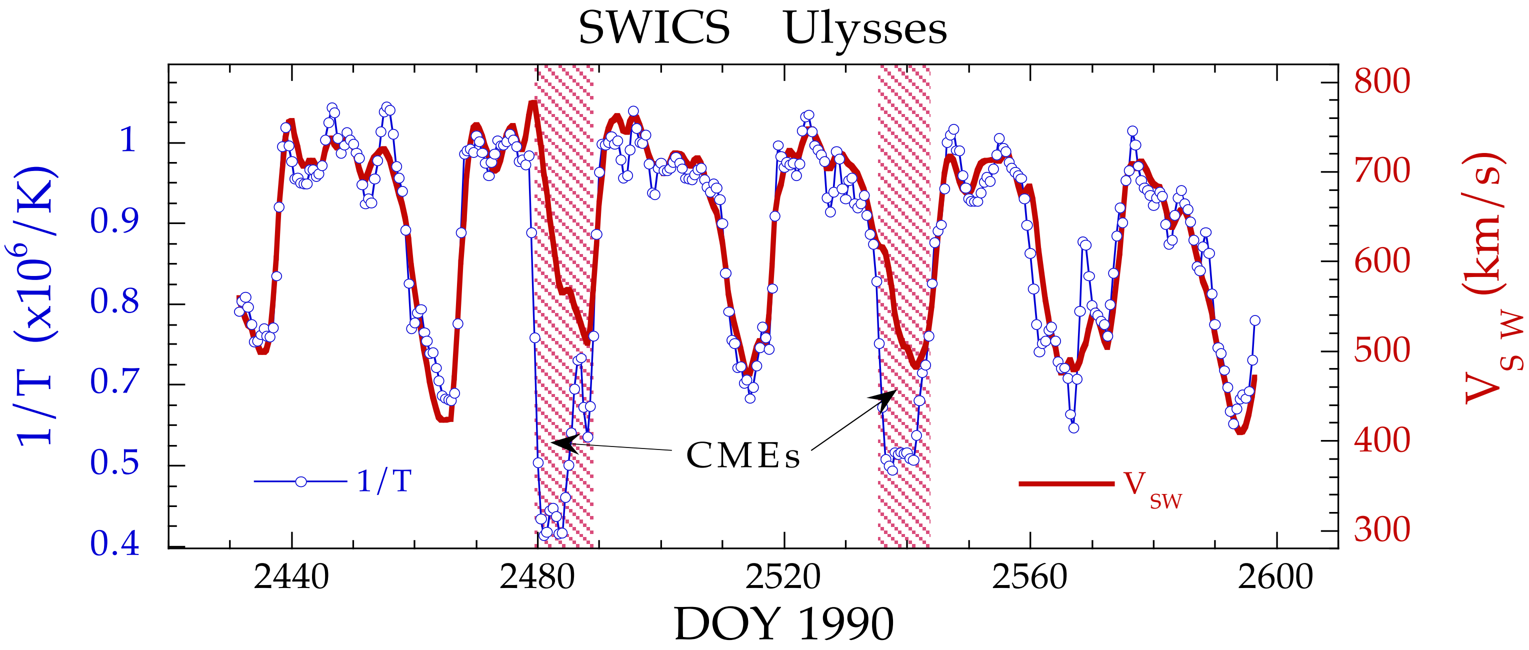
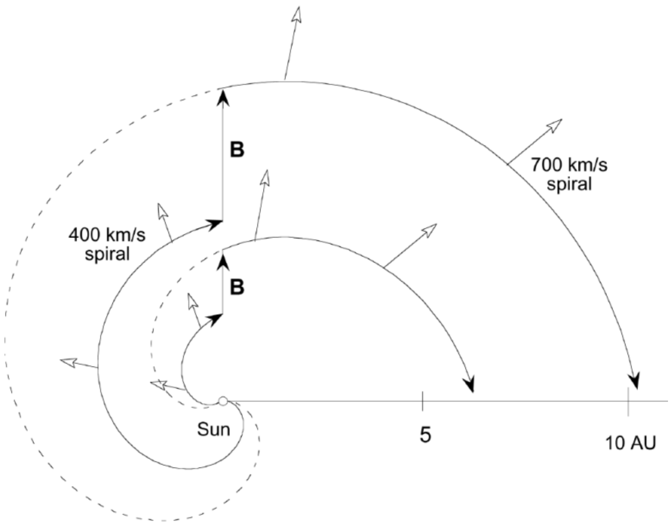
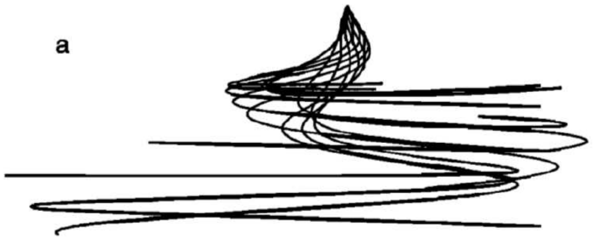


Figure 1. Variations of the inverse of the electron temperature (circles, in units of 10^6 K) and of the solar wind proton bulk speed (solid curve) during a six-months time period (August 27, 1996 – February 9, 1997) observed with SWICS on Ulysses. The tracking of the two curves is almost perfect except during the two time periods indicated by the shaded regions. Each of these two time periods coincides with a Coronal Mass Ejection event identified using bi-directional electron signatures in the Ulysses SWOOPS data (J. Gosling, private communication).

