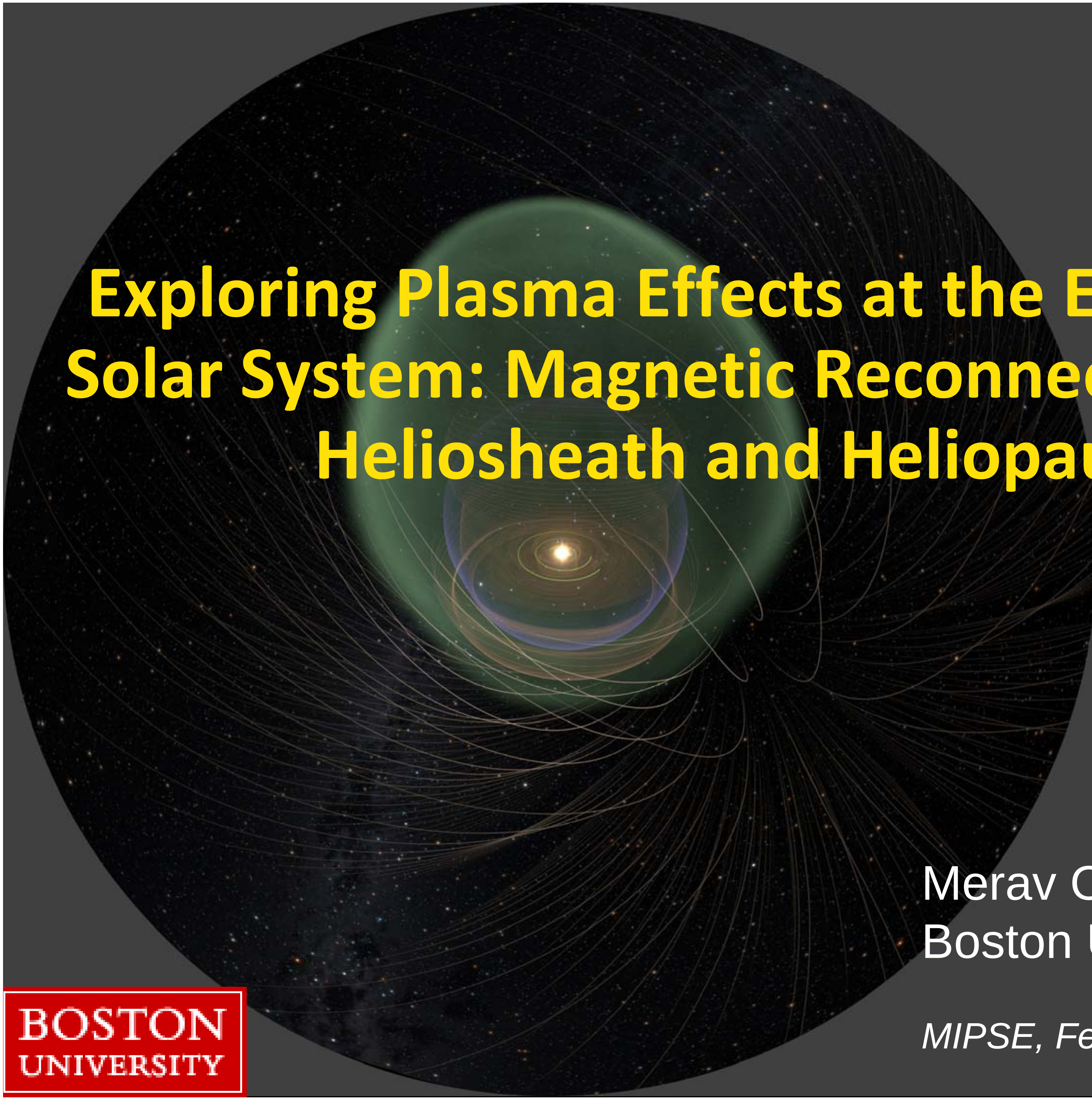

Exploring Plasma Effects at the Edge of the Solar System: Magnetic Reconnection in the Heliosheath and Heliopause

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Boston University

MIPSE, February 20, 2012

BOSTON UNIVERSITY

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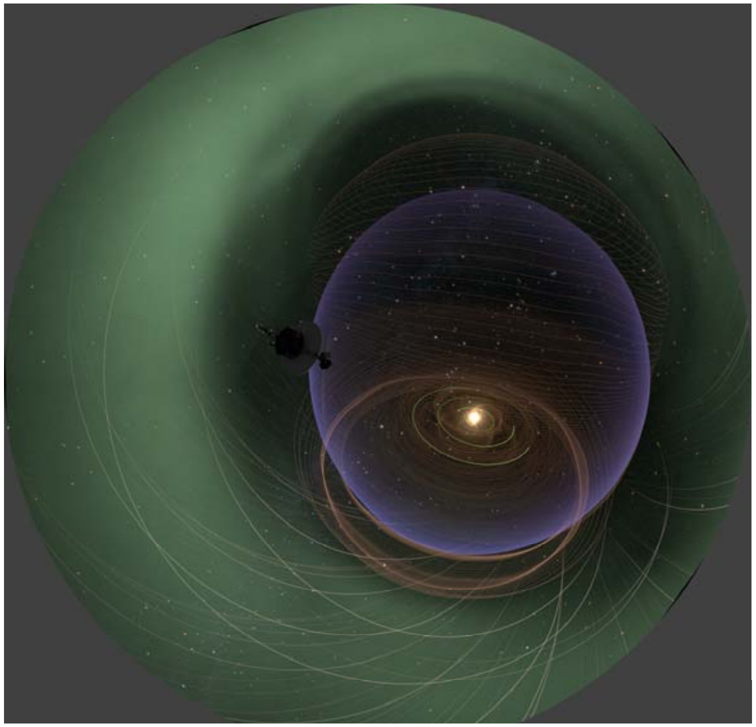
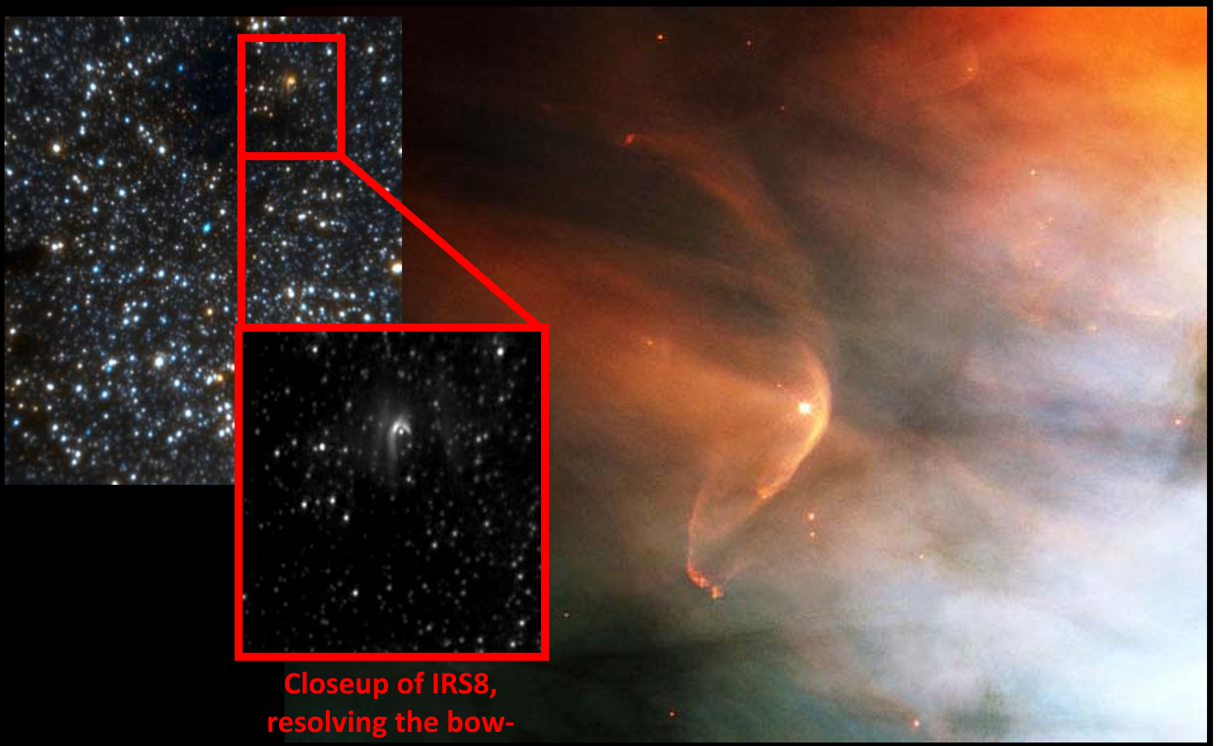
Outline:

•Some of the surprises learned
•Observations in the heliosheath that are key challenges to heliospheric models
•Reconnection scenario in the heliosheath
•Nature of the heliopause: *Magnetic Highway to the Interstellar Medium?*

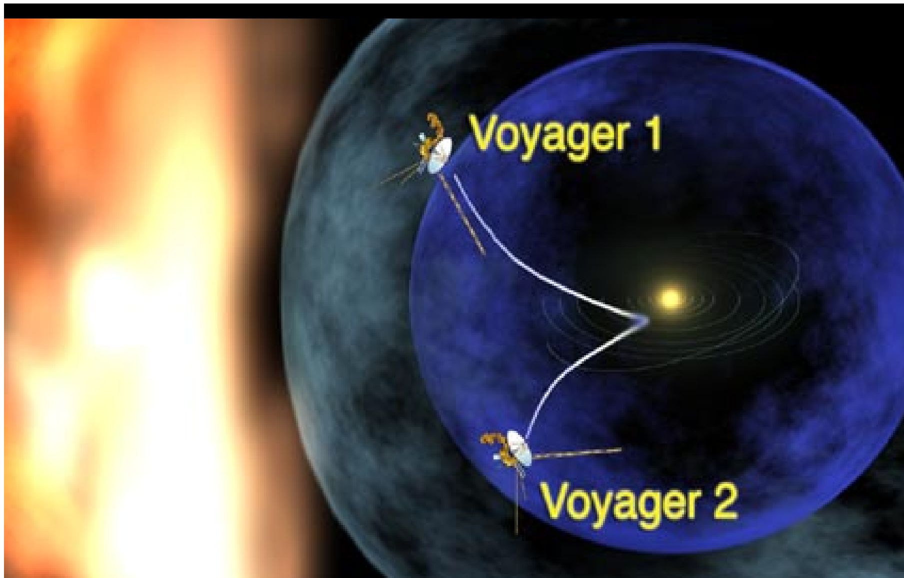


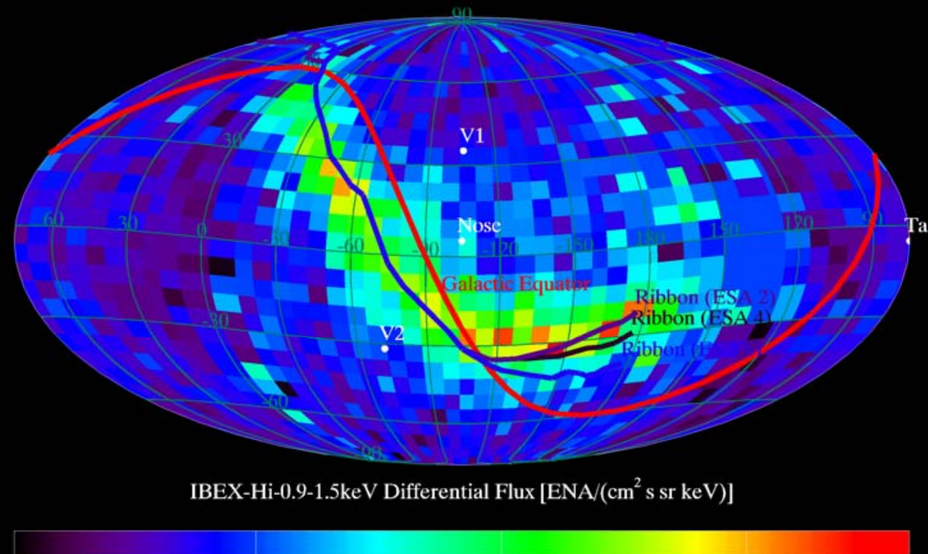
The heliosphere as test-bed for other astrospheres

WISE bow shock image, PIA13455



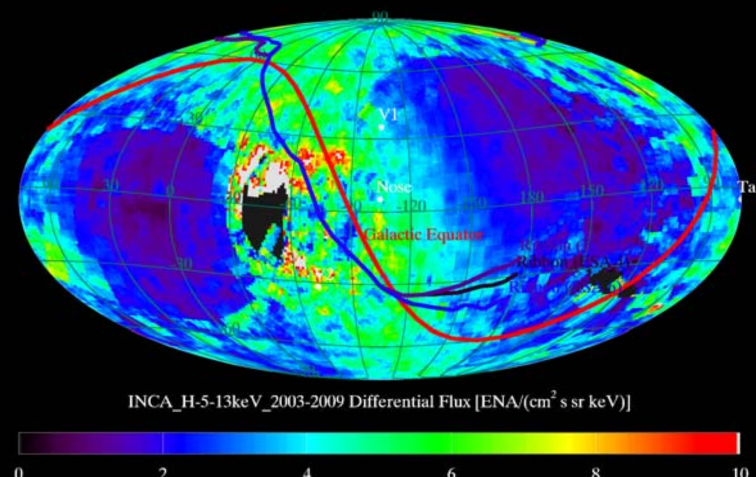
Closeup of IRS8, resolving the bow-shock of a fast-moving star

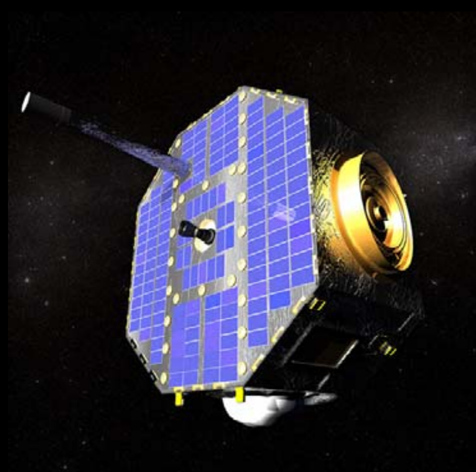




Voyager 1 in the north
Voyager 2 in the south

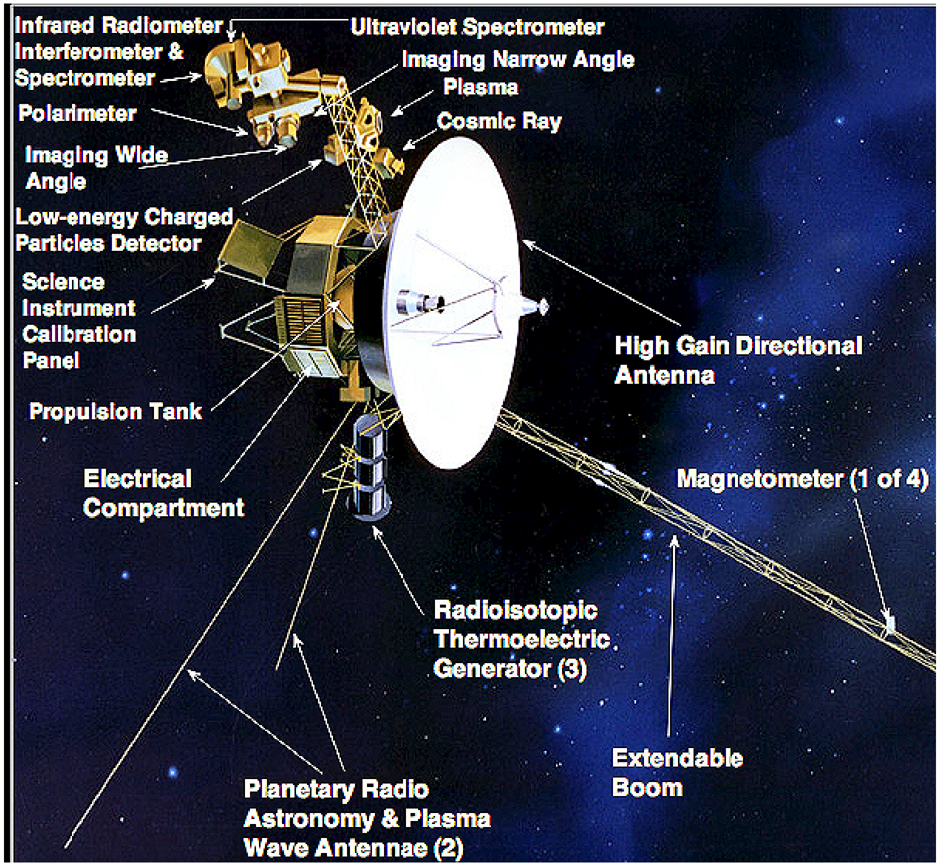
In-situ data

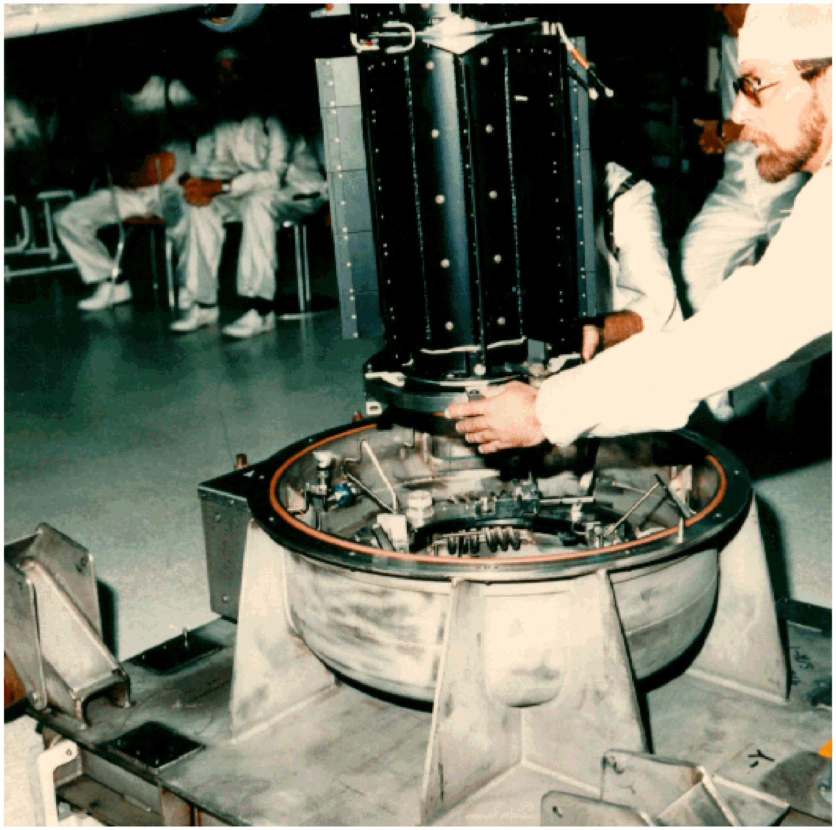




Global maps
of ENAs (IBEX, Cassini)

