The Voyagers at the Edge of the Heliospheric Bubble

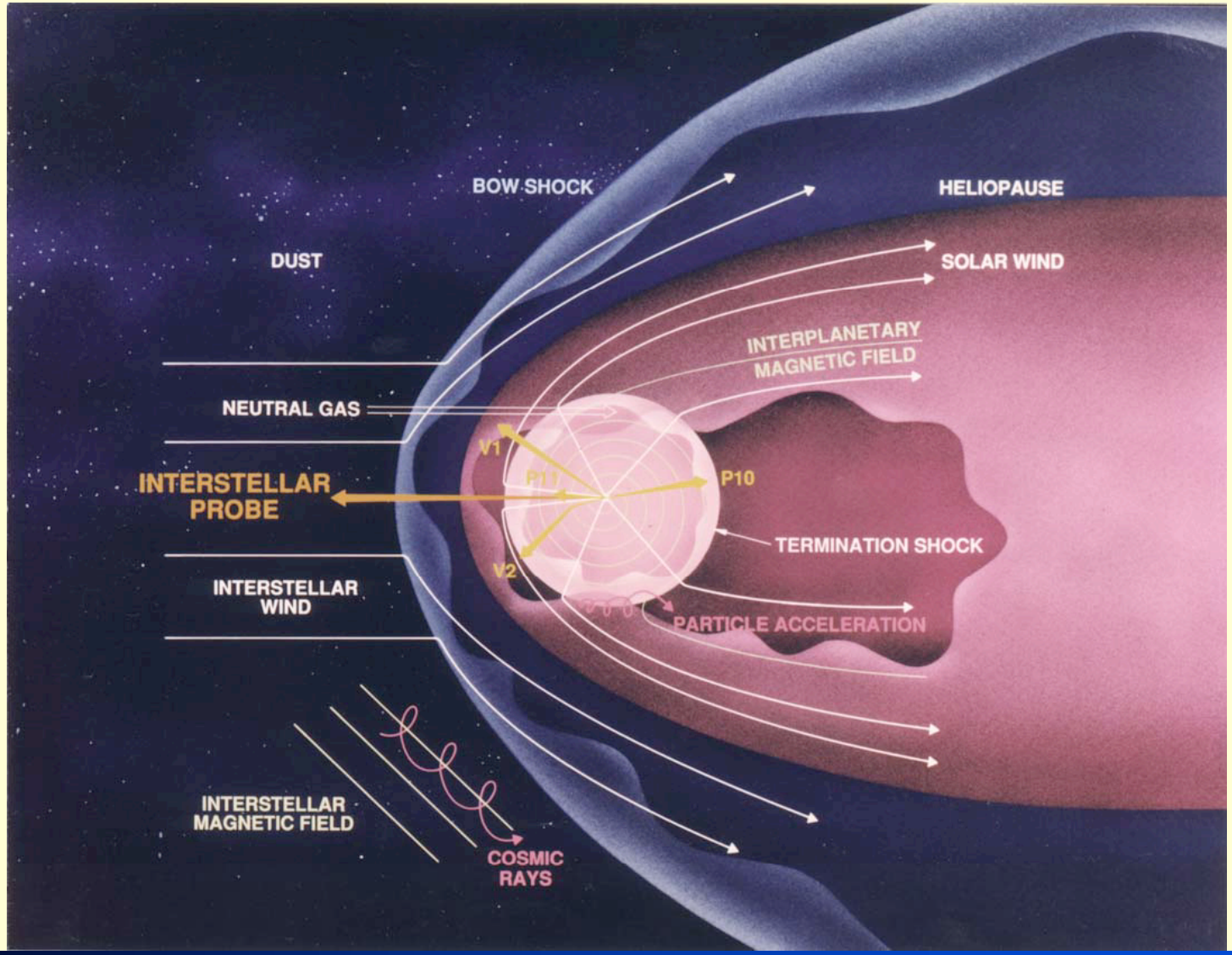
John D. Richardson (MIT)

With thanks to the Voyager team and E. Mobius

Outline

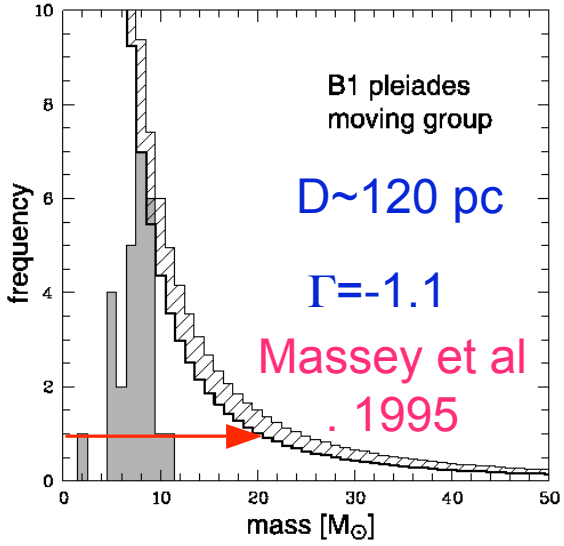
1) Our place in the Galaxy
2) The Local Interstellar Cloud (LIC)
3) The Solar Wind - LIC interaction
4) The Voyagers at the Termination Shock
5) The Future

Apropos: Sticking Our Head Out

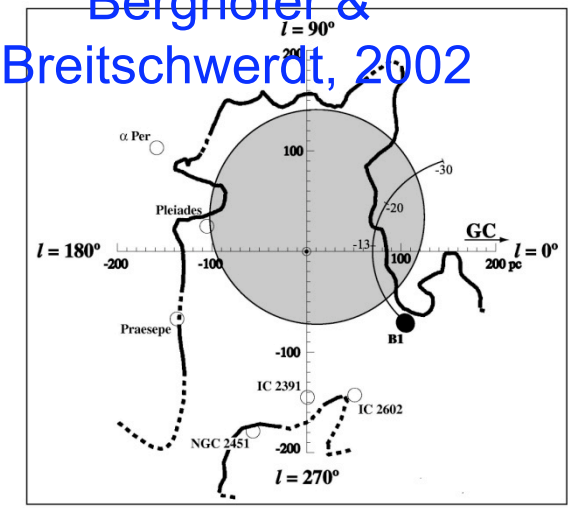


Our „County“ in the Cosmos: The Local Bubble

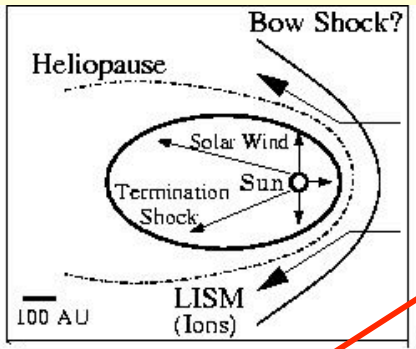
SN from Pleiades

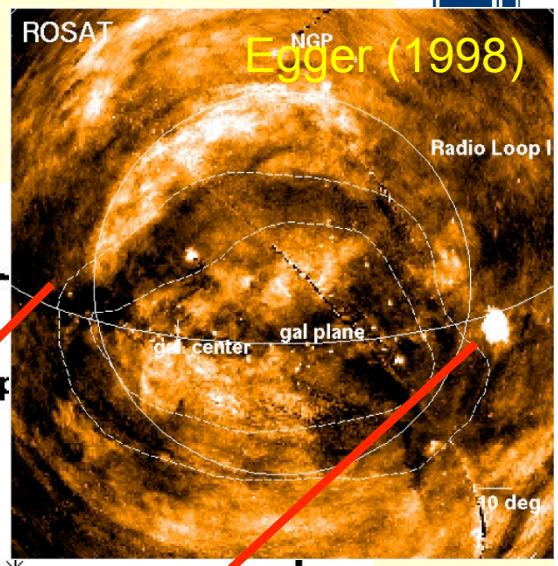


Berghöfer &
Breitschwerdt, 2002



Local Bubble and Loop I are Interacting Bubbles!



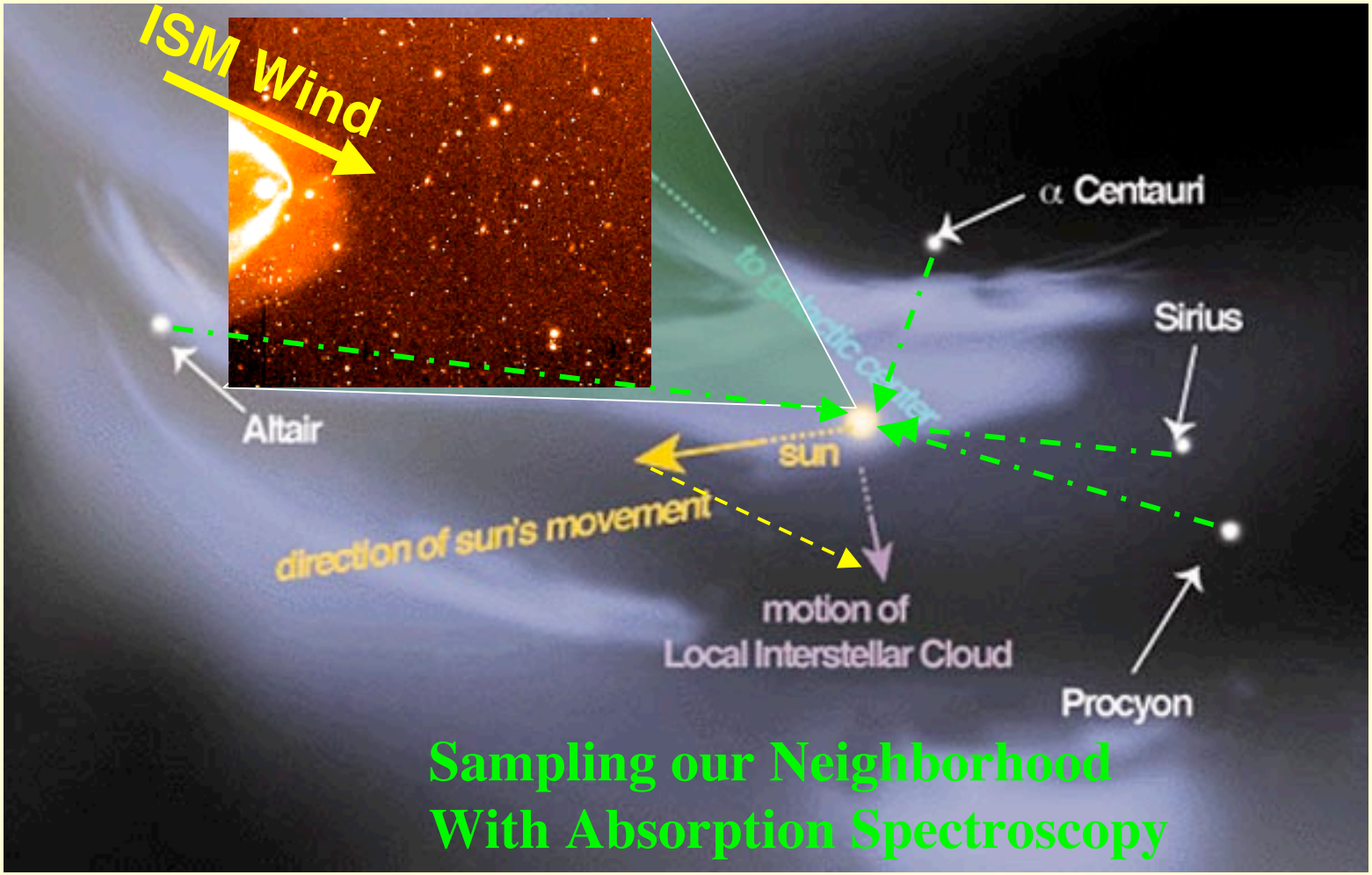


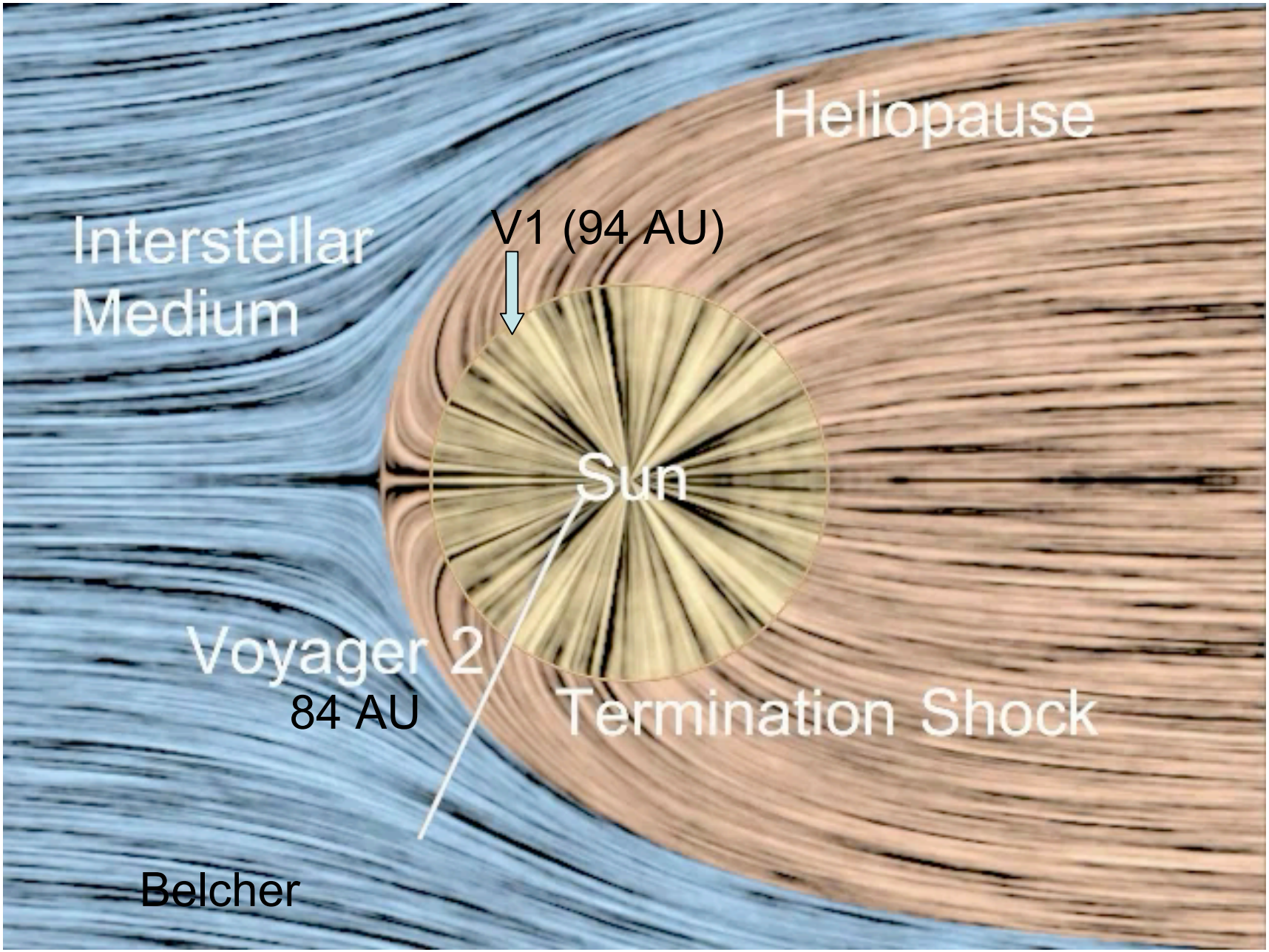
Blasts from Past

Breitschwerdt & deAvillez

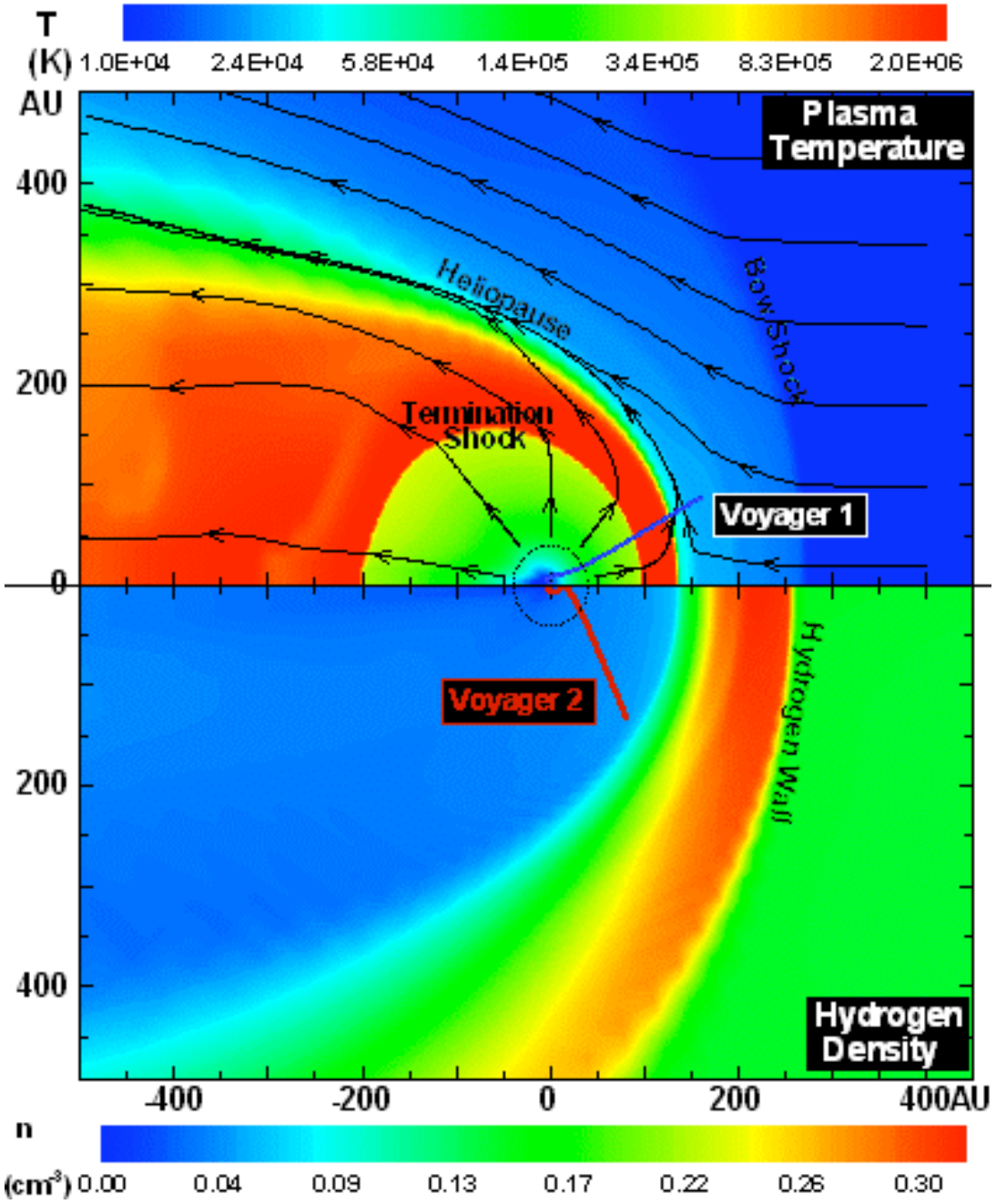
From ISSI Workshop: From the Heliosphere to the Local Bubble

