Galactic Cosmic Ray Interactions with the Very Local Interstellar Medium

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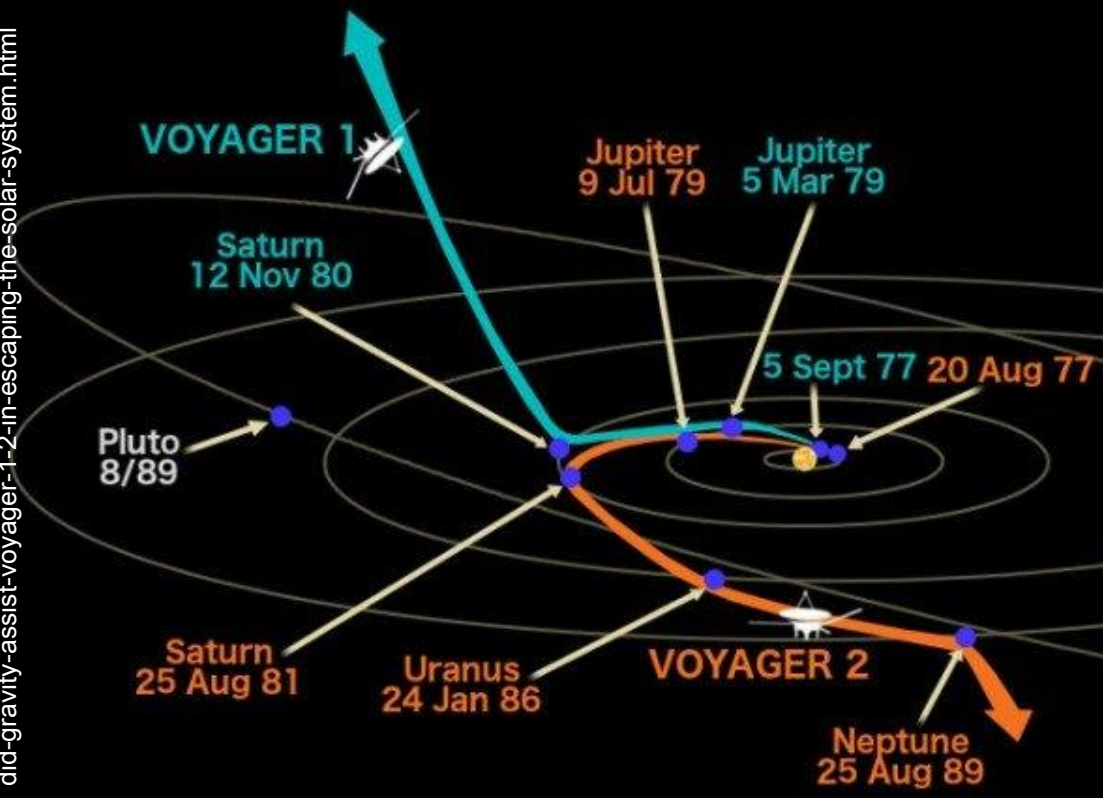
Dawn of the Interstellar Mission

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

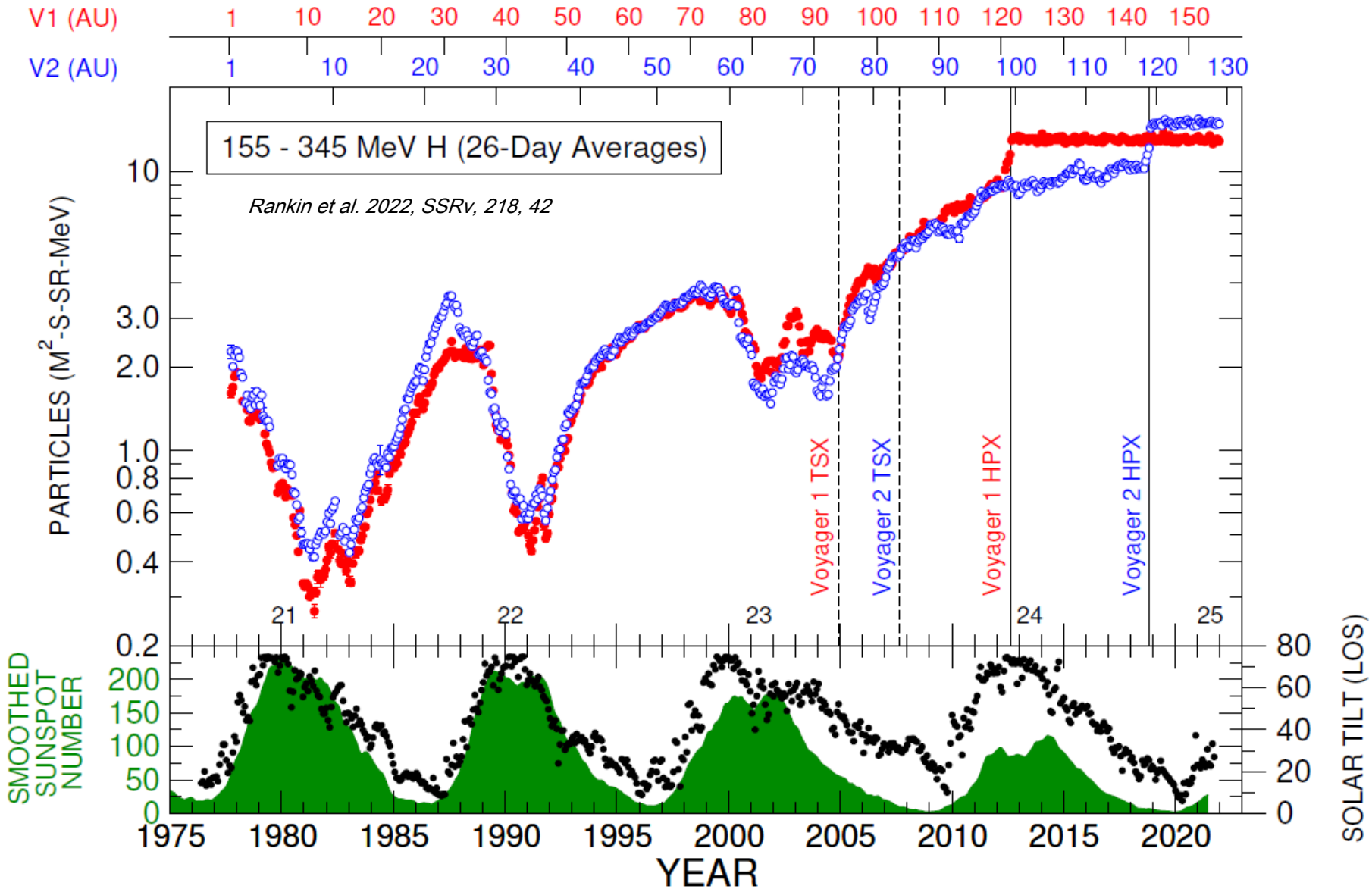


- 1977: Launch
  - Voyager 2 – August
  - Voyager 1 – September
- 1989: Last planetary encounter
  - Voyager 2, Neptune, 1989
- 1990: Last image
  - "Solar System Family Portrait" – Voyager 1

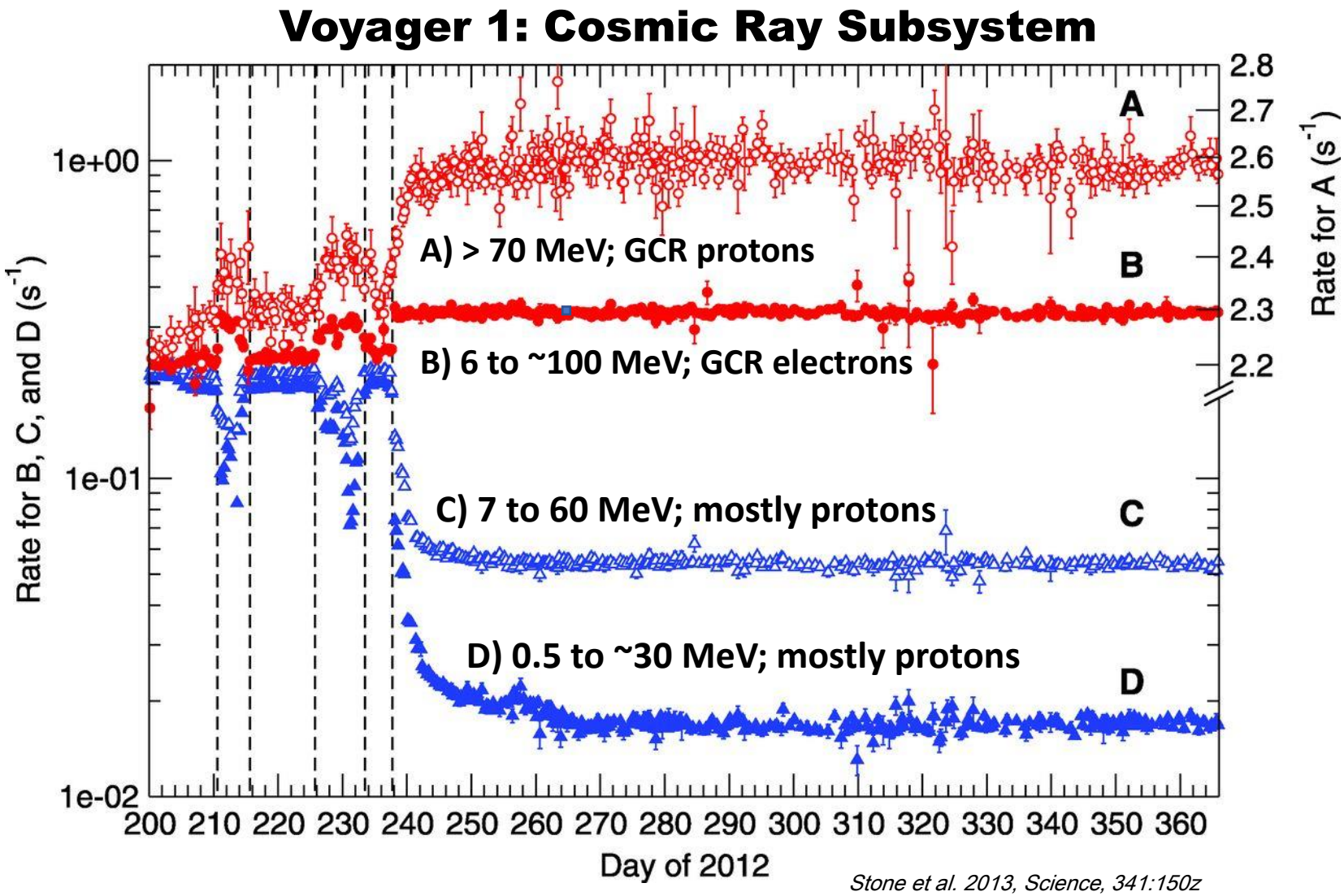
New Mission Objective:

"[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."