Voyager 1 and 2 Spacecraft



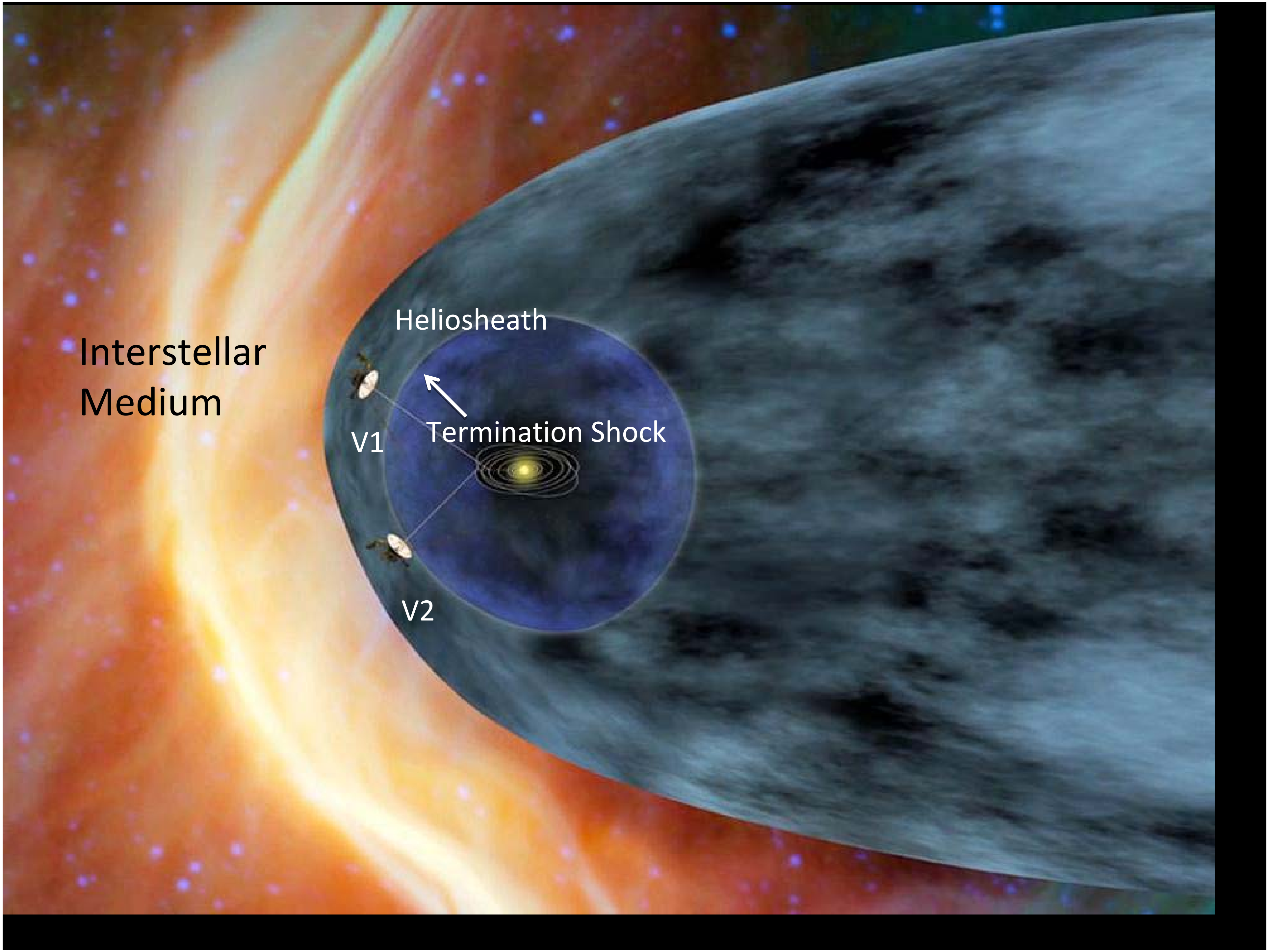


Farthest Man-Made Object

Launched
Voyager 2: 20 Aug. 1977
Now at 101 AU, S29.2° (217° HGI_long)

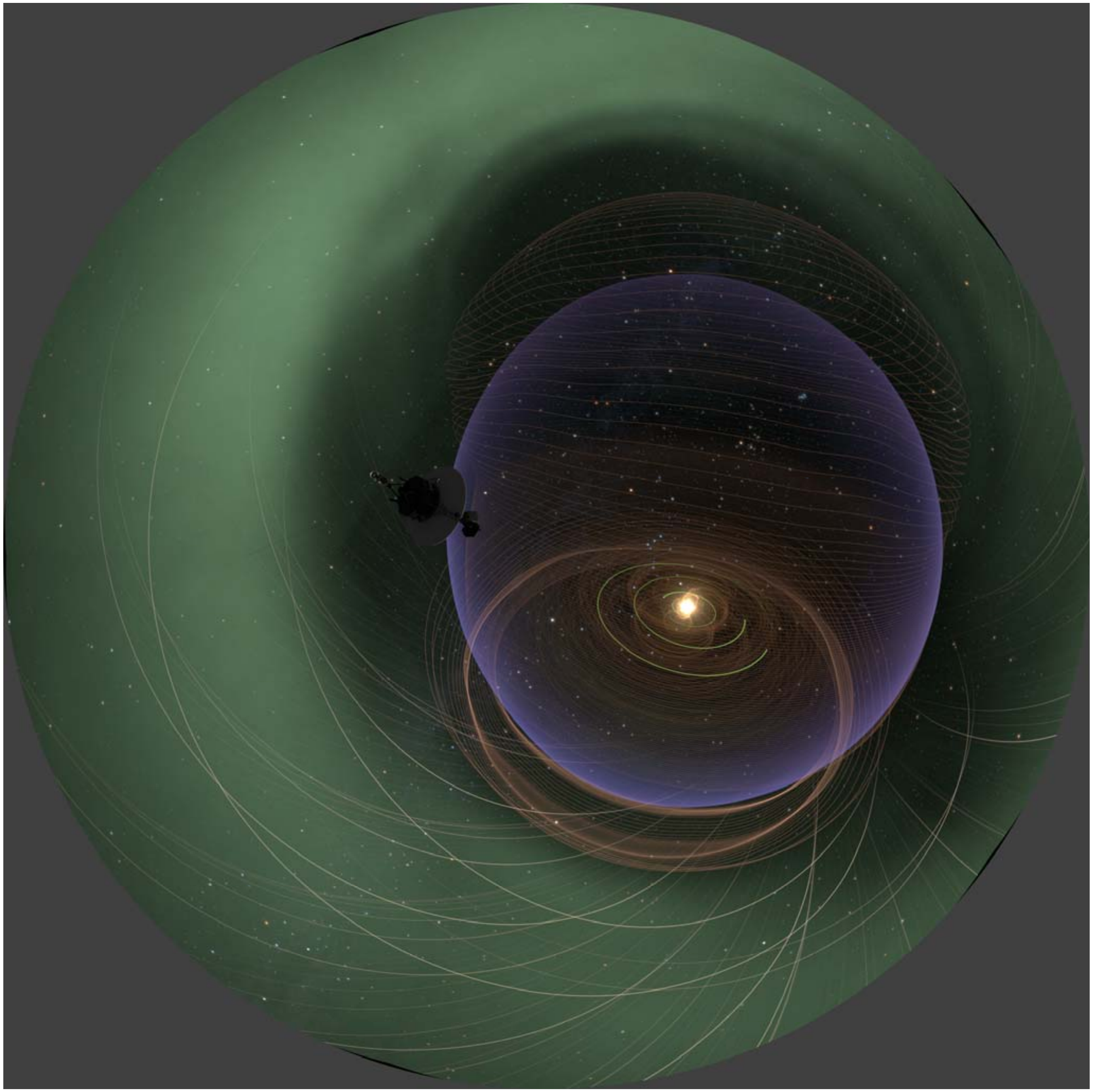
Voyager 1: 05 Sep. 1977
Now at 124 AU, N34.4° (174° HGI_long)

Separated by 125 AU in heliosheath



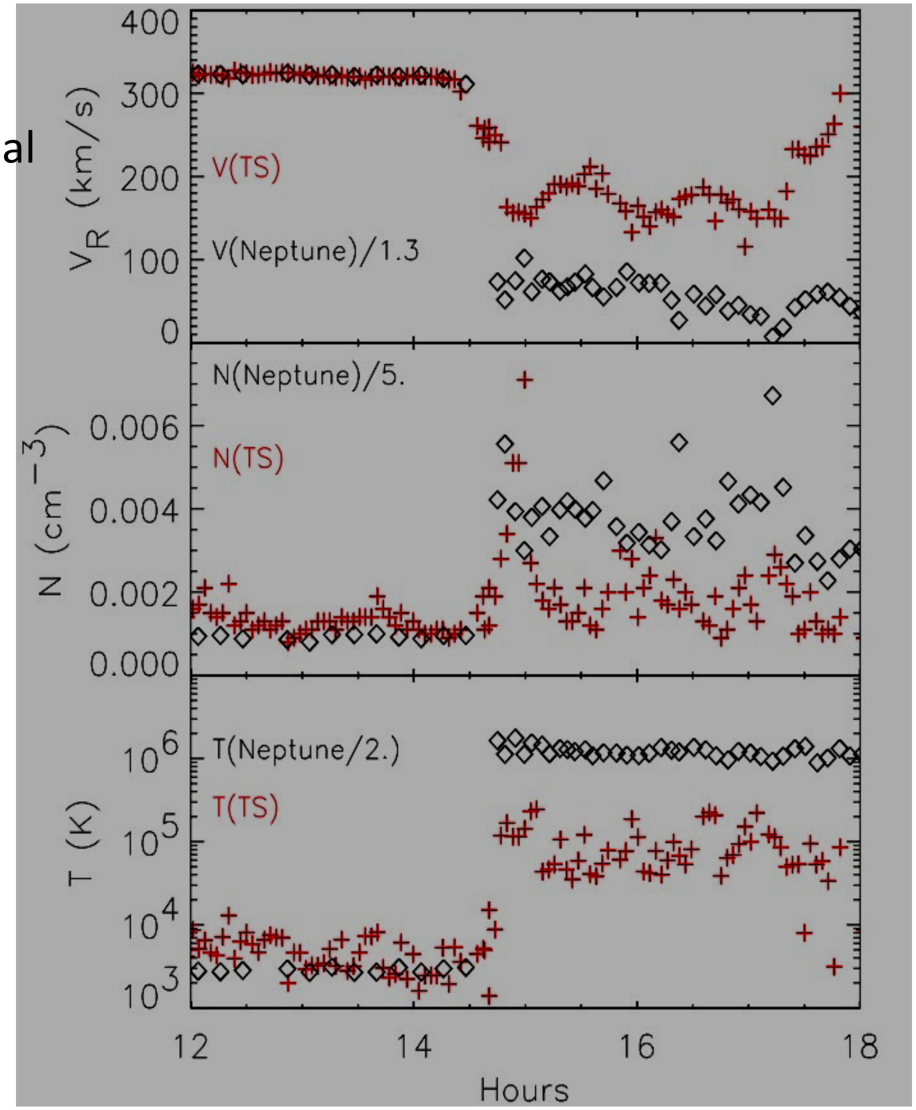
Interstellar
Medium
Heliosheath
Termination Shock
V1
V2

Some of the surprises learned



Crossing of the Termination Shock by Voyager 1 in December 2005 and Voyager 2 in August 2008

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

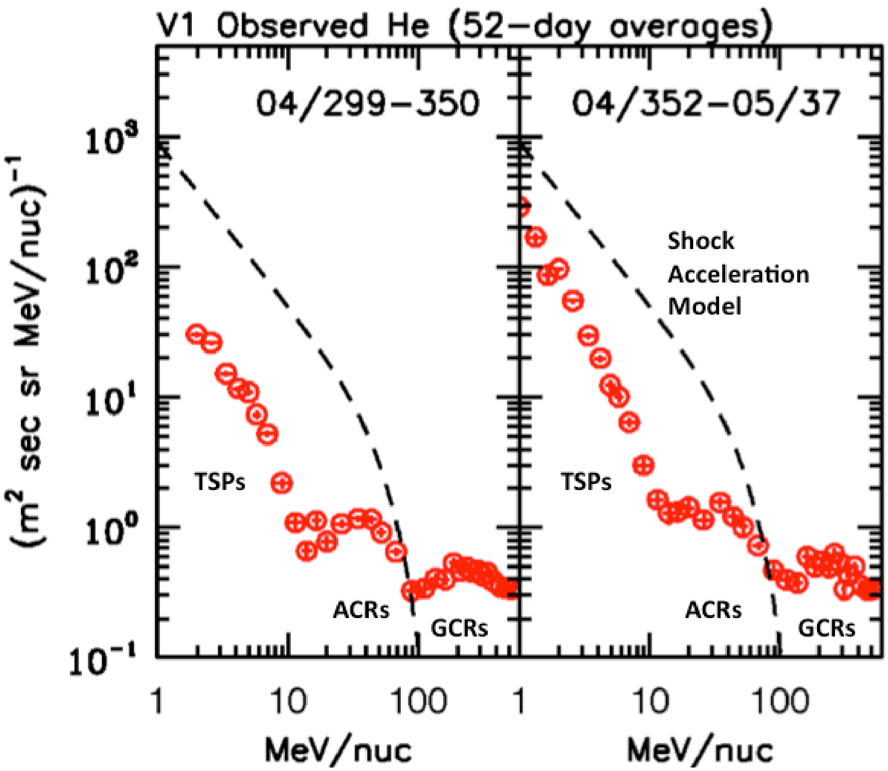


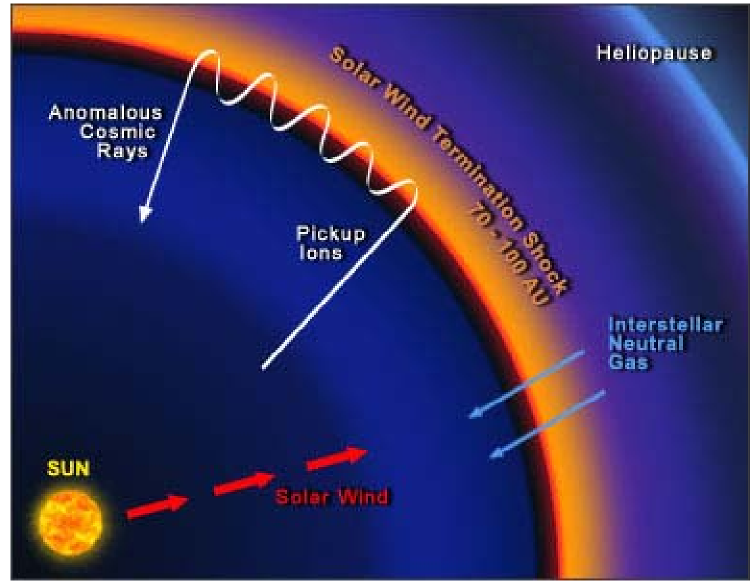
Discovery of a new paradigm:

Pickup ions carry most of the pressure

Richardson et al. Nature 2005

Source of Anomalous Cosmic Rays





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

Several proposed theories:

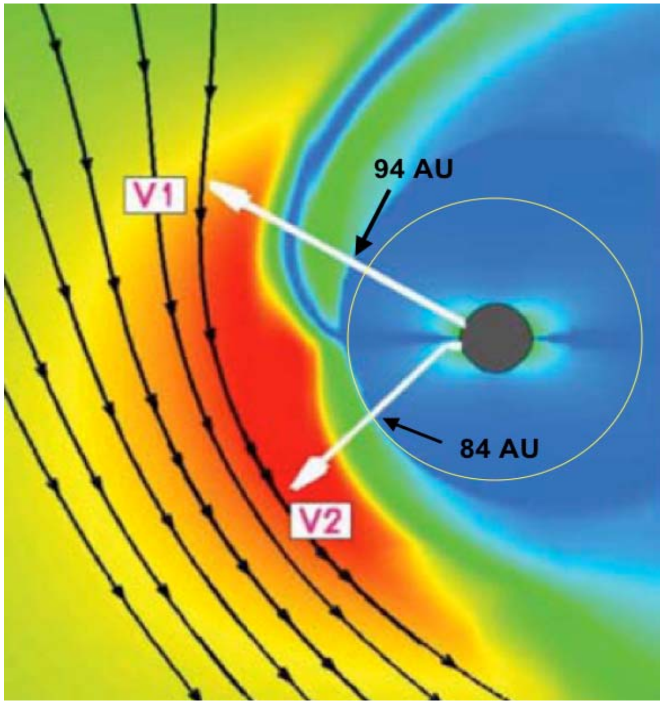
-Termination shock more efficient accelerator along the flanks (McComas and Schwadron '06)

-Heliosheath Turbulence (Fisk and Gloeckler '06)

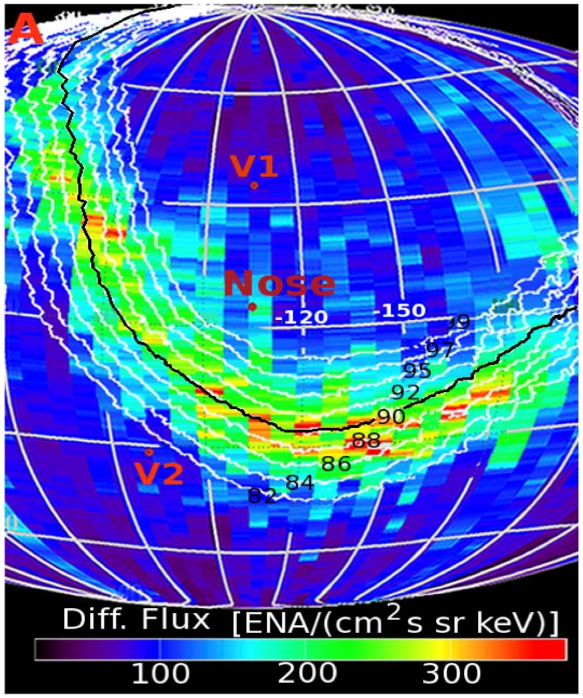
- Reconnection in the heliosheath (Lazarian and Opher '09; Drake et al. '10)

Asymmetric Heliosphere

Discovery of the Influence of the Interstellar Magnetic Field on the Heliosphere



Opher et al. ApJL 2006

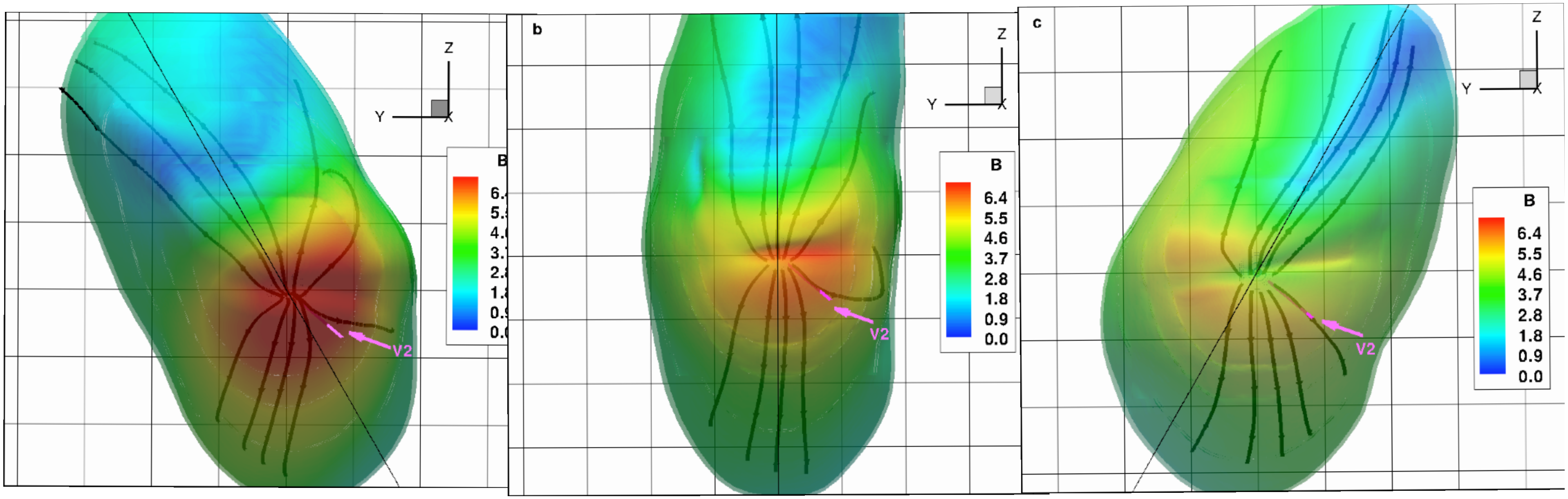


Schwadron et al. Science 2009

Also observations [by SOHO/SWAN, Voyager, IBEX, and Cassini/INCA] indicate the influence of the interstellar magnetic field on the heliosphere.