If We Could See Our Heliosphere from Outside …




Heliopause
Interstellar
Medium
V1 (94 AU)
Sun
Voyager 2
84 AU
Termination Shock
Belcher

Interstellar neutrals

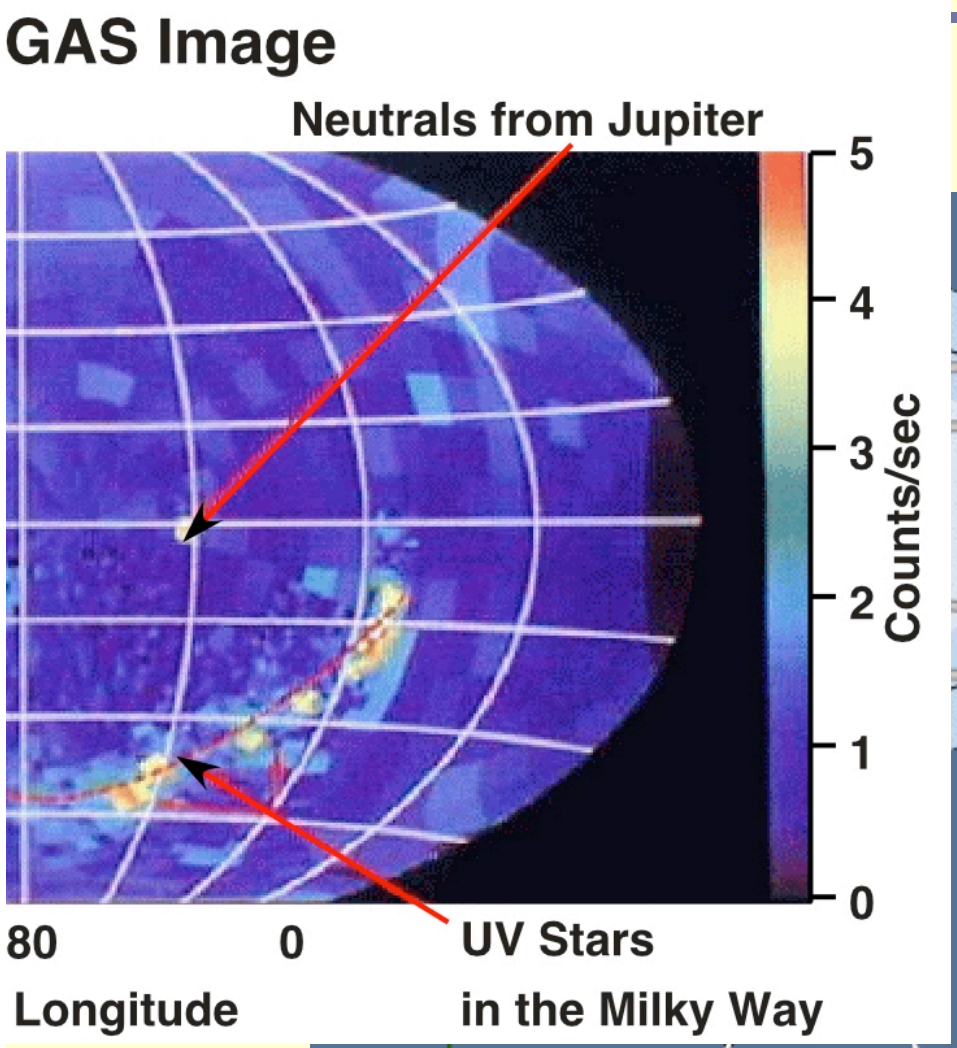


LIC neutrals are not bound by magnetic fields; some enter the heliosphere.

LIC neutrals are tied to plasma via charge exchange. Slowing of plasma in front of the heliopause creates the hydrogen wall.

Mueller et al.

Pattern of the Interstellar Gas Flow



Witte et al., Banaszkiewicz et al.

LIC He from 3 Methods

(Efforts of an ISSI Team)

Measure 1. Neutrals 2. Pickup ions 3. UV

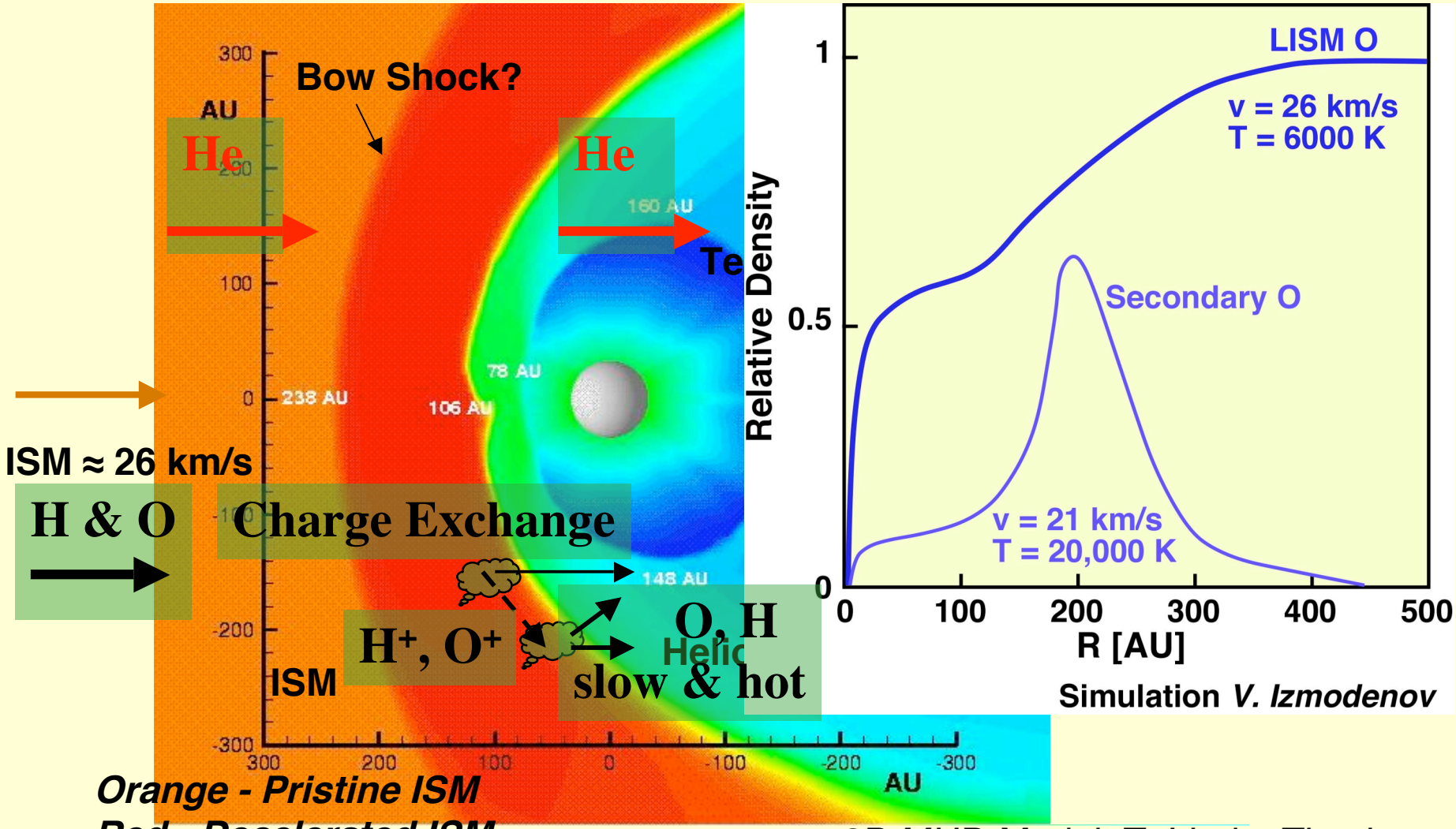
- **Velocity = 26.3±0.4 km/s**
- **Temperature = 6300±340 K**
- **Density = 0.015±0.0015 cm^{-3}**

- **LIC H Density: 0.2 ± 0.02 cm^{-3}**

Plasma Interaction with the LIC

Plasma Density Contours

Blue & Green Solar Wind

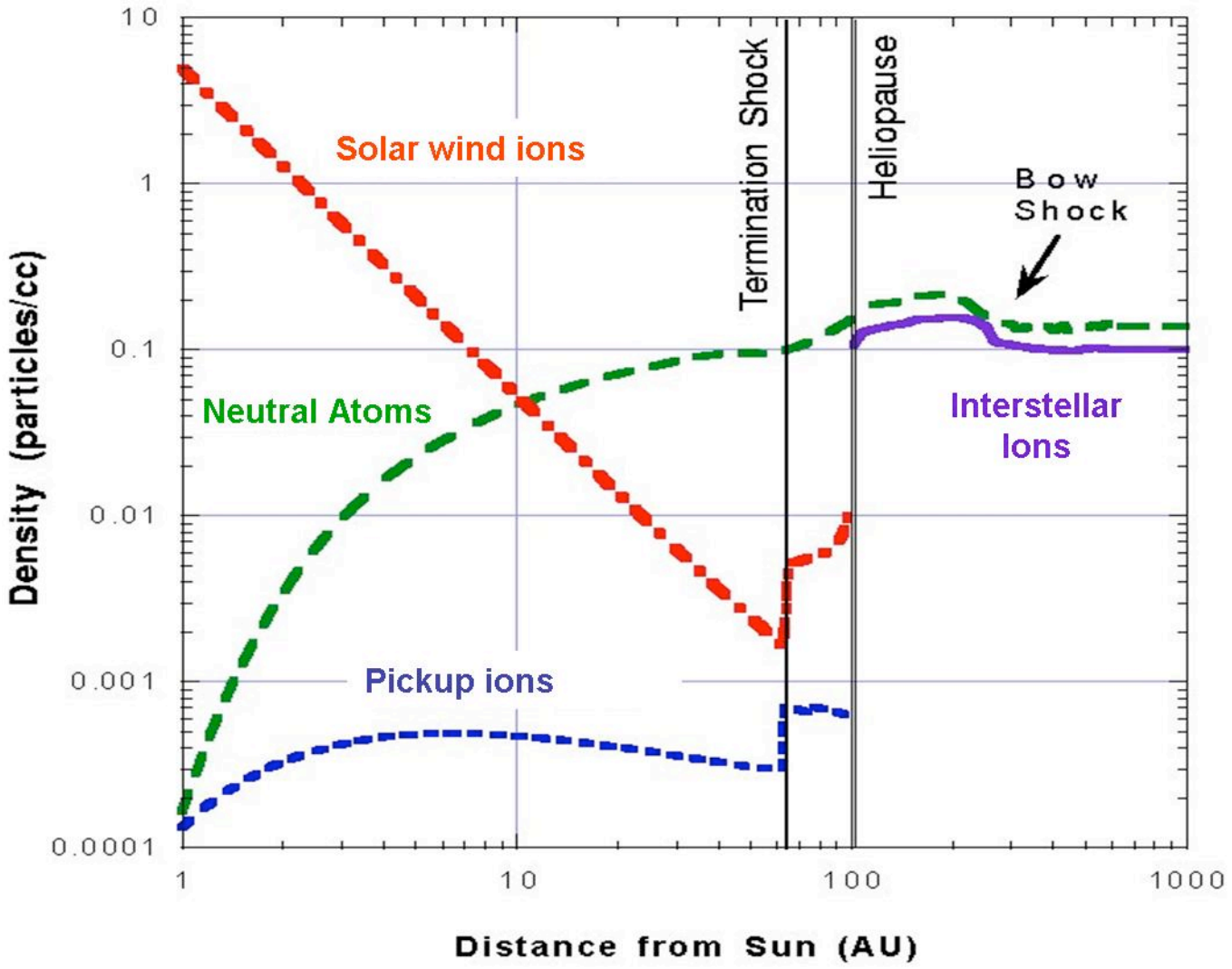


Orange - Pristine ISM

Red - Decelerated ISM

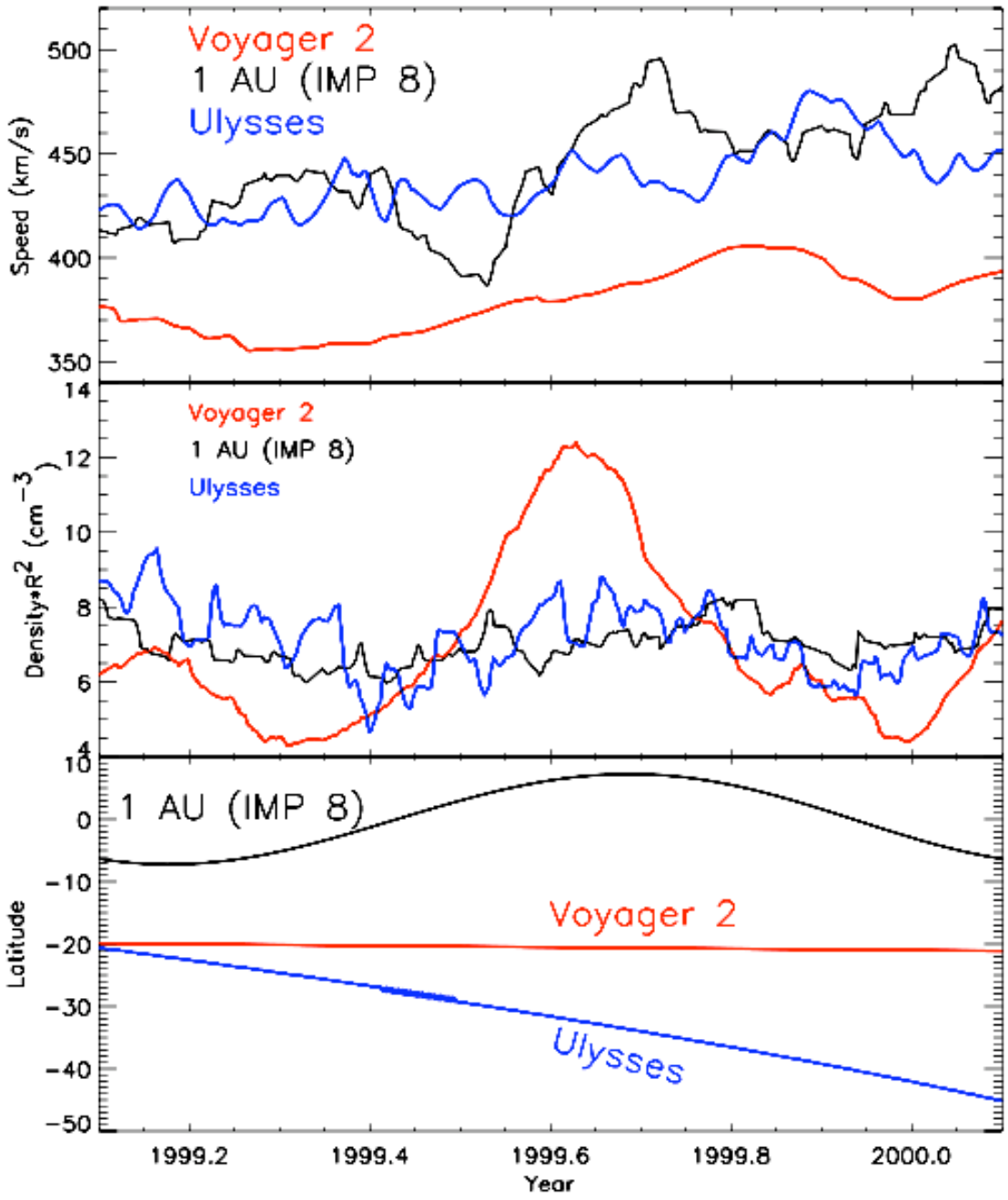
3D MHD Model T. Linde, Thesis

- Neutrals dominate density outside ~10 AU
- Pickup ions dominate thermal pressure outside 30 AU

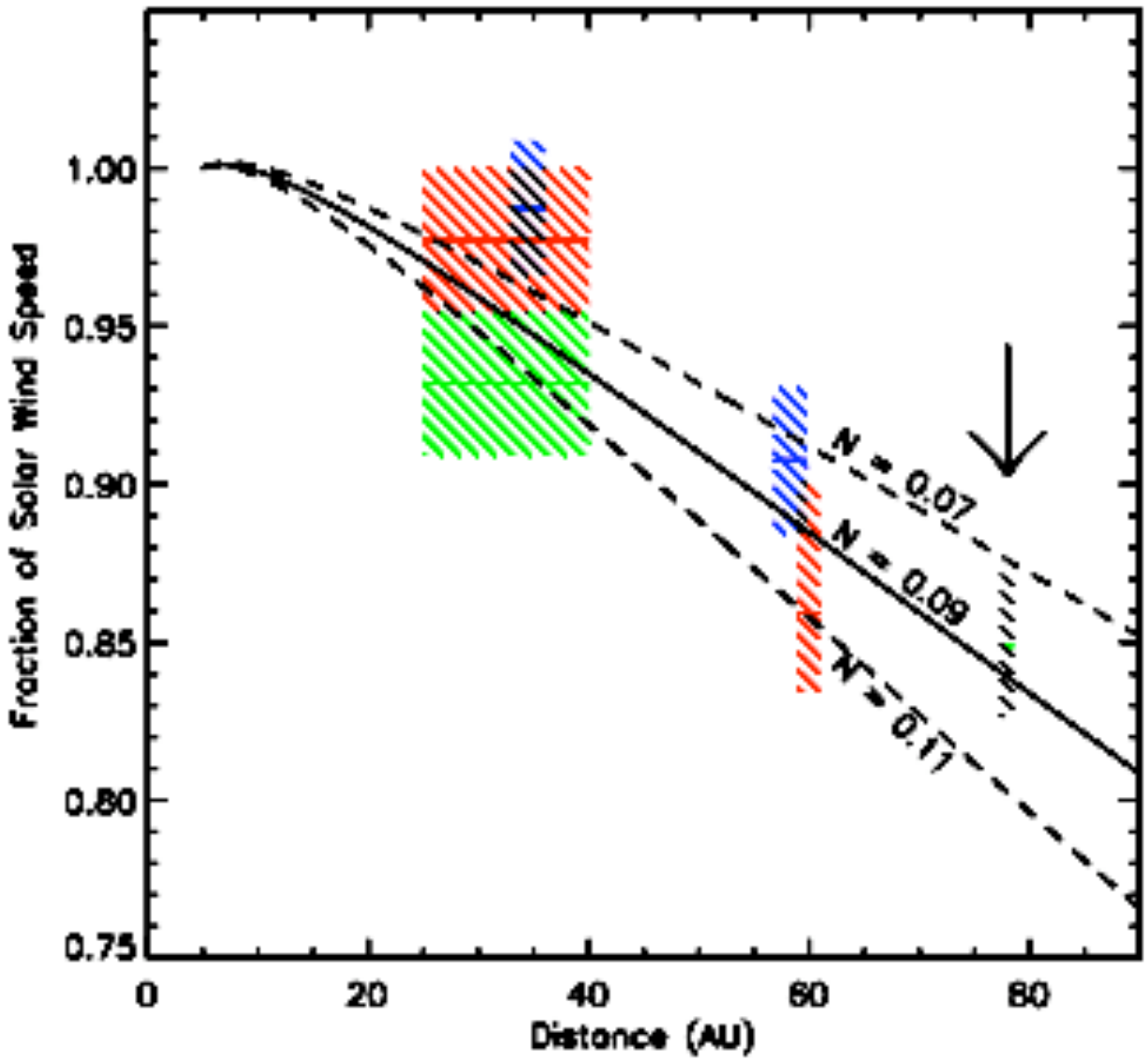


[Mewalt]

