Beyond the Heliosphere: Surprising Findings from the Voyagers’ Journeys

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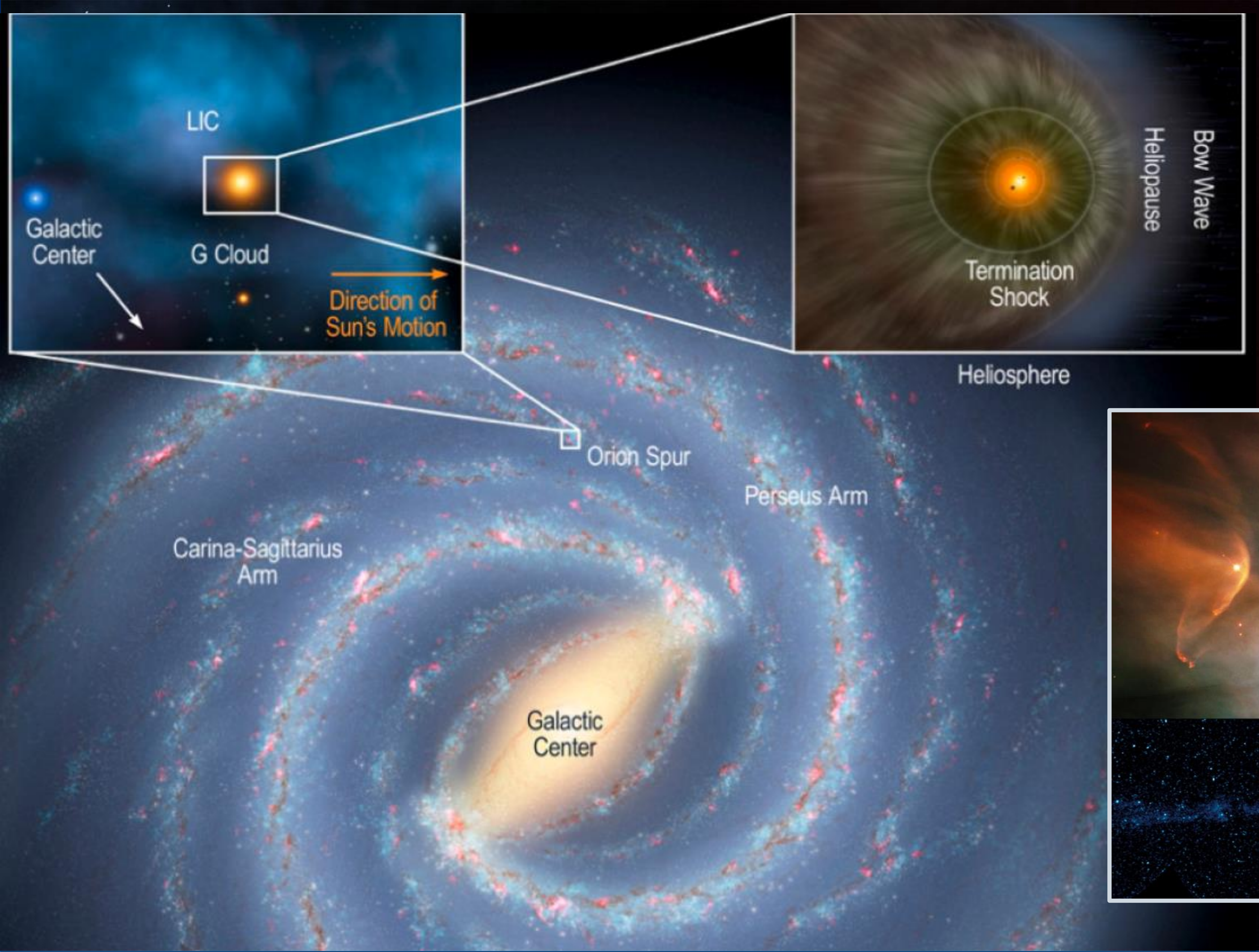
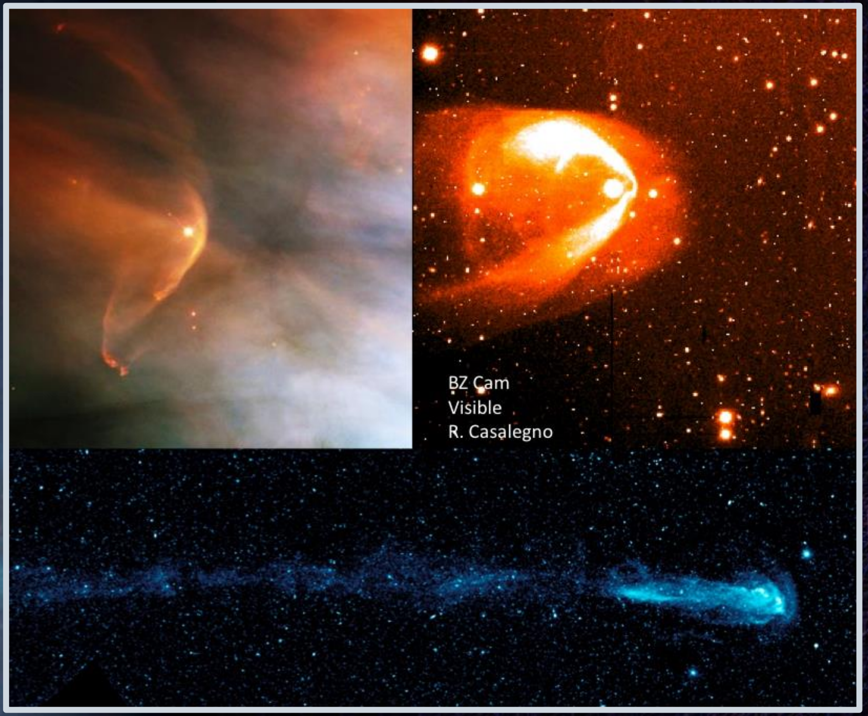
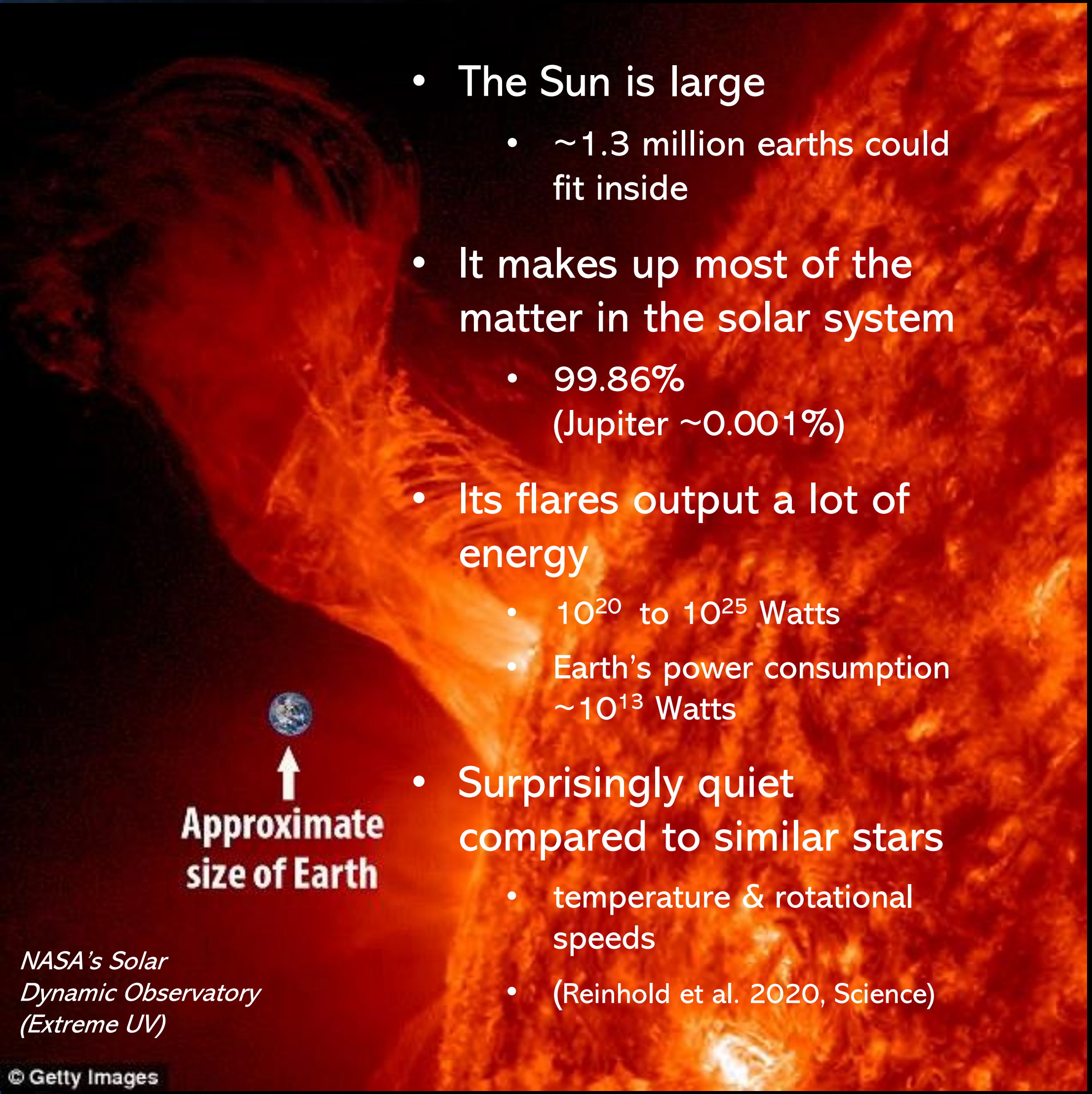
Deputy Project Scientist, Voyager Insterstellar Mission

NASA Heliophysics Education Cummunity Meeting
(Tuesday, April 1, 2025)


LIC
Galactic Center
G Cloud
Direction of Sun's Motion
Bow Wave
Heliopause
Termination Shock
Heliosphere
Orion Spur
Perseus Arm
Carina-Sagittarius Arm
Galactic Center

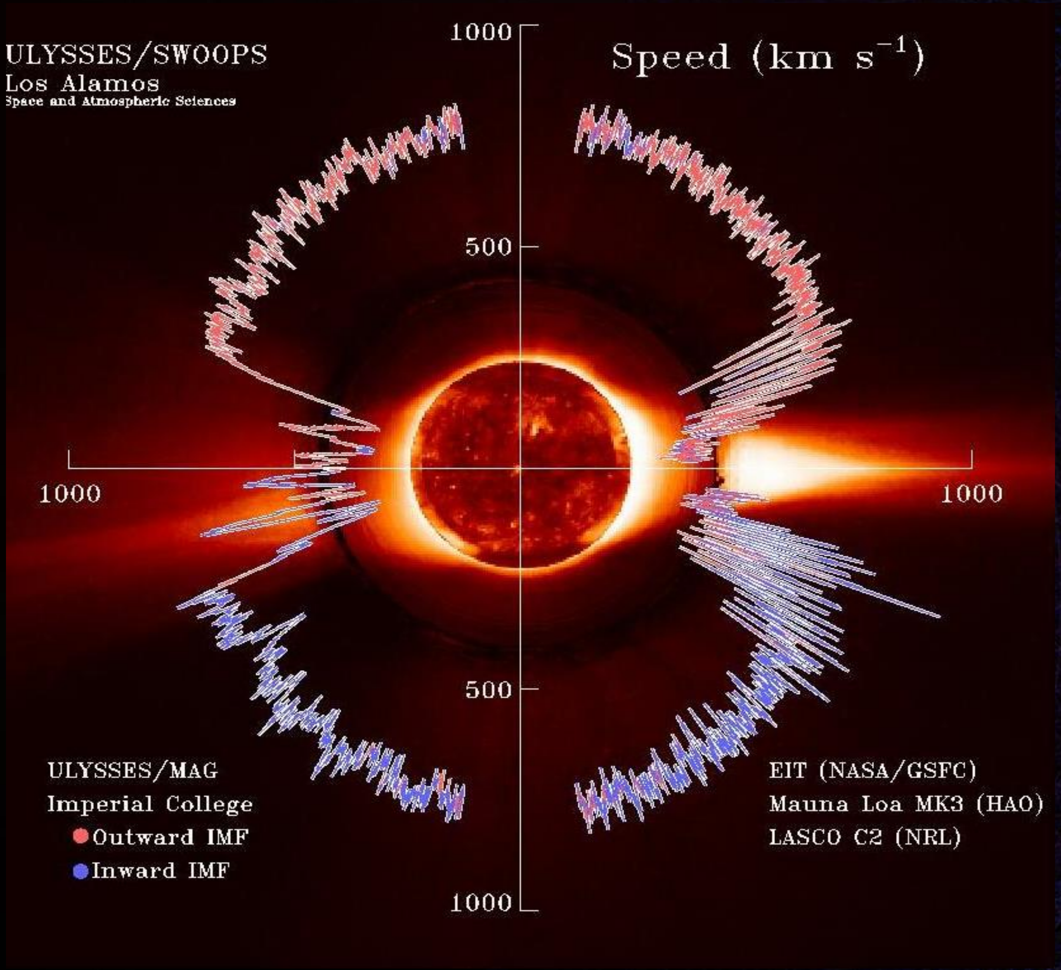

BZ Cam
Visible
R. Casalegno

Our Star…



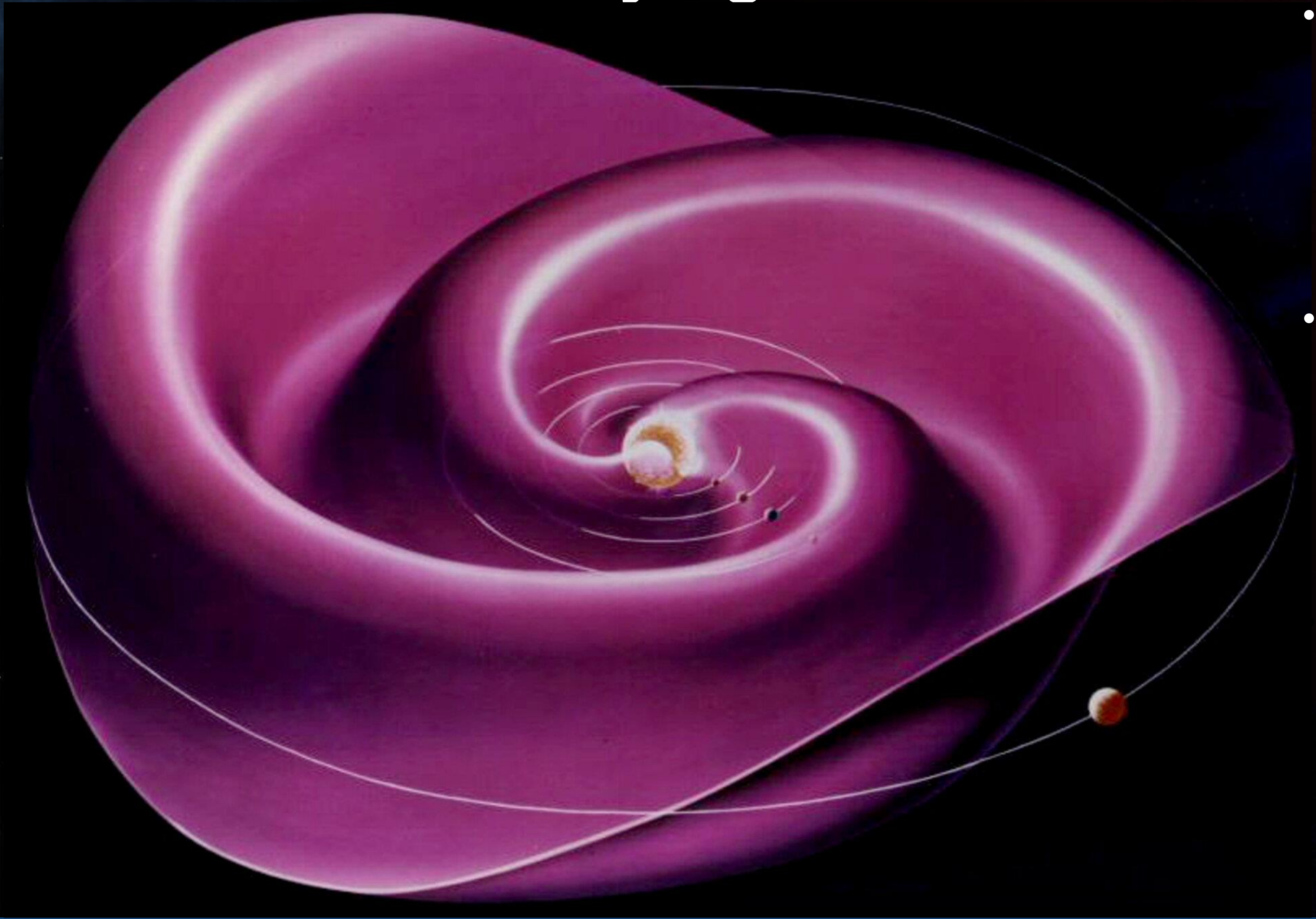
- The Sun is large
  - ~1.3 million earths could fit inside
- It makes up most of the matter in the solar system
  - 99.86%
    (Jupiter ~0.001%)
- Its flares output a lot of energy
  - 10^{20} to 10^{25} Watts
  - Earth's power consumption ~10^{13} Watts
- Surprisingly quiet compared to similar stars
  - temperature & rotational speeds
  - (Reinhold et al. 2020, Science)

NASA's Solar Dynamic Observatory (Extreme UV)



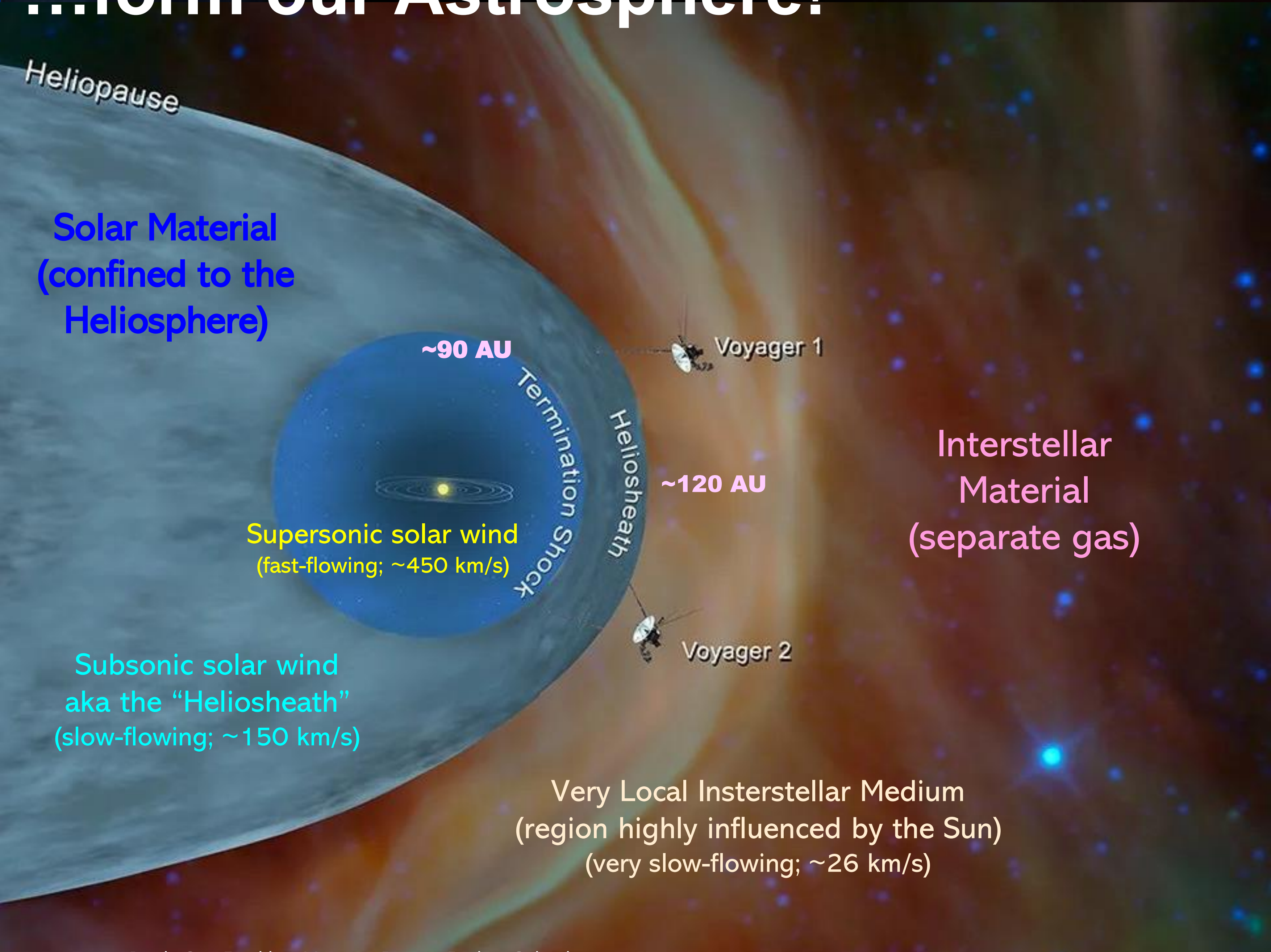
- Sun heated from thousand of deg. at the surface to millions of deg. in the corona *(within ~2000 km; century-old puzzle)*
- Charged stream of particles escapes the Sun's gravity and forms a supersonic wind *(within few solar radii; big mystery)*

