Heliophysics Shocks

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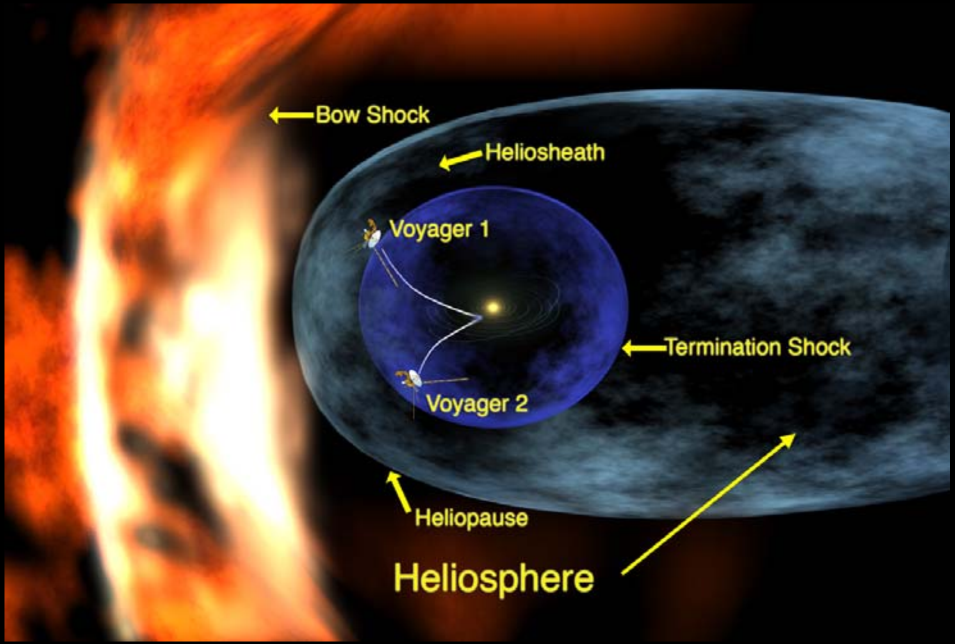

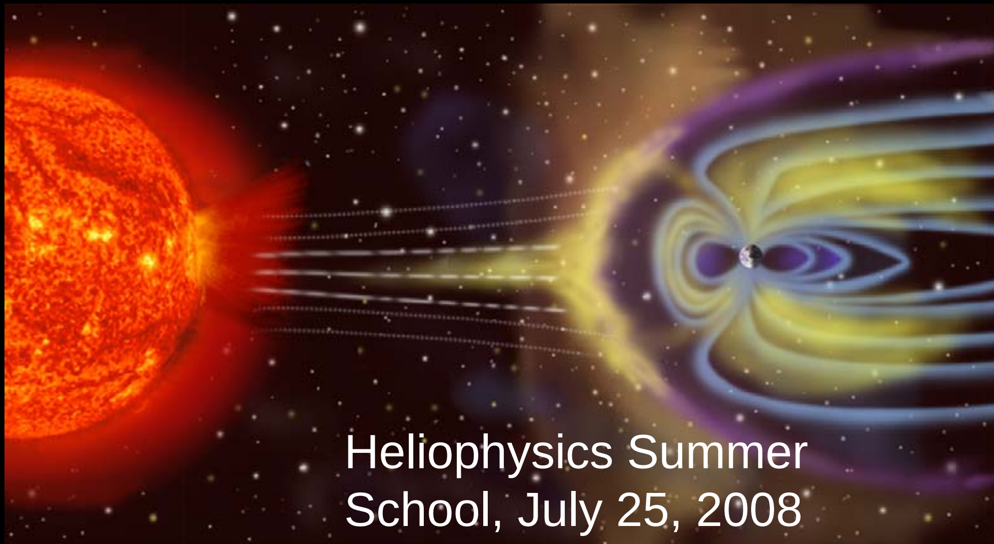

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Heliophysics Summer School, July 25, 2008

Outline

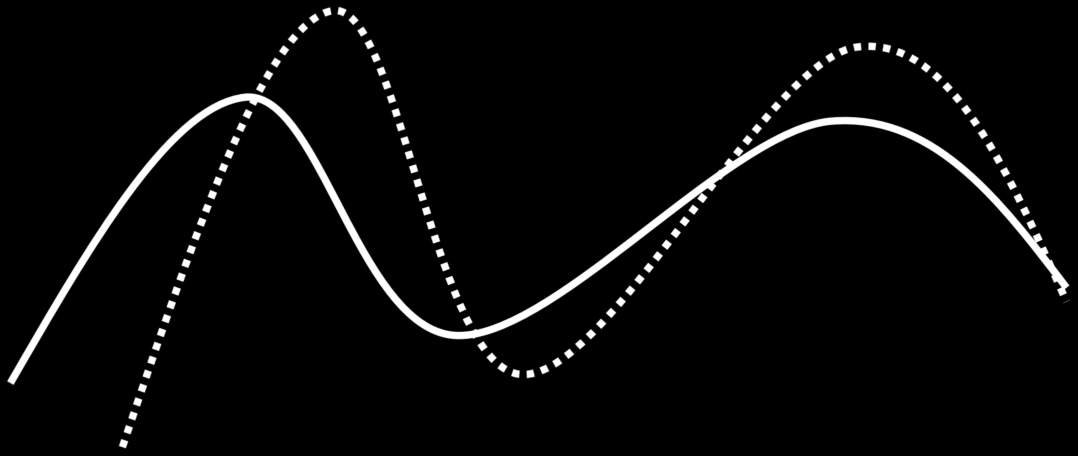
1. Why Shocks Happen: Non Linear Steepening
2. MHD jump conditions: Rankine-Hugoniot jump conditions
3. Definition and Classification of Shocks
4. Perpendicular shocks
5. Parallel shocks
6. Examples: Coronal Shocks; CME Driven Shocks; Planetary Shocks; Termination Shock Heliopause

References

- Opher, M.- Lectures 11,12,13 of *"Space Physics" http://physics.gmu.edu/~mopher*
- *Space Physics, An introduction to plasma and particles in the heliopshere and magnetosphere by May-Britt Kallenrode*
- *Interplanetary Magnetohydrodynamics by Len F. Burlaga*
- *Introduction to Plasma Physics with Space and Laboratory Applications by Donald A. Gurnett and Amitava Bhattacharjee*

Why Shocks Happen: Non Linear Steepening

- When waves moves faster than the ambient medium there is a steepening of front portion of the wave mode. Small amplitude limit the profile of an MHD wave doesn't change as it propagates
- But even a small-amplitude wave will eventually distort due to “steepening” or “wave-steepening”



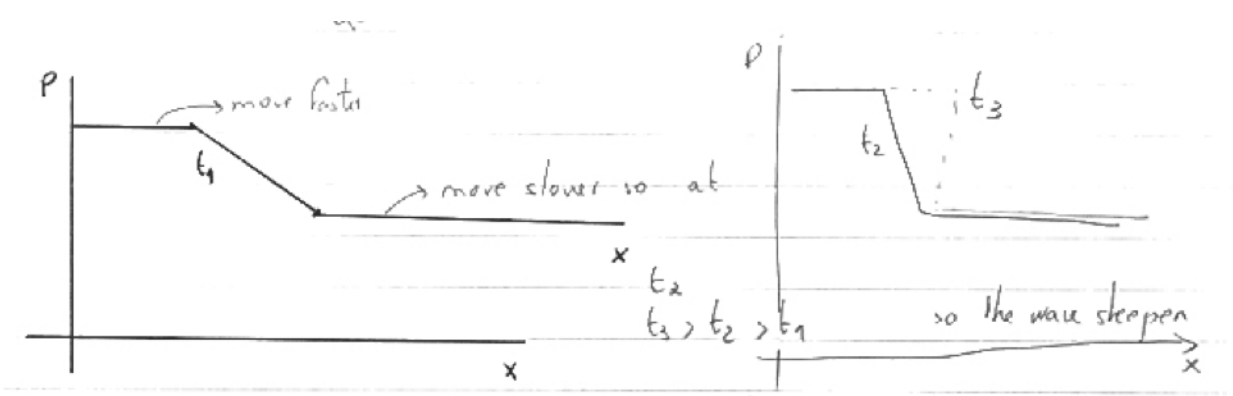
Example: propagation of sounds wave in an adiabatic medium

- Propagation of a sound wave is $v_S^2 = \frac{dP}{d\rho}$

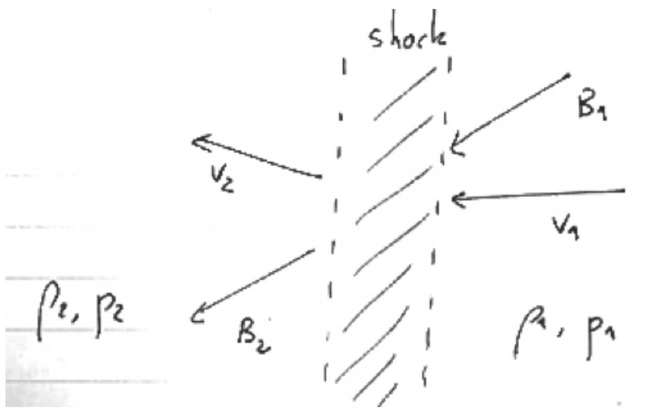
For an adiabatic equation of state:

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

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



- 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
- This is not surprising: ideal equations are valid when scales of variations are larger than mean free path.
- 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

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

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

(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

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

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

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

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

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

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

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

(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

Types of Discontinuities & Shocks

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

Contact Discontinuity

- Happens where there is no flow across the discontinuity, i.e, $U_n=0$ and $\{\rho\}\neq 0$

E.g. classic contact discontinuity

Vinegar
Olive oil

(a) If $Bn\neq 0$ contact discontinuity -> only the density Changes across the discontinuity (rarely observed In plasmas)

Tangential Discontinuity

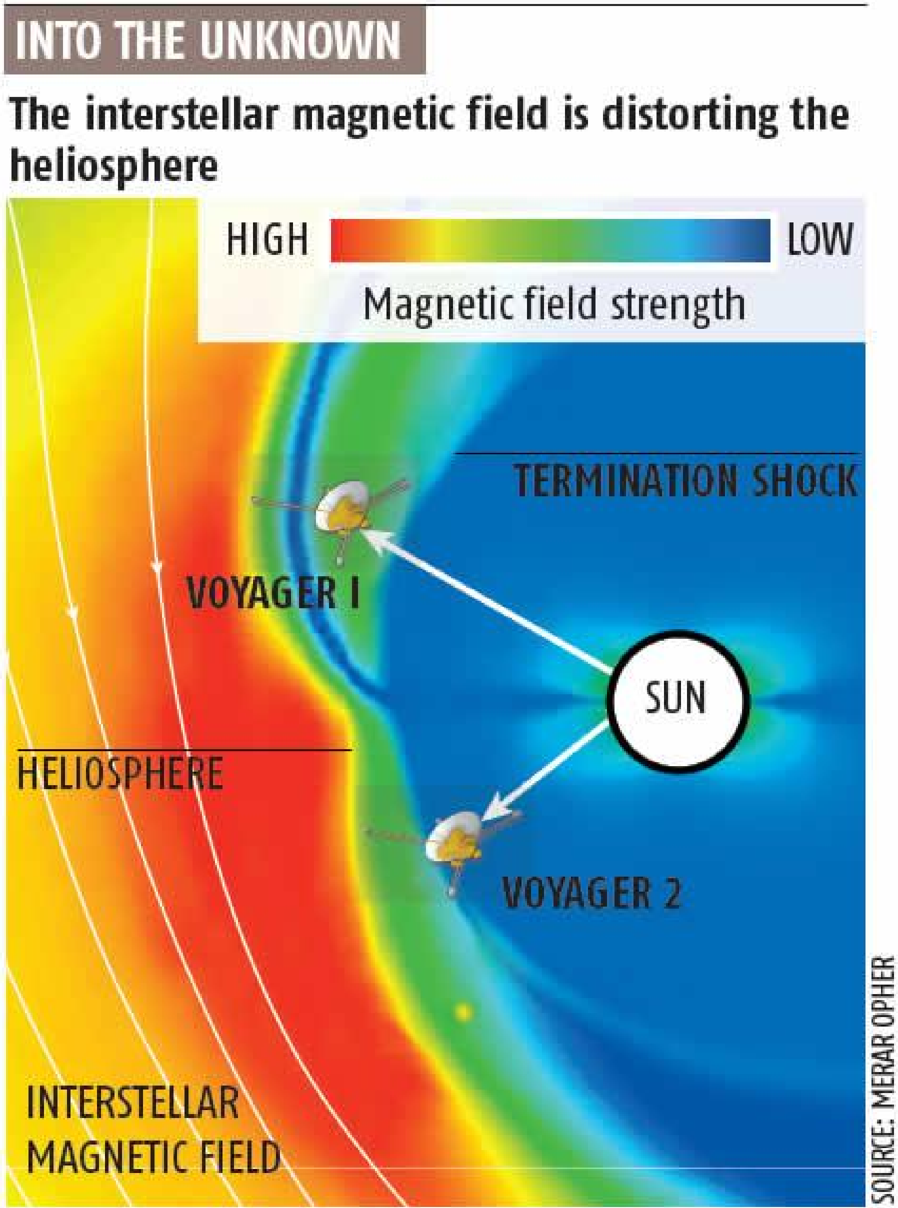
(b) When $B_n=0 \Rightarrow \{U_T\} \neq 0$

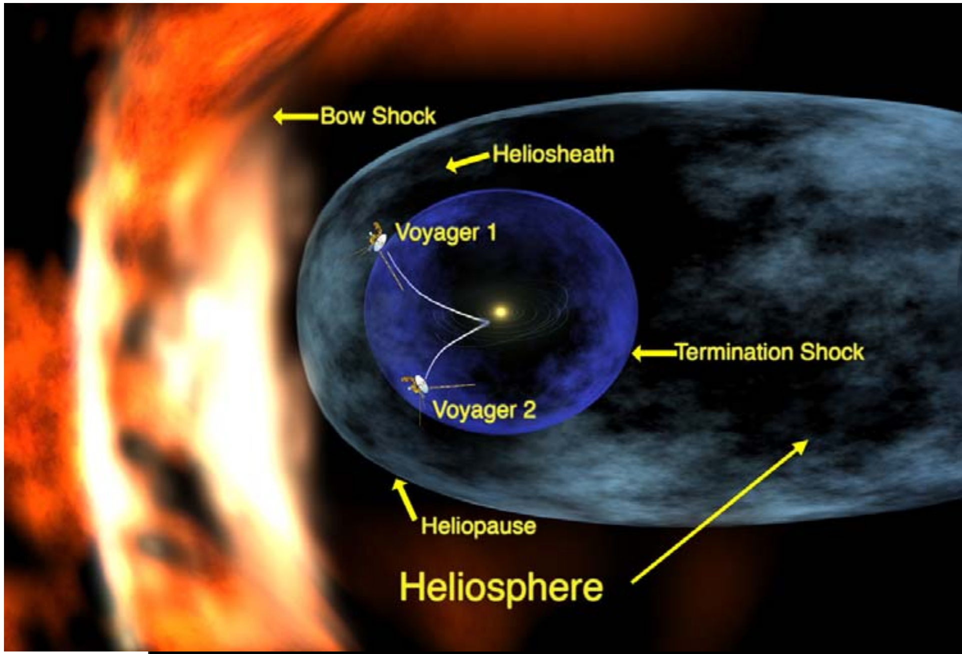
$\{B_T\} \neq 0$

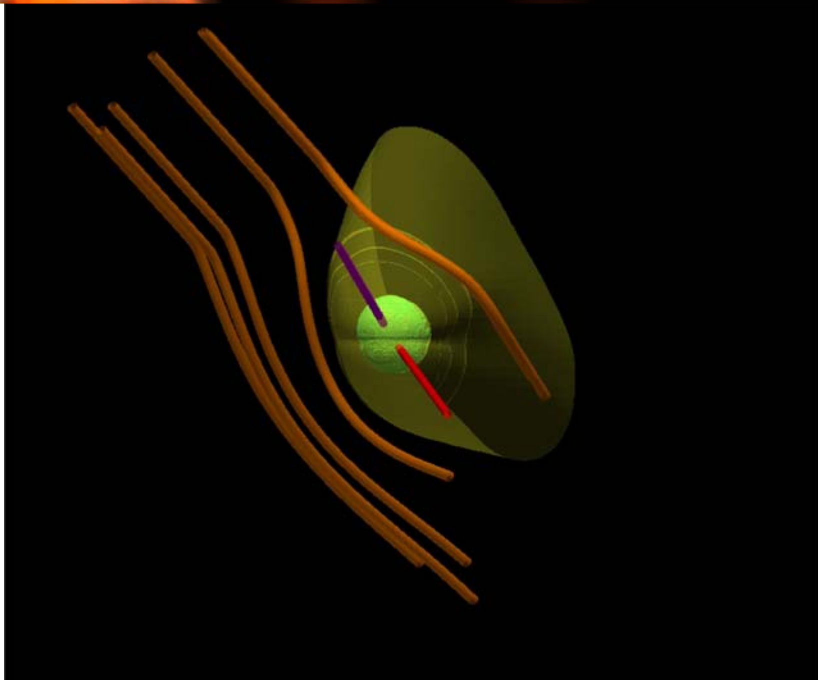
and $\{p+B^2/2\mu_0\}=0$

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.

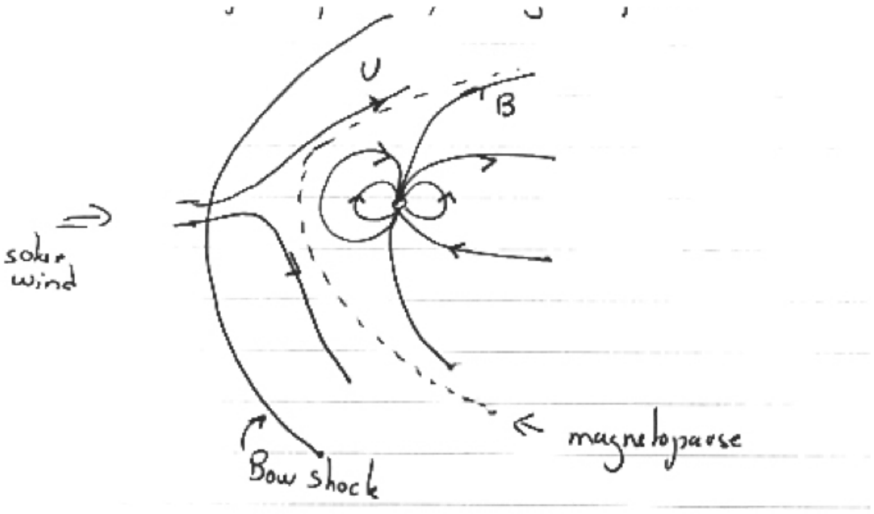
Heliopause: Tangential Discontinuity







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: $U_n \neq 0$ and $\{\rho\}=0$

From jump conditions (a) $\Rightarrow \{U_n\} = 0$ and $\left\{ p + \frac{B_T^2}{2} \right\} = 0$

$$V_1 \cdot \hat{n} = V_2 \cdot \hat{n} = V_n$$

$$\rho_1 = \rho_2$$

..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

SHOCK WAVES

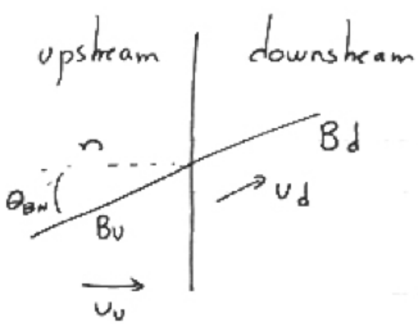
Shock waves are characterized by a fluid flows *across* the Discontinuity $U_n \neq 0$ and a non zero jump discontinuity $\{\rho\} \neq 0$

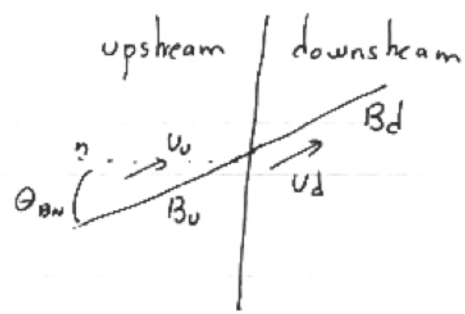
Frames of reference for MHD shocks:

(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)

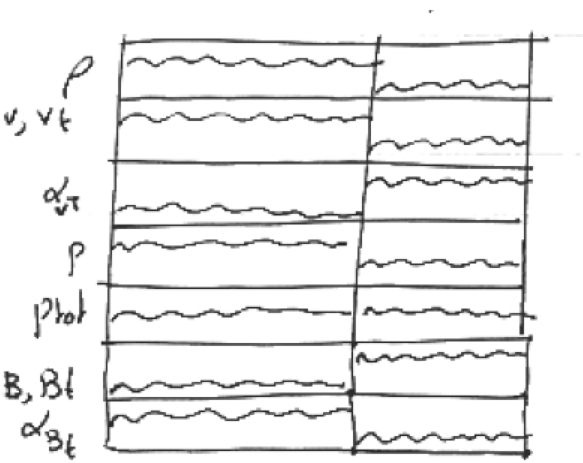
(I)



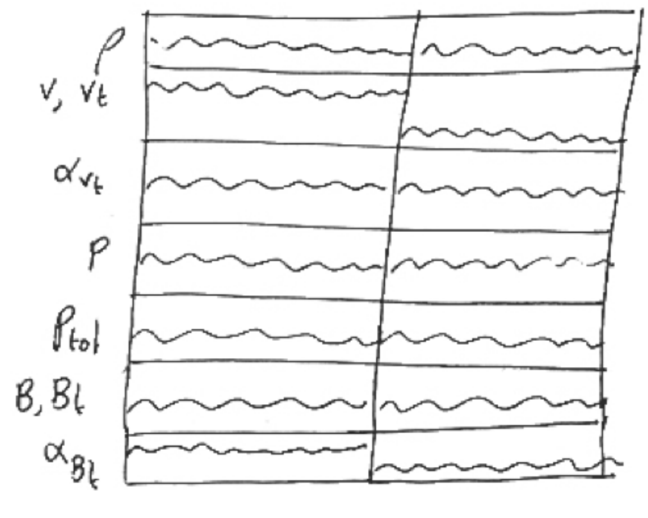


(II)

Question for class: which type of shock those are?

