Voyager 1 & 2:
Humanity's Most Distant Explorers

Oklahoma Engineering Conference
June 16, 2023

Todd J. Barber (Voyager Propulsion Engineer)
Slides Shamelessly Stolen from Suzy Dodd (Voyager Project Manager)
Jet Propulsion Laboratory/California Institute of Technology

Voyager is 1975 technology!

Voyager 1 & 2 Memory = 69k each → iPhone 5 has 240,000x the amount of memory
(but don't knock ~64k of memory; my Commodore 64 still works like a champ after 40 years!

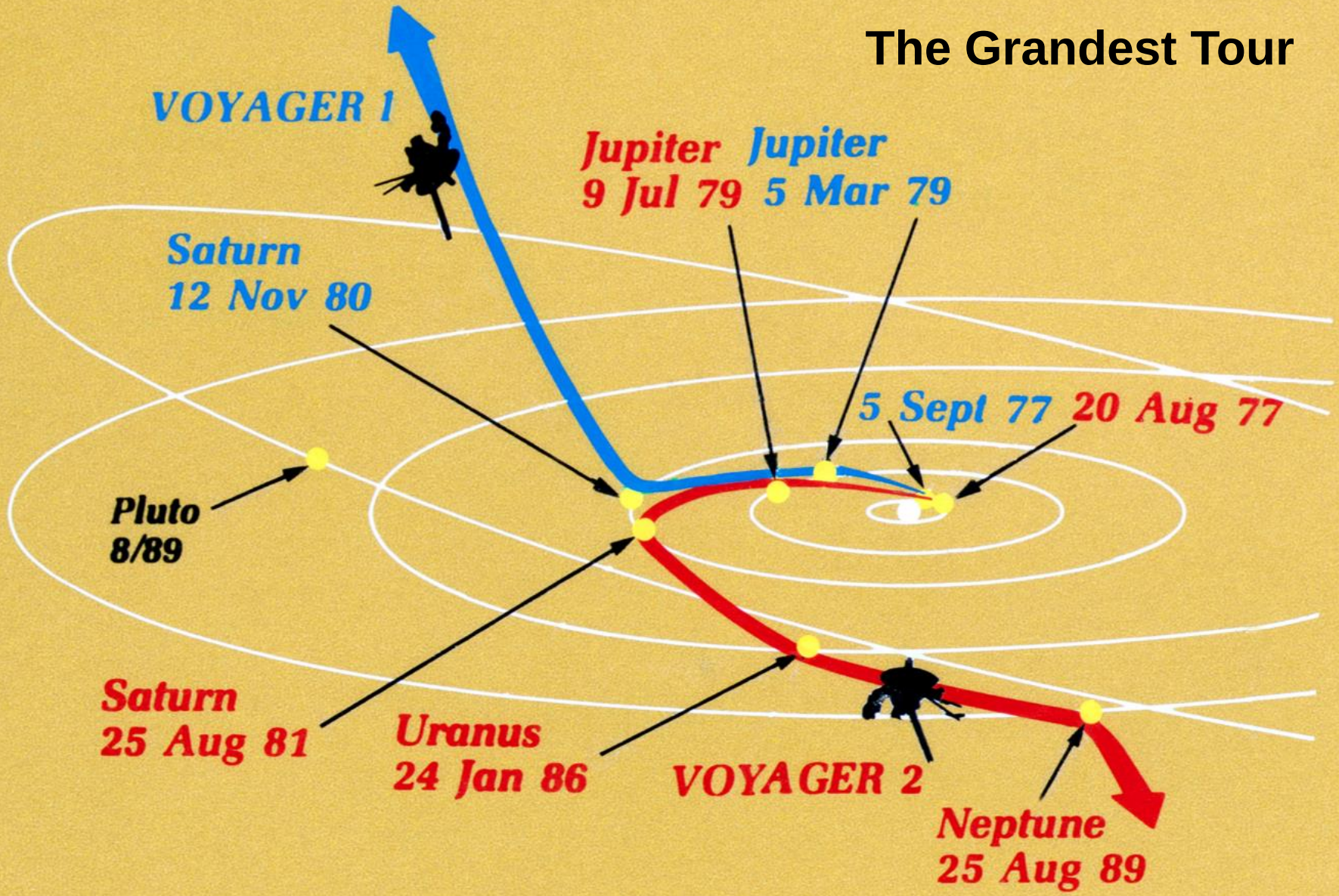
First spacecraft with autonomous fault protection, radiation-hardened parts

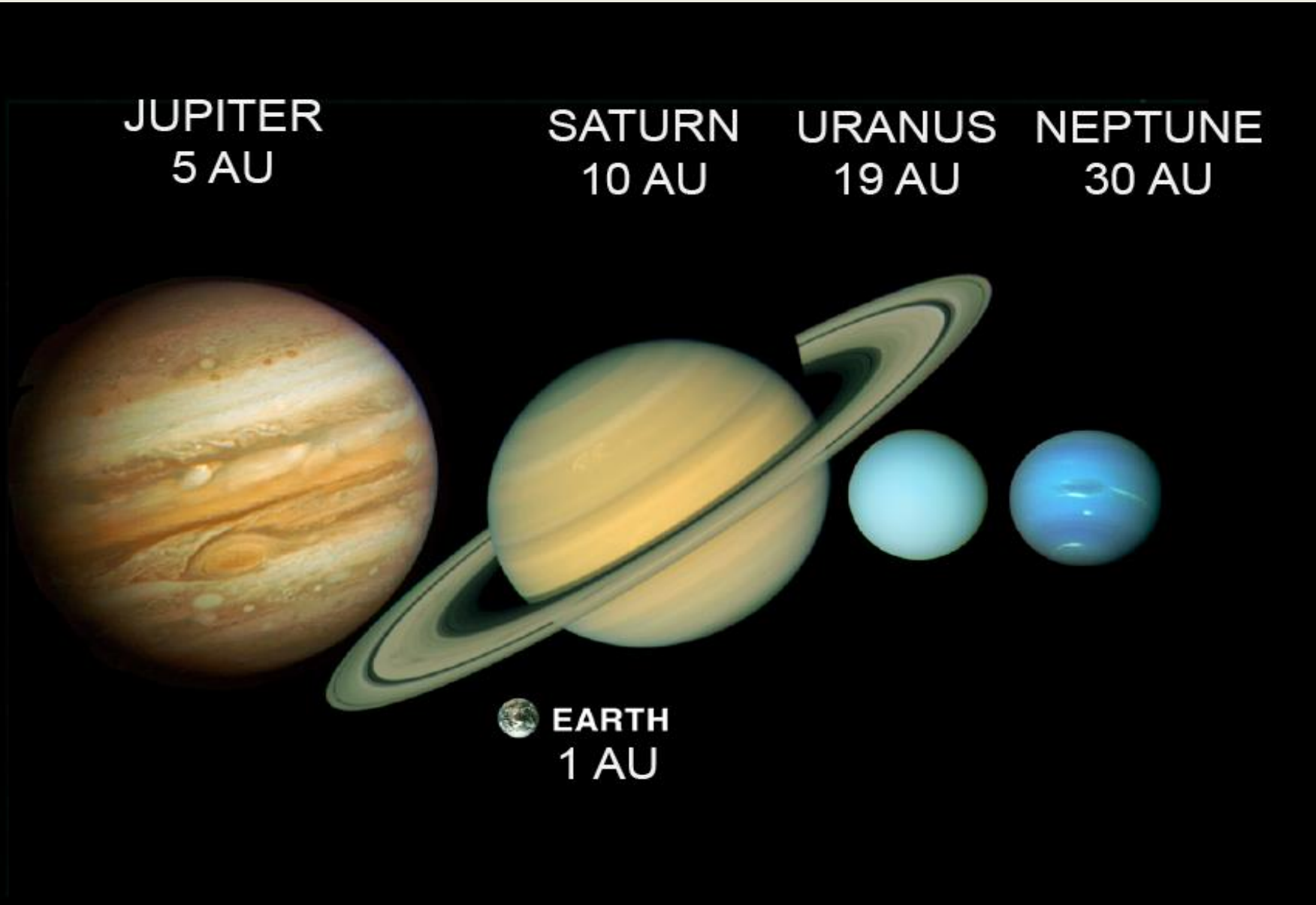
Launched in the Summer of 1977—what else was launched that year?

A little movie called "Stars Wars"…the Apple II computer…and "How Deep is Your Love?"

