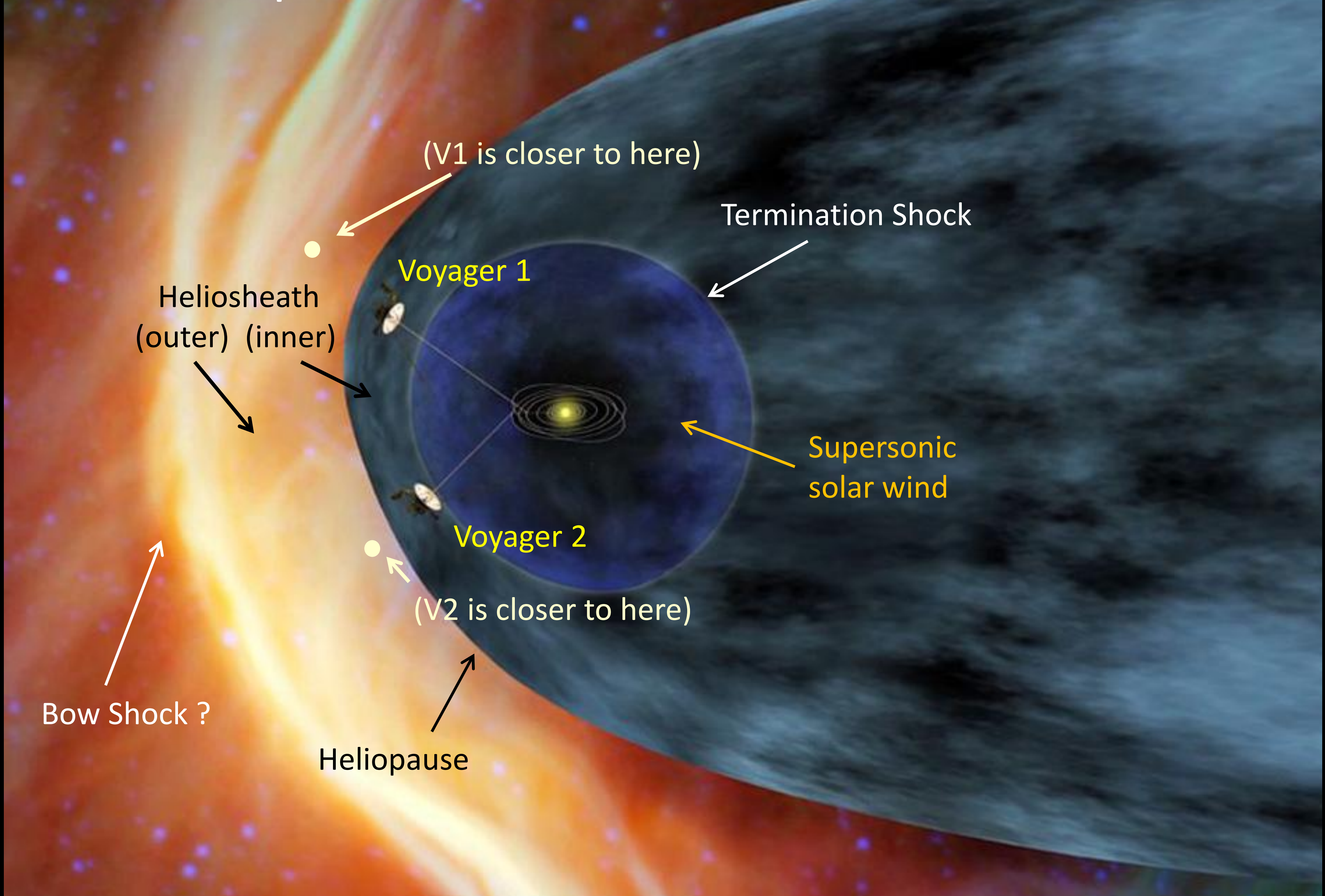
Outline for today

1. Course changes
   - Will be via ZOOM, for now.
   - Homework will be emailed and posted on website. Please email me your completed homework.
   - New schedule has been posted
2. Heliosphere finish up – miscellaneous topics
3. Current sheets
4. Sweet-Parker magnetic reconnection

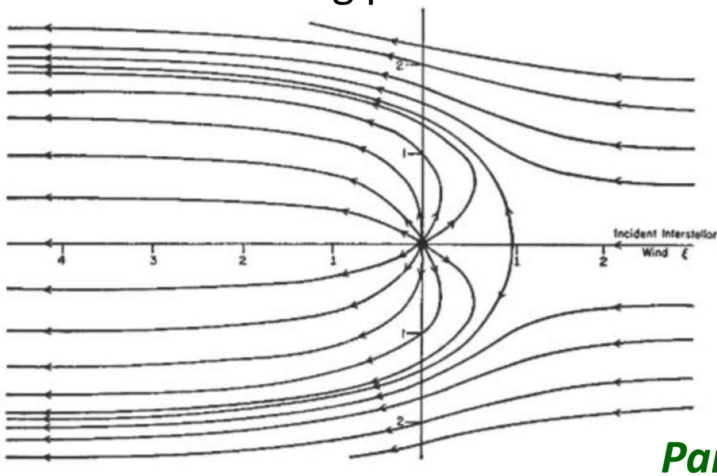
TENTATIVE SCHEDULE OF LECTURE TOPICS

	Jan 15 Course orientation. Units – cgs vs. SI	Jan 17
Jan 20 NO CLASS – MLK Holiday	Jan 22 Charged Particle orbits in constant electric and magnetic fields	Jan 24
Jan 27 Charged Particle orbits in varying electric and magnetic fields #1: drifts, invariants	Jan 29 Distribution function	Jan 31
Feb 3 Vlasov and Boltzman equations, and Liouville's theorem	Feb 5 MHD equations	Feb 7
Feb 10 Electric field in MHD. Energy equation	Feb 12 Frozen Flux theorem	Feb 14
Feb 17 Solar Magnetic Fields #1	Feb 19 Solar Magnetic Fields #2	Feb 21
Feb 24 Hydrostatic Equilibrium, Solar Atmosphere	Feb 26 Solar/Stellar Winds	Feb 28
Mar 2 Parker spiral magnetic field	Mar 4 Heliospheres/Astrospheres: Parker's potential-flow solution	Mar 6
Mar 9 NO CLASS – Spring Break	Mar 11 NO CLASS – Spring Break	Mar 13
Mar 16 NO CLASS – University Closure	Mar 18: NO CLASS (see email)	Mar 20
Mar 23: VIA ZOOM Heliosphere (cont.) Current Sheets/Magnetic reconnection	Mar 25: VIA ZOOM Plasma waves #1	Mar 27
Mar 30: VIA ZOOM Plasma waves #2	Apr 1: VIA ZOOM MHD Shocks #1	Apr 3
Apr 6: VIA ZOOM MHD Shocks #2	Apr 8: VIA ZOOM Plasma Turbulence	Apr 10
Apr 13: VIA ZOOM STUDENT PRESENTATIONS #1	Apr 15: VIA ZOOM STUDENT PRESENTATIONS #2	Apr 17
Apr 20: VIA ZOOM STUDENT PRESENTATIONS #3	Apr 22: VIA ZOOM STUDENT PRESENTATIONS #4	Apr 24
Apr 27: VIA ZOOM Particle orbits in varying electric and magnetic fields #2: diffusion	Apr 29: VIA ZOOM Particle diffusion. Cosmic-ray transport in the Heliosphere and Galaxy	May 1
May 4: VIA ZOOM Cosmic ray acceleration at shocks	May 6: VIA ZOOM Other acceleration mechanisms	May 8

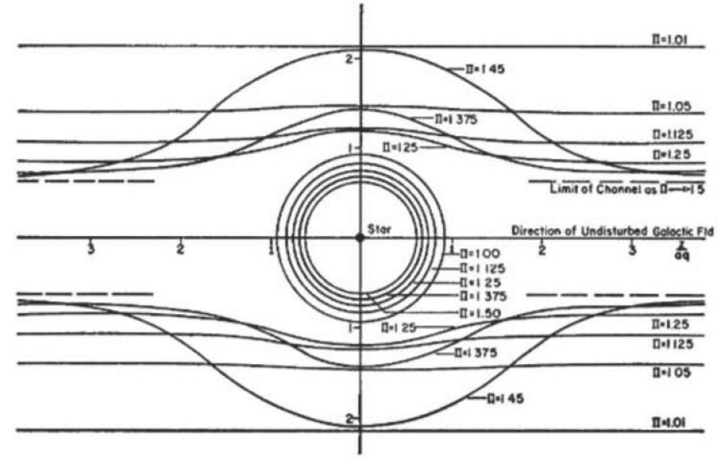
The Heliosphere



Interstellar ramming pressure dominated

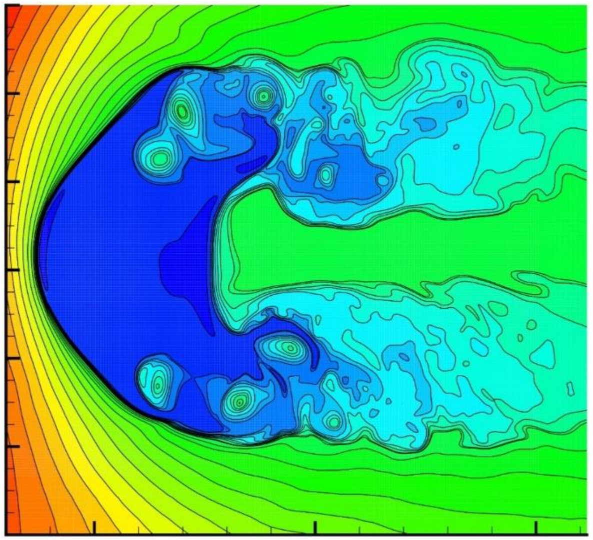


Interstellar magnetic pressure dominated

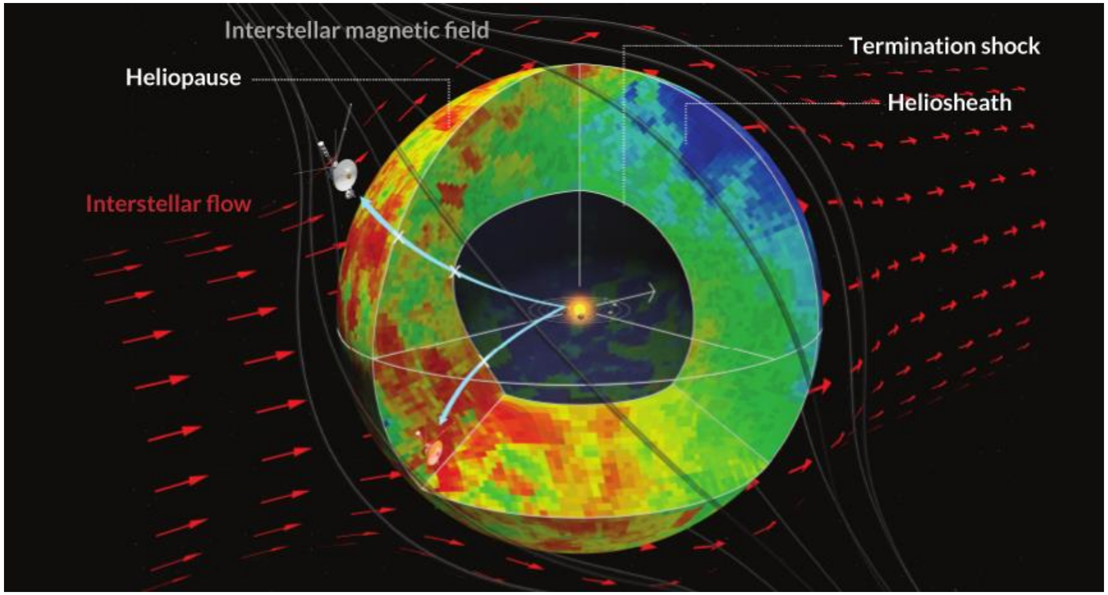


Parker, 1961

"Croissant" shaped?
(*Opher et al., 2015, 2017*)



