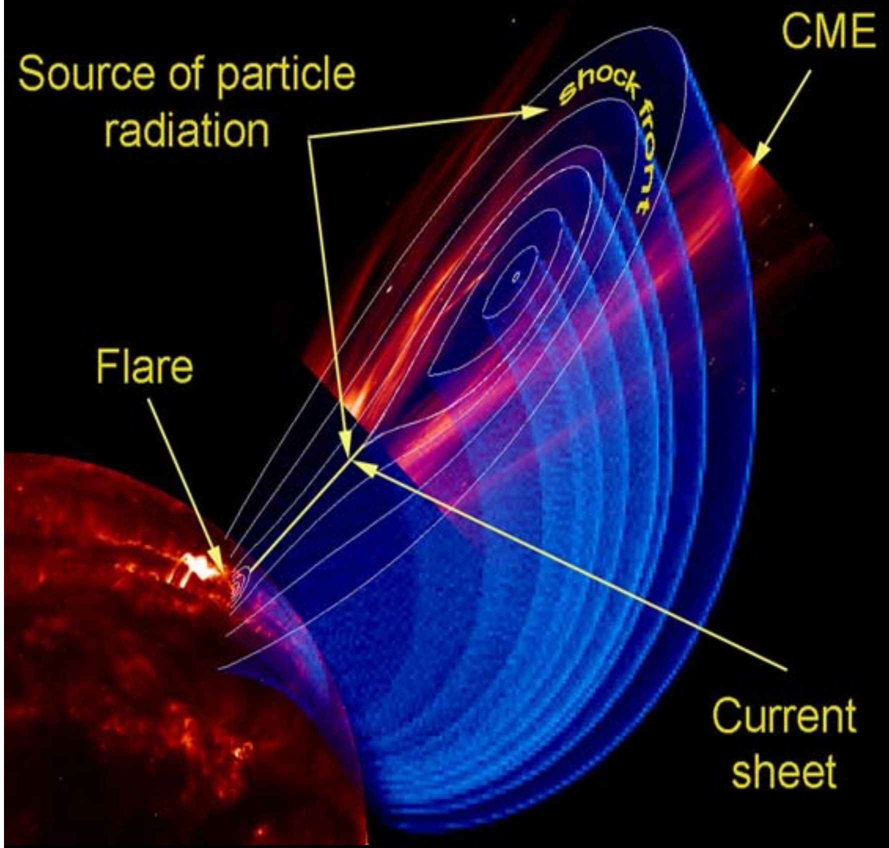
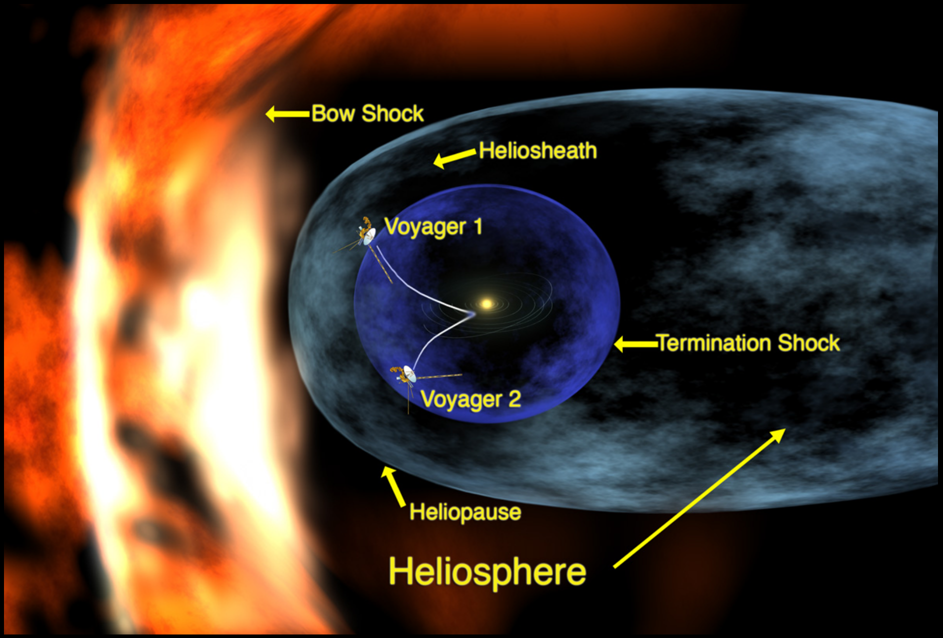
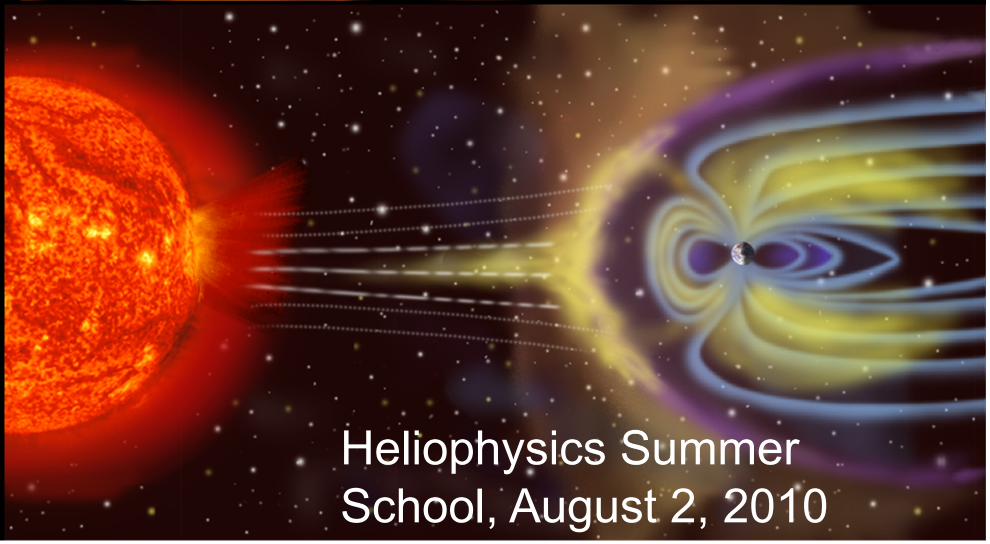
Heliophysics Shocks







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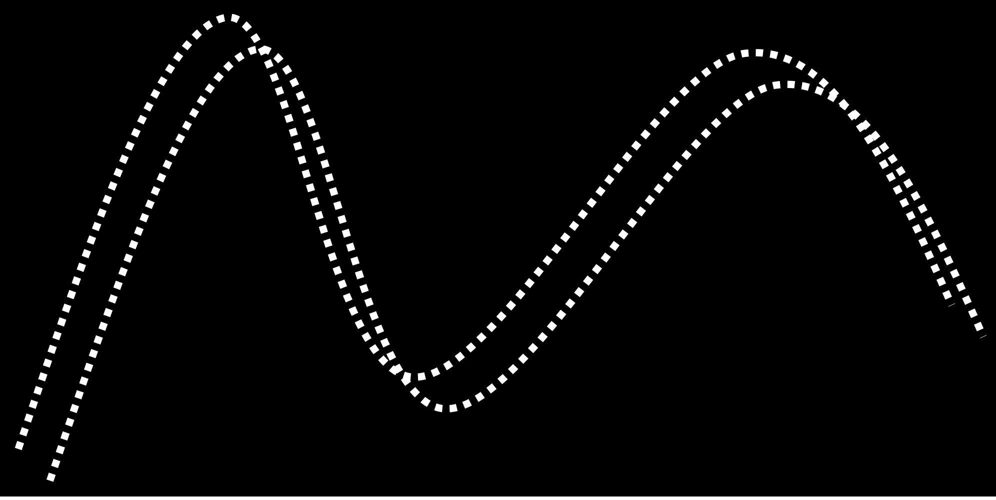
Heliophysics Summer School, August 2, 2010

Outline

1. Why Shocks Happen: Non Linear Steepening
2. MHD jump conditions: Rankine-Hugoniot jump conditions
3. Definition and Classification of Shocks/ Discontinuities
4. Contact and Tangential Discontinuities/ Examples
5. Shocks
6. Observation of Shocks: Termination Shock, CME Shocks, Planetary Shocks
7. Open questions: research being done

1. Why Shocks Happen: Non Linear Steepening

- When gradients of pressure, density and temperature become large than dissipative processes (viscosity, thermal conduction) “steepening” or “wave-steepening” occur.
- The nonlinear convective terms balance the broadening effects of dissipation



Example: propagation of sounds wave in an adiabatic medium

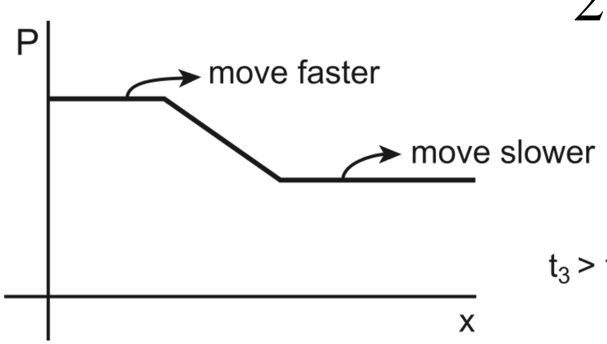
- Propagation of a sound wave is

$$v_S^2 = \frac{dP}{d\rho}$$

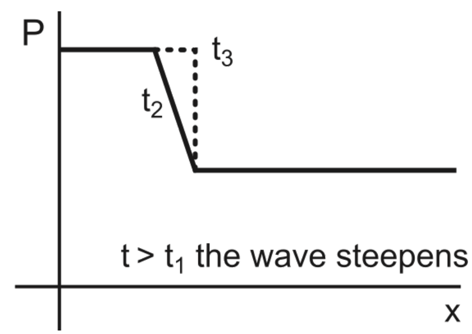
For an adiabatic equation of state:

$$P/\rho^{\gamma} = constant$$

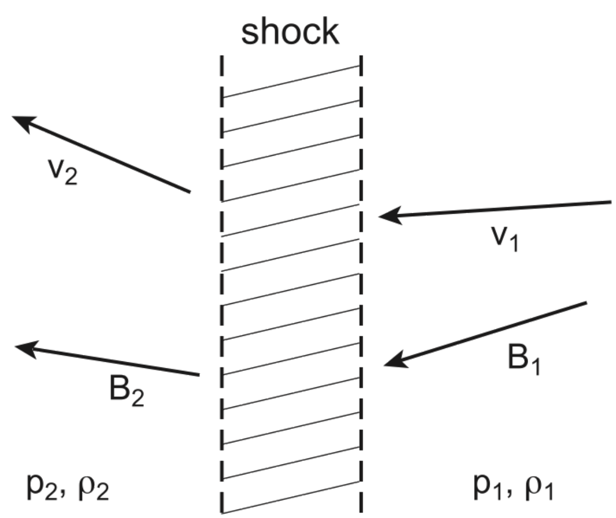
So: $v_S \propto P^{\alpha}$ where $\alpha = \dfrac{\gamma+1}{2\gamma}$



$t_3 > t_2 > t_1$



- A propagating wave solution of the ideal fluid equations leads to *infinite gradients* in a finite *time.* There is no solution for the ideal MHD equations
- The breakdown in ideal equations occurs in a very *thin* region and the fluid equations are valid everywhere else. On in this very thin region is difficult to describe the plasma in details.
- The simple picture: is a discontinuity dividing two roughly uniform fluids



Region 2 (downstream) *Region 1 (upstream)*

The transition must be such as to conserve MASS, Magnetic Flux and Energy

2. Jump Conditions which are independent of the physics of the shock itself: Rankine-Hugoniot Relations

(a) Conservation of Mass: $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \mathbf{0}$$

through regions 1 and 2 gives: $\rho_1 \mathbf{u_1} \cdot \mathbf{n} = \rho_2 \mathbf{u_2} \cdot \mathbf{n}$

that can be written as $\{\rho \mathbf{u} \cdot \mathbf{n}\} = 0$ where the symbol {}

represent differences between the two sides of the discontinuity.

(b) Conservation of Momentum

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla\cdot[\rho\mathbf{u}\mathbf{u} + \left(p + \frac{B^2}{2\mu_0}\right)\mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{\mu_0}] = 0$$

gives

$$\left\{\rho\mathbf{u}(\mathbf{u}\cdot\mathbf{n}) + \left(\mathbf{p} + \frac{\mathbf{B^2}}{\mathbf{2\mu_0}}\mathbf{n} - \frac{\mathbf{B}}{\mu_\mathbf{0}}(\mathbf{B}\cdot\mathbf{n}\right)\right\} = 0\ .$$

(c) Conservation of energy

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho U^2\frac{P}{\gamma-1} + \frac{B^2}{2\mu_0} + \nabla\cdot(\frac{\mathbf{1}}{\mathbf{2}}\rho\mathbf{U^2}\mathbf{u} + \frac{\gamma\mathbf{P}}{\gamma-\mathbf{1}}\mathbf{u} + \frac{\mathbf{1}}{\mu_\mathbf{0}}\mathbf{E}\times\mathbf{B}\right) = 0$$

gives

$$\left\{\left(\frac{1}{2}\rho U^2 + \frac{\gamma P}{\gamma-1}\right)(\mathbf{u}\cdot\mathbf{n}) + \frac{\mathbf{1}}{\mu_\mathbf{0}}(\mathbf{E}\times\mathbf{B})\cdot\mathbf{n}\right\} = 0$$

(d) The Magnetic flux conservation

$$\nabla \cdot \mathbf{B} = 0$$

gives $\{\mathbf{B} \cdot \mathbf{n}\} = \mathbf{0}$ and $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}}$

gives $\{\mathbf{E} \times \mathbf{n}\} = \mathbf{0}$

Let us consider the normal *n* and tangential *t* component relative to the discontinuity surface
so the JUMP conditions can be written as:

(a) $\{\rho_m U \cdot \hat{n}\} = 0 \Rightarrow \{\rho_m U_n\} = 0$ *

(b) $\left\{\rho_m U (U \cdot \hat{n}) + \left(p + \frac{B^2}{2\mu_0}\right)\hat{n} - \frac{\vec{B}}{\mu_0}(\vec{B} \cdot \hat{n})\right\} = 0$

$\Rightarrow \left\{\rho_m U_n^2 + p + \frac{B_t^2}{2\mu_0}\right\} = 0$ *

$\Rightarrow \left\{\rho_m \vec{U}_t U_n - \frac{\vec{B}_t}{\mu_0} B_n\right\} = 0$ *

$\vec{E} = -\vec{U} \times \vec{B}$

(c) $\left\{\left(\frac{1}{2}\rho_m U^2 + h\right)(\vec{U} \cdot \hat{n}) + \frac{1}{\mu_0}(\vec{E} \times \vec{B}) \cdot \hat{n}\right\} = 0$

$\left\{\left(\frac{1}{2}\rho_m U^2 + h + \frac{B^2}{\mu_0}\right) U_n - (\vec{U} \cdot \vec{B})\frac{B_n}{\mu_0}\right\} = 0$ *

(d) $\{B_n\} = 0$ *

(e) $\{\vec{U}_n \times \vec{B}_t + \vec{U}_t \times \vec{B}_n\} = 0$ *

$h = \frac{\gamma p}{\gamma - 1}$

The equations (*) are called the Rankine-Hugoniot jump conditions

3. Definition and Classification of Shocks/Discontinuities

	$U_n = 0$	$U_n \neq 0$
$\{\rho\} = 0$	trivial	rotational discontinuity
$\{\rho\} \neq 0$	contact discont.	shock wave

4.Contact Discontinuity

- Happens where there is no flow across the discontinuity, i.e, U_n=0 and {ρ}≠0

E.g. classic contact discontinuity

Vinegar
Olive oil

(a) If Bn≠0 contact discontinuity -> only the density changes across the discontinuity (rarely observed In plasmas)

Tangential Discontinuity

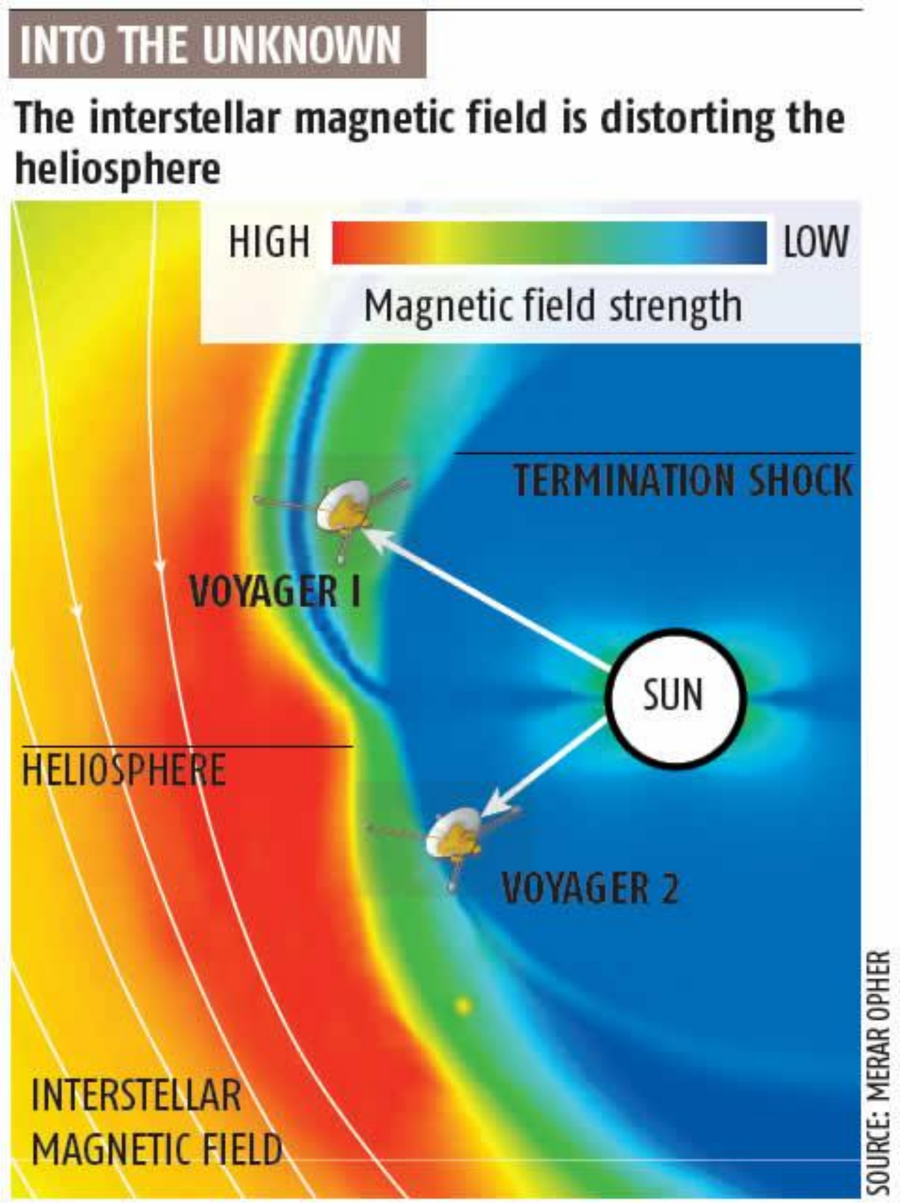
(b) When $B_n=0$ => $\{U_T\} \neq 0$

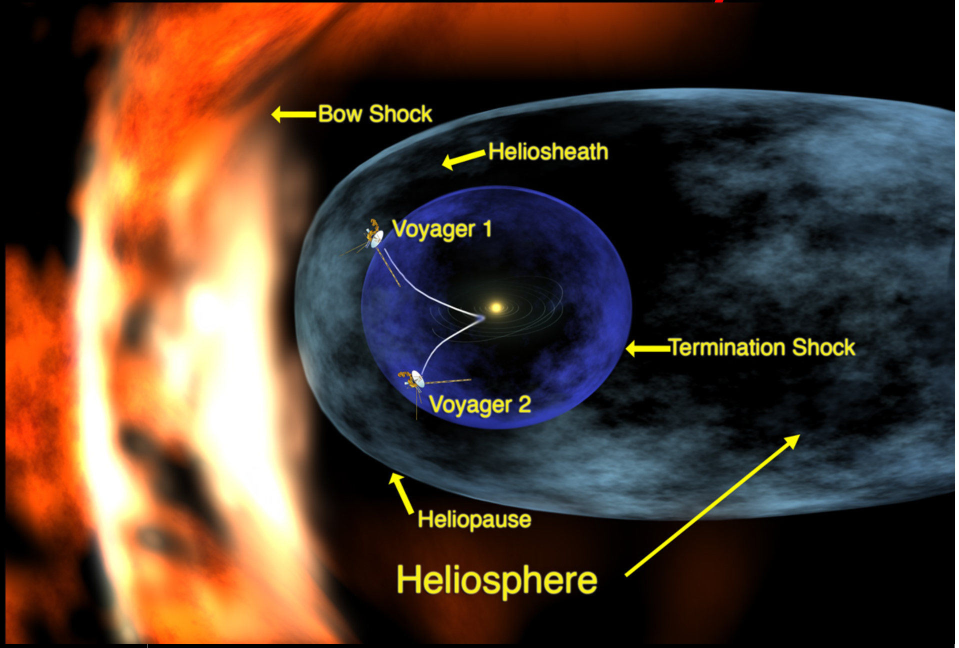
$\{B_T\} \neq 0$

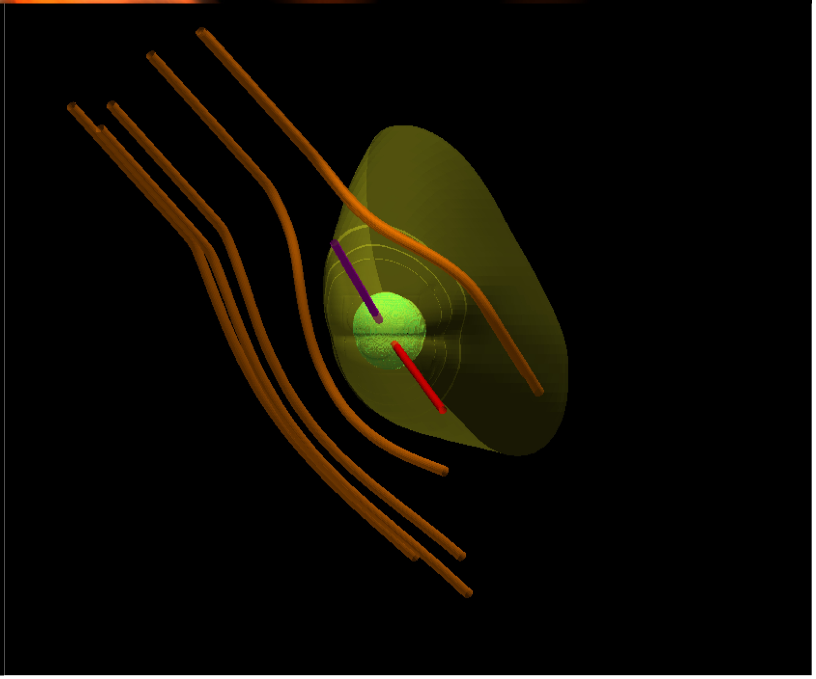
and $\{p+B^2/2\mu_0\}=0$

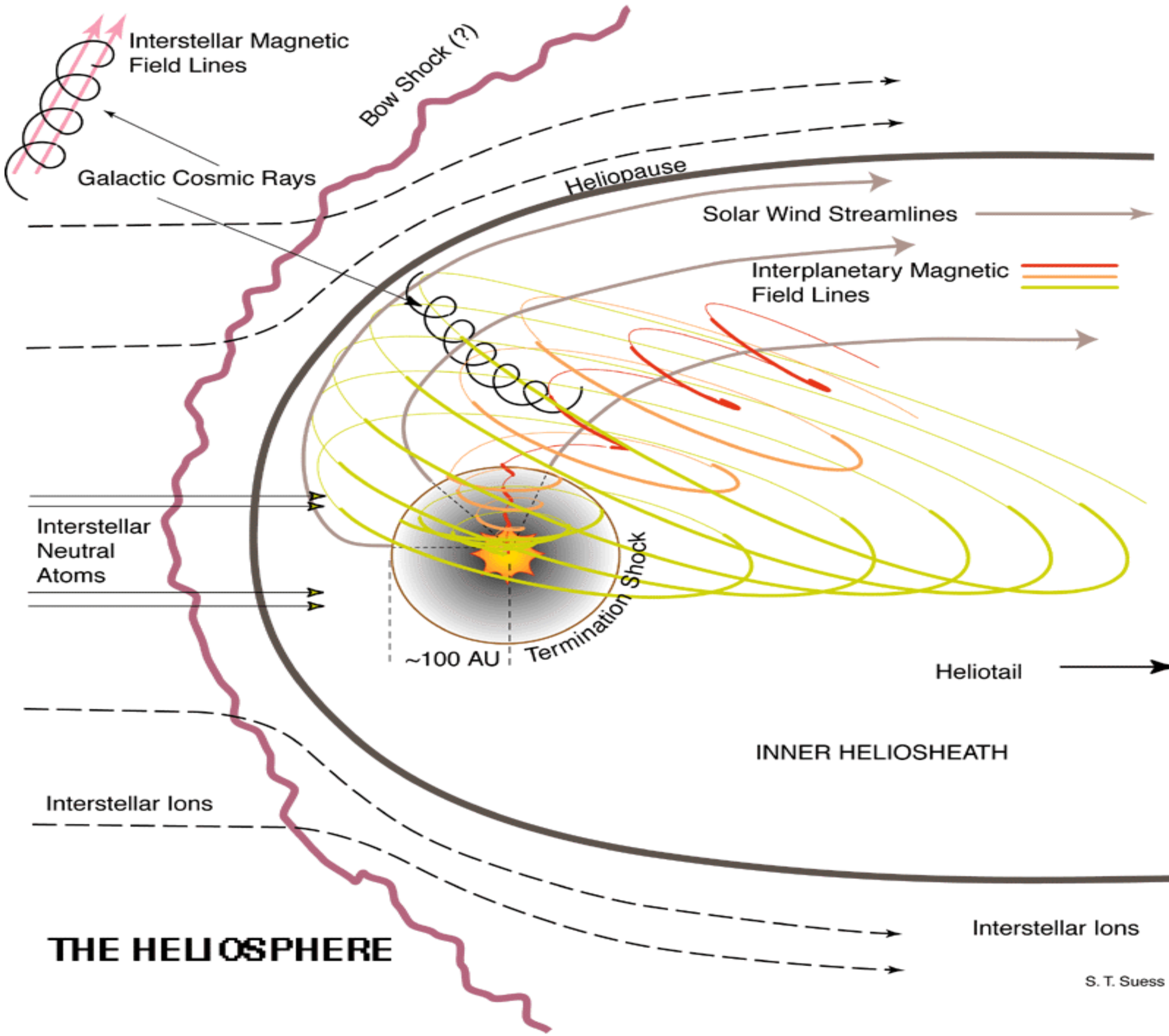
The fluid velocity and magnetic field are parallel to the surface of the discontinuity but change in magnitude and direction. The sum of thermal and magnetic pressure is constant also.

