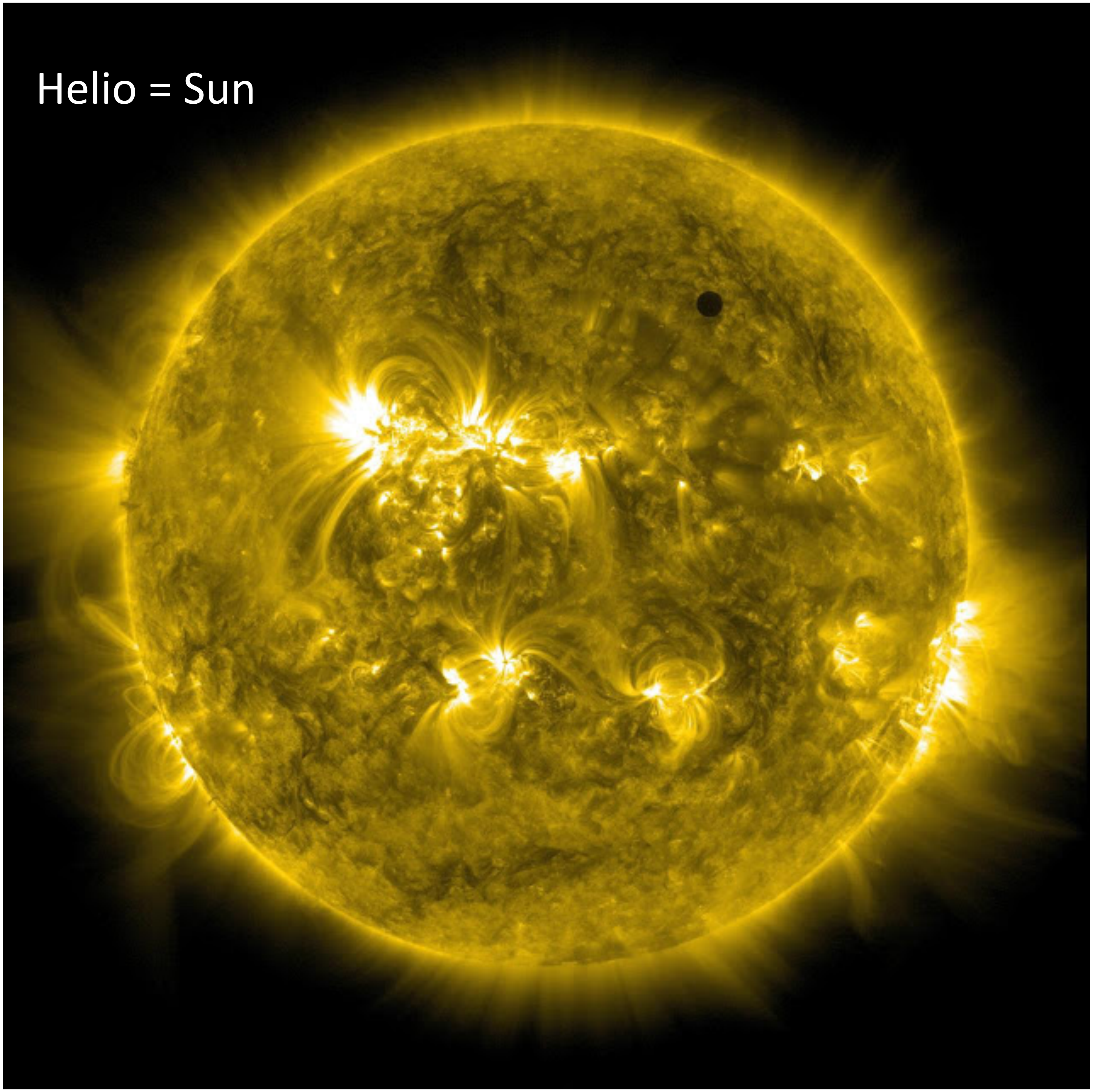
The Heliosphere's interaction with the interstellar medium: Observations and Models

John Richardson
M.I.T.

Merav Opher
Boston University

and the Voyager team

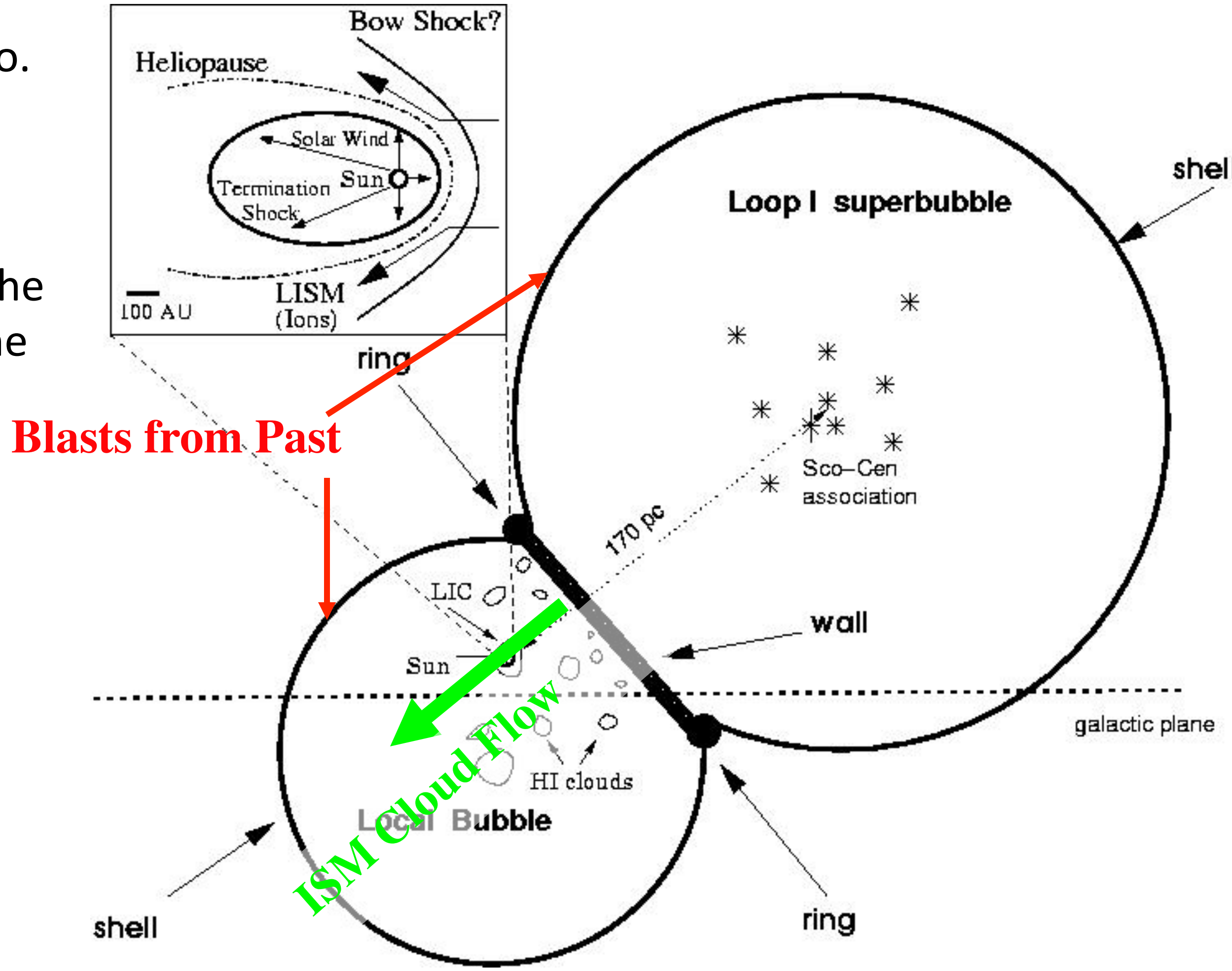

Helio = Sun

The Local Bubble

Sun is inside a hot local bubble formed by supernova explosions 10-20 million years ago.

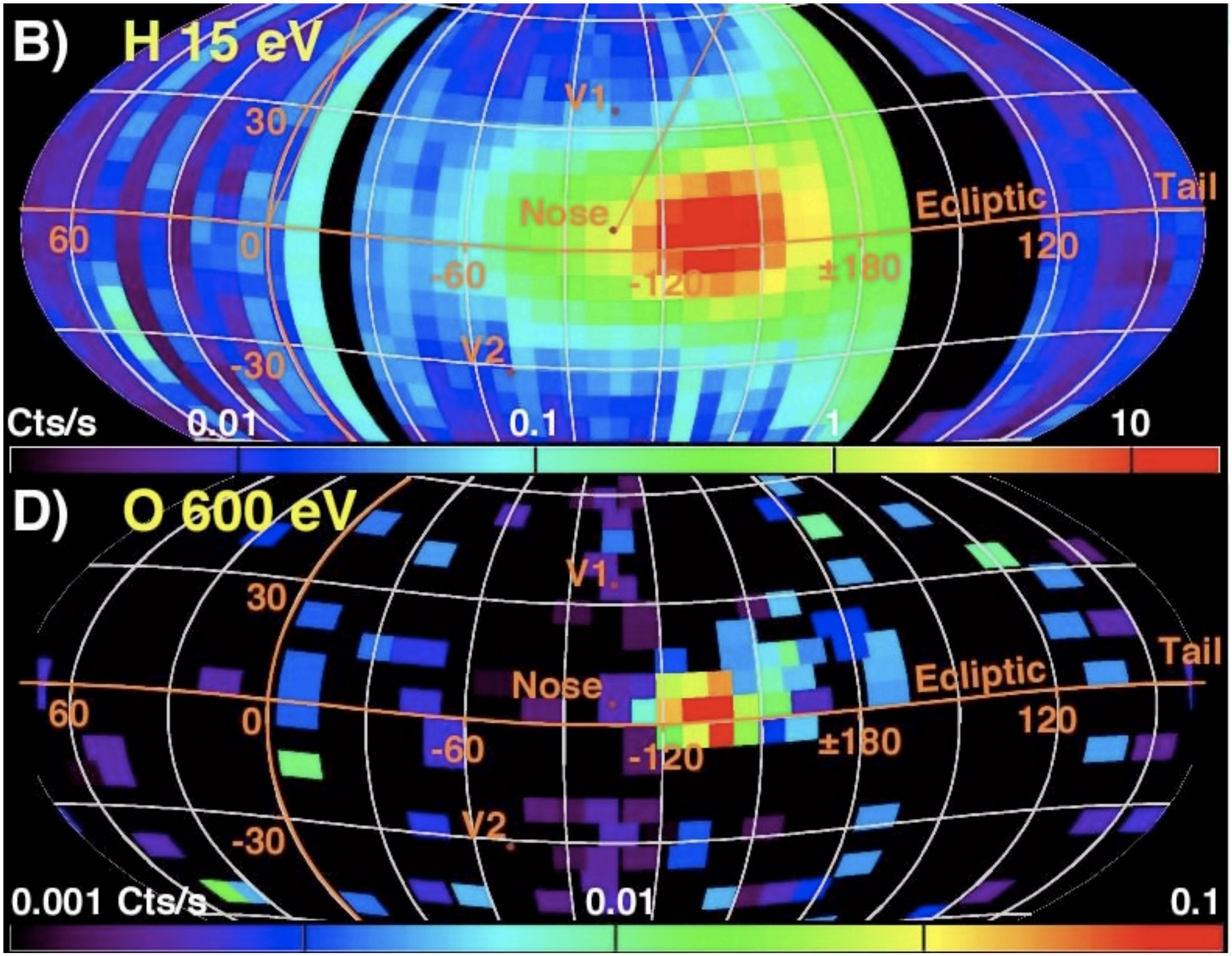
The bubble has small denser cooler clouds, perhaps breaking off the bubble boundaries. The Sun is in one of these smaller clouds.

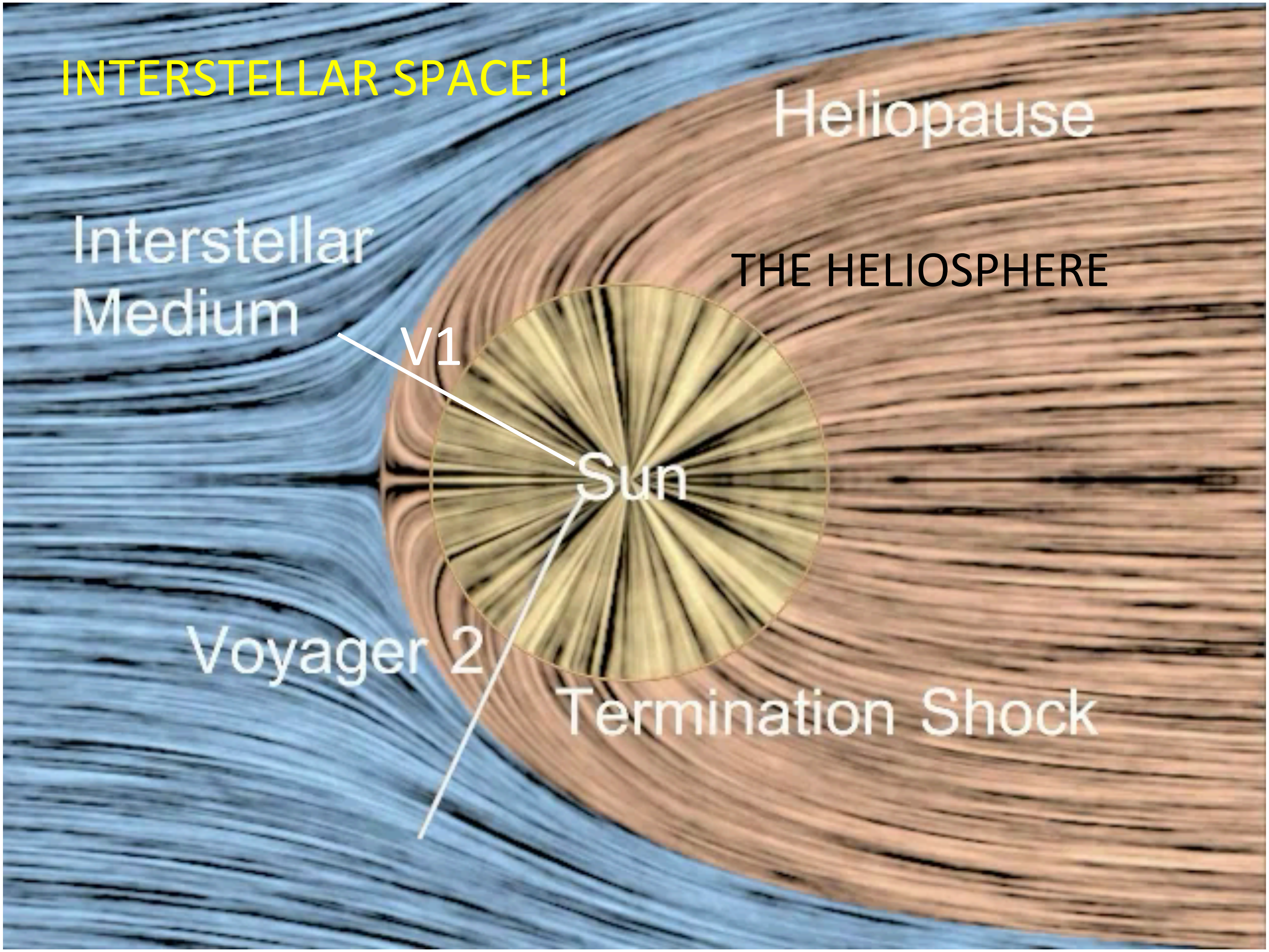
Local Bubble and Loop I are Interacting Bubbles.



Interstellar medium: neutrals observed by IBEX

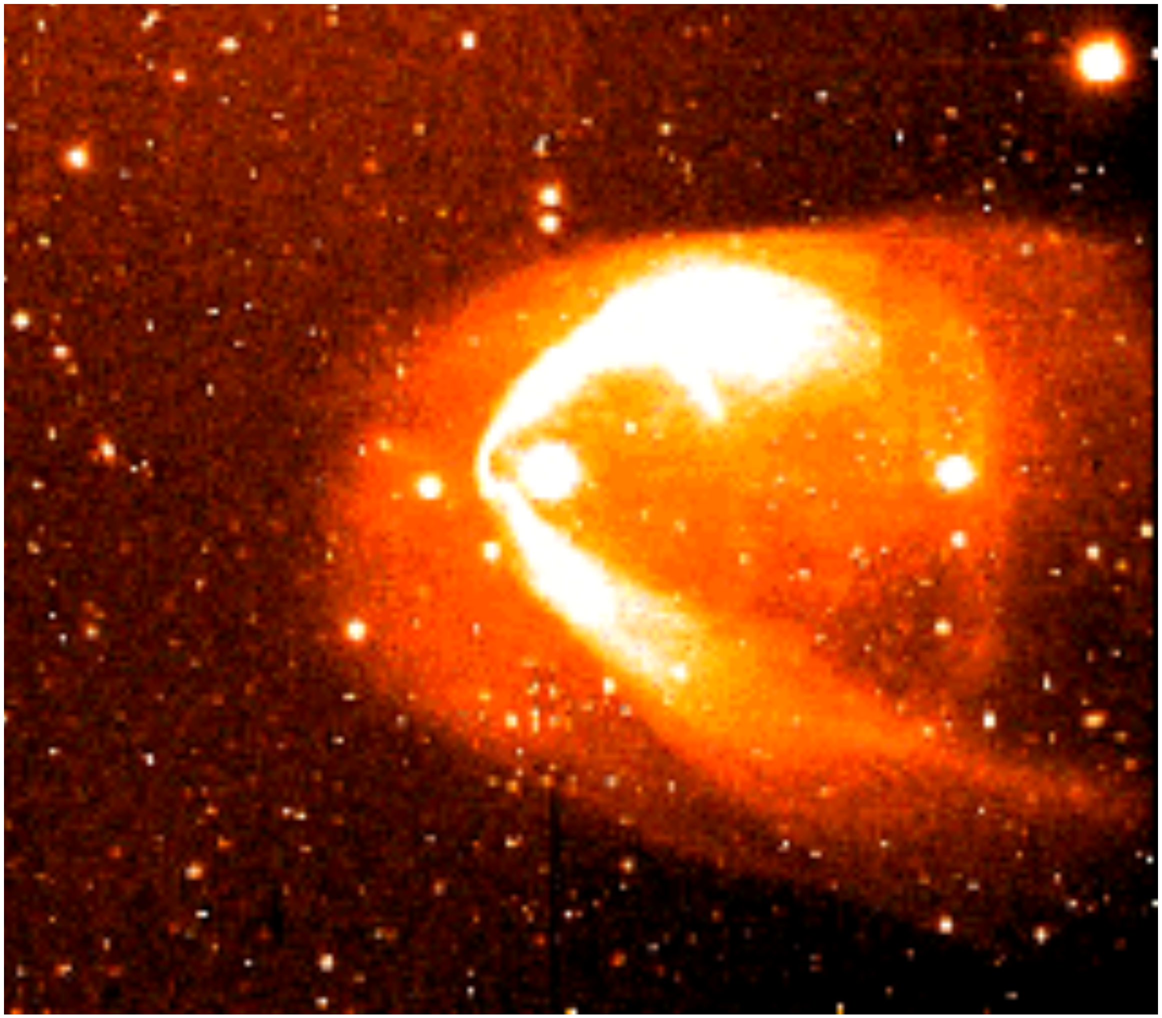
V~23.5 km/s, T ~ 6000 K, N_N~0.2 cm^{-3}, N_e~0.06 cm^{-3}

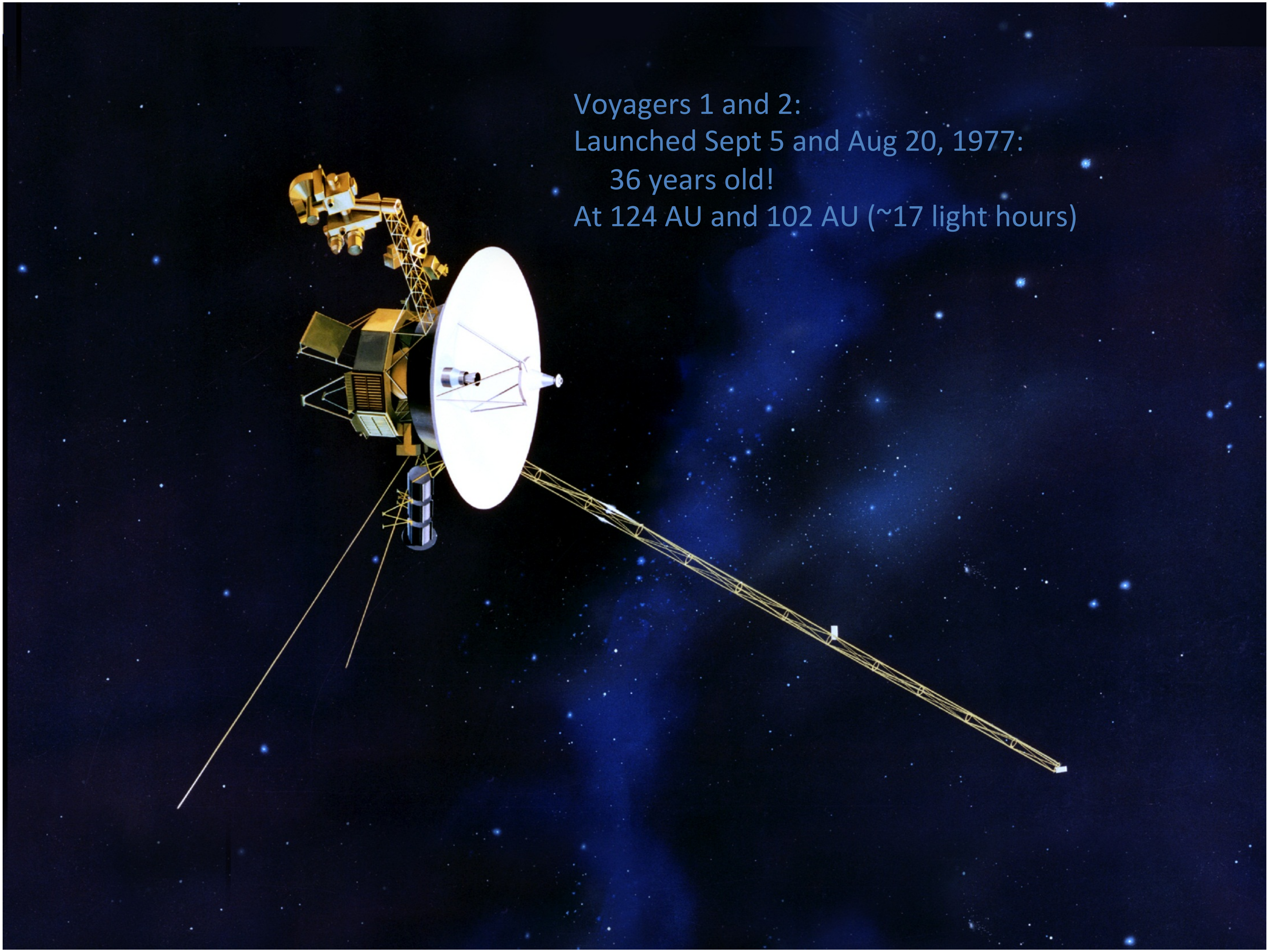




INTERSTELLAR SPACE!!
Heliopause
Interstellar
Medium
THE HELIOSPHERE
V1
Sun
Voyager 2
Termination Shock