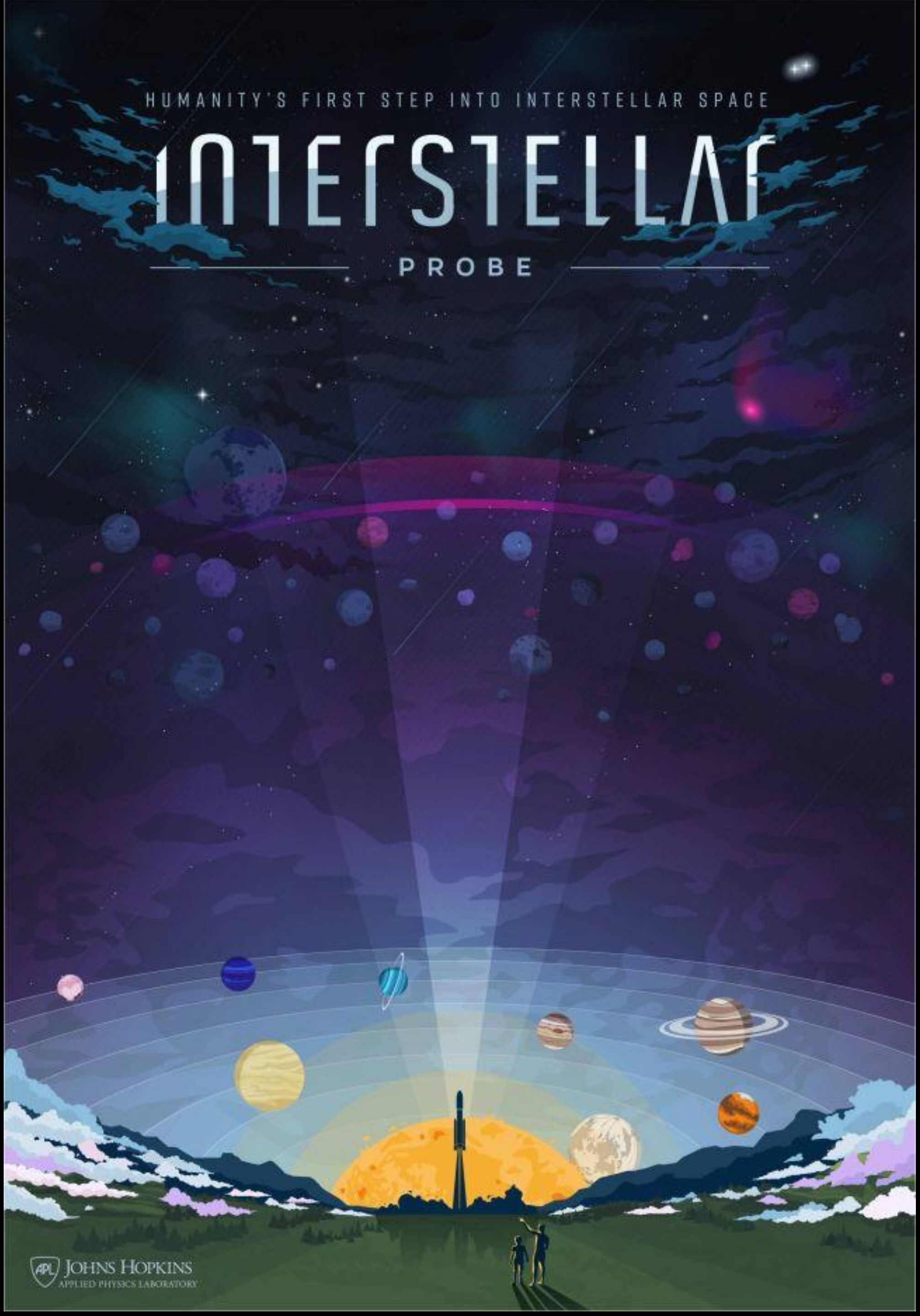
No tail?
(*Dialynas et al., 2017*)



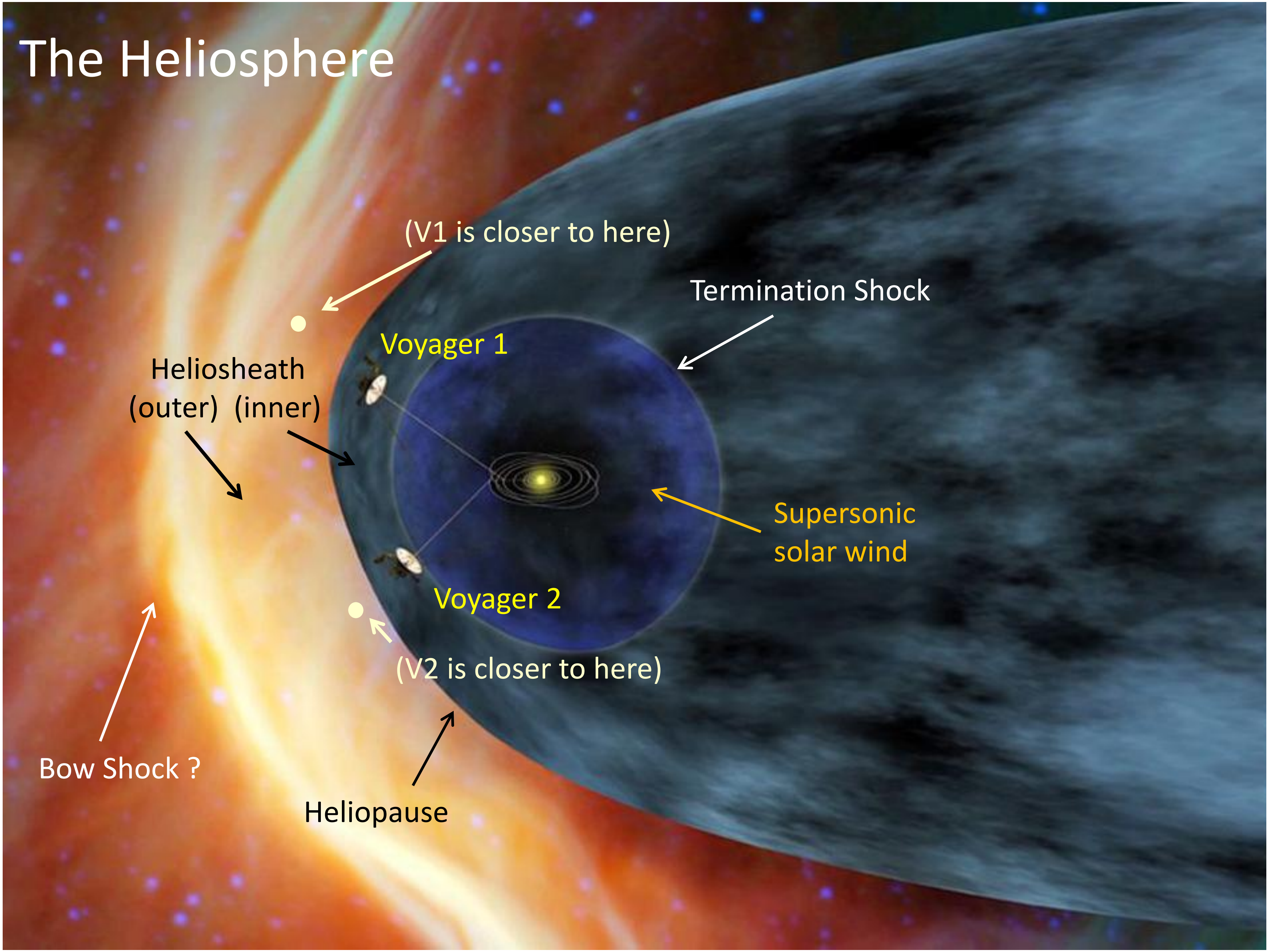
“Interstellar Probe” is a mission concept that has been in the “works” for some time.

Will it finally get an endorsement from the next Heliophysics decadal survey?

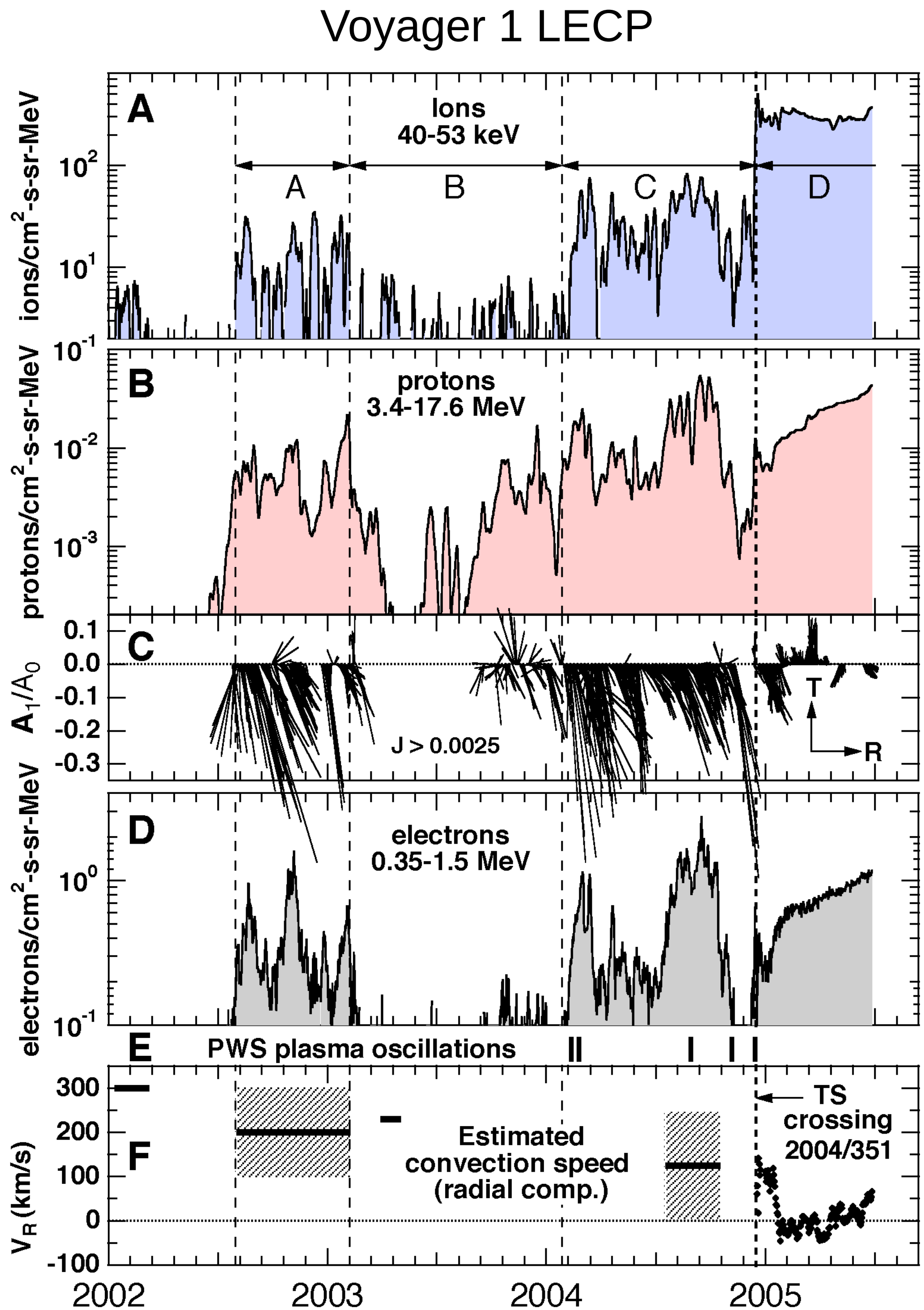
If so, it could launch as early as late 2020s, and go to about 200 AU in 15 years.