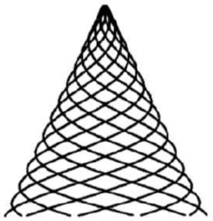
Impact of changes at solar wind source



a

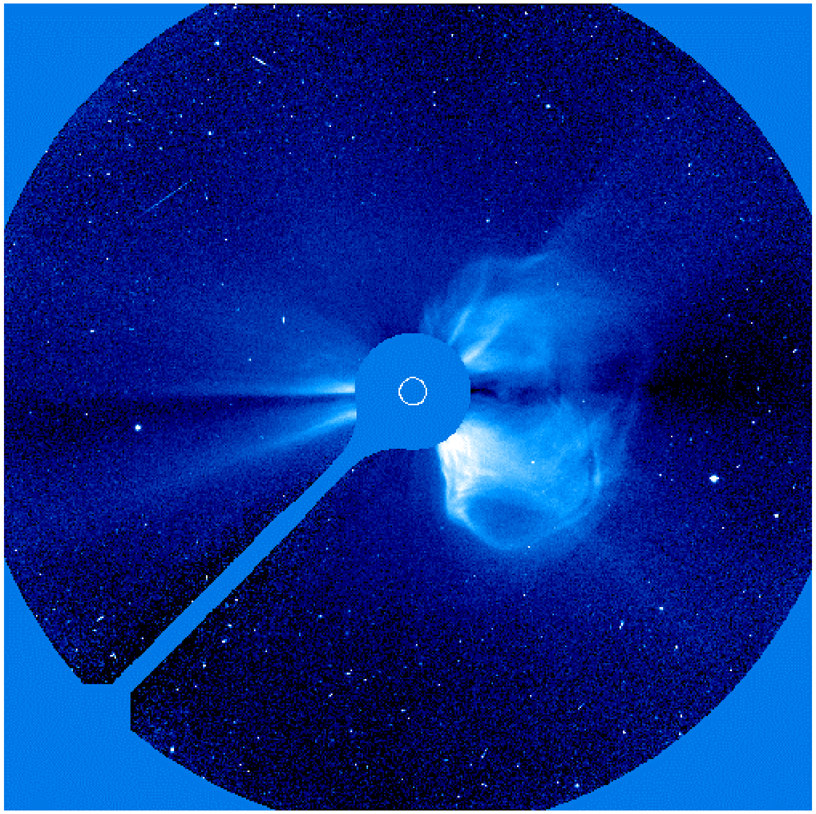


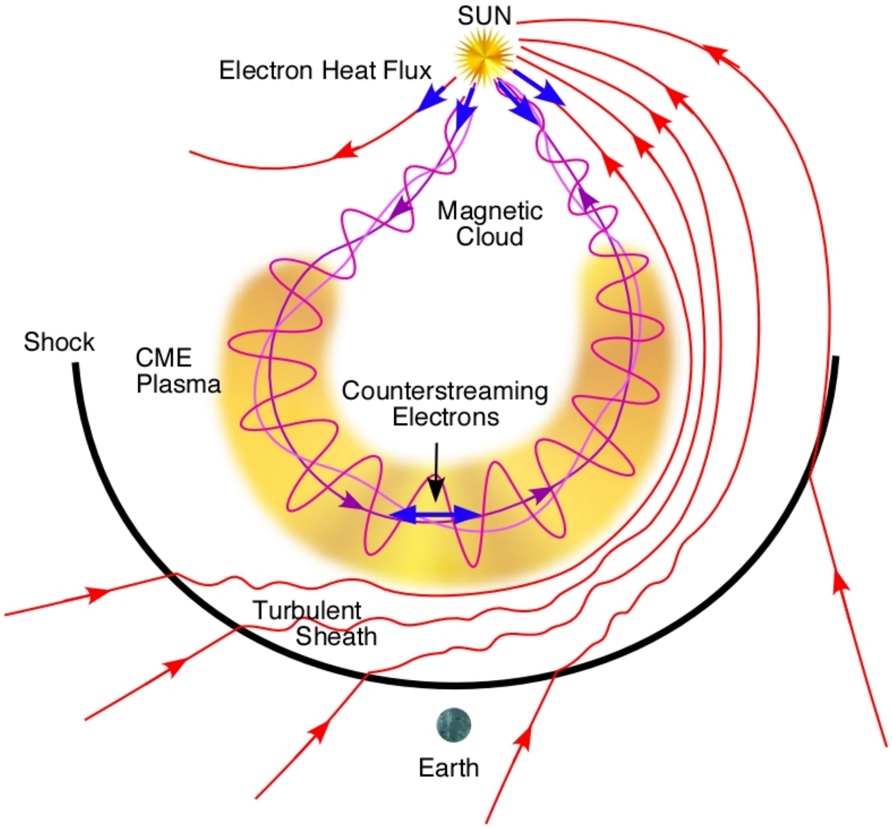
b



- Basic equation for Parker spiral makes several assumptions
  - Solar wind emerges from source region at constant speed
  - Neglects interactions of streams
  - Neglects overall motion of magnetic field within corona
- Upper example: sudden drop in speed
  - Results in radial magnetic field
- Lower example: include differential rotation and tilt of magnetic moment
  - Field lines much more complex
  - Much more magnetic connection across latitudes