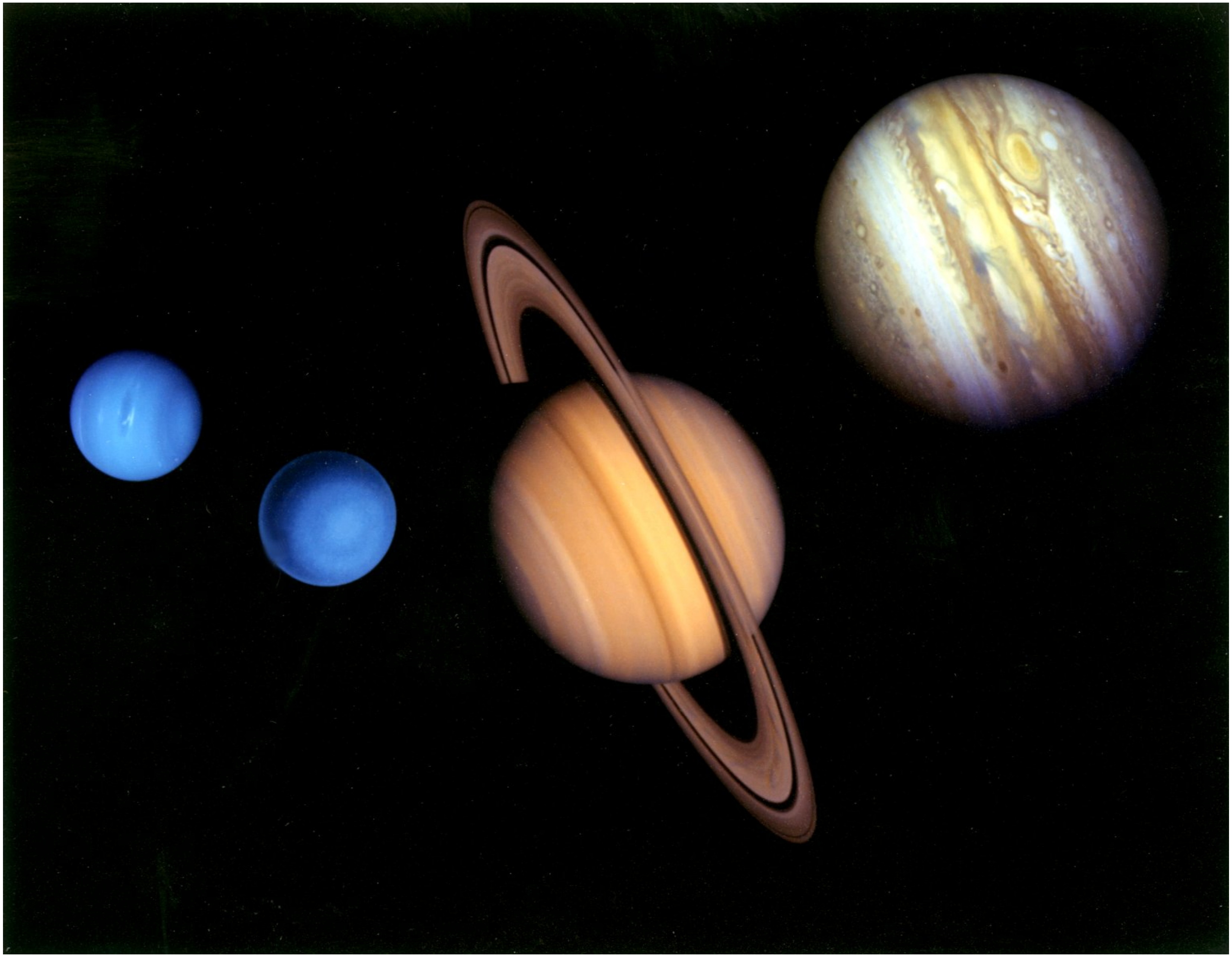
Astrosphere from Hubble




Voyagers 1 and 2:
Launched Sept 5 and Aug 20, 1977:
36 years old!
At 124 AU and 102 AU (~17 light hours)

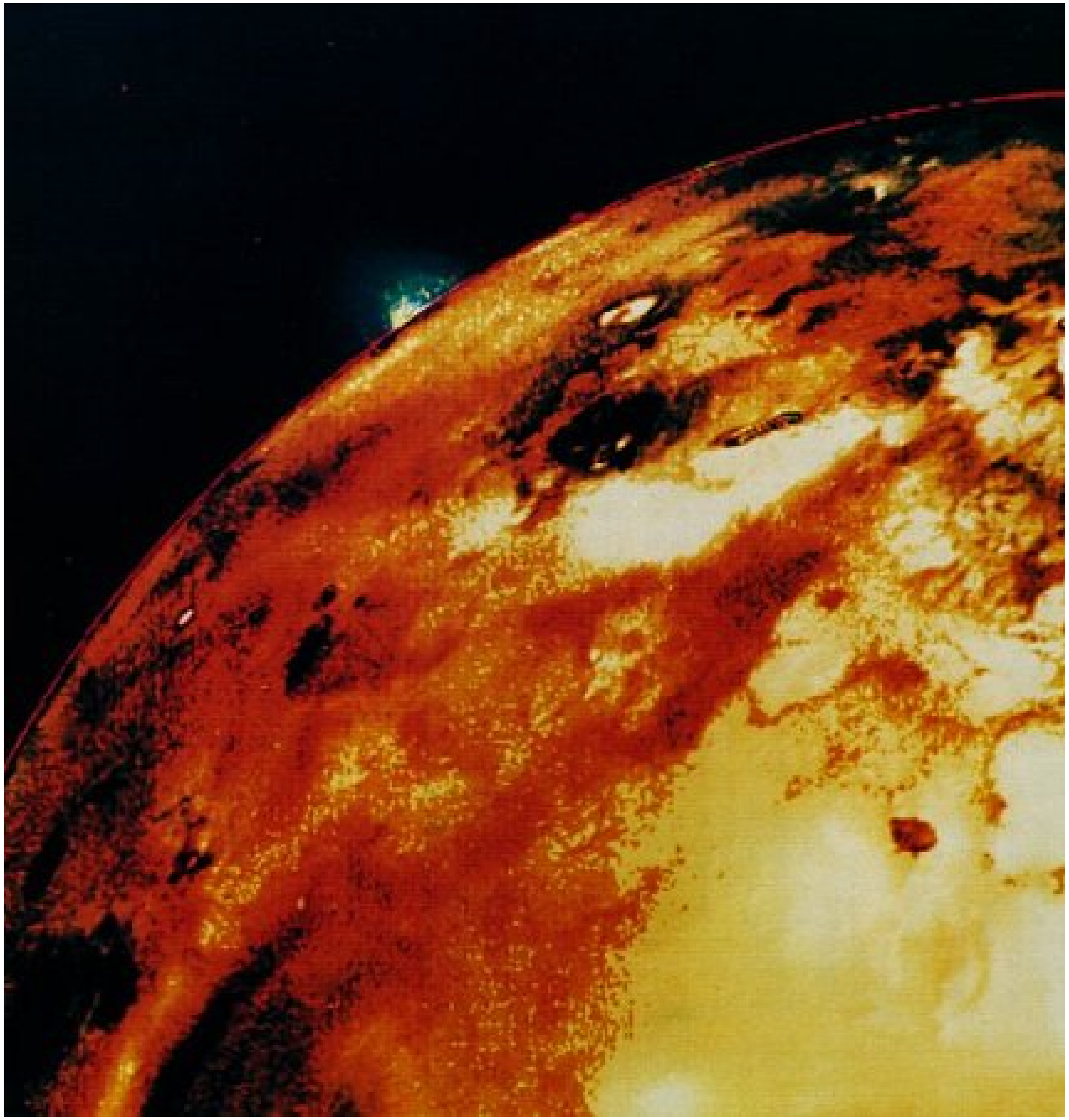
Voyager took the first picture of the Earth and Moon
11.6 million km away

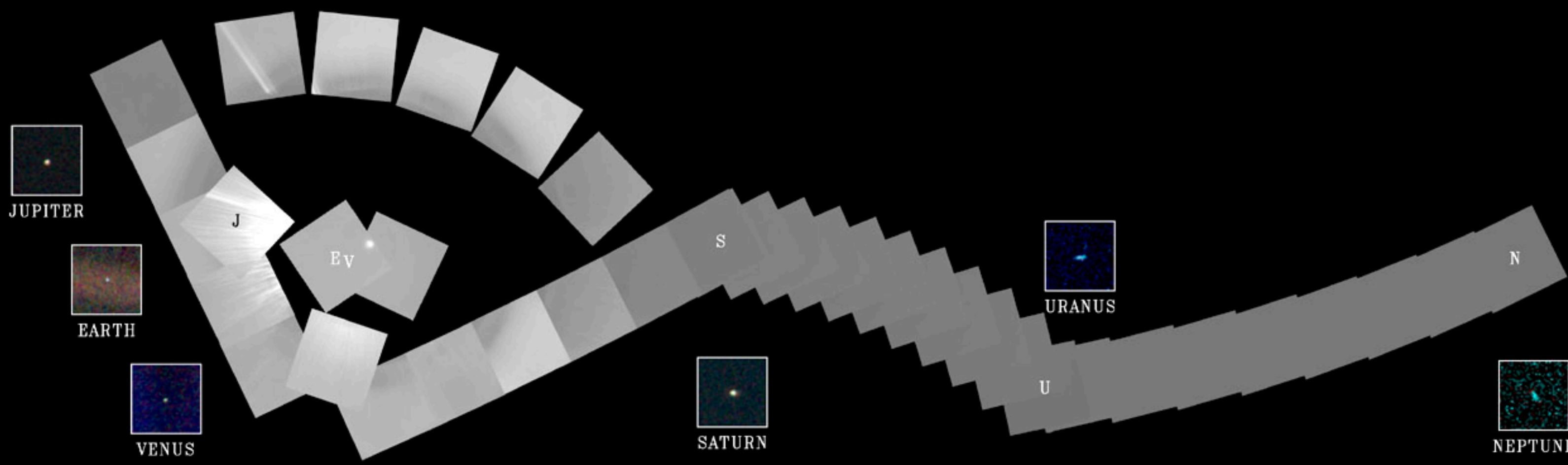
The Grand Tour: A few stops on the way out



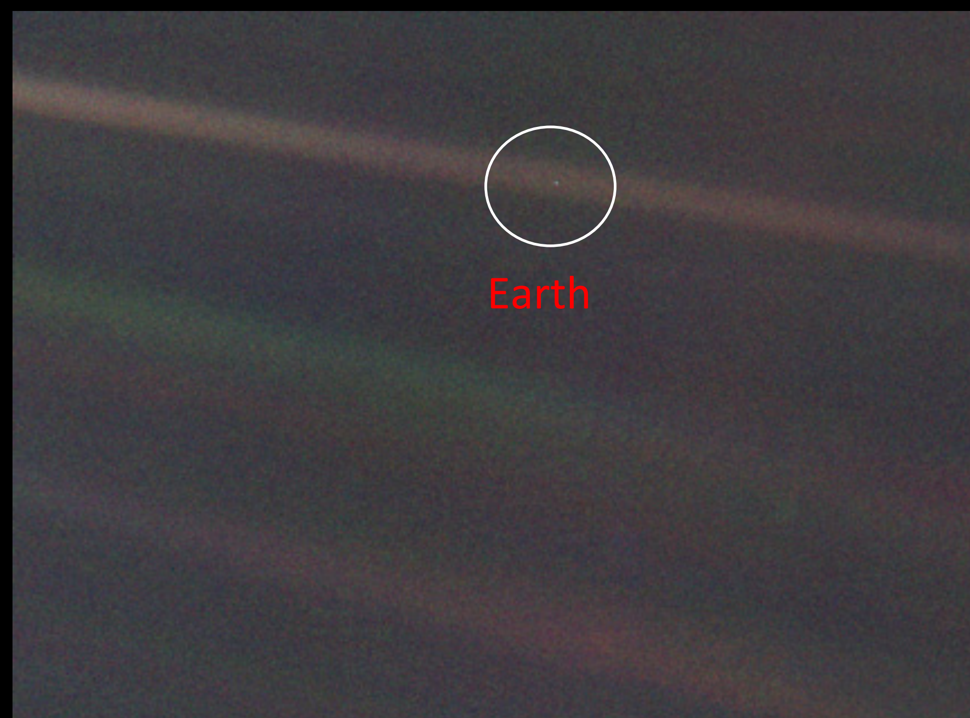
Io (Jupiter)

Most active volcanos:
1000 kg/sec of S
and O

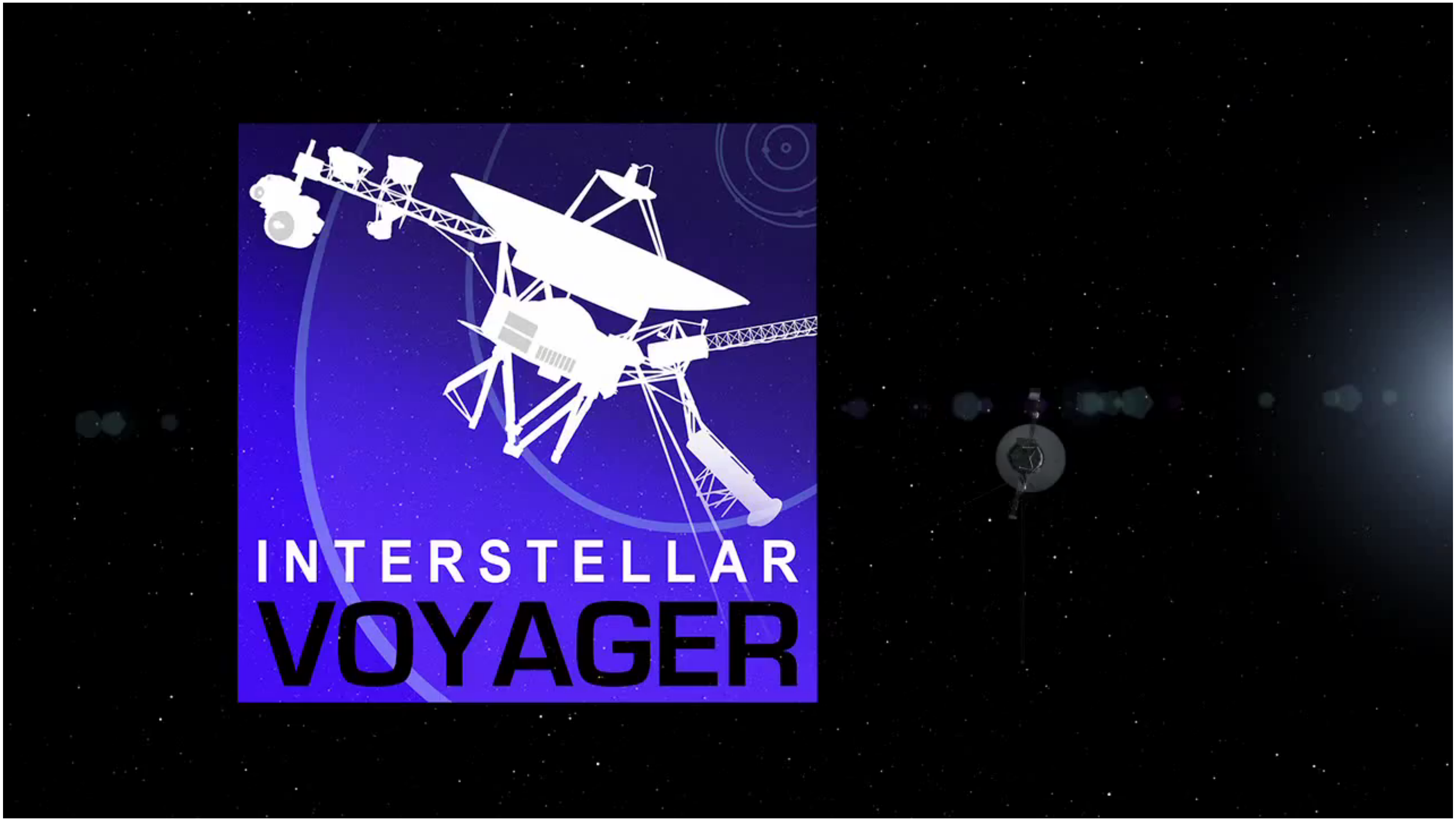




Portrait of the Solar System
Voyager 1, February 14, 1990
From 40 AU



NASA press conference, Sept. 12, 2013: V1 has entered interplanetary space!



Talk Outline

Voyager 1 has crossed the heliopause into interstellar space.

I will discuss briefly

1) The history behind the Voyager plasma experiment

2) Data showing the effects of the interstellar medium on the heliosphere

3) Data leading up to the announcement Voyager crossed the heliosphere.

4) Data that still puzzle us.

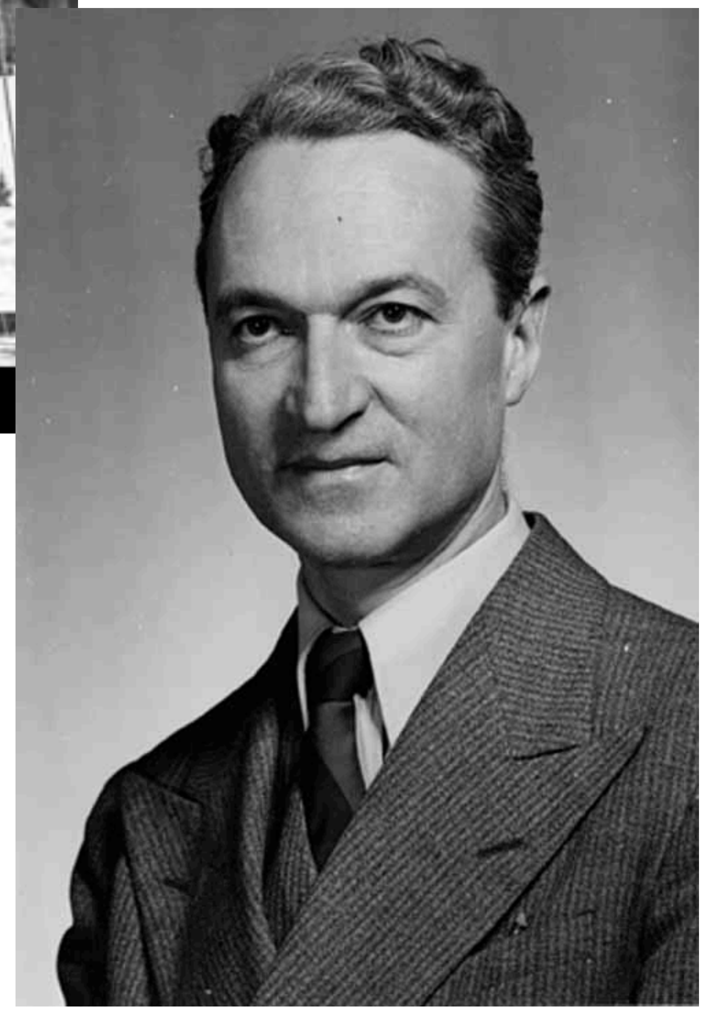
The Italian Connection
Bruno Rossi: 1905-1993

Started the cosmic ray and space plasma groups at MIT

PhD.: University of Bologna

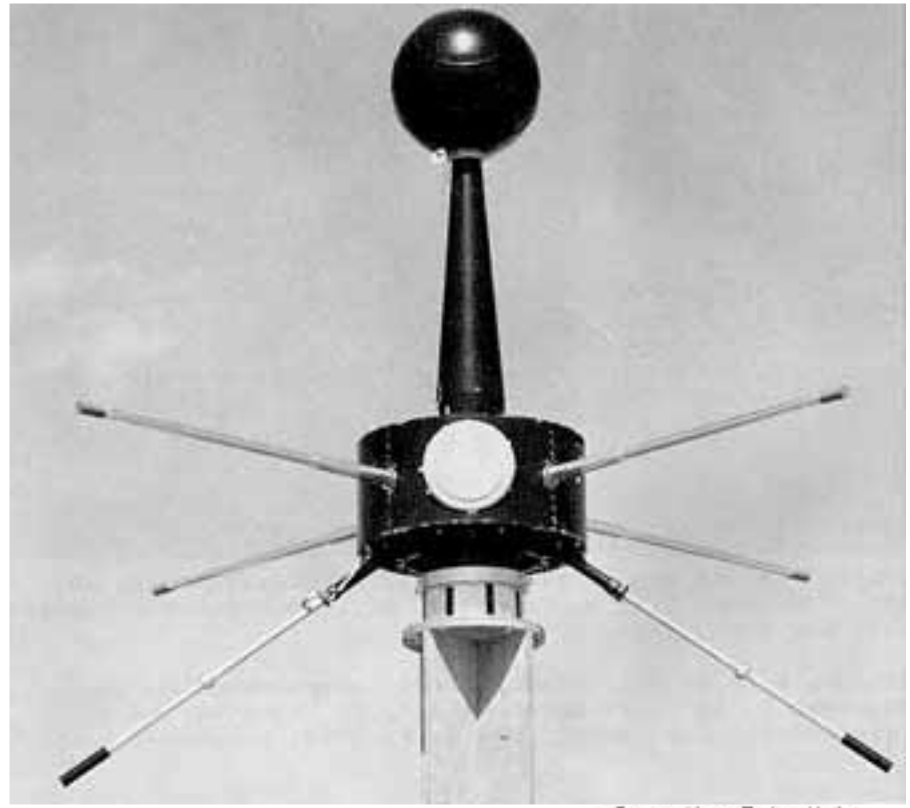
1938: Left Italy: worked with Bohr, Compton, Bethe, Fermi
WWII: joined the Manhattan Project

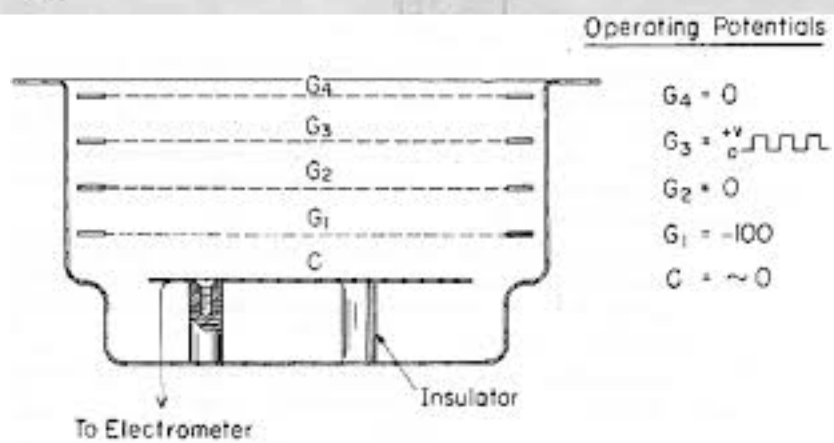
1946: Back to MIT, founded Cosmic Ray Group, which was the forefather of the Center for Space Science at MIT and is now called the Kavli Center.