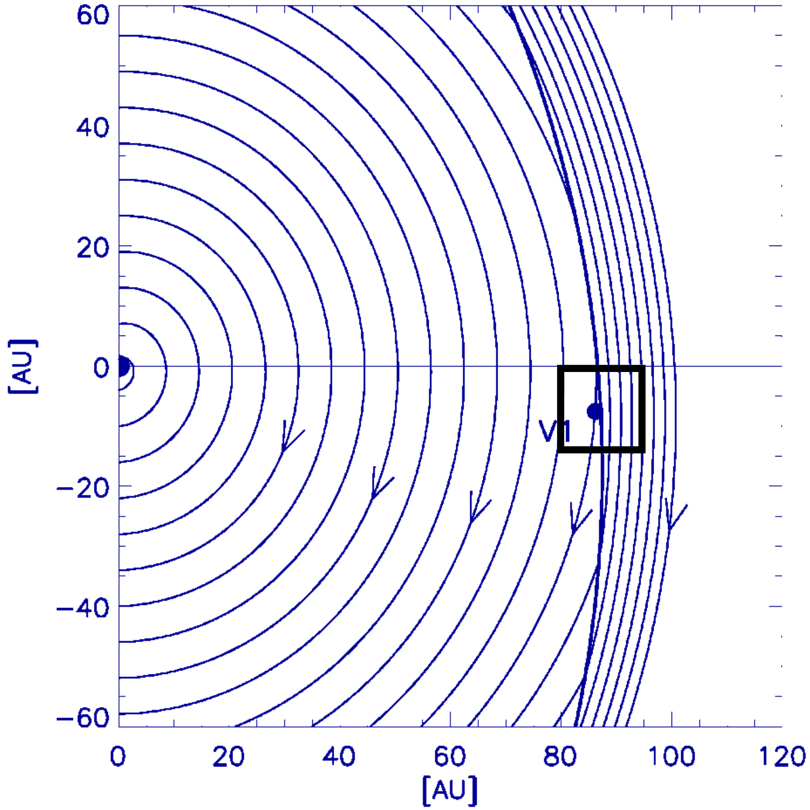
The Voyager 1 and 2 crossing of the Solar Wind Termination Shock

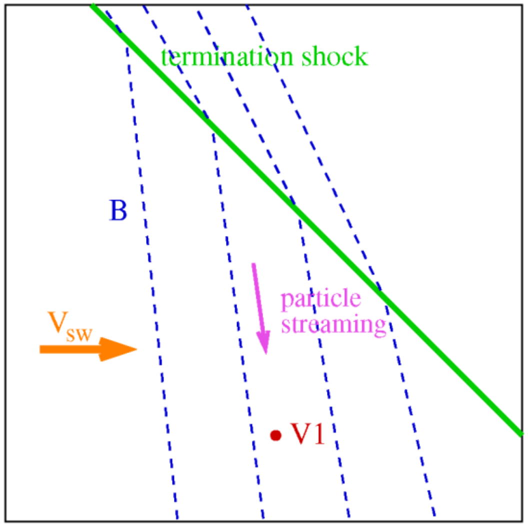

The Heliosphere
(V1 is closer to here)
Termination Shock
Voyager 1
Heliosheath
(outer) (inner)
Supersonic
solar wind
Voyager 2
(V2 is closer to here)
Bow Shock ?
Heliopause

- Prior to its crossing of the termination shock in late 2004, *Voyager 1* began seeing pre-cursor energetic particles as early as mid 2002.
- The distributions were highly anisotropic
- The particles were seen streaming along the magnetic field AWAY from the Sun
- This suggested a source located <u>inside</u> of the spacecraft

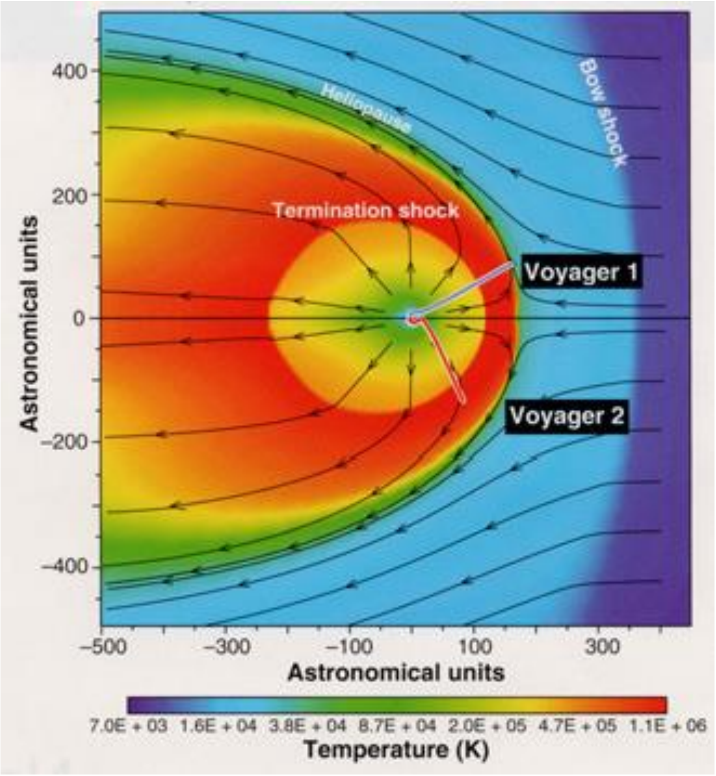


Decker et al., 2005



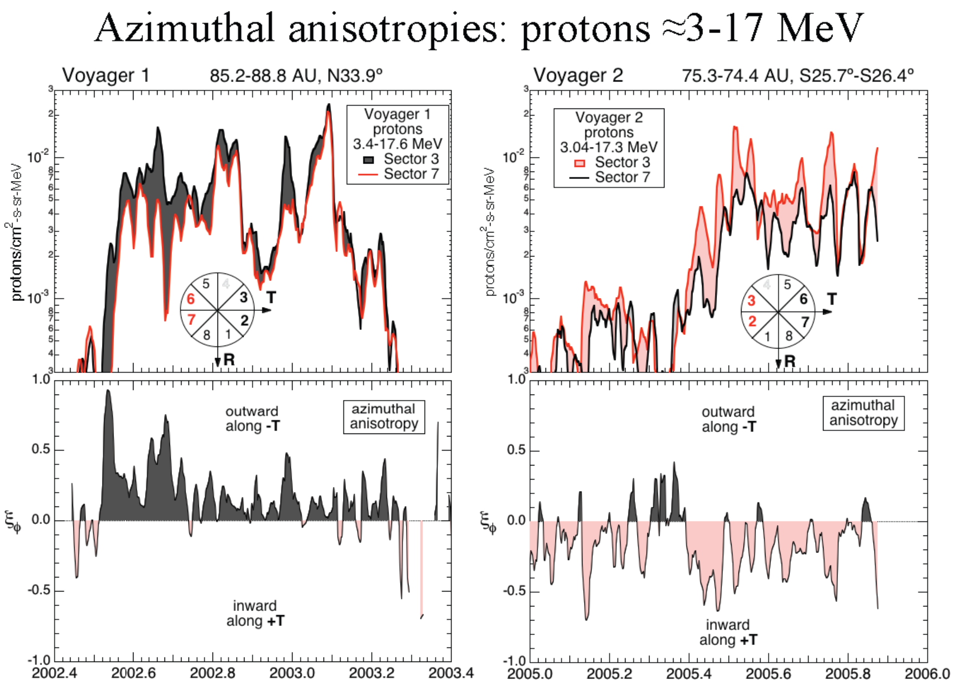


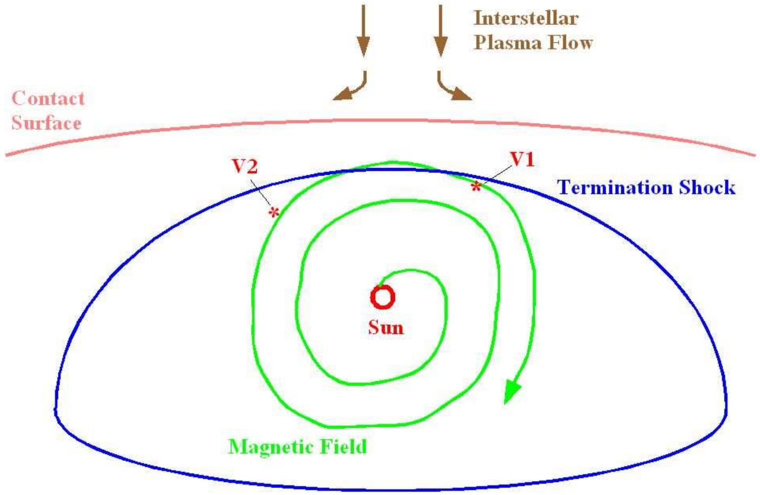
- V1 observed particle anisotropies could not be explained using a spherical termination shock
- The consensus view is that the shock is "blunt"