…and its time-varying solar wind…



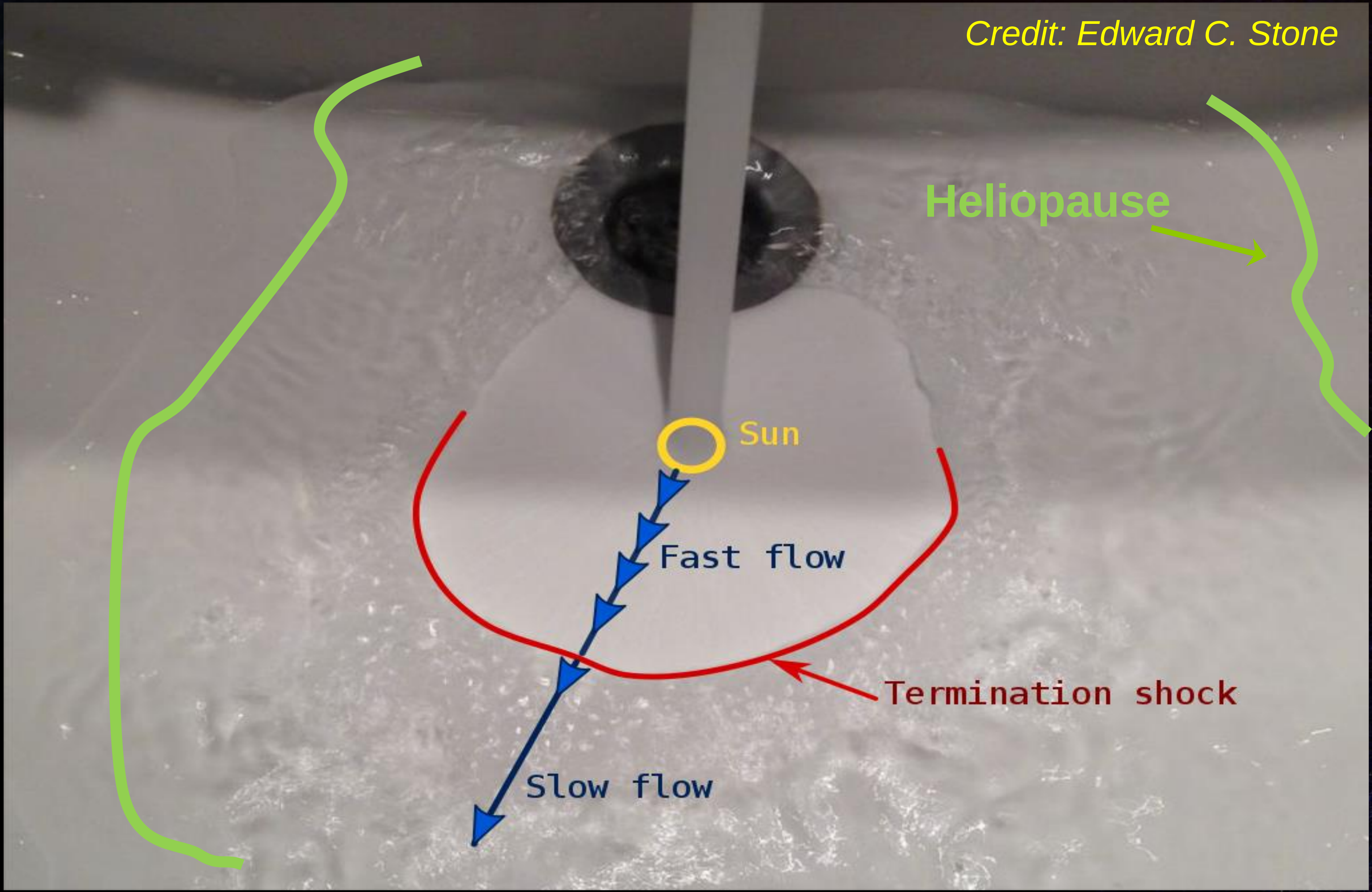
- The Sun’s rotation twists the magnetic field & its plasma into an Archimedean spiral *(Parker Spiral)*
- These winds expand outward supersonically until they lose energy & become subsonic *(Termination shock)*

…form our Astrosphere!



- The Sun's rotation twists the magnetic field & its plasma into an Archimedean spiral *(Parker Spiral)*
- These winds expand outward supersonically until they lose energy & become subsonic *(Termination shock)*
- The solar winds eventually achieve a pressure balance with the surrounding interstellar medium *(Heliopause)*

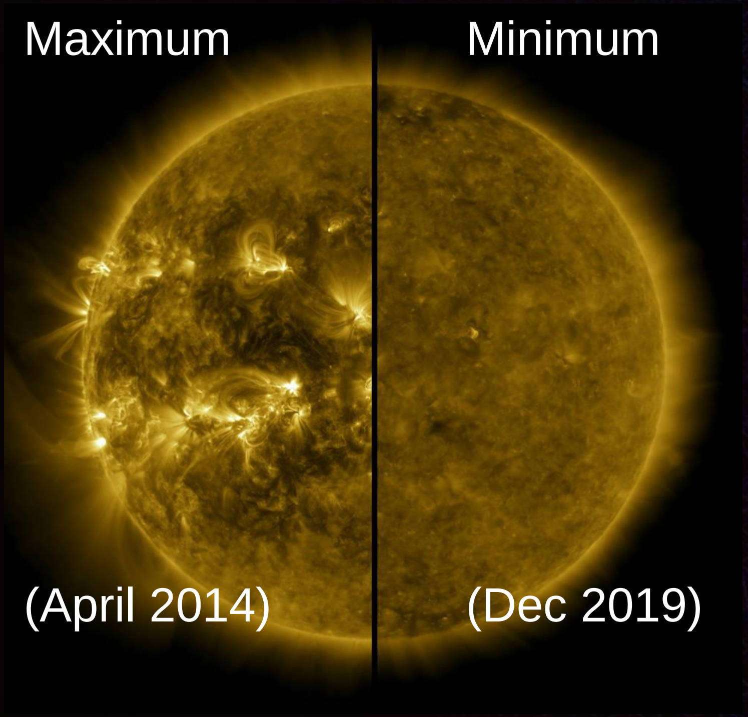
The Heliosphere…In Your Kitchen Sink!



Solar Cycle Weather Patterns from the Sun

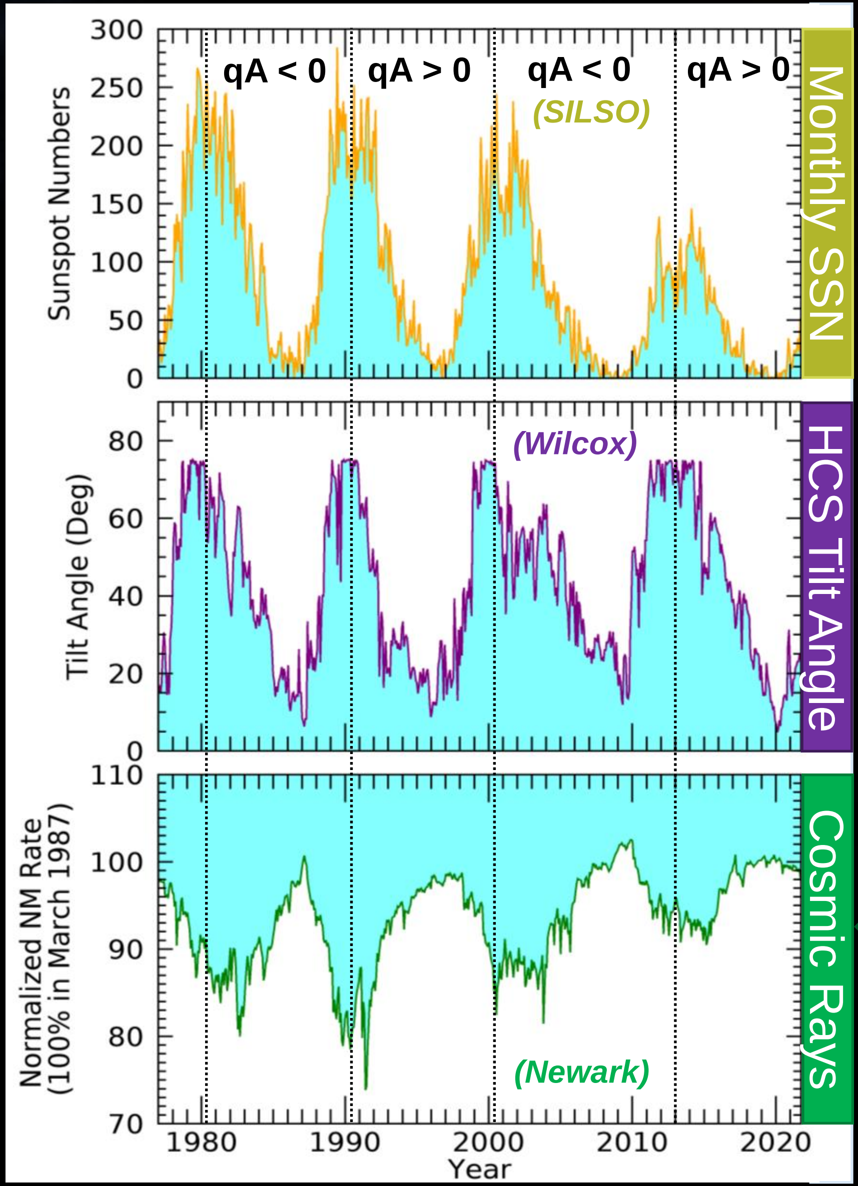
- 11-year solar activity pattern on the Sun → magnetically driven!
- The magnetic field goes from highly ordered to disordered during the 11-year solar cycle
  - solar min → ordered
  - solar max → disordered
- The fields on the Sun also undergo polarity reversal every 22 years.
- qA > 0 (positive) and qA < 0 (negative)
  - q = charge, A = solar magnetic field
  - A = negative when the magnetic axis is aligned with the Sun's rotation axis
- The polarity reversal significantly impacts particle transport (drifts)

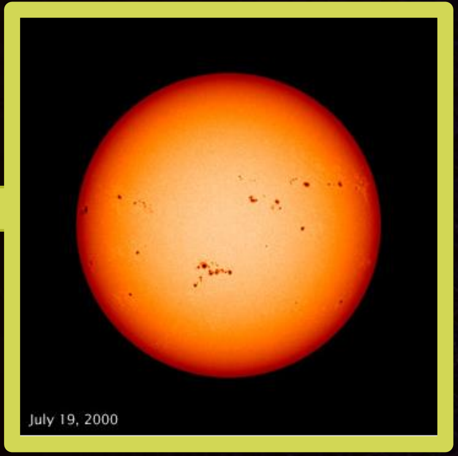
https://www.nasa.gov/press-release/solar-cycle-25-is-here-nasa-noaa-scientists-explain-what-that-means

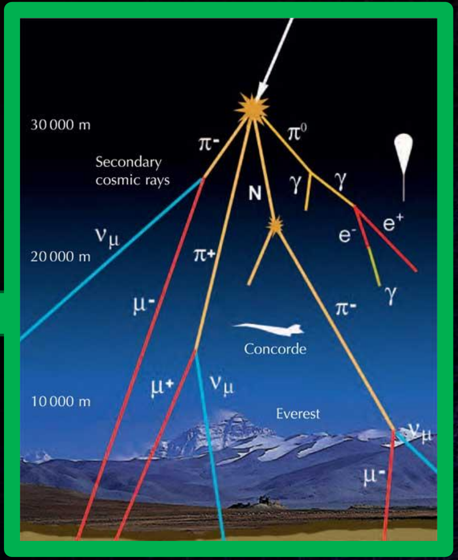


https://www.forbes.com/sites/jamiecartereurope/2020/06/09/sherpas-unravel-secrets-of-the-suns-mysterious-corona-from-the-last-total-solar-eclipse/?sh=2eca920d2f89

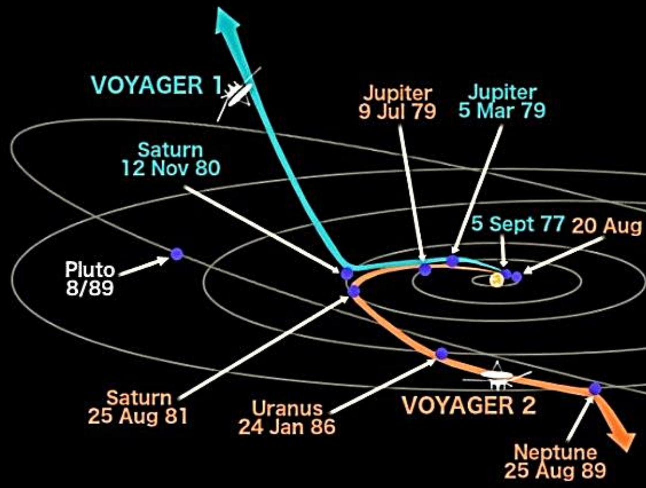
Sun-Modified Measurements of Galactic Materials







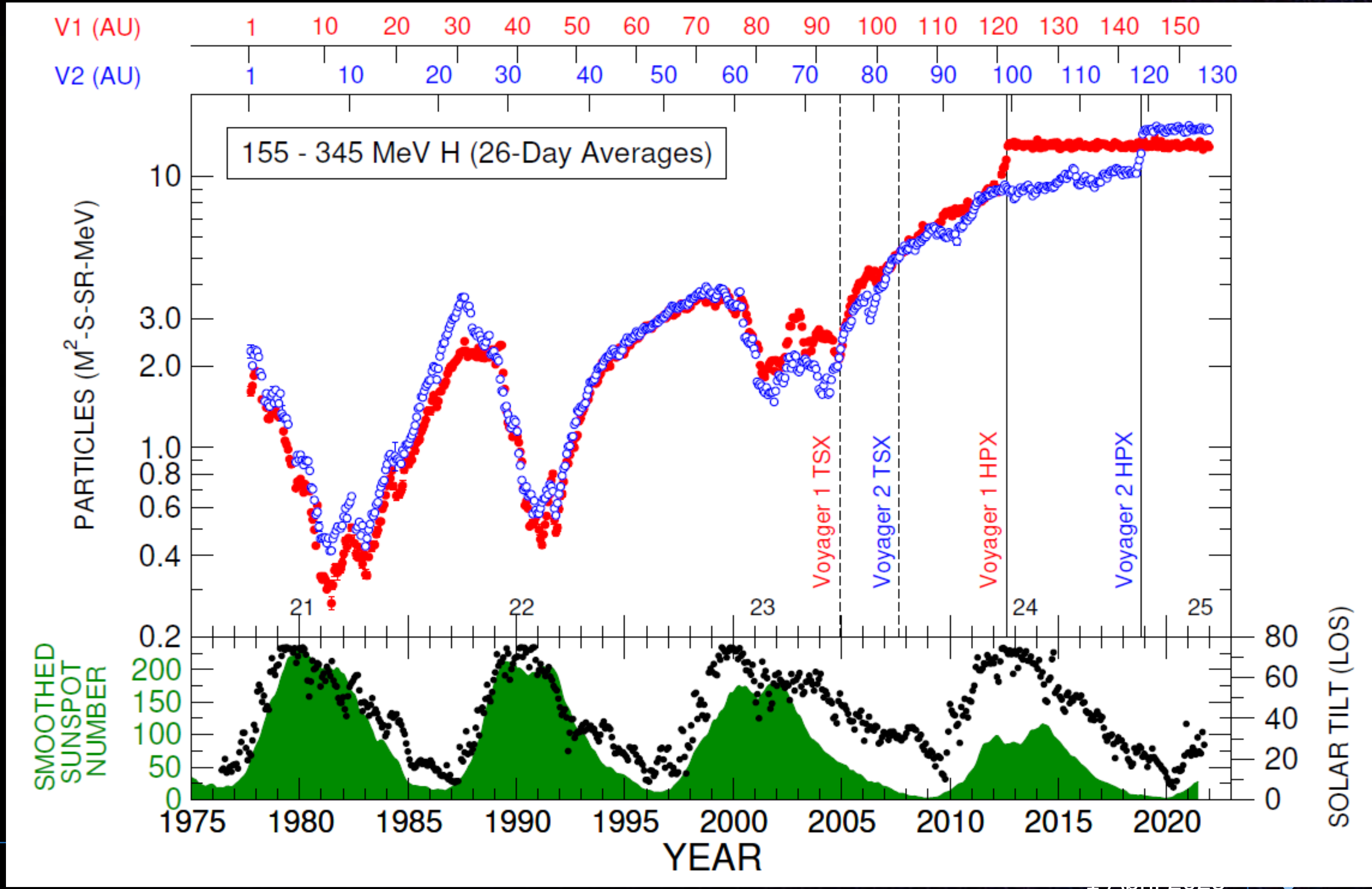
Voyagers' Journey through the Heliosphere



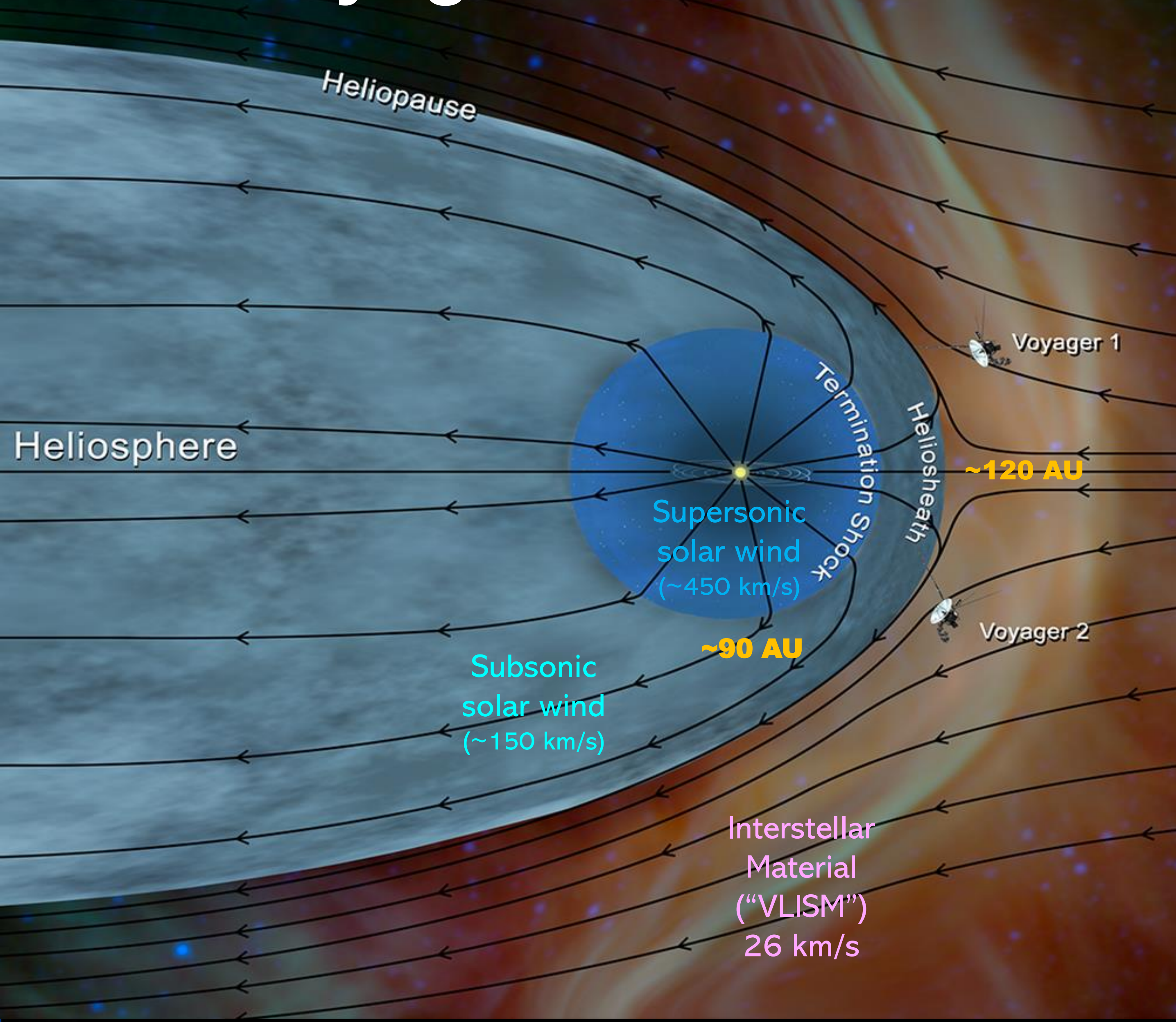
1977: Launch:

- Voyager 2 (August)
- Voyager 1 (September)

- 1989: Last planetary encounter
  - Voyager 2 @ Neptune
- 1990: Last image
  - "Solar System Family Portrait" by Voyager 1
- 2012: Voyager 1 exited the Heliosphere
- 2018: Voyager 2 joined its twin