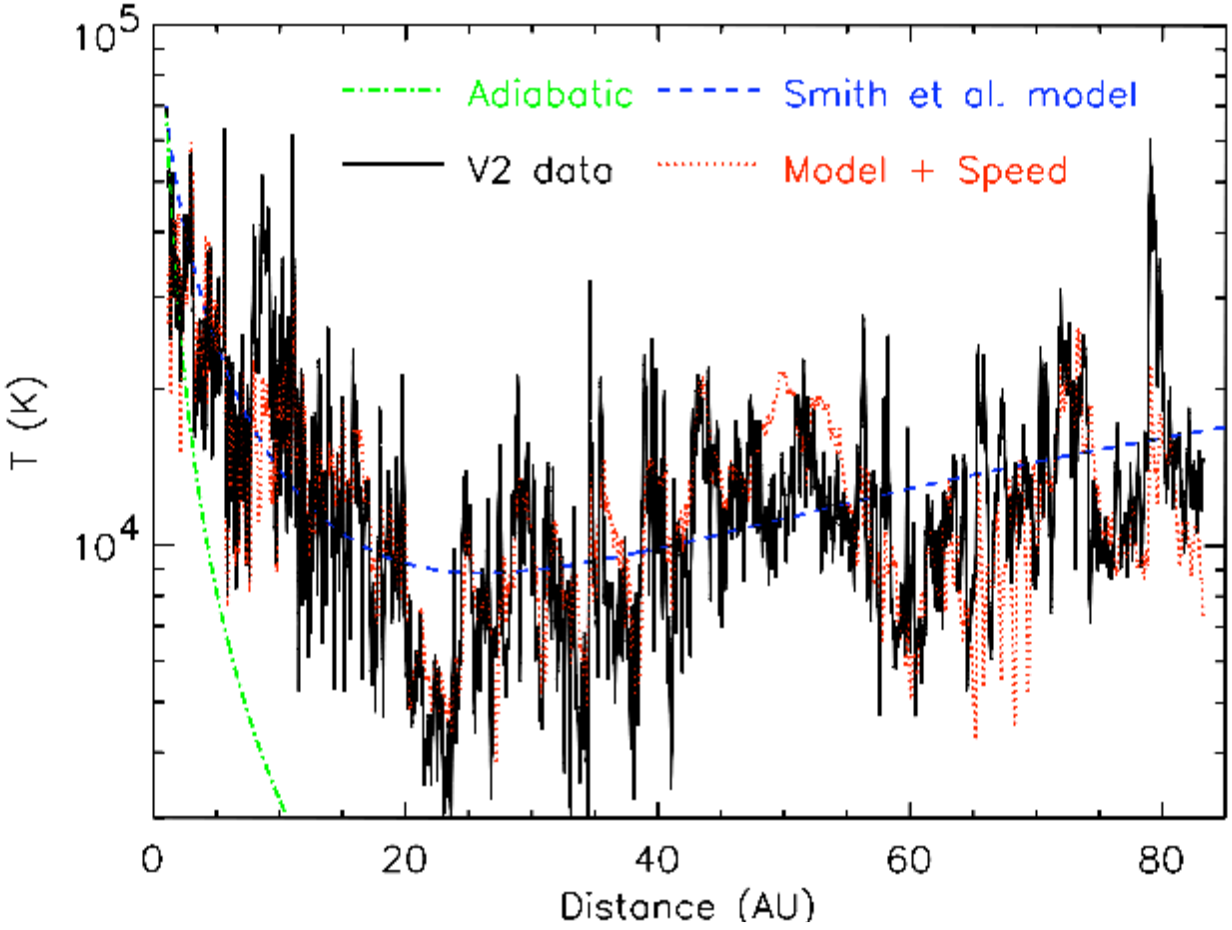
- Solar Wind Slowdown
- Can determine slowdown at solar max or when two spacecraft are at the same heliolatitude
- $dV/V = 6/7\ N_{pu}/N_{sw}$

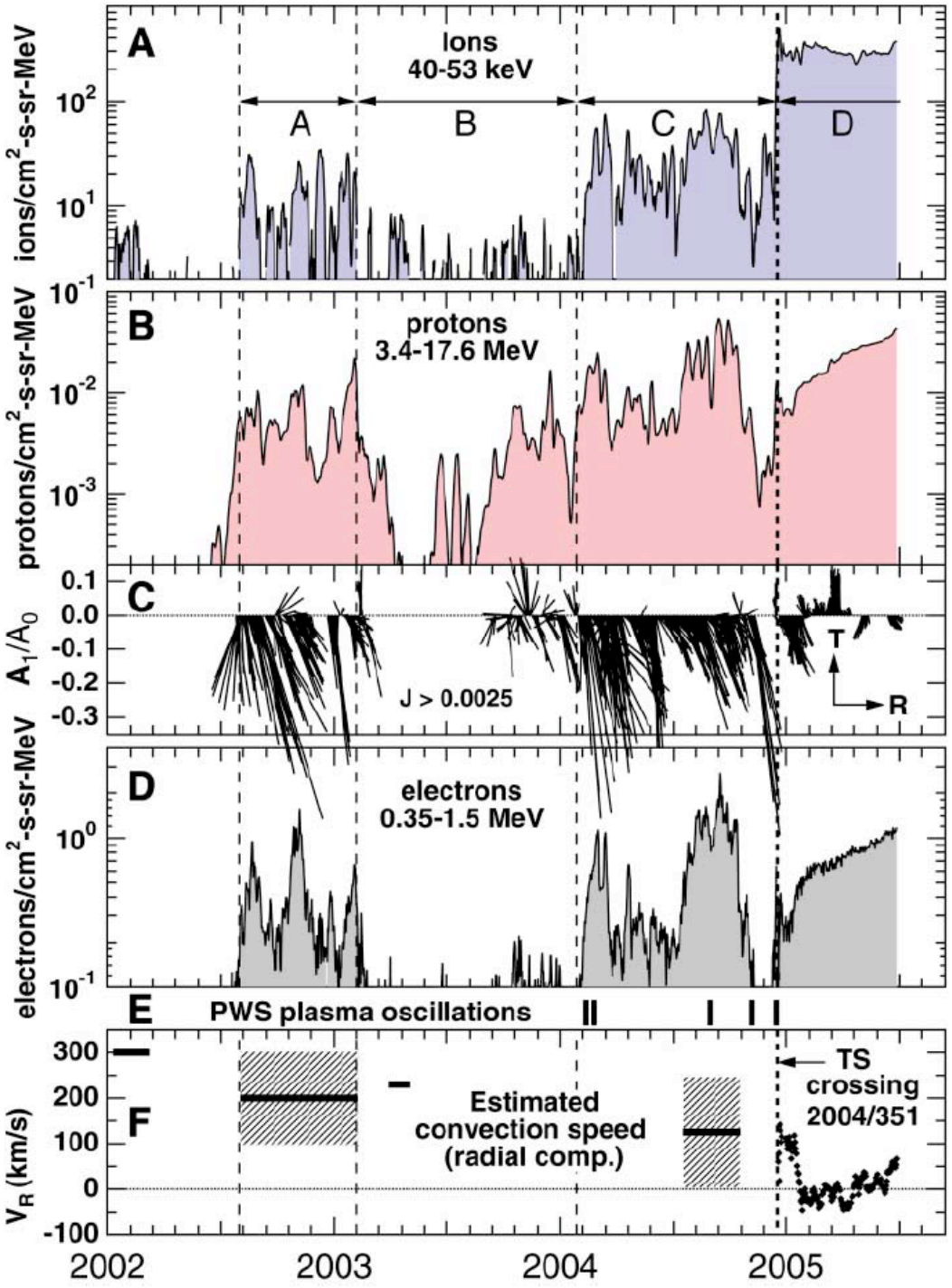


Solar Wind Slowdown



- Does pickup ion energy heat SW? YES!
- Temperature is not adiabatic; T decreases to 25 AU, then increases by a factor of 3 by 80 AU.
- Energy comes from isotropization of pickup ion ring distributions.
- More heating with higher speeds
- About 4% of isotropization energy heats solar wind





LECP V1 TS

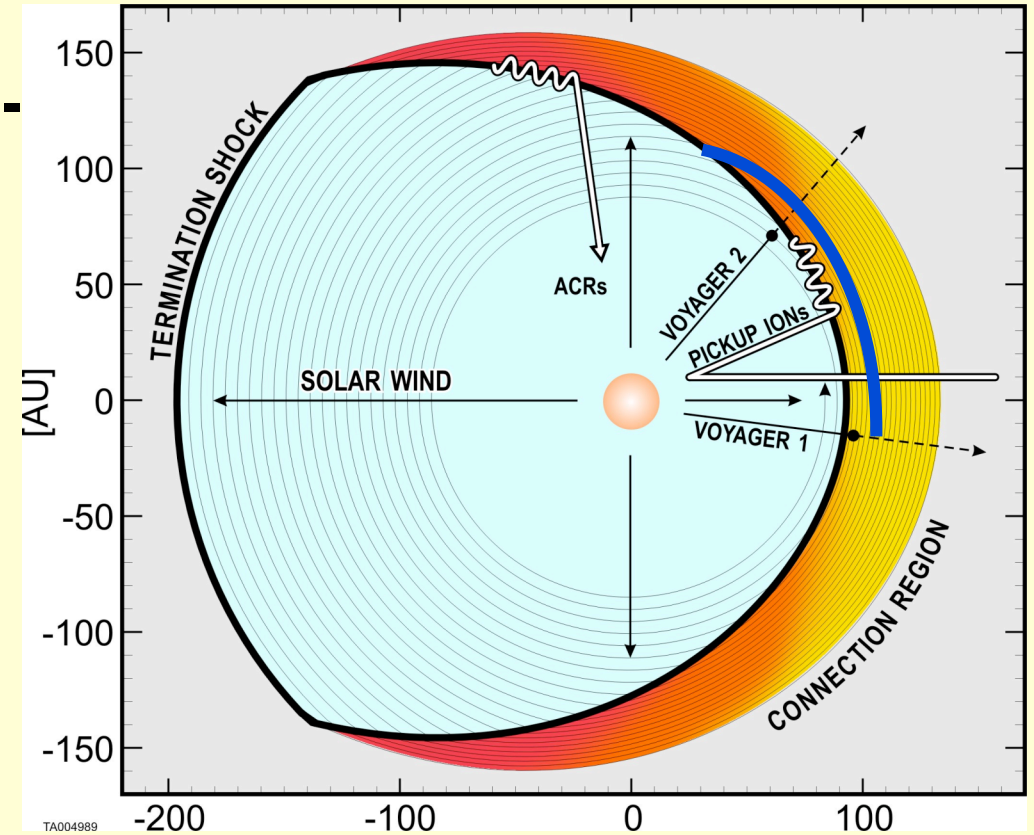
V1 - no plasma data

Ions and electrons observed beaming in foreshock but isotropic in sheath

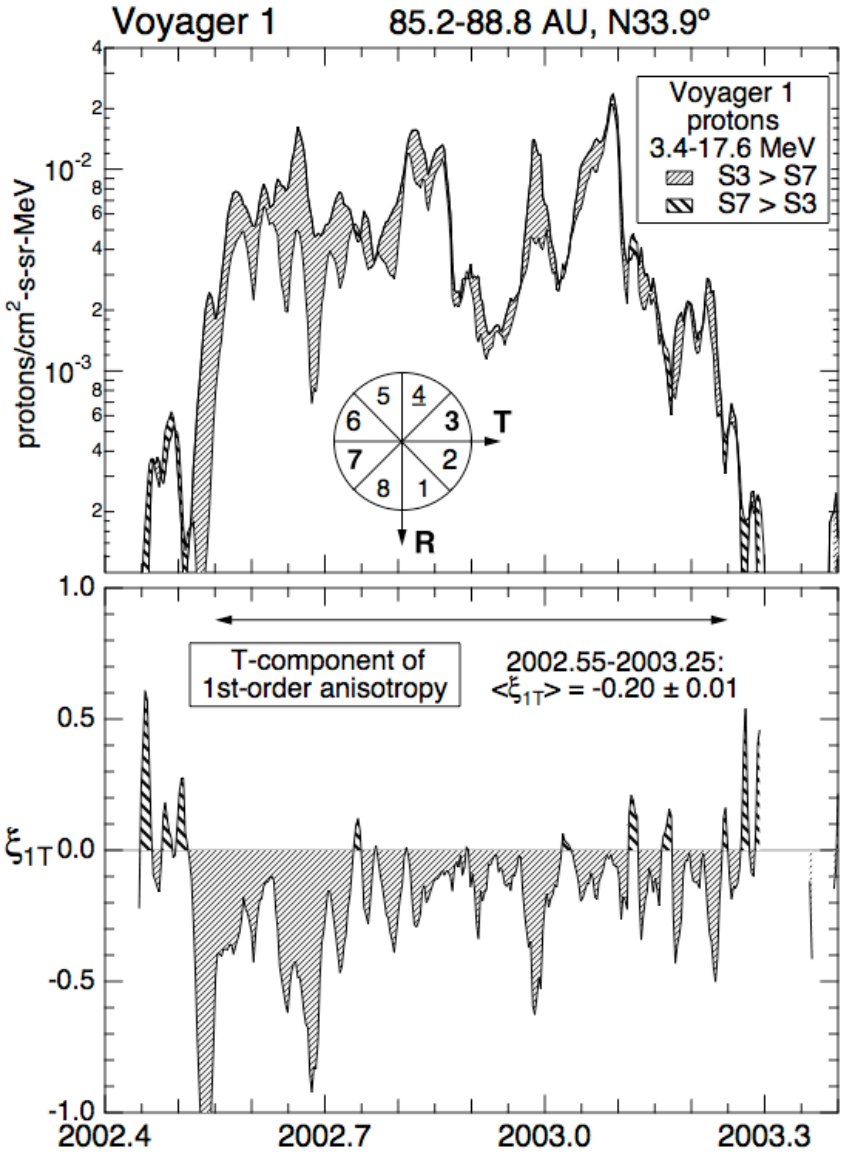
Used to estimate SW speeds - report slowing ahead of shock, -40 - 100 km/s in sheath (Decker)

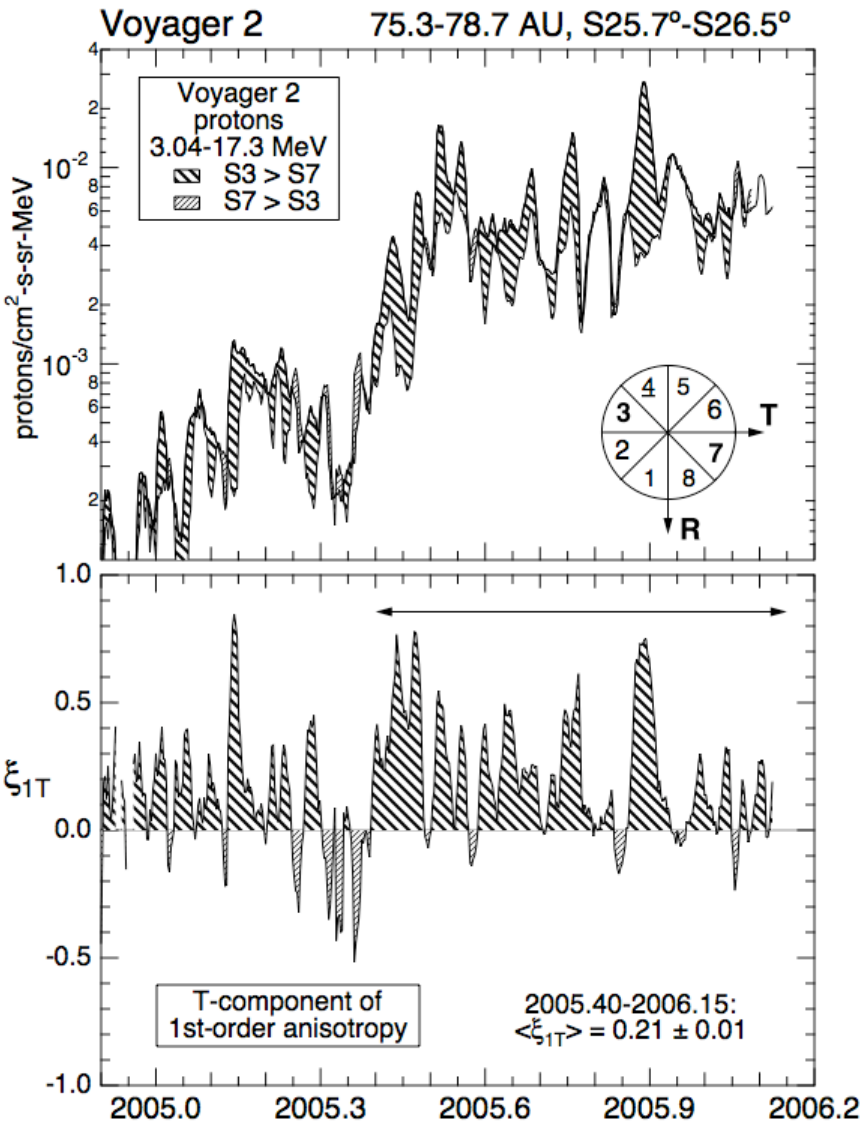
Puzzle:
Where is the Anomalous Cosmic Ray Source

- Ions come from maximum acceleration region along B-Field (*Schwadron & McComas*)
- Acceleration in Heliosheath (*Fisk & Gloeckler*)
- Acceleration of Pickup Ions with anisotropic PADs provides gap in spectra (*Florinski*)