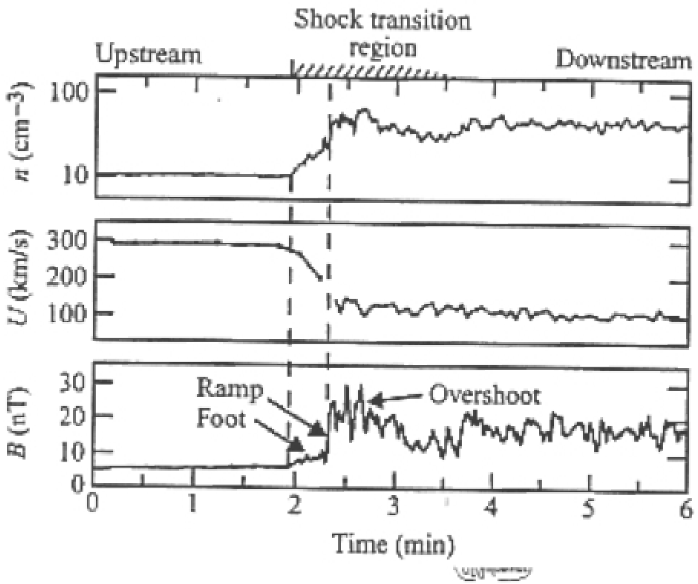


$\{p+B^2/2mu\}=0$ for TD



$\{\rho\}=0$ but $U_n \neq 0$ RD

Observations of MHD Shocks



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Earth Bow Shock (plot at a distance $15.4R_E$ upstream from Earth)
This example $\theta_1 = 76°$ (between B and n)
$U_1 = 294$km/s > $v_A = 37.8$km/s

Voyager 2 crossing the Termination Shock in August 2007

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

$$\left(U_{n1}^2 - \delta V_{A1}^2 \cos^2\theta_1\right)^2 \left[U_{n1}^2 - \frac{2\delta V_{S1}^2}{\delta+1-\gamma(\delta-1)}\right] - \delta \sin^2\theta_1 U_{n1}^2 V_{A1}^2 \left[\frac{2\delta-\gamma(\delta-1)}{\delta+1-\gamma(\delta-1)} U_{n1}^2 - \delta V_{A1}^2 \cos^2\theta_1\right] = 0$$

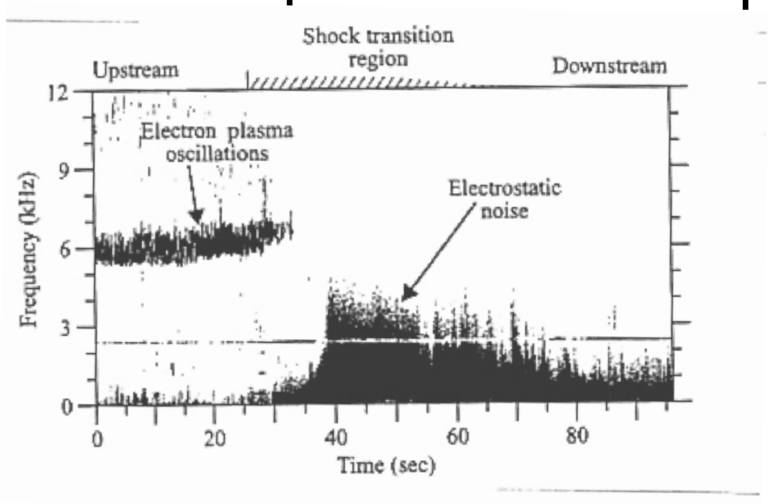
Type of Shocks

- Weak Shock Limit δ=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: θ=0°
- Perpendicular Shocks: θ=90°
- Quasi-perpendicular shocks θ>45°

Thickness of Shocks

- The thickness of the shocks and the details substructure within the shock depends on the angle θ, 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

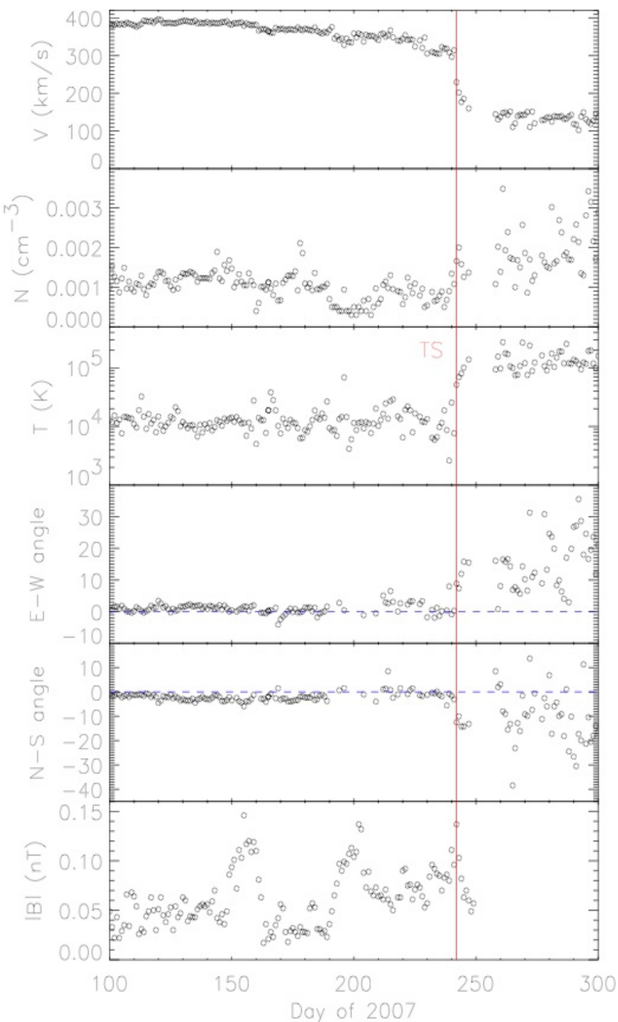


Broadband electric field noise:
Plasma wave turbulence excited
by unstable particle distribution in the shock

Jupiter's bow shock

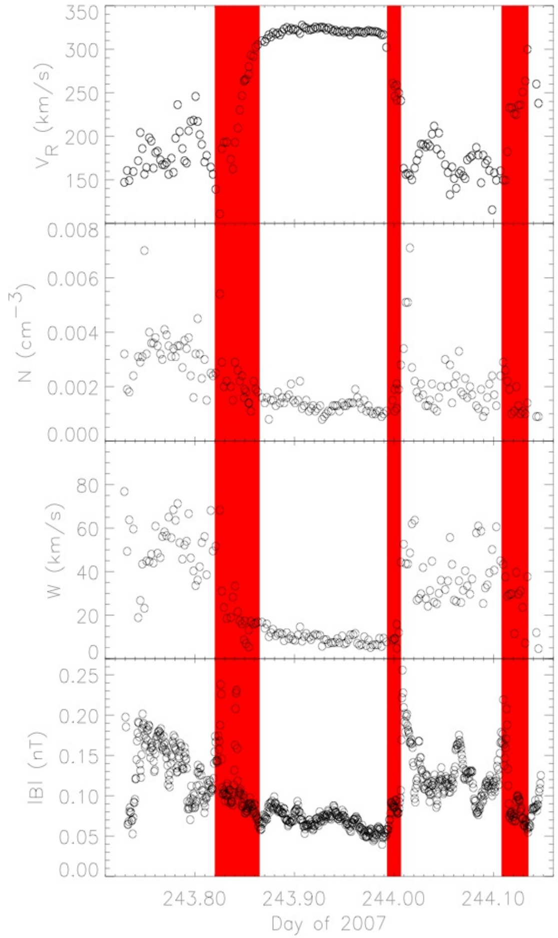
Narrow band at 6kHz:
Electron plasma oscillations
Excited by a beam
of electrons that escapes
into the region upstream
the shock

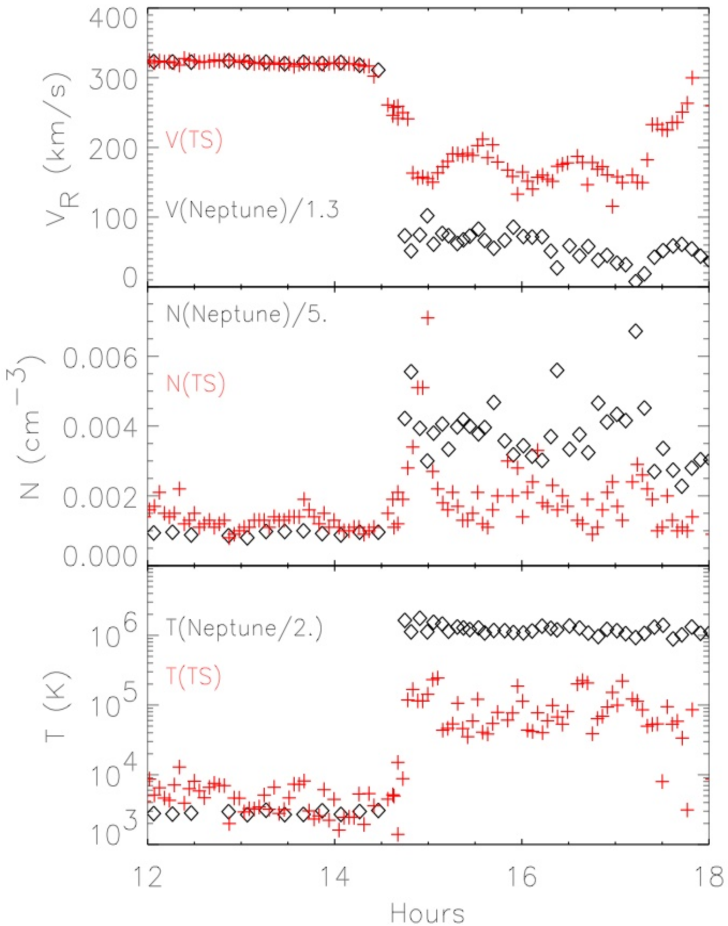
Termination Shock: Perpendicular Shock



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

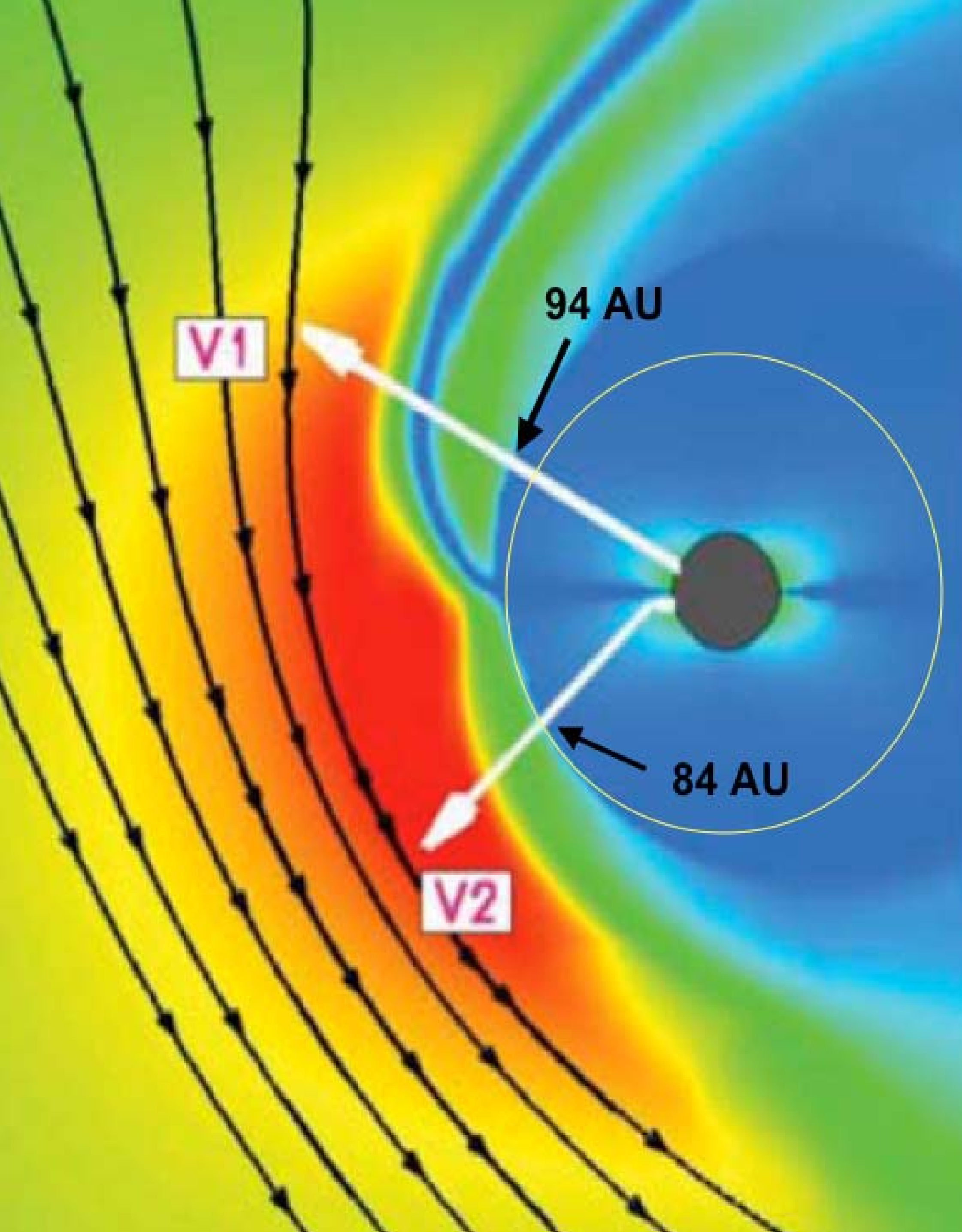
J.Richardson et al.





Several Crossings;
Shock is colder than expected

J.Richardson et al.



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

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Planetary Voyage: 1977 -1989

Jupiter

Voyager 2 Proves Solar System Is Squashed

San Francisco, CA. - NASA's Voyager 2 spacecraft has followed its twin Voyager 1 into the solar system's final frontier, a vast region at the edge of our solar system where the solar wind runs up against the thin gas between the stars.

However, Voyager 2 took a different path, entering this region, called the heliosheath, on August 30, 2007. Because Voyager 2 crossed the heliosheath boundary, called the solar wind termination shock, about 10 billion miles away from Voyager 1 and almost a billion miles closer to the sun, it confirmed that our solar system is " squashed" or " dented"- that the bubble carved into interstellar space by the solar wind is not perfectly round. Where Voyager 2 made its crossing, the bubble is pushed in closer to the sun by the local interstellar magnetic field.

"Voyager 2 continues its journey of discovery, crossing the termination shock multiple times as it entered the outermost layer of the giant heliospheric bubble surrounding the Sun and joined Voyager 1 in the last leg of the race to interstellar space." said Voyager Project Scientist Dr. Edward Stone of the California Institute of Technology, Pasadena, Calif.

The solar wind is a thin gas of electrically charged particles

From the Archives
Miranda, moon of Uranus
(More archive images)

