

The Adventures of

Voyager

Across the Solar Heliopause

Overview of the Voyage

- Voyager 1 has just rewritten what we believed about the Sun's effects on the edge of the Solar System.
- The Grand Tour fleet made dozens of first discoveries.
- Both Voyagers are still doing astronomy after almost 40 years.
- Our first interstellar probes to leave the Solar System.
 - (whenever it is that they *do* leave it)

Voyager and Companions

- First mission to outer solar system was big
 - Fleet of 4 craft
 - Pioneer 10, Pioneer 11 practiced on Jupiter
 - Voyager 1, Voyager 2 covered all the outer planets
- Why?
 - The 1970s planetary alignment made a Grand Tour possible

What they Did Along the Way

- Gravitational slingshot in a big way
- First craft to visit Jupiter and Saturn
- Only craft ever to visit Uranus and Neptune
- Discovered moons, rings, and more

Pioneer 10



- Launched March 3 1972
- First craft in asteroid belt
 - Discovered unexpectedly sparse objects
 - Proved it is safe to fly there
- First craft to Jupiter
- Found unexpected interplanetary helium
- Found unexpected hydrogen clouds around Io and Europa
- Discovered Jupiter is exothermic
- Last heard from January 23 2003

Photo: NASA

Pioneer 10

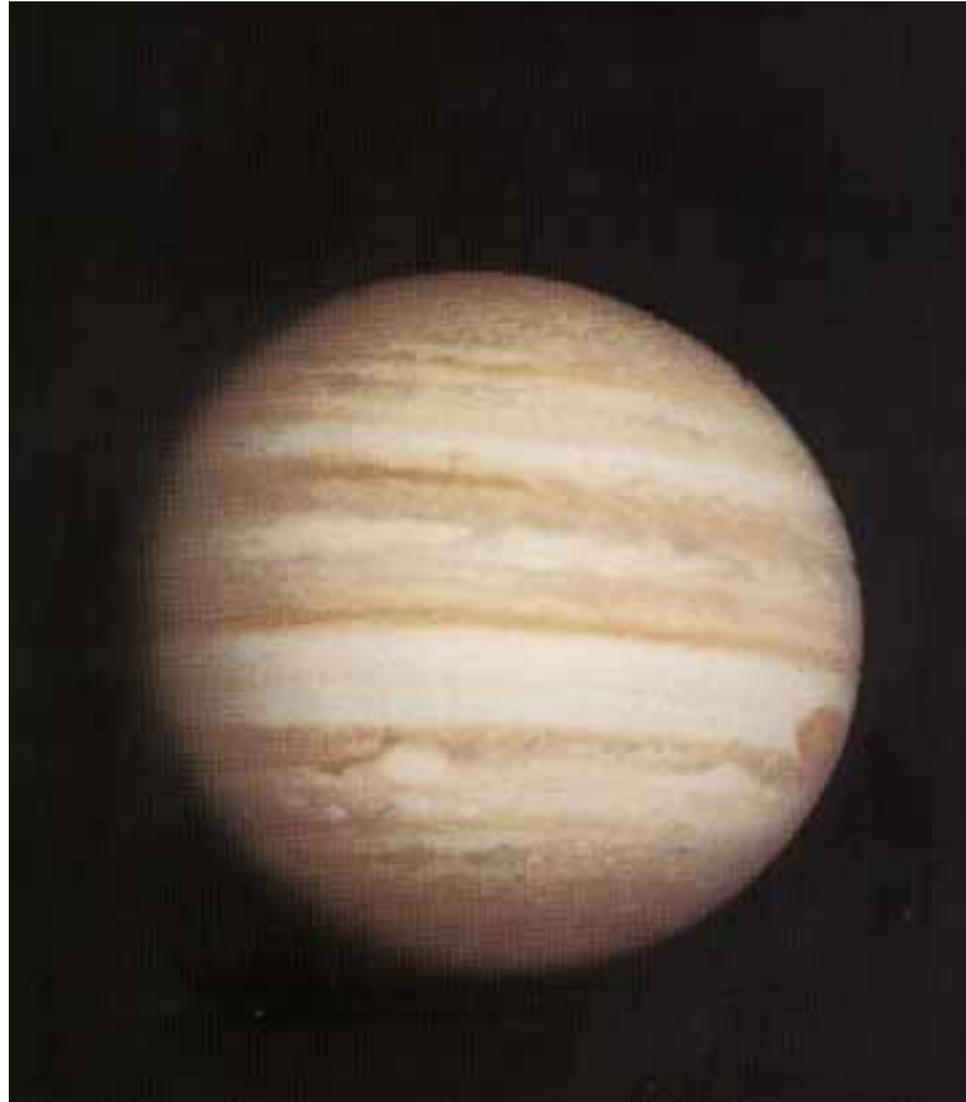


Photo: NASA

Pioneer 11



- Launched April 6 1973
- Flew by Jupiter
- First craft to Saturn

- Discovered new moons, new rings of Saturn
- Discovered Saturn is exothermic
- Last heard from November 24 1995

Pioneer 11

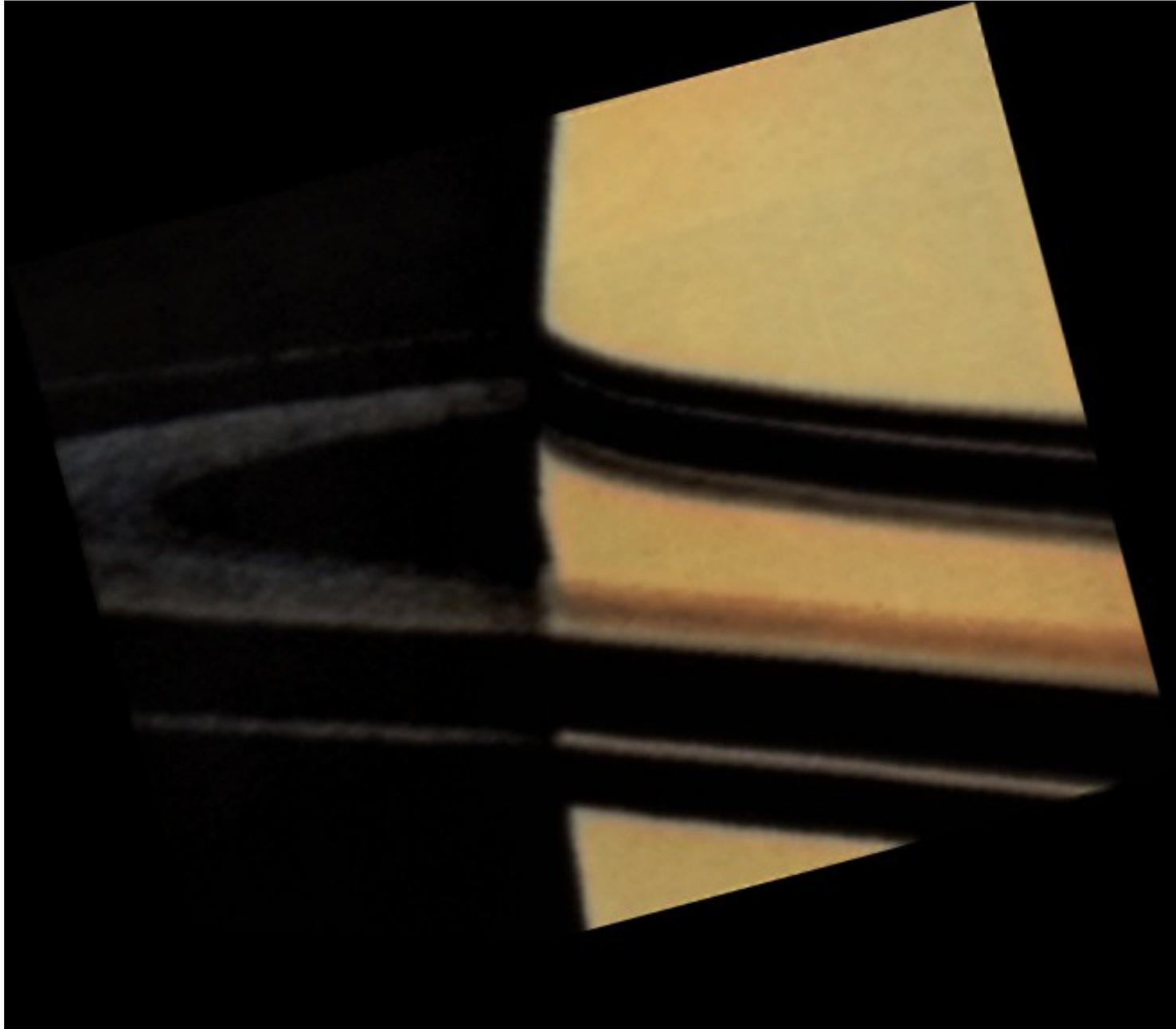
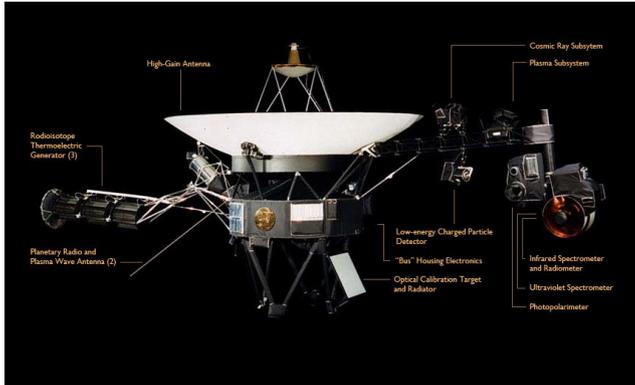