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

Local Interstellar Magnetic Field



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

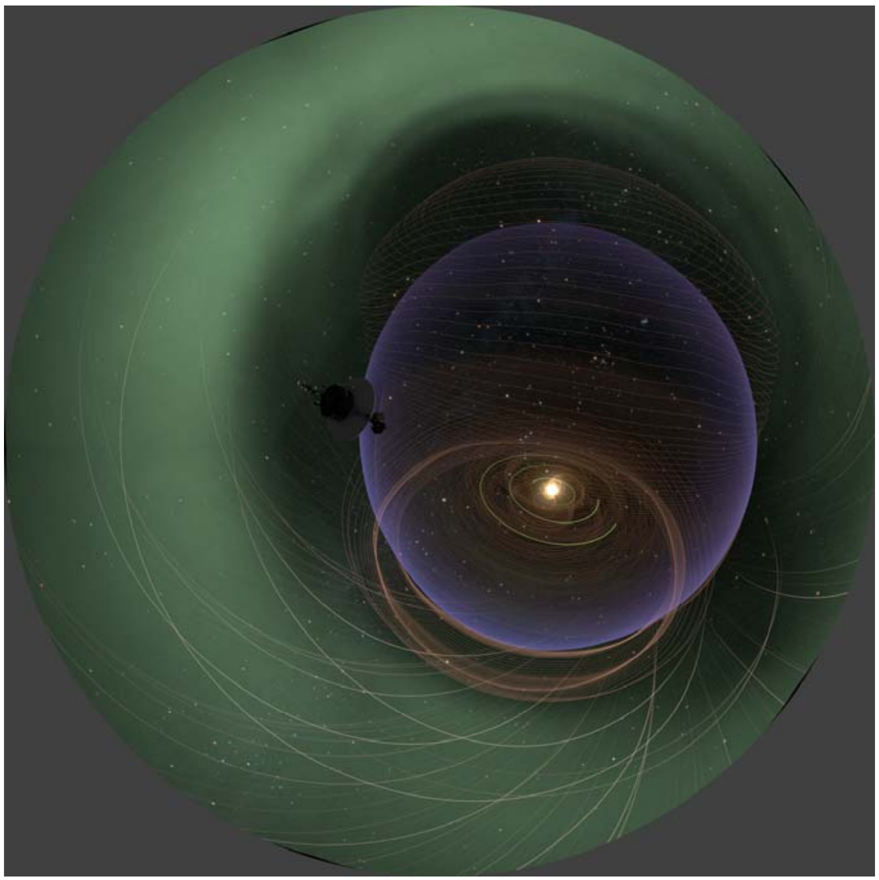
B is 3.7-5.5μG, tilted ~20-30° from the flow direction in the interstellar medium and is at an angle of about 30° from the Galactic plane.

Direction different than the field in large scale (along the galactic plane)

This is the field that can reproduce the several heliospheric asymmetries detected by Voyager

Other possible constrains: IBEX ribbon (e.g., Pogorelov & Heerikhuisen ApJ 2011; Ratkiewicz et al. 2009);

Observations in the heliosheath that are key challenges to heliospheric models

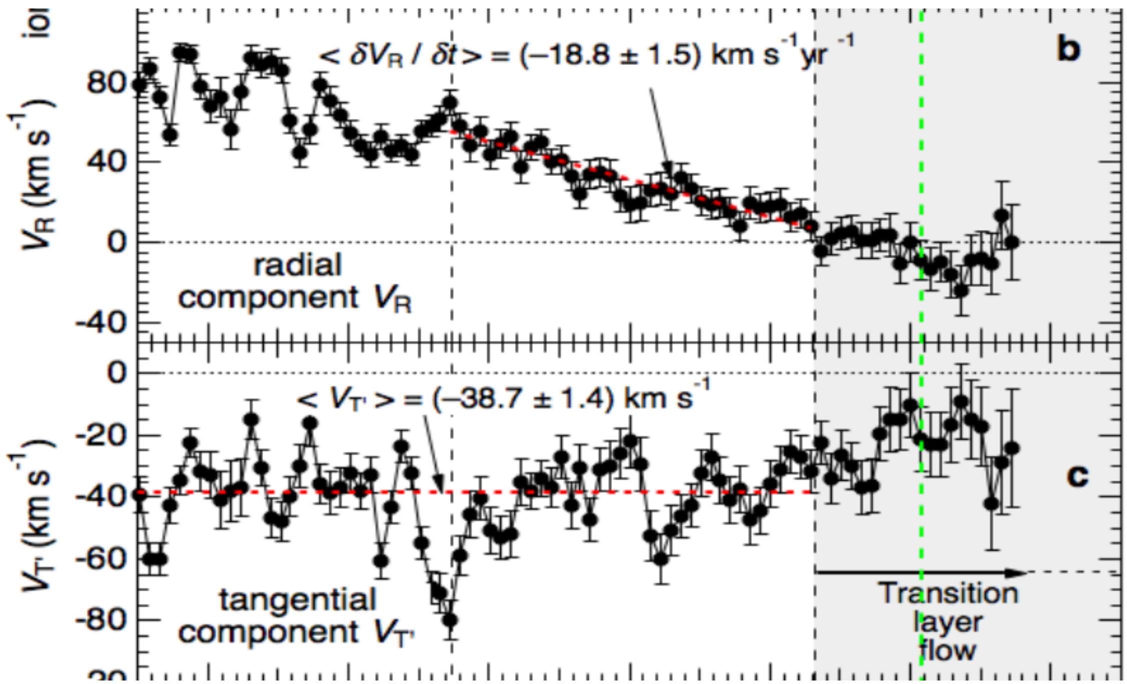


Why the speeds at Voyager 1 and 2 are so different? What causes the stagnation region seen at Voyager 1?

Quasi-stagnation region from 113 to >121 AU

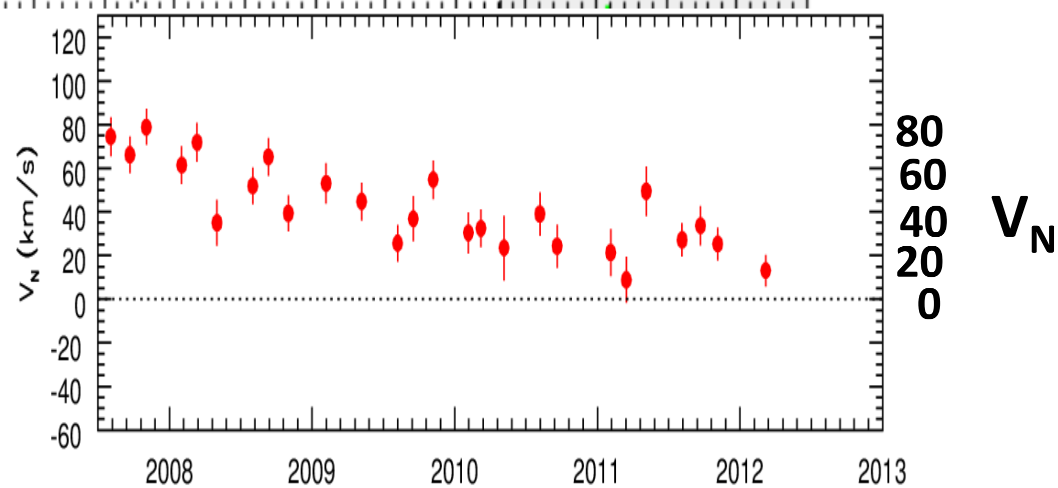
Solar wind did not turn in the N-direction

All components decreased



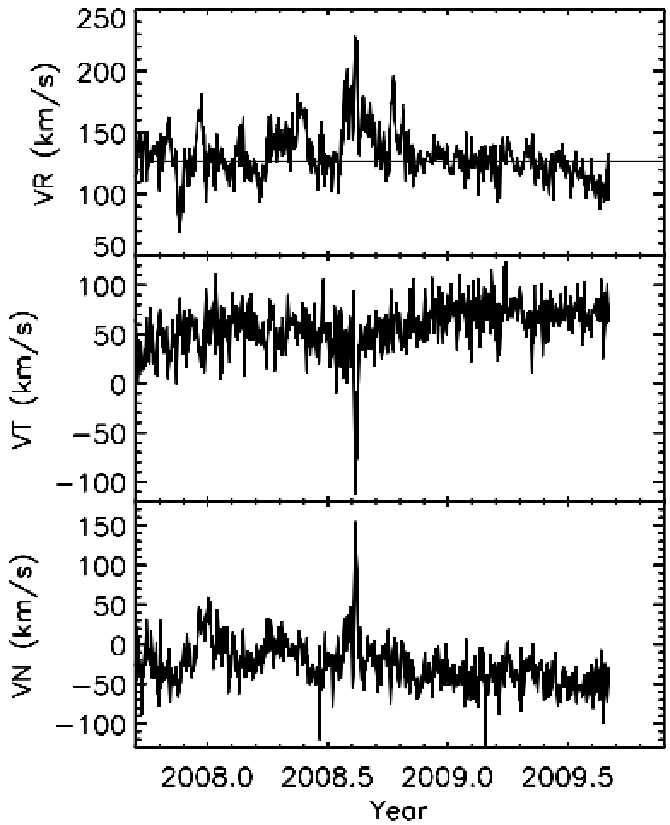
LECP

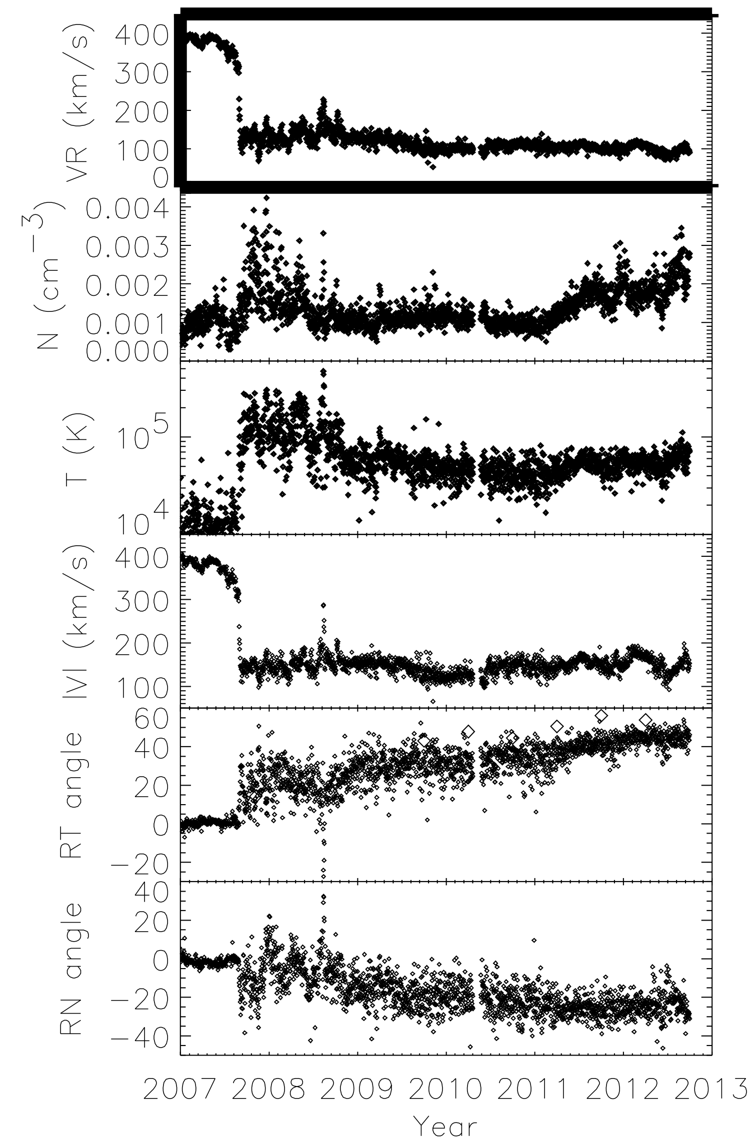
Stone & Cummings ICRC 2011



Measurements at Voyager 2

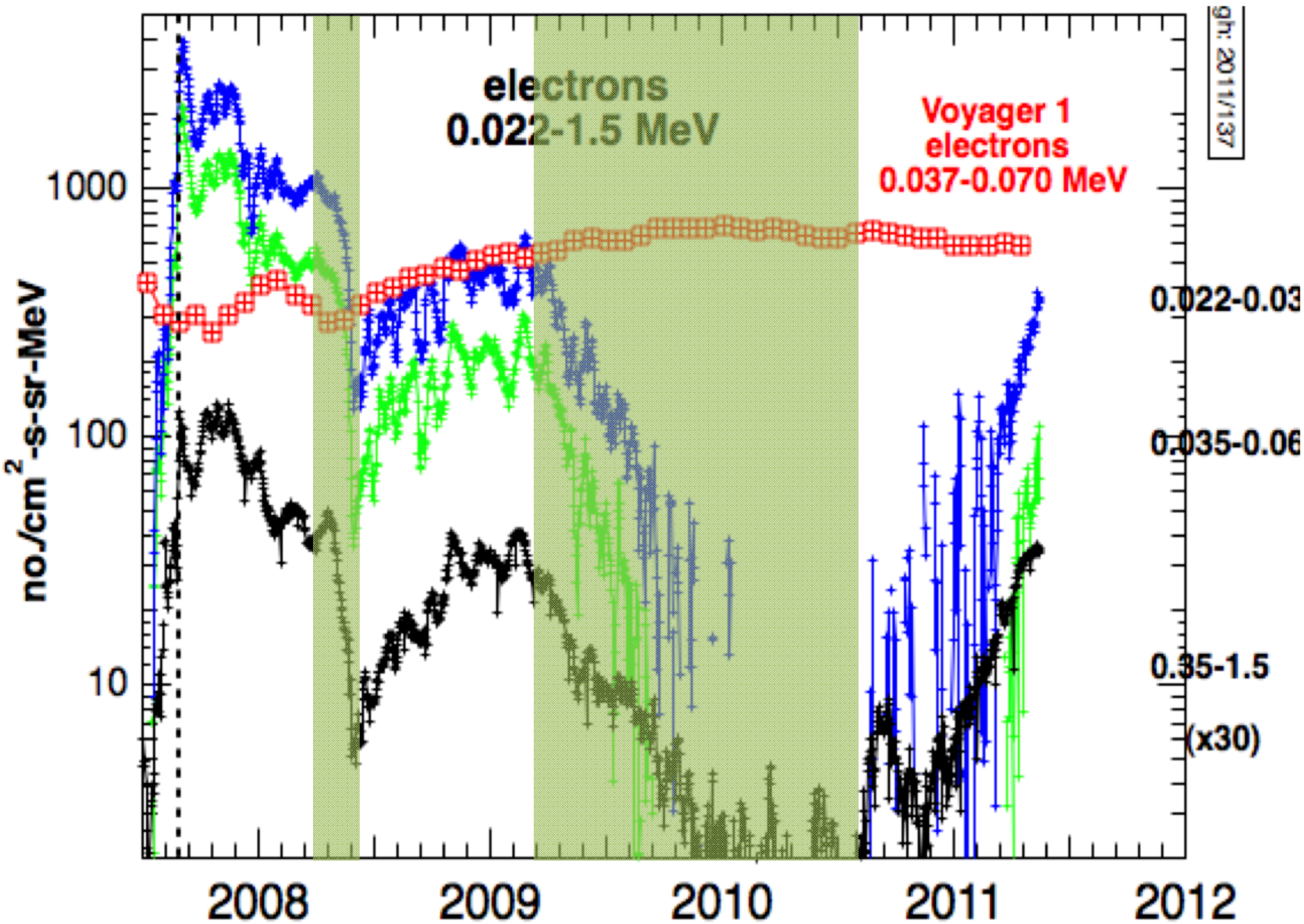
ata:
averages.





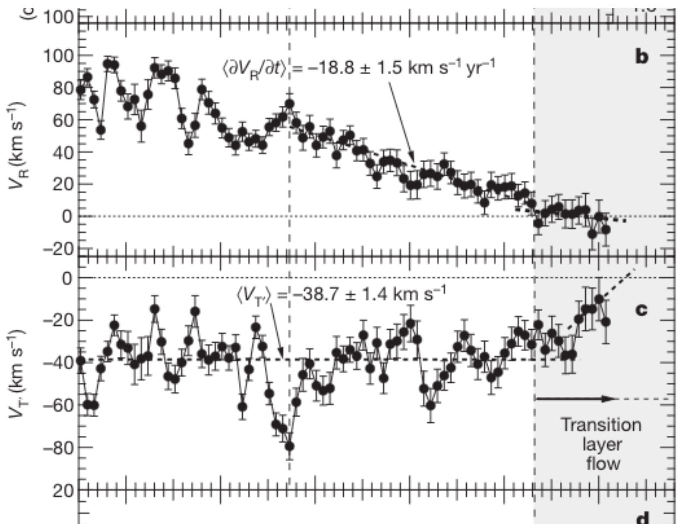
Constant V_R; and V_T ~ 50-80km/s; V_N ~ 50 km/s

What causes the dropouts of electrons and the most energetic ACRs at Voyager 2?



Shaded areas: periods when V2 was outside the sector region

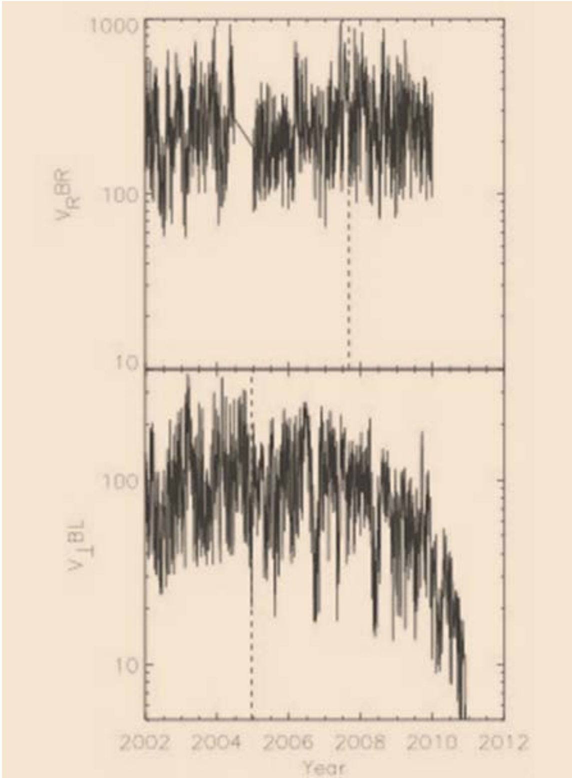
What happened to the missing azimuthal magnetic flux at Voyager 1?