SPACE PROBE RESEARCH
PROF. B. ROSSI AND DR. H. BRIDGE

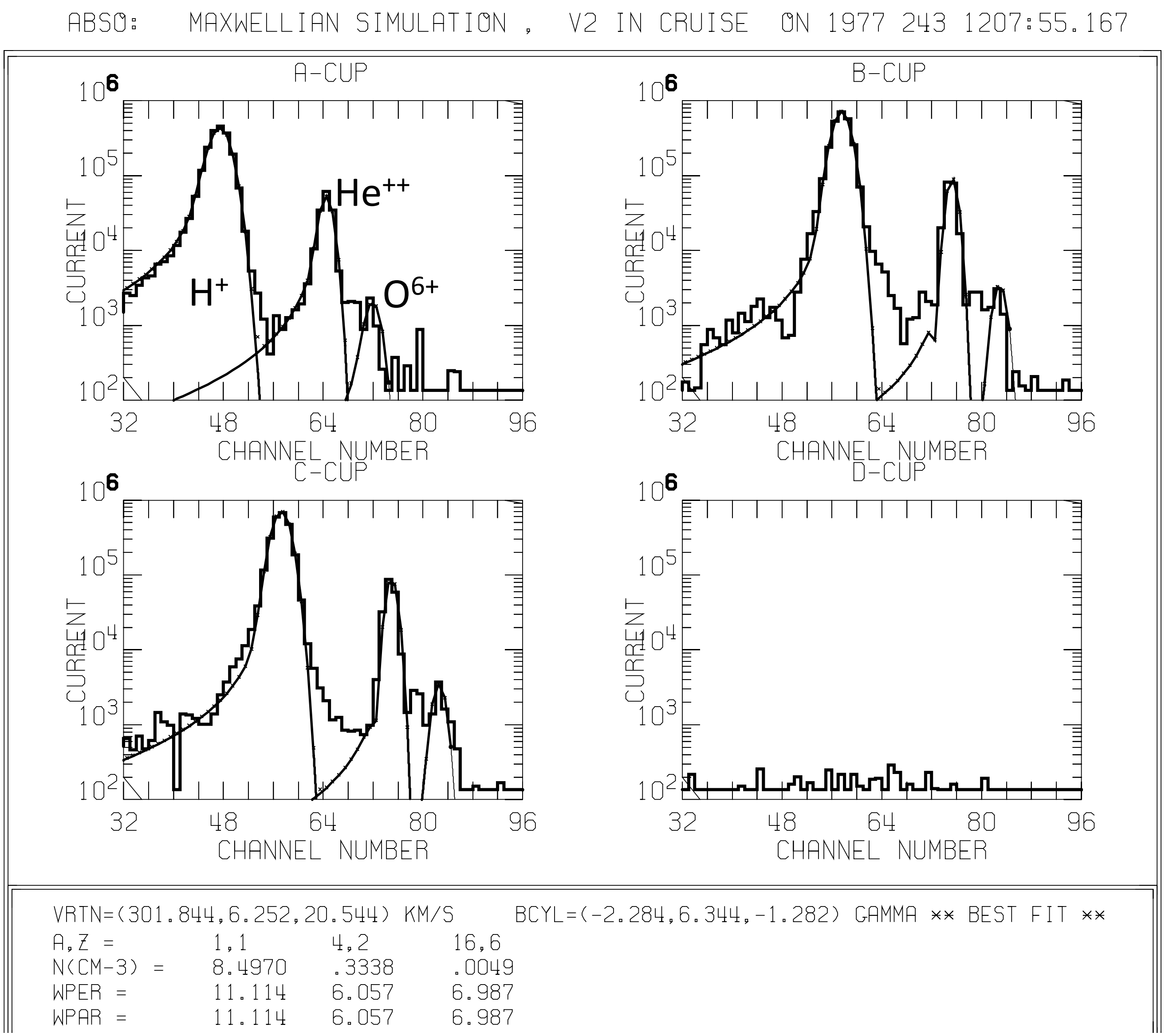
Developed Faraday Cup plasma probe with H. Bridge and made first solar wind measurements with Explorer 10 in 1961



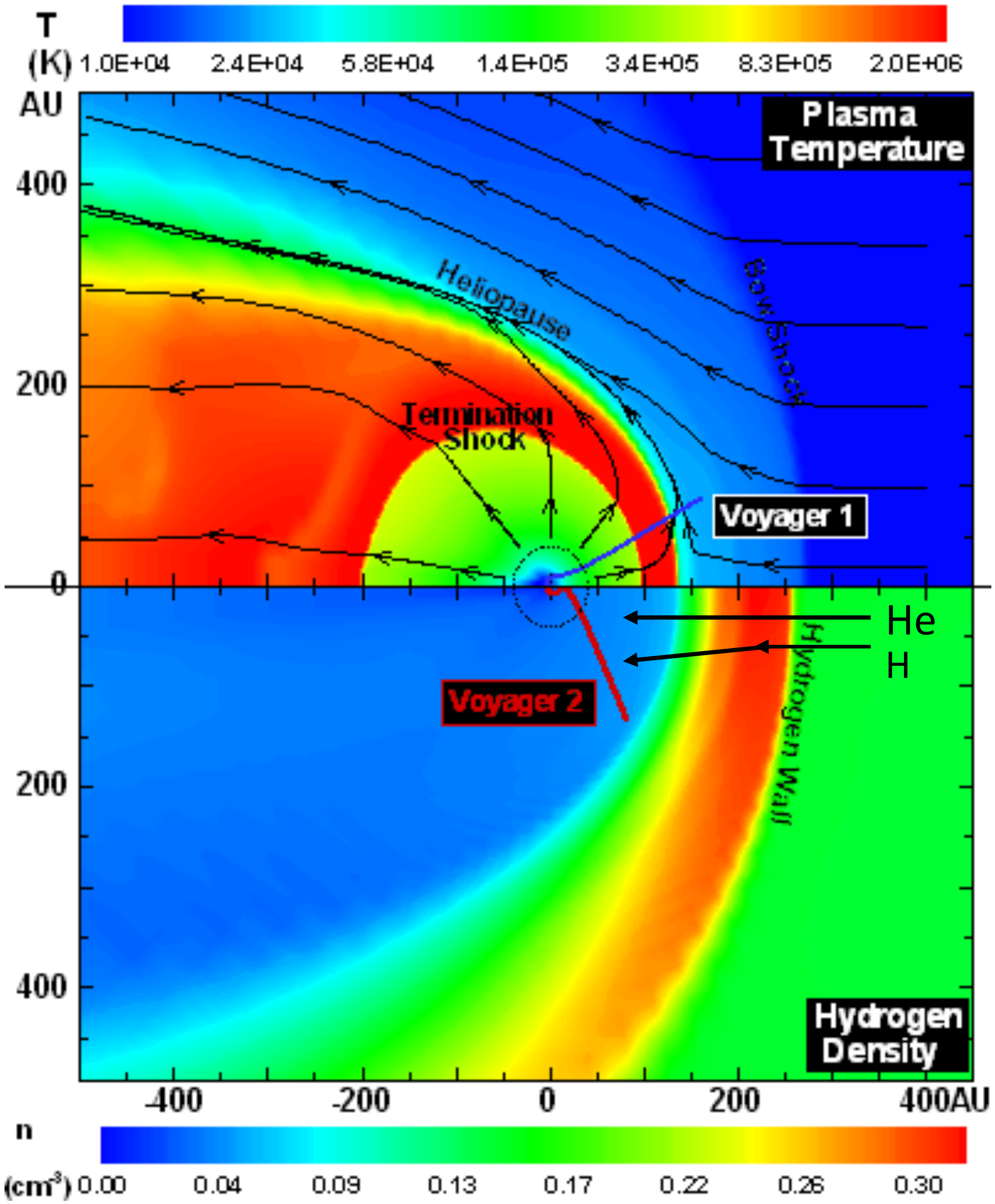



Faraday cups of similar design
have flown on many missions,
including Voyager, and are still being
flown on new missions such as Solar Probe Plus
Voyager 1 – broke n 1980 V2 – still working well

Solar Wind Spectra from the Voyager Plasma experiment



Interstellar neutrals



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

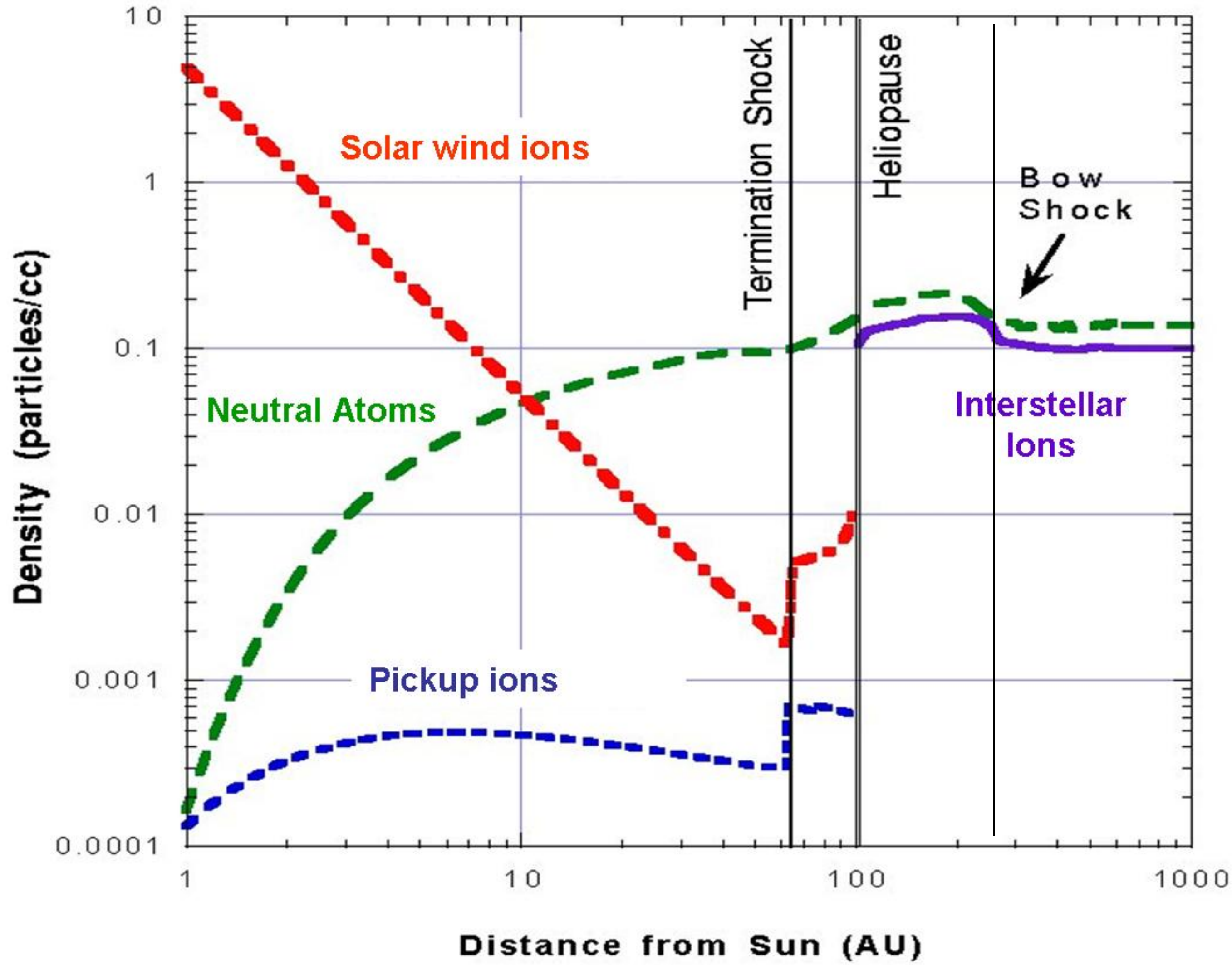
LIC H is tied to plasma via charge exchange.

Slowing of plasma and neutrals in front of the heliopause creates the hydrogen wall.

Mueller et al.

Interstellar neutrals dominate density outside ~10 AU

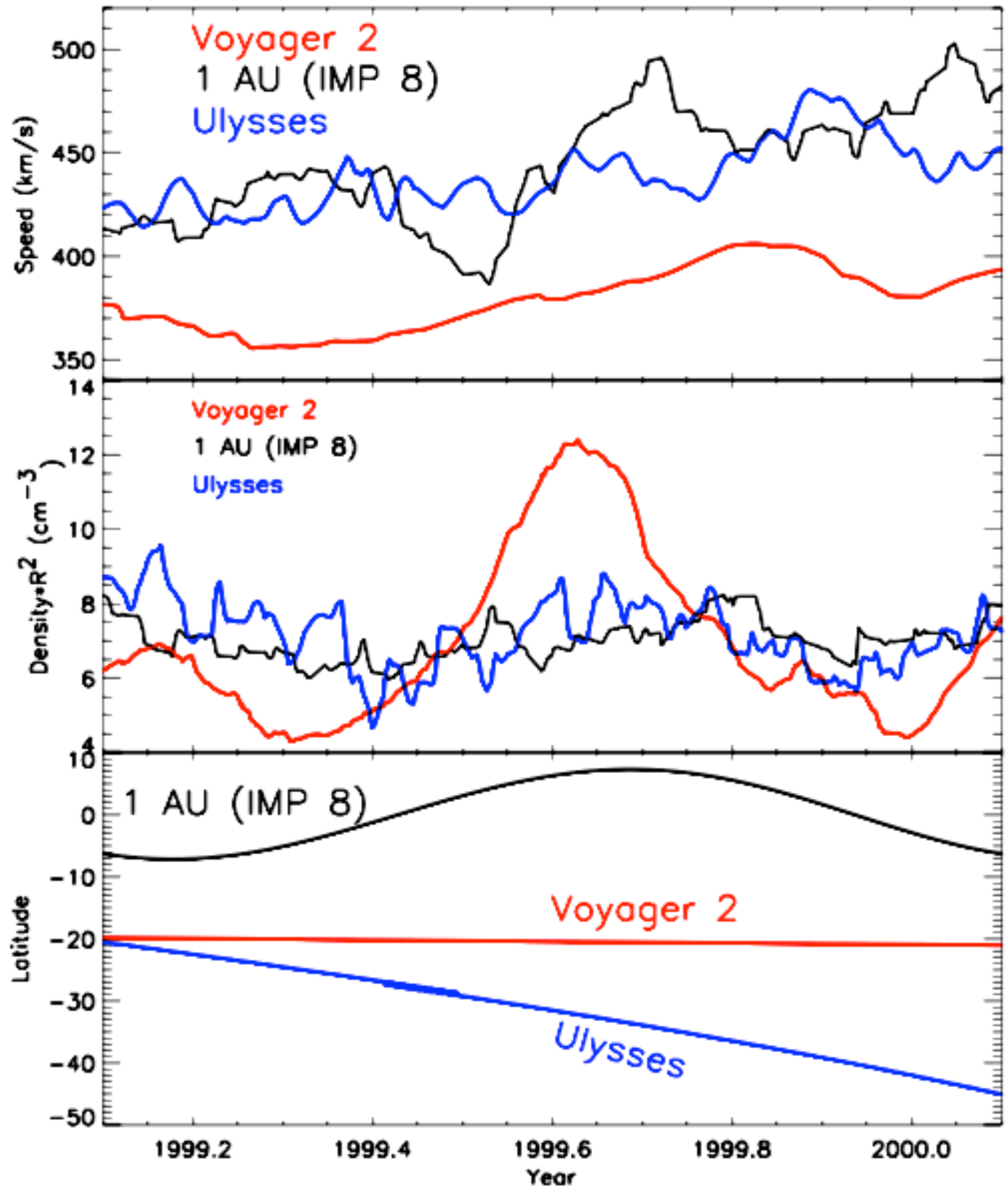
- Pickup ions dominate thermal pressure outside 30 AU
- First effects of LIC on solar wind are from these neutrals.

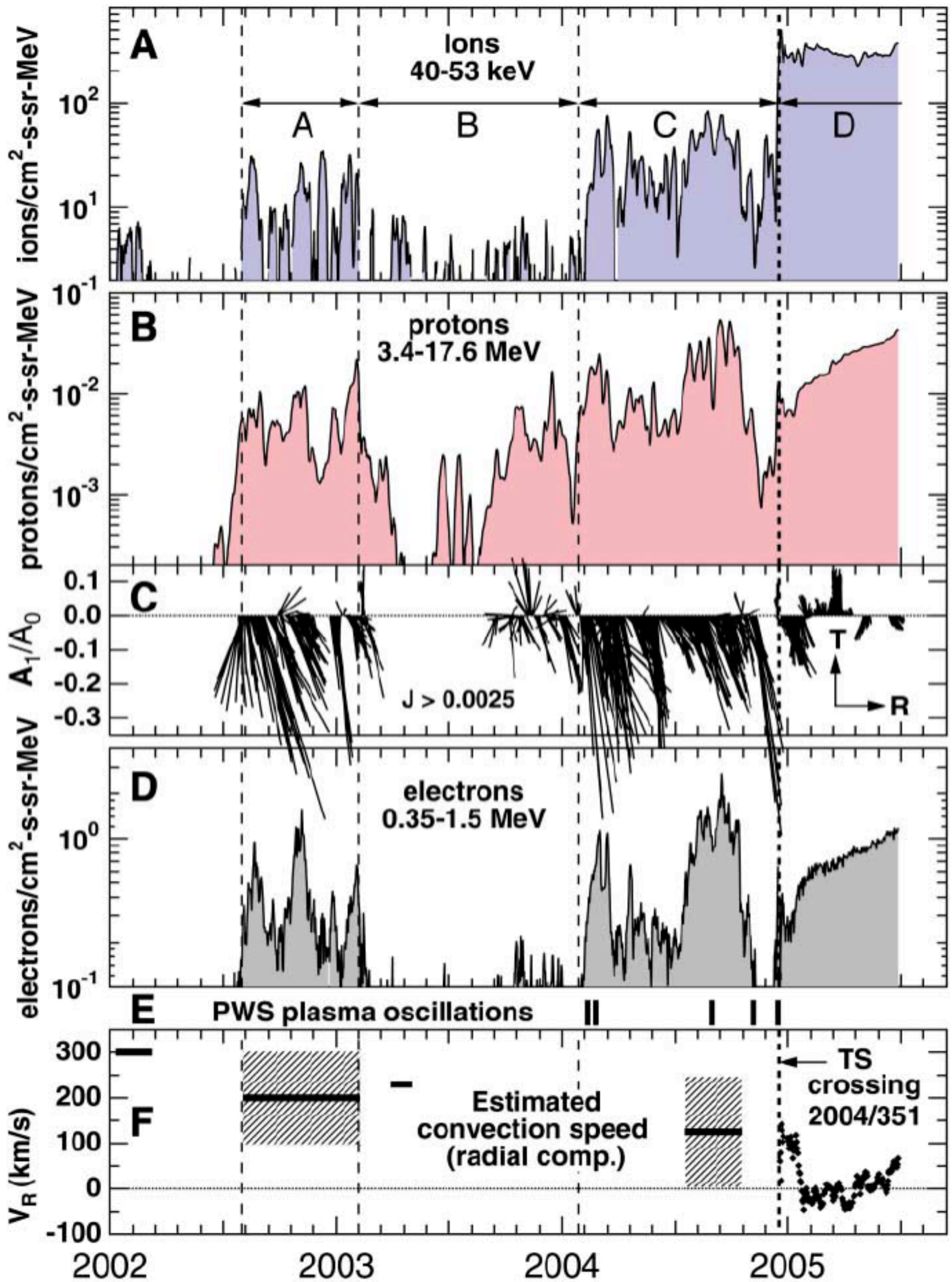


[Mewalt]

