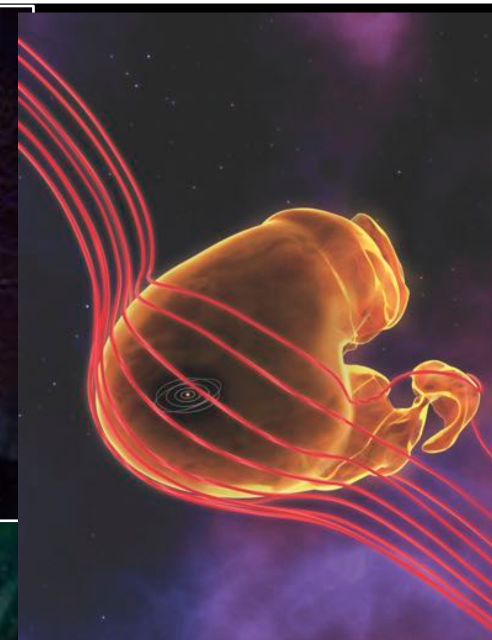
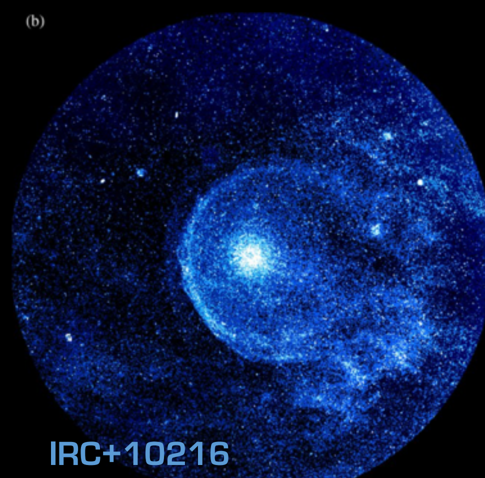
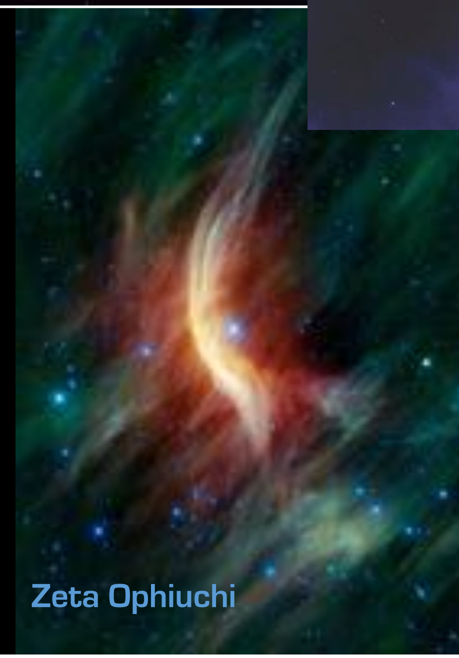
Structure of the Heliosphere- Part I

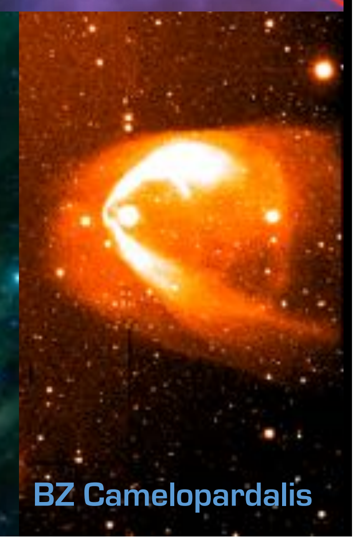
Merav Opher



Mira







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Outline of Class – Part I and Part II

- What is the heliosphere
- What are the main components of the heliosphere
- How do we measure characteristics of heliosphere
- Solar Wind
- Interplanetary Magnetic Field
- Behavior of Solar Wind at Large Distances
- Termination Shock/Heliosheath
- Some puzzles of what we don't know

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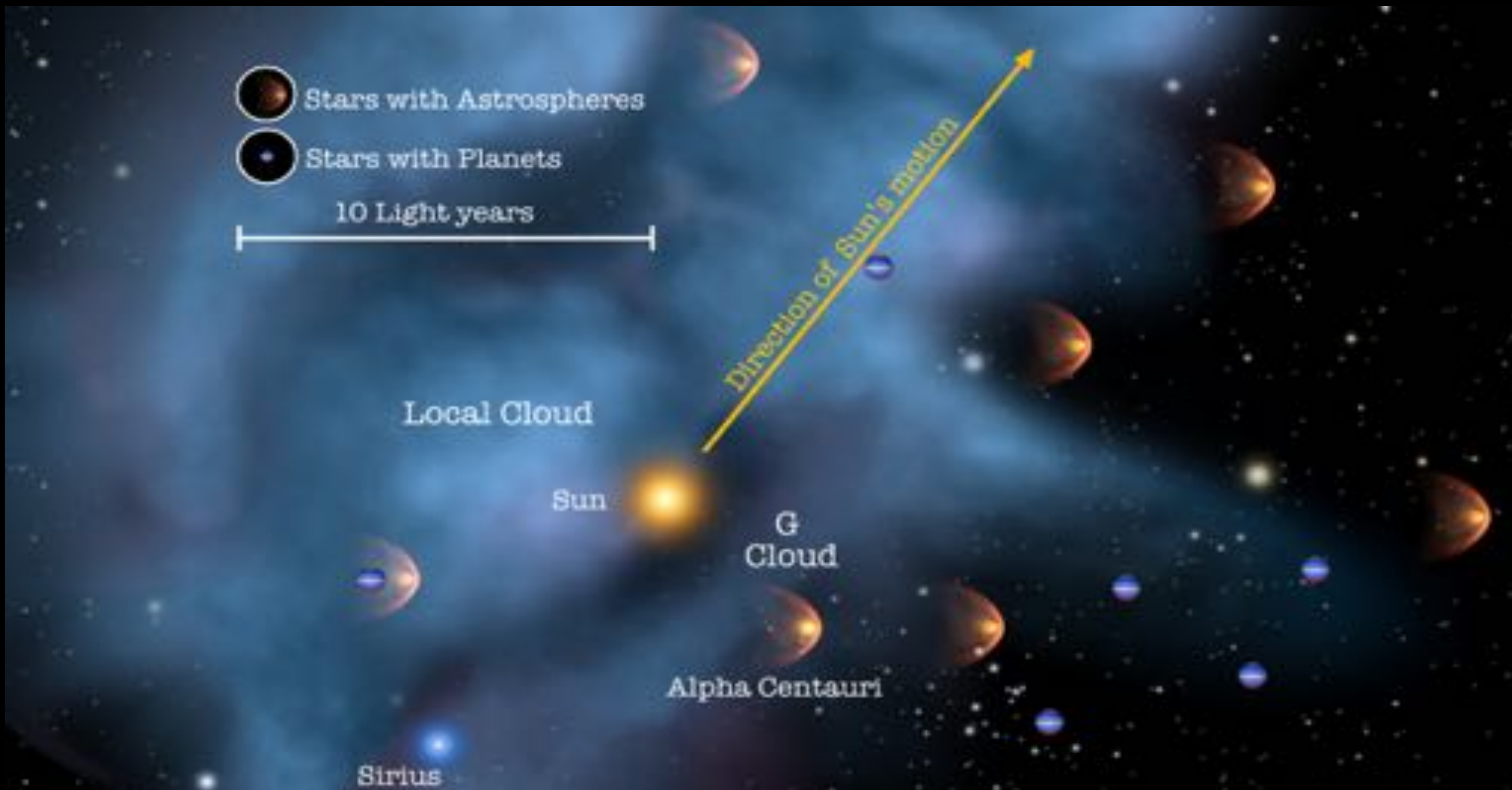
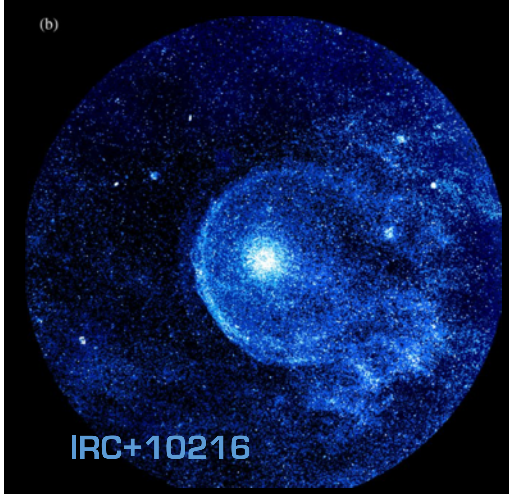
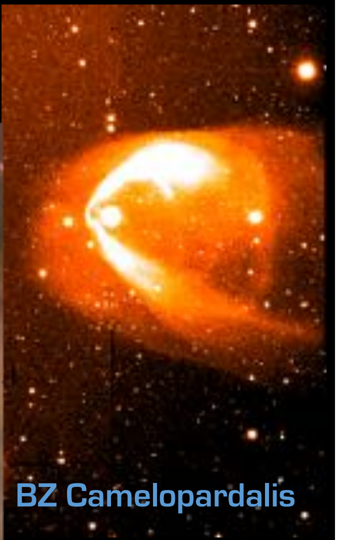
Stars have bubbles around them: astrospheres