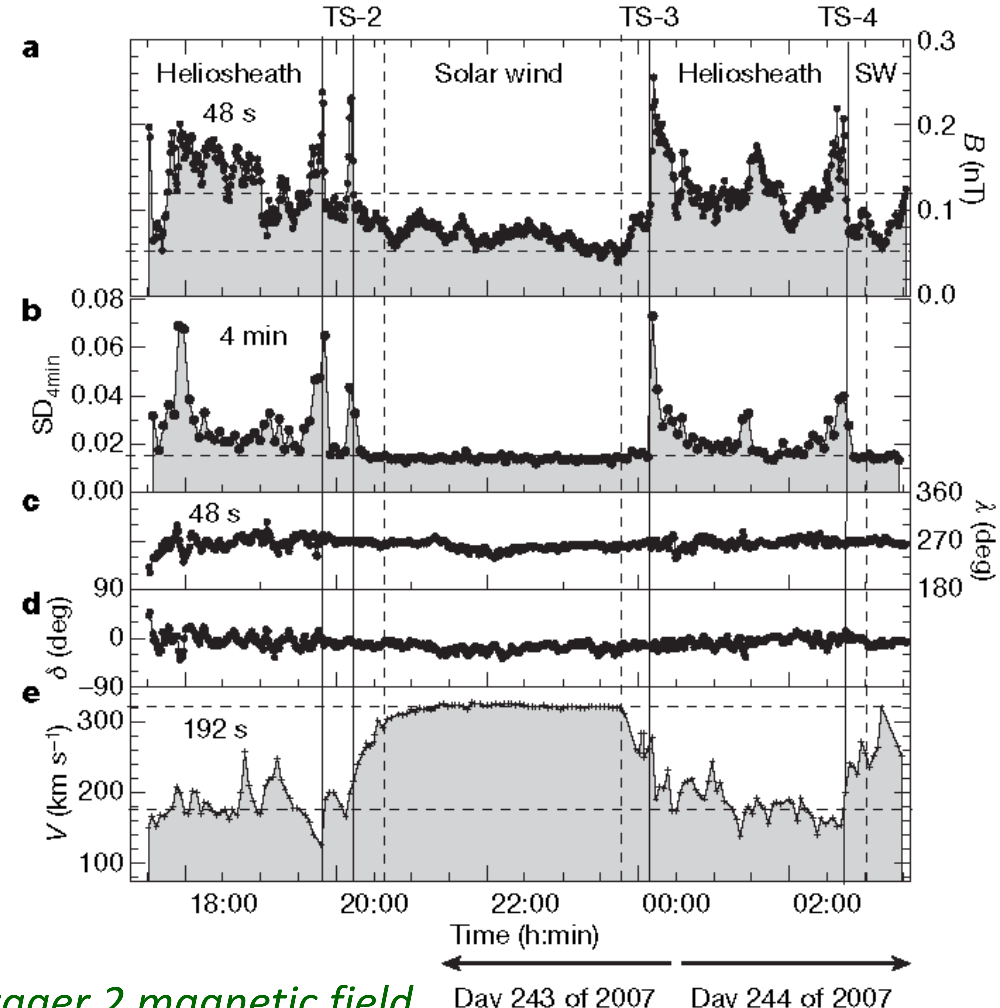
Heliosphere MHD simulation by Gary Zank

Jokipii et al. (2004) predicted the anisotropy would be reversed at V2, which was later observed



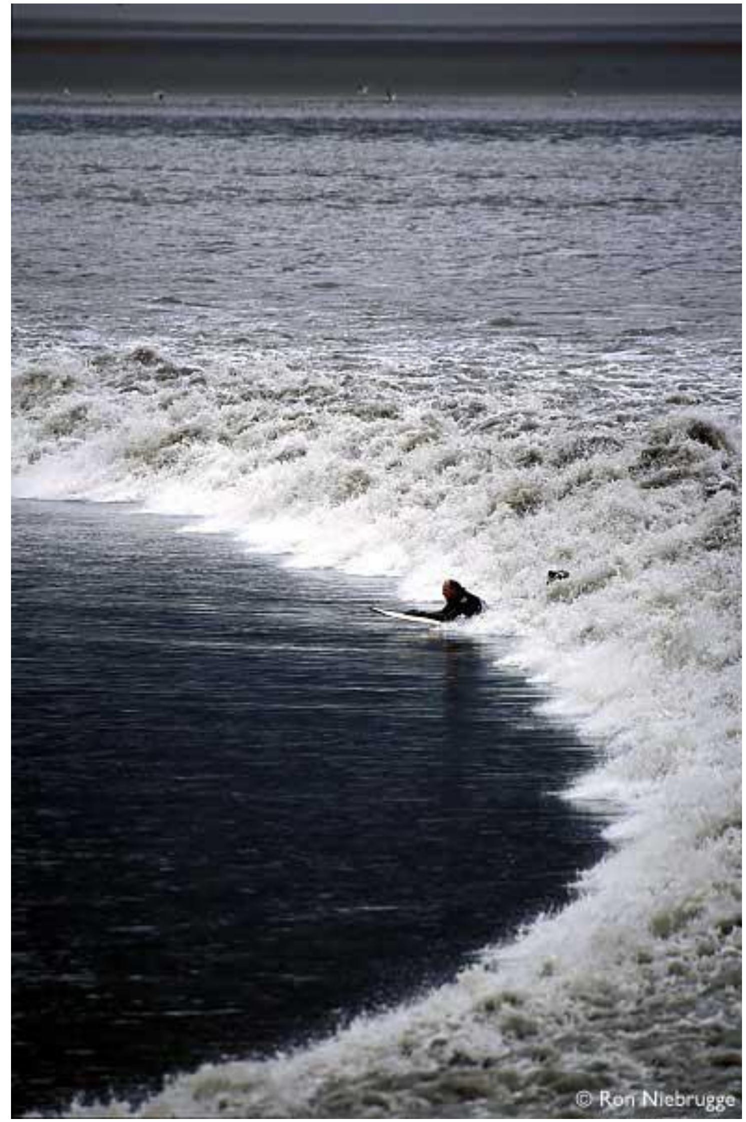


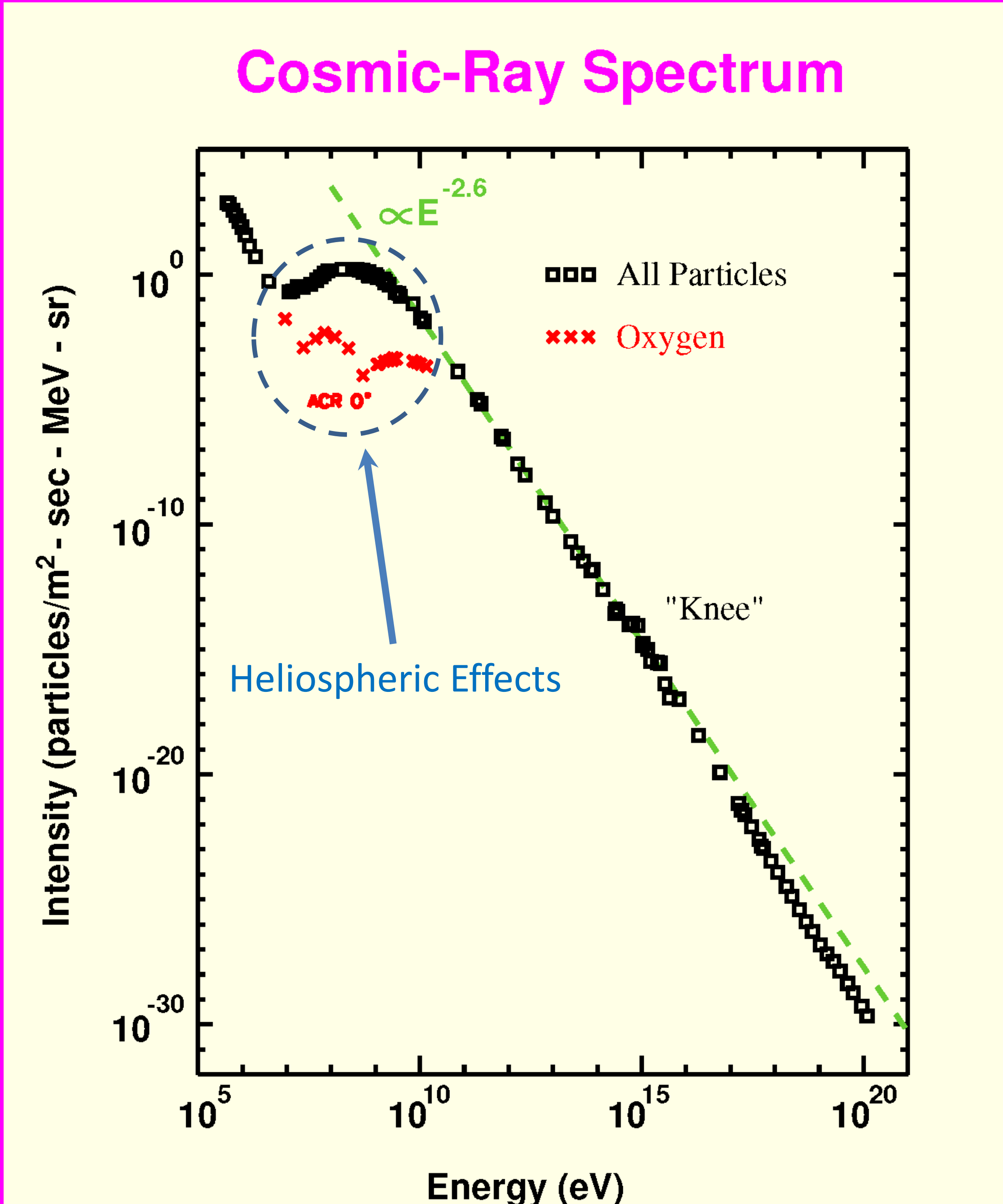
The termination shock was crossed several times by Voyager 2 suggesting it was moving in and out across the spacecraft – probably due to turbulence



Voyager 2 magnetic field and flow speed (from Burlaga et al., 2007)

The termination shock locally seems to be analogous to this tidal bore.





The heliosphere has a significant effect on GCRs with energies below about 10 GeV.

