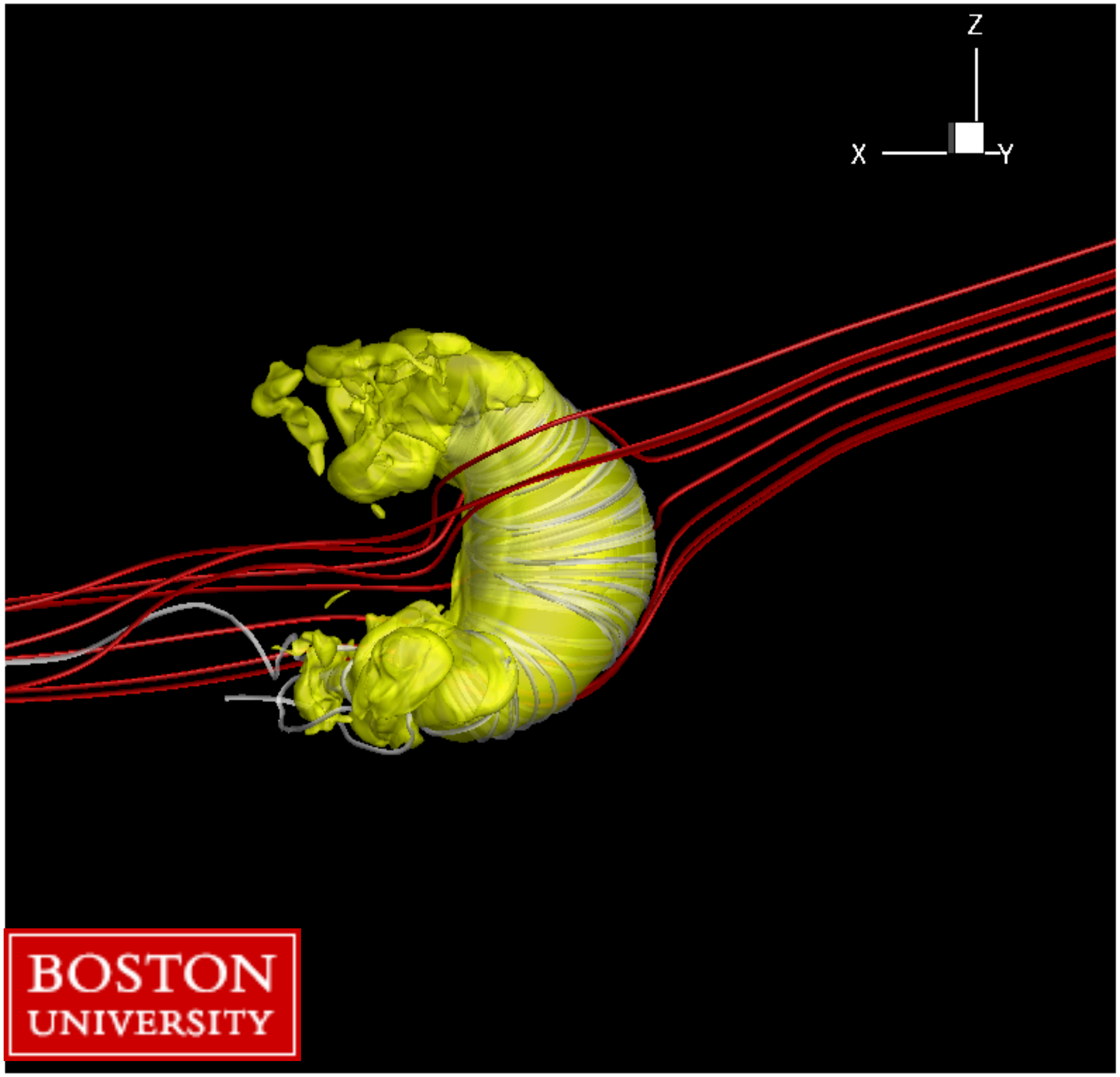
Structure of the Heliosphere Revisited



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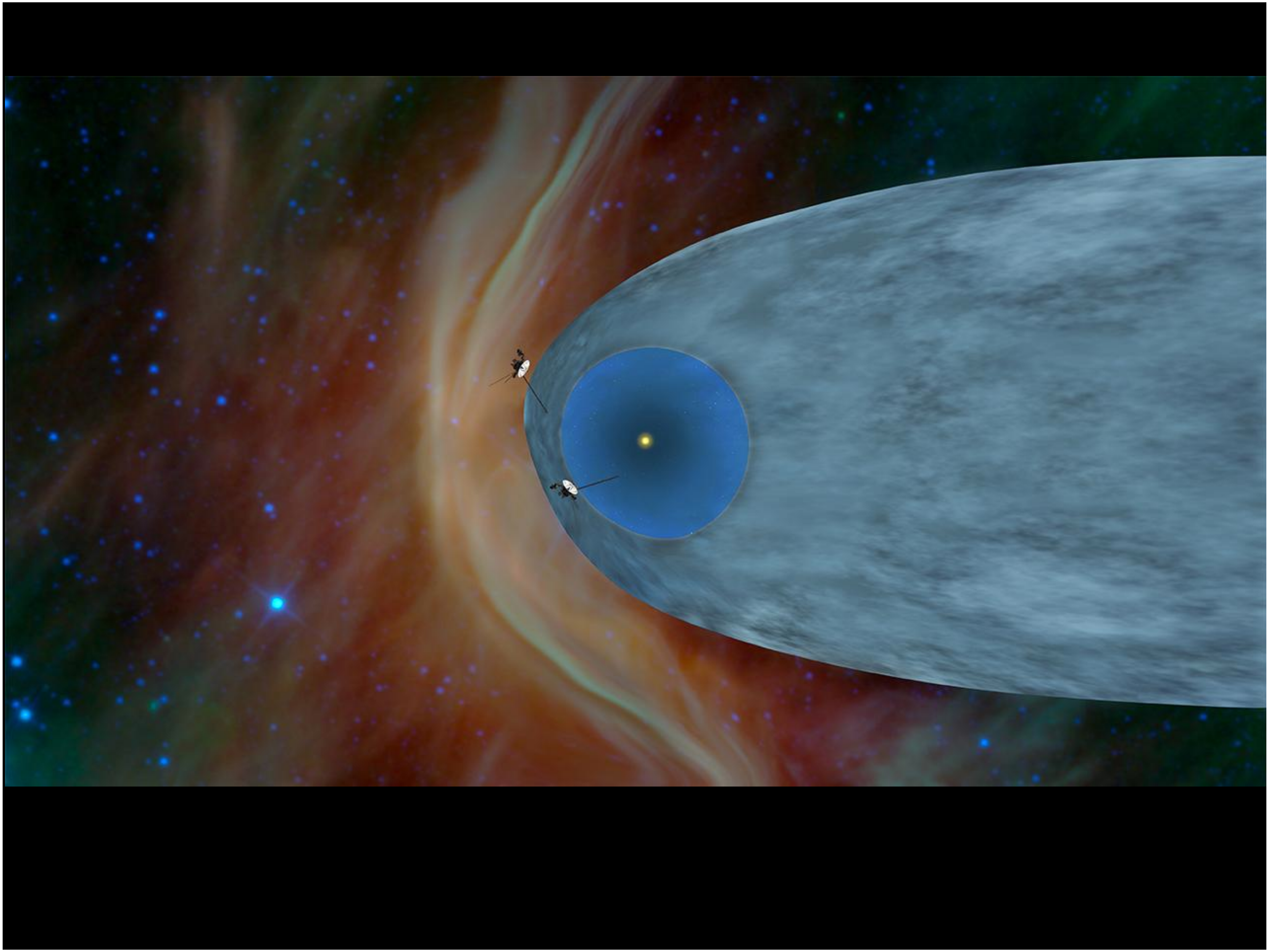
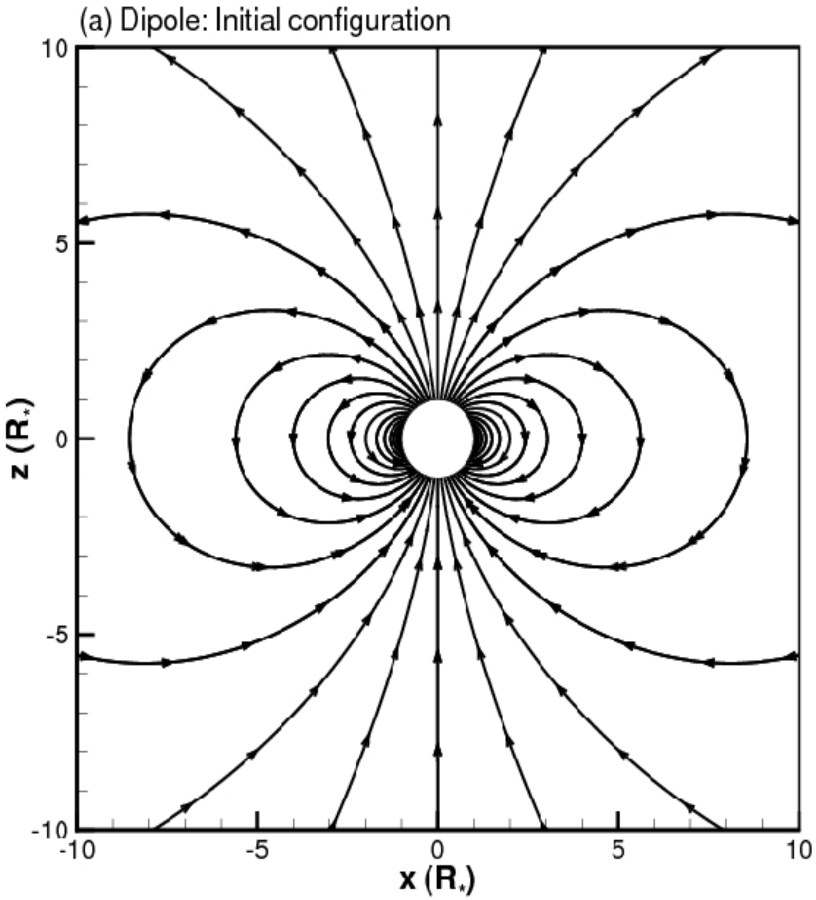
Nordita, August 2015