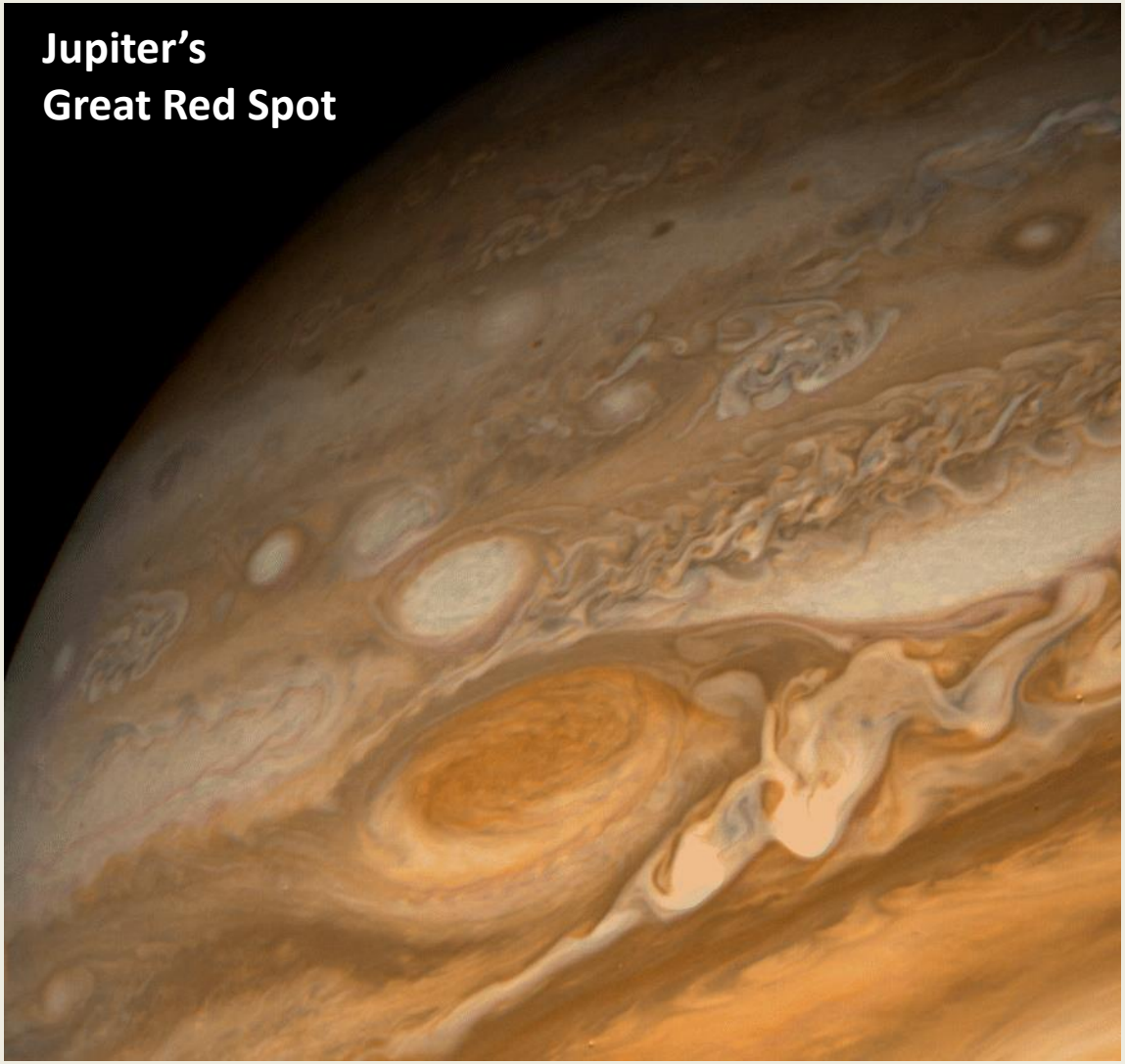
Voyager 2

The Grandest Tour

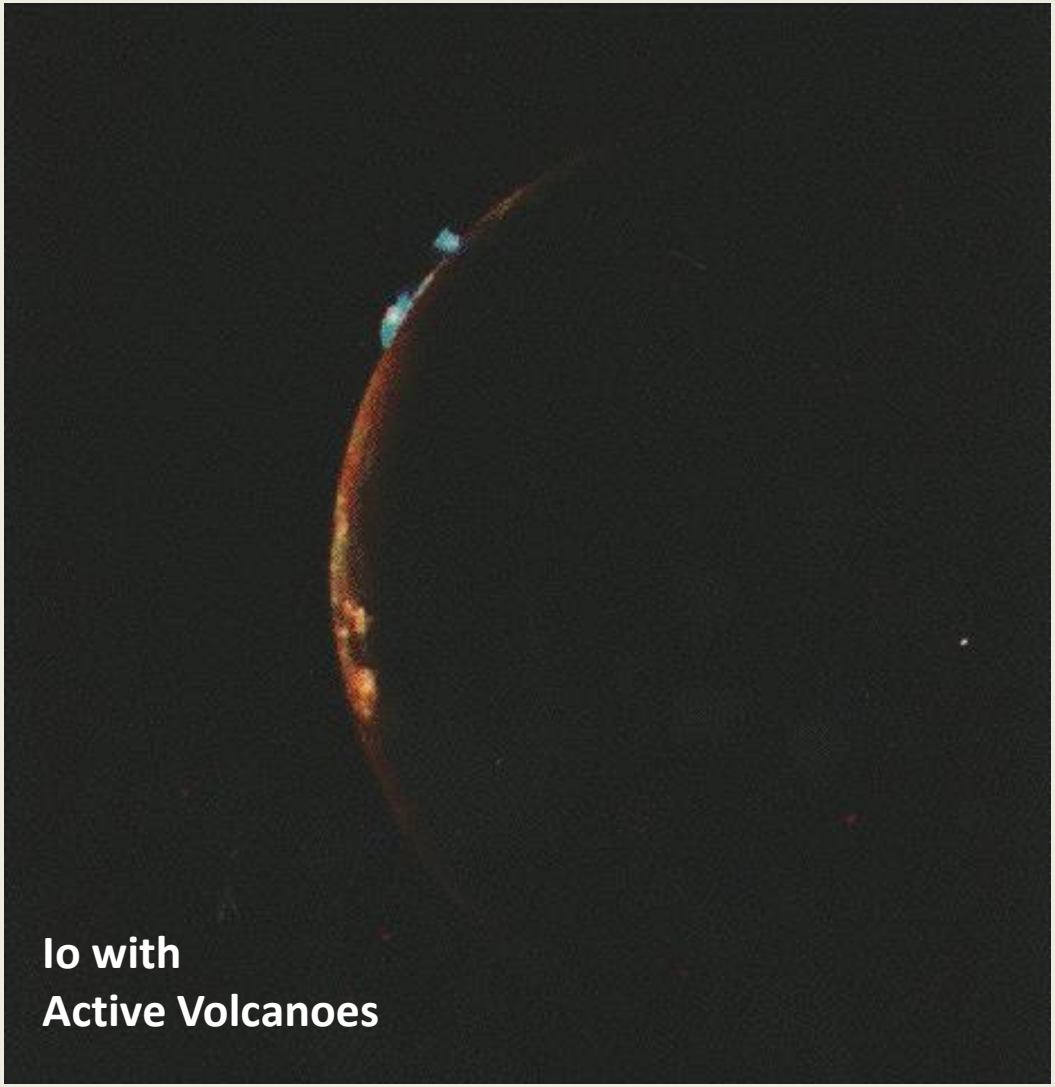




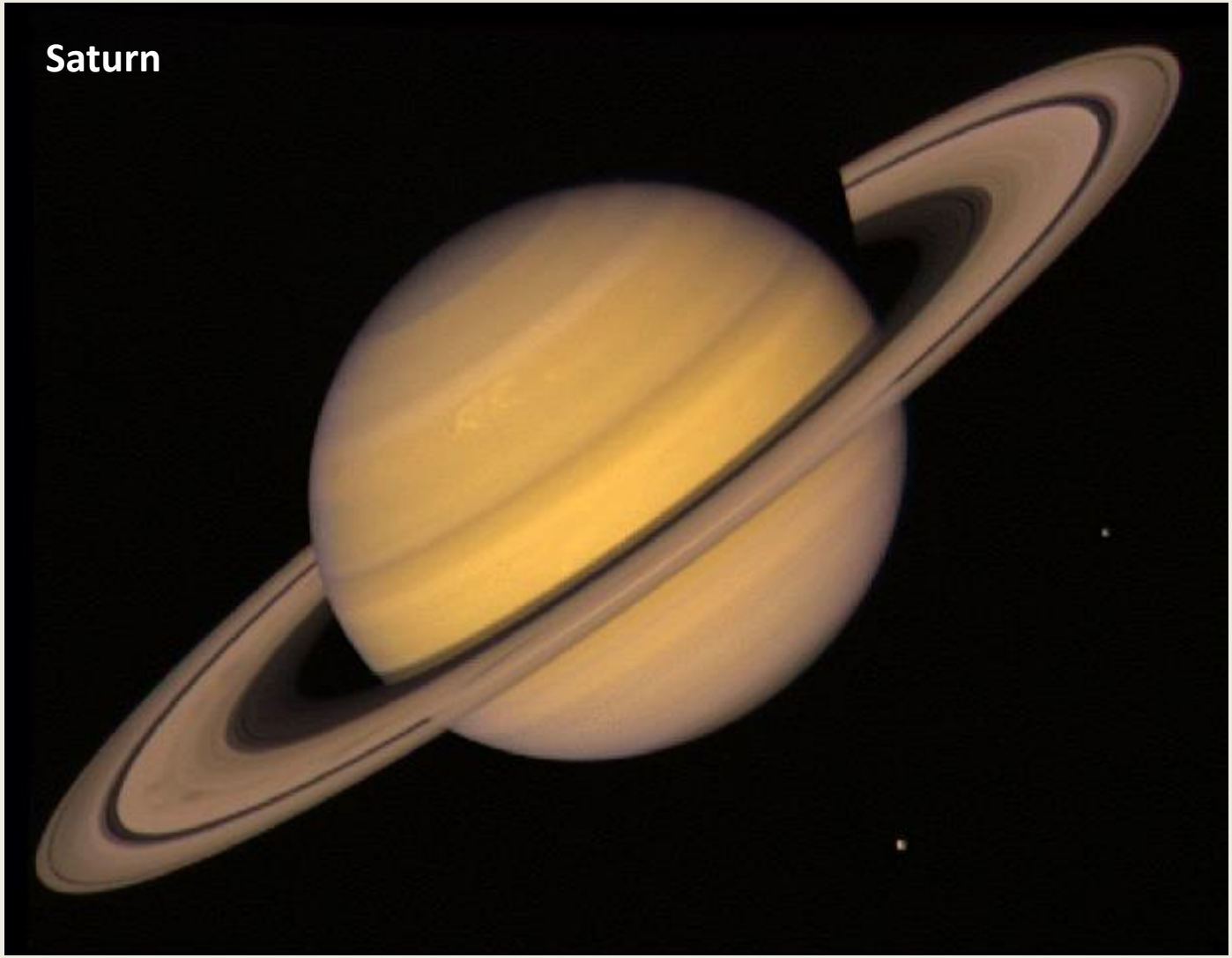
1 AU = 150 million km (93 million miles)