Photo: NASA

Voyager 1



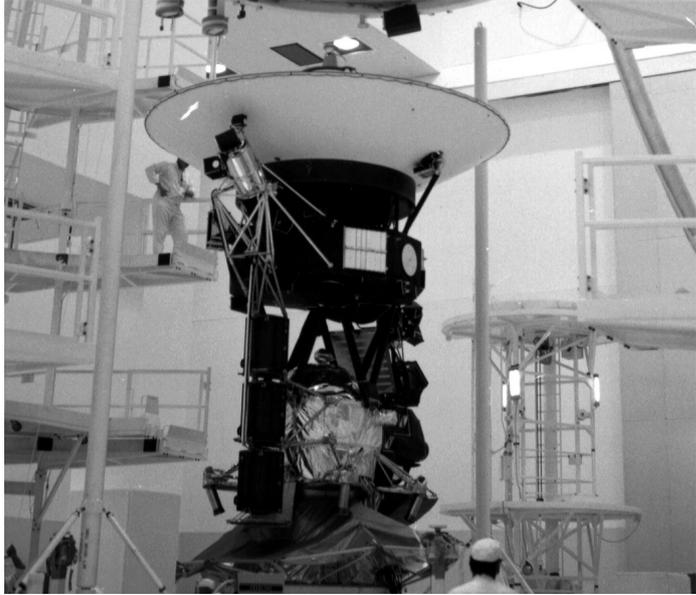
- Launched September 5 1977
- Flew by Jupiter, Saturn
- Gravity slingshot over Titan took it out of the plane of the ecliptic, so no more planets

- Discovered new rings of Jupiter
- Discovered volcanoes on Io
- Took the Family Portrait from beyond Neptune
- Still sending daily science back

Voyager 1



Photo: NASA



Voyager 2

- Launched August 20 1977
- Flew by Jupiter, Saturn
- Still our only craft to Uranus, Neptune
- Gravity slingshot over Triton meant no Pluto
- Discovered new moons of Jupiter
- Discovered that features on Jupiter, Neptune are storms
- Studied Neptune's odd magnetic field
- Still sending daily science back