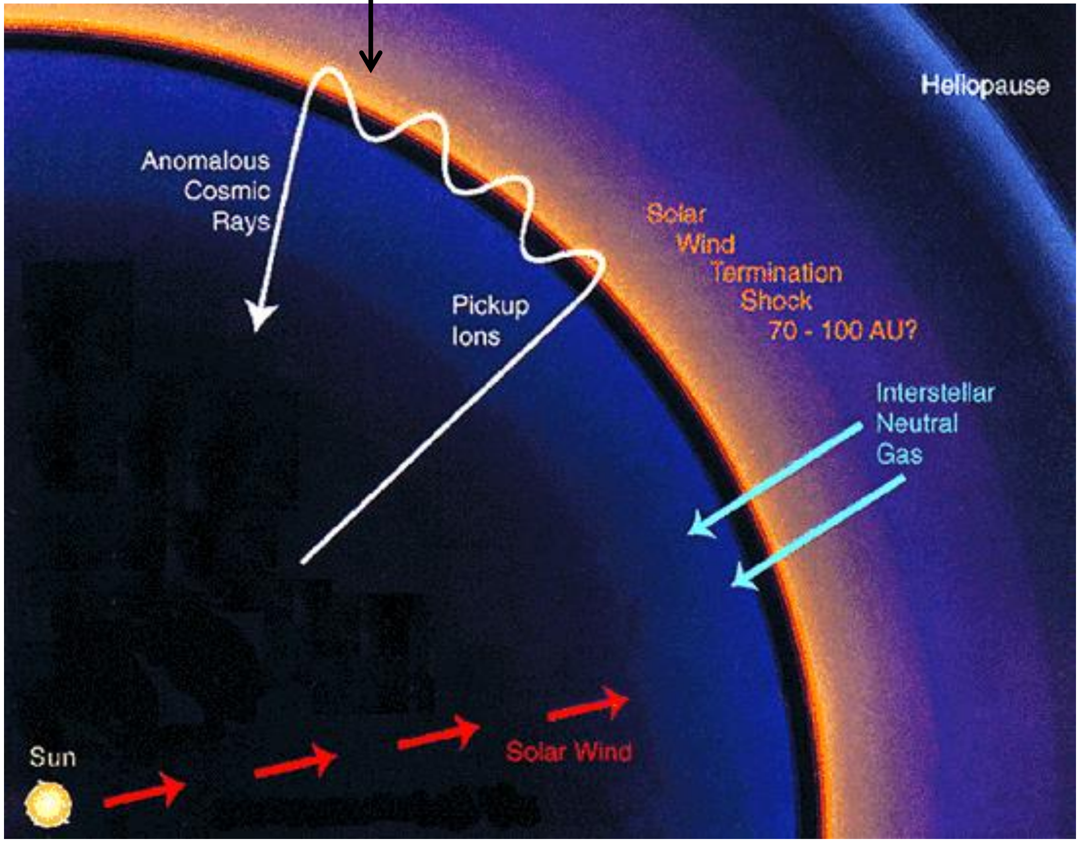
The “modulation” is due to the heliosphere – hence GCRs can also be used as probes of the heliosphere

Anomalous Cosmic Rays (ACRs) are a separate component, that are produced in the heliosphere – they are also important probes

The mechanism of acceleration ACRs will be discussed later in this talk

Anomalous Cosmic Rays

The paradigm for ACRs prior to Voyager's termination shock crossings



Voyager 1 observations of ACRs showing a rise as the s/c moved outward towards the source.

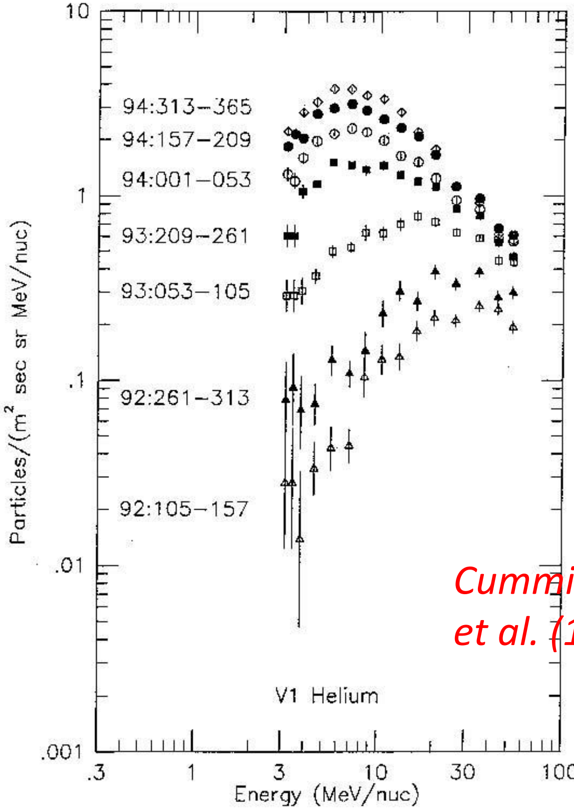
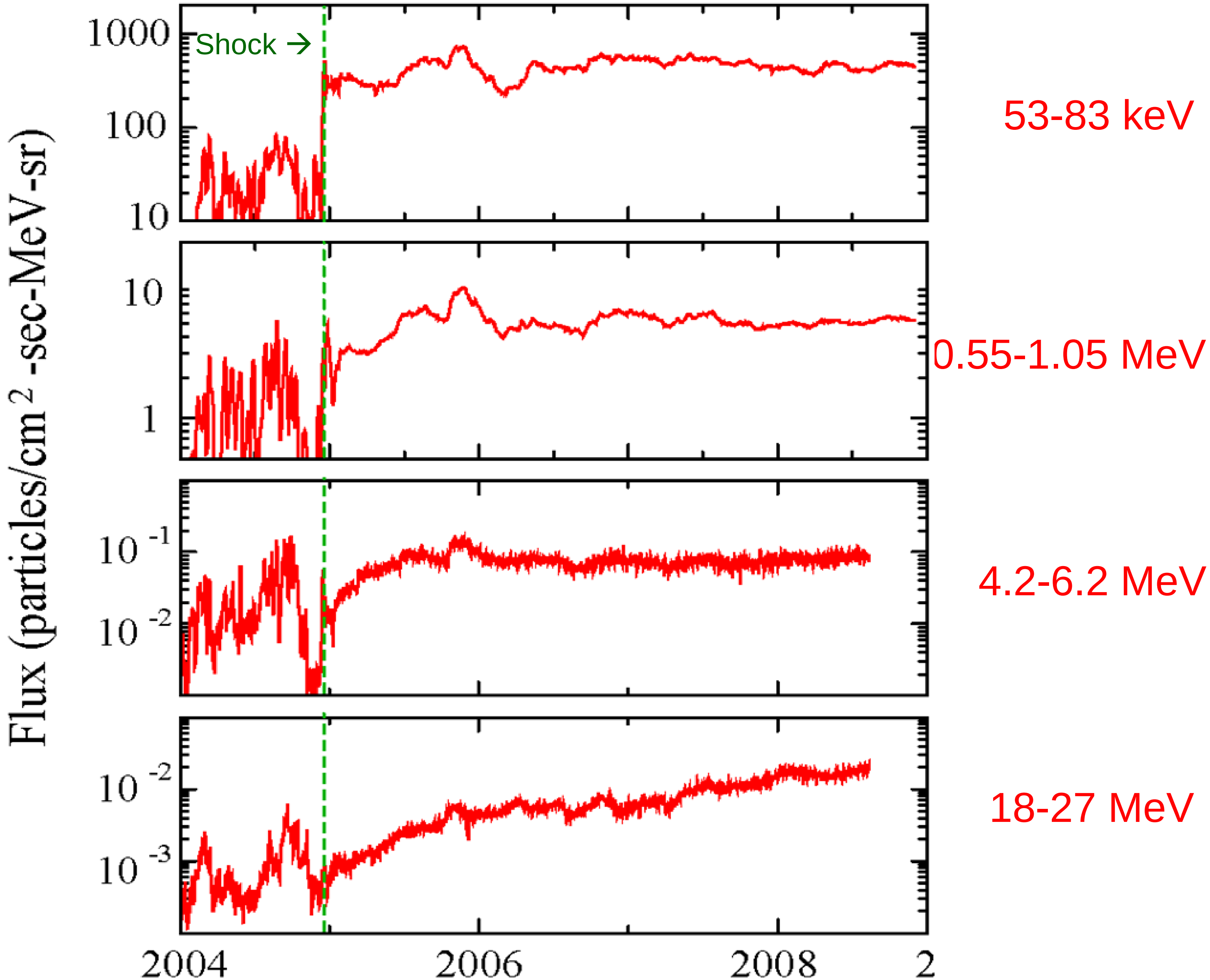


Figure 3. Energy spectrum of helium measured at V1 for seven time periods.

Cummings et al. (1996)

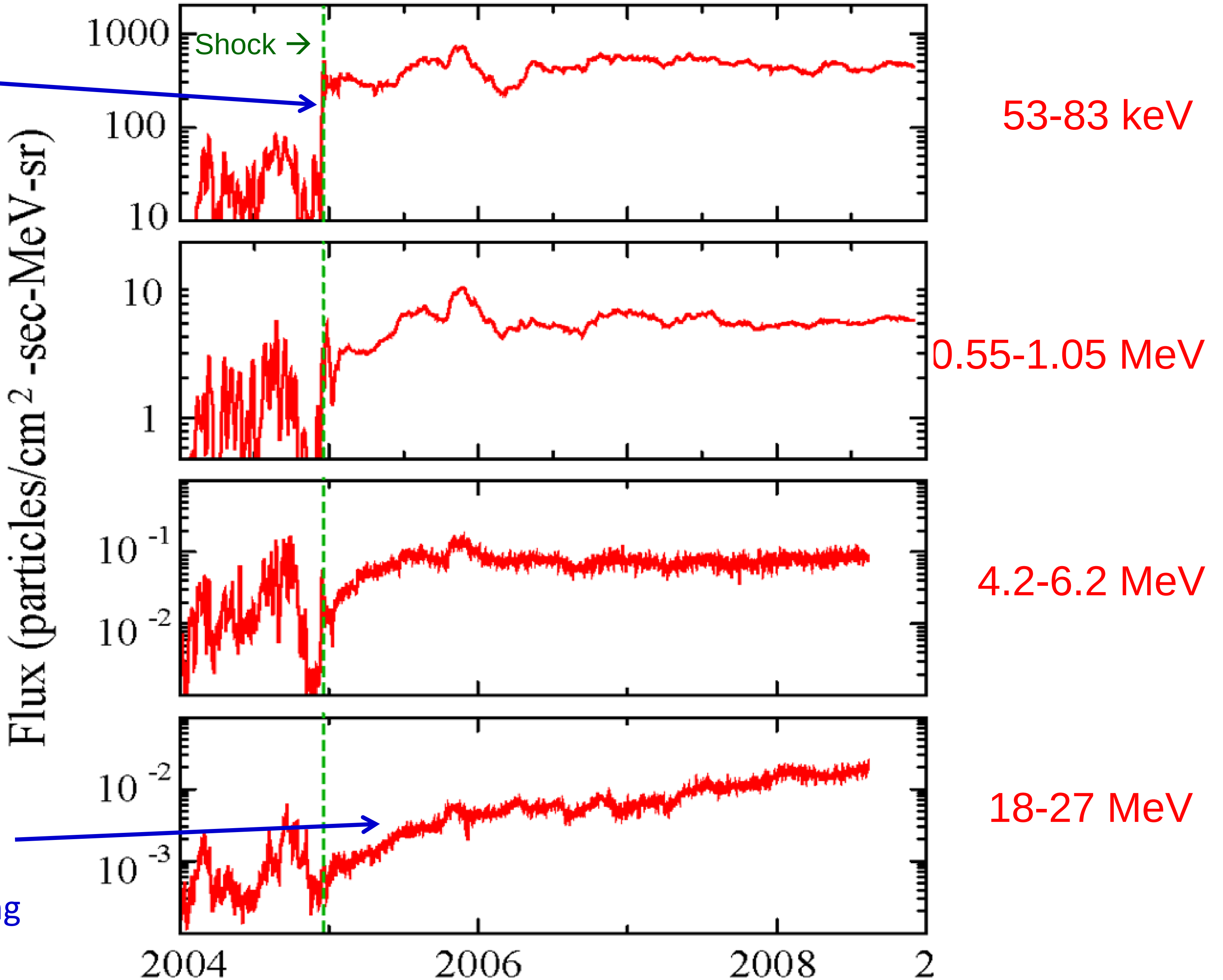
ACRs include He, O, Ne, but are noticeably absent in C. A major clue regarding their origin is that most are observed to be singly charged.