Astrospheres Protect Life

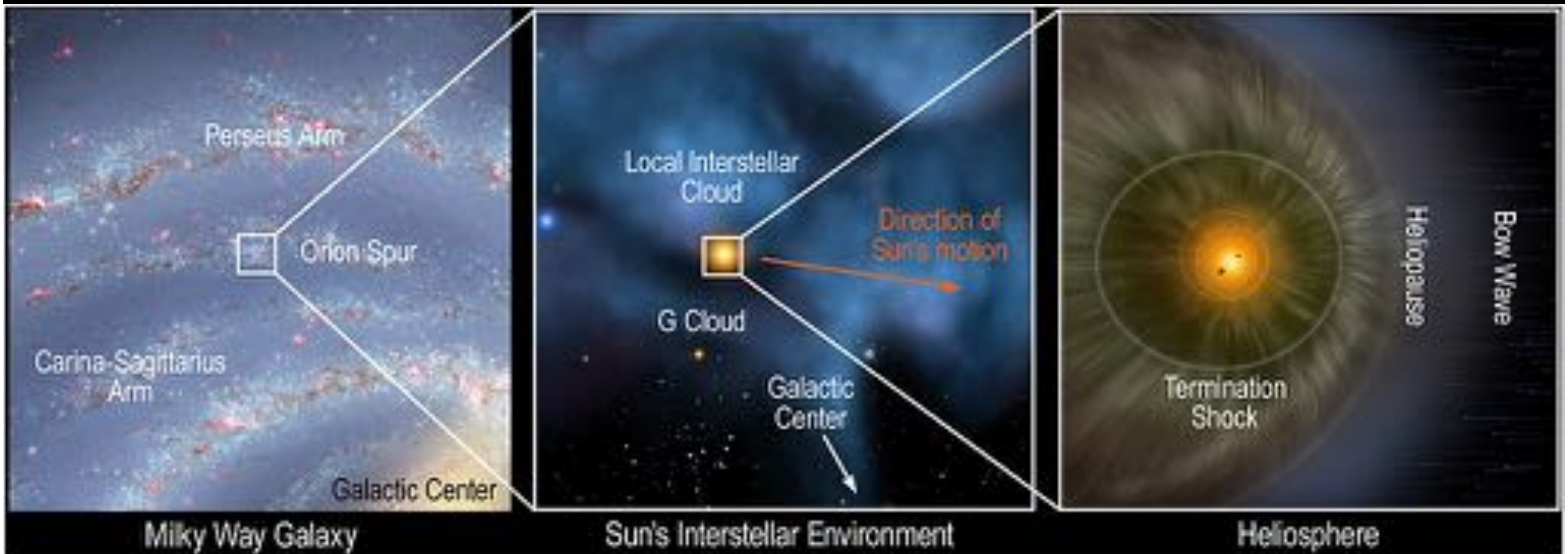


Heliosphere: the only known Habitable Astrosphere

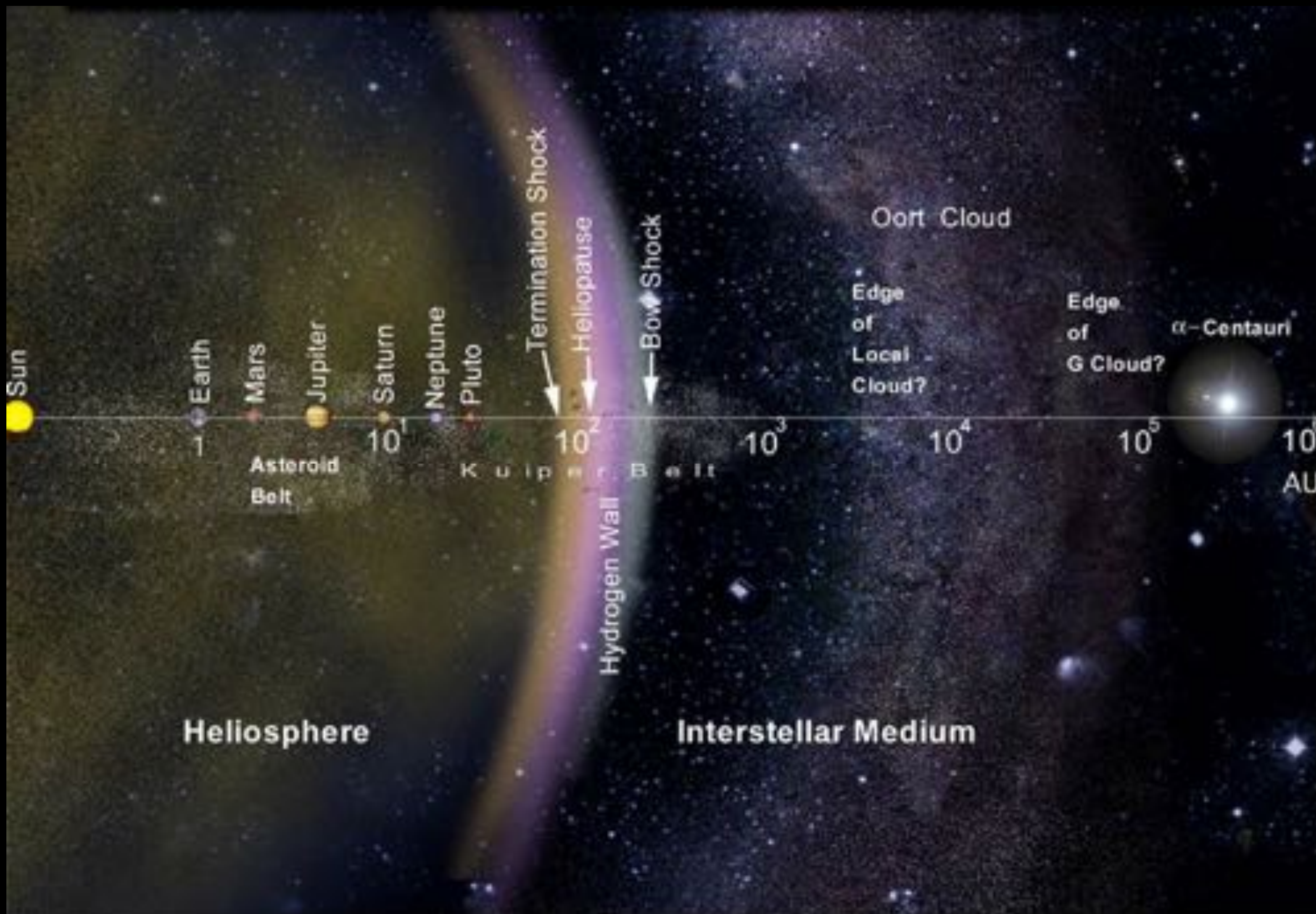




Our place in the Milky Way

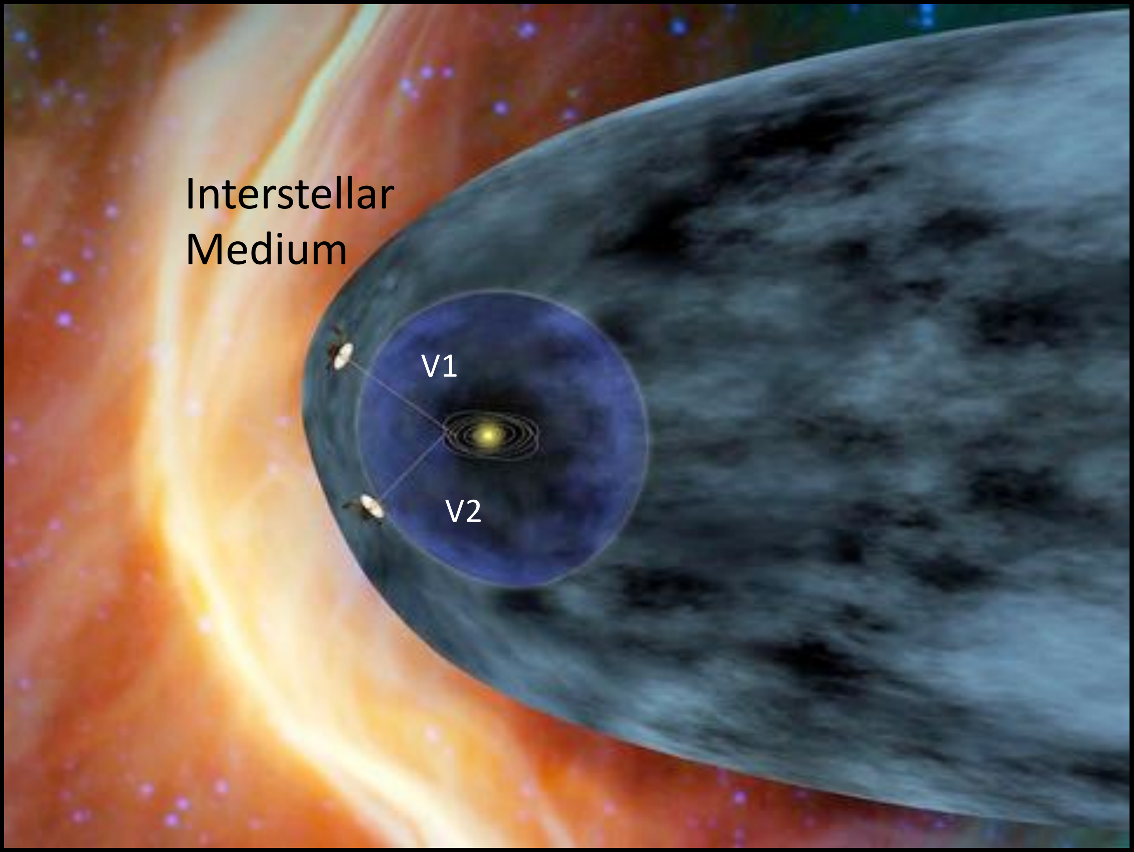


McComas et al. (2014)

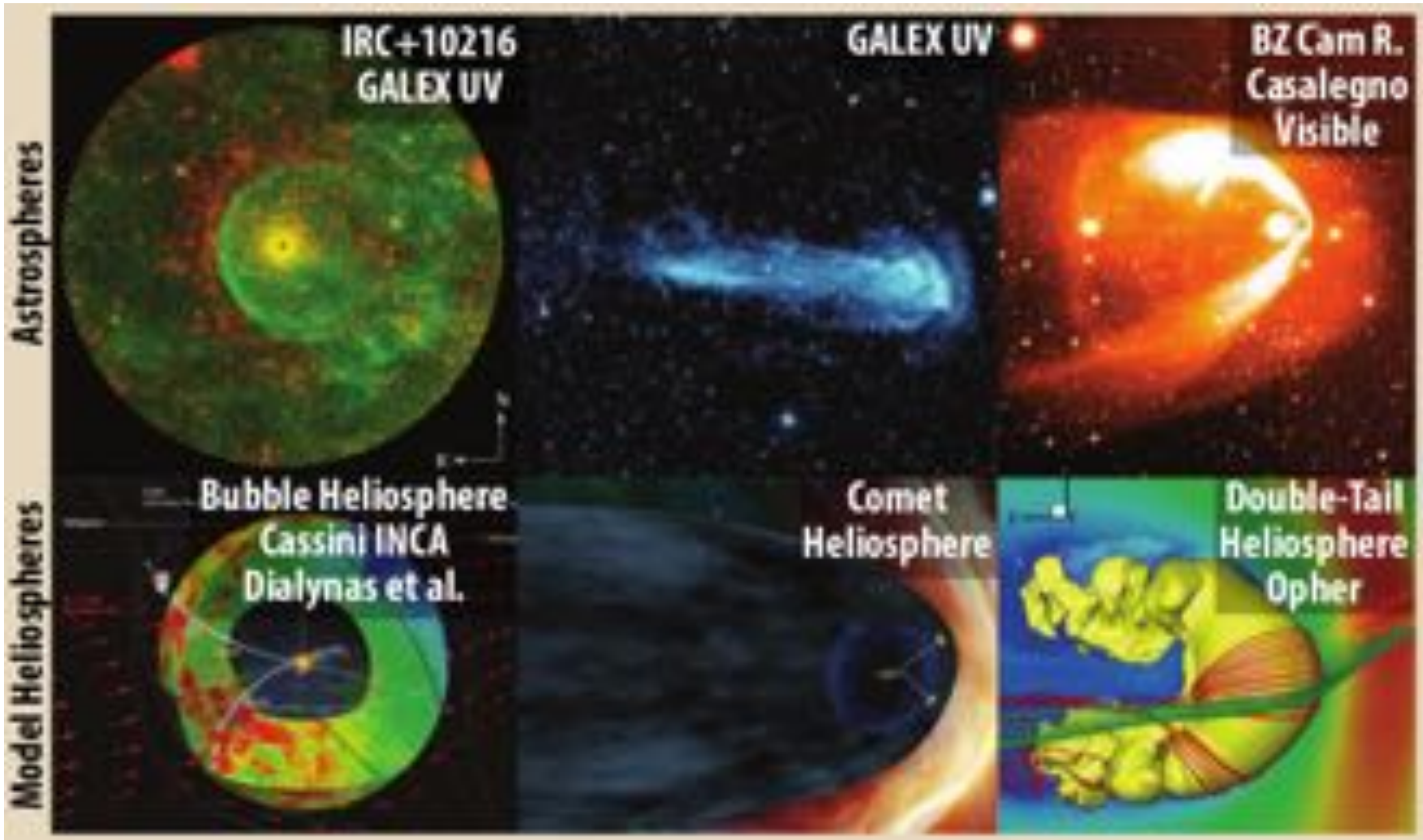


Sun
Earth
Mars
Jupiter
Saturn
Neptune
Pluto
Termination Shock
Heliopause
Bow Shock
Oort Cloud
Edge of Local Cloud?
Edge of G Cloud?
α-Centauri
1
10¹
10²
10³
10⁴
10⁵
10⁶
AU
Asteroid Belt
Kuiper Belt
Hydrogen Wall
Heliosphere
Interstellar Medium

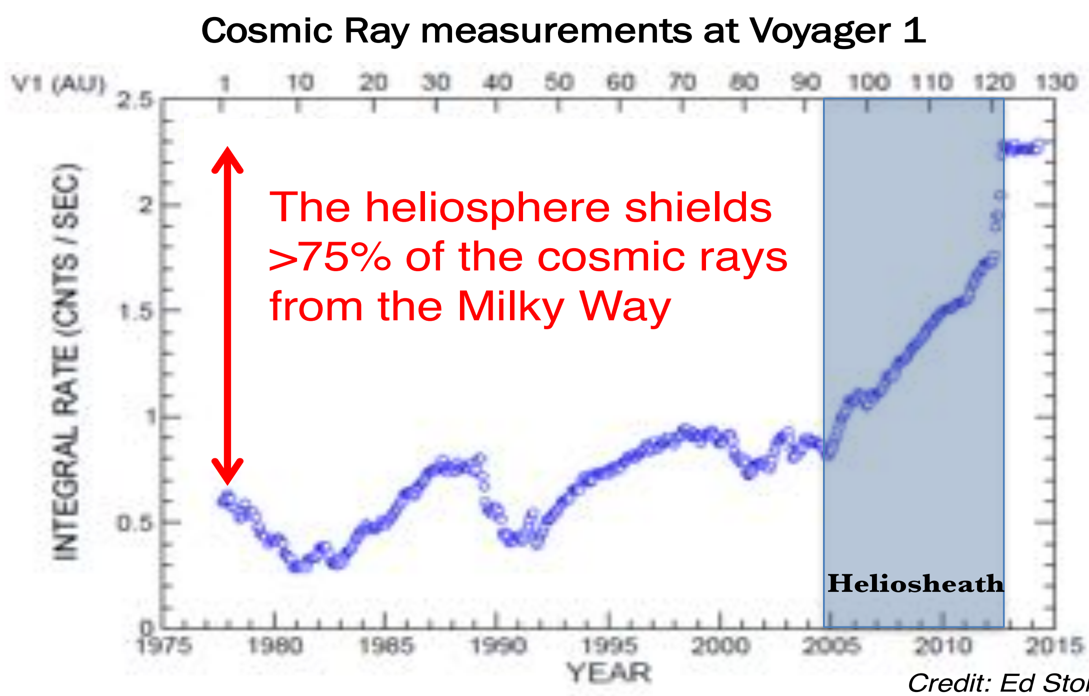
The solar wind carve a bubble in the interstellar medium



Different Views of the Heliosphere



The Heliosphere Shields 75% of Cosmic Rays (up to 1GeV)



Credit: Ed Stone

The shielding of cosmic rays by astrospheres is a fundamental, open question whose answer is critical to assessing the habitability of exoplanets.

First step is to understand the structure and the shielding properties of the Earth's Sun's heliosphere

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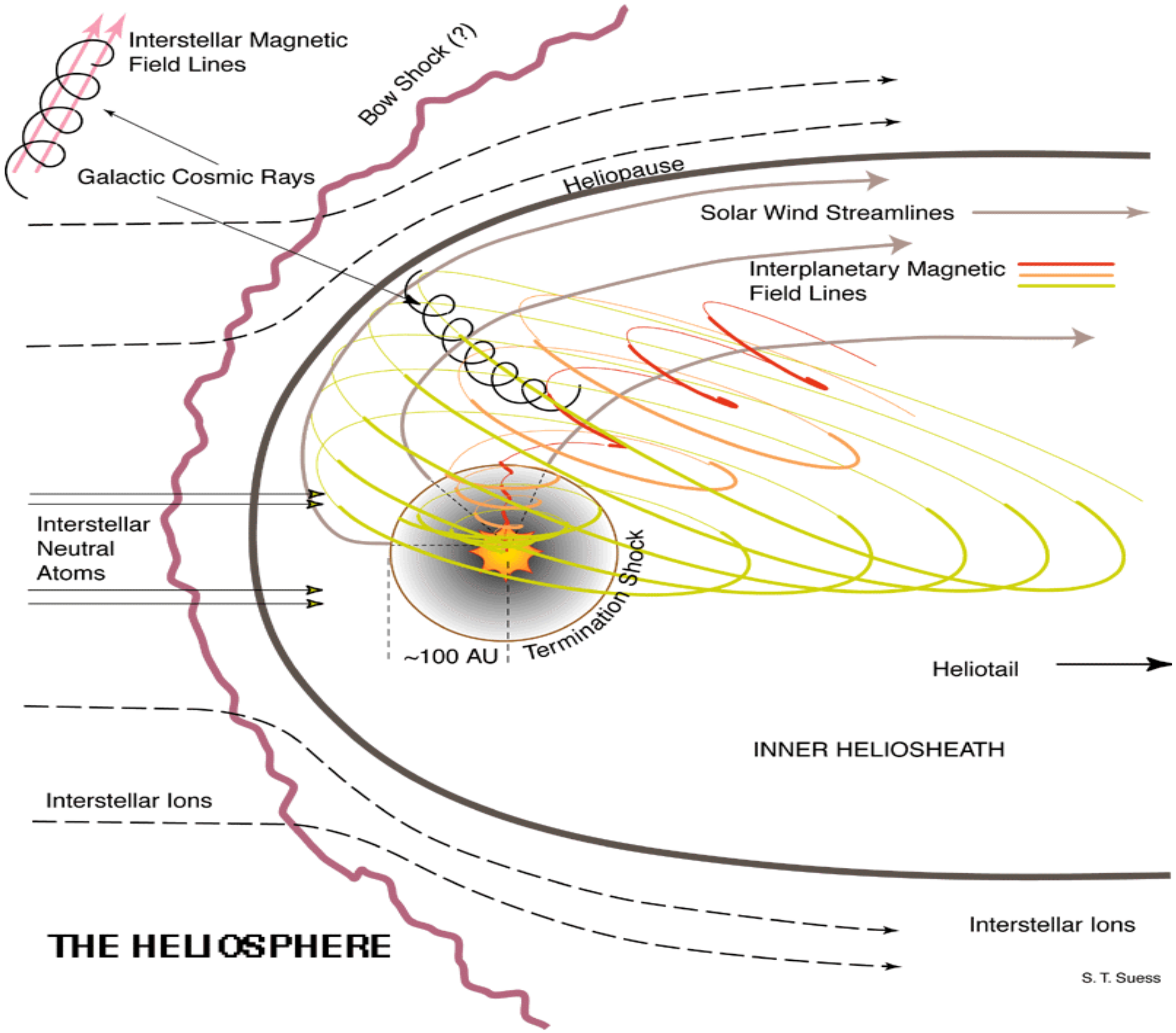