Voyager 2

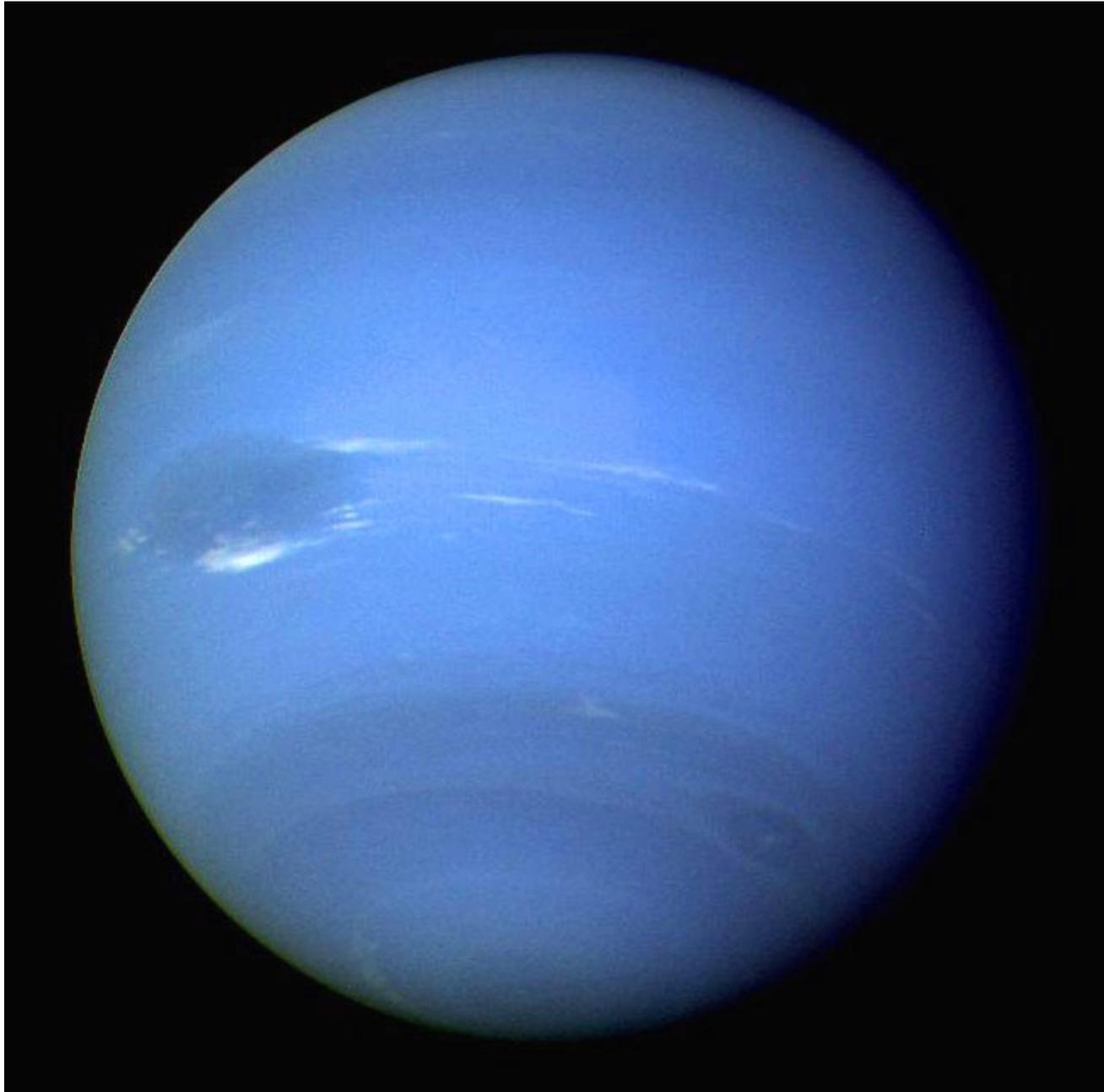
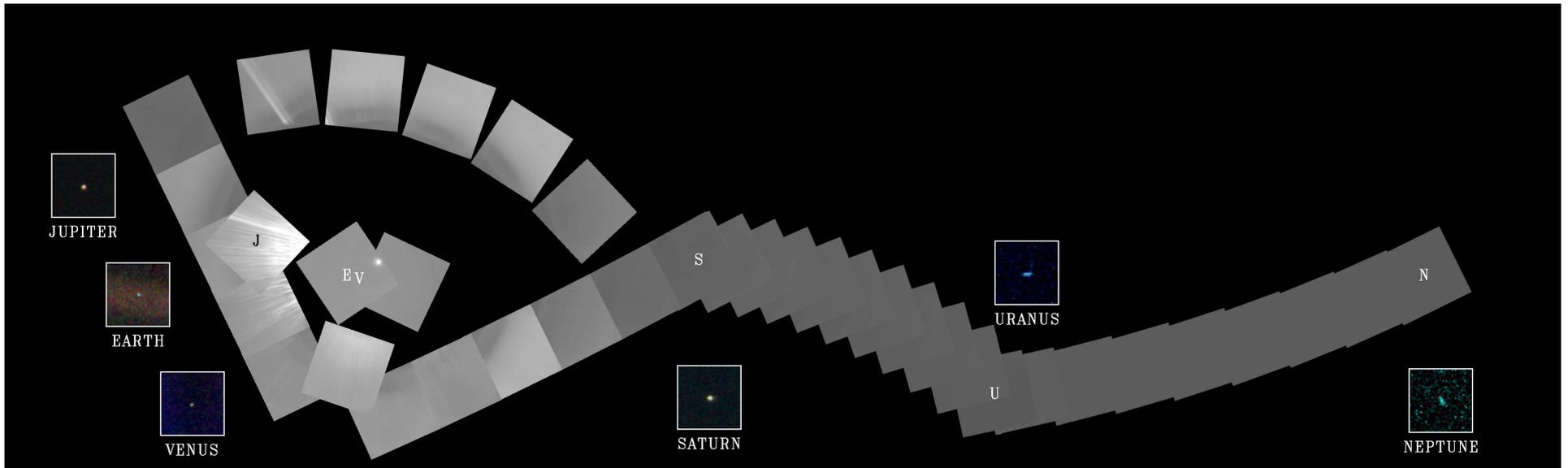