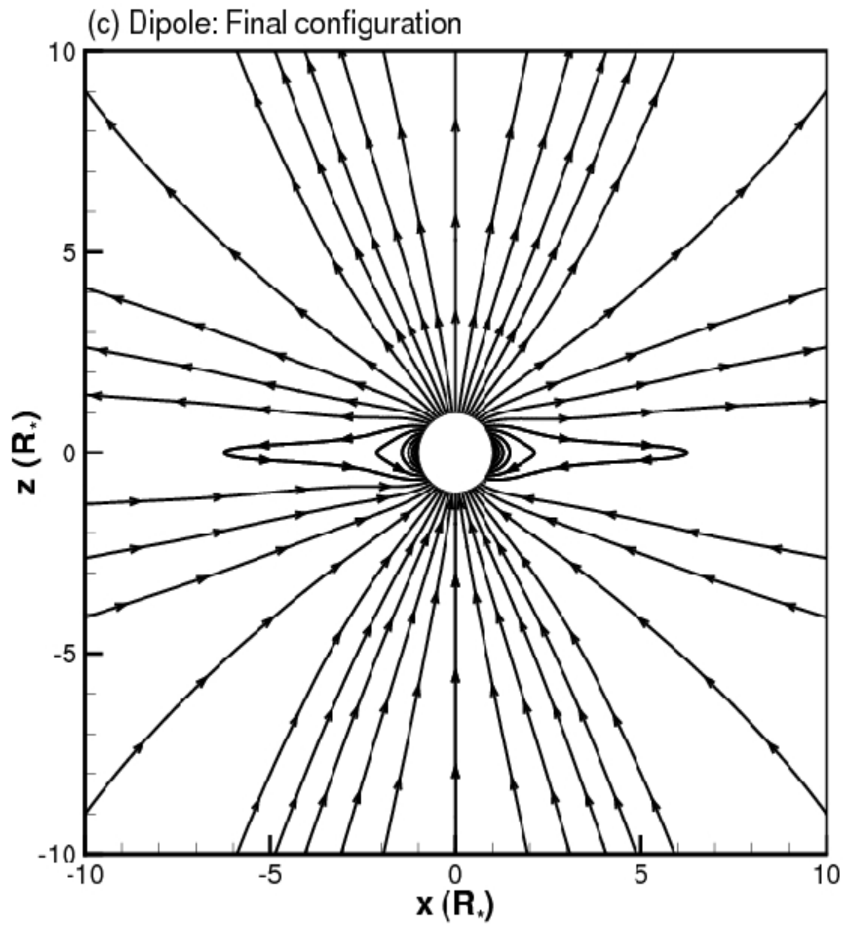


Magnetic Structure of the Sun



Start from a dipole field

Magnetic Structure of the Sun



Turn on the wind

Interplanetary Magnetic Field

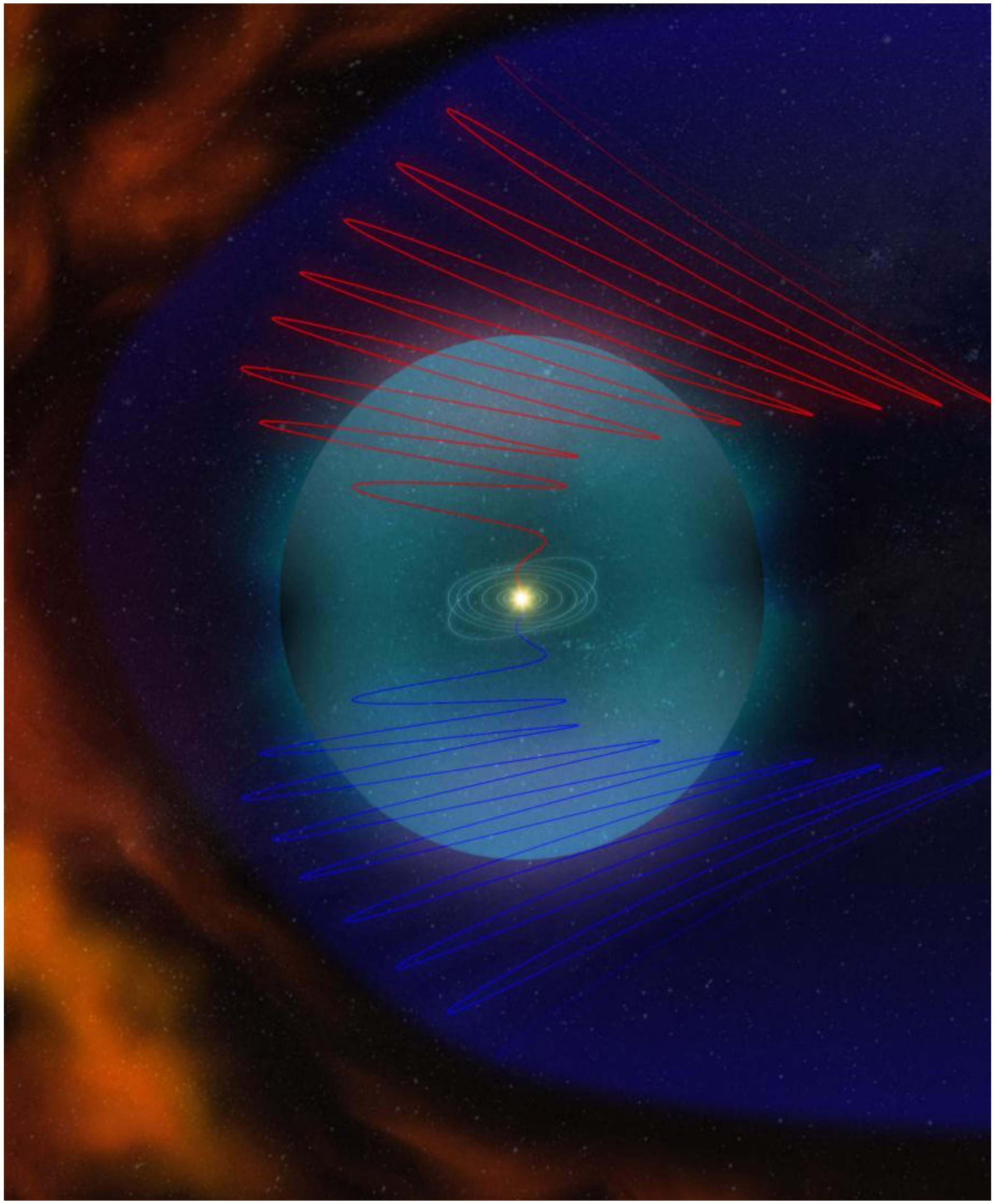
$$\boxed{\vec{B} = B_S\left(\frac{R_S}{r}\right)^2 \vec{e}_r - B_s\left(\frac{R_S}{r}\right)^2 (r - R_S)\frac{\Omega_S \sin\Theta}{u_{SW}}\vec{e}_\phi}$$

Ω: stellar rotation rate
Θ: polar angle

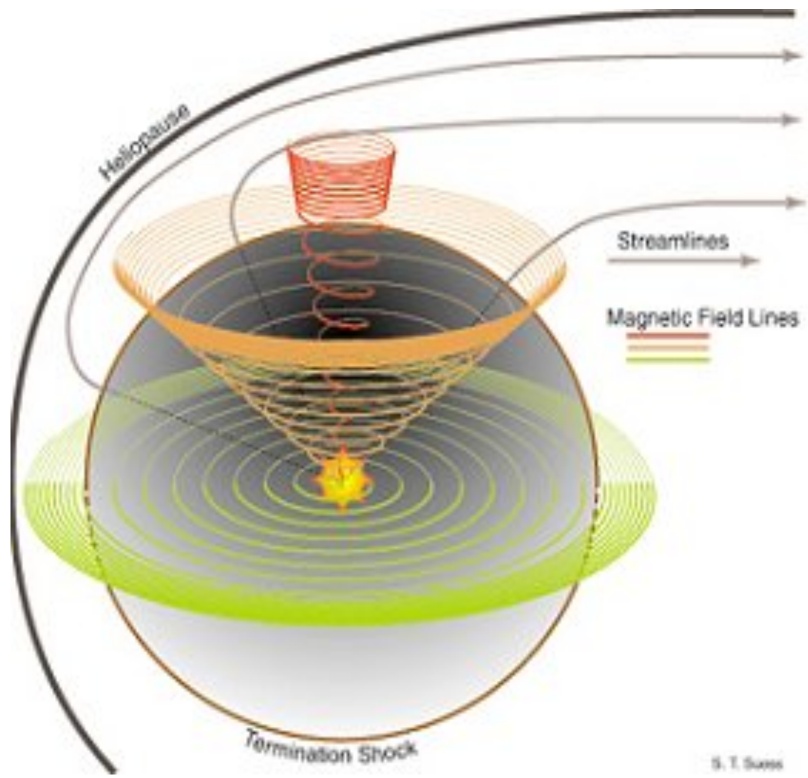
At large distances

$$\boxed{B = B_0\left(\frac{R_0}{r}\right)^2 e_r - B_0\left(\frac{R_0^2}{r}\right)\frac{\Omega \sin\Theta}{v_{\mathrm{SW}}} e_\phi,}$$

Solar Magnetic Field

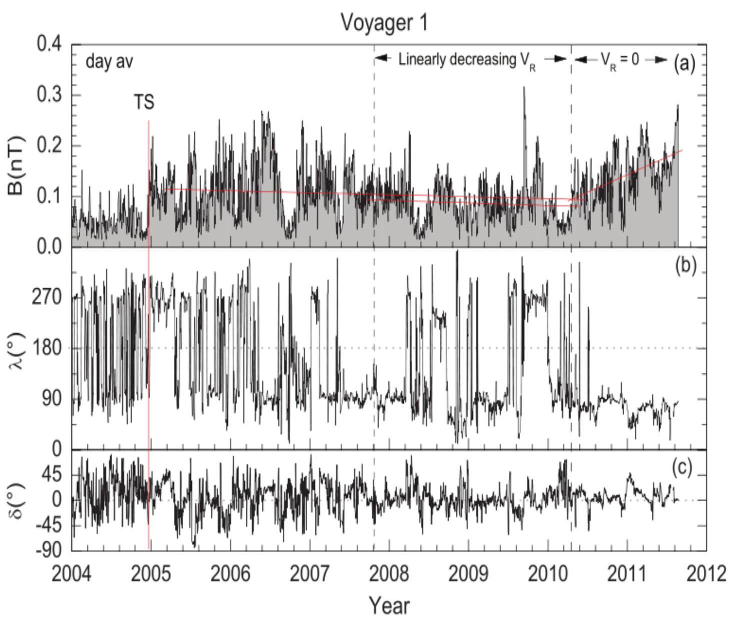


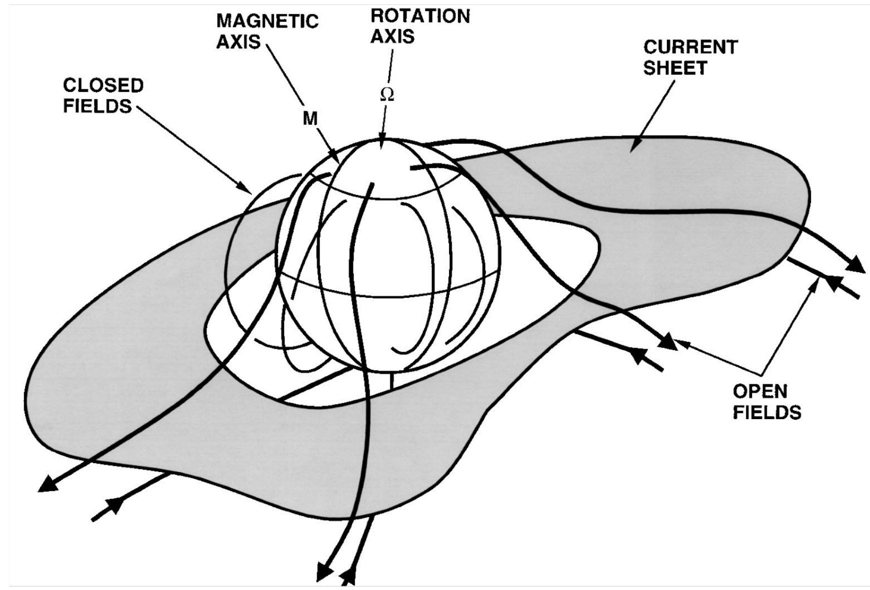
$$B = B_0\left(\frac{R_0}{r}\right)^2 e_r - B_0\left(\frac{R_0^2}{r}\right)\frac{\Omega \sin\Theta}{v_{SW}} e_\phi,$$