Interstellar Neutral Effects on the SW

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





Approach to the termination shock: V1 TS Foreshock

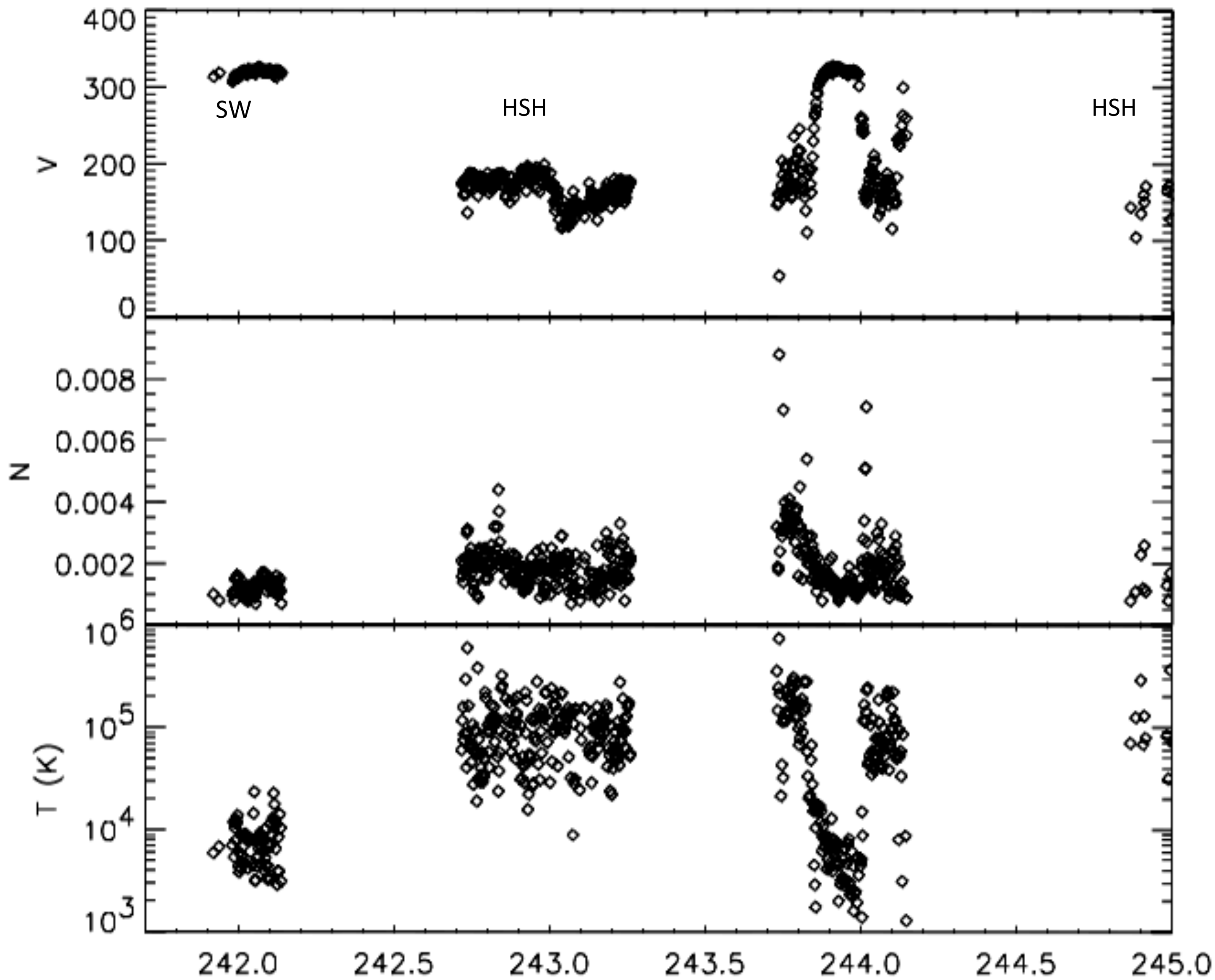
V1 - no plasma data;

We did not know TS location.

After TS crossing ion intensities were steady and isotropic in sheath.

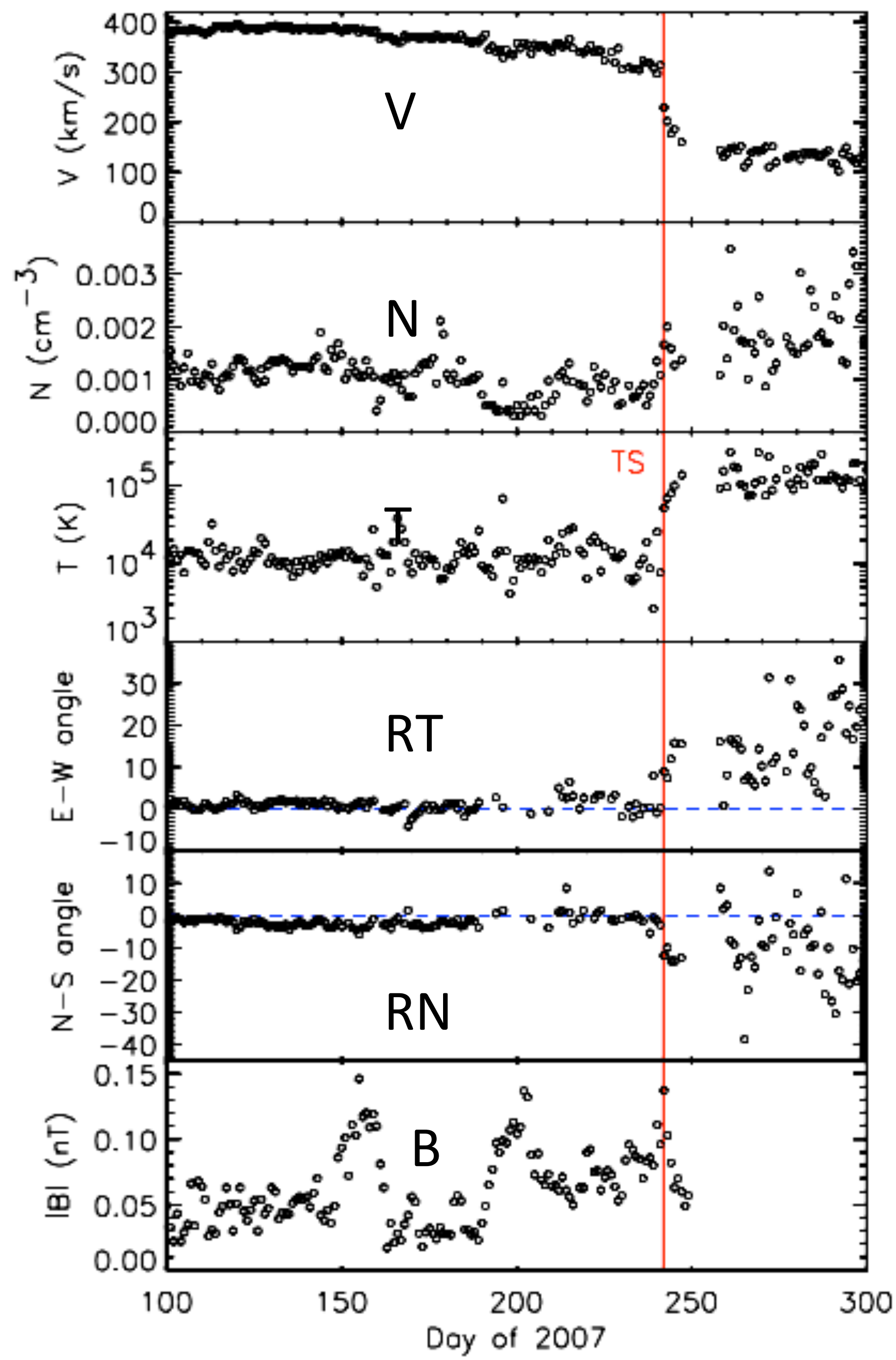
The V1 TS crossing at 94 AU revealed the spatial scale of the heliosphere.

Voyager 2 Termination Shock Crossings

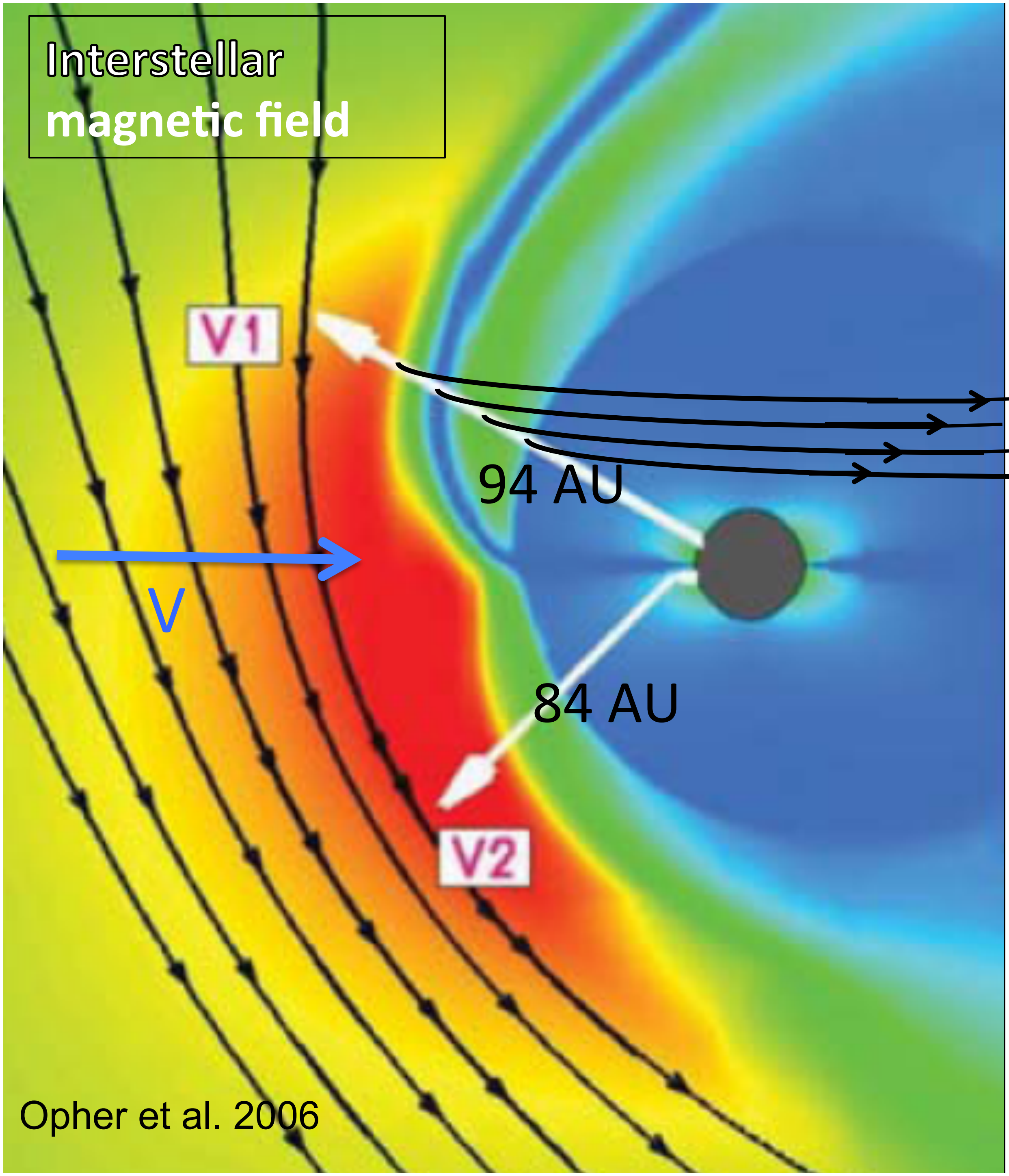


Asymmetry Observed: V2 crosses the TS In Aug. 2007 at 84 AU

- 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



Heliosphere simulation (Opher et al.)

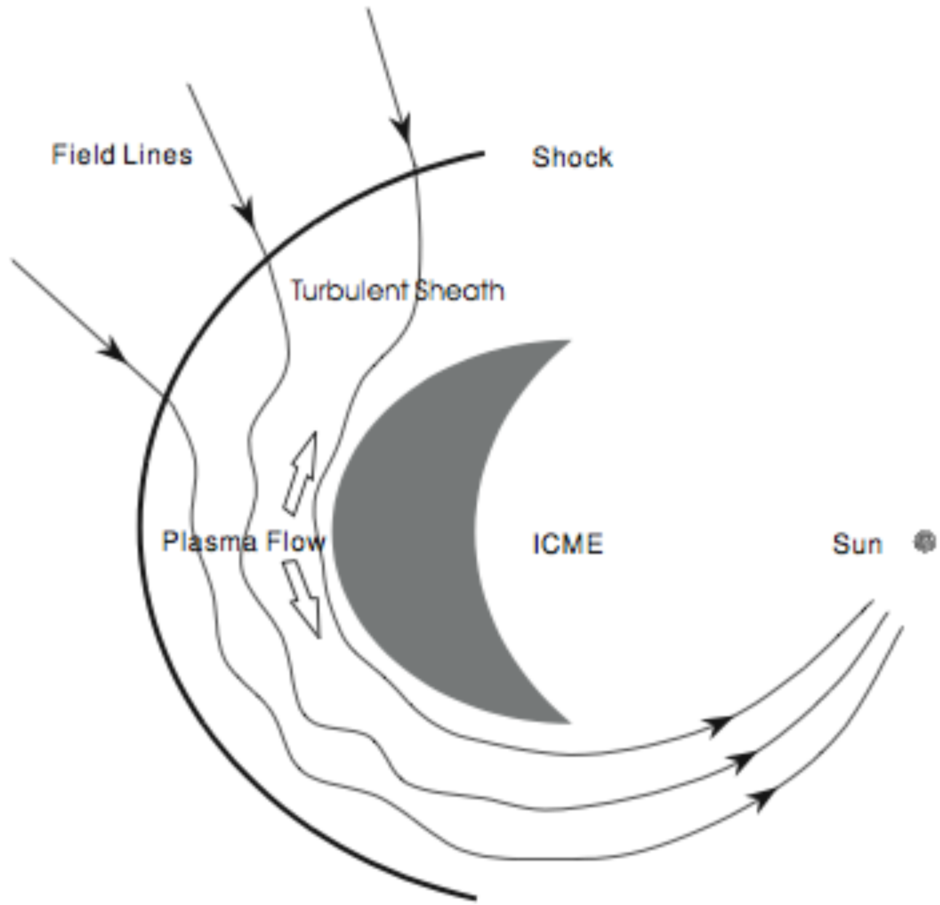
Tilted LIC magnetic field with B>0.3 nT gives N-S asymmetry

B up, direction change at HP

Flow parallel to HP -

VR ~ 0

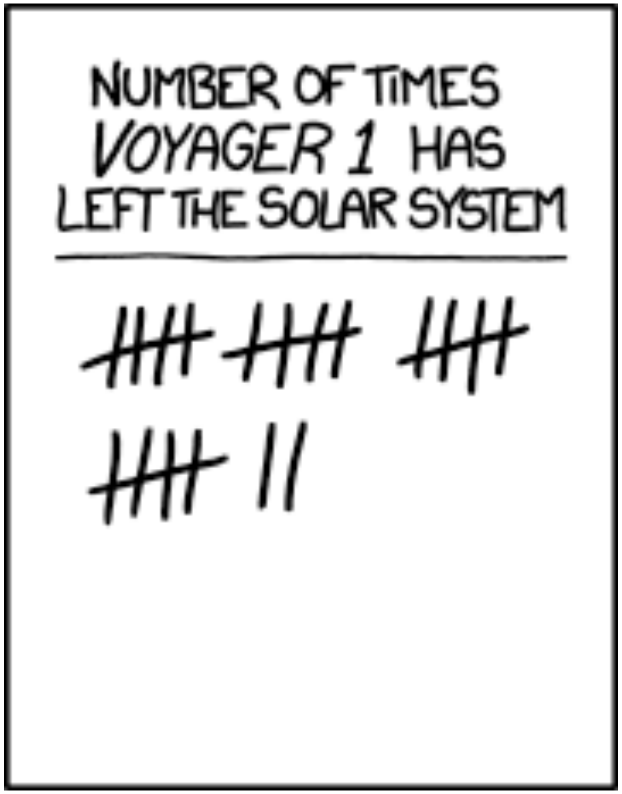
Acknowledg. Ed Stone



- ICME sheath geometry (Liu et al., 2006)
- Also observed in magnetosheaths
- Study of these asymmetries is a key part of the joint MIT – Politecnico di Torino project.

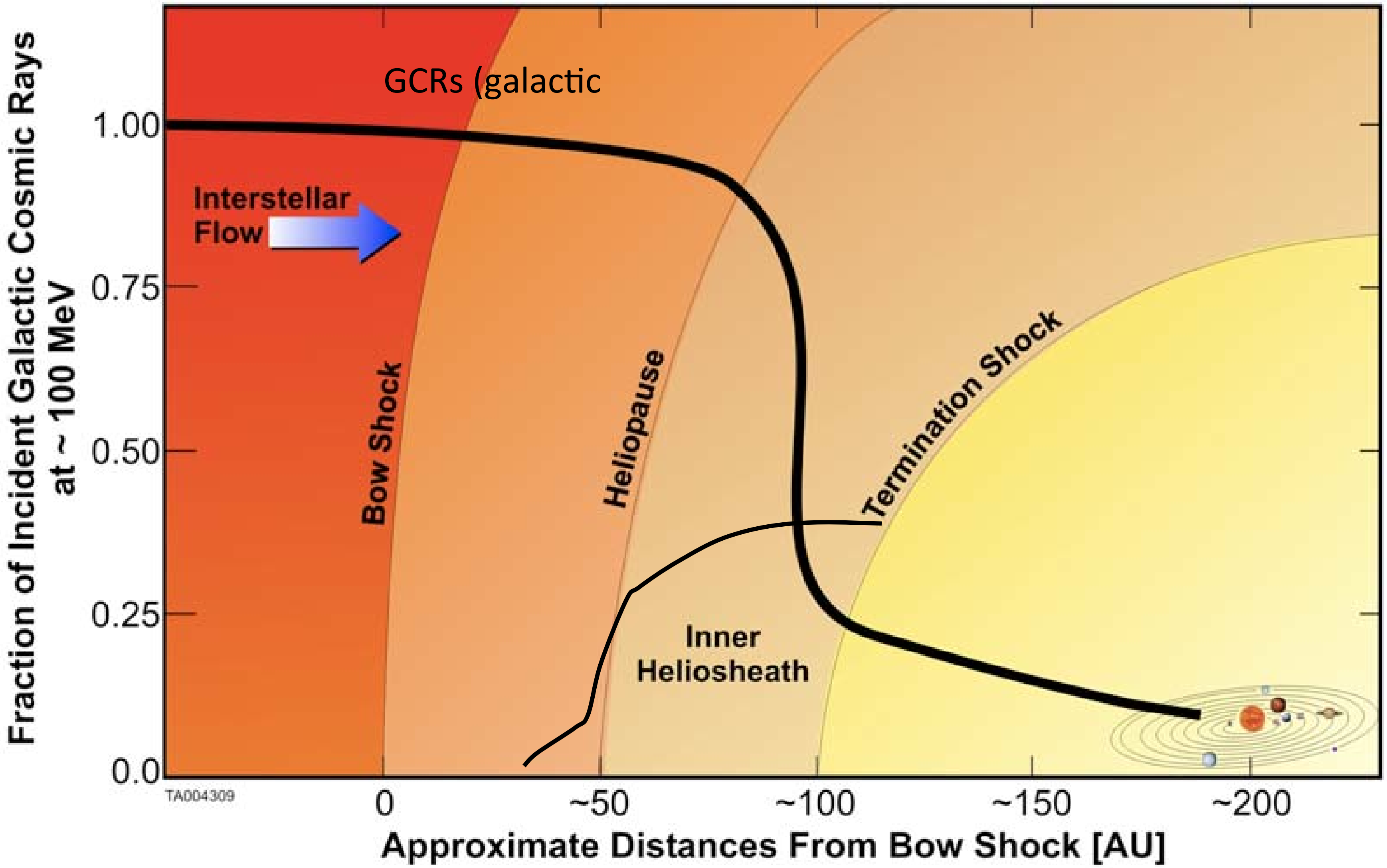
Heliopause Signatures

1) Radial speed goes to zero.
2) Heliosheath particles decrease
3) Galactic cosmic rays increase.
4) Magnetic field increases.
5) Magnetic field direction changes
6) Plasma density increases



Voyager 1 has observed 5 of these 6 signatures:

But NOT at the same time!