Galactic Cosmic Rays through the Heliosphere



Heliopause Crossing: Cosmic Rays

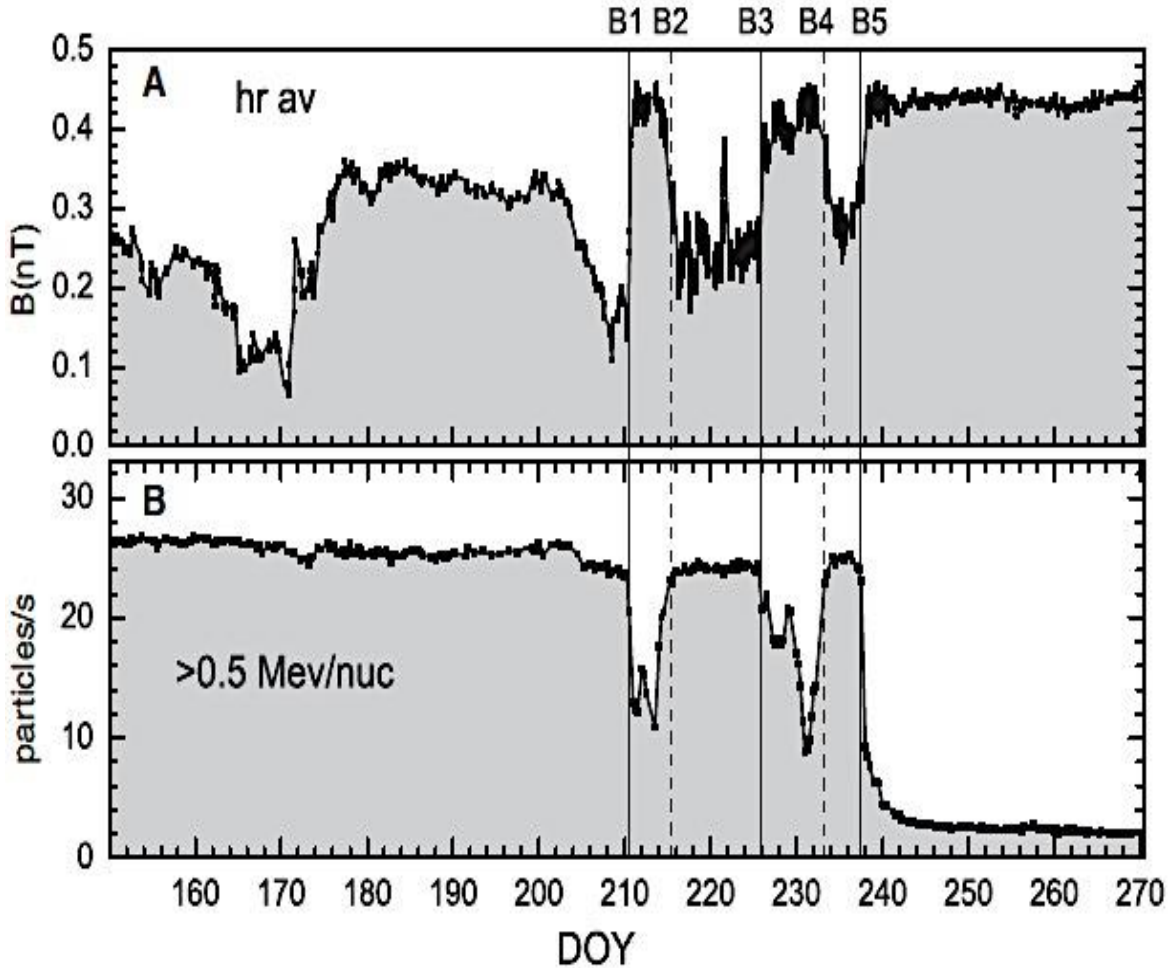


Stone et al. 2013, Science, 341:150z

Heliosheath	Very Local Interstellar Medium

Heliopause Crossing: Magnetic Fields

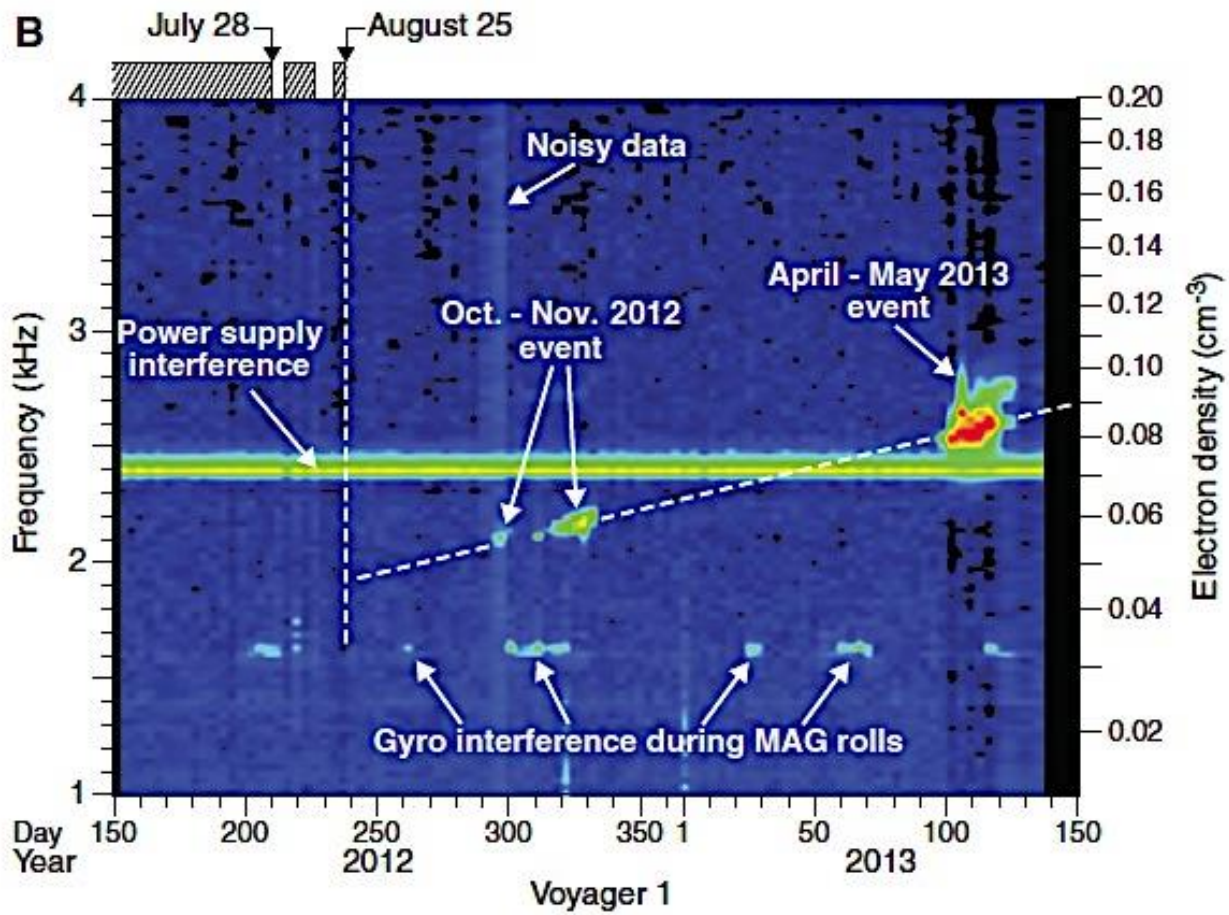
Voyager 1: Magnetometer (2012)



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

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

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

Voyager 1 & 2: Interstellar Arrival

"Space is Arbitrary" by Tom Gauld

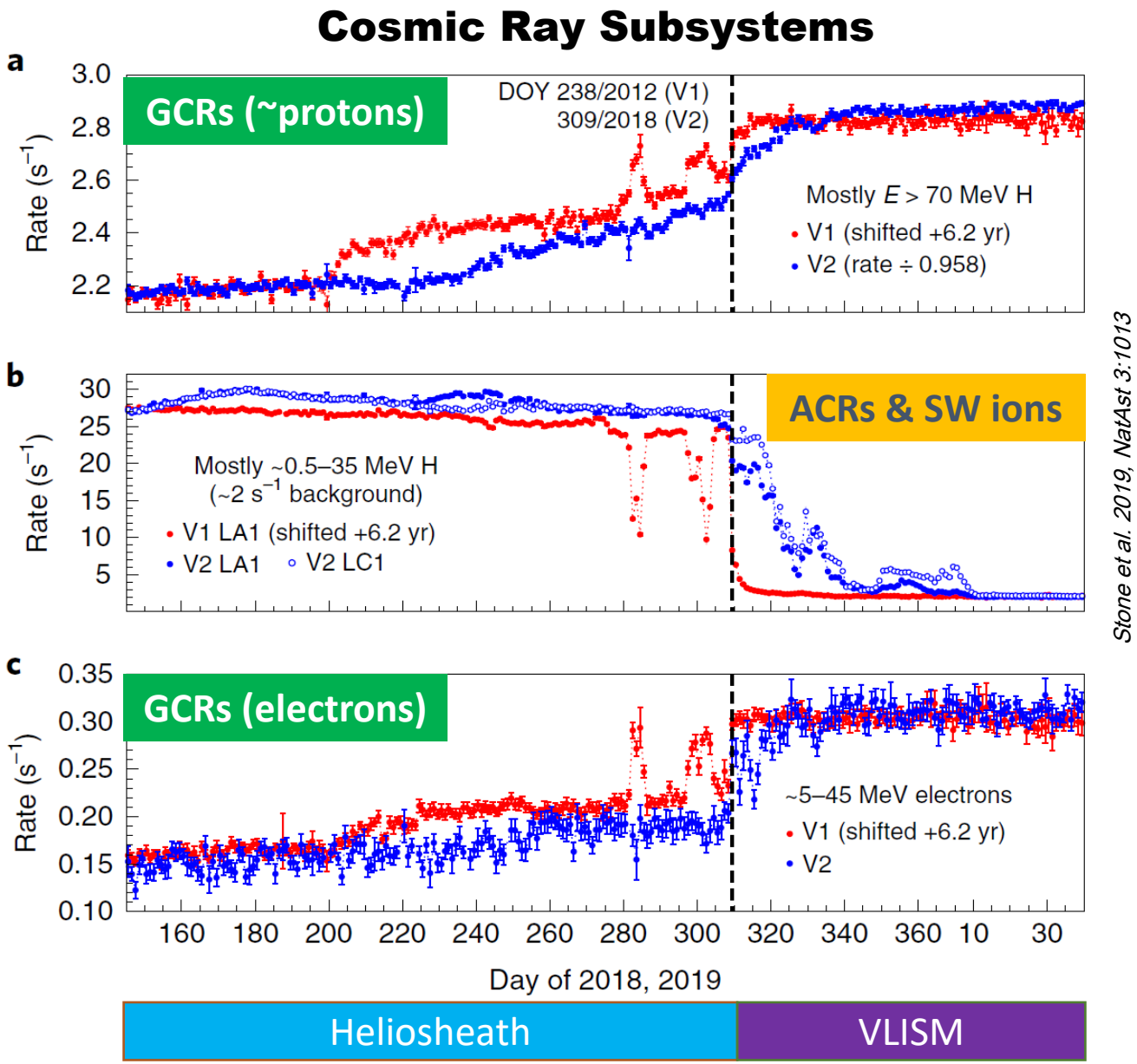
- Voyager 1
  - August 25, 2012 @ ~122 AU
  - Magnetic field strength: ~0.46 nT
    - Increased from 0.2 nT
  - Plasma density: ~0.055 cm^{-3}
  - Heliopause likely shrinking
- Voyager 2
  - November 5th, 2019 @~119 AU
  - Magnetic field strength: ~0.68 nT
    - Compressed Fields Towards Ecliptic South
  - 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 (1)

Voyager 1

Voyager 2



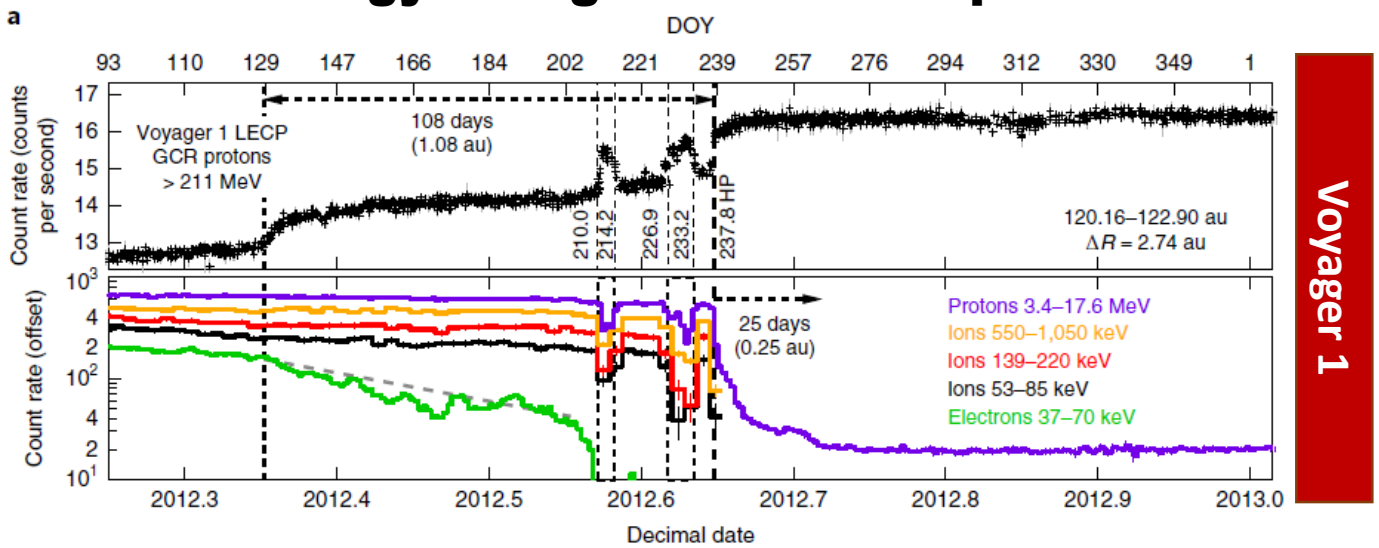
Stone et al. 2019, NatAst 3:1013

Heliopause Crossing: Energetic Particles (2)

Low Energy Charged Particle Experiments

GCRs (~protons)

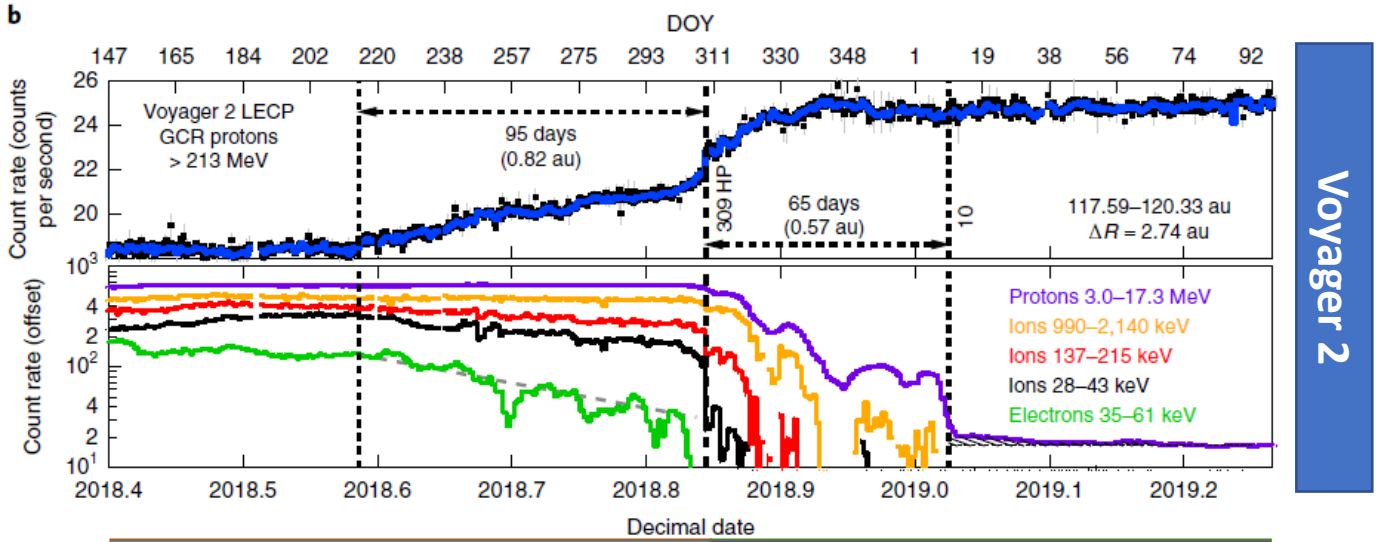
ACRs & SW ions



Voyager 1

GCRs (~protons)

ACRs & SW ions

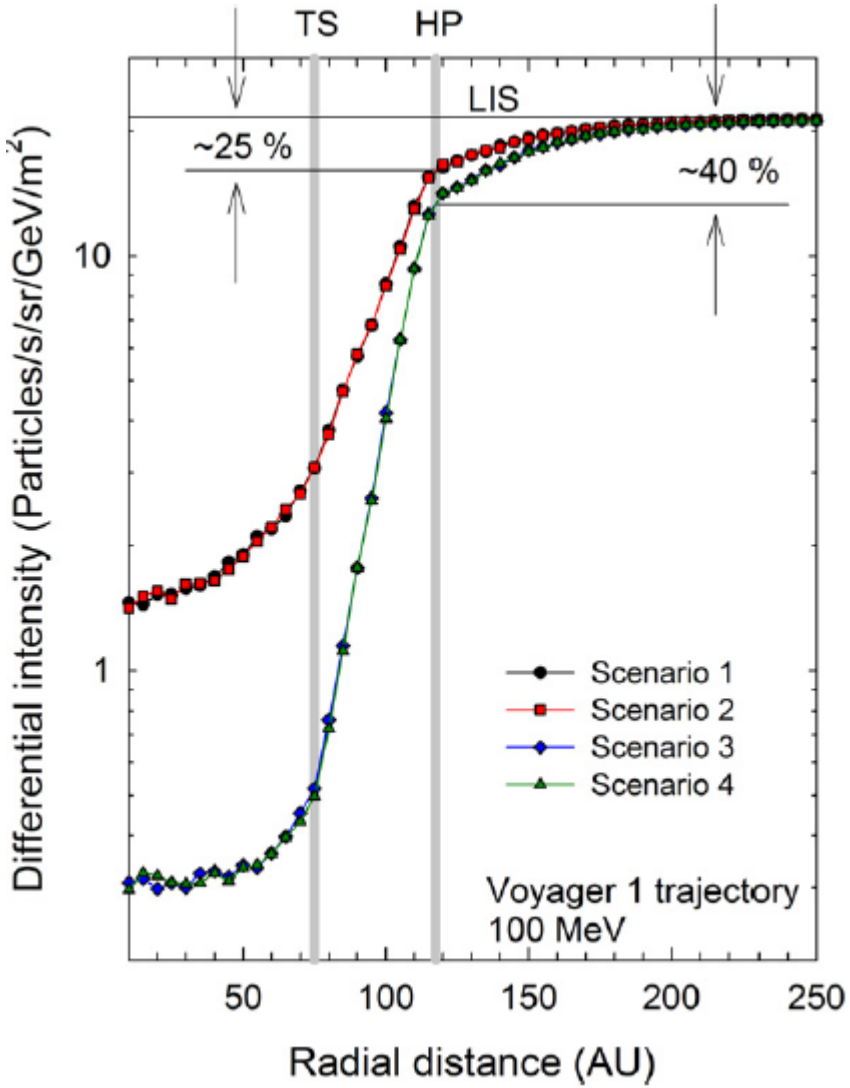


Voyager 2

Heliosheath | VLISM

Krimigis et al. 2019, NatAst, 3:997

Solar Modulation Beyond the Heliopause?