Photo: NASA

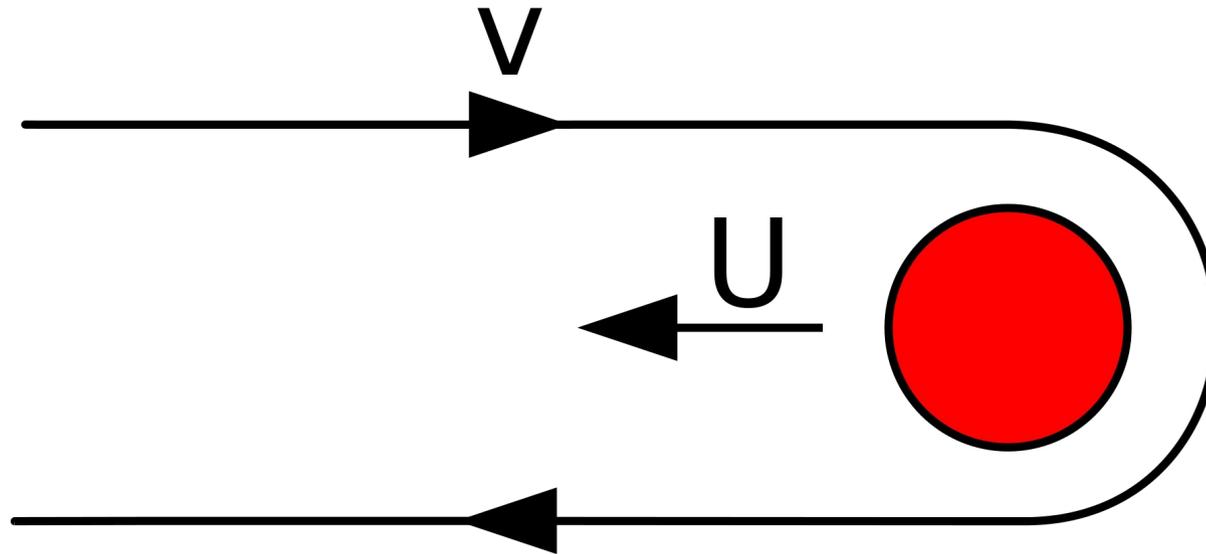
Our Family Portrait



- By Voyager 1 from beyond the orbit of Neptune
- Last photograph taken by any of these craft
- Carl Sagan lobbied to add this to the mission
- Source of “The Pale Blue Dot”
- The Sun was a magnitude -19 star at this point