Heliosphere shields the solar system from cosmic rays

Voyager's trip through the heliosphere (V2 data)

Heliopause:

V ~ constant

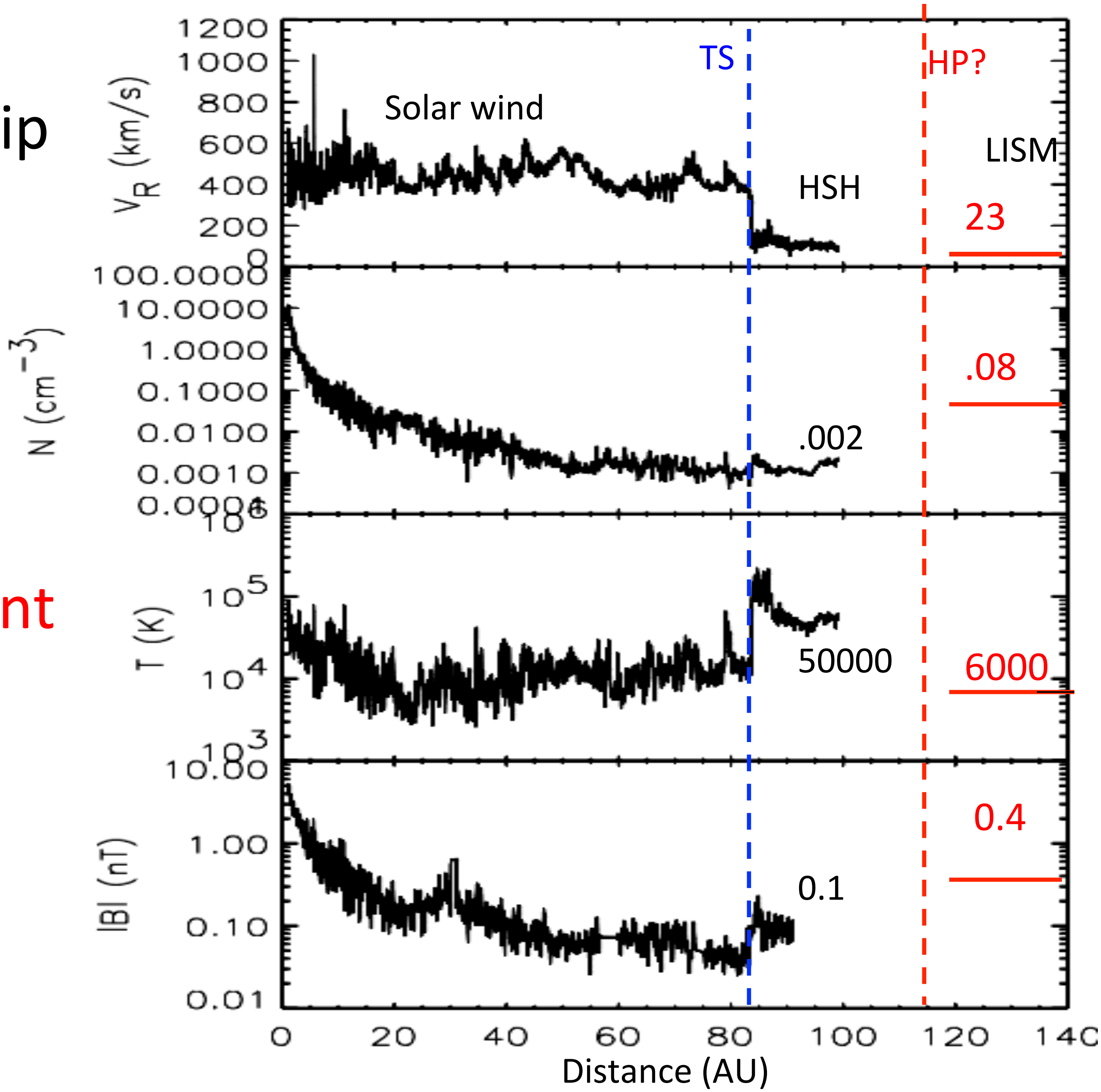
N up

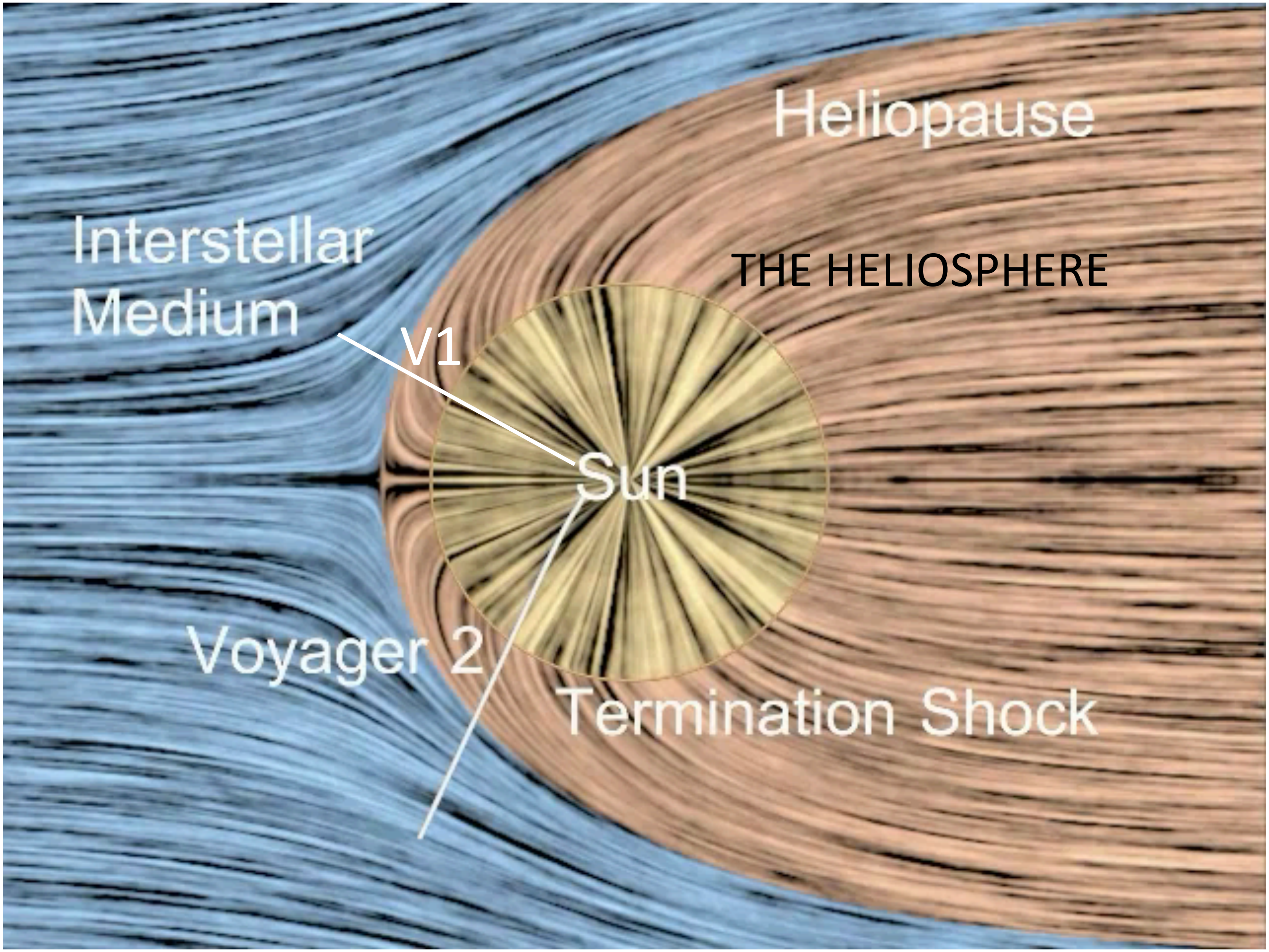
T down

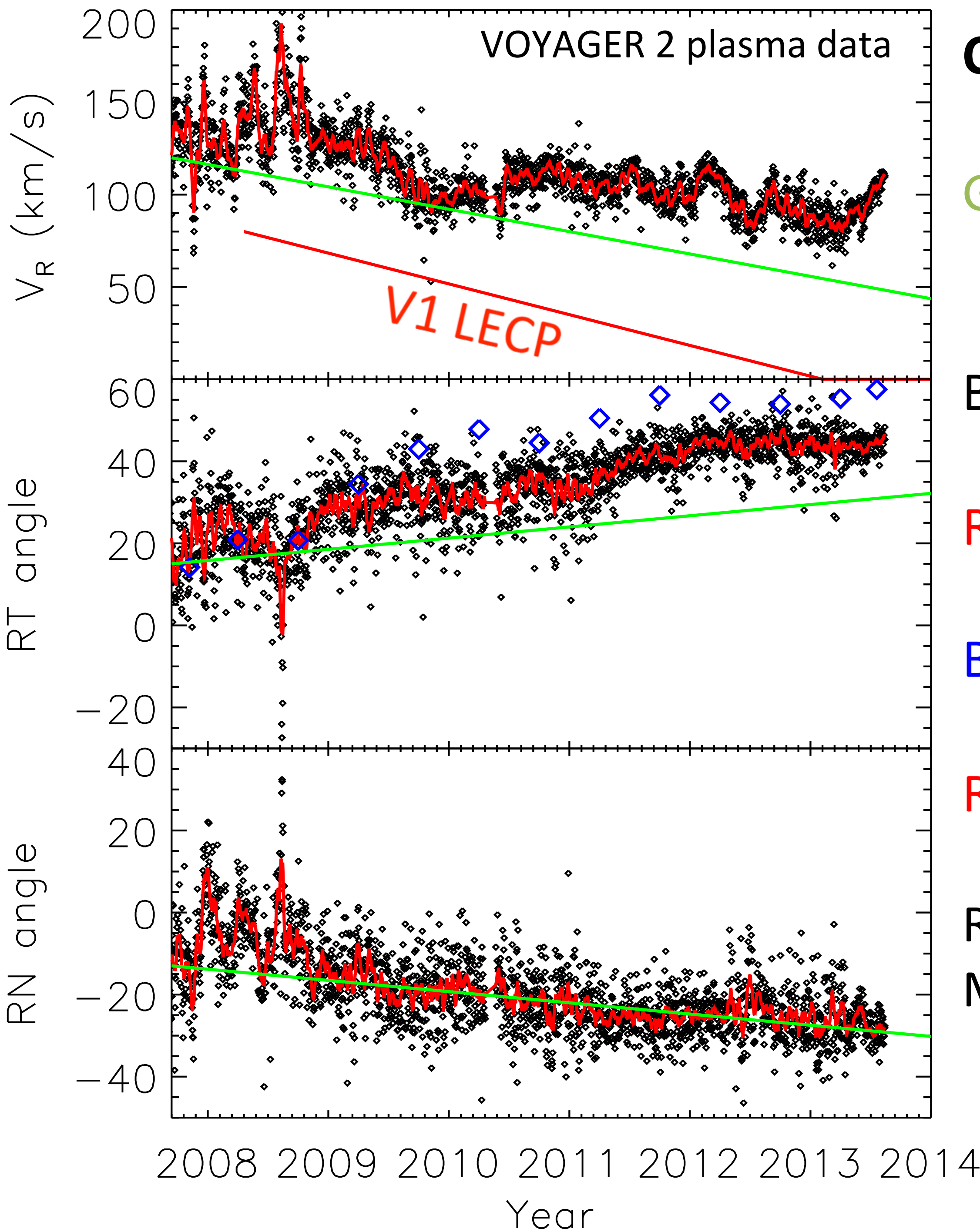
B up/tilt

ACRs down

GCRs up




Heliopause
Interstellar
Medium
THE HELIOSPHERE
V1
Sun
Voyager 2
Termination Shock



Comparison to Simulations

Green: Model values from Borovikov et al. 2011

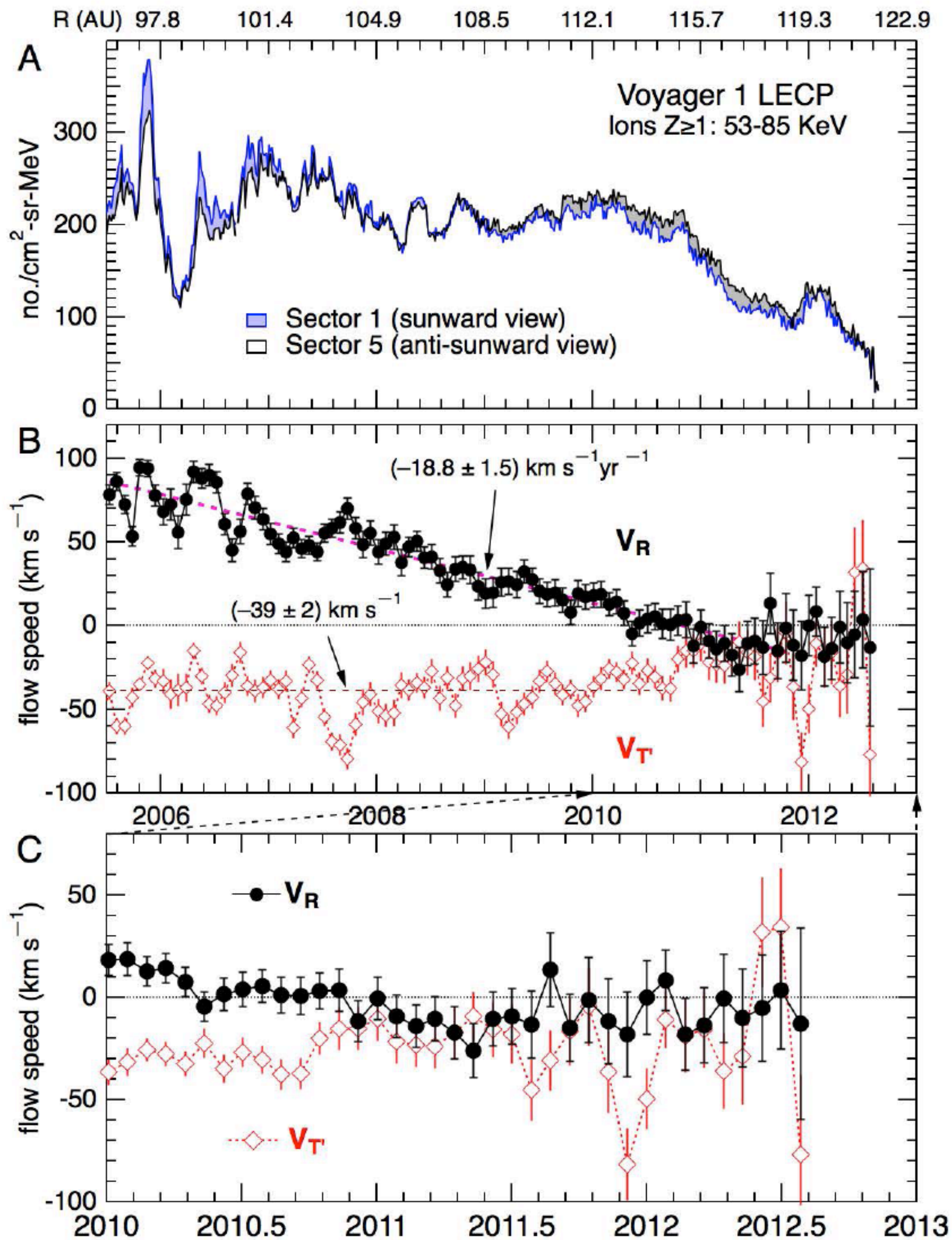
Black: V2 daily averages

Red: Smoothed V2 data

Blue: Corrected RT angles

Red line: V1 LECP (Decker)

RT angle larger than model
Model VR between V1 and V2



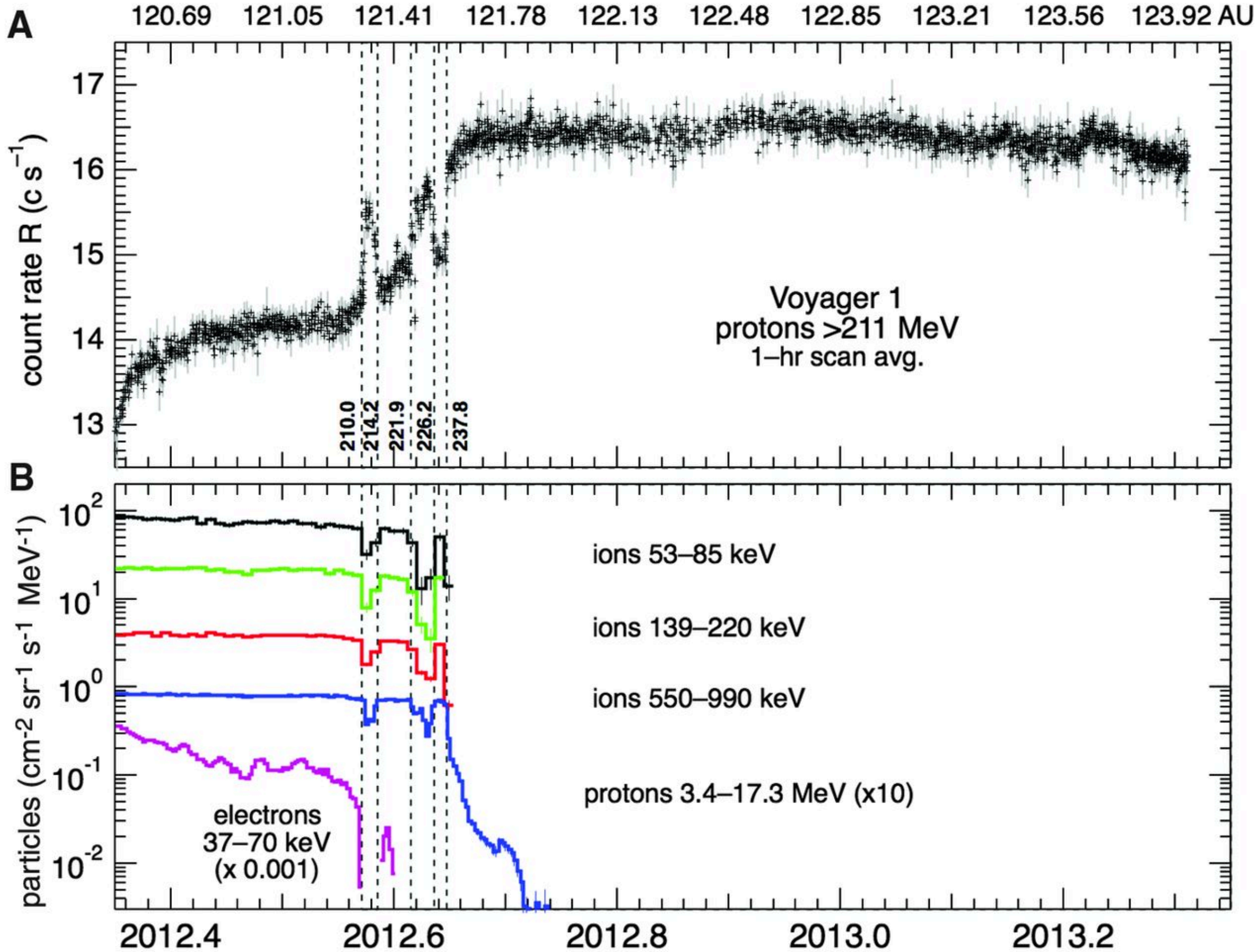
Krimigis et al. (2013)

Intensity decreased from early 2010 to dropout in 2012.

Radial speed near zero since early 2010 until dropout.

Other flow components also small.

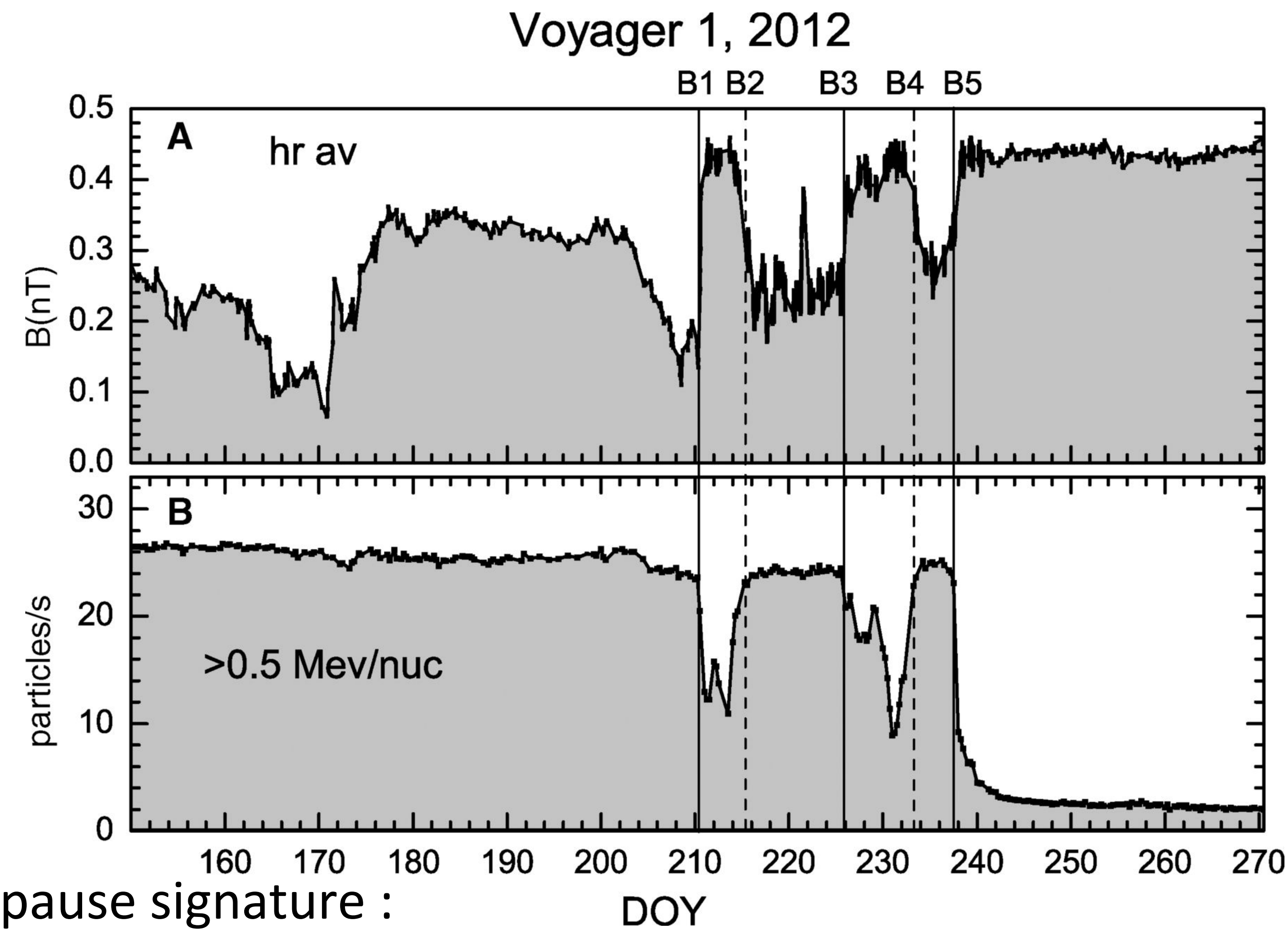
Fig. 1 Overview of energetic particle observations at V1, 2012.35 to 2013.40, showing the contrary behavior of GCRs and lower-energy particles.(A) Hourly averages of GCR activity and the pronounced boundary crossing on 25 August 2012 (day 238).



