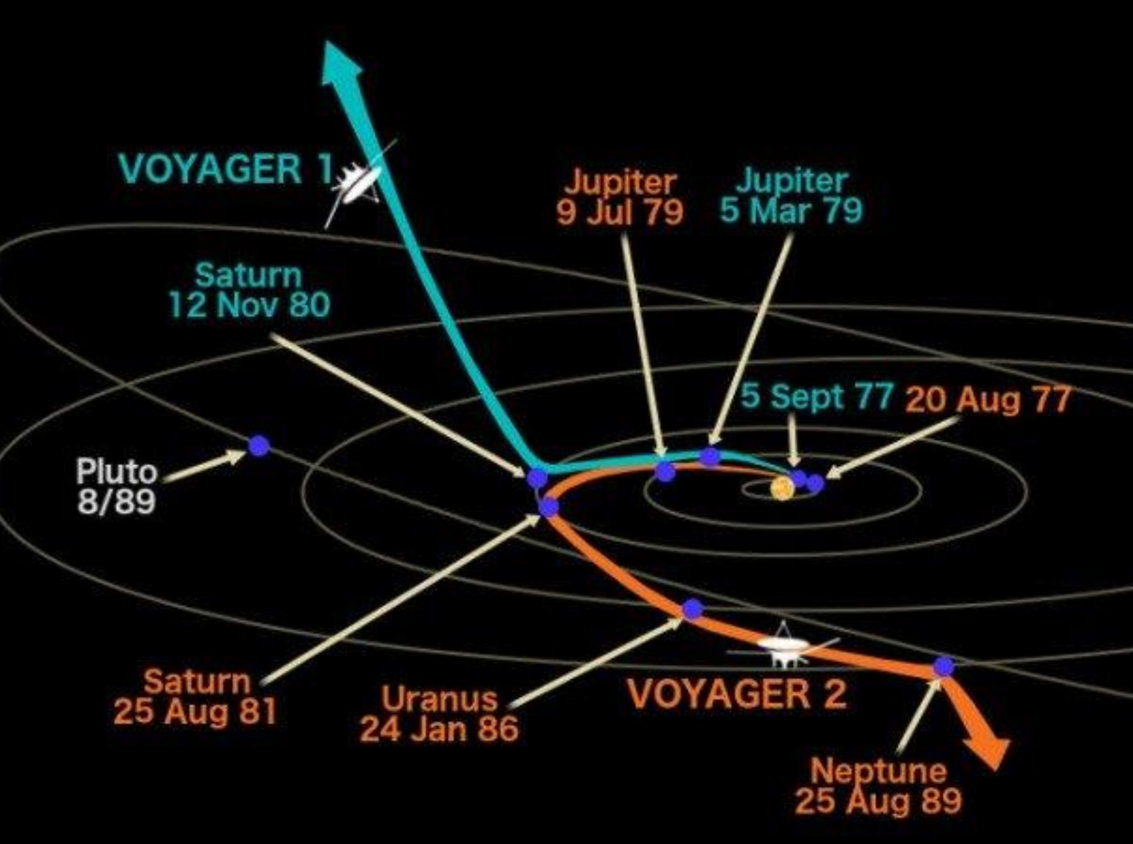
Nearly a Decade of Cosmic Ray Observations in the Very Local Insterstellar Medium

By Jamie Sue Rankin
Princeton University

ICRC, July 16, 2021

Space Physics at Princeton

Dawn of the Interstellar Mission



https://www.scienceabc.com/innovation/gravitational-slingshot-how-did-gravity-assist-voyager-1-2-in-escaping-the-solar-system.html

- 1977: Launch
  - Voyager 2 – August
  - Voyager 1 – September
- 1989: Last planetary encounter
  - Voyager 2, Neptune, 1989
- 1990: Last image
  - “Solar System Family Portrait” – Voyager 1

New Mission Objective:

“[To] extend the NASA exploration of the solar system beyond the neighborhood of the outer planets to the outer limits of the Sun's sphere of influence, and possibly beyond.”

The Sun's Surroundings

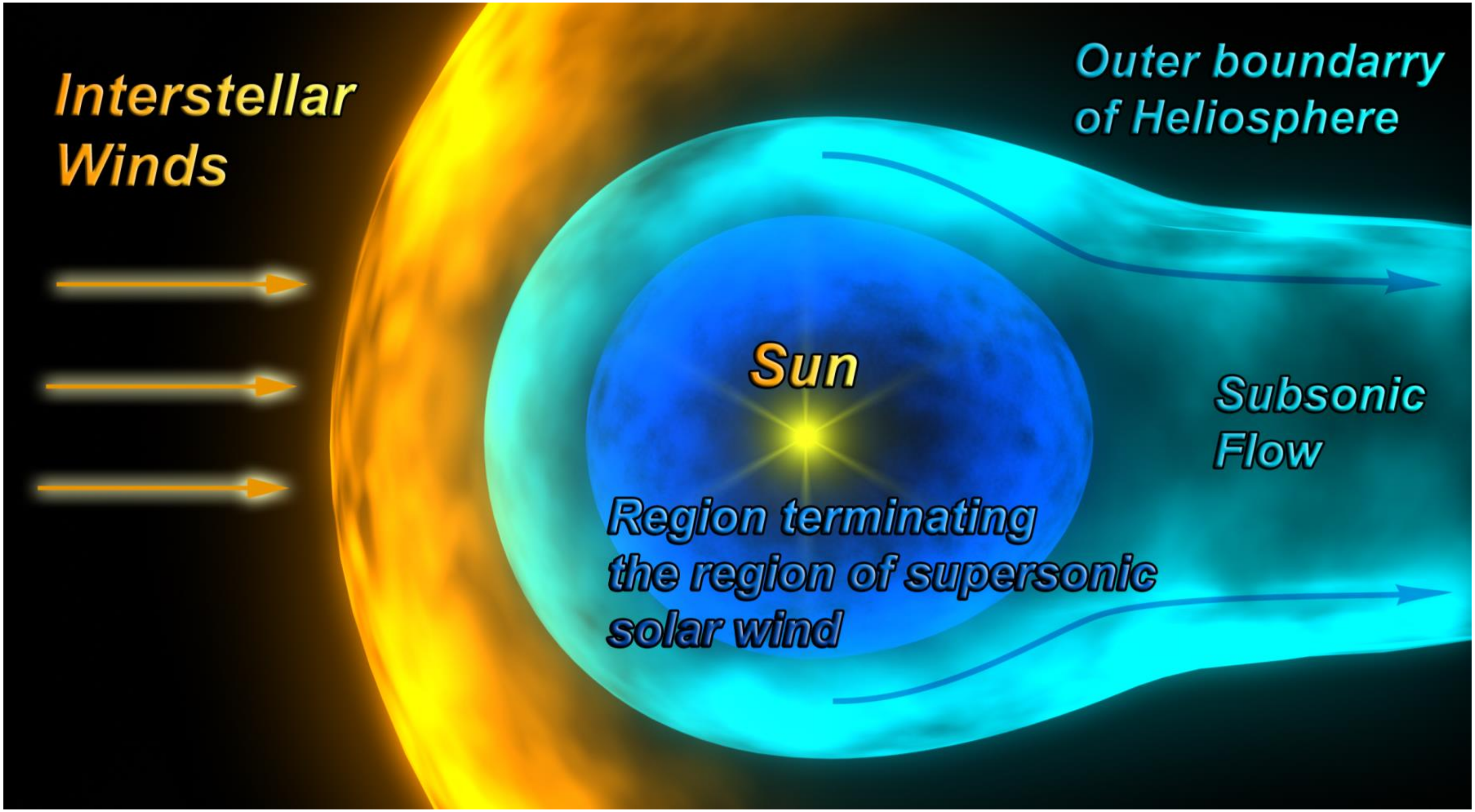
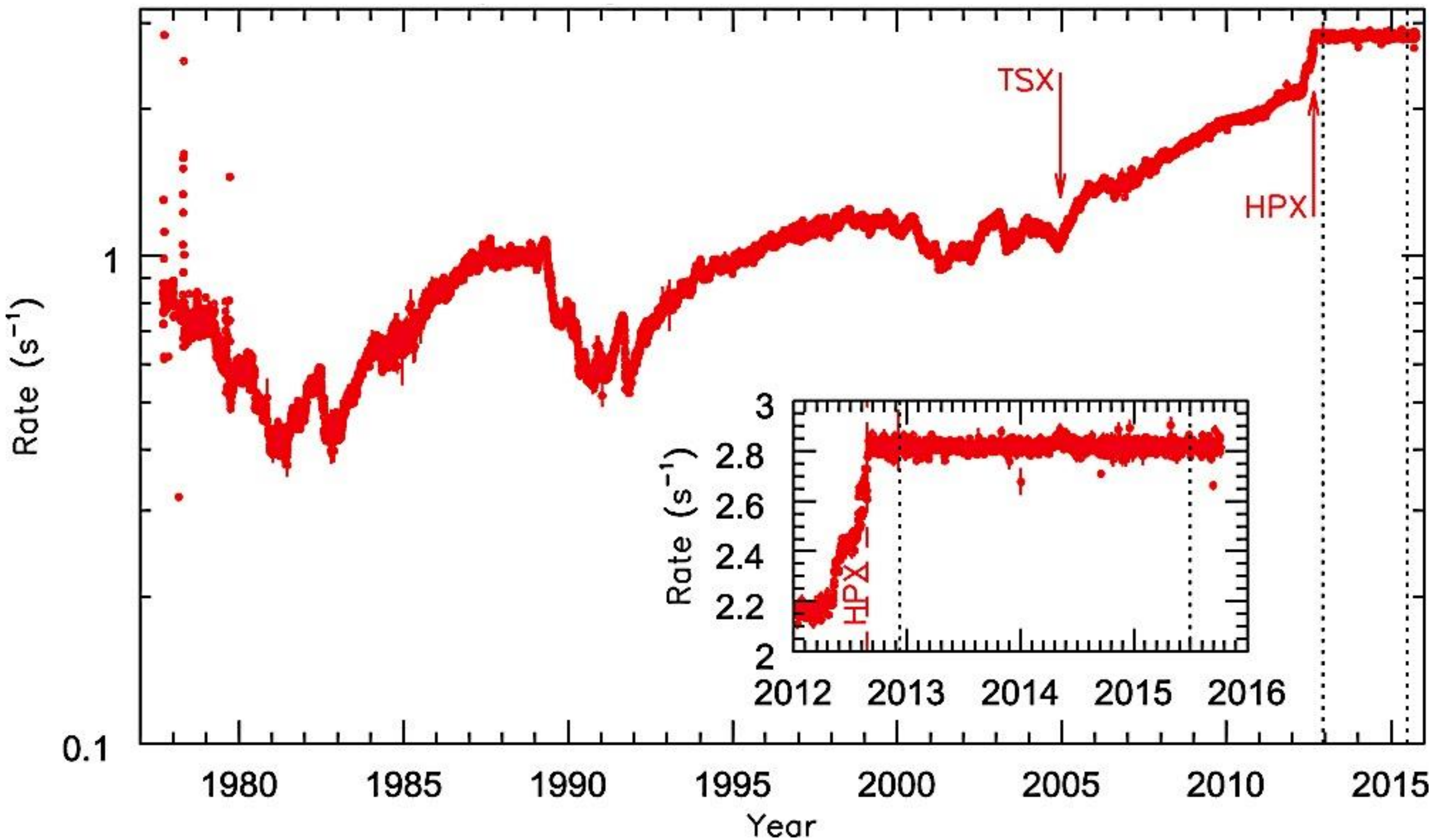


Diagram of the Heliosphere. ESA. June 2008. http://sci.esa.int/ulysses/42898-the-heliosphere/

Galactic Cosmic Rays through the Heliosphere

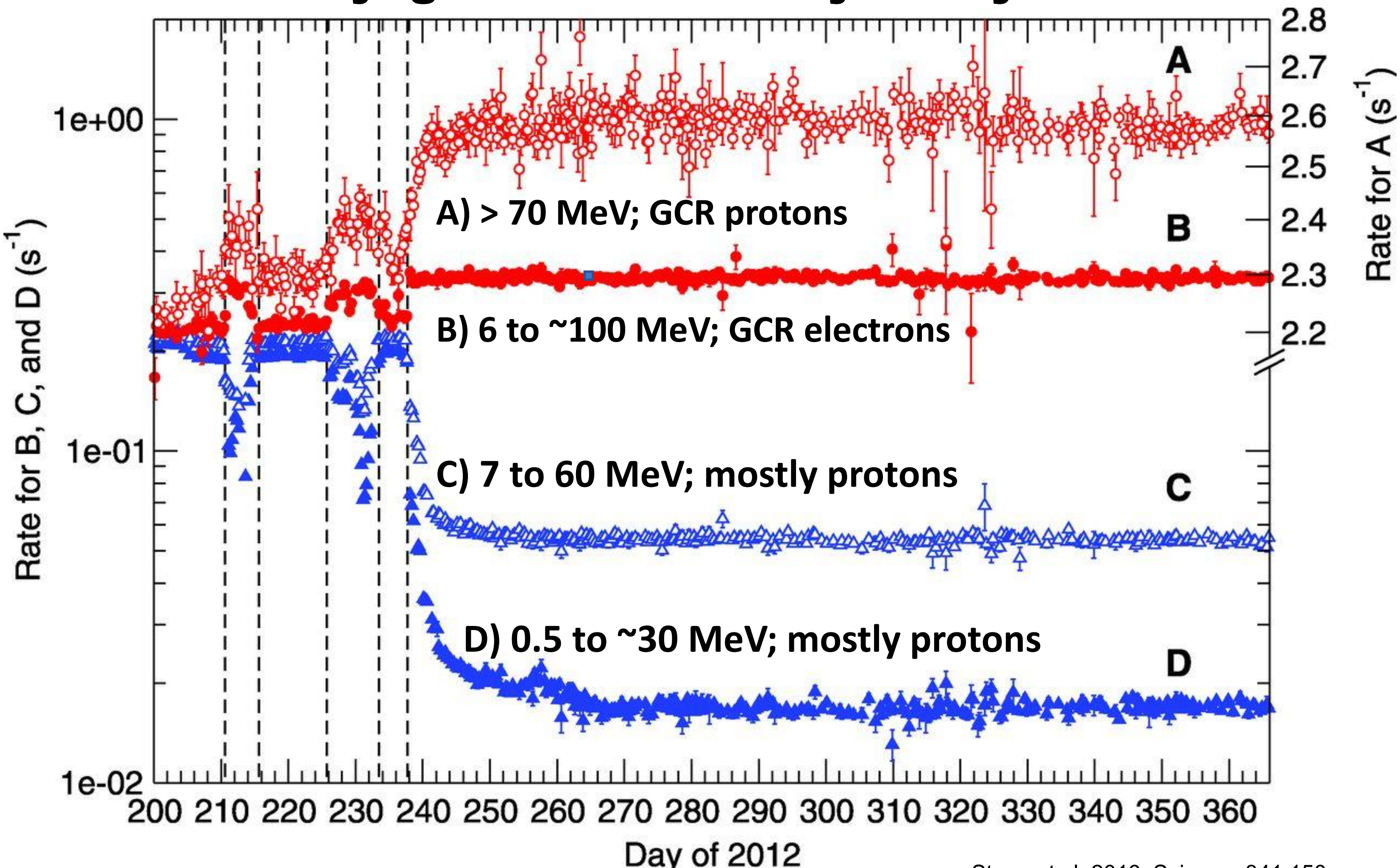
Voyager 1 Cosmic Ray Subsystem: > 70 MeV; proton-dominated