Voyager 1 (LECP/CRS)



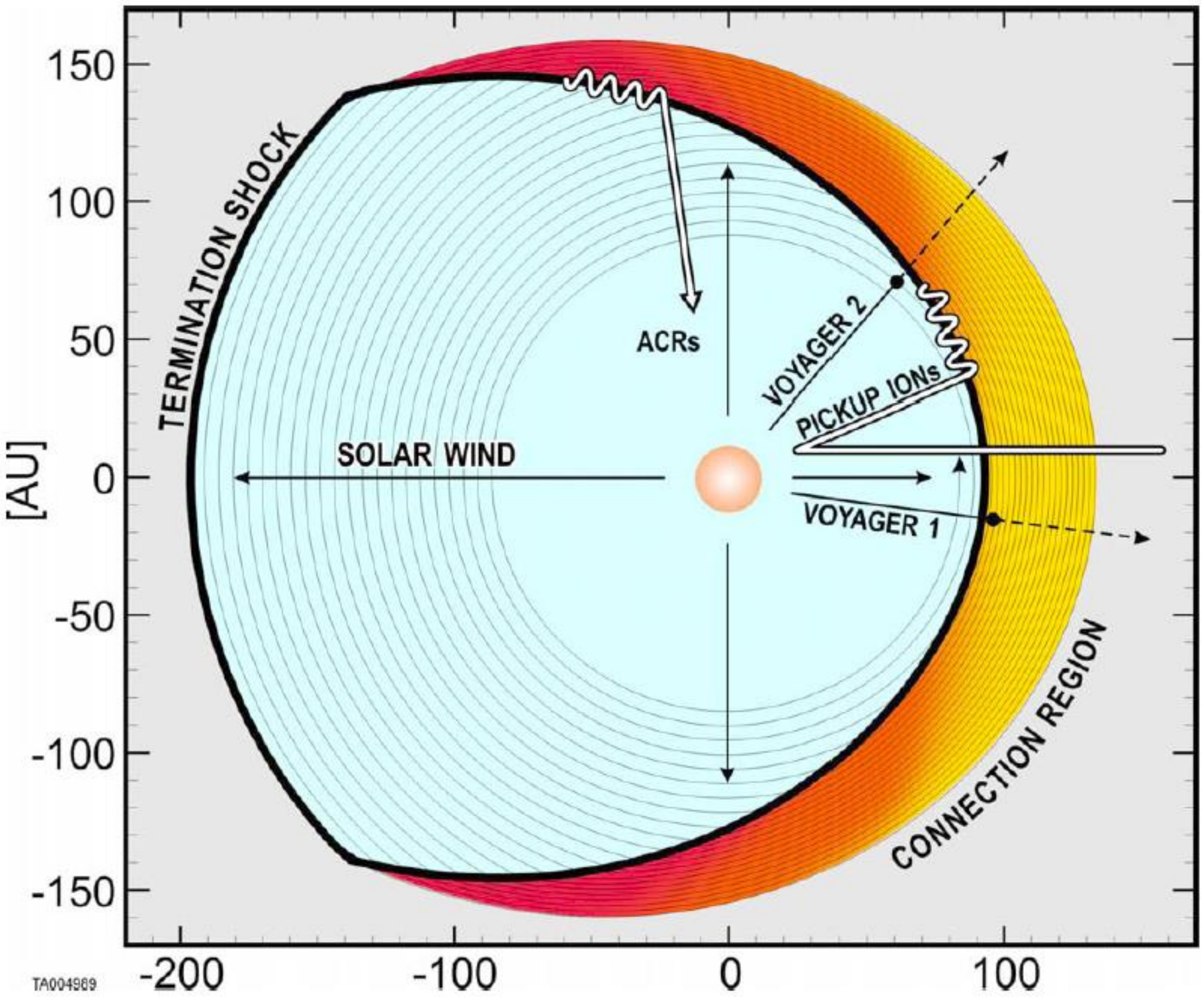
Voyager 1 (LECP/CRS)

Low-energy "ACRs" peak directly at the shock



High-energy "ACRs" continue to rise well after the shock crossing

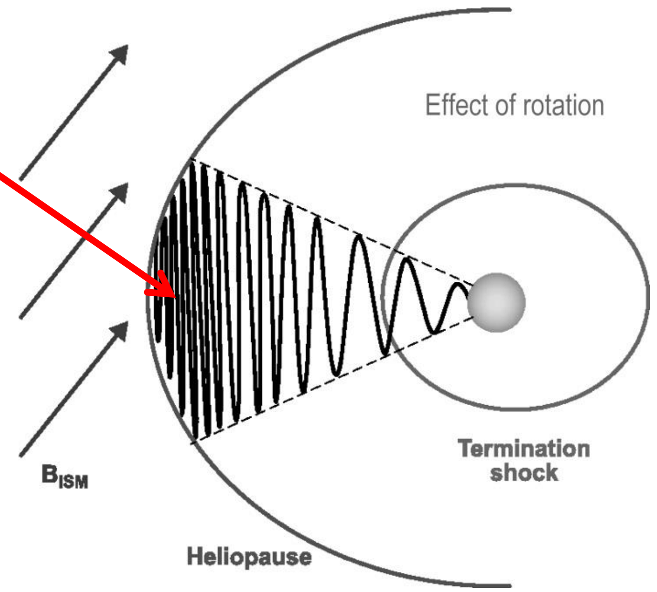
The Effect of a Blunt Shock:
Source of High-Energy ACRs at Flanks ?



McComas & Schwadron (2006)

Other proposed mechanisms for ACRs

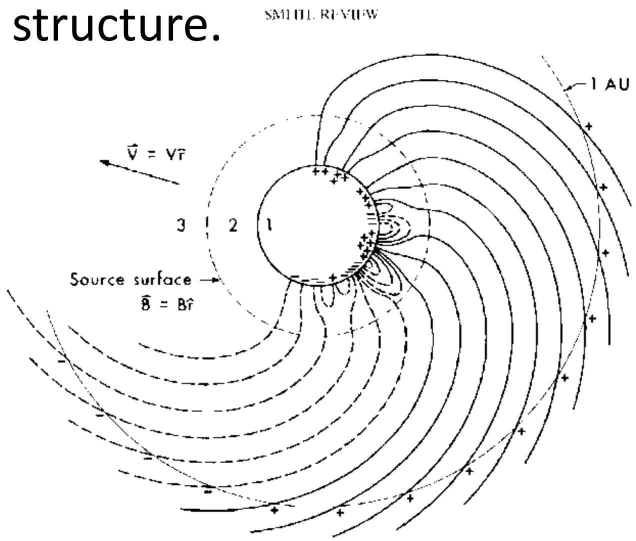
- Magnetic reconnection
  - Reconnection of HCS in the heliosheath
  - Magnetic "islands" in the reconnection exhaust (Drake and Opher, 2009)
  - ACRs are accelerated within these islands
  - Lazarian and Opher (2009) have also suggested reconnection, but rely on the dissipation of turbulence to create the reconnection event. ACRs are accelerated at each reconnection site



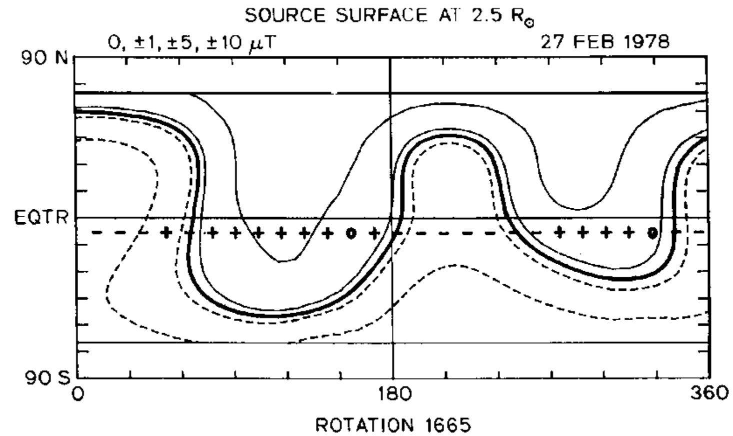
This mechanism have a number of problems, most notably that there is very little energy in the magnetic field to draw from.

Voyager has observed that $\varepsilon_{ACR} > B^2/8\pi$ in the heliosheath. Thus, for this mechanism to work, the magnetic field must be considerably stronger somewhere other than Voyager.

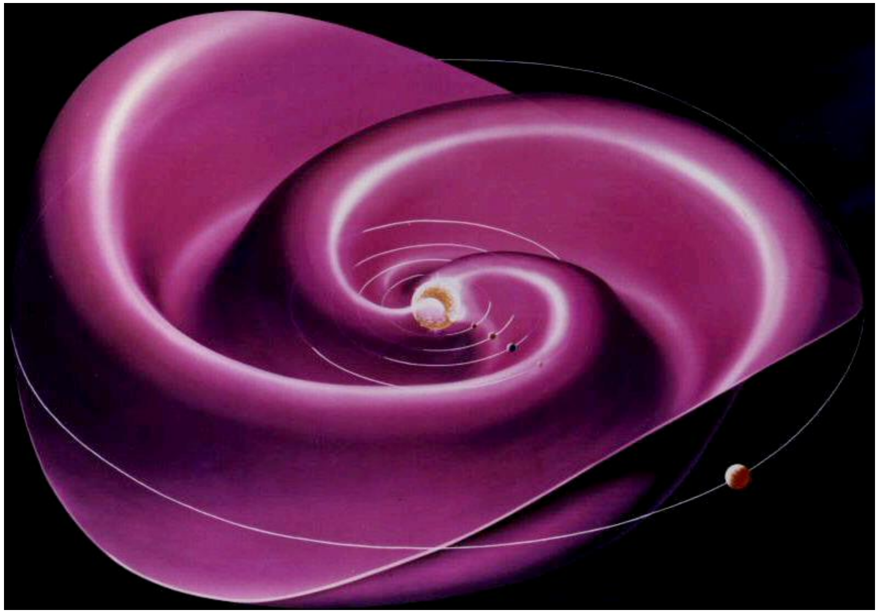
Interplanetary magnetic-field sector structure.