Voyager 5



Voyager 6



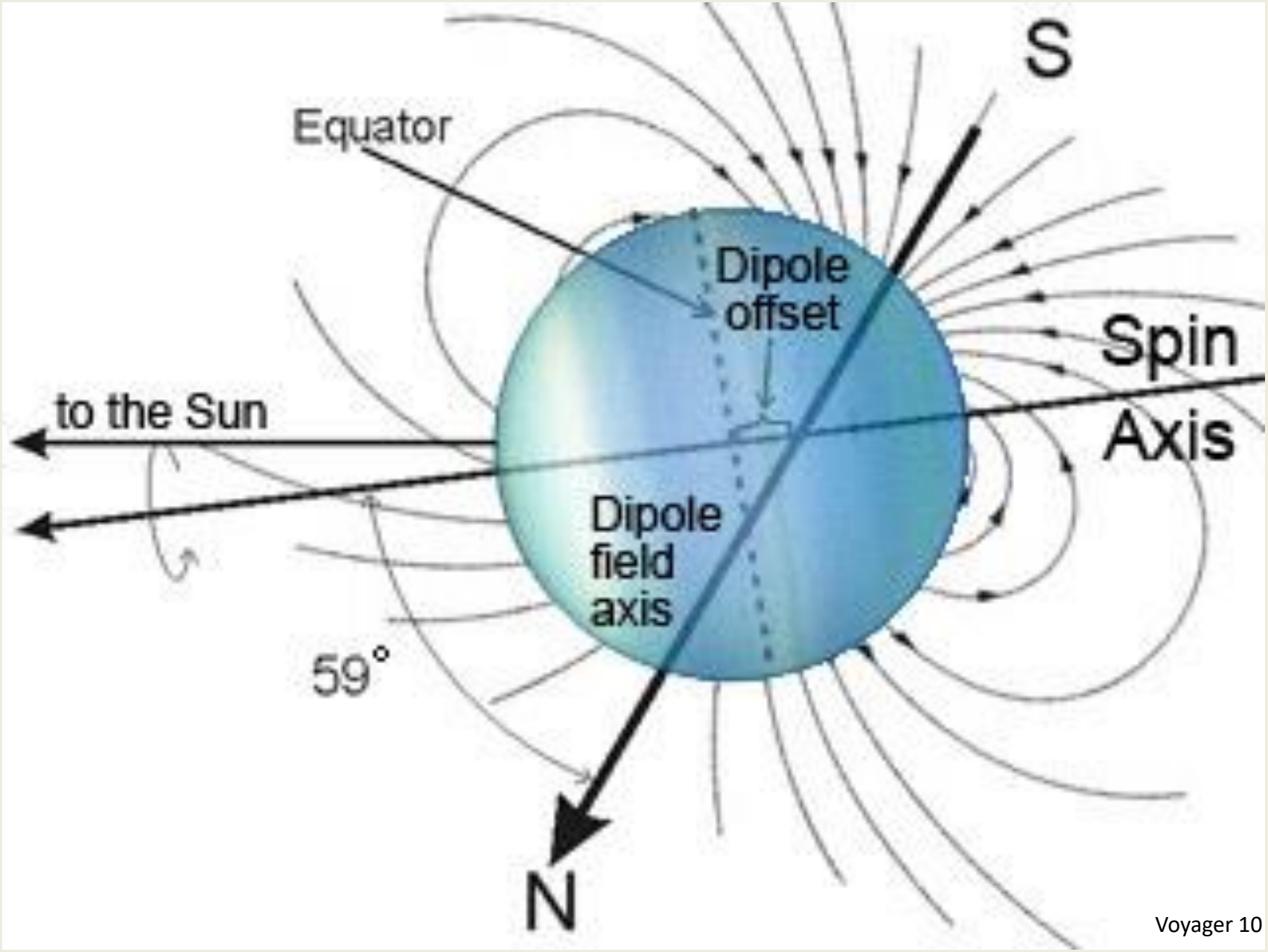
Voyager 7

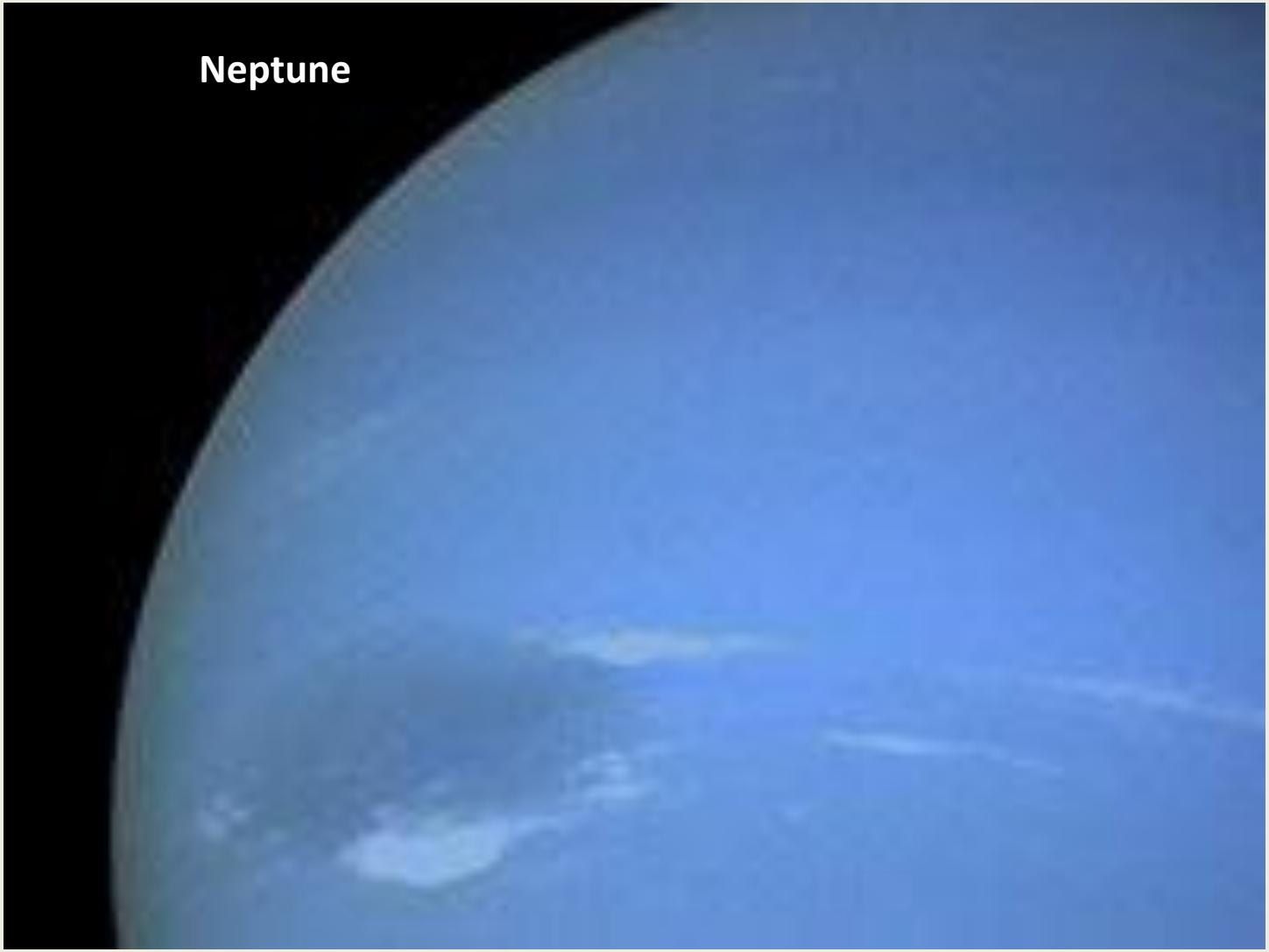
Uranus: True Color and False Color

Voyager 8

Voyager 9

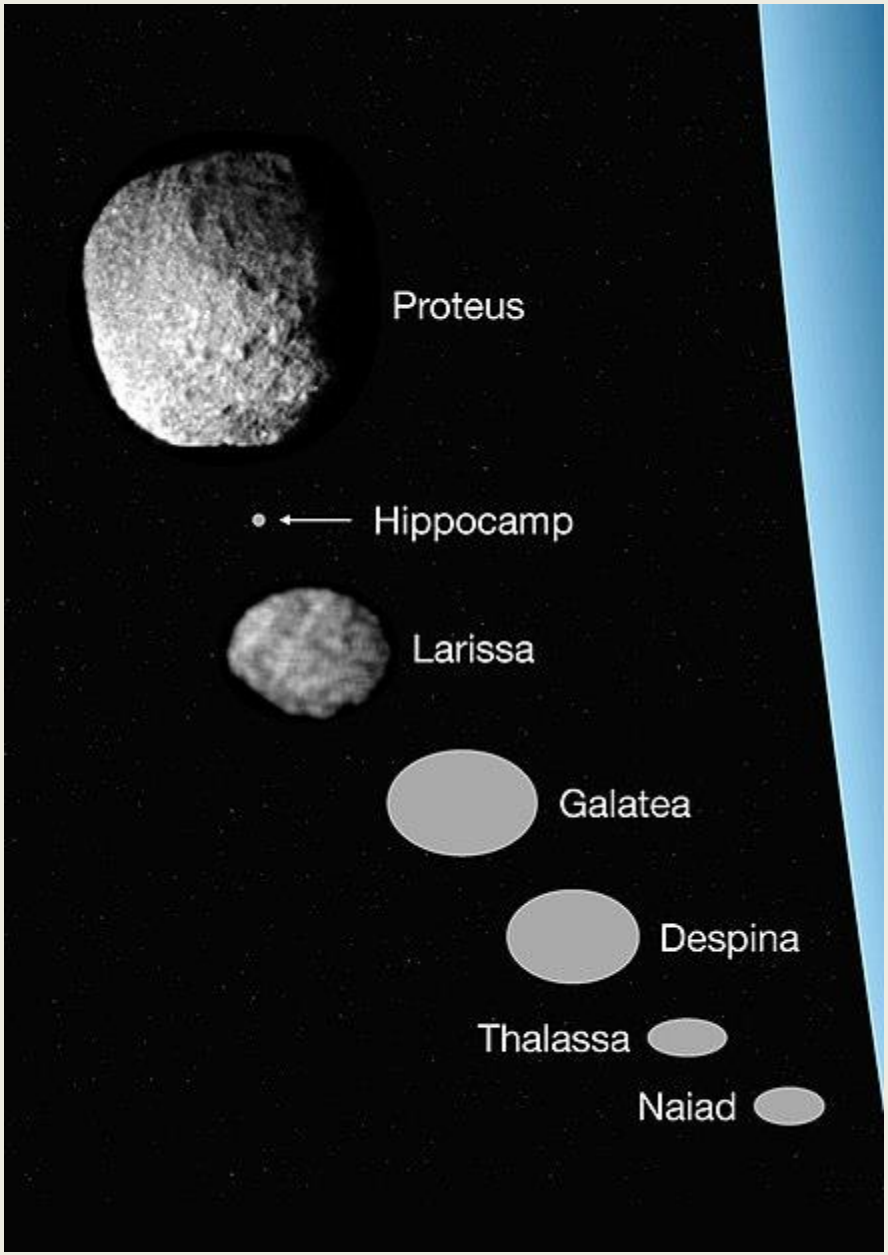
The Uranus Magnetic Field: Offset from Center and Tilted Like Mad