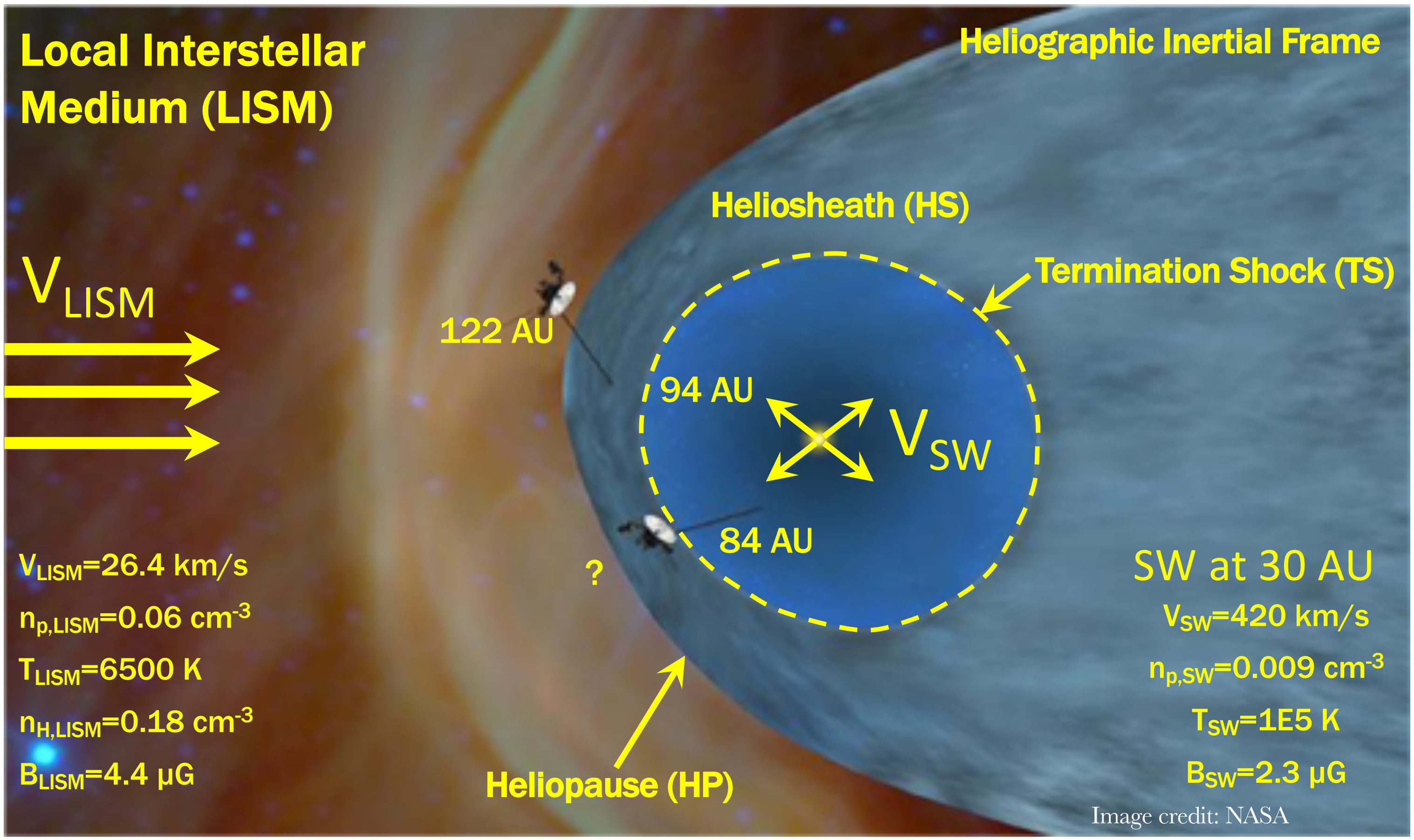
- Solar Wind (Ions + Electrons)
- Solar Magnetic Field

- Interstellar Magnetic Field
- Galactic Cosmic Rays
- Interstellar Neutrals

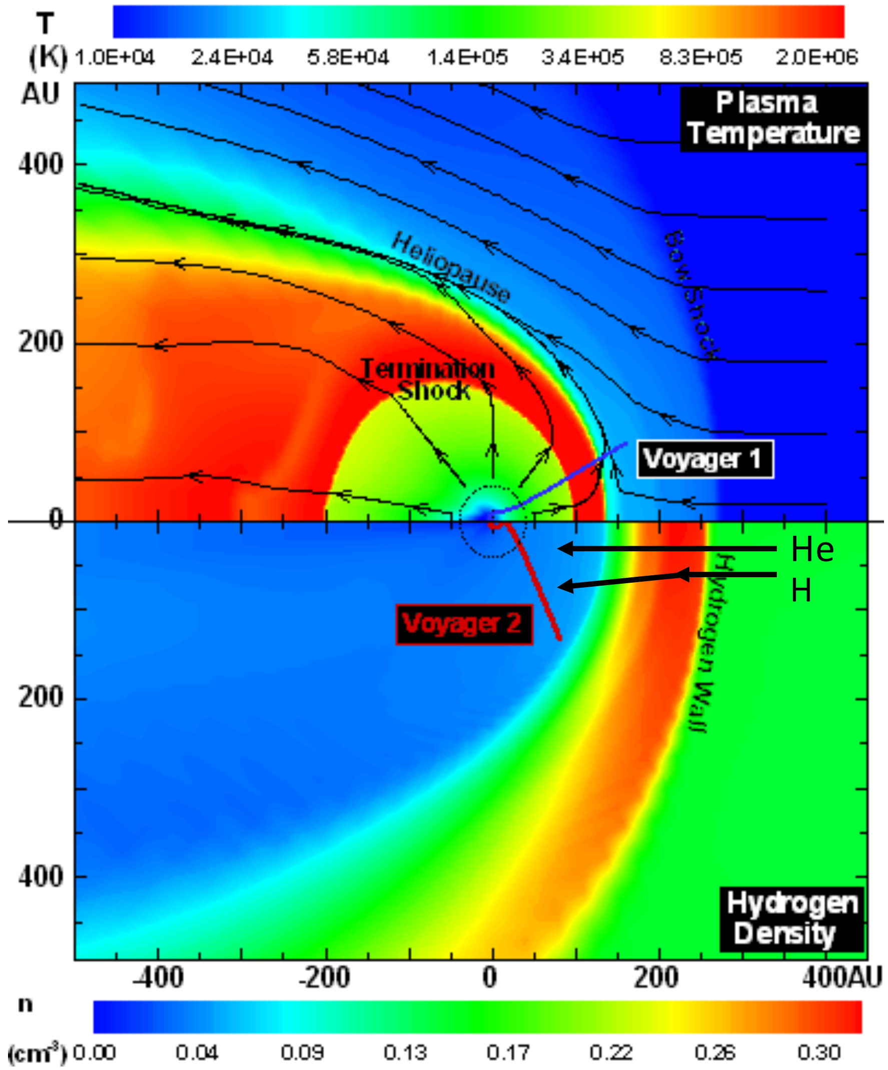
That become

- Pick-up ions (PUIs)

The Structure of the Heliosphere



Interstellar neutrals



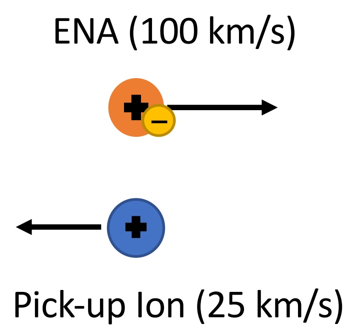
LIC neutrals are not bound by magnetic fields; some enter the heliosphere.

LIC H is tied to plasma via charge exchange.

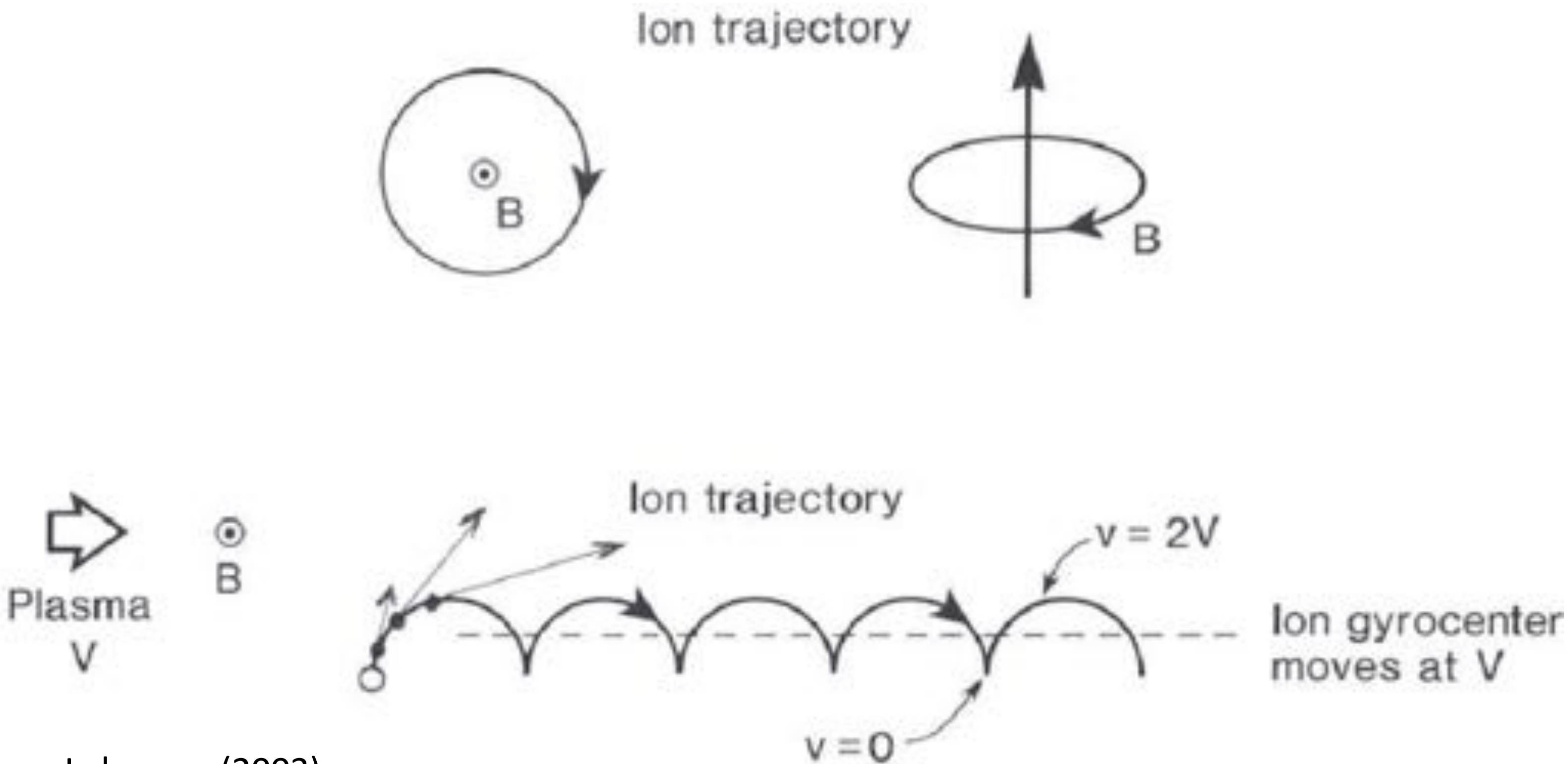
Mueller et al.