Heliopause: Tangential Discontinuity



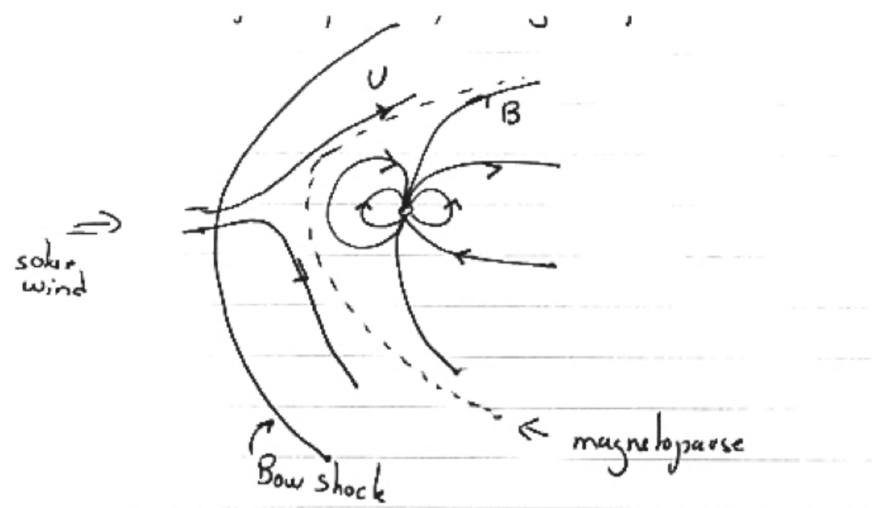






Credit: S. Suess

Planetary Magnetosphere: Tangential Discontinuity



If there is no much reconnection so Un ~ 0; B_n ~0 so solar wind plasma and magnetic field do not penetrate into the magnetosphere

Rotational Discontinuity: Un≠0 and {ρ}=0

From jump conditions $(a) \Rightarrow \{U_n\} = 0$, $V_1 \cdot \hat{n} = V_2 \cdot \hat{n} = V_n$, $\rho_1 = \rho_2$ and $\{p + \frac{B_T^2}{2}\} = 0$

..some math…we get that if $U_n^2 = \frac{B_n^2}{\mu_0 \rho_m}$

B_t remain *constant* in magnitude but rotates
in the plane of the discontinuity.

Example: if the *reconnection rate* between the solar wind
Magnetic field and the planetary magnetic field is substantial; then
The plasma can penetrate significantly into the magnetosphere:
The magnetopause becomes a rotational discontinuity

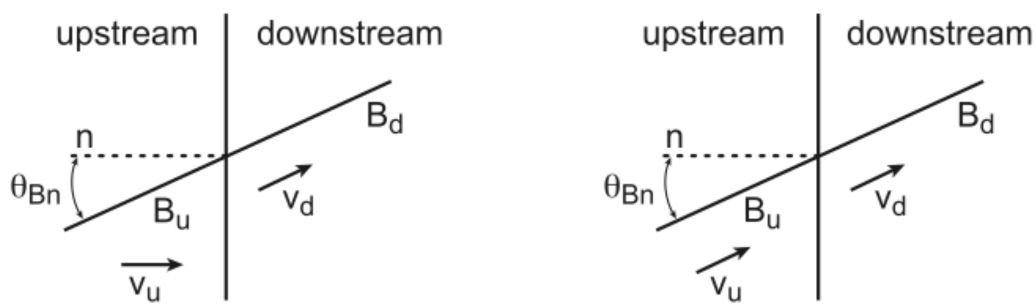
5. SHOCK WAVES

Shock waves are characterized by a fluid flows *across* the discontinuity $U_n \neq 0$ and a non zero jump discontinuity $\{\rho\} \neq 0$

Frames of reference for MHD shocks:

(I) normal incident frame (coordinate system moving along the shock front with speed U_t)

(II) de Hoffman-Teller frame (the plasma is parallel to the magnetic field on both sides and the reference frames moves parallel to the shock front with the de Hoffman-Teller speed)



(I) (II)

Strength of the Shock

- Jump equations: 12 unknowns (4 upstream parameters are specified: ρ, v_S, B_t, B_n) so we have 7 equations for 8 unknowns -> *we need to specify one more quantity*

$$\delta = \frac{\rho_2}{\rho_1}$$

Other quantities:

$$M_A = \frac{U_n}{V_A} = \frac{U_n \sqrt{\mu_0 \rho_m}}{B_n}$$ Alfvén Mach number

$$M_s = \frac{U_n}{V_s} = U_n \sqrt{\frac{\rho_m}{\gamma P}}$$ Sonic Mach number

$$\tan\theta = \frac{B_t}{B_n}$$ angle θ Between the $\vec{B}$ & shock normal

Shock Adiabatic Equation

- You can combine using the shock equations to a one single equation that gives the shock propagating speed U_{n1} as a function of shock strength δ and upstream parameters

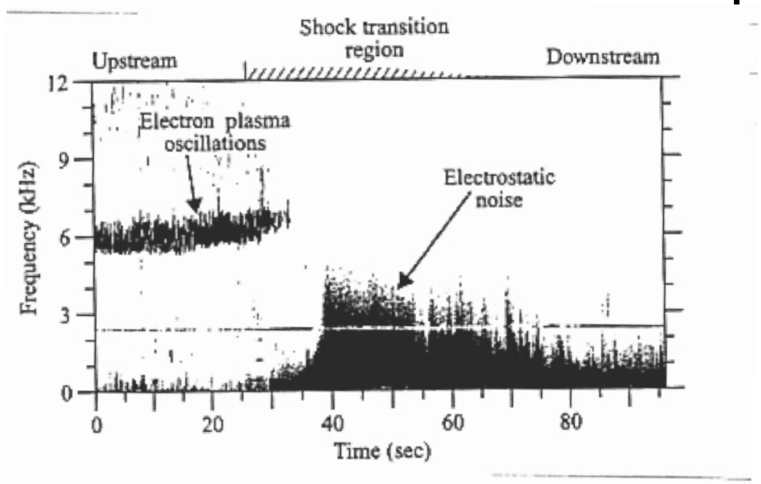
$$\left(U_{n1}^2 - \delta V_{A1}^2 \cos^2\theta_1\right)^2 \left[U_{n1}^2 - \frac{2\delta V_{s1}^2}{\delta+1-\gamma(\delta-1)}\right] - \delta \sin^2\theta_1 \, U_{n1}^2 V_{A1}^2 \left[\frac{2\delta-\gamma(\delta-1)}{\delta+1-\gamma(\delta-1)} U_{n1}^2 - \delta V_{A1}^2 \cos^2\theta_1\right] = 0$$

Type of Shocks

- Weak Shock Limit $\delta=1$ (solution of the shock equation are *slow, intermediate and fast shocks*) *(slow correspond to slow MHD wave; fast to fast MHD wave and intermediate to transverse Alfven wave)*
- Strong Shock Limit: $\delta \rightarrow \delta_m$
- Parallel Shock: $\theta=0°$
- Perpendicular Shocks: $\theta=90°$
- Quasi-perpendicular shocks $\theta>45°$

Thickness of Shocks

- The thickness of the shocks and the detailed substructure within the shock depends on the angle θ_{BN}, M_{A1},M_{A2}
- The transition region of a quasi-perpendicular shock is usually thin and well defined
- The transition region of a quasi-parallel shock is usually more complex and often appears thick

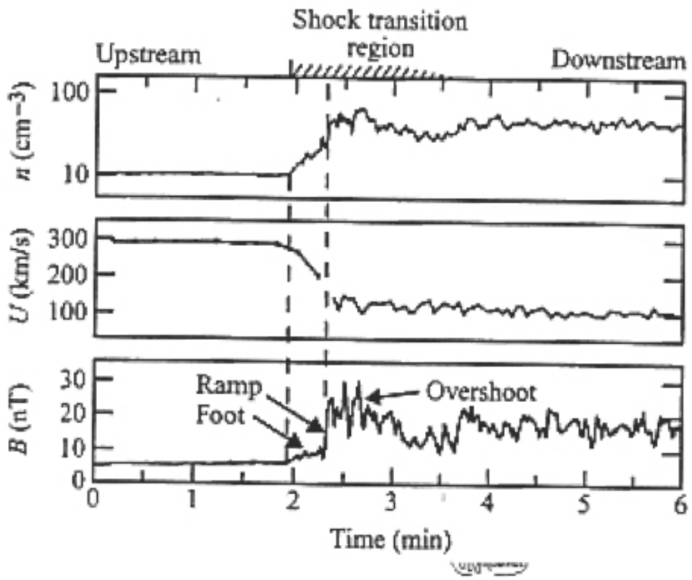


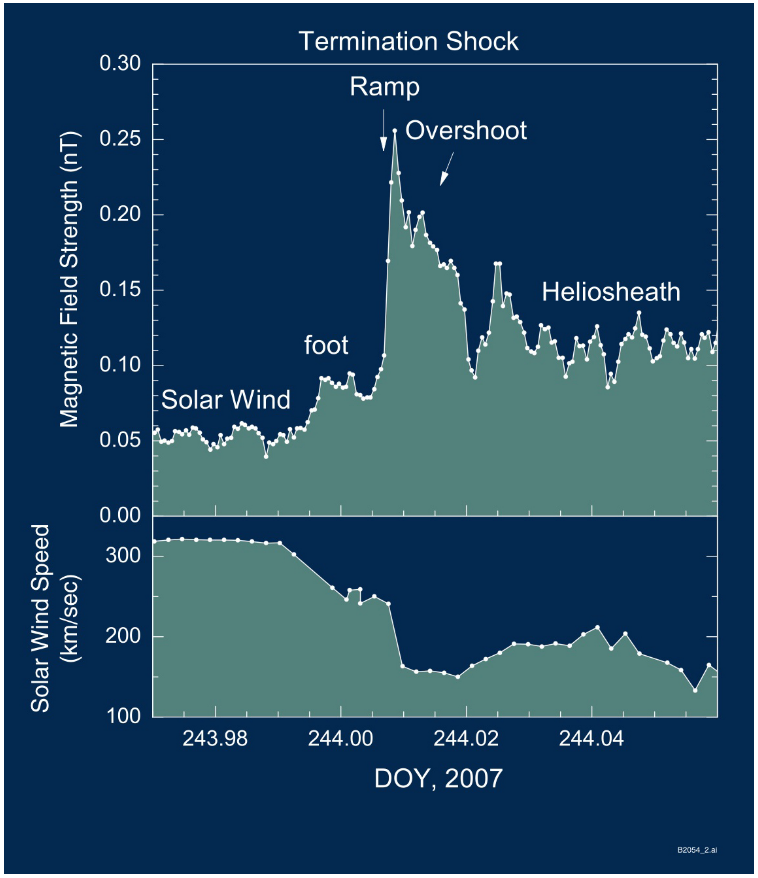
Broadband electric field noise:
Plasma wave turbulence excited
by unstable particle distribution in the shock

Jupiter's bow shock

Narrow band at 6kHz:
Electron plasma oscillations
Excited by a beam
of electrons that escapes
into the region upstream
the shock

6. Observations of MHD Shocks

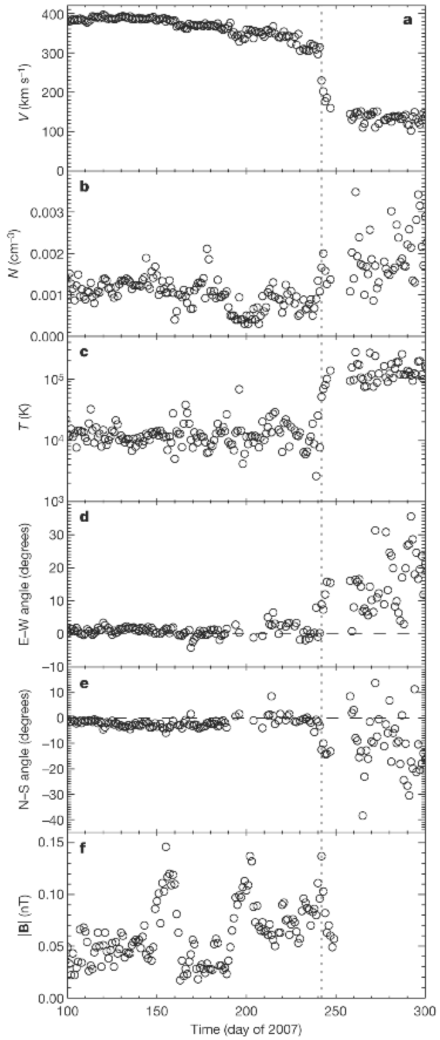




Earth Bow Shock (
at a distance 15.4R_E upstream from Earth)
This example θ_1=76°
(between B and n)
U_1=294km/s > v_A=37.8km/s

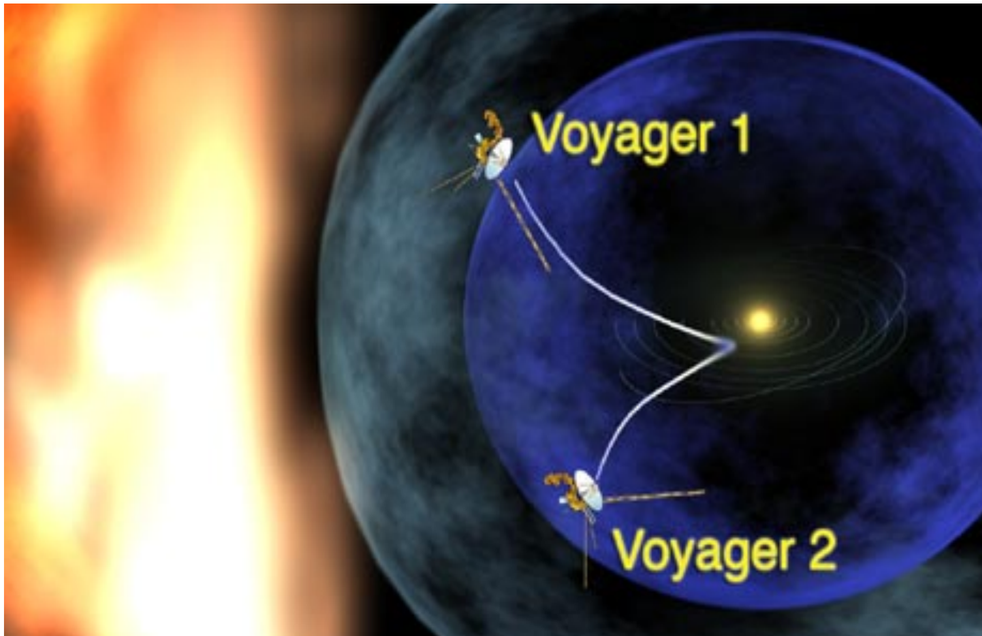
Voyager 2 crossing the Termination Shock in August 2007

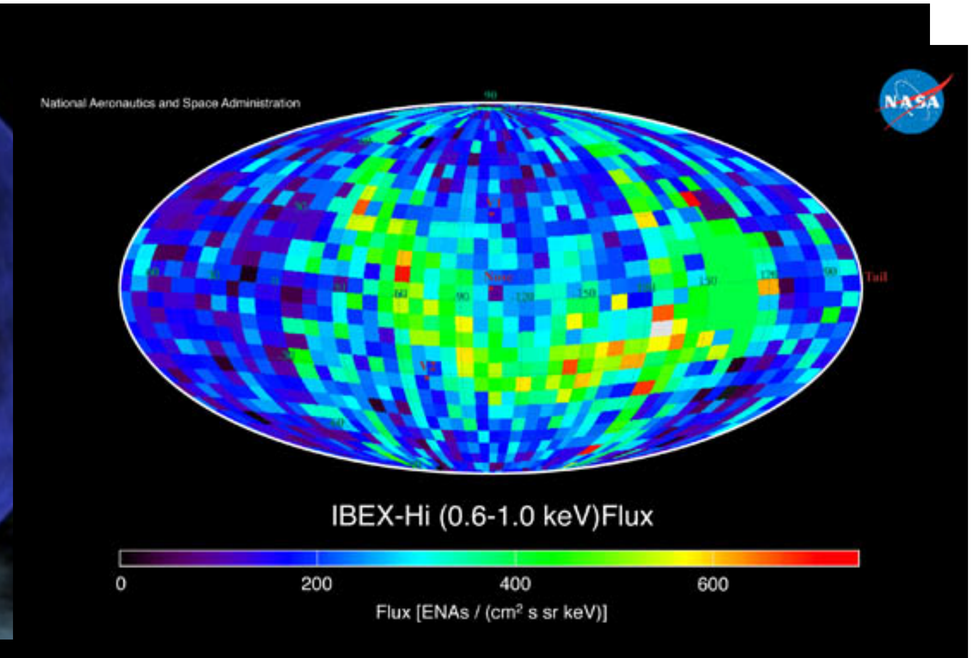
Termination Shock: Perpendicular Shock



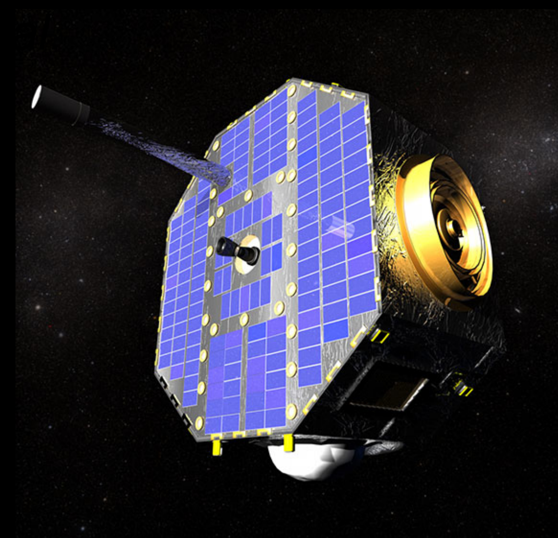
Voyager 2 crossed the Termination Shock in August 2007- (in-situ measurements of a shock)

J.Richardson et al.