Cummings et al. 2016, ApJ, 831:18

Interstellar Arrival: Galactic Cosmic Rays

Voyager 1: Cosmic Ray Subsystem

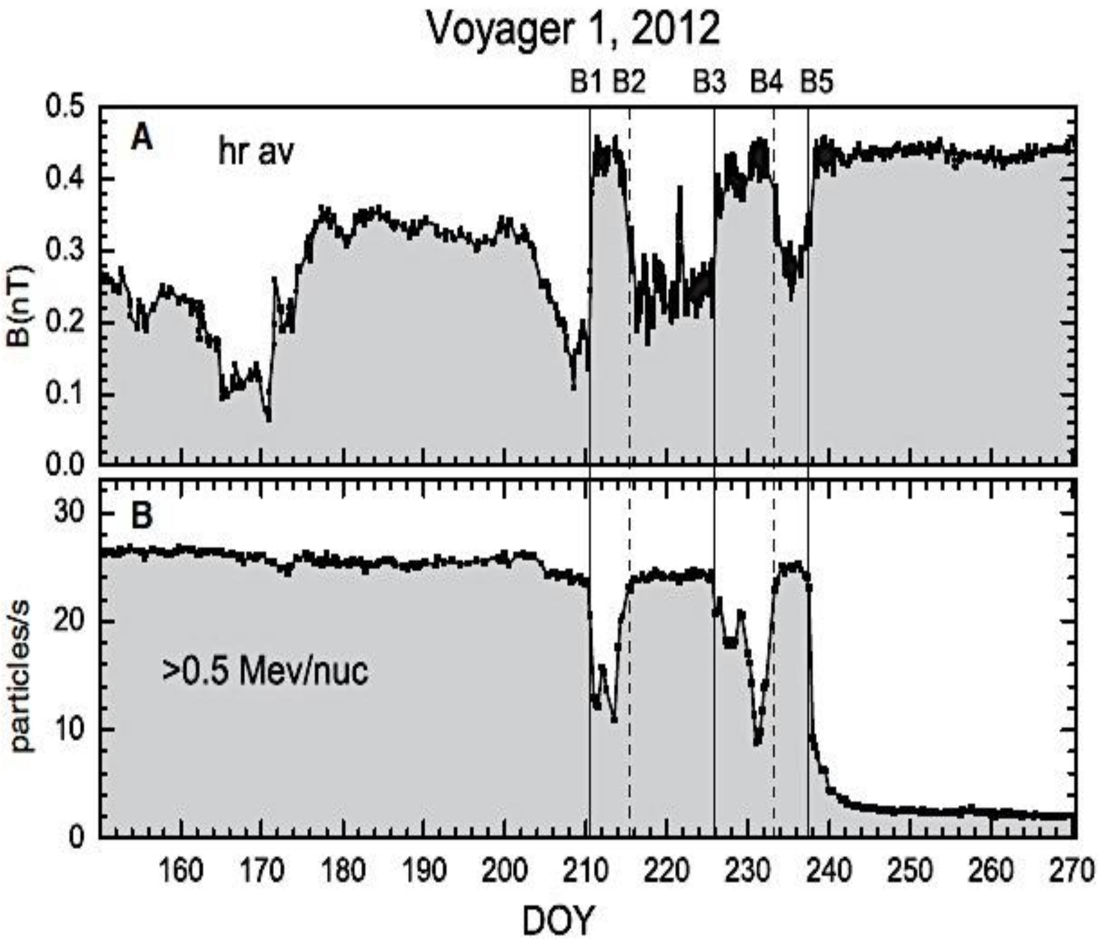


Stone et al. 2013, Science, 341:150

Heliosheath	Very Local Interstellar Medium

Space Physics at Princeton

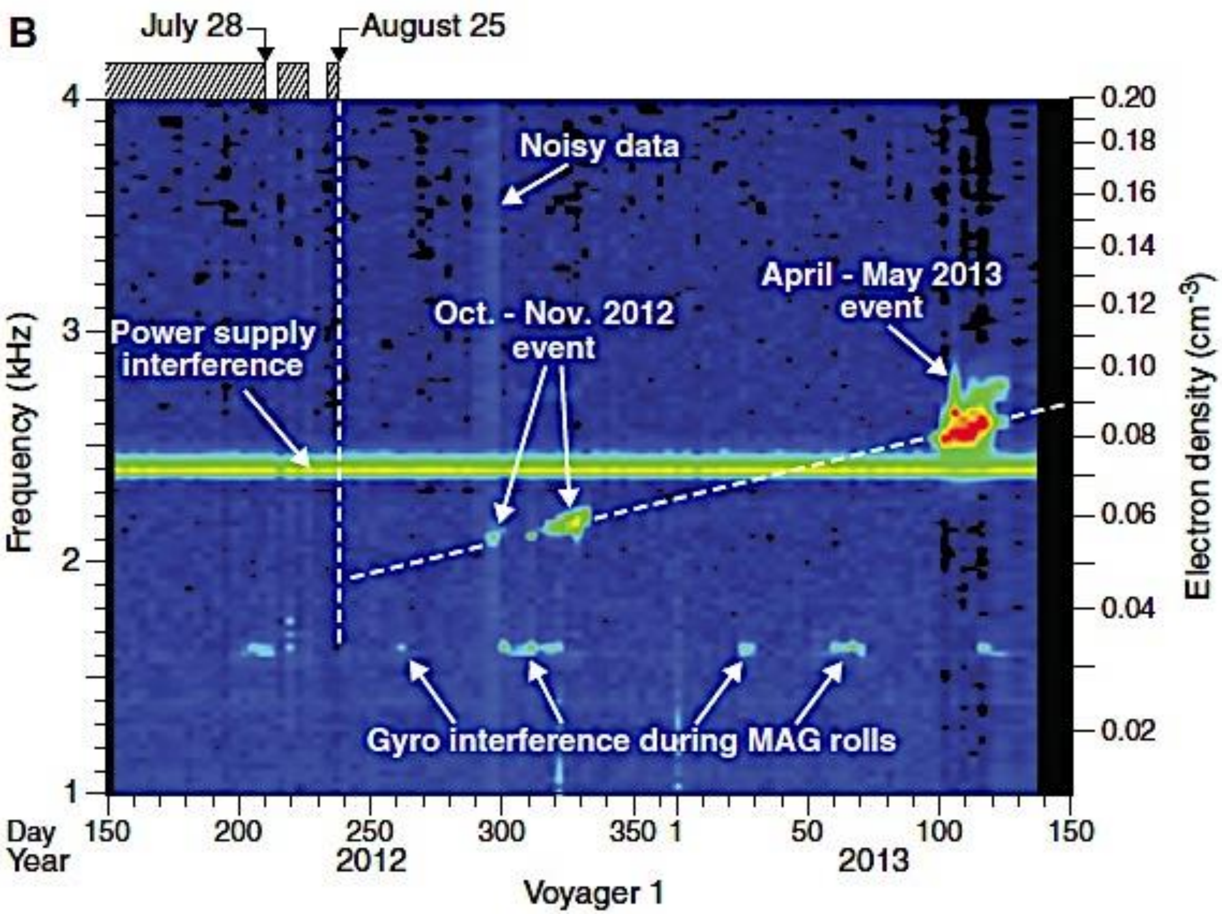
Interstellar Arrival: Magnetic Fields



Burlaga, Ness, & Stone 2013, Science, 341, 147

- Field strength increased from 0.2 nT to 0.45 nT
    - consistent with expected interstellar values
- Direction did not change
- "heliosheath depletion region" or the interstellar medium?
- Voyager 1 crossed the boundary 5 times
    - between days 210 and 238 of 2012

Fortuitous Measurements of Plasma Density



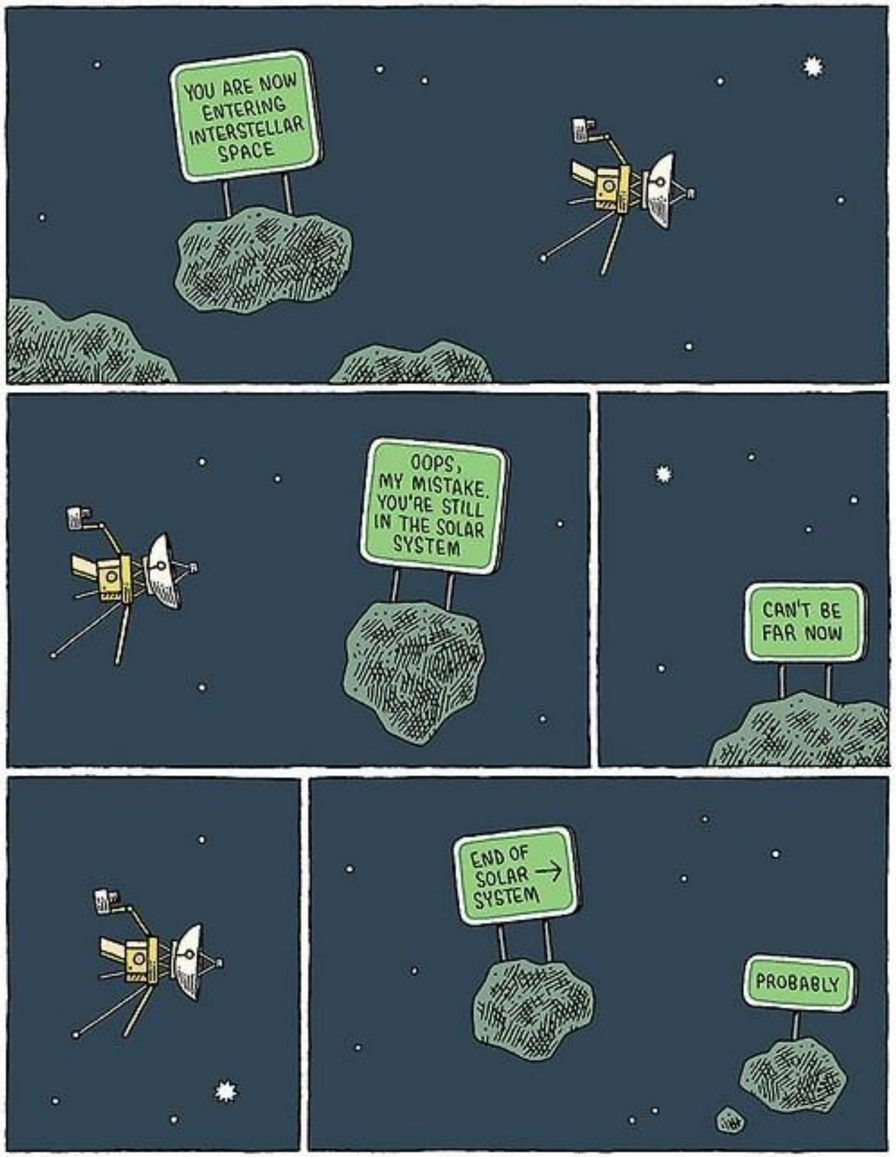
Gurnett et al. 2013, Science, 341:1489

- Outer heliosphere plasma density
  - 0.002 cm^{-3}
- Expected interstellar plasma density
  - 0.1 cm^{-3}
- Electron plasma oscillation frequency
  - 2.6 kHz