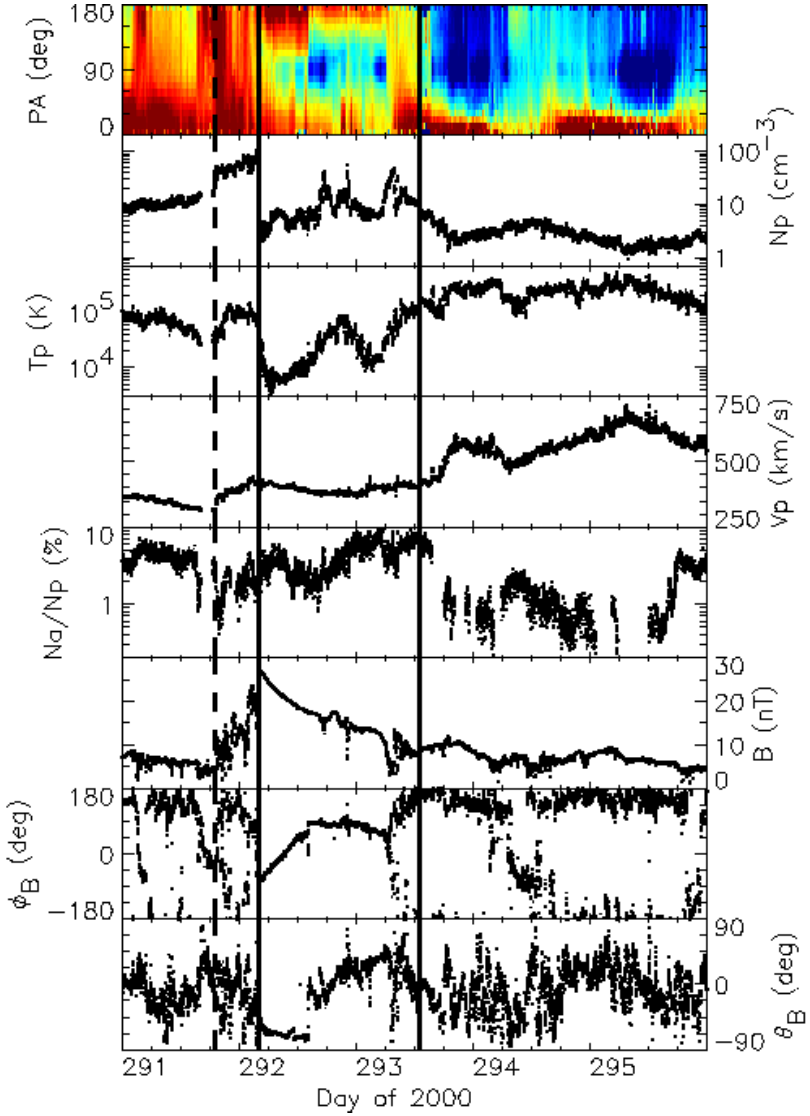
Coronal Mass Ejections





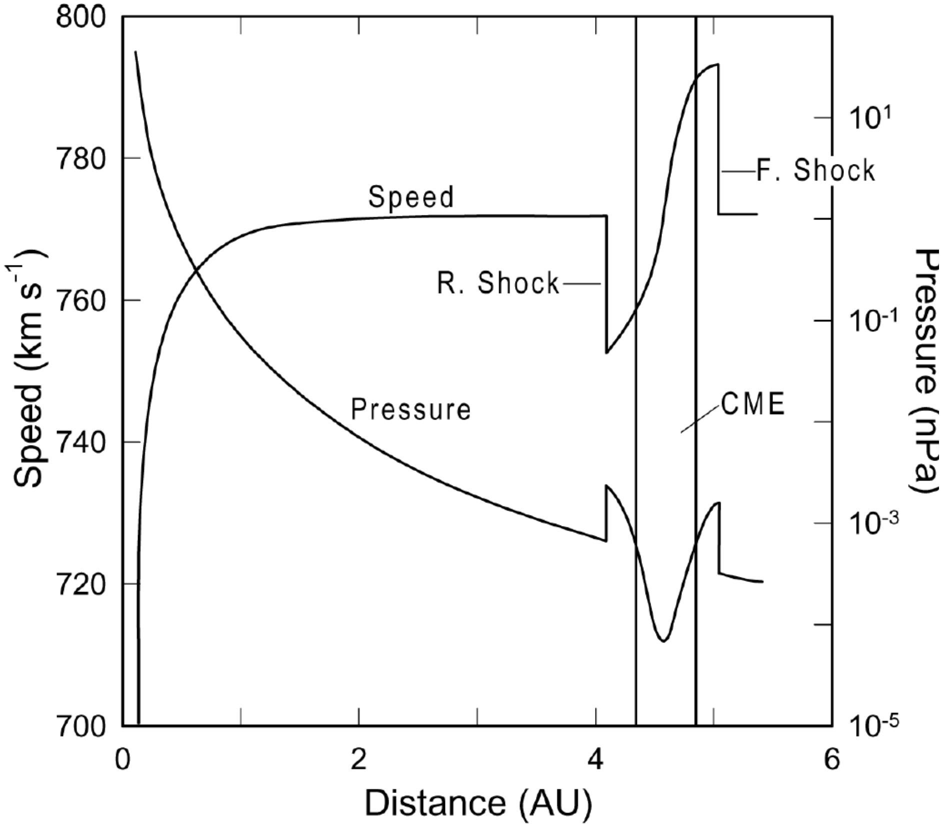
- About 70 events/yr at maximum, 8/yr at minimum
- Speeds of 300-2000 km s^{-1}
  - Produce the largest total fluence of energetic solar particles
- About 0.2 AU thick at 1 AU (over-expansion)

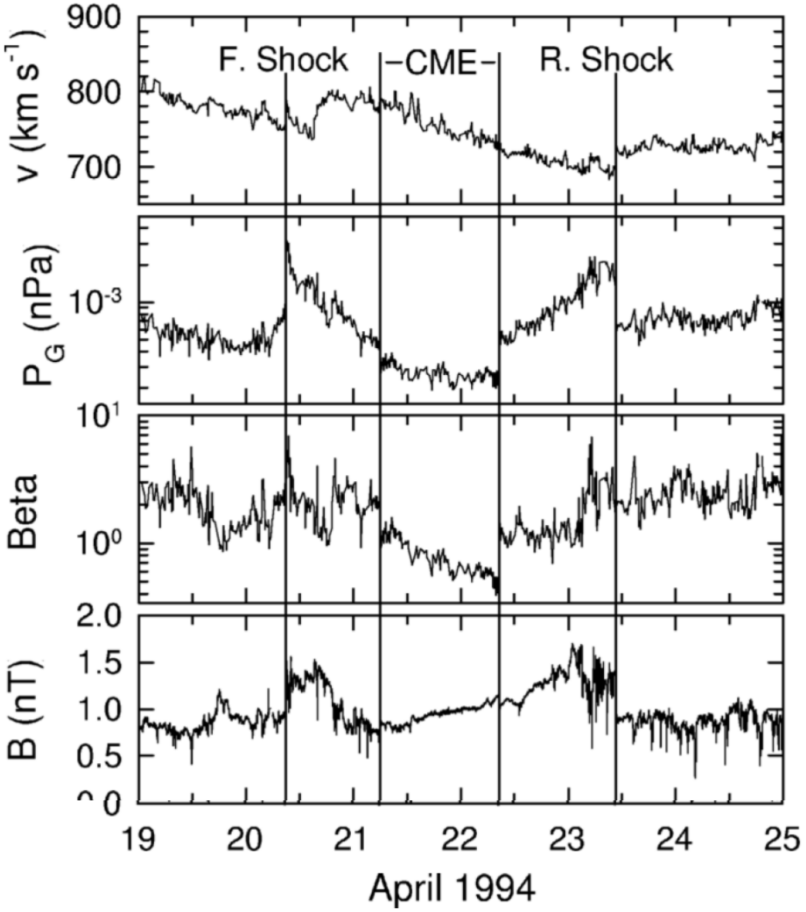
Field guide to finding CMEs



- Superathermal particles from corona counterstreaming in both directions along field
  - Electrons > 70 eV
  - Protons > 20 keV
- Unusual composition
  - He^{2+}/H^{1+} up to 20% by number density
  - He1+ seen
  - High charge states of Fe
- Magnetic signatures
  - Strong total field
  - Low plasma beta
  - Unusual field rotations (especially if in a flux rope)
  - Lower field fluctuations
- Galactic cosmic rays reduced