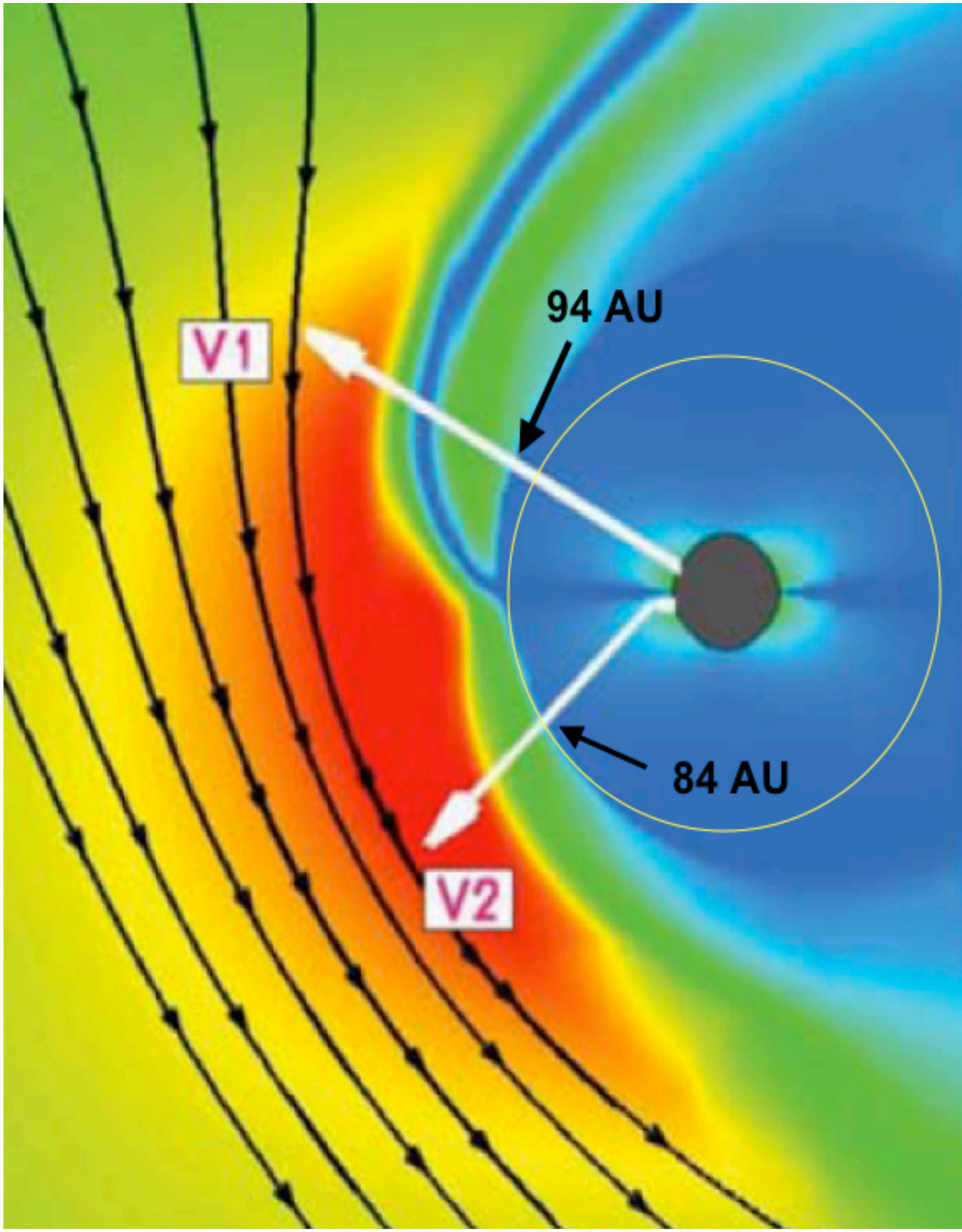


Voyager 1 in the north
Voyager 2 in the south

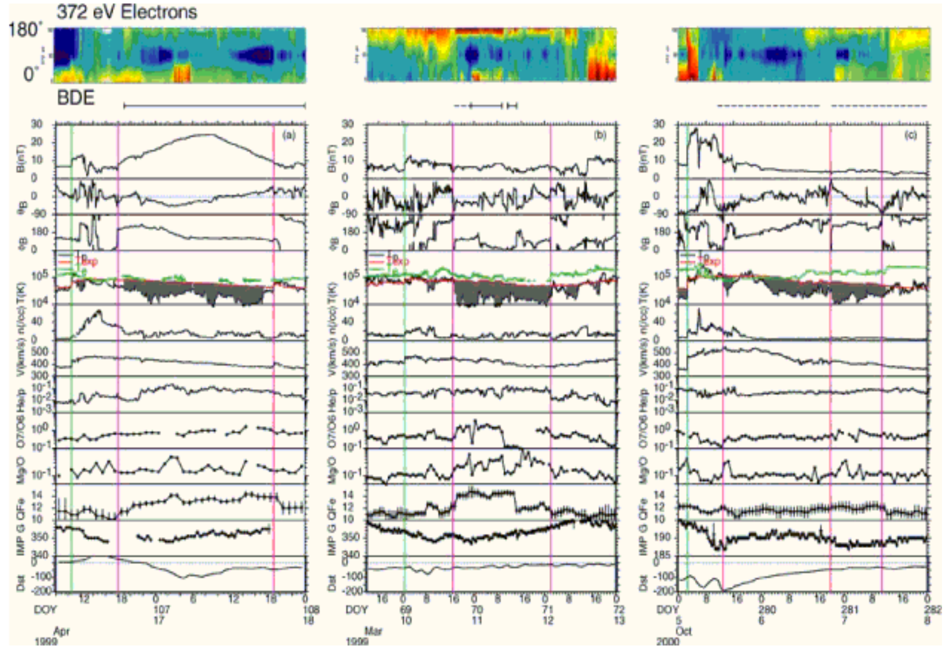


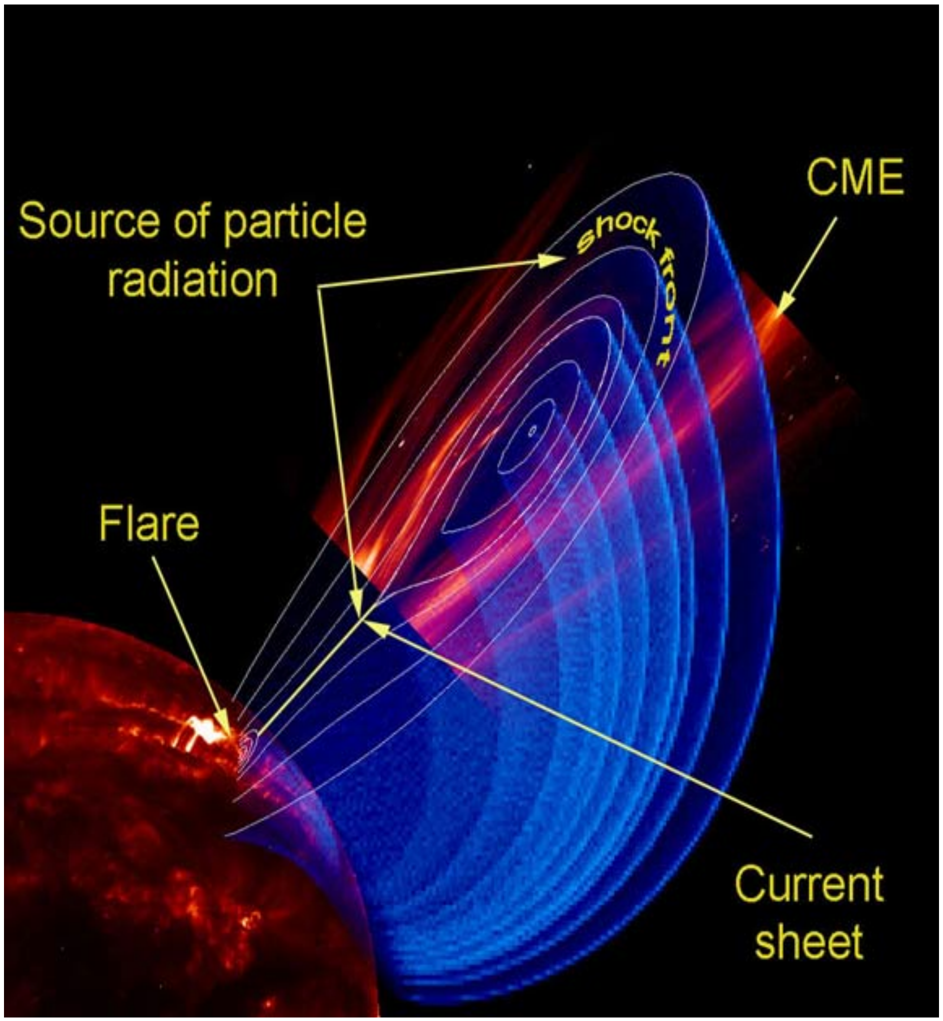
IBEX

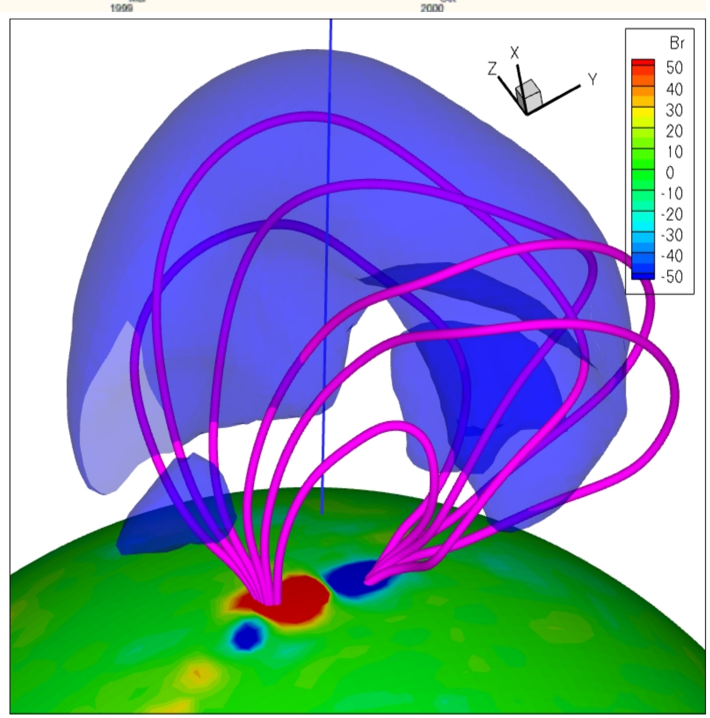
Crossing of TS by V2: closer to the Sun than V1



Shocks Driven by Coronal Mass Ejections



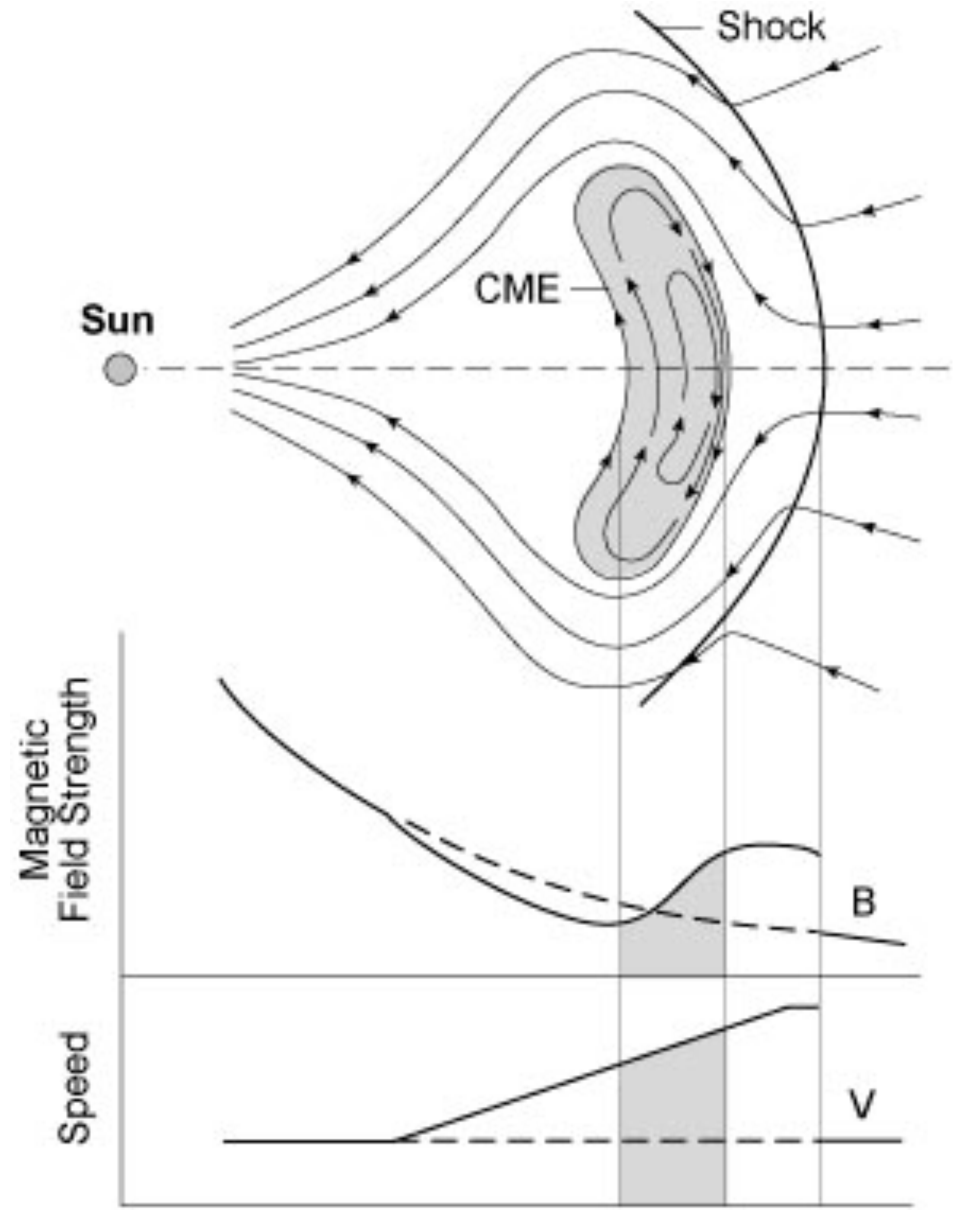




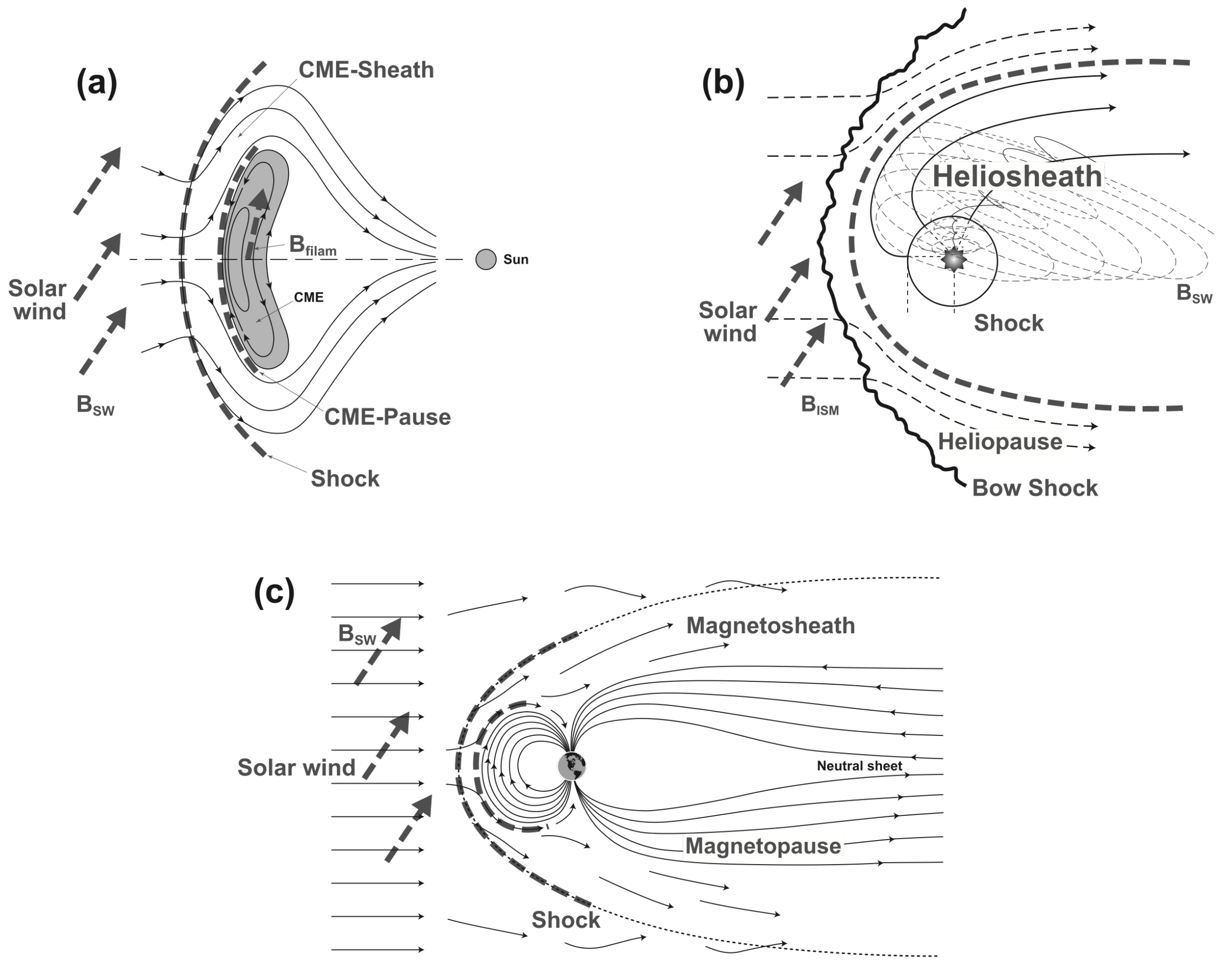
Propagating Shocks

- Shock geometry can vary if near

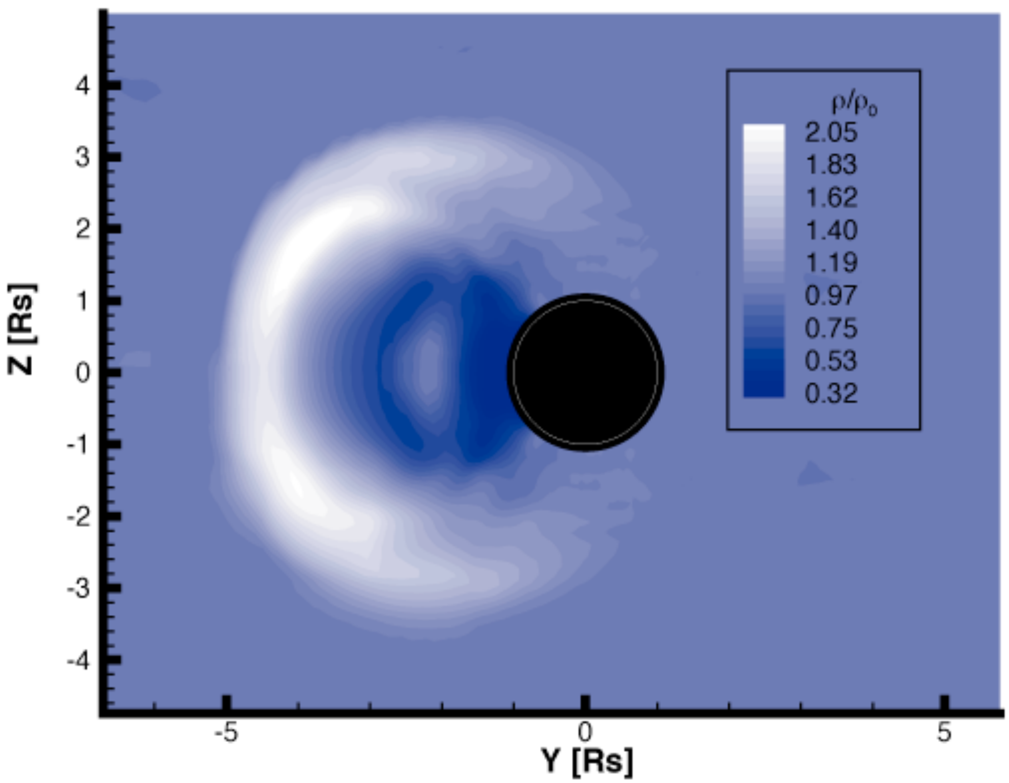
The nose or flanks

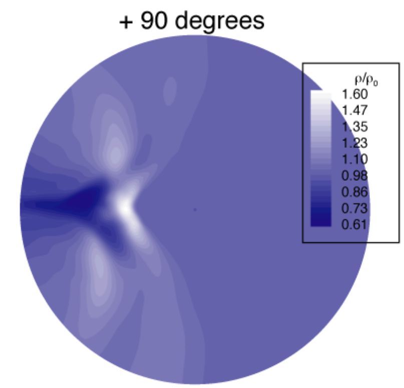


Universal Characteristics of Shocks



Synthetic Coronagraph Images of the CME: LASCO C2 and HI2



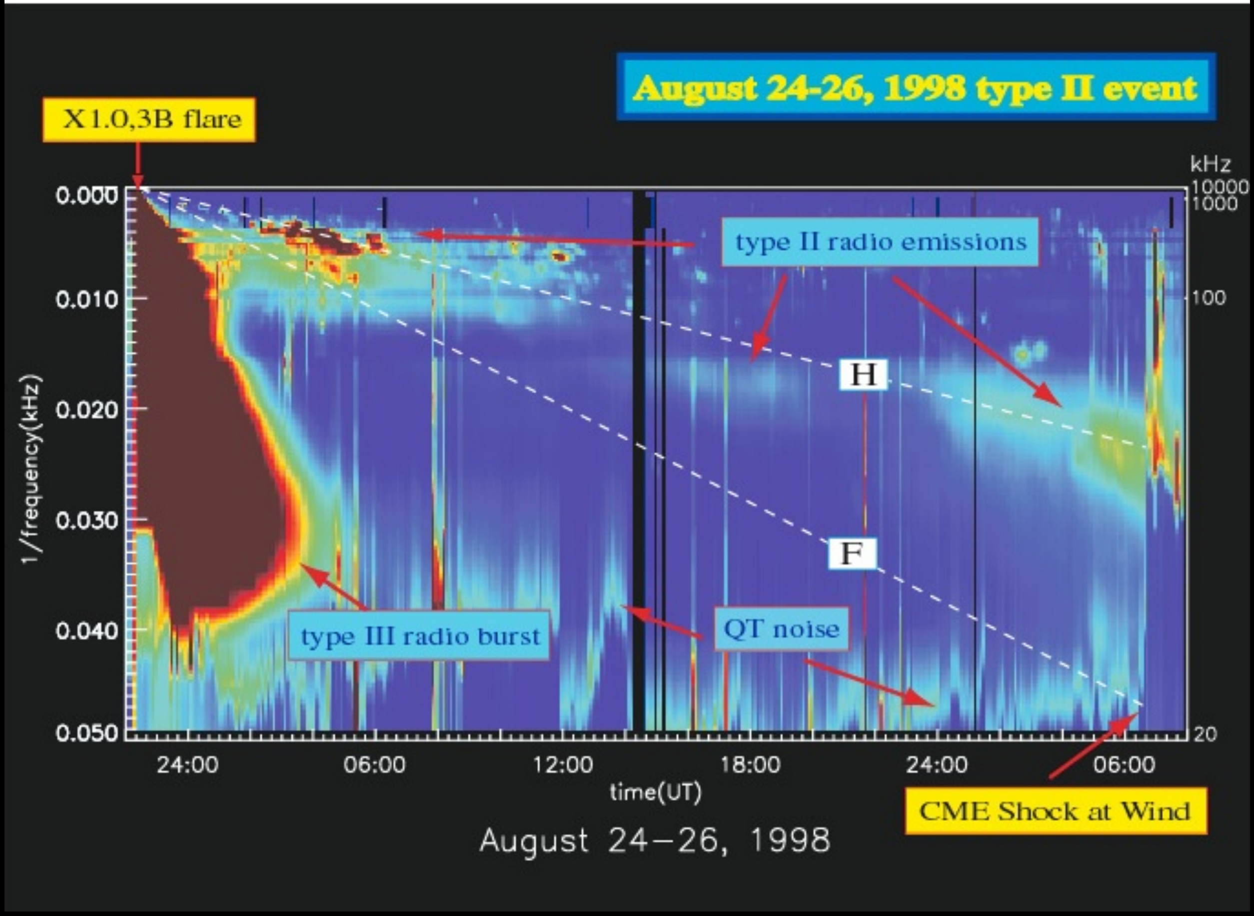


Reverse Shock

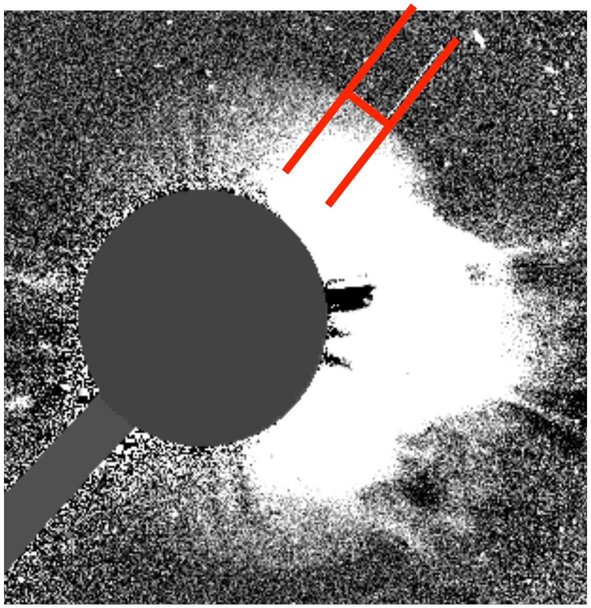
Forward Shock

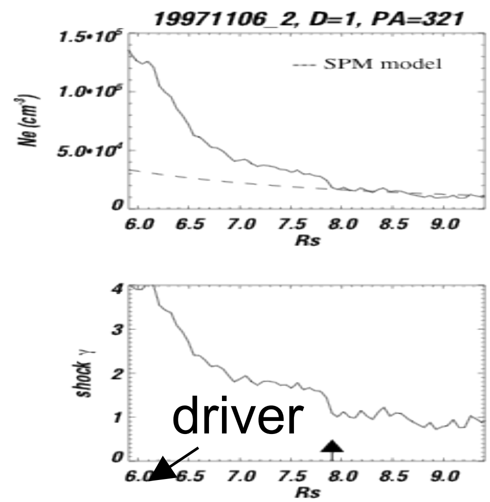
Lugaz, Manchester and Gombosi
ApJ 2005

Radio Type II emission associated with CME shocks



Measuring Shocks





shock

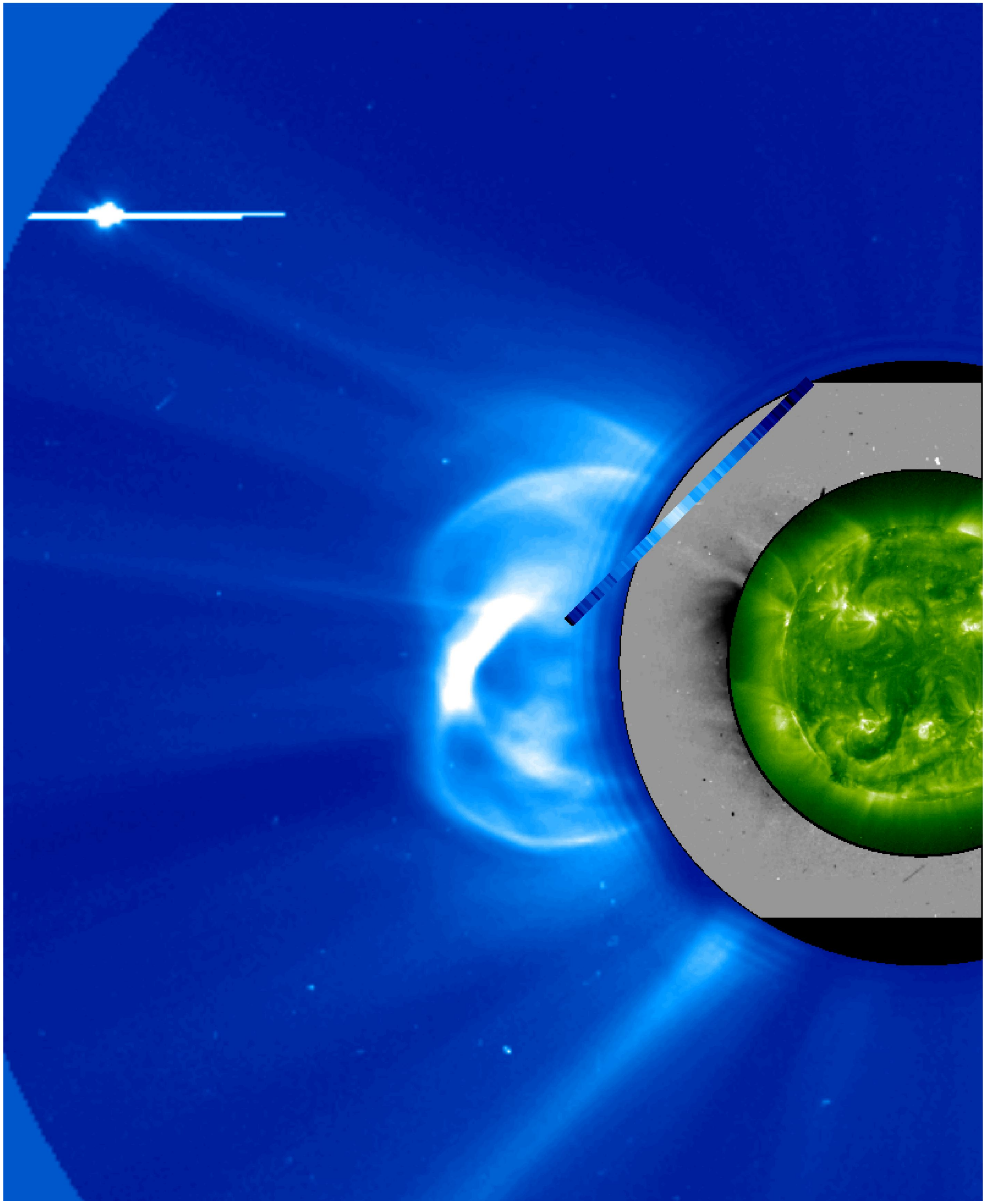
Shock brightness to density (ρ)
Shock strength, γ**=1+ρ/ρ0**
SPM model for the density of the back ground corona (ρ0).