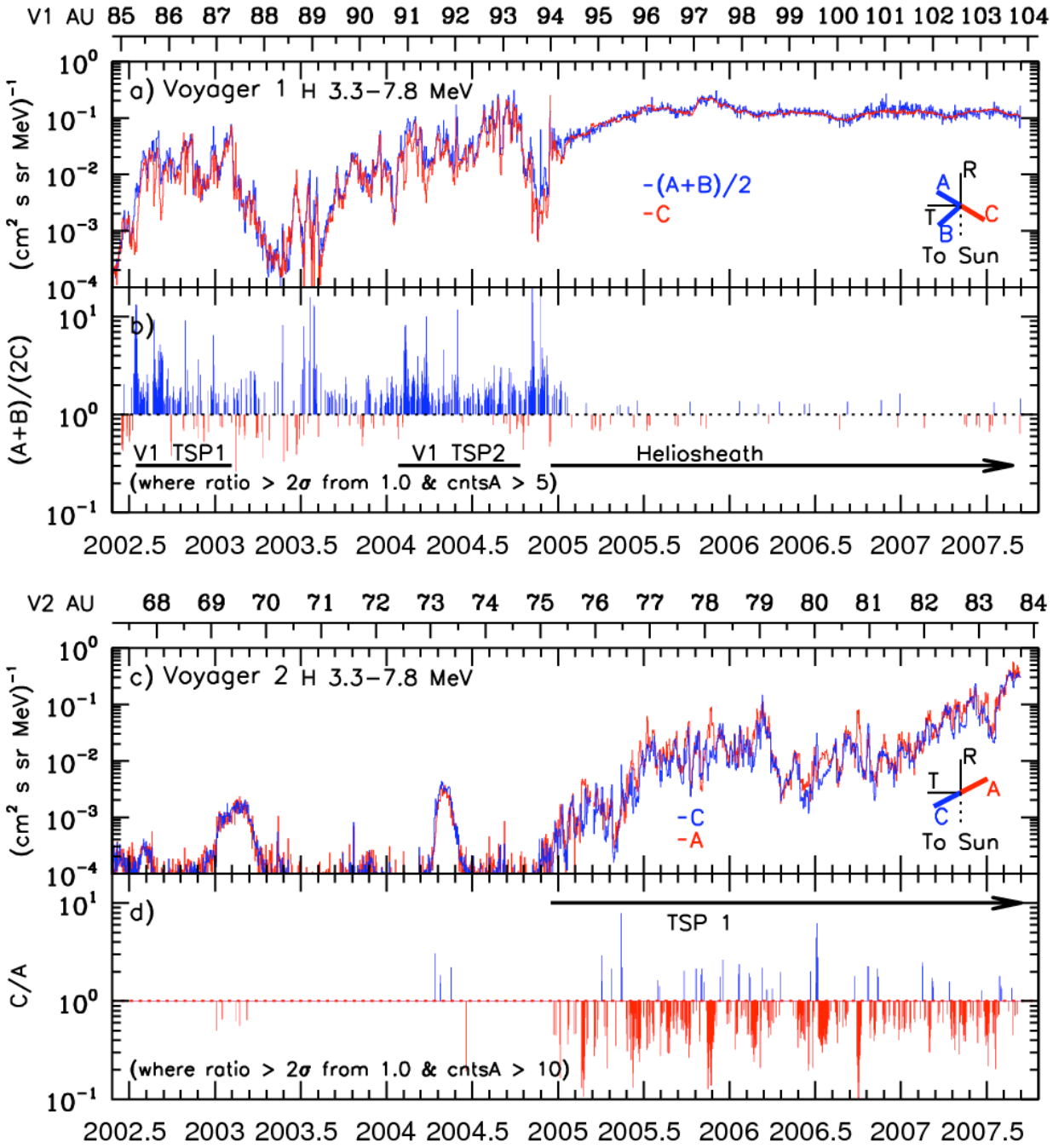
Schwadron & McComas 2006


Voyager 1
85.2-88.8 AU, N33.9°
Voyager 1
protons
3.4-17.6 MeV
S3 > S7
S7 > S3
protons/cm^2-s-sr-MeV
T
R
T-component of
1st-order anisotropy
2002.55-2003.25:
<ξ_{1T}> = -0.20 ± 0.01
ξ_{1T}
2002.4
2002.7
2003.0
2003.3

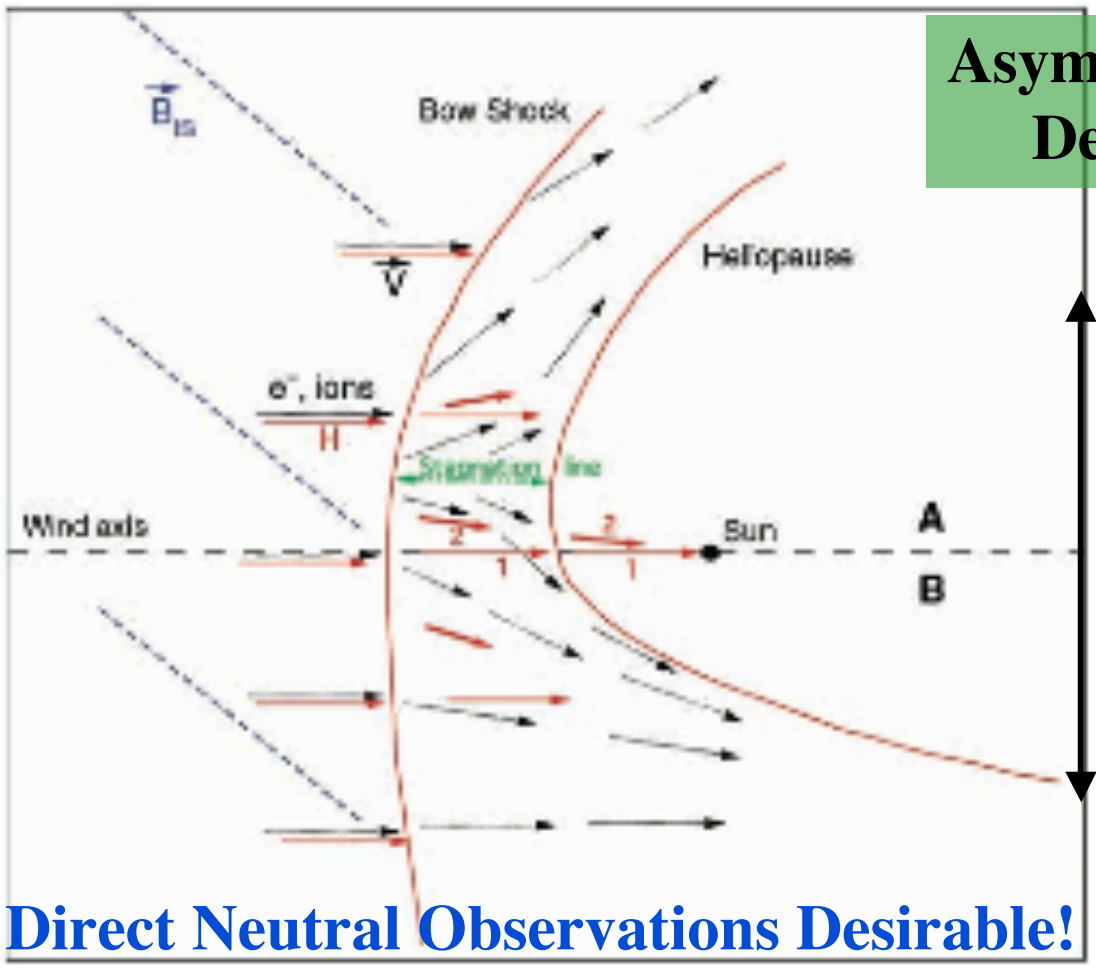

Voyager 2
75.3-78.7 AU, S25.7°-S26.5°
Voyager 2
protons
3.04-17.3 MeV
S3 > S7
S7 > S3
protons/cm^2-s-sr-MeV
T
R
ξ_{1T}
T-component of
1st-order anisotropy
2005.40-2006.15:
<ξ_{1T}> = 0.21 ± 0.01
2005.0
2005.3
2005.6
2005.9
2006.2

Heliospheric Asymmetry.

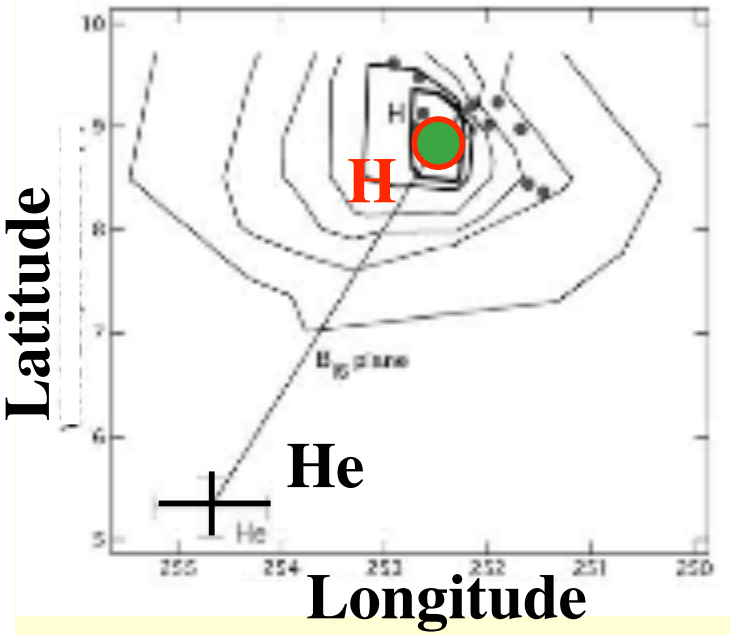
V1 enters FS region
At 85 AU, V2 enters
At 75 AU.



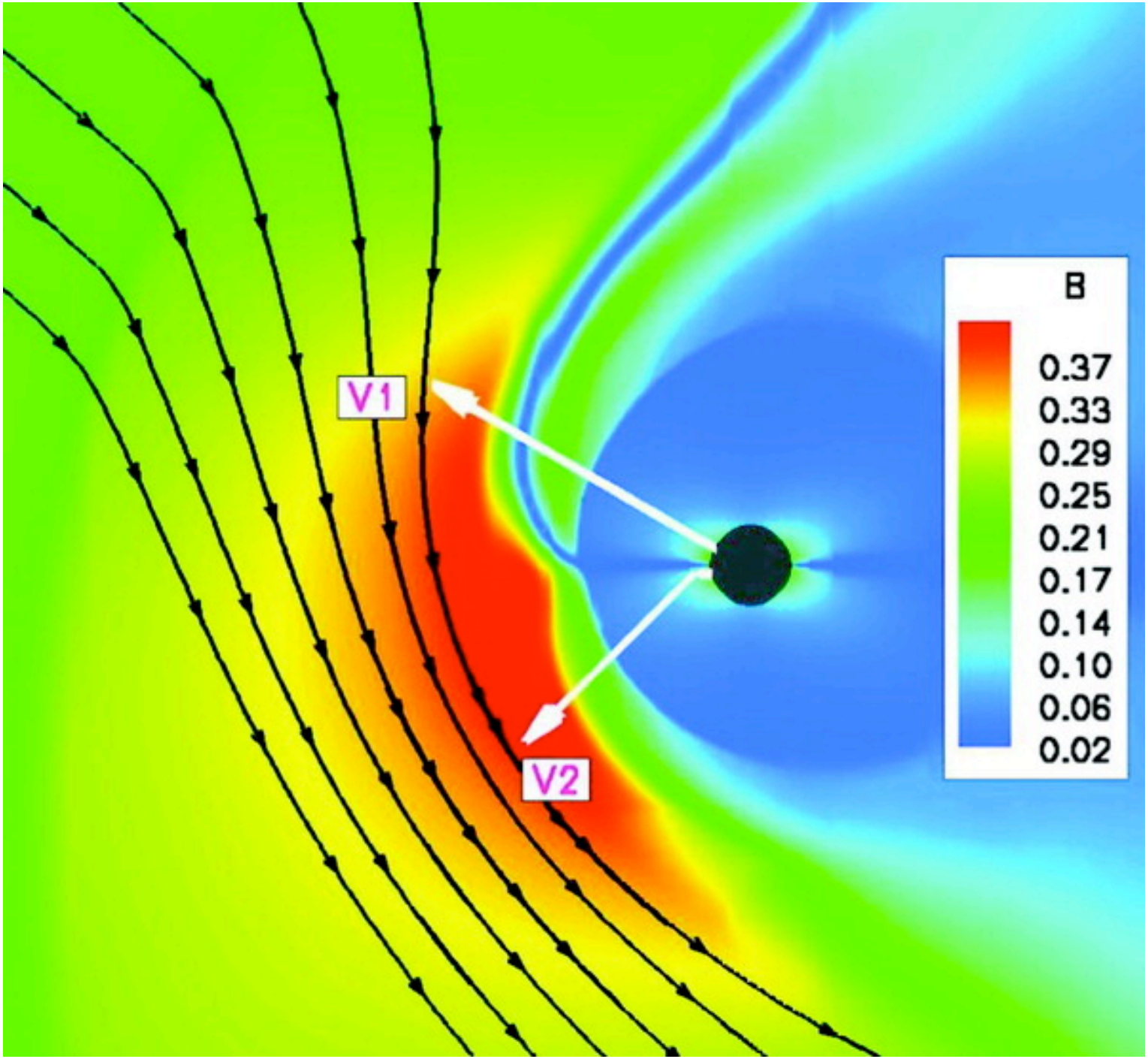
Ly α Observations Have Revealed Deflected Flow of H



Asymmetric LIC Magnetic Field Deflects the Decelerated Flow



Lallement et al. 2005



Simulation of sheath (Opher)

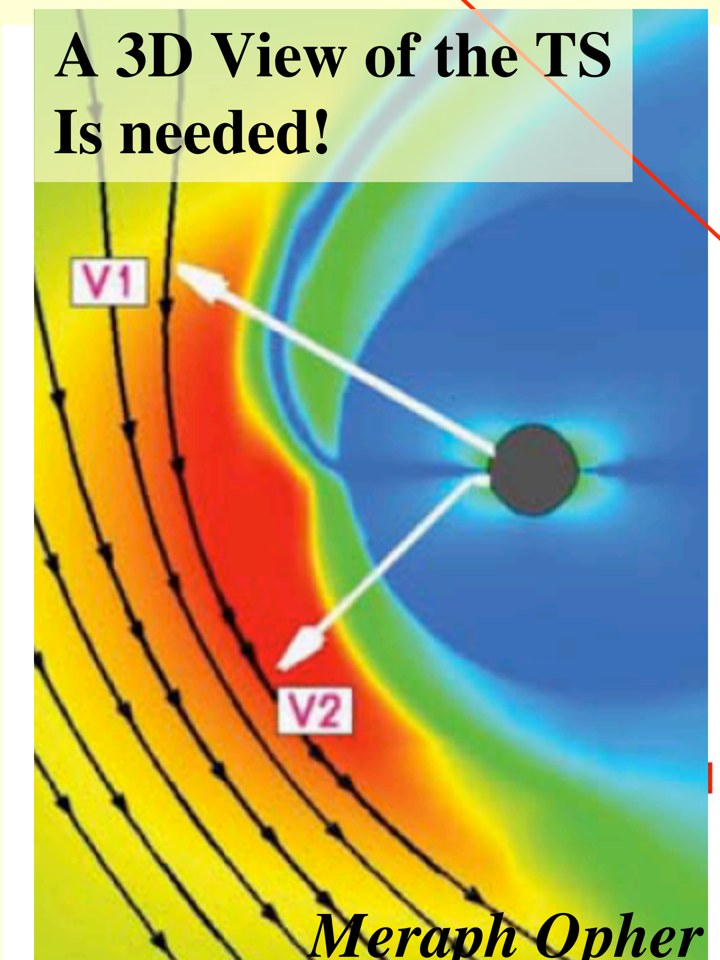
Tilted LIC magnetic field gives asymmetry

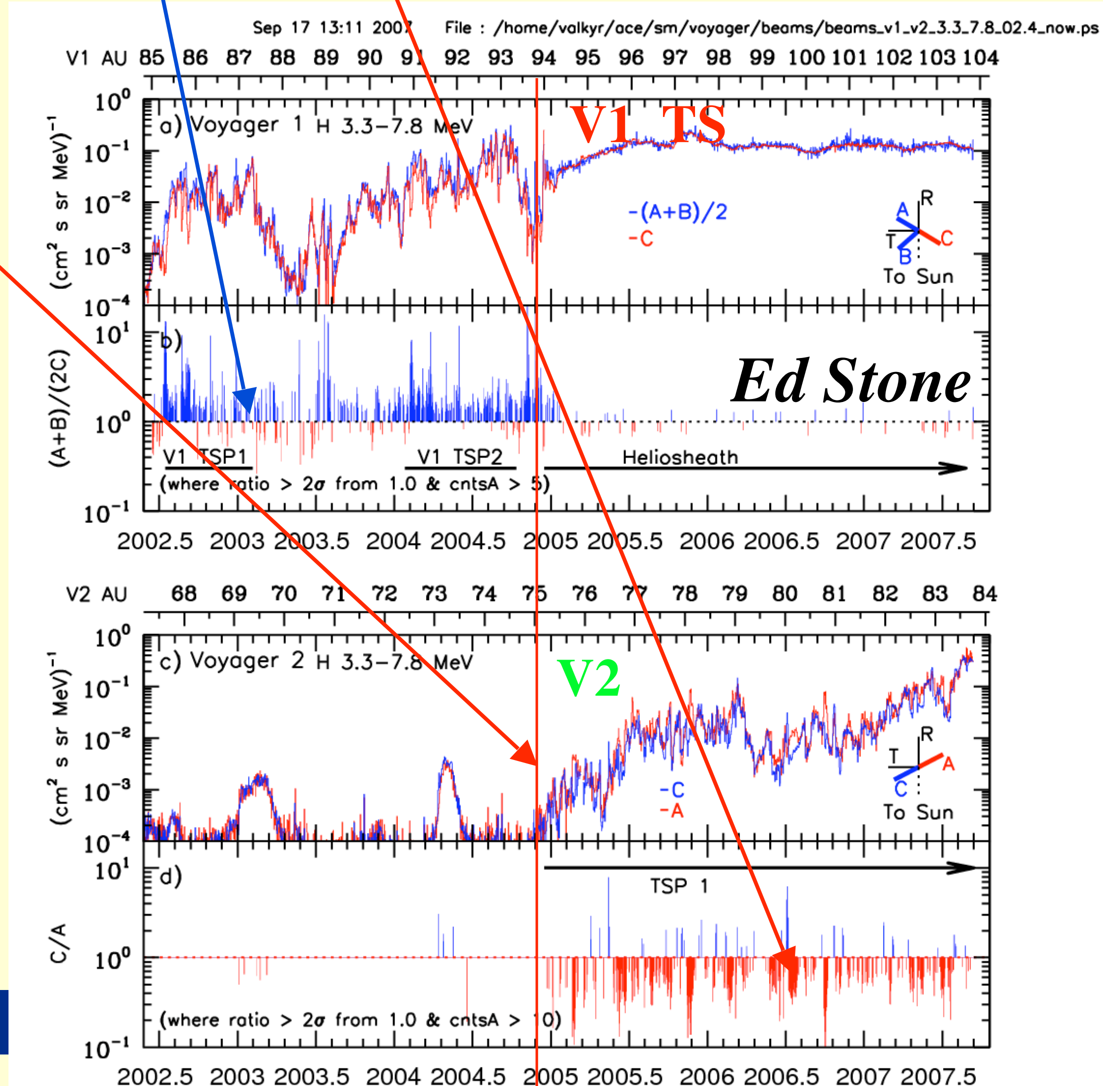
TS and HP closer in South than North.