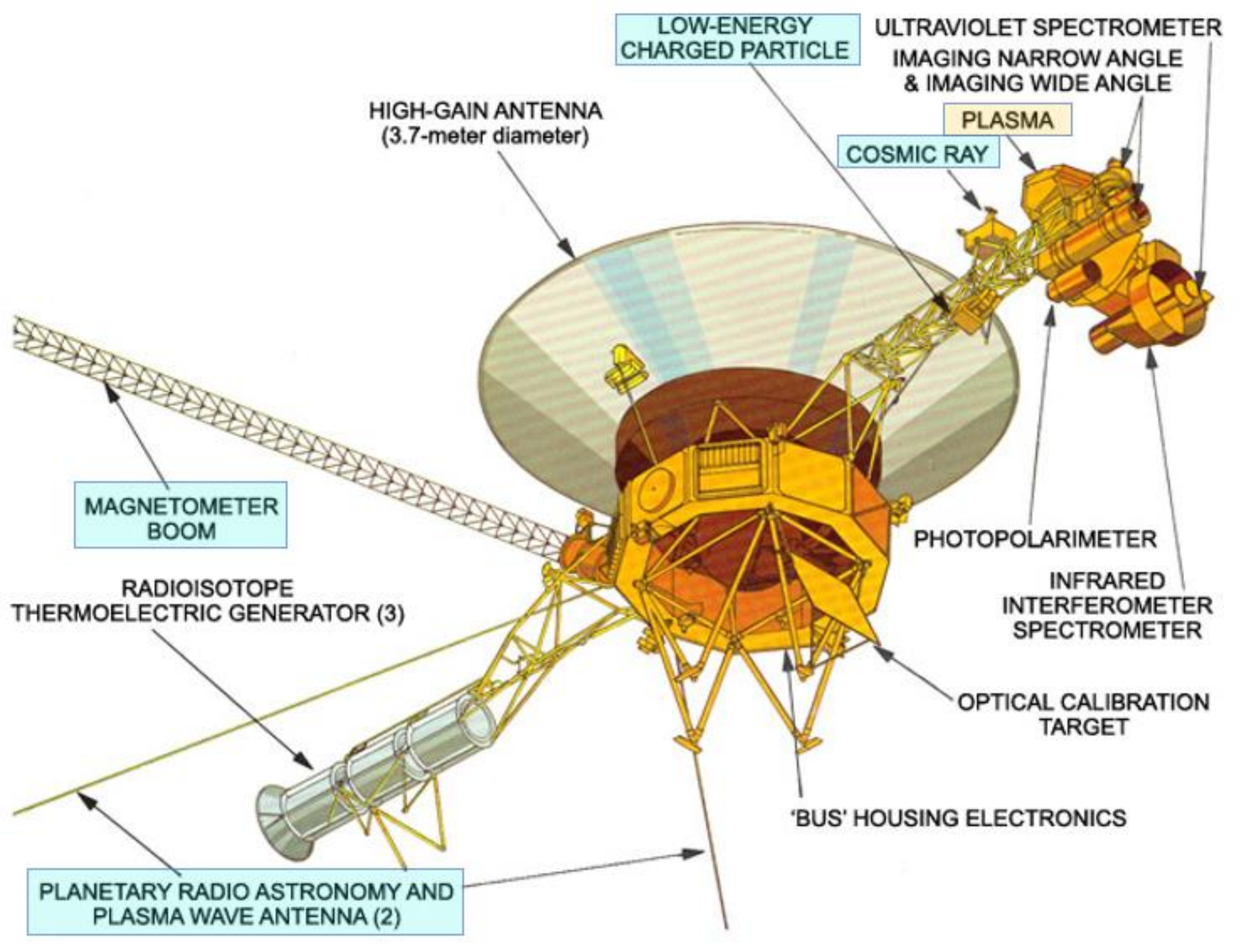


The Voyager Interstellar Mission



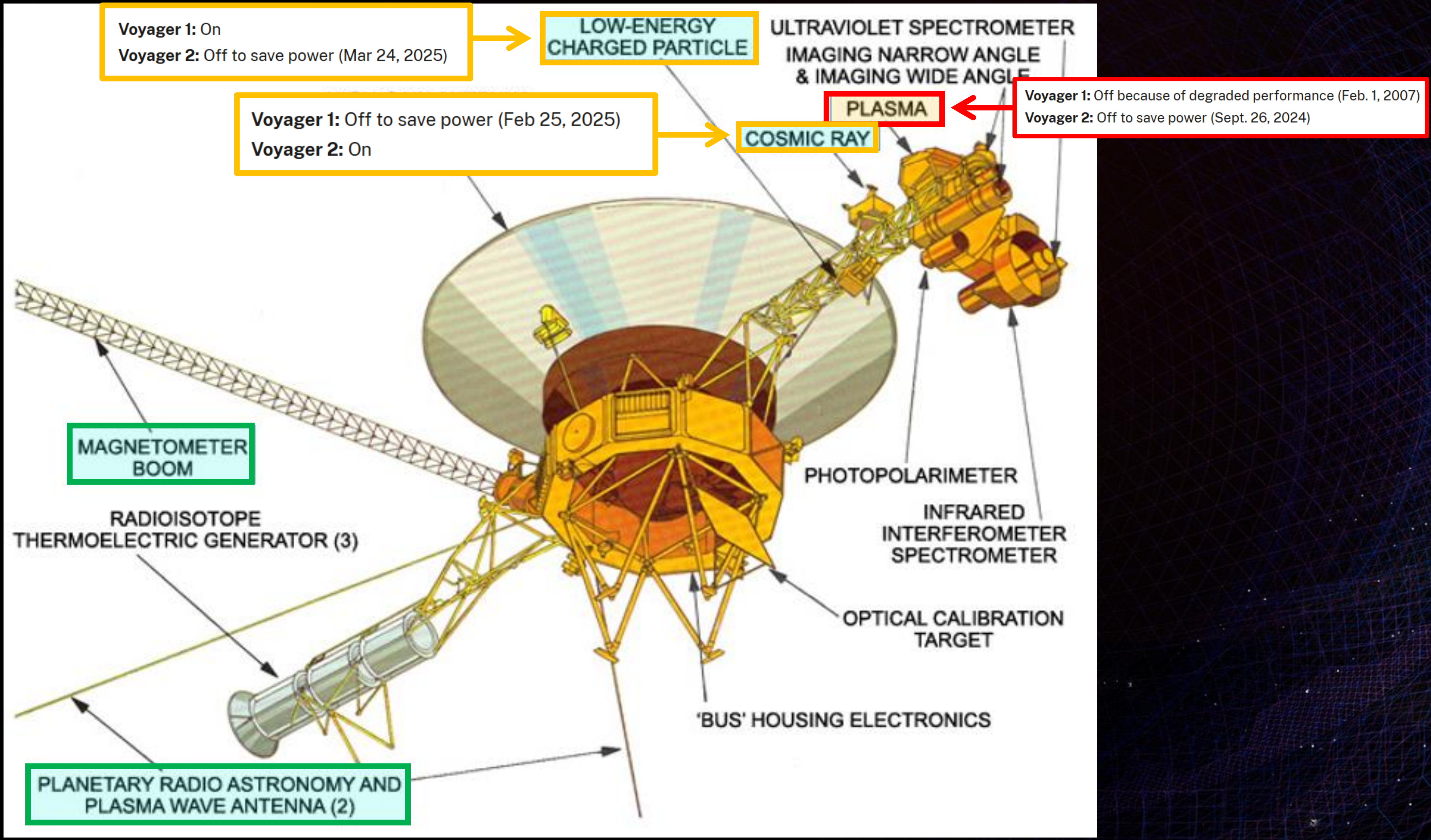
- **Voyager 1:** (now @ ~160 AU; 22 light hrs)
  - August 25, 2012 @ ~122 AU
  - Magnetic field strength: ~0.46 nT
  - Plasma density: ~0.055 cm^{-3}
  - Temperature: ~25,000 K (modeled)
- **Voyager 2**: (now @ ~133 AU; 18.5 light hrs)
  - November 5th, 2019 @ ~119 AU
  - Magnetic field strength: ~0.68 nT
  - Plasma density: ~0.039 cm^{-3}
  - Temperature ~40,000 K (measured)

Voyager Measurement Capabilities



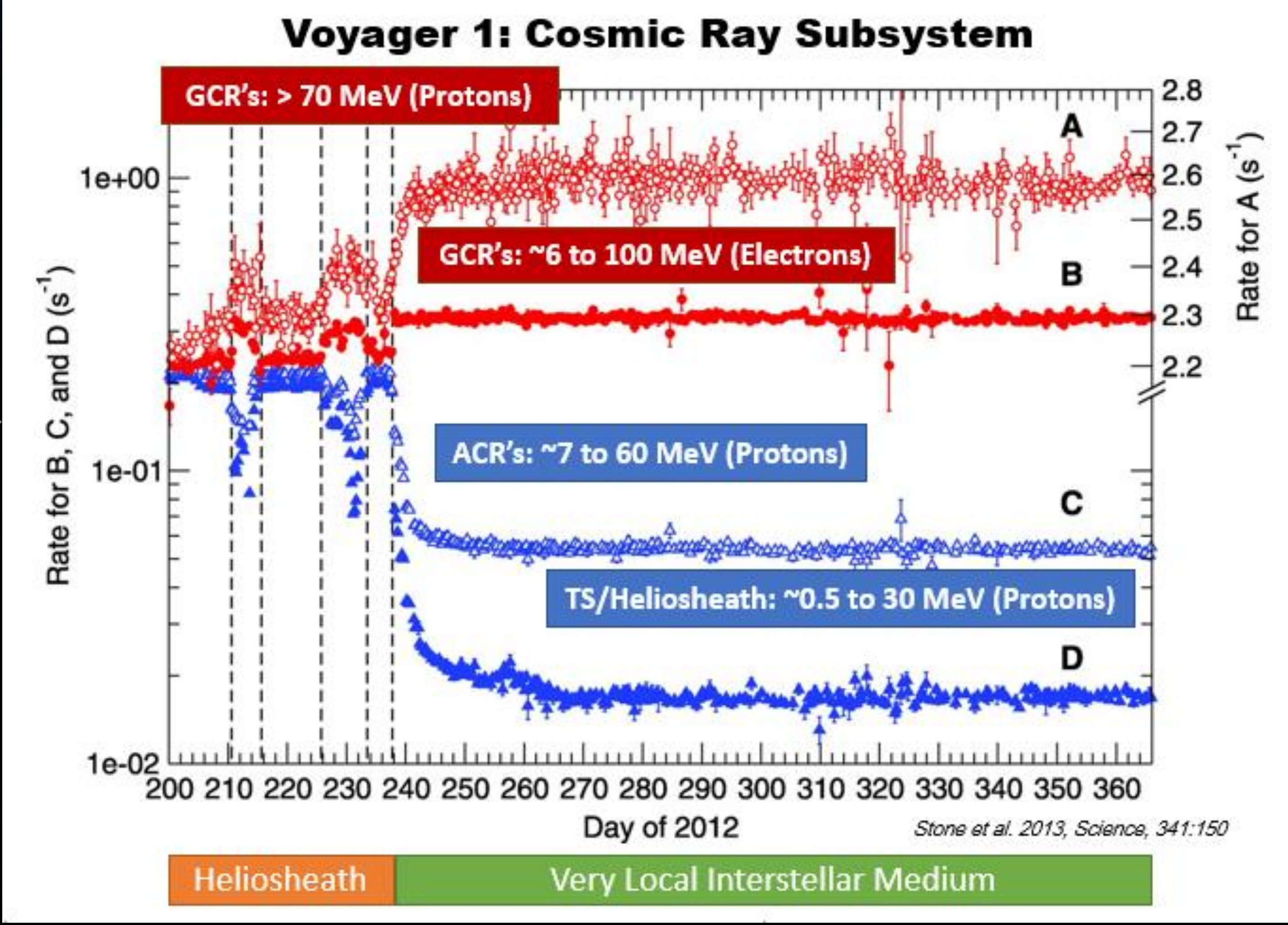
http://voyager.jpl.nasa.gov/spacecraft/instruments.html

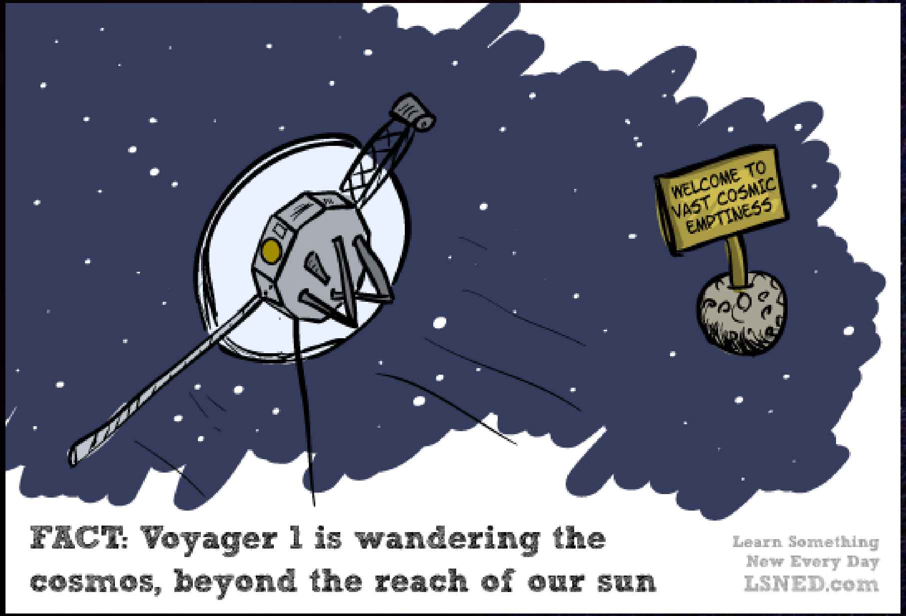
Voyager Measurement Capabilities



https://science.nasa.gov/mission/voyager/spacecraft/

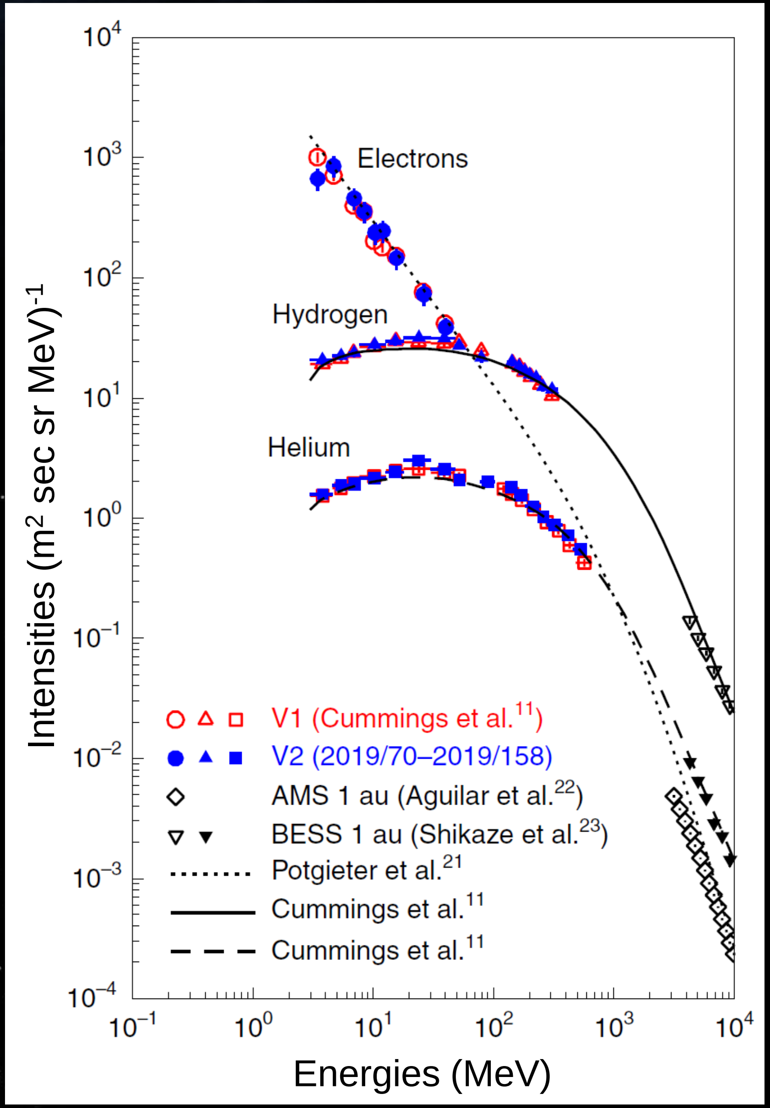
Welcome to Interstellar Space!

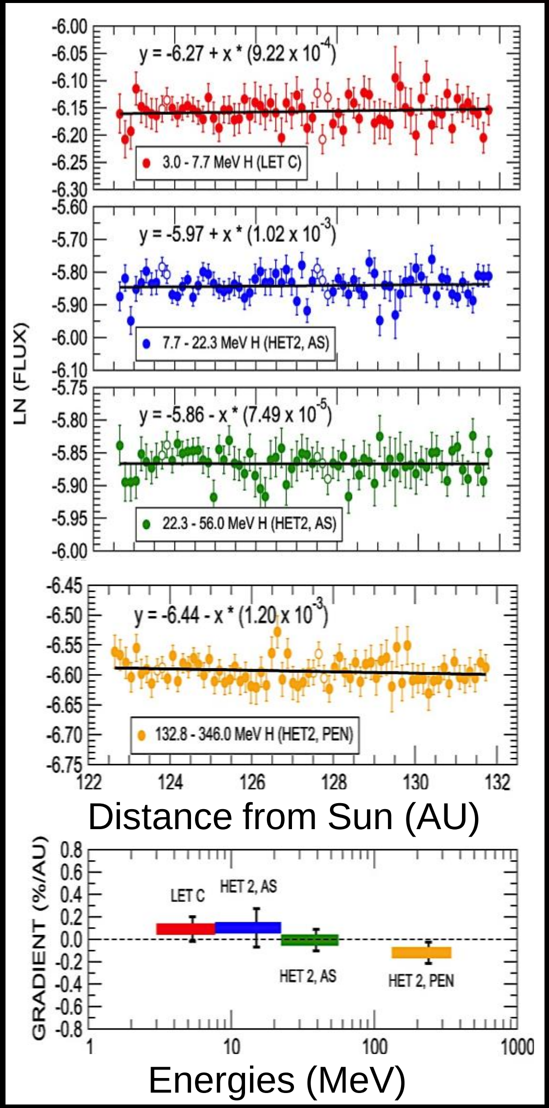


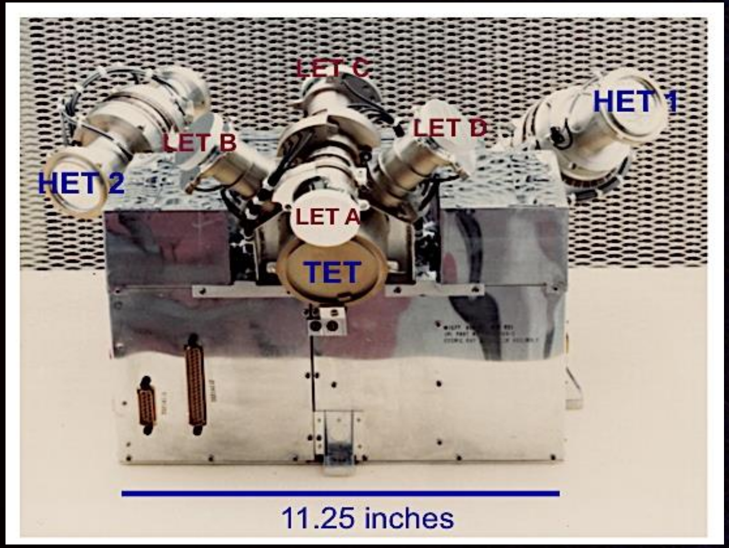


AKA: the "Very Local Interstellar Medium" (VLISM)