Vourlidas & Ontiveros 2008

Development of Coronal Shocks Seen in the UV

John Raymond

Smooth, Faint arcs are often seen in White Light. convincing identification as shocks requires MHD Simulation matching profile (Manchester et al., Vourlidas et al.)



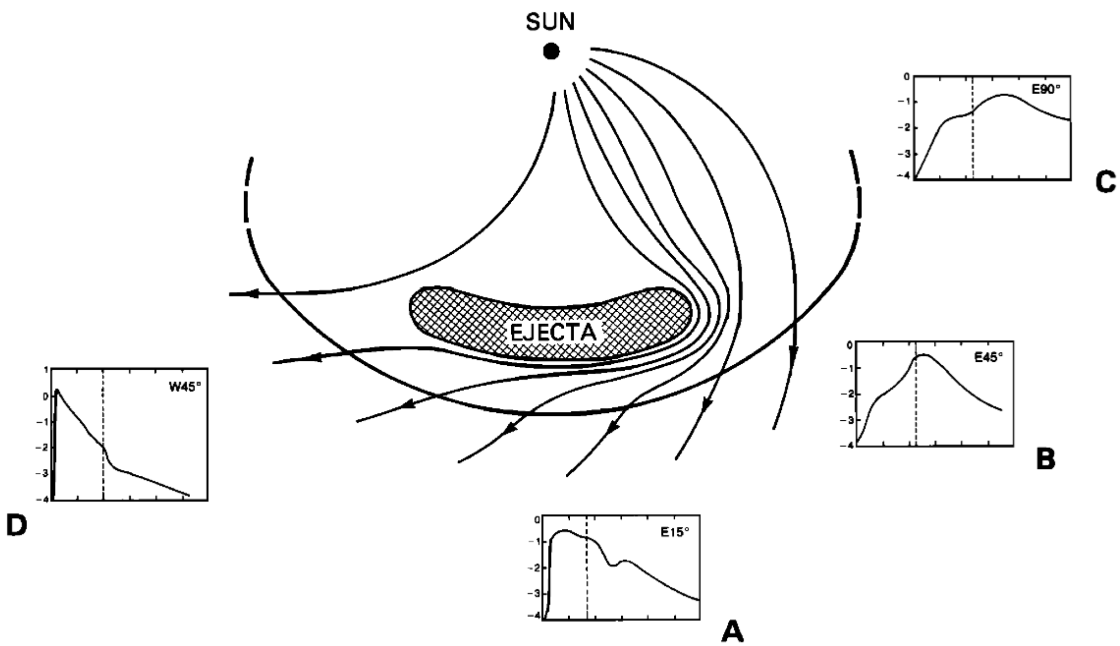
UVCS Shock Observations Analyzed so far

Date	Reference	H	V	n_0	Log T_O	X
06/11/98	Raymond et al.	1.75	1200	1×10^6	8.7	1.8
06/27/99	Raouafi et al.	2.55	1200		<8.2	
03/03/00	Mancuso et al.	1.70	1100	1×10^7	8.2	1.8
06/28/00	Ciaravella et al.	2.32	1400	2×10^6	8.1	
07/23/02	Mancuso&Avetta	1.63	1700	5×10^6	8.0	2.2

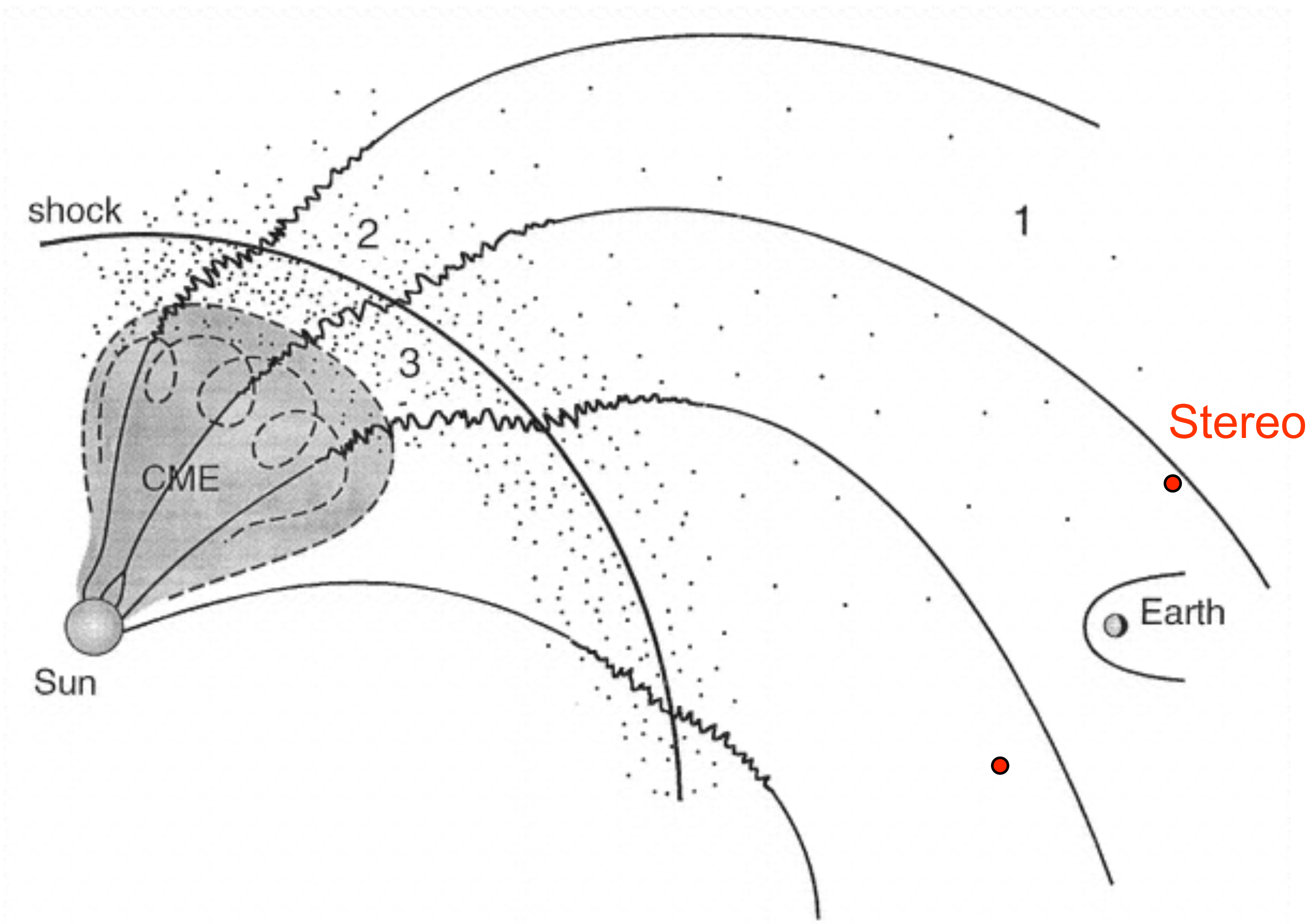
Modest heights, Modest compression, High T_O

5 other shocks not yet fully analyzed (Ciaravella et. al. 2006)

Shocks Geometry: Magnetic Connectivity

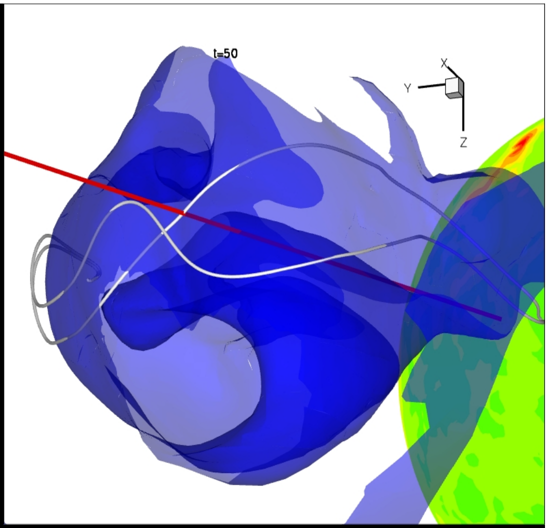


CMEs and Composition of SEPs



OPEN QUESTIONS/Research being done

8. Open Questions



How do magnetic effects affect shock evolution?

(Loesch et al. 2010; Liu et al. 2009)

Which type of flows do we get in CME sheaths?

(Evans et al. 2010)

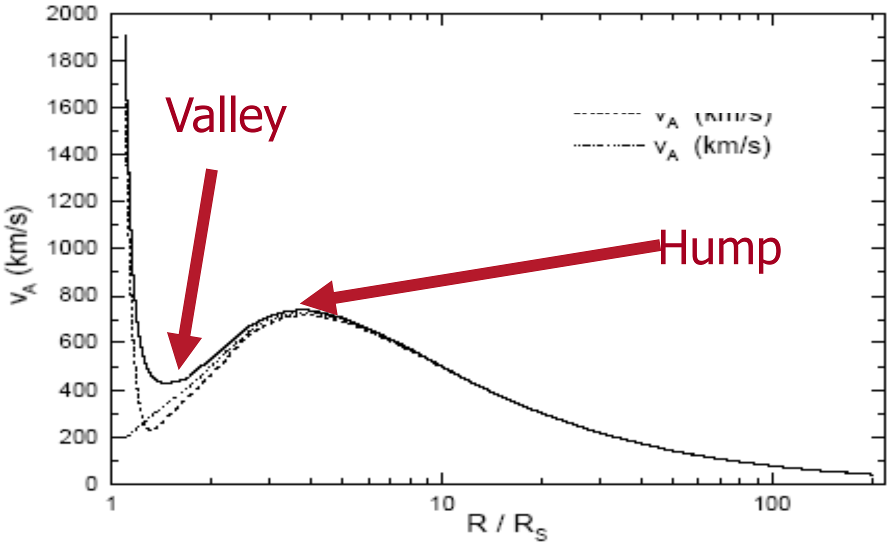
How does reconnection affect shock structures in the lower corona?

Formation of Shocks and Solar Energetic Particles

Background Solar Wind with Alfven Waves

(Evans, Rona, Opher, Gombosi, 2010; Evans et al. 2008; 2009)

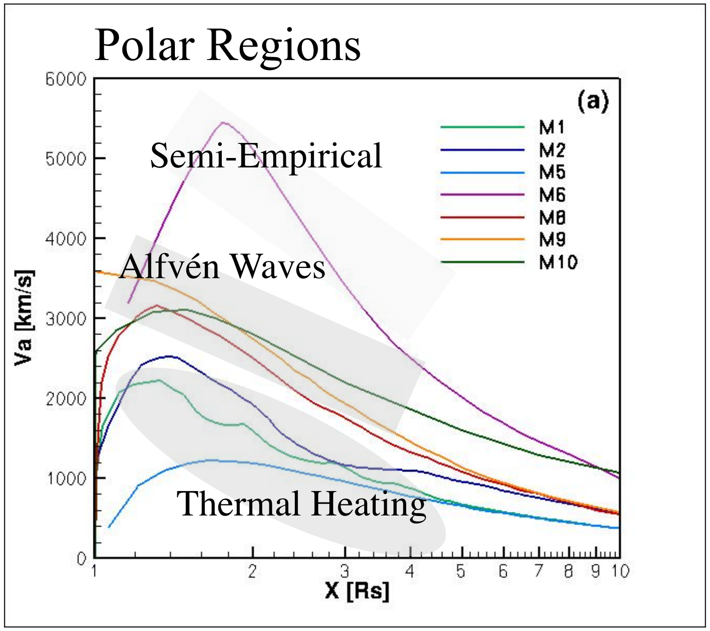
What is the Alfvén Speed Profile in the Lower Corona?

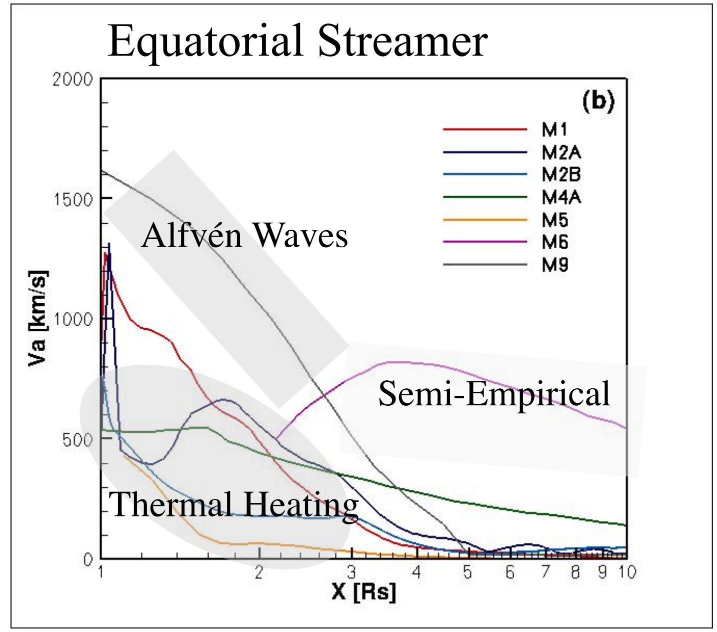


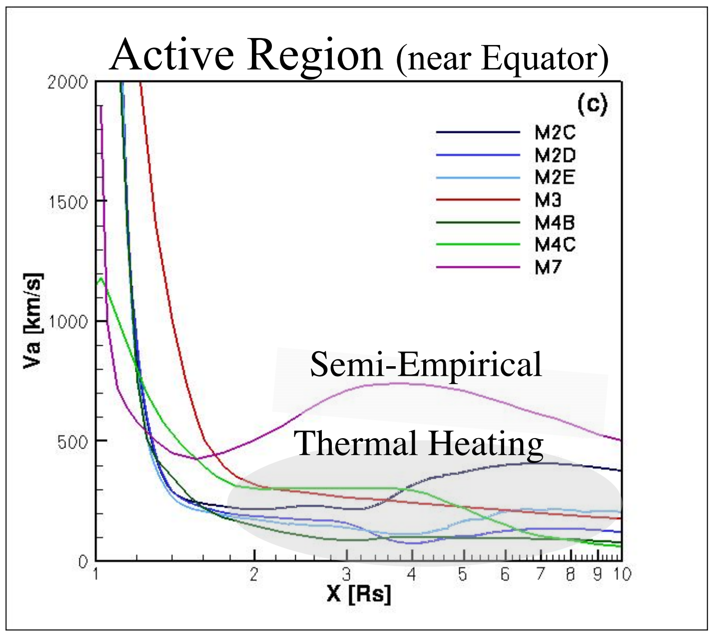
Evans et al. ApJ (2008)

- Ten Models (Solar Minimum)
  - **6 Global MHD**: Manchester et al. 2004; Cohen et al. 2007; Roussev et al. 2004; Riley 2006; Lionello et al. 2001; Usmanov & Goldstein 2006
  - **2 Local Studies**: Cranmer et al. 2007; Verdini & Velli 2007
  - **2 Semi-analytic**: Guhathakurta et al. 2006; Mann et al. 2003

- Different Strategies to Accelerate Solar Wind
  - Empirical Heating Functions
  - Non-uniform Polytropic Index
  - Inclusion of Alfvén Waves





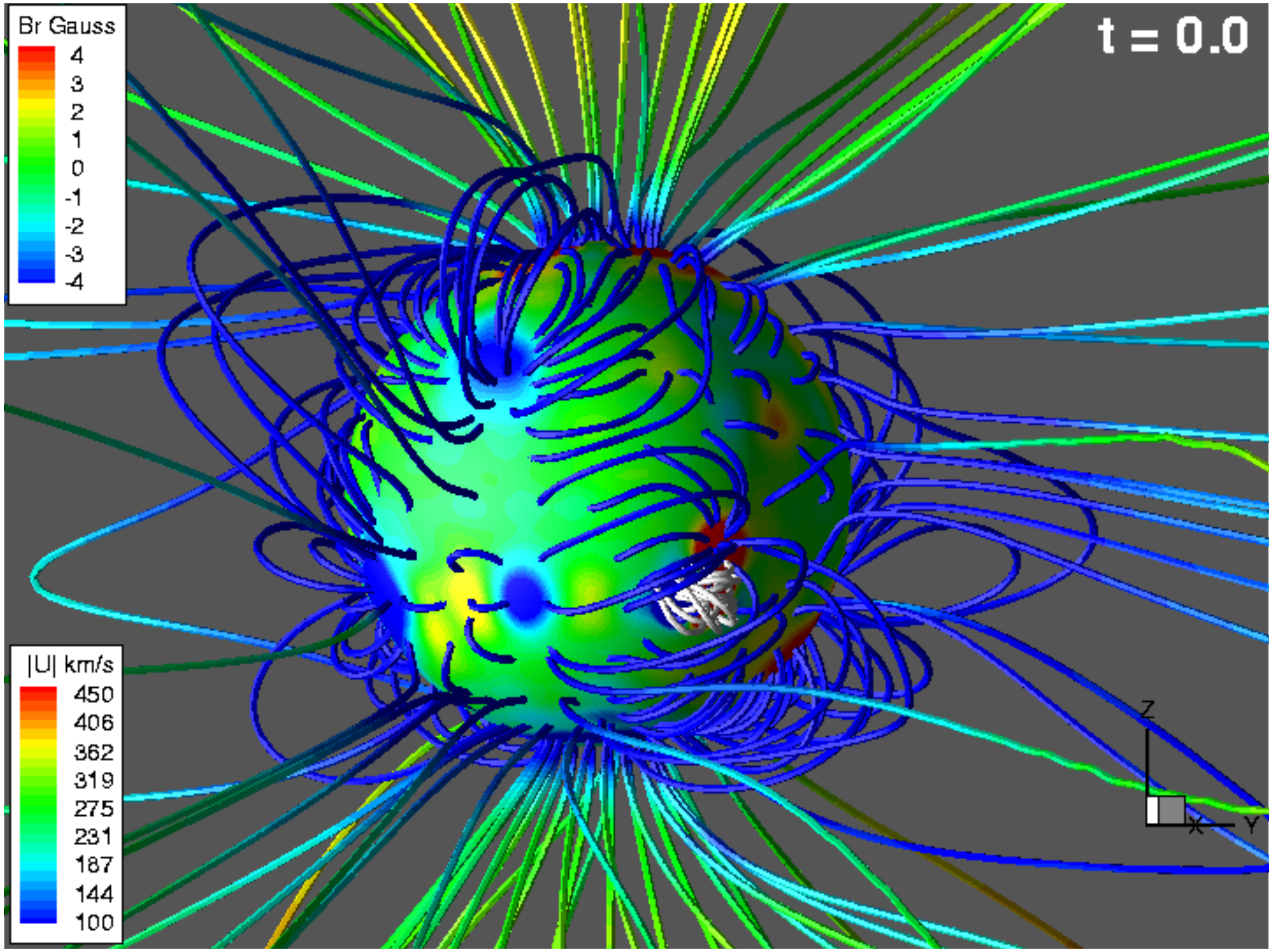


Profiles vary drastically; Almost none with a clear hump
Need more physical based solar wind to study shocks in lower corona

M1 Manchester et al. **M2** Cohen et al. **M3** Roussev et al. **M4** Riley **M5** Lionello et al.
M6 Guhathakurta et al. **M7** Mann et al. **M8** Cranmer et al. **M9** Usmanov & Goldstein **M10** Verdini & Velli

Initial Steady State in the Corona

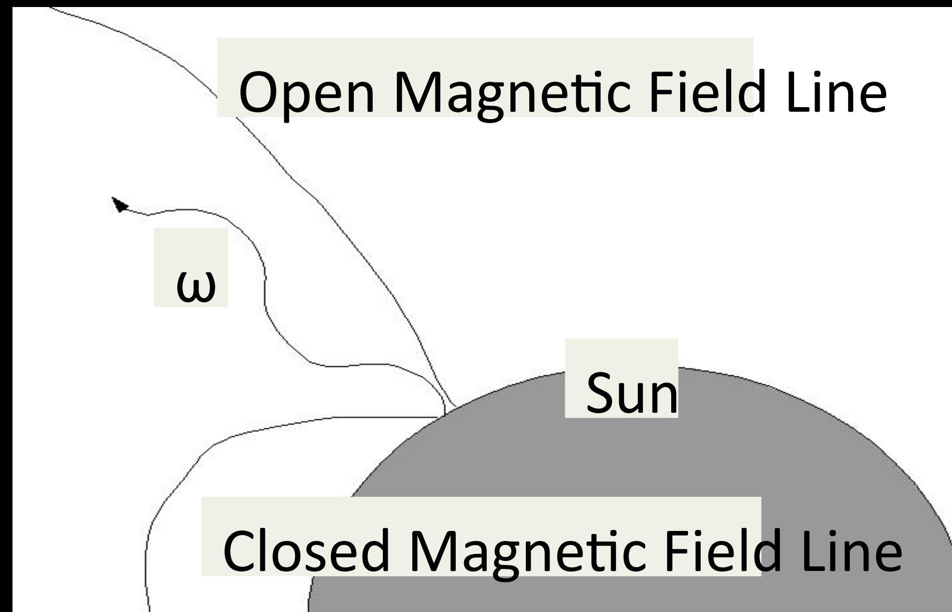
- Solar surface is colored with the radial magnetic field.
- Field lines are colored with the velocity.
- Flux rope is shown with white field lines.