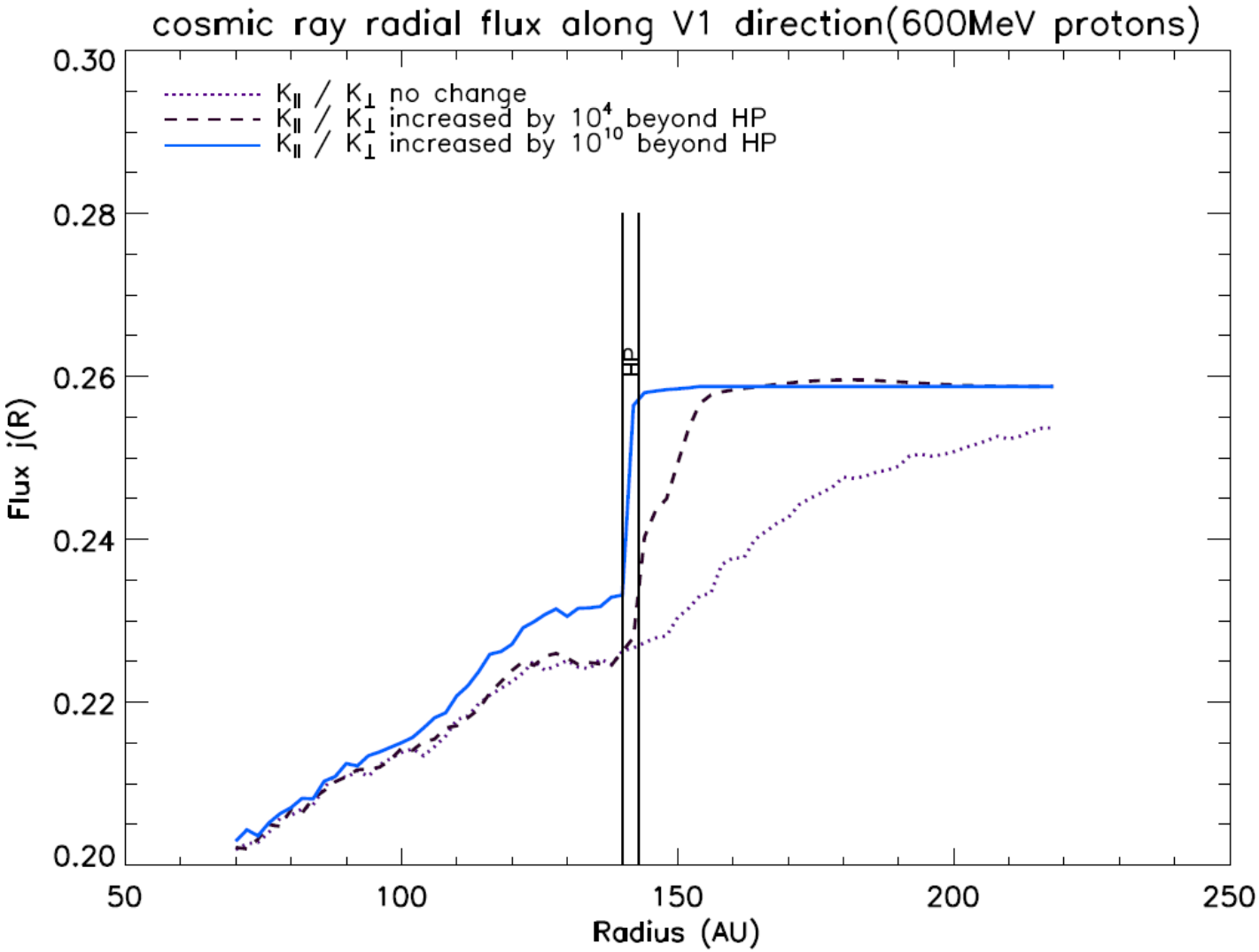


Strauss et al. 2013, ApJL, 765:L18

"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."

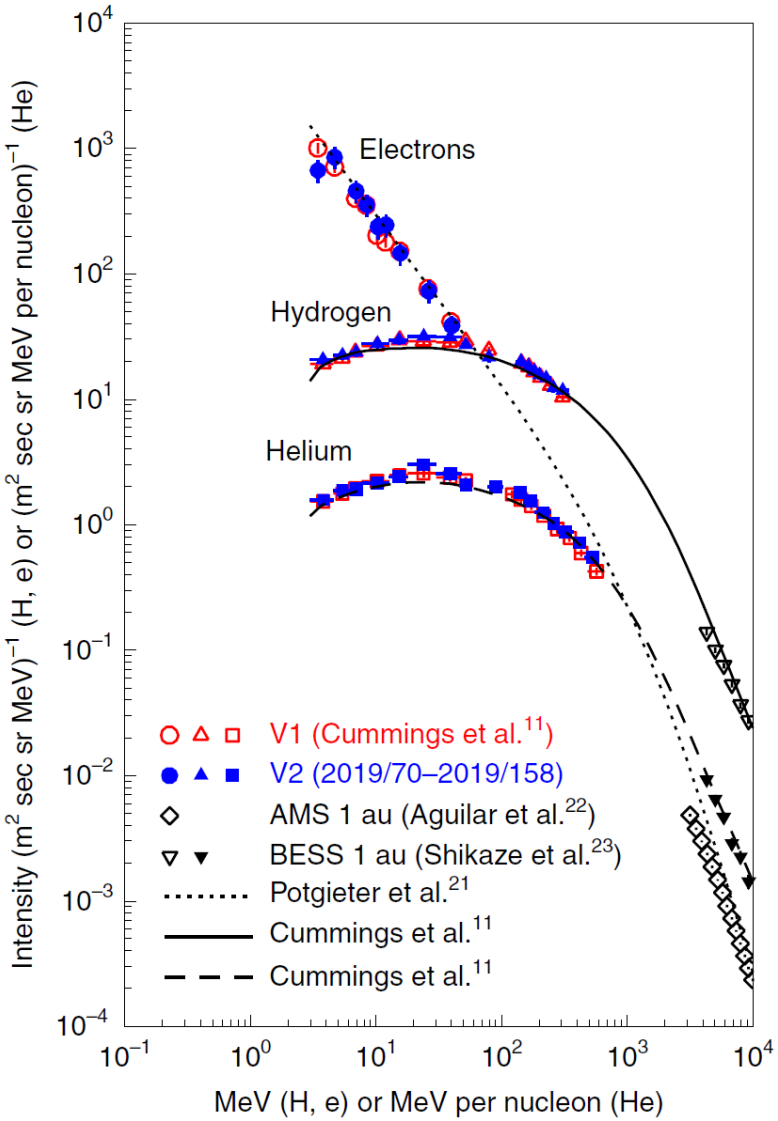
Zhang et al. 2015, Phys. Plasmas 22:091501

Solar Modulation Beyond the Heliopause?



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

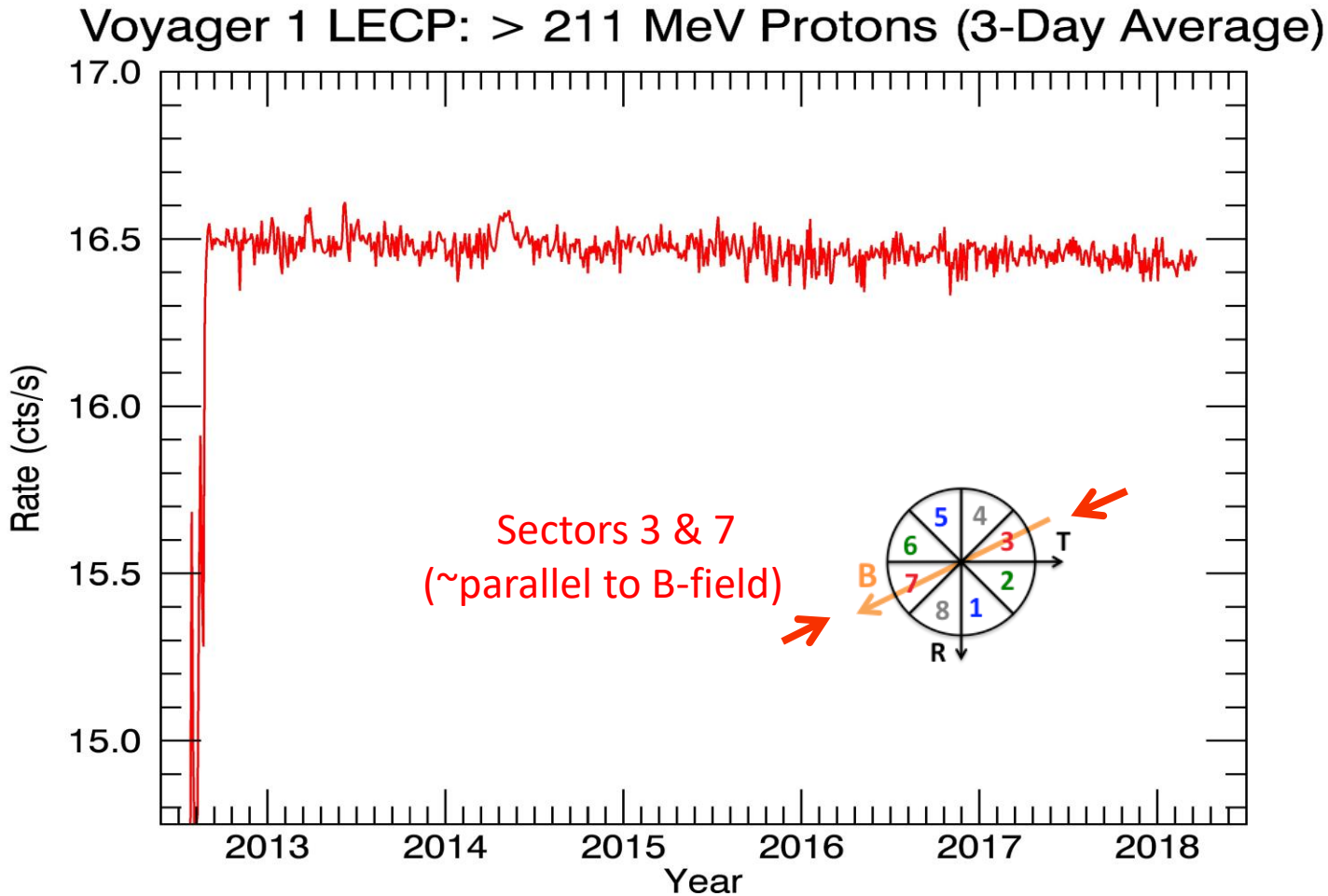
Low-Energy Interstellar Spectra!



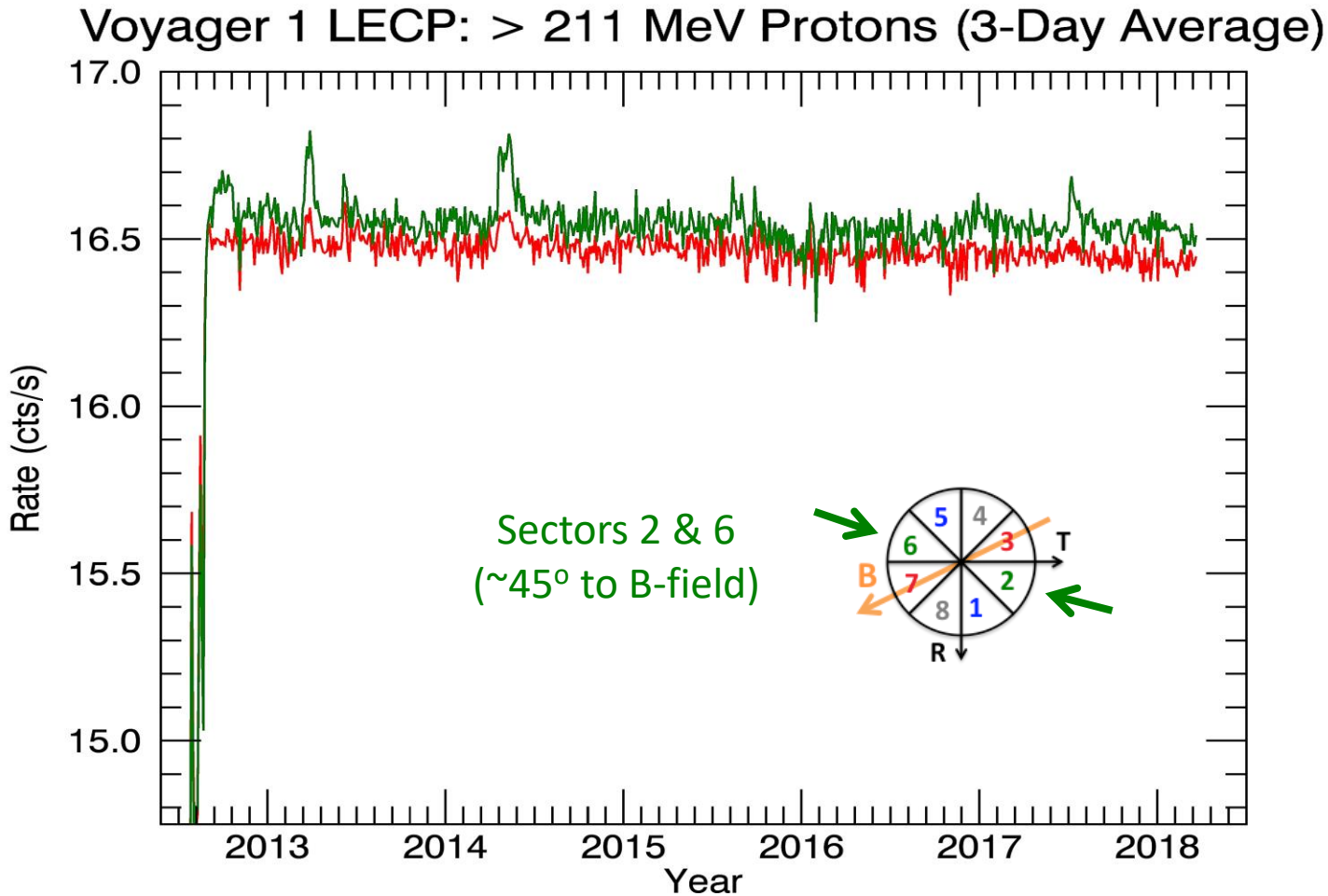
Stone et al. 2019, NatAst 3:1013

- 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 strong indications of a radial gradient at Voyager 1 (so far, at 157 AU and counting)
  - Remarkable consistency between the two spacecraft at very different longitudes and latitudes!