This asymmetry observed by Voyagers

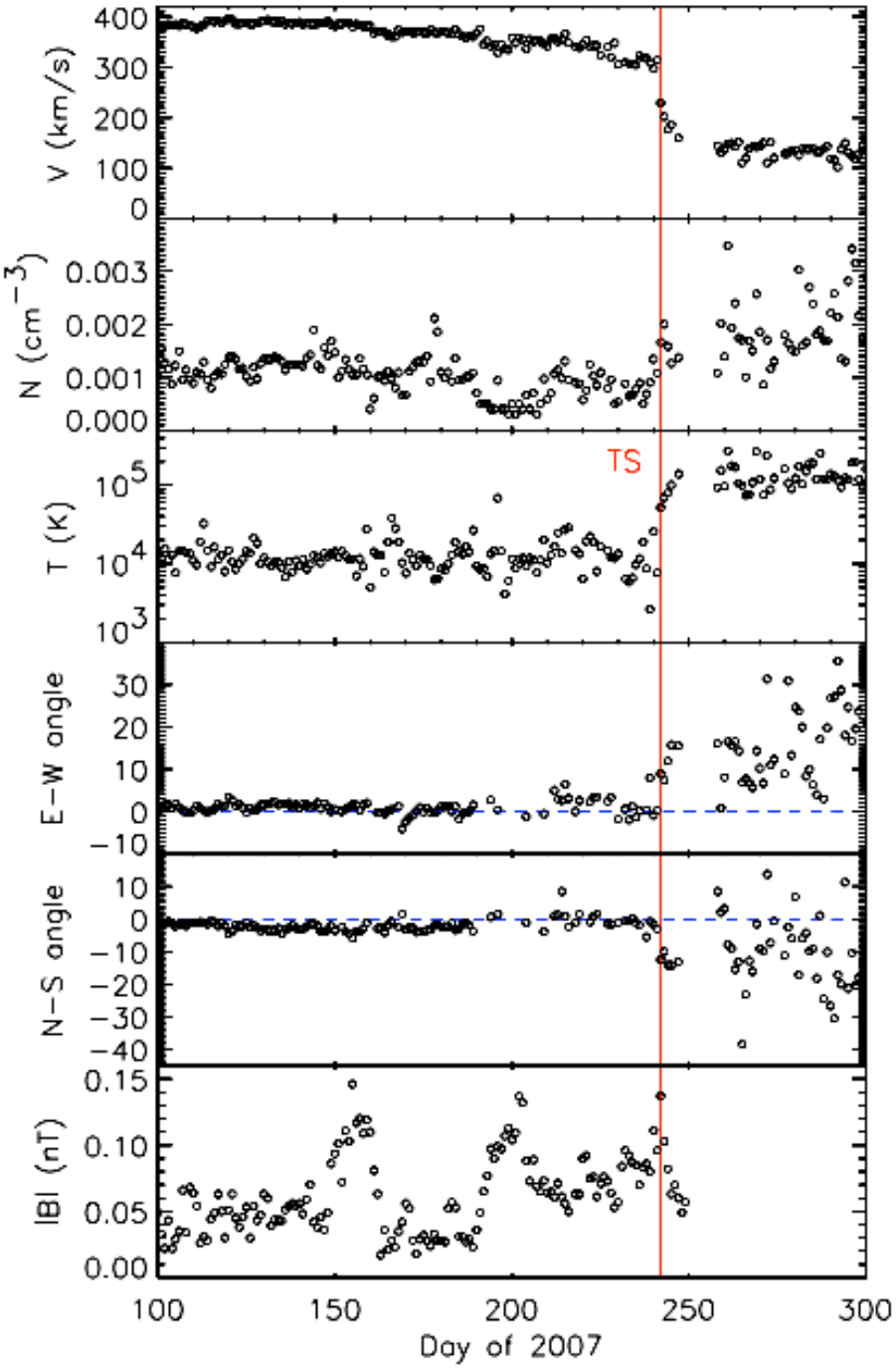
Shape of the Termination Shock

- It is blunt, as evidenced by Voyagers seeing signs of foreshock beams at V1 and V2
- TS is asymmetric: Voyager 2 sees TS earlier than V1 → asymmetric heliosphere

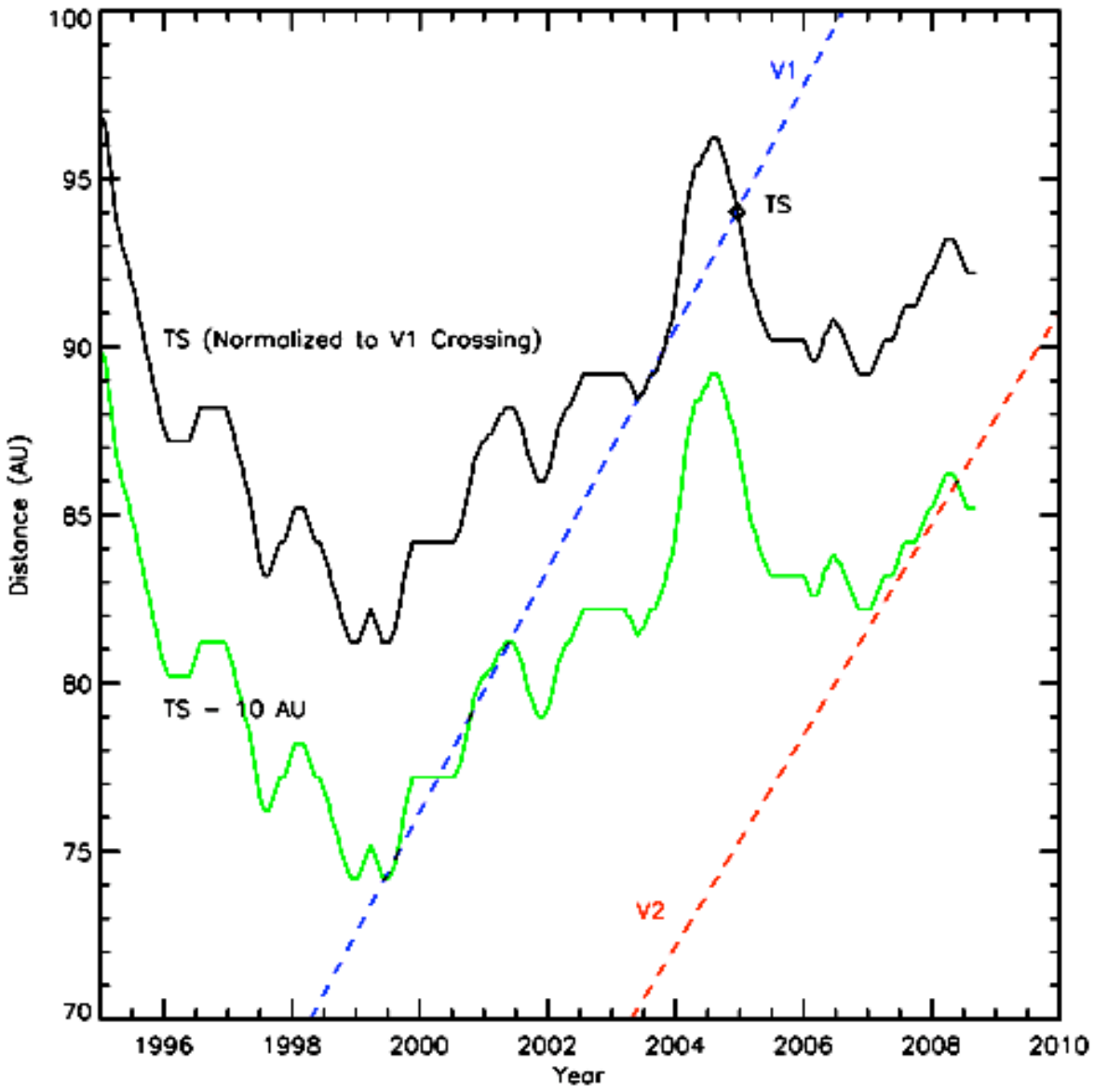




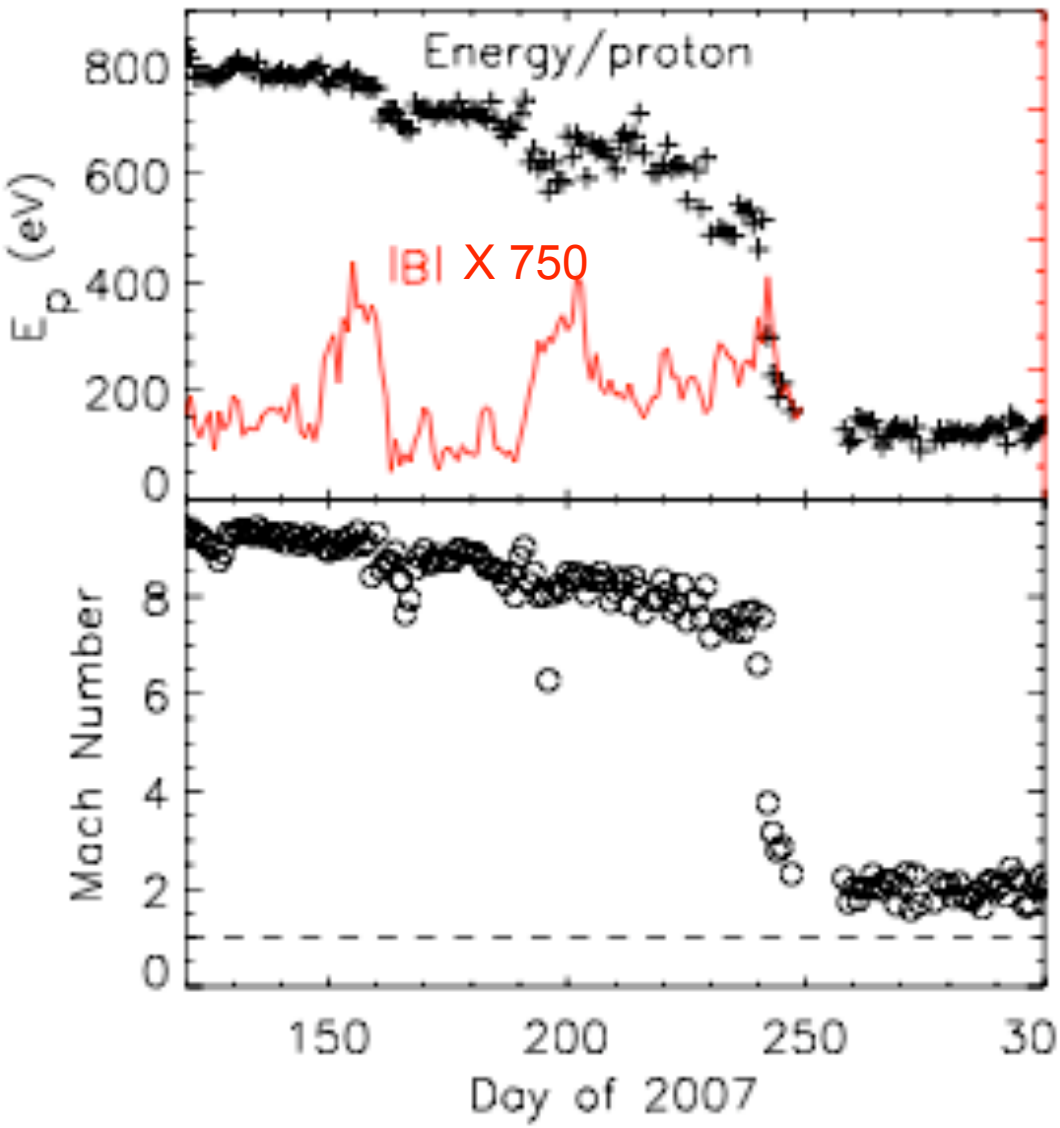
- TS Overview
- Speed decrease starts 82 days, 0.7 AU before TS
- Crossing clear in plasma data
- Flow deflected as expected
- Crossing was at 84 AU, 10 AU closer than at V1

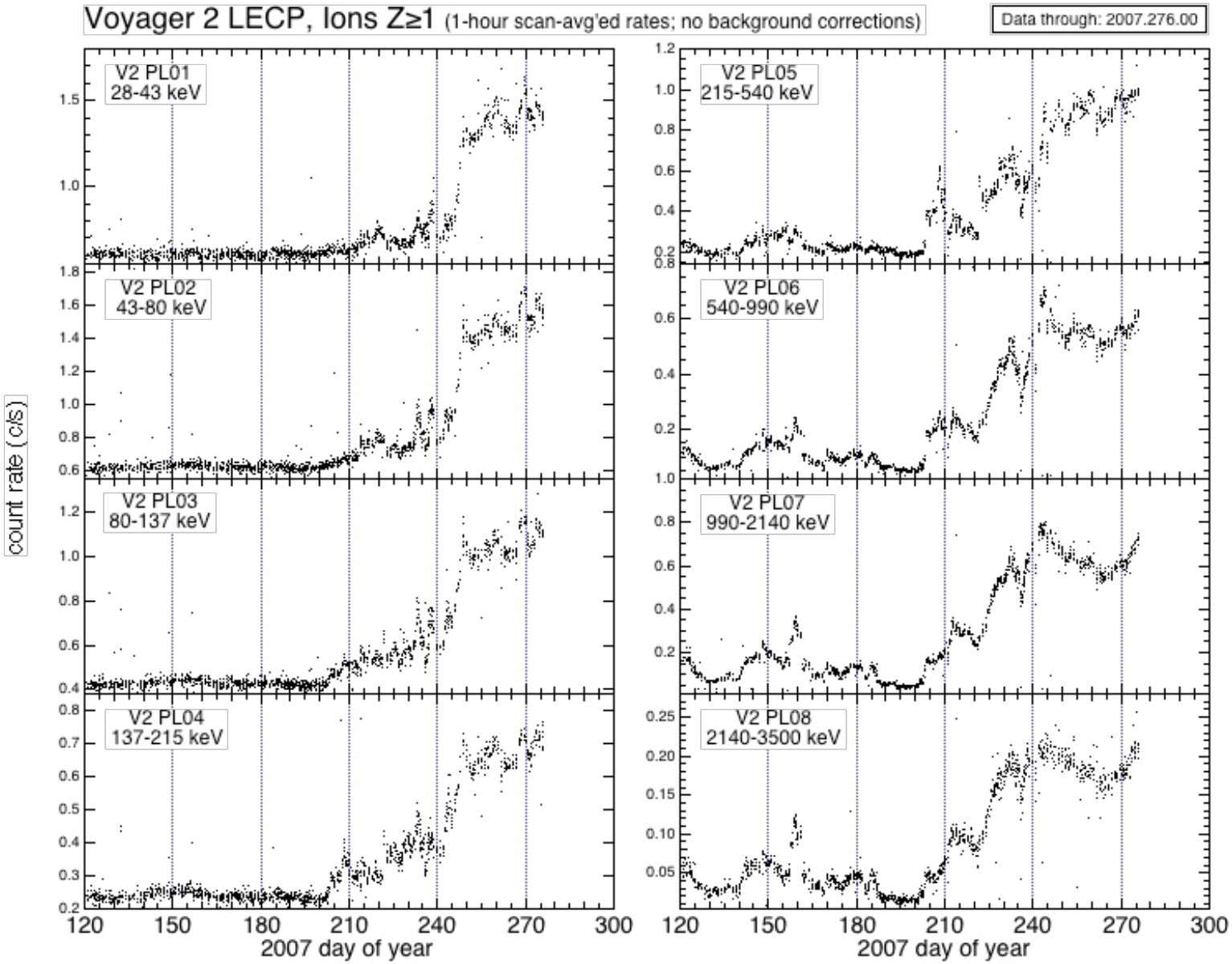


- TS location predictions
- 2-D model of Chi Wang uses V2 SW pressure as input
- Normalized to V1 crossing
- Predicts TS location ~3 AU closer than at the V1 TS crossing
- Thus TS asymmetry is 7 AU