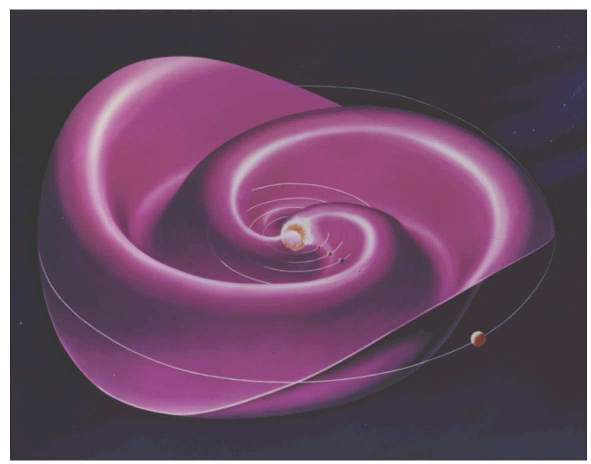


Sector structure of the heliospheric field

- 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

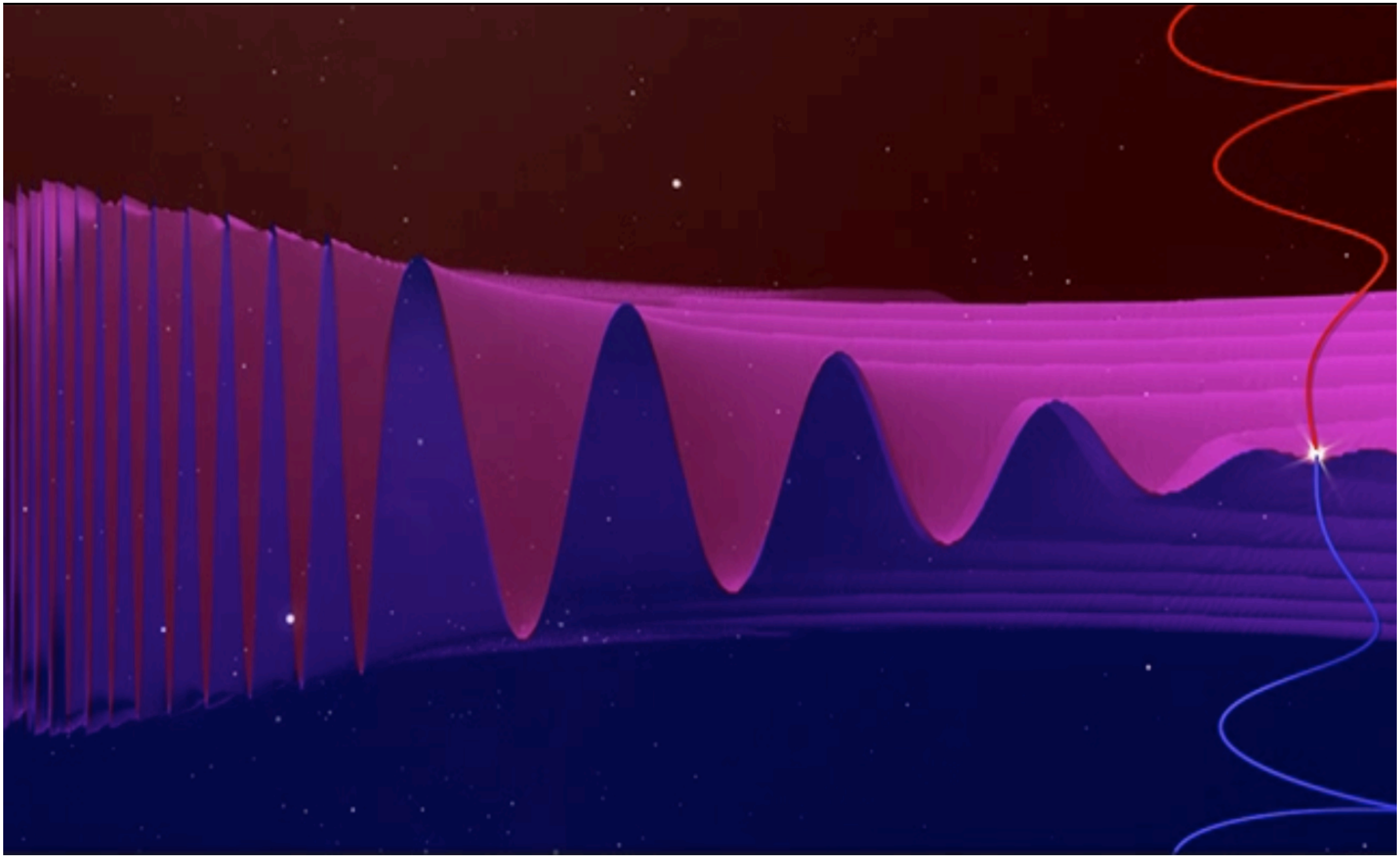




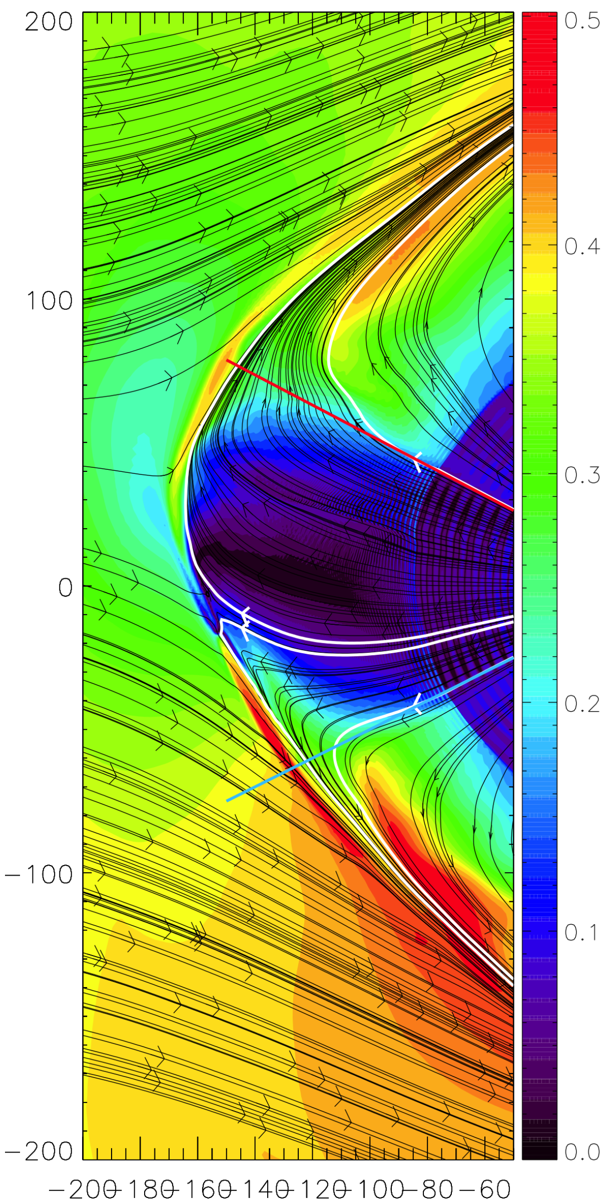


Heliospheric current sheet

Sectors get compressed after the termination shock



Onset of Collisionless Reconnection in the HS



See Opher et al. ' 2011
Drake et al. 2010; Swisdak et al. 2013

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)

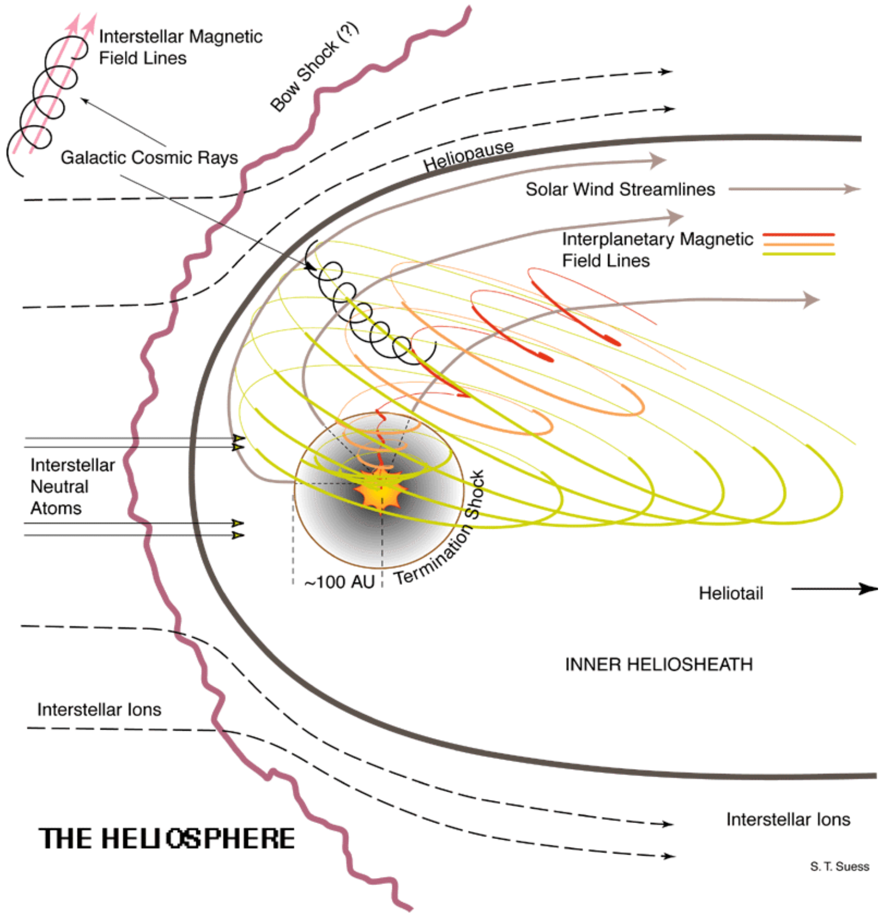
Parameters downstream of the TS

- 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

Classical View of the Heliosphere:

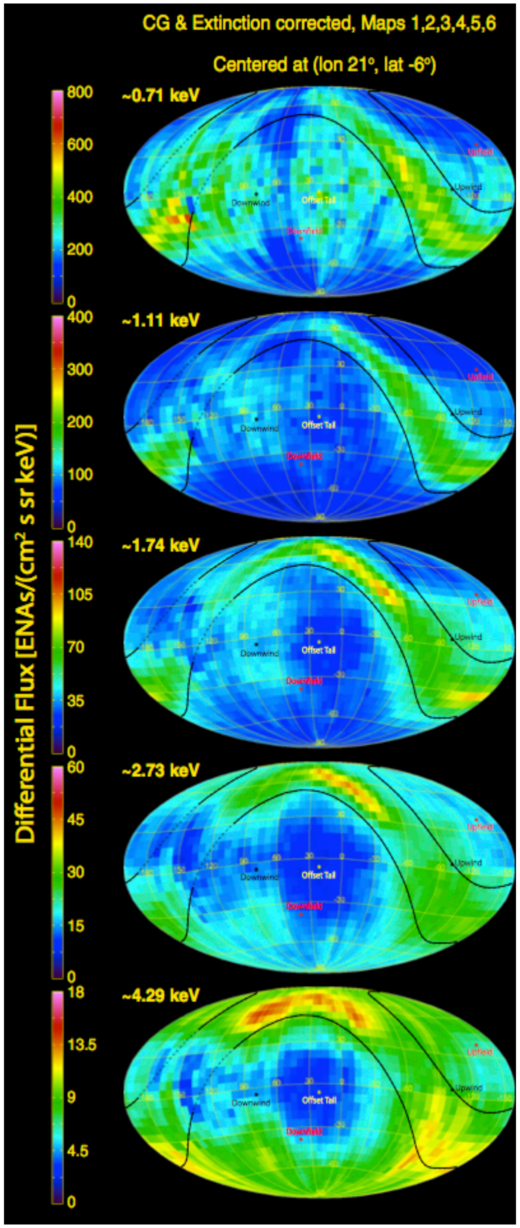
Comet-like shape with a long tail; extending to 1000’s of AUs



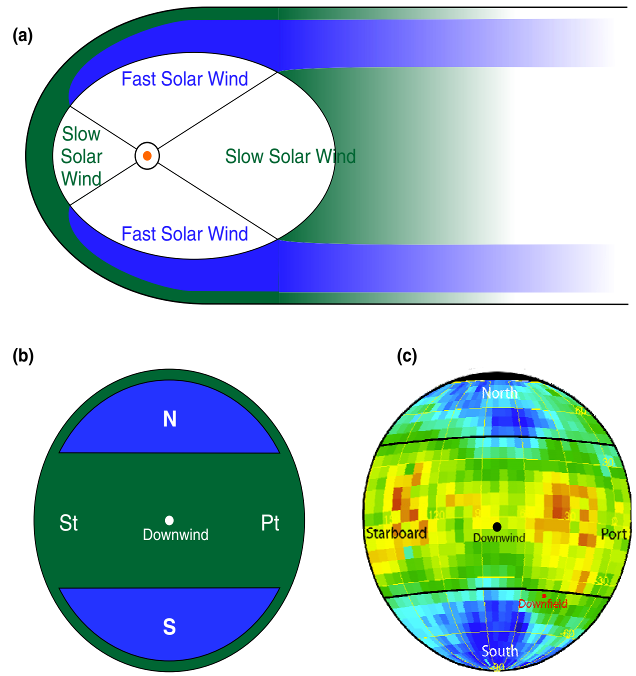
e.g. from Parker 1961; Baranov & Malama 1993

This view comes from the assumption that even though the solar wind becomes subsonic at the termination shock as it flows down the tail is able to stretch the solar magnetic field.

Imaging of the heliospheric tail through Energetic Neutral Atoms

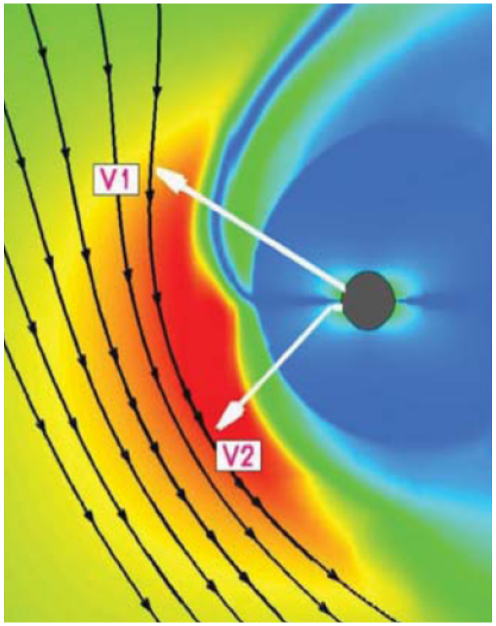


ENA images from IBEX show two lobes with an excess of low energy ENA (<1keV) and a deficit at higher energy (>2keV) around the solar equator.

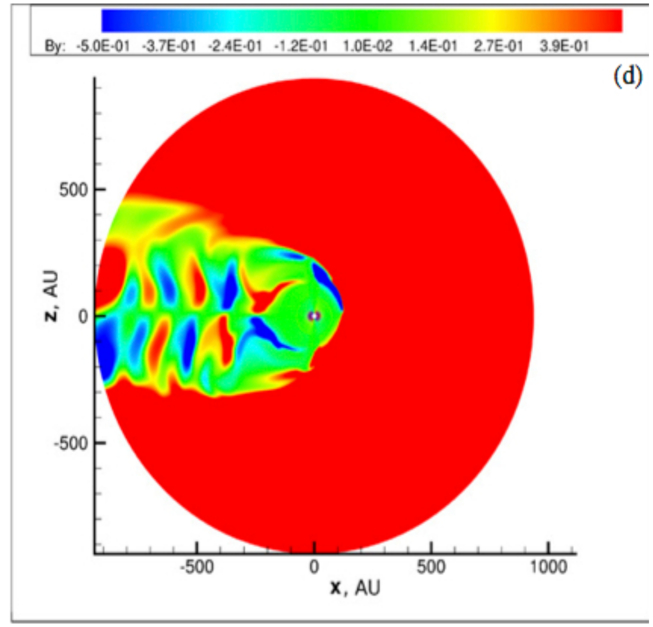


The explanation was that the slow and fast wind could explain this structure: McComas et al. 2013; Schwadron et al. 2014

Global MHD models with Dipole Field (Flipping Orientation across the current sheet)