Conservation of magnetic flux:
$B_T V_R R$ = constant

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

Expect corresponding increase in magnetic field

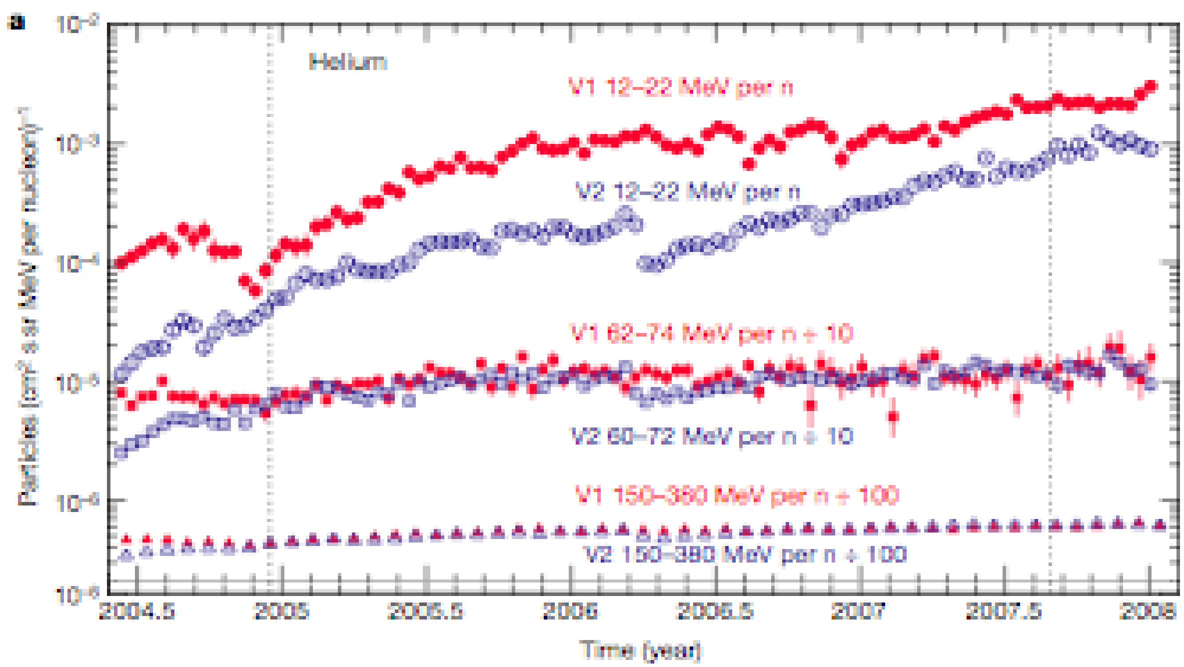


Voyager 2

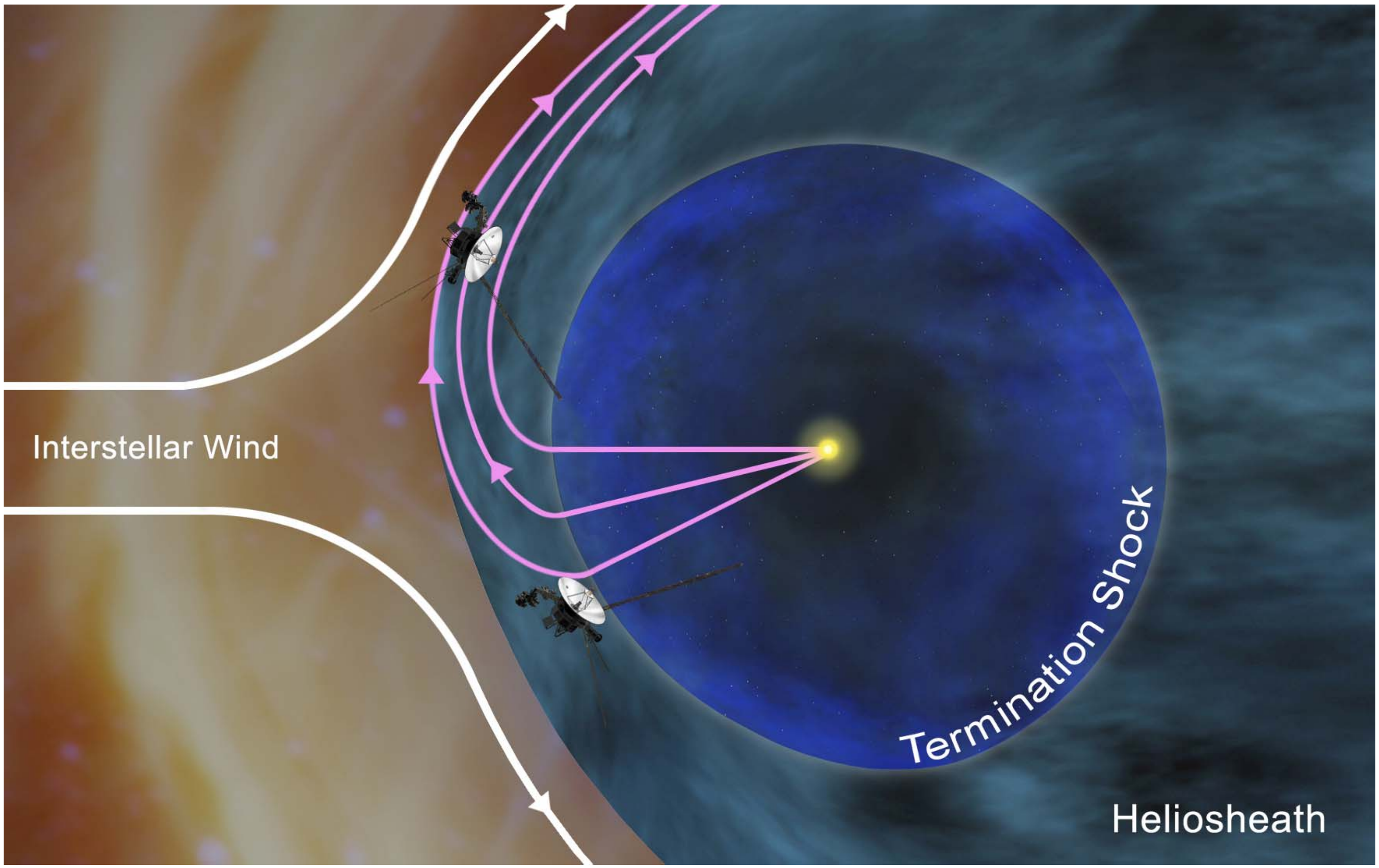
Voyager 1

Richardson et al. 2013

Why does the ACR spectrum roll out well into the heliosheath?



Nature of the Heliosheath: Spatial or Temporal?

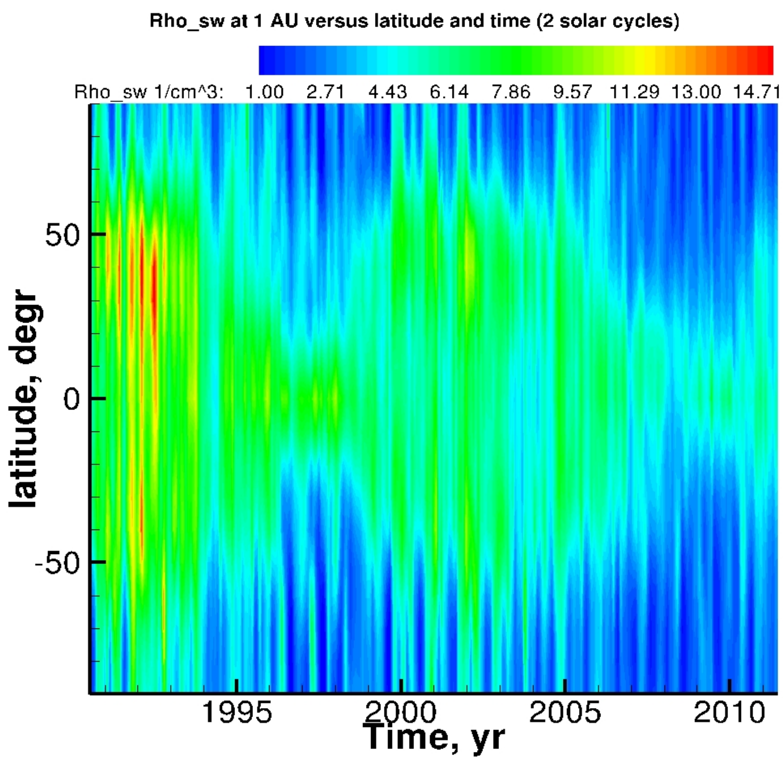


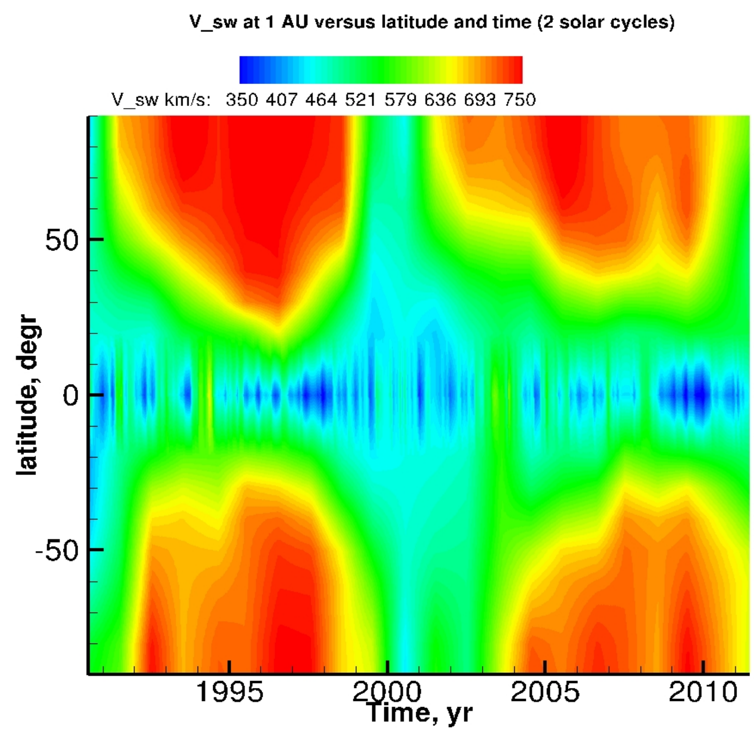
Key observational challenges for outer heliosphere models

- Why does the ACR spectrum roll out well into the heliosheath? (reconnection, flank termination shock, turbulence)
- What causes the dropouts of ~1MeV electrons and the most energetic ACRs at Voyager 2? (reconnection)
- What causes the flow stagnation region seen at Voyager 1? (time dependence, reconnection)
- What happened to the missing azimuthal magnetic flux at Voyager 1? (reconnection)

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

3D outer heliosphere with realistic solar cycle boundary conditions (time and heliolatitude variations)



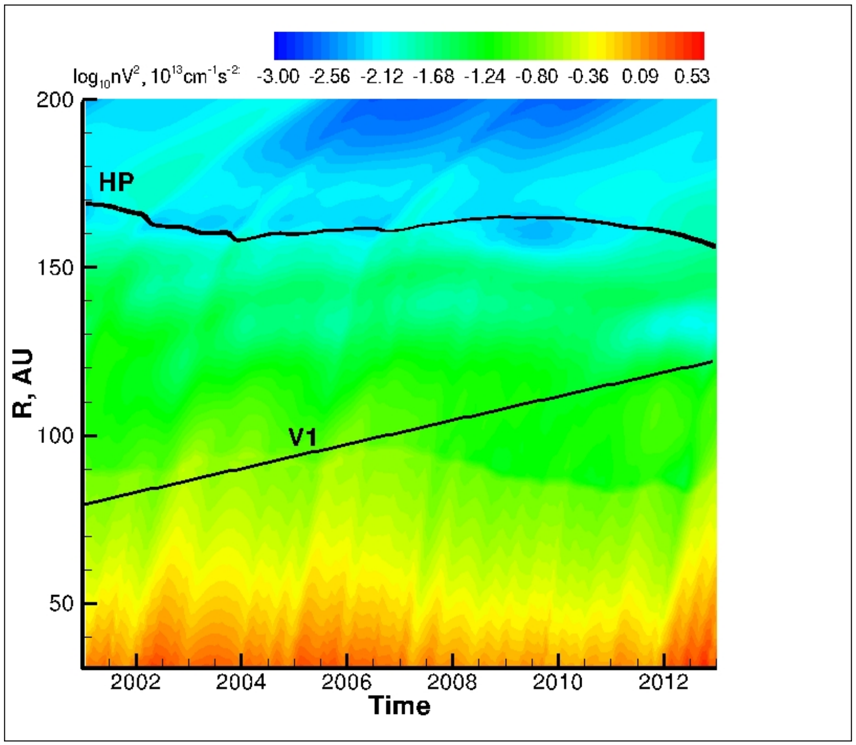


Solar wind density and velocity at 1 AU as the functions of latitude and time (1991-2011). Density is derived from the measurements of backscattered Lyman-alpha emission (Quemerais et al. 2006, Lallement et al. 2010). Velocity is obtained from from the interplanetary scintillation data (Sokol et al. 2012)

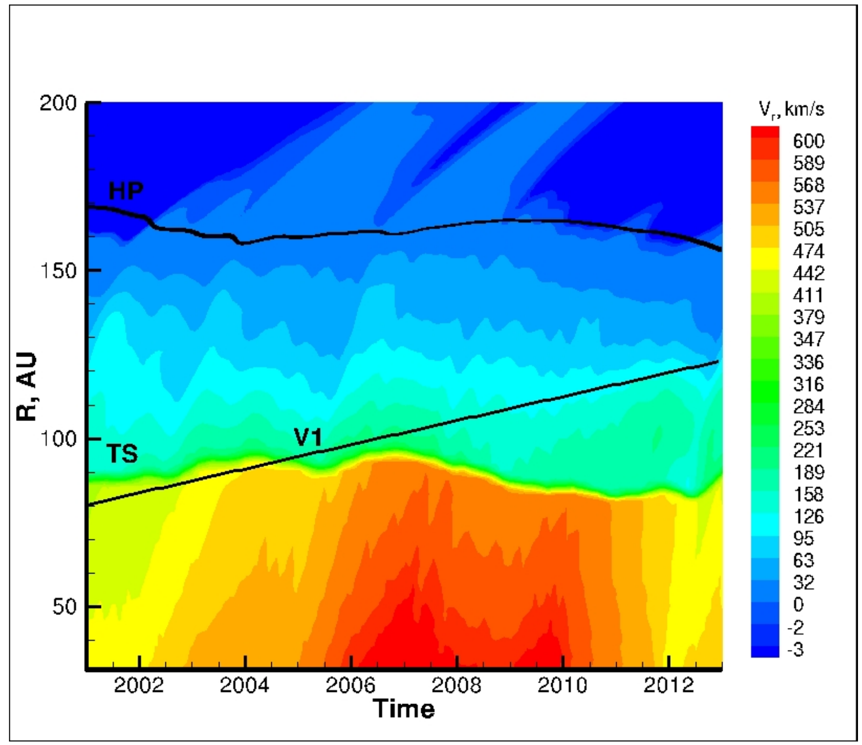
Provornikova et al. 2013

Voyager 1

Ram pressure



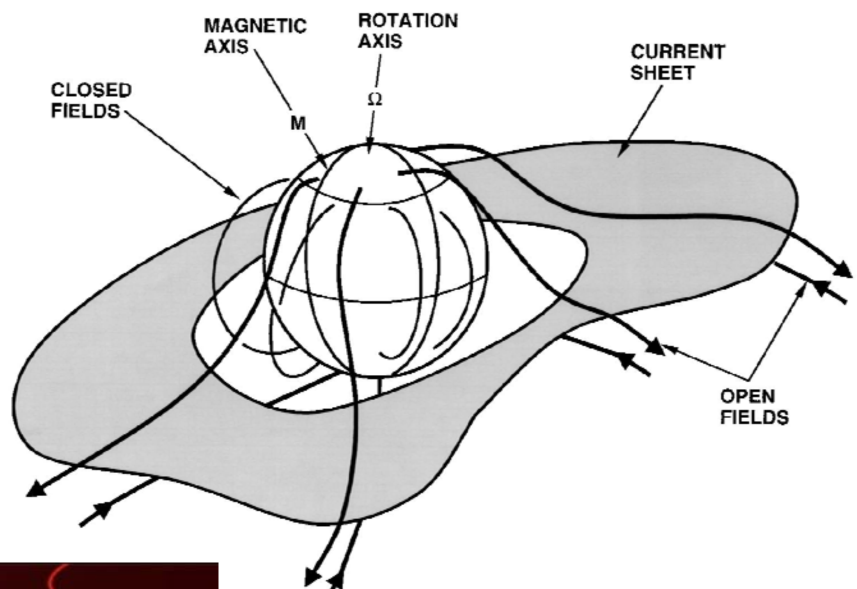
Radial velocity

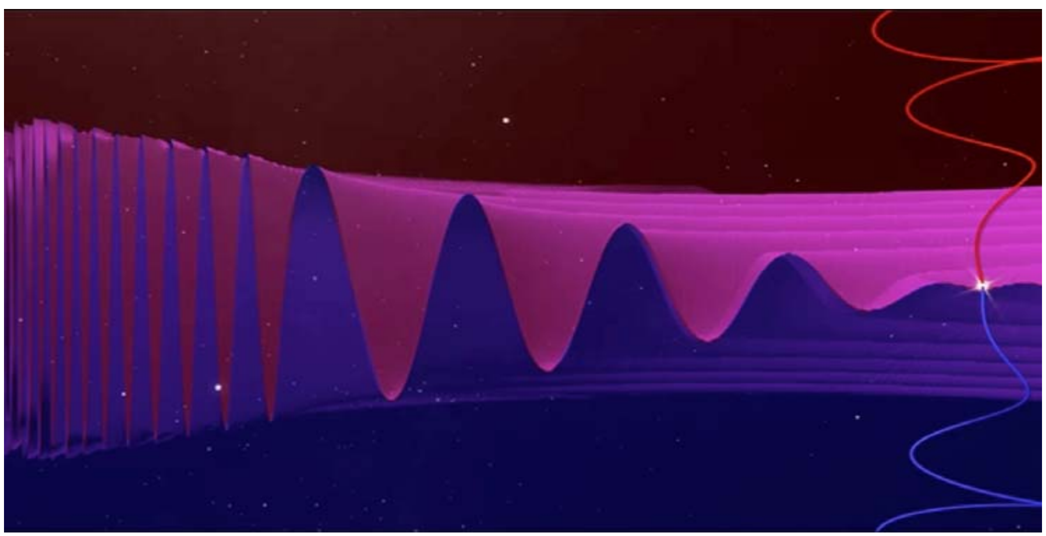


Even though this simulation *overestimate* the variations of ram pressure more than observed, it does not reproduce V1 observations of zero V_r in the stagnation region