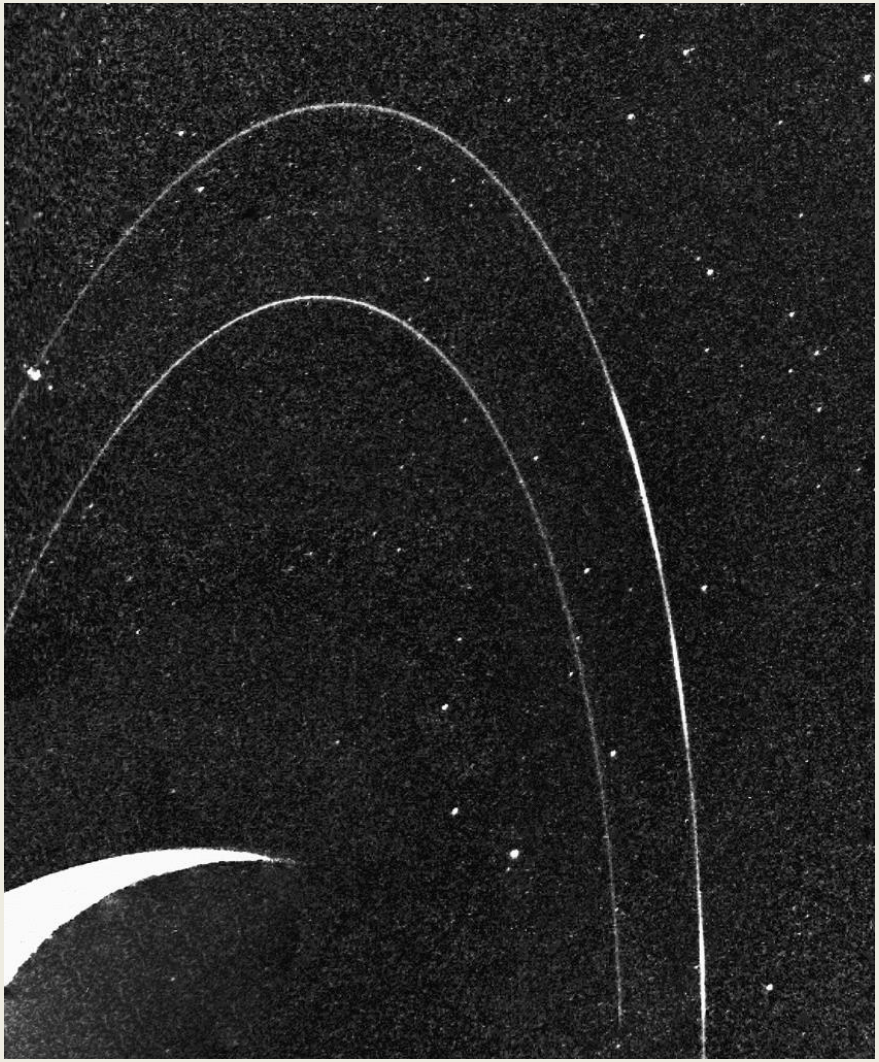




Voyager 11

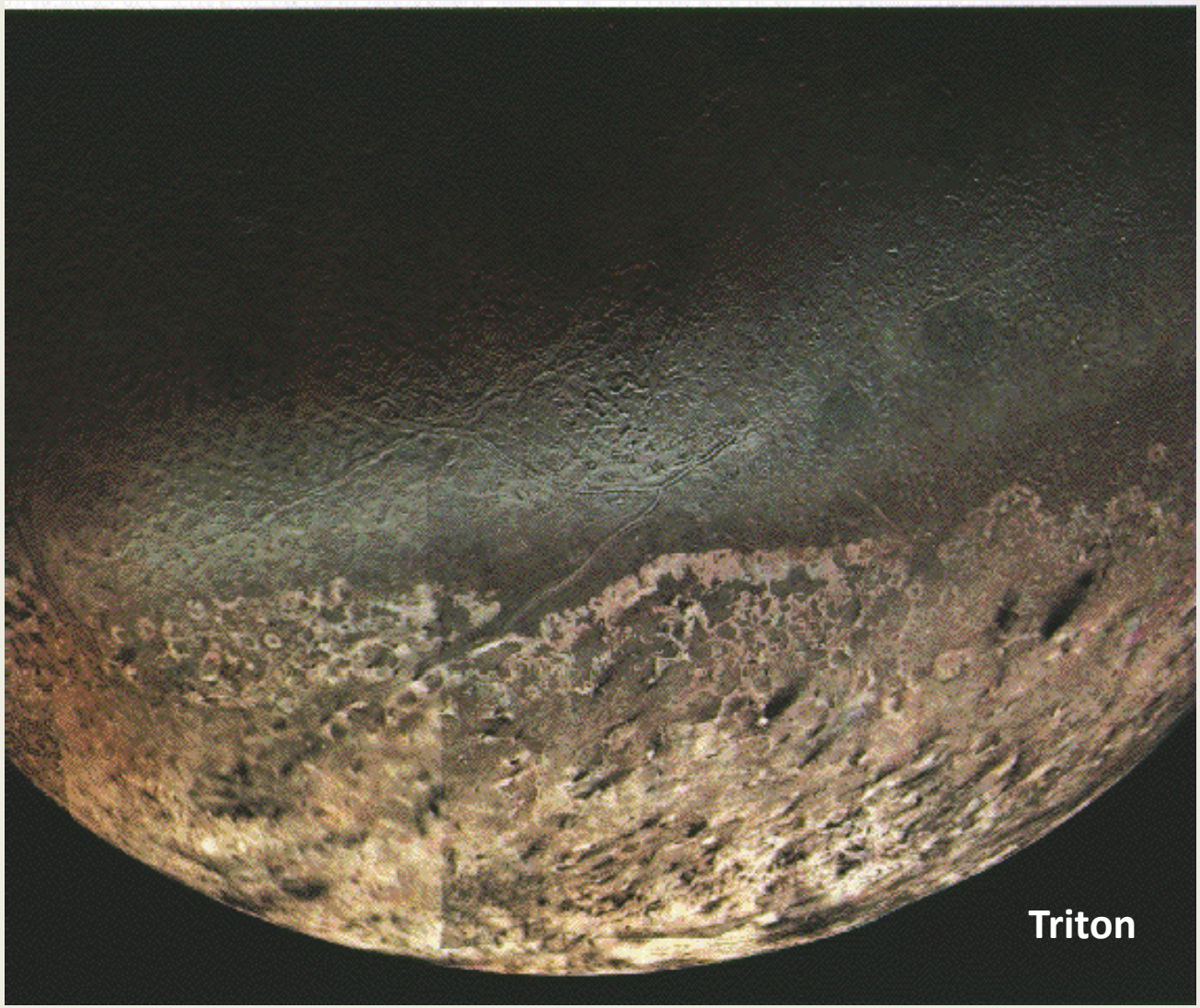
More Surprises at Neptune: Cool Moons and Clumpy Ring Arcs