Opher et al. 2006



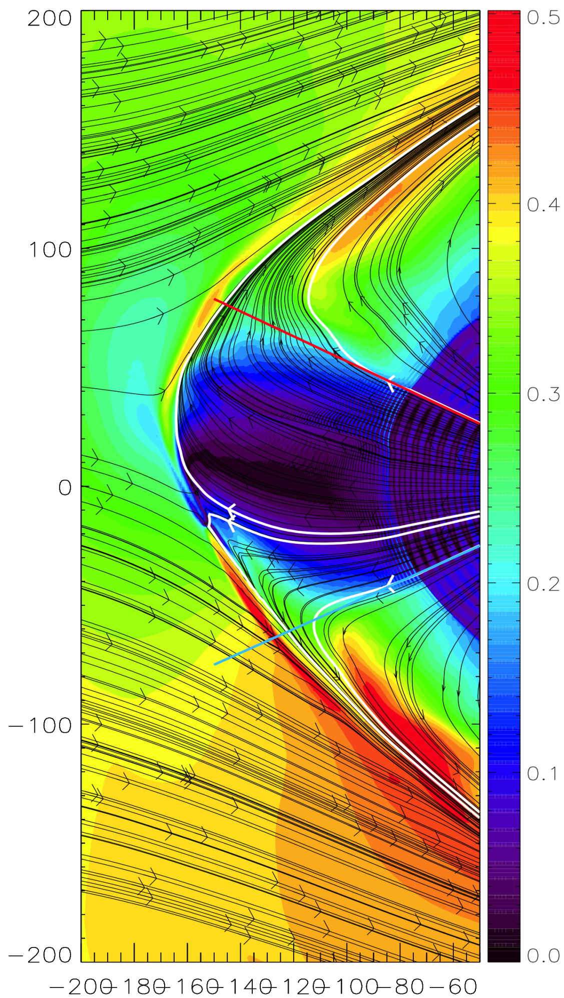
Pogorelov et al. 2009

Artificial erosion of the solar magnetic field

(e.g. Opher et al. 2006; Pogorelov et al. 2007; Opher et al. 2009; Washimi et al. 2011; Pogorelov et al. 2013; Opher & Drake 2013; etc)

Global MHD models with Sector Field

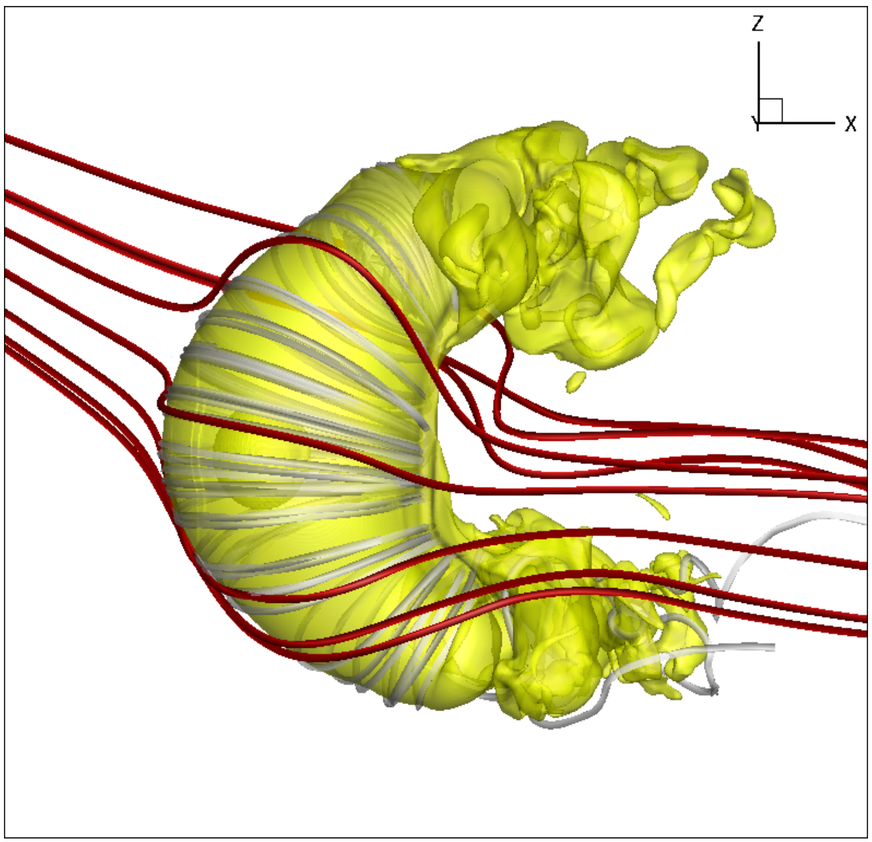
Tilting the Magnetic with Respect to the Rotation Axis



Meridional cut from a 3D MHD simulation (Opher et al. 2011).

Grid-induced reconnection that artificially eroded the solar magnetic field

- We used a technique to minimize the numerical dissipation, using a *monopole* configuration (i.e., the Parker Interplanetary Field without changing sign across the heliospheric current sheet) for the solar magnetic field and suggested a change in our view of the large-scale structure of the heliosphere.



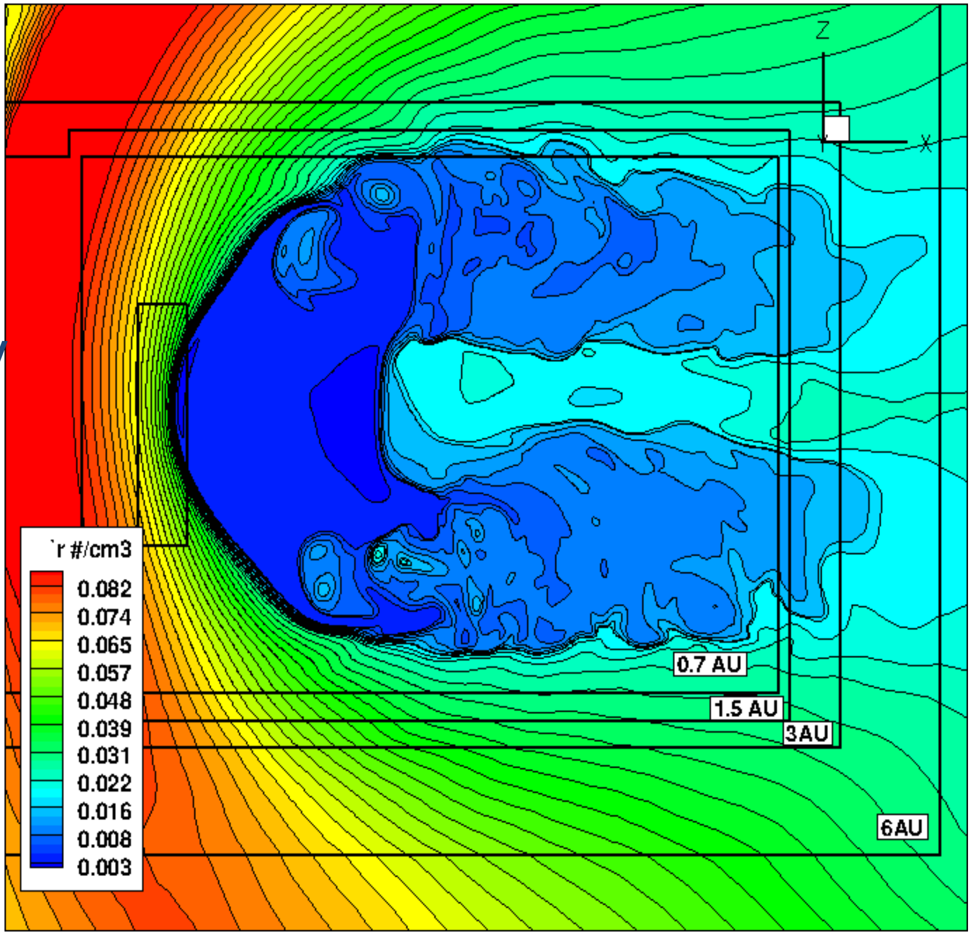
$$B = B_0 \left(\frac{R_0}{r}\right)^2 e_r - B_0 \left(\frac{R_0^2}{r}\right) \frac{\Omega \sin \Theta}{v_{SW}} e_\phi,$$

Simulations with Highly Resolved Grid at the Tail

Inner boundary conditions (at 30AU):
Uniform solar wind: 400km/s

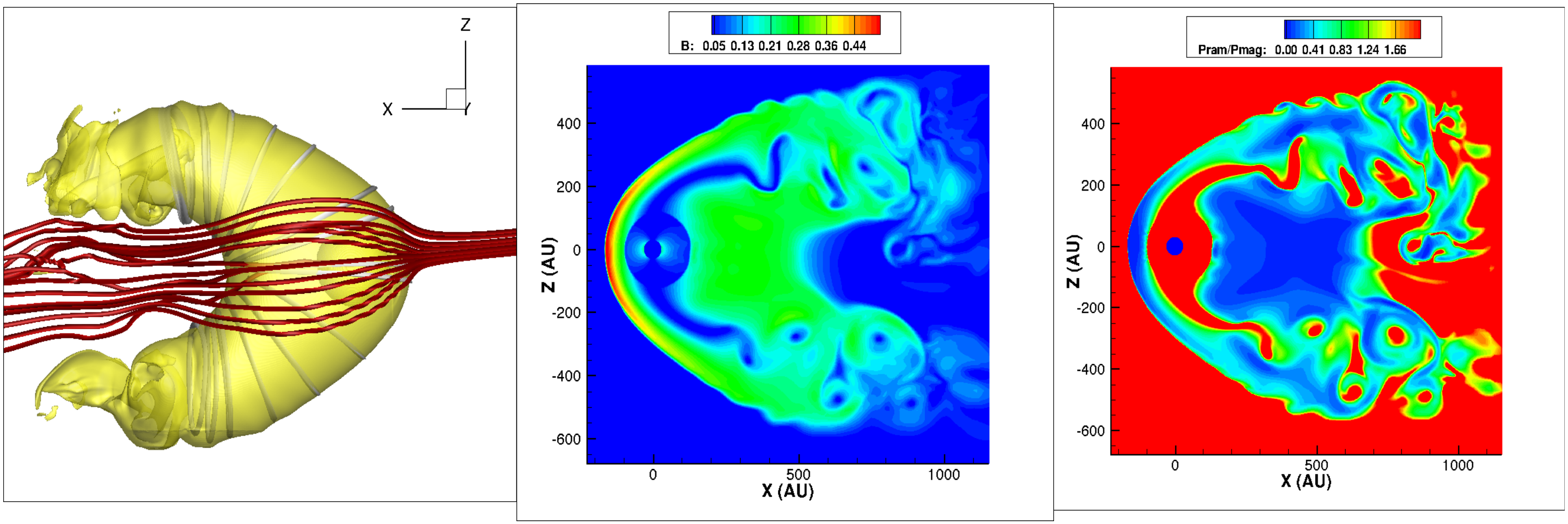
Monopole B_{SW}
parker spiral with same polarity in the north as the southern hemisphere

Outer boundary conditions:
B_{ISM} = 4.4 μG; motion Through the ISM of 25 km/s (also without B_{ISM})



3D MHD Multifluid (Opher et al. 2009)
(ionized + neutral H atoms)

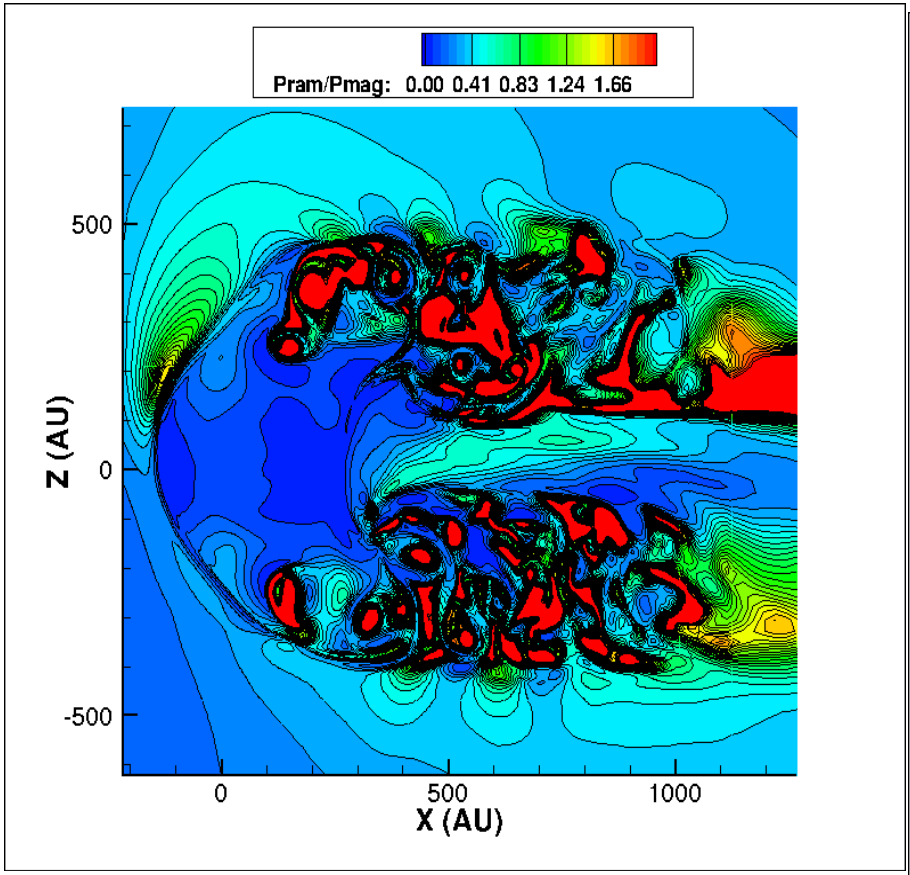
Grid with ~ 0.7AU extending to 1000AU down the tail