First Measurements of Cosmic Rays in Interstellar Space



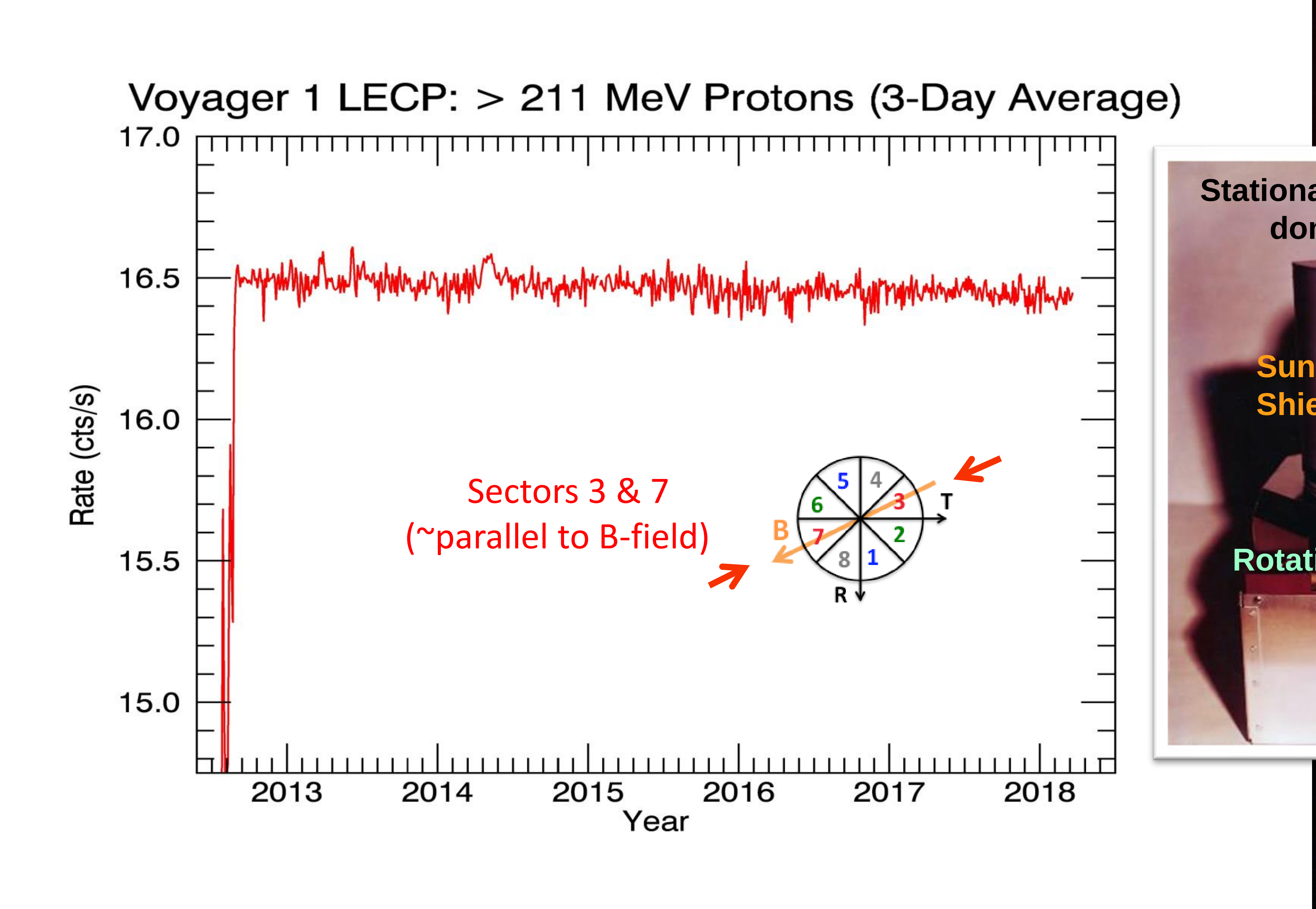




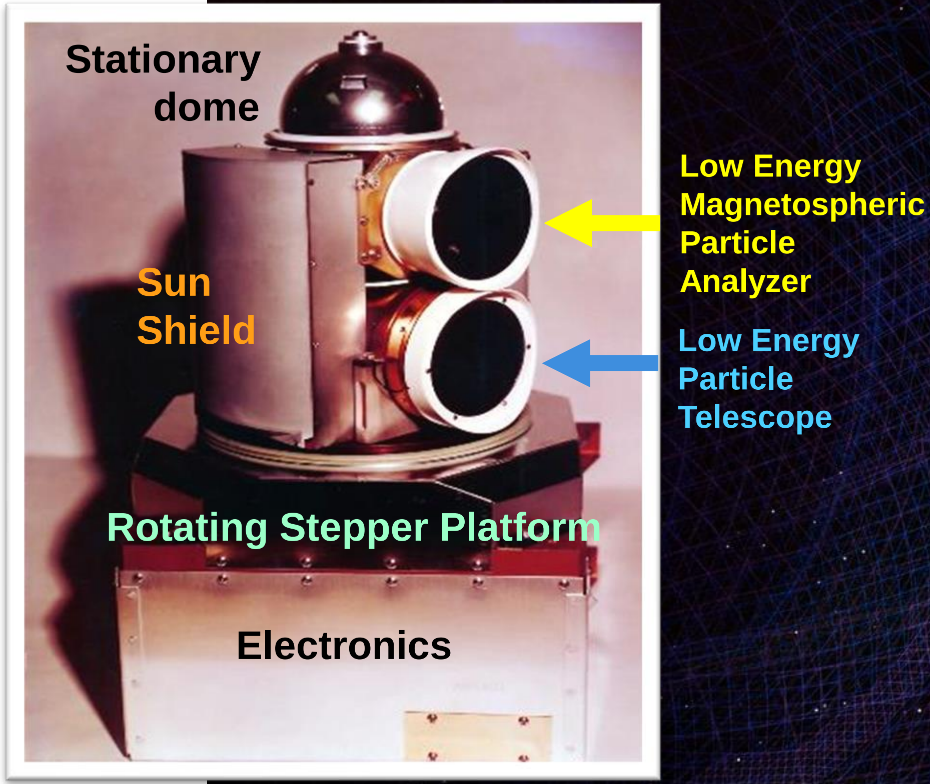
Courtesy of Voyager CRS Team

- Voyager Cosmic Ray Subsystem:
  - Protons through Nickel: ~3 to ~350 MeV
  - “electrons”: ~3 to ~75 MeV
- Lowest-energy Galactic Cosmic Rays ever observed!
- Unaffected by the Sun?
  - No clear changes over distance as Voyagers venture deeper into interstellar space
  - Both spacecraft are remarkably consistent!

First Measurements of Cosmic Rays in Interstellar Space

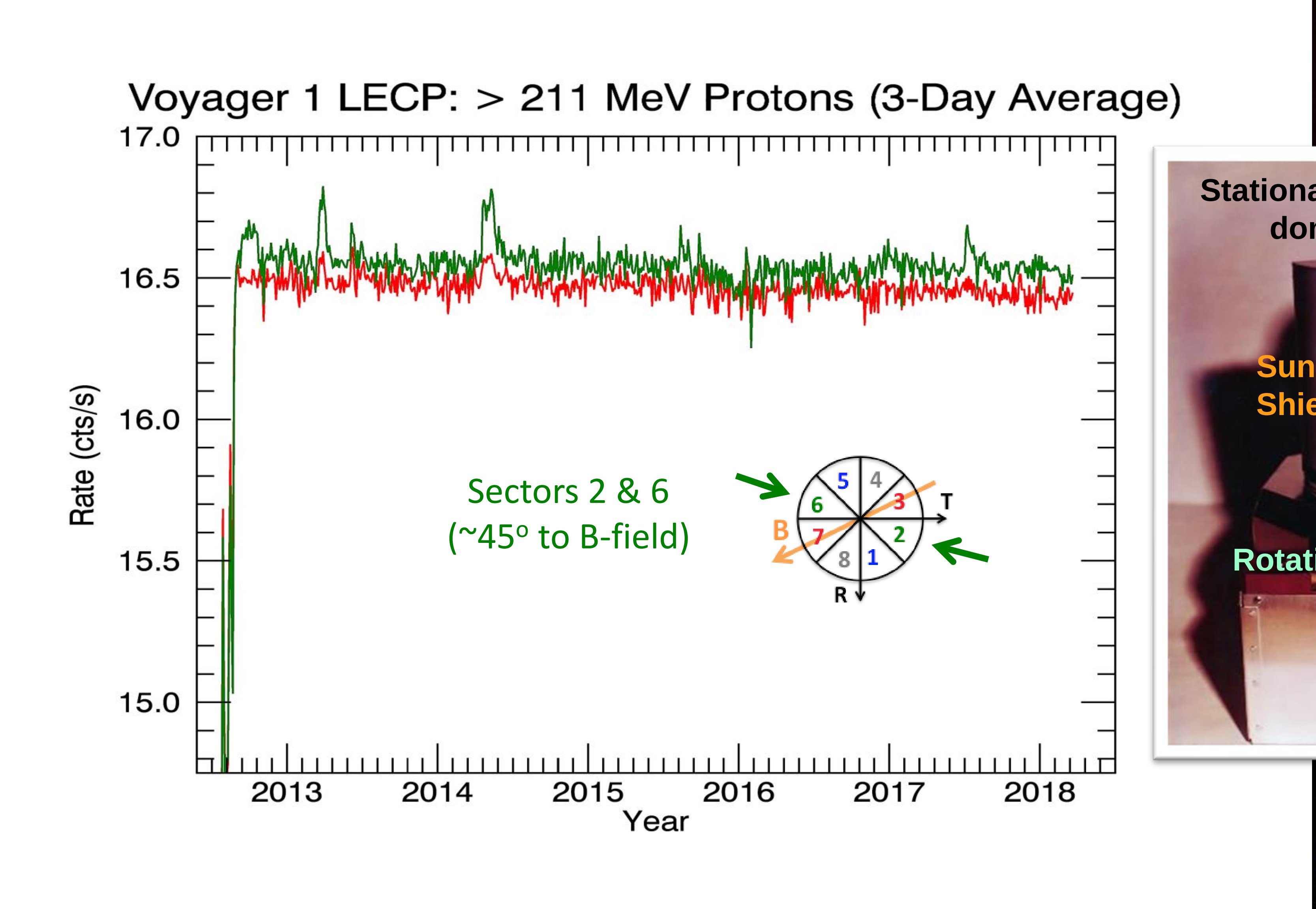


Low Energy Charged Particle Experiment (LECP)



http://space.umd.edu/group_photos/LECP_pictures.html

First Measurements of Cosmic Rays in Interstellar Space



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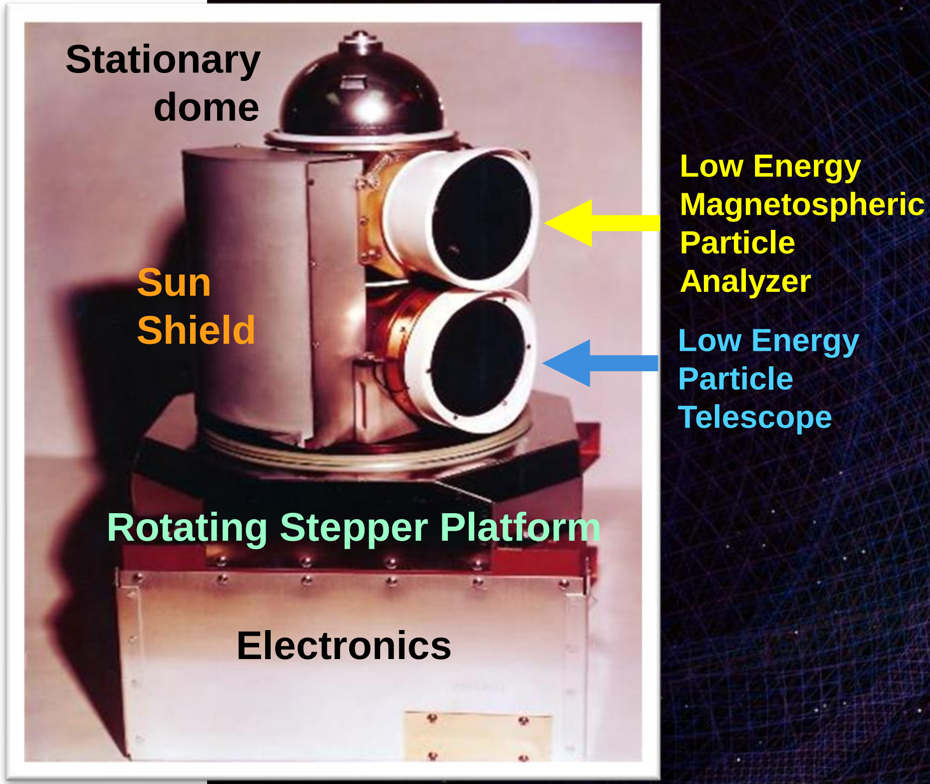

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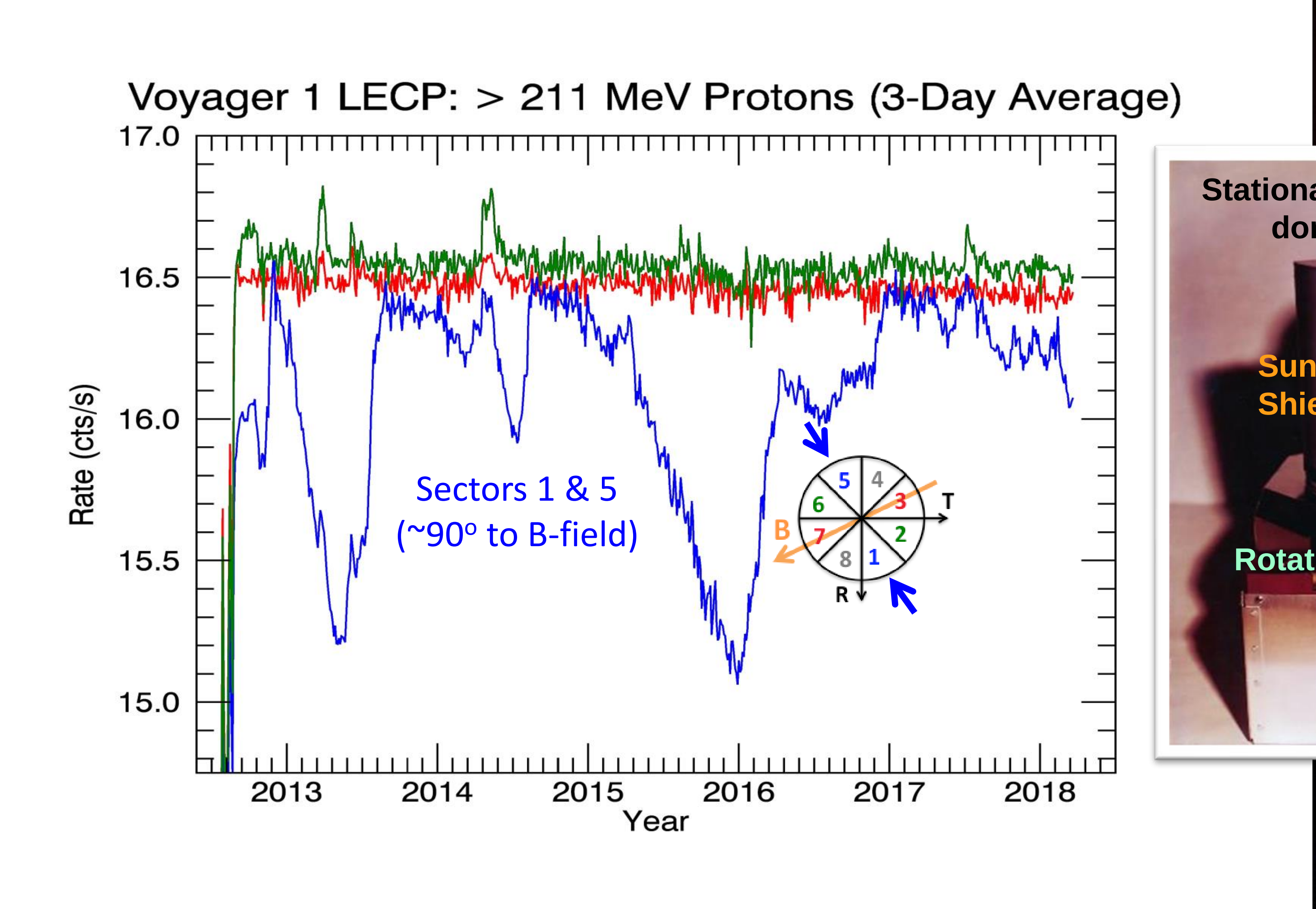

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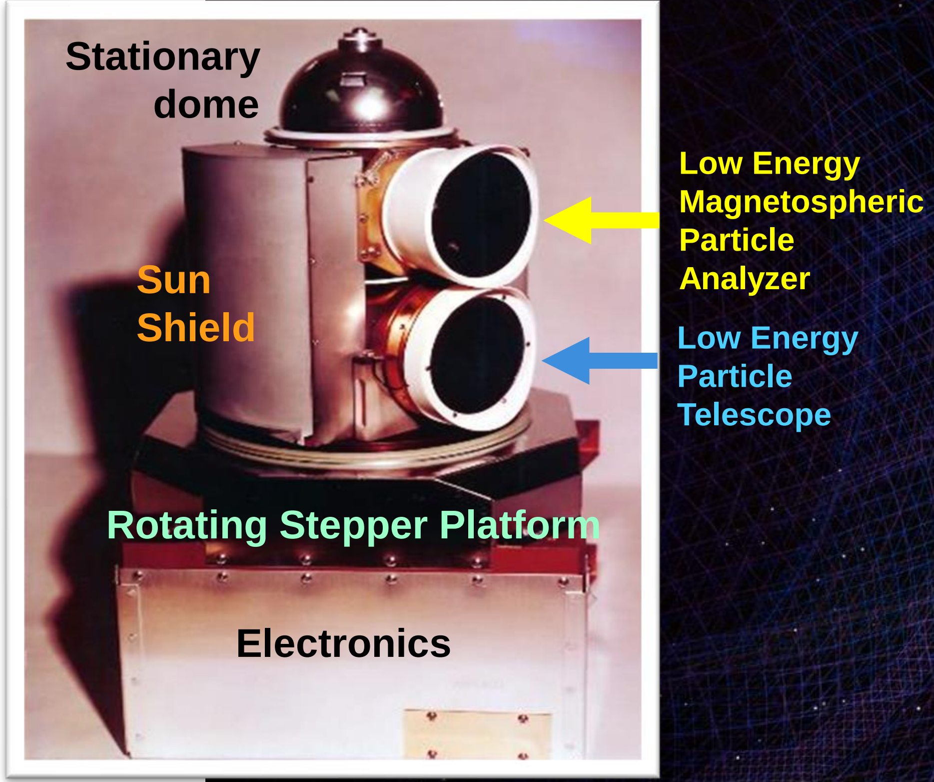
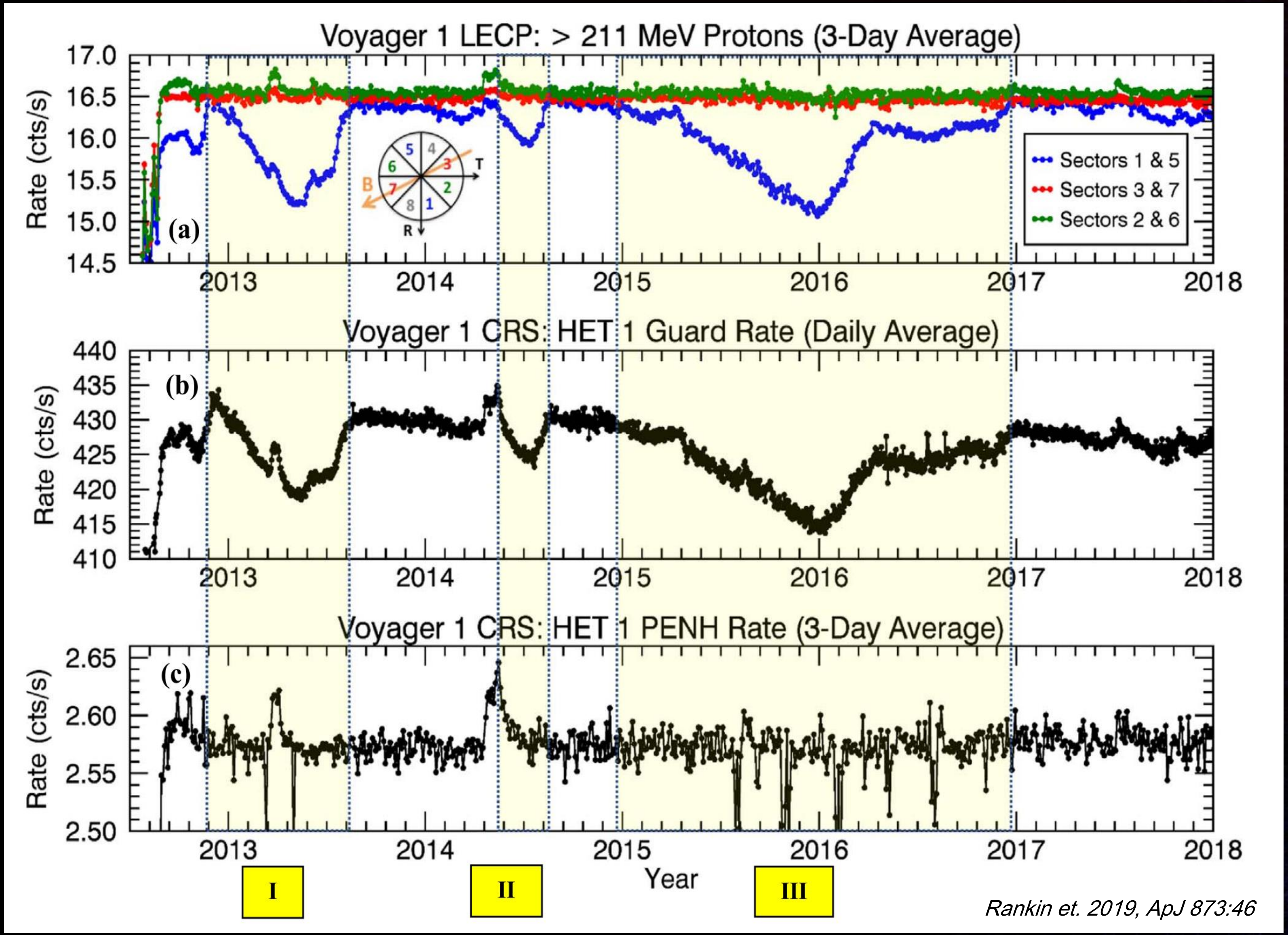
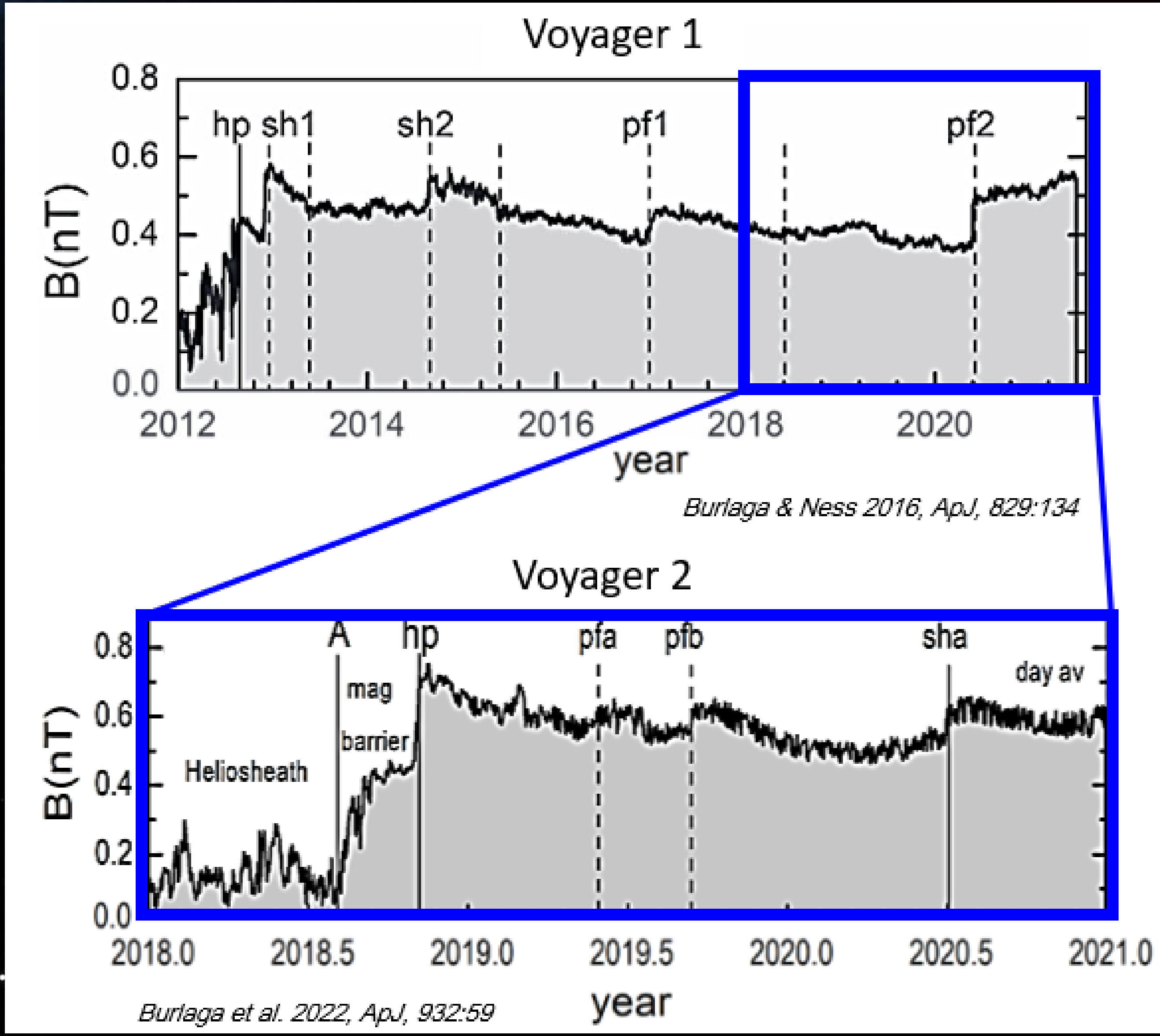


http://space.umd.edu/group_photos/LECP_pictures.html

Surprise: Time Variations in Specific Directions!