Effects of sector structure of the heliospheric field in the heliosheath

- 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

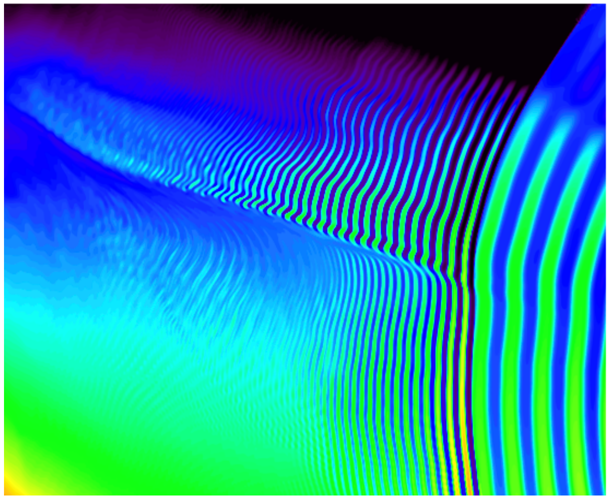




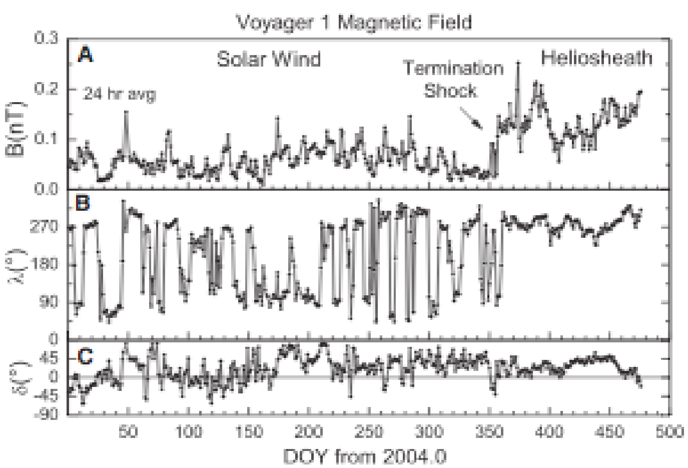
Sectors get compressed after the shock

Heliospheric current sheet

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

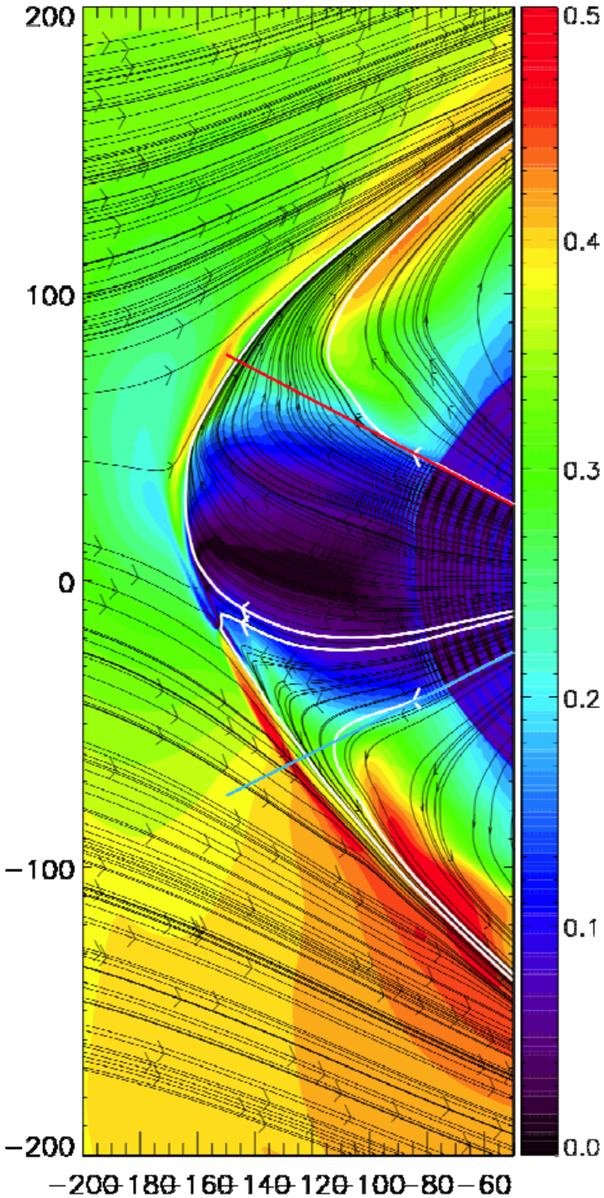
HCS thickness ~ 3,300 km based on compression from upstream

Ion inertial scale ~ 4800 km (n ~ 0.003/cm^3)

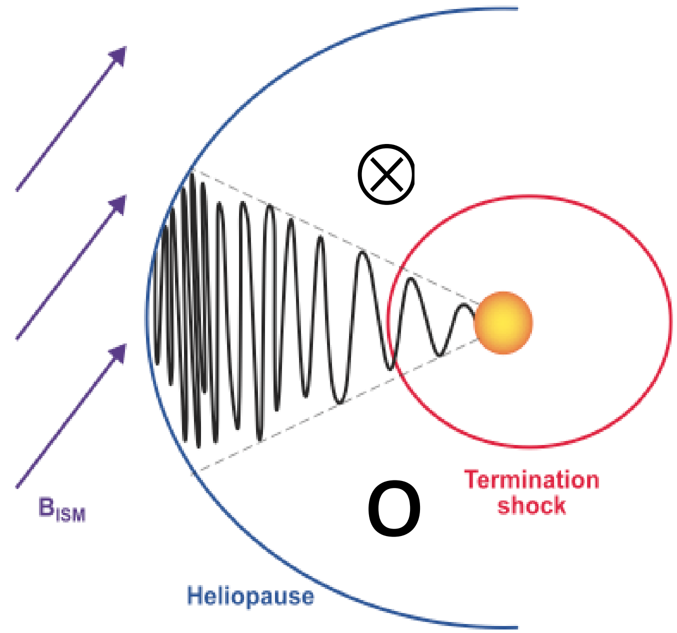
Collisionless reconnection should onset in the HS

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

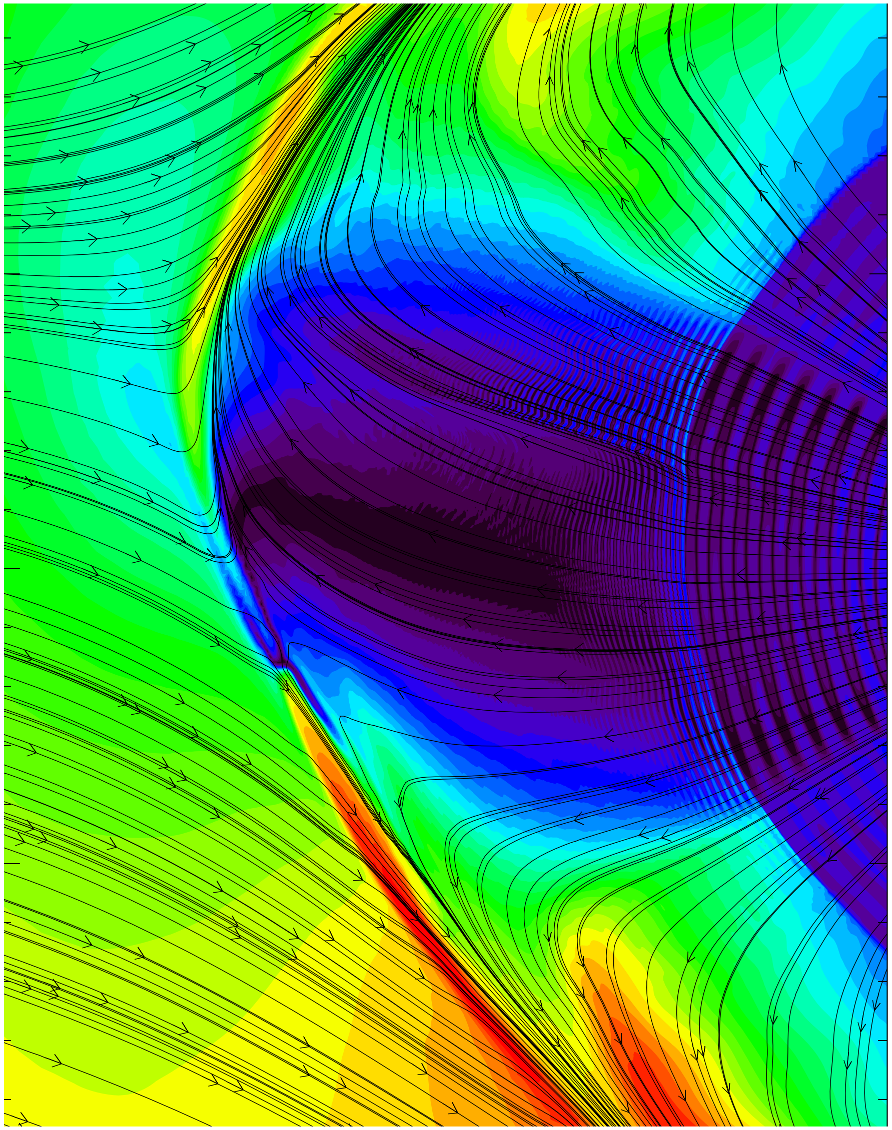


Sectors get closer to each other after the crossing of the Termination Shock

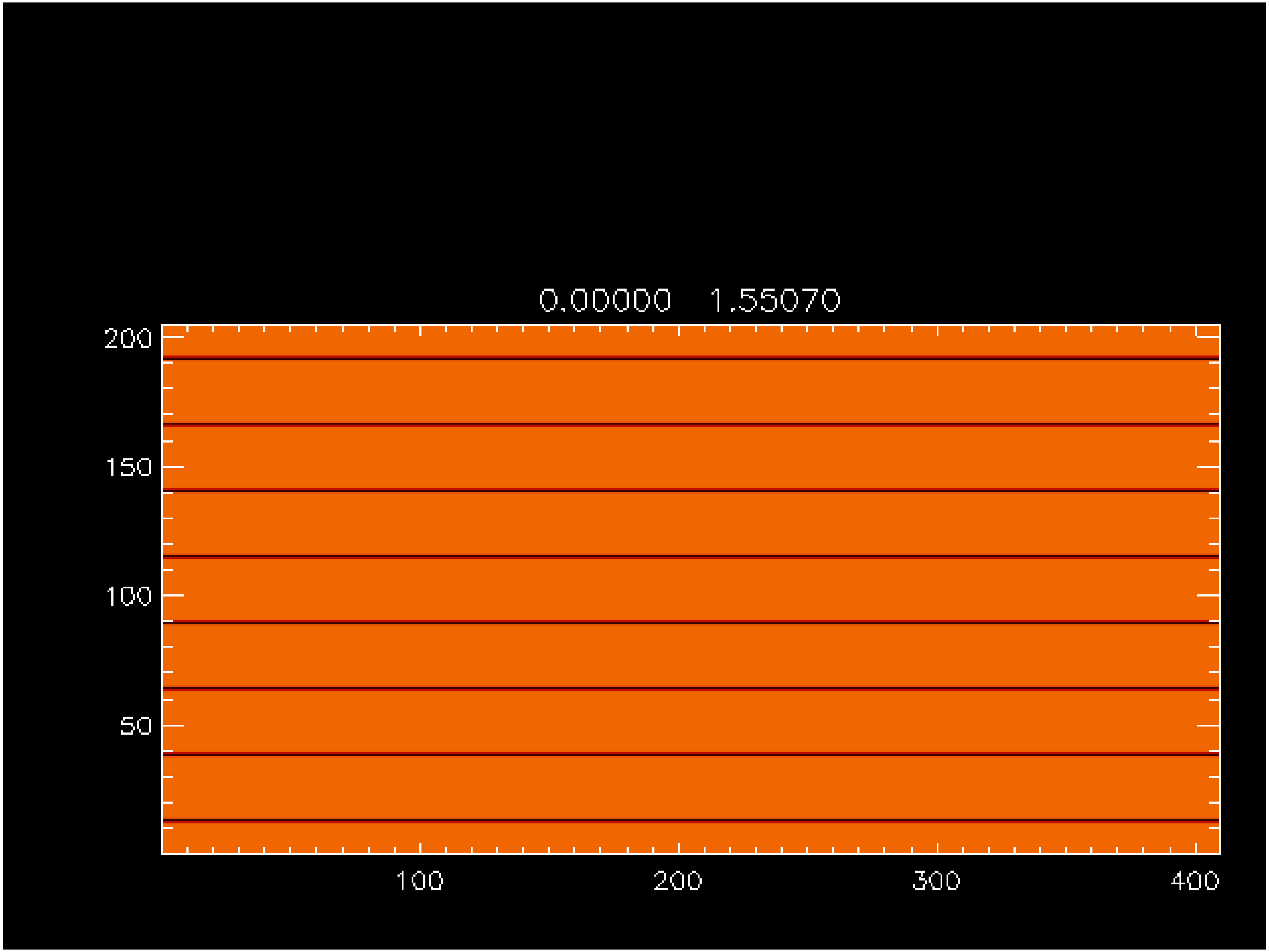
Our 3D MHD simulation resolved the sector allowing for reconnection to occur

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

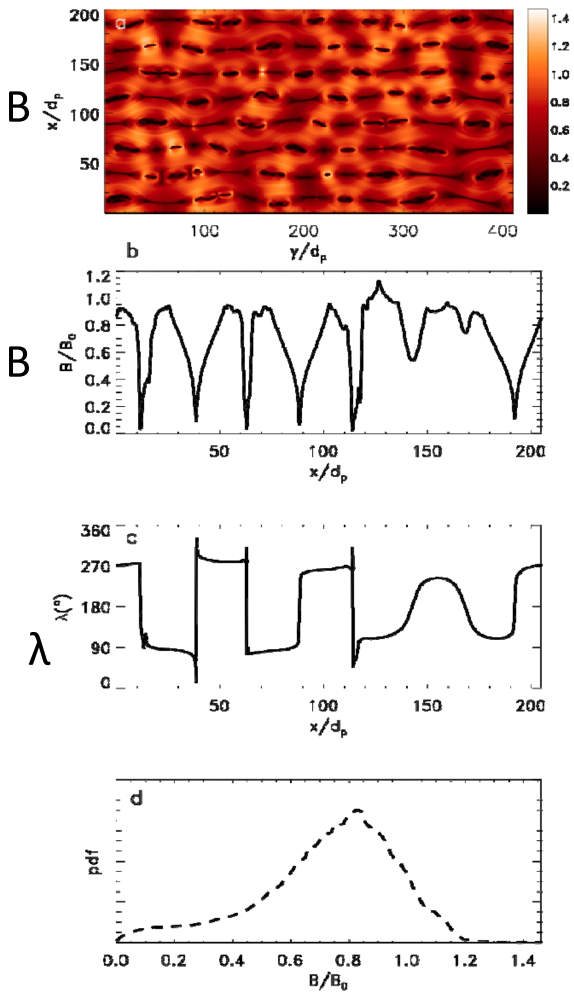
Simulation with a Sector Boundary of ±30°

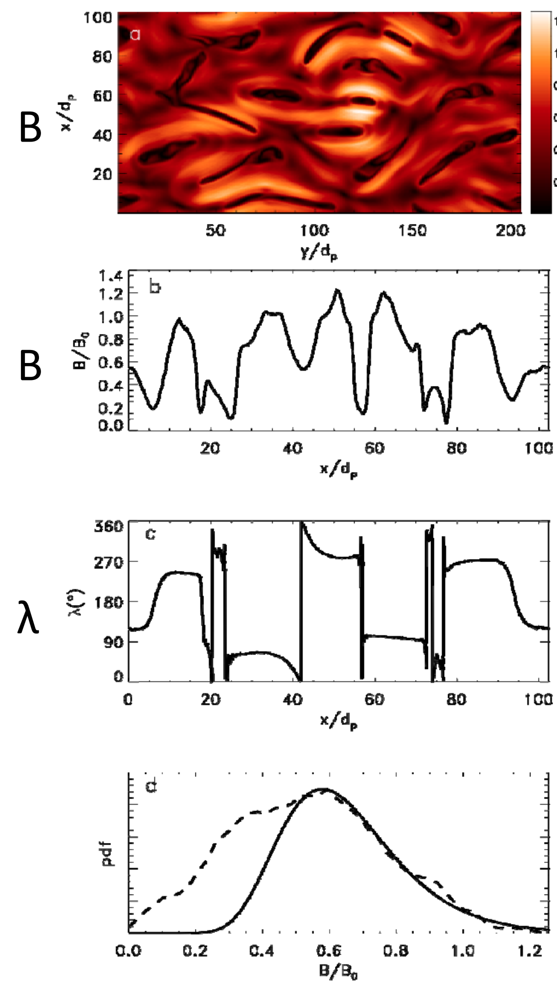


Opher et al. ApJ 2011


0.00000 1.55070
200
150
100
50
100
200
300
400

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





Early in time

“Bubbles”: Later in time

Evolution of the Islands Depend on the Plasma β

- Contracting islands increase the parallel particle pressure
- Within islands bump against the firehose condition
  - This condition limits island contraction
    - No tension in magnetic fields when the firehose condition is violated

$$\vec{F} = \frac{1}{4\pi}\left(1 - \frac{1}{2}\beta_{\parallel} + \frac{1}{2}\beta_{\perp}\right)\vec{B} \bullet \vec{\nabla}\vec{B}$$

Firehose condition

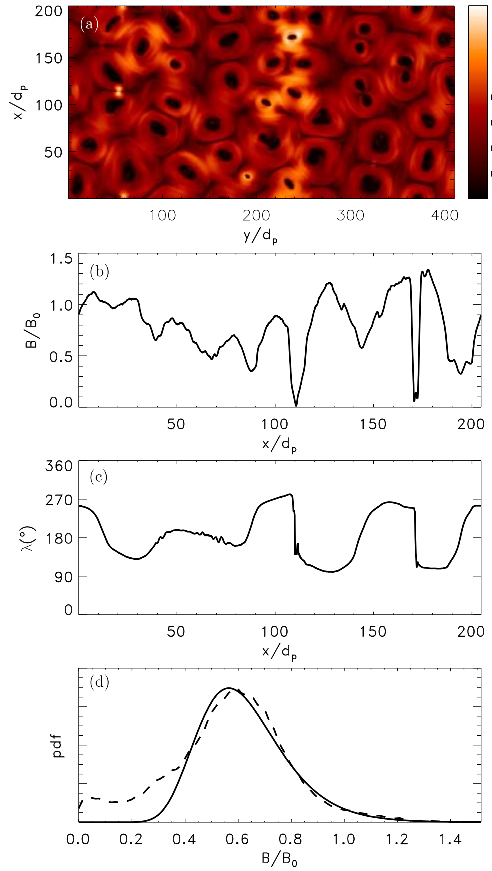


Figure 8. Same as Figure 7 but at $\Omega_p t = 150$. The solid line in (d) is a log-normal distribution.

(A color version of this figure is available in the online journal.)