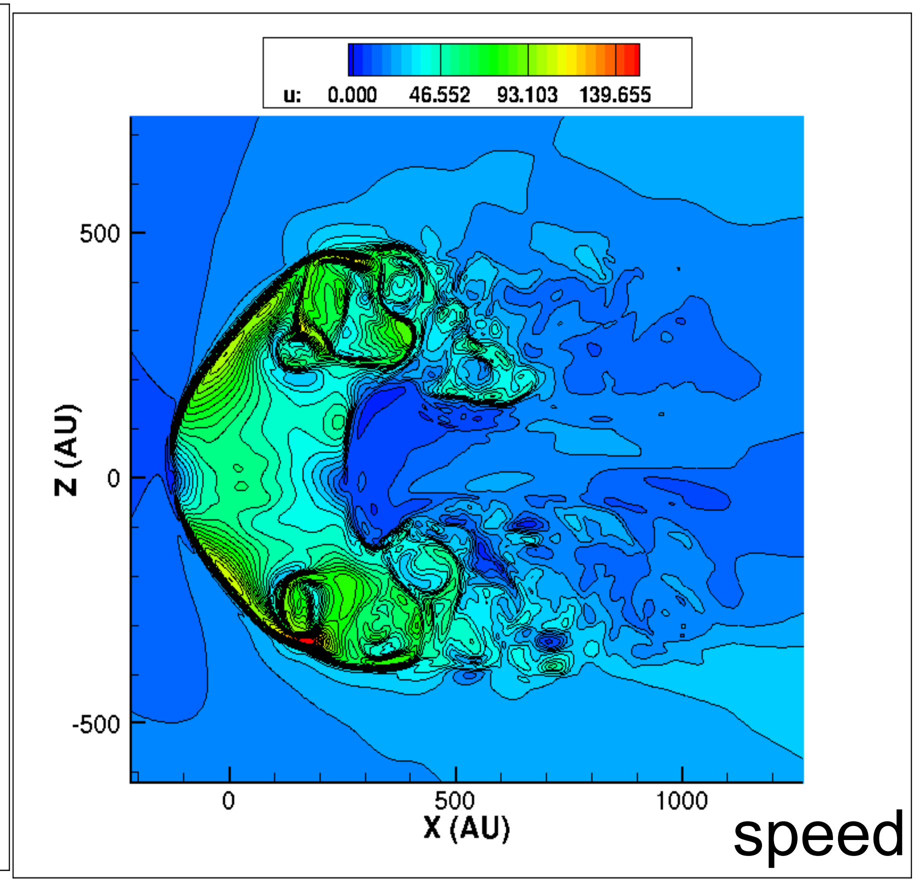


CASE with no BISM

Upstream the Termination Shock, in the supersonic regime $P_{ram}/P_B > 1$ with P_{ram} the local flow kinetic energy

But in the subsonic regime, in the heliosheath $P_{ram}/P_B < 1$



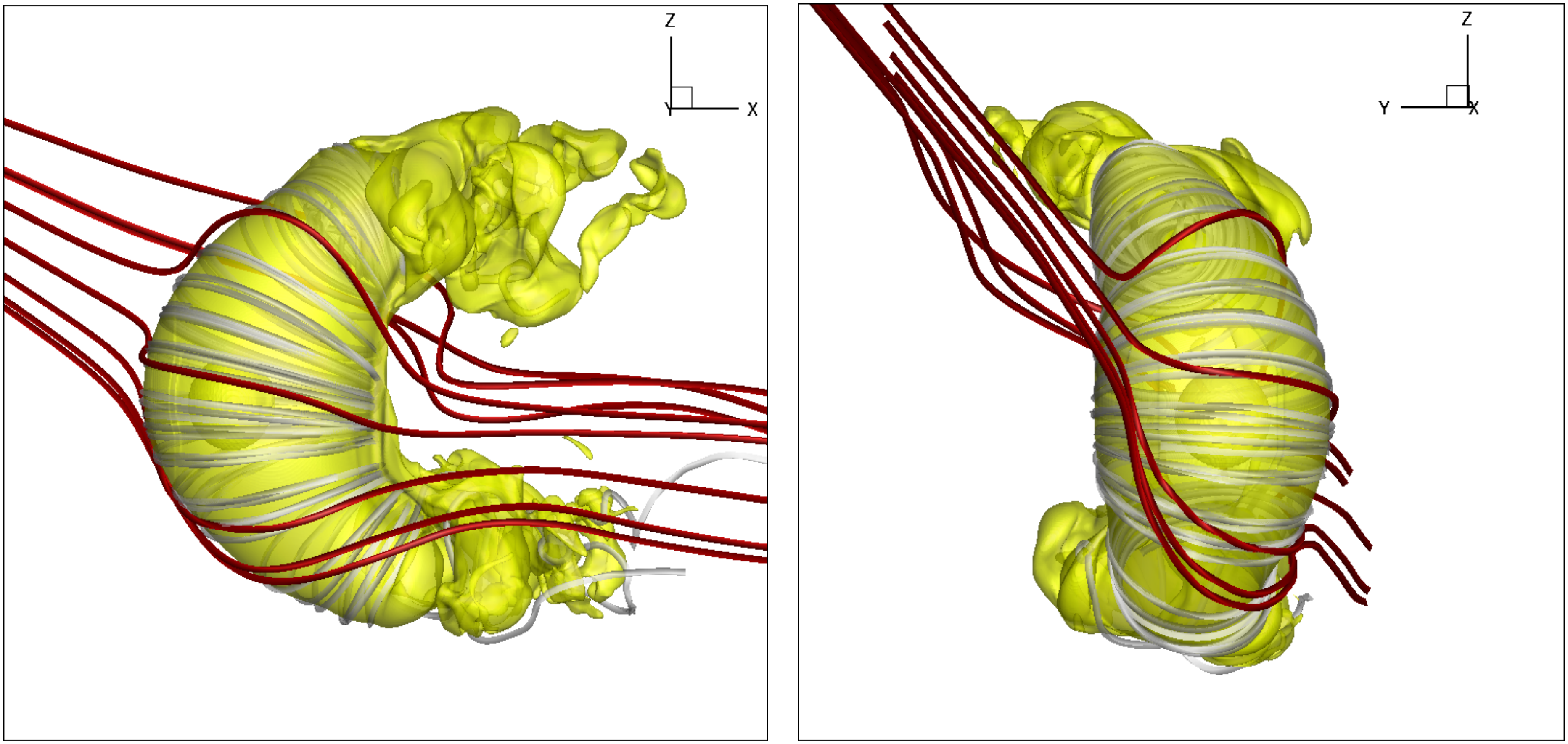


CASE with BISM

In the subsonic regime, in the heliosheath, $P_{ram}/P_B < 1$ and the solar magnetic field has sufficient tension to collimate the down-tail flow and funnel it.

Cut at y=150AU

Two solar-jets



Opher et al. ApJL 2015

Lobes present as well; organized by the solar magnetic field

Resistance of the solar magnetic field to being stretched

The tension on a field line with a radius of curvature *R* is

so .

$$F_{tension} = \left|B \cdot \nabla B\right| / 4\pi \approx \left(B^2 / 8\pi\right)\left(2 / R\right) \qquad F_{tension} \approx 2P_B / R$$

The force stretching the magnetic field due to the flows is

$$F_{streatching} \approx \rho\left|\mathrm{v} \cdot \nabla \mathrm{v}\right| / 2 \approx \rho \mathrm{v}^2 \kappa_V \big/ 2 \approx \rho \mathrm{v}^2 \big/ 2R \approx P_{ram} \big/ R$$

so the ratio between the two forces is

$$F_{streatching} \big/ F_{tension} \approx P_{ram} \big/ 2P_B$$

Resistance of the solar magnetic field to being stretched

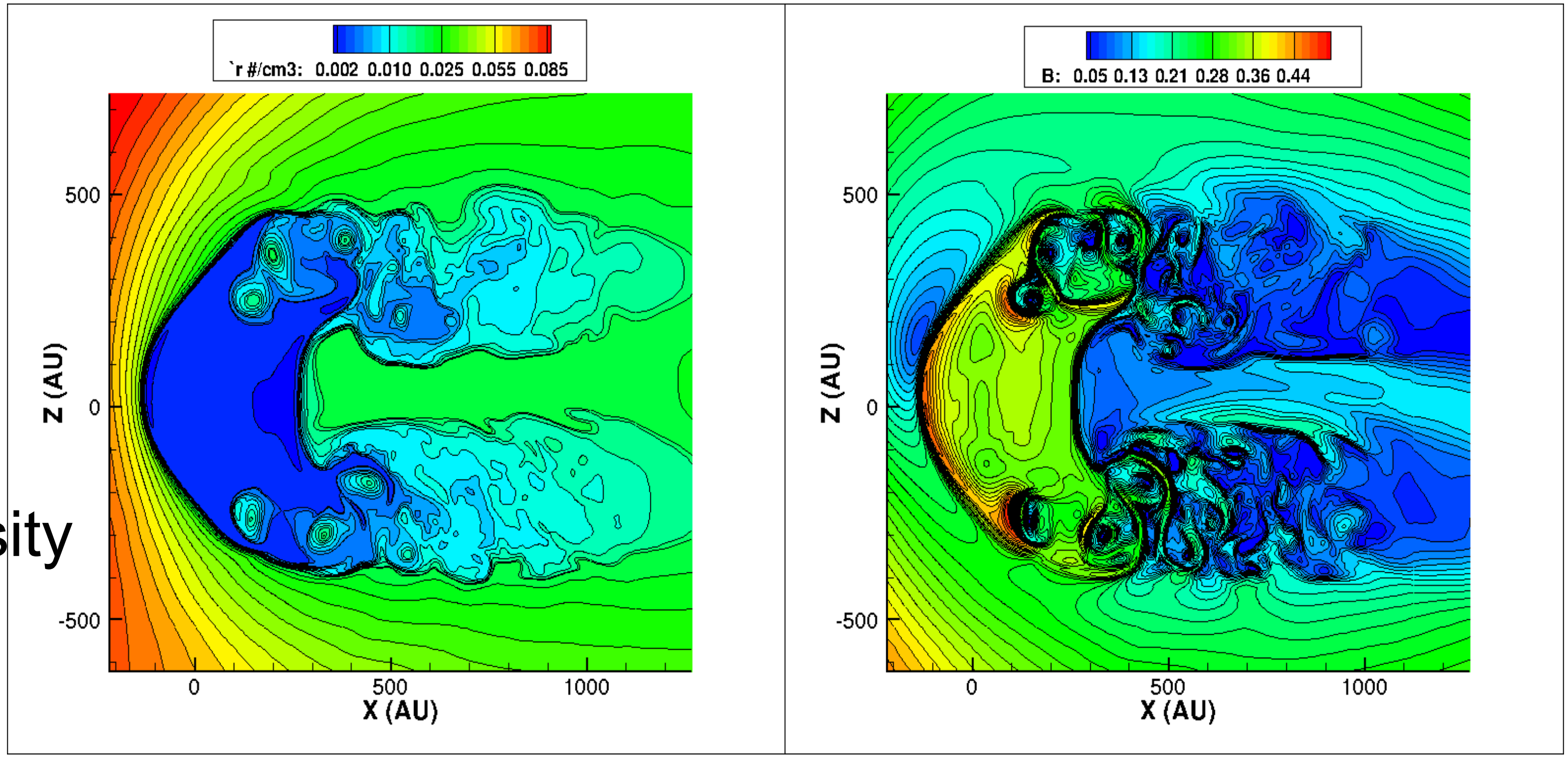
The ratio between the two forces is

$$\frac{F_{streatch}}{F_B} = \left(\frac{\rho(\#/cm^3)}{10^{-3}}\right)\left(\frac{u(km/s)}{50}\right)^2\left(\frac{0.1}{B(nT)}\right)^2 0.175$$

Taking nominal values u = 50km/s; ρ ~ 0.001#/cm^3

For B > 0.04nT $\qquad F_B > F_{streatch}$

Turbulent Lobes



Density

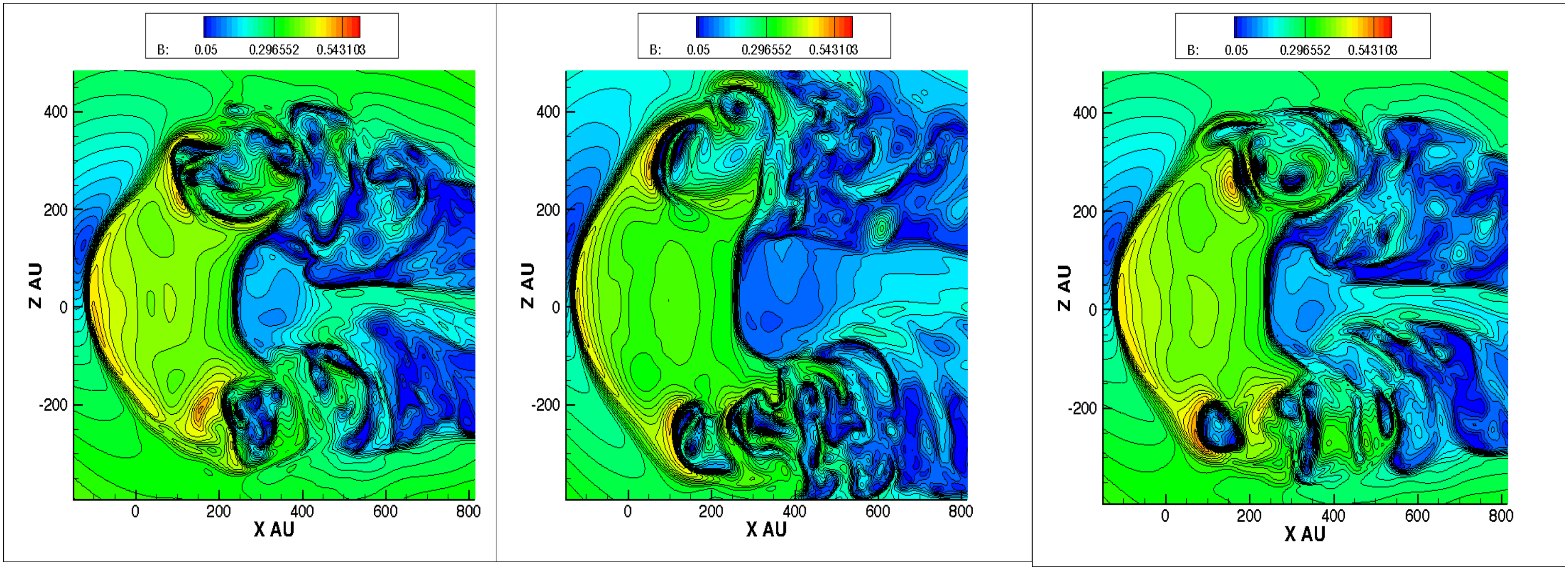
B

In this case the distance to the heliopause down the tail between the two lobes is much closer to the Sun (250AU as opposed to 560AU in the case with no B_{ISM}).