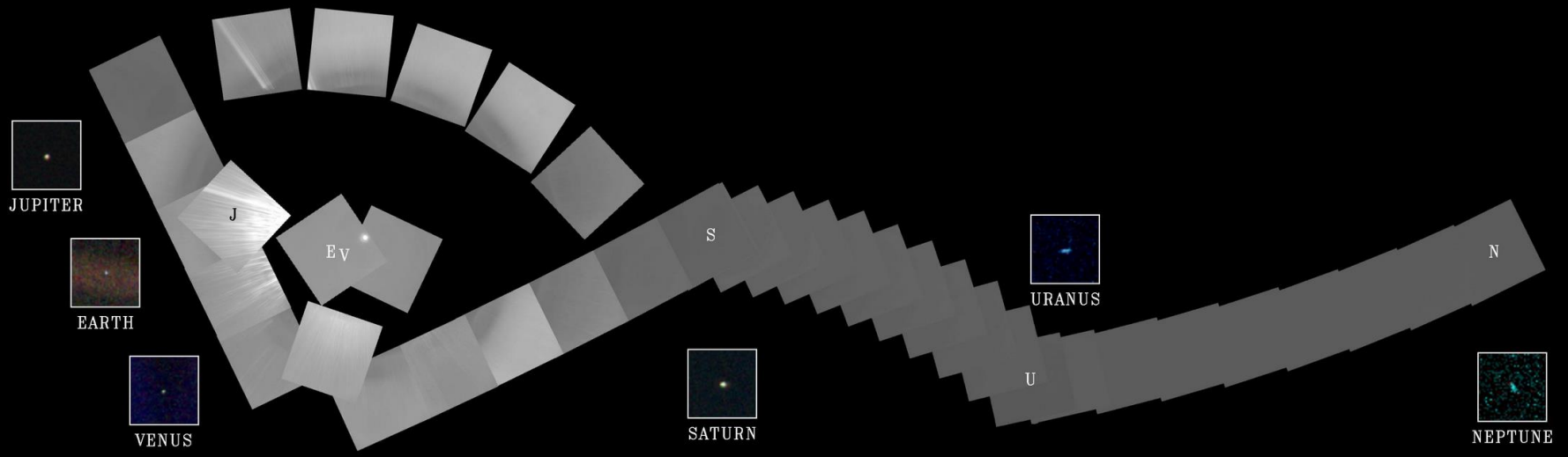




Voyager 12

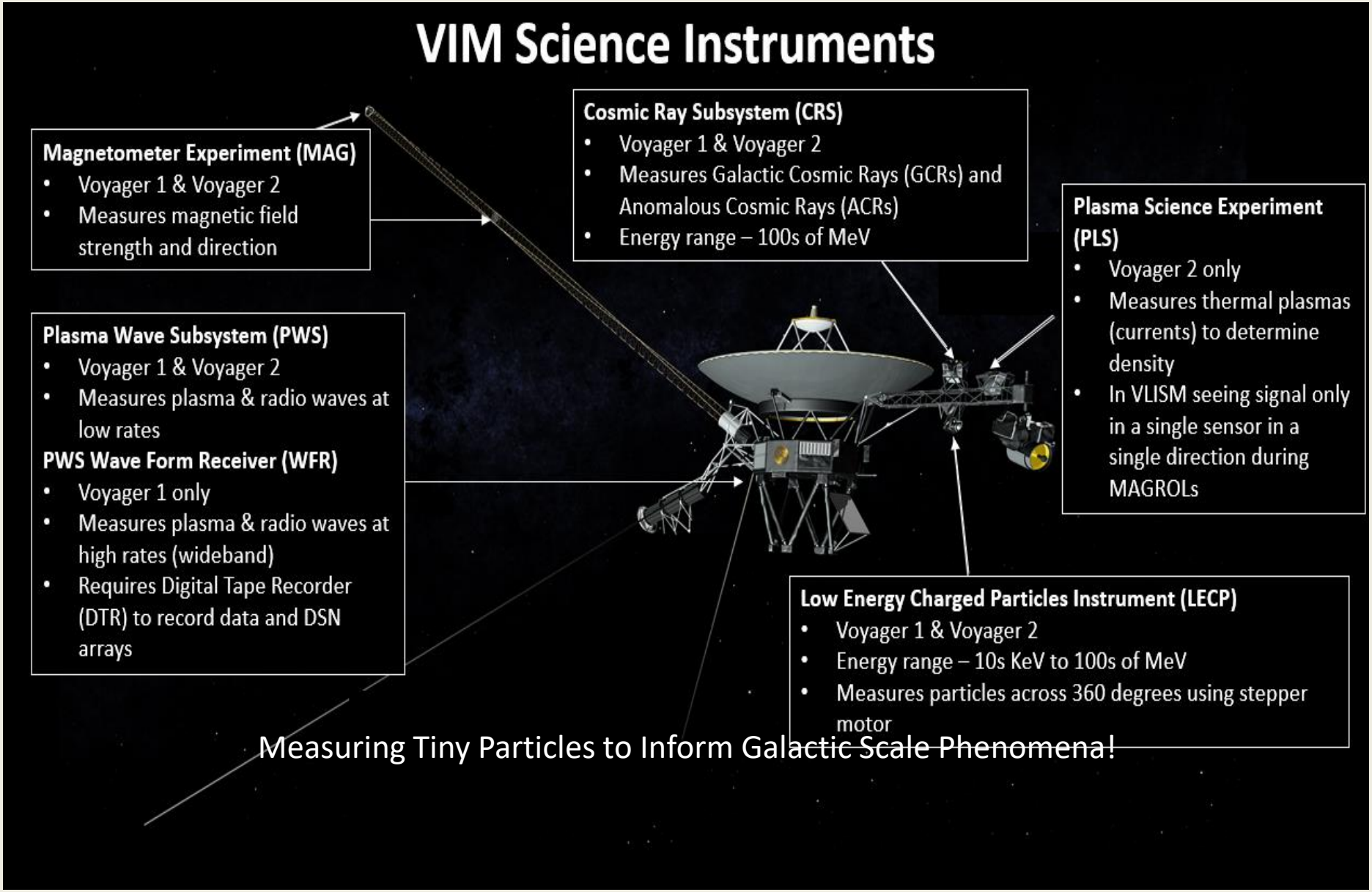
…but Triton Stole the Show (Active Nitrogen Geysers, Barely Above Absolute Zero!)



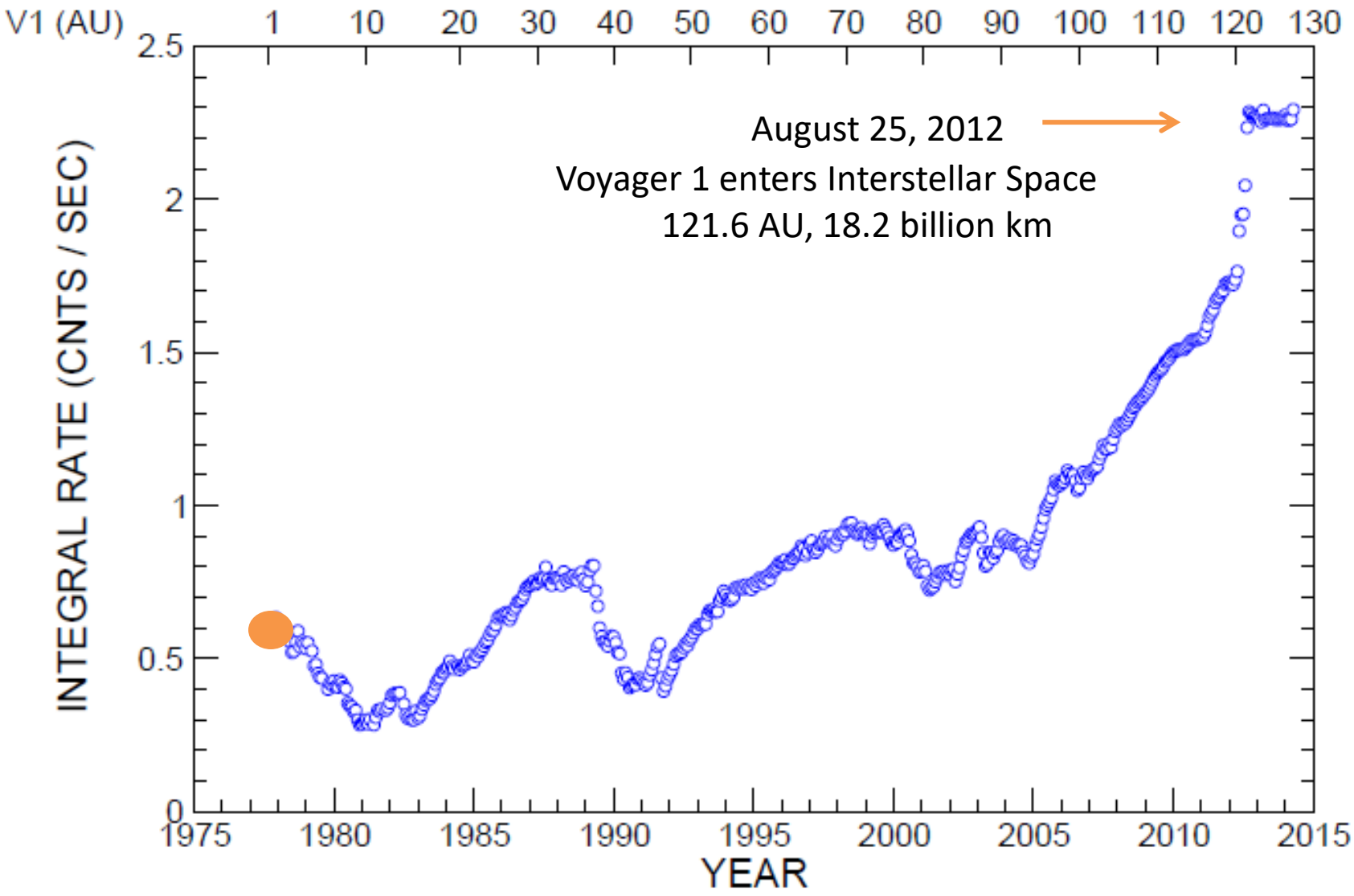


The Big Picture

VIM Science Instruments



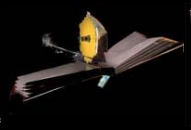
Cosmic Rays from Milky Way Galaxy



The DSN is very busy!