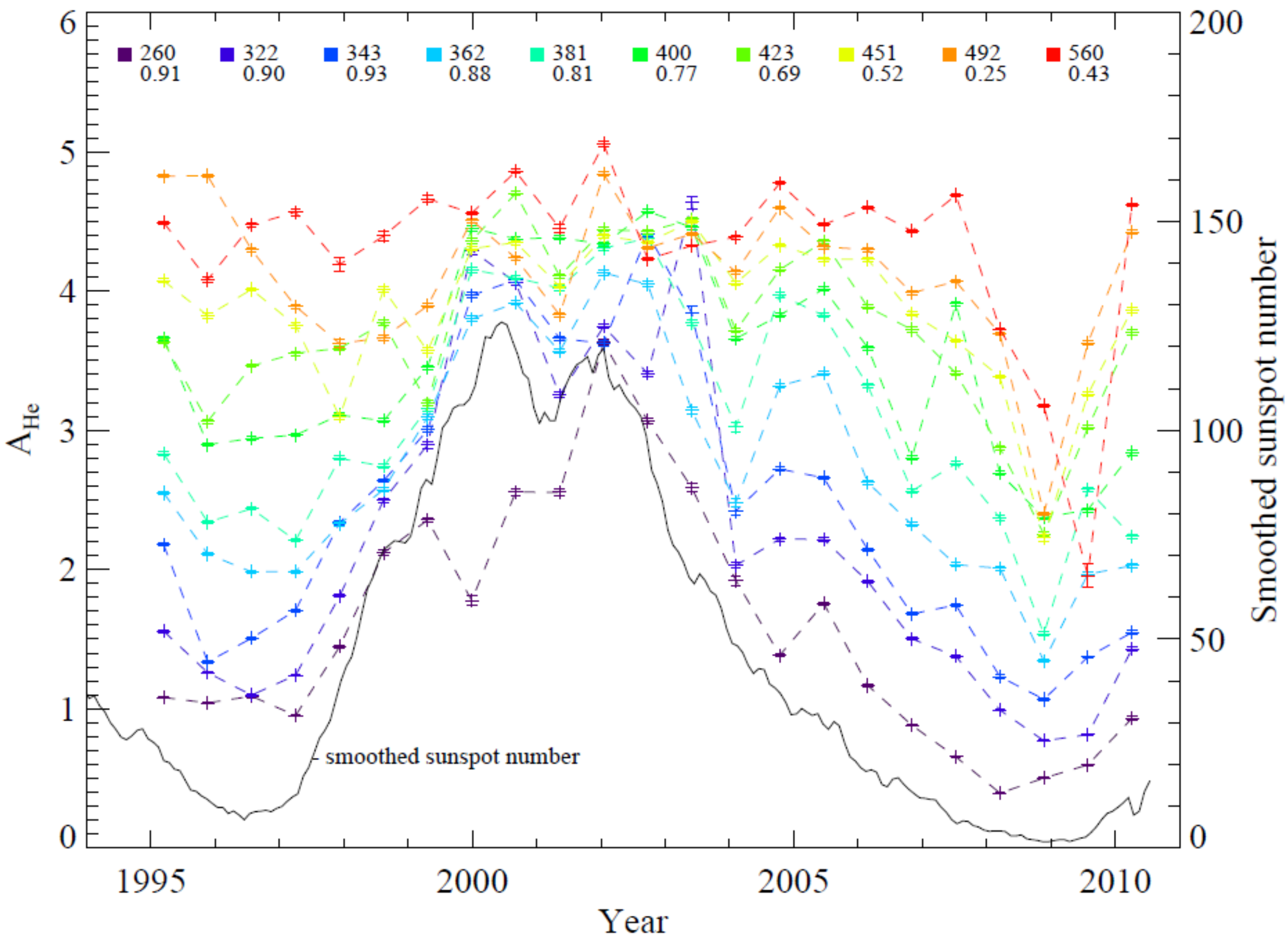
Generation of shocks by CMEs





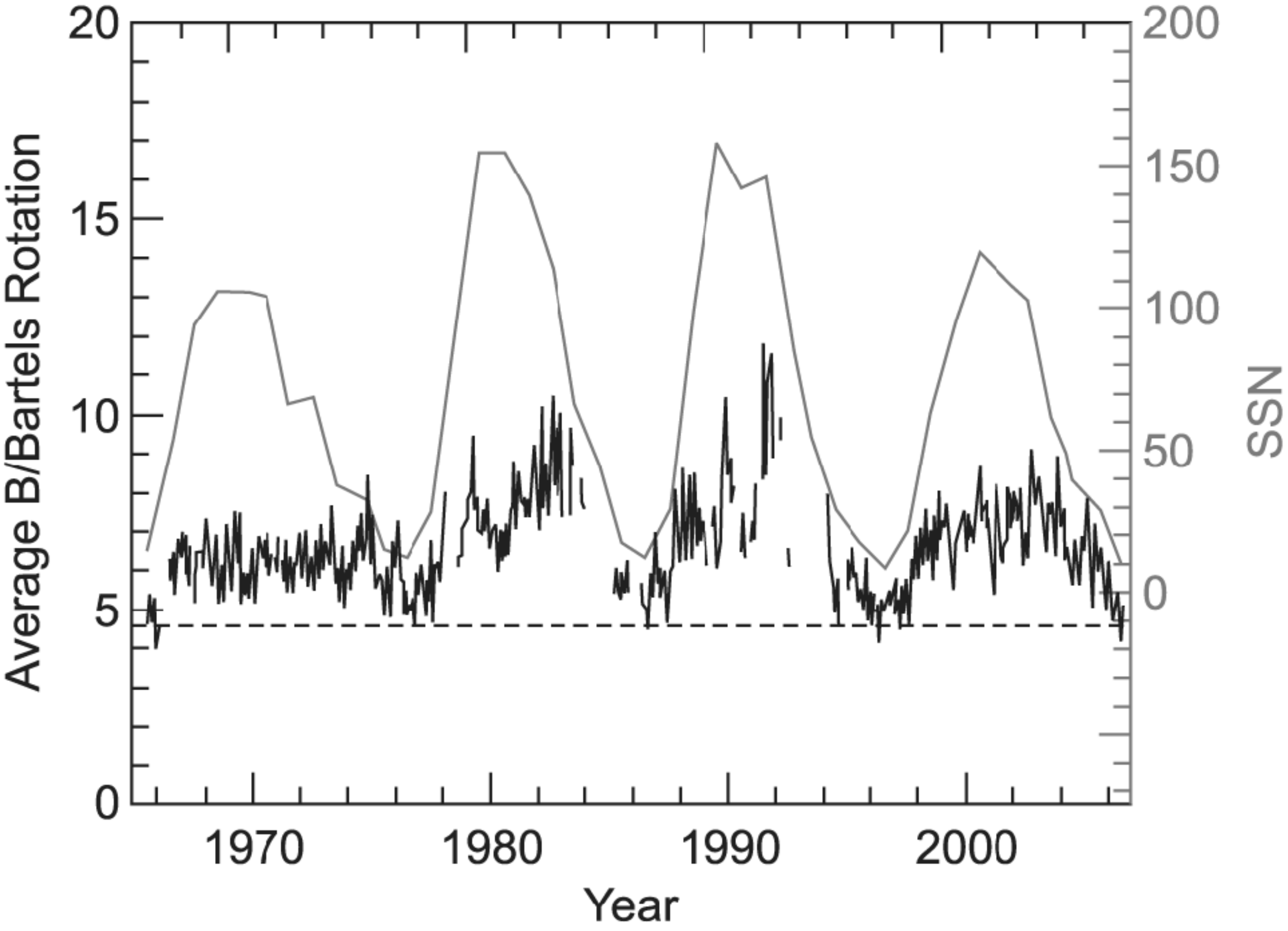