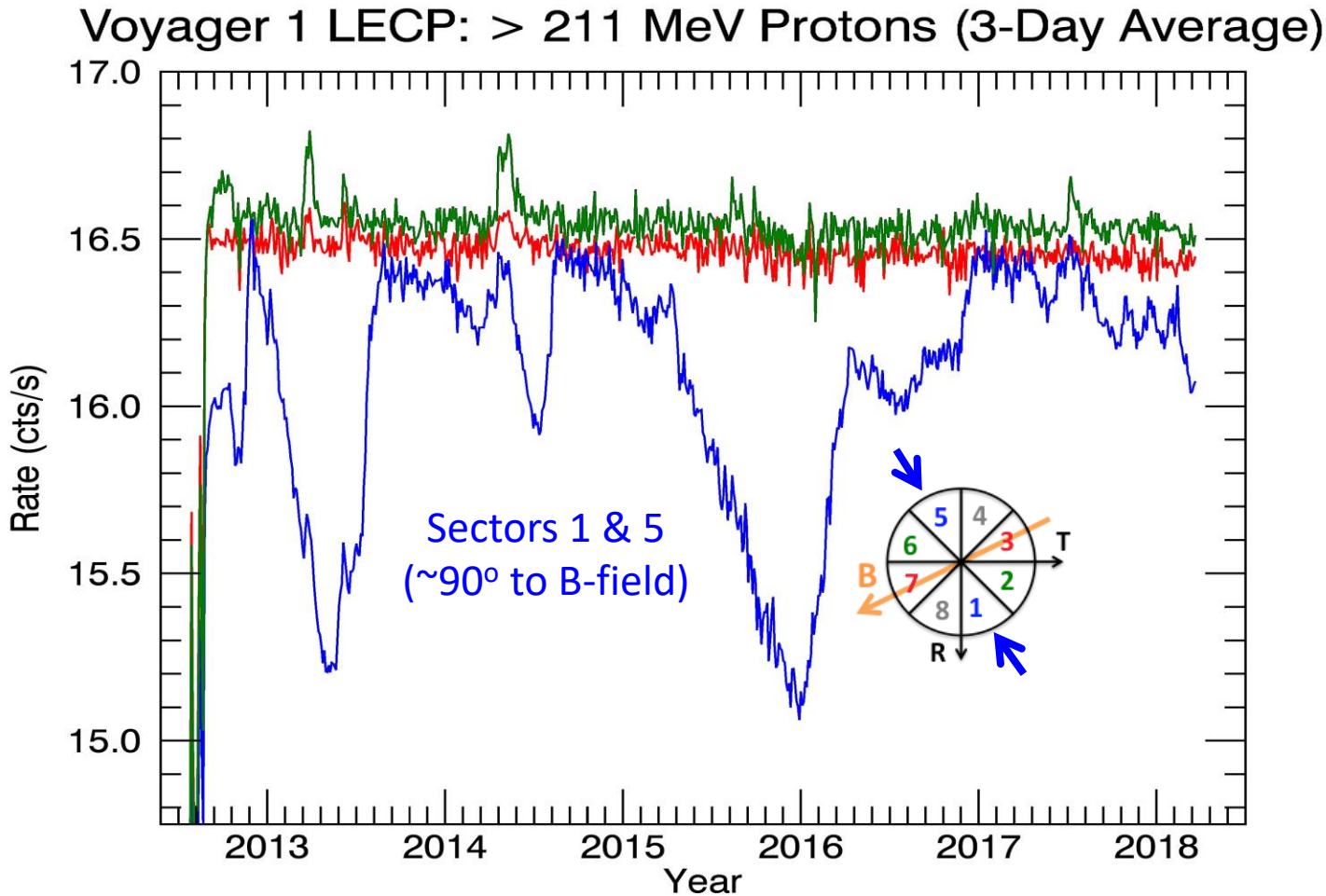
Uniform Intensities in Galactic Cosmic Rays



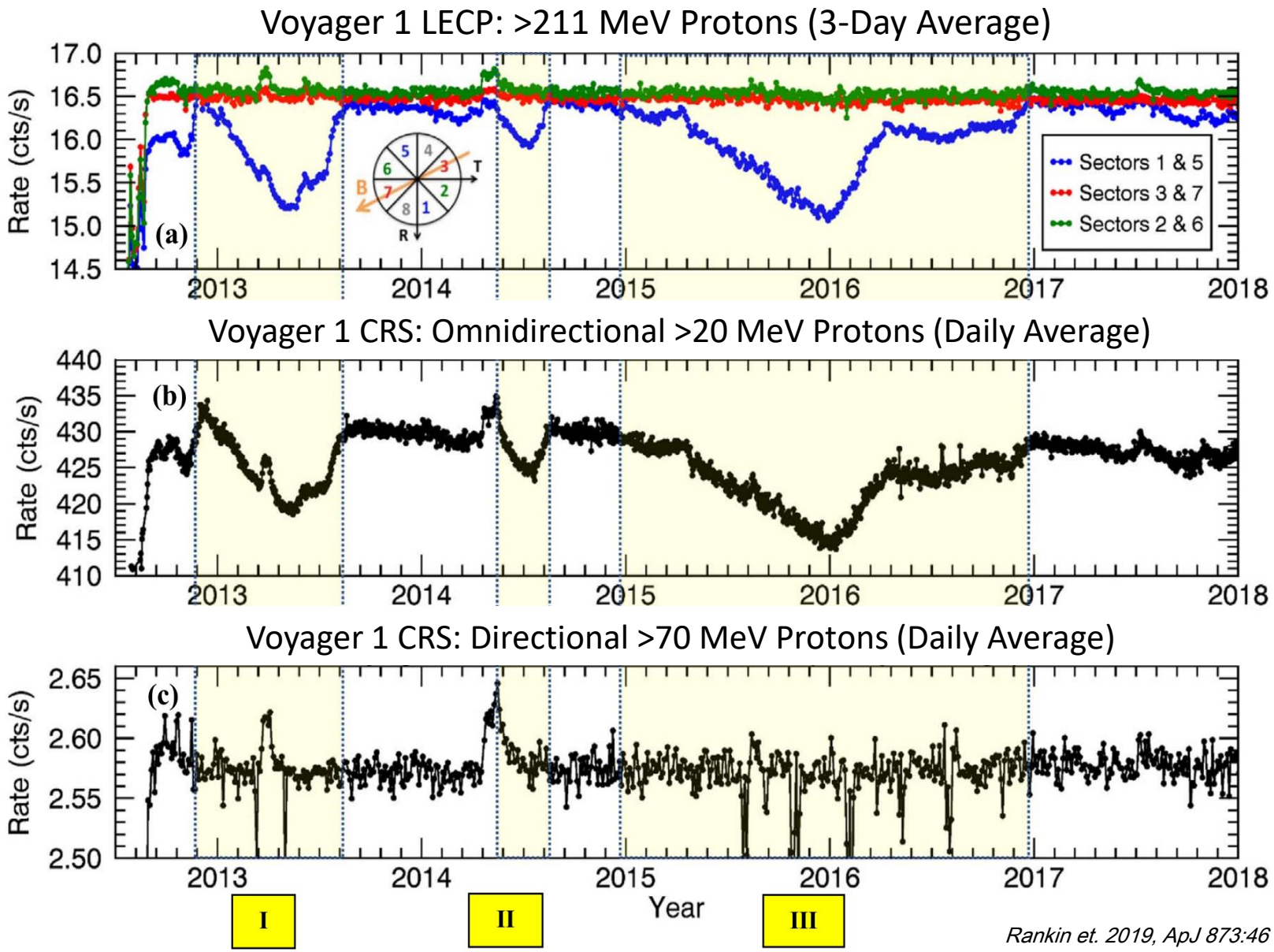
Uniform Intensities in Galactic Cosmic Rays



Uniform Intensities in Galactic Cosmic Rays!?