Flash Feature
Voyager
The Great Adventure Continues

Golden Record
Earth's Greeting to the universe

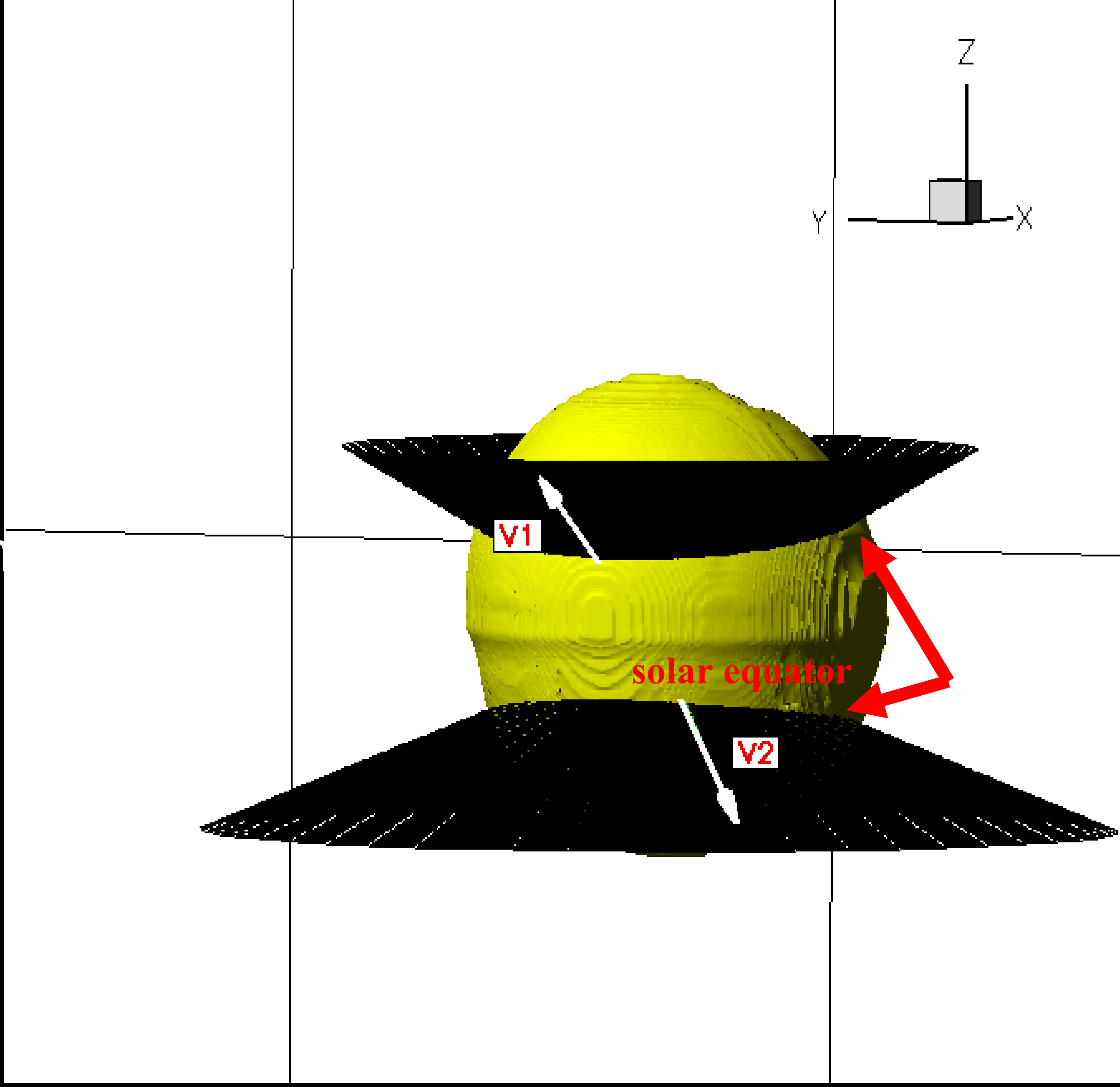
An Epic Journey
25 Years of Voyager

Featured Video

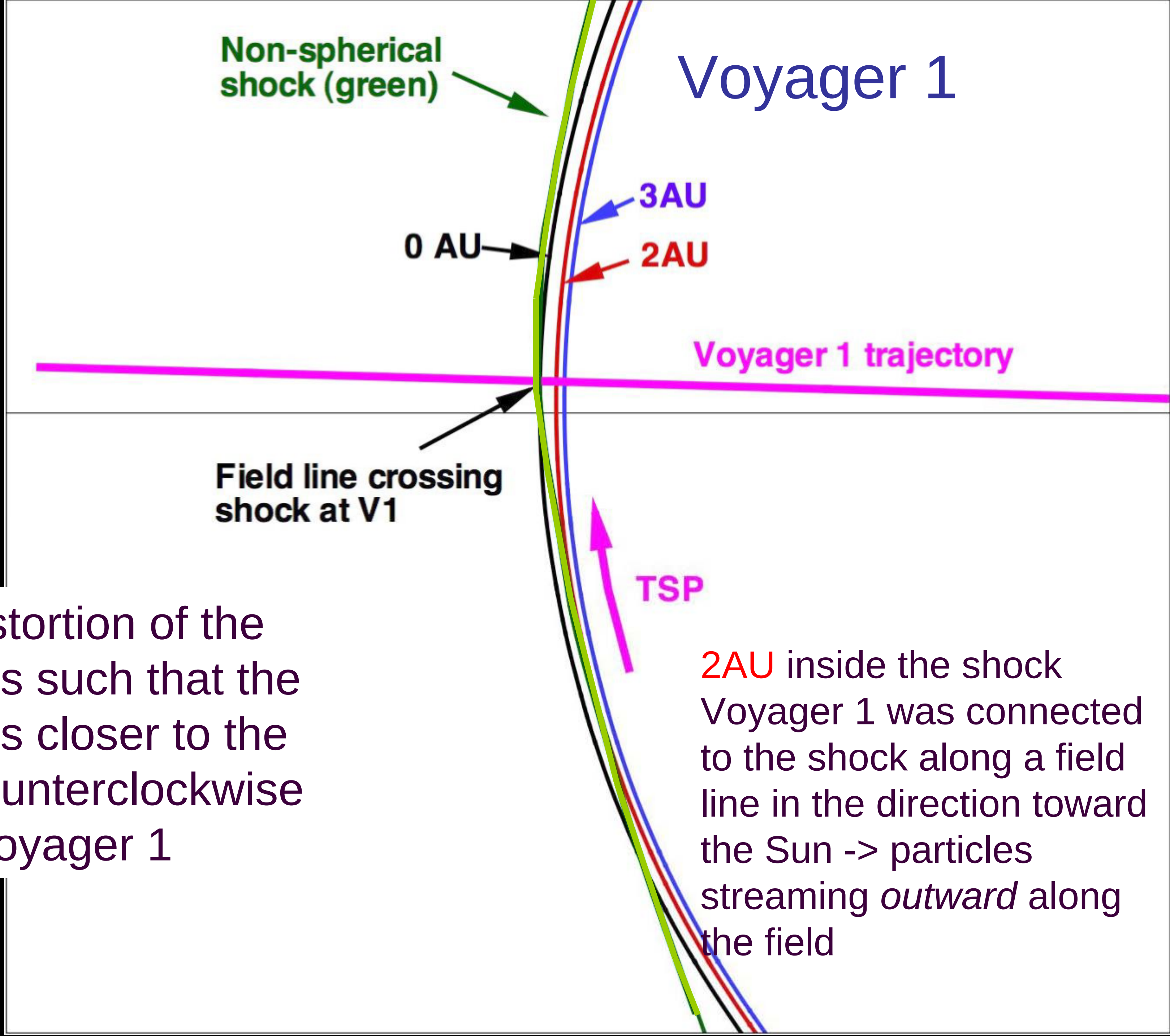
Spiral Magnetic Field Crossing V1 and V2

Shock closer to the Sun near nose than in the flanks

In both Northern and Southern Hemisphere the cones intersect the Termination Shock closer to the equator near the nose



Voyager 1

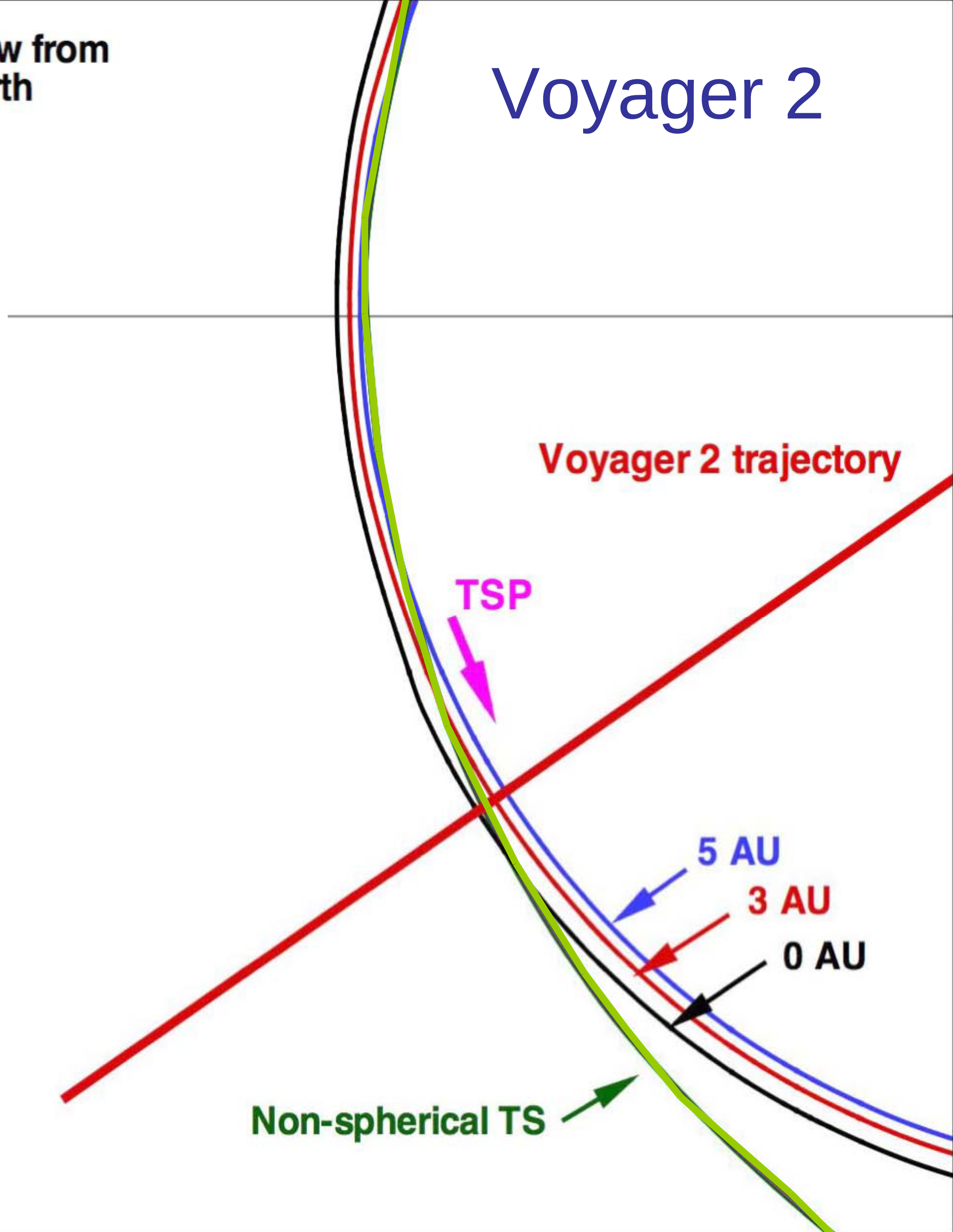


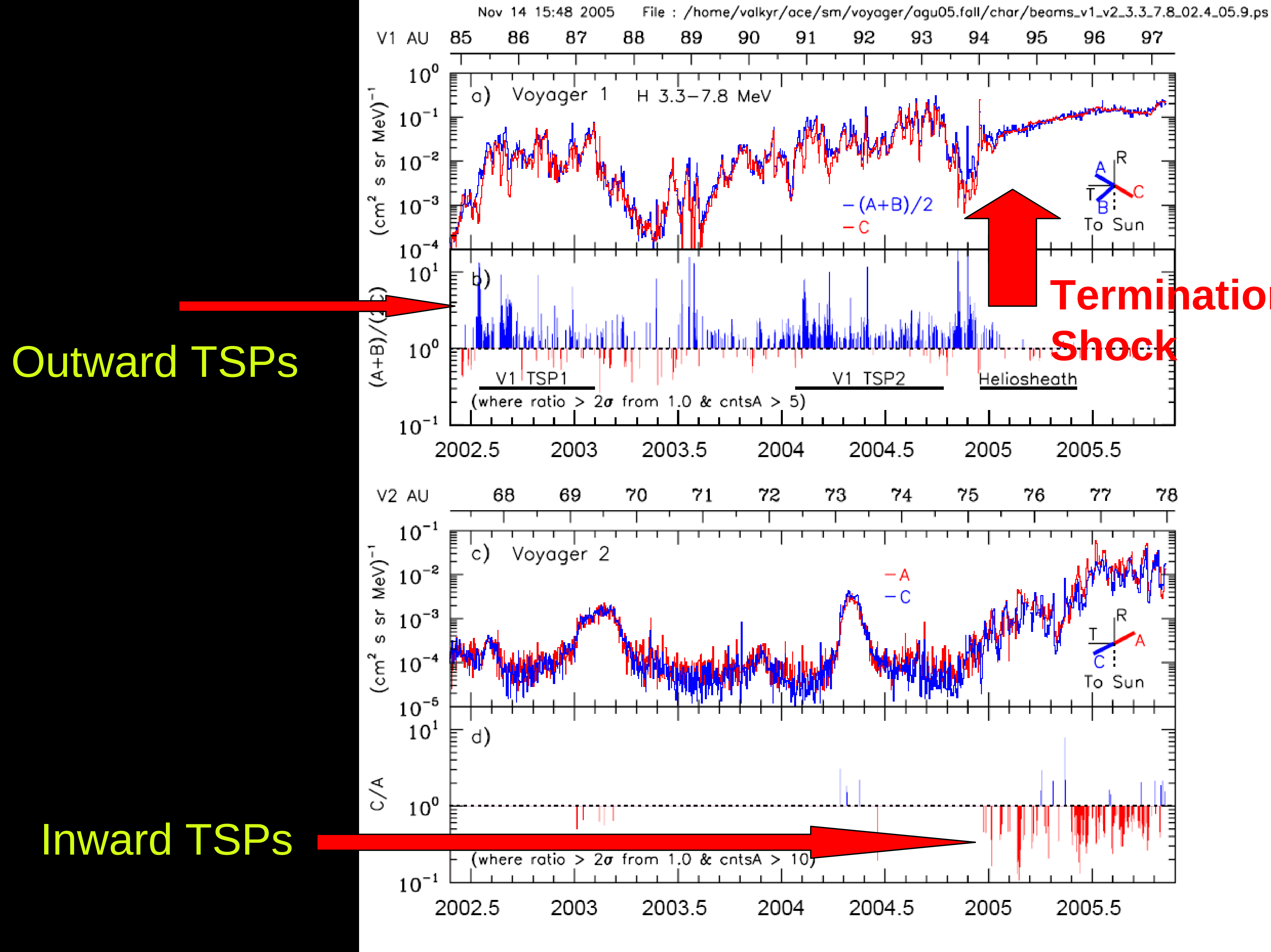
The distortion of the shock is such that the shock is closer to the Sun counterclockwise from Voyager 1

2AU inside the shock Voyager 1 was connected to the shock along a field line in the direction toward the Sun -> particles streaming *outward* along the field

The distortion is such that the shock is closer to the Sun clockwise from V2 -> TSPs streaming *inward* along the field line

The distortion is larger in the southern hemisphere -> field lines 5AU from the shock are connected to V2




Nov 14 15:48 2005 File : /home/valkyr/ace/sm/voyager/agu05.fall/char/beams_v1_v2_3.3_7.8_02.4_05.9.ps
V1 AU
a) Voyager 1 H 3.3–7.8 MeV
(cm^2 s sr MeV)$^{-1}$
– (A+B)/2
– C
To Sun
b)
(A+B)/(2C)
V1 TSP1
V1 TSP2
Heliosheath
(where ratio > 2σ from 1.0 & cntsA > 5)
Termination Shock
Outward TSPs
V2 AU
c) Voyager 2
– A
– C
To Sun
d)
C/A
(where ratio > 2σ from 1.0 & cntsA > 10)
Inward TSPs

Shocks Driven by Coronal Mass Ejections

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TIFF (Uncompressed) decompressor
are needed to see this picture.

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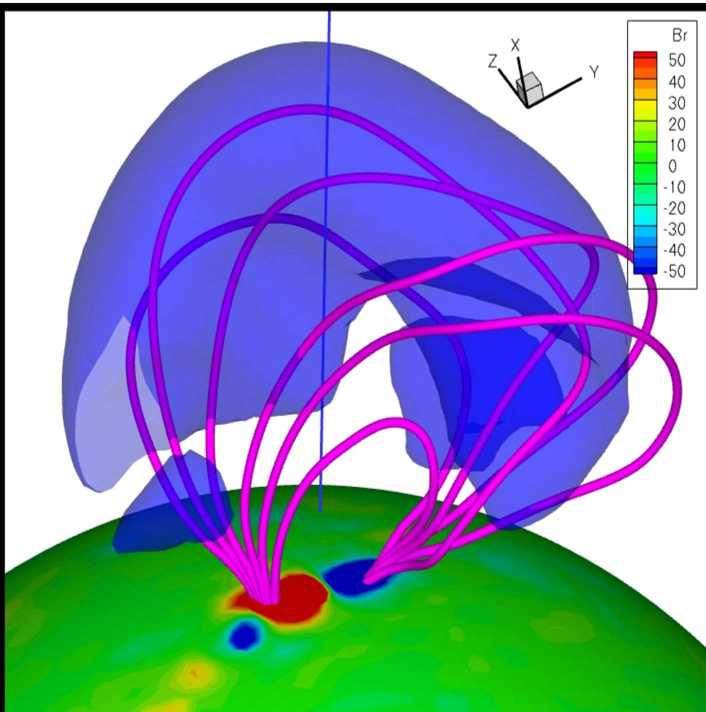
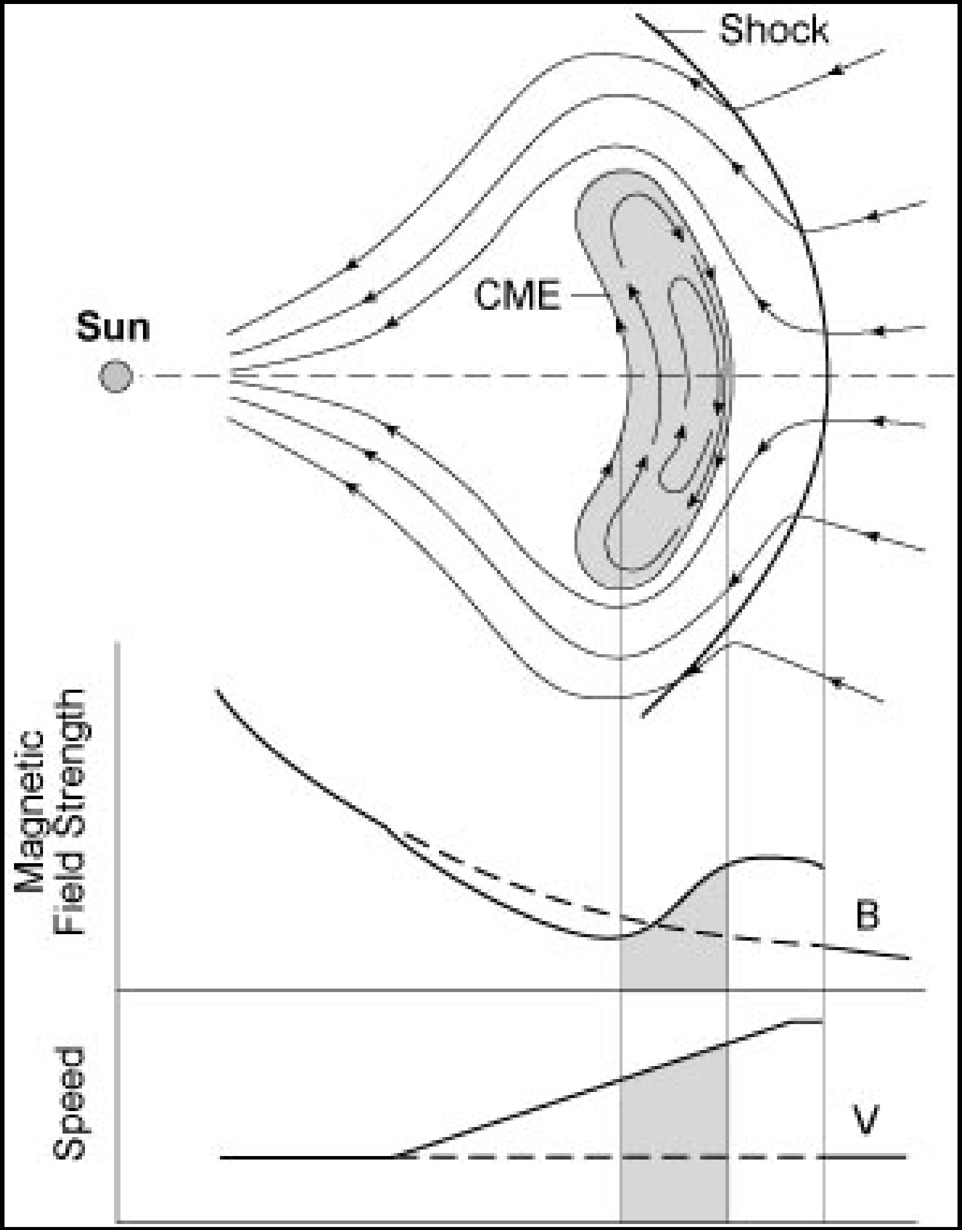
TIFF (Uncompressed) decompressor
are needed to see this picture.