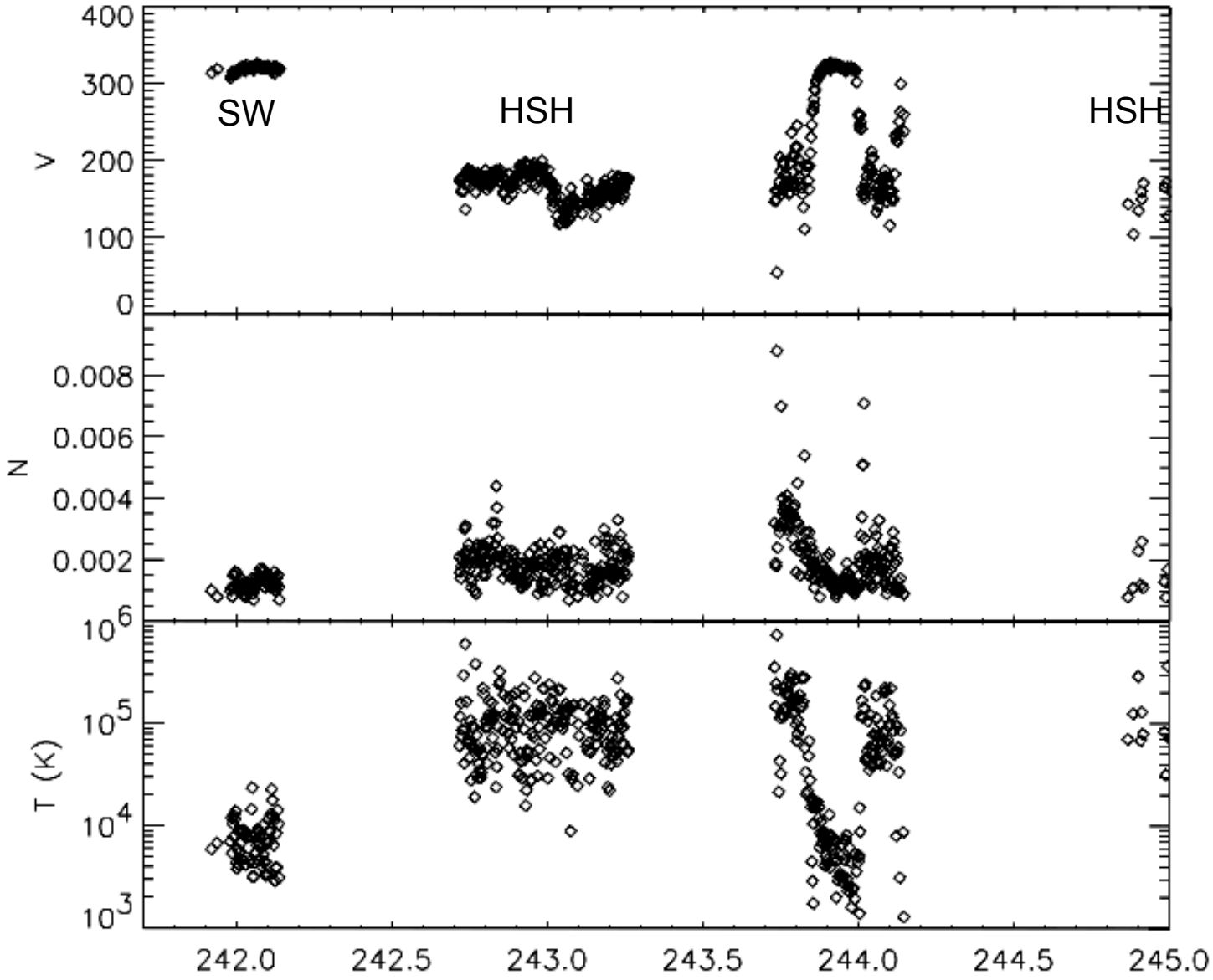
- SW energy drops in discrete steps before TS (associated with MIRs?)
- 40% of sw flow energy is lost before TS

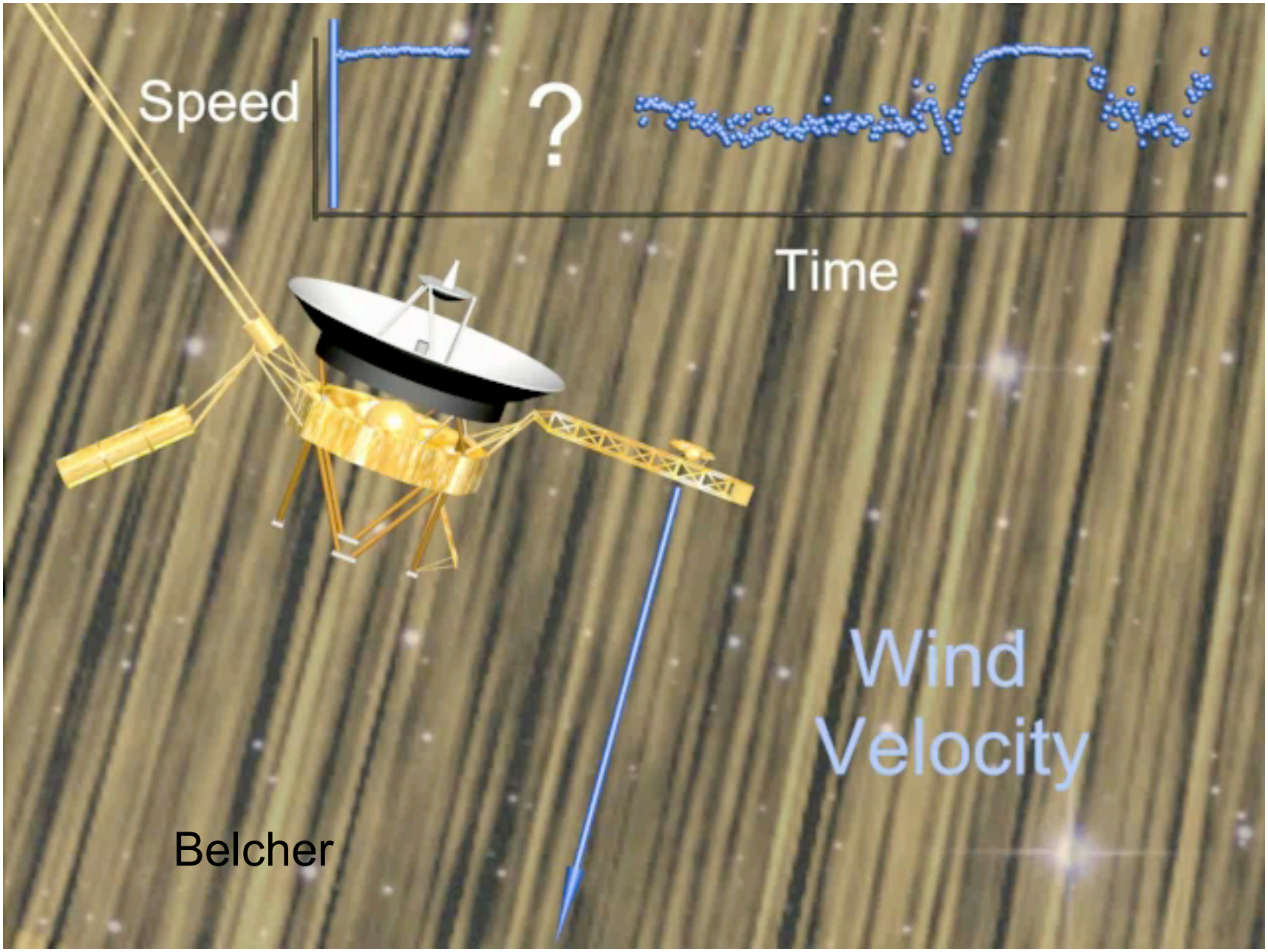




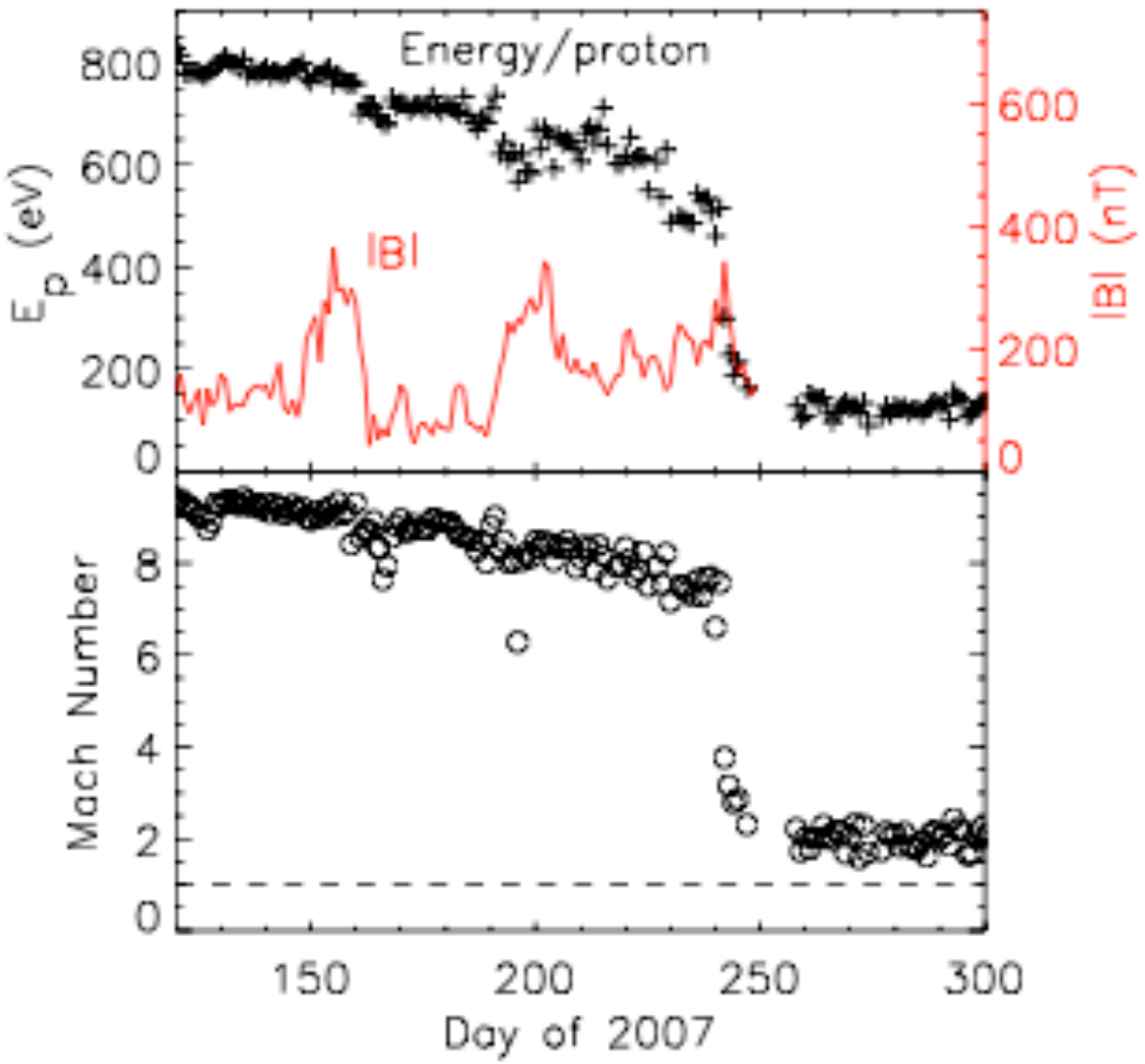
Energetic particles at V2 (Decker)

Voyager 2 Termination Shock Crossings

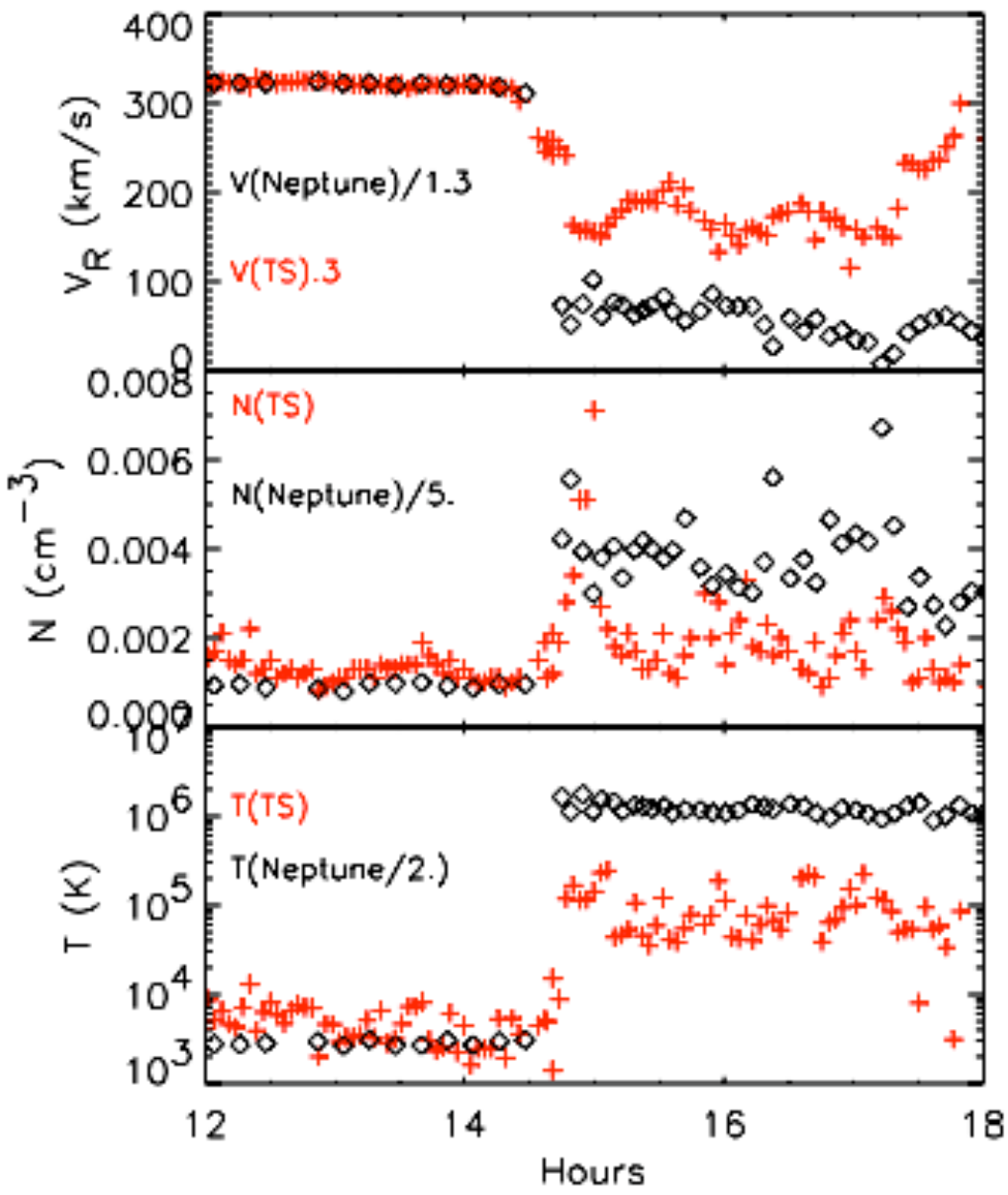



Speed
?
Time
Wind
Velocity
Belcher

- Flow remains supersonic wrt thermal plasma in sheath.
- Energy must reside in pickup ions



- Neptune BS - TS comparison
- Normalize SW to values at TS
- Same time scale.
- Neptune BS much stronger and much more plasma heating