Creating an ENA: Charge Exchange

Creating an ENA: Charge Exchange



Creating an ENA: Pick-up Ions (PUIs)



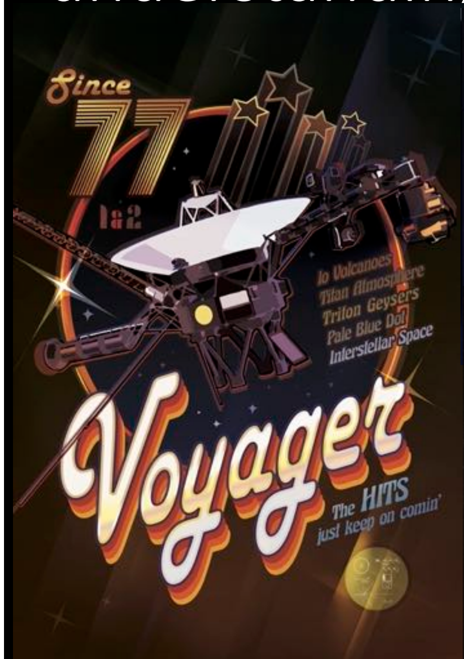
Luhmann (2003)

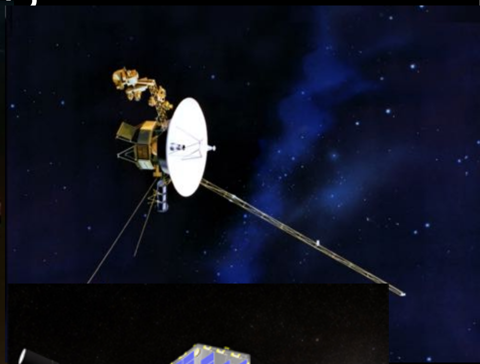
Heliopause: Boundary between solar plasma and interstellar plasma

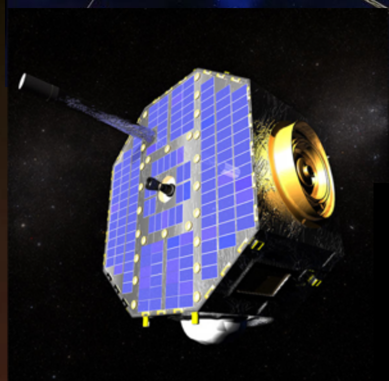
Where is it?
Pressure Balance:

- Solar Wind: $P = MnV^2\,(1\ \mathrm{AU})/R_{HP}{}^2$
- $P(LIC) = MnV^2 + P(mag) + P(particles)$

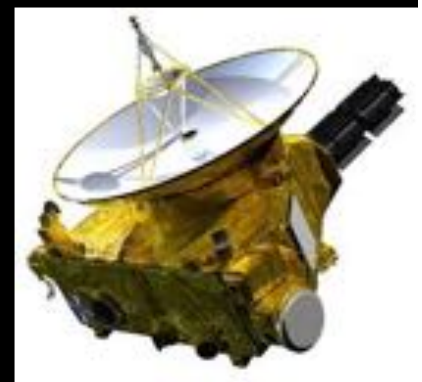
Space science is at a pivotal point of generating new understandings of the heliosphere

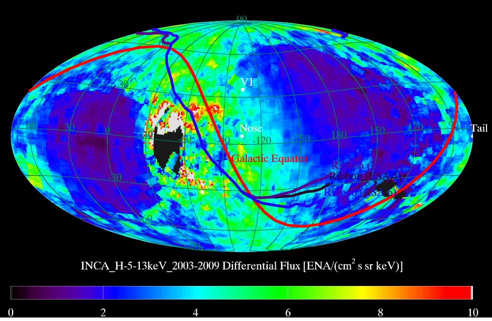


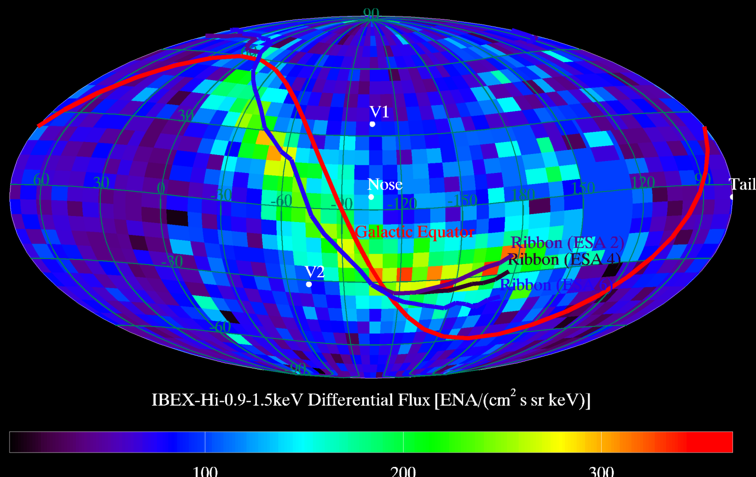


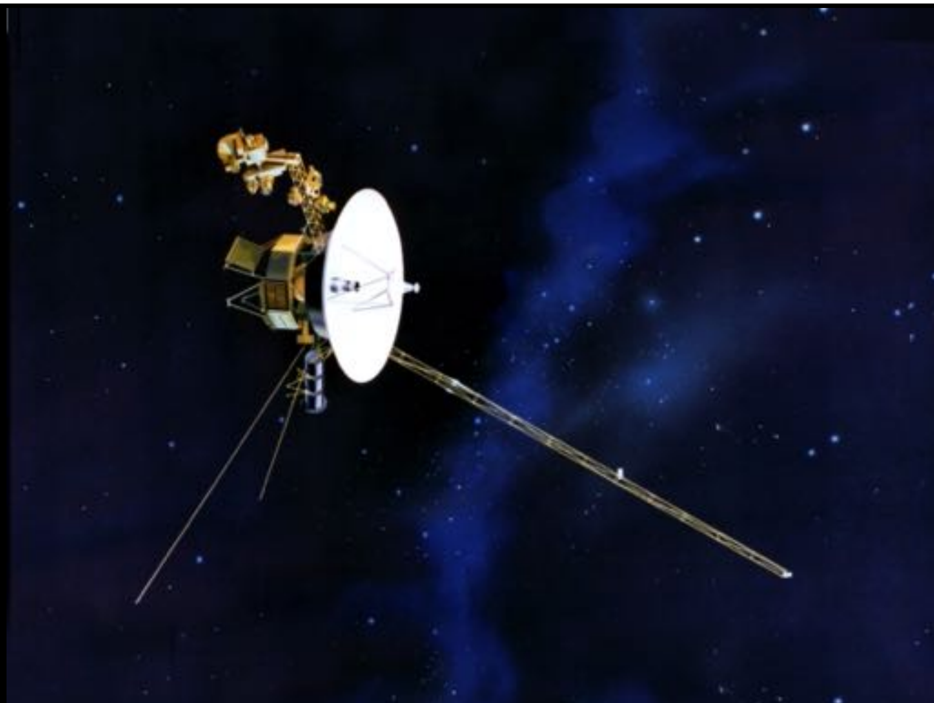


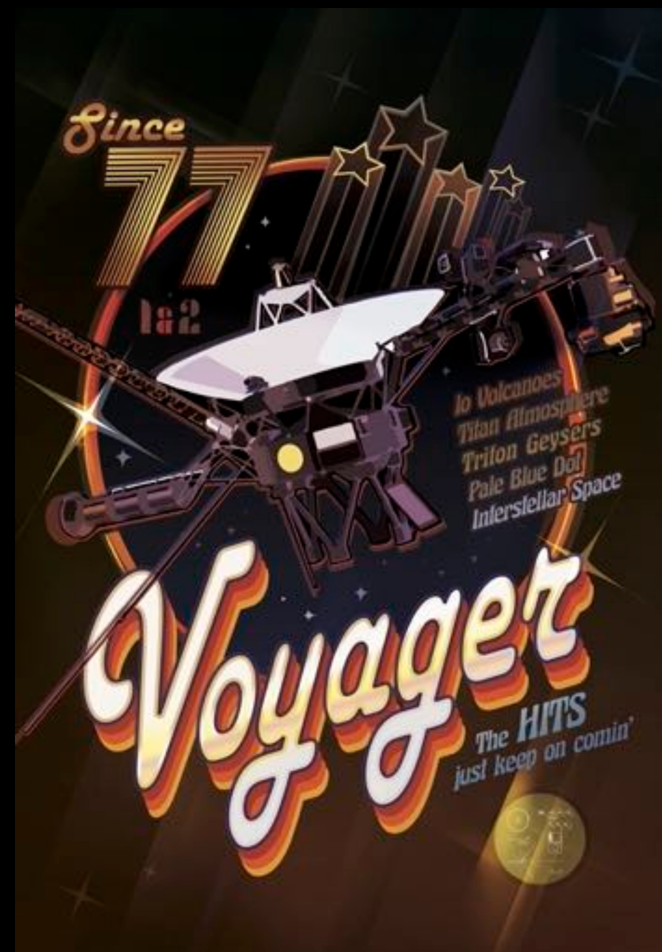
New data from
Voyager, IBEX, Cassini, New Horizons



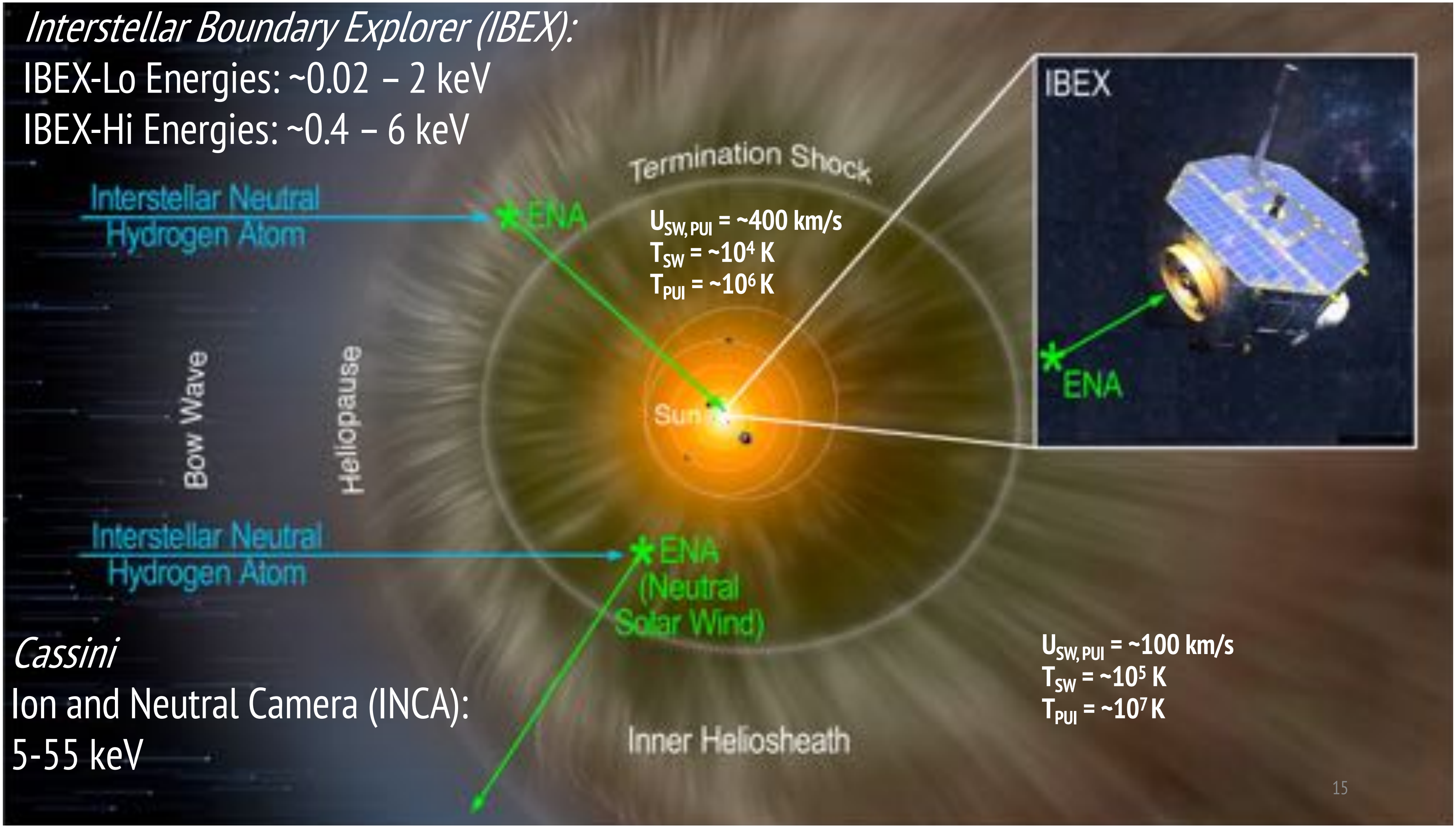




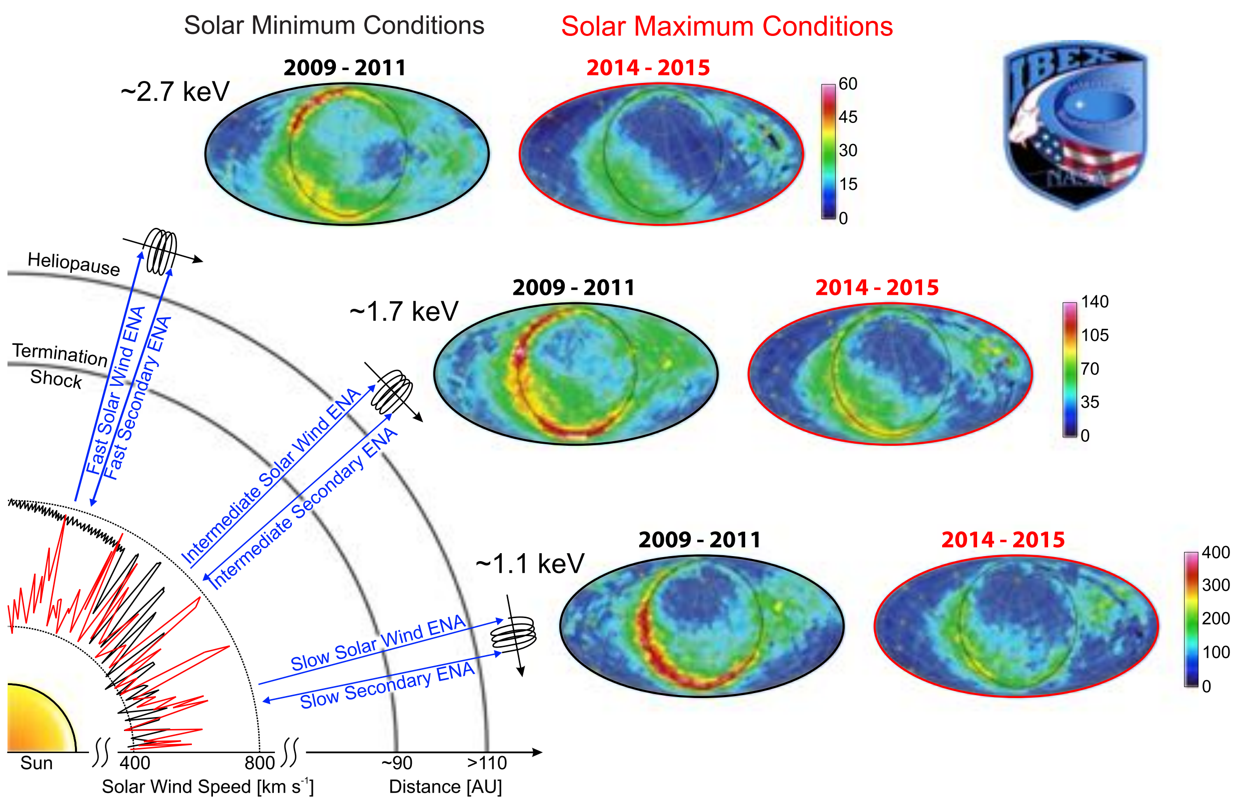




Voyagers 1 and 2:
Launched Sept 5 and Aug 20, 1977:
40 years old
At 140 AU and 115 AU (~17 light hours)
We receive 8-12 hours of data/day