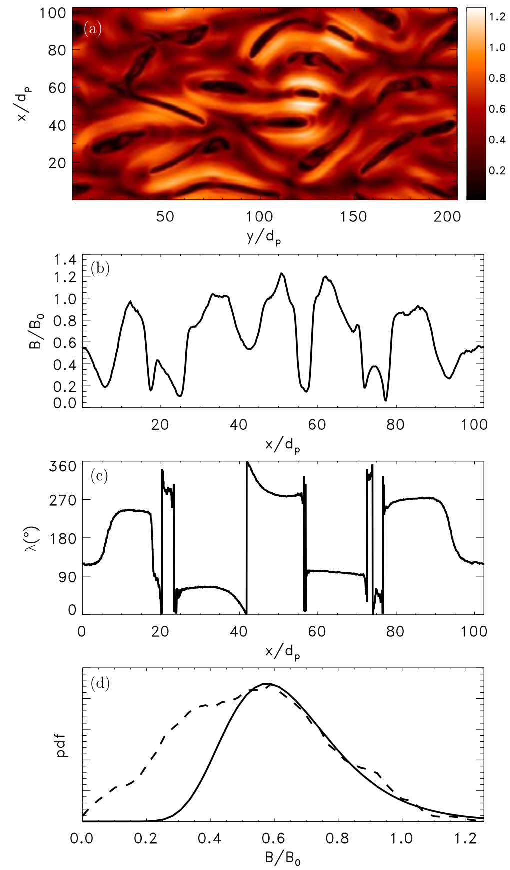


Figure 12. Same as Figure 8 for a case with $\beta = 4.8$ in the initial state. Panels (b) and (c) show cuts along x for $y = 127.5d_p$. The solid line in (d) is a log-normal distribution.

(A color version of this figure is available in the online journal.)

β=0.1

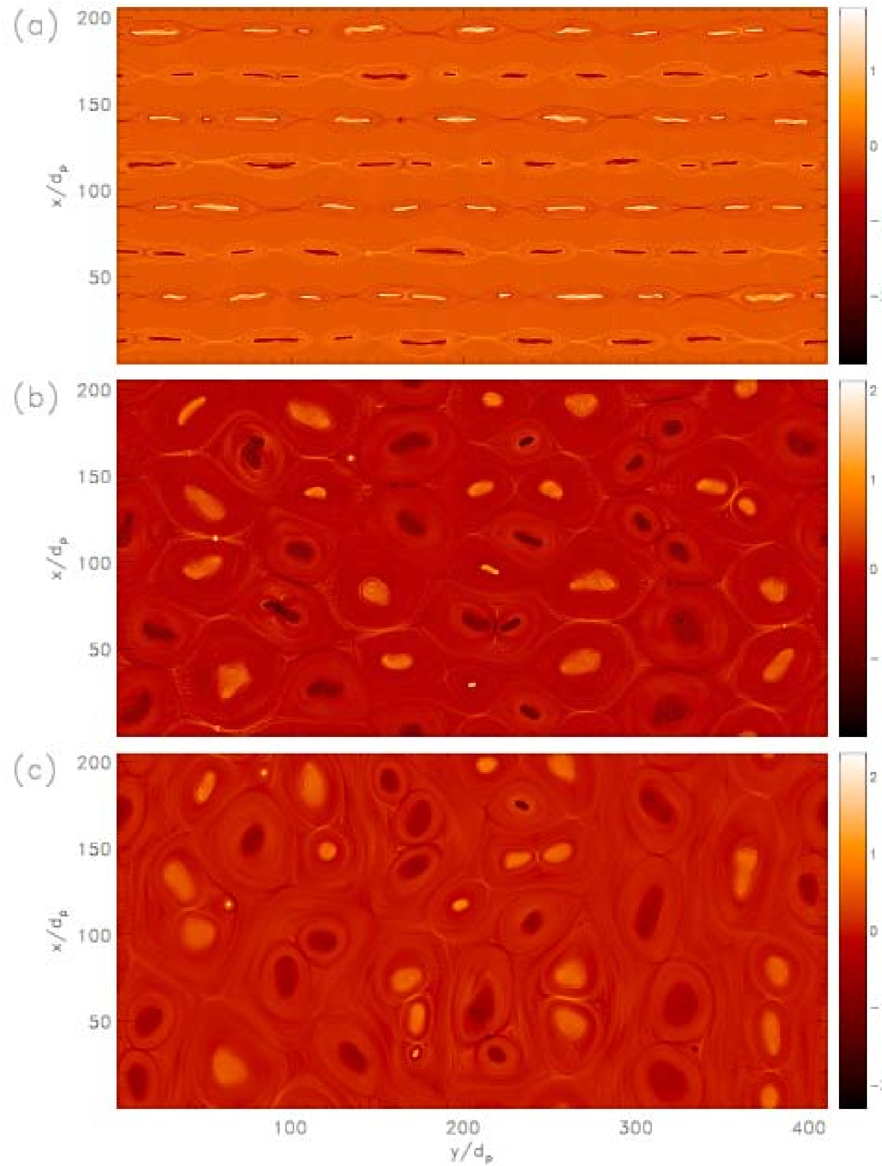
β=5.0

β = particle pressure/magnetic pressure

A reconnection model of the ACRs

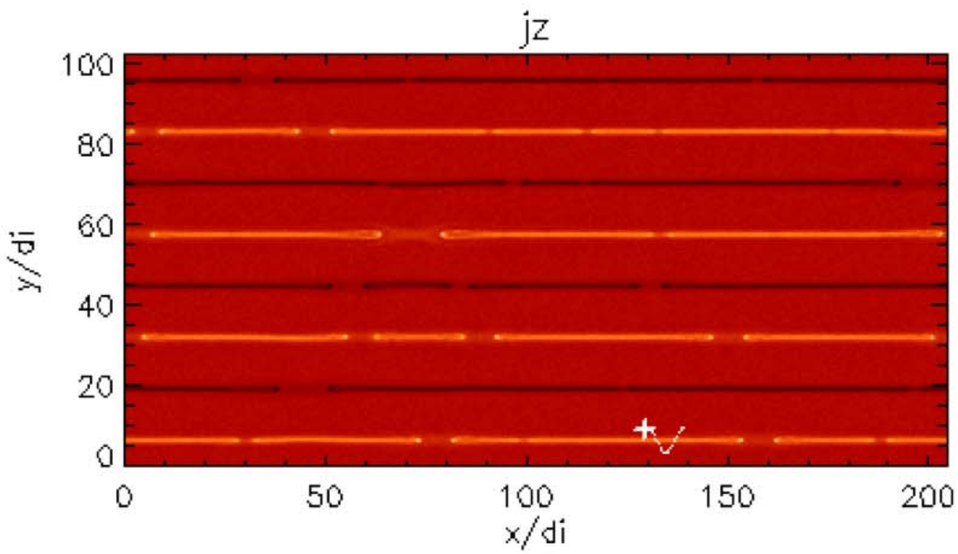
- The sectored field is stable to reconnection upstream of the TS because the width of the current sheet is wider than the ion inertial length
  - Collisionless reconnection is very weak
- The current layers compress on their approach to the heliopause
  - This is well documented in the case of the Earth's magnetosphere
  - Dissipation of nearly all of the magnetic energy ~ 85%
- The original idea was this will happen only close to the HP- we extended it (Opher et al. 2011) that it can happen downstream the TS

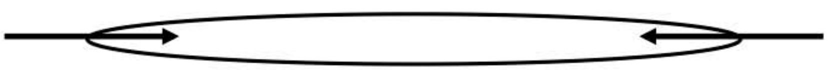
Drake, Opher, Swisdak *et al* ApJ 2010



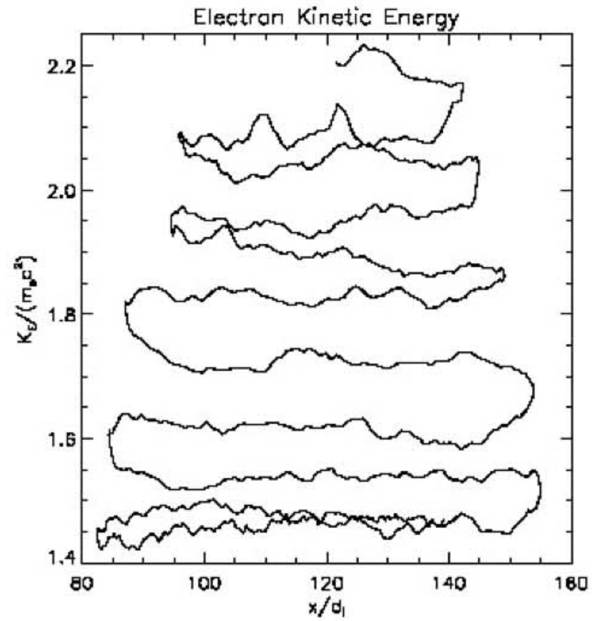
Fermi acceleration

- How do the most energetic particles gain energy?
  - Reflection from the ends of contracting islands
  - Increase of parallel energy and pressure $p_{||}$





C_{Ax}

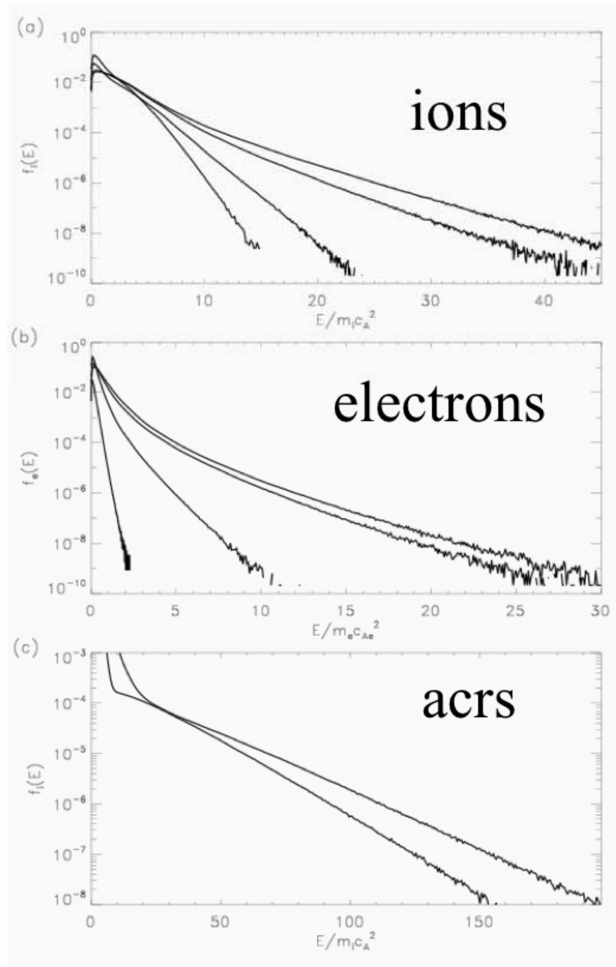


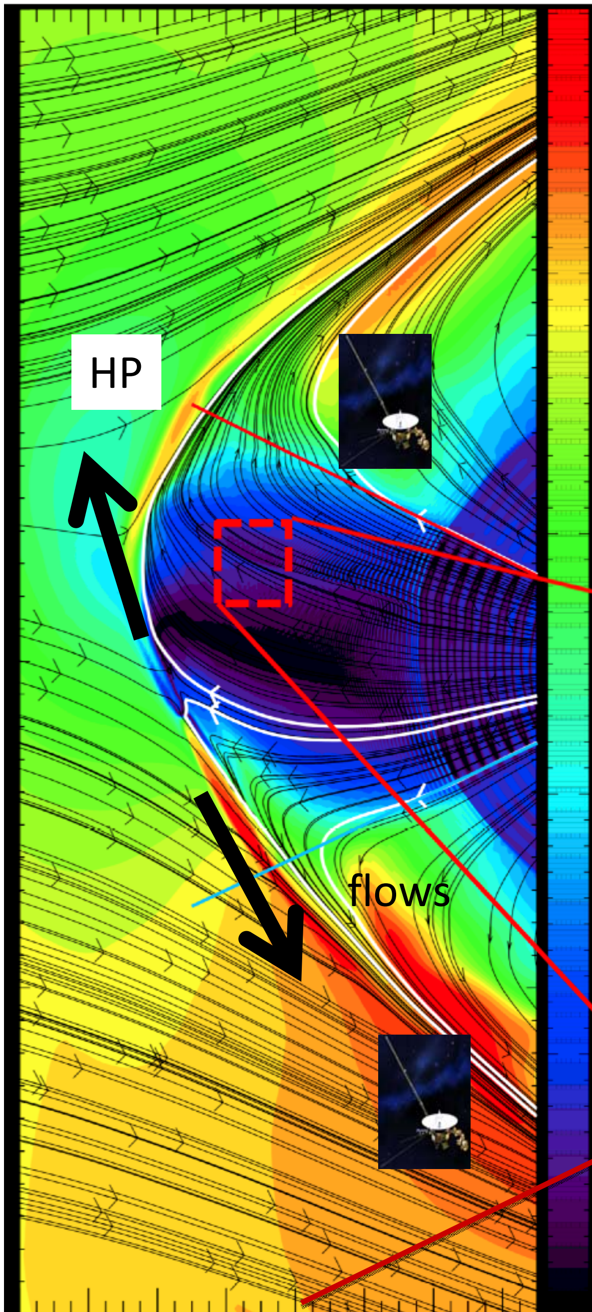
$$\frac{d\varepsilon_{||}}{dt} \sim 2\varepsilon_{||}\frac{c_A}{L_x}$$

Schoeffler et al 2011

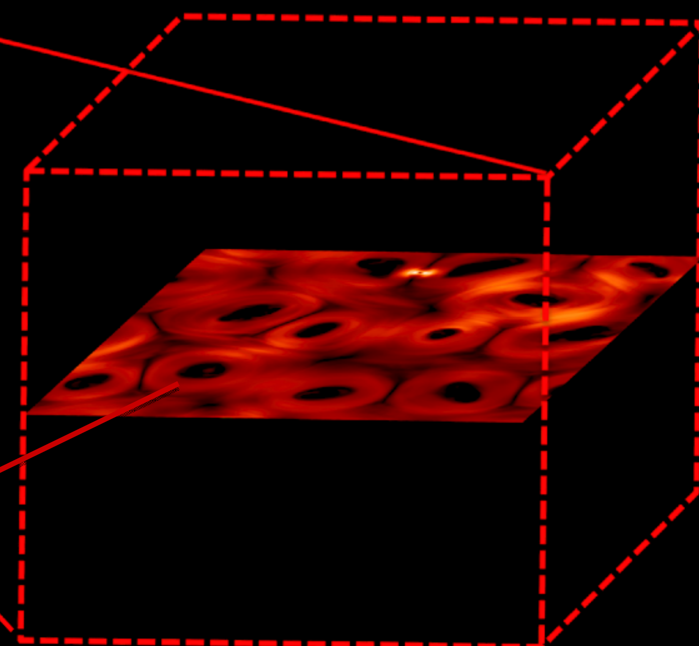
Electron and ion energy spectra

- Both ions and electrons gain energy
- Include 5% population of pickup particles to simulate the production of ACRs
  - These particles are super-Alfvenic in the initial state
  - They gain the most energy because they start with higher energy





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

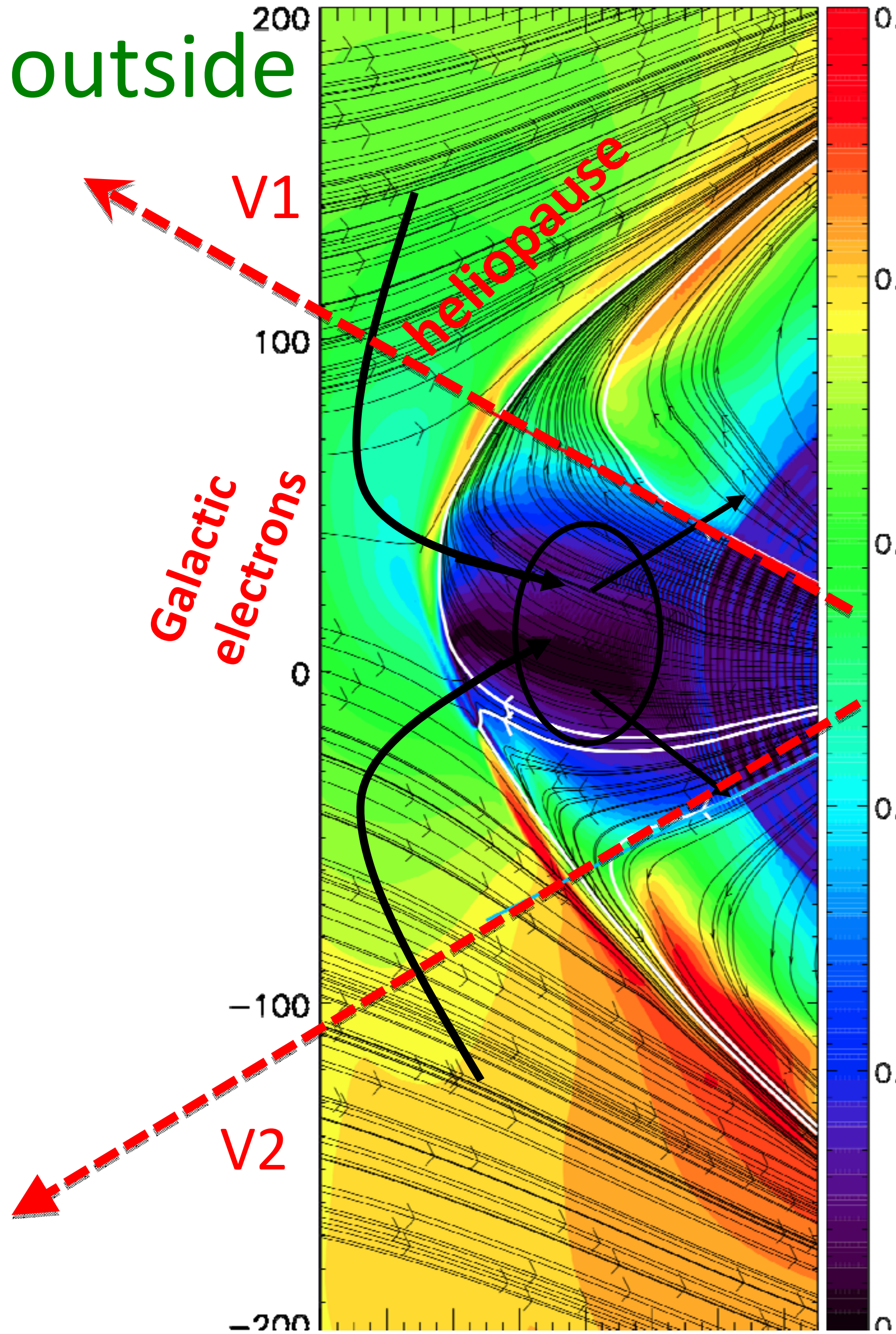
Transport inside the sector will be different than outside

•*Bubbles* act as local traps of energetic electrons (both GCR and low-energy)