$$f_p = 8980\sqrt{n_e}\,\text{Hz},$$

- Observed plasma density
  - 0.08 cm^{-3}

Heliopause Crossing



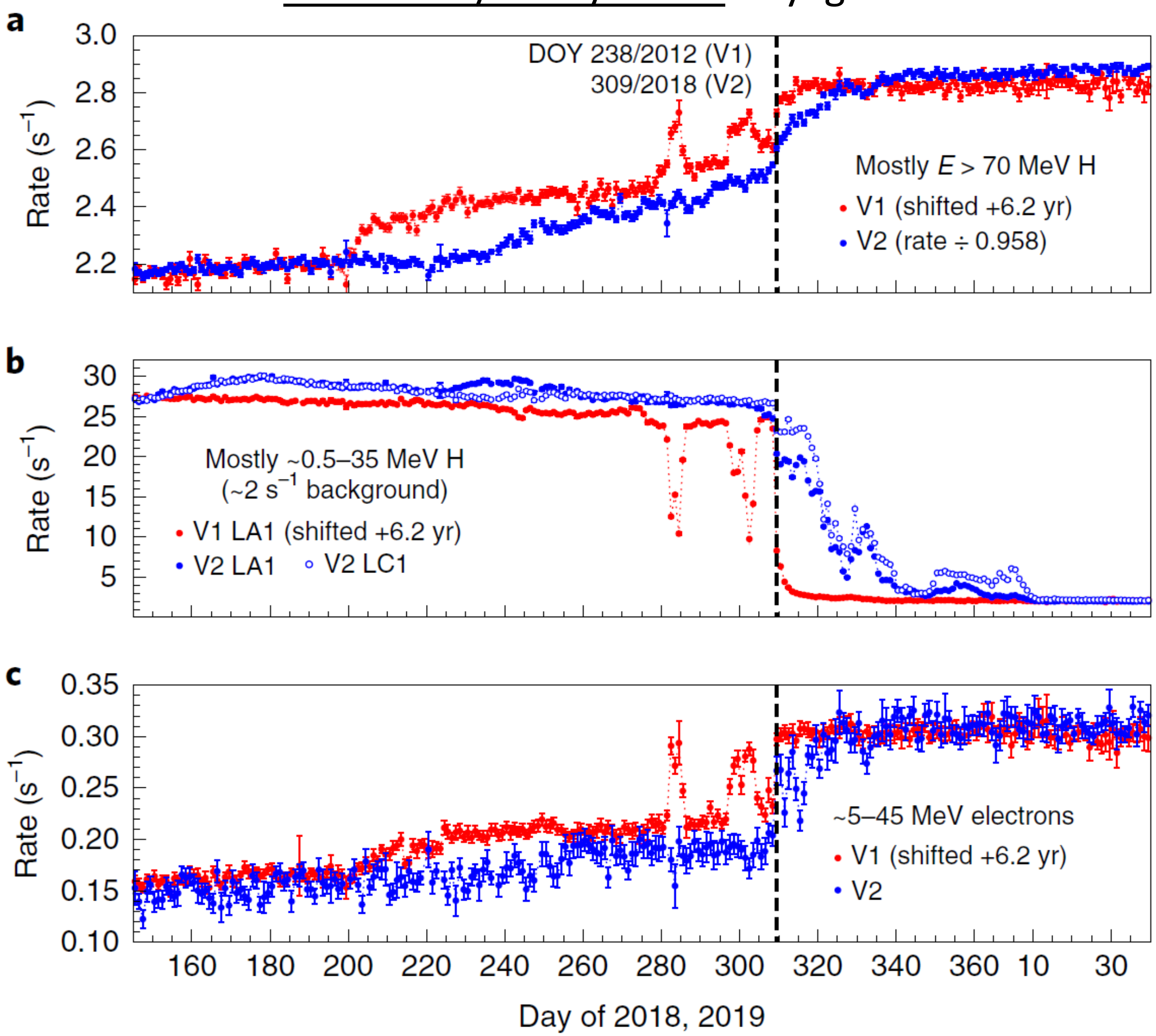
"Space is Arbitrary" by Tom Gauld

- Voyager 1
  - August 25, 2012 @ ~122 AU
  - Magnetic field strength: ~0.46 nT
  - Plasma density: ~0.055 cm^{-3}
  - Heliopause likely shrinking
- Voyager 2
  - November 5th, 2019 @~119 AU
  - Magnetic field strength: ~0.68 nT
    - Compressed Fields Towards Ecliptic South
  - Plasma density: ~0.039 cm^{-3}
  - Temperature ~30,000 to 50,000
  - Heliopause likely expanding

Washimi et al. 2017, ApJL, 846:L9

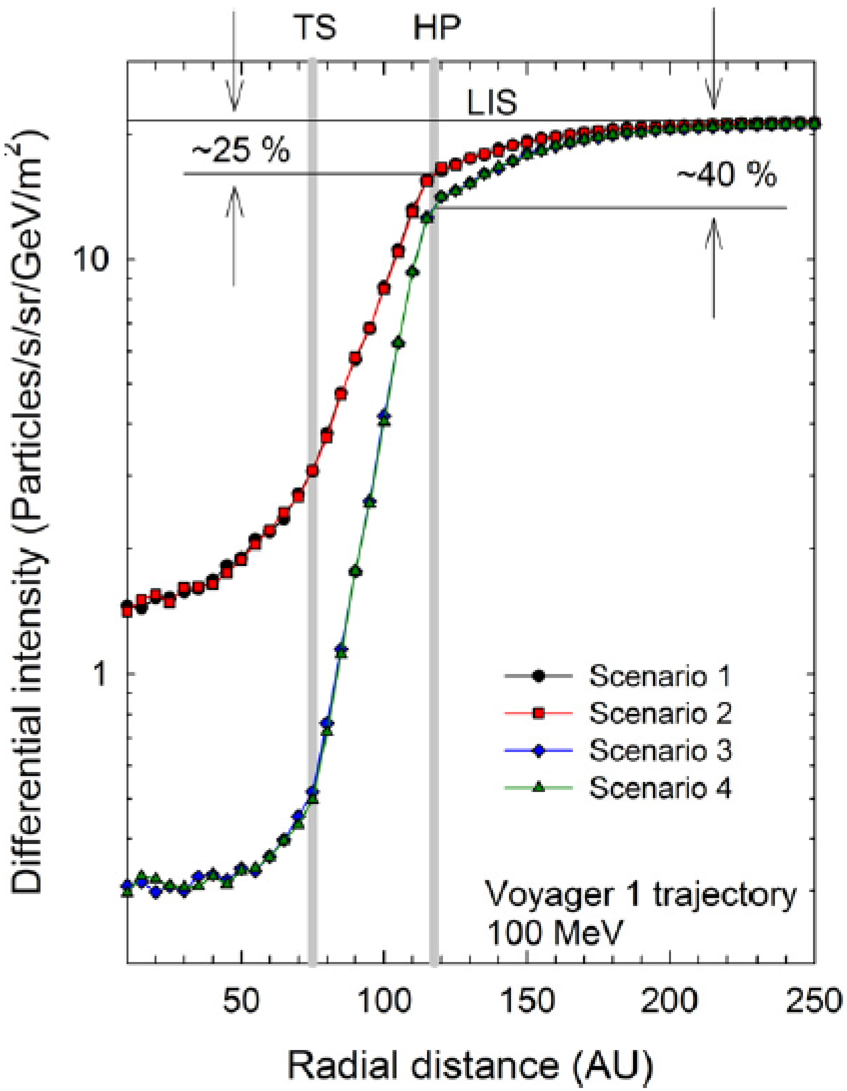
Heliopause Crossing: Energetic Particles

Cosmic Ray Subsystems: Voyagers 1 & 2



Stone et al. 2019, NatAst 3:1013

Solar Modulation Beyond the Heliopause?

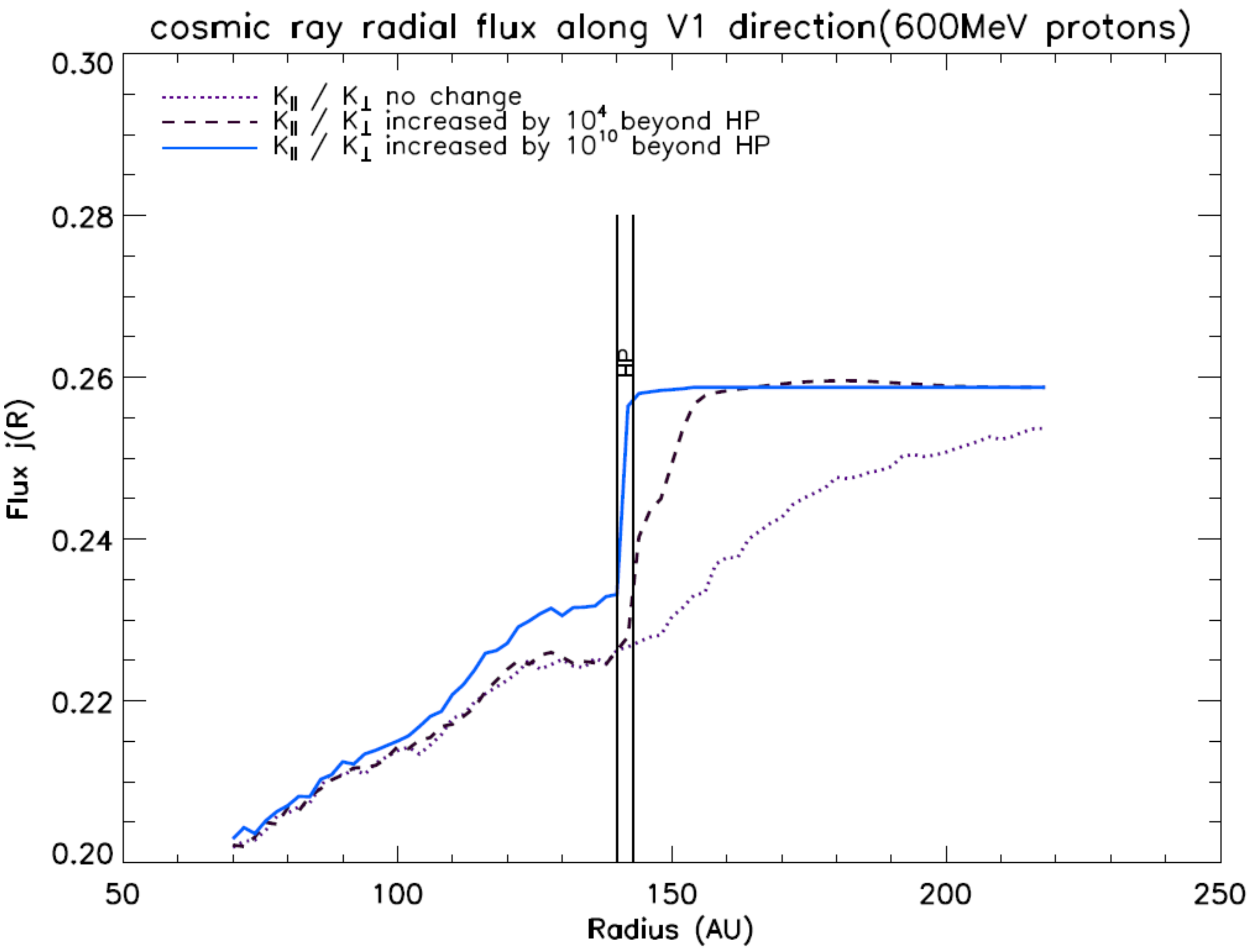


Strauss et al. 2013, ApJL, 765:L18

"The observation of cosmic-ray intensity variation at the heliopause is a partial surprise. We expect the cosmic-ray intensity to rise towards the heliopause, and there may or may not be, depending on the particle diffusion coefficient, a radial gradient in the outer heliosheath. However, no one predicted there is a sharp, almost step-wise, increase of cosmic rays at the heliopause."

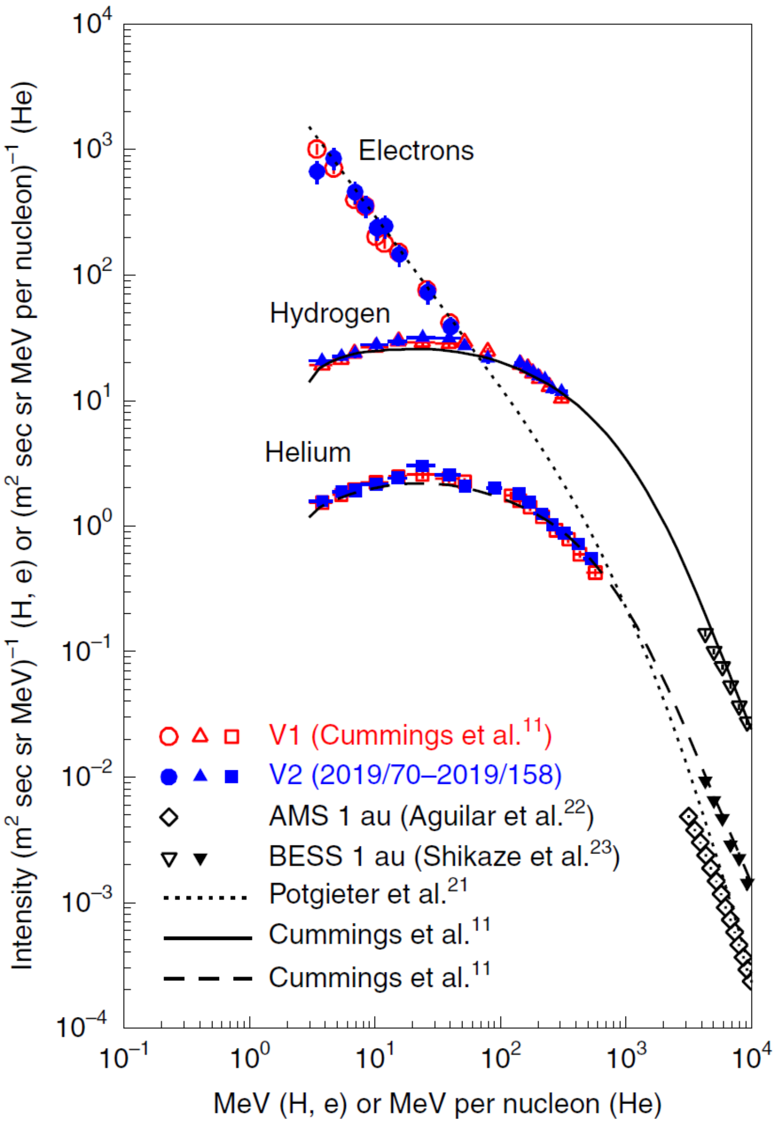
Zhang et al. 2015, Phys. Plasmas 22:091501

Solar Modulation Beyond the Heliopause?