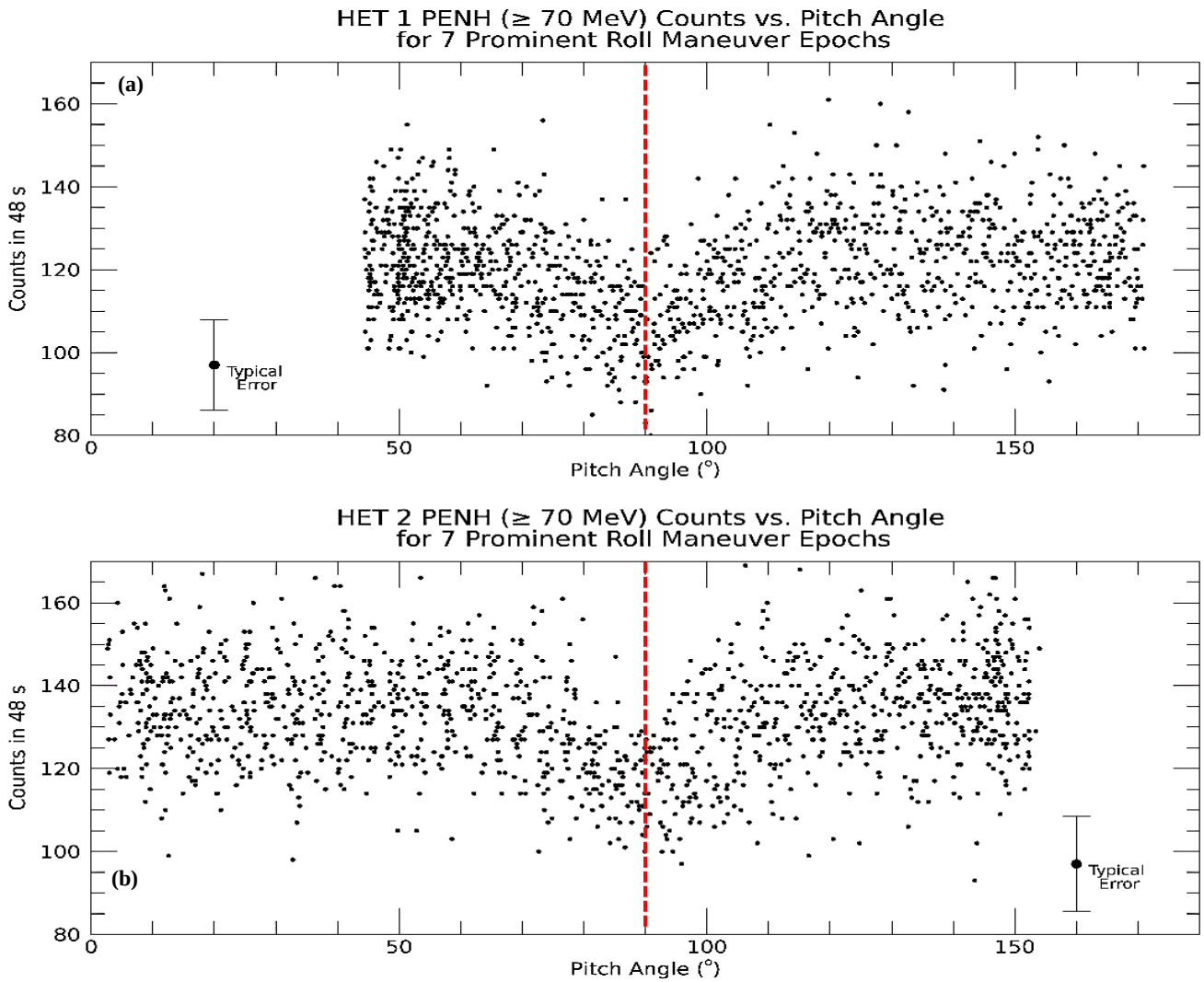


Galactic Cosmic Ray Anisotropy



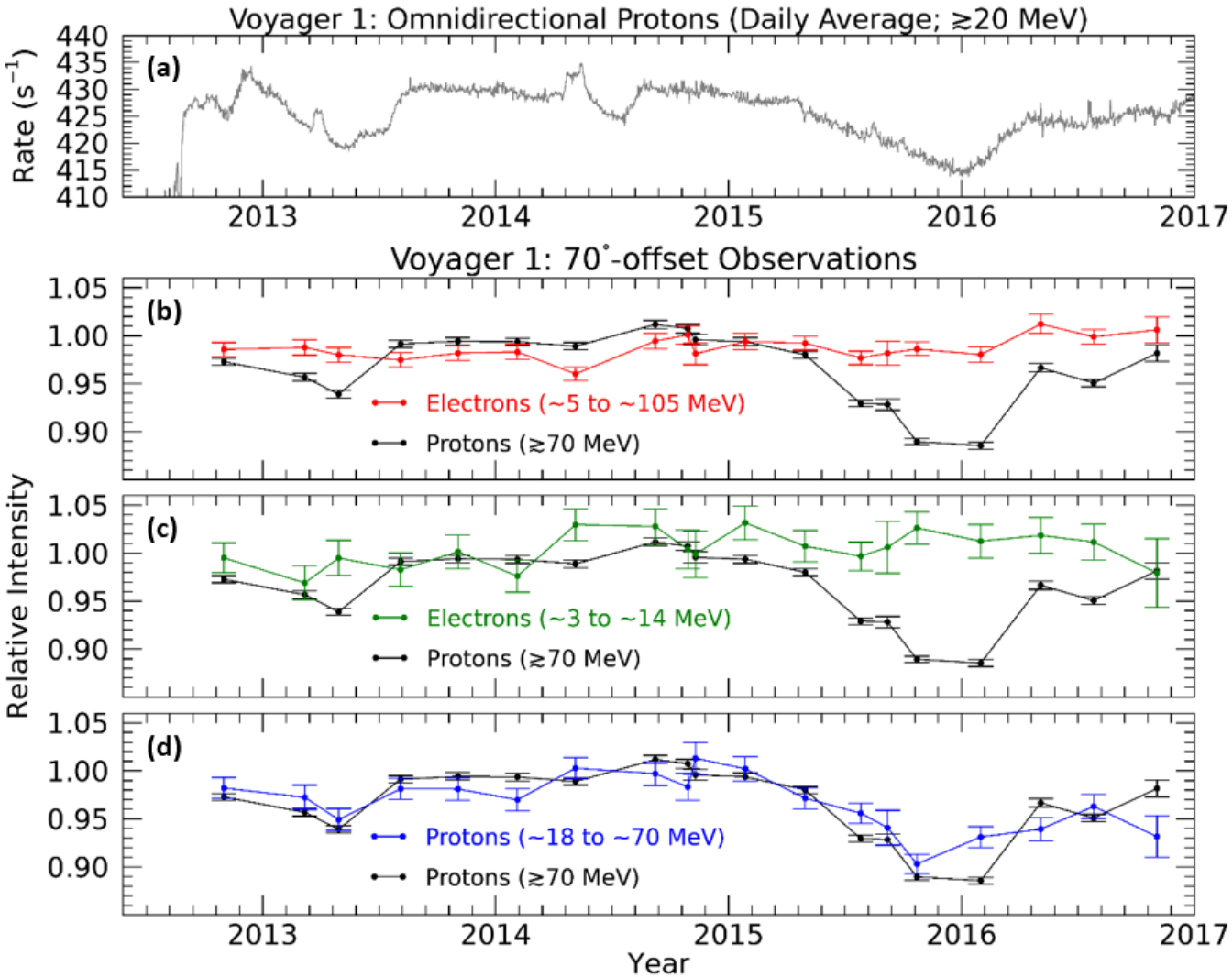
Rankin et. 2019, ApJ 873:46

Anisotropy Centered on 90° Pitch Angle



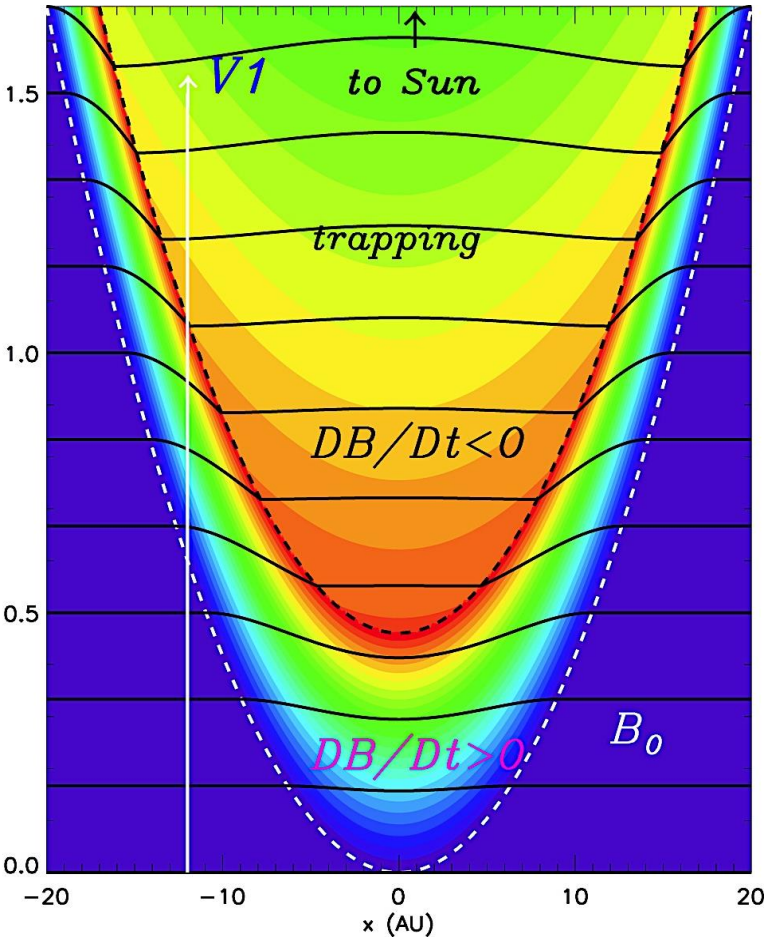
Rankin et al. 2019, ApJ 873:46

Pitch Angle Anisotropy: Species Dependent

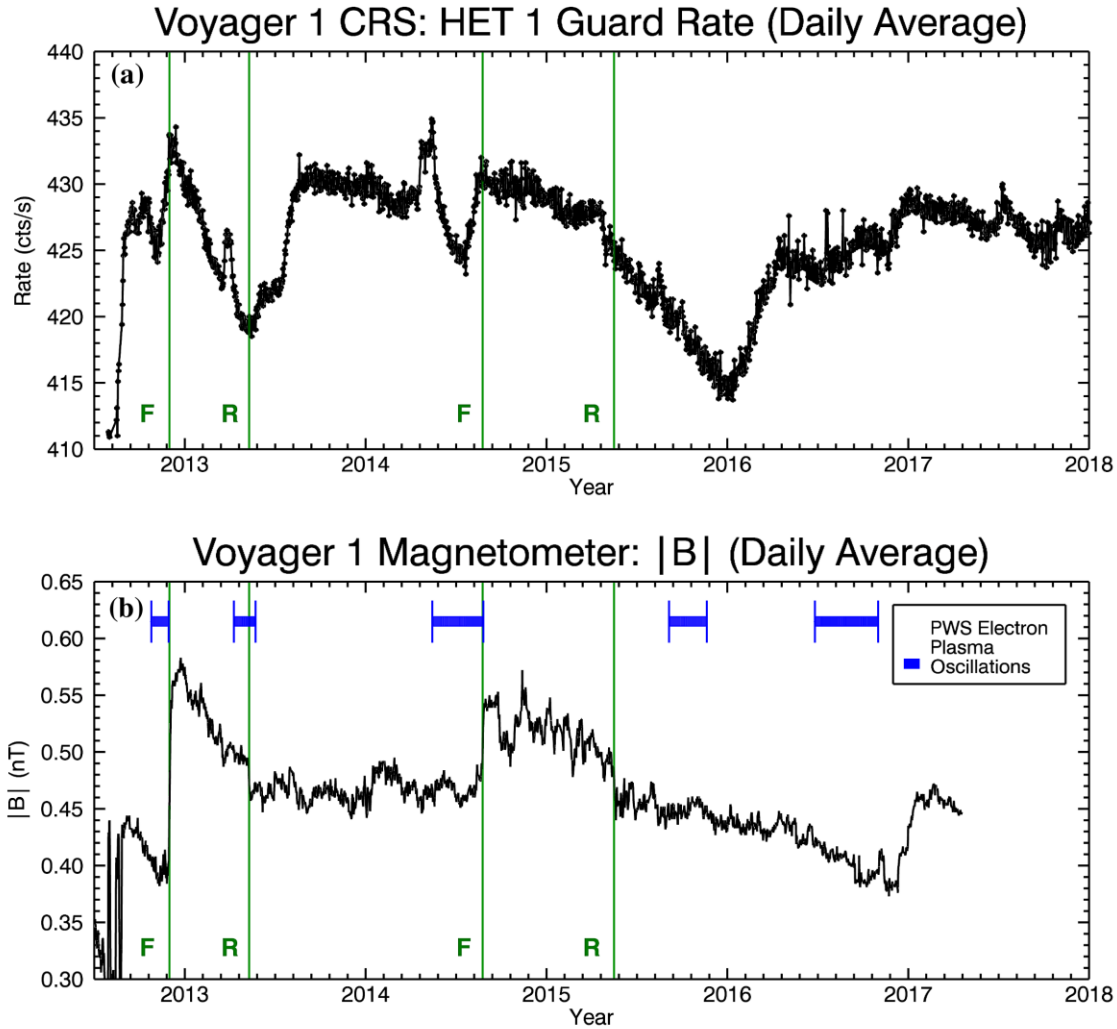


Rankin et al. 2020, ApJ, 895:103

Trapping and Cooling Downstream of Shocks?

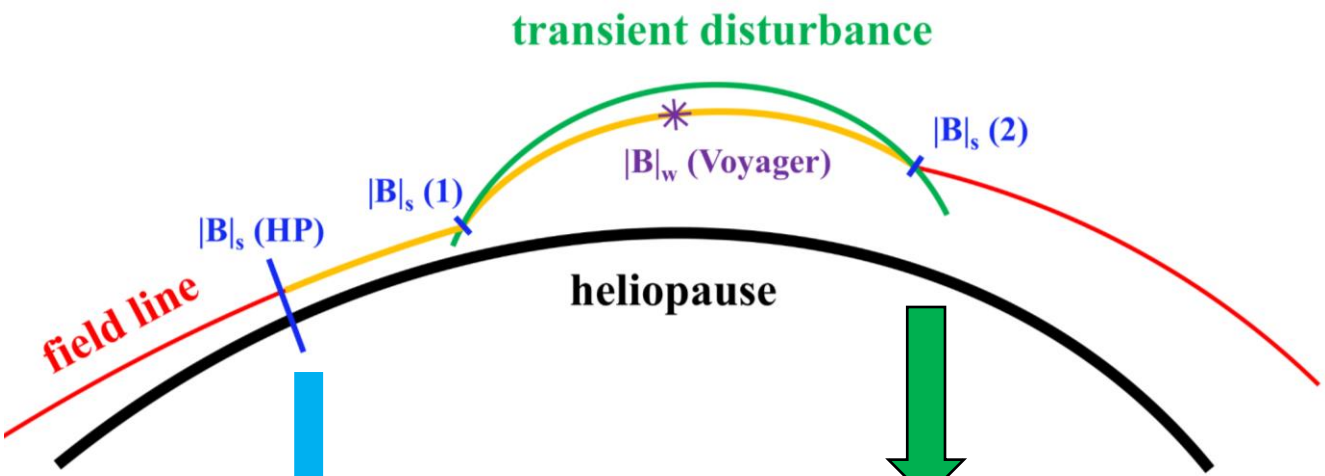


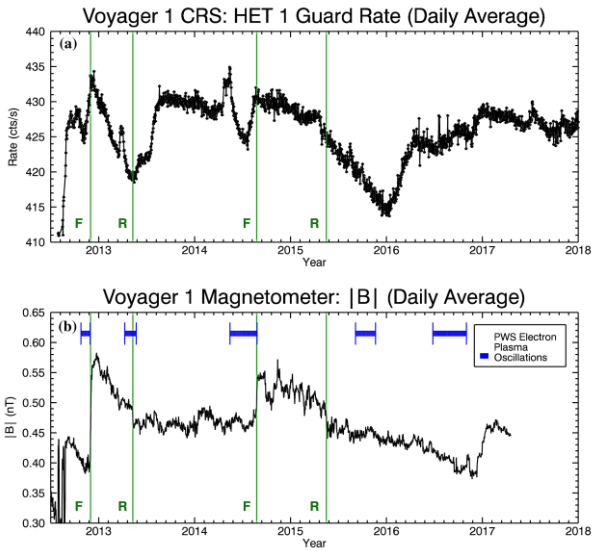
Kóta & Jokipii, 2017, ApJ 839:126

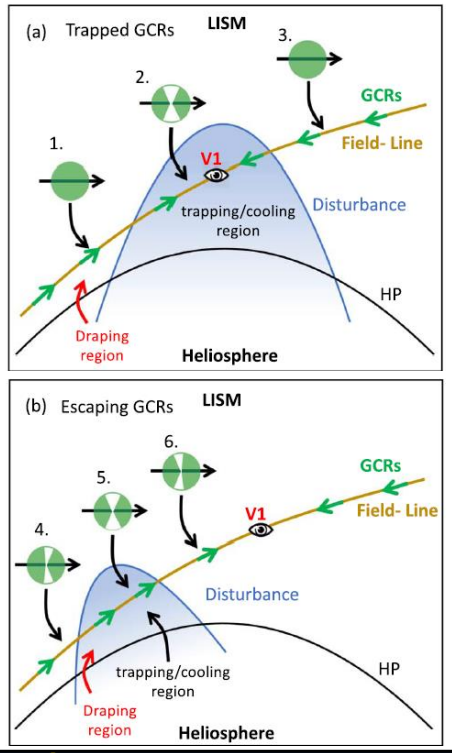


Rankin et al. 2019, ApJ 873:46

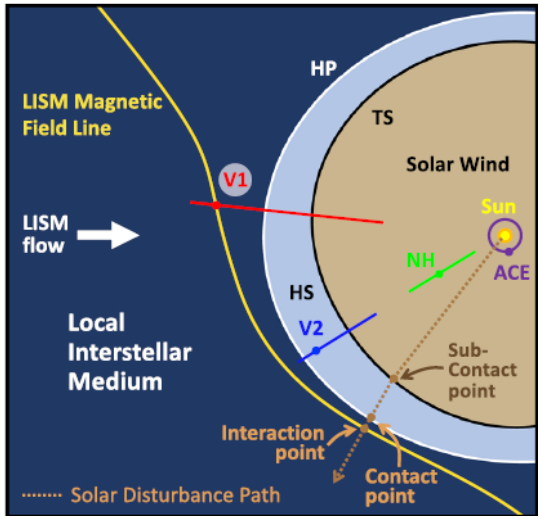
Influenced by the Large-Scale Structure of the Heliosphere?