Photo: NASA

Gravity Slingshots

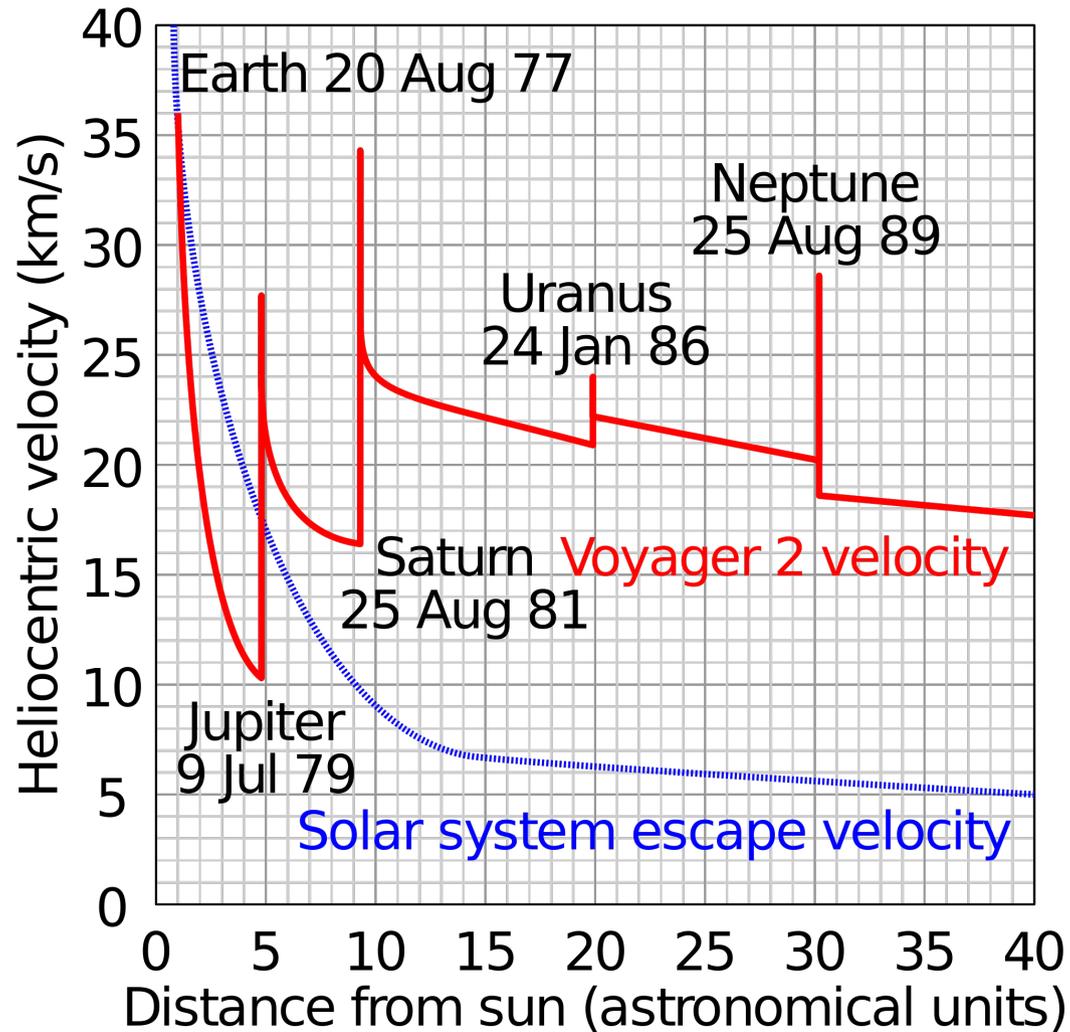


$$2U + v$$

Image: Wikicommons

- Theory developed long ago
- First used in 1965 (appeared in Star Trek 1967)
- Very significant to the Grand Tour (Jupiter to Saturn in 2 years!)
- Only technology known with a chance to save the Earth from the Sun's red giant phase

Effects of Gravity Slingshot



The Pioneer Anomaly

- All craft are influenced by Sun's gravity
 - Net acceleration = sum of acceleration due to gravity and propulsion from all sources
- Pioneers slowing more quickly than expected
- Not experienced by Voyagers
 - But they use more frequent adjustments by thrusters, which overwhelms the small effect seen in the Pioneers
- Also measured in Cassini