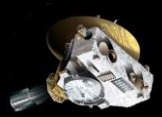
- The DSN communicates with ~40 missions in flight every day

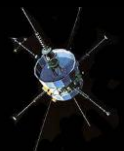

Voyager 1 & 2


JWST


TESS


INTEGRAL


New Horizons


Geotail


Mars Odyssey


Curiosity


Perseverance

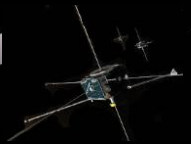

TGO

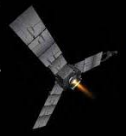

OSIRIS-REx

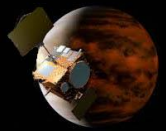

LRO


PSP


XMM

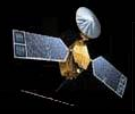

THEMIS


JUNO


Planet-C

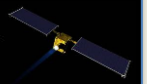

MAVEN


Mars Express

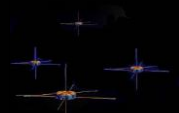

Mars Reconn. Orbiter


InSight

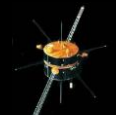

EMM

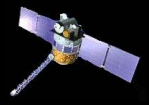

DART


Chandra


MMS

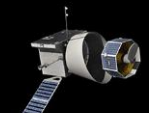

STEREO A


Wind

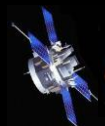

DSCOVR


GAIA

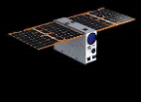

SOHO


Bepi Colombo


Hayabusa-2


ACE


Lucy

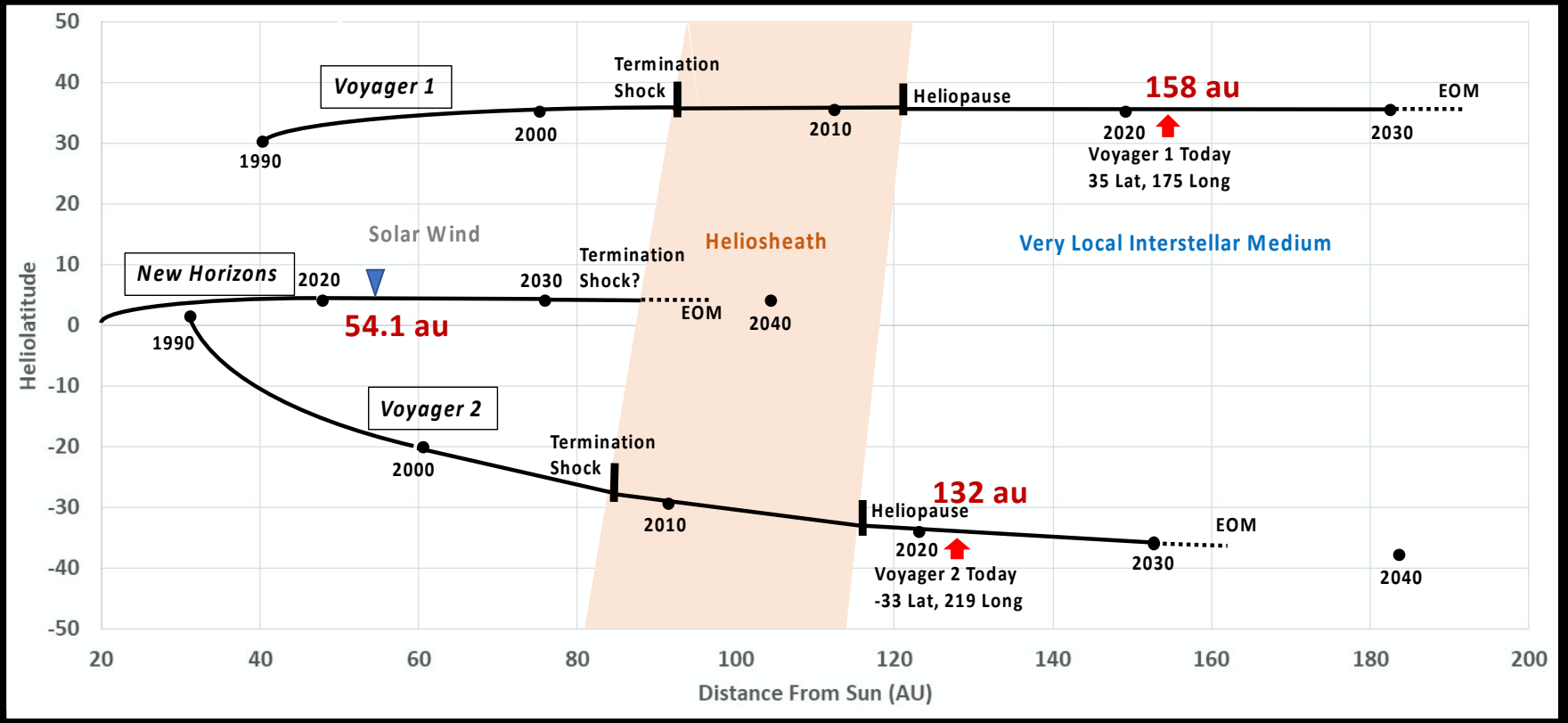

LICIACube

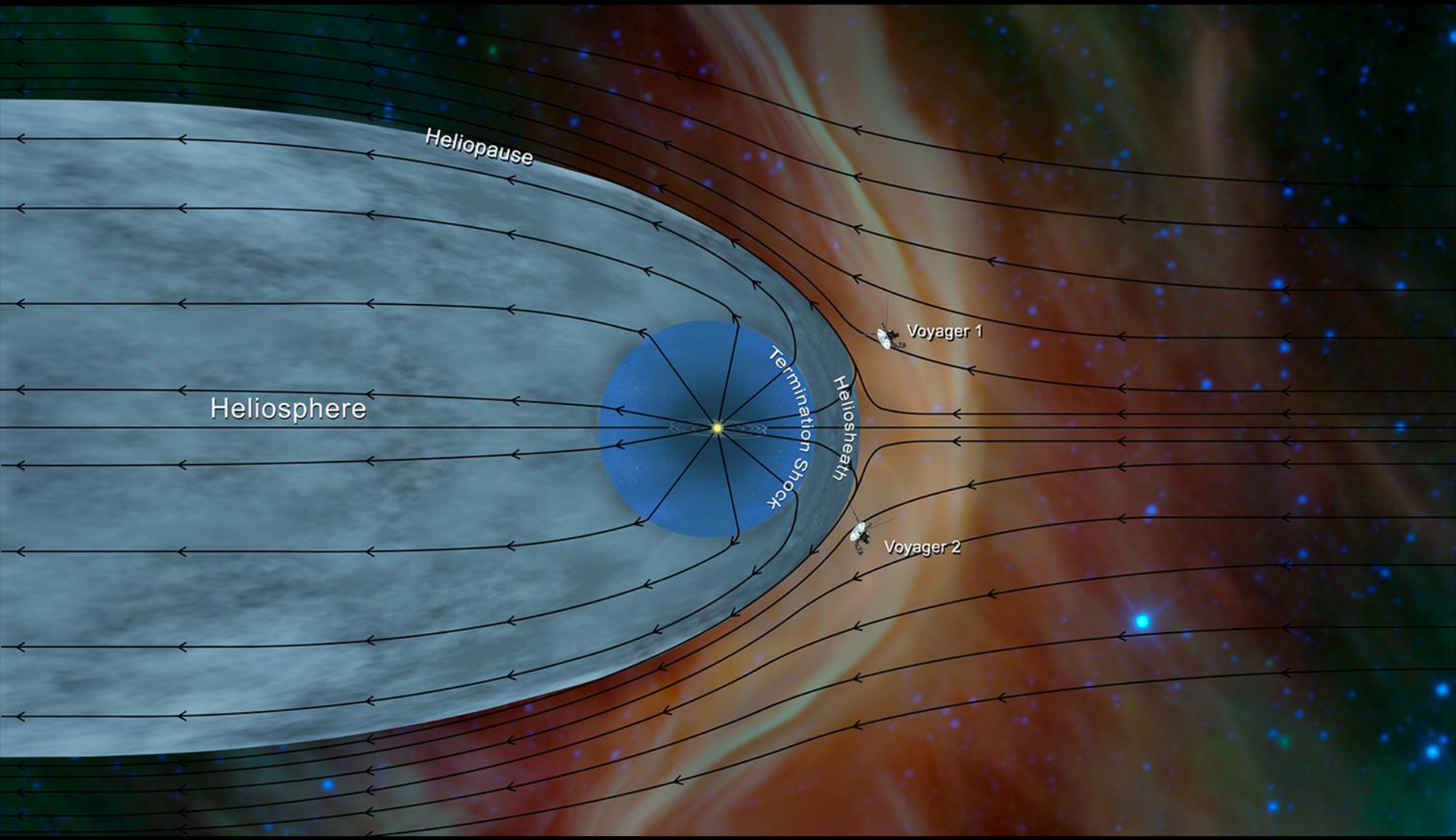
- But the DSN has only 14 operational antennas
- And there is planetary alignments involved

Voyager 18

Voyager 19

VIM Trajectory




Heliopause
Heliosphere
Termination Shock
Heliosheath
Voyager 1
Voyager 2

Voyager Latest Mission Status (as of 6/9/2023)

	Voyager 1	Voyager 2
Launch Date	Mon, 05 Sept 1977 12:56:00 UTC	Sat, 20 Aug 1977 14:29:00 UTC
Mission Elapsed Time	45 : 09 : 04 : 05 : 27 : 11 YRS MOS DAYS HRS MINS SECS	45 : 09 : 20 : 03 : 54 : 11 YRS MOS DAYS HRS MINS SECS
Distance from Earth	14,813,750,325 mi	12,355,005,458 mi
	159.36341518 AU	132.91272103 AU
Distance from Sun	14,890,847,691 mi	12,417,489,907 mi
	160.19281350 AU	133.58491646 AU
Velocity with respect to the Sun (estimated)	38,026.77 mph	34,390.98 mph
One-Way Light Time	22:05:23 (hh:mm:ss)	18:25:24 (hh:mm:ss)
Cosmic Ray Data		

https://voyager.jpl.nasa.gov/

Results and Future Objectives

All nine of the remaining powered instruments have produced a 43-year-long, complementary data set, with both spacecraft having explored the outer Heliosphere

What is the shape of the Heliosphere?!

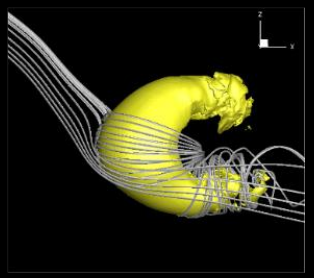
Heliosheath characteristics varied greatly at the two different locations sampled by the two spacecraft. What causes these variations?

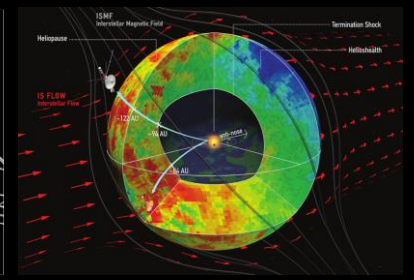
The Heliopause is a surprisingly dynamic and complex boundary region; Voyager 1 found unexpected structure and variability in this boundary and a surprisingly contiguous magnetic field across it. What causes the variability and structure?