Luo et al. 2016, AIP Conf. Proc., 1720:070005

Low-Energy Interstellar Spectra!

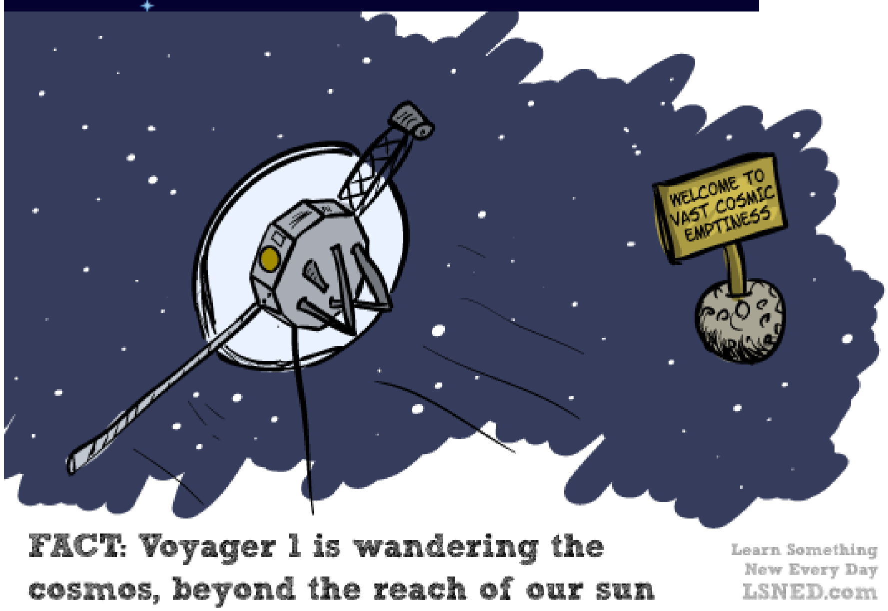


Stone et al. 2019, NatAst 3:1013

- Lowest energies typically measured at 1 AU: ~ few GeV
- Voyager "electrons"
  - Consistent with spectra derived from solar wind observations [Potgeiter et al. 2015]
- Unmodulated spectra?
  - Remarkably uniform flux; no clear indications of a radial gradient (so far)
  - Remarkable consistency between the two spacecraft at very different longitudes and latitudes!

Very Local Interstellar Medium (VLISM)

https://spaceplace.nasa.gov/interstellar/en/



- Original Definition: [Holzer 1989]
  - Local Interstellar Medium: within 100 pc of the sun
  - Very Local Interstellar Medium: within 0.01 pc of the Sun (~2000 au)

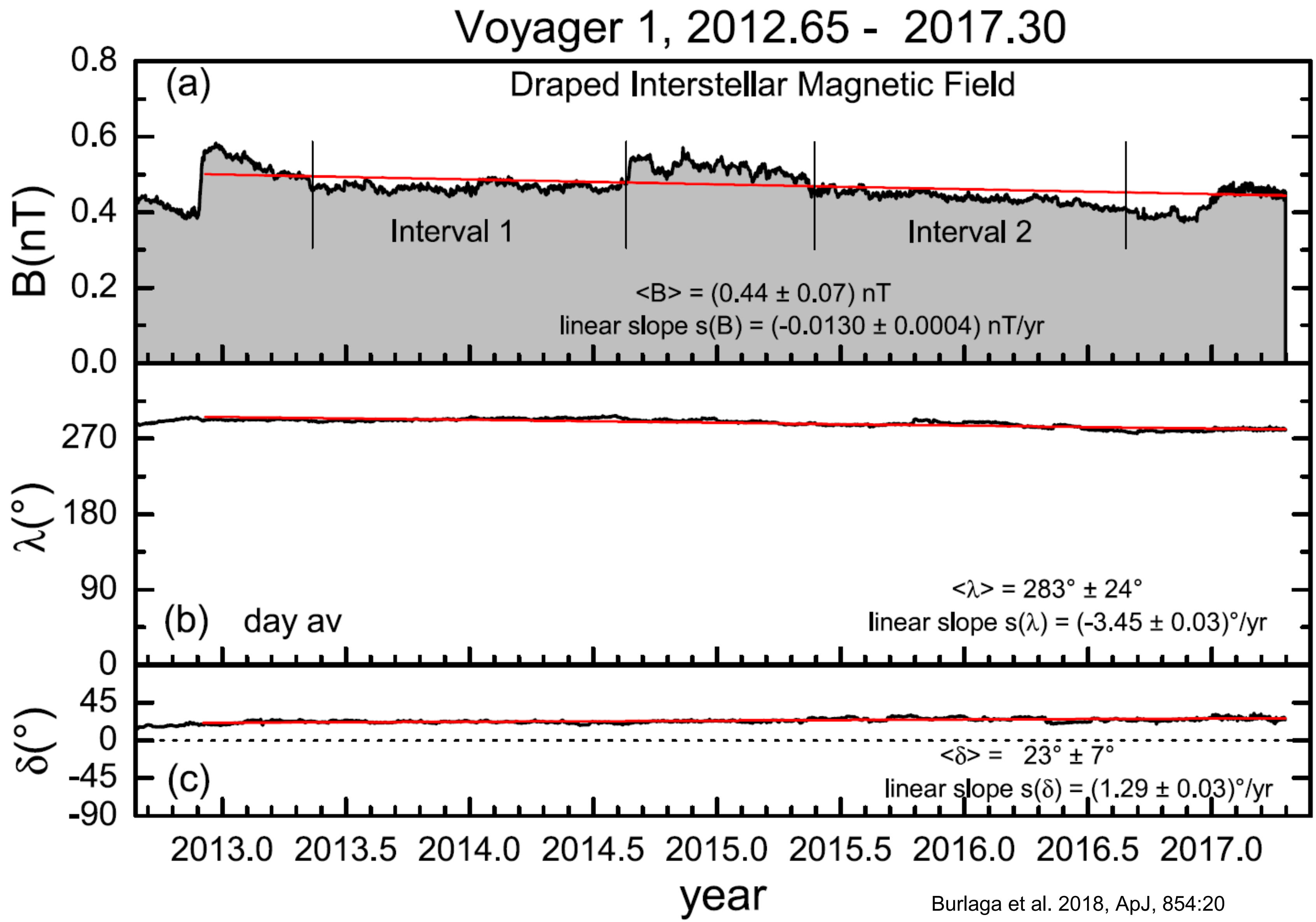
Very Local Interstellar Medium (VLISM)

https://spaceplace.nasa.gov/interstellar/en/

- Original Definition: [Holzer 1989]
  - Local Interstellar Medium: within 100 pc of the sun
  - Very Local Interstellar Medium: within 0.01 pc of the Sun (~2000 au)
- New Definition: [Zank 2017]

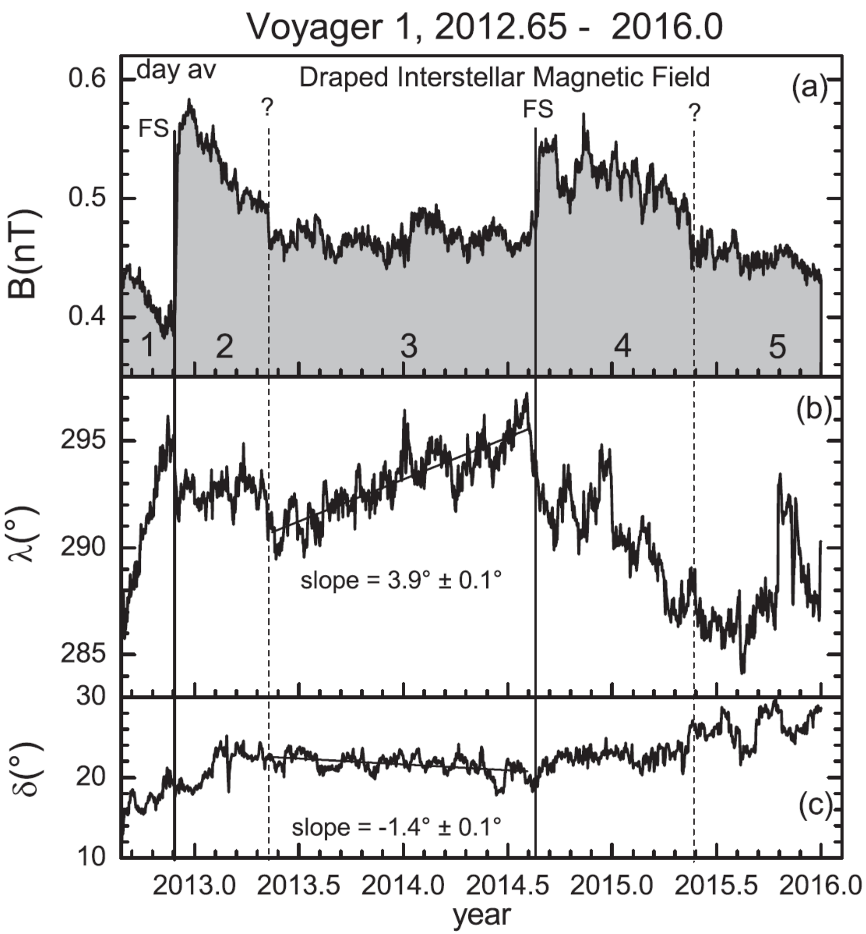
"[The] region of the interstellar medium surrounding the Sun that is modified or mediated by heliospheric processes or material."