Interstellar Boundary Explorer (IBEX):
IBEX-Lo Energies: ~0.02 – 2 keV
IBEX-Hi Energies: ~0.4 – 6 keV
Termination Shock
Interstellar Neutral Hydrogen Atom
ENA
$U_{SW, PUI}$ = ~400 km/s
T_{SW} = ~10^4 K
T_{PUI} = ~10^6 K
IBEX
ENA
Bow Wave
Heliopause
Sun
Interstellar Neutral Hydrogen Atom
ENA (Neutral Solar Wind)
Cassini
Ion and Neutral Camera (INCA):
5-55 keV
Inner Heliosheath
$U_{SW, PUI}$ = ~100 km/s
T_{SW} = ~10^5 K
T_{PUI} = ~10^7 K

With ENA maps we can see the Heliosphere Evolve in Time



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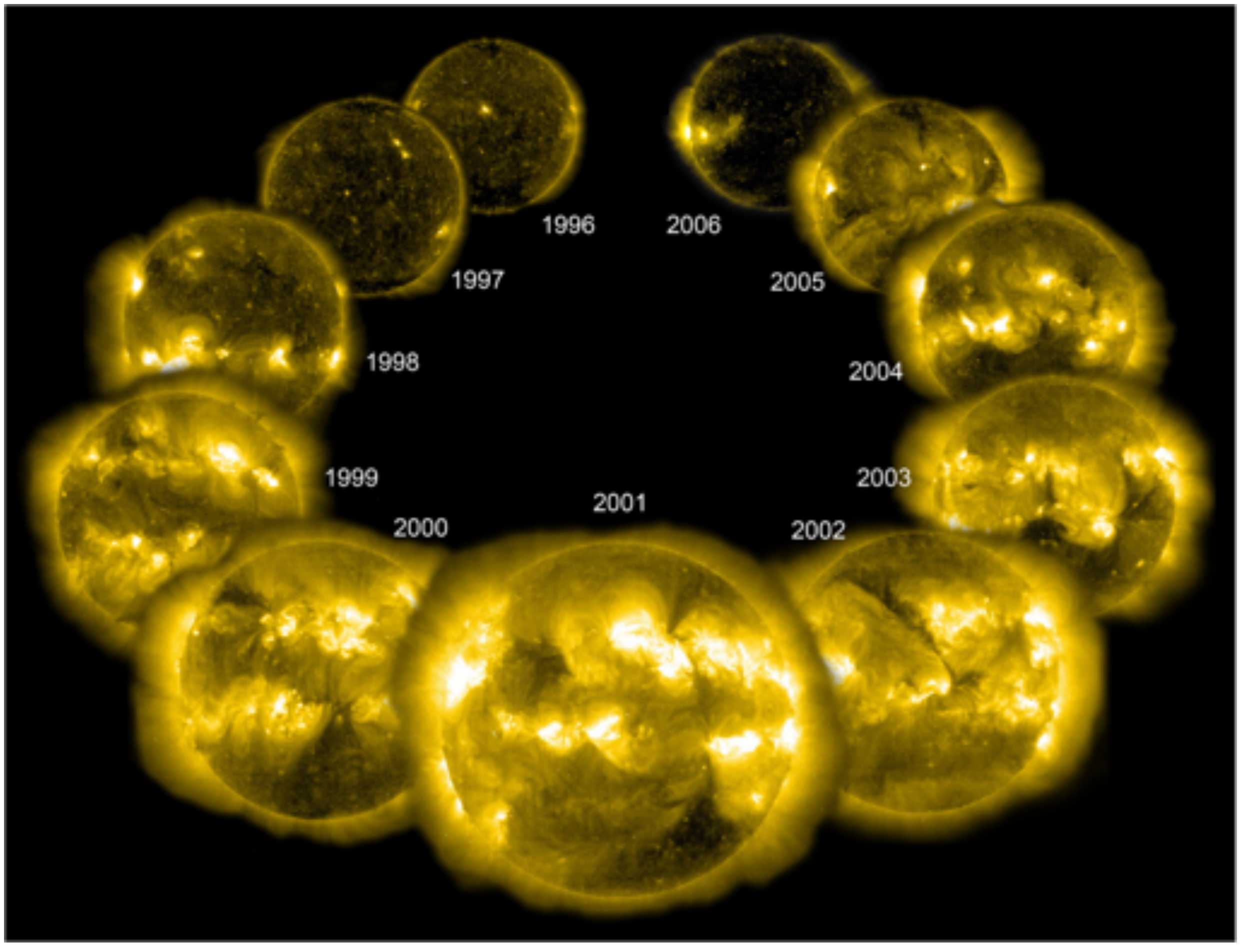
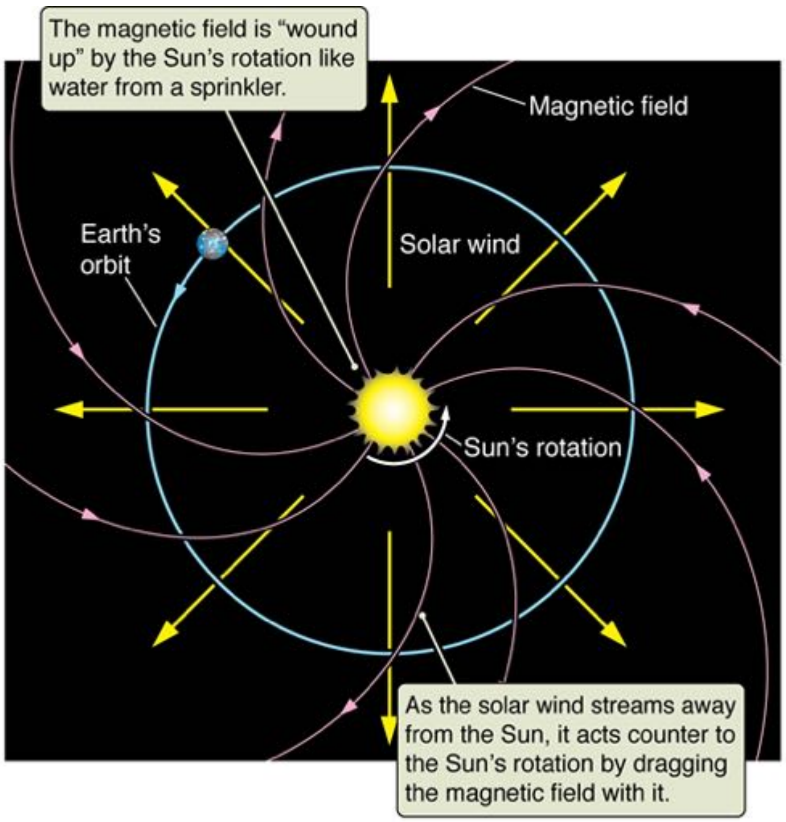
Coronal Changes Over the Solar Cycle

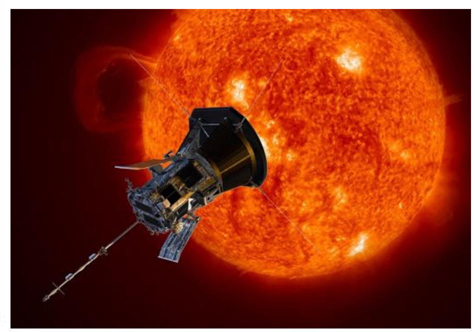


The Solar Wind



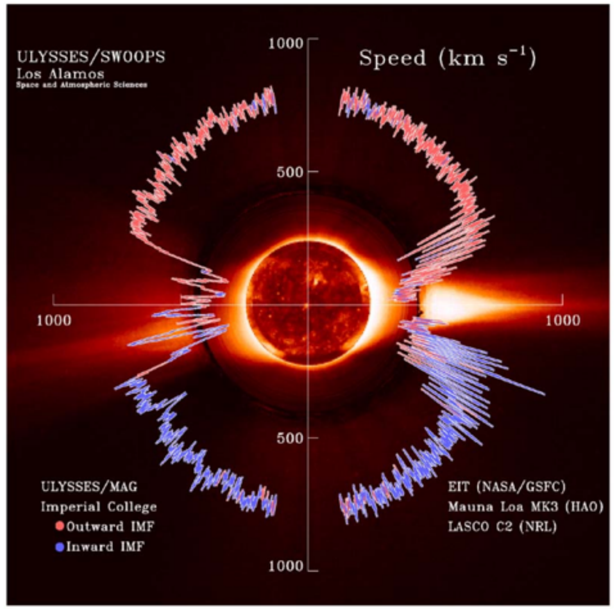
Eugene Parker

Marcia Neugebauer



Parker Solar Probe

Solar Wind: Bi-Modal Structure



Property (1 AU) Slow Wind Fast Wind

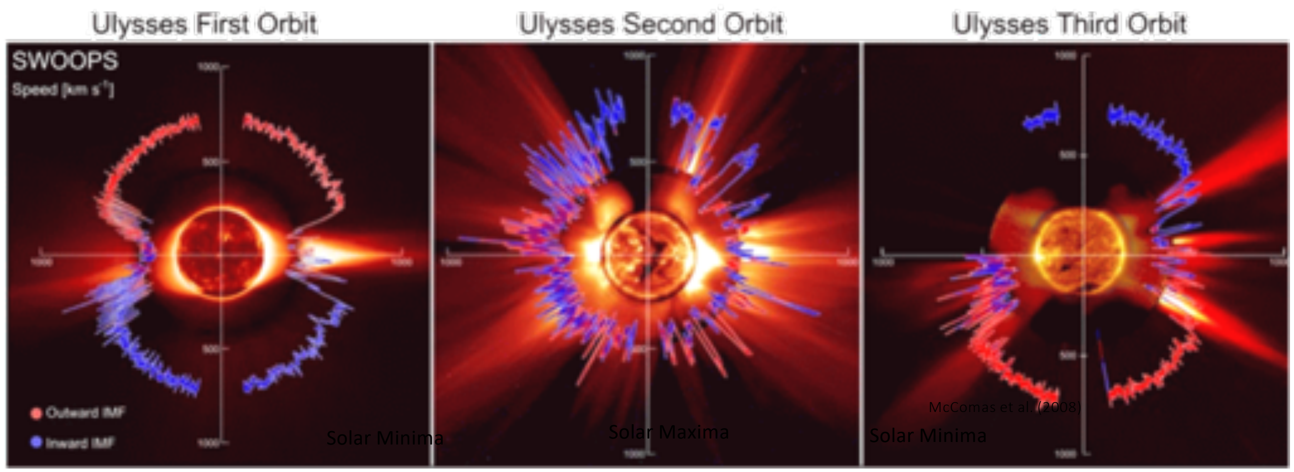
Flow Speed 400 km/s 750 km/s

Density 7 cm^{-3} 3 cm^{-3}

Variance "large", >50% Variance "small", <50%

Temperature T(proton, 1AU) ~ 200,000 K T(proton, 1 AU) ~ 50,000 K

Fast and slow solar wind



The magnetic field becomes much more complex in solar maxima

Solar Wind

First theory of an extended corona (hot atmosphere of 10^6 K of the sun) was done by Chapman (1957): Static atmosphere with energy transfer by conduction alone.

The mathematical theory was put forward by Eugene Parker (Astrophysical Journal 1958) –notes attached

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.

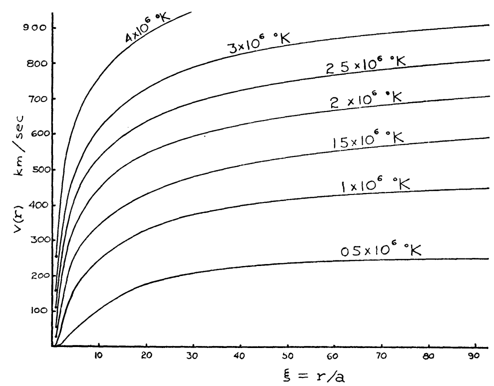
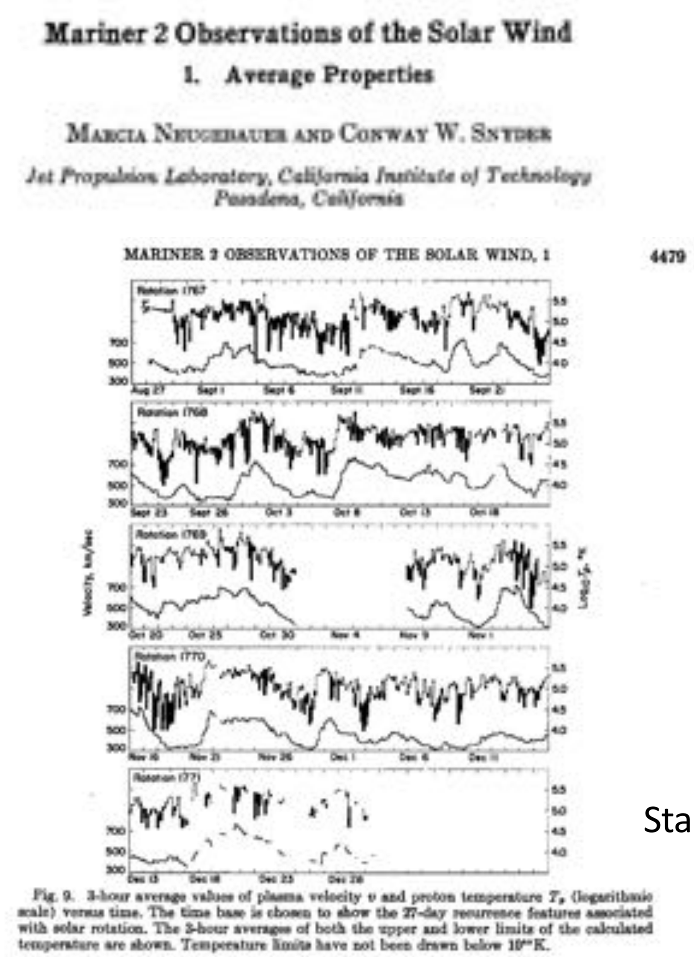


FIG. 1 —Spherically symmetric hydrodynamic expansion velocity $v(r)$ of an isothermal solar corona with temperature T_0 plotted as a function of r/a, where a is the radius of the corona and has been taken to be 10^{11} cm

Parker prediction of a wind of~ 400km/s was very controversial until Mariner 2 measured it.