The lobes are more eroded as well as a result of instabilities and reconnection in the flanks

Cut at y=150AU

Turbulent Lobes

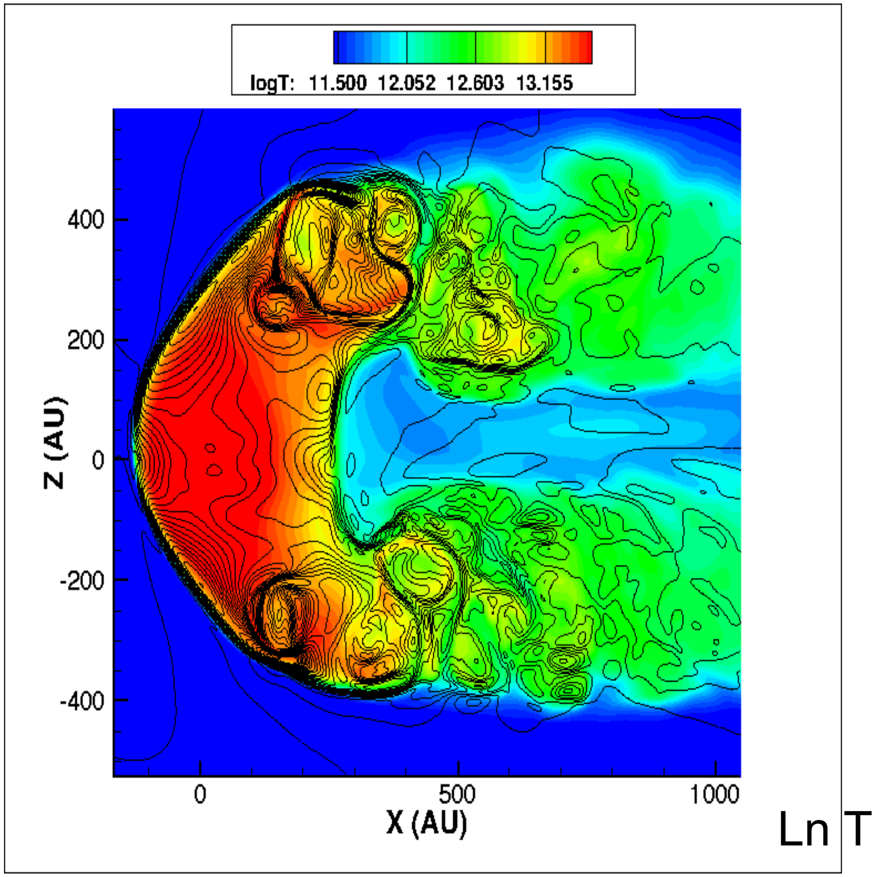


375 years | 404 years | 546 years

Absence of instabilities in astrophysical jets: high expansion rate of astrophysical jets leads to a causal disconnection of the opposite sides of the jet (Porth & Komissarov (2014)

In the subsonic flow regime the jets are causally connected at their largest spatial scales.

Implication for Particle Acceleration



The presence of turbulent lobes has significant implications for reconnection and particle acceleration and might even generate shocks

- Could be a site for Anomalous Cosmic Rays?

An analytic model of the outer heliosphere

- Construct an analytic model of the outer heliosphere with the termination shock as the inner boundary condition and the LISM as the outer boundary condition
- Axi-symmetric solution – V_{LISM} and B_{LISM} zero
- Goals
  - What is the radius of the HP and what controls it?
  - What drives the jets to the North and South?
  - What is the structure of B, n, P and **V**?
  - Why does the weak magnetic field in the HS control the global structure of the heliosphere?

Drake, Swisdak, Opher ApJL 2015

Basic MHD equations

- Axi-symmetric system with no V_{LISM} and no B_{ISM}
- Pressure of ISM: PLISM
- Steady state
- Continuity $\vec{\nabla} \bullet n\vec{V} = 0$ $\qquad \vec{V} = \frac{1}{n}\vec{\nabla}\varphi \times \vec{\nabla}\psi$
  - Where ψ is the stream function
- Pressure $\qquad \frac{P}{n^{\Gamma}} = f(\psi)$
- Magnetic field

$$\vec{\nabla} \times (\vec{V} \times \vec{B}) = 0 \qquad \frac{B}{nr} = g(\psi)$$

- Boundary Conditions at the TS – spherical TS at radius R_0
  - $P = P_0$, $n = n_0$, $B = B_0 \sin(\theta)$ where $\theta = 0$ along the axis and $\pi/2$ at the equator, uniform radial flow V_0

Basic MHD equations

- Axi-symmetric system with no V_{LISM} and no B_{ISM}
- Pressure of ISM: PLISM
- Steady state

$$\nabla \cdot n\mathbf{V} = 0,$$

$$\nabla \cdot P^{1/\Gamma}\mathbf{V} = 0,$$

$$M\nabla \cdot n\mathbf{V}\mathbf{V} = -\nabla\left(P + \frac{B^2}{8\pi}\right) - \frac{B^2}{4\pi r}\nabla r,$$

$$\nabla \times (\mathbf{V} \times \mathbf{B}) = 0,$$

- Boundary Conditions at the TS with a radius R_0
  - $P = P_0$, $n = n_0$, $B = B_0 \sin(\theta)$ where $\theta = 0$ along the axis and $\pi/2$ at the equator, uniform radial flow V_0

Basic MHD equations (cont)

- Boundary Conditions at the TS of radius R_0
  - $P = P_0$, $n = n_0$, $B = B_0 \sin(\theta_0)$ where $\theta_0 = 0$ along the axis and π/2 at the equator, uniform radial flow V_0.. One found that:

$$\frac{P}{n^{\Gamma}} = f(\psi) = \frac{P_0}{n_0^{\Gamma}} \qquad \frac{B}{nr} = g(\psi) = \frac{B_0}{n_0 R_0}$$

  - Where ψ is the stream function
  - Consequence is that P, n and B are linked throughout the HS

$$P = P_0 \left(\frac{BR_0}{B_0 r} \right)^{\Gamma}$$

The Heliosheath: High β limit

- The plasma in the HS has high β so carry out an expansion of the momentum equation in the weak field limit with subsonic flows e.g.

$$P = P^{(0)} + P^{(1)} + \ldots..$$

- To lowest order

$$0 = -\vec{\nabla} P^{(0)}$$

  – So $P^{(0)} = P_0$ is a constant everywhere in the HS

$$P^{(0)} = P_0 = P_0 \left(\frac{BR_0}{B_0 r} \right)^{\Gamma}$$

  – Or

$$B^{(0)} = B_0 \frac{r}{R_0}$$

(Axford 1972; Chevalier & Lou 1994)

The Heliosheath: High β limit

- Expanding in β; with β >>1
- First order – keep inertia and B

$$mn_0 \vec{\nabla} \bullet \vec{V}^{(0)} \vec{V}^{(0)} = -\vec{\nabla} \left(P^{(1)} + \frac{B_0^2 r^2}{8\pi R_0^2} \right) - \frac{B_0^2 r}{4\pi R_0^2} \vec{\nabla} r$$

- Neglect the inertia in the r direction and integrate from the TS outwards

$$P^{(1)}(r) = -\frac{B_0^2}{4\pi R_0^2}(r^2 - R_0^2 \sin^2 \theta_0)$$

$$P(r) = P_0 - \frac{B_0^2}{4\pi R_0^2}(r^2 - R_0^2 \sin^2 \theta_0)$$

Radius of the HP

- From the pressure balance at the HP

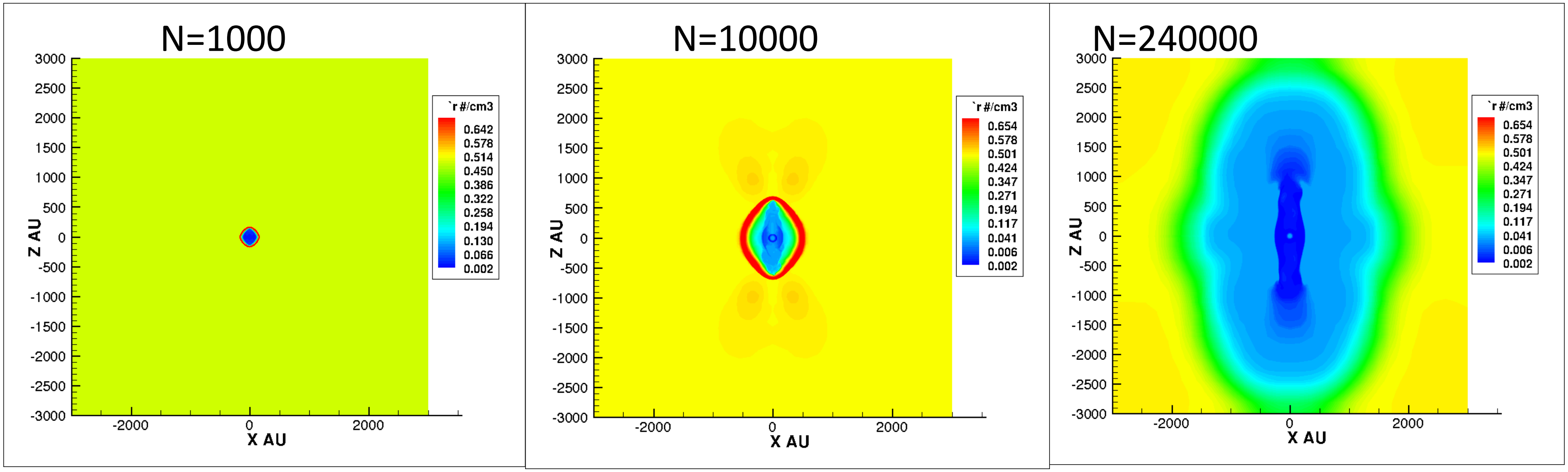
$$P(r_{hp}) + \frac{B_0^2 r_{hp}^2}{8\pi R_0^2} = P_{LISM}$$

- This yields the HP radius r_{hp}

$$\frac{r_{hp}^2}{R_0^2} = \frac{8\pi}{B_0^2}(P_0 - P_{LISM}) + 2\sin^2\theta_0$$

- The requirement that the mass flow into the HS balance that our of the jets constrain P_0-P_{LISM} (Drake et al. 2015)

MHD results (no BISM; no VISM)