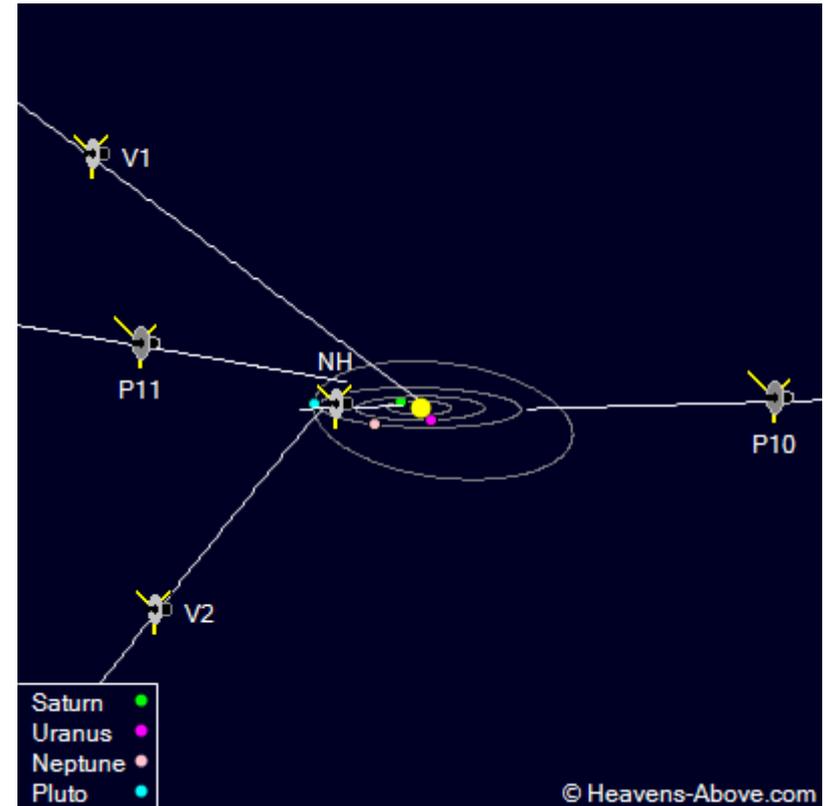
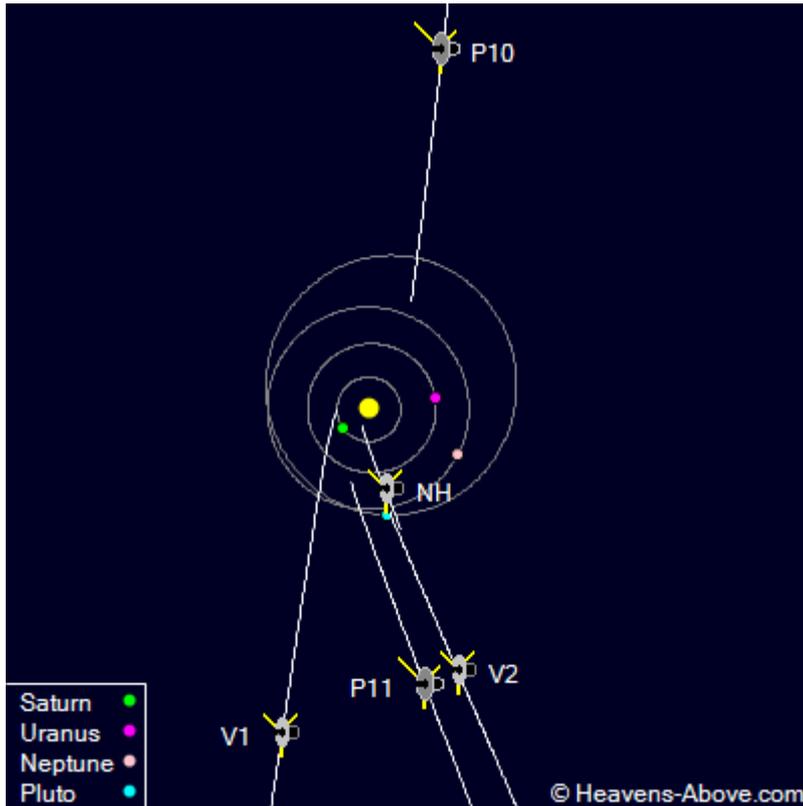
Causes of the Pioneer Anomaly?

- Extra gravity of dark matter in our Solar System?
 - Not seen in other natural objects.
- Expansion of the Universe?
 - Only measured on larger scales.
- New physics for gravity or inertia?
 - No experimental data
- Heat radiated unevenly by nuclear generators?
 - Several 2012 publications made this the best-accepted explanation

Where Are They Now?

- Each on a different course toward interstellar space
- The Voyagers are faster, so have overtaken the Pioneers
- The heliosphere layers seem to be at different places on each route
- Voyager 2 is probably at the edge of the solar wind

Where Are They Now?