LONG TERM VARIATION

He/H through two solar minima



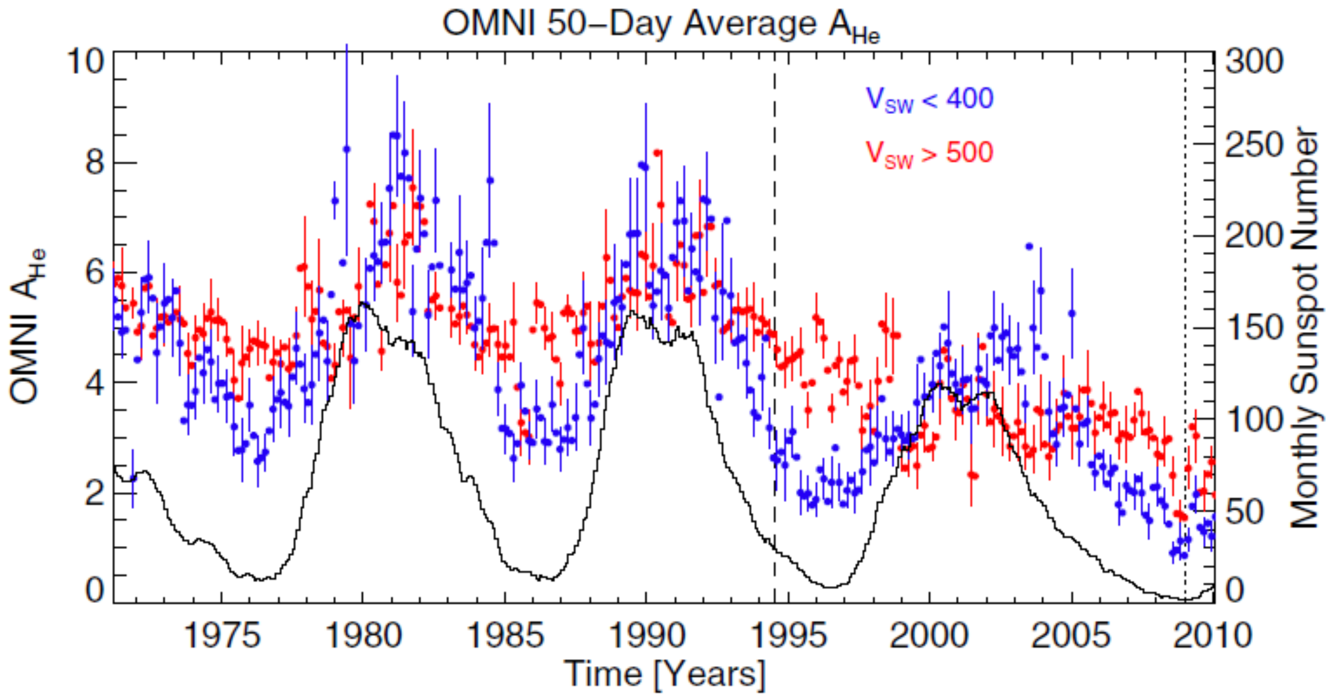
Kasper et al. (2012)