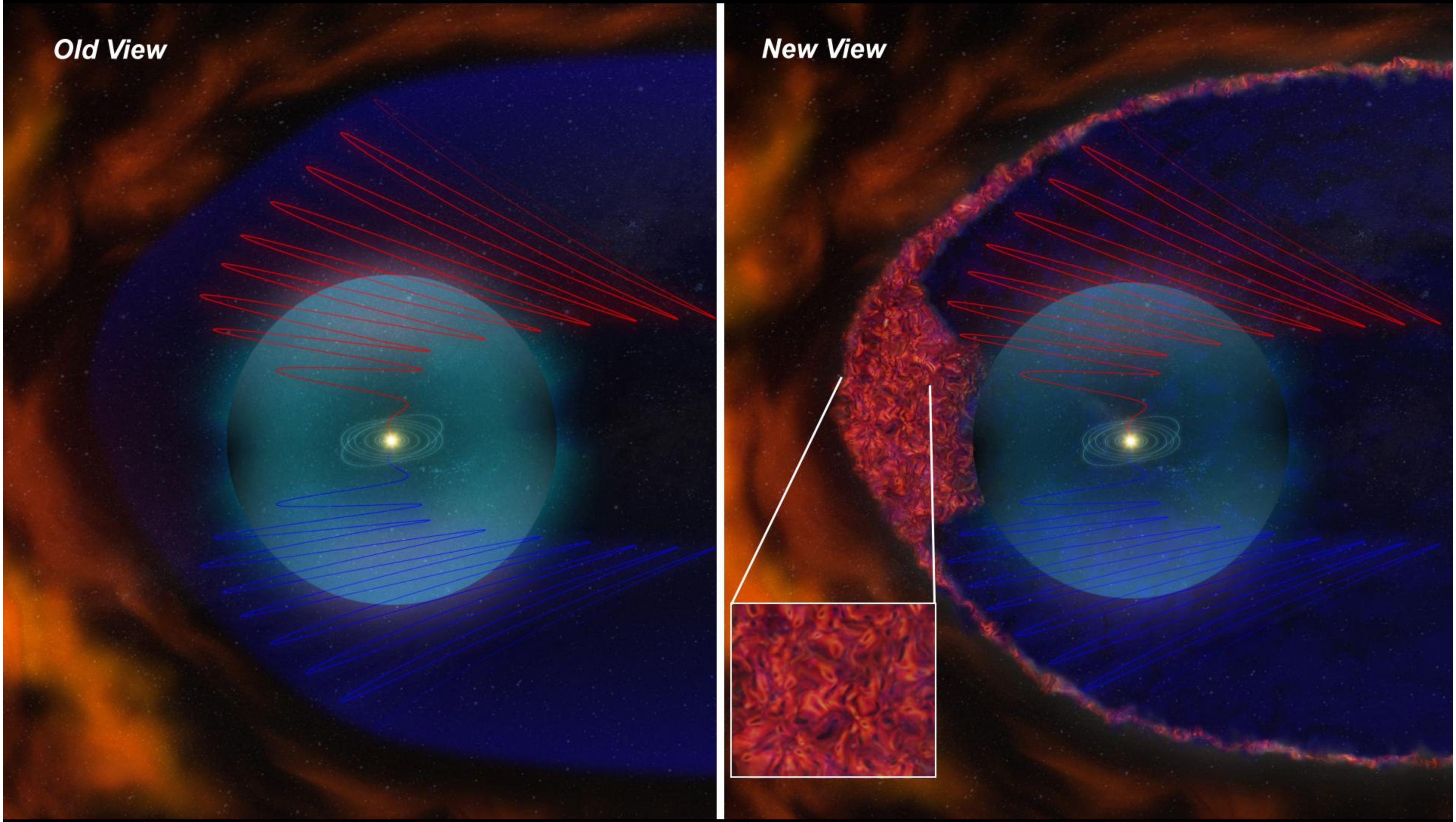
•Galactic electrons enter the heliosphere by percolating upstream through the "bubbles" regions of the sector region of the heliosheath

• The edges of the sector region act as loss boundaries

•Electrons leaving the sector region quickly migrate into the inner heliosphere



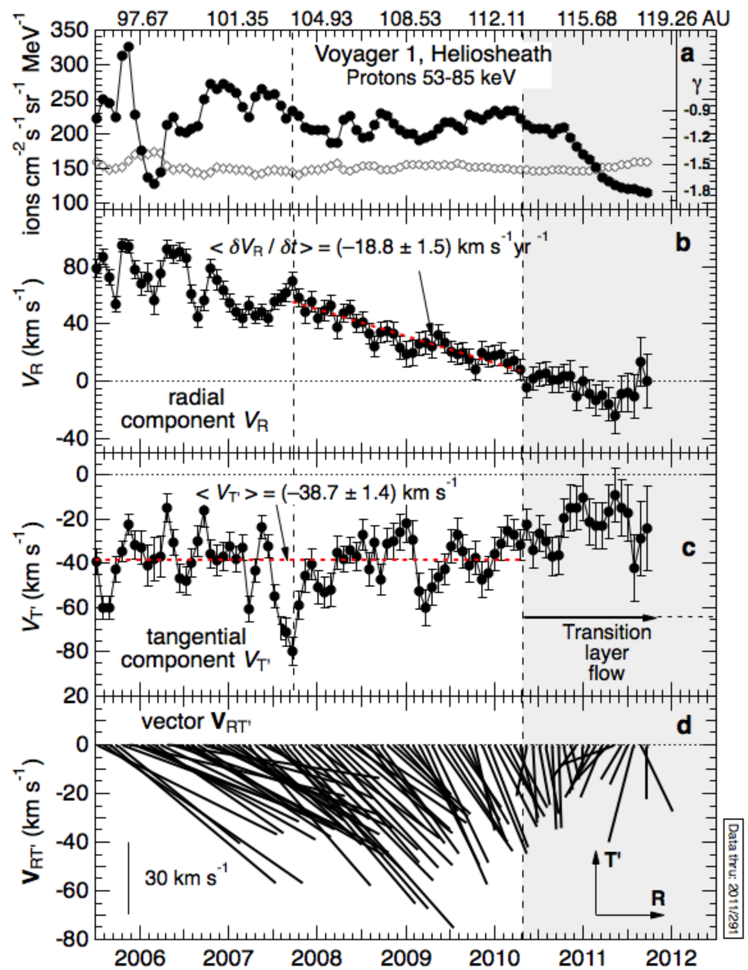
Old and a New View: The permeable heliosphere

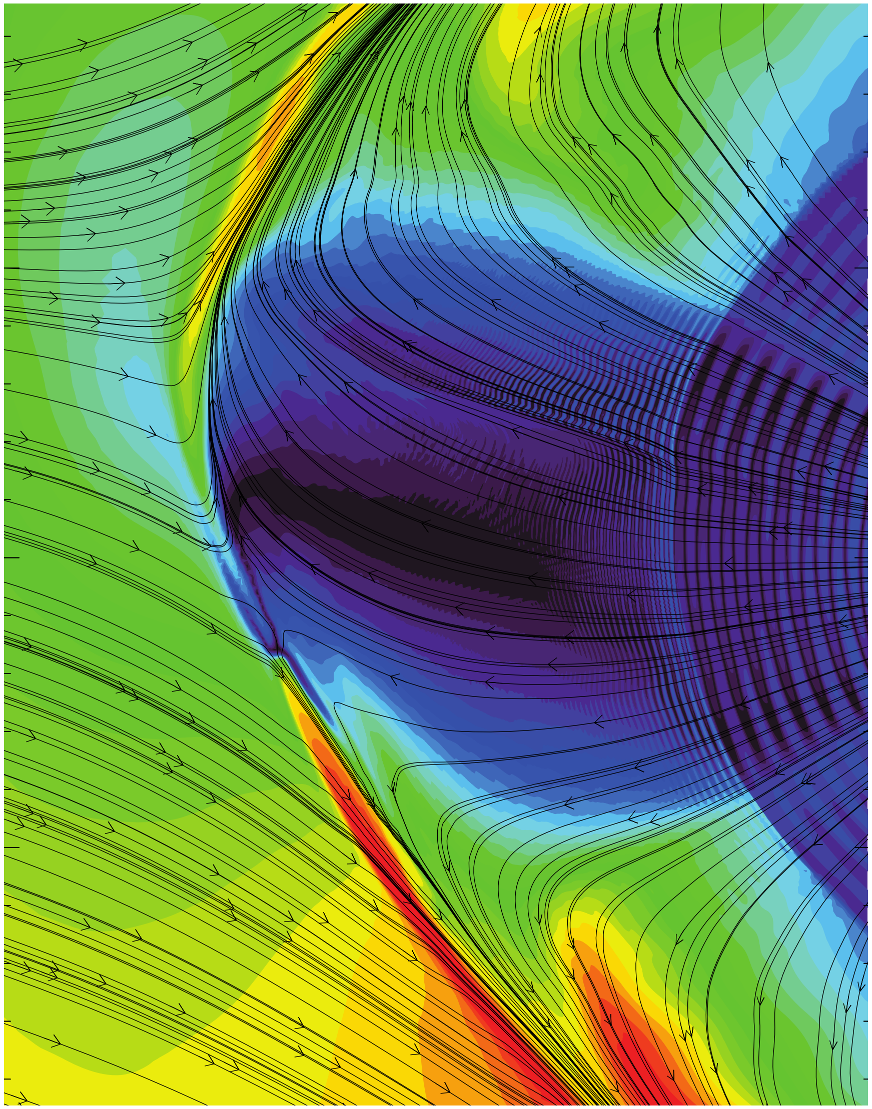


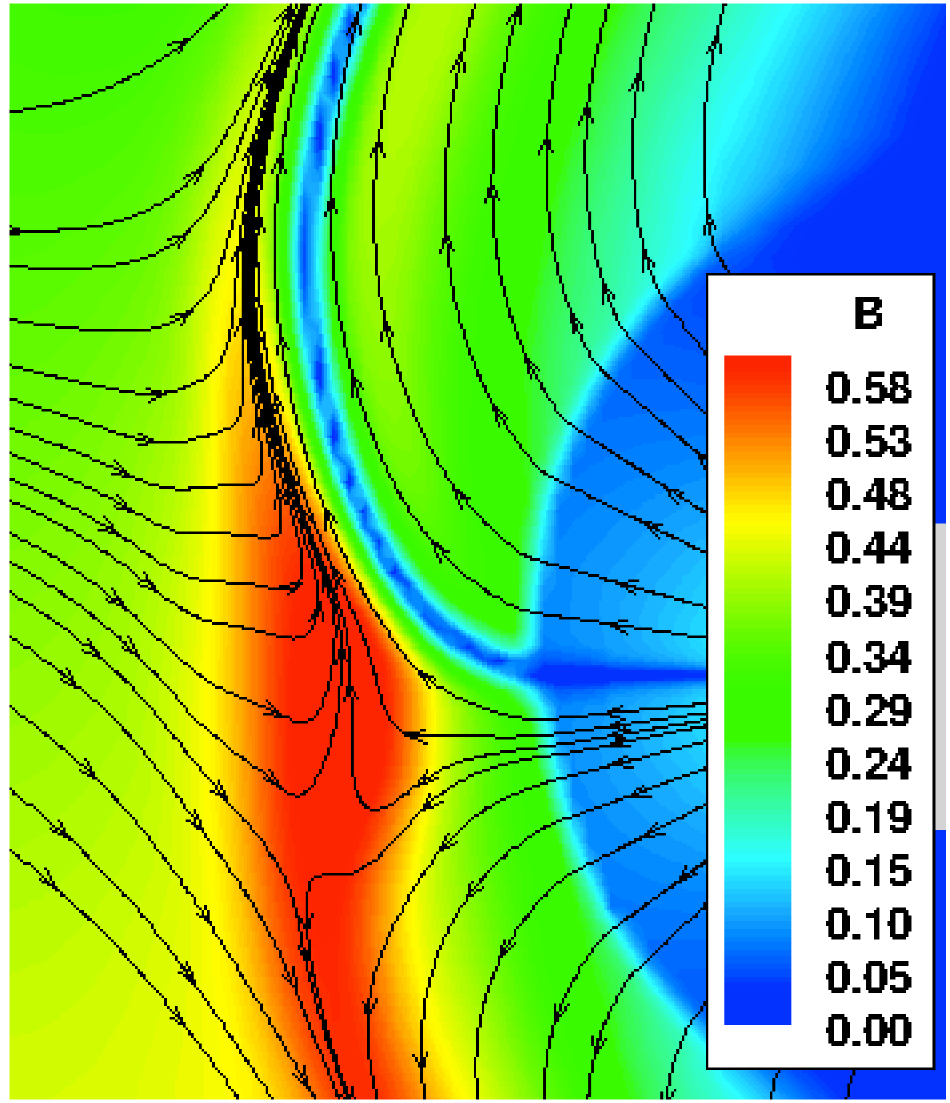
Implications of Reconnection for Flows Dynamic

Observations

- Change in the gradient of VR in April 2010; VR ~ 0km/s and negative
- Thickness of the “Transition Layer Flow” of at least 7AU.
- VT start increasing at the end of 2011.







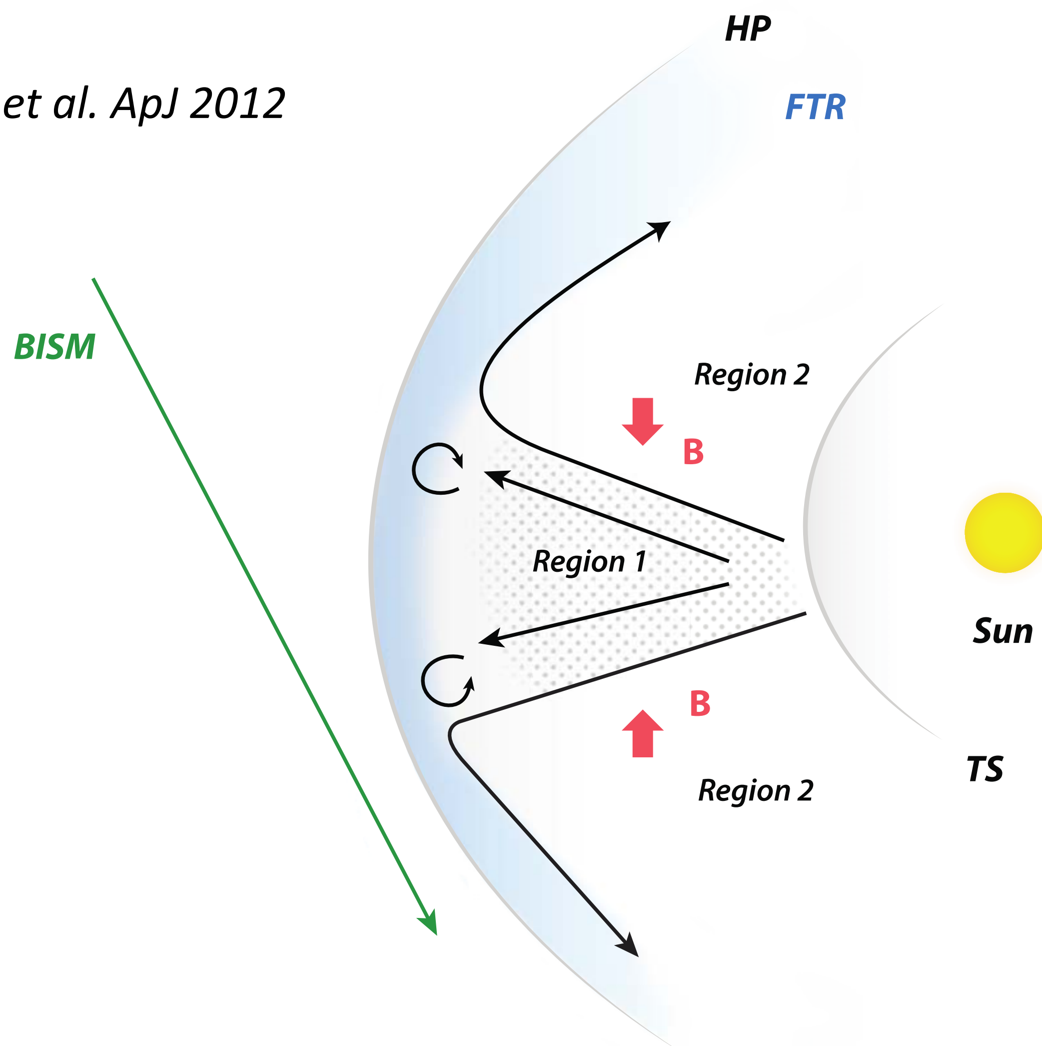
Zoom in the Heliosheath

Simulation with the sector region

Simulation without the sector region

Two Different Flows in the Heliosheath

Opher, Drake et al. ApJ 2012

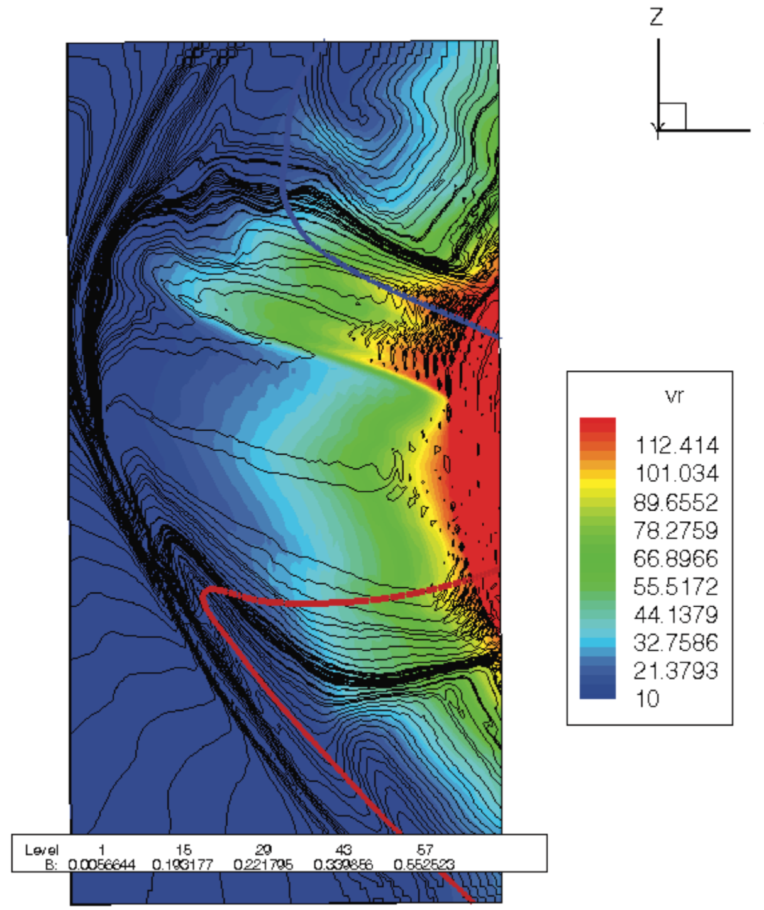


Magnetic Field act as a skeleton organizing the flows in region 2

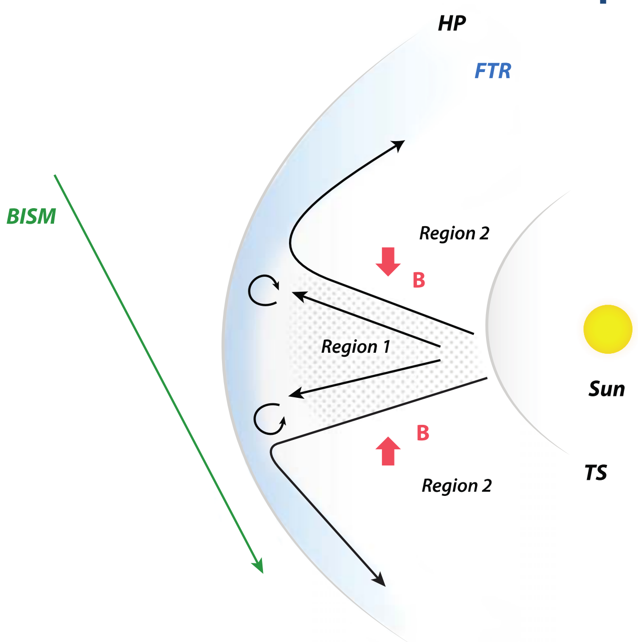
Flows in region 1: filled with disconnected magnetic structures (no magnetic tension) behaves as un-magnetized flows