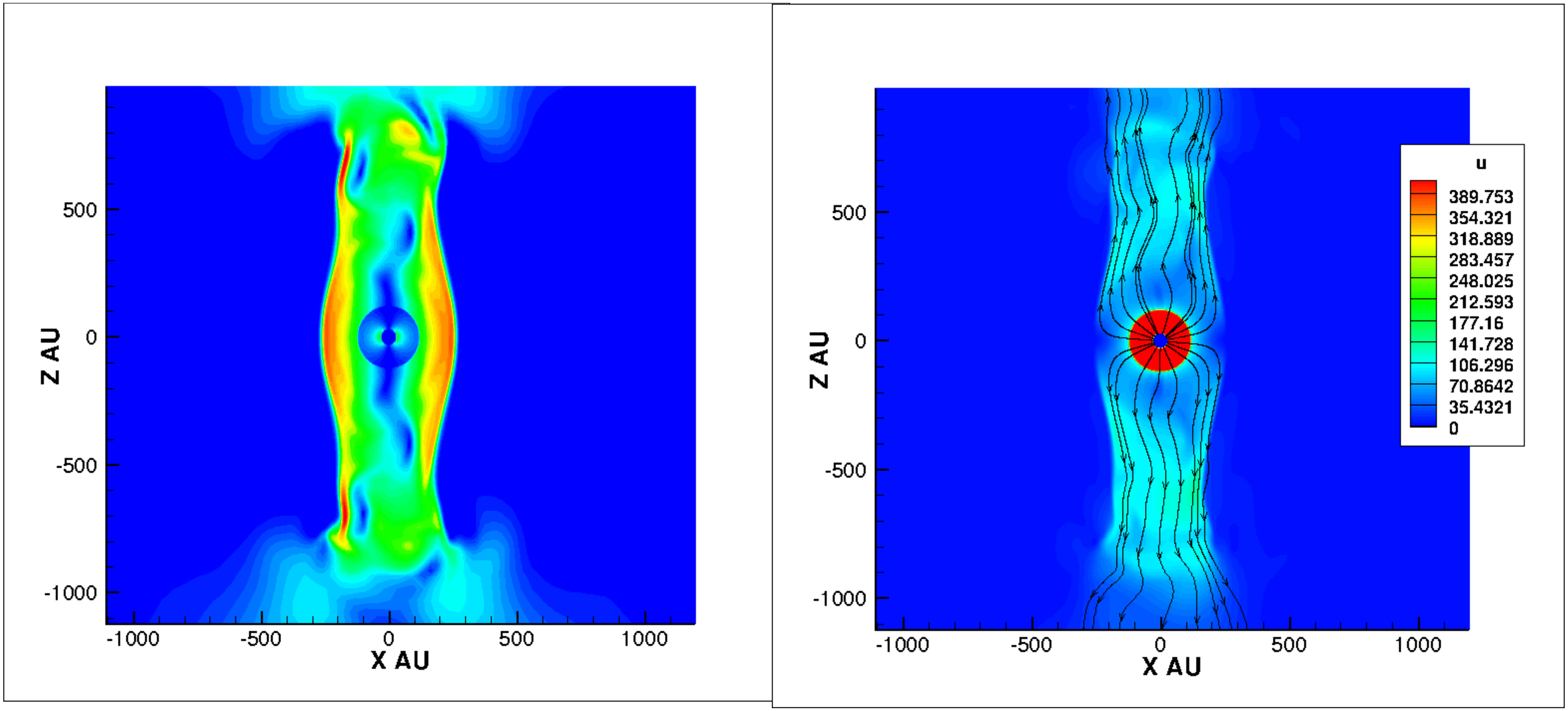


n_{ISM} = 0.4#/cm^3 so p_{ISM}=8.72E-14

Heliosphere as it expands into the ISM collimate the heliosheath (subsonic) flows in two jets

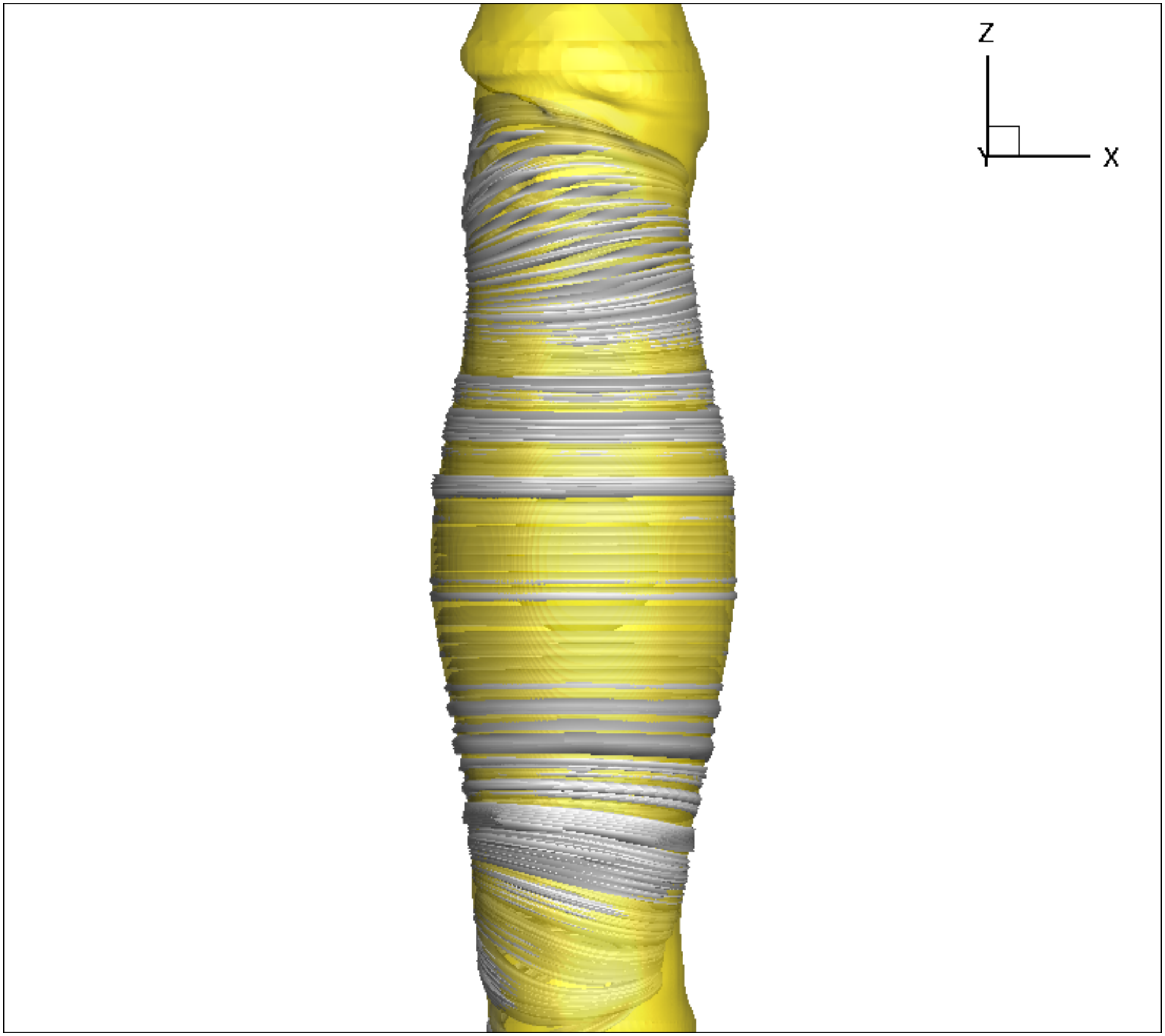
Drake, Swisdak, Opher ApJL 2015

Magnetic field and speed



Drake, Swisdak, Opher ApJL (*2015*)

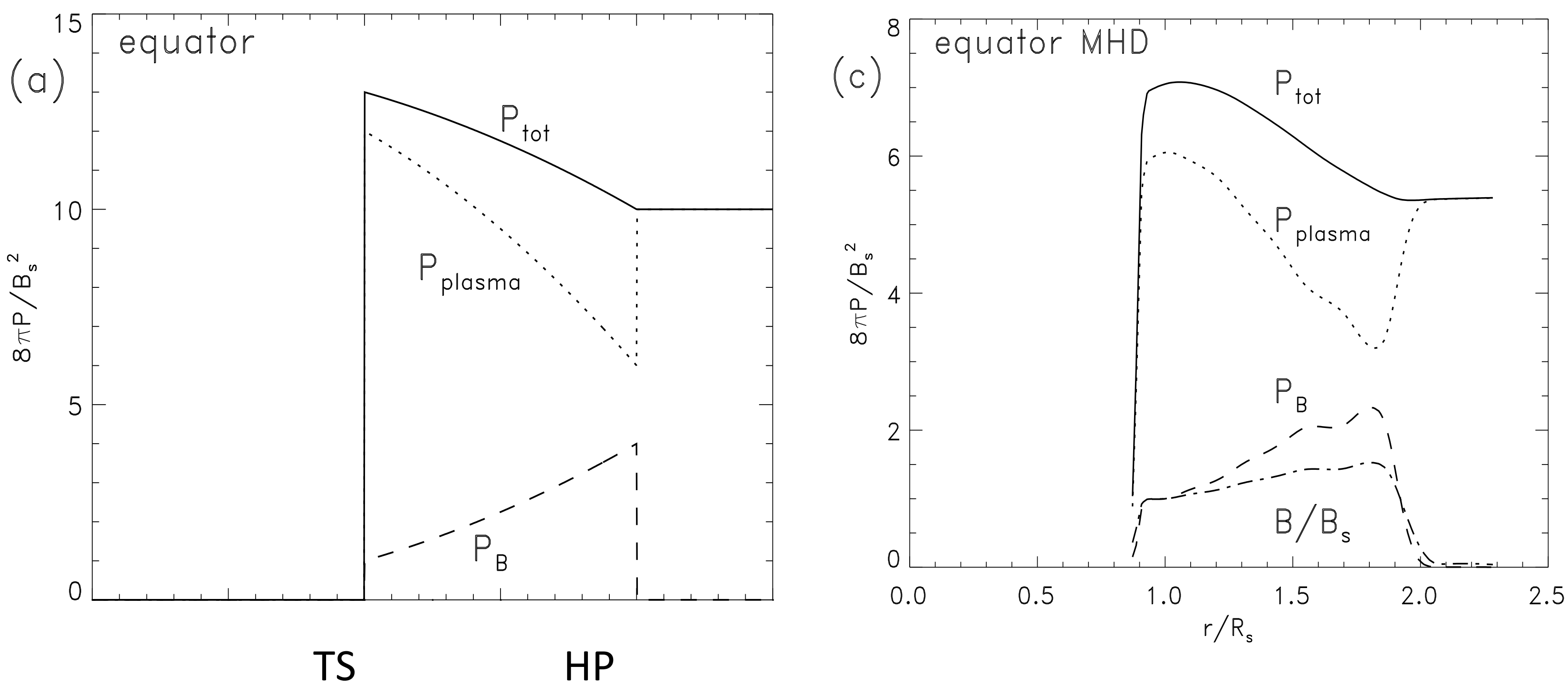
Radial flows gets collimated in the Heliosheath



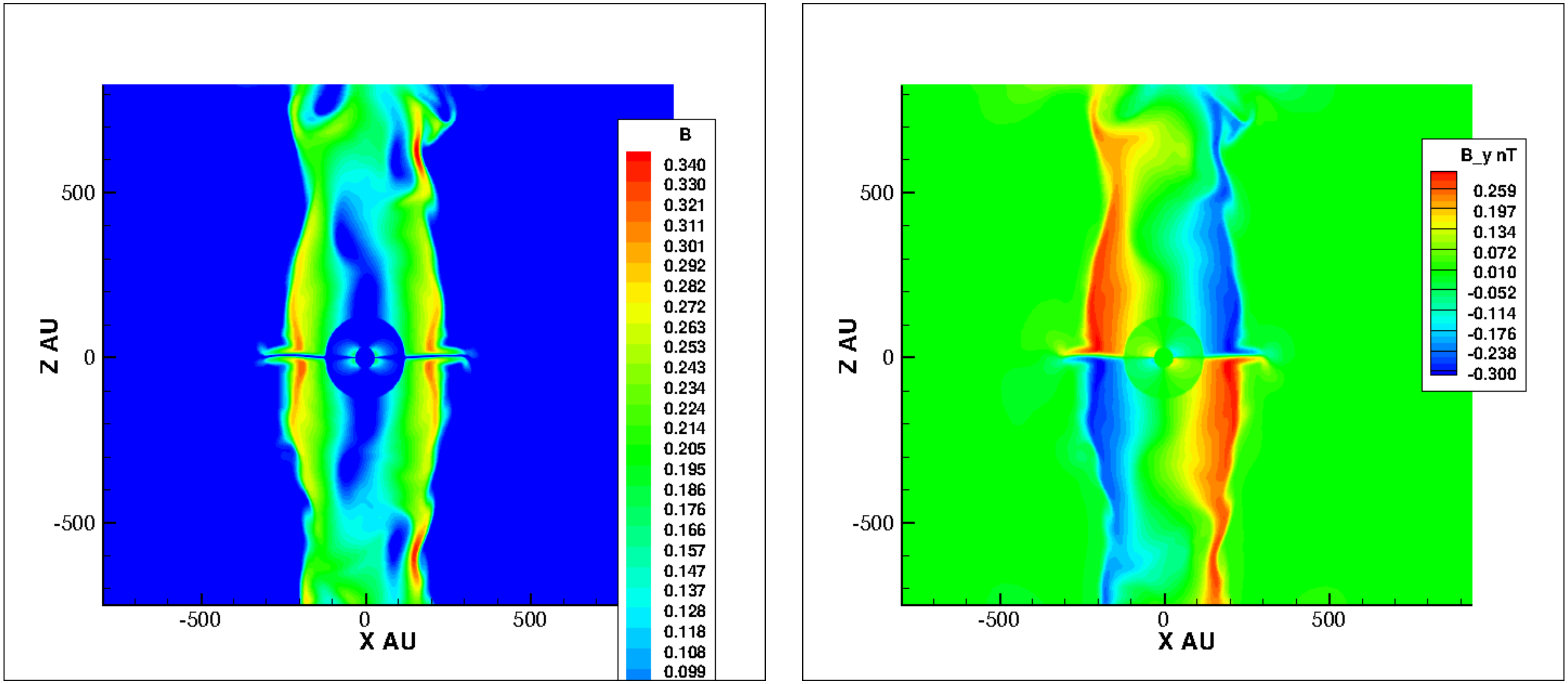
HP yellow
Iso surface
at logT=13.9

Analytic versus MHD solution

- Analytic vs the MHD results;
- Note that P_B remains $\ll P_{plasma}$ throughout the HS