Mariner 2 Observations of the Solar Wind

1. Average Properties

MARCIA NEUGEBAUER AND CONWAY W. SNYDER

Jet Propulsion Laboratory, California Institute of Technology
Pasadena, California

MARINER 2 OBSERVATIONS OF THE SOLAR WIND, 1 4479

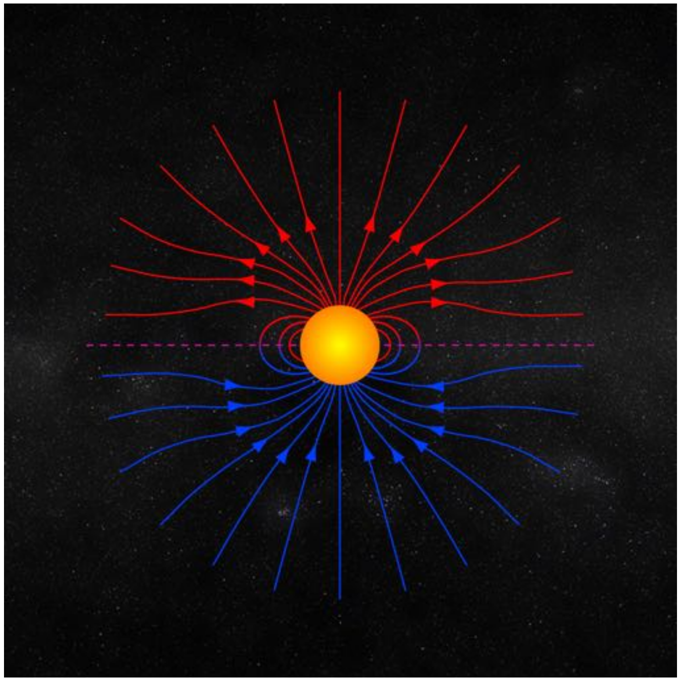
Fig. 9. 3-hour average values of plasma velocity v and proton temperature T_p (logarithmic scale) versus time. The time base is chosen to show the 27-day recurrence features associated with solar rotation. The 3-hour averages of both the upper and lower limits of the calculated temperature are shown. Temperature limits have not been drawn below $10^{4.0}$°K.

Stars have winds!

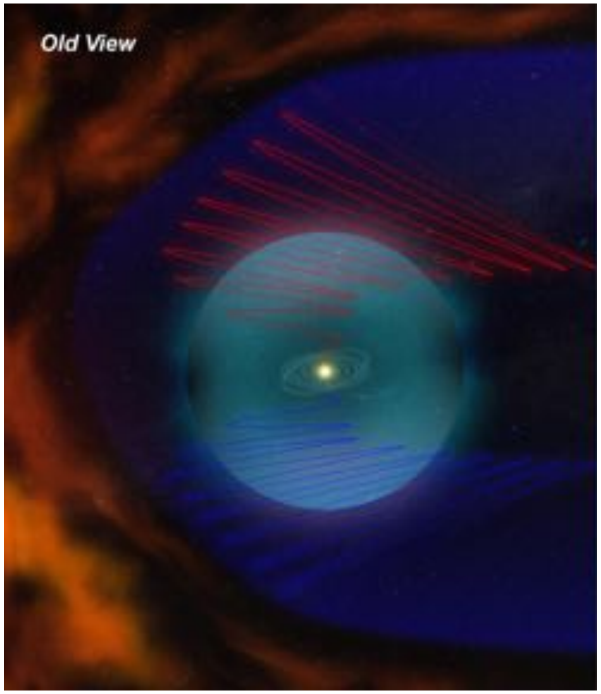
Mariner 2 data

Marcia Neugebauer

From the Sun to Interplanetary Space: Magnetic Field Structure

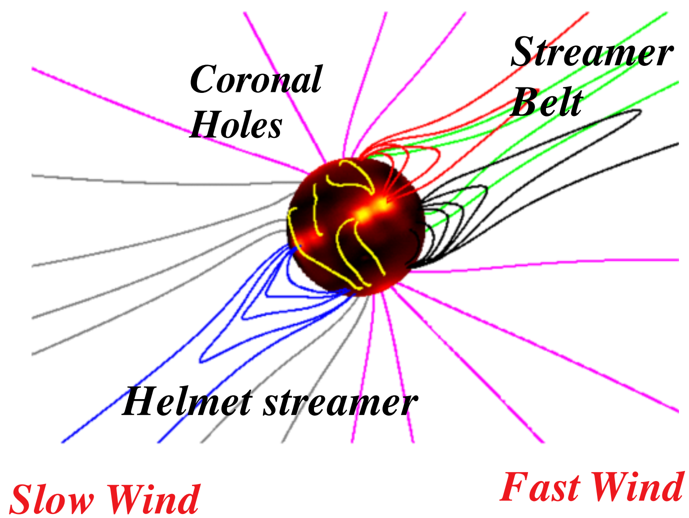


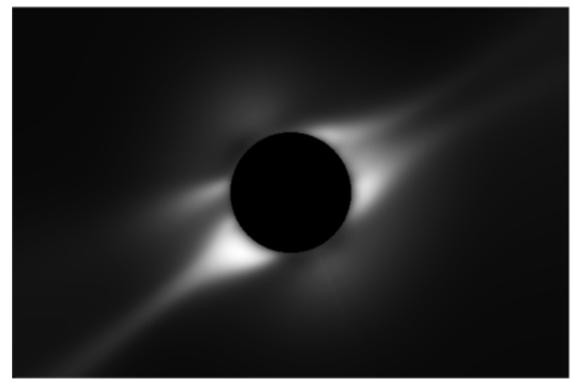
Near the sun



At large distances

Magnetic Structure of the Sun

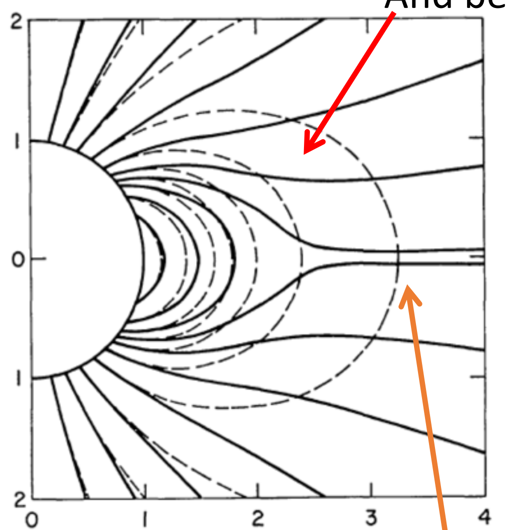




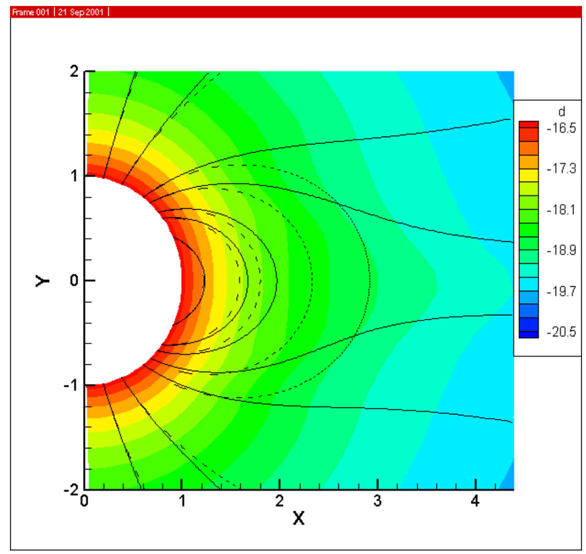
If you start with a dipole structure and turn on a wind, what will happen?

From a Dipole to Coronal Streamers

The lines are drawn outward by the plasma
And become open



Field lines
from opposite
polarities:
Heliospheric
Current Sheet



Initial State: solid lines-Dipole
Final State: dashed lines

MHD model Zeus-3D
(Asif ud-Duola, Stan Owcki)

Coronal plasma in static equilibrium: balance between
Pressure gradient and gravity

From Maxwell Equations: $\vec{\nabla} \cdot \vec{B} = 0$ in spherical coordinate system is

$$\vec{\nabla} \cdot \vec{B} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 B_r) + \frac{1}{r\sin\Theta}\frac{\partial B_\phi}{\partial \phi}$$

$$= \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 B_r) - \frac{(r - R_S)\Omega_S}{r u_{SW}}\frac{\partial B_r}{\partial \phi} = 0$$

And $\frac{\partial B_r}{\partial \phi} = 0$ Axisymmetric model so $\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 B_r) = 0$ that leads to $B_r(r) = B_S\left(\frac{R_S}{r}\right)^2$

Substi. In the expression of B we get:

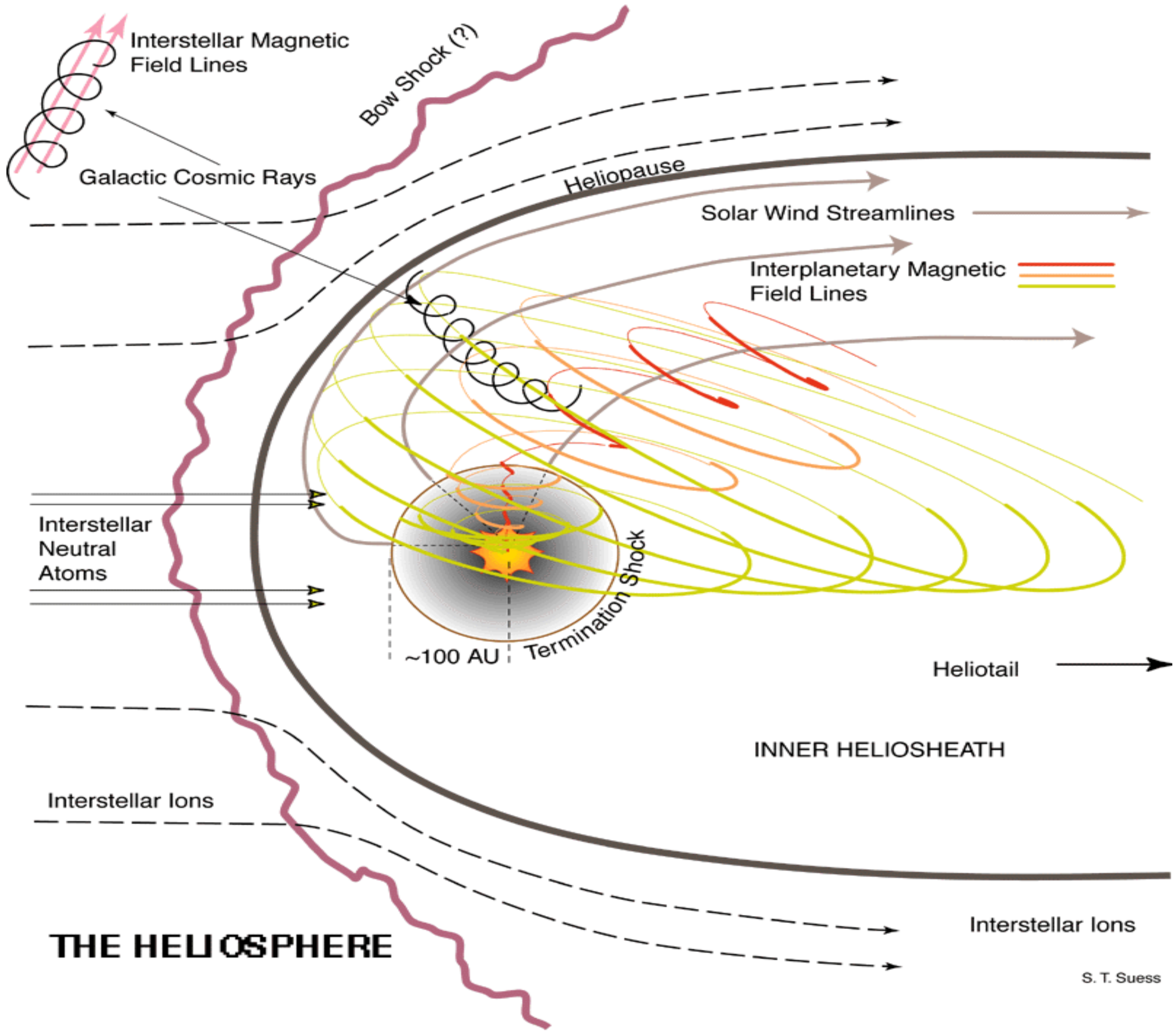
$$\vec{B} = B_S\left(\frac{R_S}{r}\right)^2 \vec{e}_r - B_s\left(\frac{R_S}{r}\right)^2 (r - R_S)\frac{\Omega_S \sin\Theta}{u_{SW}}\vec{e}_\phi$$