Time-Varying Changes in the Magnetic Field

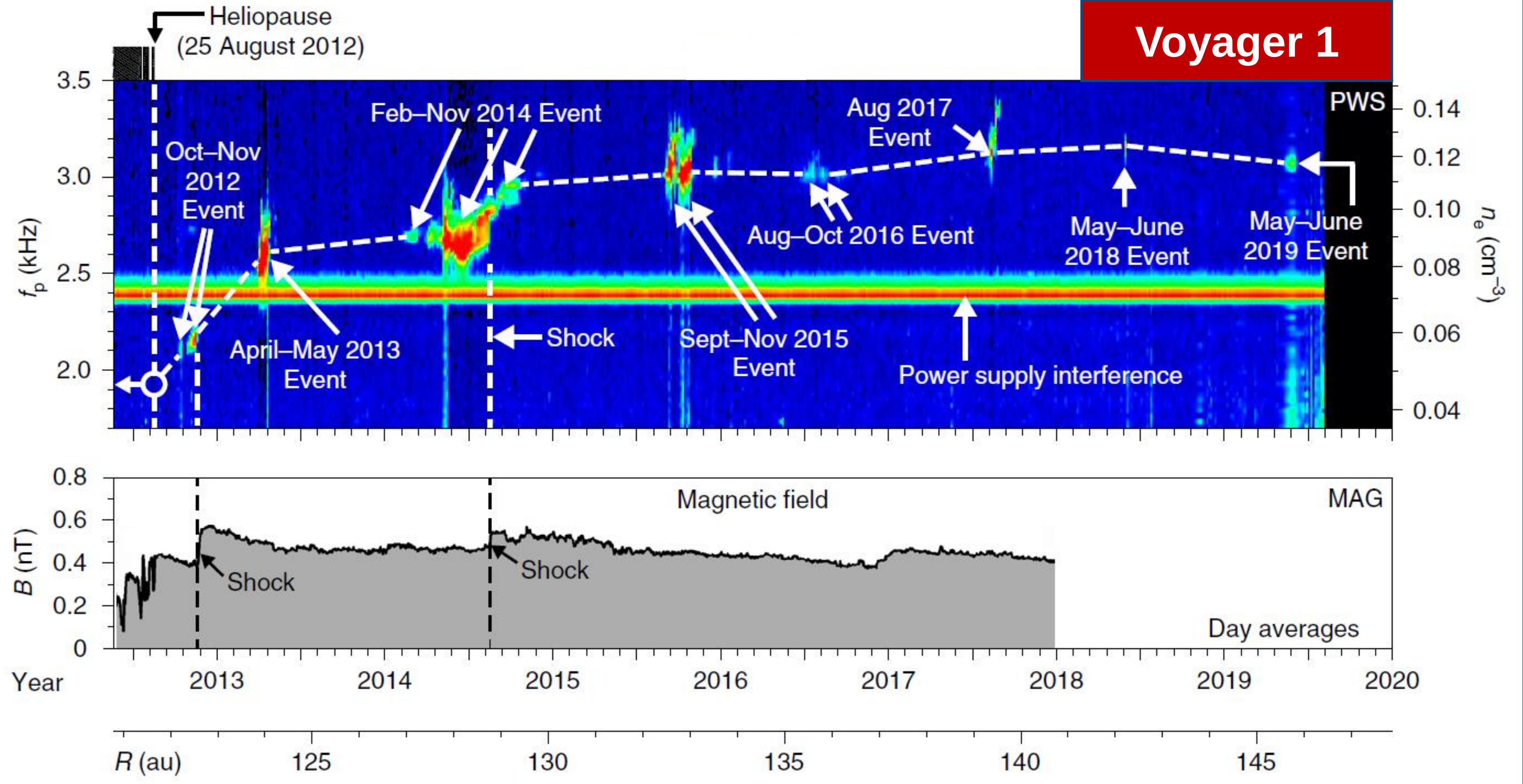


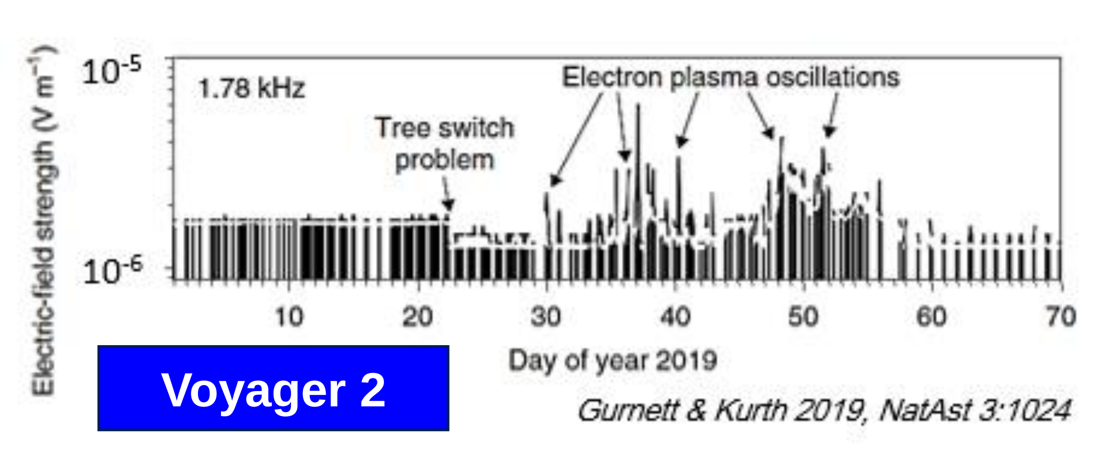
- **The Very Local Interstellar Medium (VLISM) has a very weak magnetic field!**
  - Voyager 1: ~0.46 nT
  - Voyager 2: ~0.68 nT
    - Solar Wind: 5 nT
    - Earth at Sea Level: ~50,000 nT
  - Compressed Towards Ecliptic South
  - Puzzle: field direction did not change
- **Voyager 1 & 2 encountered "Shocks"**
  - Very long lasting!
    - VLISM: ~weeks to months
    - Solar System: ~hours to days
  - Very Weak!
    - VLISM: 20% to 50% jump
    - Solar System: 500% to 1000% jump
  - Very Thick! (10^7 km)
    - 1000 x's thicker than solar-system counterparts

Plasma Beams at Radio Frequencies

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}



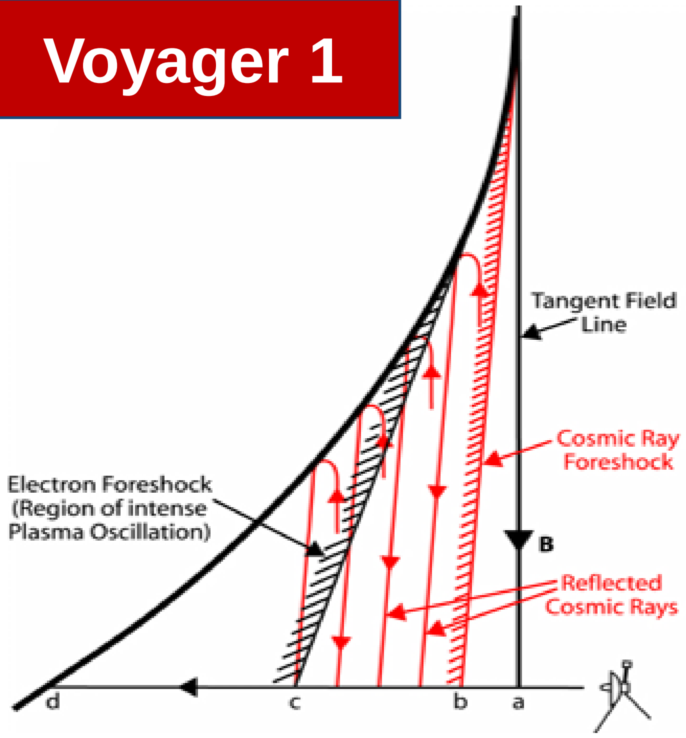


Voyager 2: Plasma Wave Subsystem

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

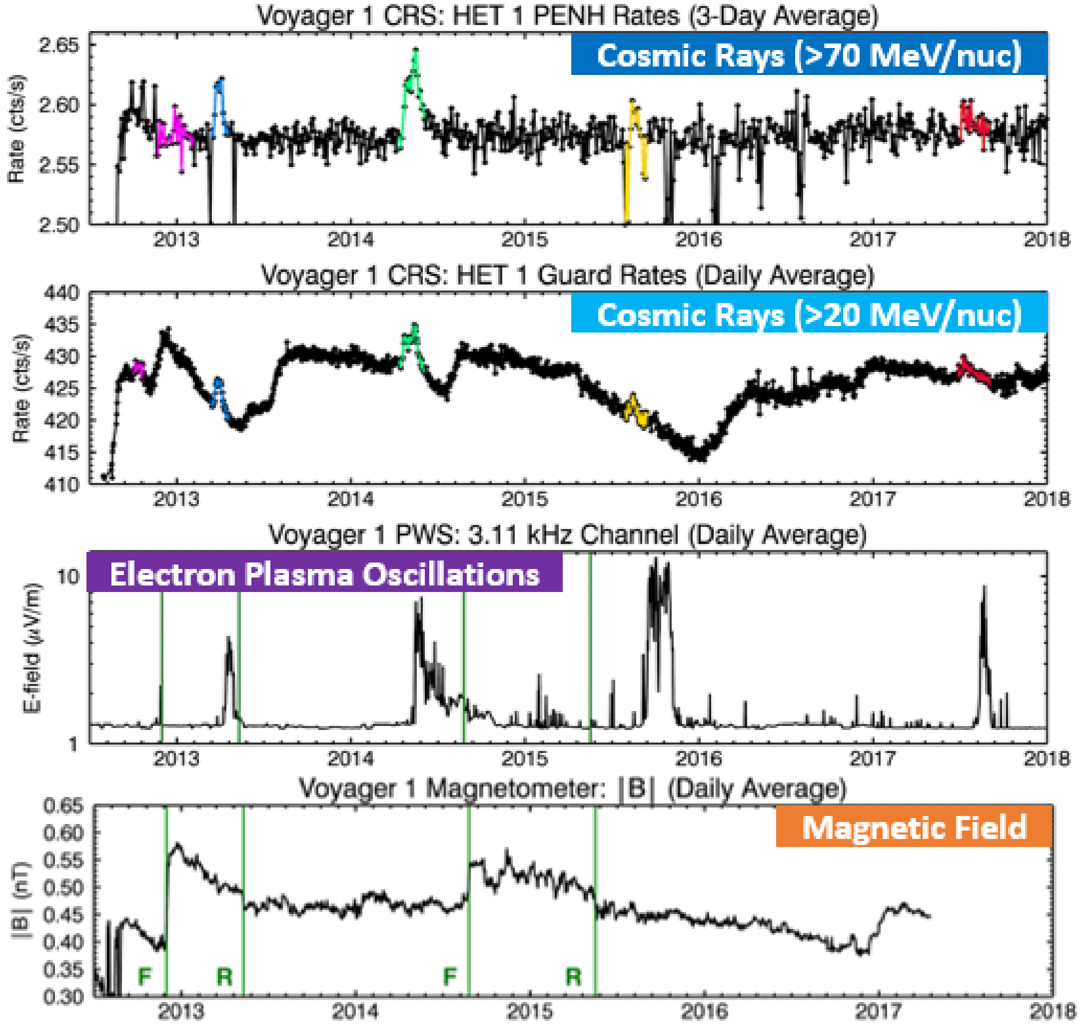
Shock-Energized Particles Out in Interstellar Space!?

Voyager 1



Gurnett et al. 2015, ApJ, 809:121

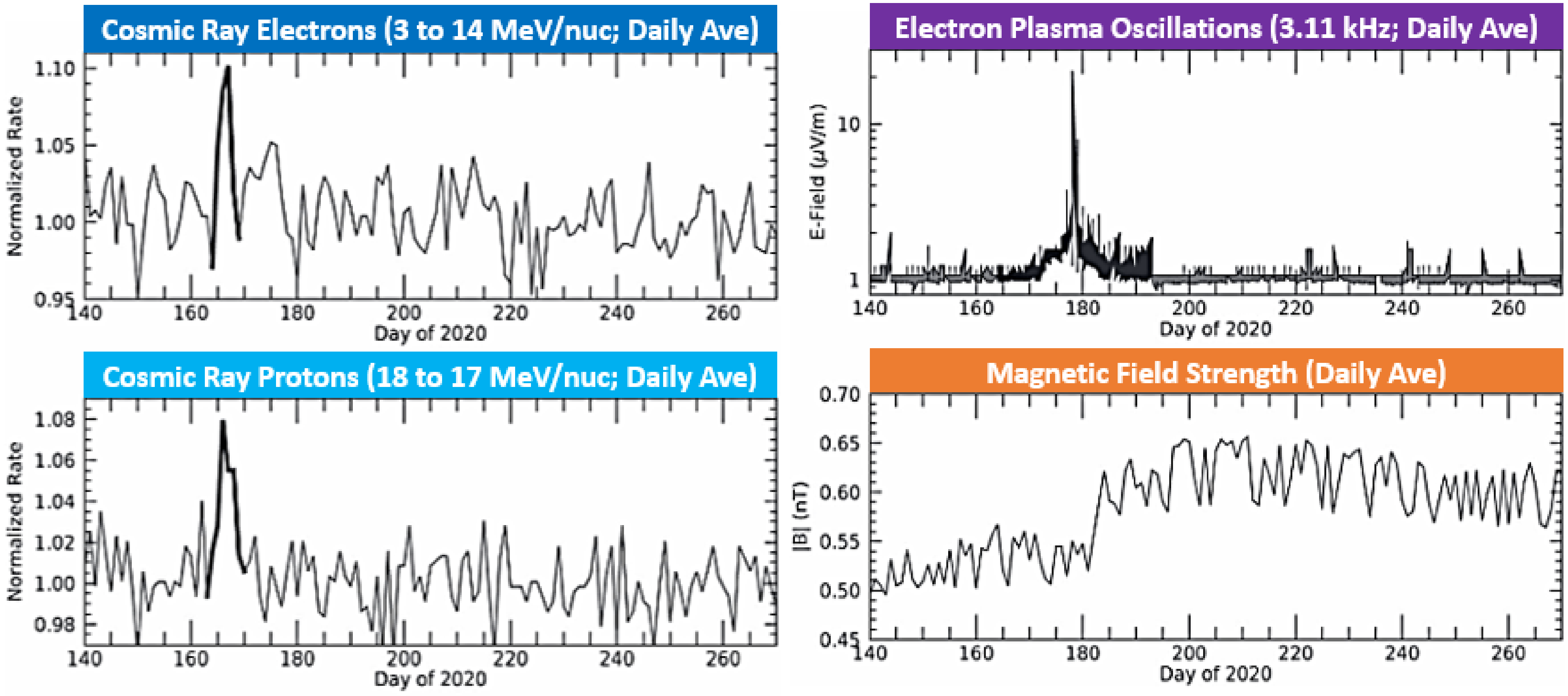
- Estimated energy of the electron beams: ~20-100 eV
  - *Gurnett et al. 2021, ApJ 161:11*
  - Derived from relative timing of cosmic rays and plasma oscillations



Rankin 2018, Caltech PhD Thesis (adapted)

Shock-Energized Particles Out in Interstellar Space!?