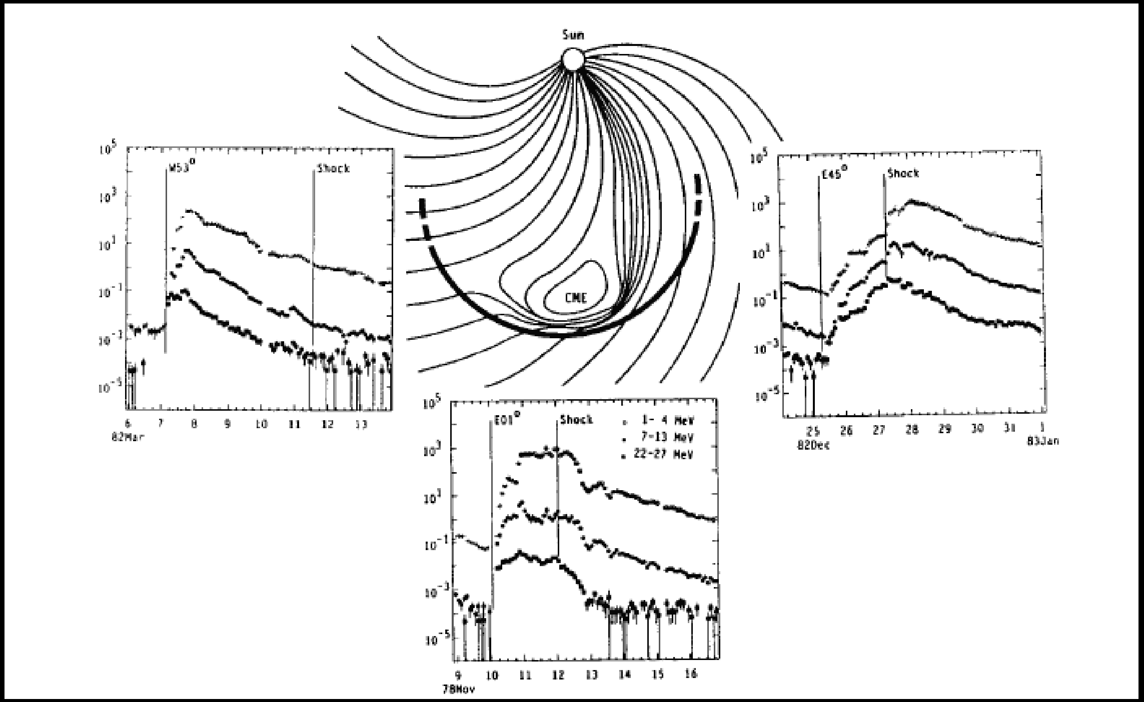
Propagating Shocks

- Shock geometry can vary if near

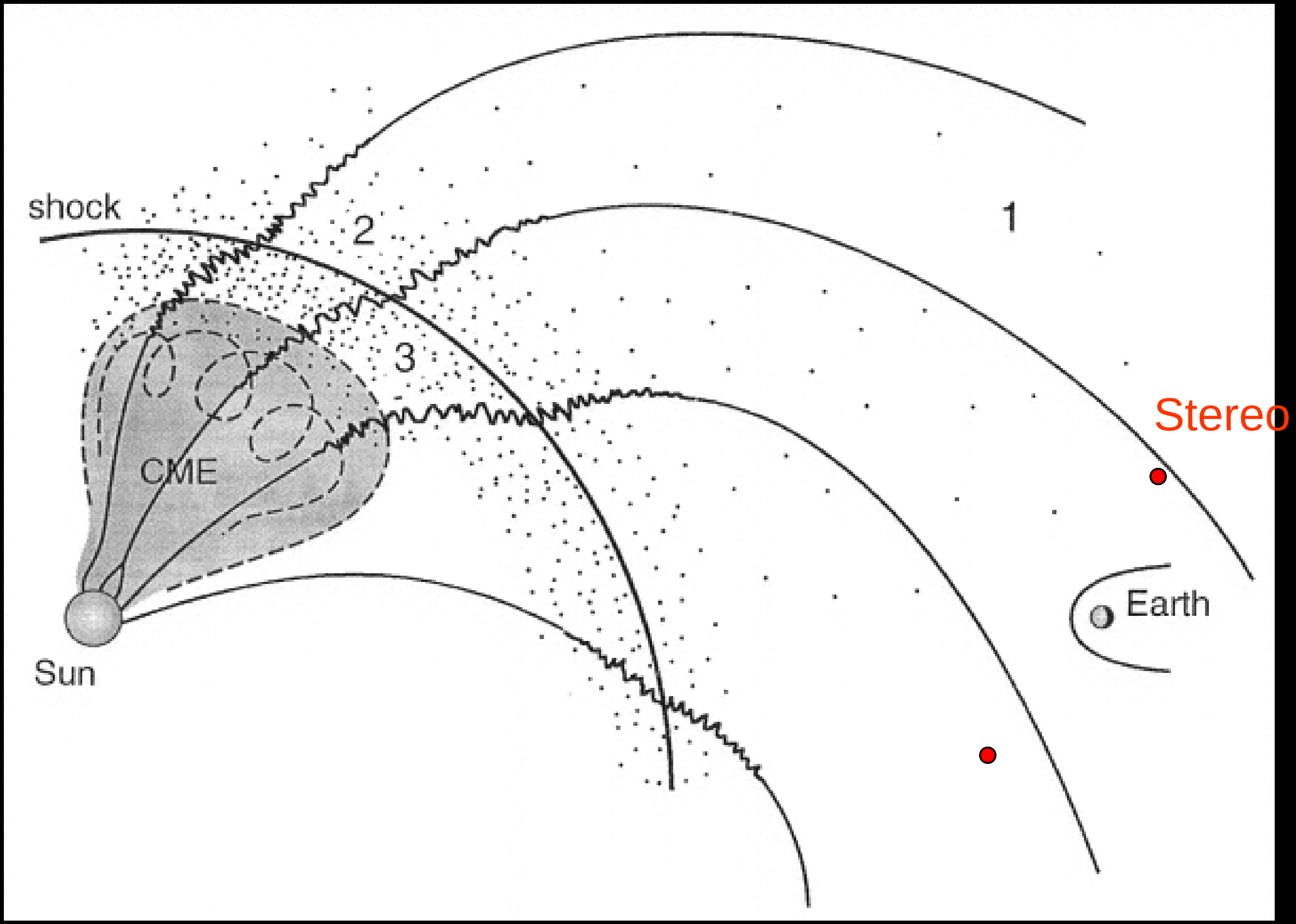
The nose or flanks



Shocks Geometry: Magnetic Connectivity

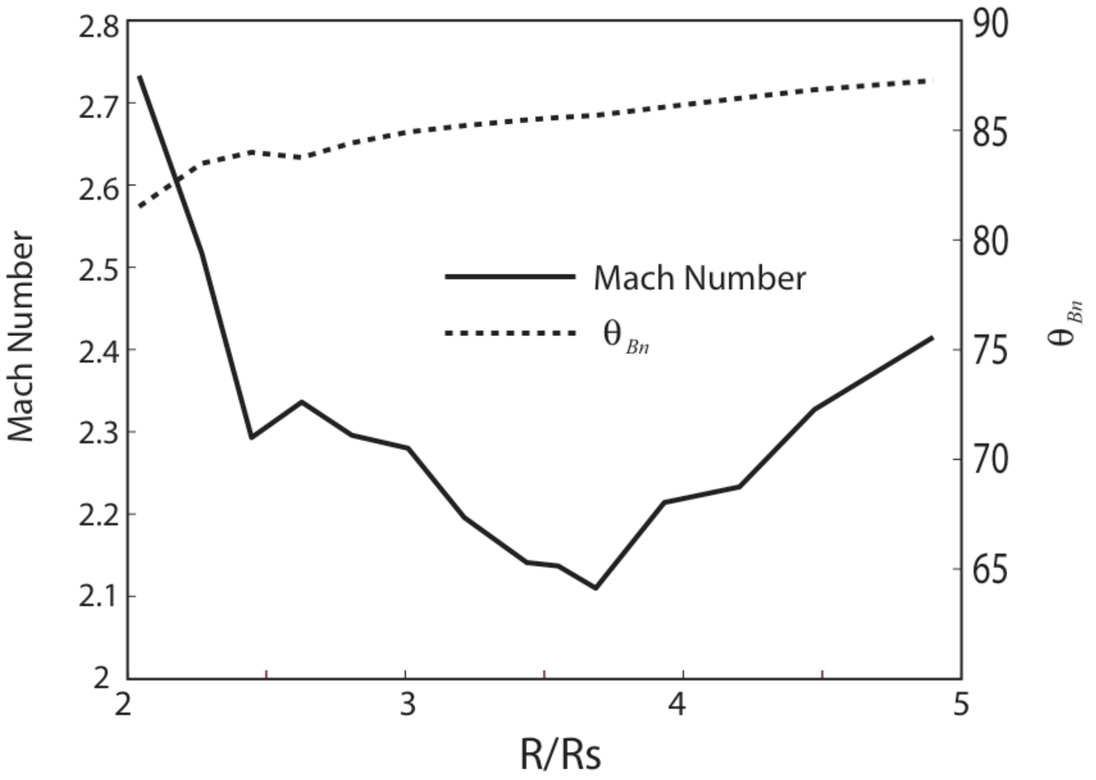


CMEs and Composition of SEPs



Modified from Lee, 2005

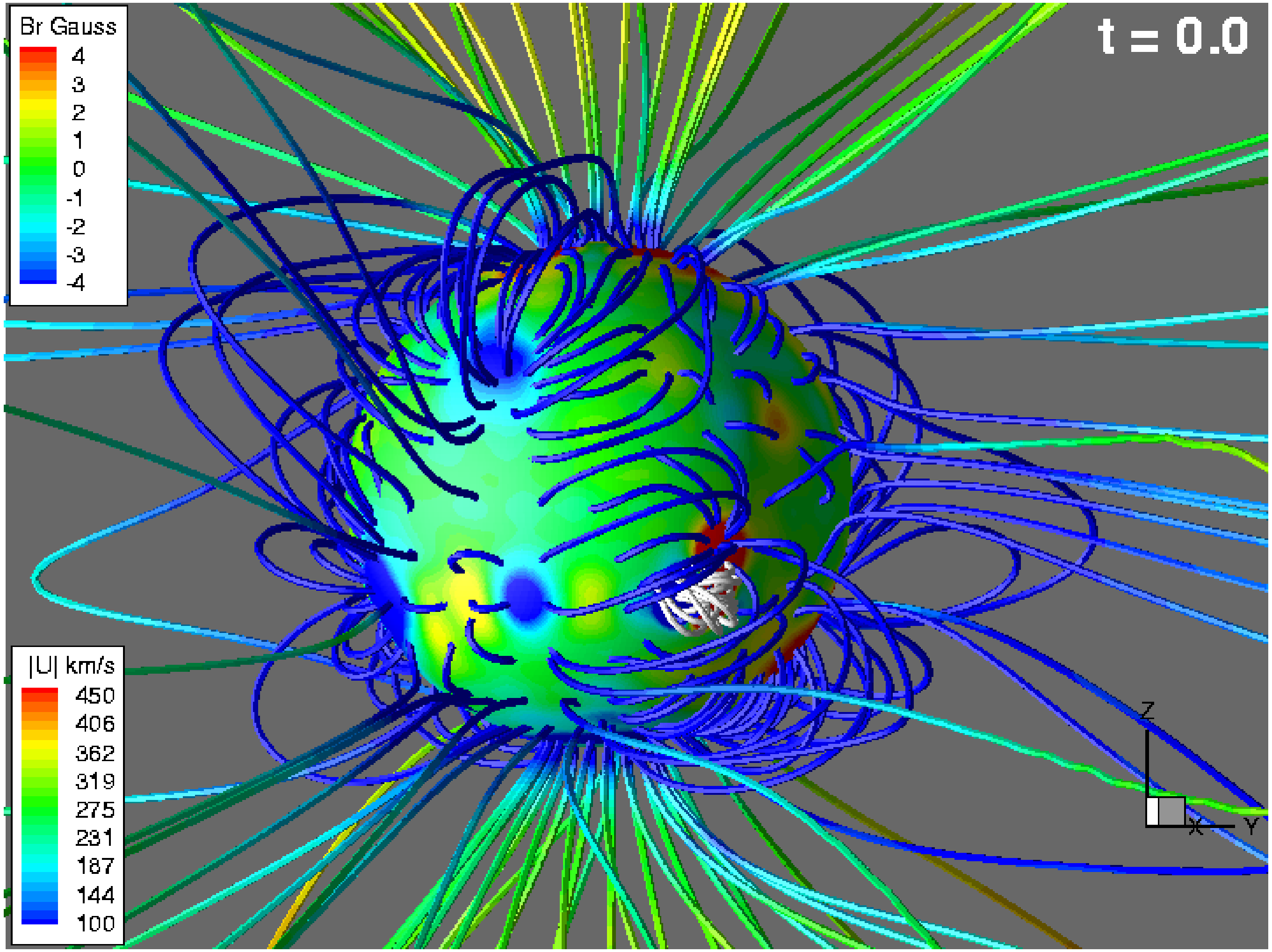
CME: near the nose: Quasi-Parallel Shocks



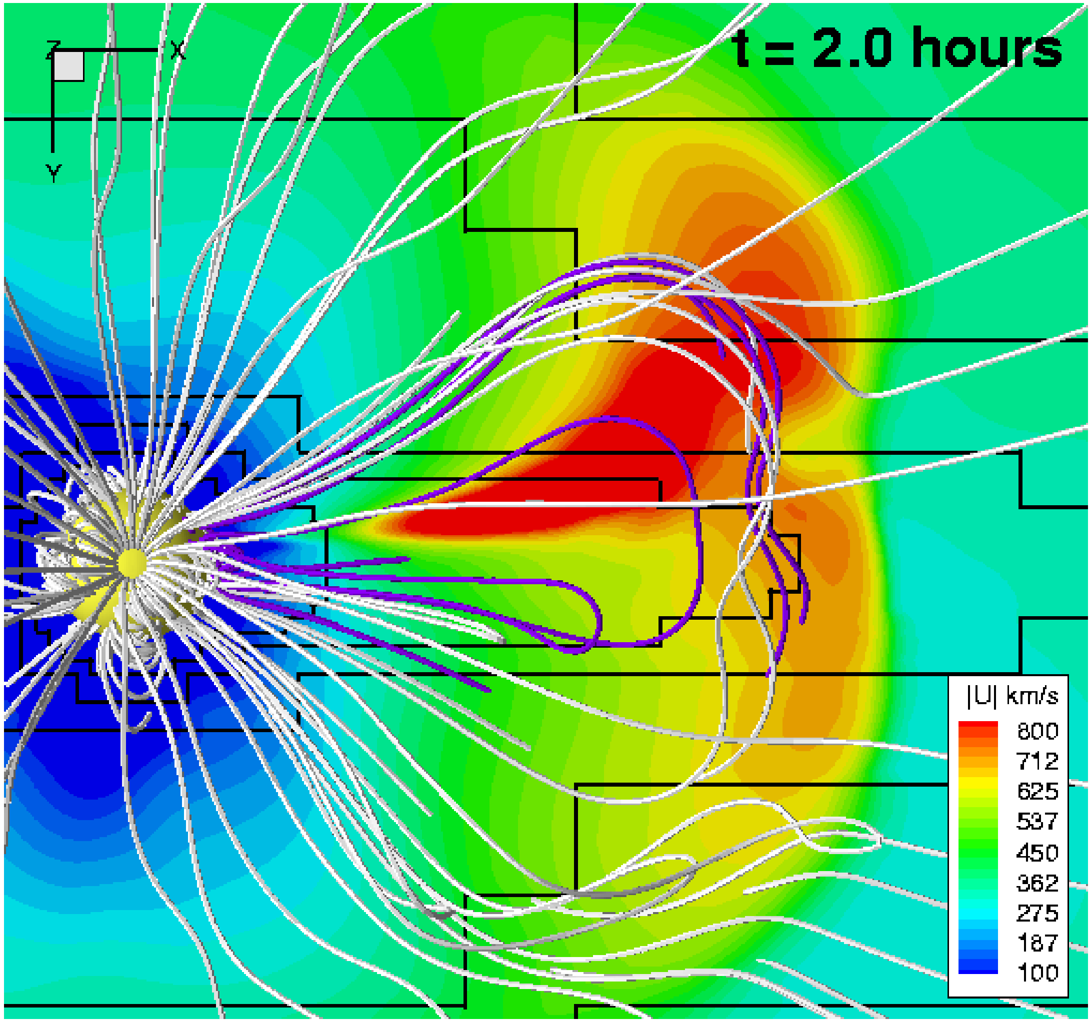
Liu, Opher et al. 2008

Initial Steady State in the Corona

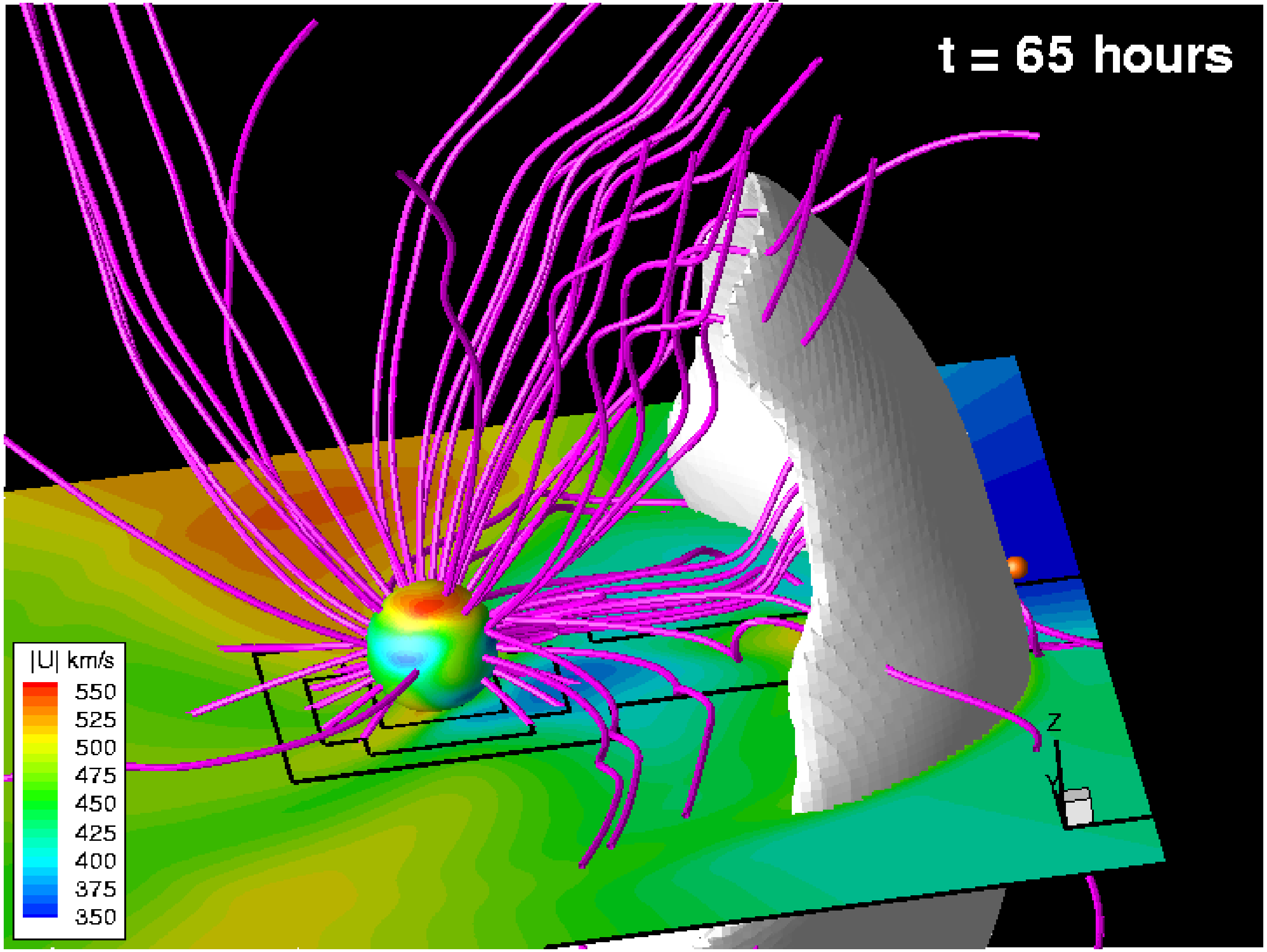
- Solar surface is colored with the radial magnetic field.
- Field lines are colored with the velocity.
- Flux rope is shown with white field lines.