S M Krimigis et al. Science 2013;341:144-147

Published by AAAS

Fig. 1 Relationship between the magnetic field intensity and the energetic particle counting rate. Hour averages of magnetic field strength B (A).



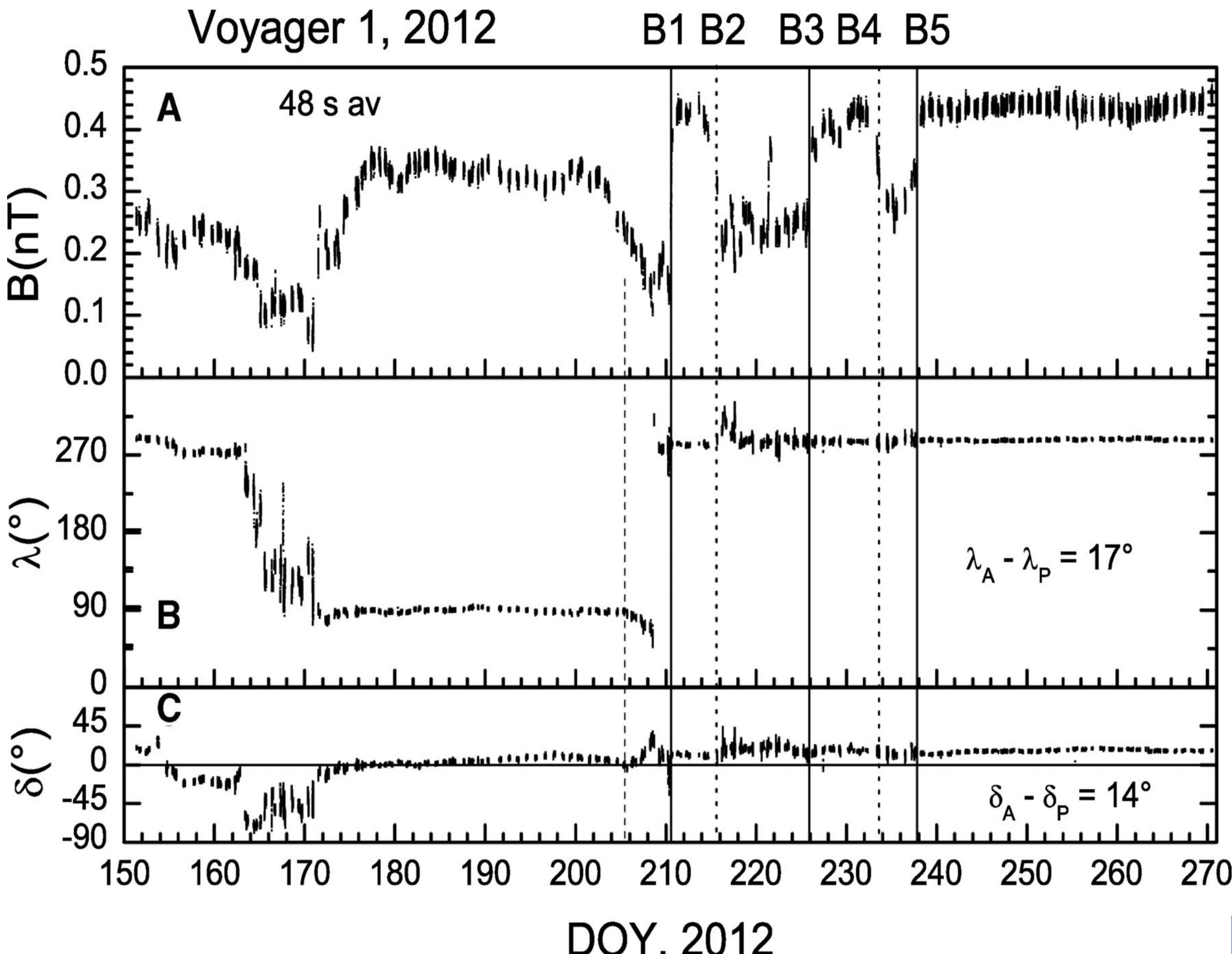
Heliopause signature :

4) Magnetic field increases

Science AAAS

Published by AAAS L F Burlaga et al. Science 2013;341:147-150

Fig. 2 High-resolution observations of the magnetic field strength and direction.48-s averages of the magnetic field strength B (A), azimuthal angle λ (B), and elevation angle δ (C), as a function of time measured from DOY 150 to 270, 2012.



Heliopause signature : 5) Magnetic field direction changes

NOT OBSERVED

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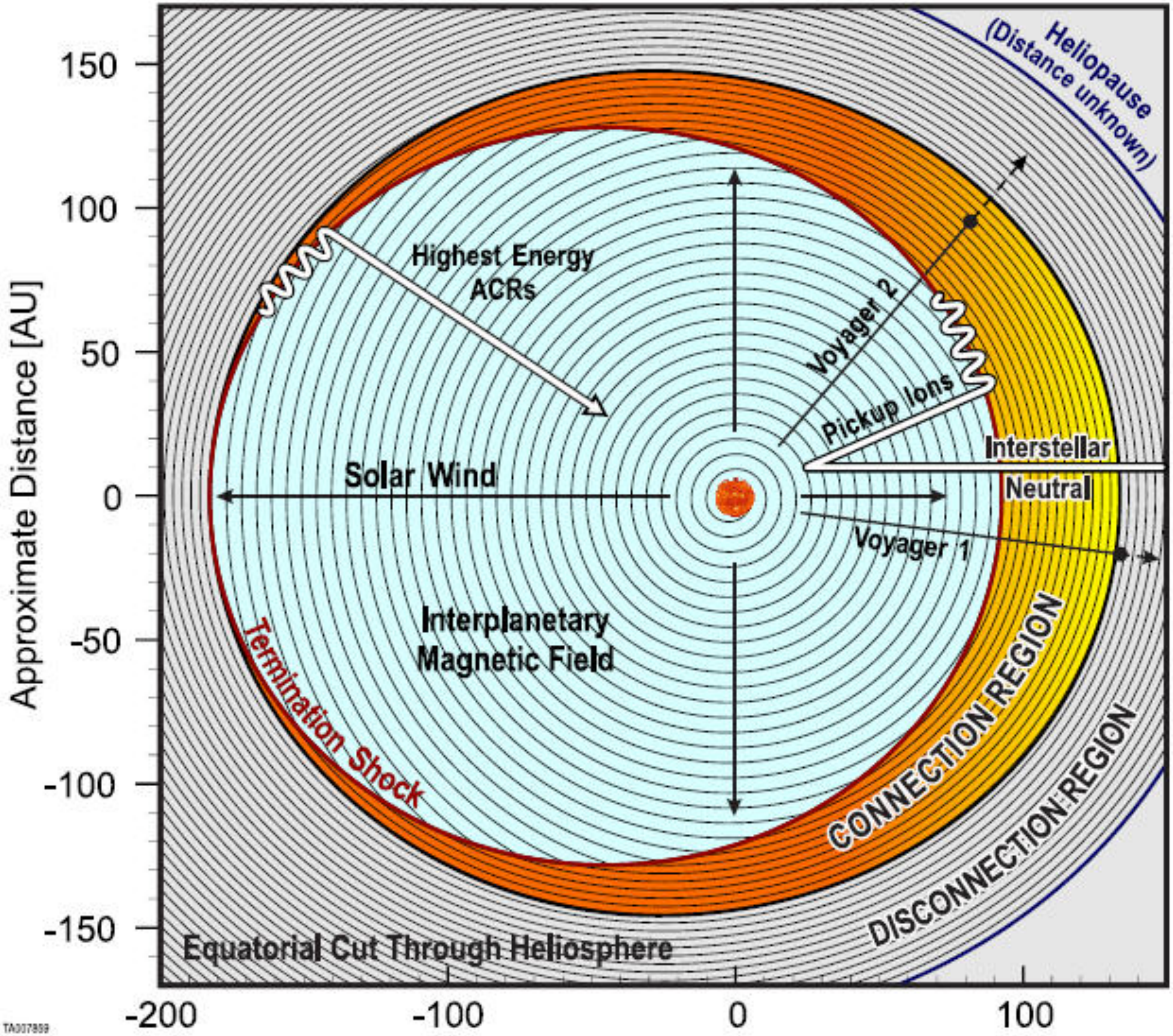
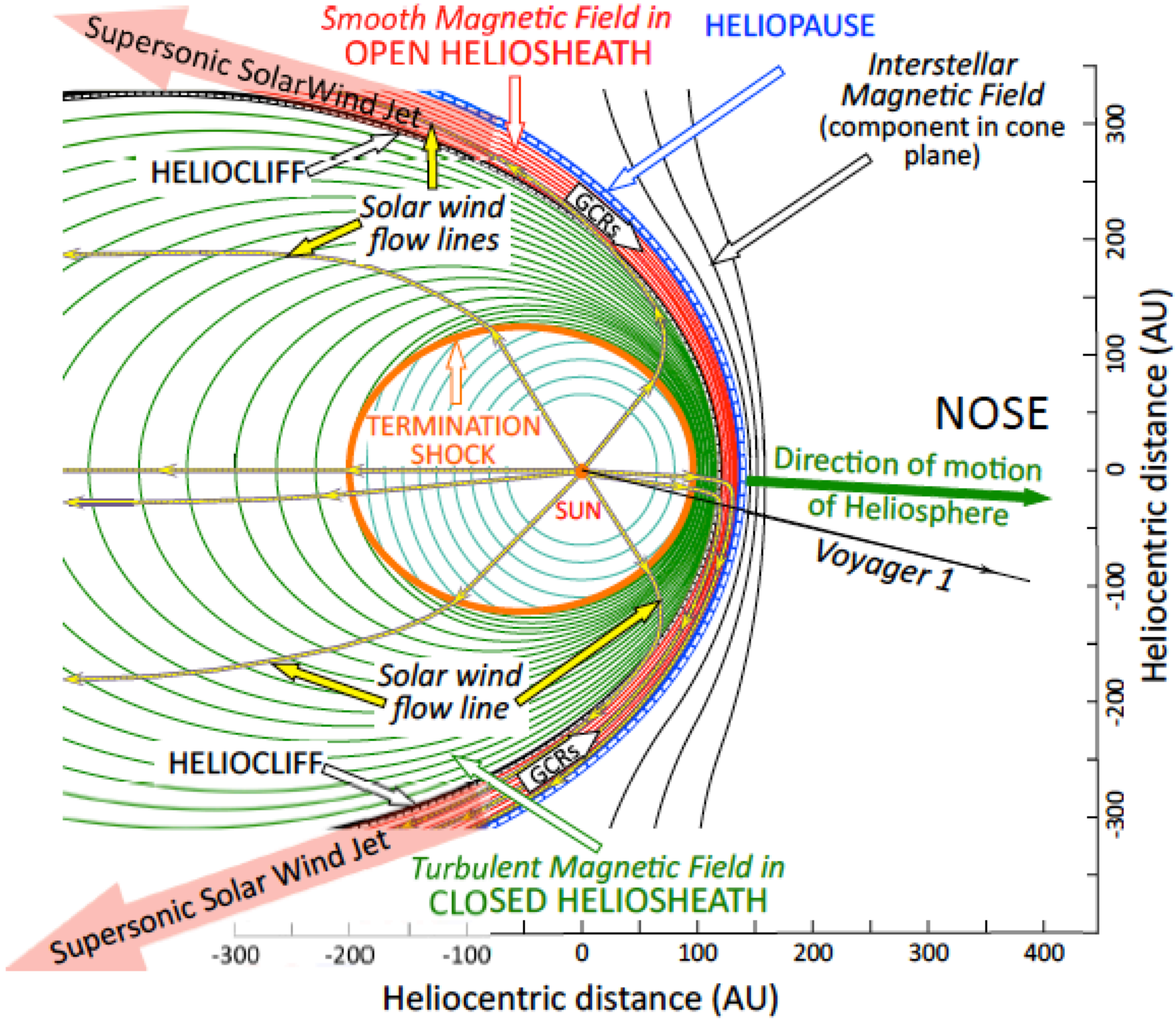
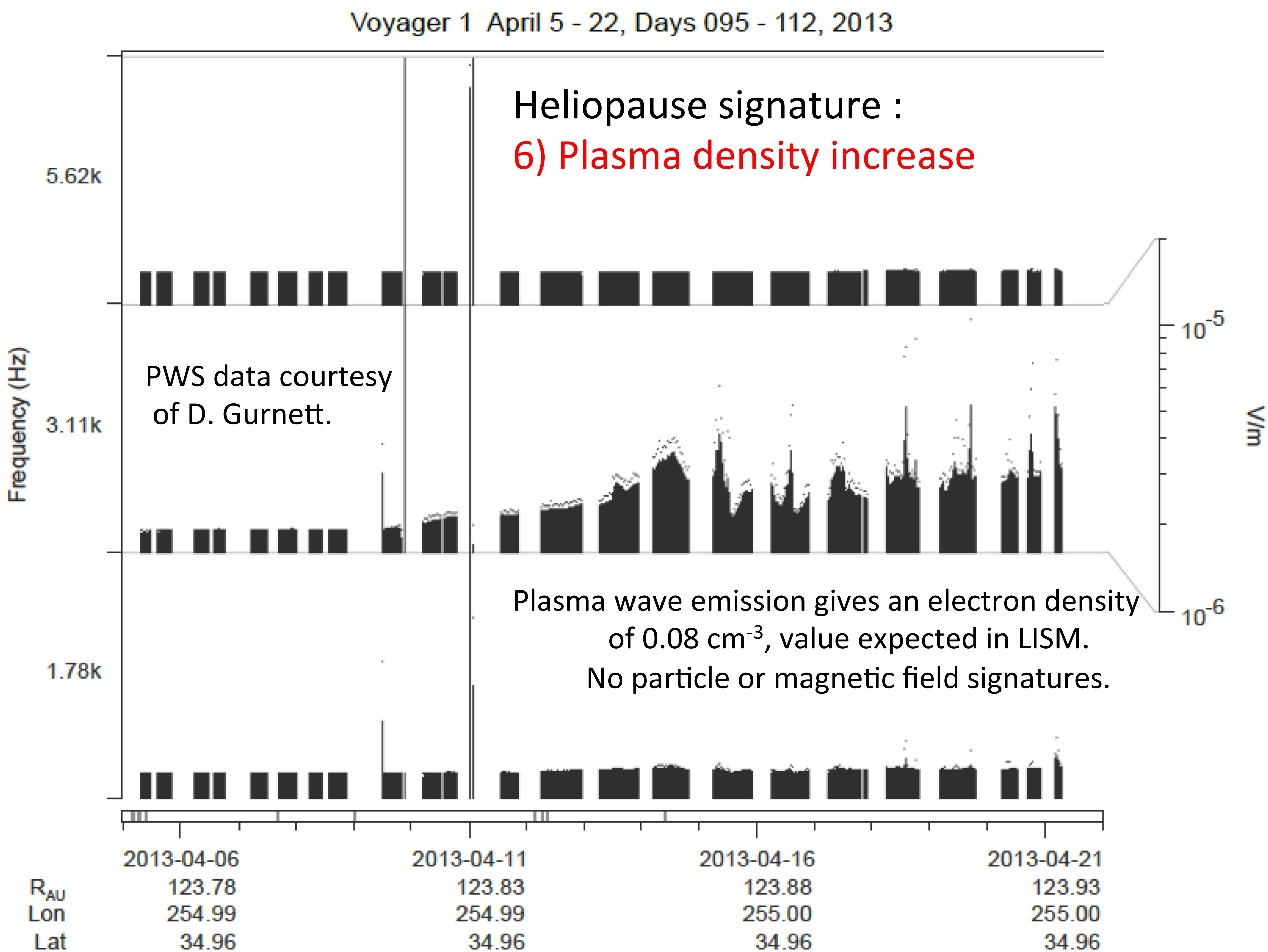
Science AAAS

L F Burlaga et al. Science 2013;341:147-150

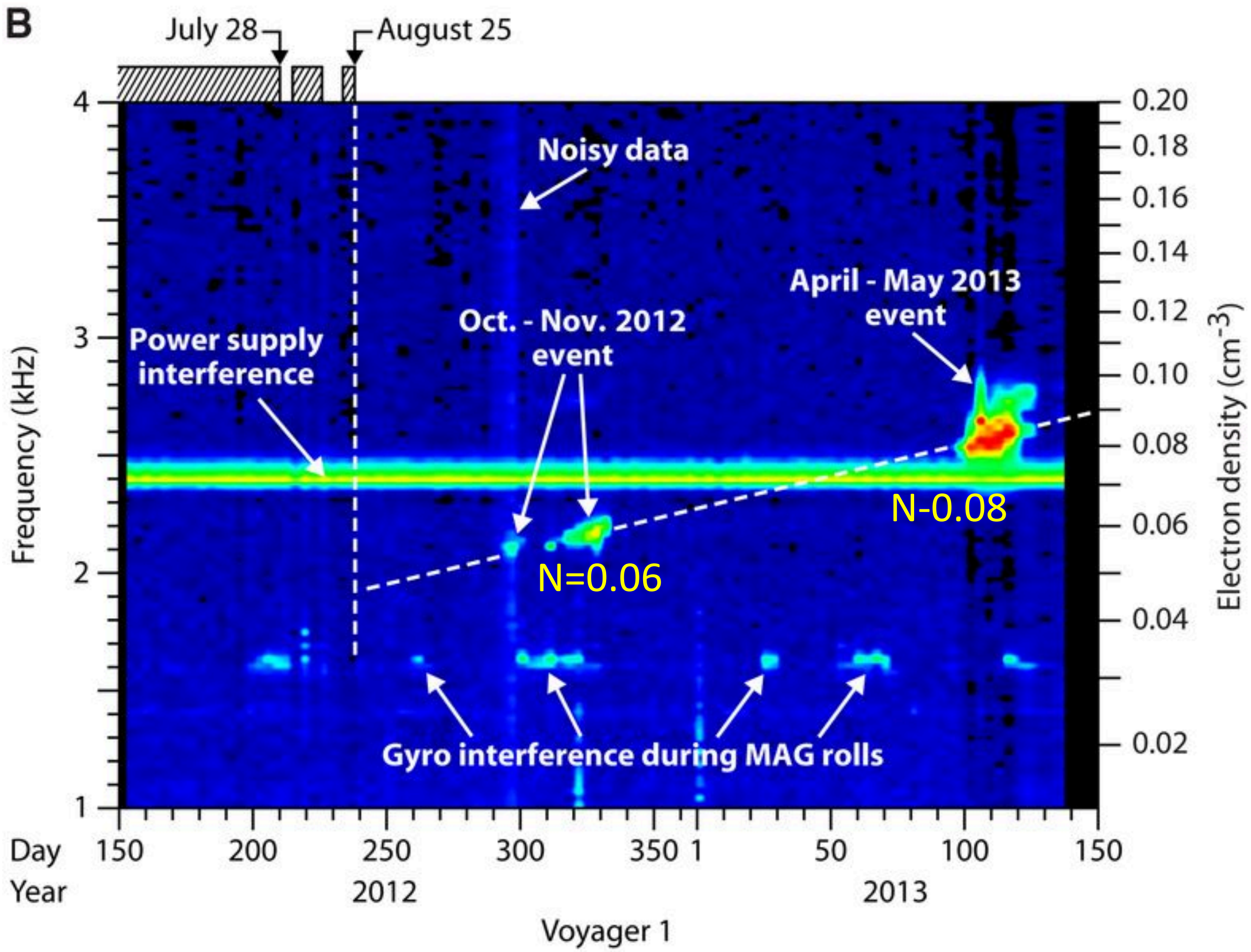

Heliopause
(Distance unknown)
Highest Energy
ACRs
Voyager 2
Pickup Ions
Interstellar
Neutral
Solar Wind
Voyager 1
Interplanetary
Magnetic Field
Termination Shock
CONNECTION REGION
DISCONNECTION REGION
Equatorial Cut Through Heliosphere
Approximate Distance [AU]
150
100
50
0
-50
-100
-150
-200
-100
0
100
TA007859

Gloeckler et al.