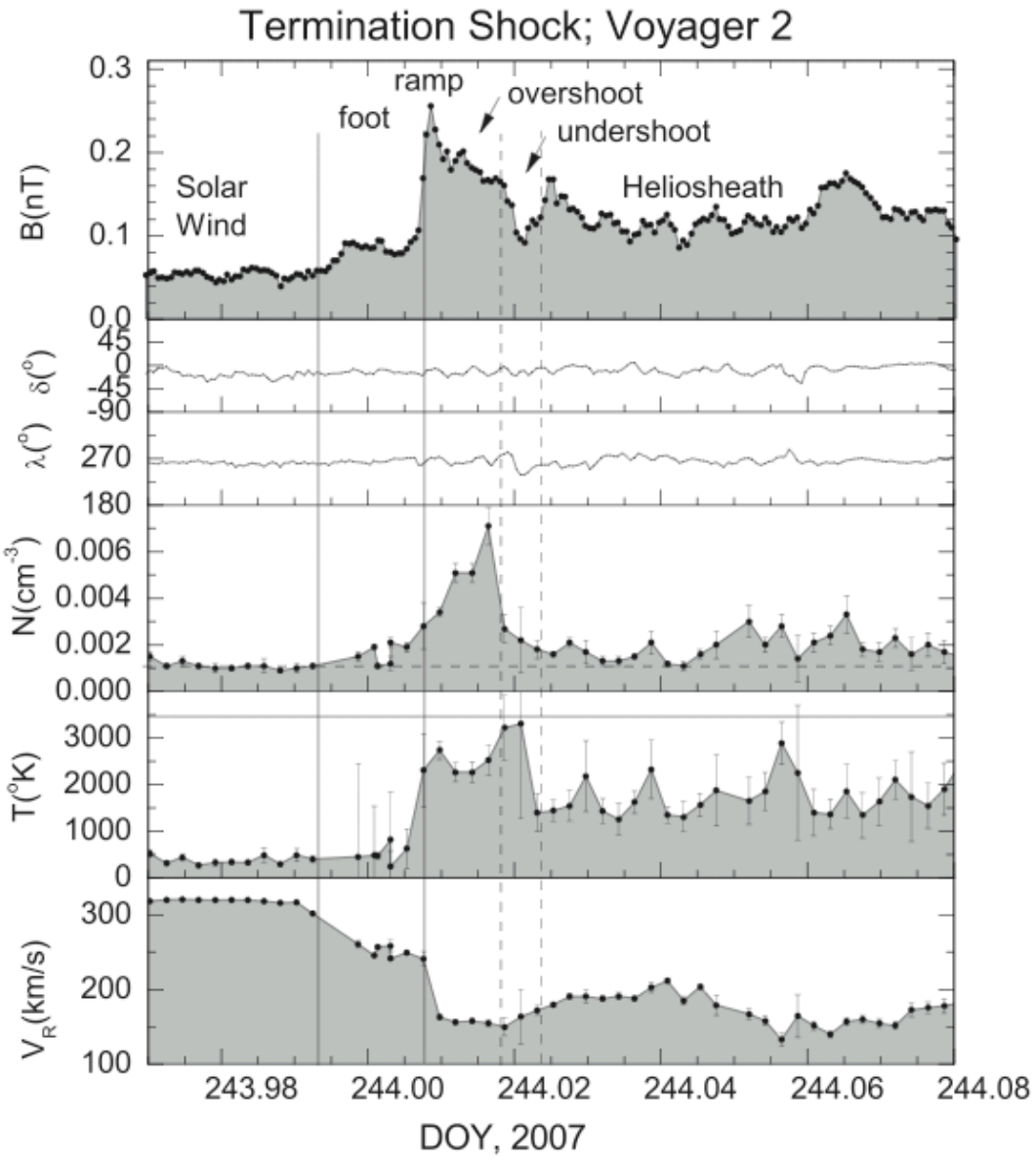


Termination Shock Jumps

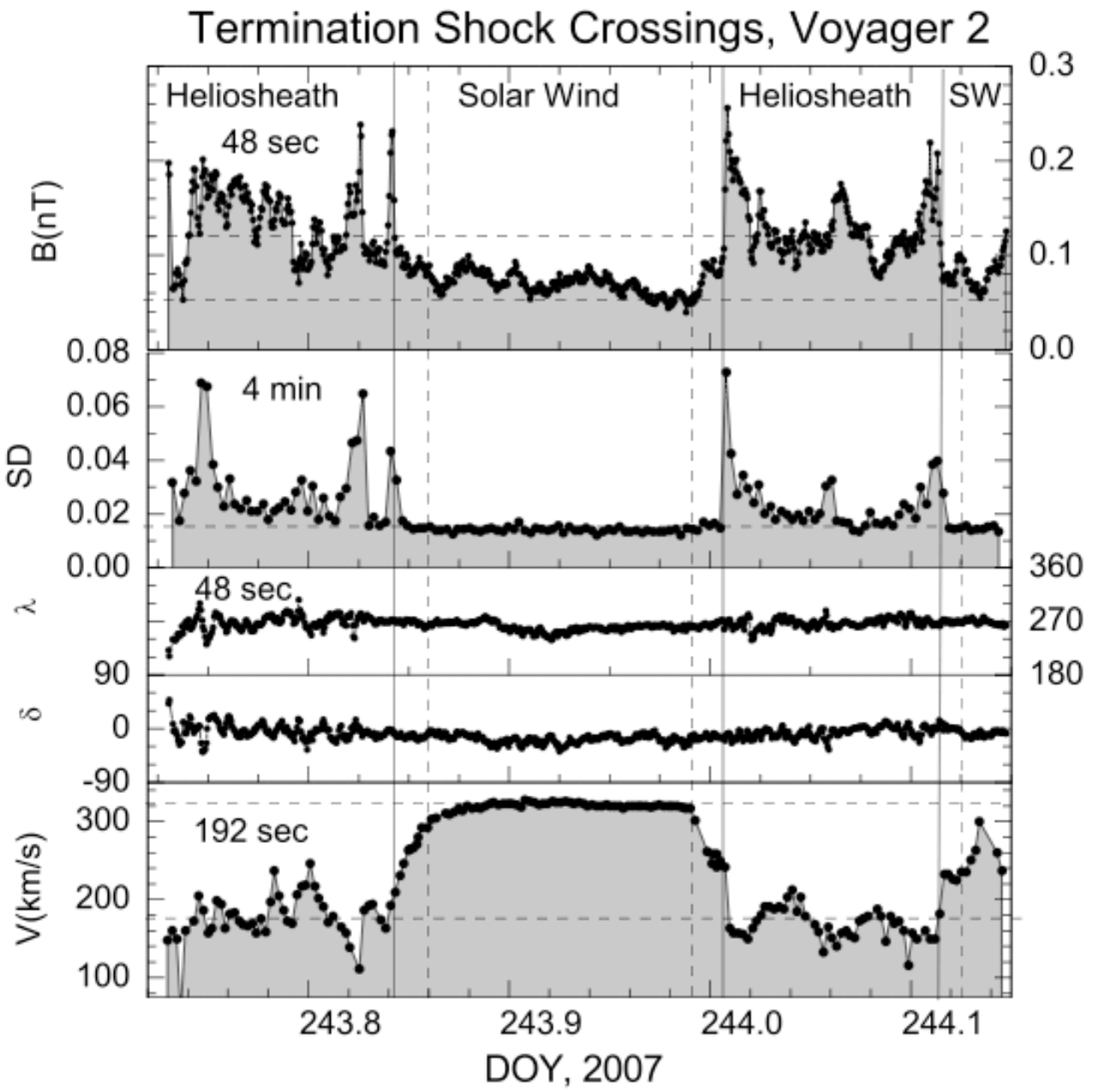
	Upstream	Downstream
|V|	320.5	172
N	0.0012	0.0024
W	10	50
Vt	9	38
Vn	-26	-32
EW	1.6	14
NS	-5	-12

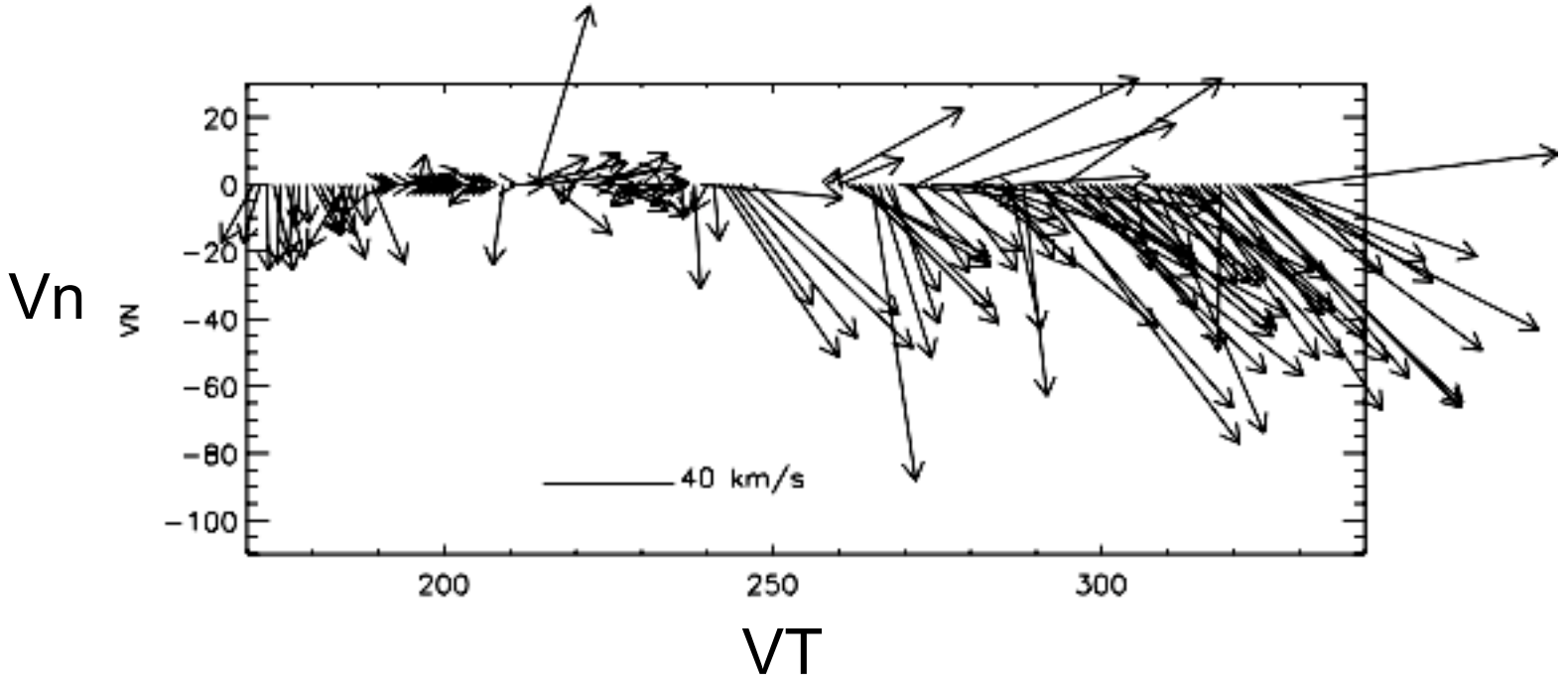
- Termination shock with classic structure: foot, ramp, shock.

(Burlaga et al.)



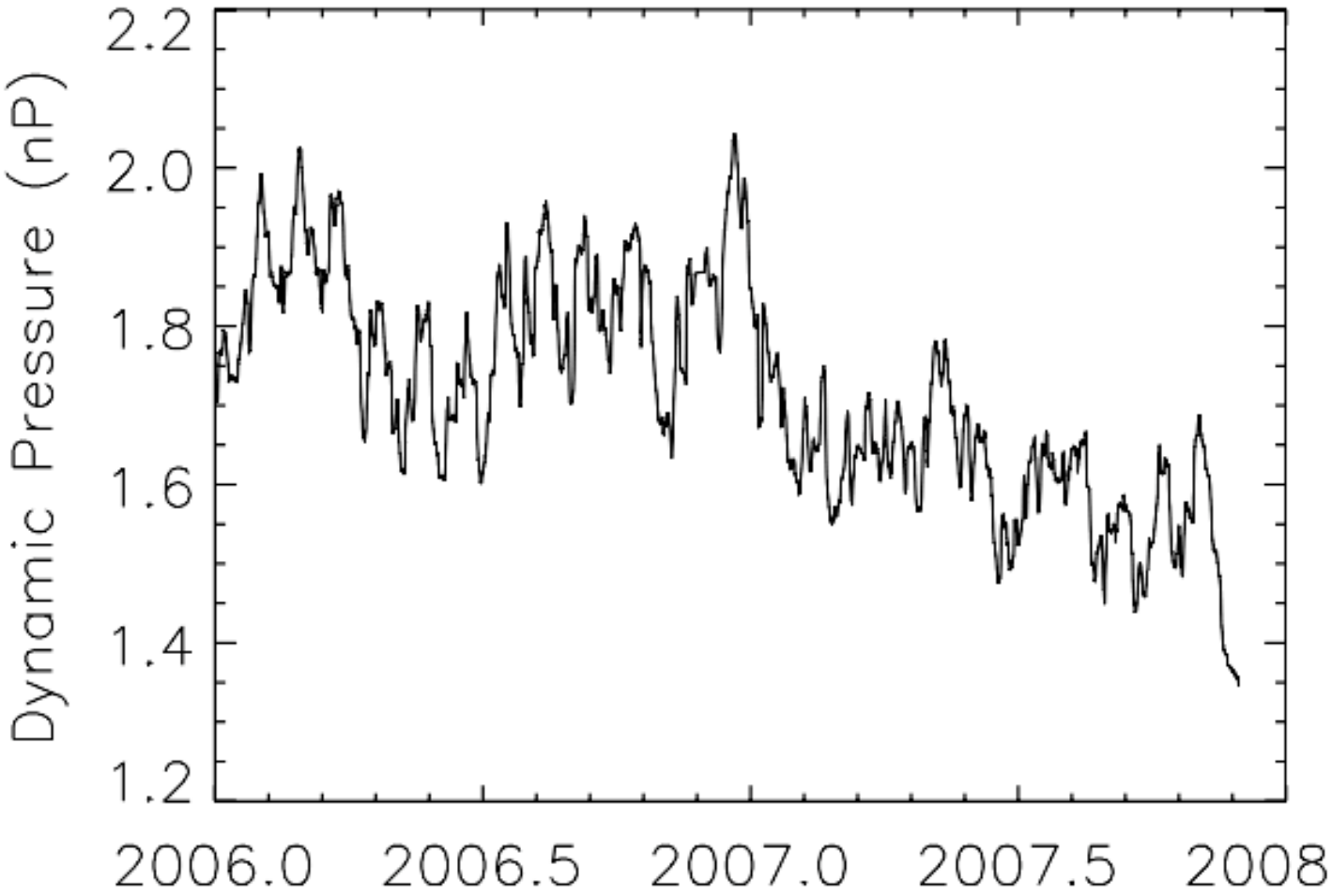
Structure of first TS crossing is very different: there appear to be two ramps. Shock may be reforming downstream (Burlaga et al.)



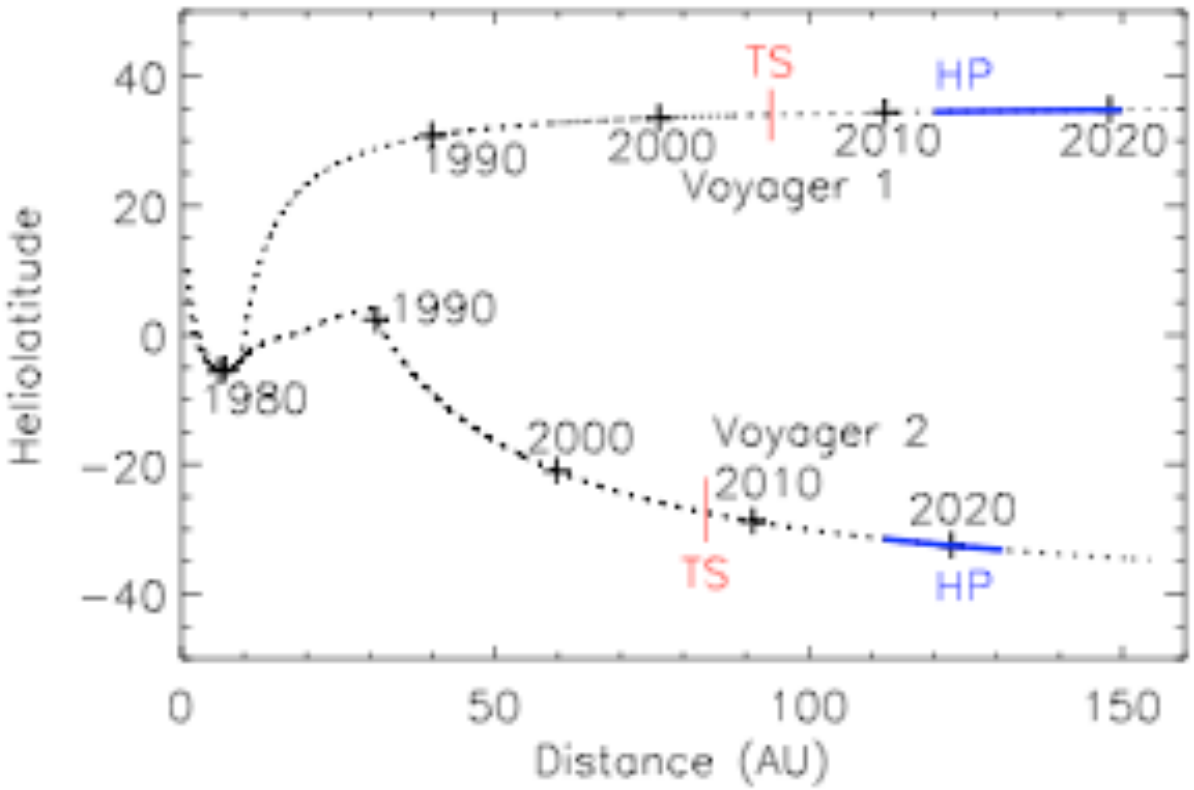


- Flow directions: as expected, flow diverts in T and -N directions
- Flow in -N before shock

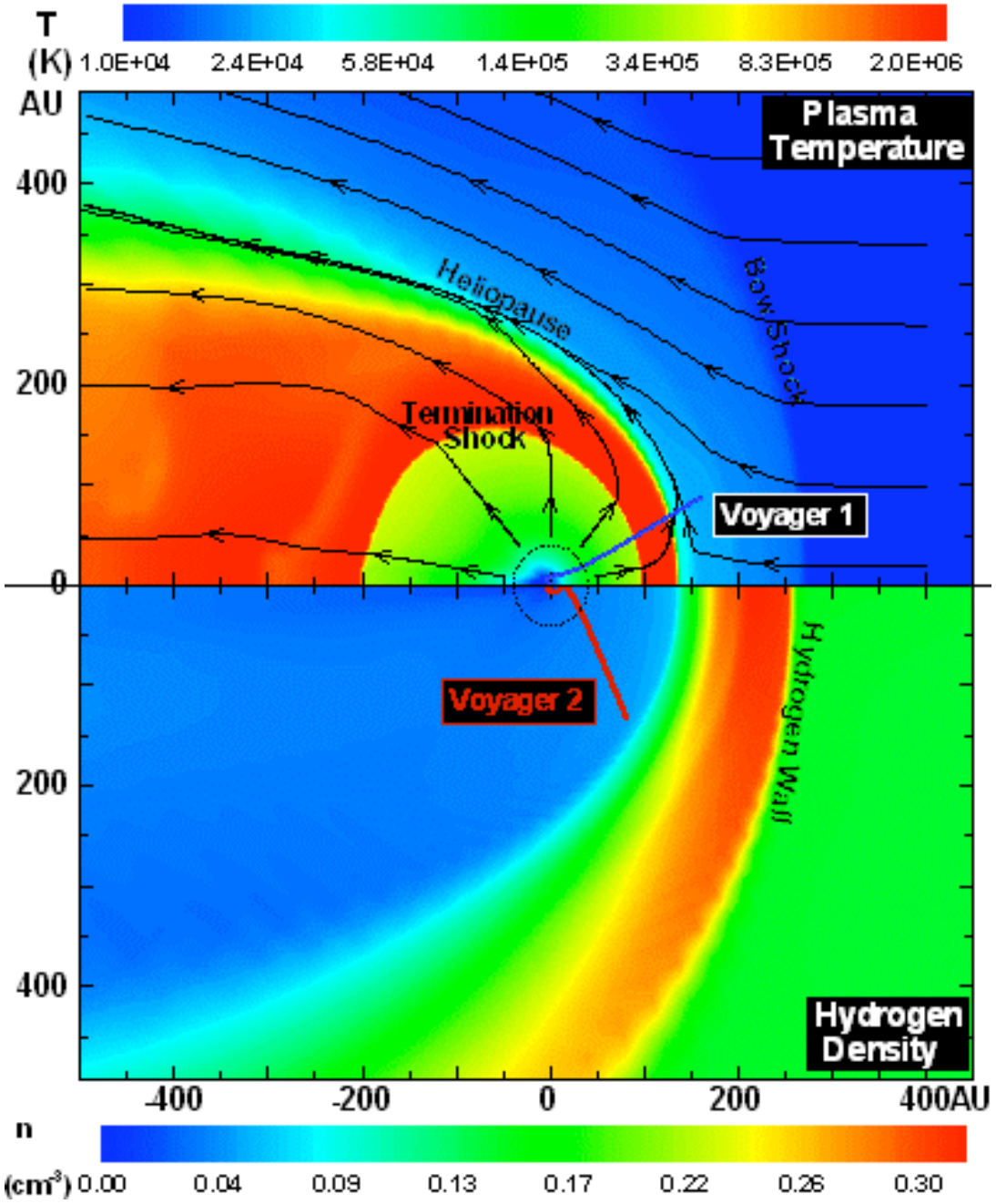
Will V2 cross TS again?