Beyond the Heliopause: Unfolding Magnetic Field



Burlaga et al. 2018, ApJ, 854:20

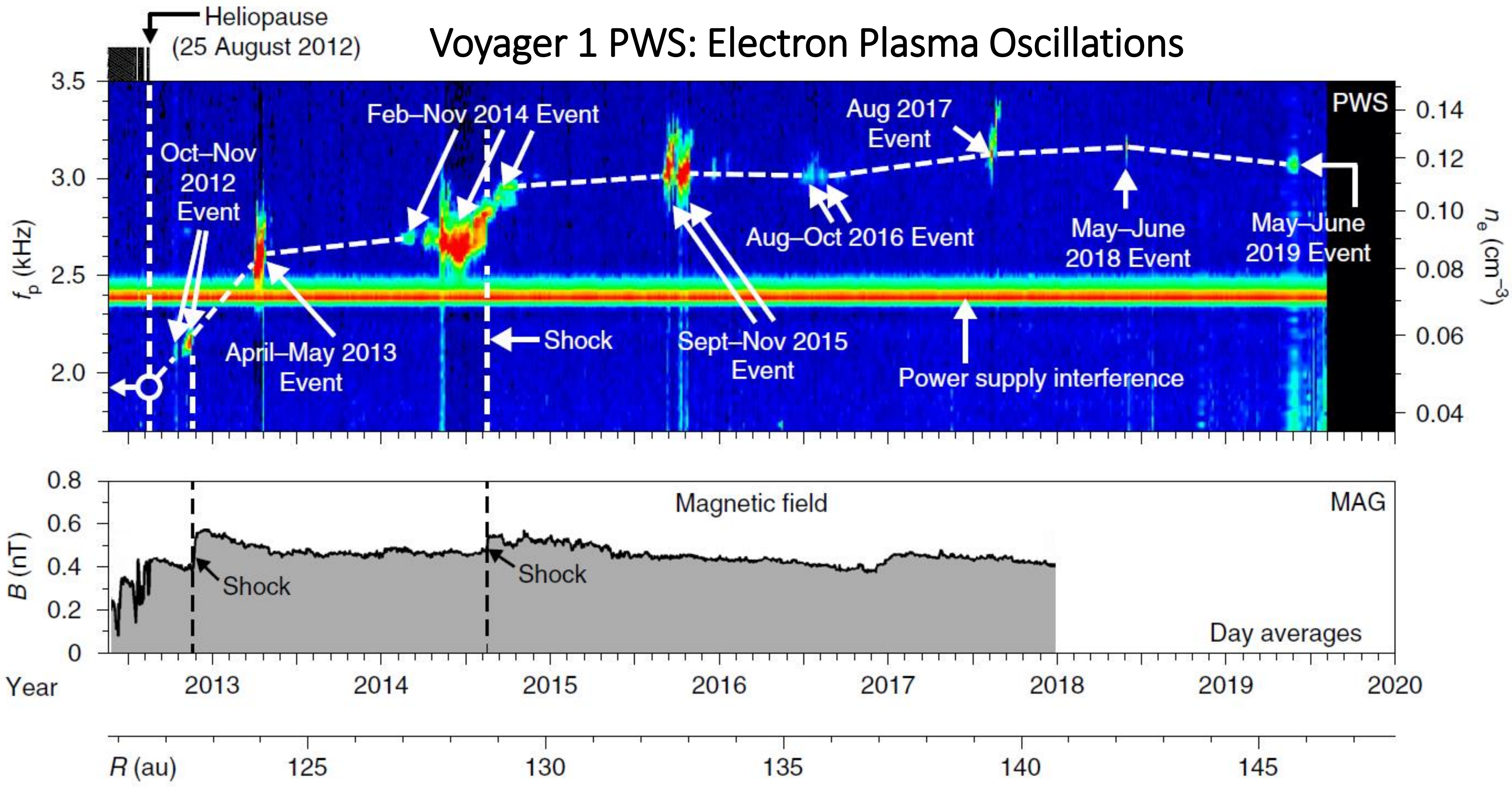
Transient-Perturbed Magnetic Field



Burlaga & Ness 2016, ApJ, 829:134

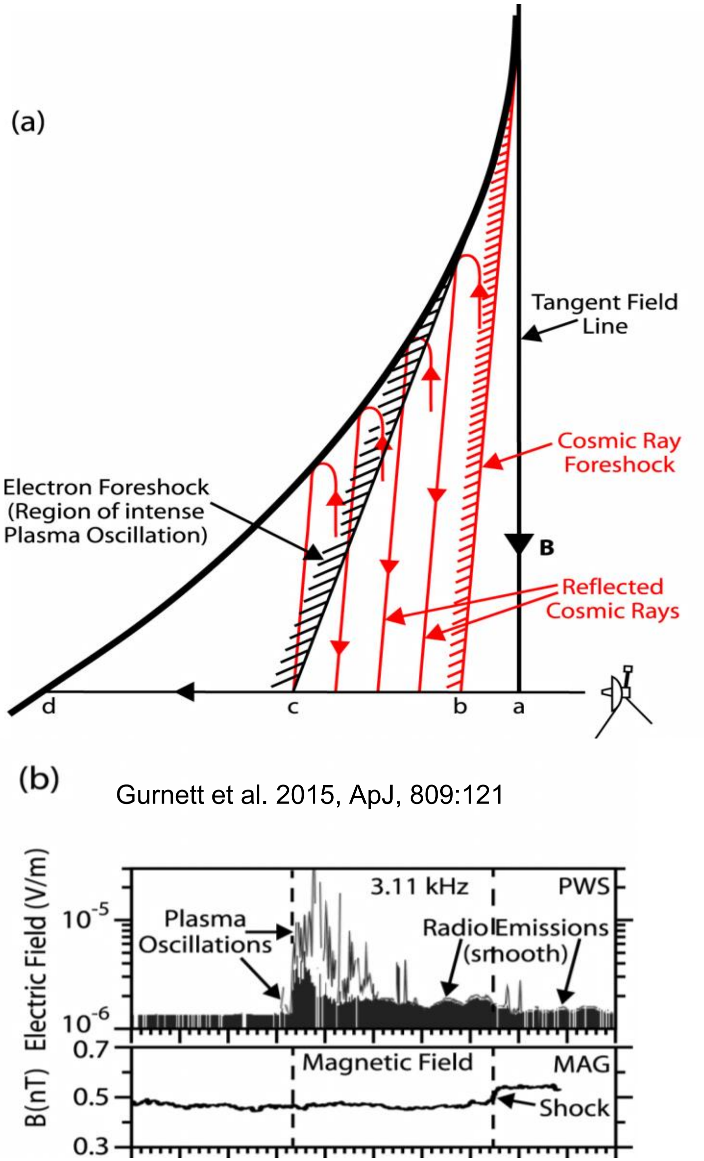
- "Shocks"
  - weak, subcritical, laminar, resistive, and quasi-perpendicular.
  - 10^7 km thick (1000 x's thicker than 1-AU counterparts)
  - small jump ratios (~1.4 in 2012; ~1.1 in 2014)
  - Likely collisional