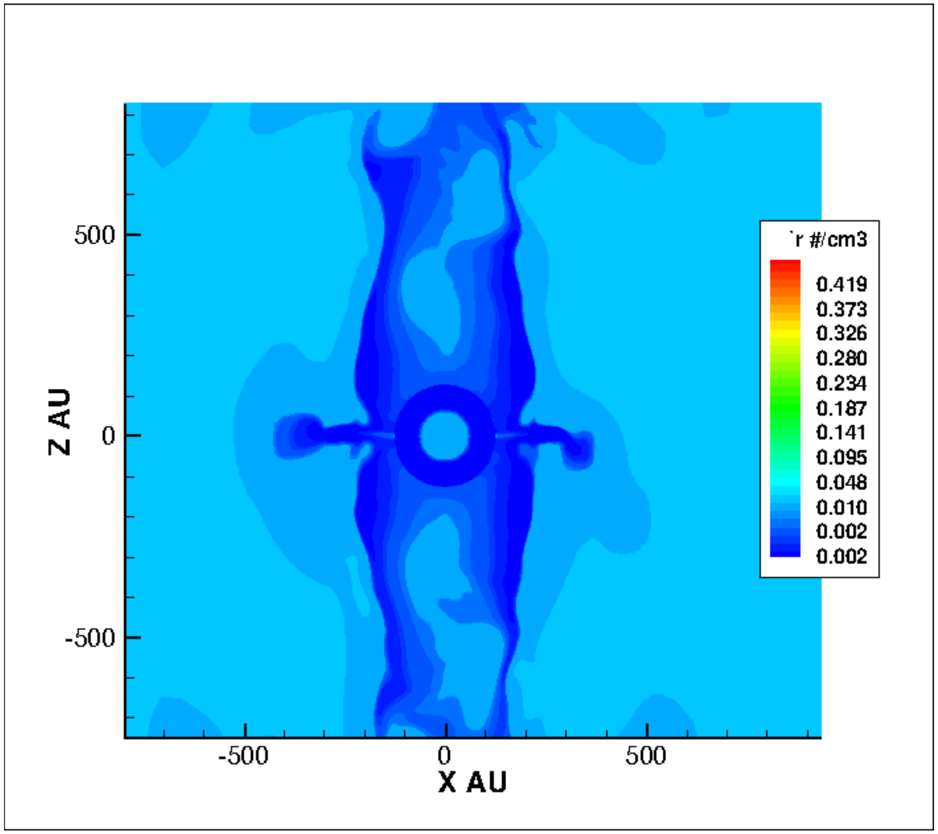


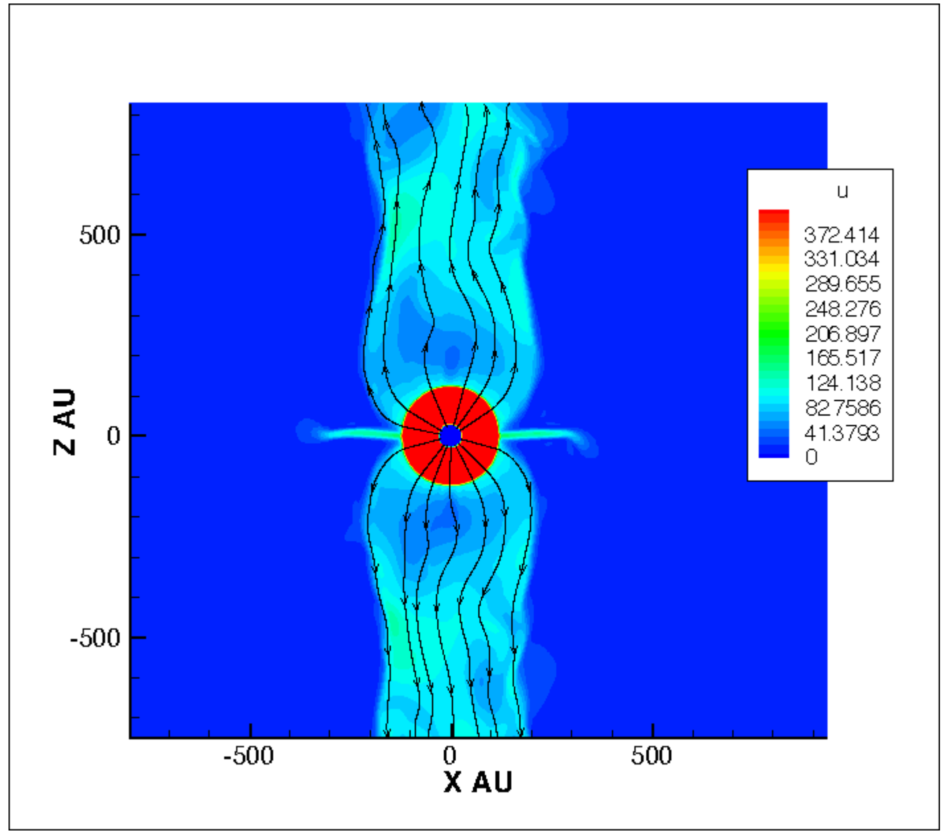
Case with Dipole Magnetic Field

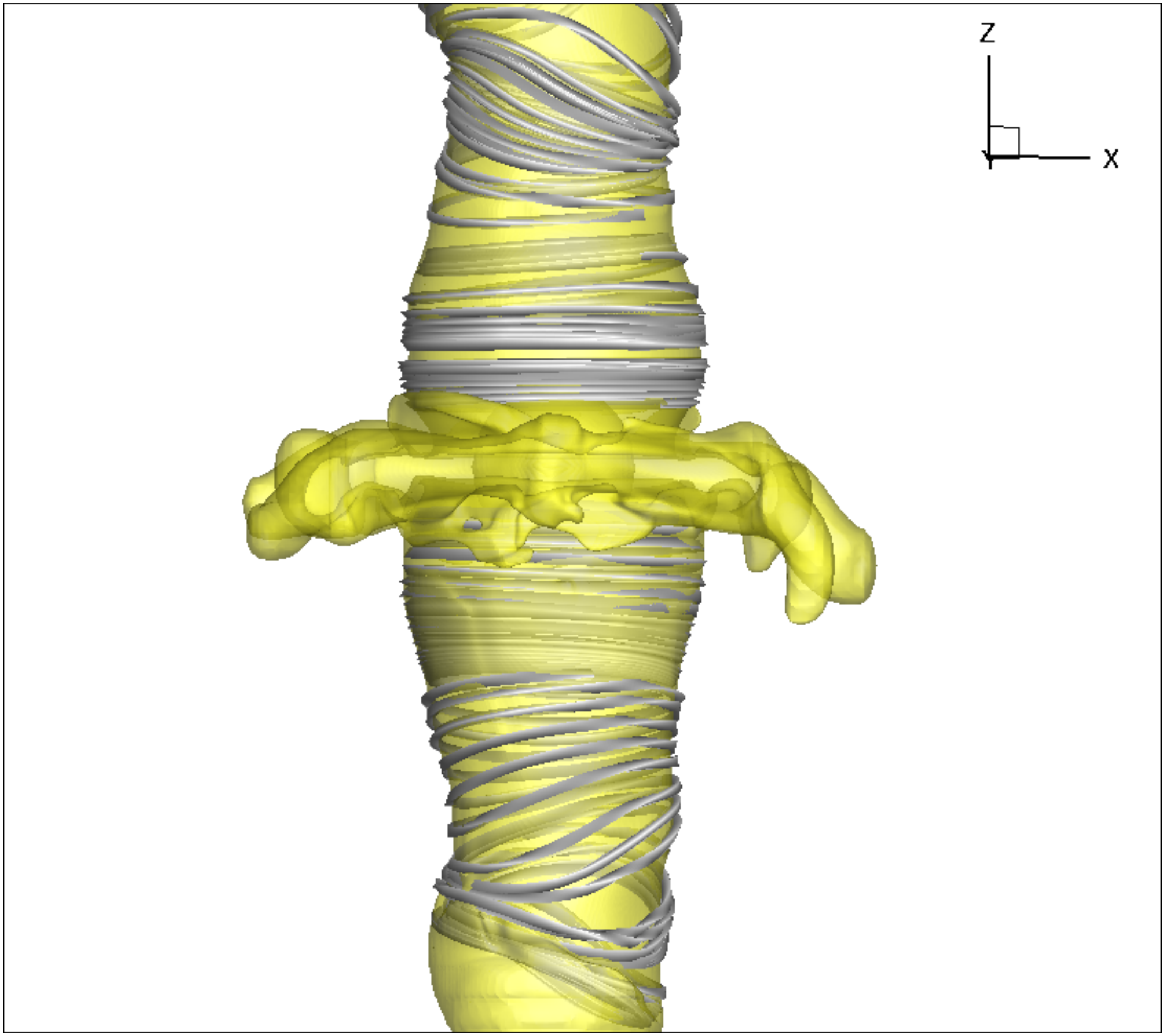


The jets are still present besides in locations where there is artificial dissipation of the magnetic field due to numerical reconnection in the current sheet;

Density and Speed






Z
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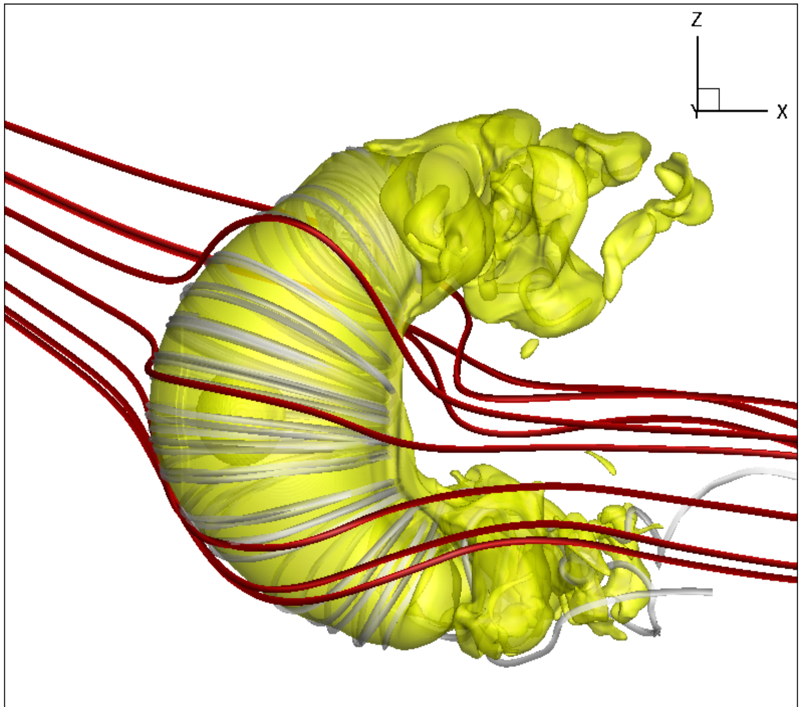
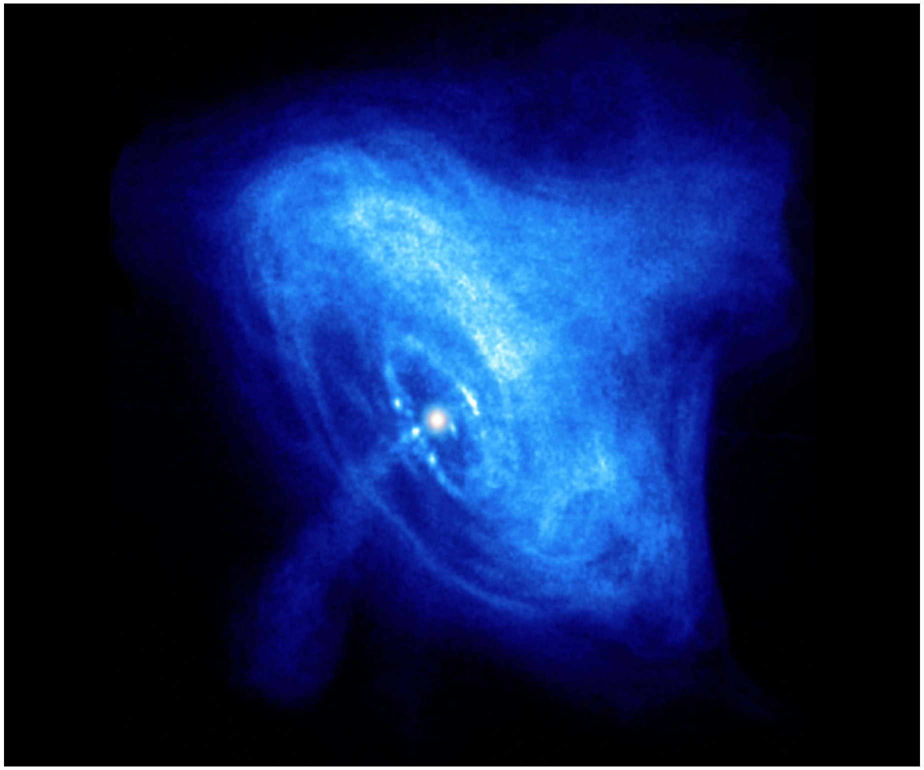
Two-lobe structure heliosphere: similar to astrophysical jets



Opher et al. ApJL 2015



X-Ray image of the Crab Nebula Jets

The jets in the case of the heliosphere are driven downstream of the termination shock similar to what was proposed for the Crab Nebula (Chevalier & Luo 1994; Lyubarsky 2002). In this region of subsonic flow the magnetic tension (hoop) force is strong enough to collimate the wind. The tension force is also the primary driver of the outflow.