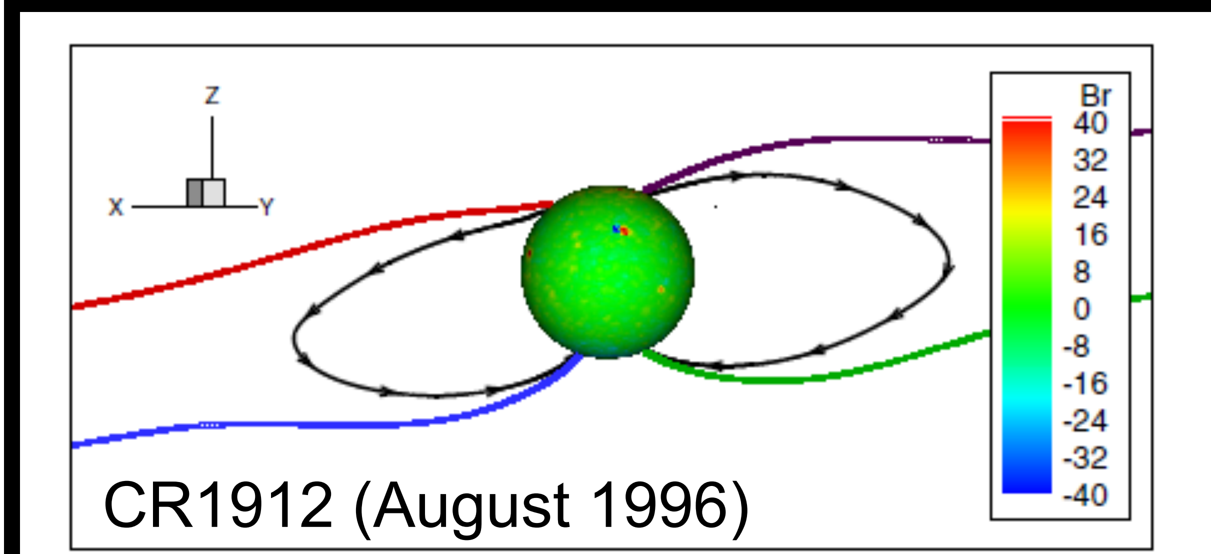


Surface Alfven Waves

- Dissipate in regions with strong gradients in B, ρ (boundary of open/closed field lines)

$$L_{SW} = L_0 \left(\frac{r_0}{r}\right)^{S/2} \left(\frac{v_A}{v_{A0}}\right)^2 (1 + M_A)$$





- Calculated L_{SW} along field lines
- Damped wave flux is comparable to heating due to variable polytropic index

Evans et al. ApJ 2008, 2009

Surface Alfven Wave-Driven Wind

$$\frac{\partial E_w^{\pm}}{\partial t} + \nabla \cdot \left(E_w^{\pm}(\vec{u} \pm \vec{v}_A)\right) + p_w^{\pm} \nabla \cdot \vec{u} = -\gamma^{\pm} E_w^{\pm}$$

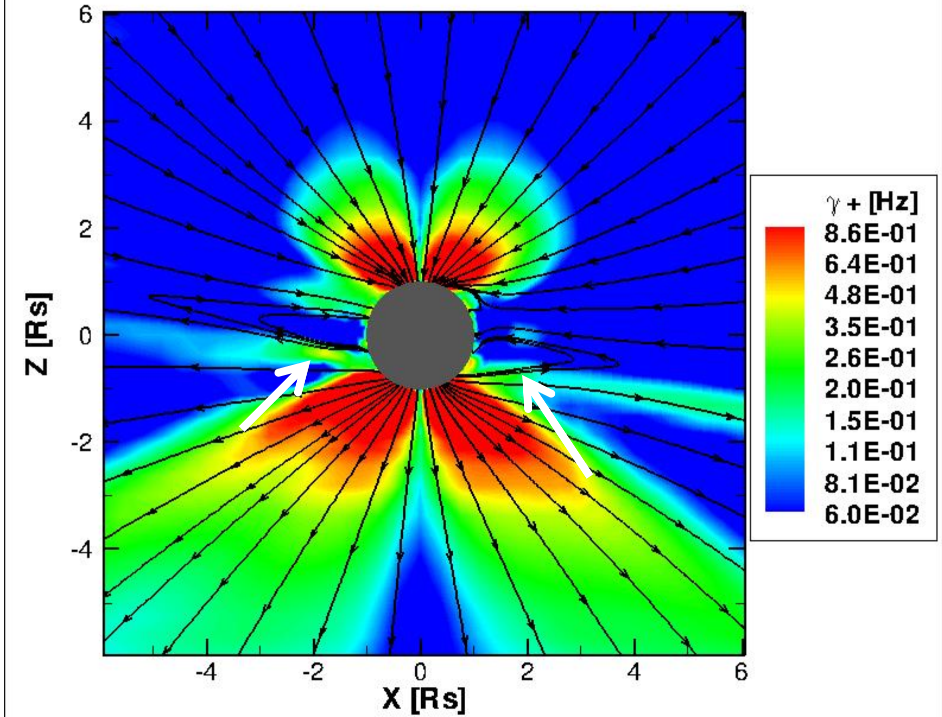
$$\frac{\partial E}{\partial t} + \nabla \cdot \left(E\vec{u}\right) + p\nabla \cdot \vec{u} = \gamma^{+} E_w^{+} + \gamma^{-} E_w^{-}$$

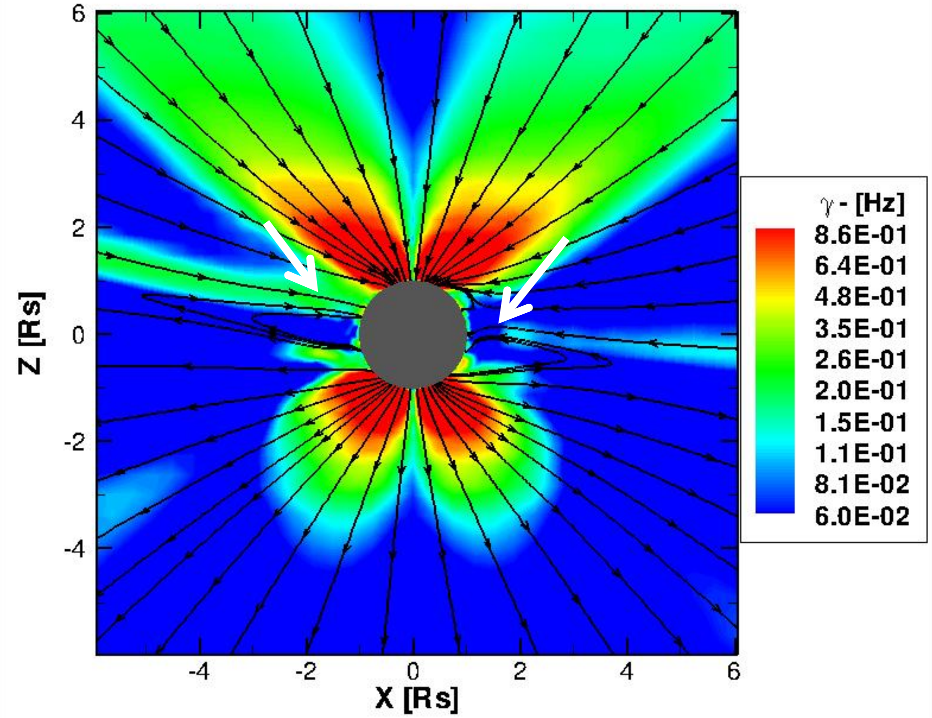
γ=5/3 *van der Holst et al. 2010*

$$\gamma^{\pm} = \frac{(u \pm v_A)}{L}$$

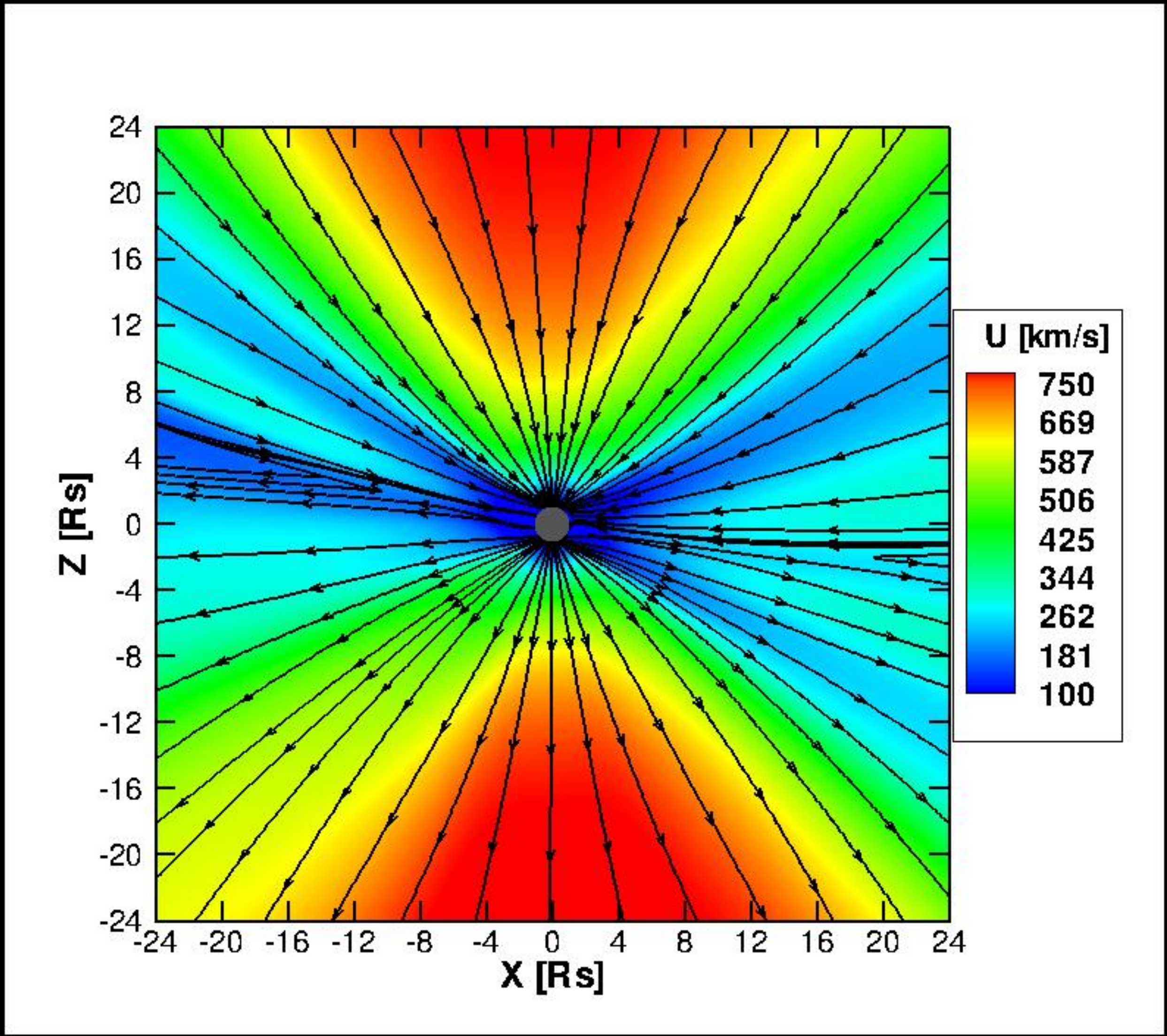
$$L_i = C_{SW} \frac{\rho}{\sqrt{\left(\left(\partial\rho / dx_j\right)^2 + \left(\partial\rho / dx_k\right)^2\right)}}$$

Evans et al. 2010,





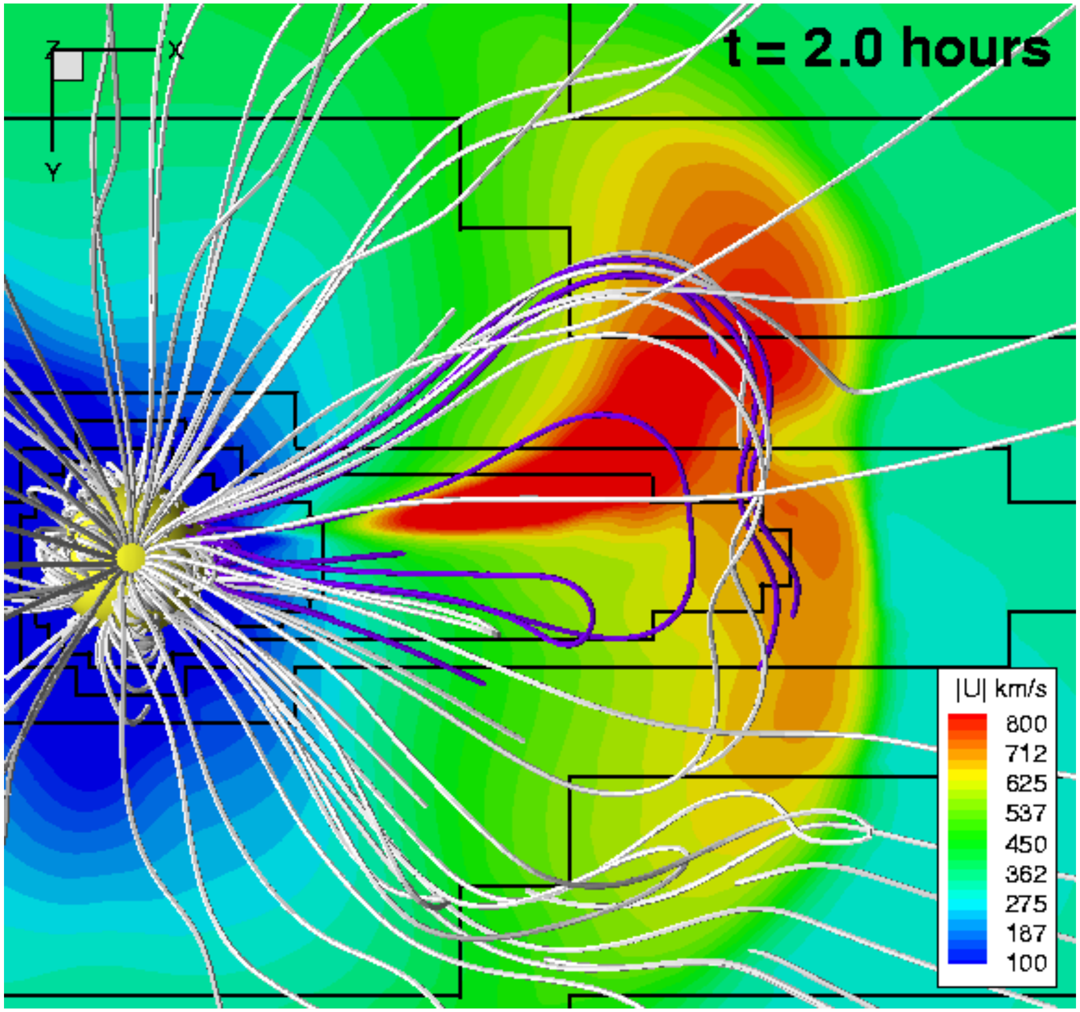
Surface Alfven Wave-Driven Wind



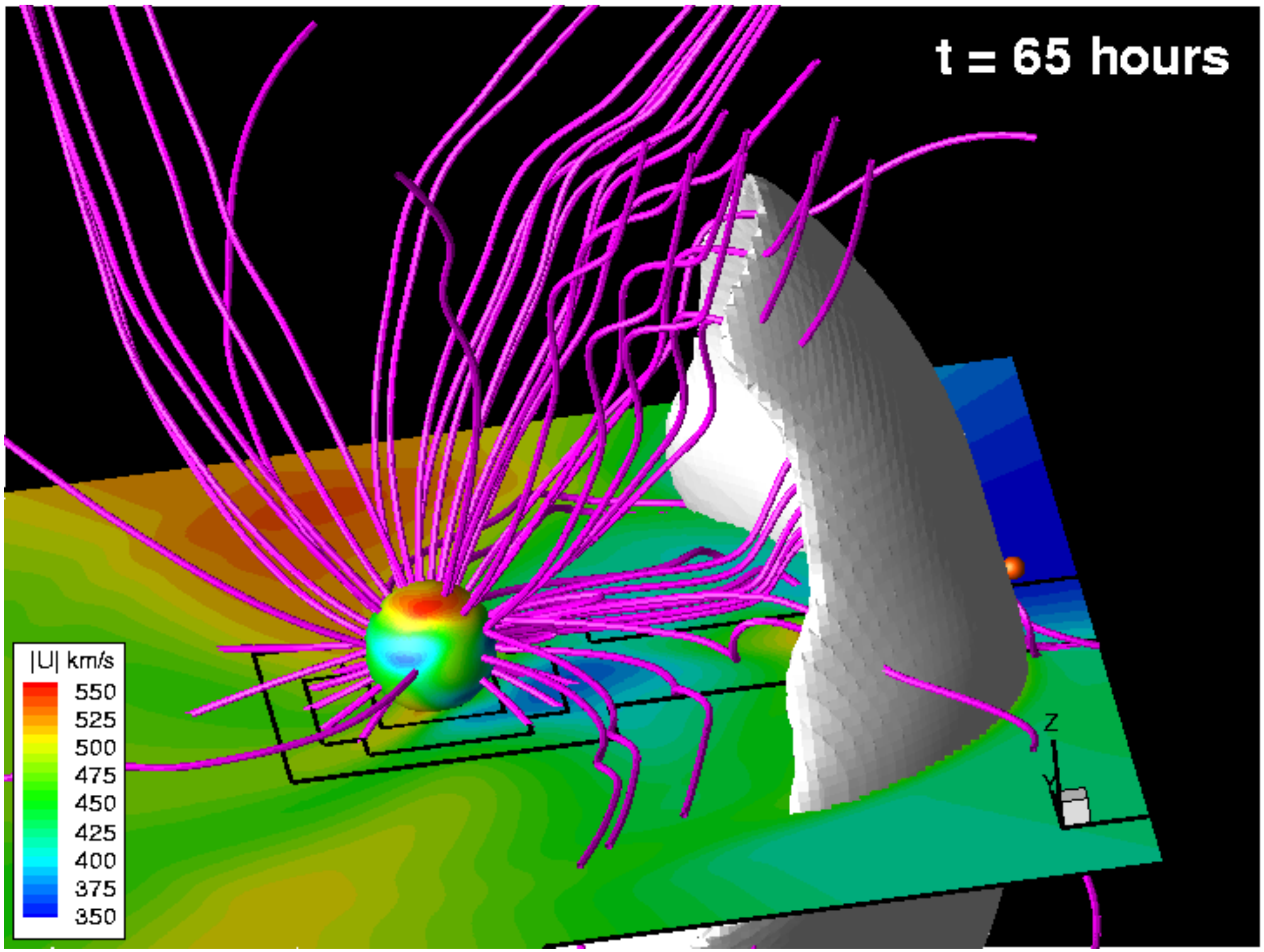
Evans et al. 2010

Future plans: Incorporate into a frequency-dependent model

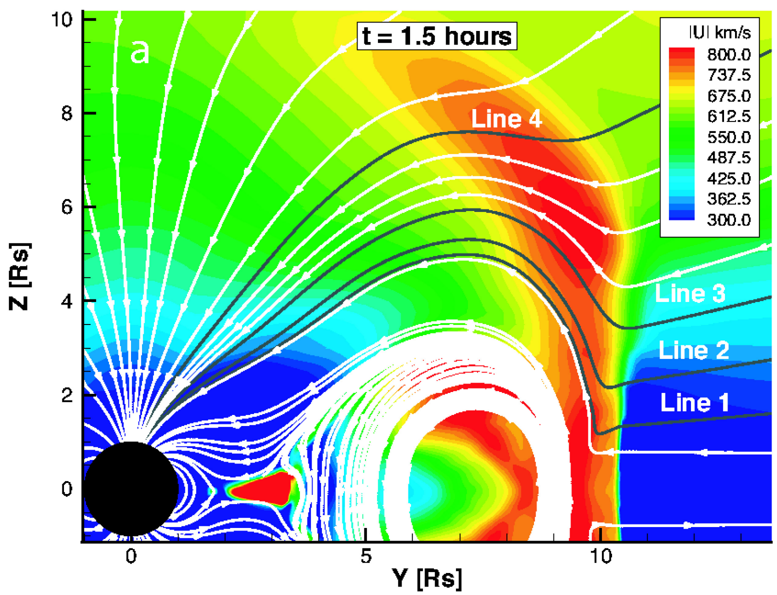
Two Hours After Eruption in the Solar Corona

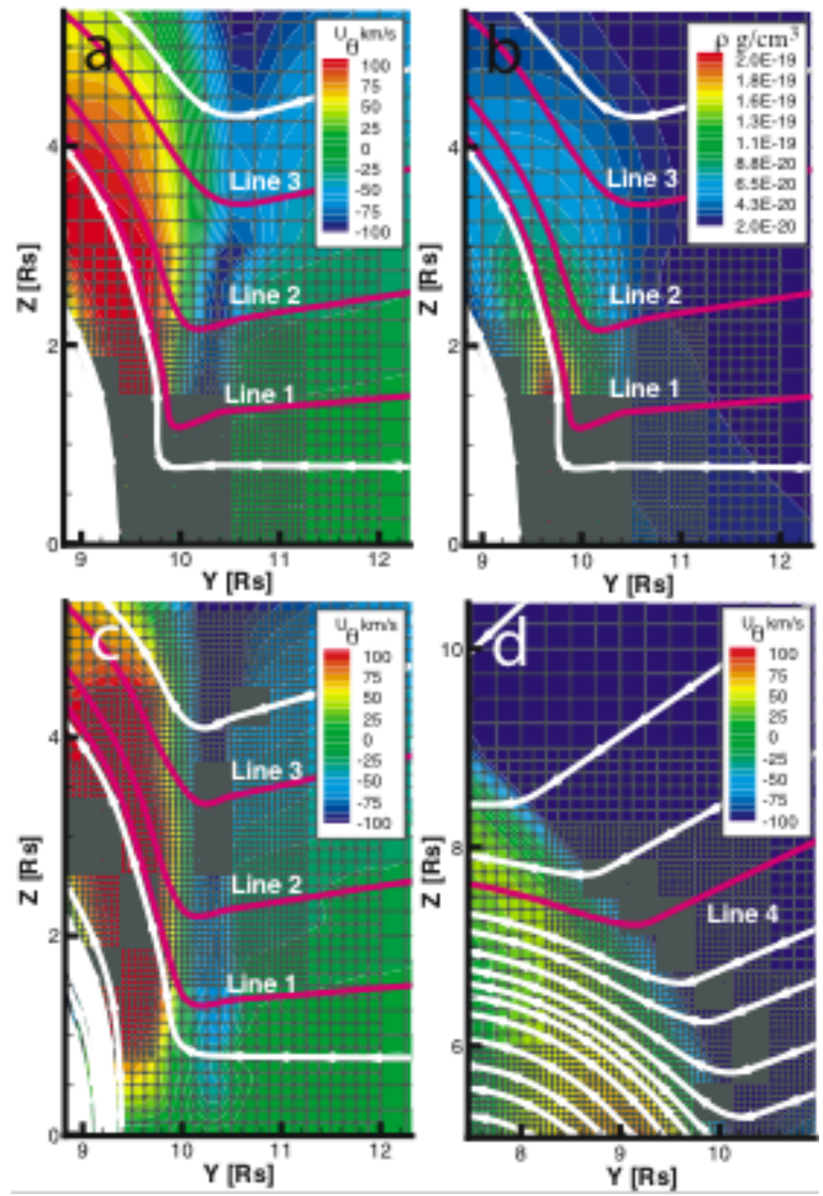


65 Hours After Eruption in the Inner Heliosphere



Fine Shock Structure

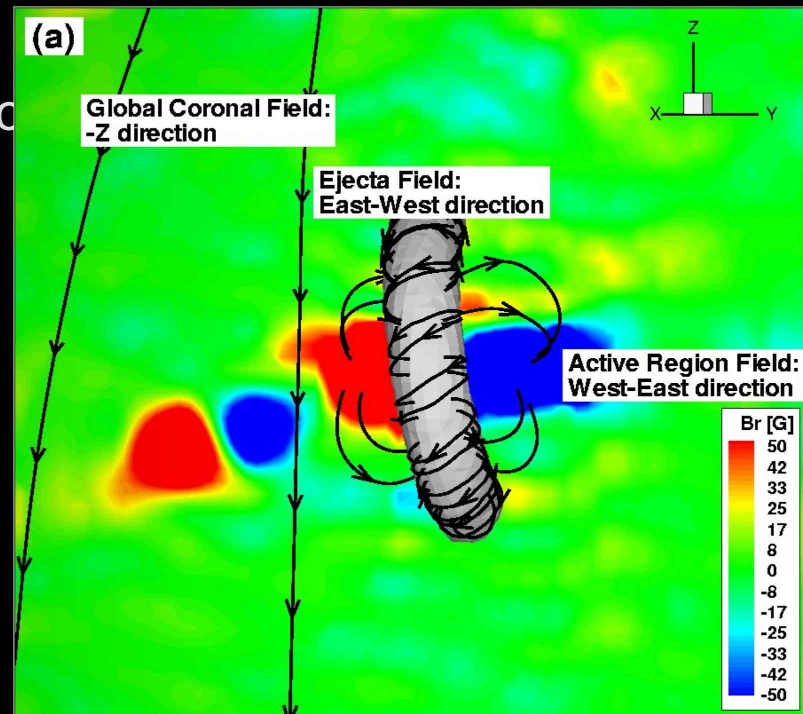




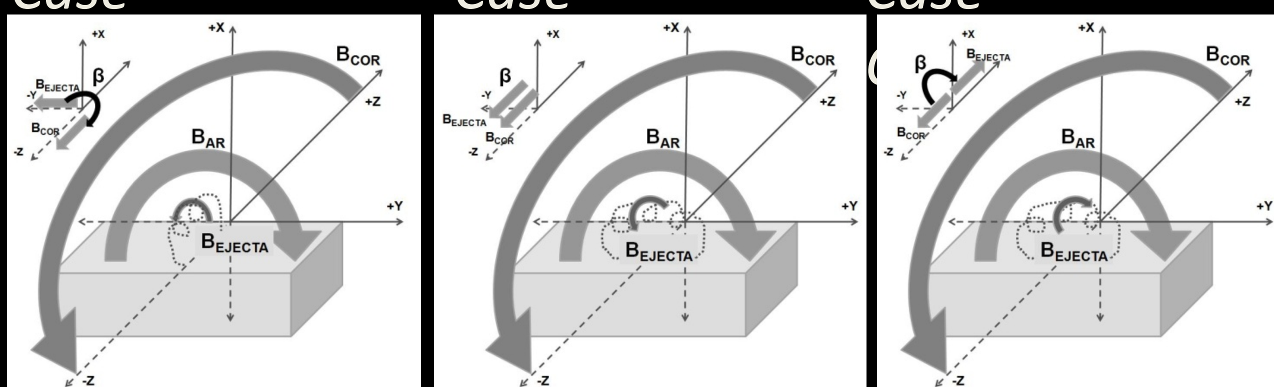
Manchester et al. 2004

Flows In CME-Sheath

- Background solar wind:
  - 3D MHD Code BATS-R-US (U. of Mic
  - *Cohen et al. 2007* Polytropic Model
  - CR1922 (May 1997)
- CME Initiation
  - Modified Titov-Demoulin FR
    - Torus line current only
  - 3 Orientations of B_{ejecta}
    - 2 along neutral line; 1 across
    - Same initial free energy