Flows in region 2: magnetized

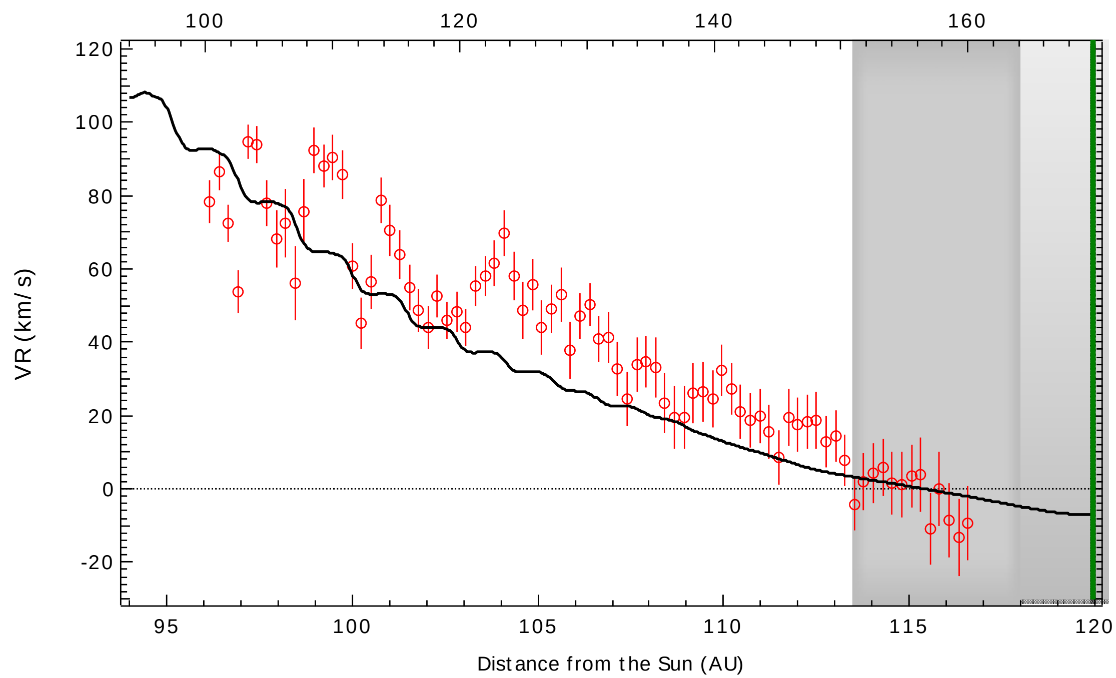
Radial Flows: More collimated inside the sector



Flows near the HP (Stagnation Region) Spatial or Temporal Feature



Opher et al. 2012



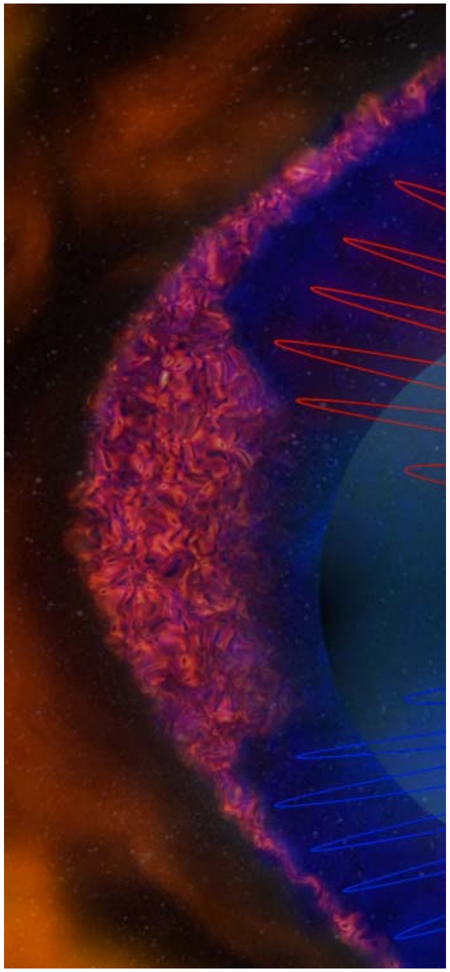
The reconnection in the sector creates two type of flows in the heliosheath (Opher et al. 2012).

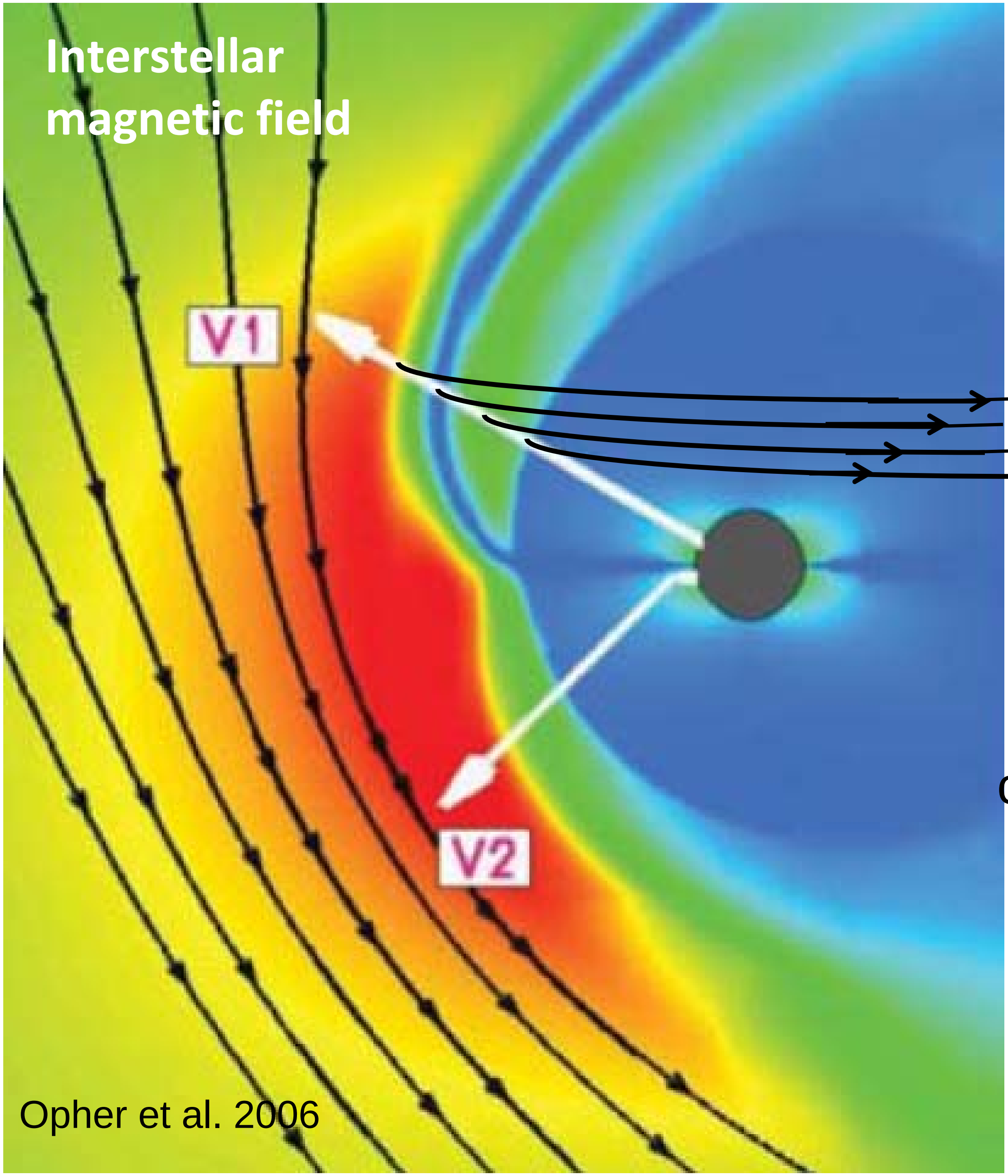
Global feature: a stagnation region at all latitudes in front of the HP

Other proposals: temporal (Washimi et al. 2011; Pogorelov et al. 2012)

Porous Heliopause

In this scenario the HP is not just a tangential discontinuity but a *porous boundary*





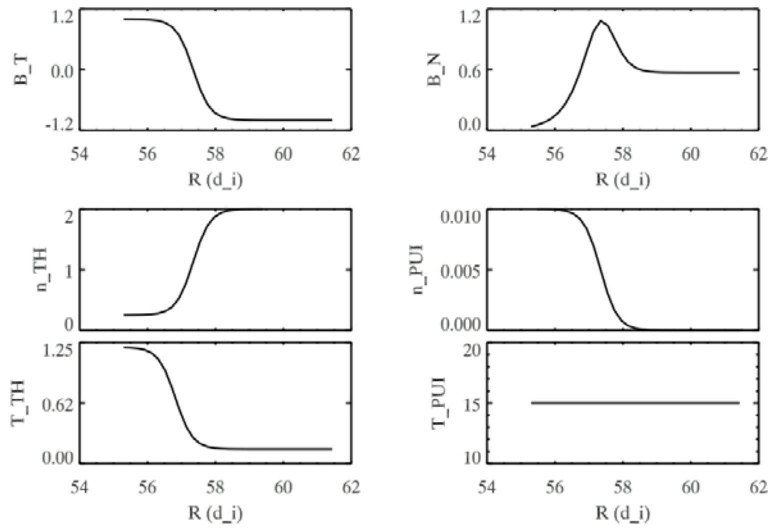
Spiral magnetic field from solar rotation is east-west

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

When crossing the HP one should expect a change in magnetic field due to draping.

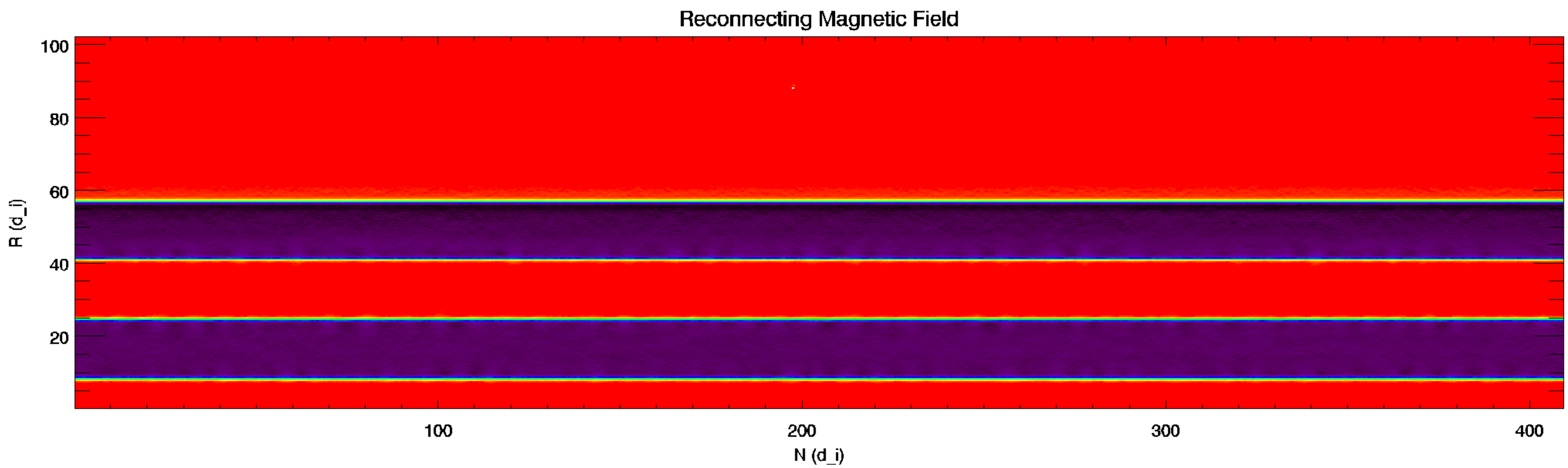
Acknowledg. Ed Stone

Heliopause Reconnection: PIC Magnetic Field



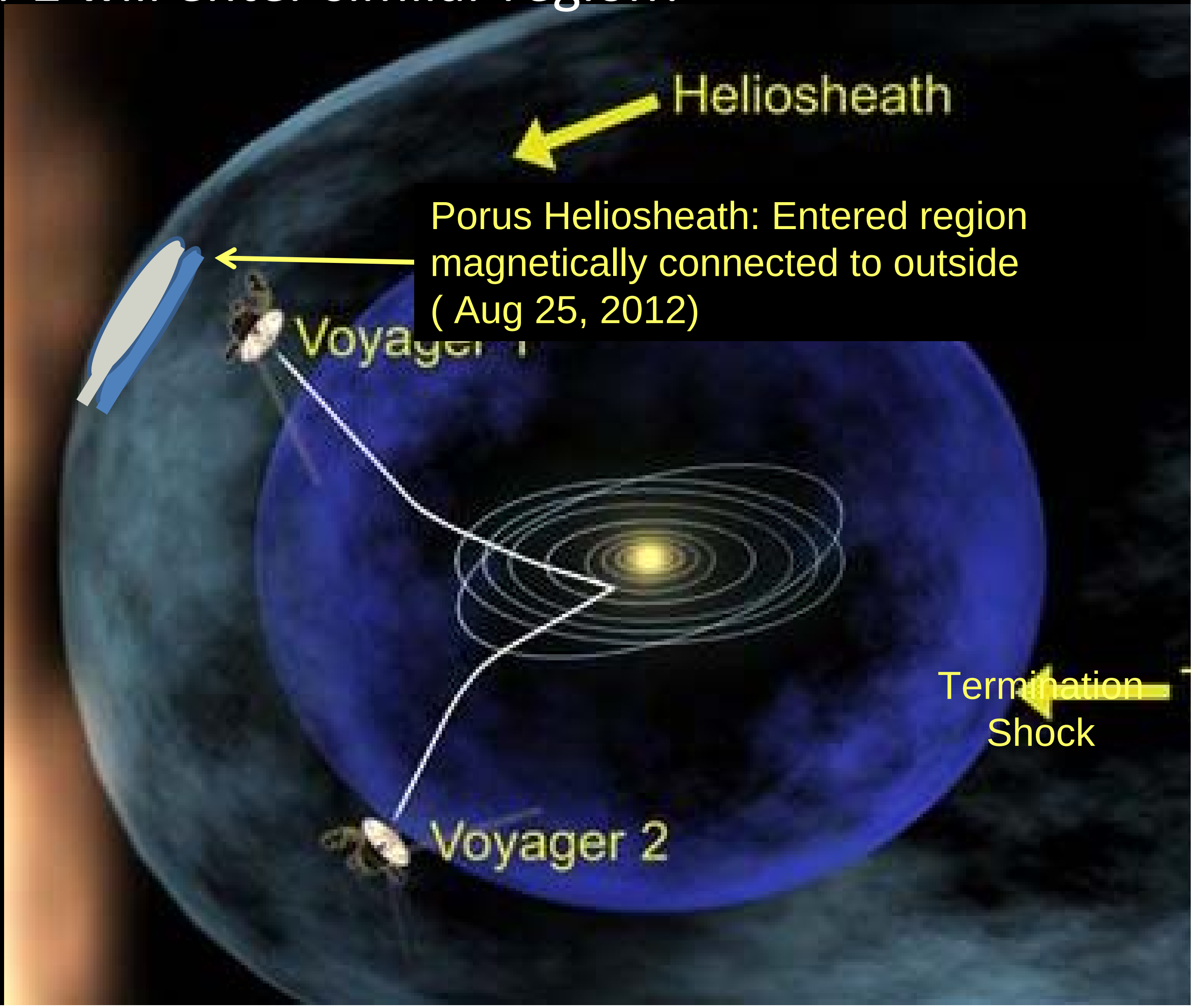
Swisdak et al. *in prep* 2013

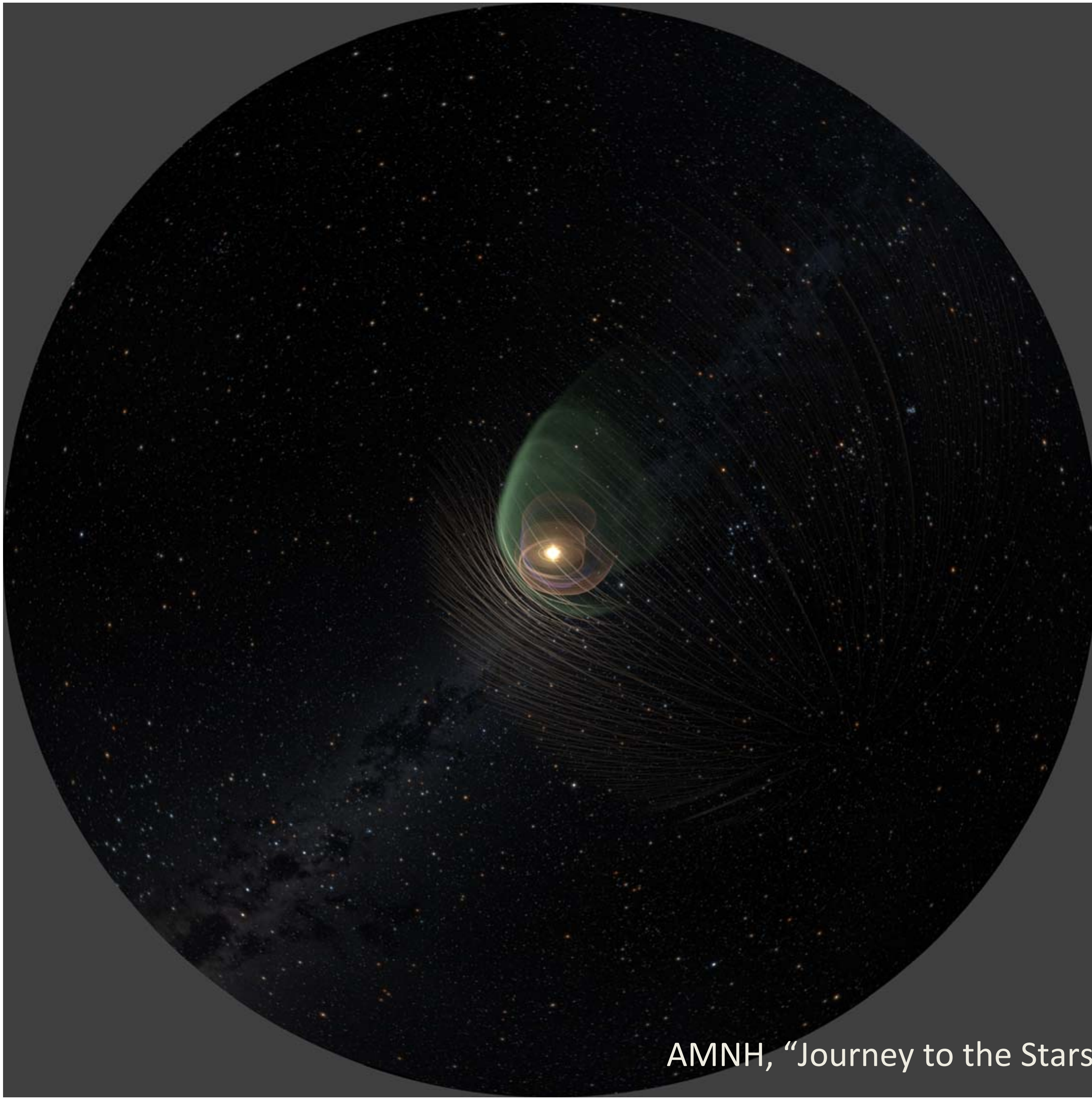
Cuts from MHD model (Prested et al. 2012)



Where is the Heliopause?

When Voyager 2 will enter similar region?





Thank you!

AMNH, “Journey to the Stars”, 2009