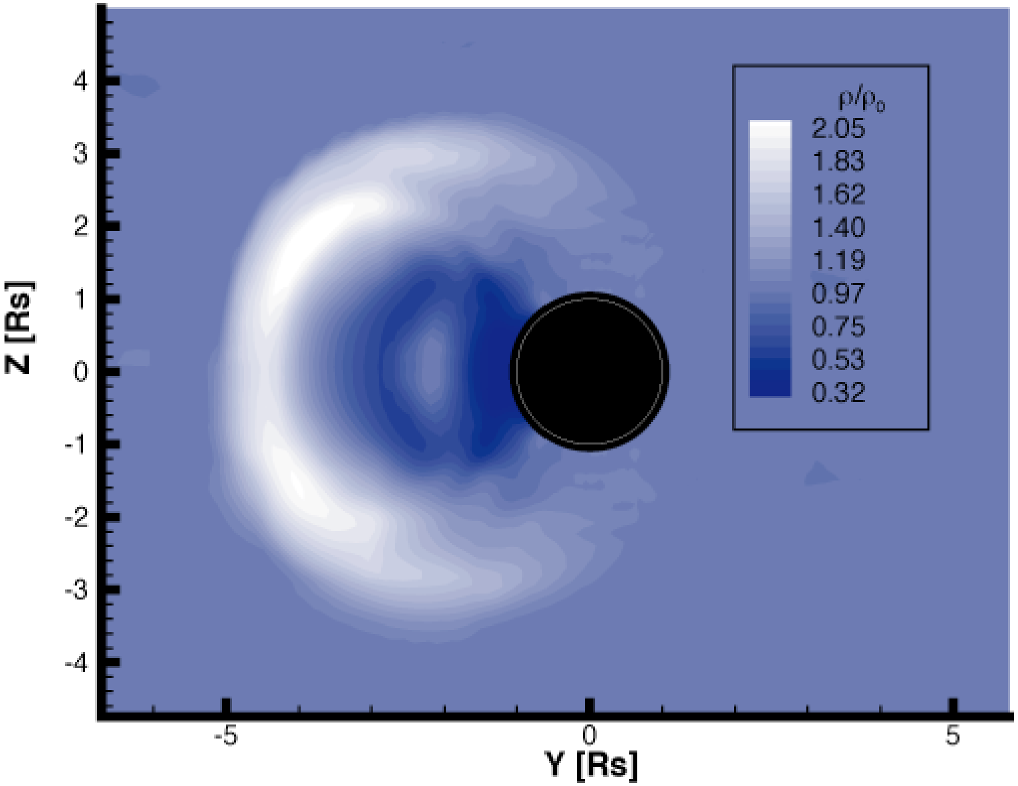
Two Hours After Eruption in the Solar Corona

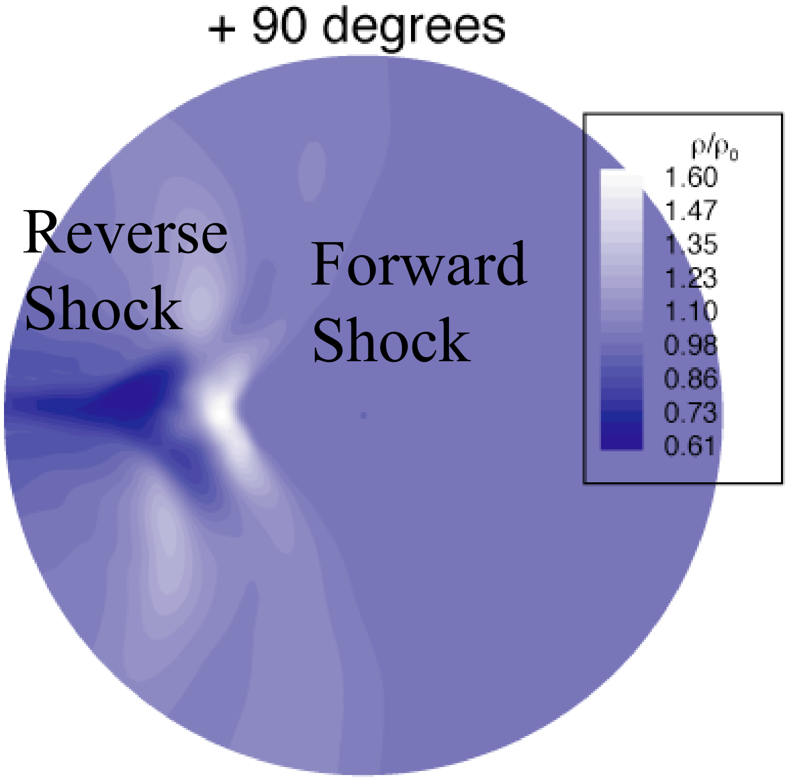


65 Hours After Eruption in the Inner Heliosphere



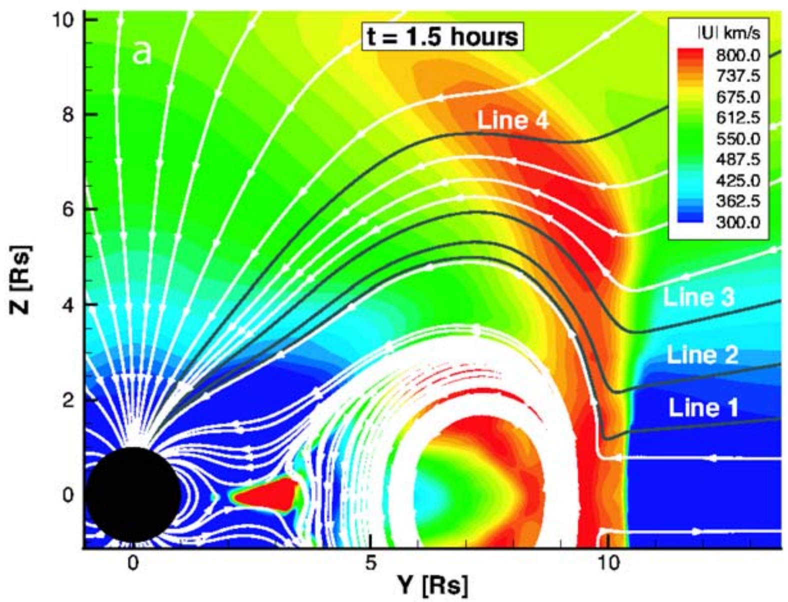
Synthetic Coronagraph Images of the CME: LASCO C2 and HI2

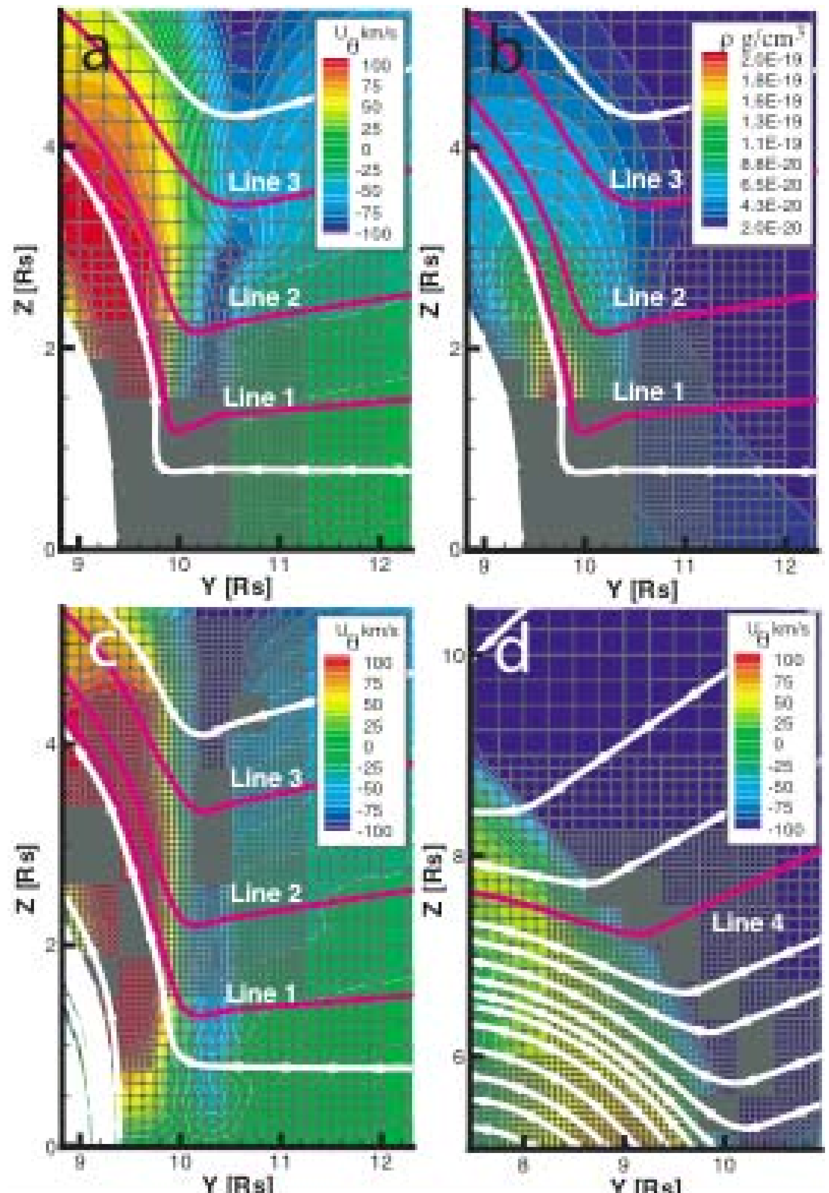




Lugaz, Manchester and Gombosi
2005 ApJ, 627, 1019

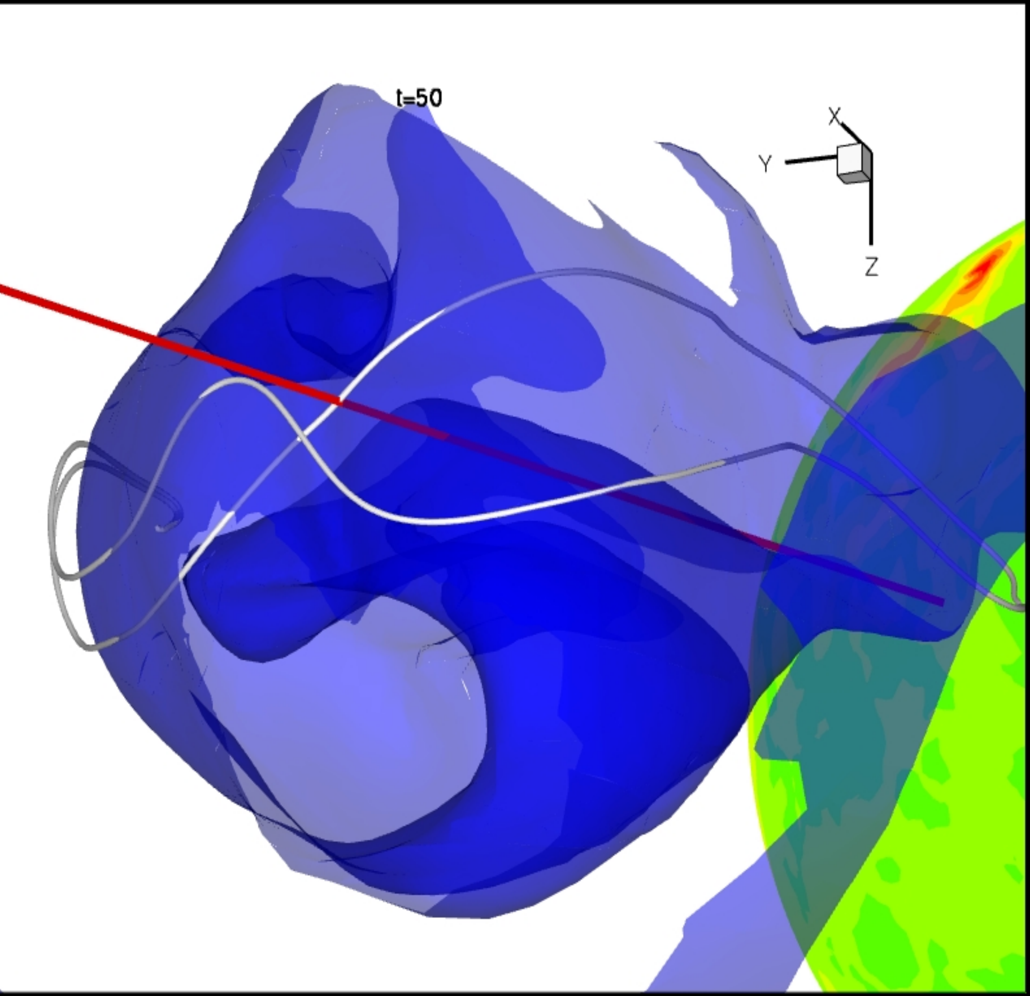
Fine Shock Structure





Manchester et al. 2004

Evolution of Magnetized Shocks



Y. Liu et al. 2008b

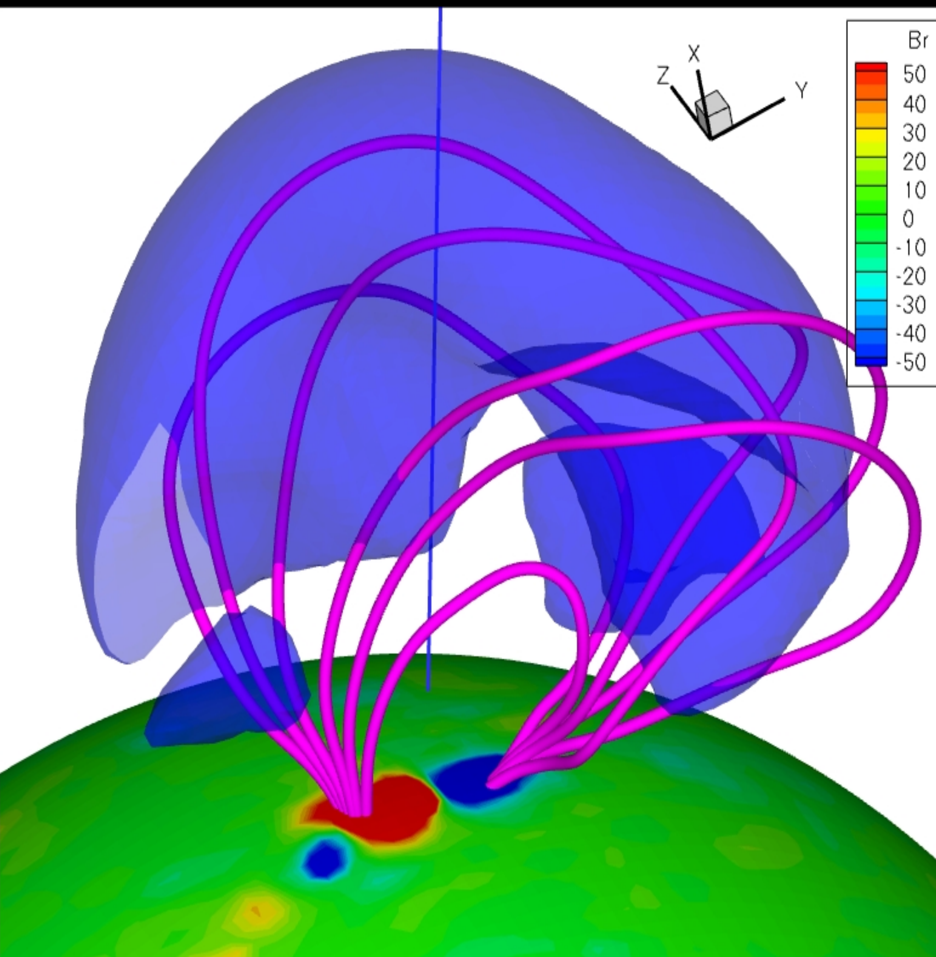
How magnetic effects affect shock evolution?

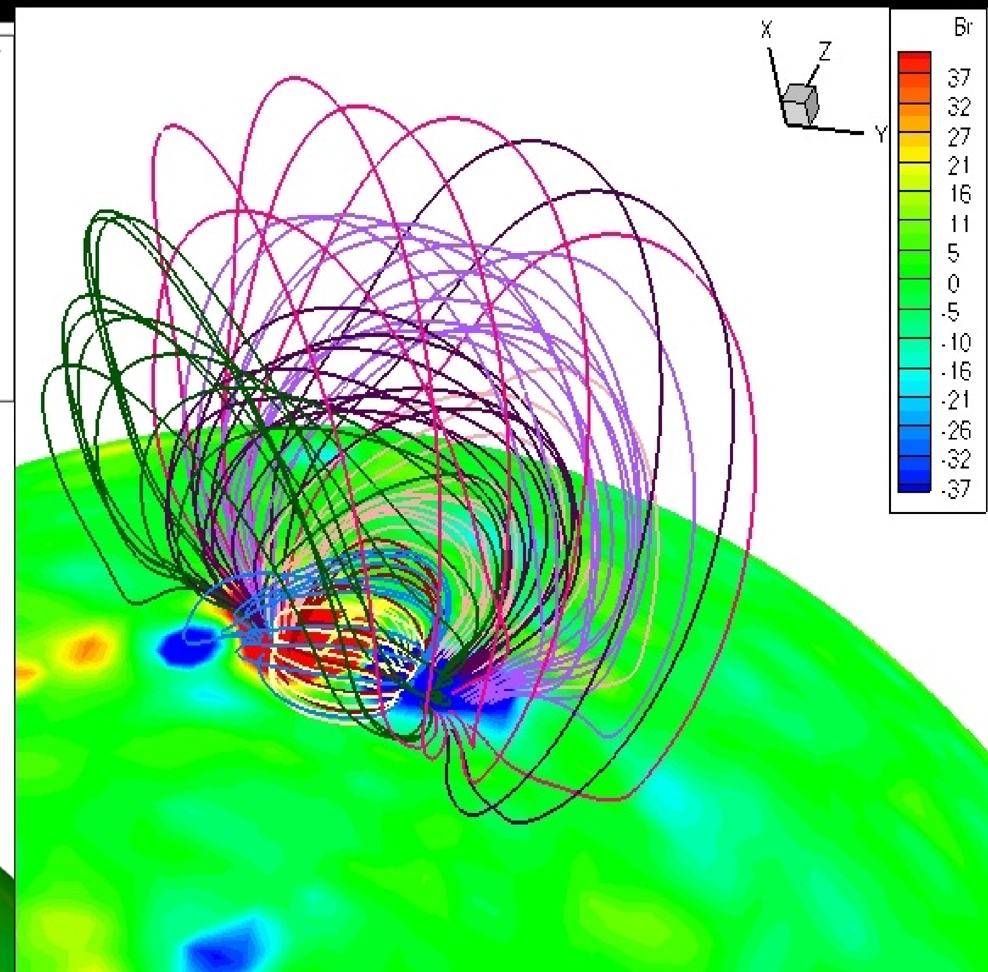
Which type of flows we get in shocks?

MHD instabilities?

How reconnection affect shock structures?

Evolution of Magnetized Shocks in the Lower Corona



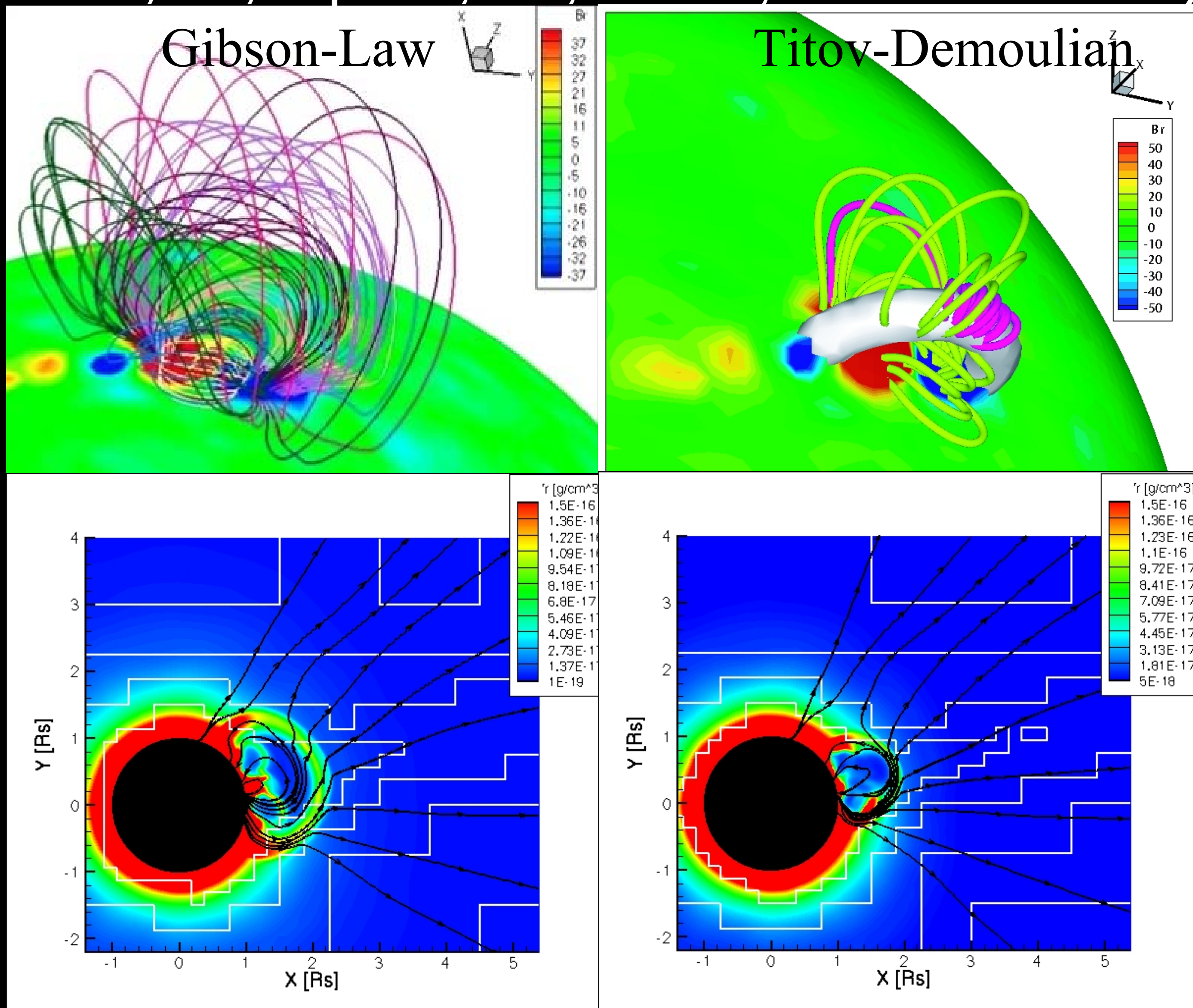


Liu, Opher et al. (2008)