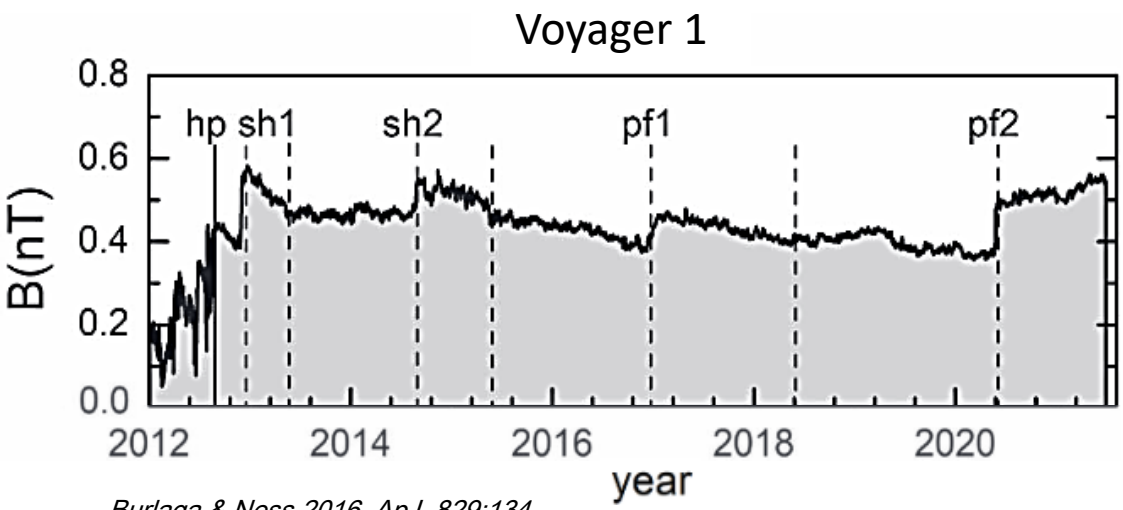


Hill et al. 2020, ApJ 905:69

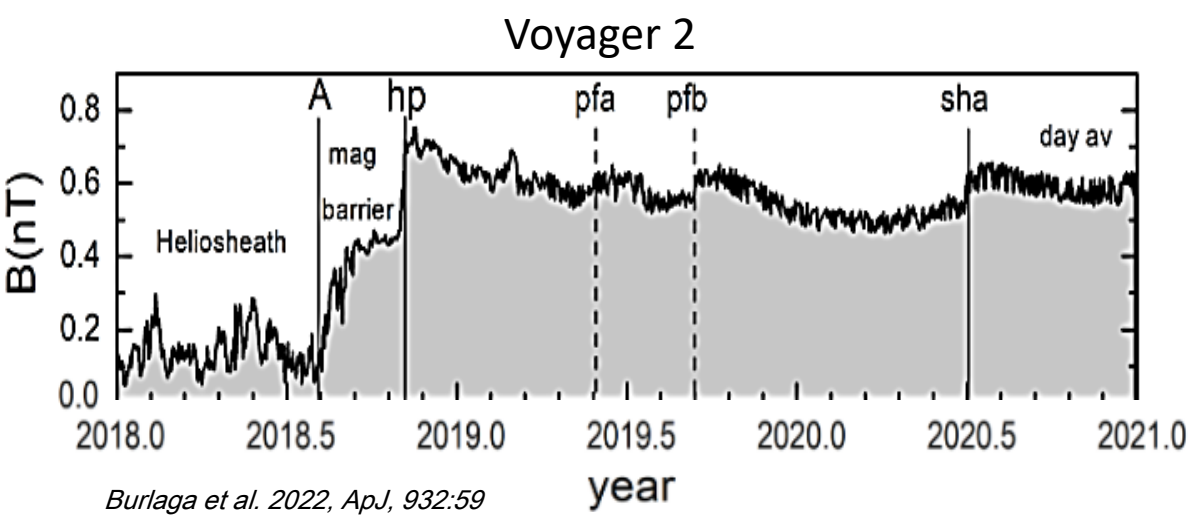


Rankin et al. 2019, ApJ 873:46

Transient-Perturbed Magnetic Field



Burlaga & Ness 2016, ApJ, 829:134



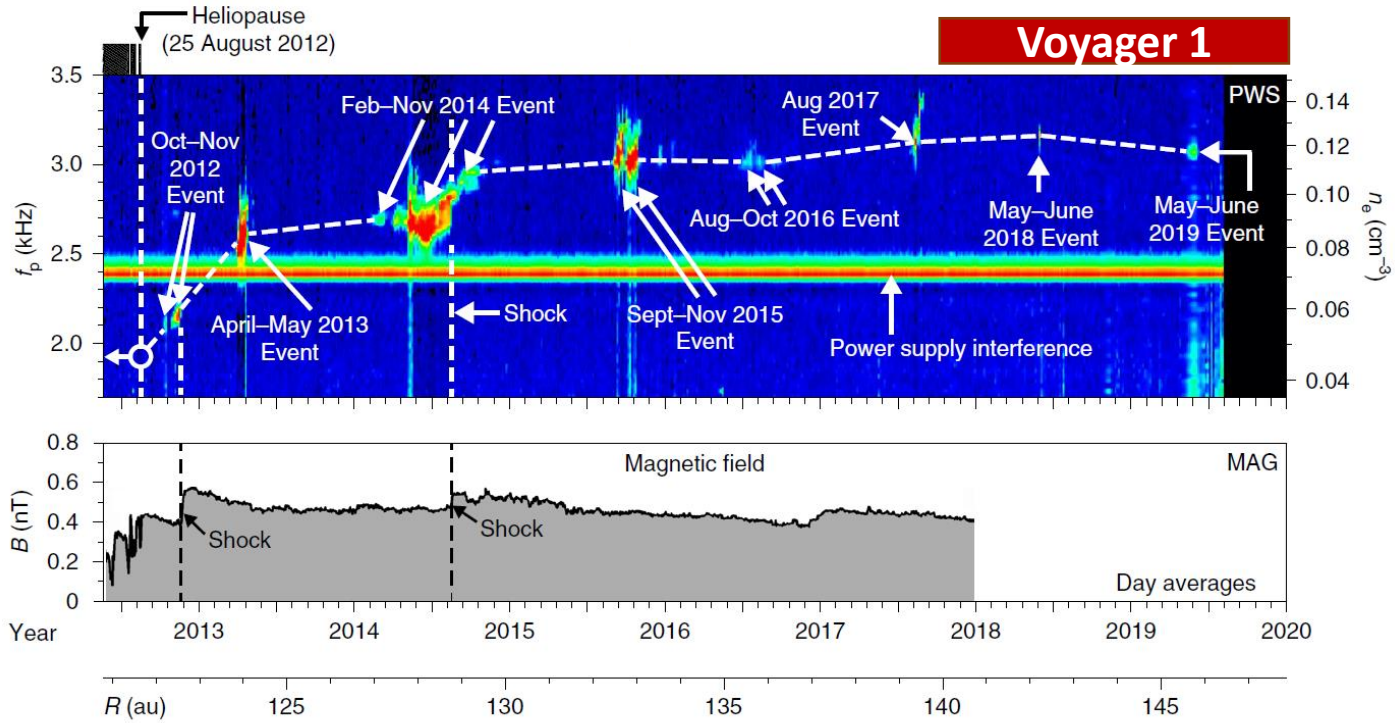
Burlaga et al. 2022, ApJ, 932:59

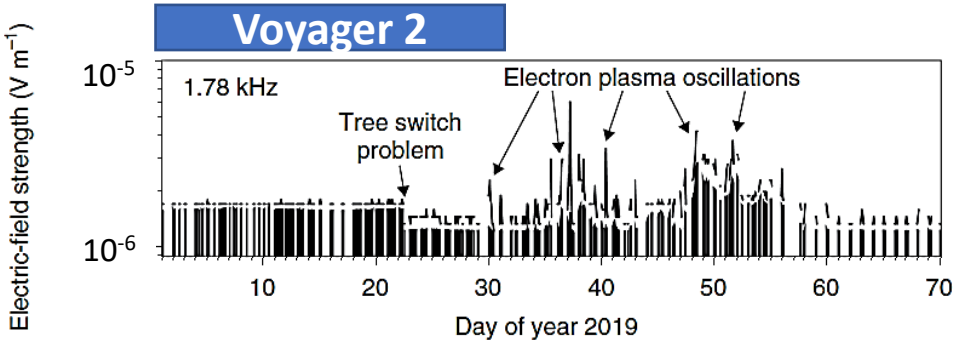
- Voyager 1 & 2 "Shocks"
  - weak, subcritical, laminar, resistive, and quasi-perpendicular
  - 10^7 km thick
    - 1000 x's thicker than 1-AU counterparts
  - small jump ratios
    - ~1.4 in 2012
    - ~1.1 in 2014
  - Likely collisional
    - Mostafavi & Zank 2018, ApJ 854:L15

Transient Electron Plasma Oscillations

Voyager 1: Plasma Wave Subsystem

- Wideband Receiver
- Emission frequency: 2.65 kHz to 3.11 kHz
- First event's plasma density: 0.055 cm^{-3}
- Radial distance: 122.6 AU
- Peak plasma density: 0.12 cm^{-3}



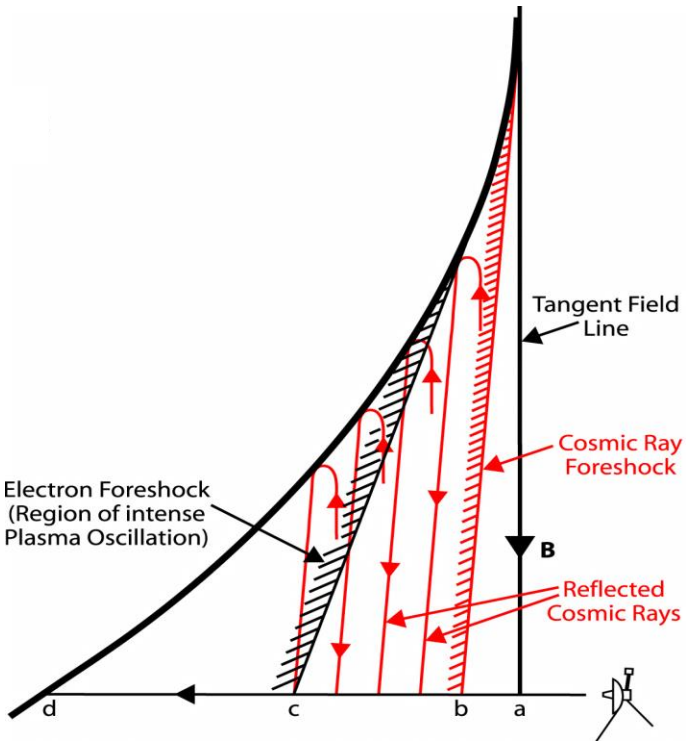


Gurnett & Kurth 2019, NatAst 3:1024

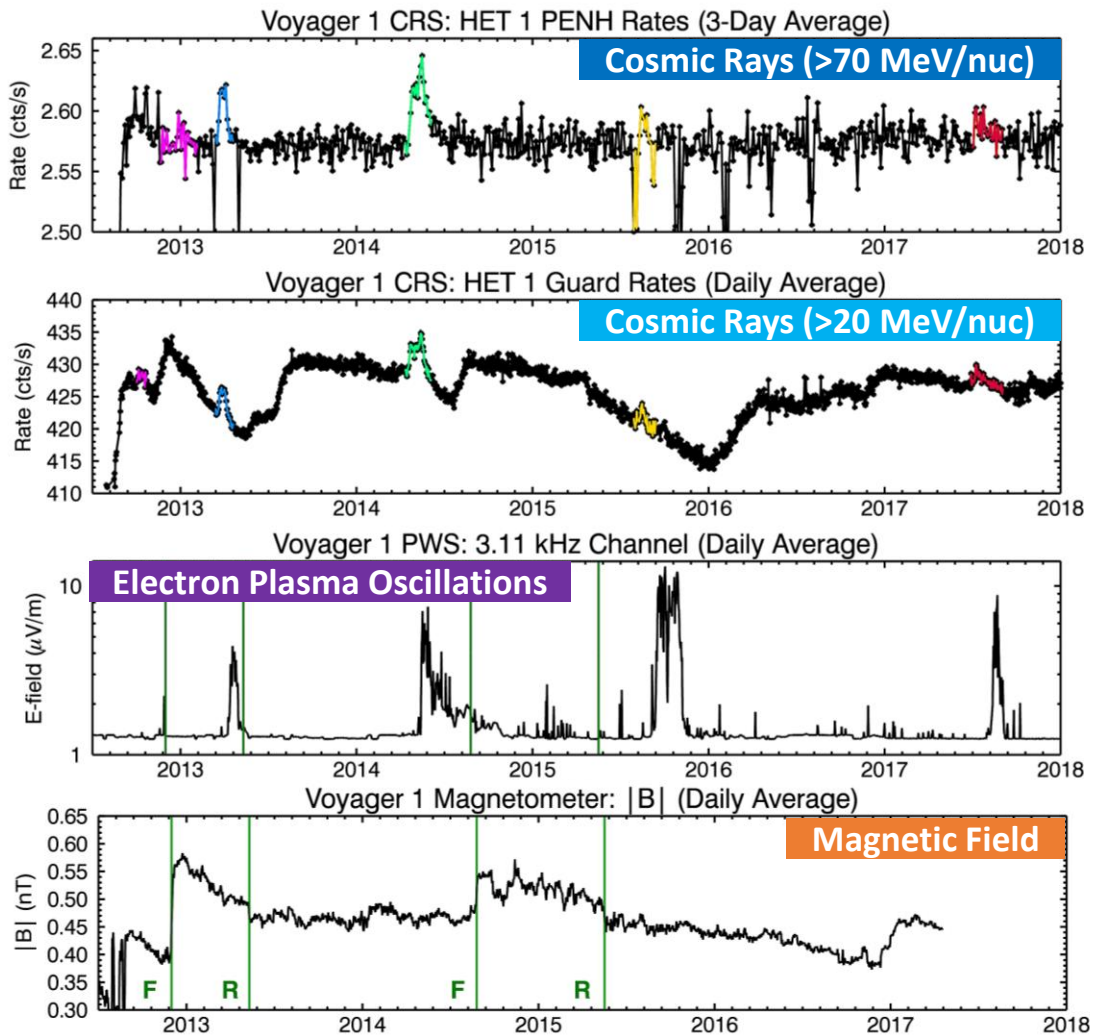
Voyager 2: Plasma Wave Subsystem

- 16-channel Spectrum analyzer
- Emission frequency: 1.78 kHz
- Plasma density: 0.039 cm^{-3}
- Radial distance: 119.7 AU

Interstellar Transients: Voyager 1



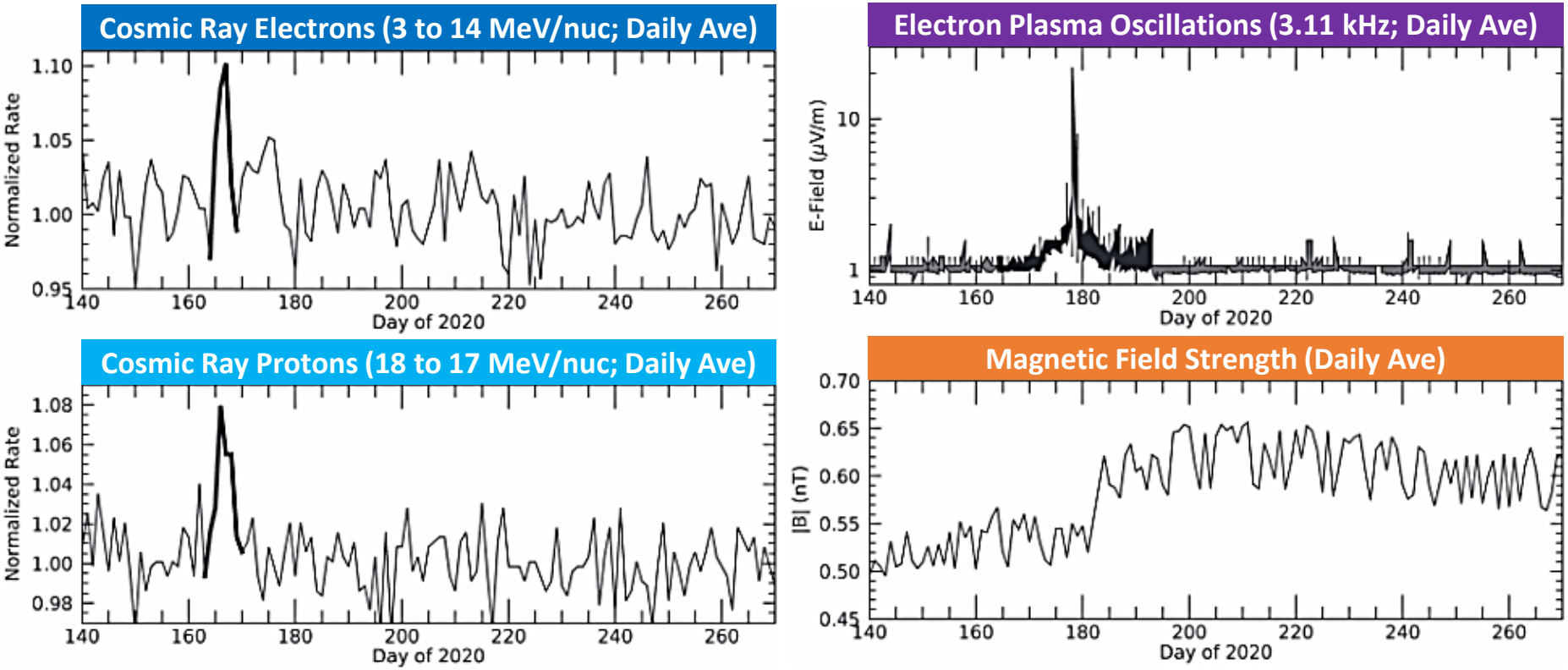
Gurnett et al. 2015, ApJ, 809:121



Rankin 2018, Caltech PhD Thesis (adapted)