Magnetic flux in heliosphere



Long term solar wind trends

- Link with charge state variation over solar cycle, predict using measured mass flux
- Link to solar conditions (e.g. do small supergranular length scales produce low A_{He}?)

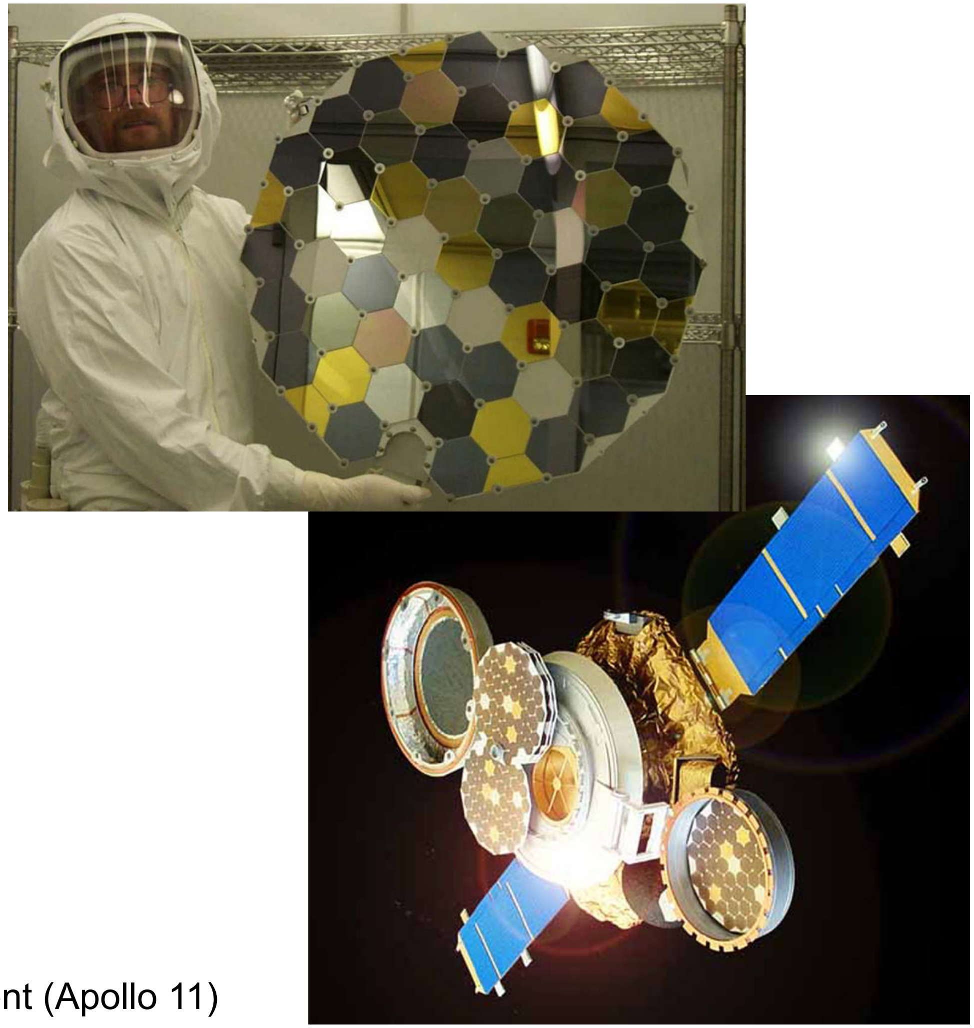


McIntosh et al. (2011)