Neutral line at the solar source surface



Heliospheric current sheet →



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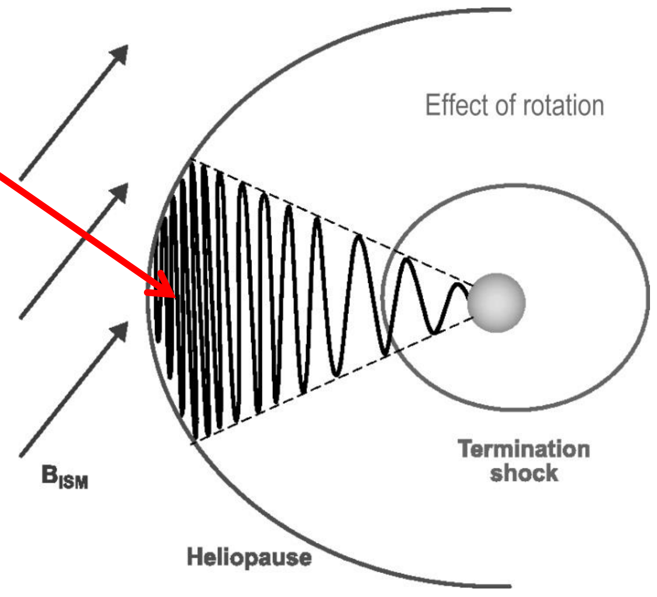

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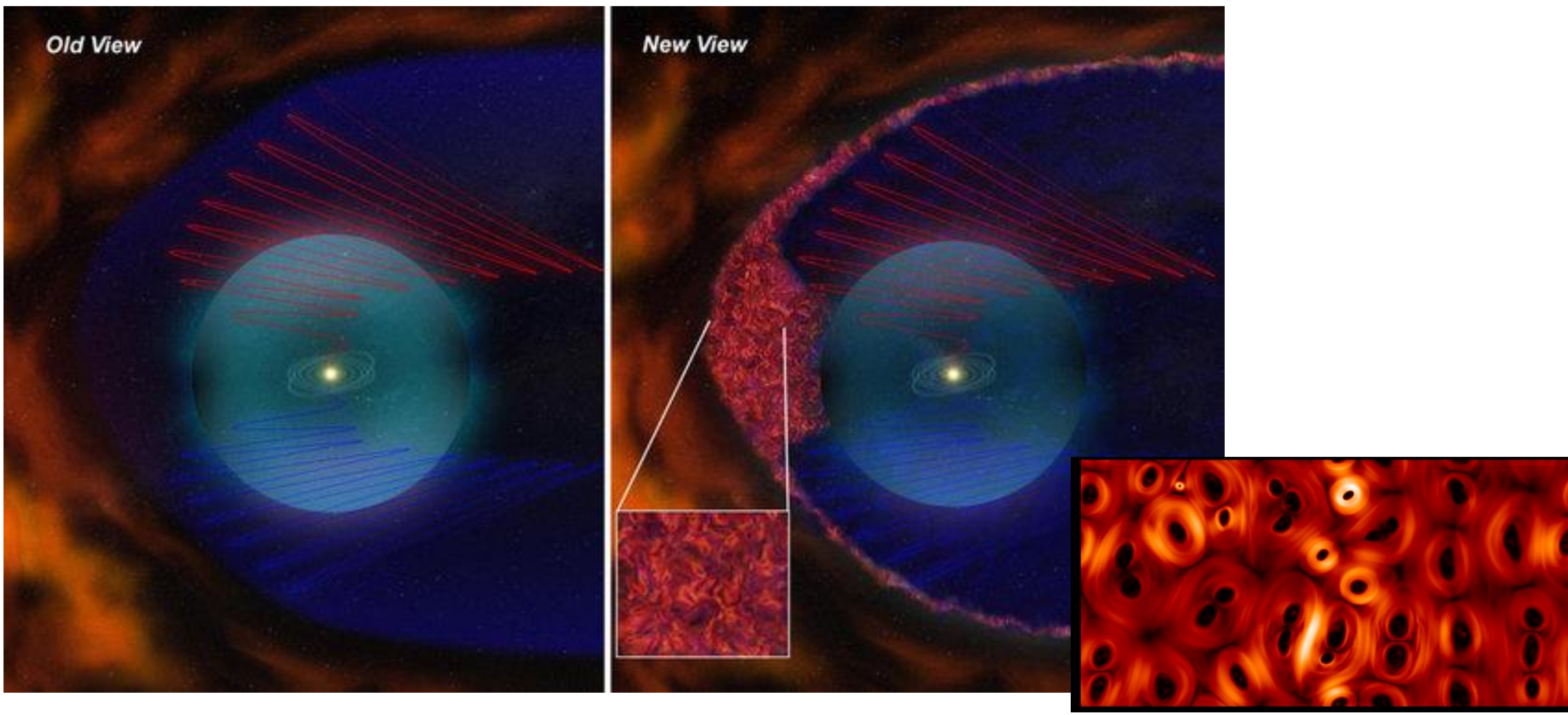
“bubbles” due to magnetic reconnection in the heliosheath ??



Other proposed mechanisms for ACRs

- Acceleration by random plasma compressions
  - The heliosheath contains numerous compressive fluctuations which can accelerate particles (Fisk and Gloeckler, 2008; Lee and Jokipii, 2010).
  - Particles gain energy by moving through many compressions. They gain energy at a compression, and lose energy at a rarefaction. The process is a classic random walk in the *log of the momentum*, so that there is actually a net energy gain in terms of momentum.
  - The process works in principal, but is very slow.

Voyager 1 and 2 observed the 50-keV-1 MeV proton intensity was essentially constant in the heliosheath – thus, this mechanism clearly cannot be working locally.

While high-energy ACRs did not peak at the termination shock, lower-energy "suprathermal" ions clearly jumped at the shock – by as much as an order of magnitude or more.

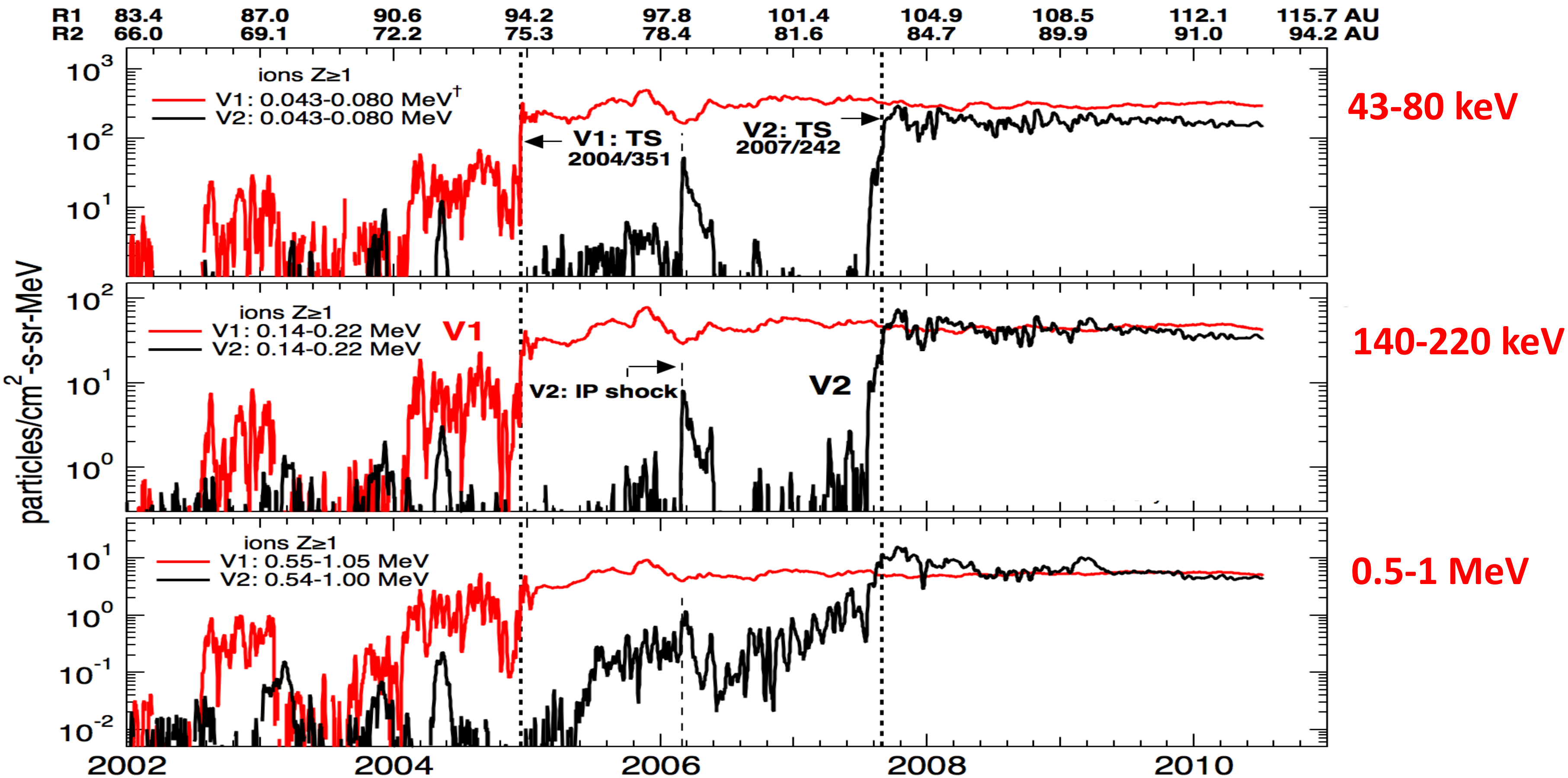
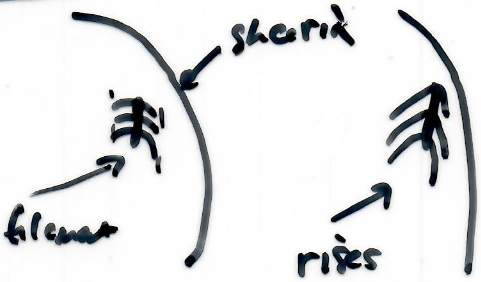
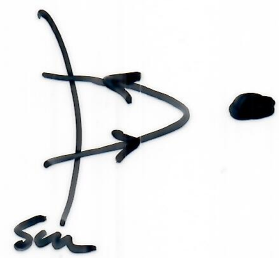