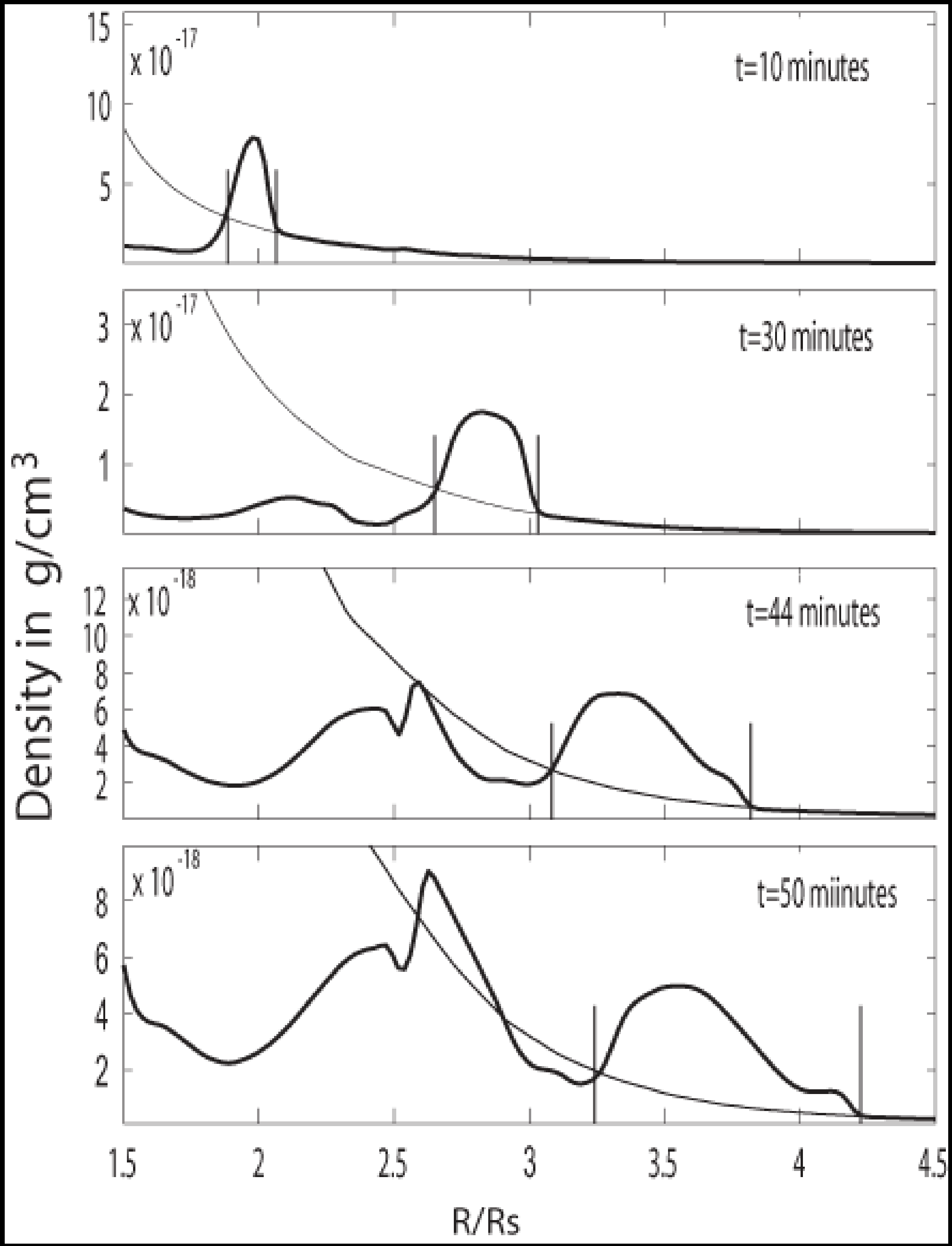
Loesch, Opher, Alves et al. 2008

Coronal Mass Ejection in the Lower Corona: Comparison of Two Initiation Models

(Loesch, C., Opher, M., Alves, M. et al. 2008)

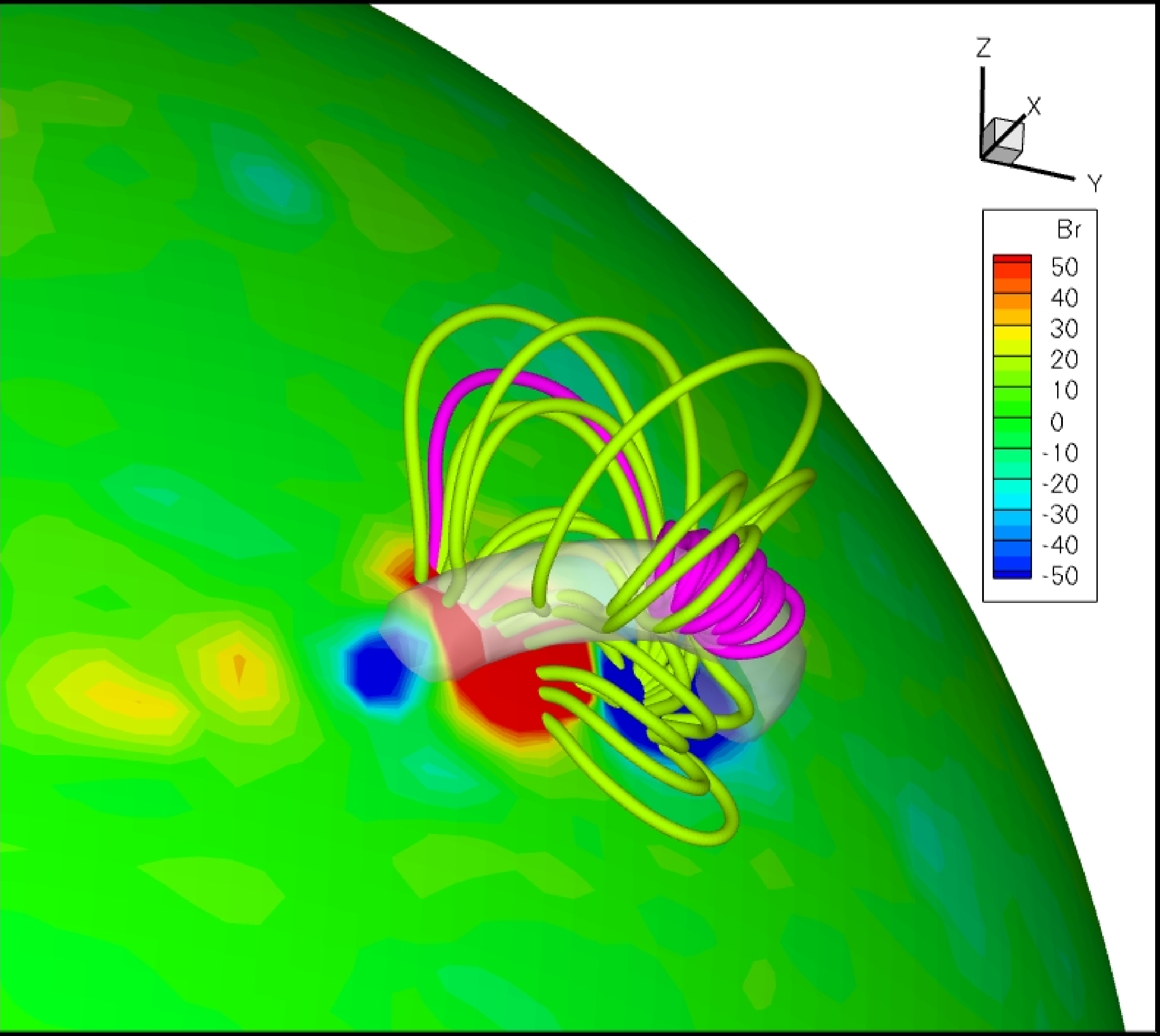


Evolution of the Shock Structures in the Lower Corona



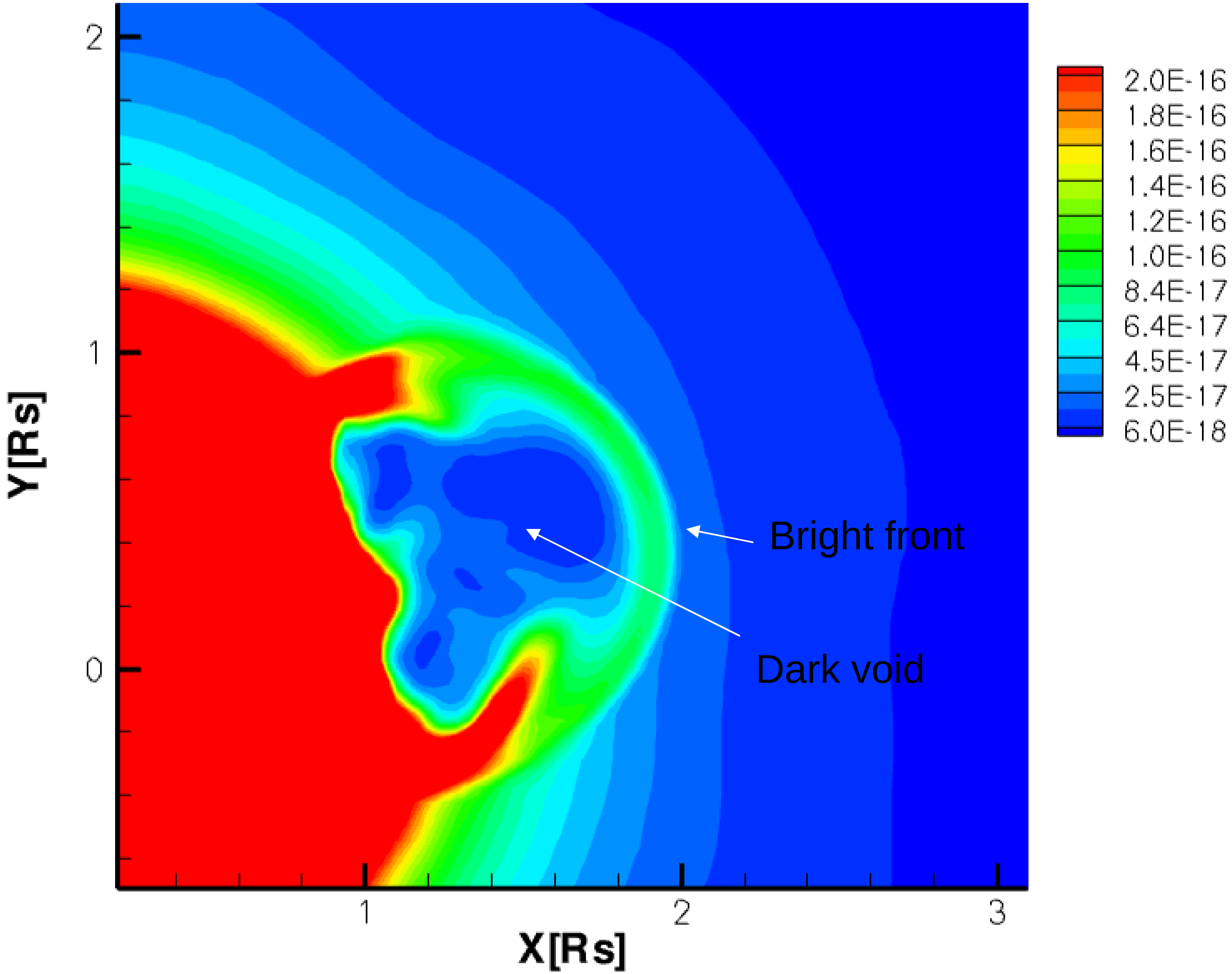
Liu, Opher, et al. ApJ in press (2008)

The inserted TD flux rope



Liu, Opher, et al.
ApJ in press
(2008)

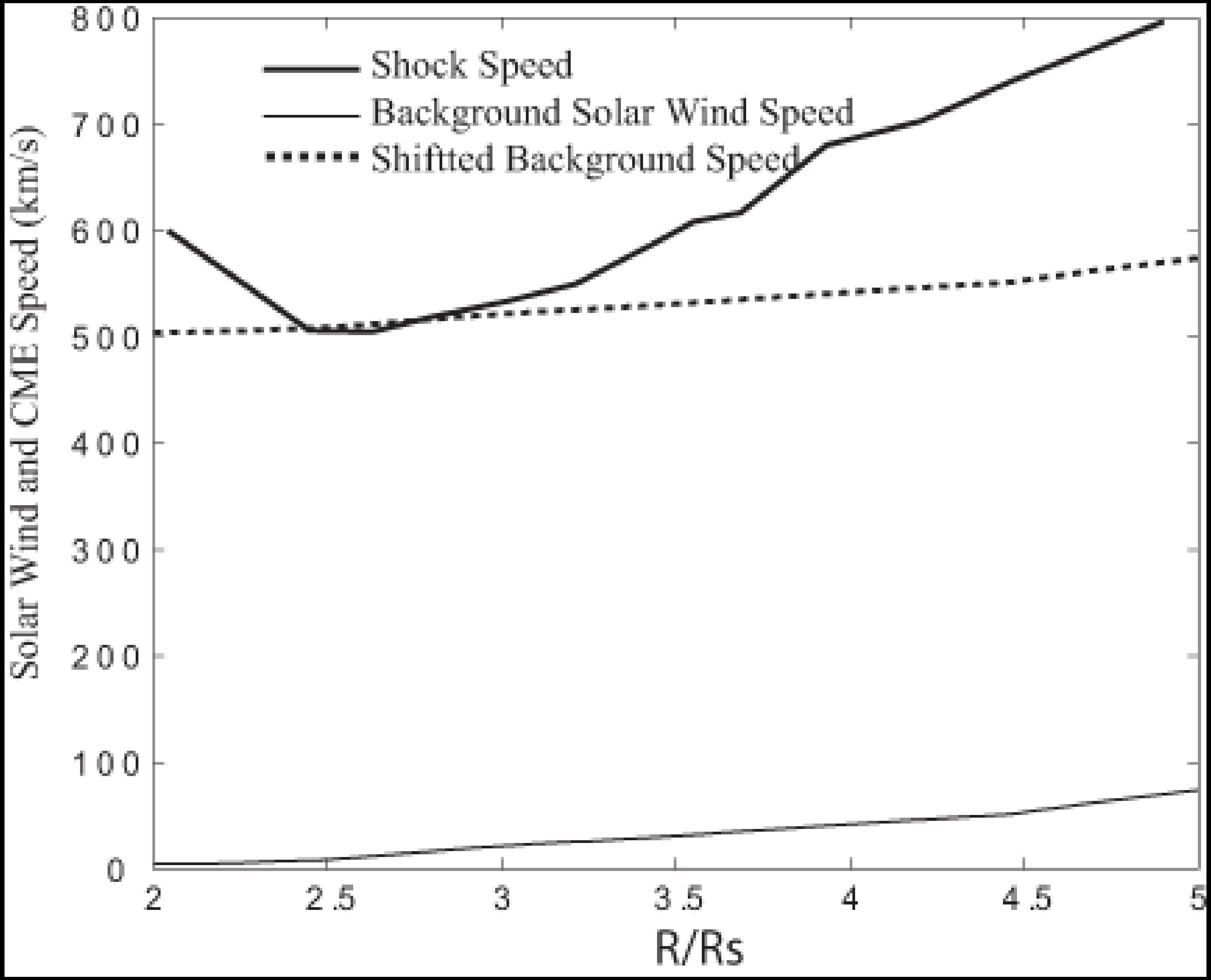
Bright Front and Dark Void



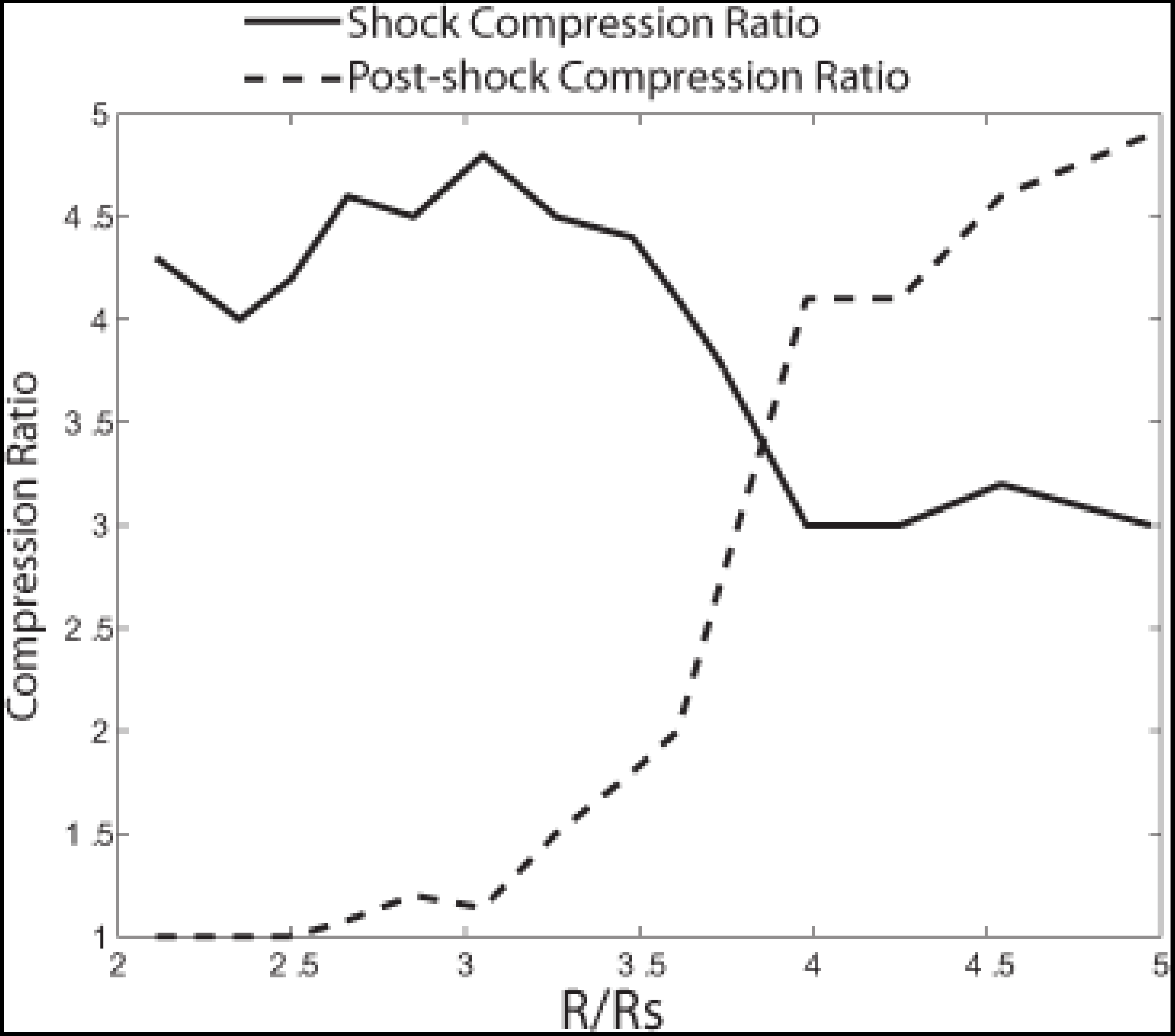
2D slice at Z=0.11

t=10 minutes

Shock Speed and the background solar wind speed



Shock and Post Shock Compression Ratio



The post shock acceleration exists in 3-5 Rs

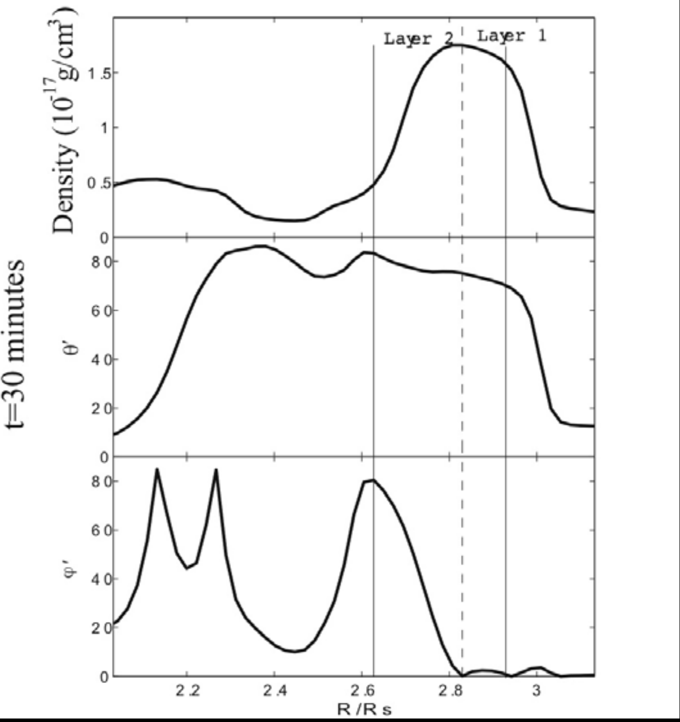
Evolution of Flows, Field Lines in CME sheath