Beyond the Heliopause: Interstellar Plasma

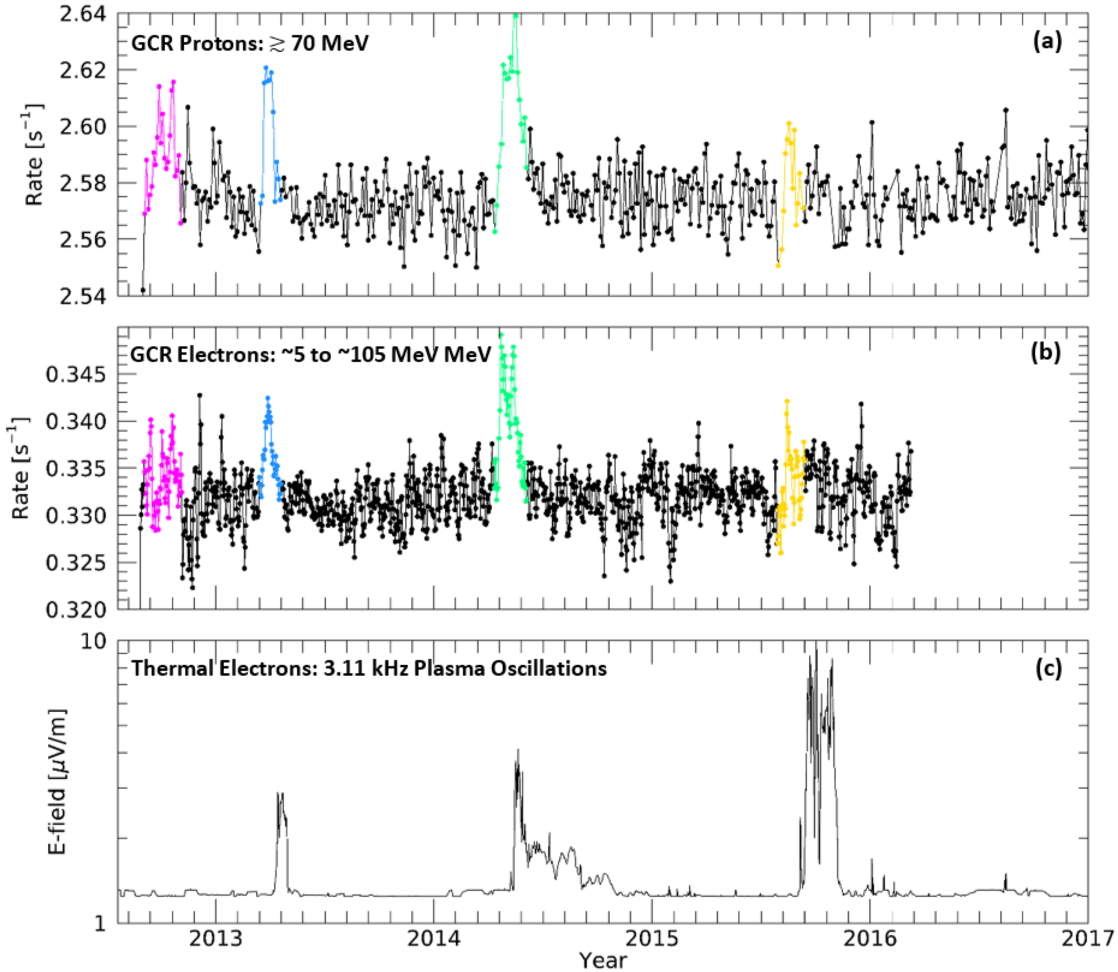


Gurnett & Kurth 2019, NatAst 3:1024

Shock-Energized Plasma and Cosmic Ray Transients

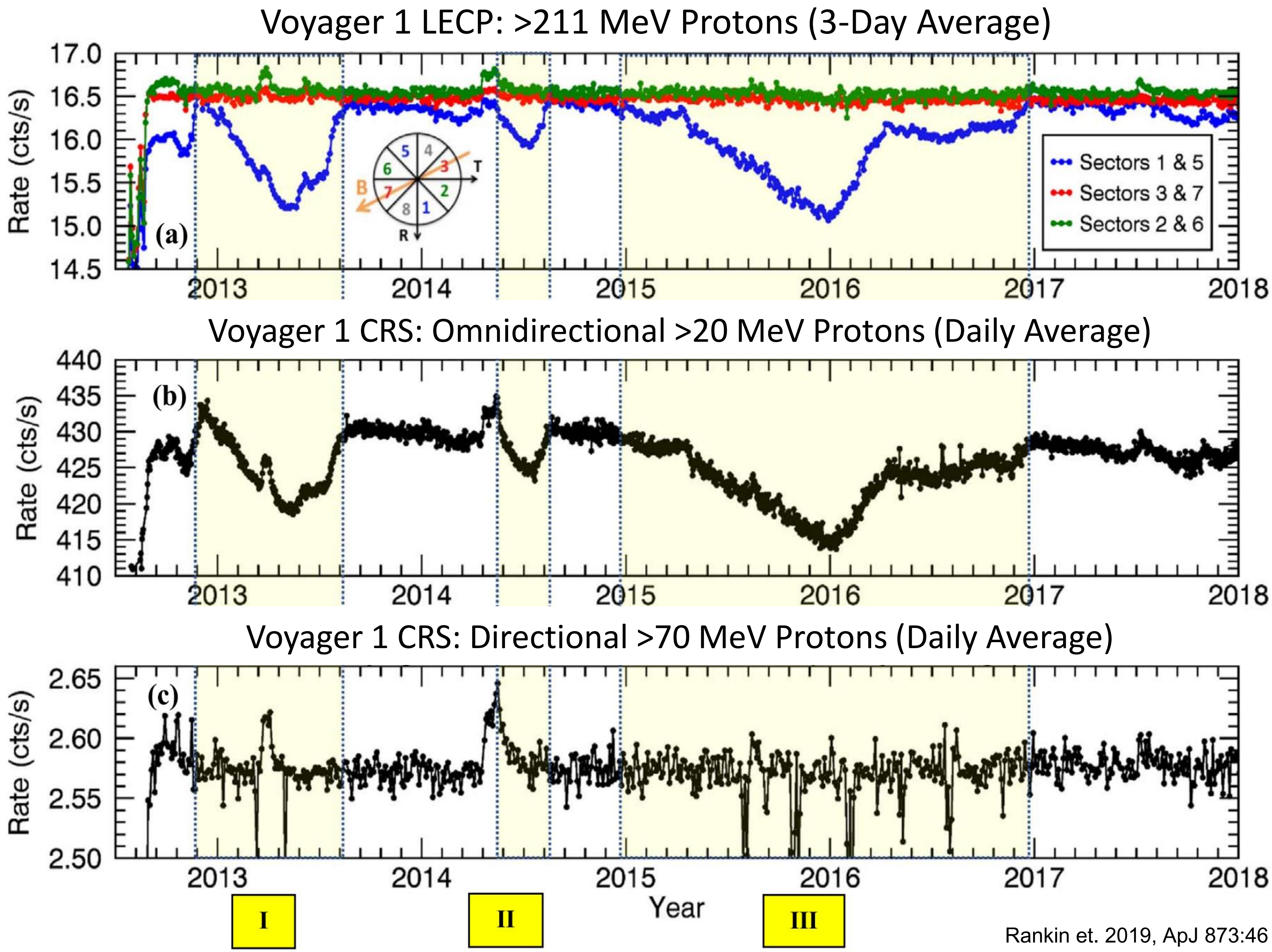


Gurnett et al. 2015, ApJ, 809:121



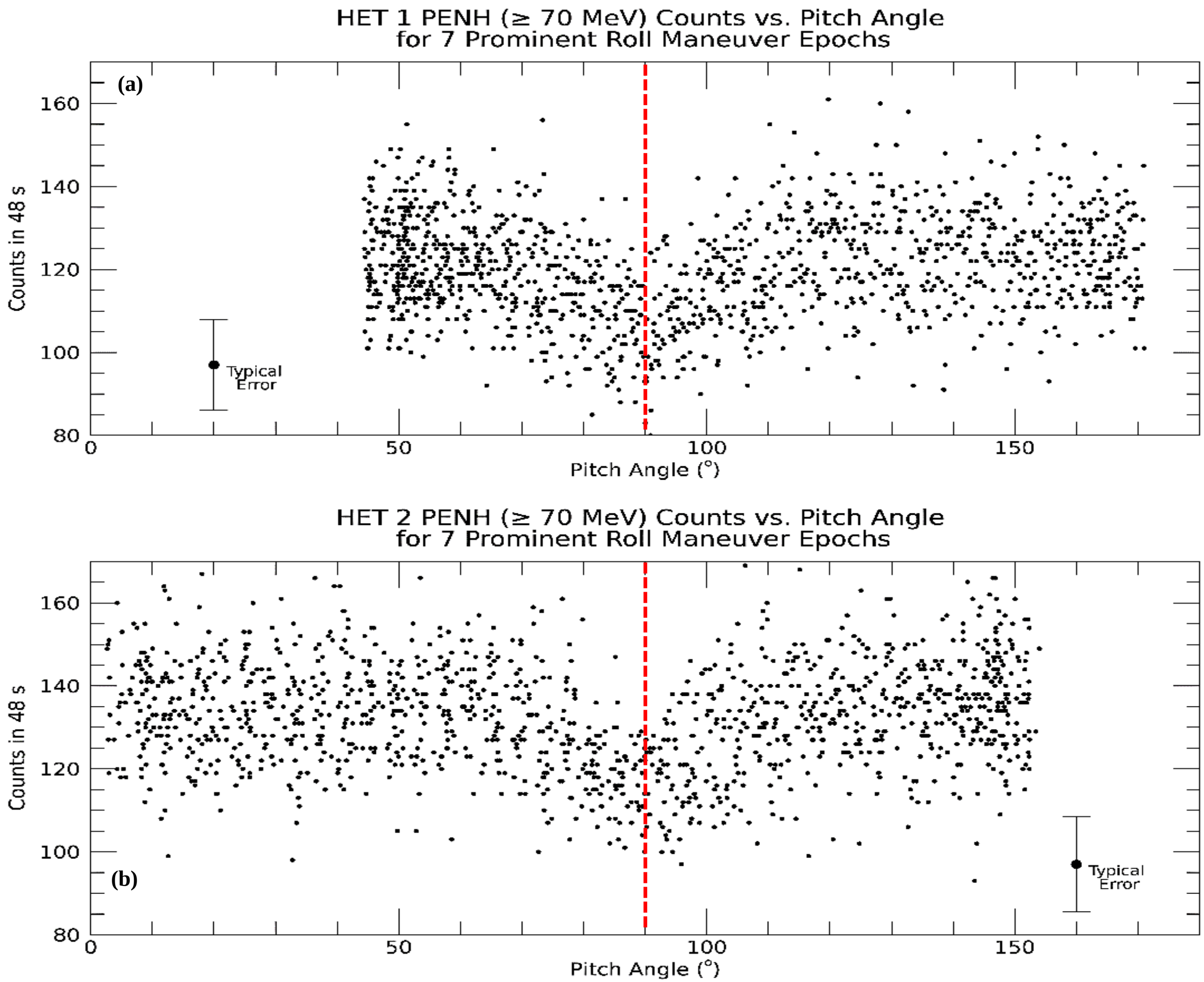
Rankin et al. 2019, ApJ 883:101

Galactic Cosmic Ray Anisotropy



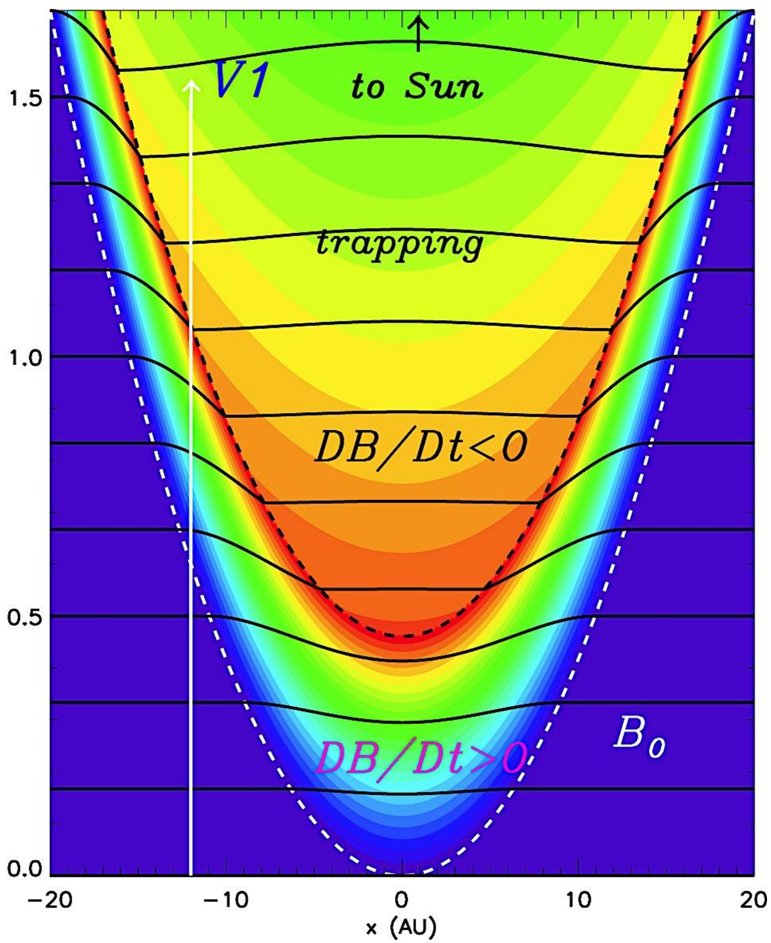
Rankin et. 2019, ApJ 873:46

Anisotropy Centered on 90° Pitch Angle

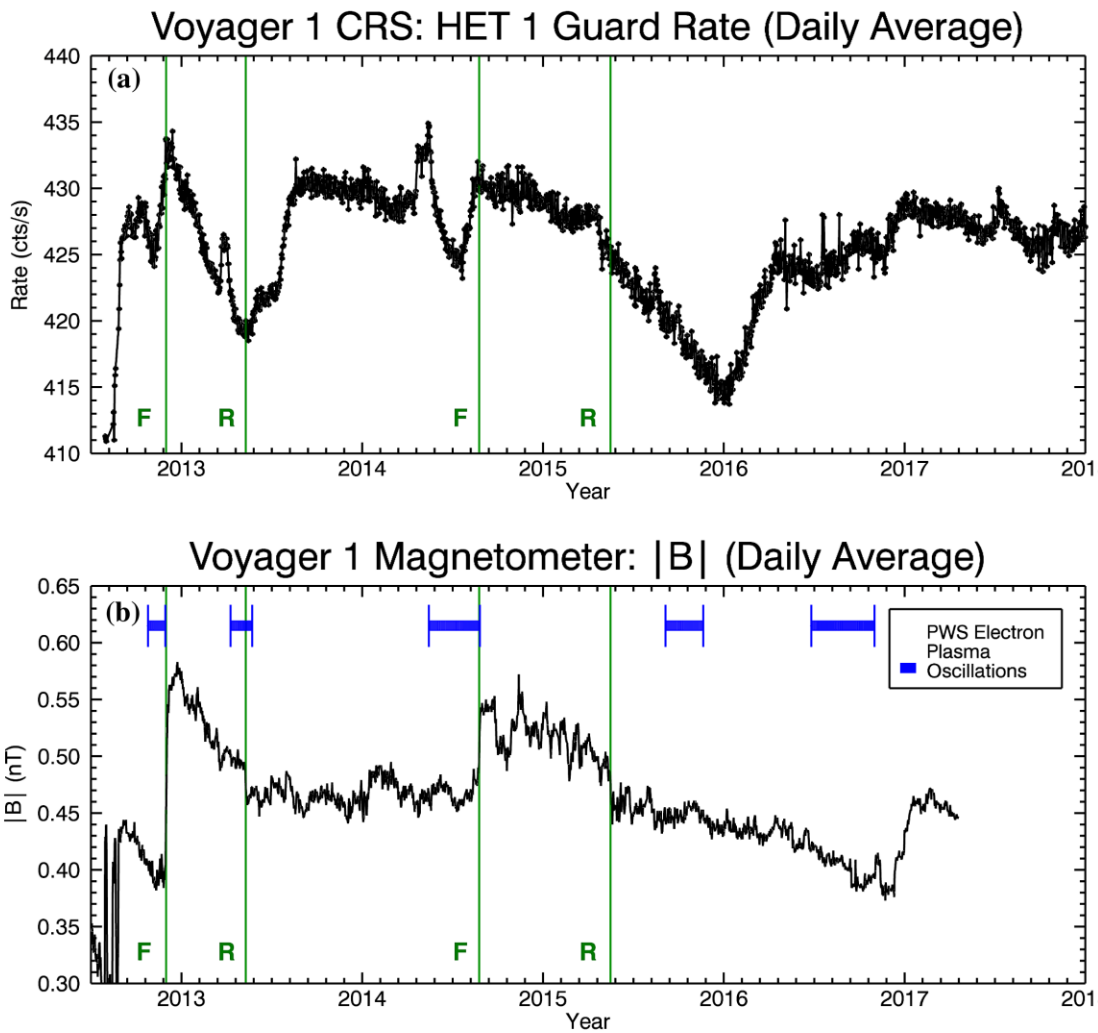


Rankin et al. 2019, ApJ 873:46

Trapping and Cooling Downstream of Shocks?

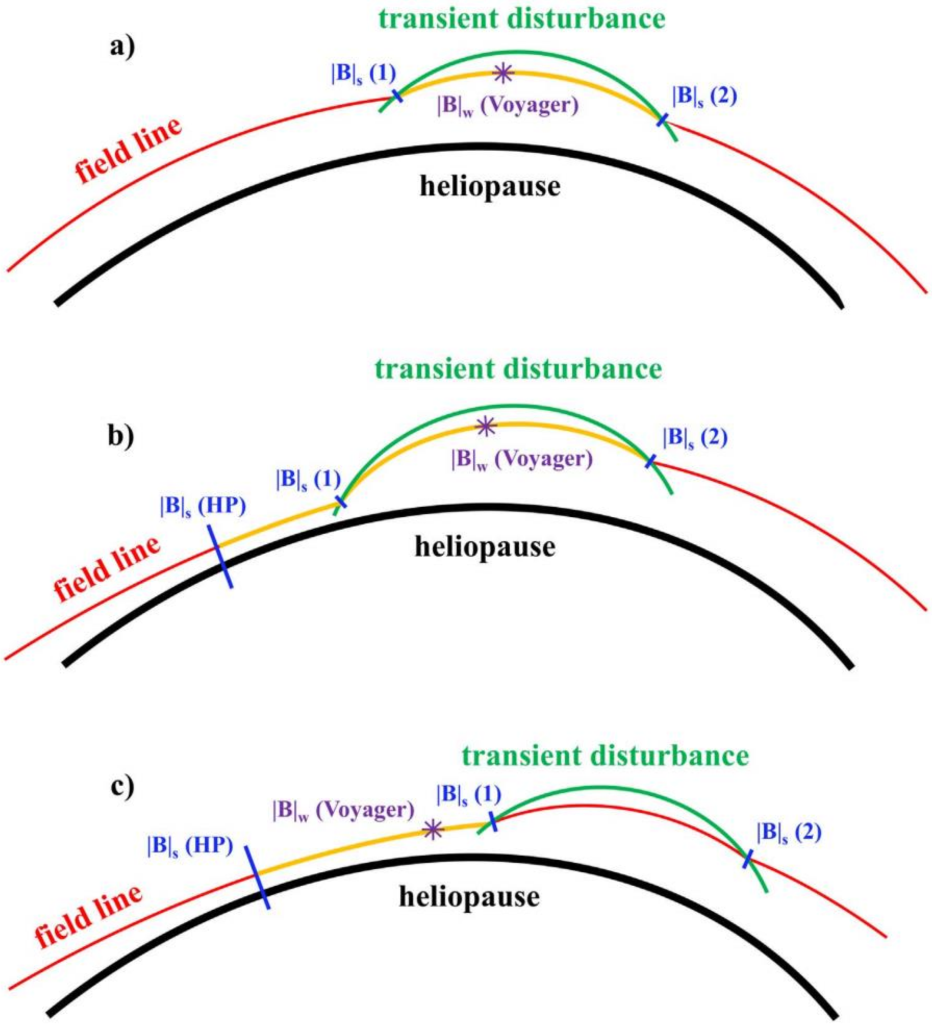


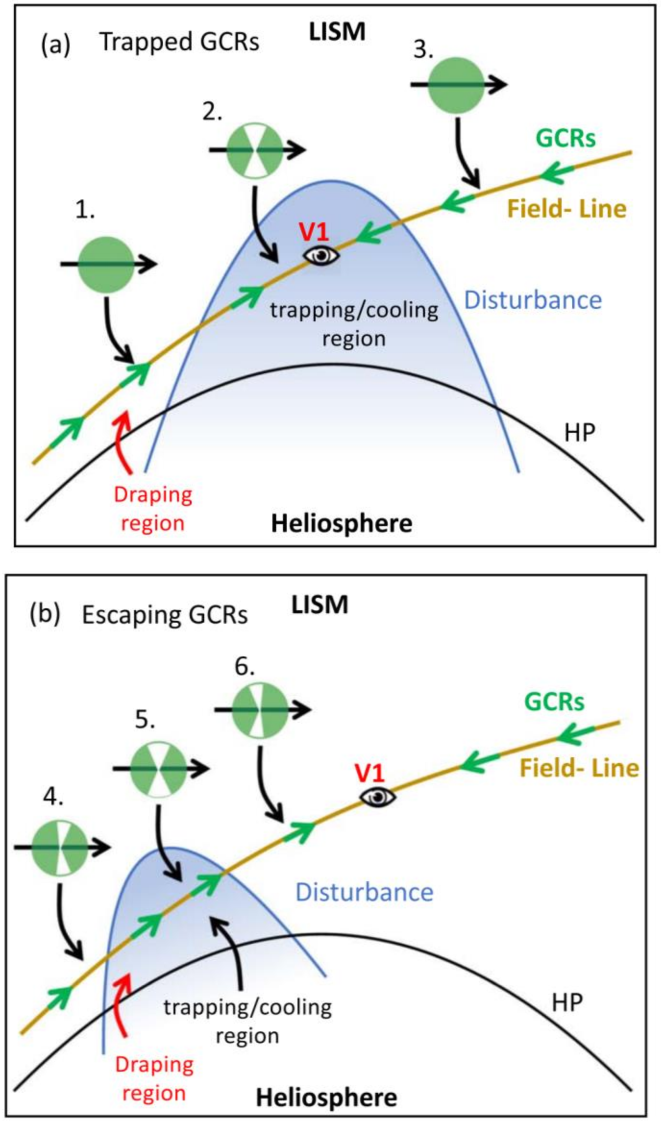
Kóta & Jokipii, 2017, ApJ 839:126



Rankin et al. 2019, ApJ 873:46

Influenced by the large-scale structure of the Heliosphere?