Rare solar wind elements and isotopes

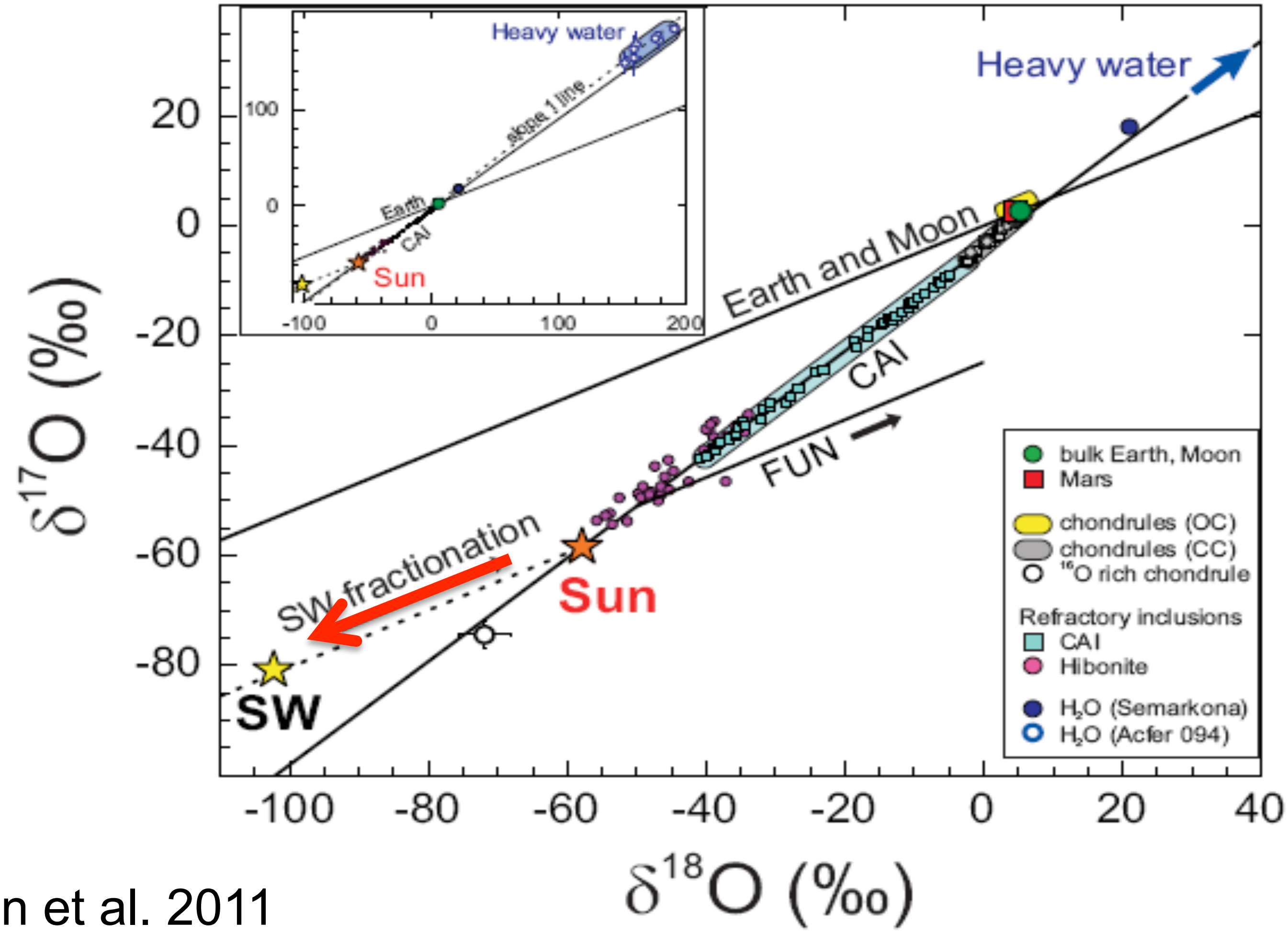
Buzz Aldrin and Solar Wind Composition Experiment (Apollo 11)

Genesis mission (2001-2004)



Sun and planets had different origins

Part per 1000 differences in $^{17}O/^{16}O$ and $^{18}O/^{16}O$ relative to standard sample



McKeegan et al. 2011

Historical Resources

- DeVorkin, David H. "Solar Physics from Space," in Exploring the Unknown: Selected Documents in the History of the U. S. Civil Space Program, John Logsdon, ed., vol. 6: Space and Earth Science (Washington, D.C.: NASA SP-4407, 2004), pp. 1-36.
- Hufbauer, Karl. Exploring the Sun: Solar Science since Galileo (Baltimore and London: Johns Hopkins University Press, 1991).
- Naugle, John. First Among Equals, http://www.hq.nasa.gov/pao/History/SP-4215/toc.html
- Neugebauer, M., Pioneers of space physics: A career in the solar wind, J. Geophys. Res., 1997, http://www.witi.com/center/witimuseum/halloffame/1997/mneugebauer_article.pdf