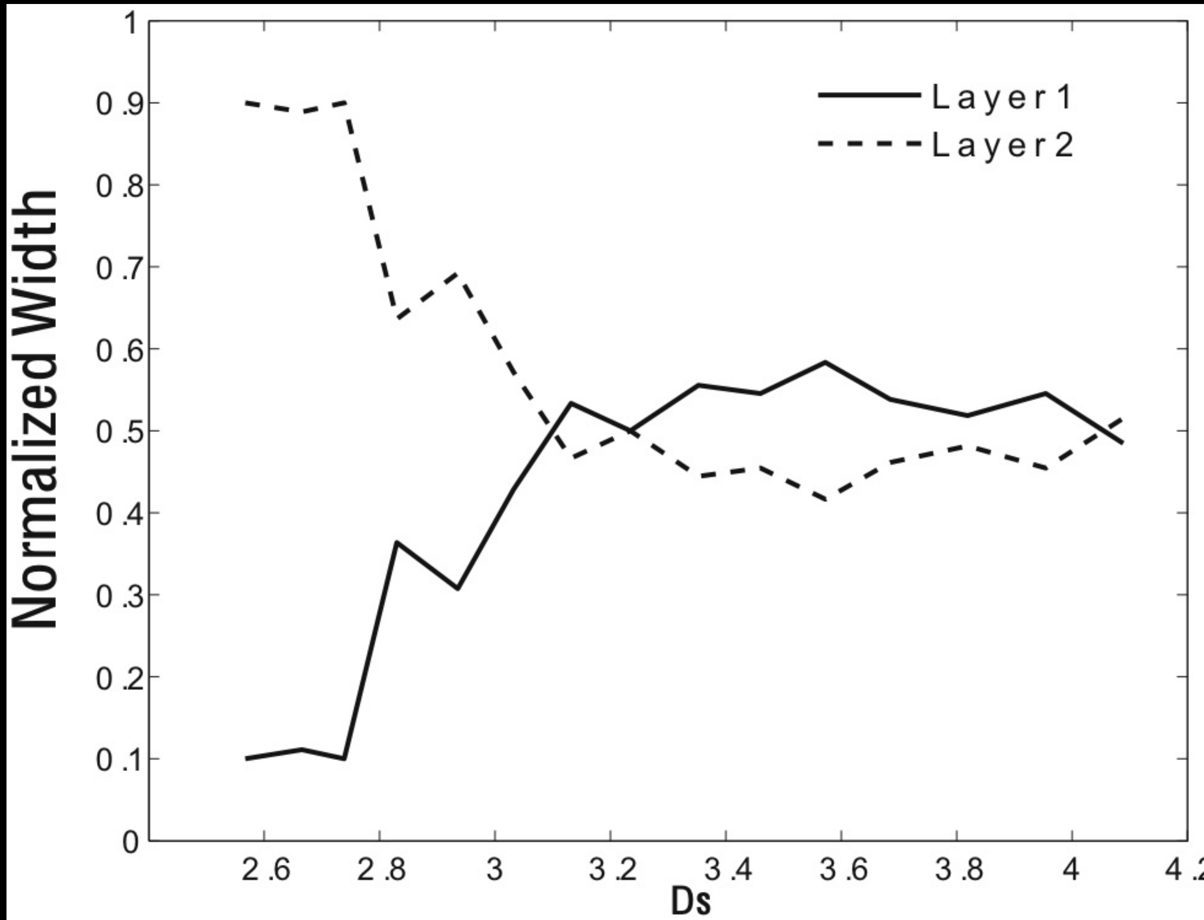
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Magnetic Field Lines Rotation

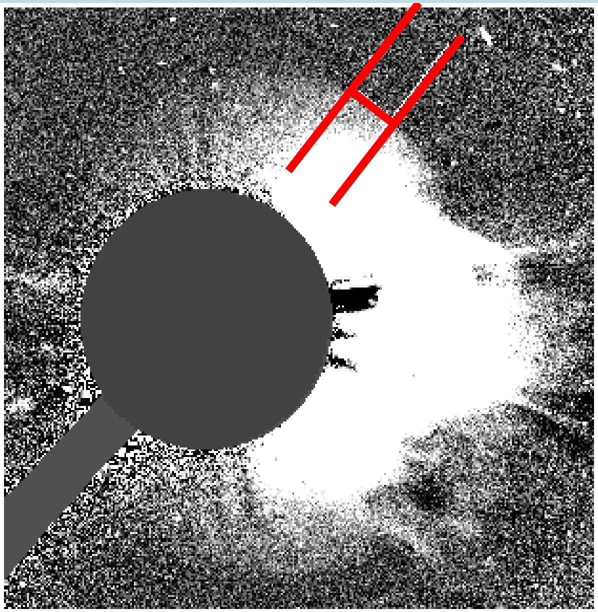
Liu, Opher, Gombosi
ApJ (2008b)

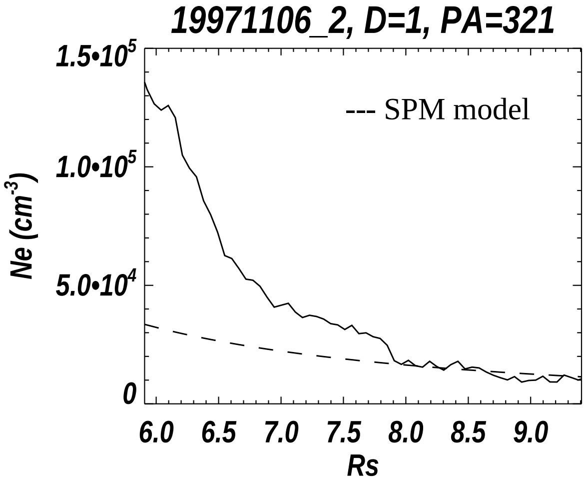
Behavior of the Magnetic Field in the Sheath

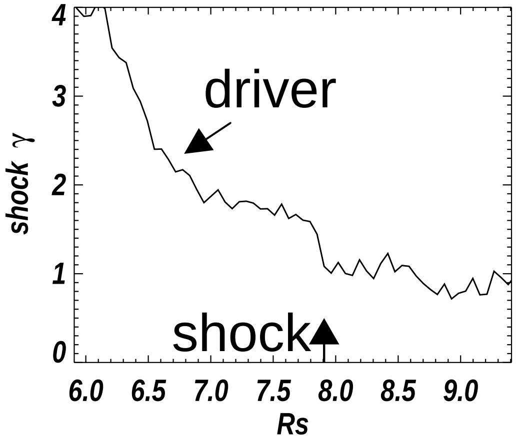




Measuring Shocks







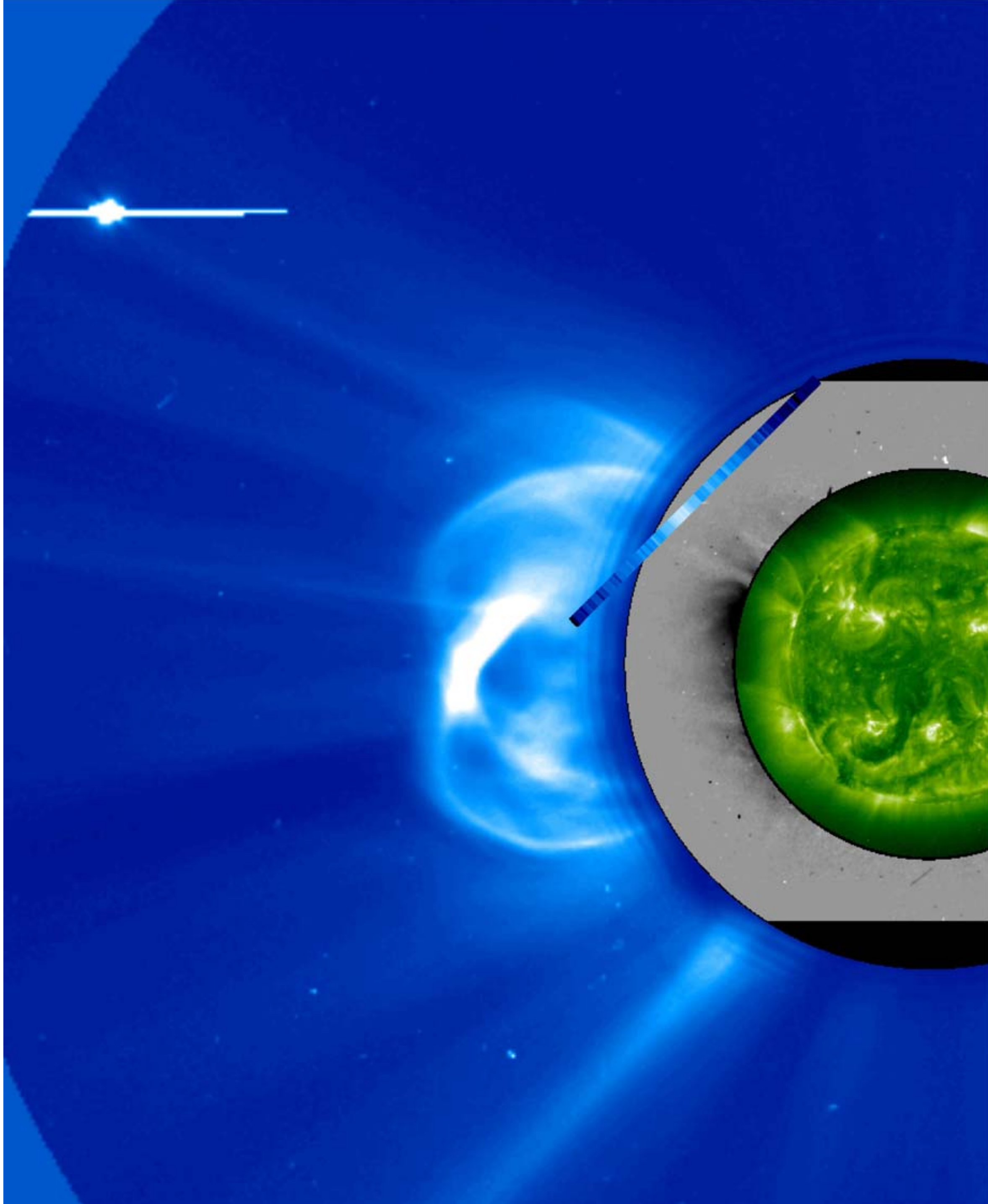
Shock brightness to density (ρ)
Shock strength, **$\gamma=1+\rho/\rho 0$**
SPM model for the density of the back ground corona (ρ0).

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.)



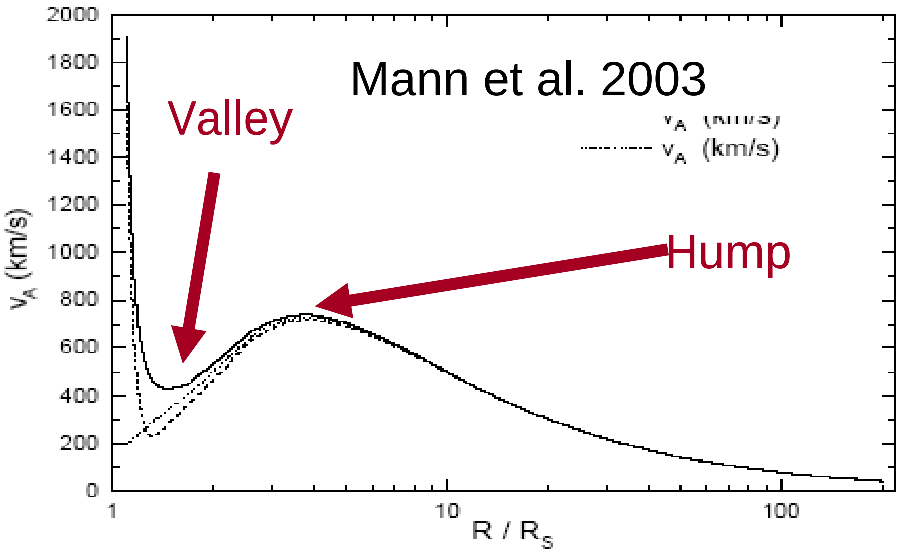
UVCS Shock Observations Analyzed so far

Date	Reference	H	V	n_0	Log T_O	X
06/11/98	Raymond et al.	1.75	1200	$1x10^6$	8.7	1.8
06/27/99	Raouafi et al.	2.55	1200		<8.2	
03/03/00	Mancuso et al.	1.70	1100	$1x10^7$	8.2	1.8
06/28/00	Ciaravella et al.	2.32	1400	$2x10^6$	8.1	
07/23/02	Mancuso&Avetta	1.63	1700	$5x10^6$	8.0	2.2

Modest heights, Modest compression, High T_O

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

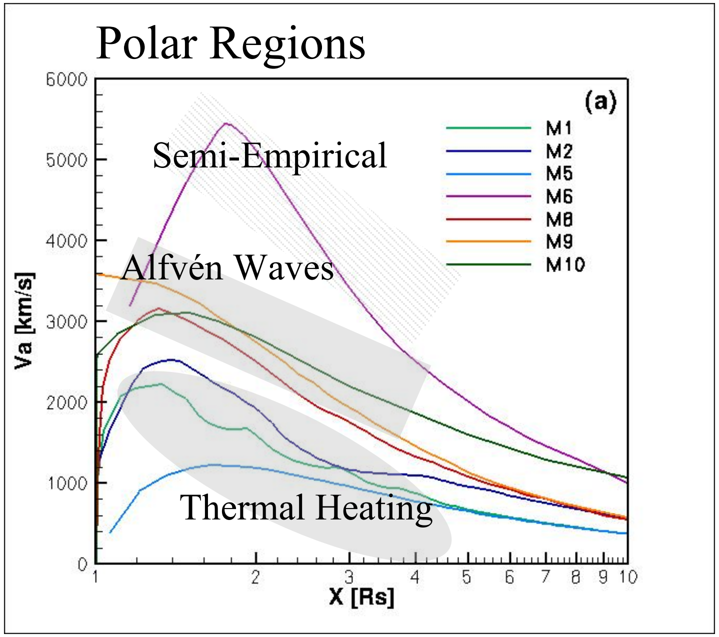
What is the Alfvén Speed Profile in the Lower Corona?

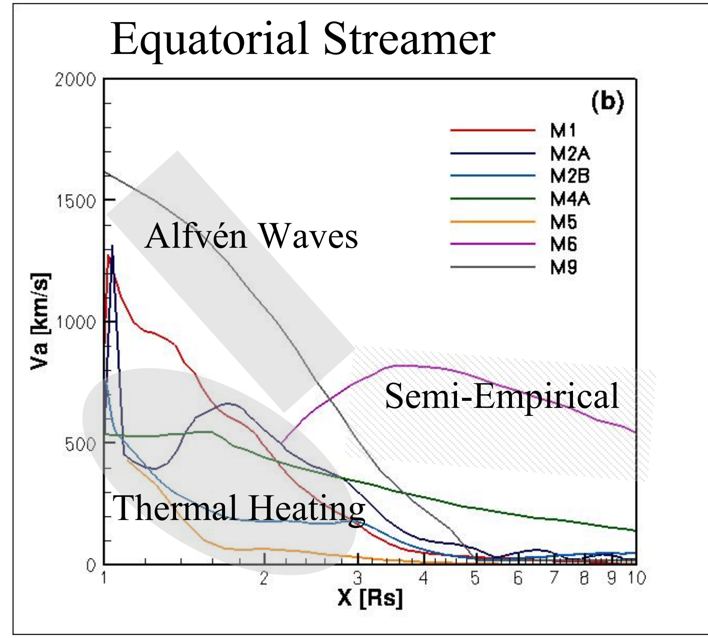


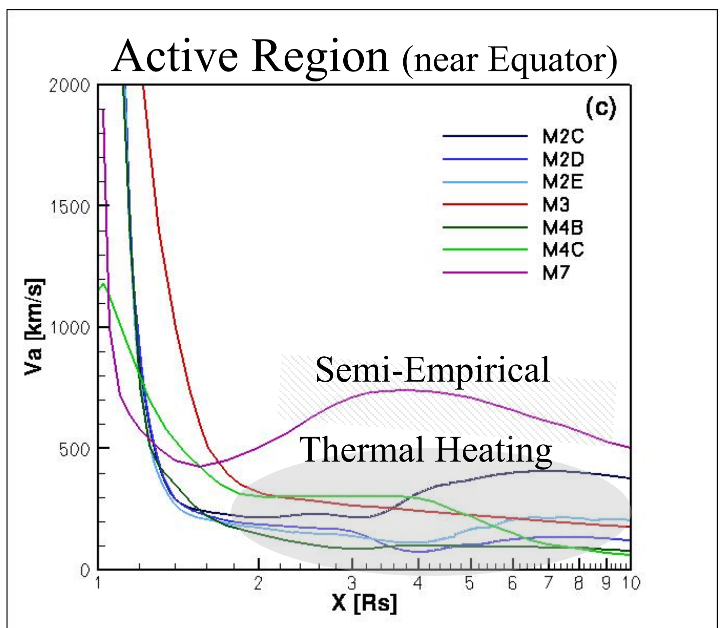
Evans, R., Opher, Manchester, Gombosi ApJ (2008)