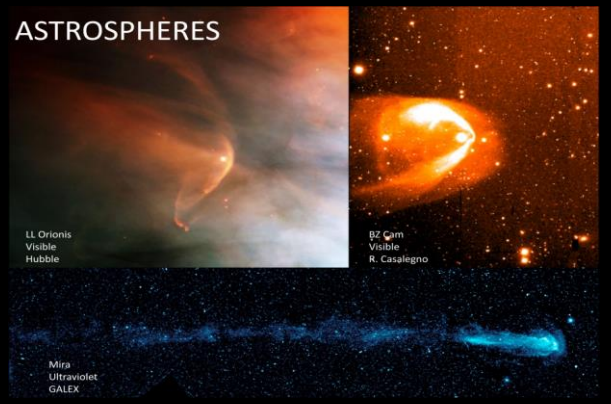
The Bow Shock is the shock wave that may form due to movement of the Heliosphere through the Local Interstellar Medium (LISM). Is there a Bow Shock? What is the plasma density in the LISM?

The Voyagers provide direct observation of Galactic Cosmic Rays (GCRs) before they are modulated by the solar environment and of Anomalous Cosmic Rays (ACRs) near possible source regions. What are the elemental and isotopic abundances of GCRs and ACRs? What are the ACR source regions?

The Voyagers have really just started to answer the most interesting questions of the Interstellar Mission. They are exploring stellar shock environments in situ and we may not have this opportunity again for many, many decades!

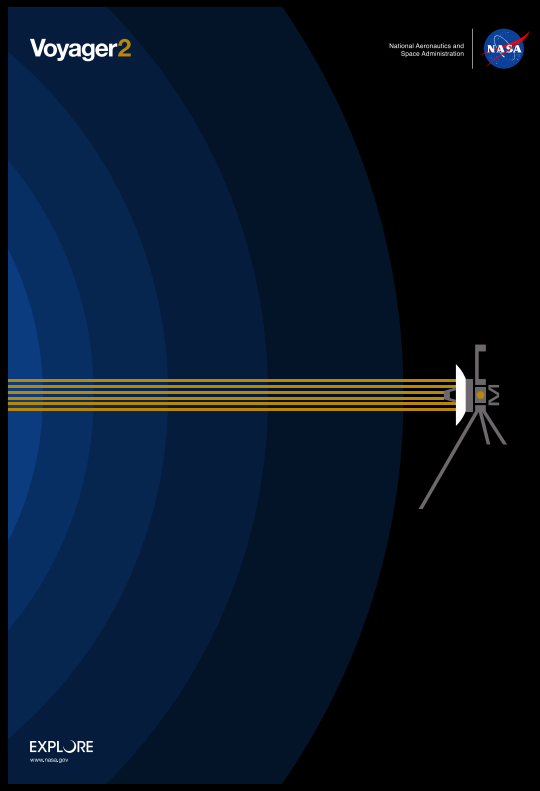






VIM Challenges

- The two spacecraft differ operationally from each other due to hardware degradation and thermal behavior
- Need to manage diminishing power coupled with decreasing spacecraft temperature
- Long round trip light time and low data rate require mission operations to be simple and the spacecraft to be as autonomous as possible
- Aging Hardware and Software
  - Spacecraft degradations and failures occur
  - Upgrades to ground software are required
- Knowledge capture and documentation is very important for a long duration mission
- Other Challenges
  - No hardware Testbed, Limited Memory, Antiquated Language, …



Voyager 1 Press Release 1/2017: TCM Thruster Swap

If you tried to start a car that's been sitting in a garage for decades, you might not expect the engine to respond. But a set of thrusters aboard the Voyager 1 spacecraft successfully fired up Wednesday after 37 years without use.

Voyager 1, NASA's farthest and fastest spacecraft, is the only human-made object in interstellar space, the environment between the stars. The spacecraft, which has been flying for 40 years, relies on small devices called thrusters to orient itself so it can communicate with Earth. These thrusters fire in tiny pulses, or "puffs," lasting mere milliseconds, to subtly rotate the spacecraft so that its antenna points at our planet. Now, the Voyager team is able to use a set of four backup thrusters, dormant since 1980.

"With these thrusters that are still functional after 37 years without use, we will be able to extend the life of the Voyager 1 spacecraft by two to three years," said Suzanne Dodd, project manager for Voyager at NASA's Jet Propulsion Laboratory, Pasadena, California.

Since 2014, engineers have noticed that the thrusters Voyager 1 has been using to orient the spacecraft, called "attitude control thrusters," have been degrading. Over time, the thrusters require more puffs to give off the same amount of energy. At 13 billion miles from Earth, there's no mechanic shop nearby to get a tune-up.

The Voyager team assembled a group of propulsion experts at NASA's Jet Propulsion Laboratory, Pasadena, California, to study the problem. Chris Jones, Robert Shotwell, Carl Guernsey and Todd Barber analyzed options and predicted how the spacecraft would respond in different scenarios. They agreed on an unusual solution: Try giving the job of orientation to a set of thrusters that had been asleep for 37 years.

“The Voyager flight team dug up decades-old data and examined the software that was coded in an outdated assembler language, to make sure we could safely test the thrusters," said Jones, chief engineer at JPL.

In the early days of the mission, Voyager 1 flew by Jupiter, Saturn, and important moons of each. To accurately fly by and point the spacecraft's instruments at a smorgasbord of targets, engineers used "trajectory correction maneuver,” or TCM, thrusters that are identical in size and functionality to the attitude control thrusters, and are located on the back side of the spacecraft. But because Voyager 1's last planetary encounter was Saturn, the Voyager team hadn't needed to use the TCM thrusters since November 8, 1980. Back then, the TCM thrusters were used in a more continuous firing mode; they had never been used in the brief bursts necessary to orient the spacecraft.

All of Voyager's thrusters were developed by Aerojet Rocketdyne. The same kind of thruster, called the MR-103, flew on other NASA spacecraft as well, such as Cassini and Dawn.

On Tuesday, Nov. 28, 2017, Voyager engineers fired up the four TCM thrusters for the first time in 37 years and tested their ability to orient the spacecraft using 10-millisecond pulses. The team waited eagerly as the test results traveled through space, taking 19 hours and 35 minutes to reach an antenna in Goldstone, California, that is part of NASA's Deep Space Network.

Lo and behold, on Wednesday, Nov. 29, they learned the TCM thrusters worked perfectly -- and just as well as the attitude control thrusters.

Voyager 2 Press Release 2/2020: Undervoltage Trip

Voyager 2 Engineers Working to Restore Normal Operations

UPDATED on Feb. 5, 2020

Mission operators report that Voyager 2 continues to be stable and that communications between Earth and the spacecraft are good. The spacecraft has resumed taking science data, and the science teams are now evaluating the health of the instruments following their brief shutoff.

Engineers for NASA's Voyager 2 spacecraft are working to return the mission to normal operating conditions after one of the spacecraft's autonomous fault protection routines was triggered. Multiple fault protection routines were programmed into both Voyager 1 and Voyager 2 in order to allow the spacecraft to automatically take actions to protect themselves if potentially harmful circumstances arise. At NASA's Jet Propulsion Laboratory in Pasadena, California, engineers are still communicating with the spacecraft and receiving telemetry.

Launched in 1977, Voyager 1 and Voyager 2 are both in interstellar space, making them the most distant human-made objects in the solar system. On Saturday, Jan. 25, Voyager 2 didn't execute a scheduled maneuver in which the spacecraft rotates 360 degrees in order to calibrate its onboard magnetic field instrument. Analysis of the telemetry from the spacecraft indicated that an unexplained delay in the onboard execution of the maneuver commands inadvertently left two systems that consume relatively high levels of power operating at the same time. This caused the spacecraft to overdraw its available power supply.

The fault protection software routine was designed to automatically manage such an event, and by design, it appears to have turned off Voyager 2's science instruments to make up for the power deficit. As of Jan. 28, Voyager engineers have successfully turned off one of the high-power systems and turned the science instruments back on but have not yet resumed taking data. The team is now reviewing the status of the rest of the spacecraft and working on returning it to normal operations.

Voyager's power supply comes from a radioisotope thermoelectric generator (RTG), which turns heat from the decay of a radioactive material into electricity to power the spacecraft. Due to the natural decay of the material inside the RTG, Voyager 2's power budget goes down by about 4 watts per year. Last year, engineers turned off the primary heater for the Voyager 2 cosmic ray subsystem instrument in order to compensate for this power loss, and the instrument continues to operate.

In addition to managing each Voyager's power supply, mission operators must also manage the temperature of certain systems on the spacecraft. If, for example, the spacecraft fuel lines were to freeze and break, Voyager would no longer be able to point its antenna back at Earth to send data and receive commands. The temperature of the spacecraft is maintained either through the use of heaters or by taking advantage of excess heat from other onboard instruments and systems.

Voyager 1 Press Release 8/2022: Telemetry Anomaly

A critical system aboard the probe was sending garbled data about its status. Engineers have fixed the issue but are still seeking the root cause.