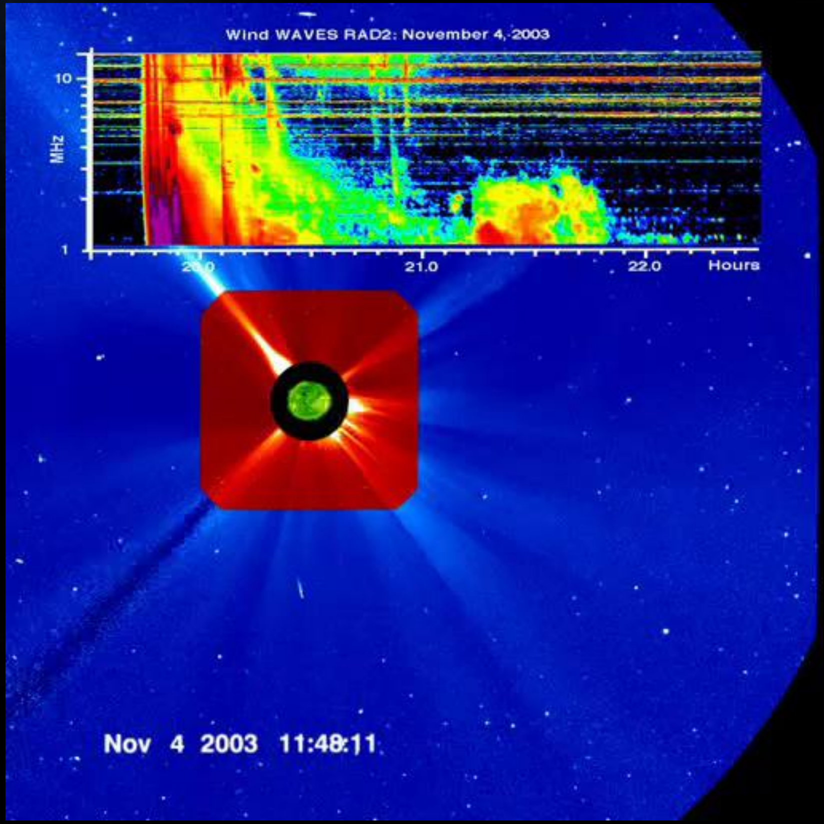
Voyager 2

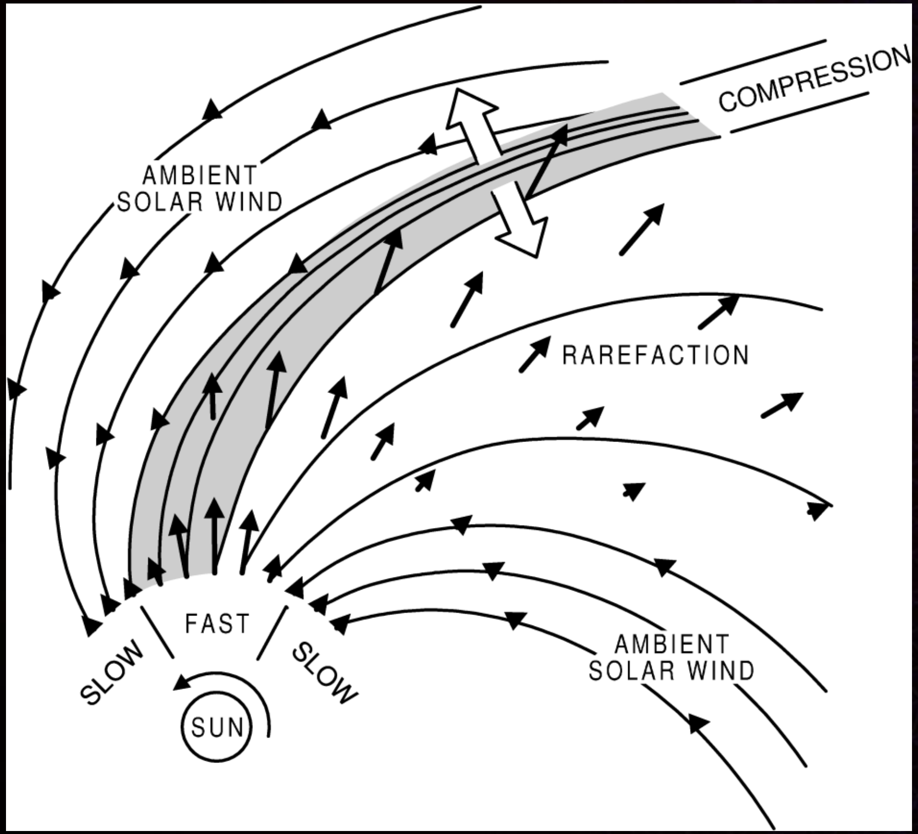


Burlaga et al. 2022, ApJ, 932:59

Outward-Traveling events that blast off from the Sun…

https://svs.gsfc.nasa.gov/2936





Coronal Mass Ejection

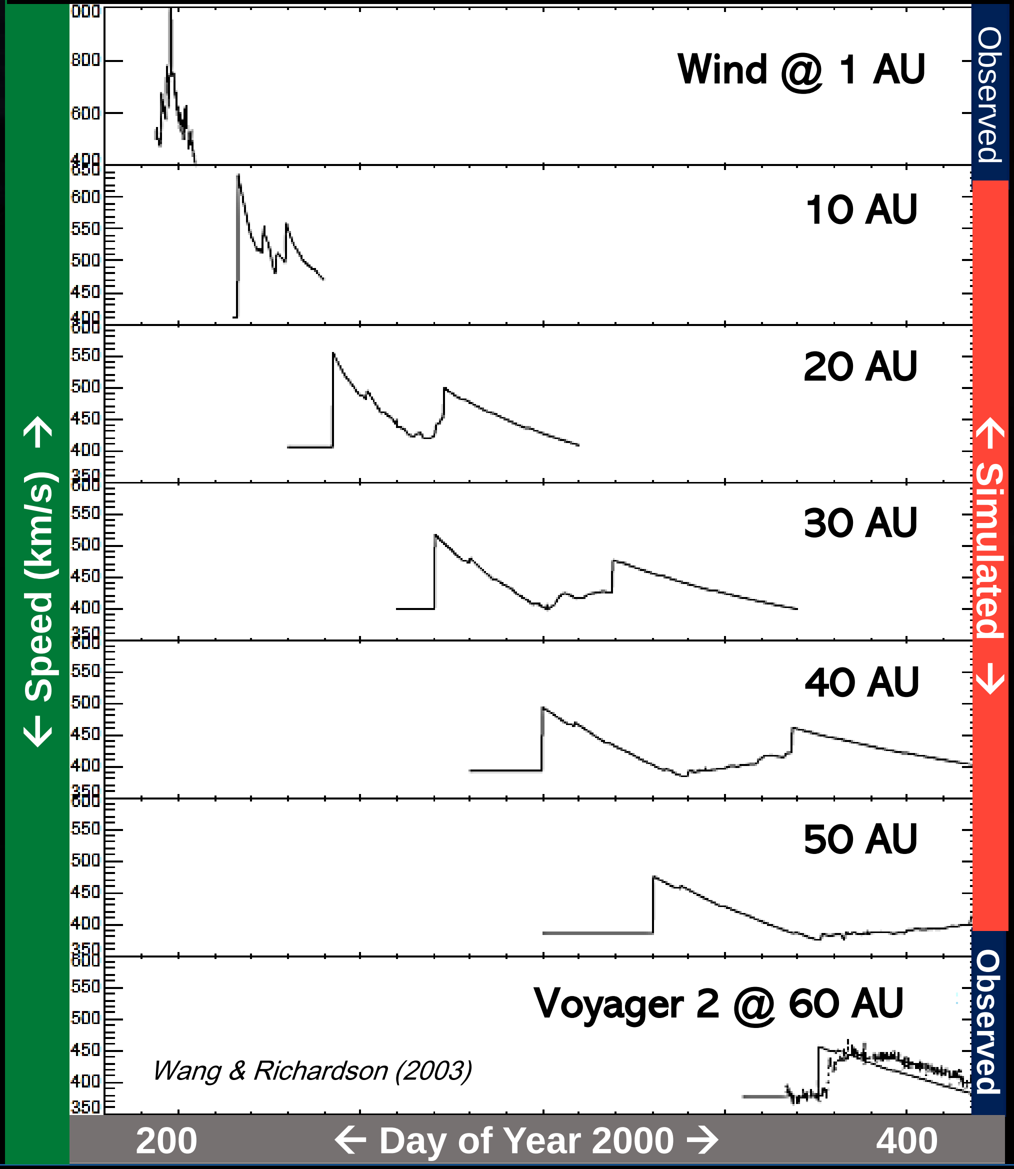
- Large flares often associated with huge ejections of mass from the sun (up to 100 billion kg of material loss)
- Speeds can reach up to 1000 km/s
- Resulting shocks accelerate particles ahead of the loop

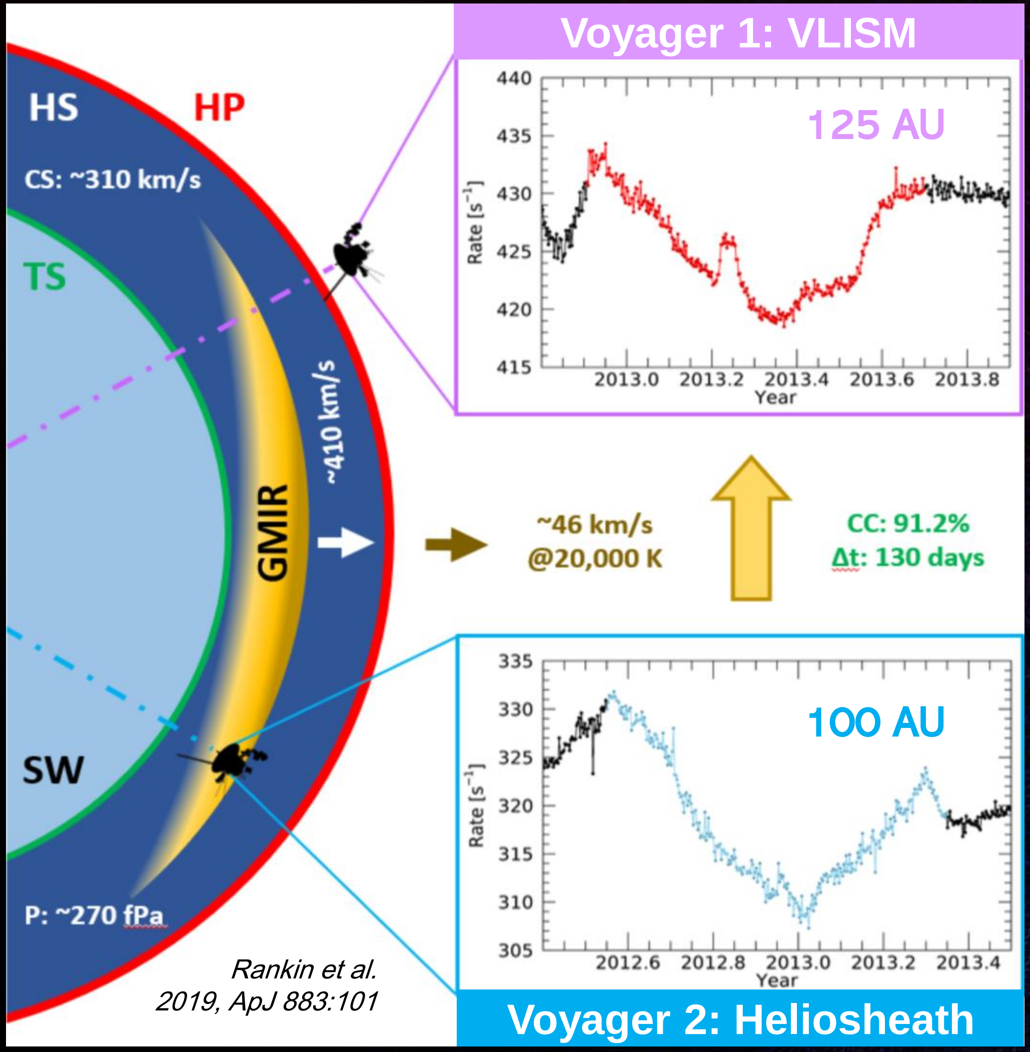
Corotating Interaction Region

- A fast stream runs into the slow wind, forming a compression region between the two, which results eventually in the formation of a forward-reverse shock pair
- Pattern rotates with the sun (source: long-lived coronal holes)

Can merge as they travel past the planets…(how far can they go?)

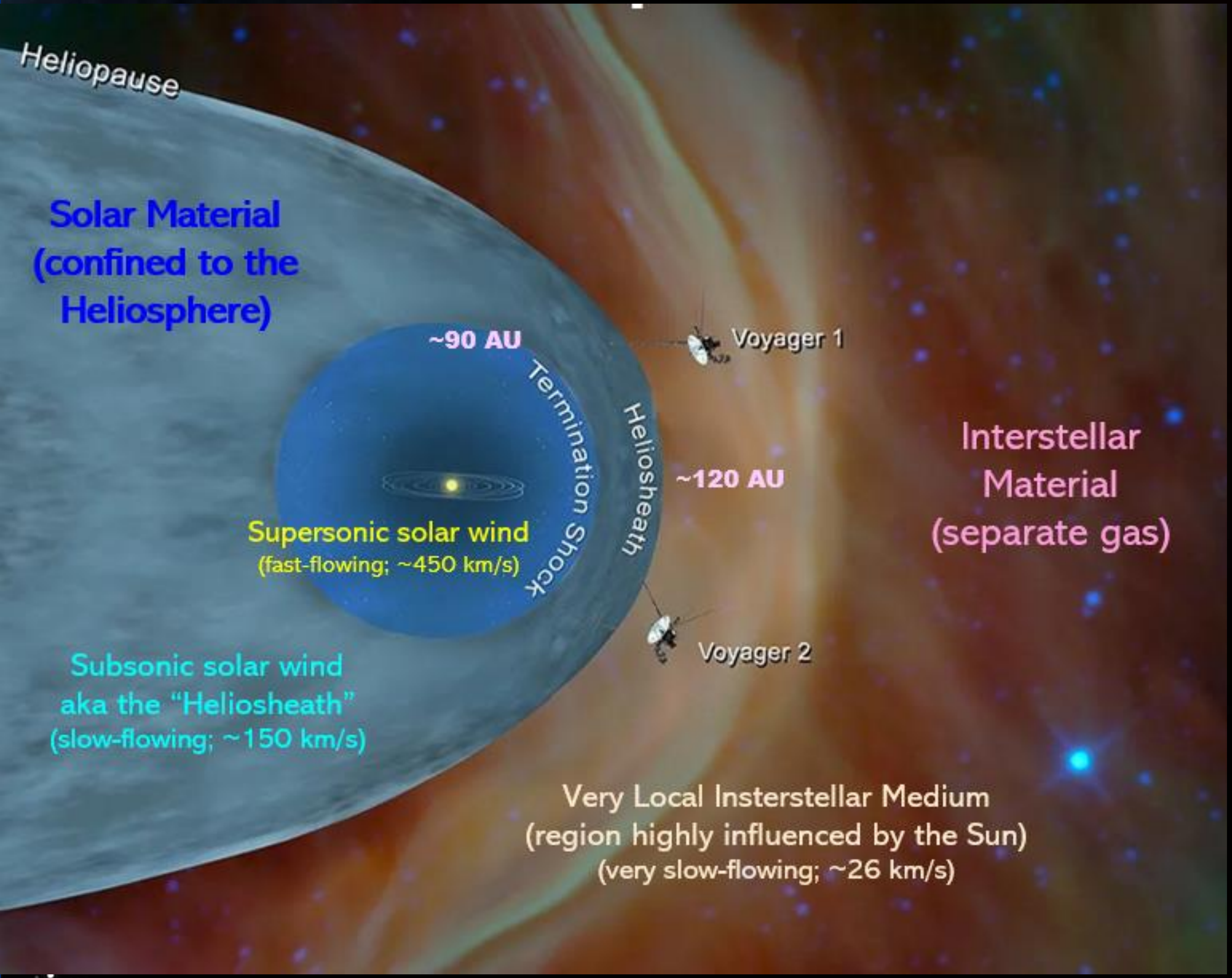
Plasma Disturbance from 1 to 60 AU

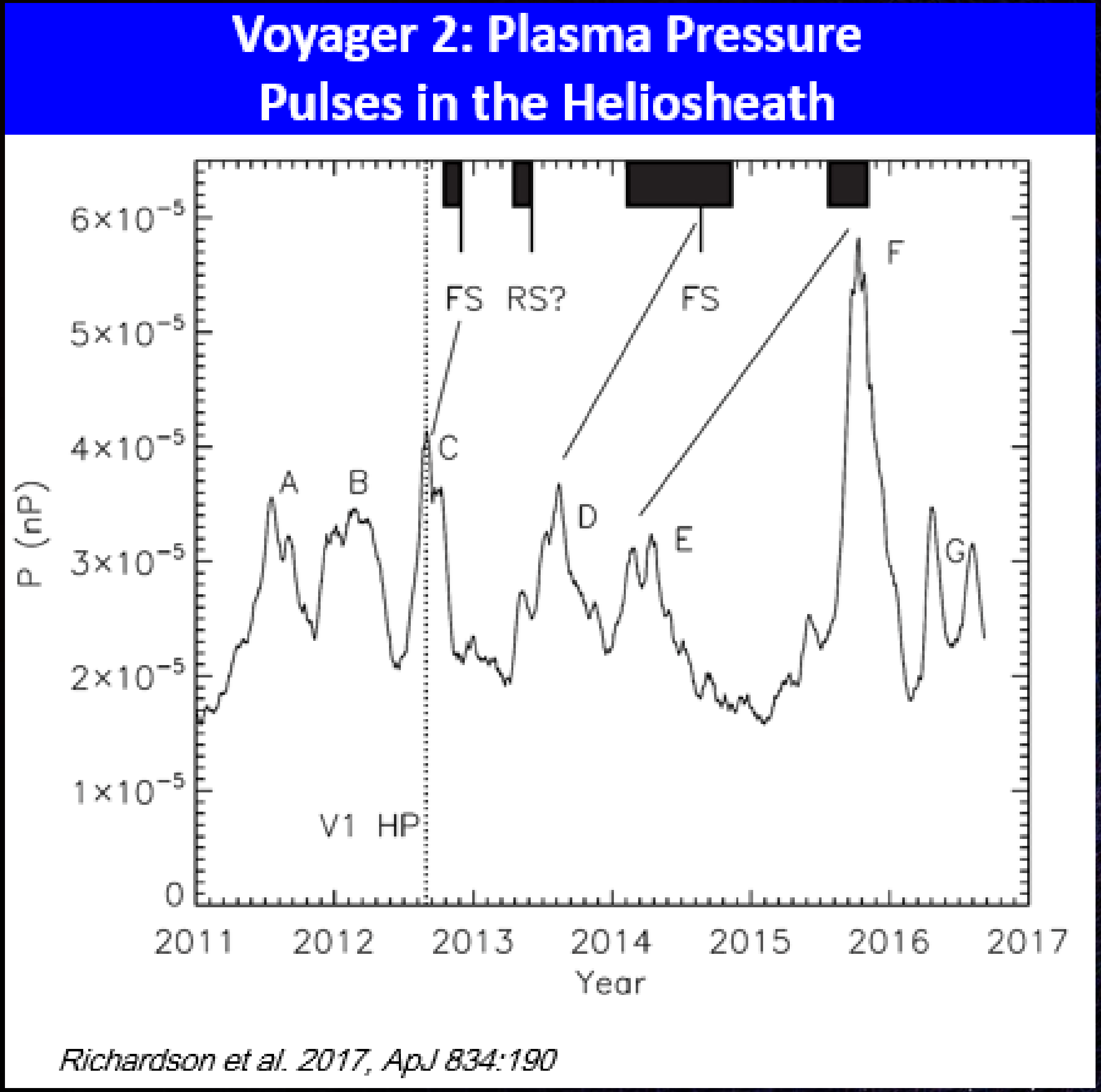




Particle Disturbances from 100 to 125 AU

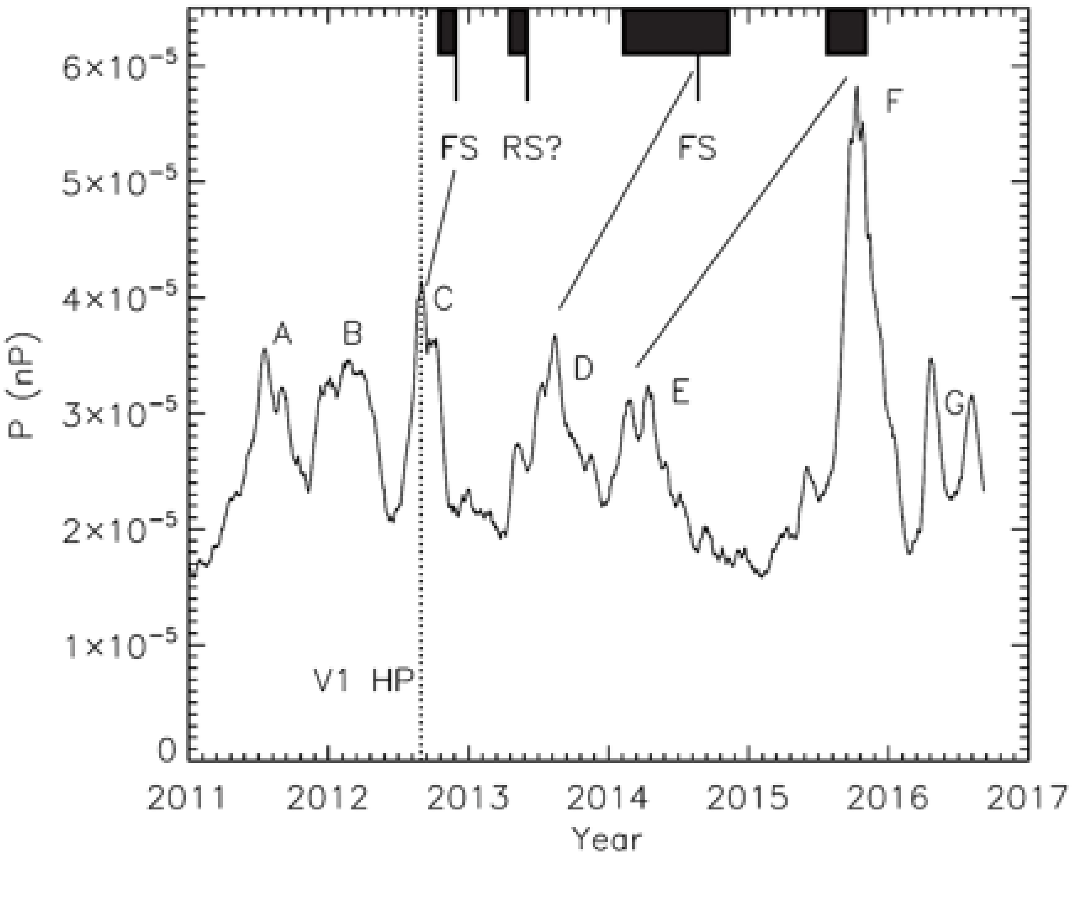
…to eventually collide with the edge of the Heliosphere…





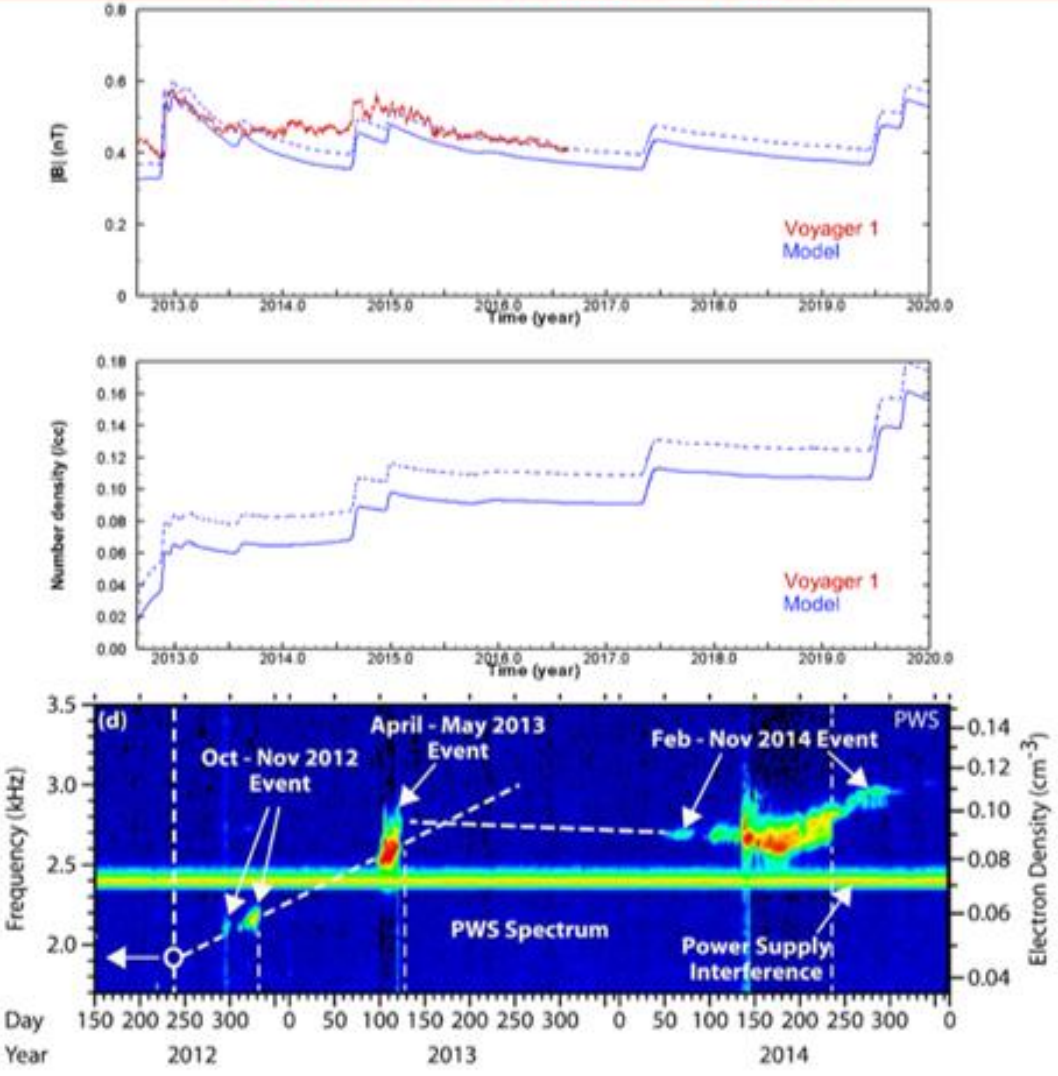
…and send ripples into the surrounding interstellar space!