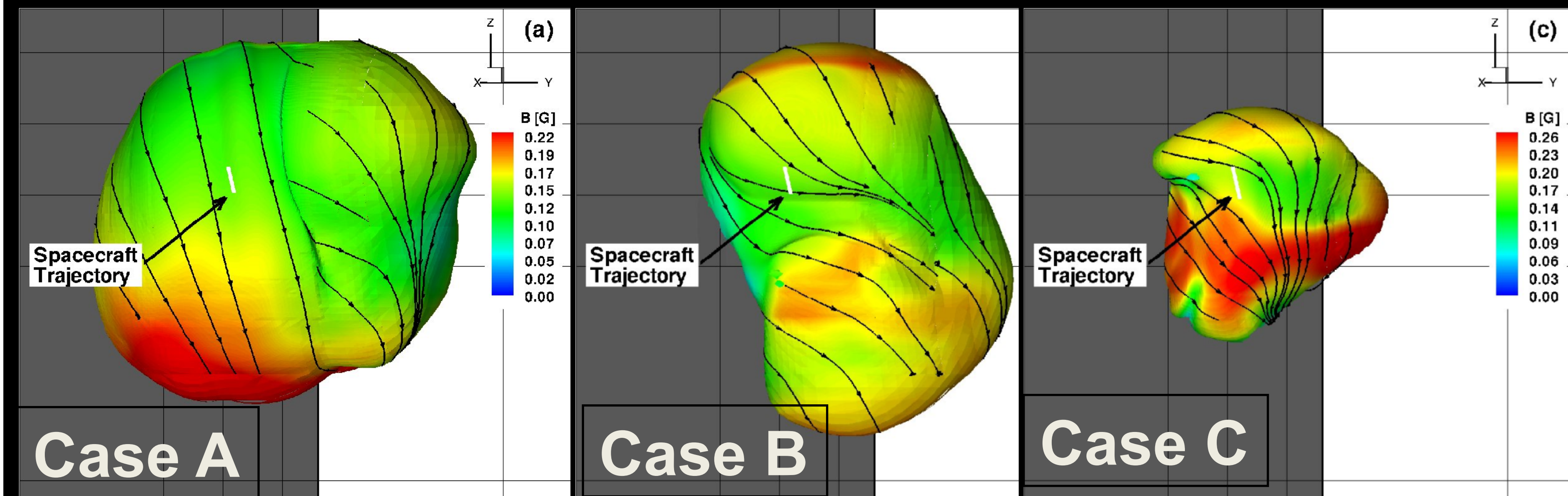
Case *Case* *Case*



Evans, Opher & Gombosi ApJ 2010

CME-Pause

- Viewpoint: looking back towards Sun



Evans, Opher & Gombosi ApJ 2010

→We expect the CME-sheath flows to deflect around the pause differently

1. Flow deflection angle along a velocity streamline $\theta_F = \tan^{-1}(V_N / V_T)$ (RTN coordinates)

	θ_F at CME-shock	θ_F at CME-pause
Case A	-86°	-66°
Case B	-82°	-47°
Case C	-77°	35°

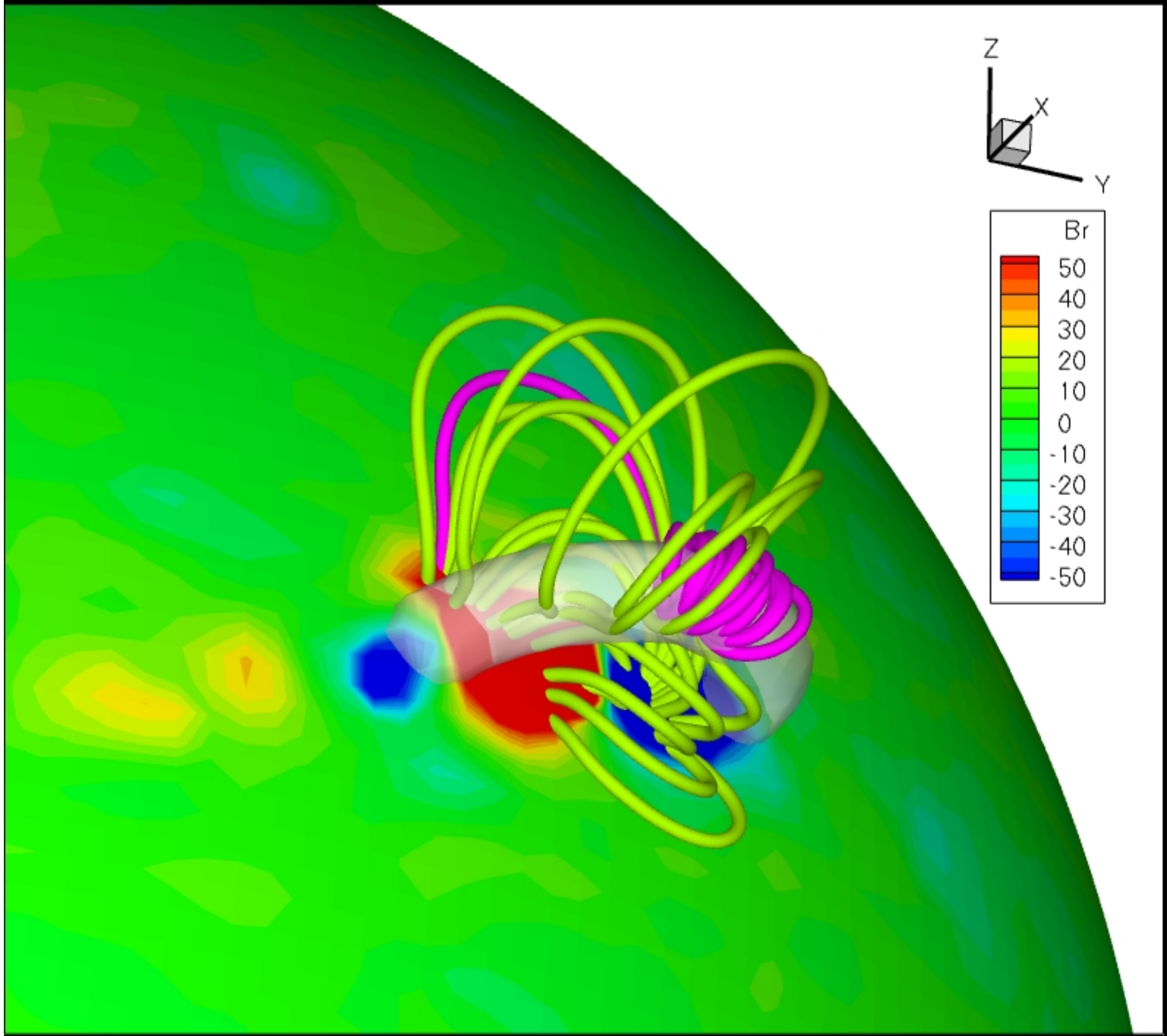
θ_F is different by 15-78° at the CME-pause

2. Flow deflection angle evolution

Rotation slows to <2°/$R_\odot$ when R_{shock}=6 $R_\odot$ (for cases A & C)

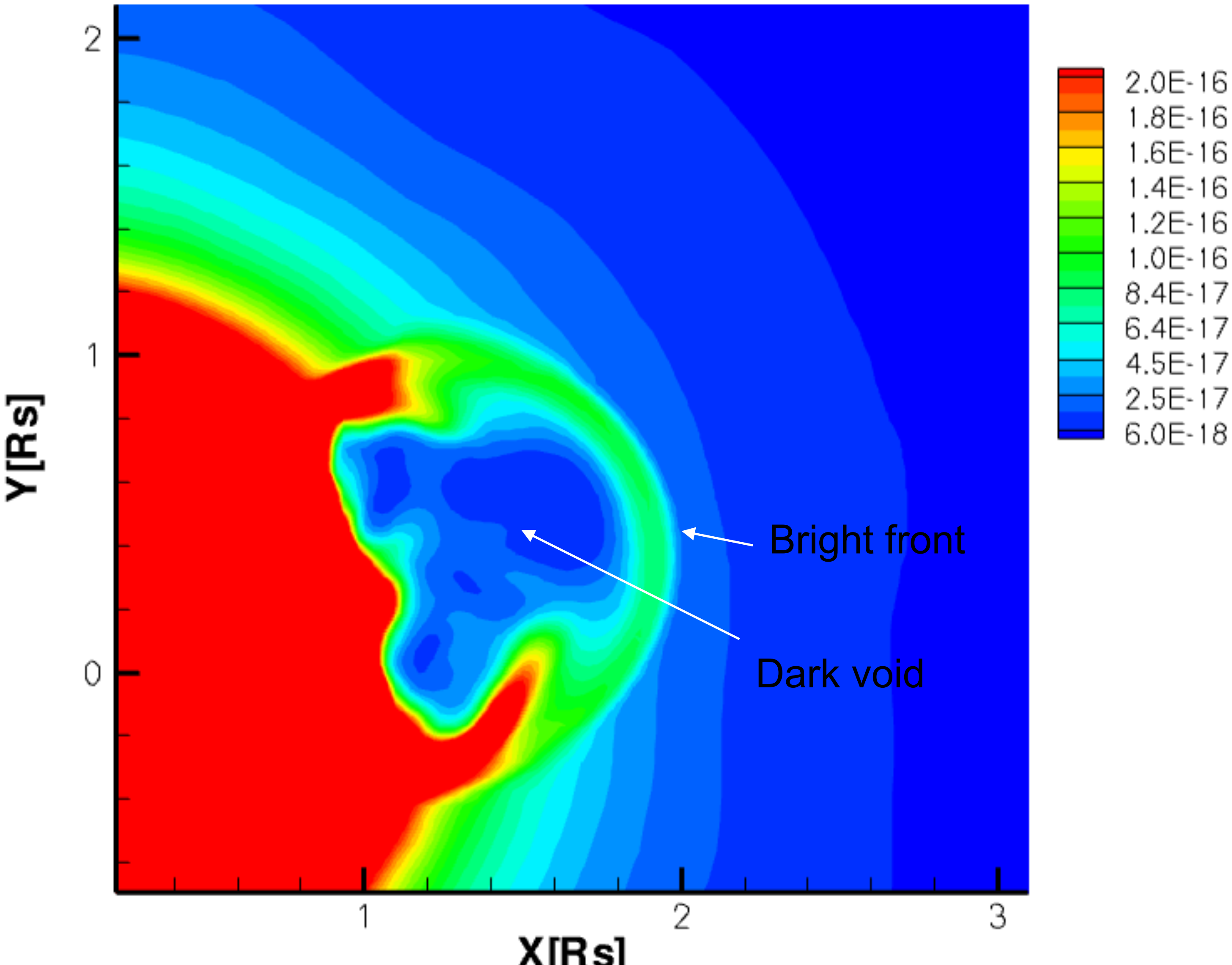
Flows in the CME sheath are sensitive to B_{ejecta}, and can be used as a diagnostic for its orientation

Evolution of a Flux Rope in the Lower Corona



Liu et al. ApJ (2008)

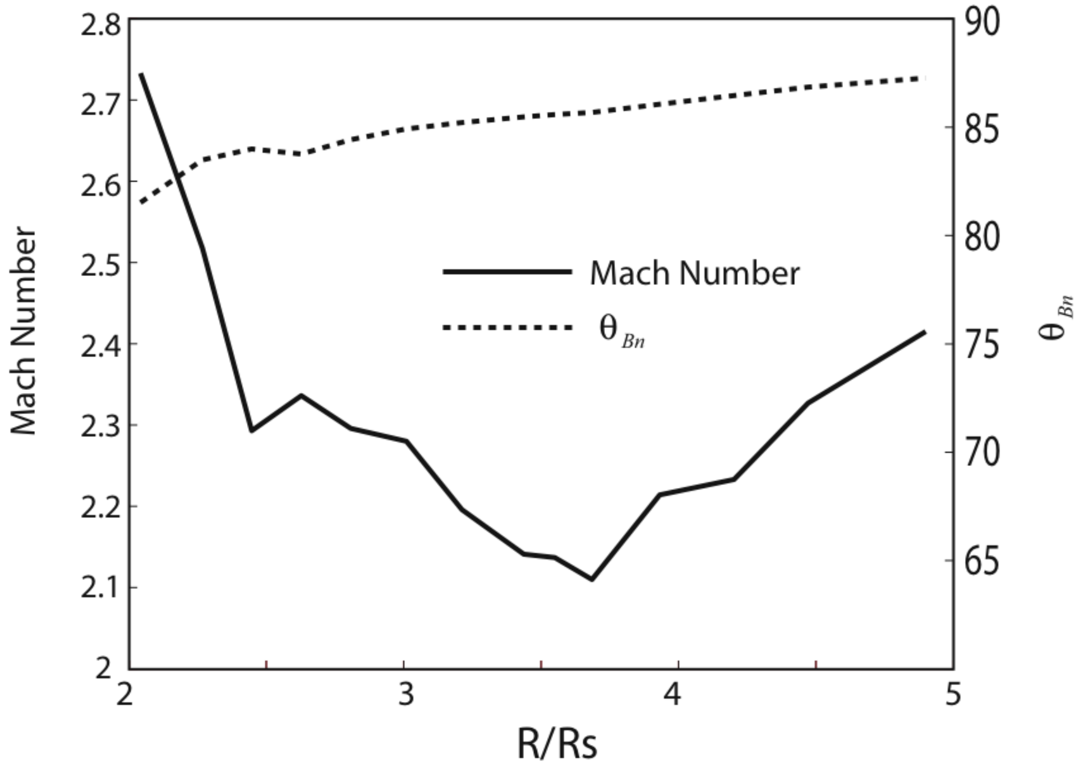
Bright Front and Dark Void



2D slice at Z=0.11

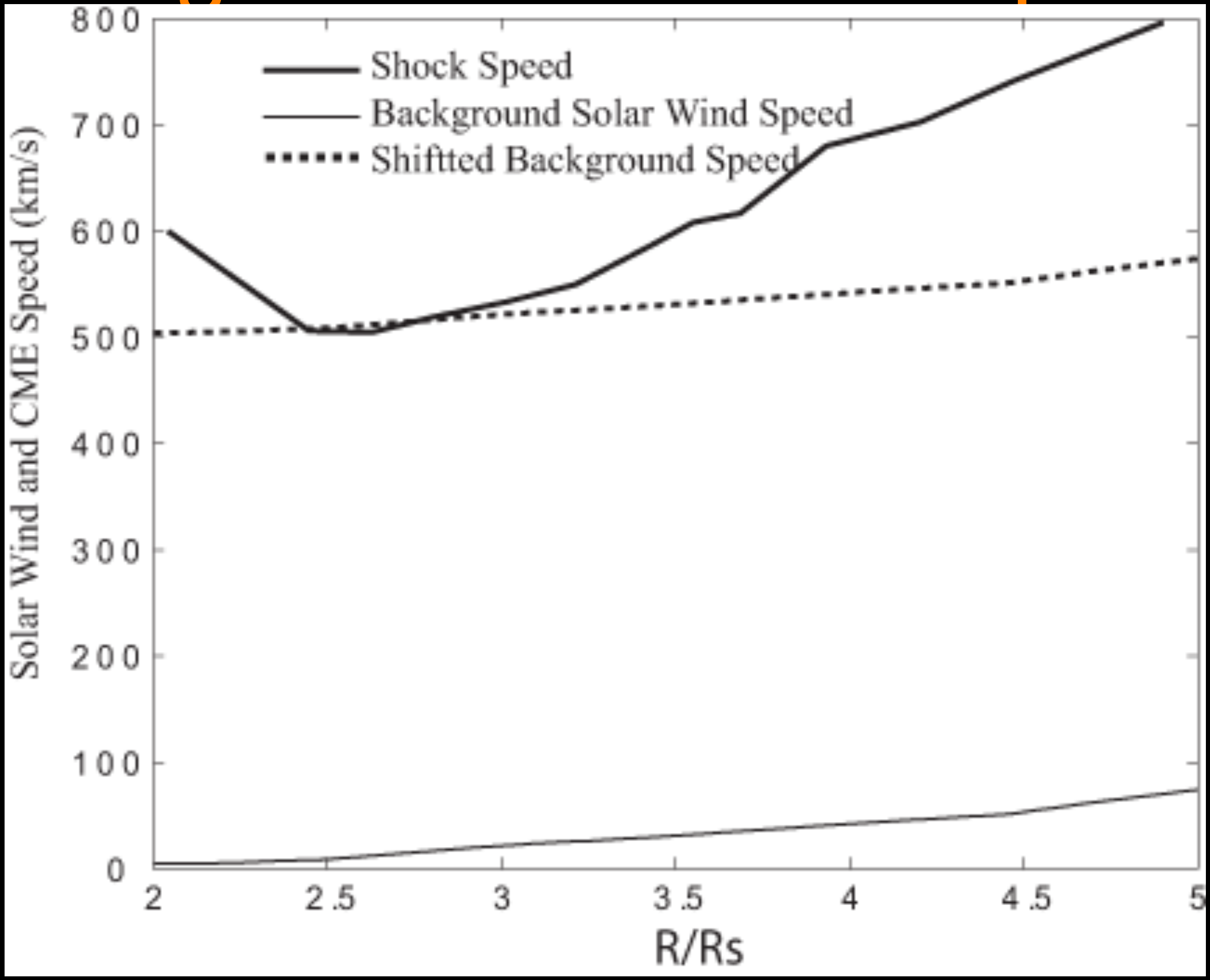
t=10 minutes

CME: near the nose: Quasi-Parallel Shocks

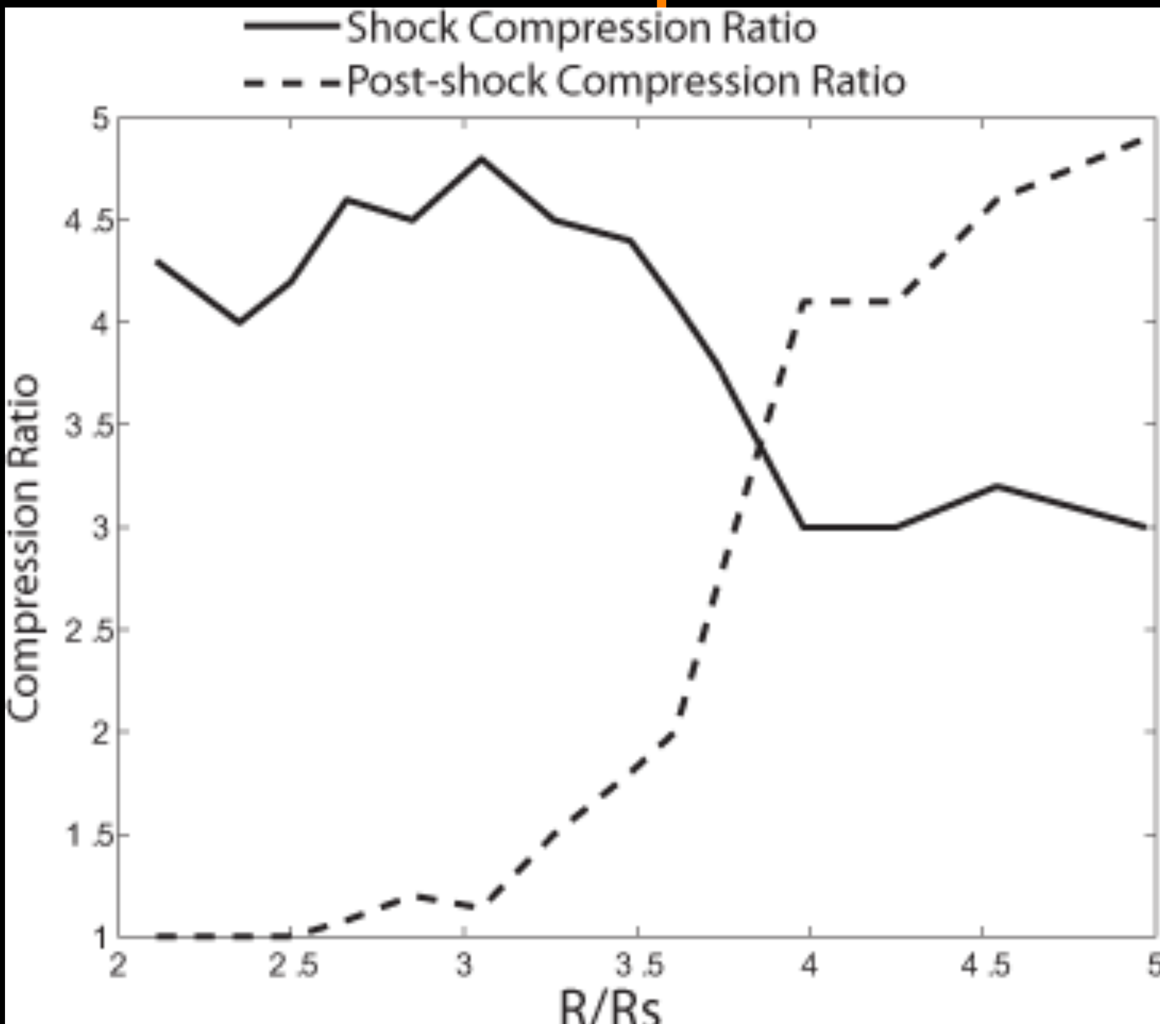


Liu et al. ApJ 2008

Shock Speed and the background solar wind speed

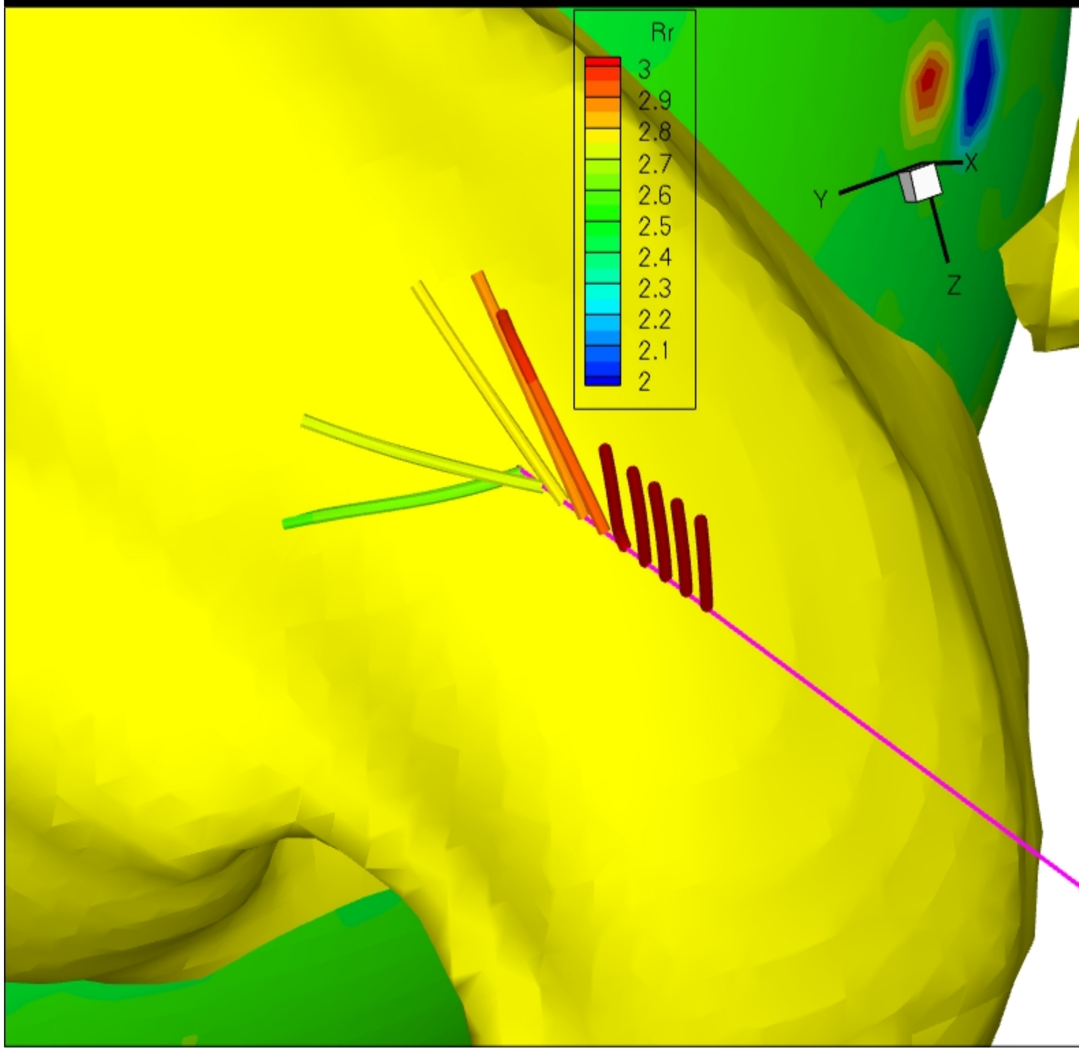


Shock and Post Shock Compression Ratio



The post shock acceleration exists in 3-5 Rs

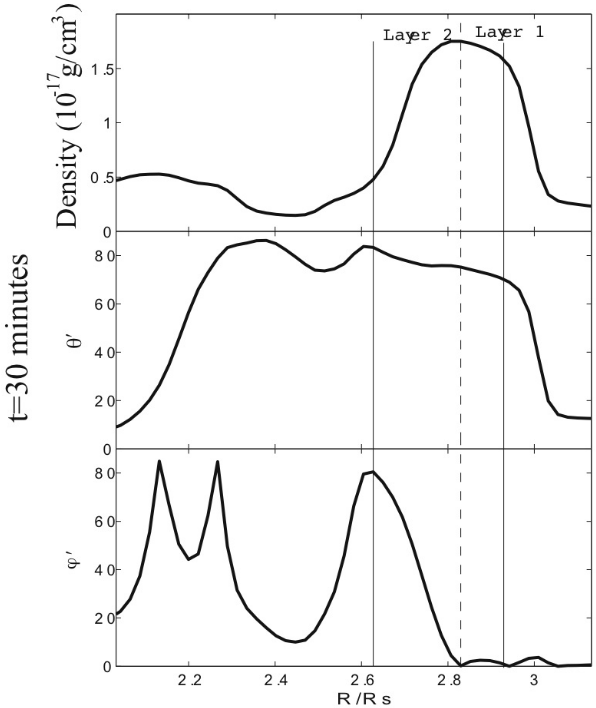
Evolution of Flows, Field Lines in CME sheath