Figure courtesy Rob Decker

Current Sheets & Magnetic reconnection

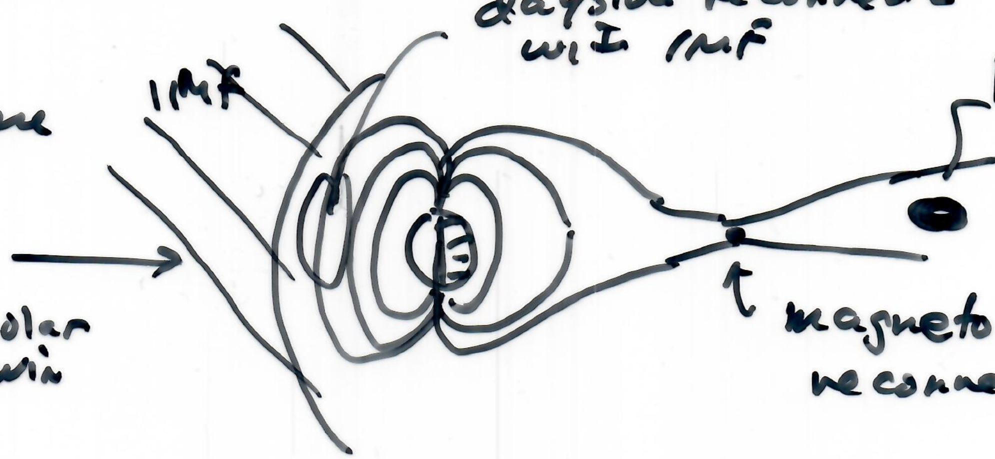
examples





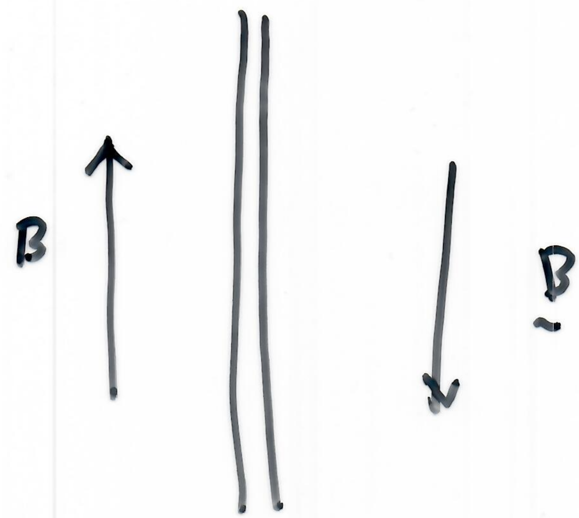
nano-flares (Parker idea)

magnetosphere



* heliosheath (Opher & Drake)
* rapidly rotating stars
* turbulent reconnection

Consider a current sheet



Suppose, no flow, low β limit ($P \ll B^2/8\pi$)
(ignore gravity)

in <u>ideal</u> MHD, this is a stable "discontinuity" because ~~there is no momentum~~ MHD momentum eq. is invariant to $\underset{\sim}{B} \to -\underset{\sim}{B}$

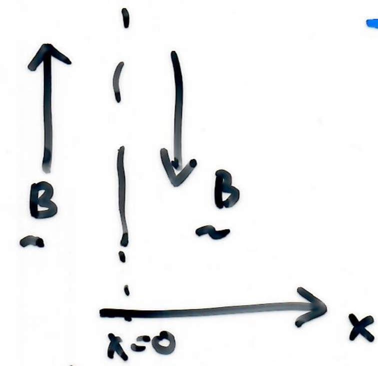
Ideal MHD doesn't have a length scale! so, ~~what~~ this is a discontinuity, but does not describe its structure.

go to non-ideal MHD, include diffusivity
recall magnetic induction eq.

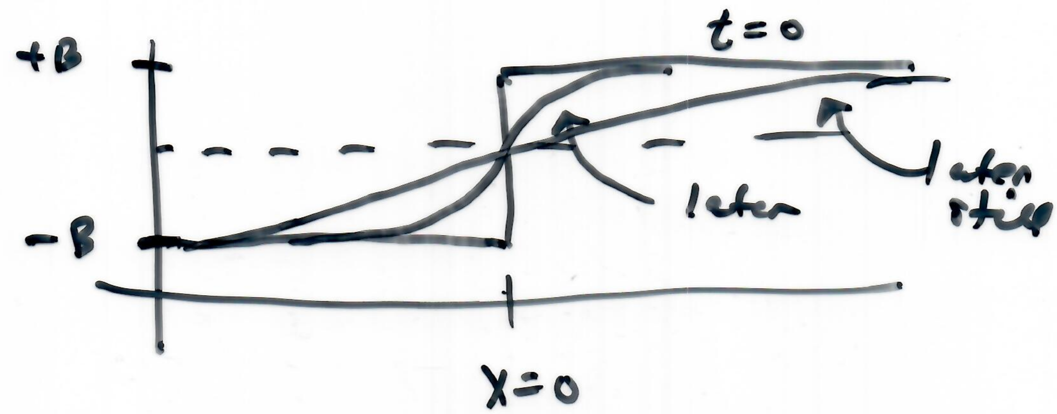
$$\frac{\partial \underset{\sim}{B}}{\partial t} = \nabla \times (\underset{\sim}{u} \times \underset{\sim}{B}) + \eta_D \nabla^2 \underset{\sim}{B}$$

($\underset{\sim}{u} \to 0$: no flows; η_D: diffusivity)

$$\frac{\partial B}{\partial t} = \eta_D \frac{\partial^2 B}{\partial x^2}$$



$\Rightarrow$ no steady state is possible!



slowly annihilating $\underset{\sim}{B}$

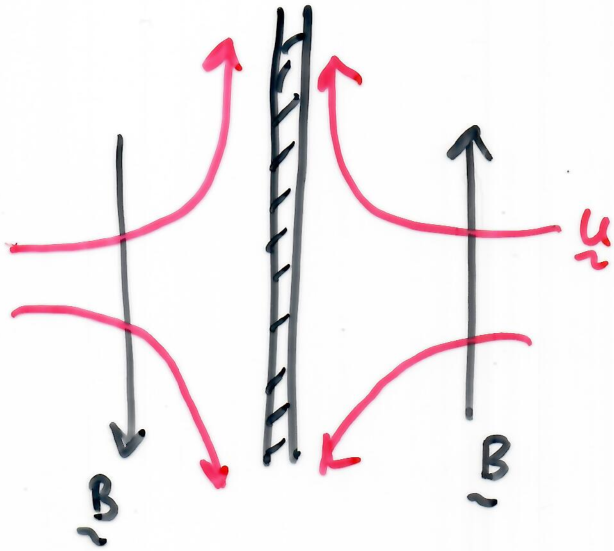
this energy goes into heating the plasma through energy eq.

ηJ^2 ← ohmic dissipation

resistivity

$$\eta_D = \frac{\eta c^2}{4\pi}$$

An example of a steady state current sheet



including plasma flows

flows result from drop in ~~total~~ pressure in "diffusion" region

Consider

$$u_x = -u_0 \, x/a$$

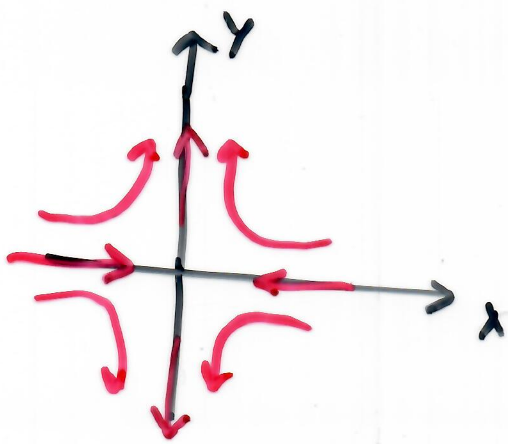
$$u_y = u_0 \, y/a$$

$$\underset{\sim}{B} = B(x)\,\hat{y}$$

$\nabla \cdot \underset{\sim}{u} = 0$

$\Rightarrow \rho =$ constant along streamlines

Since $\rho = \rho_0$ far from current sheet, $\rho = \rho_0$ everywhere.



streamlines defined by

$$xy = \text{constant}$$

Solve mag. induction eq.

$$\frac{\partial \underset{\sim}{B}}{\partial t} = \nabla \times (\underset{\sim}{u} \times \underset{\sim}{B}) + \eta_D \nabla^2 \underset{\sim}{B}$$

$$(\underset{\sim}{u} \times \underset{\sim}{B} = u_x B \hat{z})$$

$$= \frac{\partial}{\partial y}(u_x B)\hat{x} - \frac{\partial}{\partial x}(u_x B)\hat{y} + \eta_D \nabla^2 \underset{\sim}{B}$$

$$\Rightarrow \frac{\partial B}{\partial t} = -\frac{\partial}{\partial x}(u_x B) + \eta_D \nabla^2 B = 0 \quad \text{steady state}$$

jump sideways

$$\underset{\sim}{E} = -\frac{1}{c}\underset{\sim}{u} \times \underset{\sim}{B} + \eta \underset{\sim}{J}$$

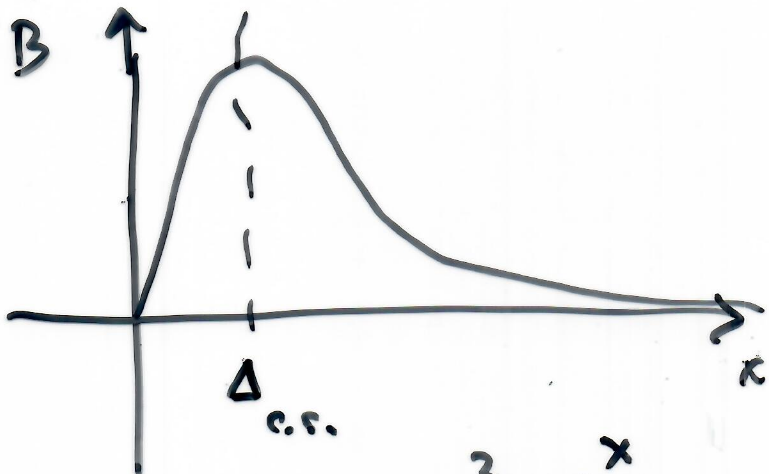
$$= -\frac{1}{c} u_x B \hat{z} + \eta \frac{c}{4\pi}\frac{dB}{dx}\hat{z}$$

note $\nabla \times \underset{\sim}{E} = -\frac{1}{c}\frac{\partial B}{\partial t} = 0$ in steady state

$$\Rightarrow \underset{\sim}{E} = \text{constant!}$$

$$\therefore \quad -\frac{1}{c} u_x B + \frac{\eta c}{4\pi}\frac{dB}{dx} = E_0 = \text{constant}$$

$$\Rightarrow \boxed{\frac{u_0 \times B}{ac} + \frac{\eta c}{4\pi}\frac{dB}{dx} = E_0}$$ eq. to solve for B



$$B = C e^{-\frac{u_0 x^2}{2a\eta c^2}} \int_0^x e^{\frac{u_0 x'^2}{2a\eta c^2}} dx'$$

$(\text{for } x > 0)$

it can be shown that approximate width of the "diffusion region"

$$\Delta_{c.s.} = \left(\frac{\eta c^2 a}{4\pi u_0}\right)^{1/2} = \left(\frac{\eta_0 a}{u_0}\right)^{1/2}$$

look @ rate at which B is advected in to rate @ which it is annihilated

$$\eta J^2 \times A \Delta_{c.s.} = \frac{B^2}{8\pi} u_0 \times A \qquad A = \text{area}$$

ηJ^2: dissipation rate; $A\Delta_{c.s.}$: volume; $\frac{B^2}{8\pi}u_0$: magnetic energy flux; A: area

"Energy conservation"

$J \approx \frac{c}{4\pi}\frac{B}{a}$, and manipulate, we find

$$u_0 = \frac{\eta c^2}{\pi a} \propto \frac{1}{R_M} \qquad R_M = \text{magnetic Reynolds \#}$$

↑

this is called the "reconnection rate"

in the Sun, e.g. $R_M \sim 10^9$

$\Rightarrow$ very slow rate of reconnection