Voyager 2: Plasma Pressure Pulses in the Heliosheath



Richardson et al. 2017, ApJ 834:190

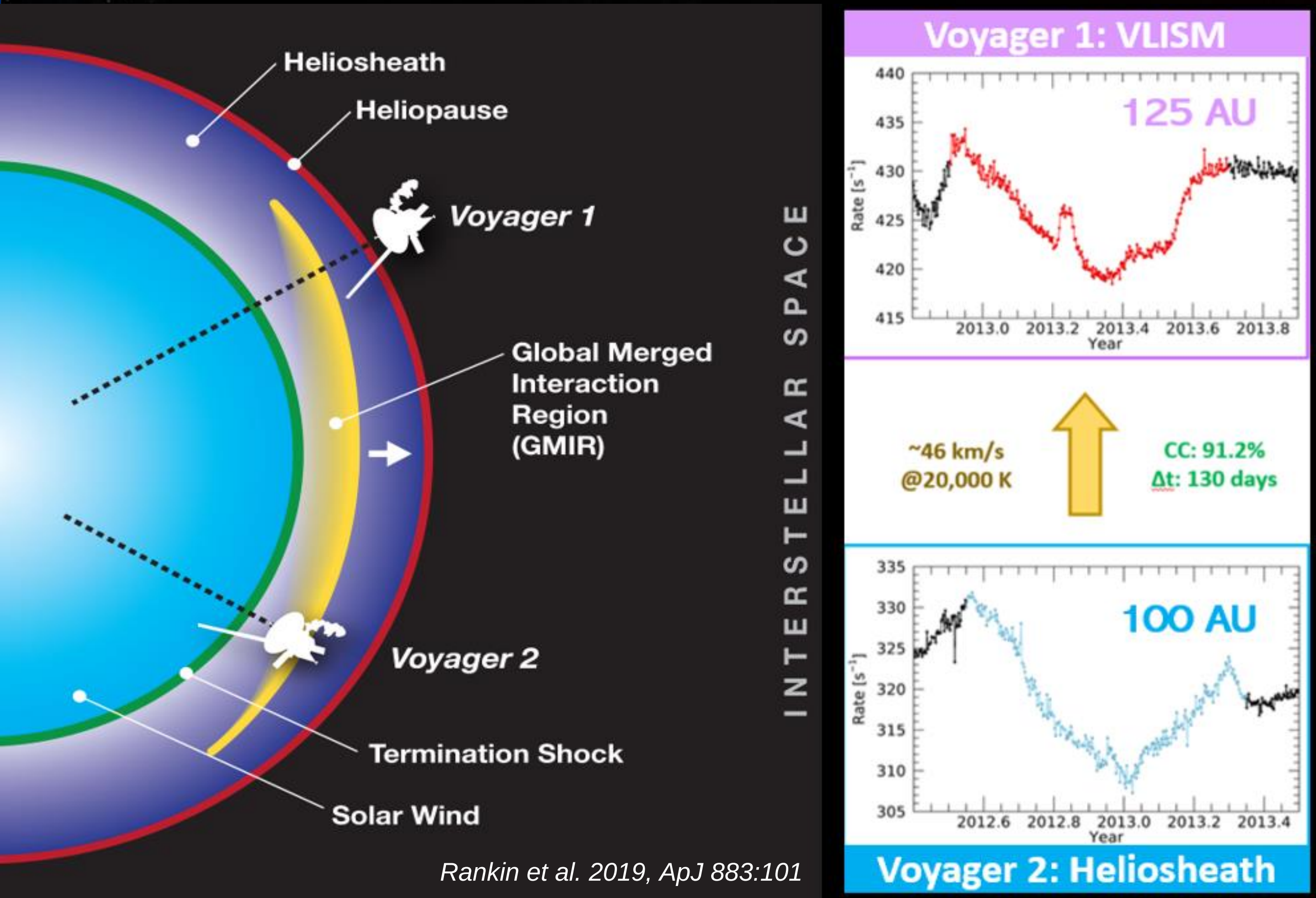
Voyager 1: Magnetic Fields & Radio Waves in the VLISM



Kim et al. 2017, ApJ 843:2

Discovery: Pressure Runs High at the Solar System's Edge!

Rare event from Voyager 2 → Voyager 1 enabled first-time measurements of the healiosheath's total pressure!



Rankin et al. 2019, ApJ 883:101

- **Very Local Interstellar Medium**
  - Temperature: 20,000 K
  - Plasma Speed: ~46 km/s
- **Heliosheath**
  - Event Speed: ~ 410 km/s
  - Wave Speed: ~ 310 km/s
  - Total Pressure: $\sim 3.92 \times 10^{-17}$ psi

Discovery: Pressure Runs High at the Solar System's Edge!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Pressure at the Edge of the Solar System Is Far Higher Than Expected, Scientists Discover

Published Oct 10, 2019 at 5:36 AM EDT | Updated Oct 12, 2019 at 2:36 PM EDT

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  - Plasma Speed: ~46 km/s
- **Heliosheath**
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  - Total Pressure: ~3.92×10^{-17} psi
- **What factors contribute?**
  - Solar Wind Plasma & Magnetic Field: ~15%
  - Energized Interstellar Particles: ~45%
  - Cosmic Rays: ~22%
  - Remaining: ~18% *(source unknown)*

Rankin et al. 2019, ApJ 883:101

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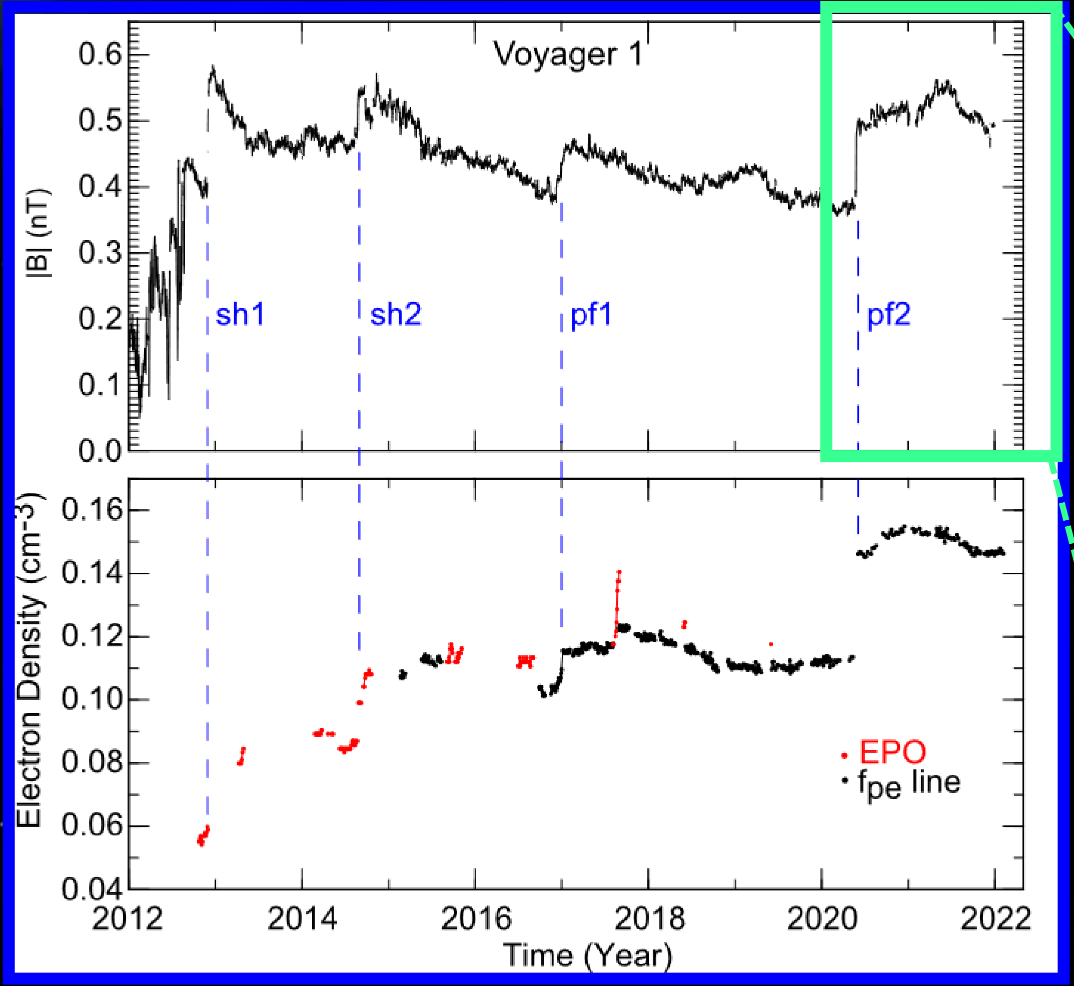
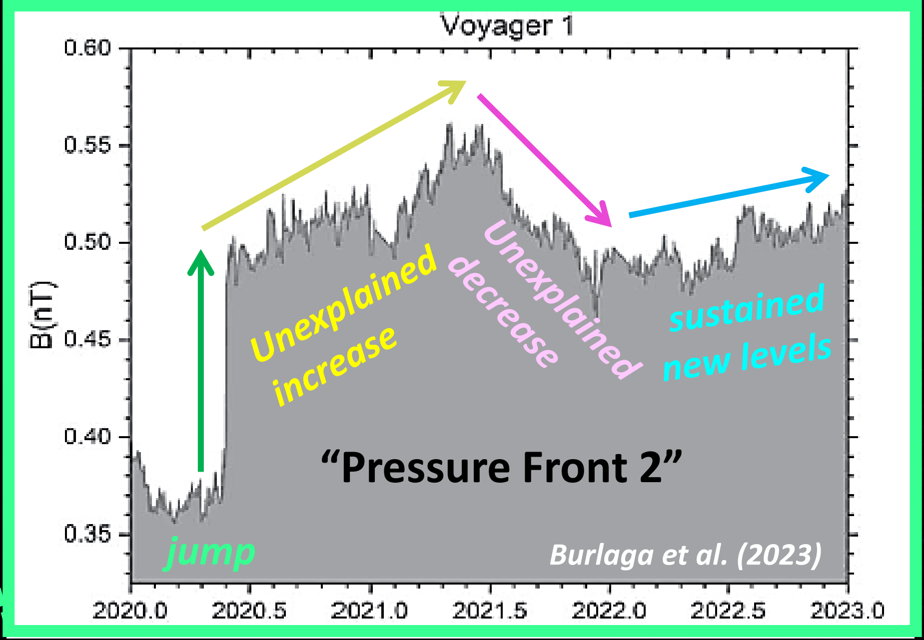
Happening Now: The Strangest Event Yet!

14 billion miles from the Sun, Voyager 1 observed a puzzling increase in pressure that continues to this day!





Key observations:
sudden increase in magnetic field strength & electron number density (concentration of electrons).

Scientists are wondering:

- Could this extended region of increased pressure be due to a solar cycle effect and the Sun's lingering influence on what's outside?
- Or, could this region be telling us something new about the nature of the interstellar medium?

Voyager 1 has been monitoring Sun-caused disturbances of the Very Local Interstellar Medium for over a decade, but the event currently being tracked by the magnetic field (MAG) and radio instruments (PWS) is the strangest yet.

Kurth, W. S. et al., *ApJ 951:71,* (2023)
https://iopscience.iop.org/article/10.3847/1538-4357/acd44c
Burlaga L. F. et al., *ApJ 953:135,* (2023)
https://iopscience.iop.org/article/10.3847/1538-4357/acd6eb

Big Trending Questions

How far into the interstellar medium can these events travel?

What is the heliosphere's 3D size & shape?

What caused the strange new event at Voyager 1?

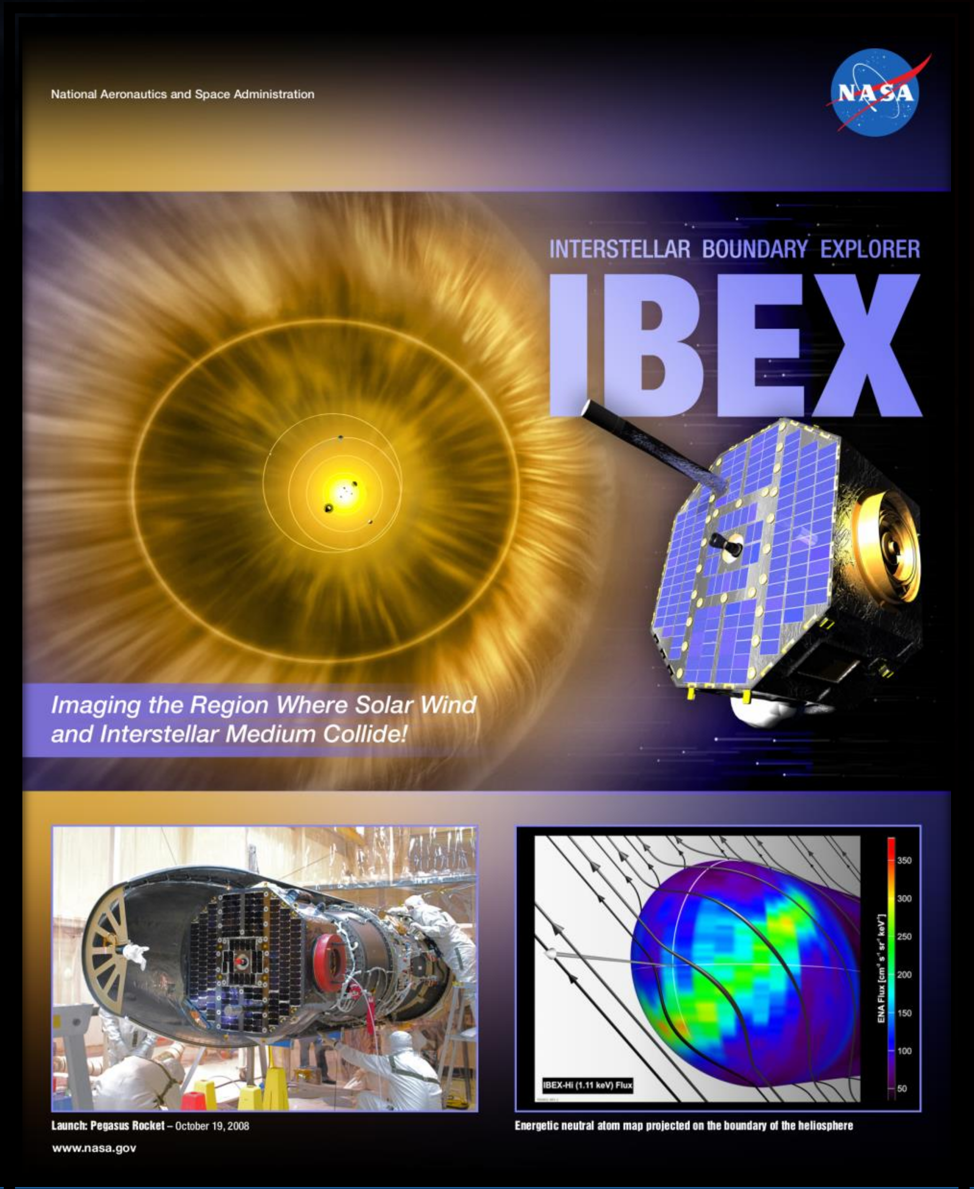
How does the Sun and its materials influence our interstellar surroundings?

Without the heliosphere, would life event exist?

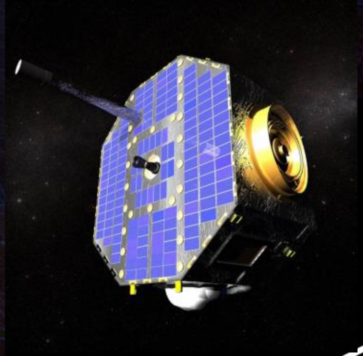
How does the interstellar medium influence the Sun and our Solar System?

Backups

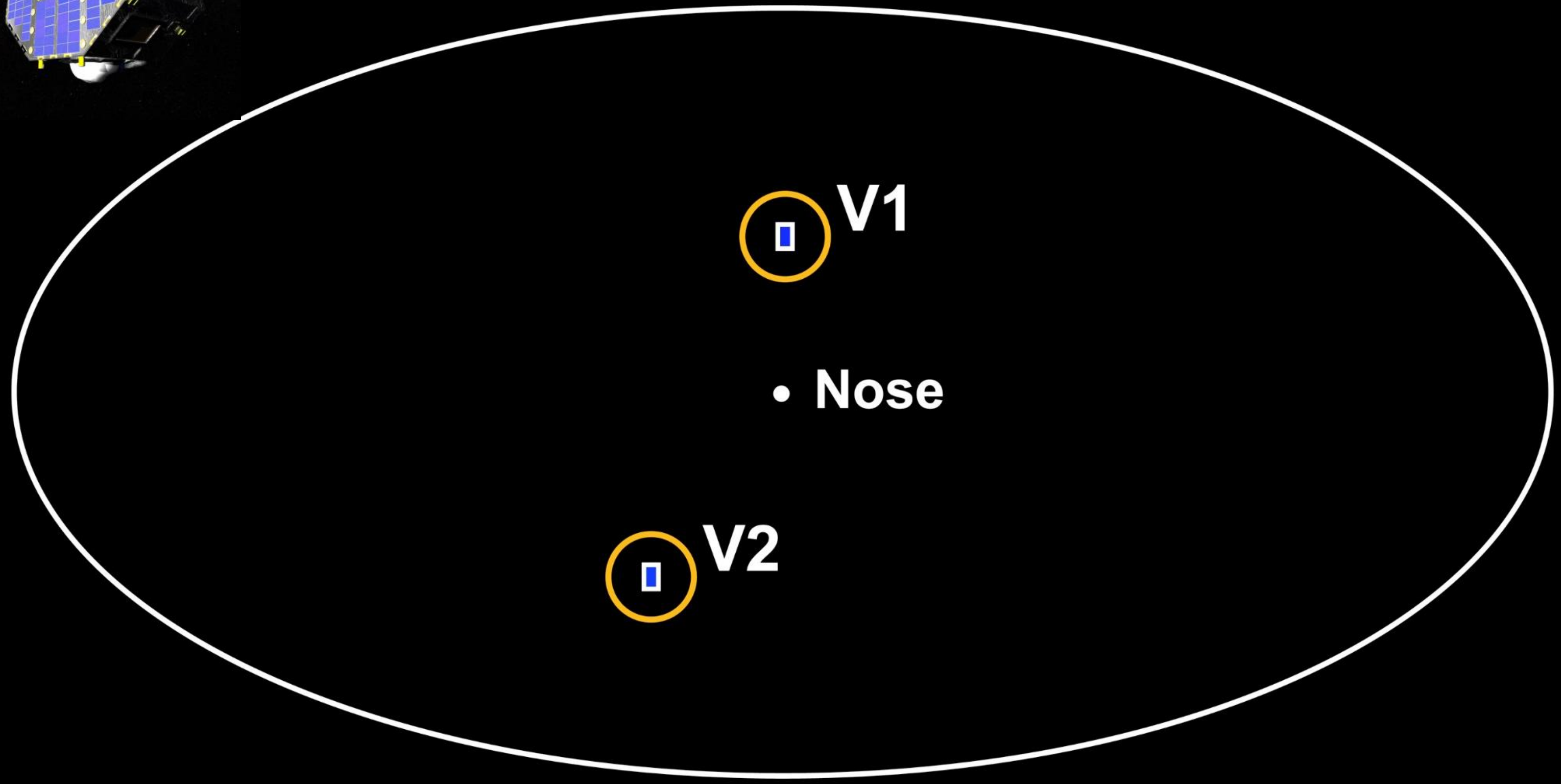
Interstellar Boundary Explorer (IBEX)



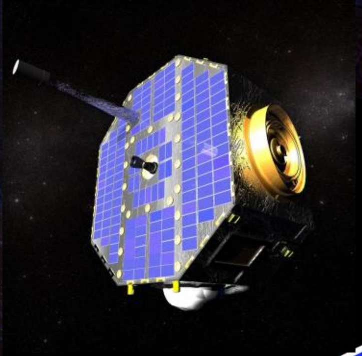
- <u>Mission Summary</u>
- NASA's first mission designed to "discover the nature of the interactions between the solar wind and the interstellar medium at the edge of our solar system."
- NASA Small Explorer (SMEX) – Proposed 2003 (~$100M)
  - PI Mission (SwRI prime – now Princeton University)
  - International: Switzerland (incl. key flight hardware development), Poland, Germany Russia, others
- Launched 19 October 2008
- Two year mission now in 15th year of service