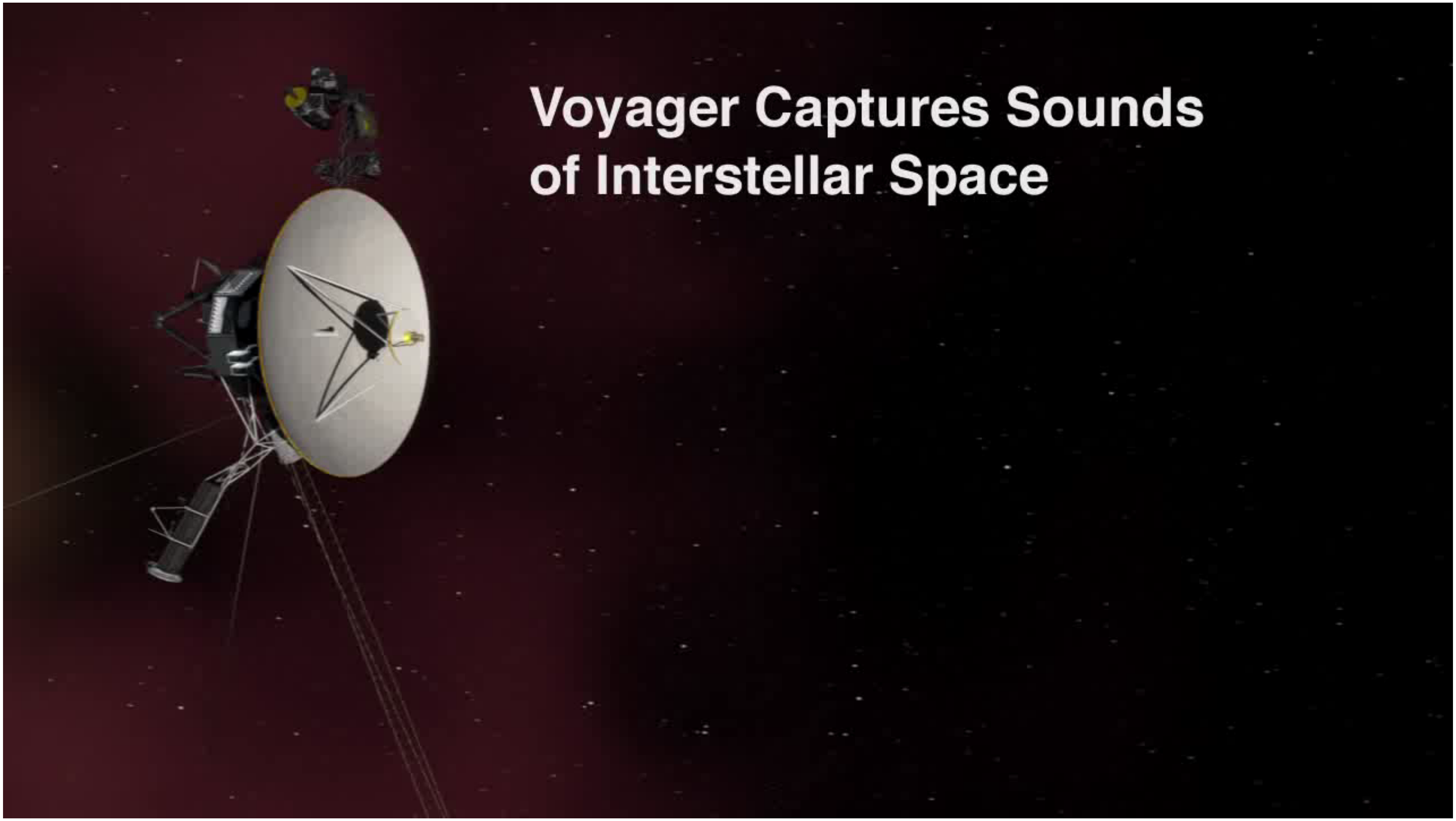


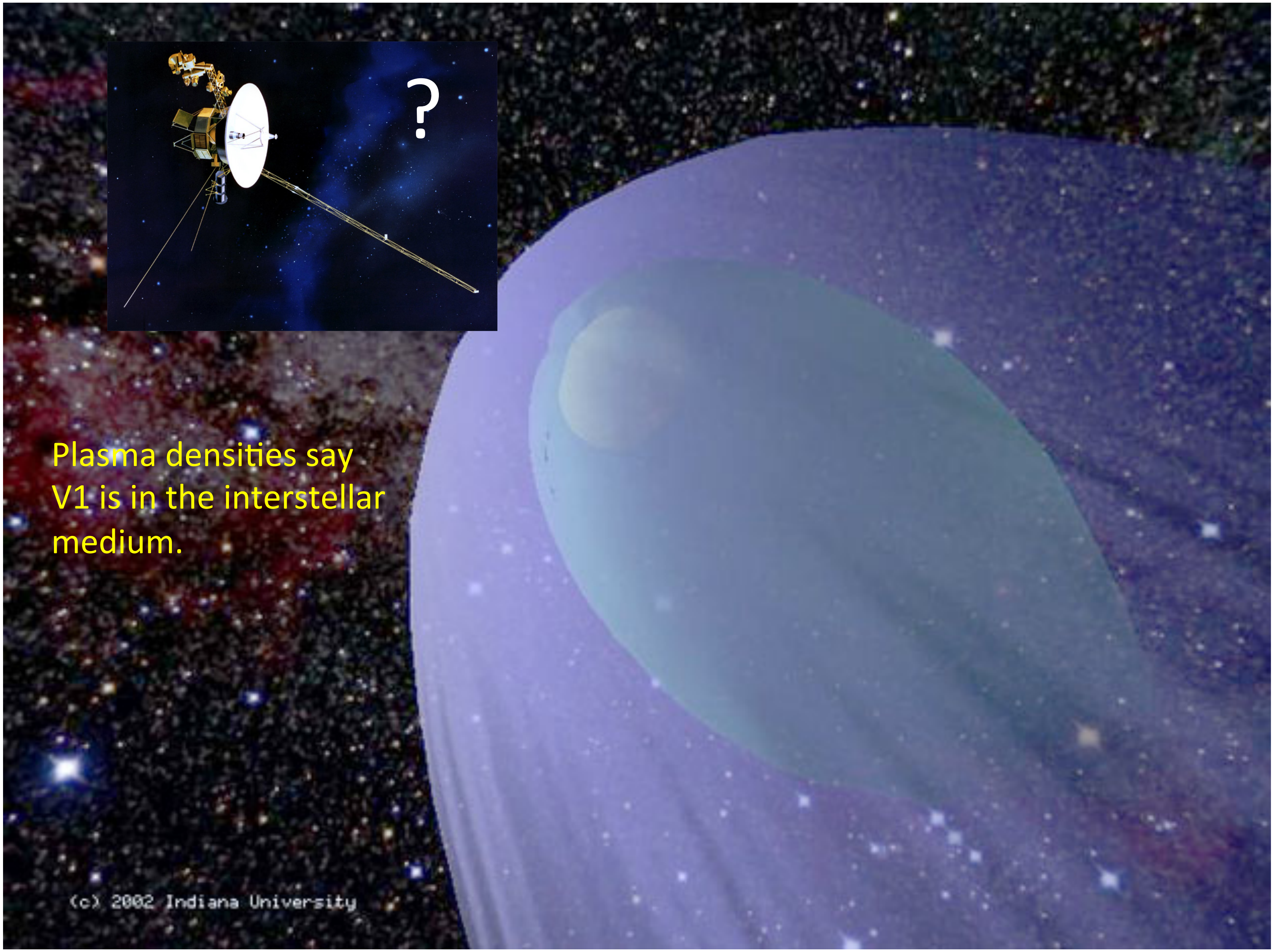


Voyager 1 April 5 - 22, Days 095 - 112, 2013
Heliopause signature :
6) Plasma density increase
PWS data courtesy
of D. Gurnett.
Plasma wave emission gives an electron density
of 0.08 cm-3, value expected in LISM.
No particle or magnetic field signatures.
Frequency (Hz)
5.62k
3.11k
1.78k
10-5
10-6
V/m
2013-04-06
2013-04-11
2013-04-16
2013-04-21
RAU
123.78
123.83
123.88
123.93
Lon
254.99
254.99
255.00
255.00
Lat
34.96
34.96
34.96
34.96



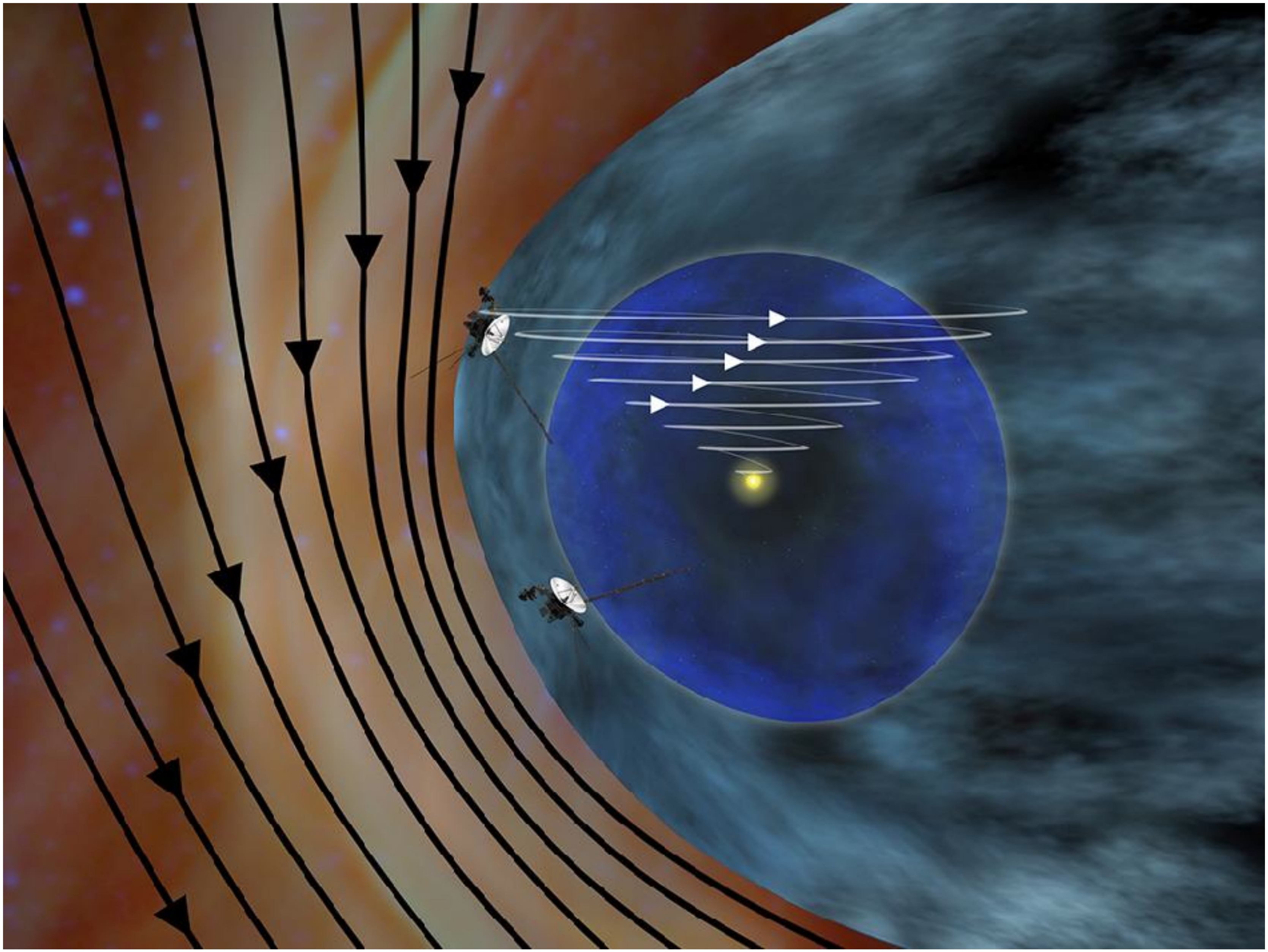
Densities are interstellar medium densities – so V1 crossed heliopause!


Voyager Captures Sounds
of Interstellar Space

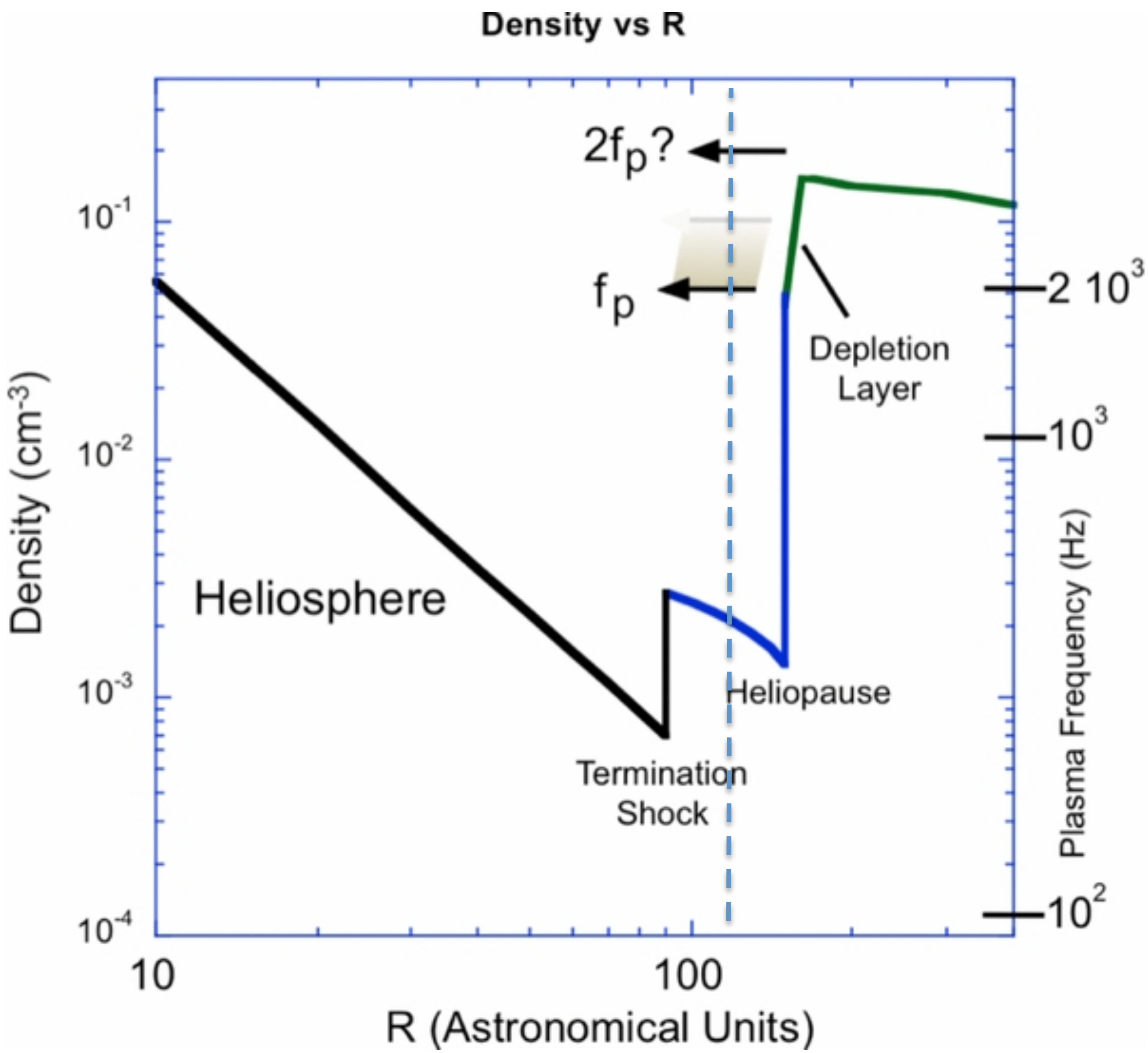

?
Plasma densities say V1 is in the interstellar medium.
(c) 2002 Indiana University

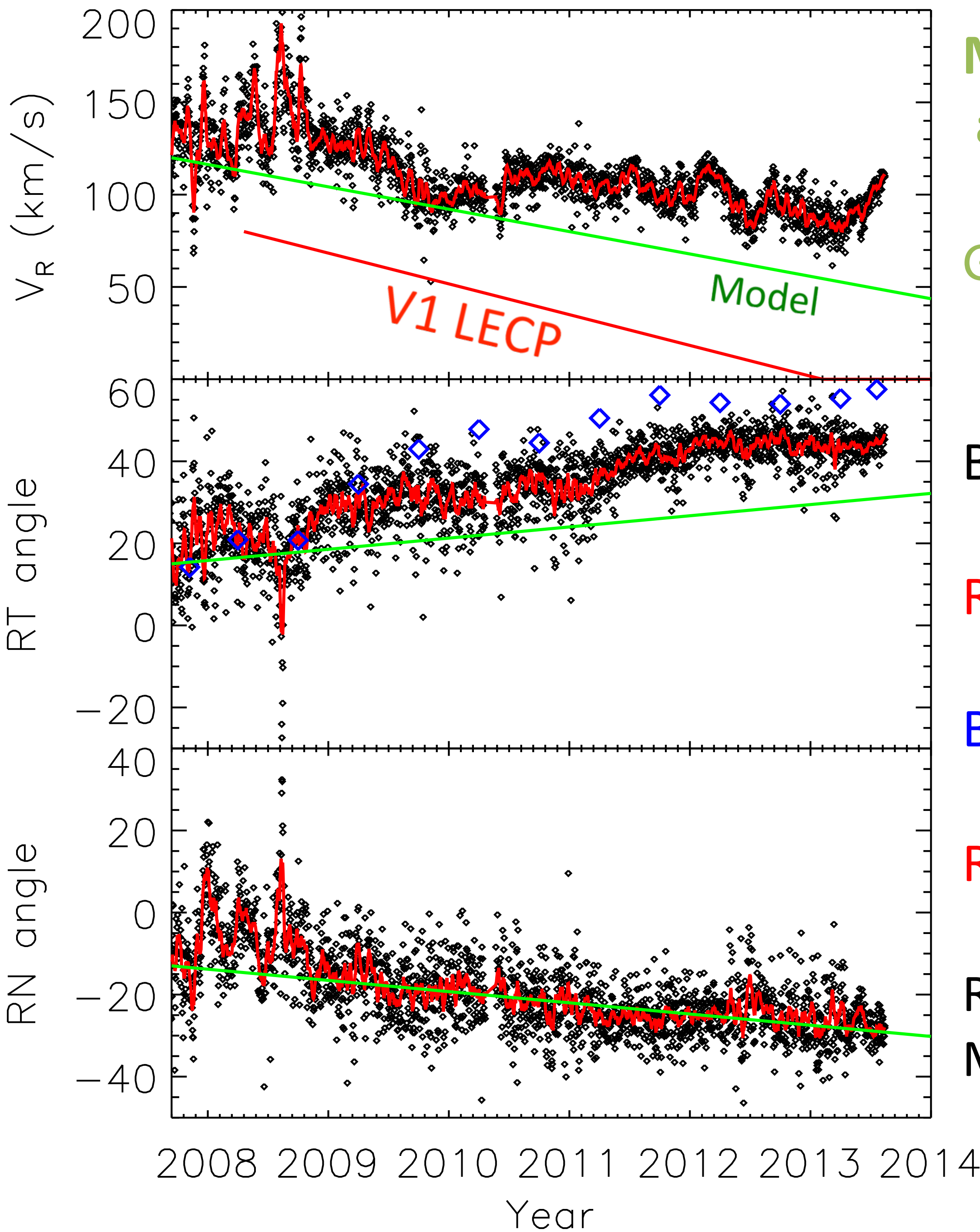
Mysteries

1. Why didn't the magnetic field change direction?



Mystery: 2. Why is the heliopause so close? 121 AU, only 27 AU from TS. Models predict 40-60 AU from TS





Mytery: 3. Why are speeds at V1 and V2 so different?

Green: Model values from Borovikov et al. 2011

Black: V2 daily averages

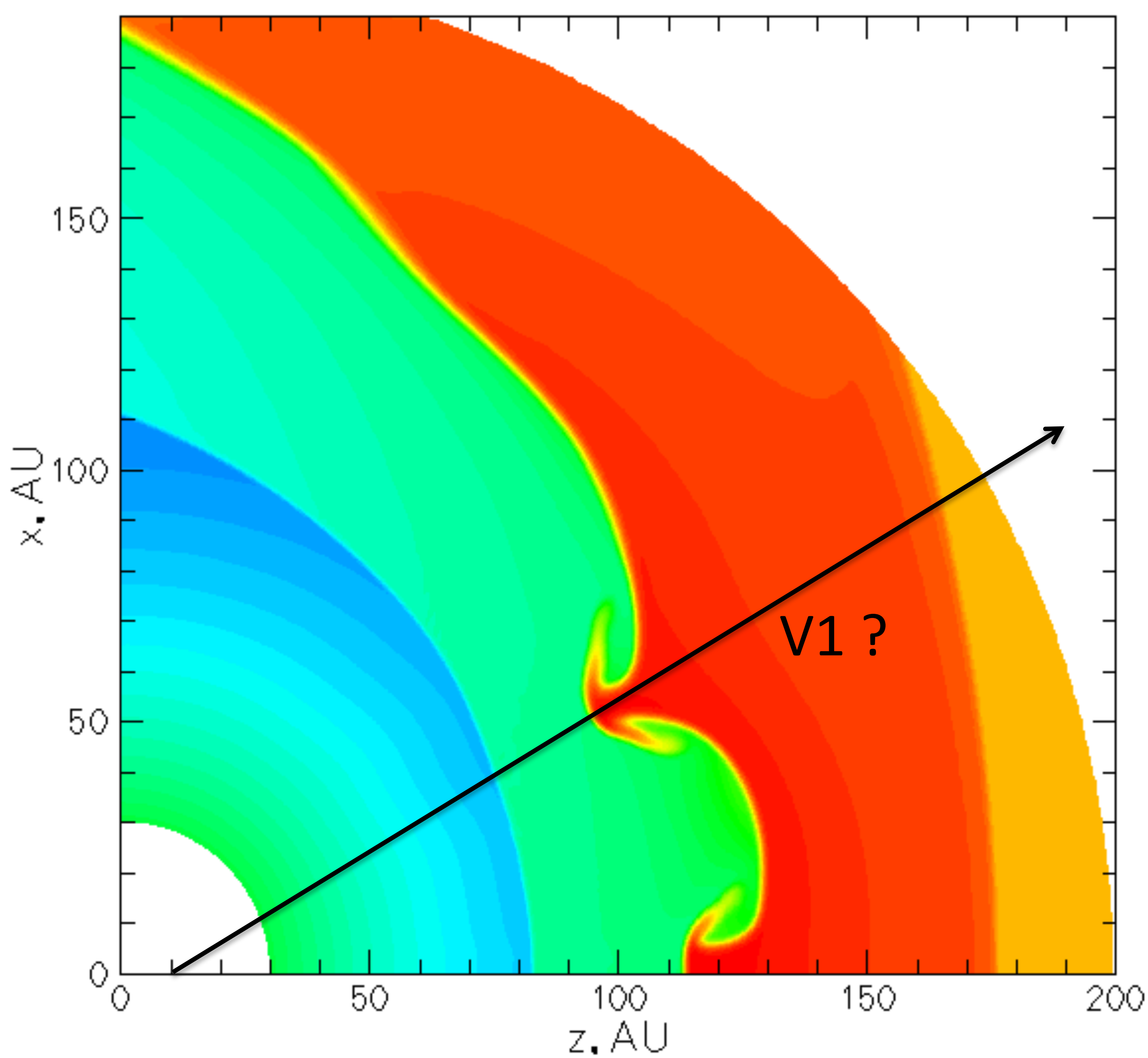
Red: Smoothed V2 data

Blue: Corrected RT angles

Red line: V1 LECP (Decker)