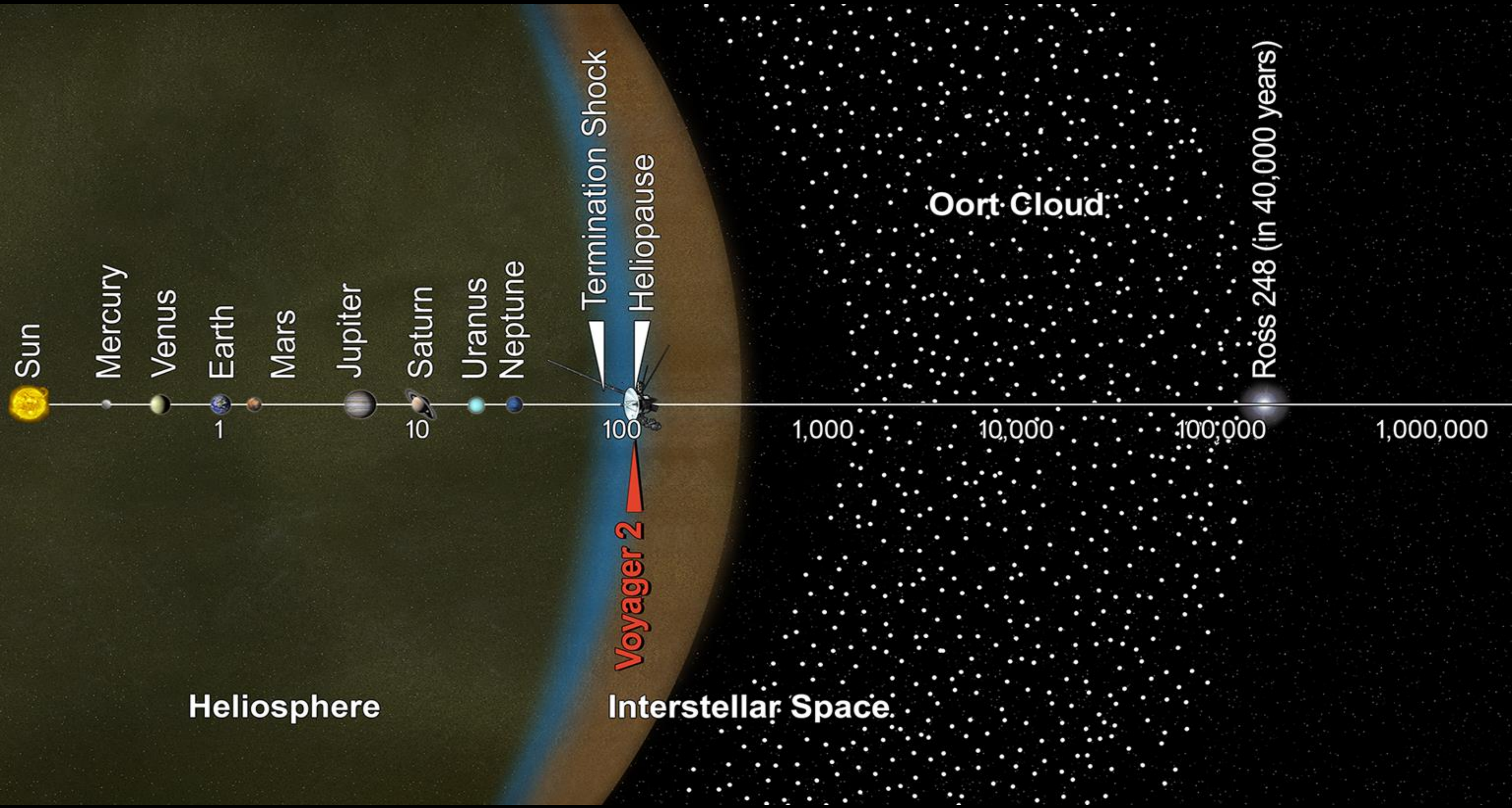
Engineers have repaired an issue affecting data from NASA's Voyager 1 spacecraft. Earlier this year, the probe's attitude articulation and control system (AACS), which keeps Voyager 1's antenna pointed at Earth, began sending garbled information about its health and activities to mission controllers, despite operating normally. The rest of the probe also appeared healthy as it continued to gather and return science data.

The team has since located the source of the garbled information: The AACS had started sending the telemetry data through an onboard computer known to have stopped working years ago, and the computer corrupted the information.

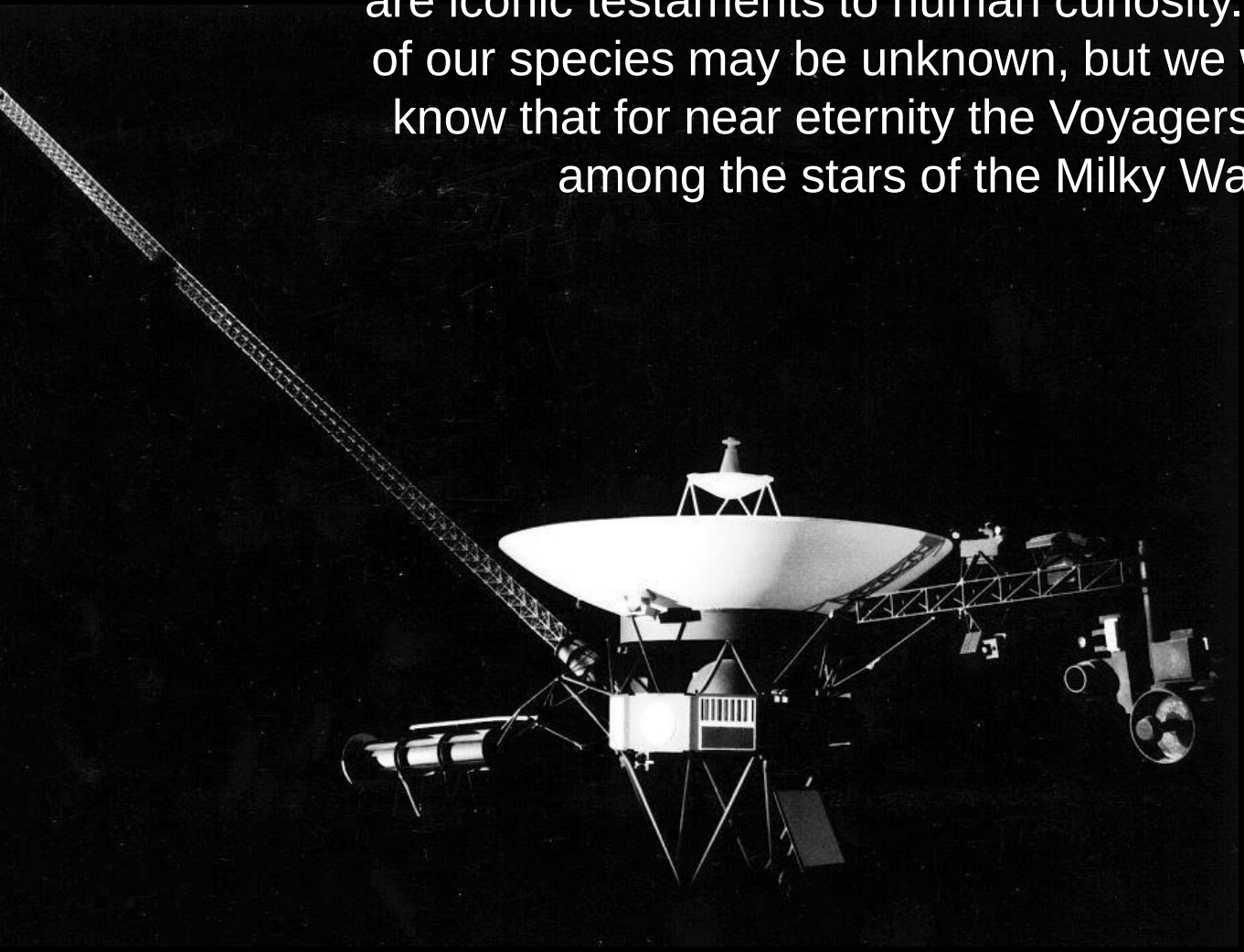
Suzanne Dodd, Voyager's project manager, said that when they suspected this was the issue, they opted to try a low-risk solution: commanding the AACS to resume sending the data to the right computer.

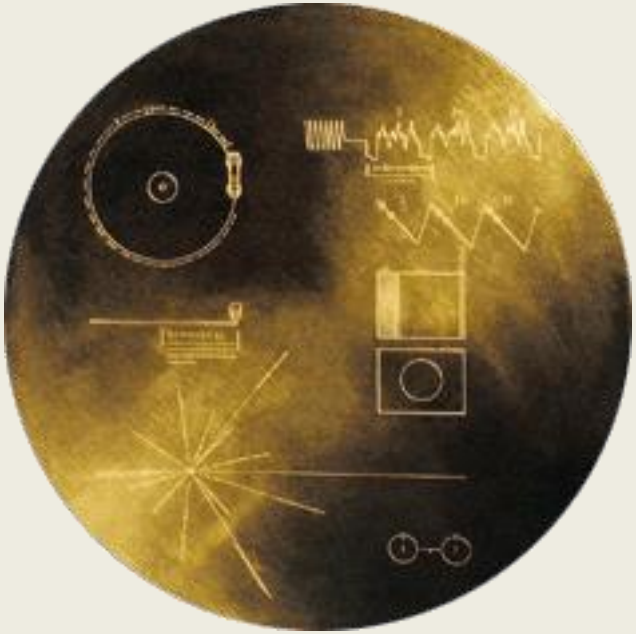
Engineers don't yet know why the AACS started routing telemetry data to the incorrect computer, but it likely received a faulty command generated by another onboard computer. If that's the case, it would indicate there is an issue somewhere else on the spacecraft. The team will continue to search for that underlying issue, but they don't think it is a threat to the long-term health of Voyager 1.

"We're happy to have the telemetry back," said Dodd. "We'll do a full memory readout of the AACS and look at everything it's been doing. That will help us try to diagnose the problem that caused the telemetry issue in the first place. So we're cautiously optimistic, but we still have more investigating to do."


Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Termination Shock
Heliopause
Ross 248 (in 40,000 years)
Oort Cloud
1
10
100
1,000
10,000
100,000
1,000,000
Voyager 2
Heliosphere
Interstellar Space

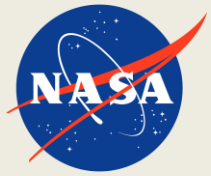
Whatever their future discoveries, the twin Voyagers are iconic testaments to human curiosity. The future of our species may be unknown, but we will always know that for near eternity the Voyagers will glide among the stars of the Milky Way.





Voyager's Golden Record: Scenes from Earth and Greetings to the Universe in 55 Different Languages

…oh, yeah, and some rock'n'roll, too! ☺



Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov