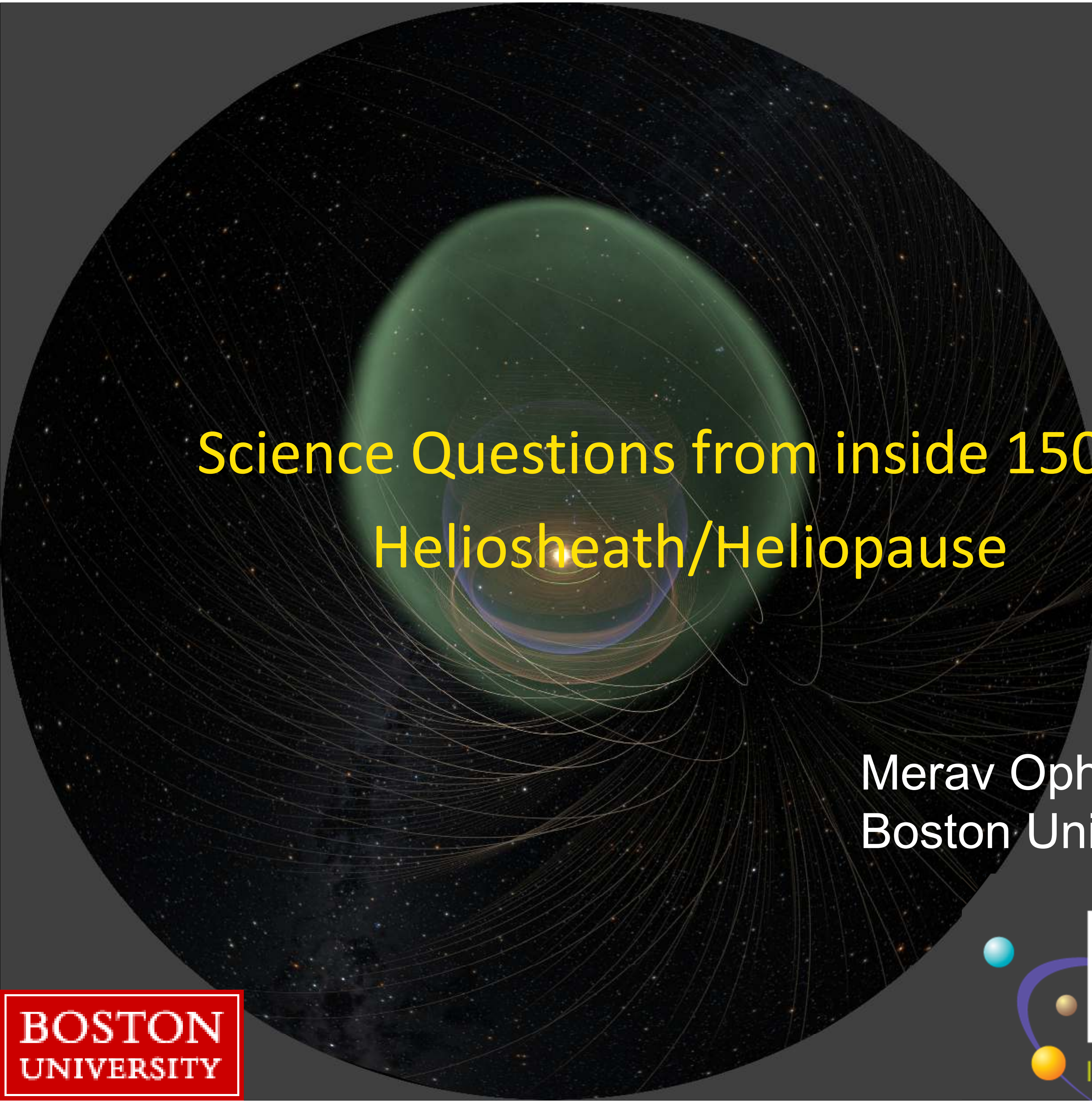


Science Questions from inside 150AU
Heliosheath/Heliopause

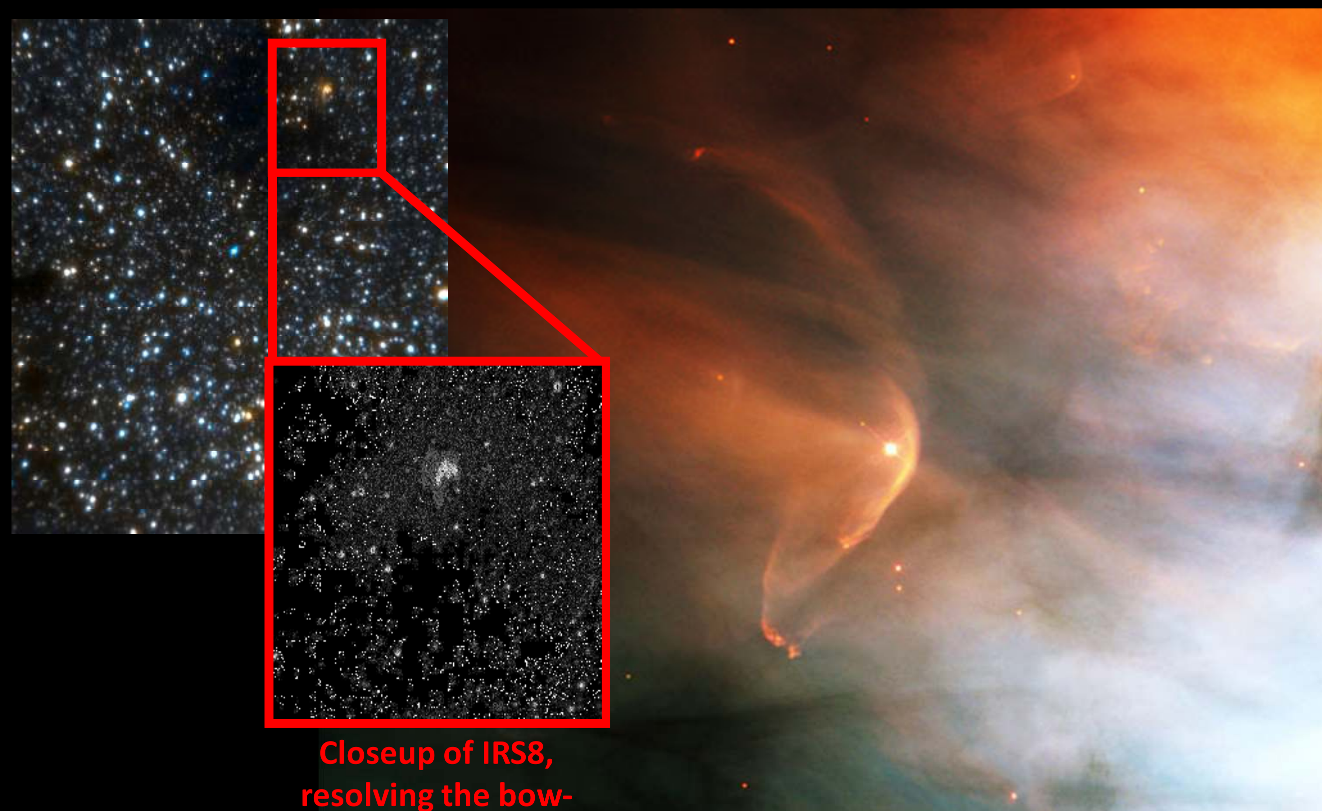
Merav Opher
Boston University

BOSTON UNIVERSITY

Keck
INSTITUTE FOR SPACE STUDIES

The heliosphere as test-bed for other astrospheres

WISE bow shock image, PIA13455



Closeup of IRS8, resolving the bow-shock of a fast-moving star

We need to understand first the only astrosphere that we have *in-situ data;* in particular the *sheath* and interface (pause)

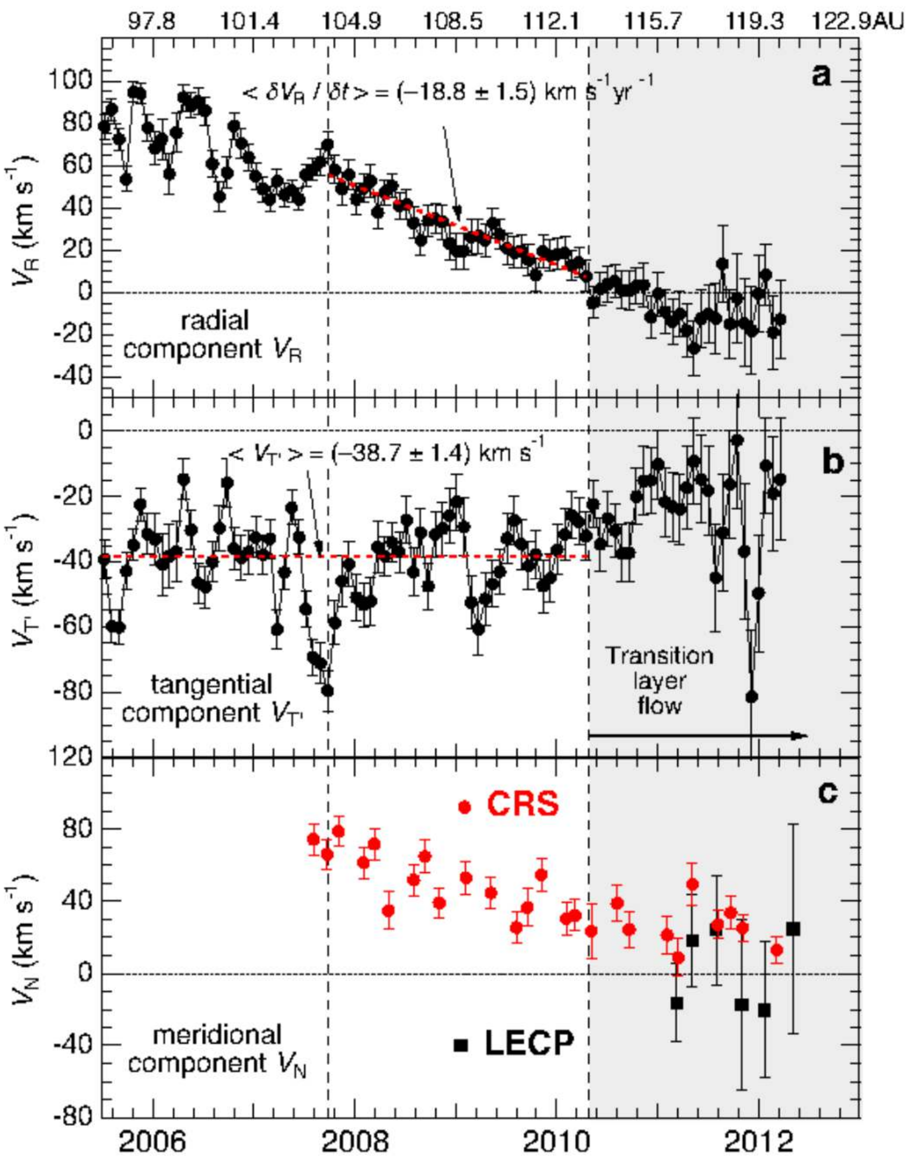
Overview of What We Don't Understand from the Heliosheath/Heliopause:

- Why the flows are different at Voyager 1 and 2?
- Why the energetic particles are different at Voyager 1 and 2?
- Why does the Anomalous Cosmic Rays spectrum roll out well into the heliosheath?
- Pick-up ions thermodynamic dominated heliosheath

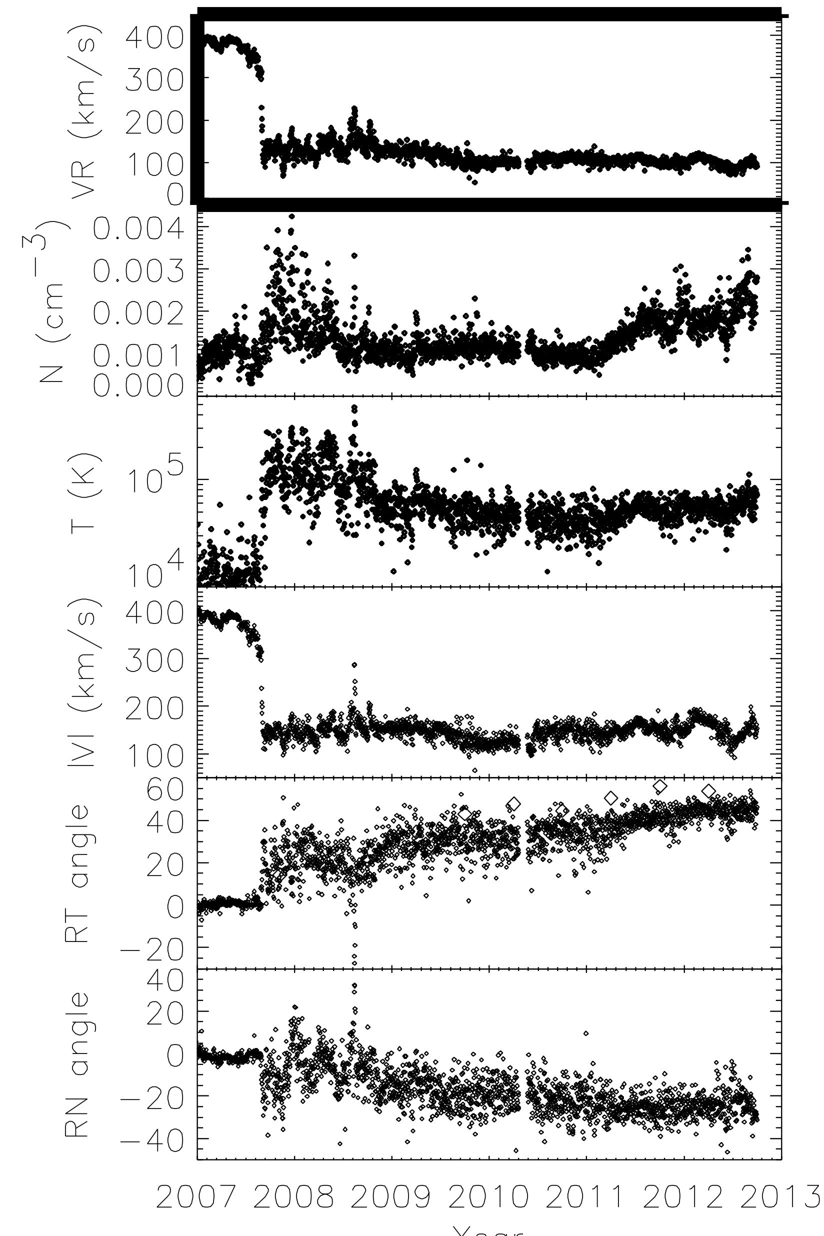
Overview of What We Don’t Understand from the Heliosheath/Heliopause - cont:

- The unexpectedly narrow width of the heliosheath.
- The complex particle and field structure near the heliopause.
- The puzzling orientation of the interstellar magnetic field beyond the heliopause.
- What happened to the missing azimuthal magnetic flux at Voyager 1?

- Why the flows are different at Voyager 1 and 2?

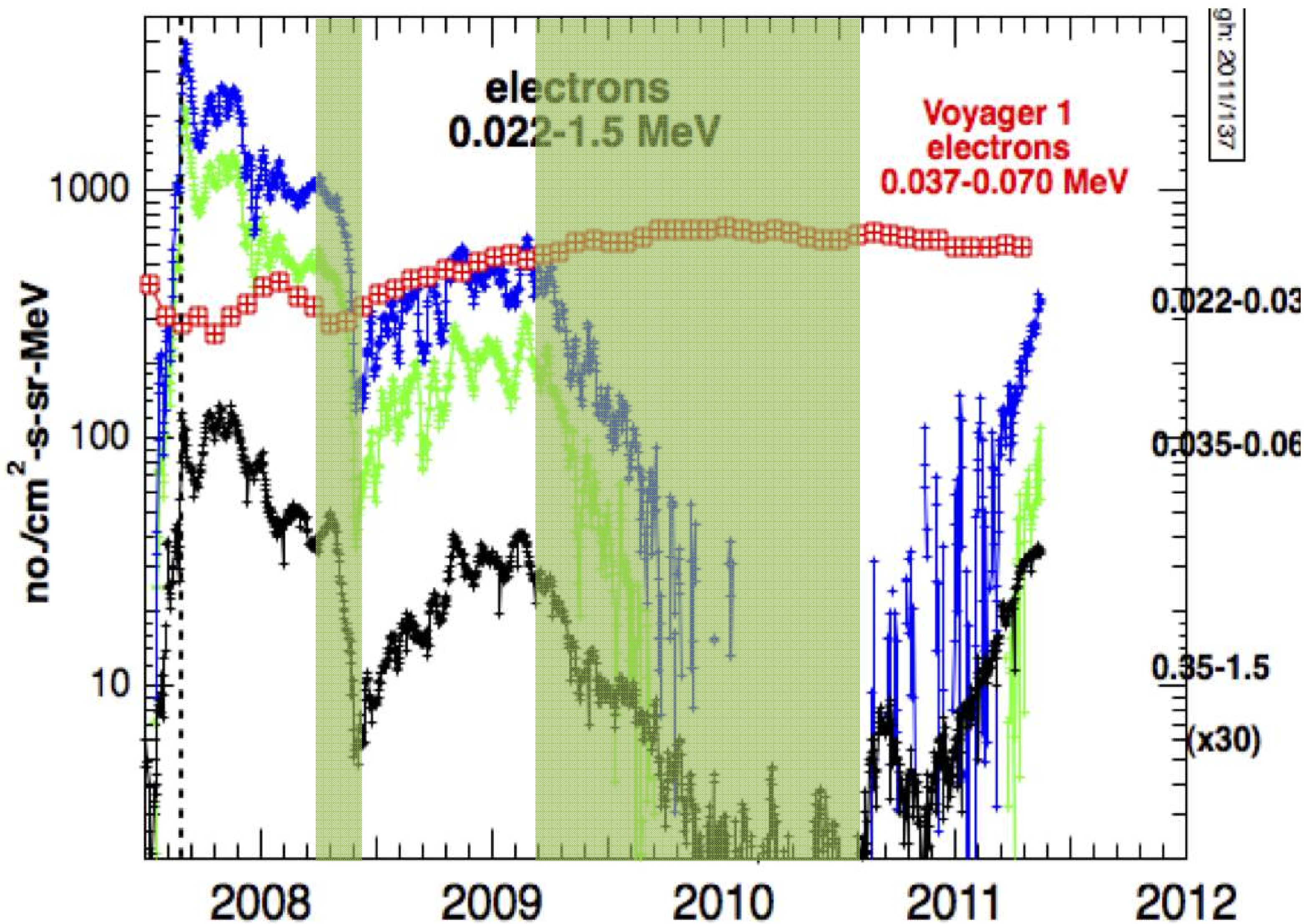


Voyager 1



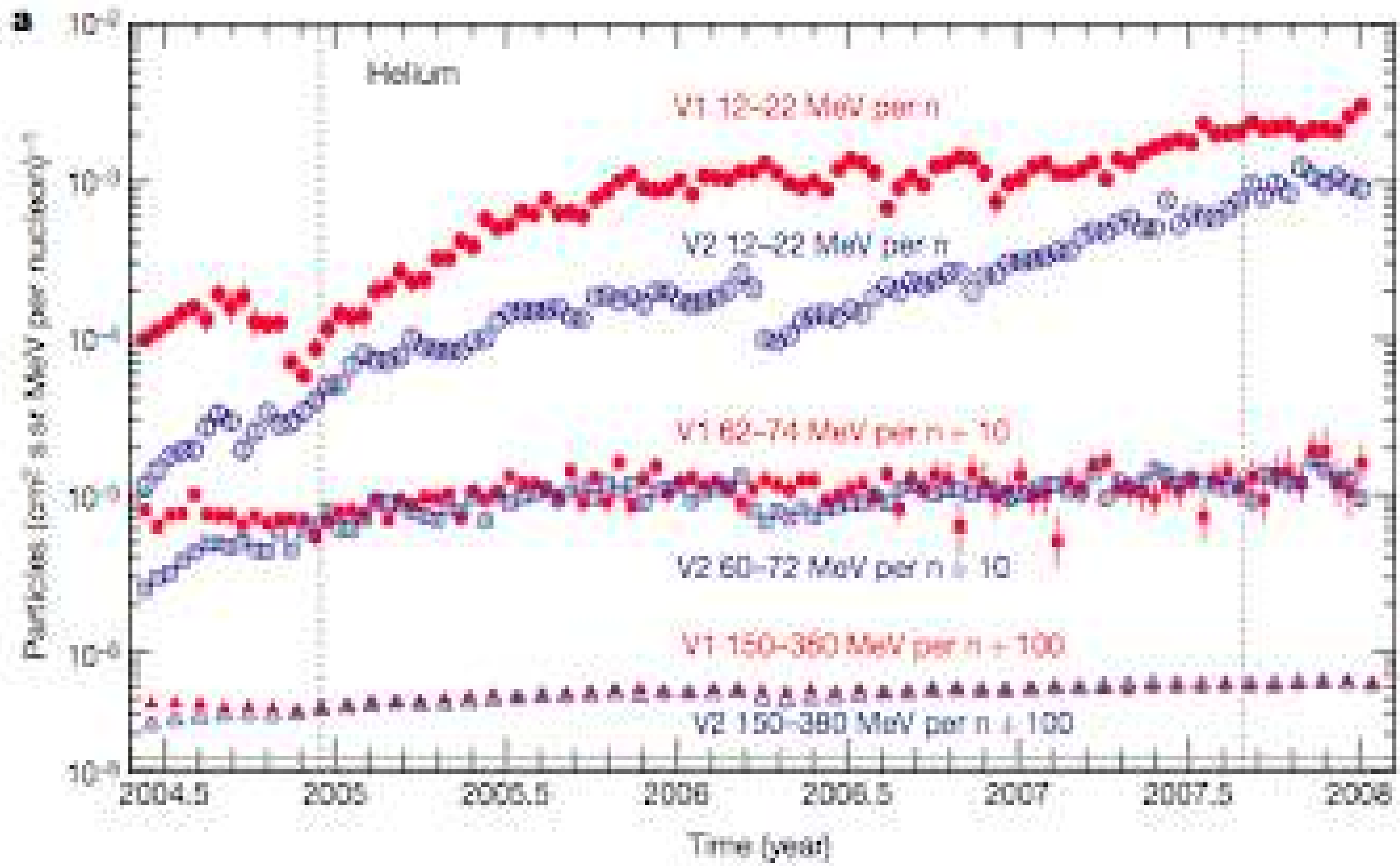
Voyager 2

- Why the energetic particles are different at Voyager 1 and 2?

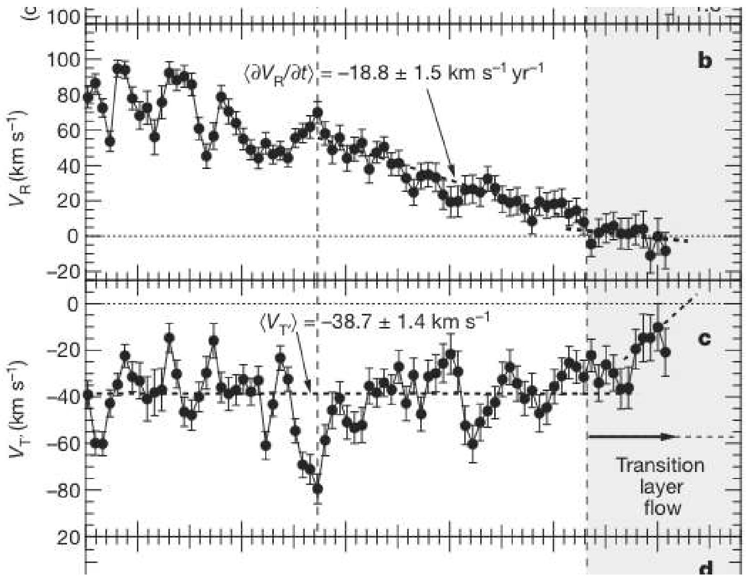


Shaded areas: periods when V2 was outside the sector region

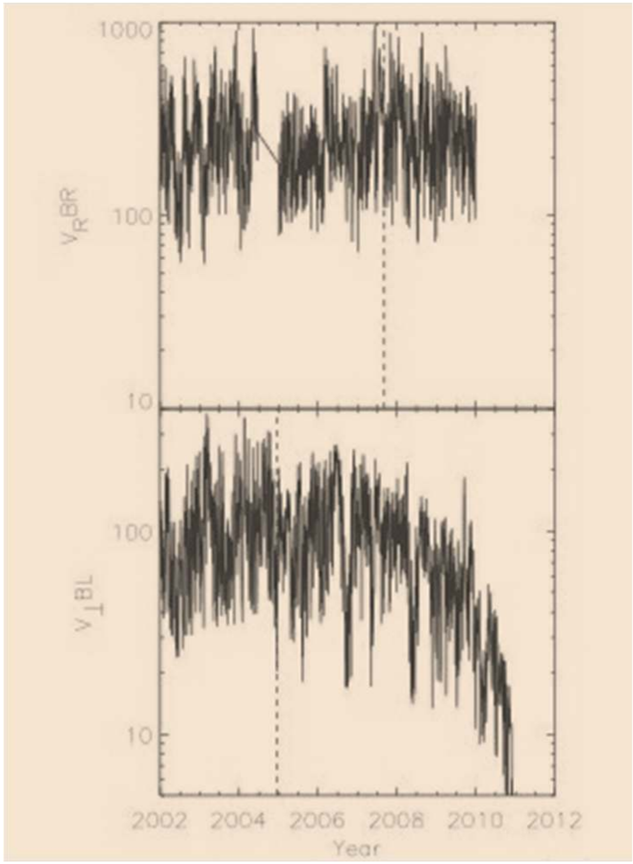
Why does the Anomalous Cosmic Rays spectrum roll out well into the heliosheath?



What happened to the missing azimuthal magnetic flux at Voyager 1?



Expect corresponding increase in magnetic field



Conservation of magnetic flux:

$B_T V_R R$ = constant

However, while VR was decreasing B was constant <B> = 0.1

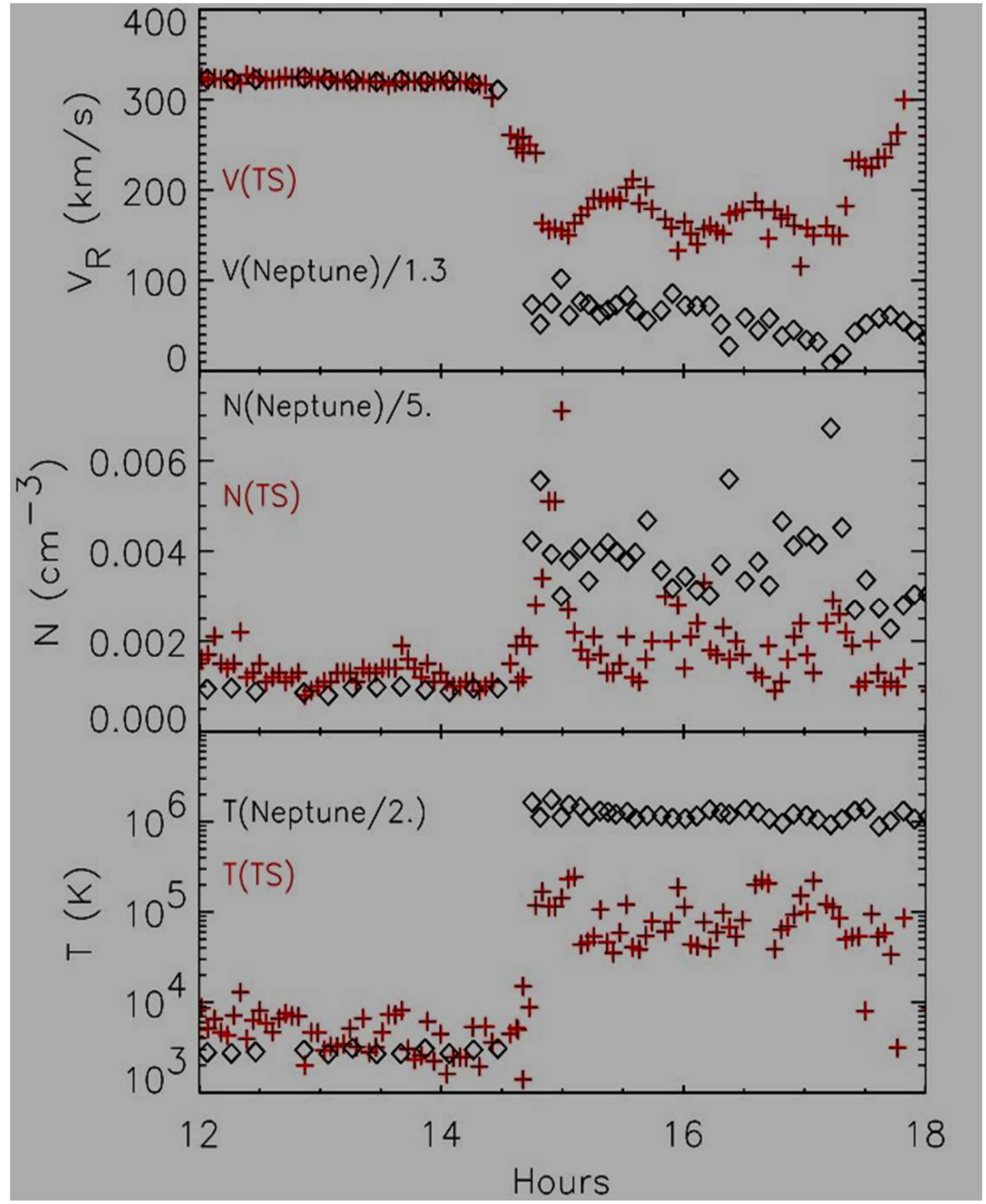
Richardson et al. 2013

Pick-up Ions Dominated Heliosheath

- Shock is much colder than expected
- ~ 80% of the energy goes into supra-thermal particles

Discovery of a new paradigm:

Pickup ions carry most of the pressure



Richardson et al. Nature 2005

Structure of the Heliopause; is it Porous? Is it a Boundary? Region?

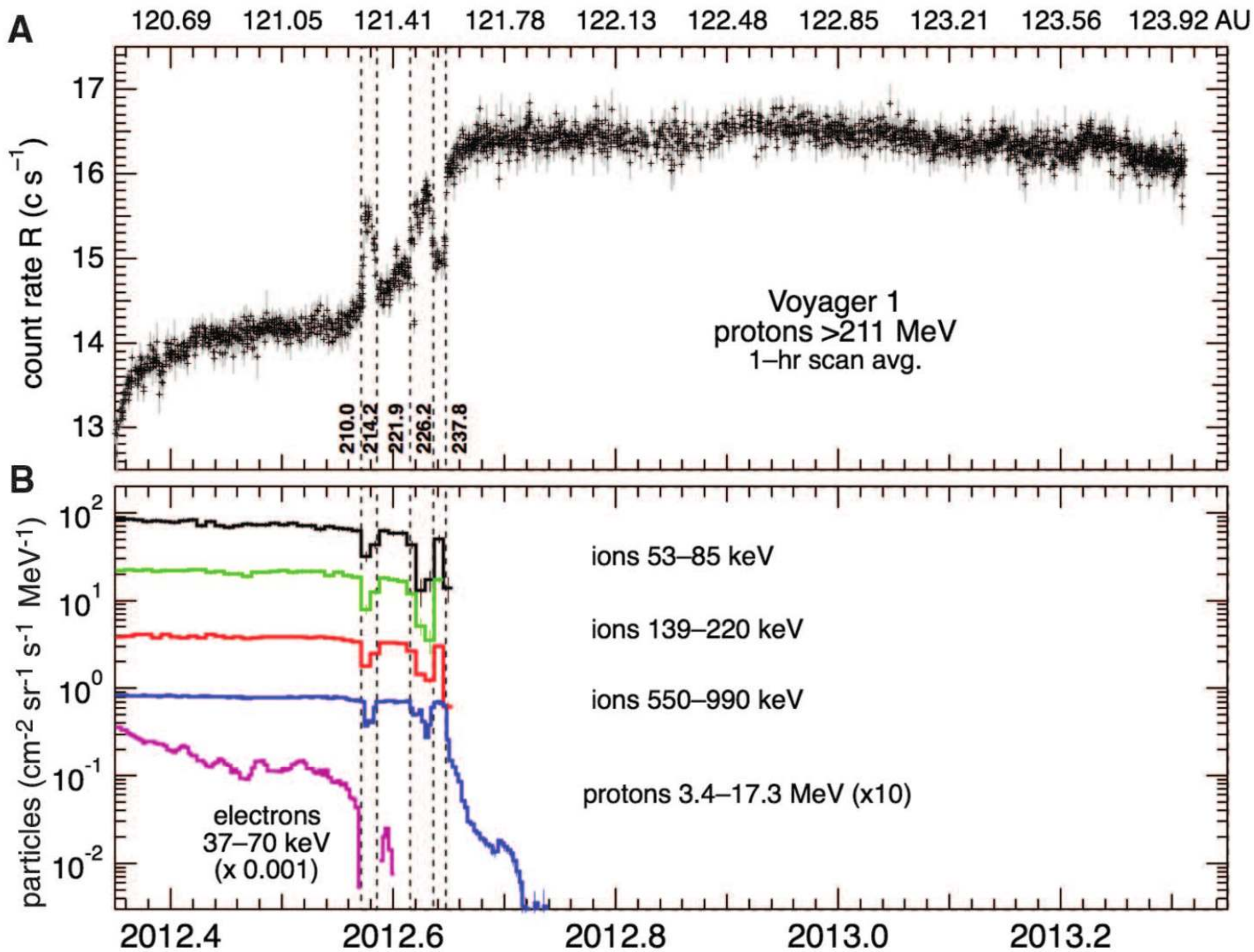
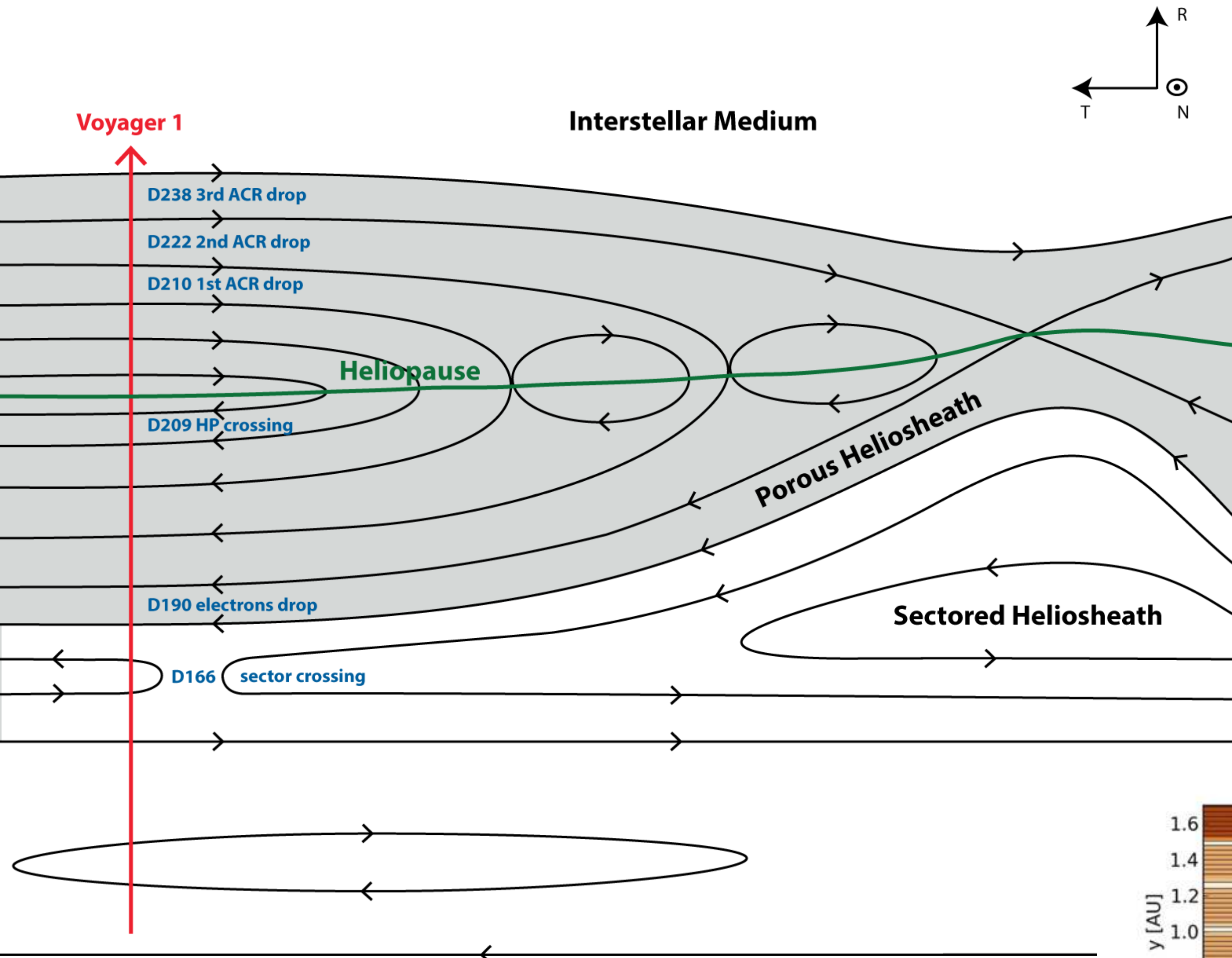


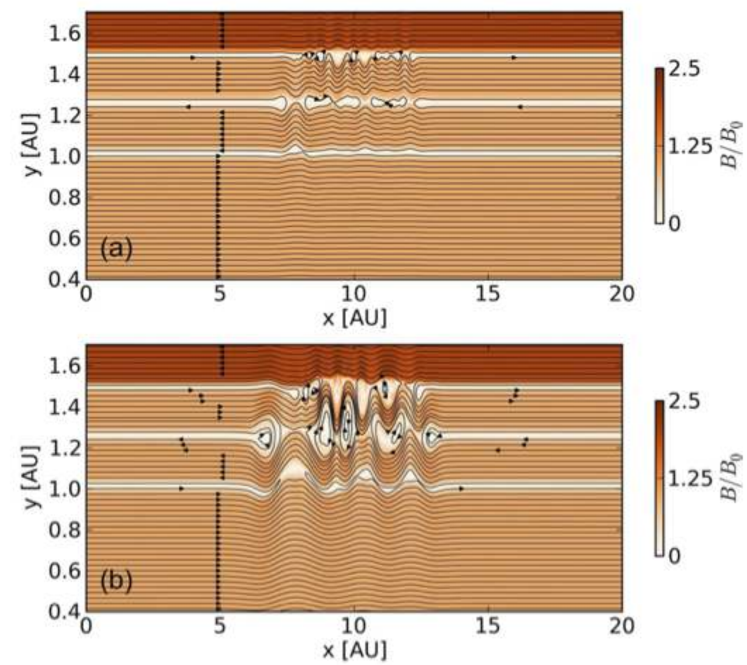
Fig. 1. Overview of energetic particle observations at V1, 2012.35 to 2013.40, showing the contrary behavior of GCRs and lower-energy particles. (**A**) Hourly averages of GCR activity and the pronounced boundary crossing on 25 August 2012 (day 238). GCR error bars are $\pm 1\sigma$. (**B**) Intensities of low- to medium-energy ions and low-energy electrons. The time evolution is very different, depending on energy and species.

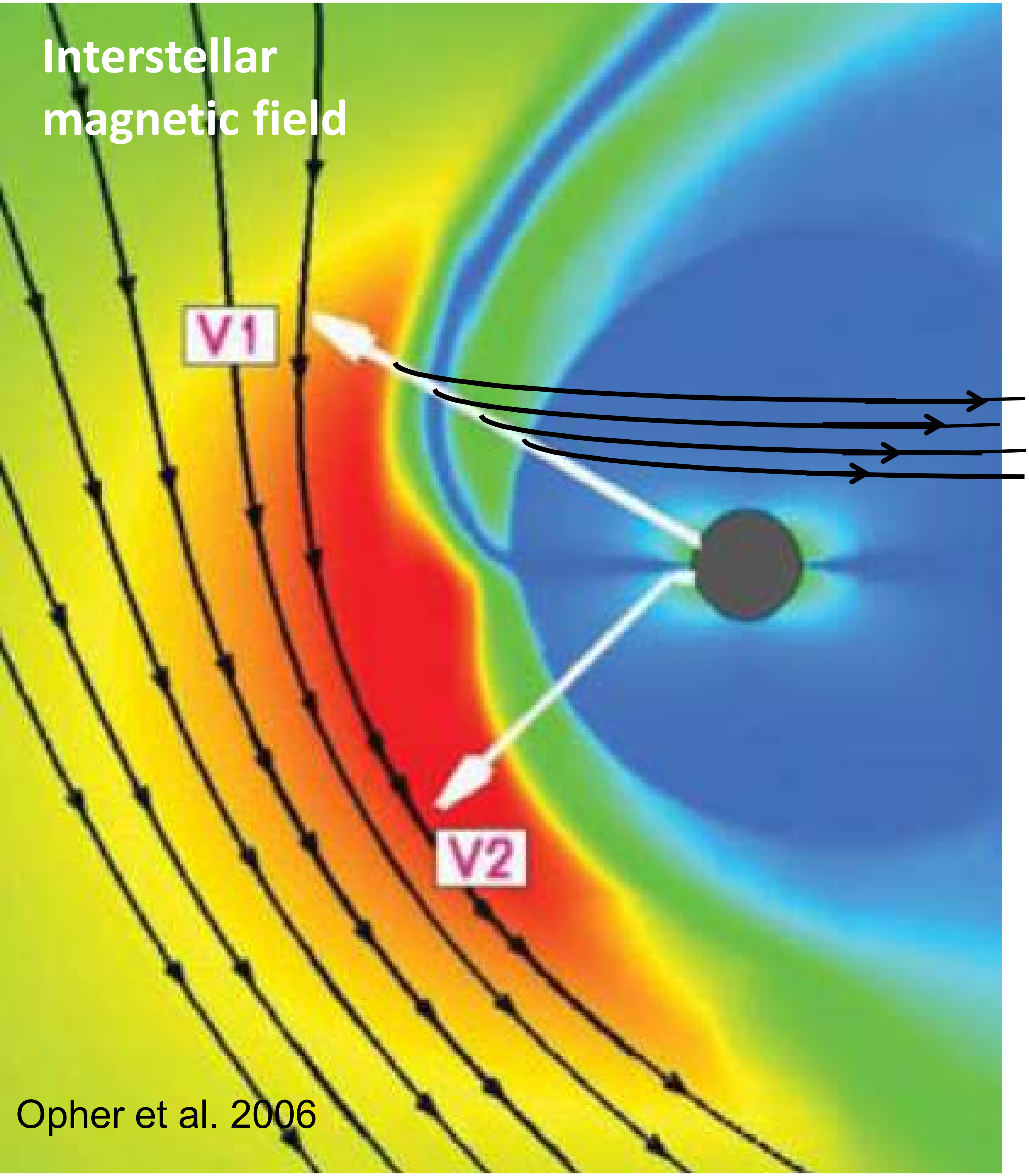
Krimigis et al. *Science* 2013



Swisdak et al. 2013;

Other proposals: Fisk & Gloeckler
Schwadron & McComas (FTRs)
Strumik et al. 2013



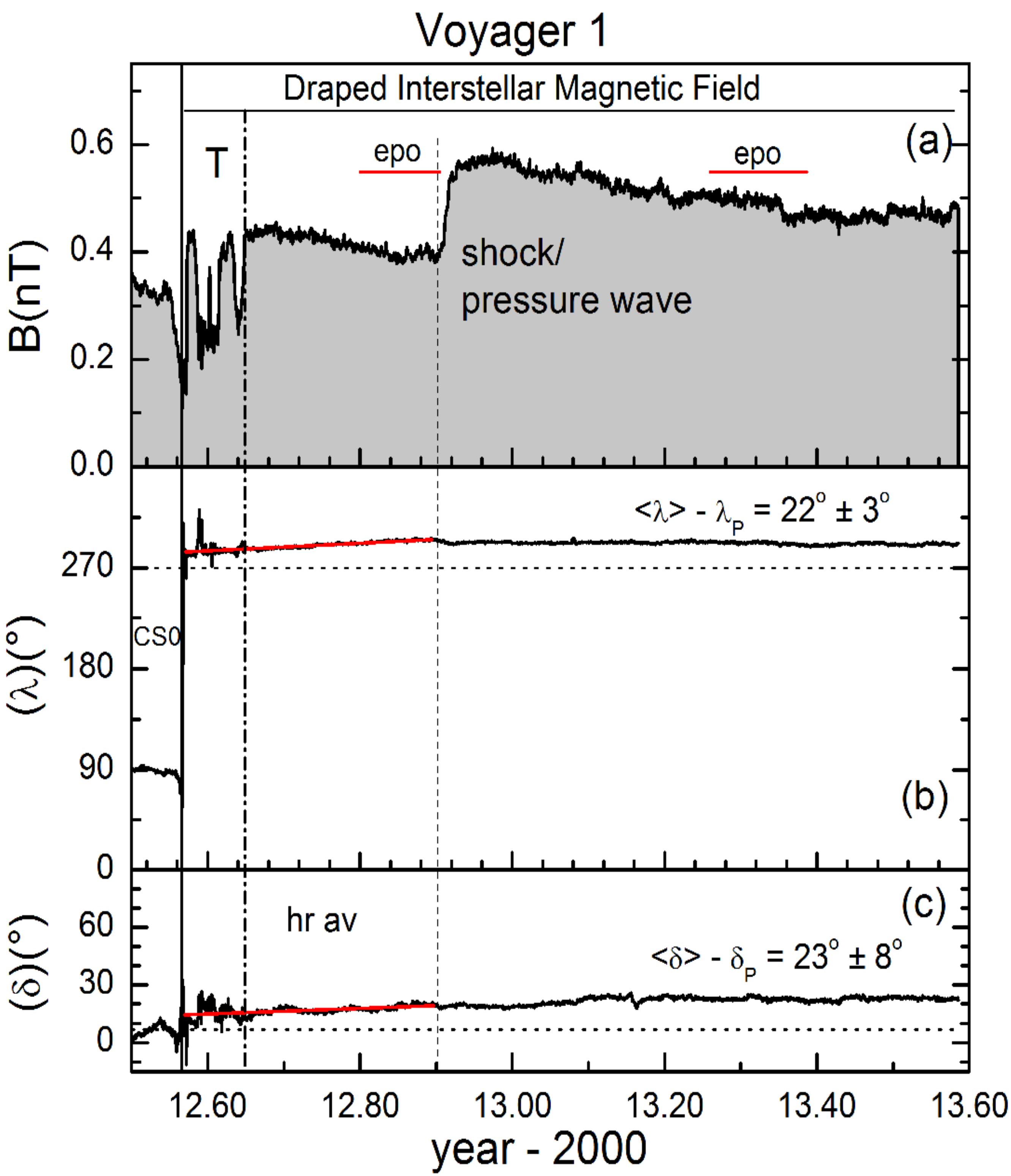


Spiral magnetic field from solar rotation is east-west

Interstellar magnetic field is inclined about 60° to the east-west direction

There is an expectation that the magnetic field direction will rotate dramatically across the heliopause

Acknowledg. Ed Stone



From Burlaga & Ness *ApJ* 2014

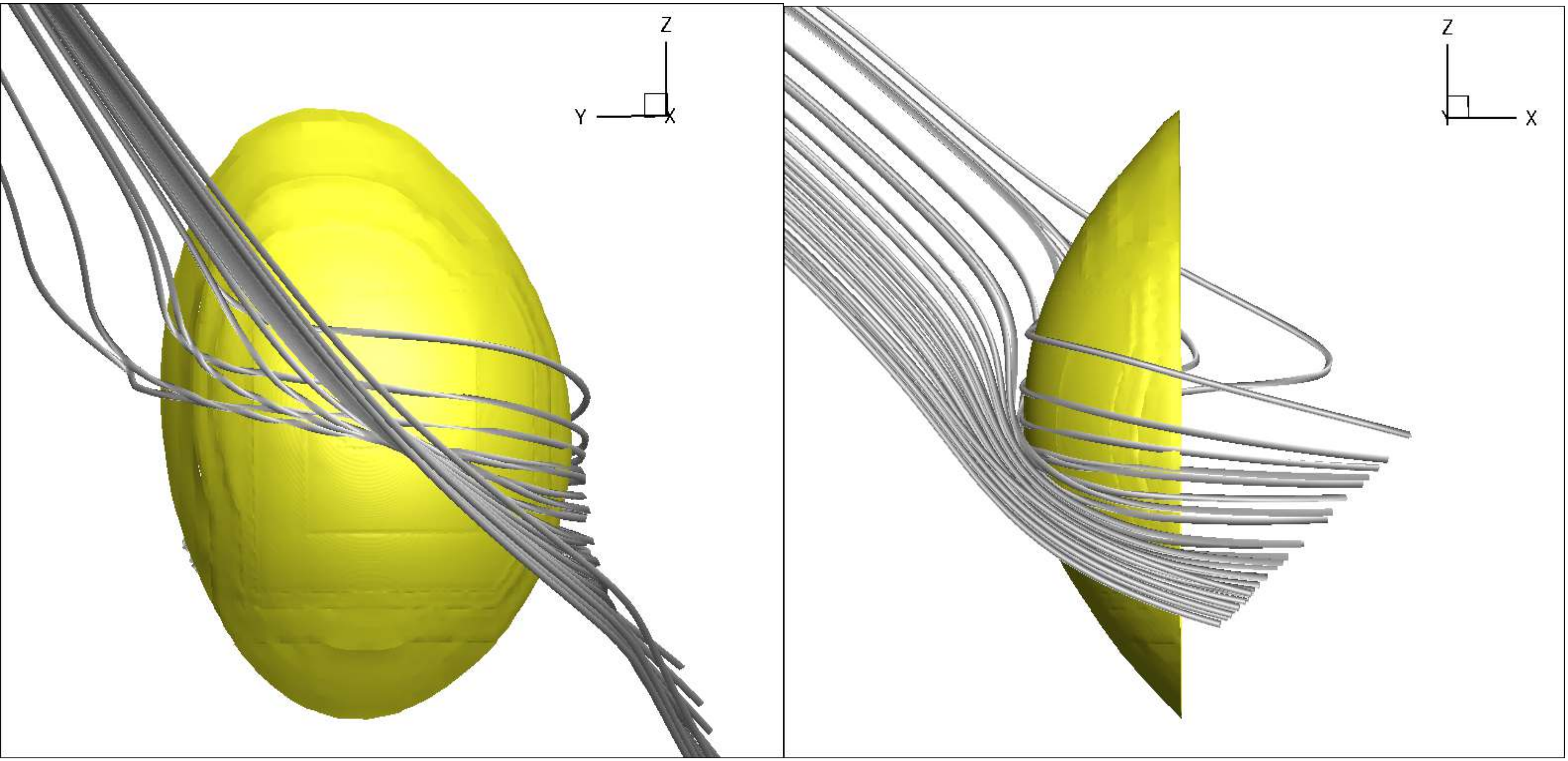
$\delta = 15^{\circ} \pm 8^{\circ}$ near CS0 2012.56
to
$\delta = 23^{\circ} \pm 8^{\circ}$ in 2013.3855

~ 2.7°/AU

$\lambda = 284^{\circ} \pm 3^{\circ}$ near CS0 2012.56
to
$\lambda = 292^{\circ} \pm 3^{\circ}$ in 2013.3855
~ 2.7°/AU

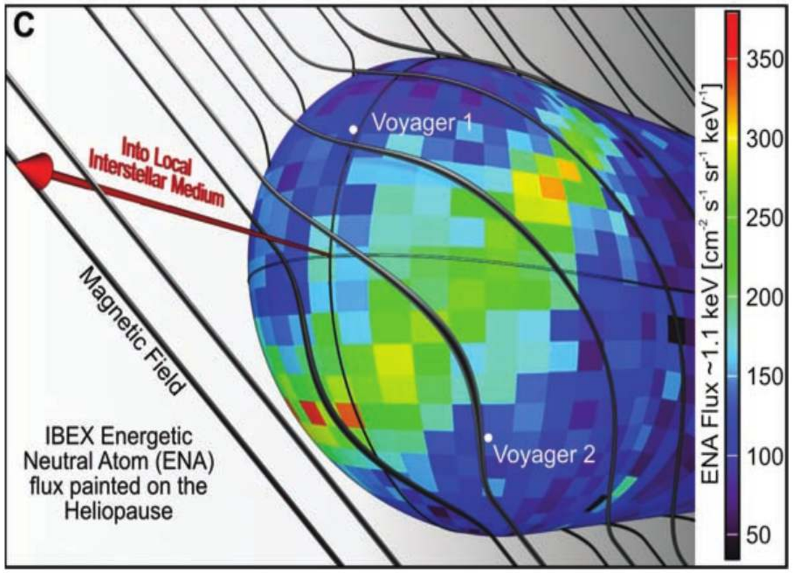
STRONG TWIST OF THE INTERSTELLAR MAGNETIC FIELD ahead of the Heliopause

Opher & Drake *ApJL* 2013

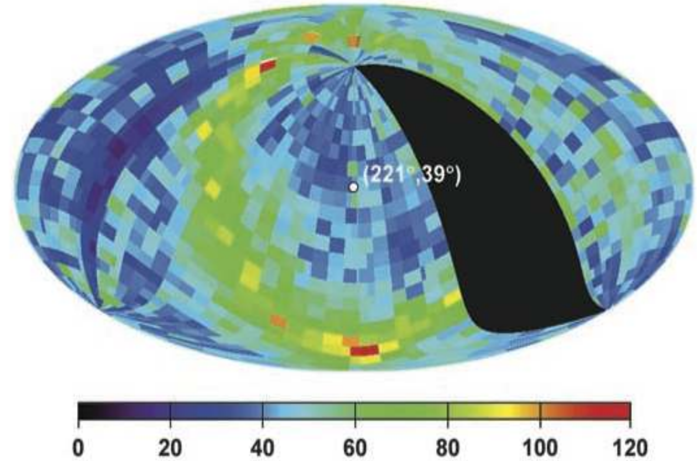


At large distances outside of the HP the interstellar field lines are inclined to the T direction (east-west direction) and then twist dramatically in the T direction as they approach the Heliopause.

The IBEX ribbon was suggested to be aligned with the B_{ISM}•r=0 outside the Heliopause

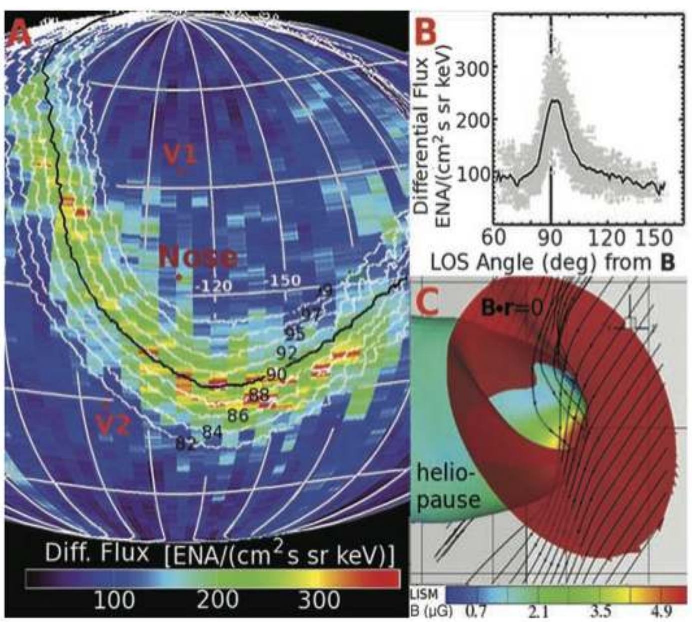


McComas et al. 2009



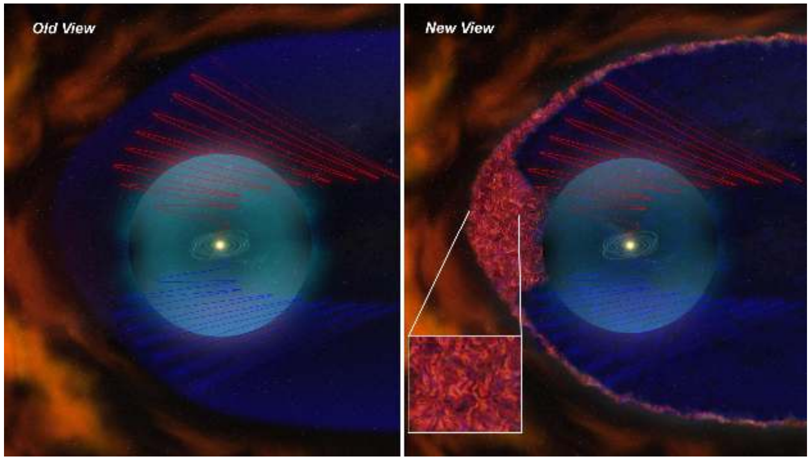
Funsten et al. 2009

And the centroid to be the direction of B_{ISM}

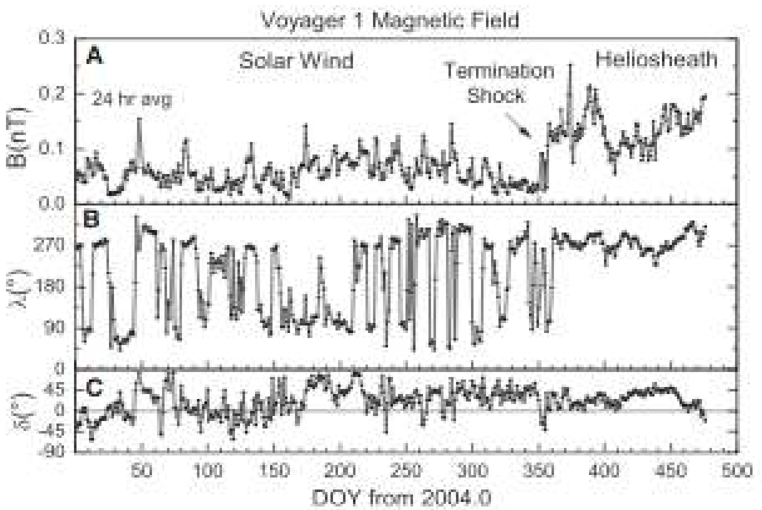


Schwadron et al. 2009

Onset of Collisionless Reconnection



Magnetic Field



Parameters upstream of the Termination Shock (TS)

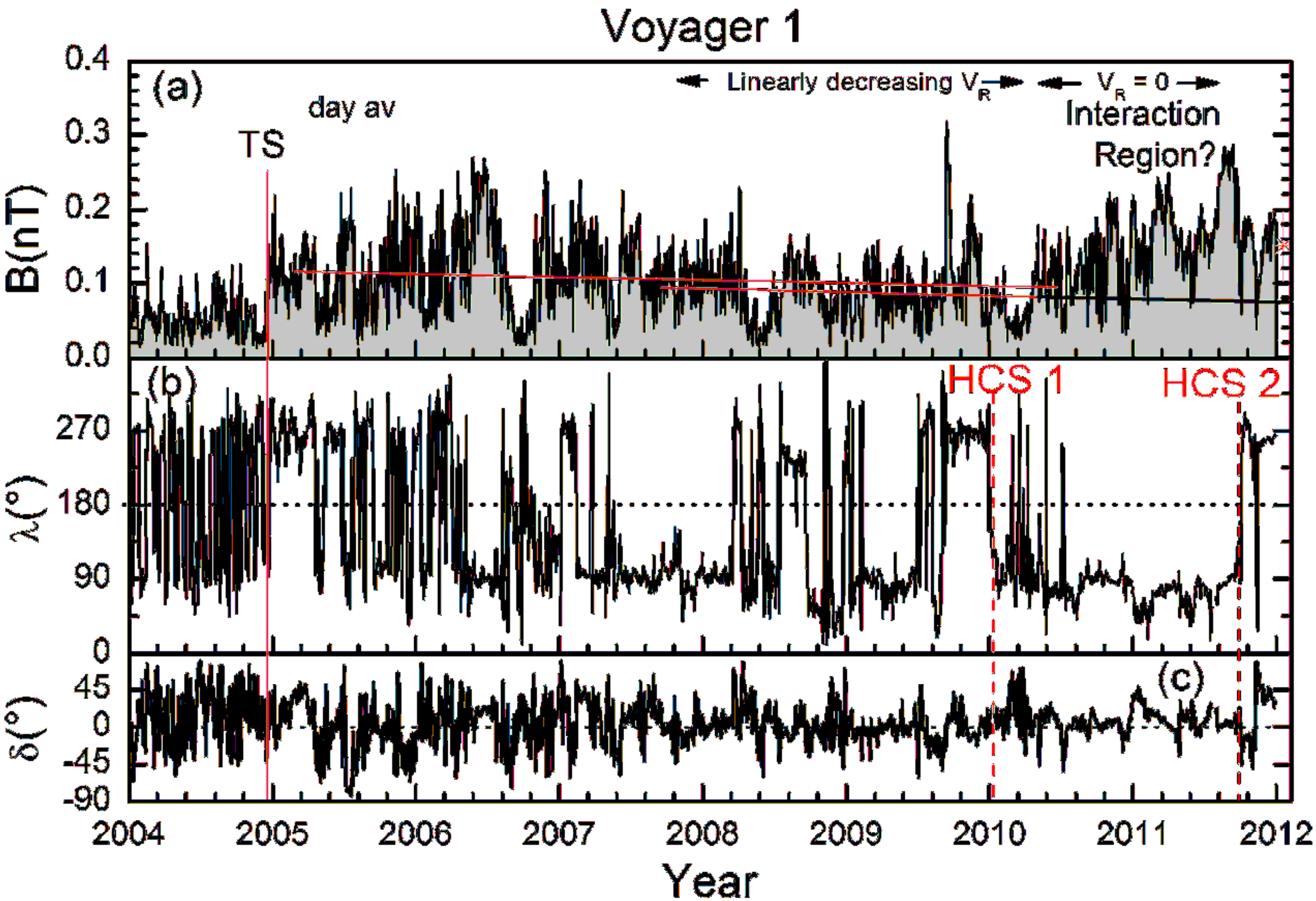
- HCS thickness ~ 10,000 km based on 1AU – *Winterhalter et al. 1994*
  - This is a significant uncertainty – need 48s mag data upstream
- Ion inertial scale ~ 8400 km (n ~ 0.001/cm^3)

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 1σ uncertainty in each component of the magnetic field ***B*** is ±0.04 nT

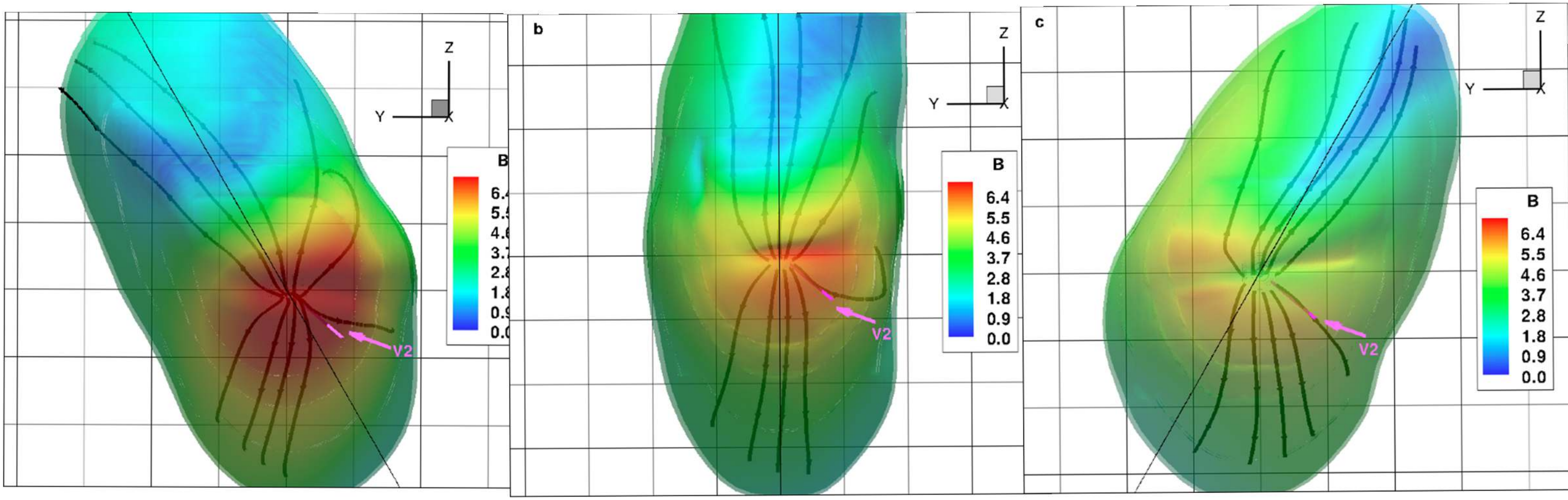
Requirements for Science

- Magnetometer; high cadency (48s) (high sensitivity)
- Plasma instrument with capability to measure

Not just the thermal but supra-thermal (PUI).

- (Besides LECP/Cosmic Ray/)

Local Interstellar Magnetic Field



B is 3.7-5.5μG, tilted ~20-30° from the flow direction in the interstellar medium and is at an angle of about 30° from the Galactic plane.

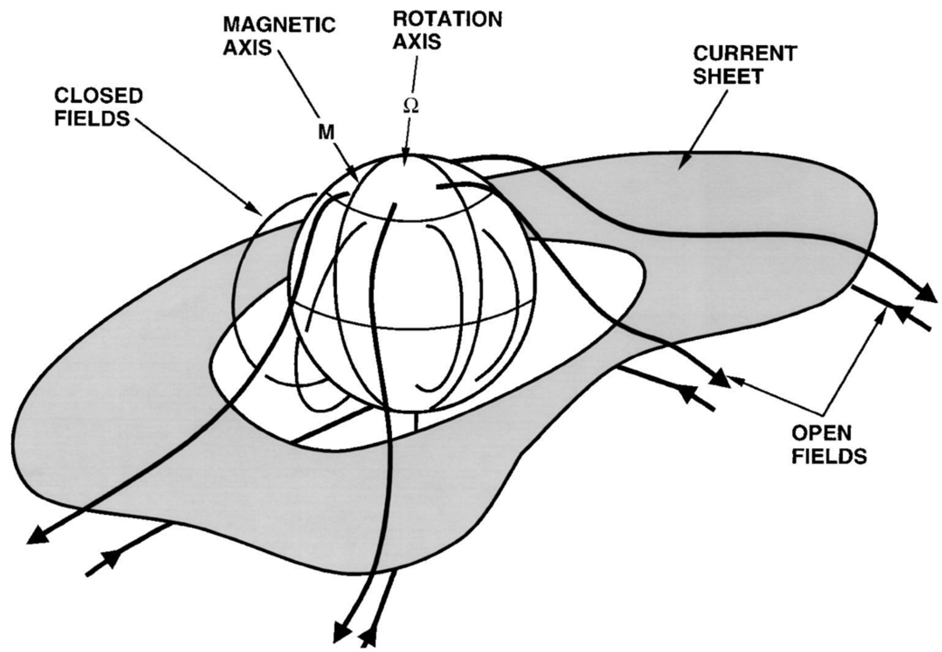
Opher, Stone & Gombosi *Science* (2007);
Opher et al. *Nature* (2009)
Izmodenov et al. Space Scien Rev (2009)

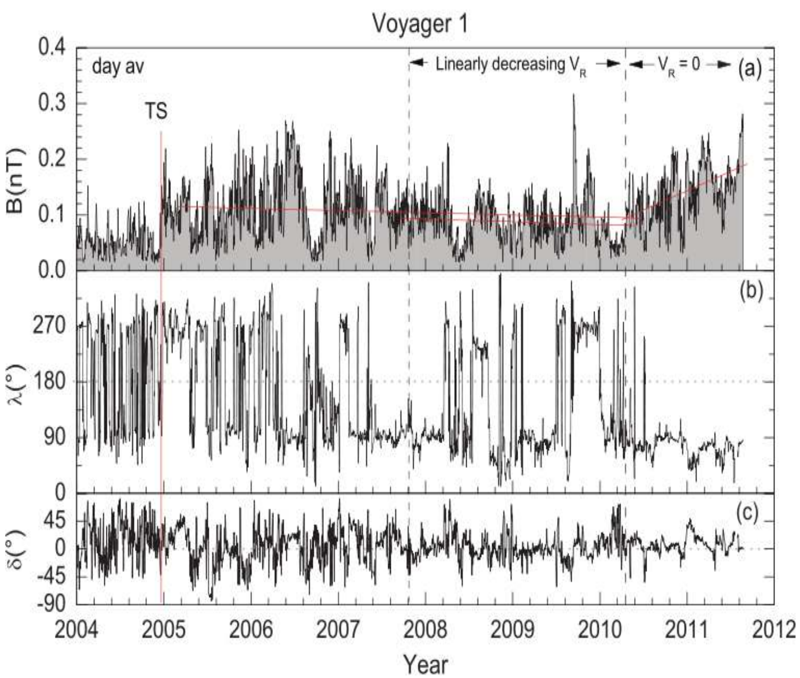
This is the field that can reproduce the several heliospheric asymmetries detected by Voyager as TS asymmetries and values of the crossing (including 7AU of assymetry-Richardson Et al. Nature 2008), the radio band; and particles streaming to the shock

Extra Slides

Sector structure of the heliospheric field

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





Heliospheric current sheet

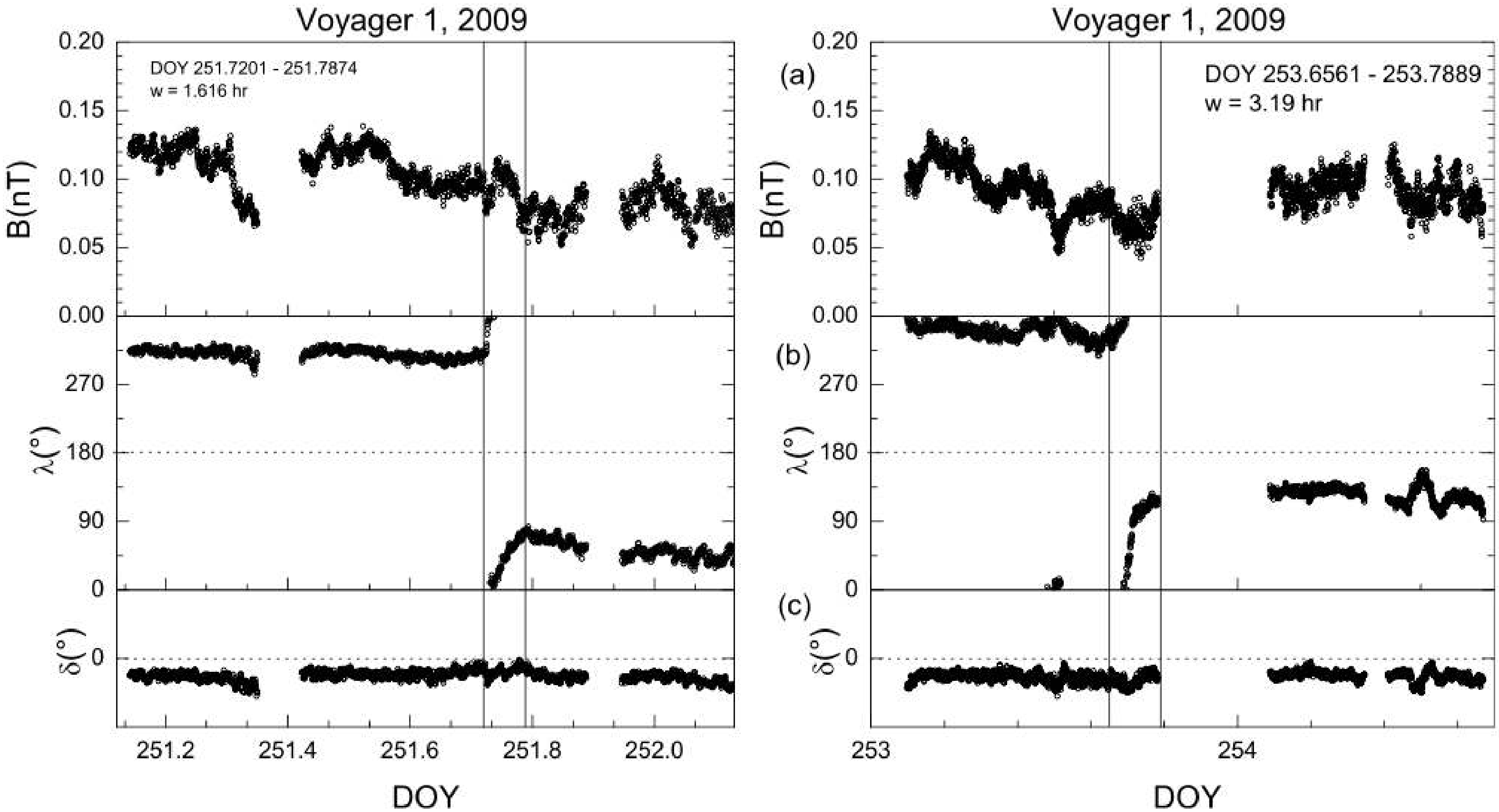
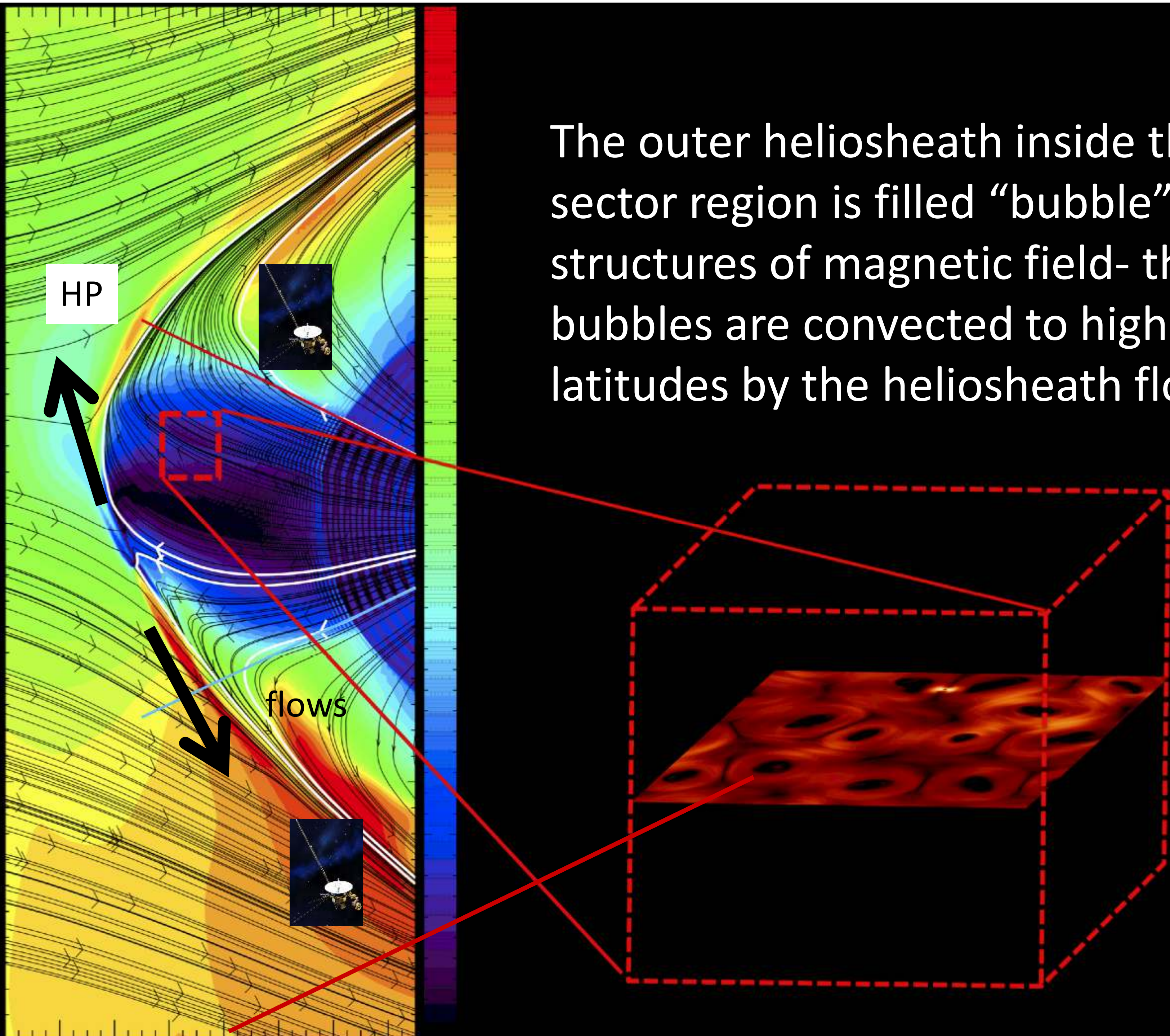


Figure 10. Observations of two current sheets, each associated with a sector boundary. The format is the same as that in Figure 1.

The 1σ uncertainty in each component of the magnetic field ***B*** is ±0.04 nT before 2011 and ± 0.02 nT thereafter. A detailed discussion of the experimental uncertainties is given by Berdichevsky (2009).3 The 1σ uncertainty in *B* (the magnitude of ***B***) is ± 0.05 nT before 2011 and ± 0.03 nT after 2011.

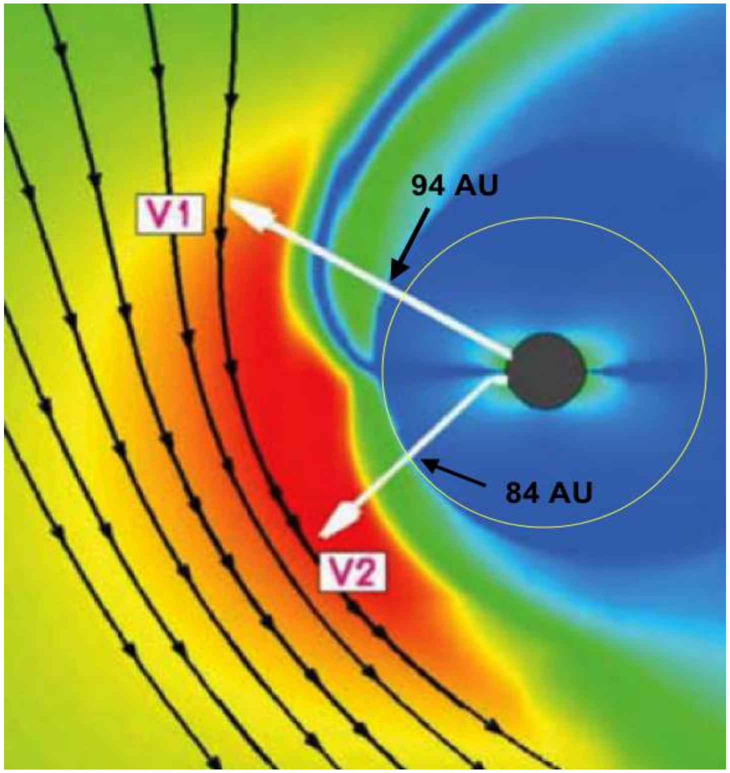


The outer heliosheath inside the sector region is filled “bubble”-like structures of magnetic field- the bubbles are convected to higher latitudes by the heliosheath flows

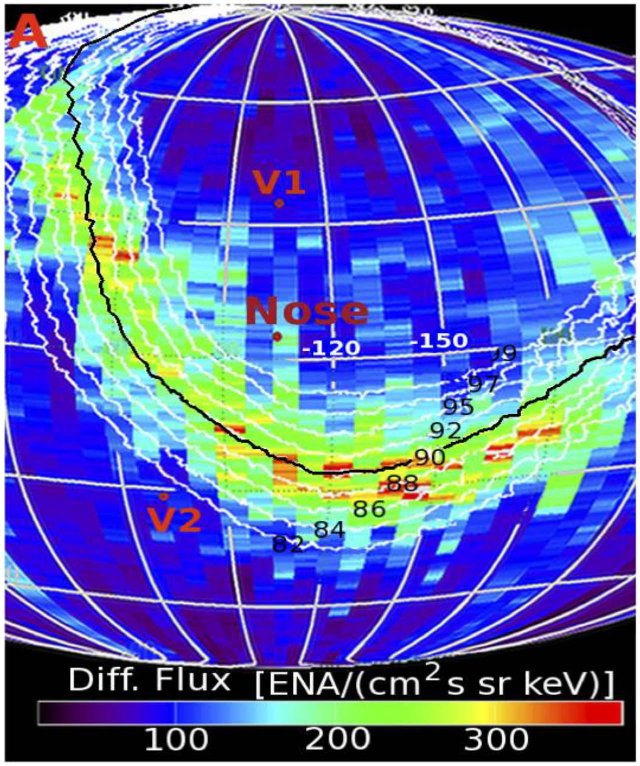
Opher et al. ApJ 2011

Asymmetric Heliosphere

Strong Influence of the Interstellar Magnetic Field on the Heliosphere



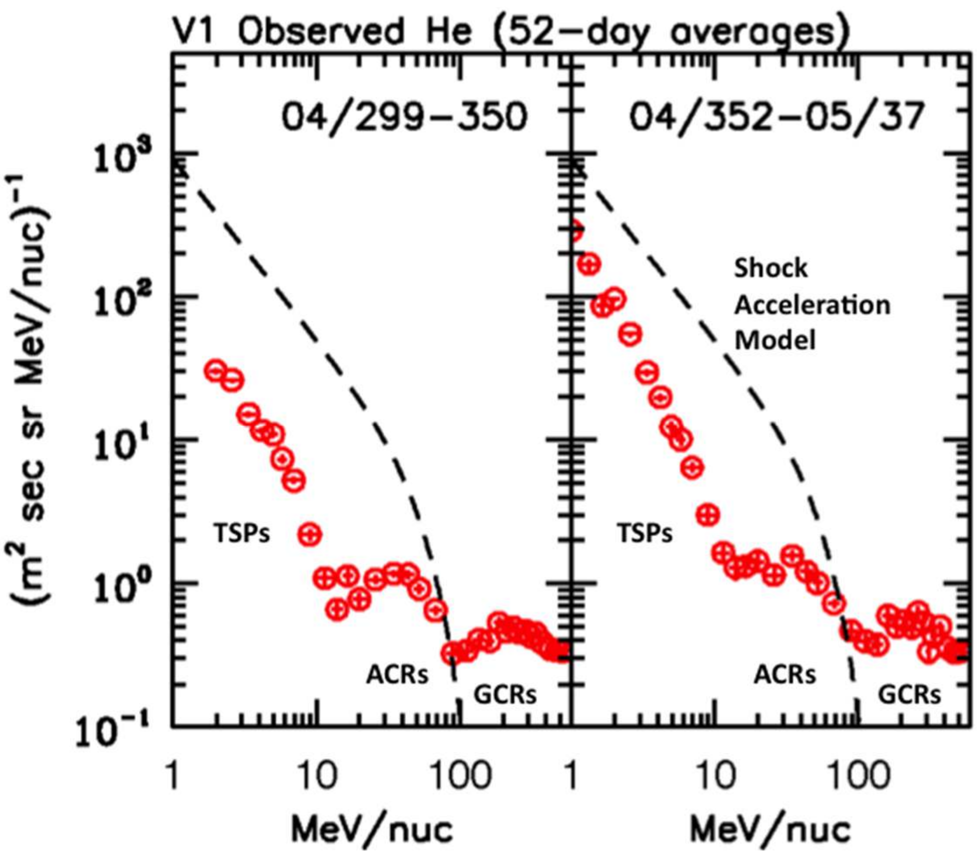
Opher et al. ApJL 2006

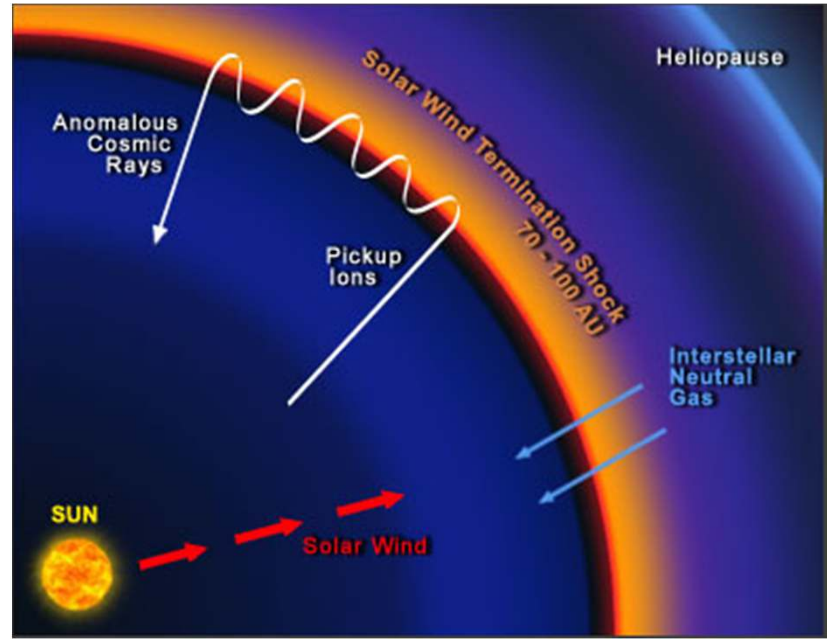


Schwadron et al. Science 2009

Time Dependent effects account for a motion of 3 AU only (Richardson et al. *Nature* 2008)

Source of Anomalous Cosmic Rays





- Voyager-1 revealed that anomalous cosmic rays ≈ are not peaked at the termination shock.

Several proposed theories:

- Termination shock more efficient accelerator along the flanks (McComas and Schwadron '06)

- Heliosheath Turbulence (Fisk and Gloeckler '06)

- Reconnection in the heliosheath (Lazarian and Opher '09; Drake et al. '10)

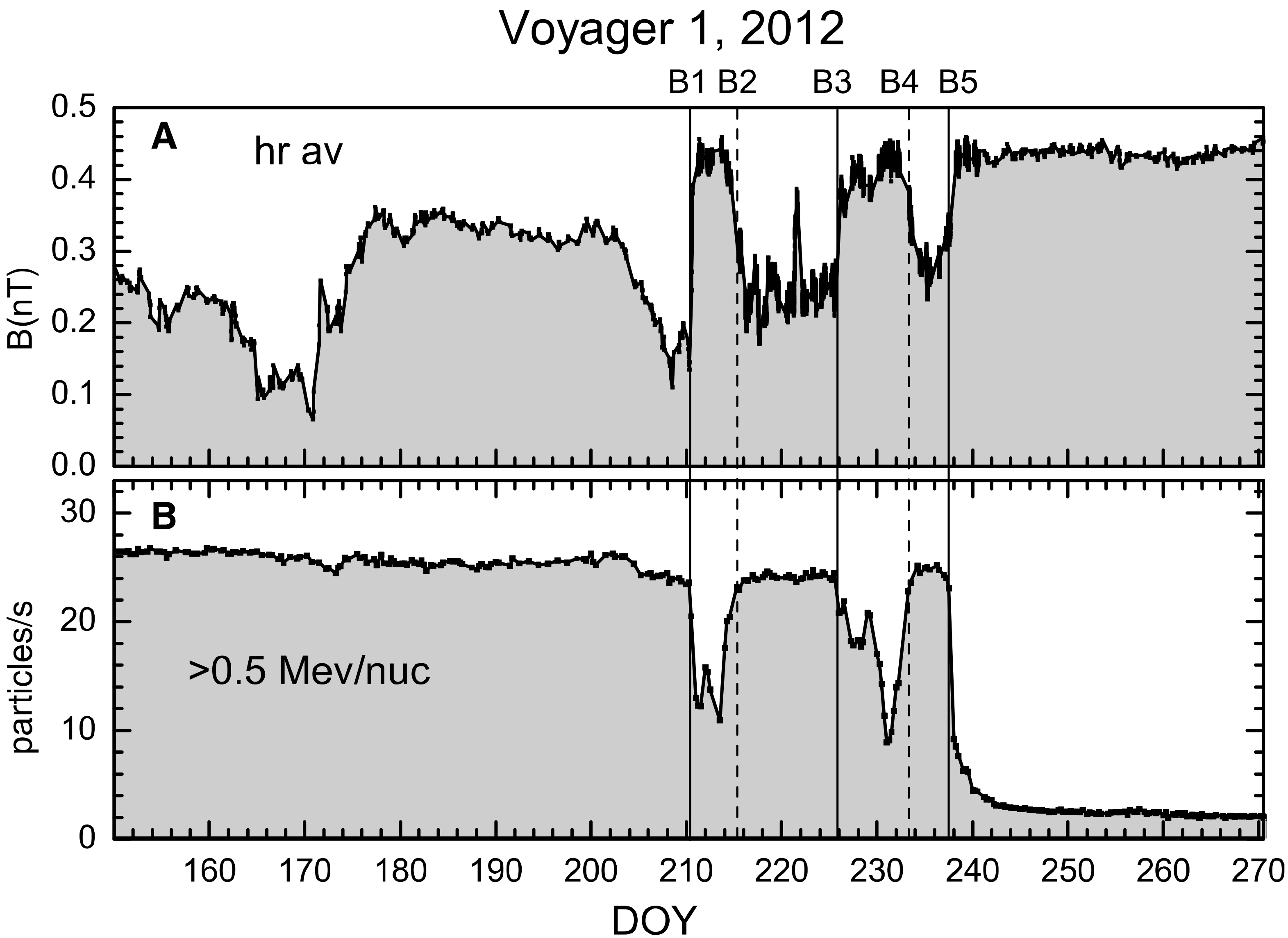
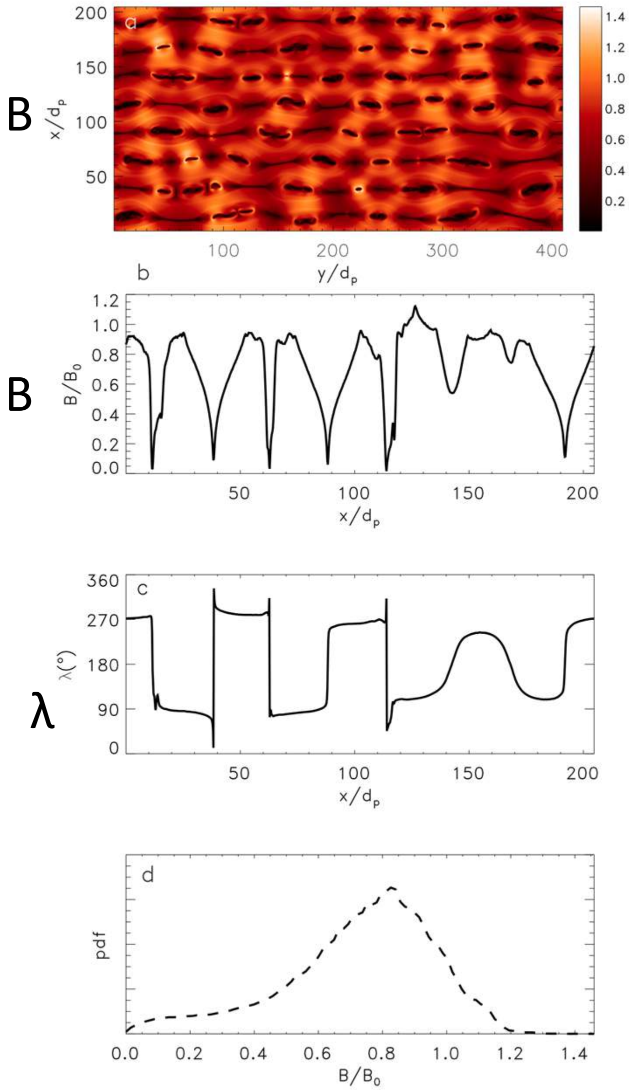
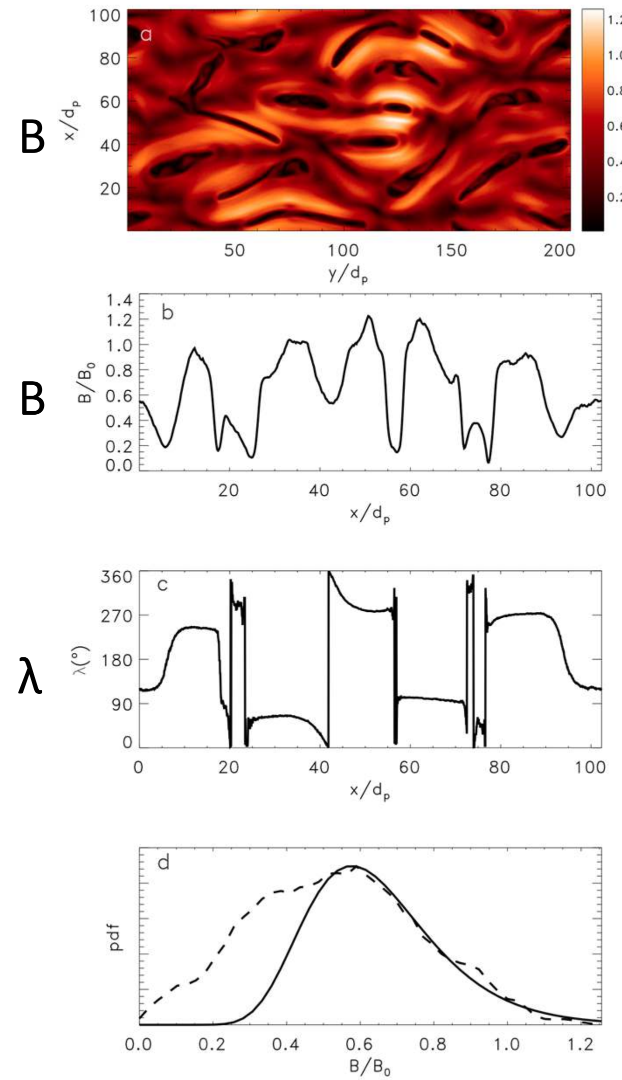


Fig. 1. Relationship between the magnetic field intensity and the energetic particle counting rate. Hour averages of magnetic field strength *B* (**A**). The counting rate of energetic particles >0.5 MeV/nuc to ~30 MeV (**B**).

Burlaga et al . *Science* 2013

“Bubbles” stage: signatures very different than the usual signatures of reconnection

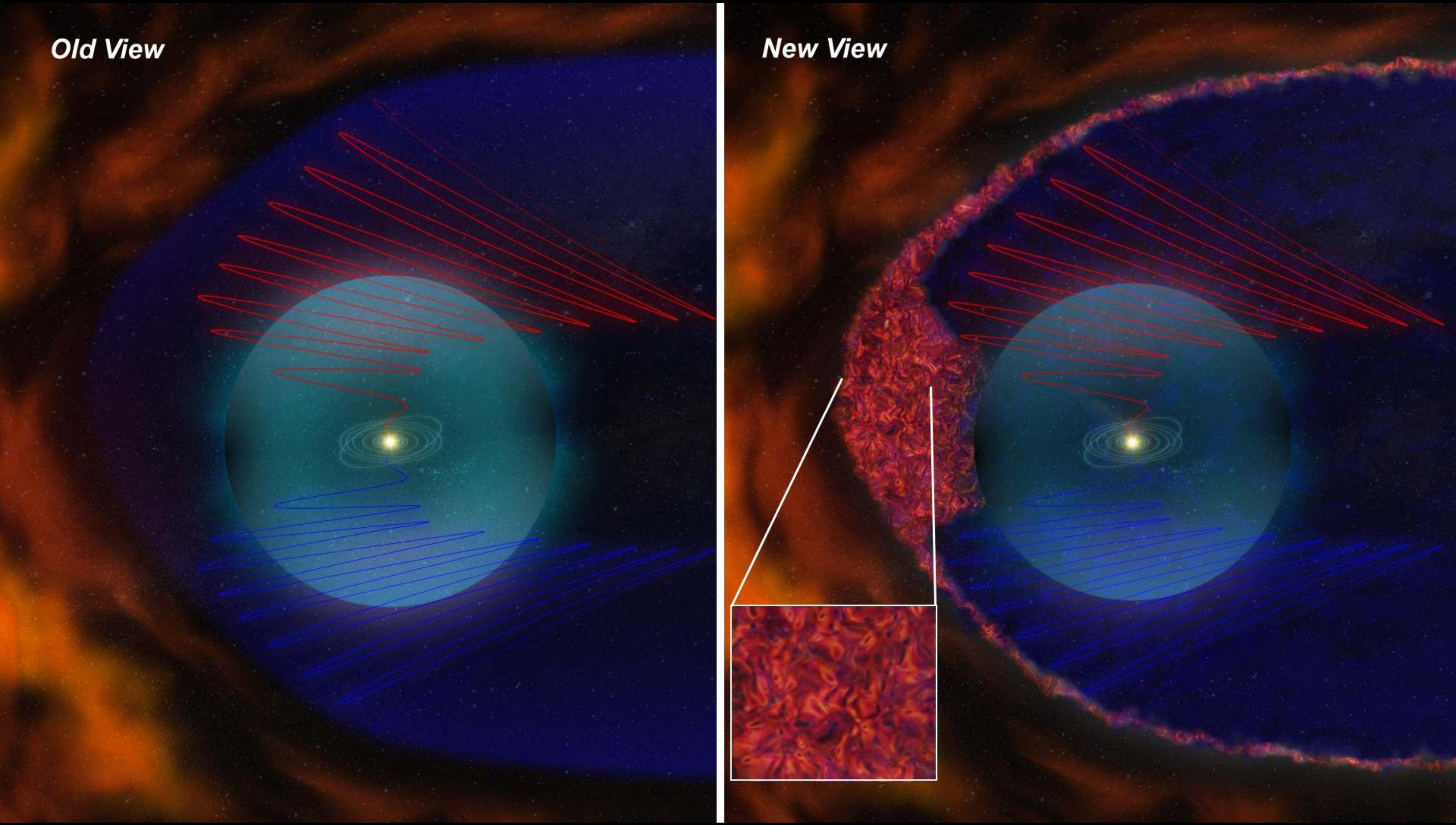




Early in time

“Bubbles”: Later in time

Old and a New View: The permeable heliosphere



Key observational challenges for outer heliosphere models

- Why does the Anomalous Cosmic Rays spectrum roll out well into the heliosheath? (reconnection- -Drake, Opher et al. *ApJ* 2010; Opher & Lazarian 2009, flank termination shock, turbulence)

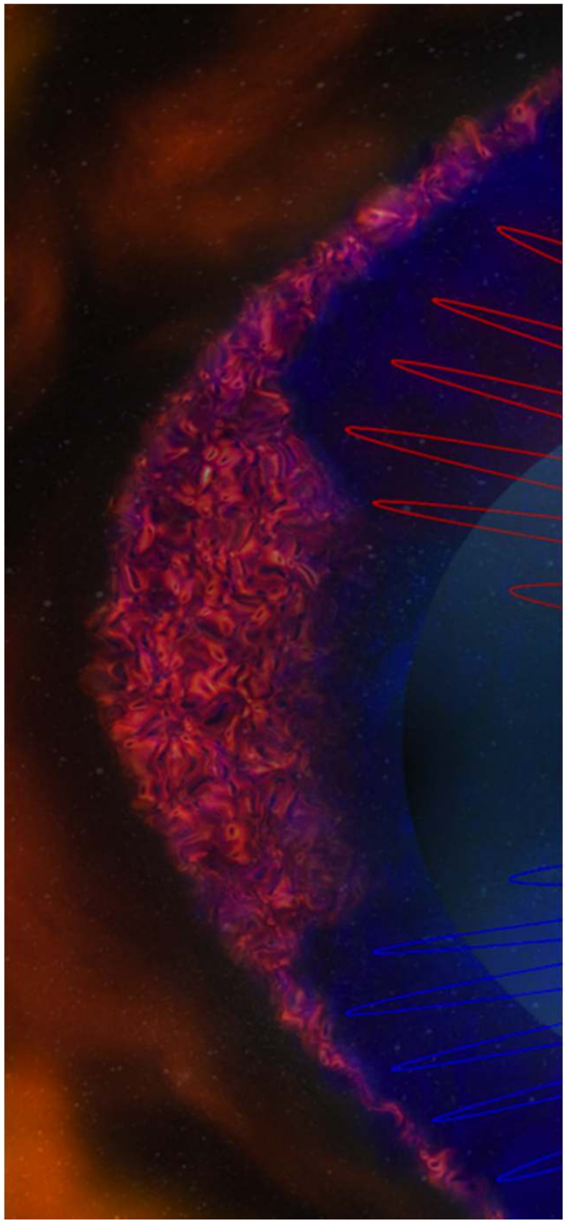
- What causes the dropouts of ~1MeV electrons and the most energetic ACRs at Voyager 2? (reconnection – Opher, Drake et al. *ApJ* 2011)

- What causes the flow stagnation region seen at Voyager 1? (time dependence, reconnection – Opher et al. *ApJ* 2012)

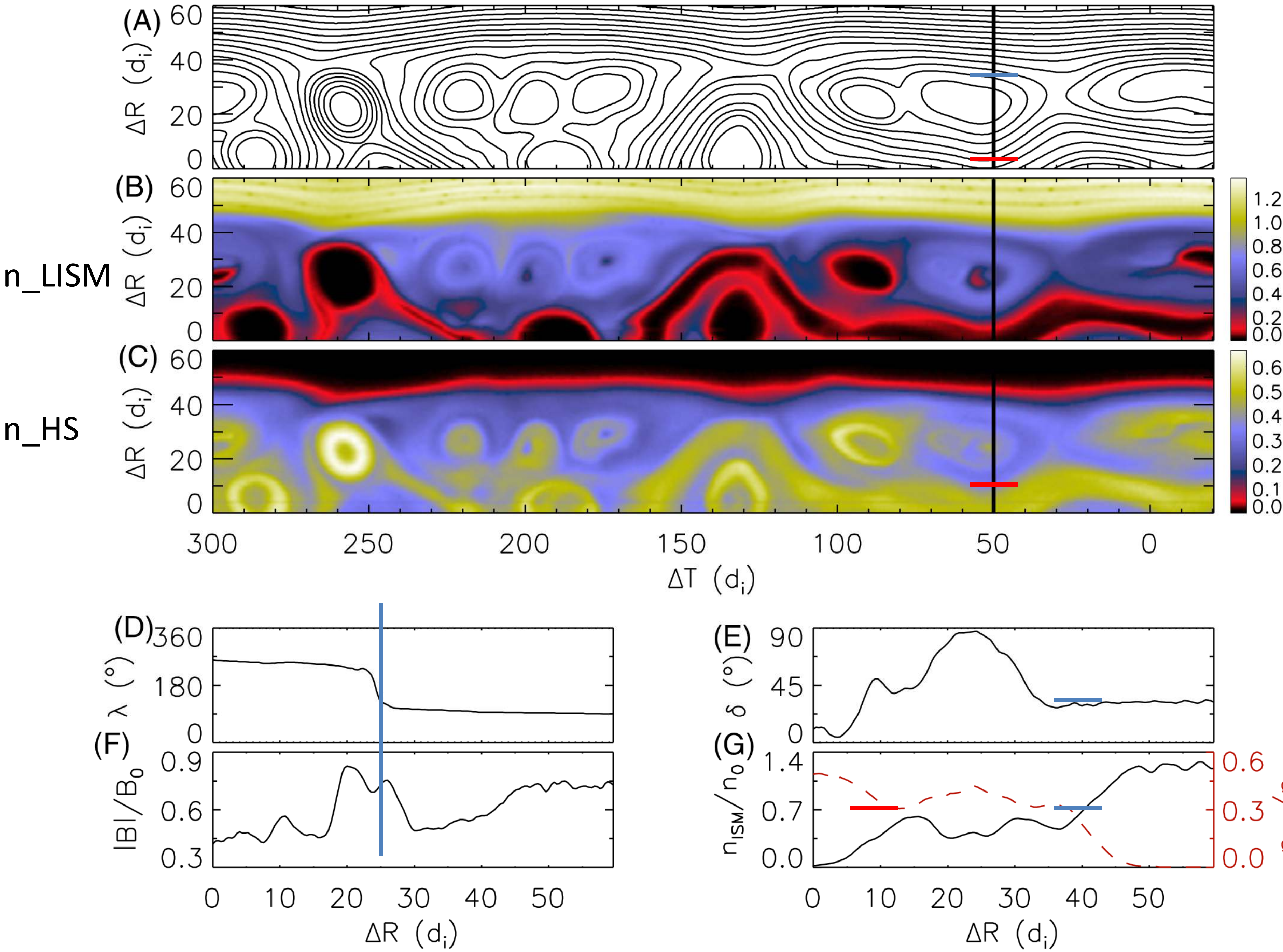
- What happened to the missing azimuthal magnetic flux at Voyager 1? (reconnection – Richardson et al. 2013)

- Reconnection of the sectored magnetic field can potentially explain all of these observations

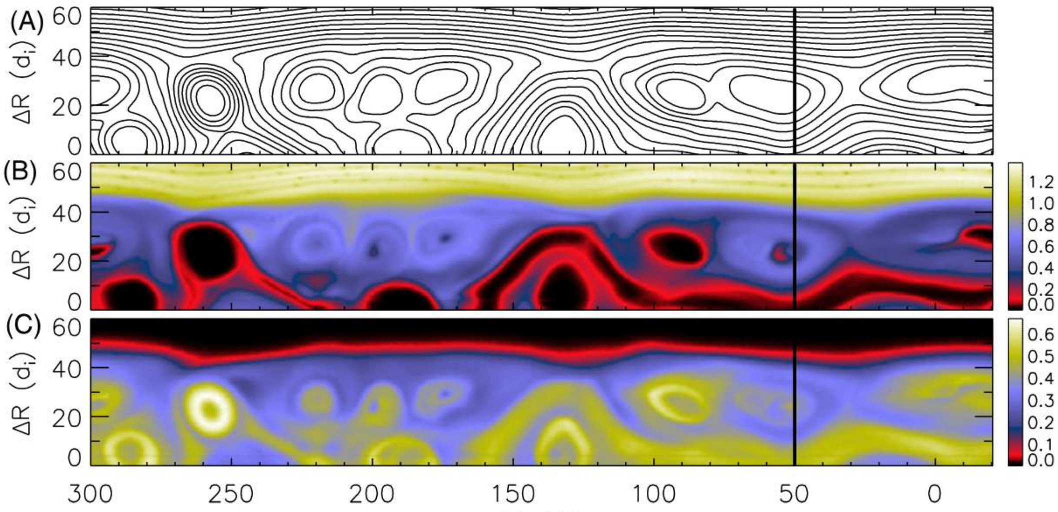
Porous Layered Heliopause



Swisdak, Drake, Opher ApJL 2013



Swisdak, Drake & Opher, *ApJL* 2013



Suggestions that *reconnection* at

Swisdak, Drake & Opher, *ApJL* 2013

Sectors get compressed after the shock