RT angle larger than model
Model VR between V1 and V2

One Solution? Florinski et al: Instabilities on the Heliopause

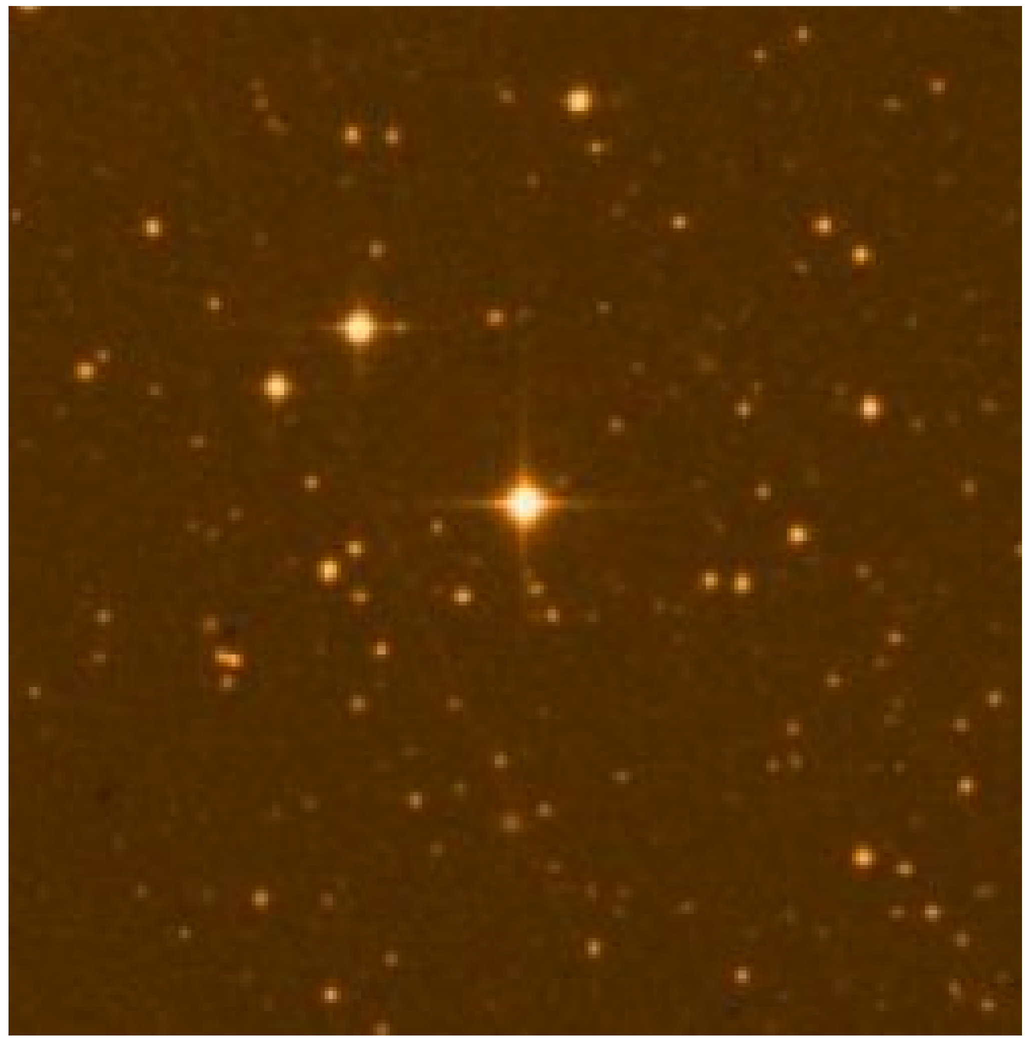


The Future

- Sufficient power until the year 2025
- Voyagers will then wander the Milky Way
  - Voyager 1 within 1.6 light years of the star Gliese 445 in 40,000 years
  - Voyager 2 within 1.7 light years of Ross in 40,000 years

Where next? Ross 248

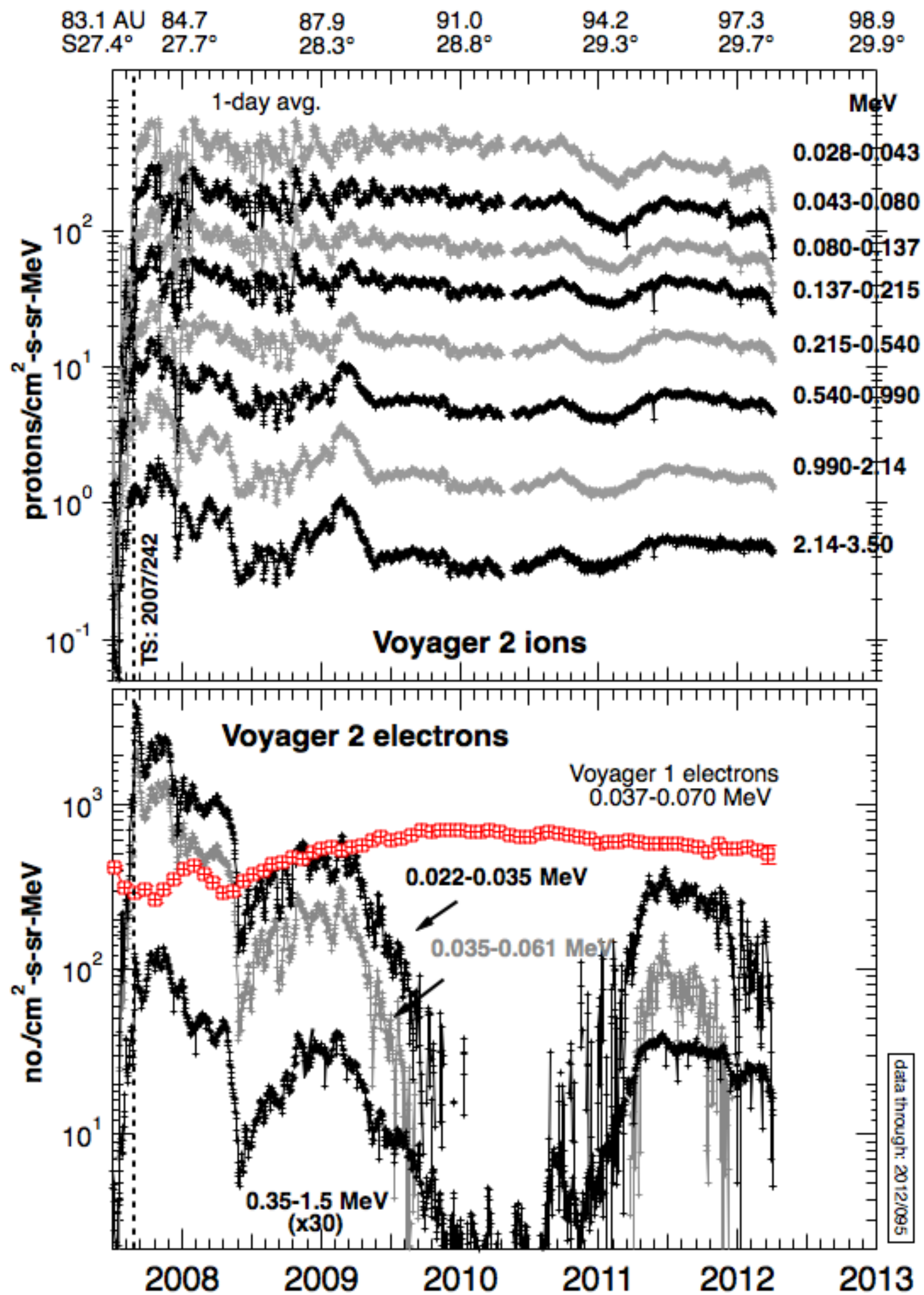
A nearby red dwarf, 10 light years away, in the constellation Andromeda



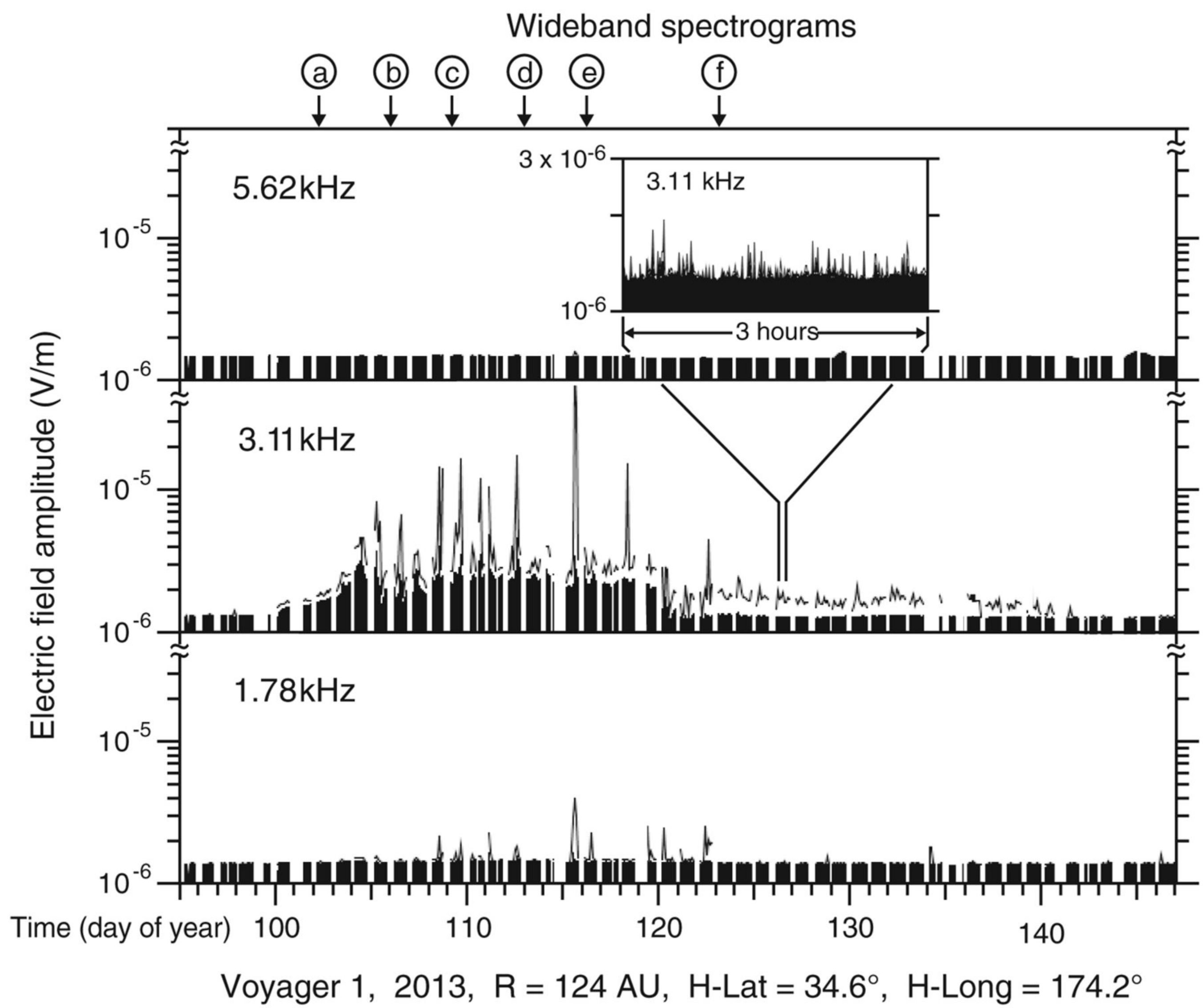

THE SOUNDS OF EARTH
UNITED STATES OF AMERICA
PLANET EARTH

Summary

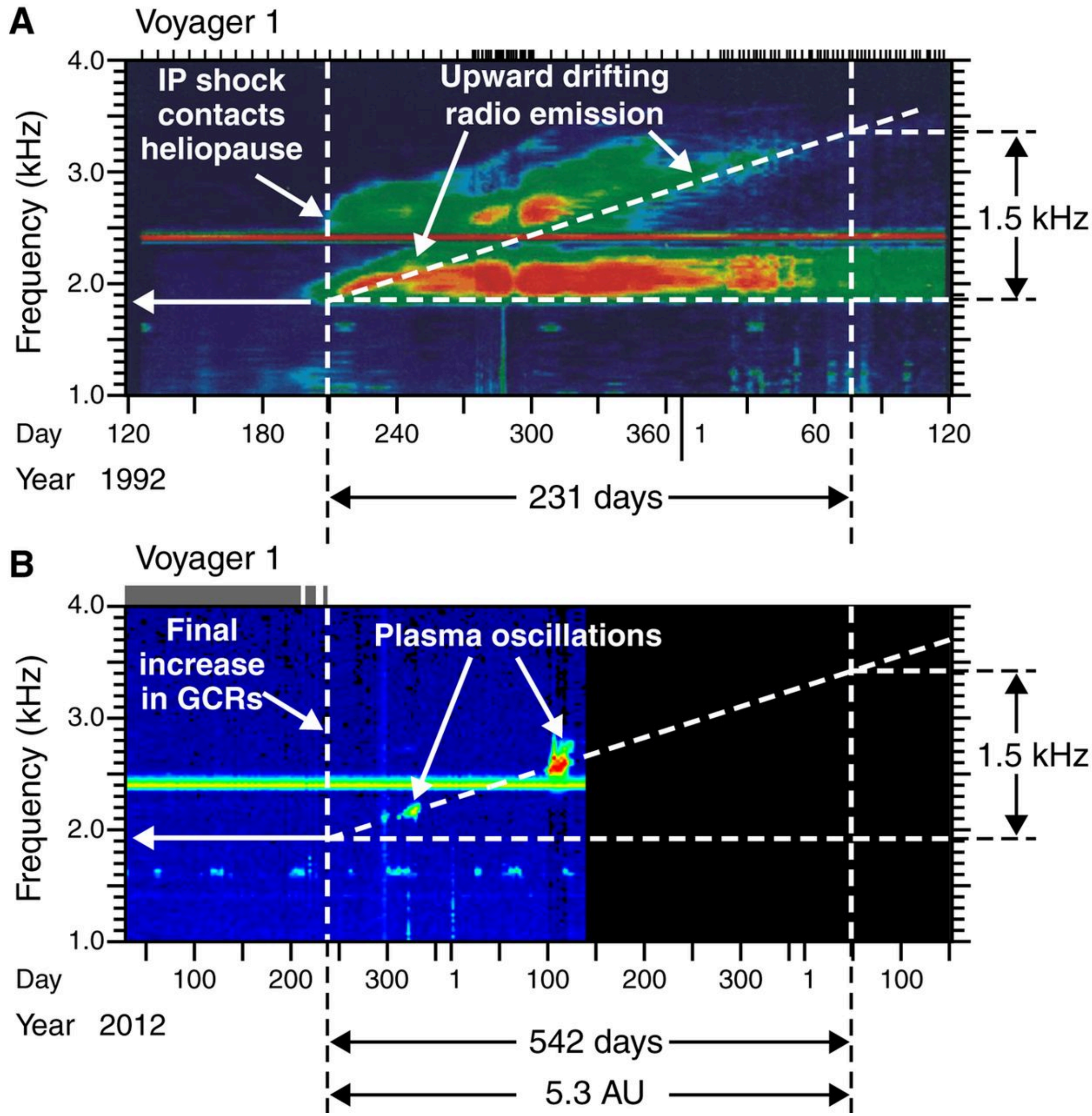
- After 35 years, Voyager 1 has left the heliosphere and is in the interstellar medium.
- Many puzzles still remain about the location, magnetic field direction, and plasma flows.
- Voyager 2, with a working MIT plasma experiment, will help resolve these issues.
- Voyager continue sending data until 2025.
- THANK YOU!!



83.1 AU
S27.4°
84.7
27.7°
87.9
28.3°
91.0
28.8°
94.2
29.3°
97.3
29.7°
98.9
29.9°
1-day avg.
MeV
0.028-0.043
0.043-0.080
0.080-0.137
0.137-0.215
0.215-0.540
0.540-0.990
0.990-2.14
2.14-3.50
protons/cm2-s-sr-MeV
TS: 2007/242
Voyager 2 ions
Voyager 2 electrons
Voyager 1 electrons
0.037-0.070 MeV
0.022-0.035 MeV
0.035-0.061 MeV
0.35-1.5 MeV
(x30)
no./cm2-s-sr-MeV
data through: 2012/095
2008
2009
2010
2011
2012
2013



Wideband spectrograms
a
b
c
d
e
f
5.62kHz
3.11kHz
1.78kHz
3 x 10^-6
3.11 kHz
10^-6
3 hours
10^-5
10^-6
Electric field amplitude (V/m)
Time (day of year)
100
110
120
130
140
Voyager 1, 2013, R = 124 AU, H-Lat = 34.6°, H-Long = 174.2°



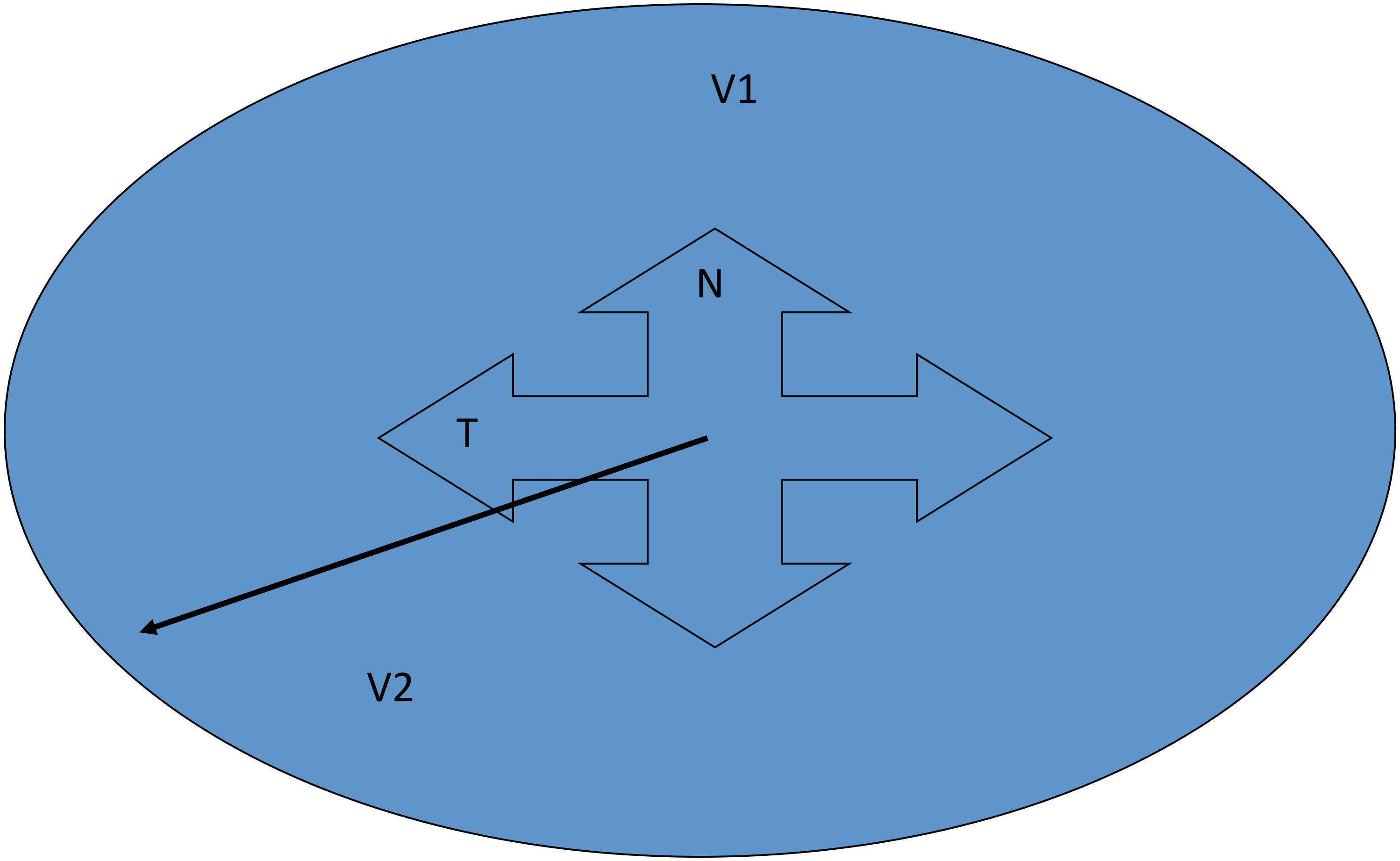
D A Gurnett et al. Science 2013;science.1241681

Charge exchange: ion and neutral collide and ion takes an electron. $H^+ + H \rightarrow H + H^+$

New neutral H moves with plasma speed

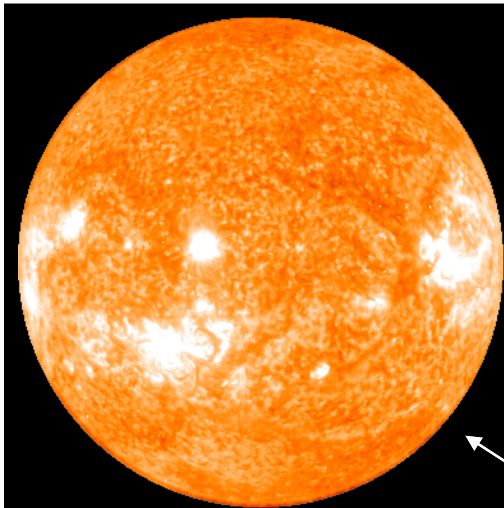
New H^+ is accelerated to plasma speed and has initial thermal energy equal to the plasma energy (1 keV in solar wind): is called a pickup ion.

The energy/momentum come from plasma flow, so plasma slows down.



V2 flow more in T than N direction.
Initially due to TS shape (blunter in T than N)
So Heliosphere is squashed, blunt, and asymmetric.

What is an Astronomical Unit (AU)??



Distance between Sun and Earth

~150 million kilometers
Or ~8.3 light minutes