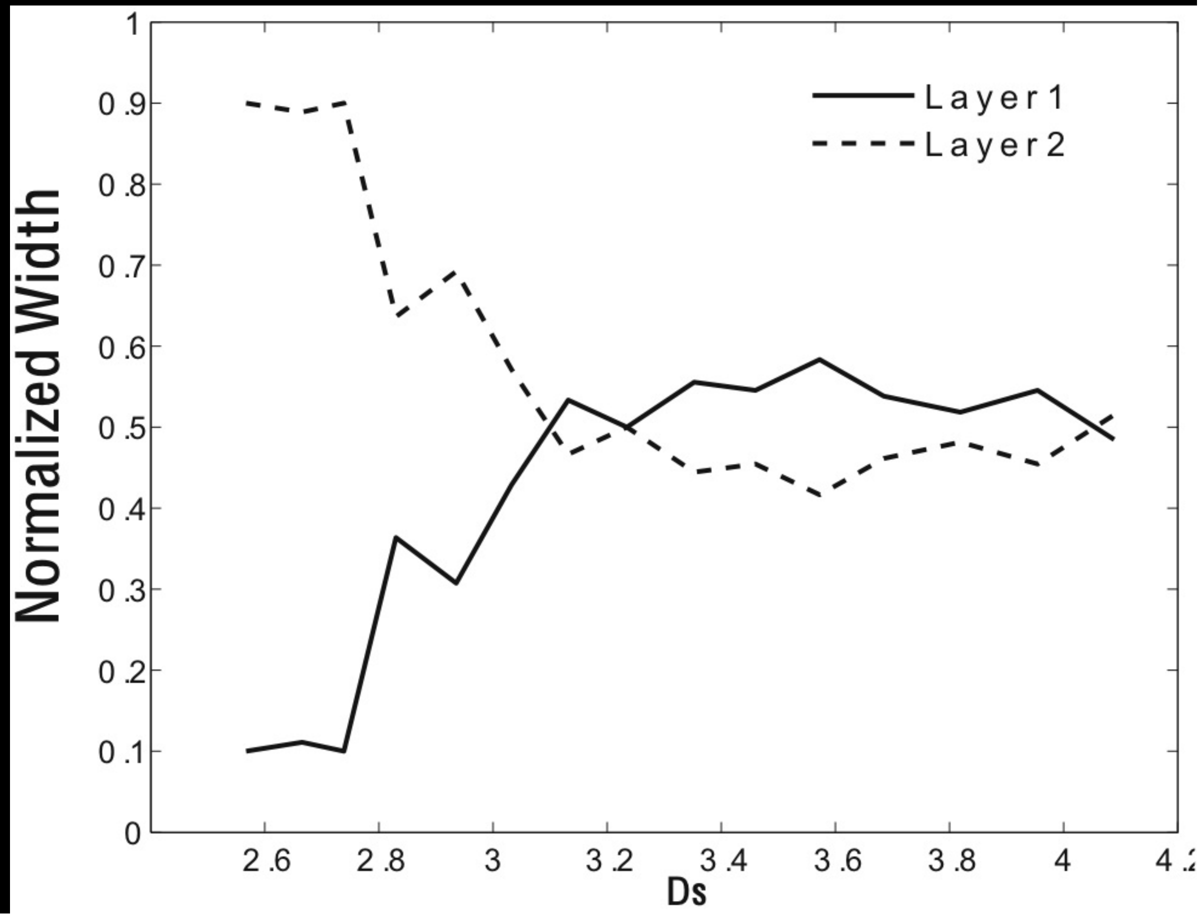


Magnetic Field Lines Rotation

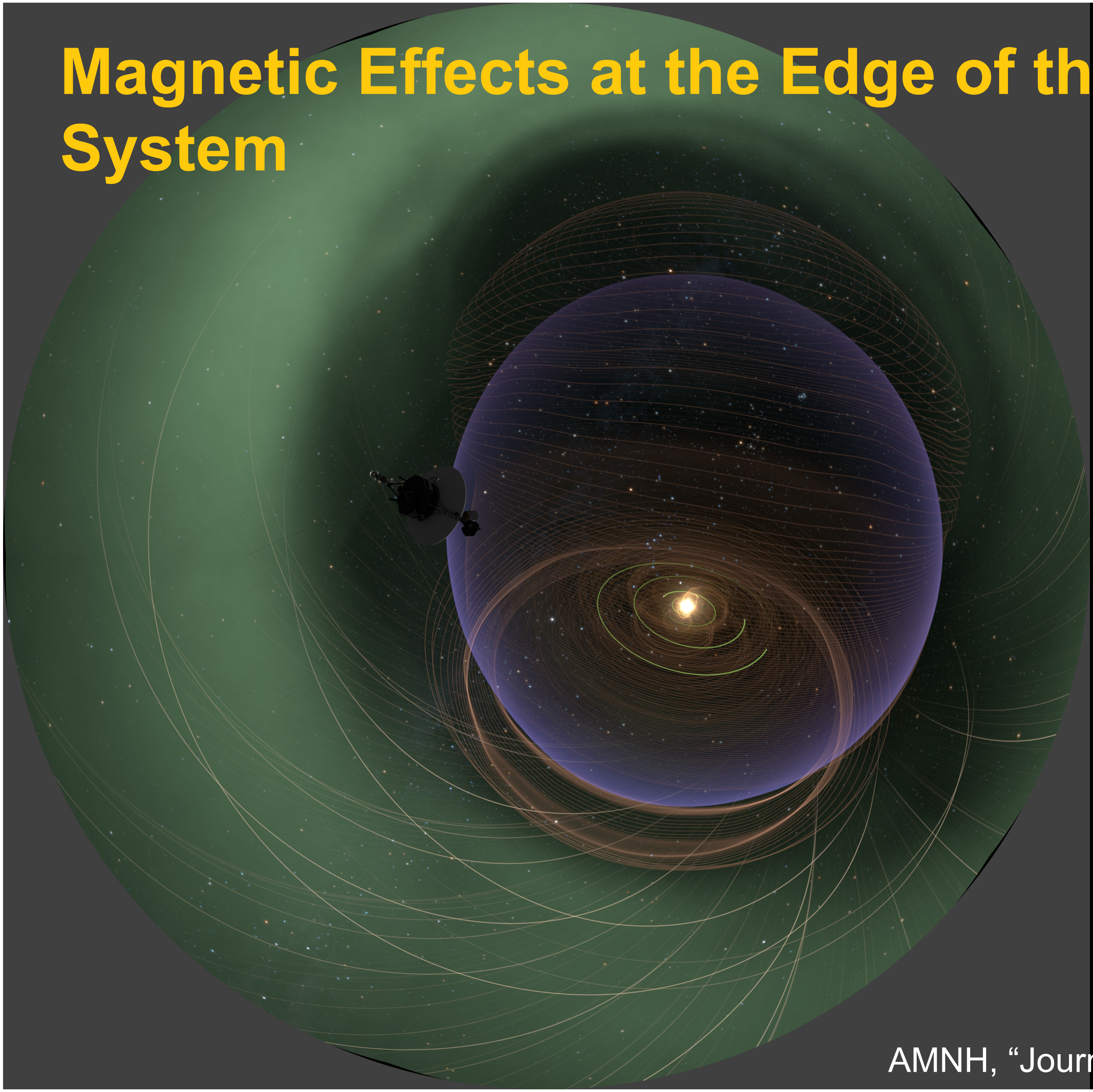
Liu et al. A&A 2010

Behavior of the
Magnetic Field in the Sheath





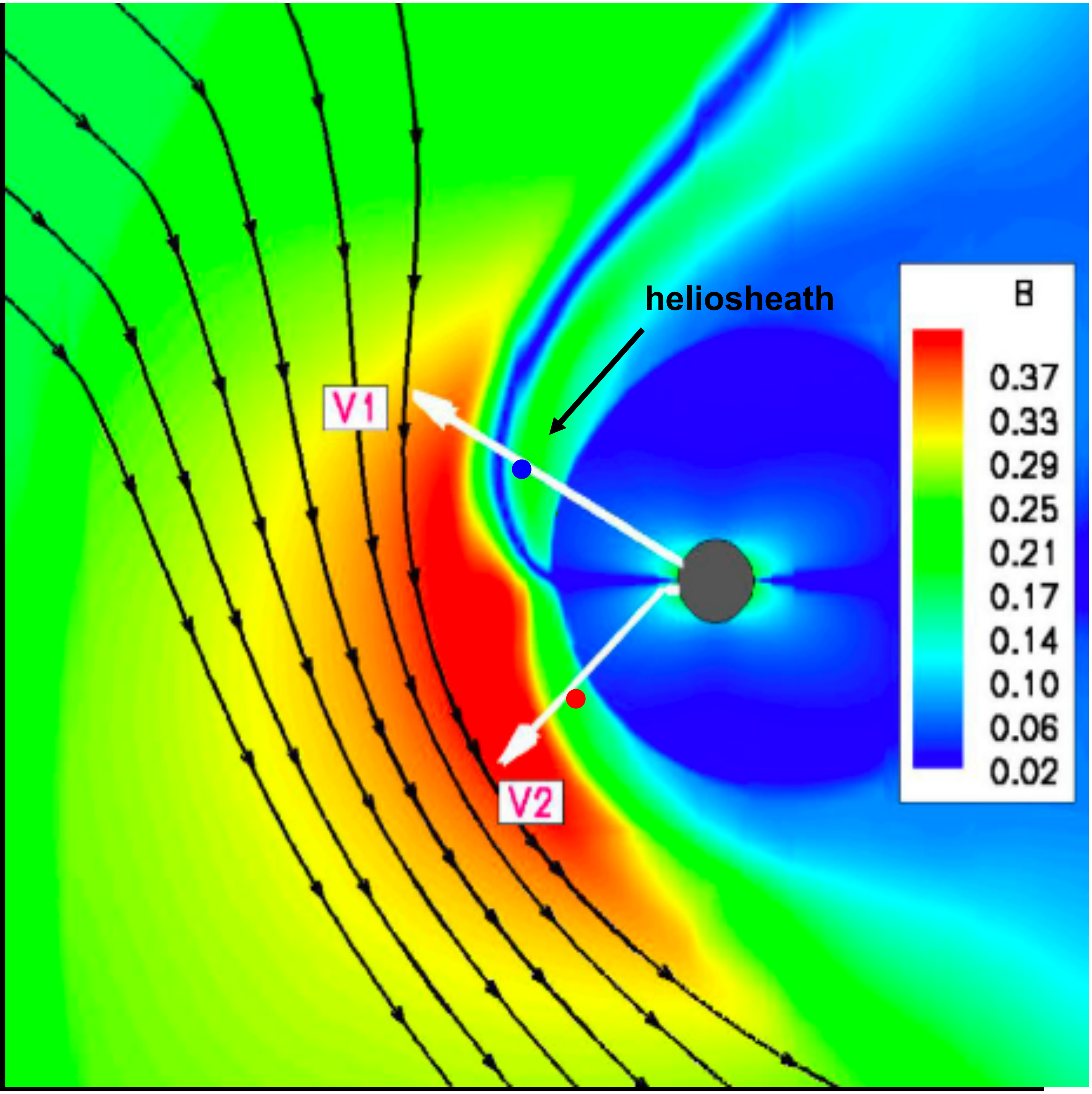
Magnetic Effects at the Edge of the Solar System



AMNH, “Journey to the Stars”, 2009

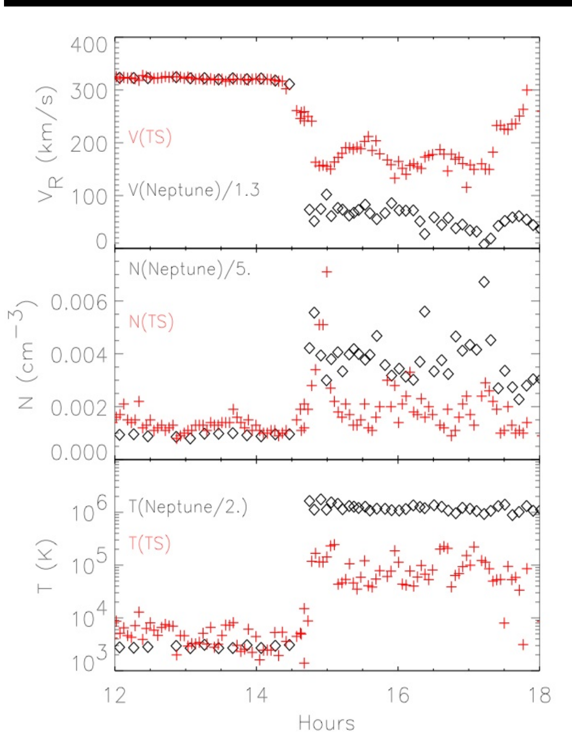
V1 is beyond 100 AU at 34.1° (latitude) and 173° (longitude) (HGI coord).

V2 is beyond 90 AU at -26.2° (latitude) and 216° (longitude)



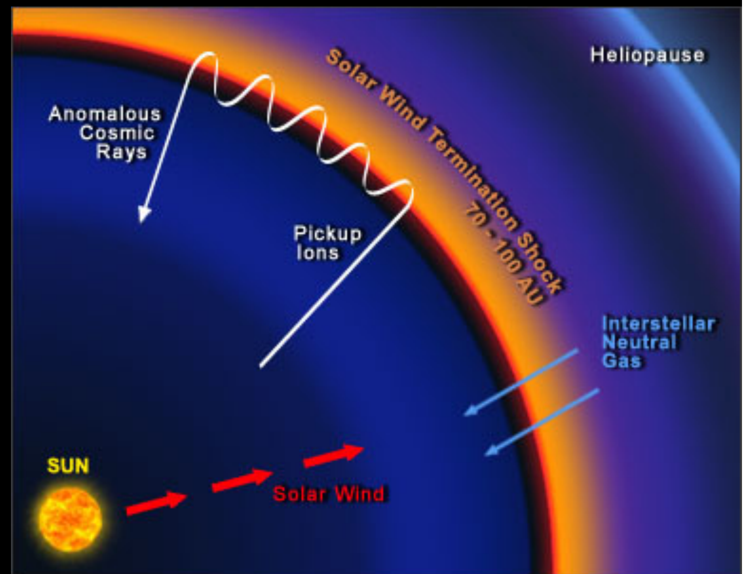
Paradigm Shift

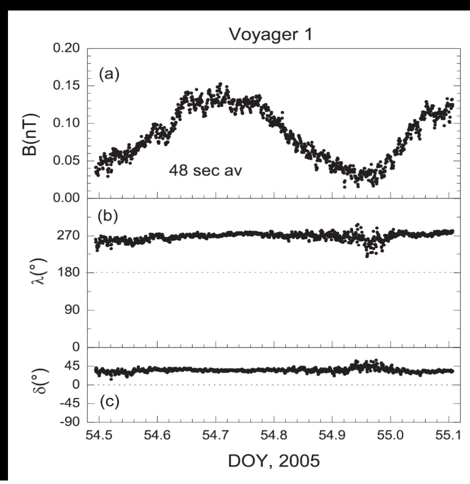
Importance of tails



Shock is colder than expected

Particle acceleration





No evidence of the source of anomalous cosmic rays

Magnetic holes

Bulaga et al. 2007

Heliospheric Asymmetries

-Position of the Termination Shock at V1 and V2

-Particle Data: Streaming Ions from the shock (TSPs)

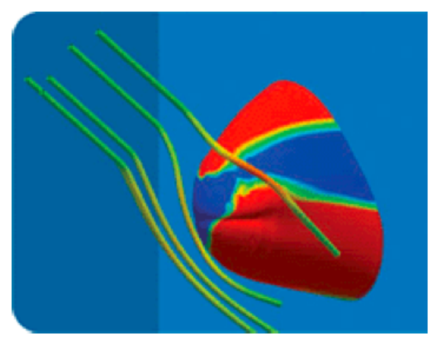
-Radio Data: 2-3kHz

-Flows in the Heliosheath at V2

Opher, et al *ApJL* 2006
Opher et al. *Science* 2007
Opher *et al Nature* 2009
Prested et al.JGR 2010

Science 11 May 2007:
Vol. 316. no. 5826, p. 793
DOI: 10.1126/science.316.5826.793a

THIS WEEK IN *SCIENCE*



The two Voyag
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bubble that en
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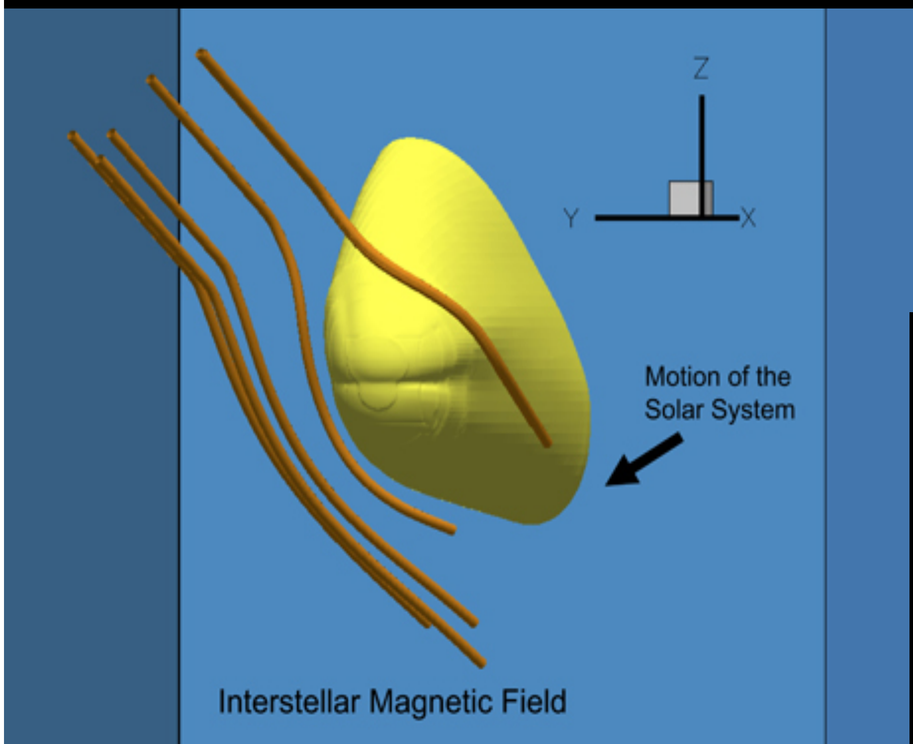
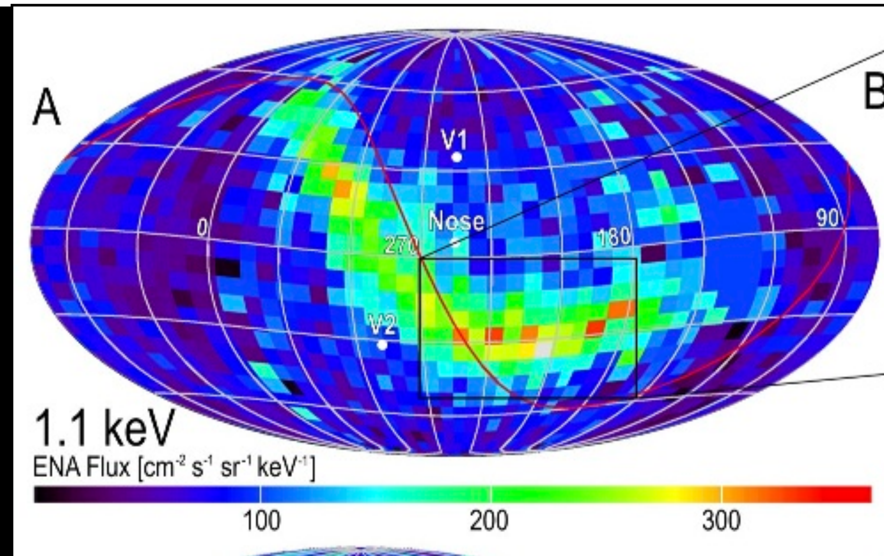
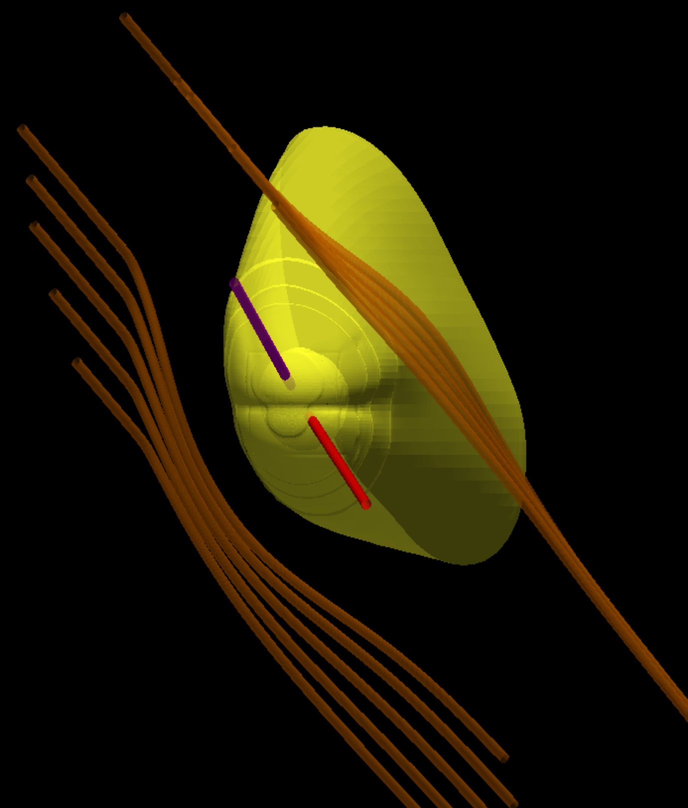
direction of the
field in this reg
the local field introduces asymmetries that affect the lo
emission and the streaming direction of ions from the t
the solar wind. Others have assumed that the magnetic
the galactic plane, as it is on large scales in the Milky W