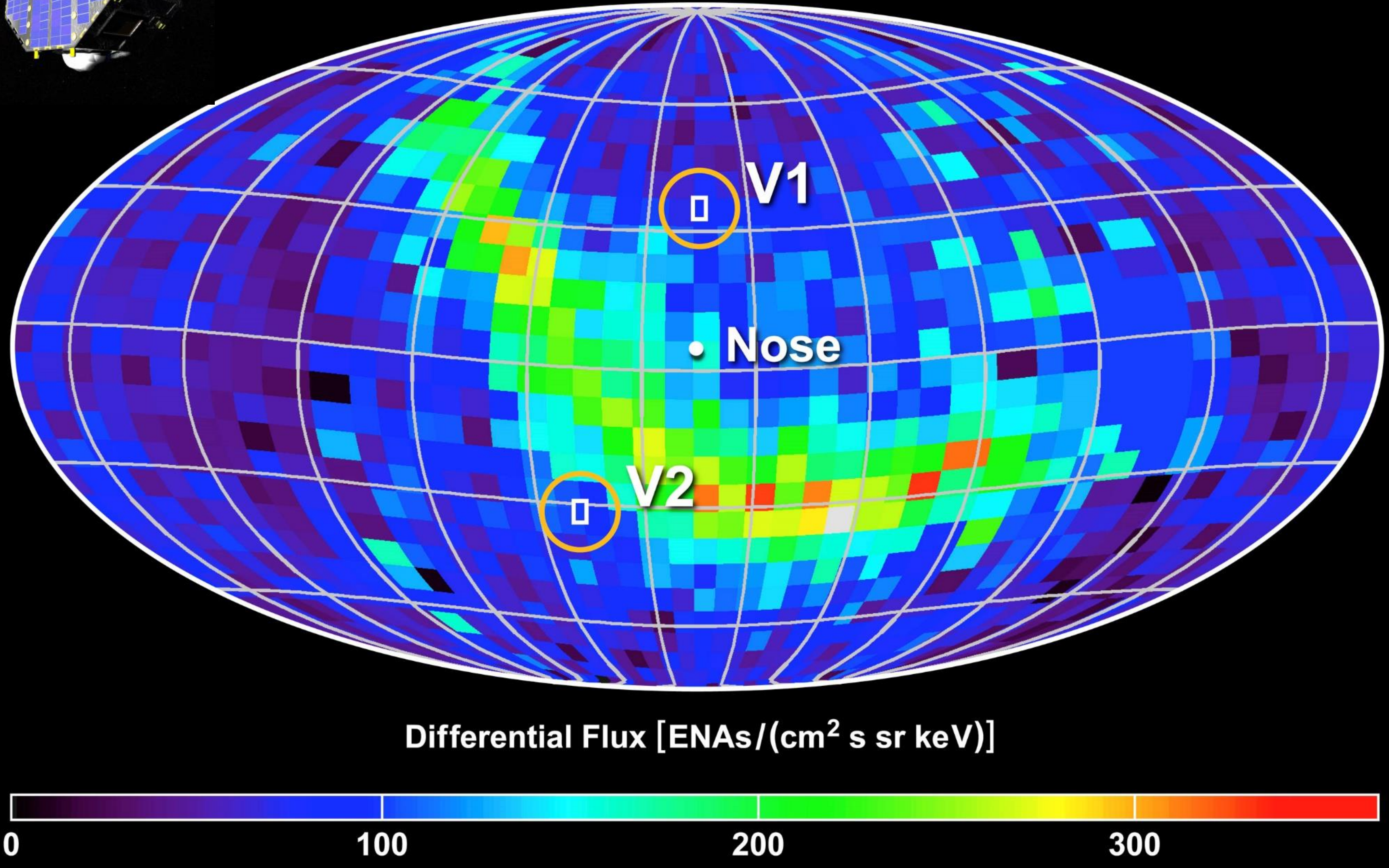
IBEX-Hi (0.9-1.5 keV)



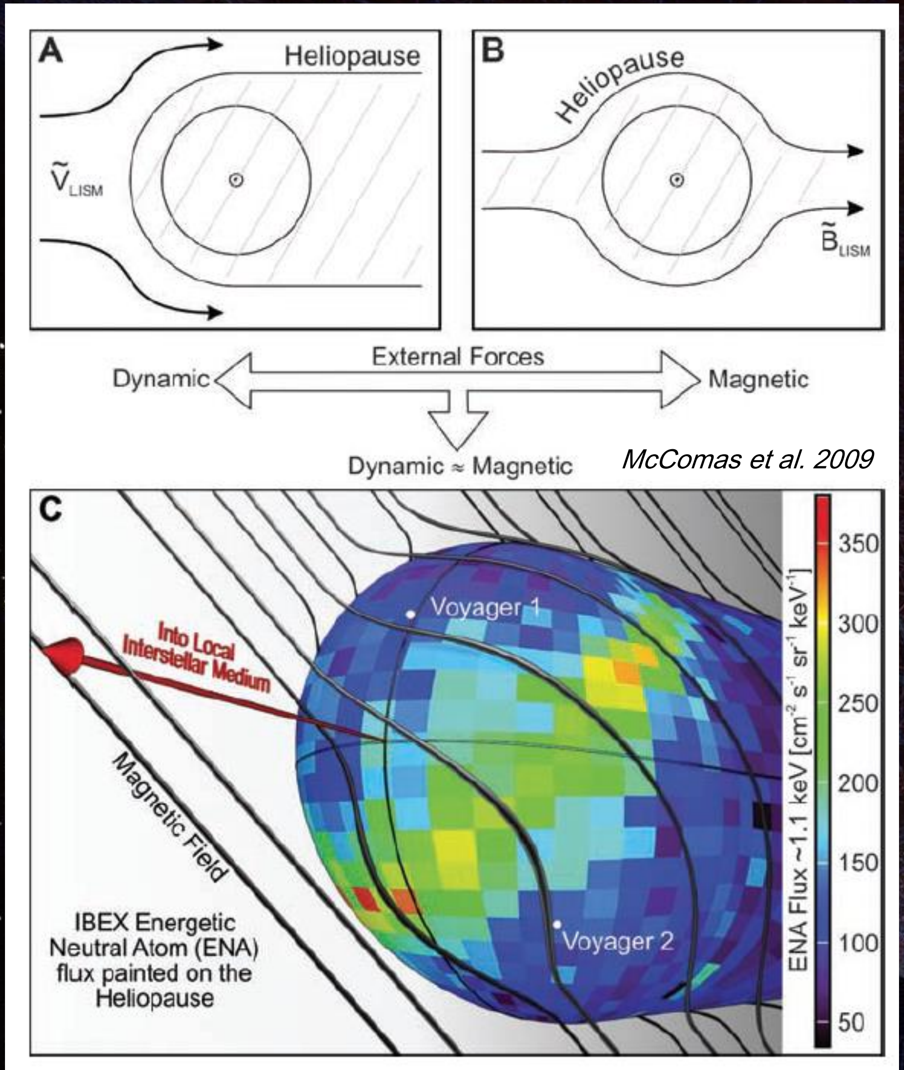
Mollweide all-sky projection showing locations of Voyagers
Voyagers provide detailed information in these two directions



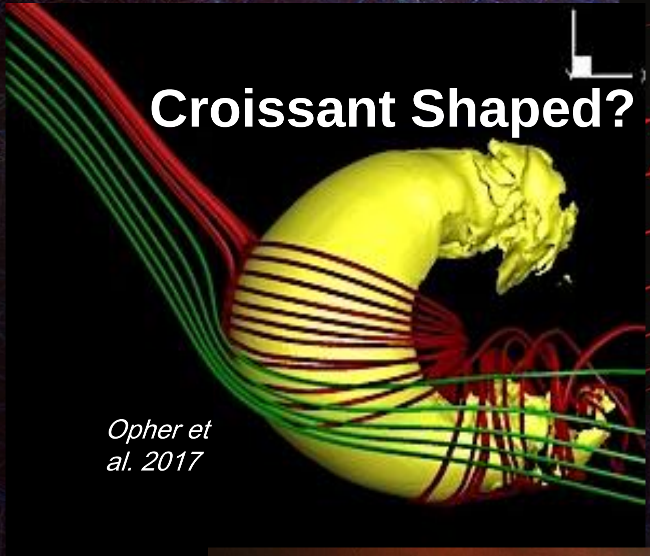
IBEX-Hi (0.9-1.5 keV)



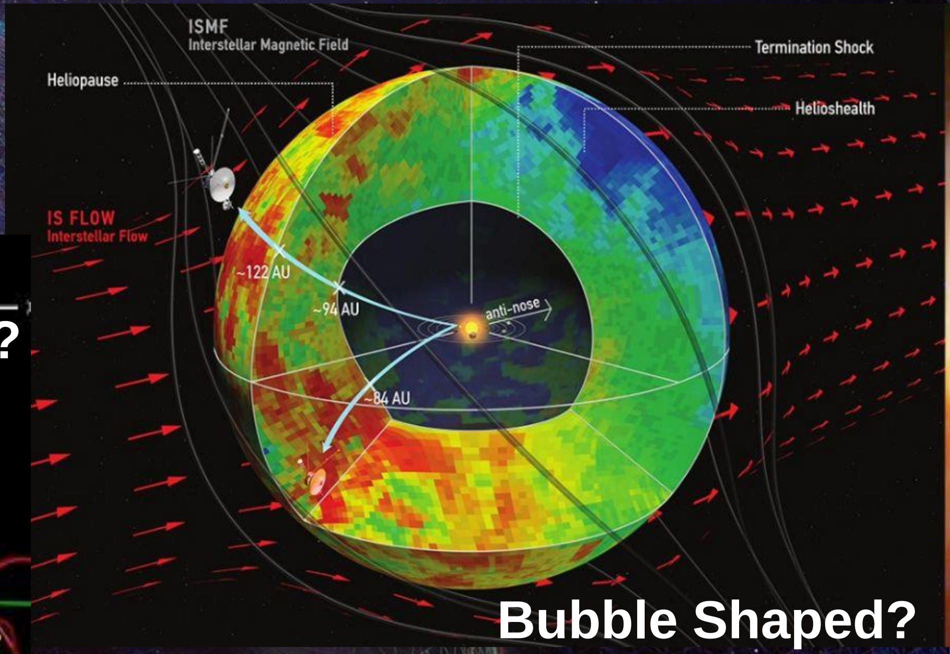
Hot Topic: What is the Heliosphere's Shape?



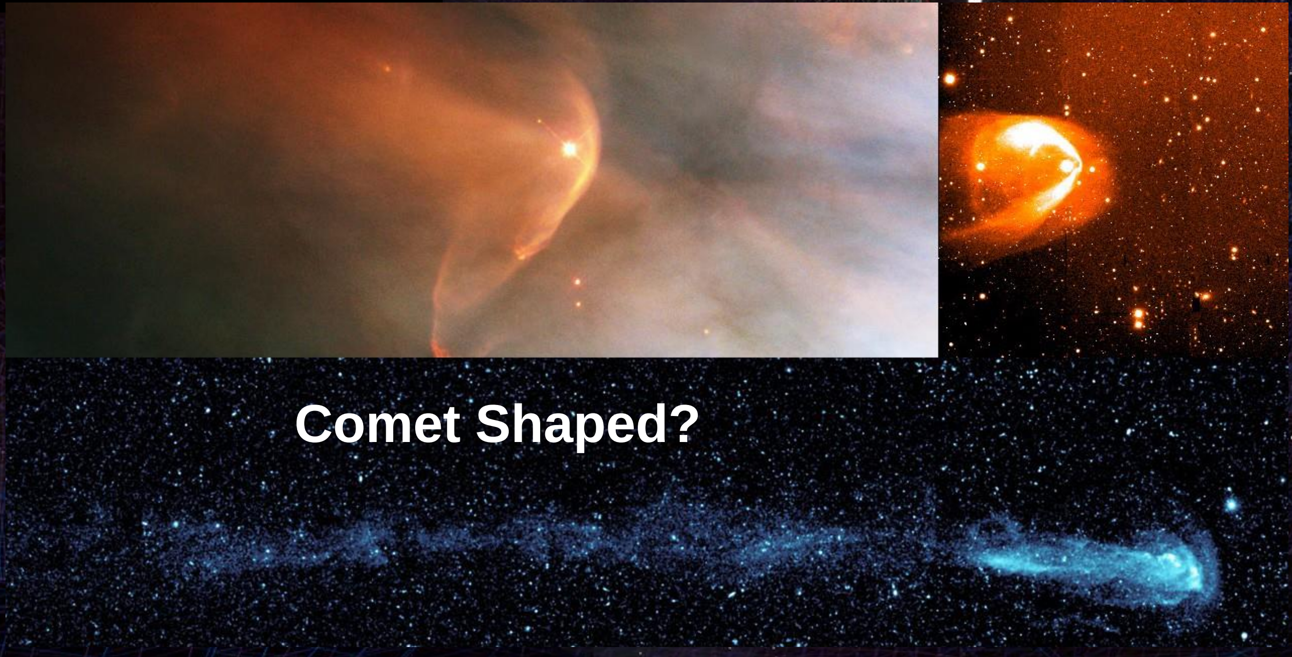
McComas et al. 2009



Opher et al. 2017



https://watchers.news/2017/04/24/new-data-show-heliosphere-is-nearly-round-and-symmetrical/



Coming Soon: Interstellar Mapping and Acceleration Probe (IMAP)

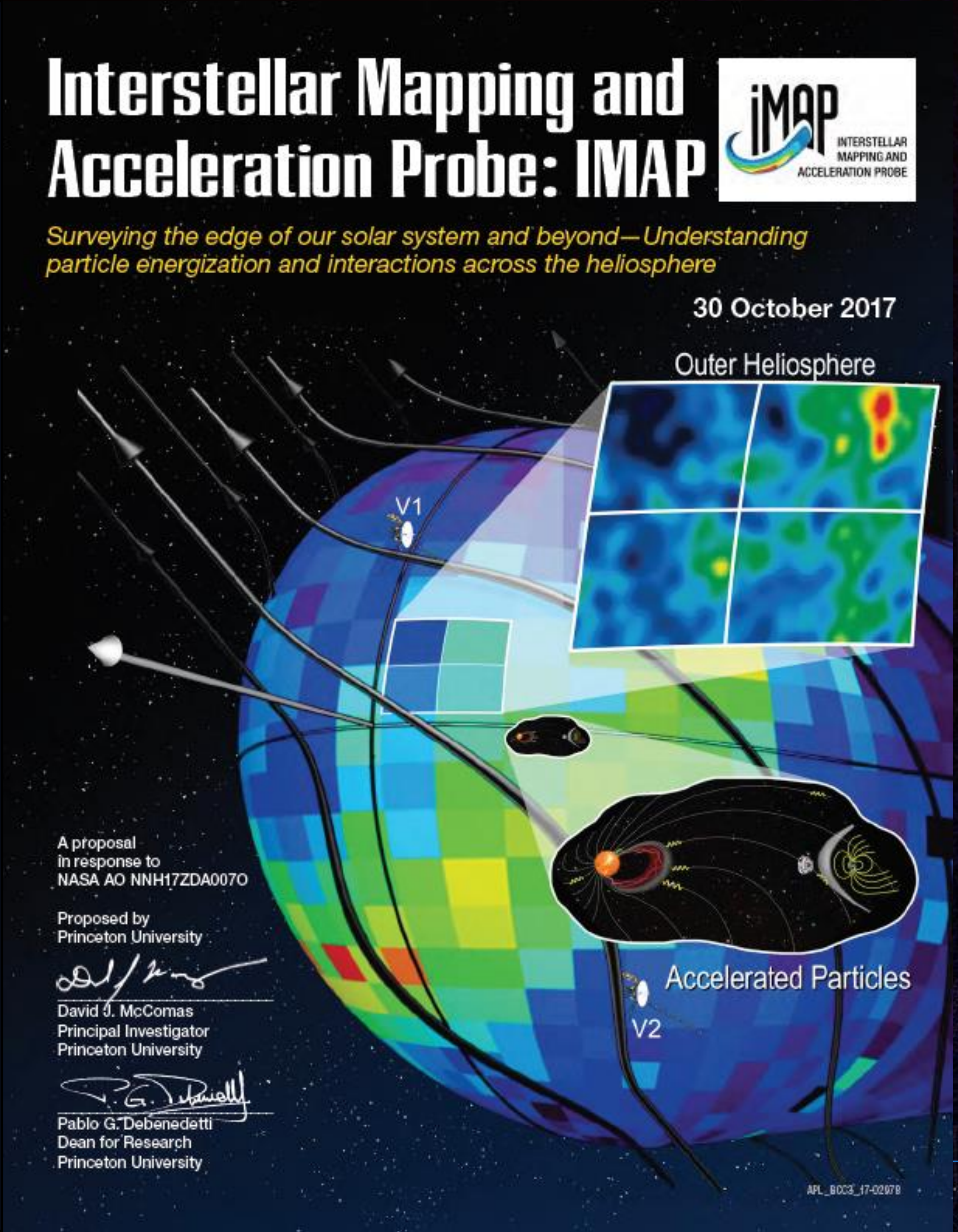
Unique combination of local and remote observations

Mission PI: Dave McComas

- "IMAP is the next big step in the quest to understand our solar neighborhood – from our own solar system and heliosphere to the local interstellar medium"
- "IMAP will go far beyond the work of IBEX and other missions, exploring and revealing the intricacies of the outer heliosphere in three dimensions to a much higher level than ever before imagined."

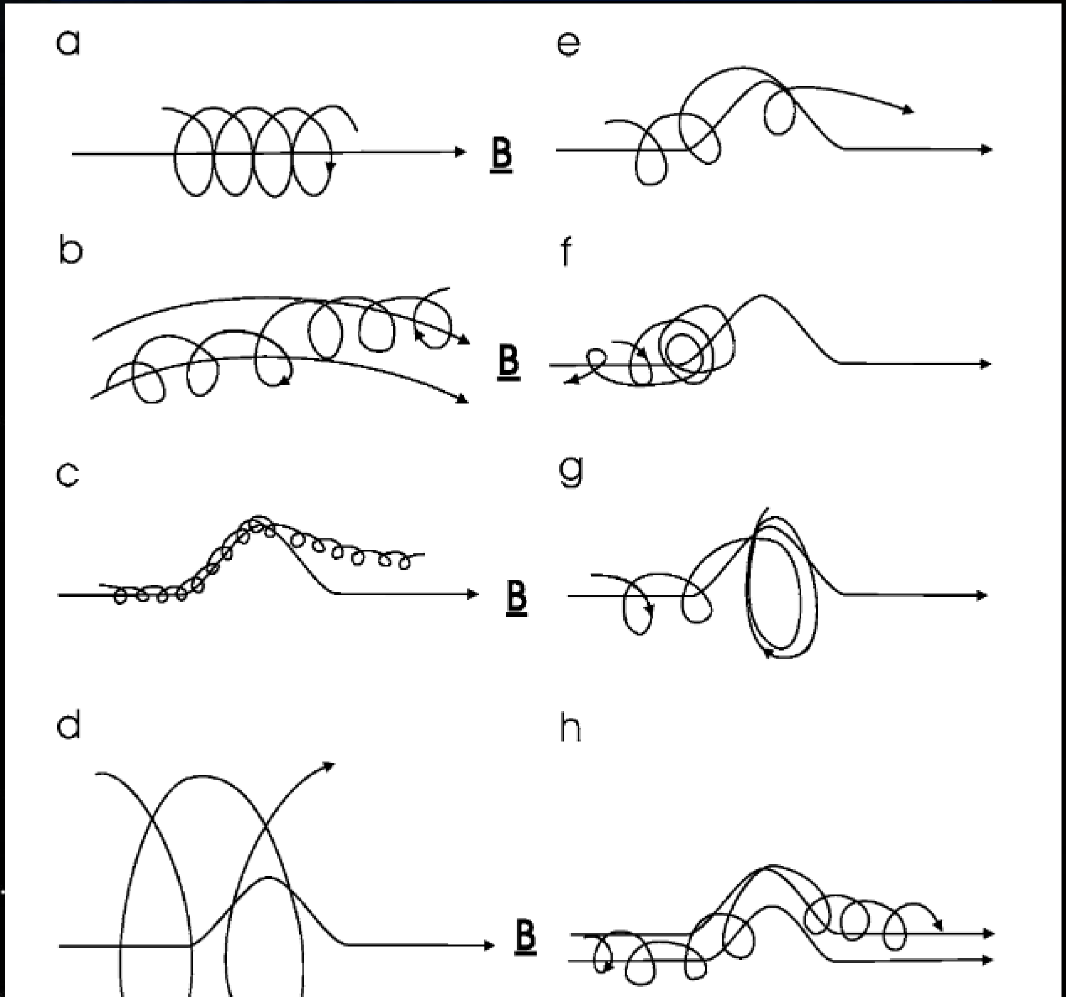
- Expected launch date: Mid-2025

IMAP NASA PRINCETON UNIVERSITY APL JOHNS HOPKINS APPLIED PHYSICS LABORATORY



An Intuitive Look at Cosmic Ray Transport

Charged Particle Motion in a Magnetic Field



Moraal (2013), SSRv 176:299-319

- $E^2 = p^2c^2 + m_0^2\, c^4$
- Lorentz force: $F = \mathbf{q}(E + \mathbf{v} \times \mathbf{B})$
  - But the electric field cannot do work:
    - $\nabla \times E = 0$
  - Therefore: $F = q\, v \times B = q\, v\, B \sin \alpha = mv^2/r$
  - → can solve for the radius of curvature of the particle's motion known as the particle's gyroradius:
    - $r_g = mv \sin \alpha/(qB) = P/B\, c$