- 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

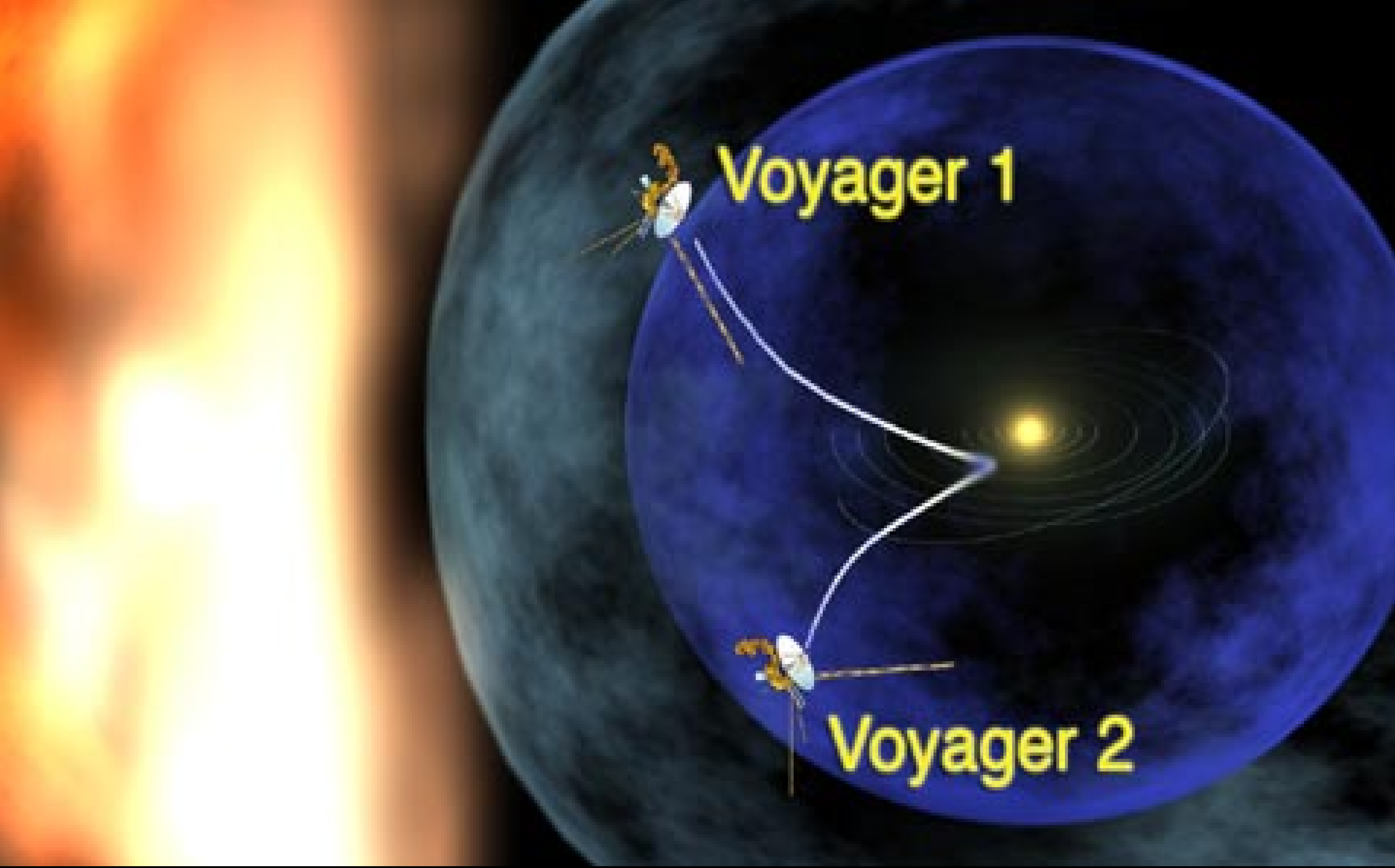






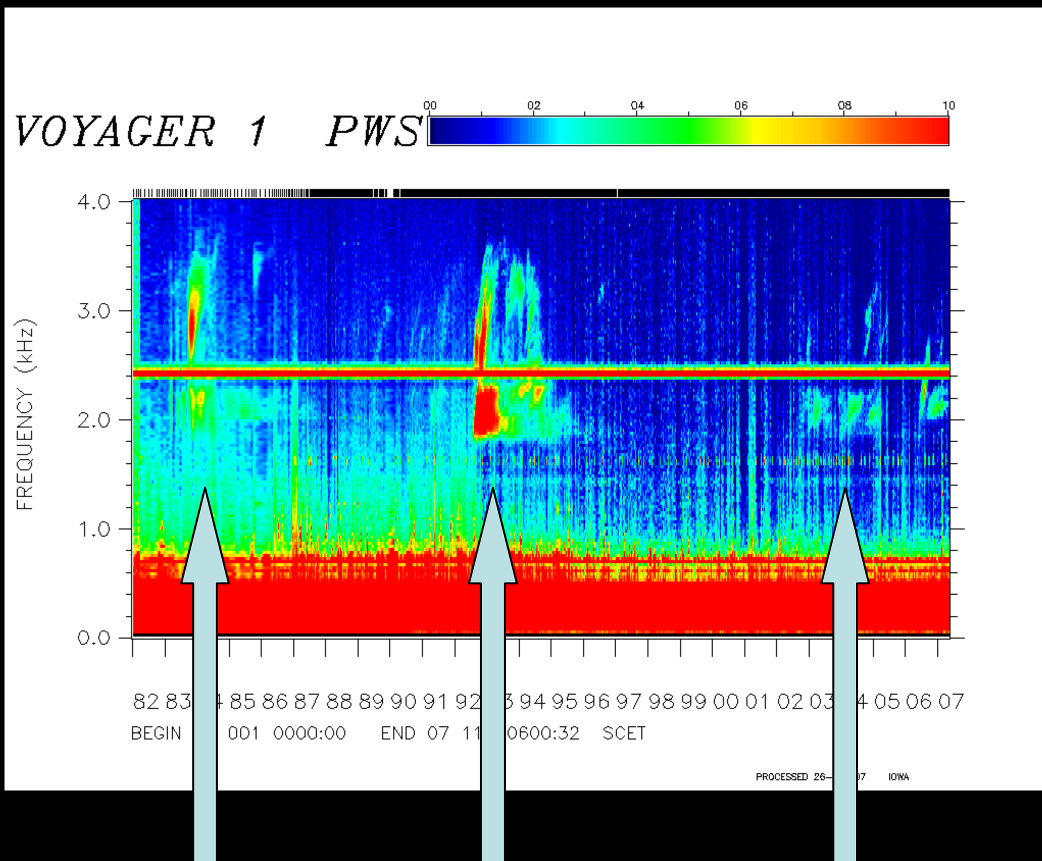
Profiles vary drastically; Almost none with a clear hump
Need more physical based solar wind to study shocks in lower corona

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



Voyager 1 in the Northern Hemisphere;
and Voyager 2 in the Southern Hemisphere

2-3kHz Radio Emissions were detected each solar cycle



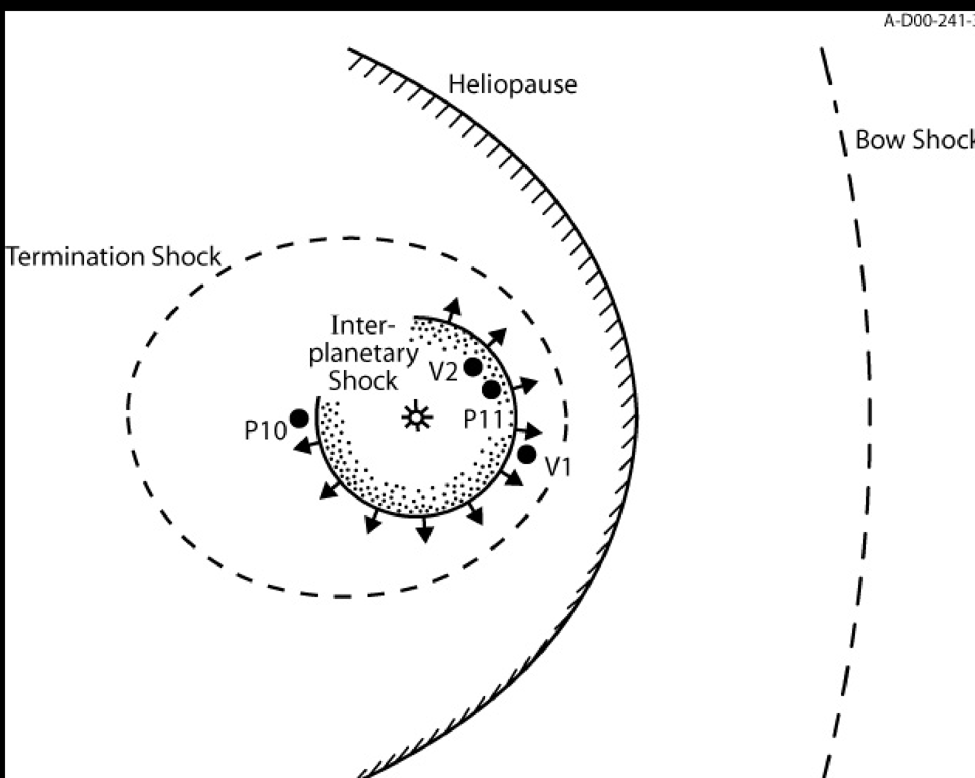
Solar Cycle 21

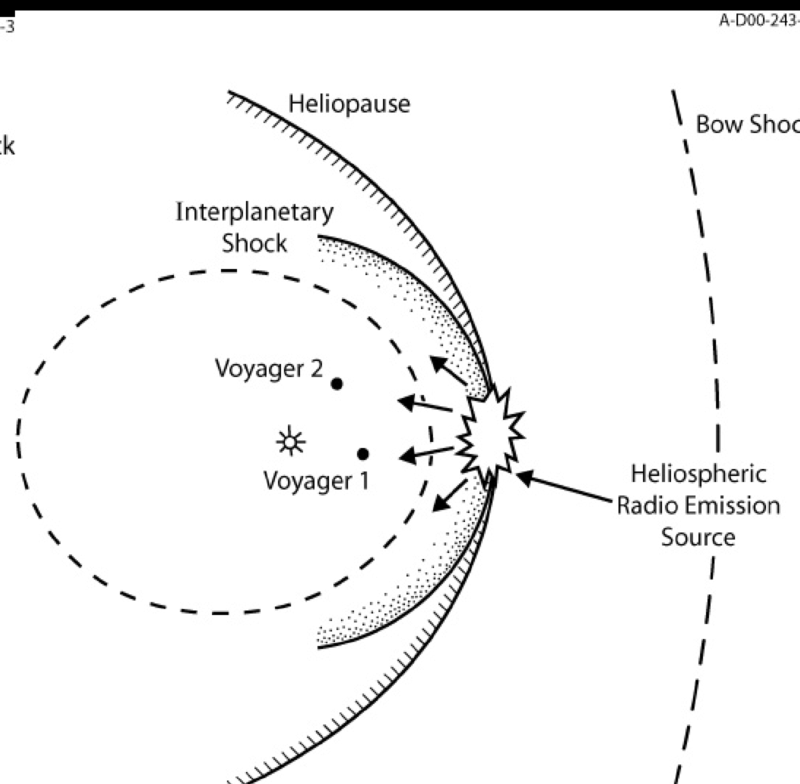
Solar Cycle 22

Solar Cycle 23

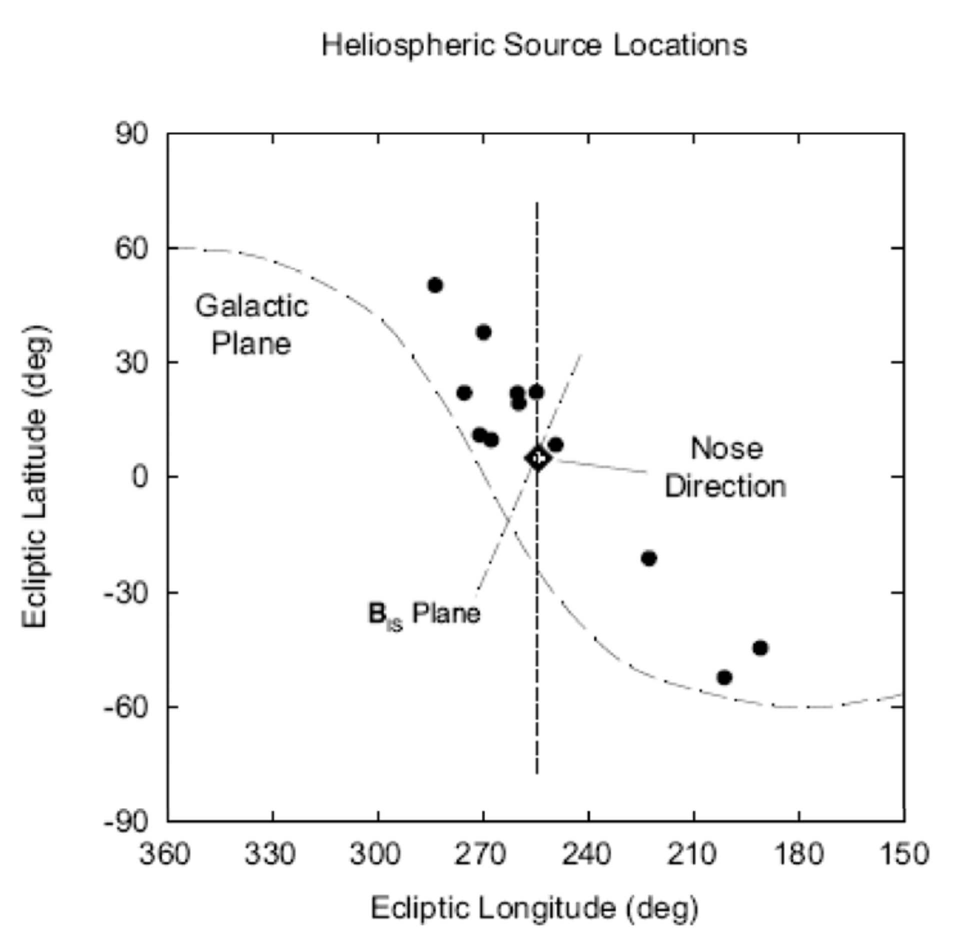
Kurth et al. ‘84
Gurnett et al. ‘93
Gurnett, Kurth and Stone, ‘03

Current accepted scenario:
radio emissions are generated when a strong interplanetary shock reaches the vicinity of the heliopause (Gurnett et al. ‘03, Gurnett & Kurth ‘95)



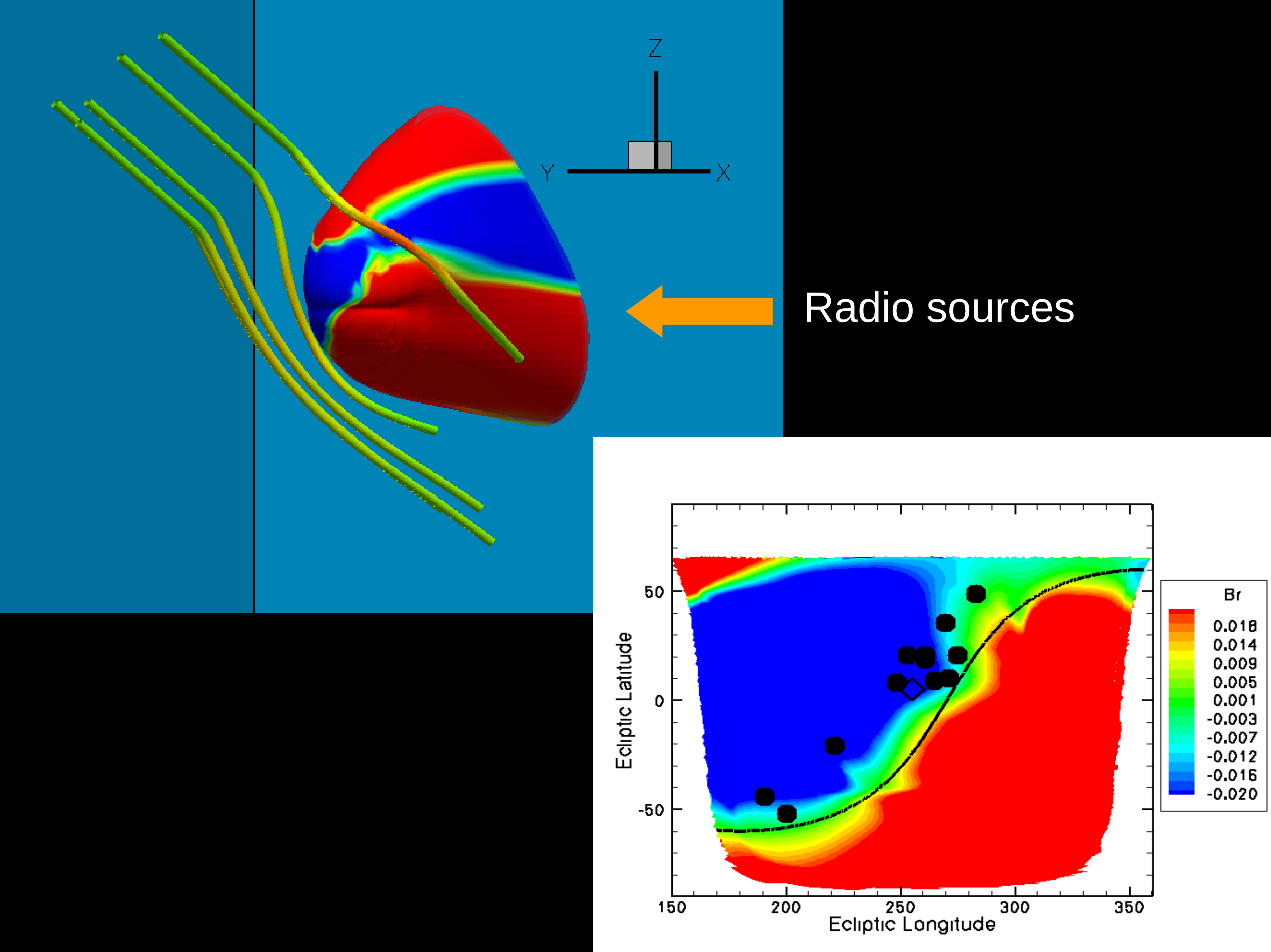


Radio Source Locations



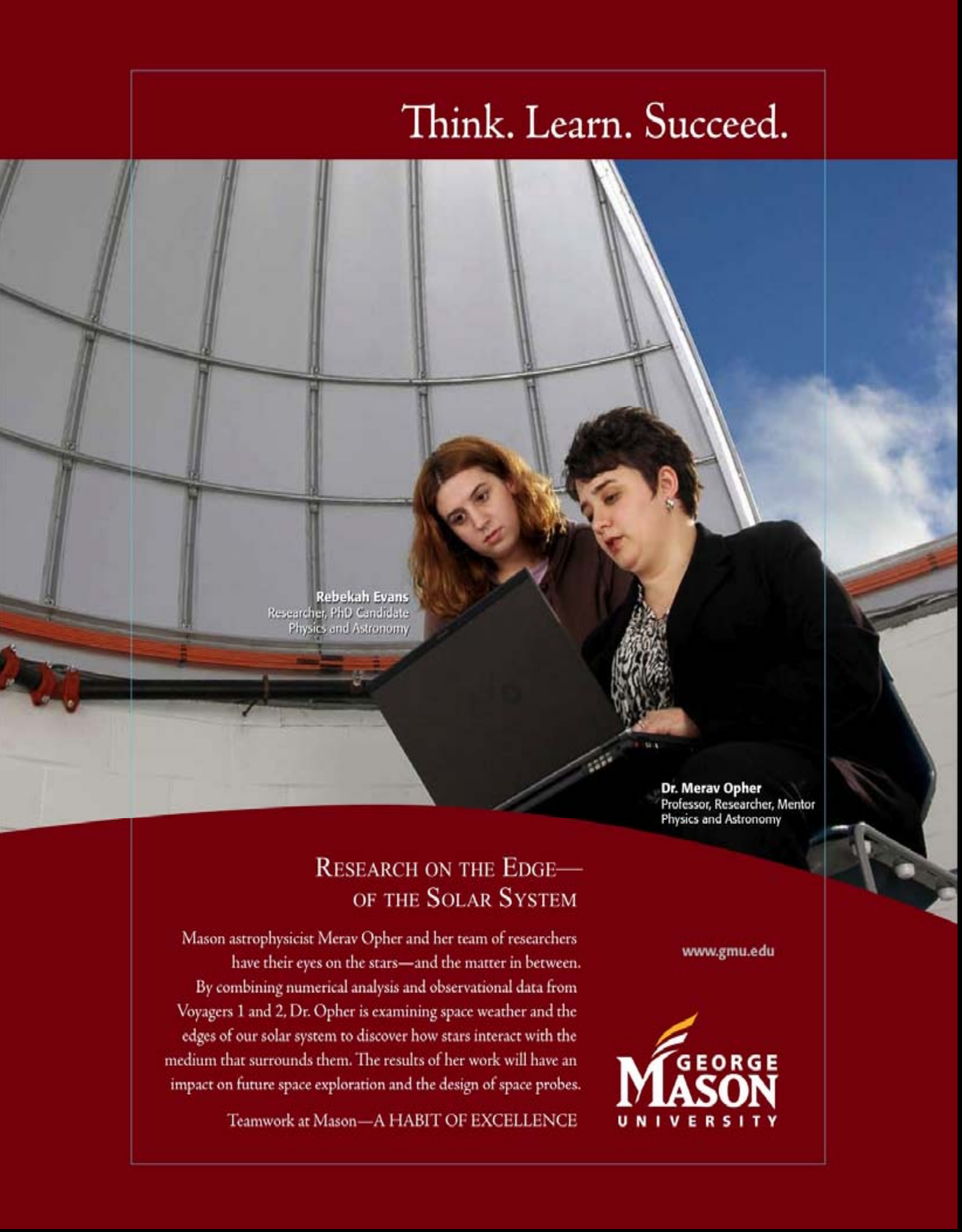
From radio direction-finding measurements from V1 and V2

Kurth & Gurnett ‘2003


Z
Y
X
Radio sources
Br
0.018
0.014
0.009
0.005
0.001
-0.003
-0.007
-0.012
-0.016
-0.020
50
0
-50
Ecliptic Latitude
150
200
250
300
350
Ecliptic Longitude

Shock Geometry can affect acceleration of particles
E.g: Termination Shock

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



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