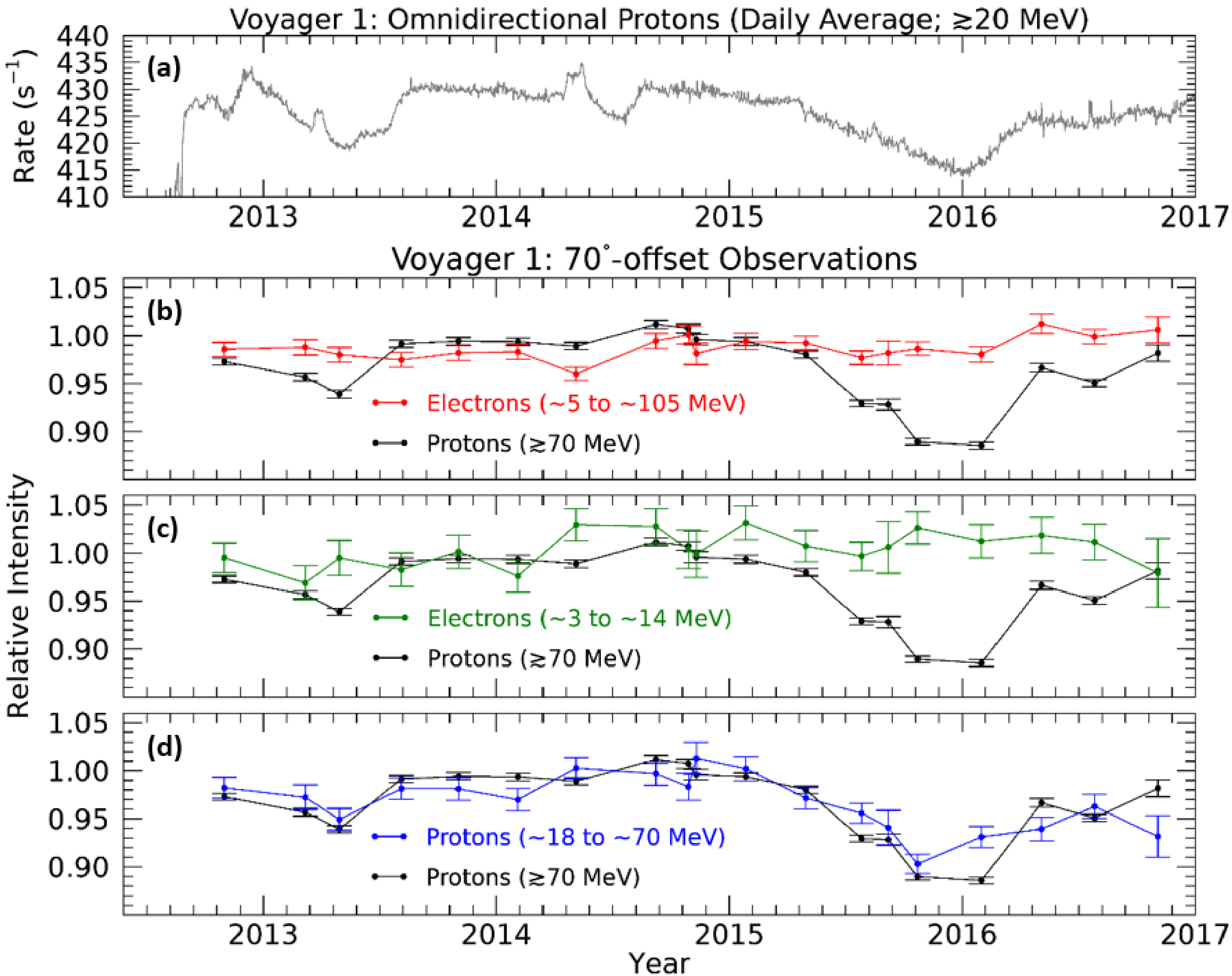




Rankin et al. 2019, ApJ 873:46

Hill et al. 2020, ApJ 905:69

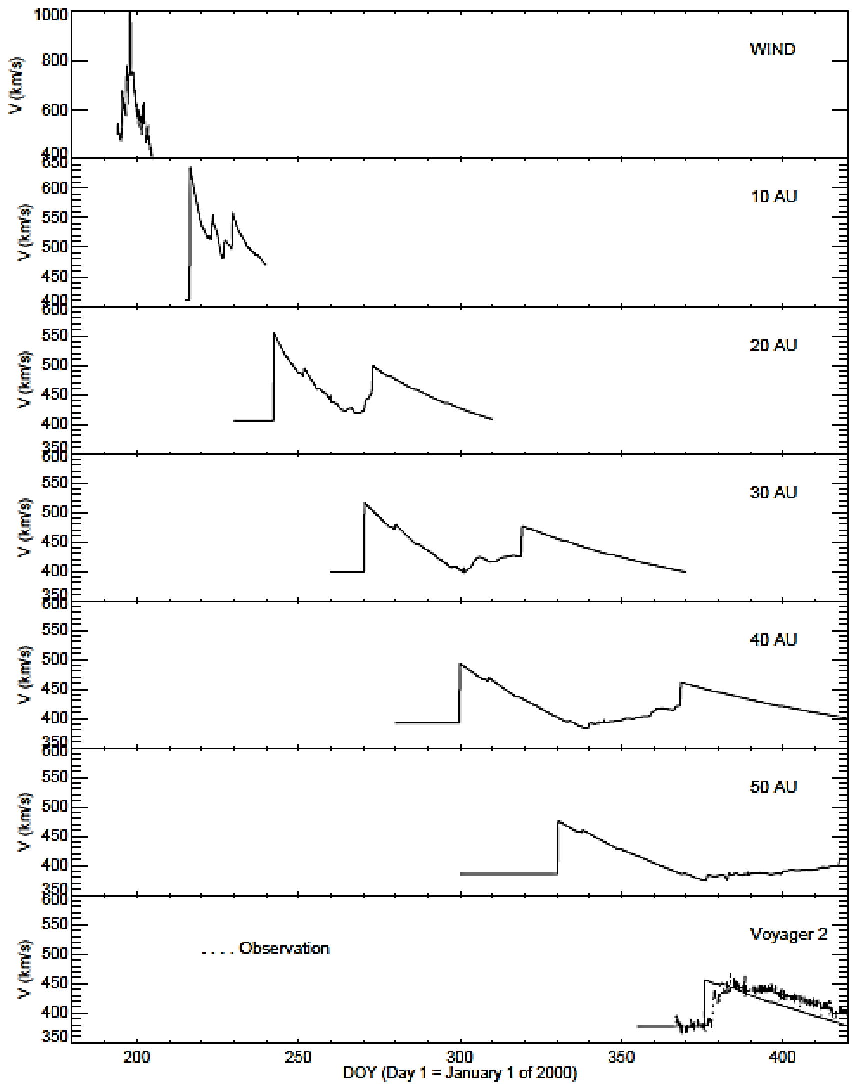
Galactic Cosmic Ray Anisotropy: Species Dependent



Rankin et al. 2020, ApJ, 895:103

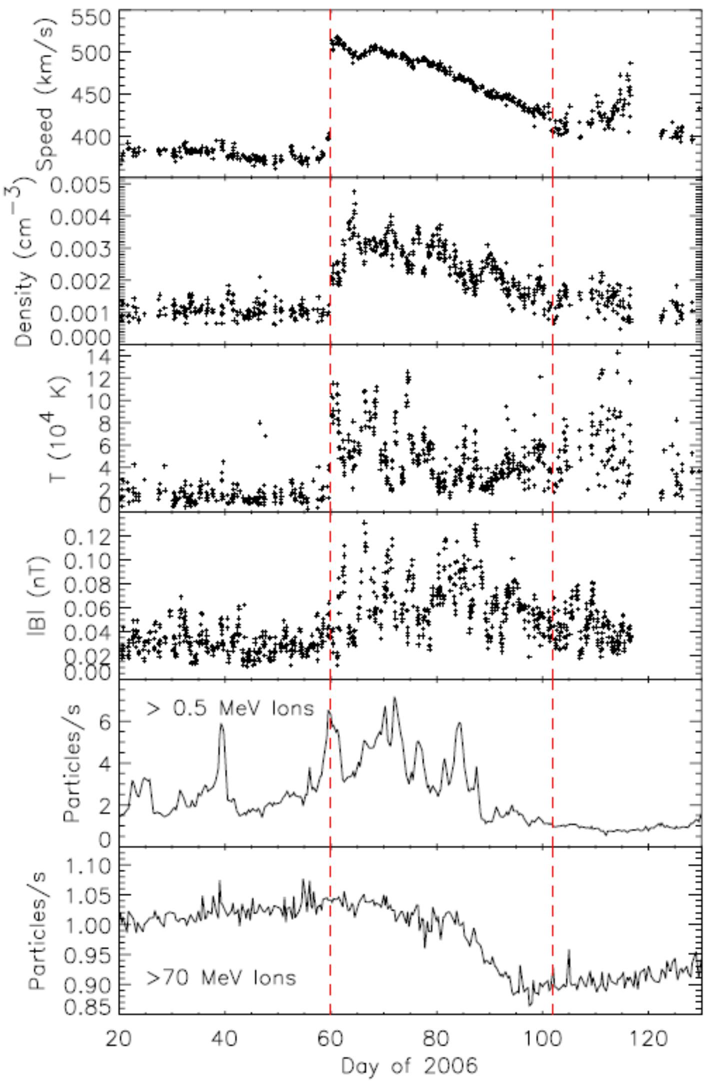
Transient Propagation & Evolution

Evolution of Interaction Regions from 1 to 60 AU



Wang & Richardson 2003, AIP Conf. Proc. 679:725

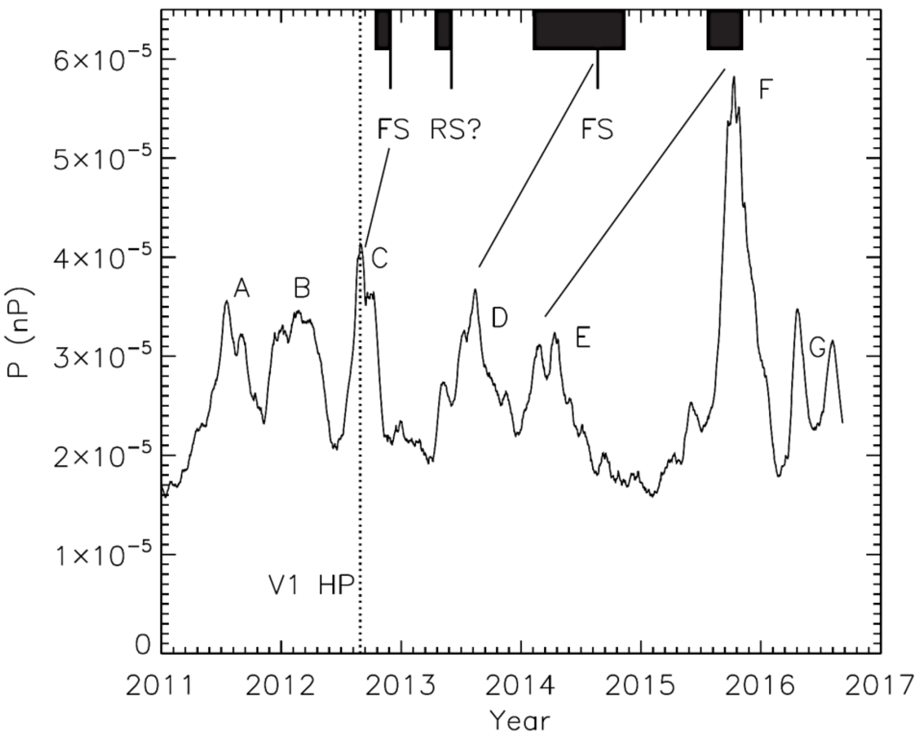
Merged Interaction Region at 79 AU



Richardson et al. 2006, GRL 33:L23107

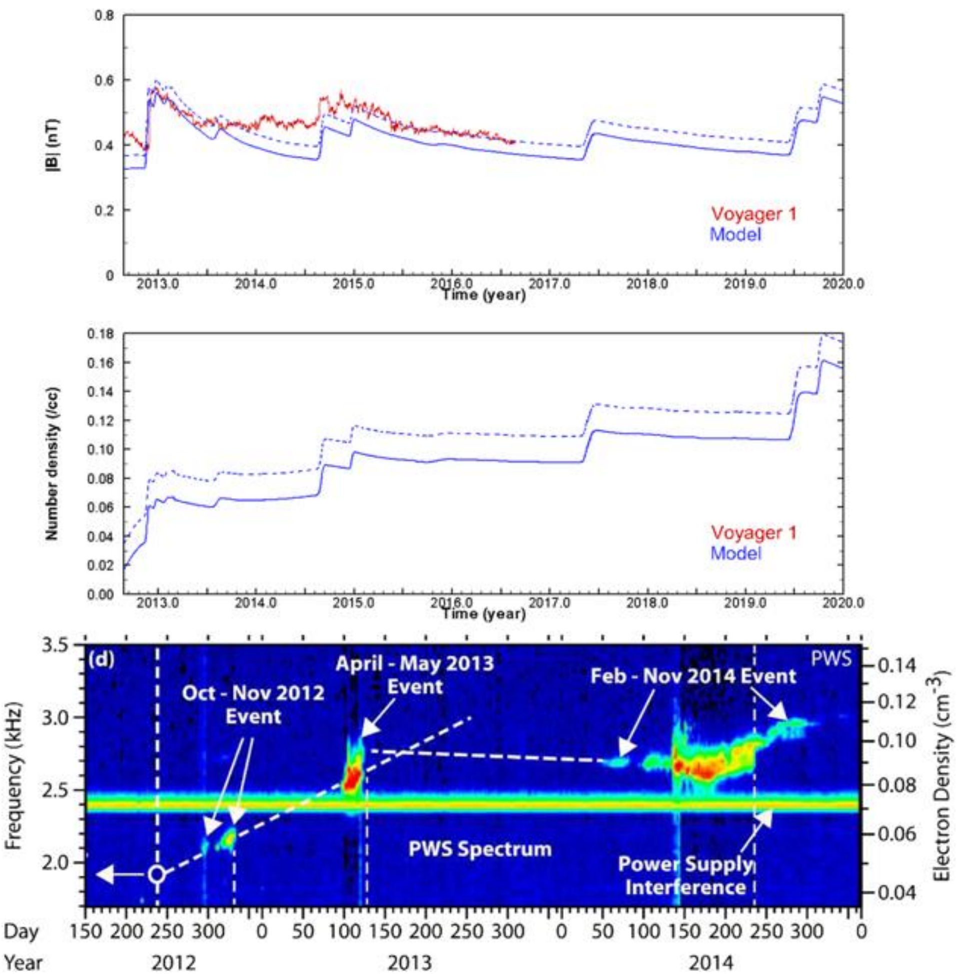
Pressure Pulses in the Heliosheath: Drivers of Interstellar Transients?