At large distance from the Sun $r \gg R_S$

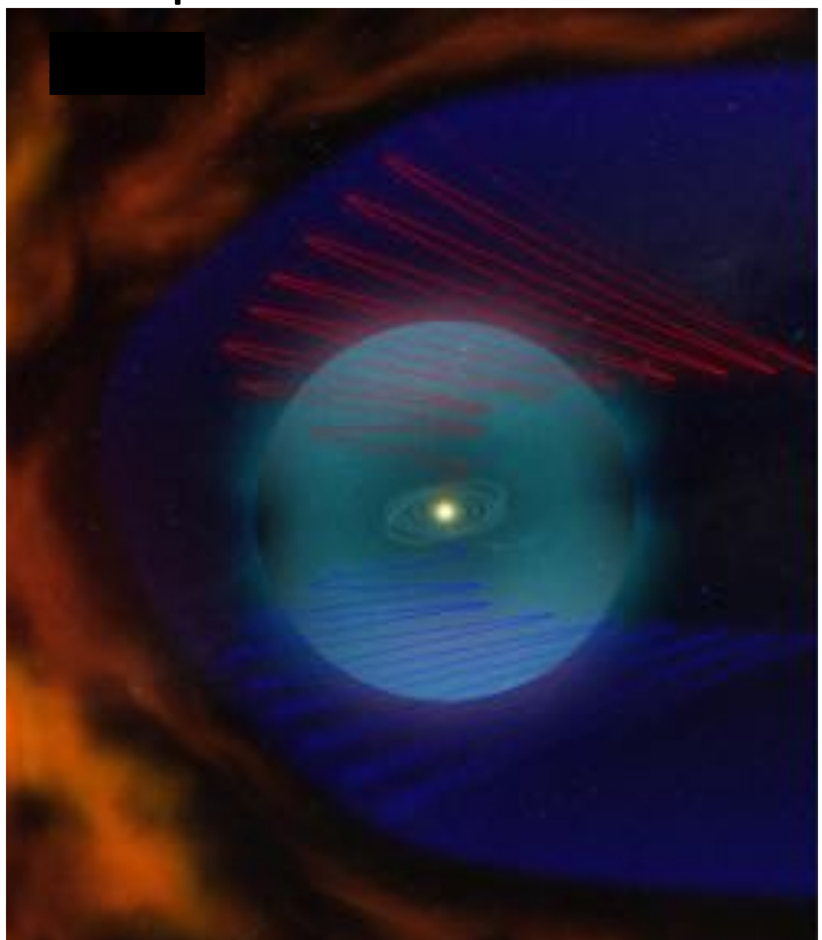
$$\vec{B} = B_S \left(\frac{R_S}{r} \right)^2 \vec{e}_r - B_s \left(\frac{R_S^2}{r} \right) \frac{\Omega_S \sin\Theta}{u_{SW}} \vec{e}_\phi$$

We can see that $B_r \propto r^{-2}$ and $B_\phi \propto r^{-1}$ (fall more slowly!)

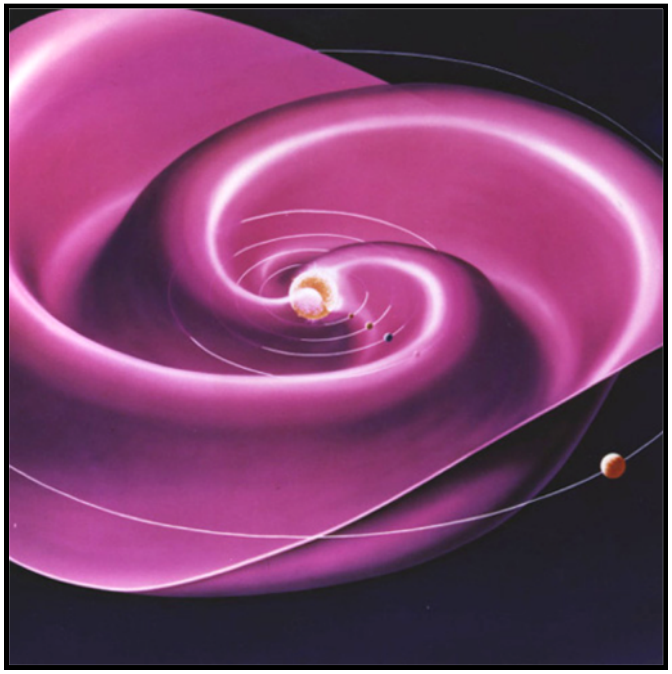
As we go outward in the solar system
the magnetic field becomes more and more
azimuthal

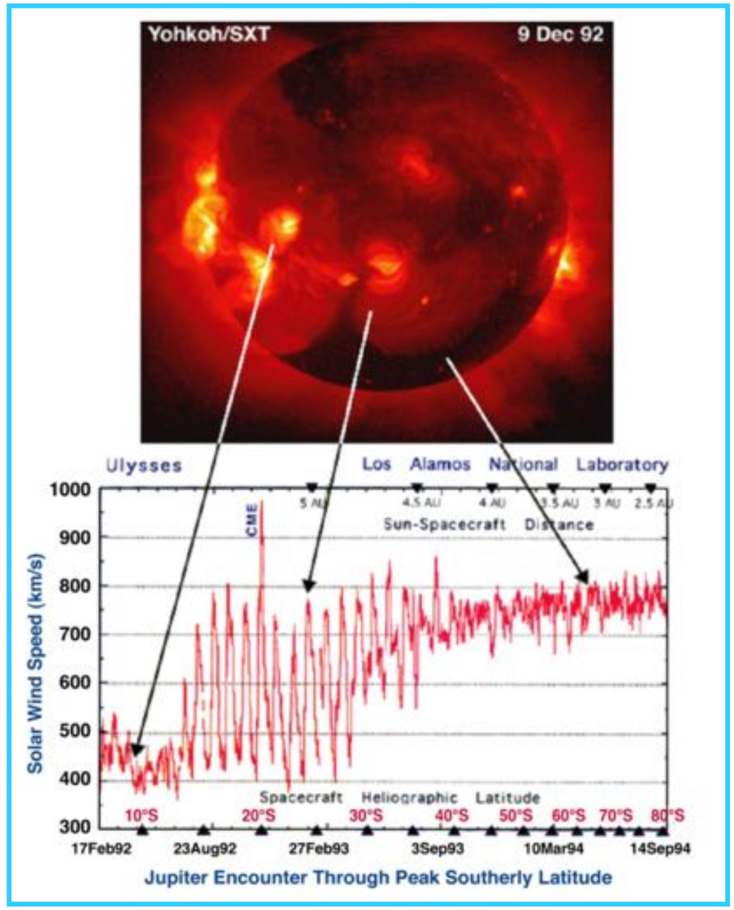

Interstellar Magnetic
Field Lines
Bow Shock (?)
Galactic Cosmic Rays
Heliopause
Solar Wind Streamlines
Interplanetary Magnetic
Field Lines
Interstellar
Neutral
Atoms
Termination Shock
~100 AU
Heliotail
INNER HELIOSHEATH
Interstellar Ions
Interstellar Ions
THE HELIOSPHERE
S. T. Suess

Our Heliosphere



The Heliospheric Current Sheet – “Ballerina Skirt”

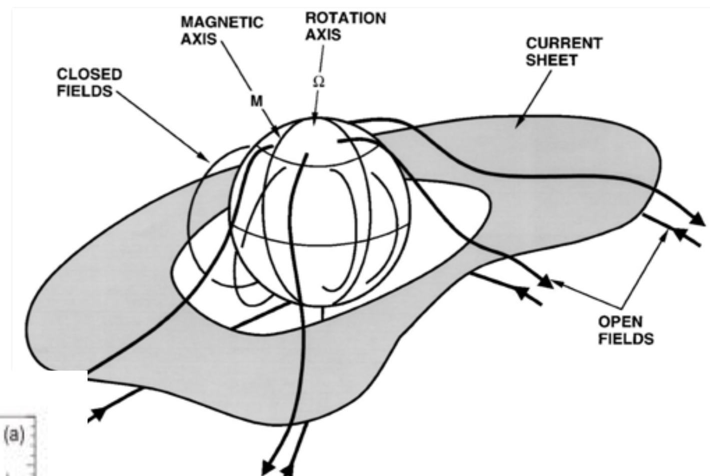


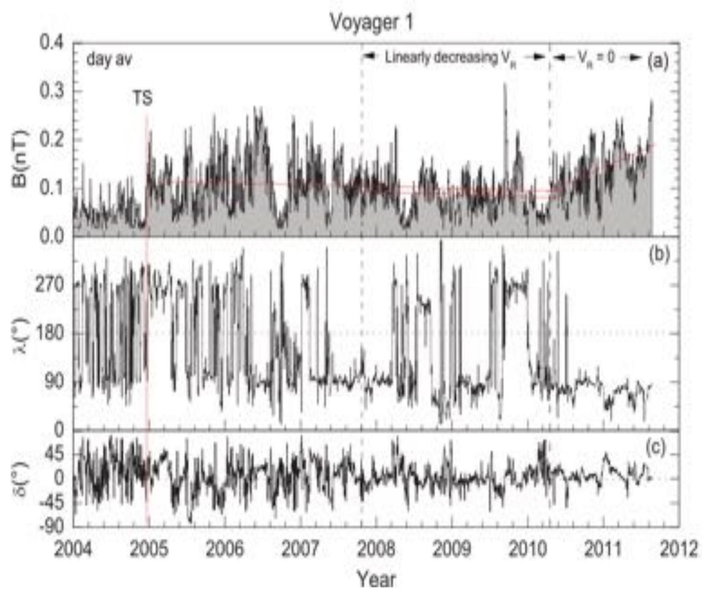


Not clear where the heliospheric Current sheet forms

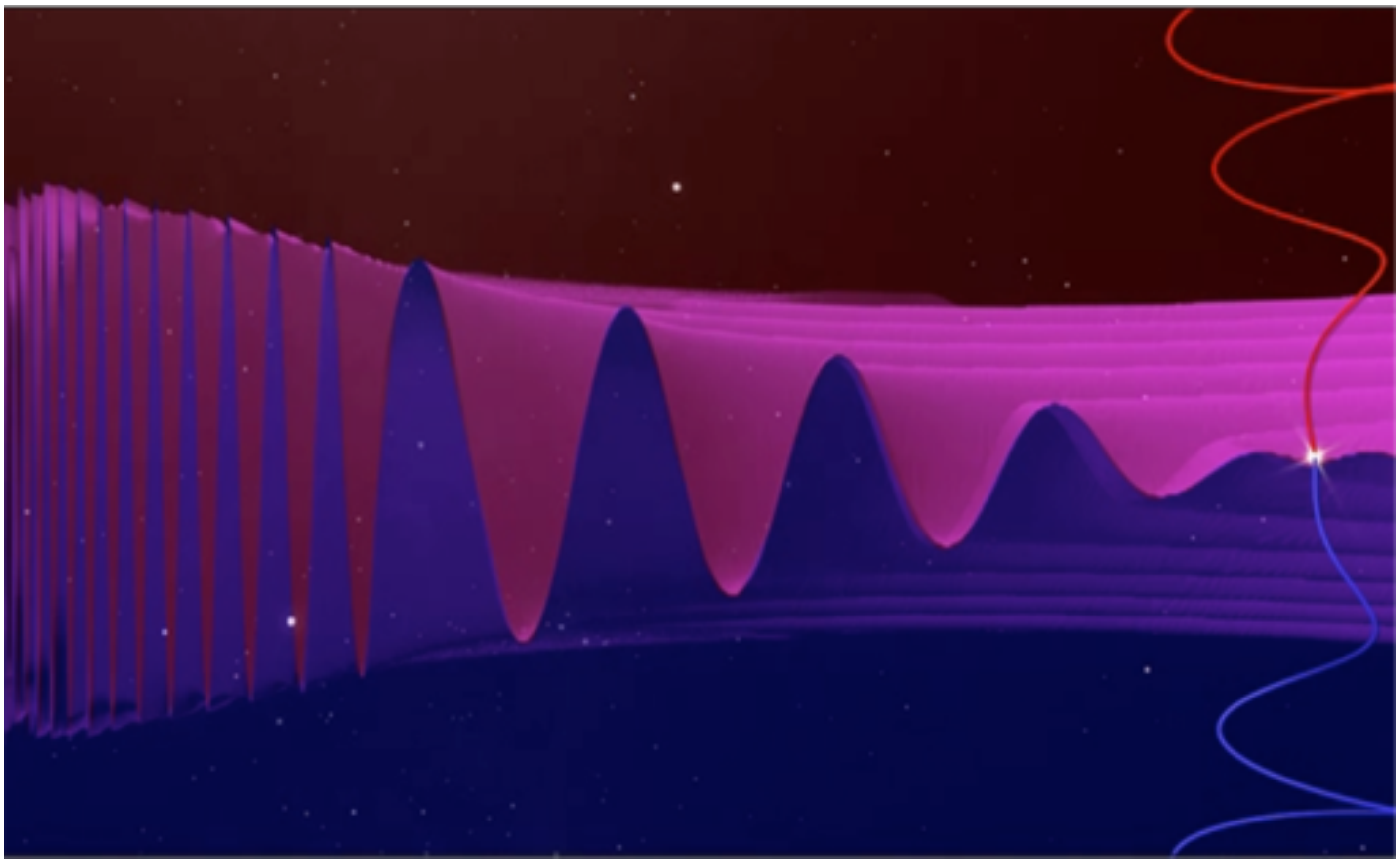
Sector structure of the heliospheric field – is seen all the way to large distances from the Sun

- The Parker spiral field produces the heliospheric current sheet
- Misalignment of the magnetic and rotation axes causes the current sheet to flap
- Periodic reversal of B_ϕ

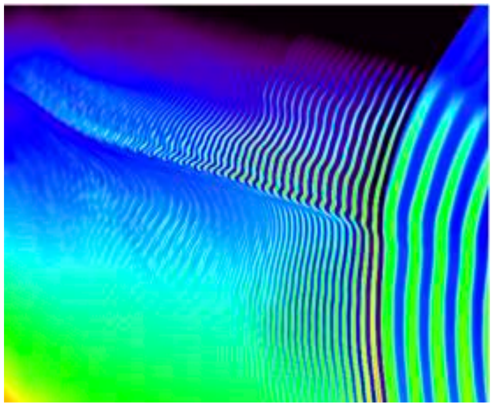




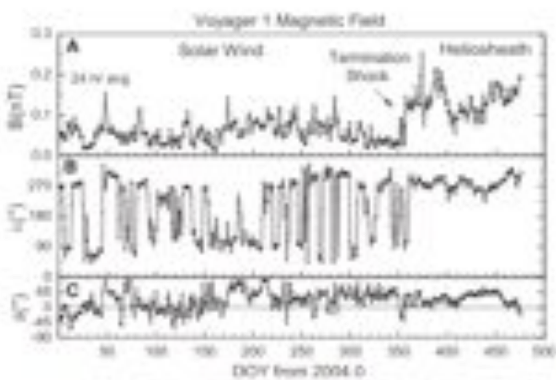
Sectors get compressed after the shock



Onset of Collisionless Reconnection



Magnetic Field



Collisionless reconnection onsets when the current layer falls below the ion inertial scale