- Dynamic pressure at 1 AU (Wind)
- Decreases through 2007


40
20
0
−20
−40
Heliolatitude
0
50
100
150
Distance (AU)
TS
HP
1990
2000
2010
2020
Voyager 1
1980
1990
2000
Voyager 2
2010
2020
TS
HP

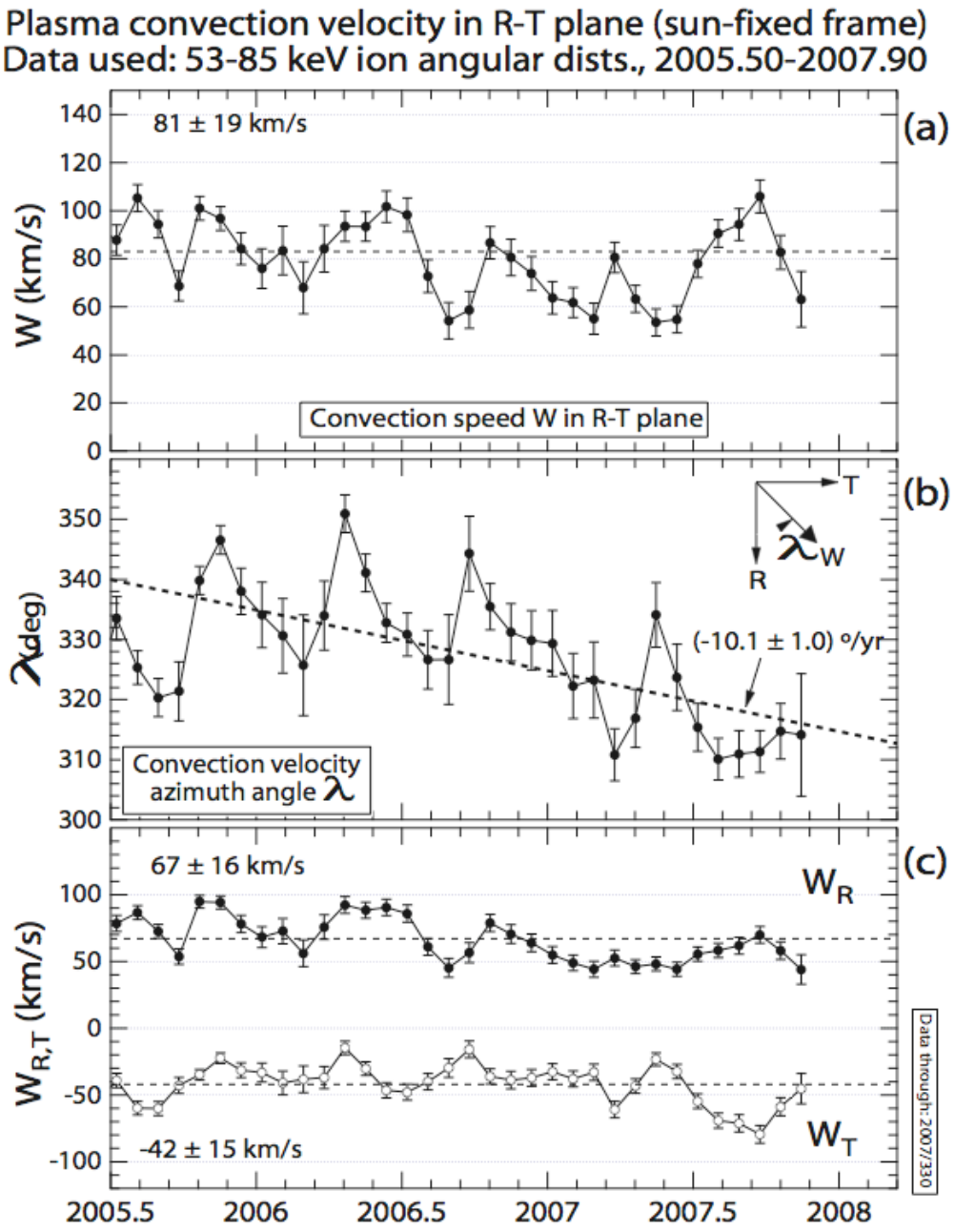
Interstellar neutrals



Flow angle changes across HSH

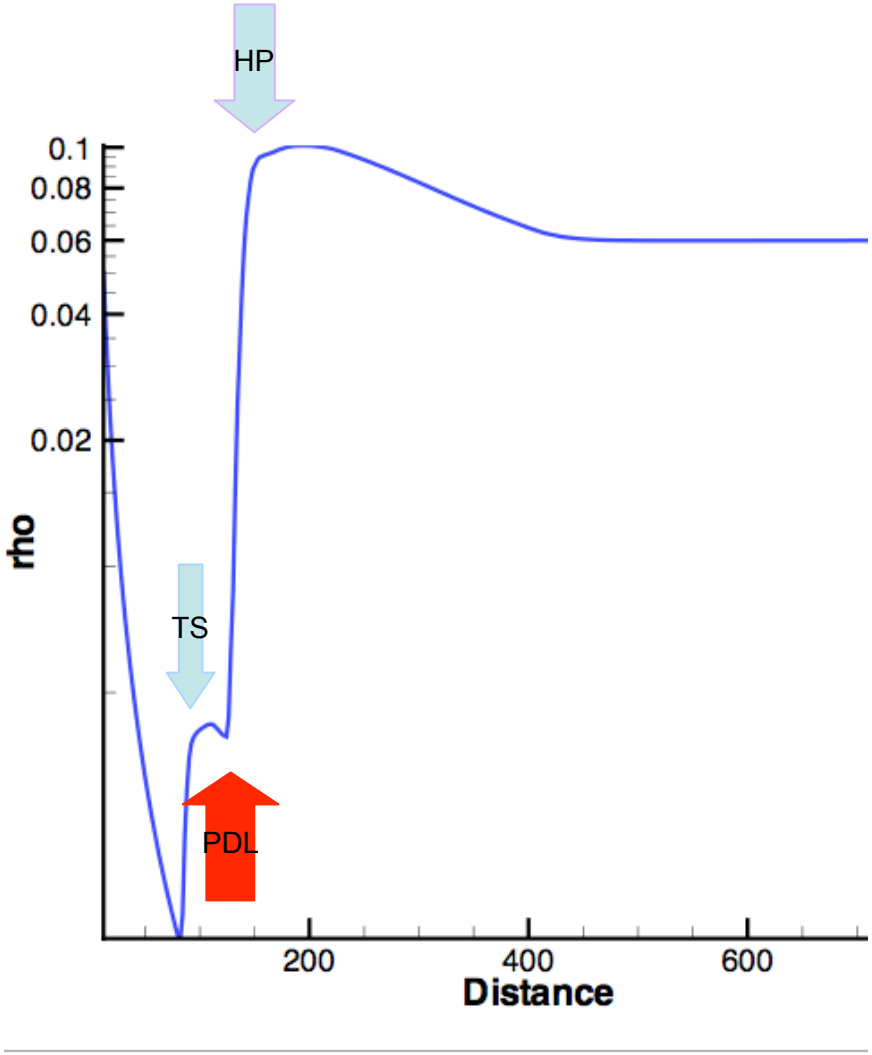
Mueller et al.

- Flow turns across HSH and must be parallel to the HP at the HP.
- Decker et al. show that angle is changing; gives a HP thickness of 30 AU.

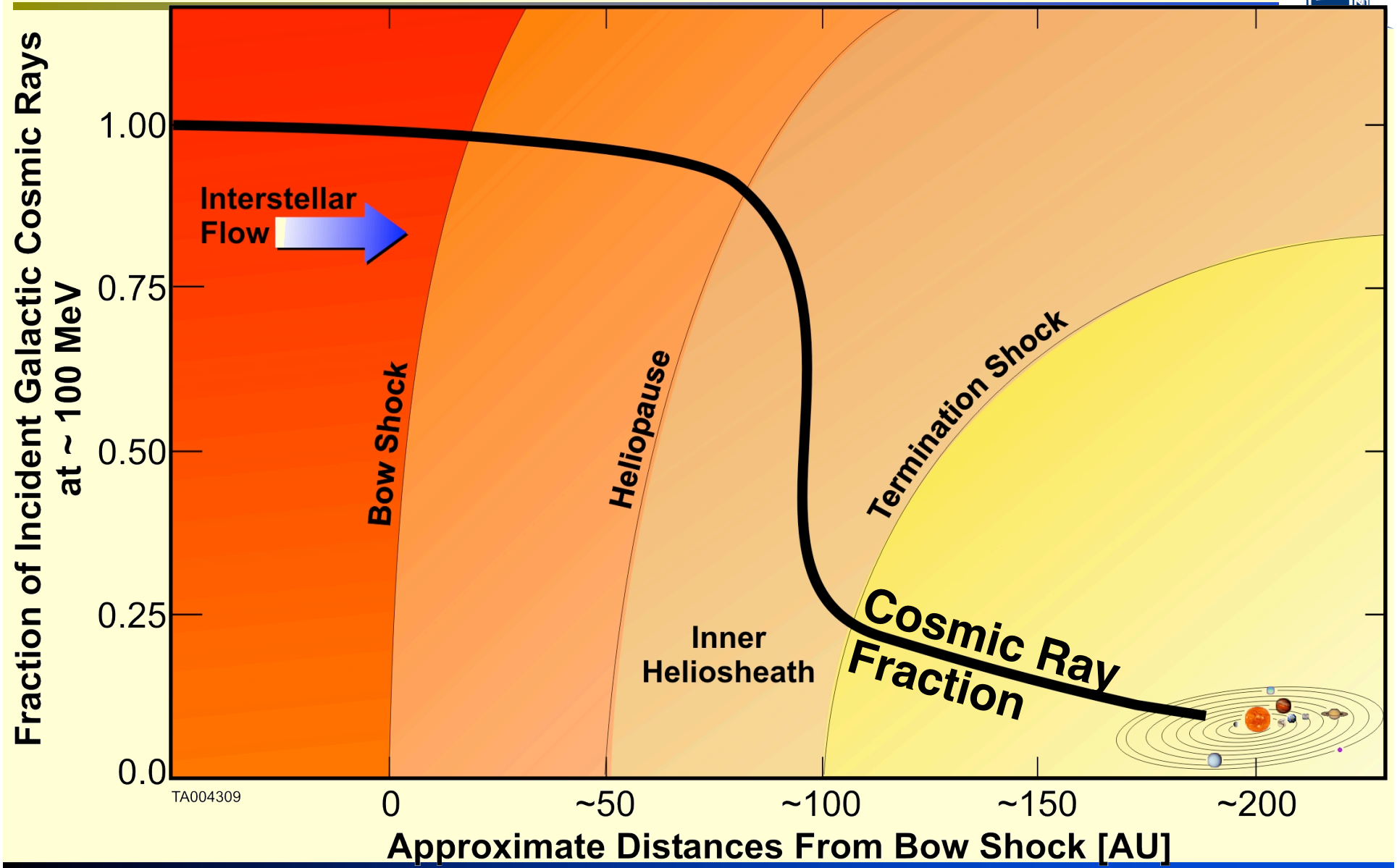


Heliosheath PDL?

- Axford-Cranfill postulate increased magnetic field at HP boundary.
- Models also suggest a magnetic barrier may form. (Pogorelov et al., 2006)
- Results in plasma depletion layer in model.



Relevant to Exploration: Cosmic Ray Shielding



Courtesy: *D. McComas*

LIC He from 3 Methods

(Efforts of an ISSI Team)

- Velocity = 26.3±0.4 km/s
- Temperature = 6300±340 K
- Density = 0.015±0.0015 cm^{-3}

- **LIC H Density: 0.2 ± 0.02 cm^{-3}**

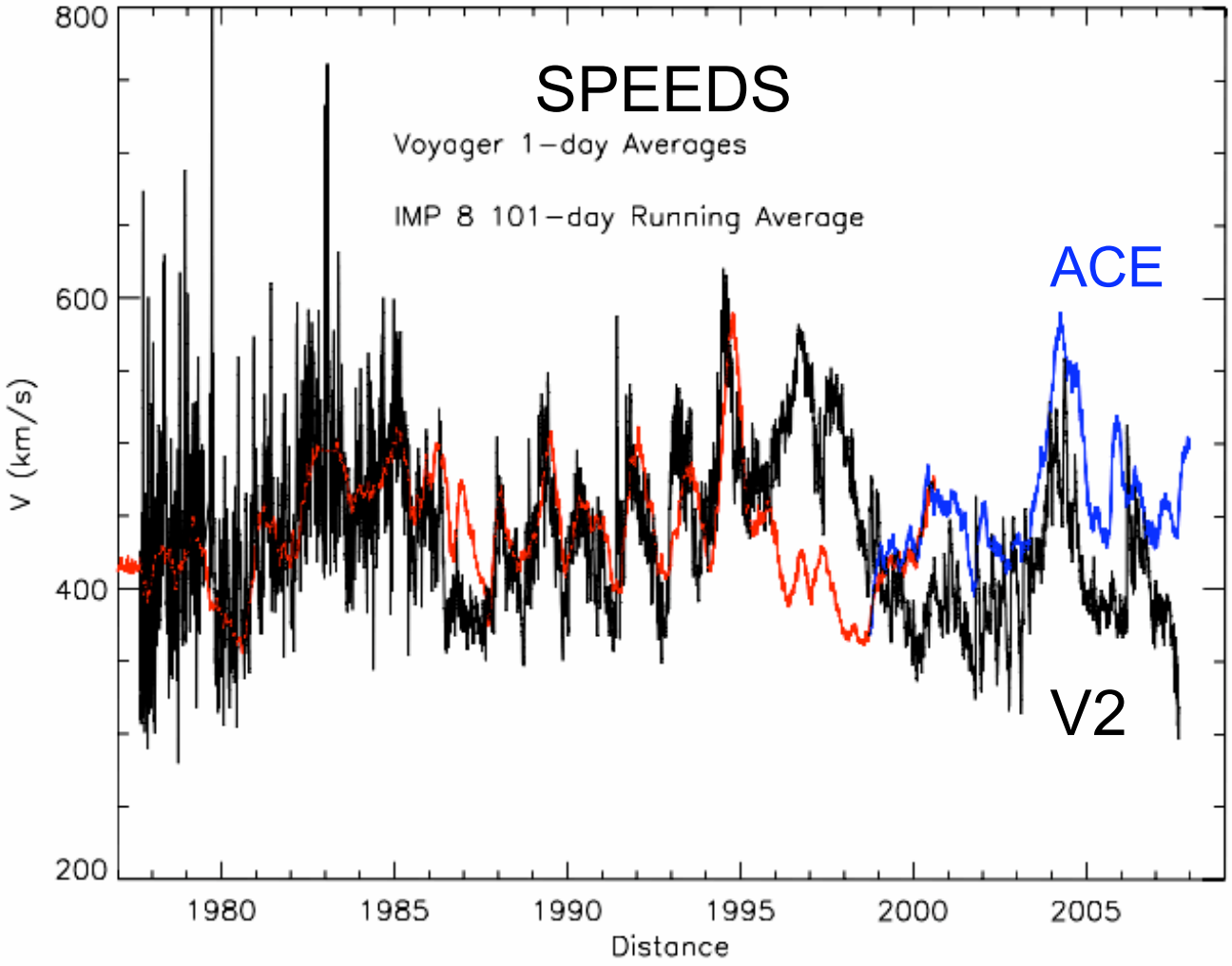
Summary

- Voyager 2 crossed the TS in Aug. 2007
- Showed heliosphere is asymmetric
- Shock strongly modulated by pickup ions
- TS effects start 0.7 AU upstream of TS

Why Interstellar Helium? (and not Hydrogen)

- **Has the Highest Ionization Potential**
  i.e. ***Reaches 1 AU***
- **Can be Observed with 3 Methods:**
  Neutrals, Pickup, Scattering of Solar UV
- **Second Most Abundant Species**
  i.e. ***Is an Important Species in the LIC***
- **Not Affected by the Heliospheric Interface**
  i.e. ***Provides an Unbiased Account of the LIC***

- How do LIC neutrals effect the SW?
- They start the transfer of SW flow energy into heating of plasma and particles.
- Energy acquired by pickup ions slows down SW
- 1 AU (IMP 8 and ACE) and V2 speeds.
- V2 speeds in outer heliosphere are less than those at 1 AU.



Charge exchange: ion and neutral collide and ion takes an electron. H+ + H -> H + H+

New neutral H is moving with solar wind speed and escapes

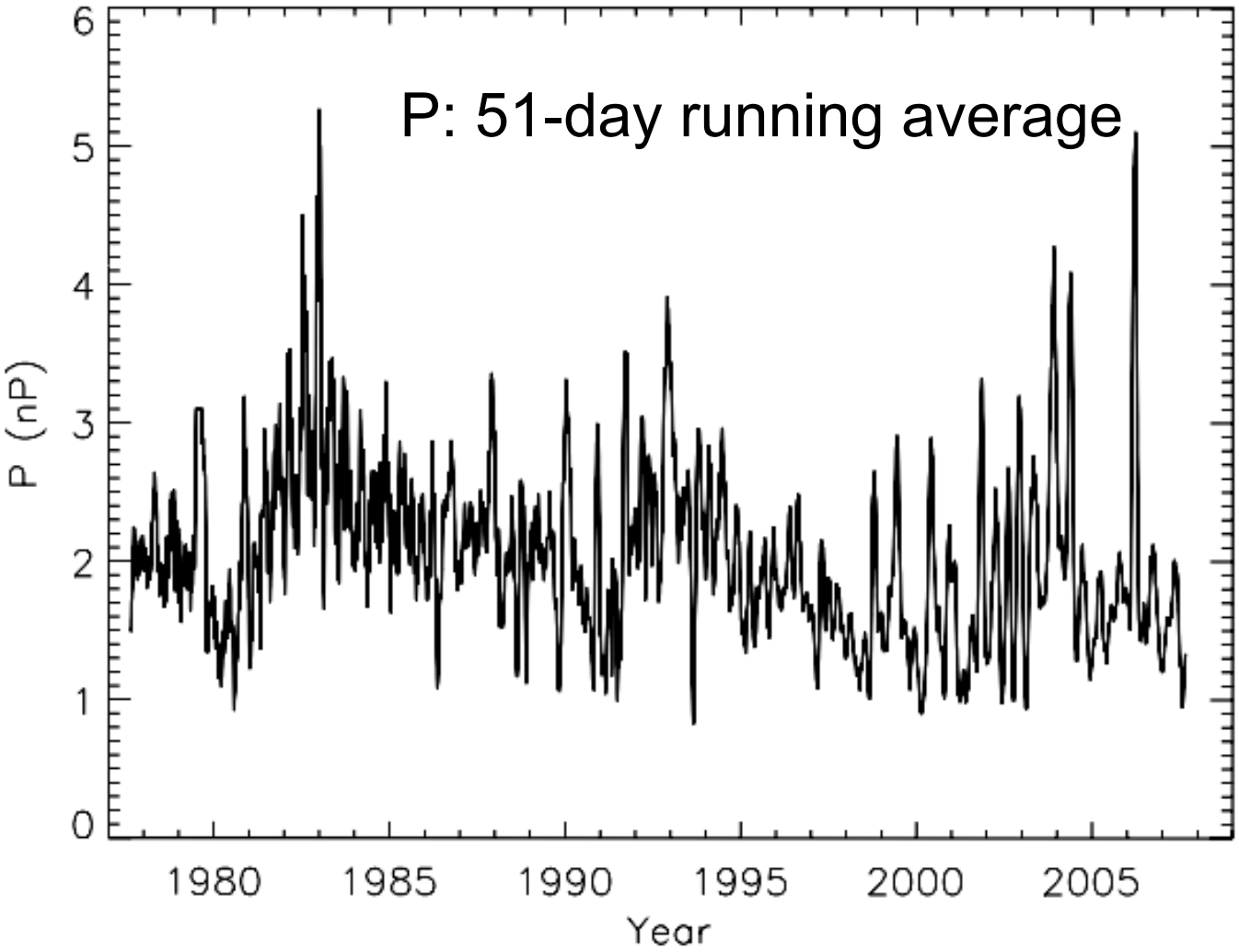
New H+ has solar wind speed and energy equal to the solar wind energy (1 keV): is called a pickup ion.

The energy/momentum come from solar wind, so solar wind slows down.

Dynamic Pressure mnV^2

Solar cycle dependence:

Factor of >2 change with peak after solar maximum



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