Voyager 2: Pressure Pulses



Richardson et al. 2017, ApJ 834:190

Data-Driven Model of Solar Transients

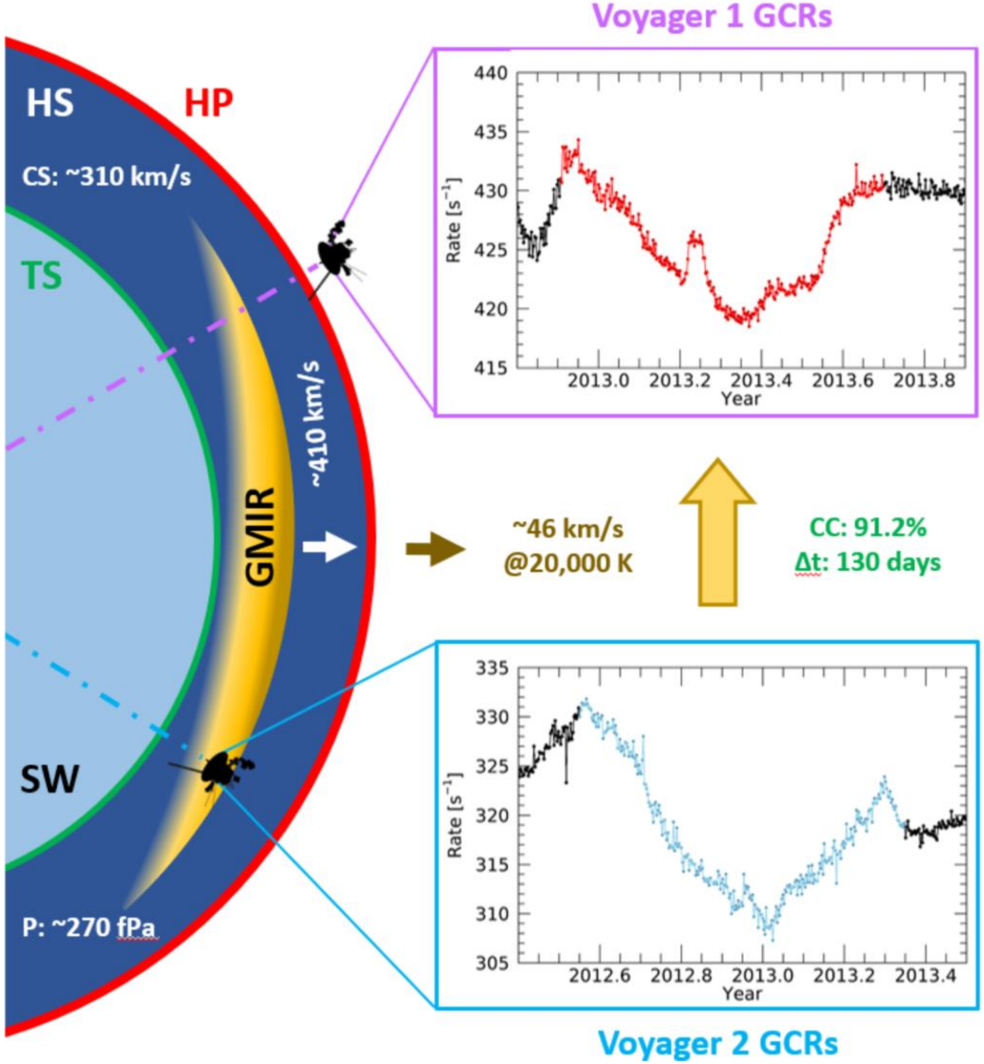


Kim et al. 2017, ApJ 843:2

Space Physics at Princeton

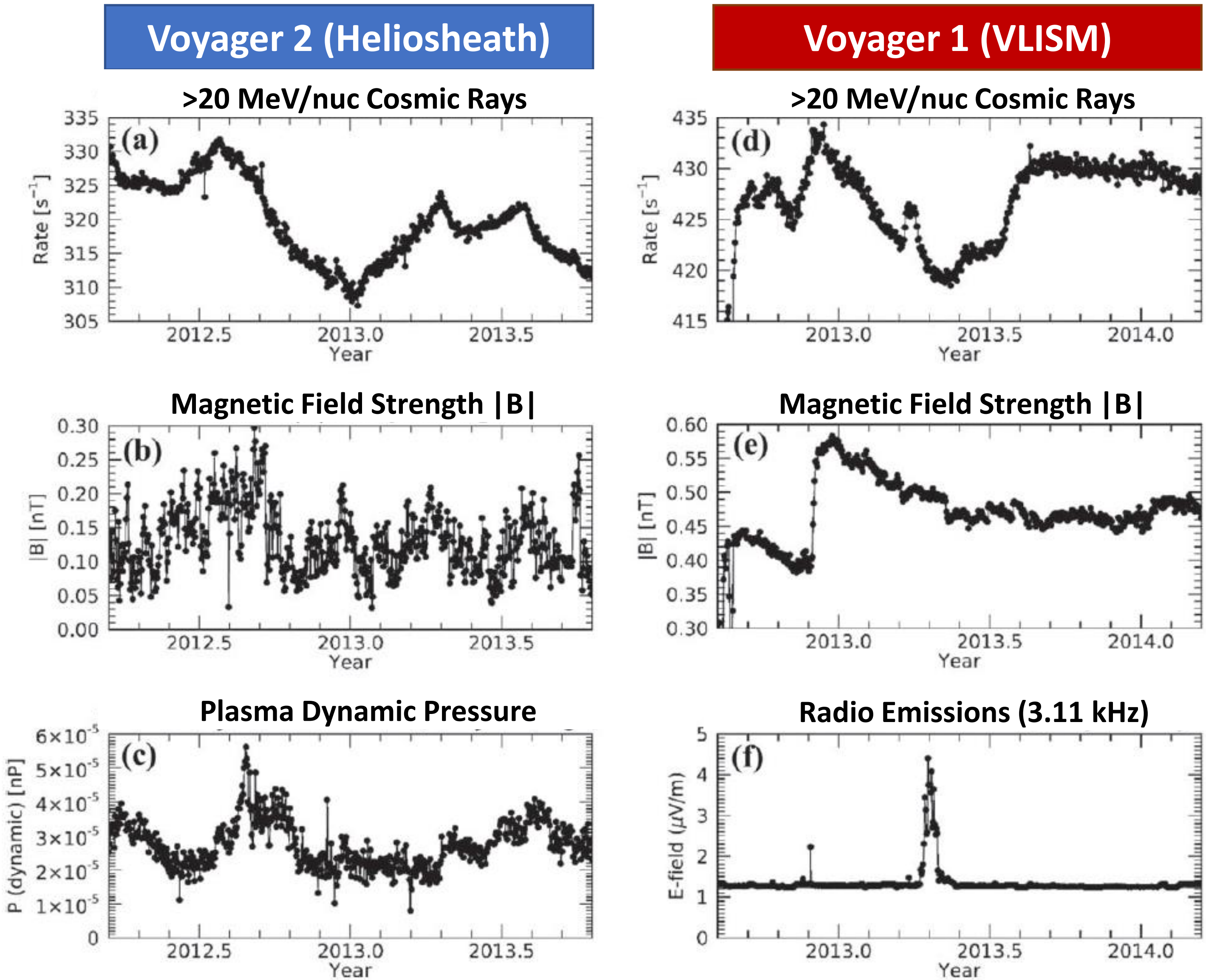
Voyager 1 to Voyager 2 Transient

- Heliosphere-VLISM Pressure Balance: key unknowns
  - interstellar temperature & heliosheath pressure
- Rankin et al. 2019
  - P_{Total} ~ 270 fpa
    - Magnetic, thermal, dynamic: ~15%
    - Pickup Ions: ~45%
    - ACR/GCR: ~22%
    - Remaining: ~18%
- Dialynas et al. 2020, ApJ 905:L24
  - Cassini, Voyager, & IBEX observations
  - P = 251 fpa
- Fahr et al. 2020, A&A 642:A144



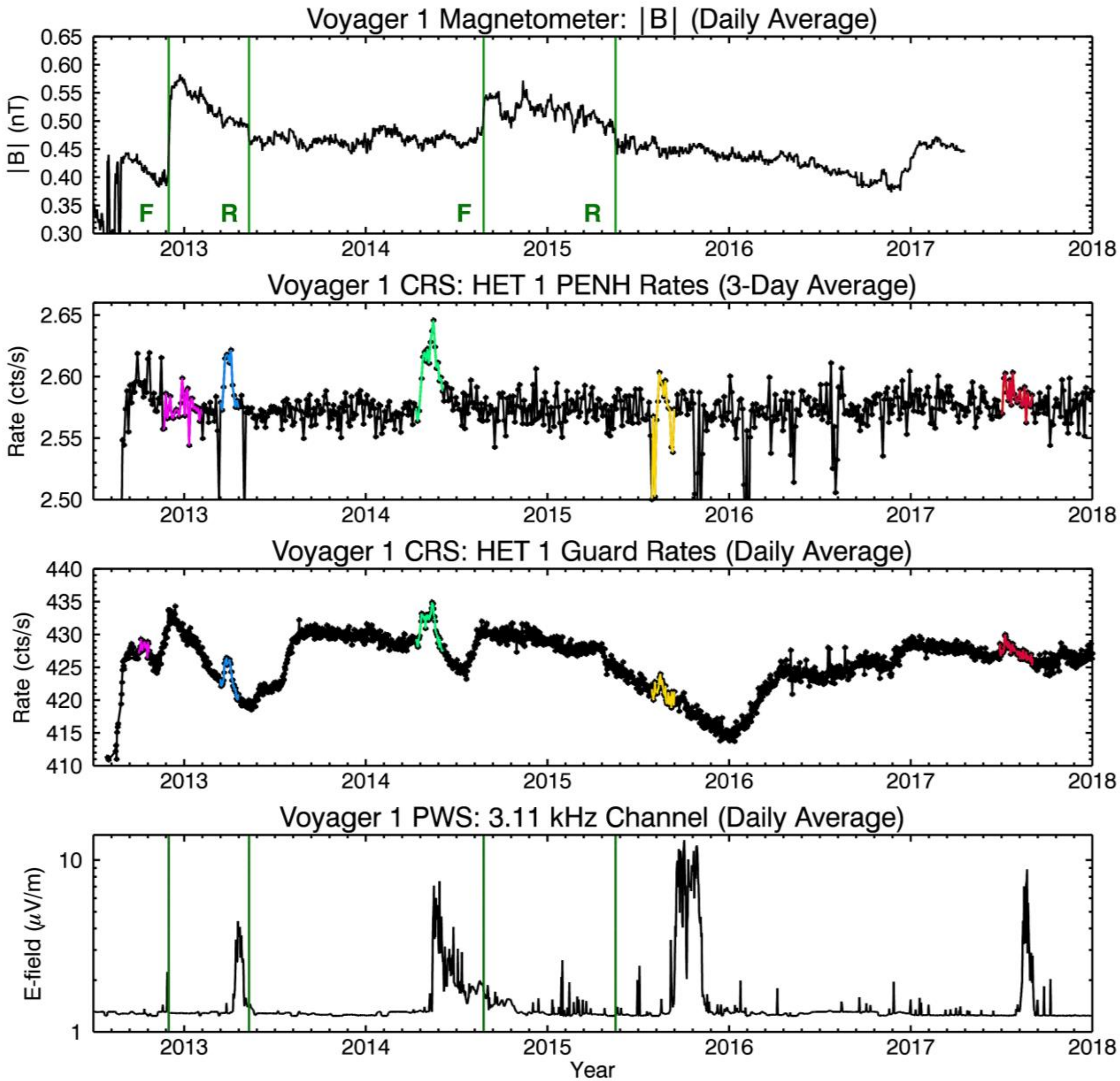
Rankin et al. 2019, ApJ 883:101

A Perspective from the Outside-In



Rankin et al. 2019, ApJ 883:101

The VLISM: A New, Exciting Regime



Rankin 2018, Caltech PhD Thesis

Significant Discoveries & Open Questions

- Notable cosmic ray observations
  - heliopause boundary
  - low-energy interstellar spectra
  - pitch-angle anisotropy
  - interstellar transients
- Significant progress made on larger heliophysics questions:
  - What determines the interaction of the Sun with the Solar System and the interstellar medium? Decadal Survey Goal 3
  - → the relationship is a lot more dynamic than we think!
  - What can we discover about our own star by looking at it from outside-in rather than inside-out?
  - How do our interstellar surroundings influence the Sun and our Solar System?
- Open questions
  - How far beyond the heliopause does the Sun and its material influence our interstellar surroundings?
  - How do temporal changes at the Sun impact the global structure of the heliosphere?
  - Where is the cosmic ray modulation boundary?
  - What is the underlying physics that governs the cosmic ray pitch angle anisotropy?
  - What are fundamental processes that occur both within the heliosphere and throughout the universe? Decadal Survey Goal 4

Rich data set, new plasma regime; cosmic ray experts welcome!