- Reconnection simulations (Cassak et al ’05), lab experiments (Yamada ‘07), magnetosphere observations (Phan et al ’07)

Parameters upstream of the Termination Shock (TS)

- HCS thickness ~ 10,000 km based on 1AU – *Winterhalter et al. 1994*
  - This is a significant uncertainty – need 48s mag data upstream
- Ion inertial scale ~ 8400 km (n ~ 0.001/cm^3)

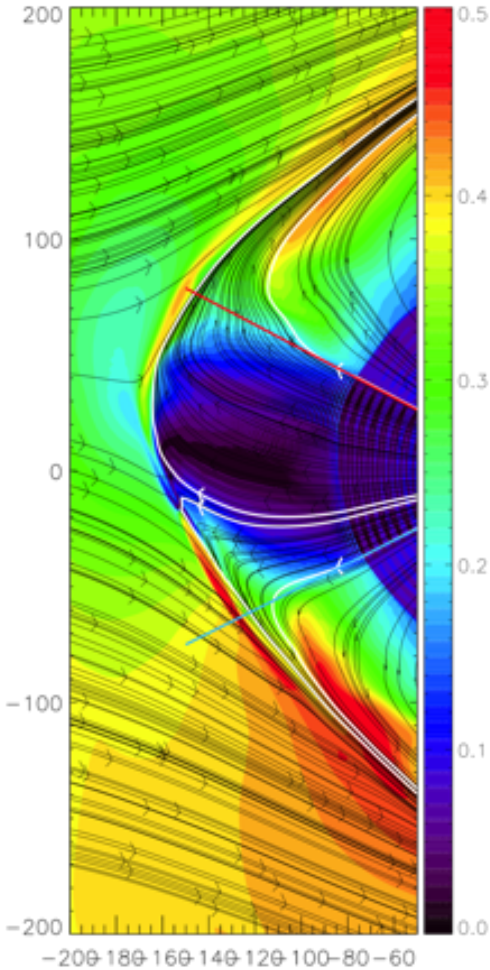
Parameters downstream of the TS

- HCS thickness ~ 3,300 km based on compression from upstream
- Ion inertial scale ~ 4800 km (n ~ 0.003/cm^3)

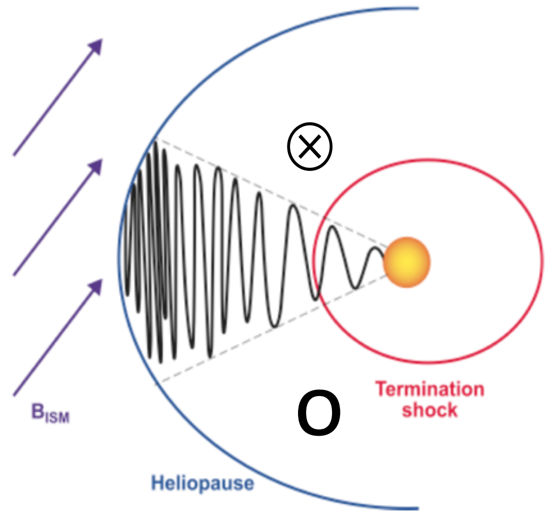
Collisionless reconnection should onset in the HS

- Similar compression and onset seen in Earth’s magnetosphere (Phan et al ‘07)

The structure of the sectored magnetic field



Opher et al. ApJ 2011

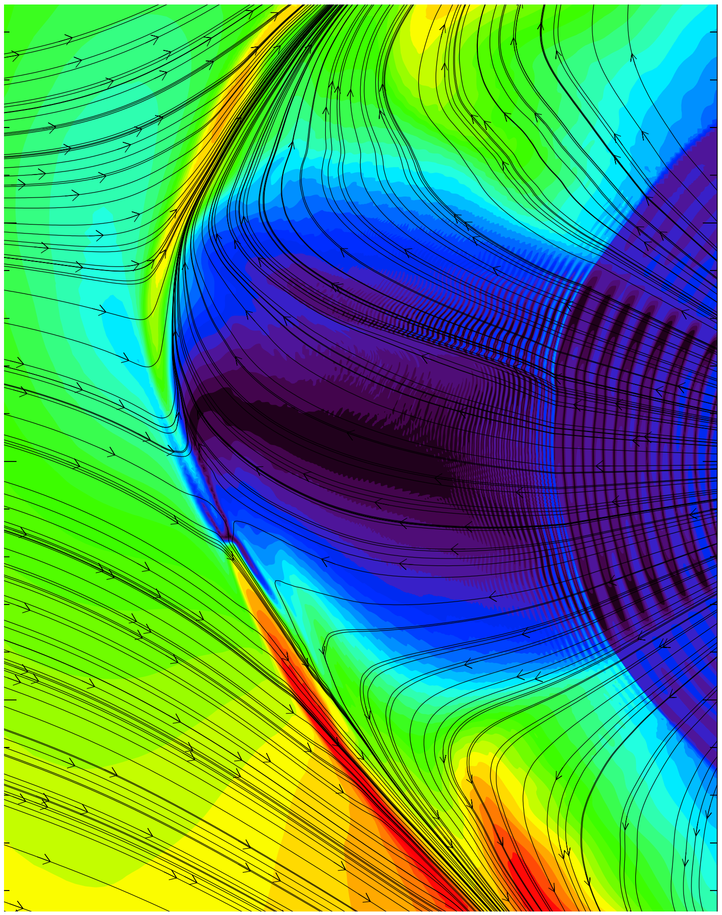


Sectors get closer to each other after the crossing of the Termination Shock

Our 3D MHD simulation resolved the sector allowing for reconnection to occur

(works such as Czechowski et al. (2010) and Borovikov et al. (2011) did include the tilt, but did it kinematically)

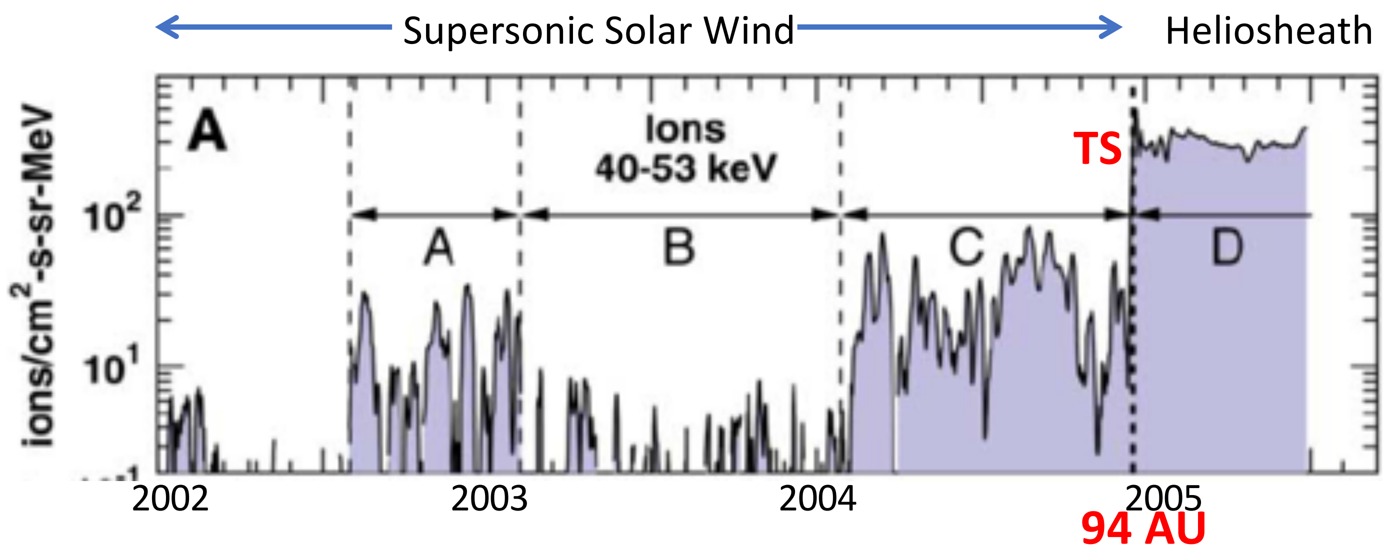
Simulation with a Sector Boundary of ±30°



Opher et al. ApJ 2011

Outline of Class – Part I

- What is the heliosphere
- What are the main components of the heliosphere
- How do we measure characteristics of heliosphere
- Solar Wind
- Interplanetary Magnetic Field
- Behavior of Solar Wind at Large Distances
- Termination Shock/Heliosheath
- Some puzzles of what we don't know



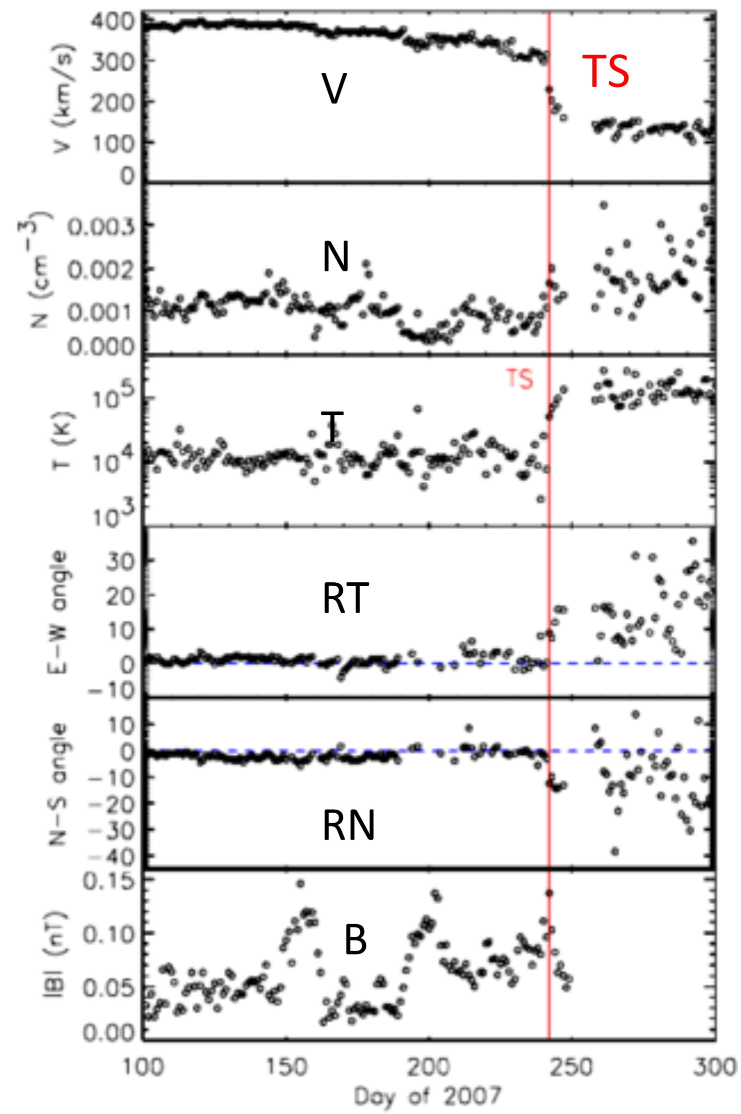
Termination shock particles:

1) accelerated at the termination shock
2) some leak a small distance into the heliosphere
3) fill the heliosheath region

The V1 TS crossing at 94 AU revealed the spatial scale of the heliosphere. Based on MHD models, the heliopause should be at 135-155 AU.

Asymmetry:
V2 crosses the TS
In Aug. 2007 at 84 AU

- V2 TS Overview
- Speed decrease starts 82 days (0.7 AU) before TS
- Crossing clear in plasma data
- Flow deflected as expected
- Crossing was at 84 AU, 10 AU closer than at V1



Richardson et al., 2008

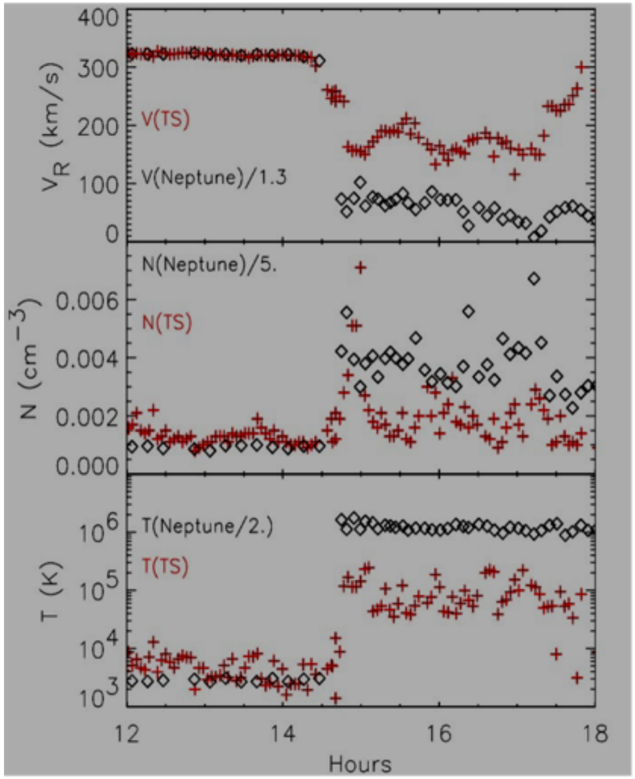
New Paradigm:

Realization that the Energetic Particles - created streaming of neutral H from ISM – *Pick-Up ions (PUIs)* are the dominant species in the distant solar wind

Voyager data of the crossing of the Termination Shock:

Plasma was colder by one order of magnitude the PUIs carry all the energy

Previous Global Models: Cold Solar Wind + PUIs = one fluid



Richardson et al. Nature 2005