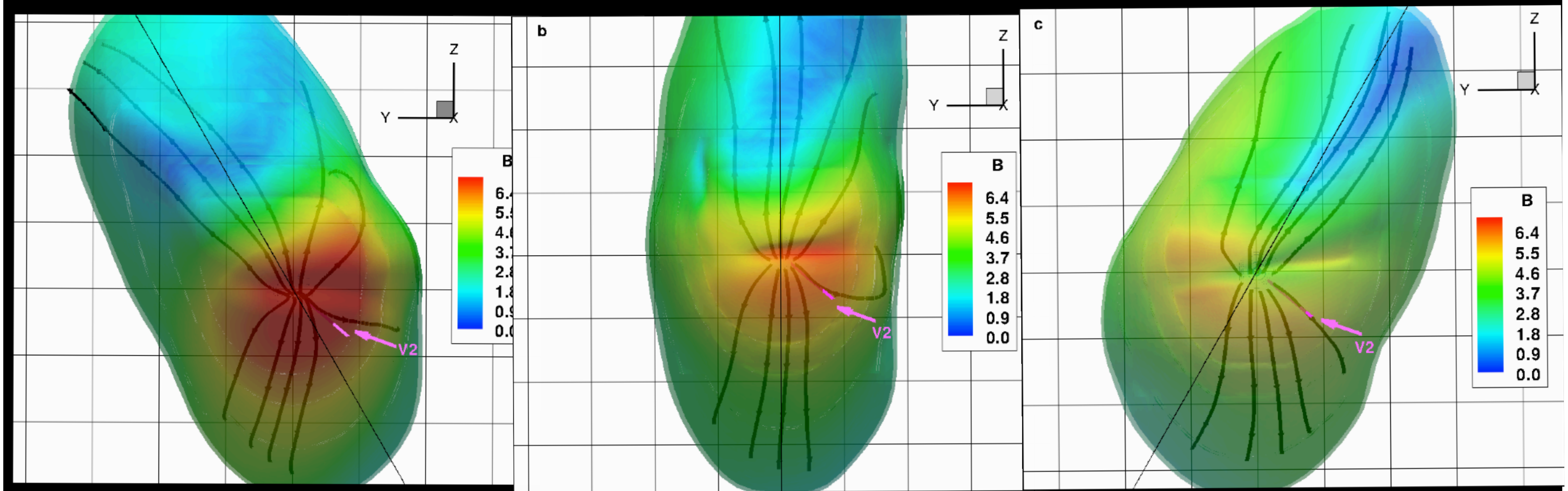
Importance of Magnetic Field







Heliosheath Flows

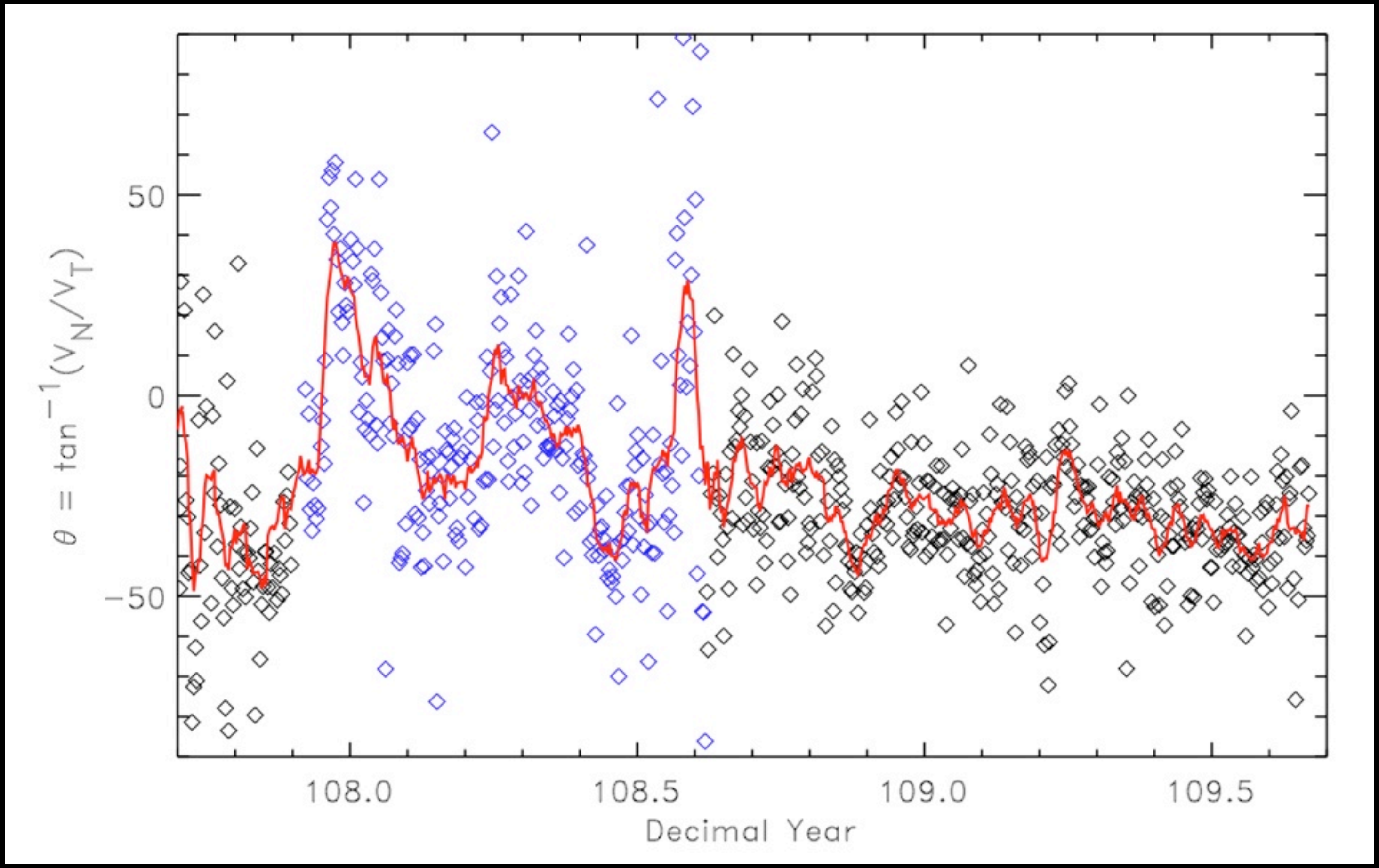


Subsonic flows sensitive to the boundary ahead

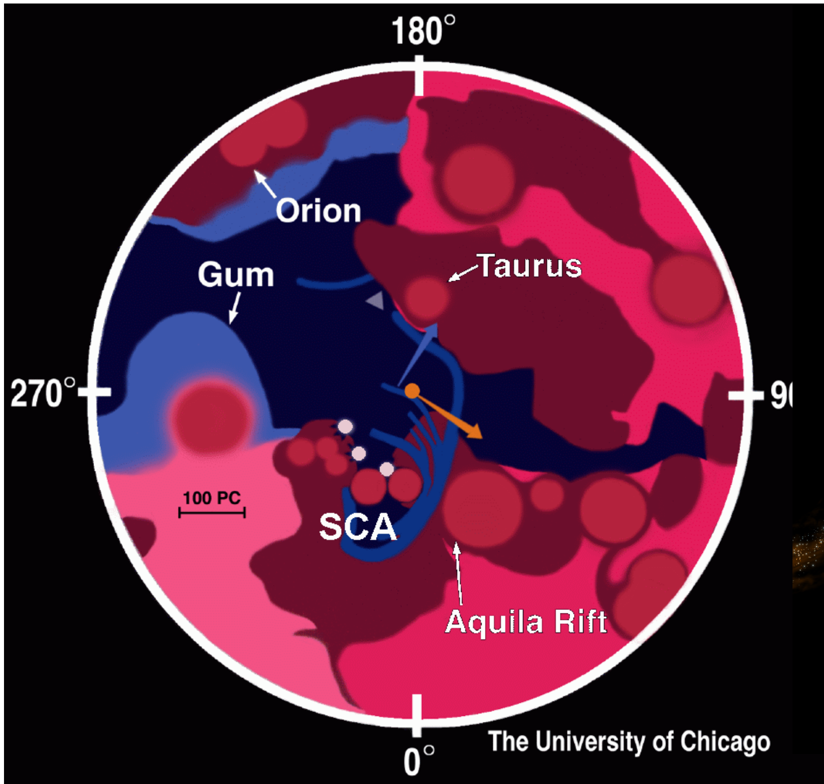
Opher et al. *Nature* (2009)

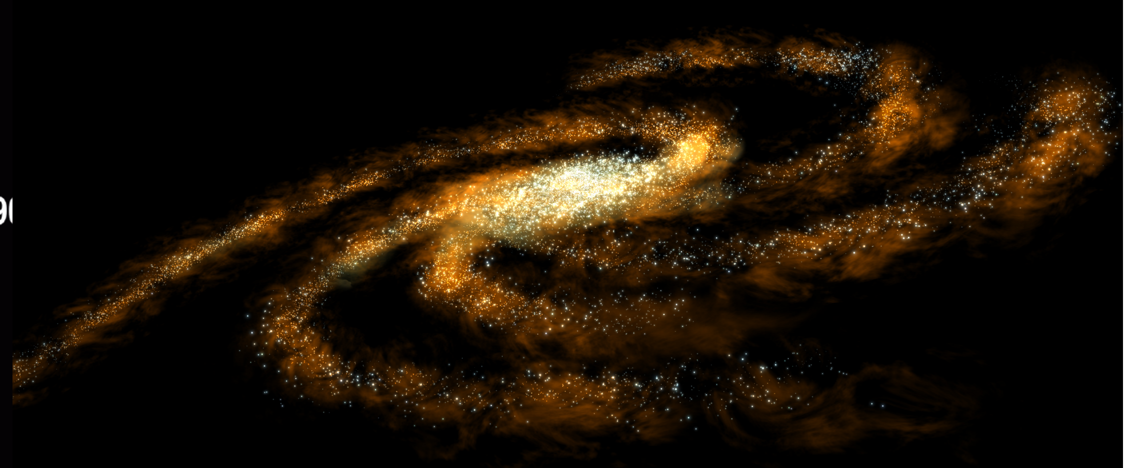
Model with ionized+neutral H (5 fluid model)

The flow angle $\theta=\tan^{-1}(V_N/V_T)$ in the Heliosheath from day 277 of 2007 to day 245 of 2009

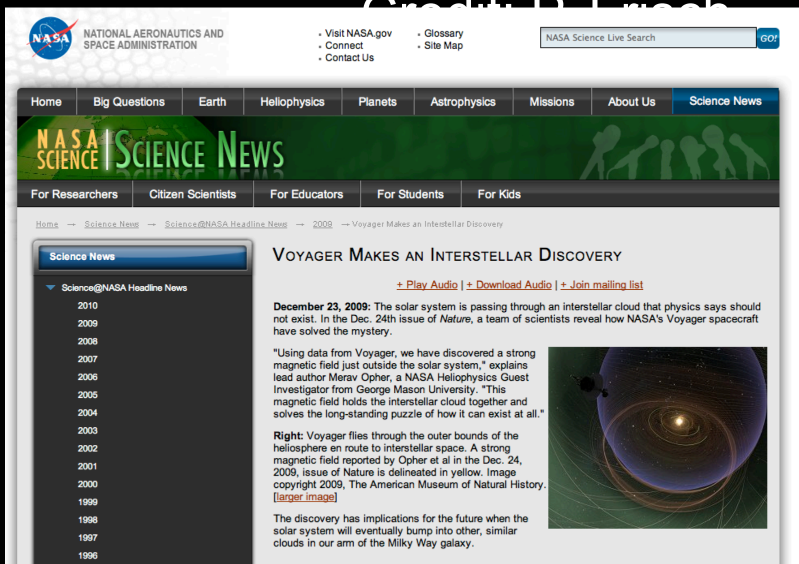


The period between 2007.95 and 2008.62 (blue points) seems to be dominated by transients





Credit: P. Frisch



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Voyager Makes an Interstellar Discovery

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December 23, 2009: The solar system is passing through an interstellar cloud that physics says should not exist. In the Dec. 24th issue of *Nature*, a team of scientists reveal how NASA's Voyager spacecraft have solved the mystery.

"Using data from Voyager, we have discovered a strong magnetic field just outside the solar system," explains lead author Merav Opher, a NASA Heliophysics Guest Investigator from George Mason University. "This magnetic field holds the interstellar cloud together and solves the long-standing puzzle of how it can exist at all."

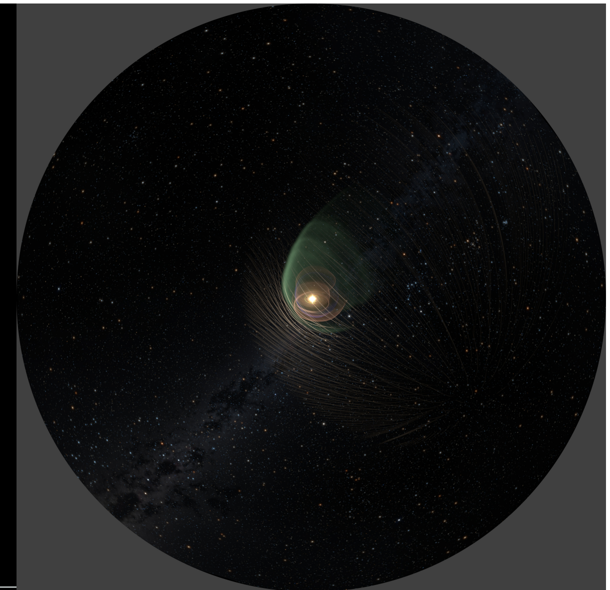
Right: Voyager flies through the outer bounds of the heliosphere en route to interstellar space. A strong magnetic field reported by Opher et al in the Dec. 24, 2009, issue of Nature is delineated in yellow. Image copyright 2009, The American Museum of Natural History. [larger image]

The discovery has implications for the future when the solar system will eventually bump into other, similar clouds in our arm of the Milky Way galaxy.

Astronomers call the cloud we're running into now the Local Interstellar Cloud or

This suggests that the interstellar magnetic field in the
Local Interstellar Cloud differs from a larger-scale
Interstellar magnetic field

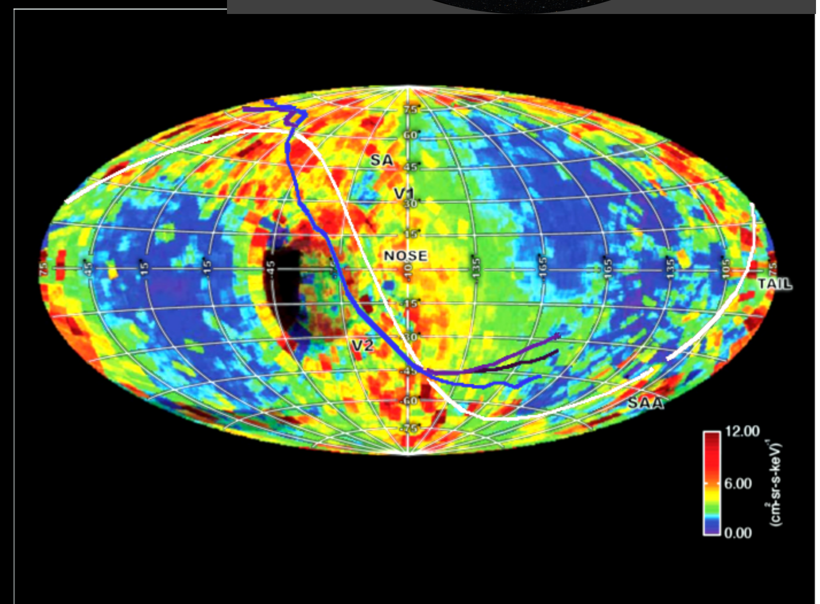
More Open Questions



Tilted Heliospheric Current Sheet

Role of reconnection; turbulence, solar cycles

(Opher, Drake, Swisdak 2010)



Acceleration of particles

Role of tails (pickup ions)

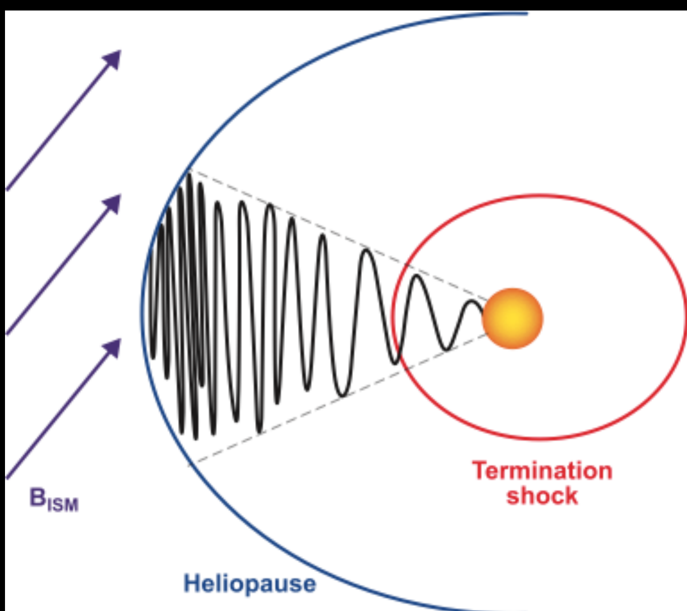
Kinetic neutrals-MHD

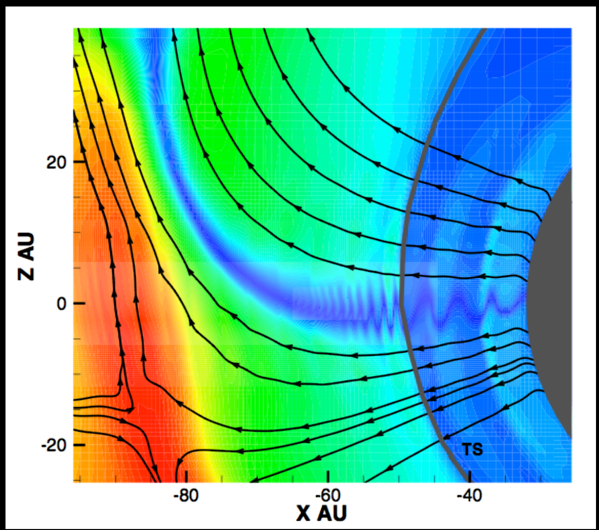
Krimigis et al.

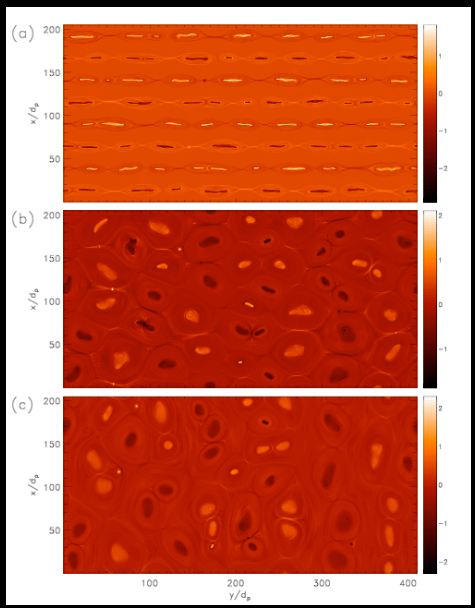
(Alouani, Opher, Izmodenov 2010)

Dissipation of the sectored heliospheric magnetic field: a mechanism for the generation of ACRS

Drake, Opher, Swisdak, ApJ 2009; Lazarian & Opher ApJ 2009





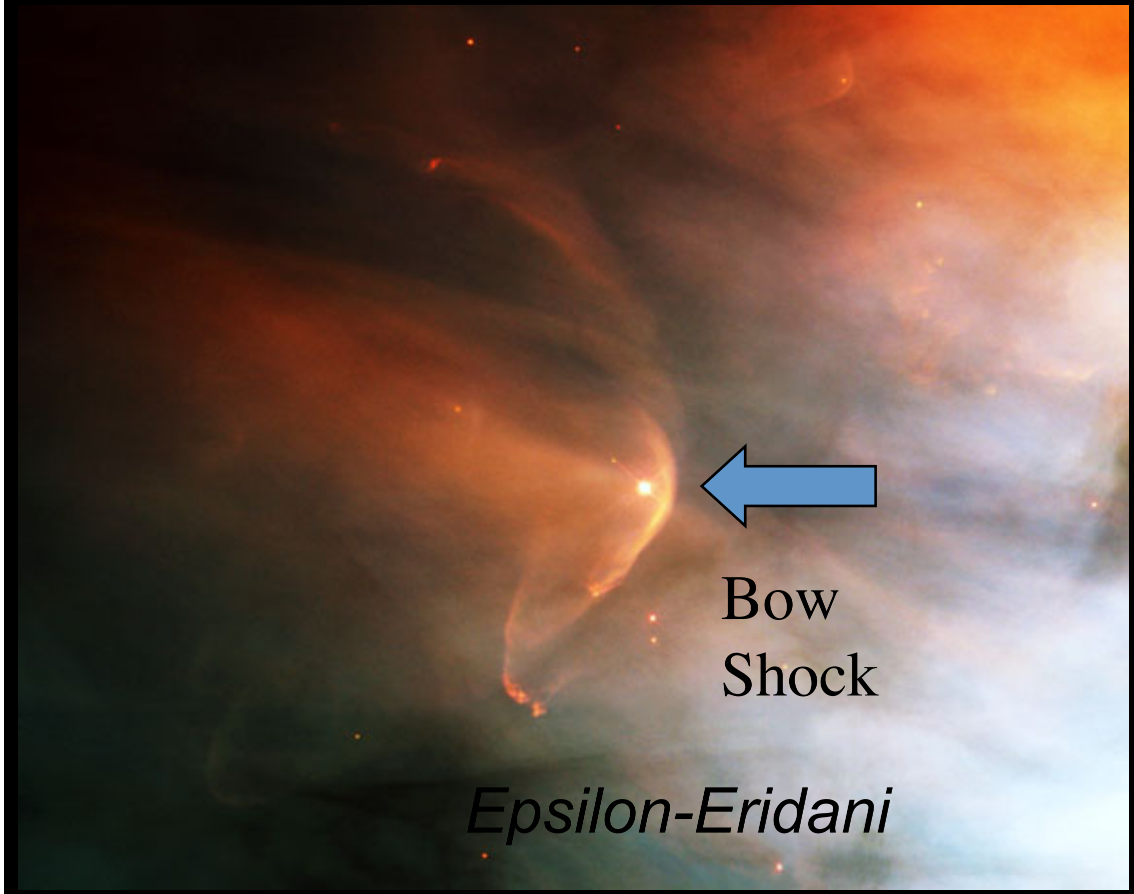


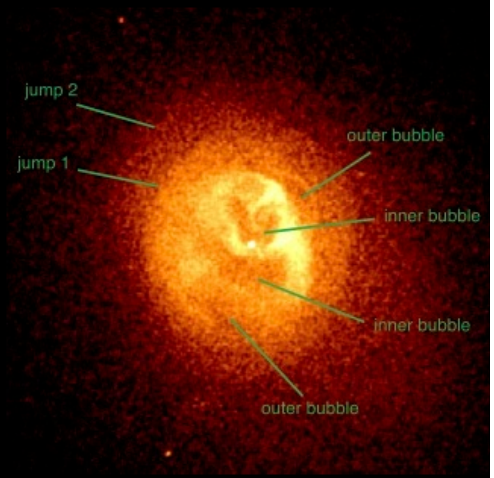
MHD

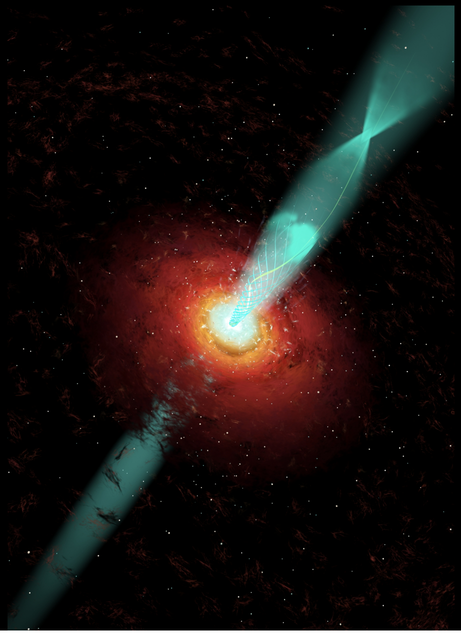
PIC

example of MHD-coupled with PIC code

Learning from the heliosphere about astrospheres and shocks







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