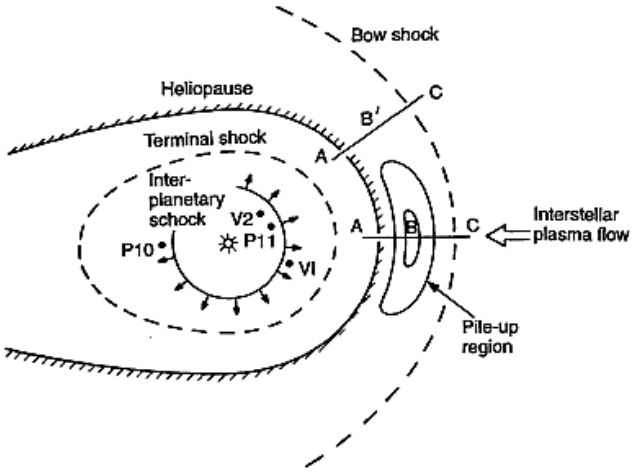
- Estimated energy of the electron beams: ~20-100 eV
  - *Gurnett et al. 2021, ApJ 161:11*
  - Derived from relative timing of cosmic rays and plasma oscillations

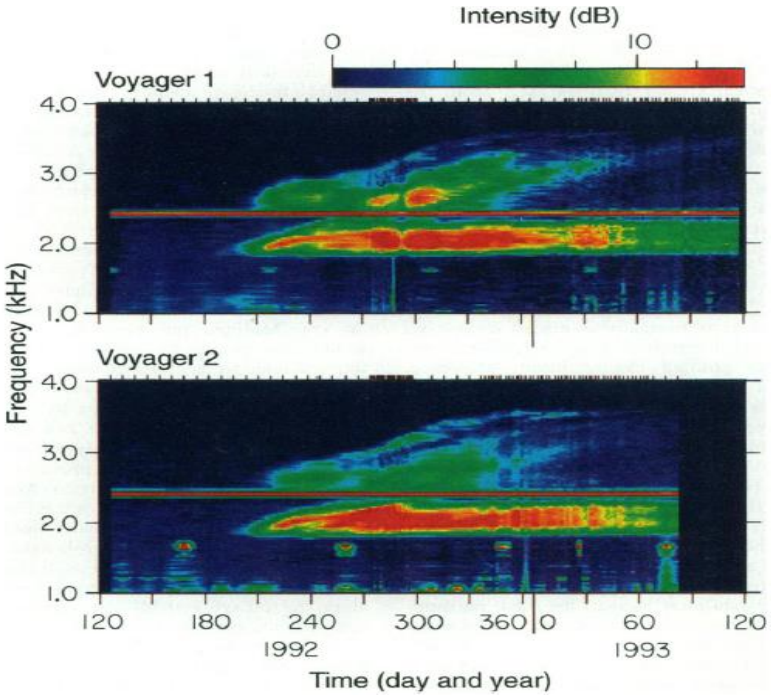
Interstellar Transients: Voyager 2



Burlaga et al. 2022, ApJ, 932:59

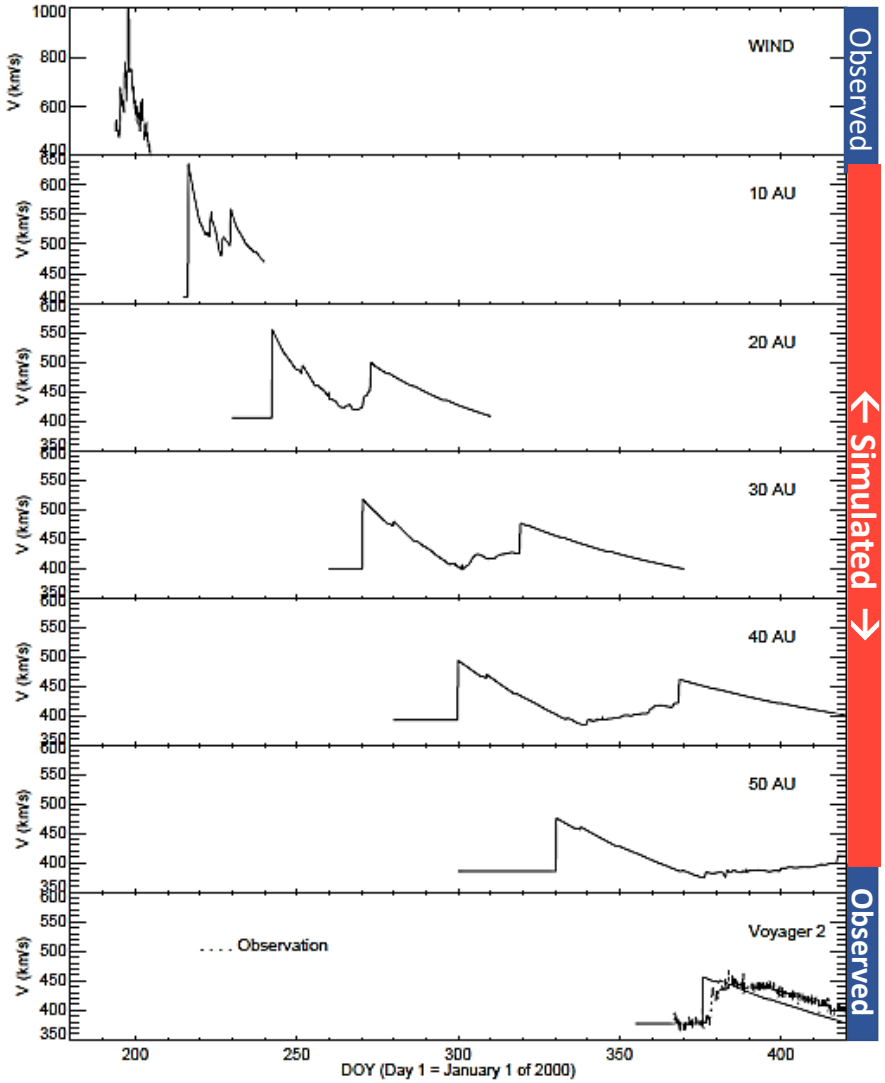
Transients through the Heliosphere





Gurnett et al. 1993, Science, 262:5131

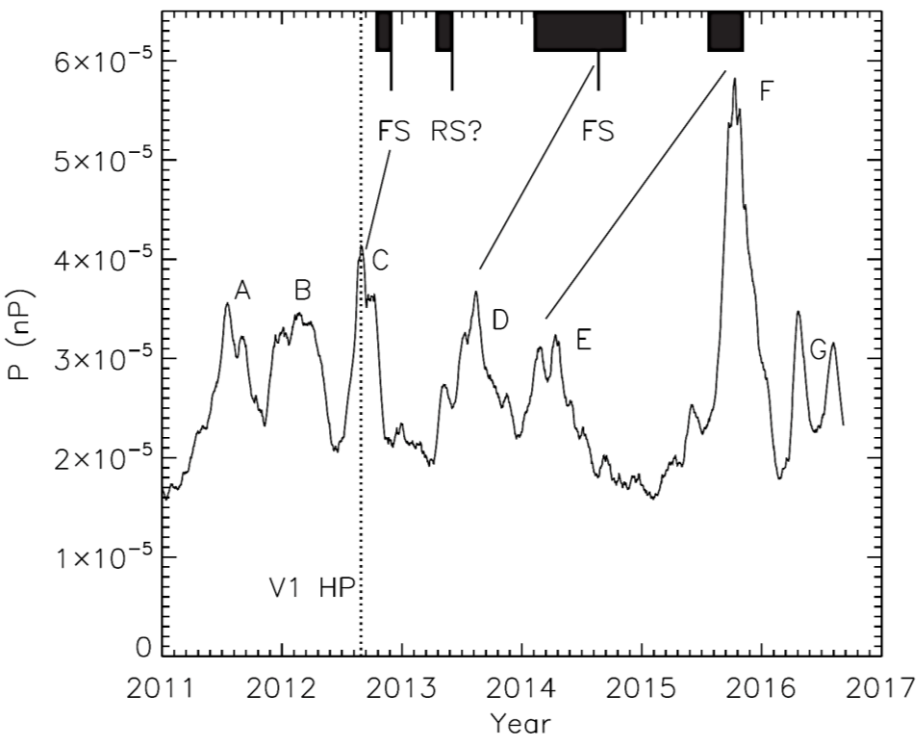
Evolution of Interaction Regions from 1 to 60 AU



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

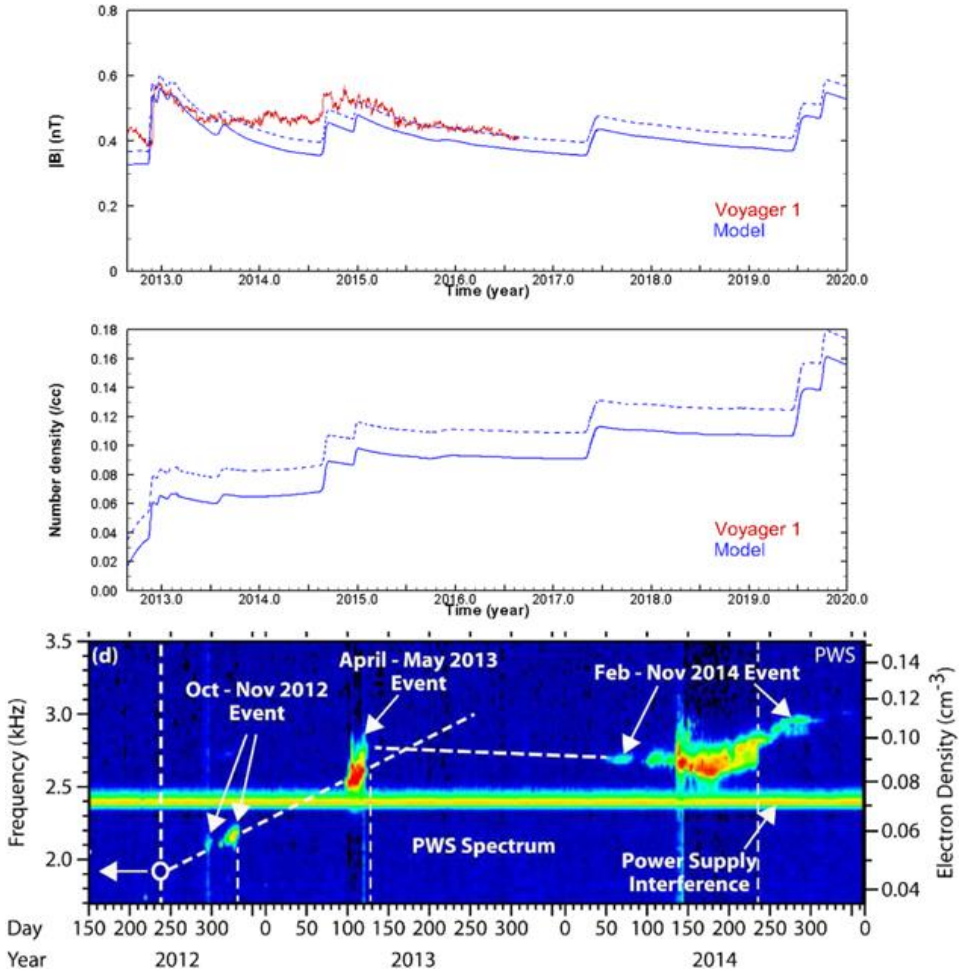
Heliosheath → Very Local Interstellar Medium

Heliosheath: Voyager 2 Plasma Pressure Pulses



Richardson et al. 2017, ApJ 834:190

Solar Transients: Data-Driven Model



Kim et al. 2017, ApJ 843:2

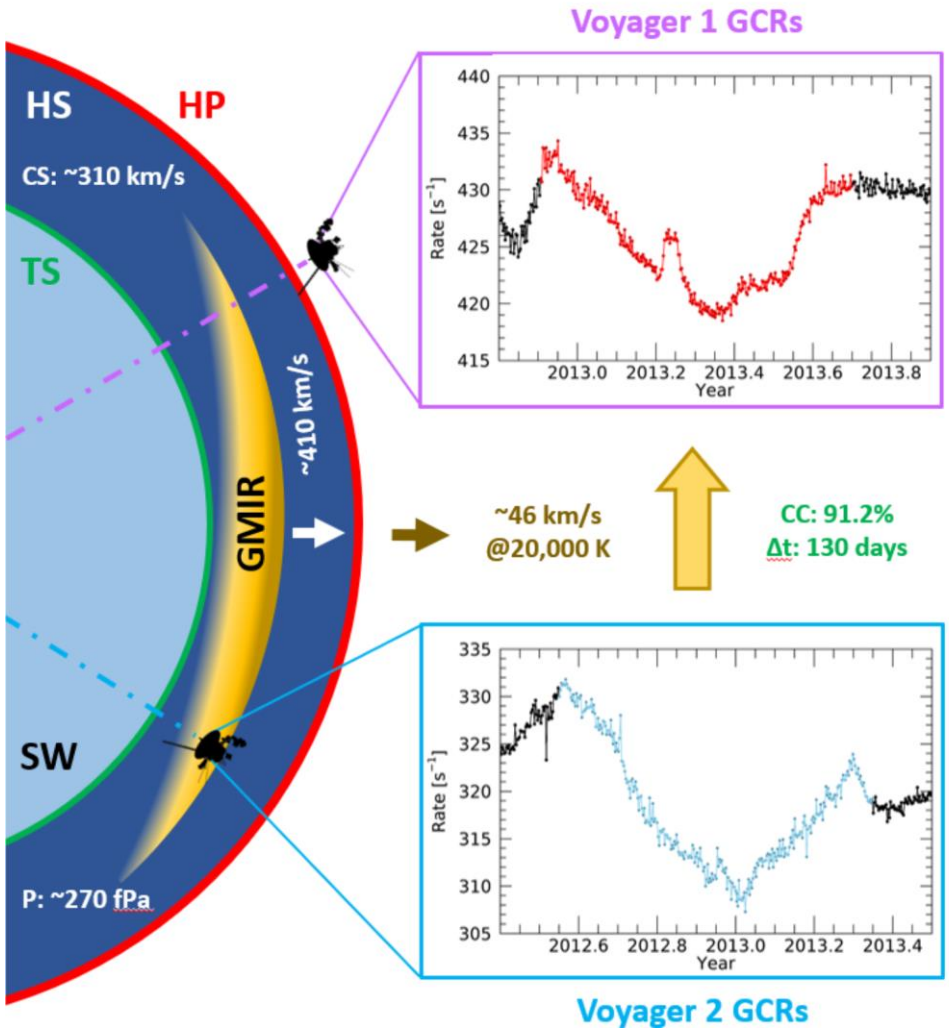
Voyager 2 → Voyager 1 GMIR

Heliosphere-VLISM Pressure Balance:

- key unknowns
  - interstellar temperature & heliosheath pressure
- $P_{Total} \sim 270$ fpa (T = 20,000 K)
  - Magnetic, thermal, dynamic: ~15%
  - IBEX PUI: ~45%
  - ACR/GCR: ~22%
  - Remaining: ~18%
- $P_{Total} \sim 242$ fpa (T = 40,000 K)
  - Voyager 2 VLISM Temperature

Heliosheath sound speed:

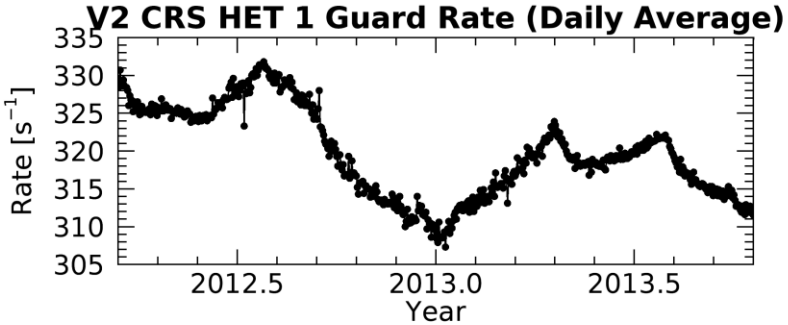
- $C_{HS} = 314 \pm 32$ km s^{-1}
  - T = 20,000 K
- $C_{HS} = 299 \pm 31$ km s^{-1}
  - T = 40,000 K

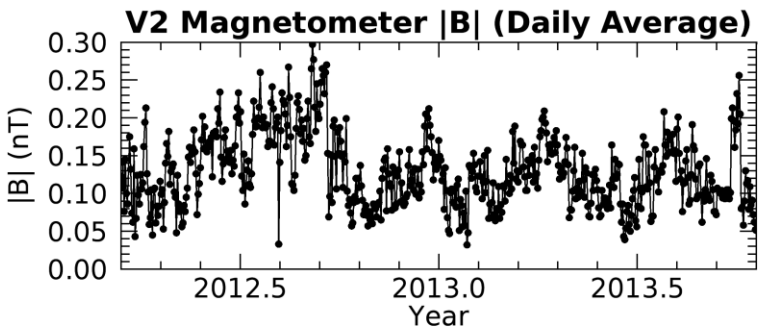


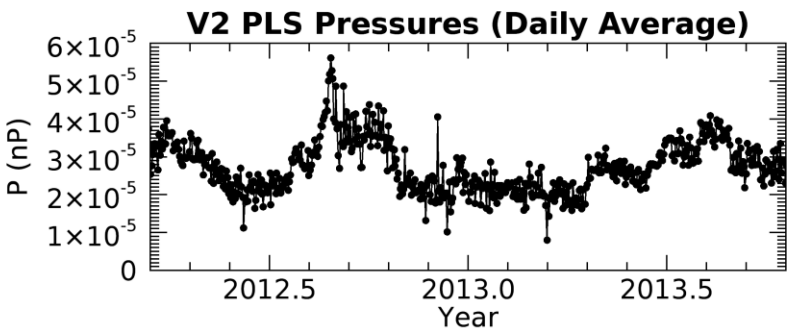
Rankin et al. 2019, ApJ 883:101

Transients in the Heliosheath vs. VLISM

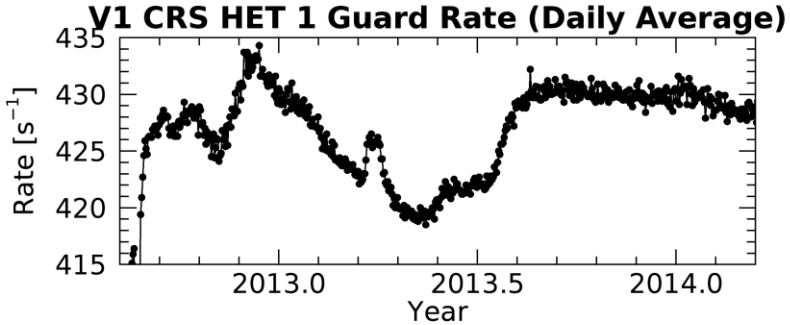
Voyager 2 (Heliosheath)

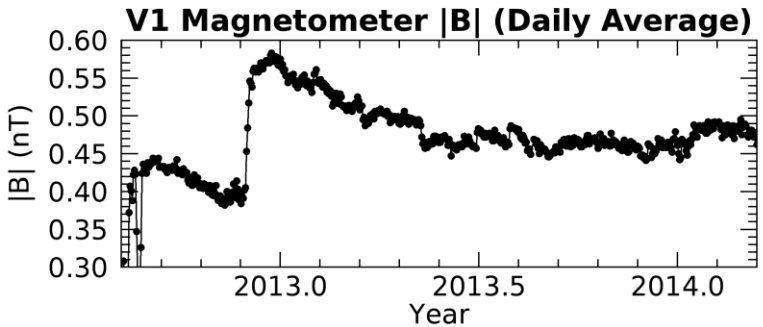


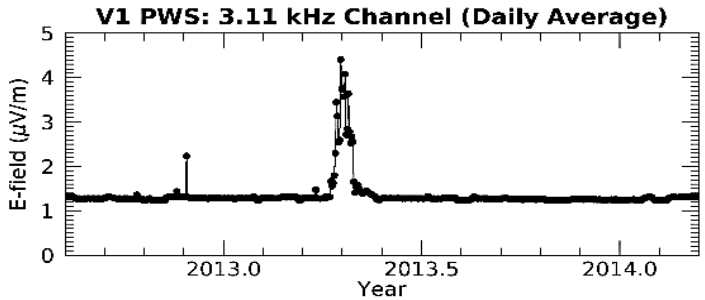




Voyager 1 (VLISM)



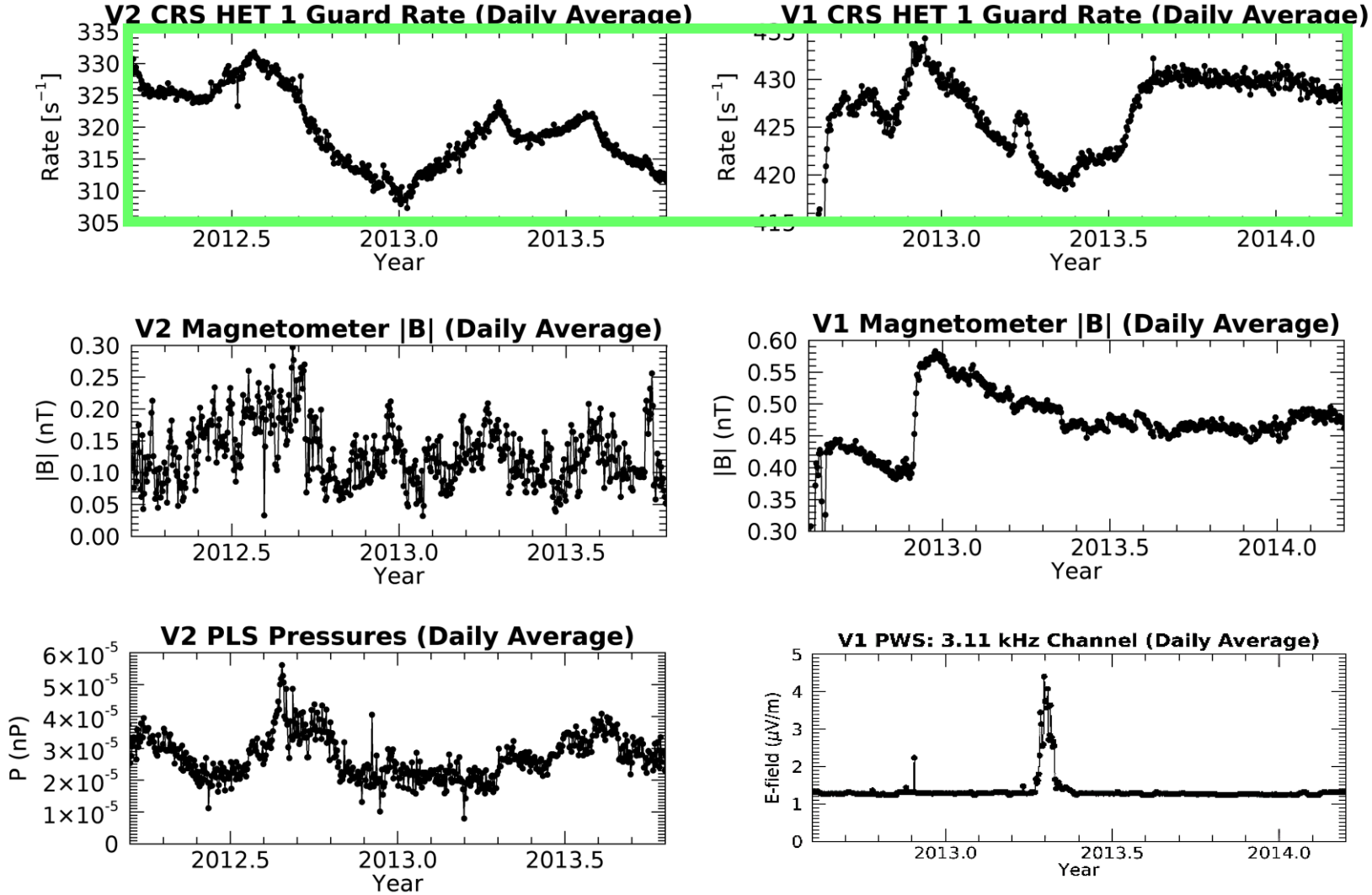




Rankin et al. 2019, ApJ 883:101

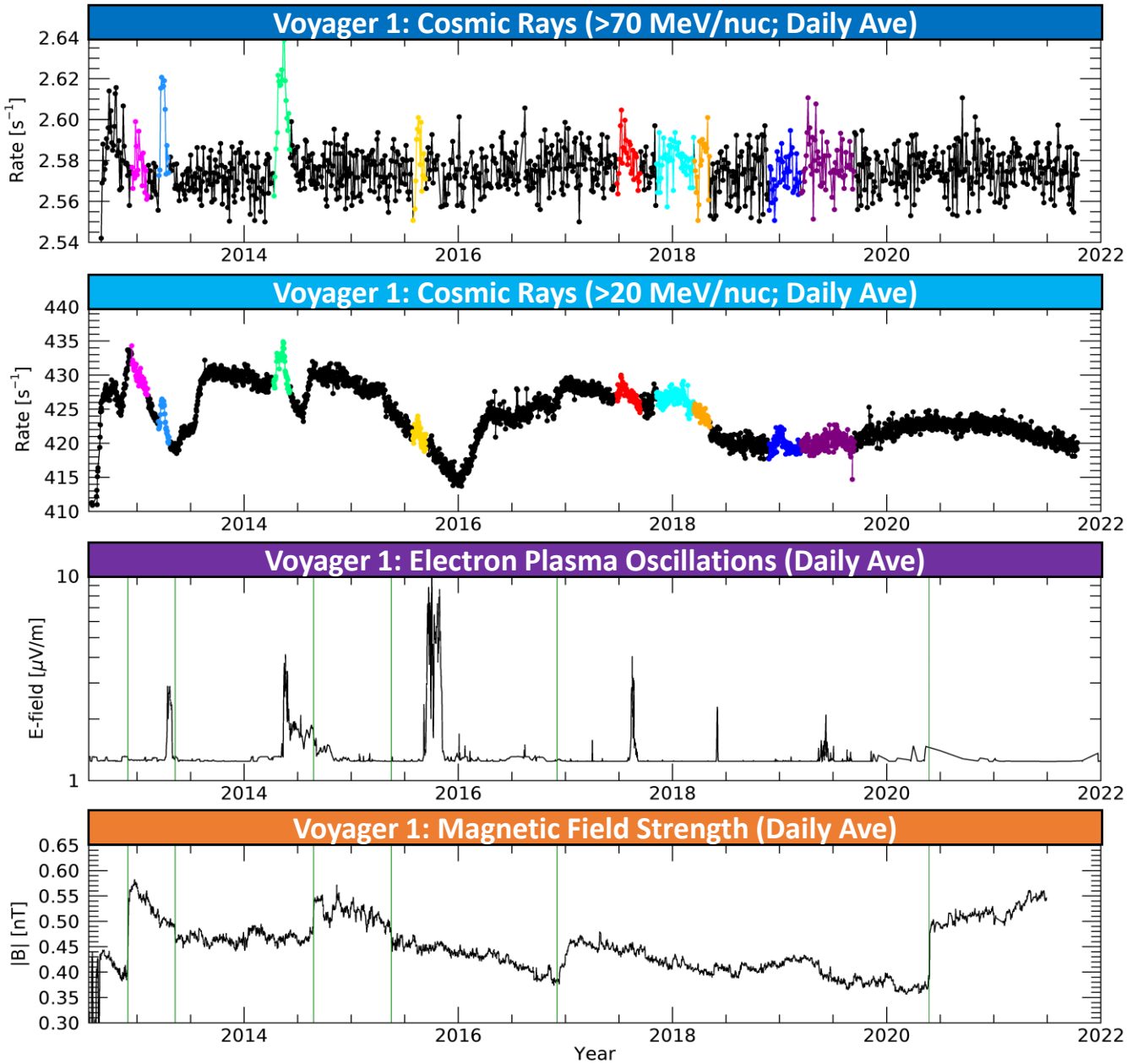
Transients in the Heliosheath vs. VLISM

Voyager 2 (Heliosheath) | **Voyager 1 (VLISM)**



Rankin et al. 2019, ApJ 883:101

A New, Exciting Regime



Summary & Takeaways

- Nearly a decade of remarkable measurements of Galactic Cosmic Rays made by both Voyager space probes in the Very Local Interstellar Medium
  - 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? → 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?

Rich data set, new plasma regime; cosmic ray experts welcome! *jsrankin@princeton.edu*