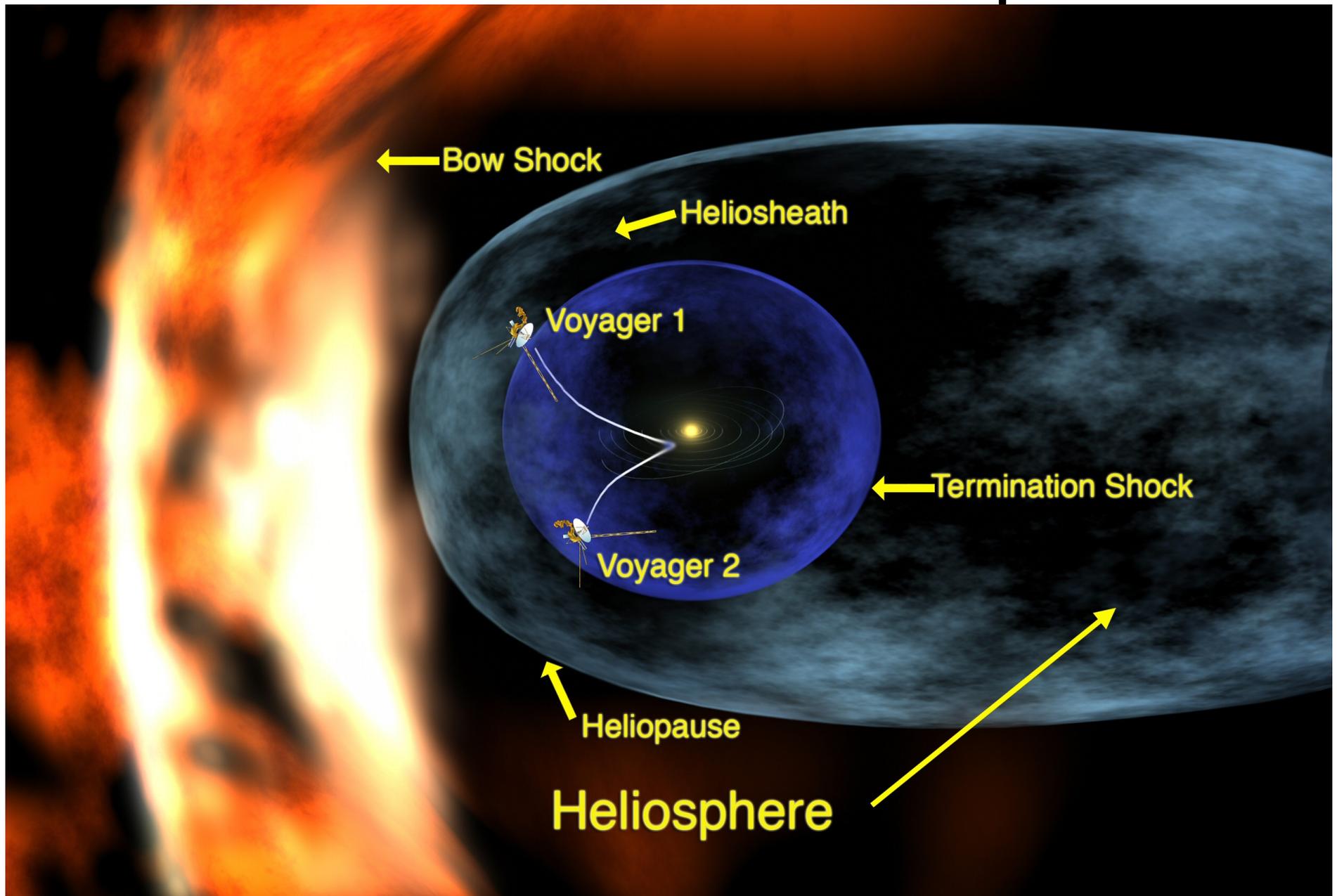


Images: Wikicommons

Where are they going?

	Dist. from Sun	Speed, km/s	Destination	Years to Arrive
Pioneer 10	108 AU 15 lh	12	Aldebaran	2,000,000
Pioneer 11	88 AU 12 lh	11	Someplace in Aquila	4,000,000
Voyager 1	124 AU 17 lh	17	Gliese 445	40,000
Voyager 2	101 AU 14 lh	15 (3.5 AU/year)	Sirius	496,000
New Horizons	26 AU 4 lh	15.2	Pluto	2

Old model of the heliosphere



We thought solar wind was like dust



Photo: NASA

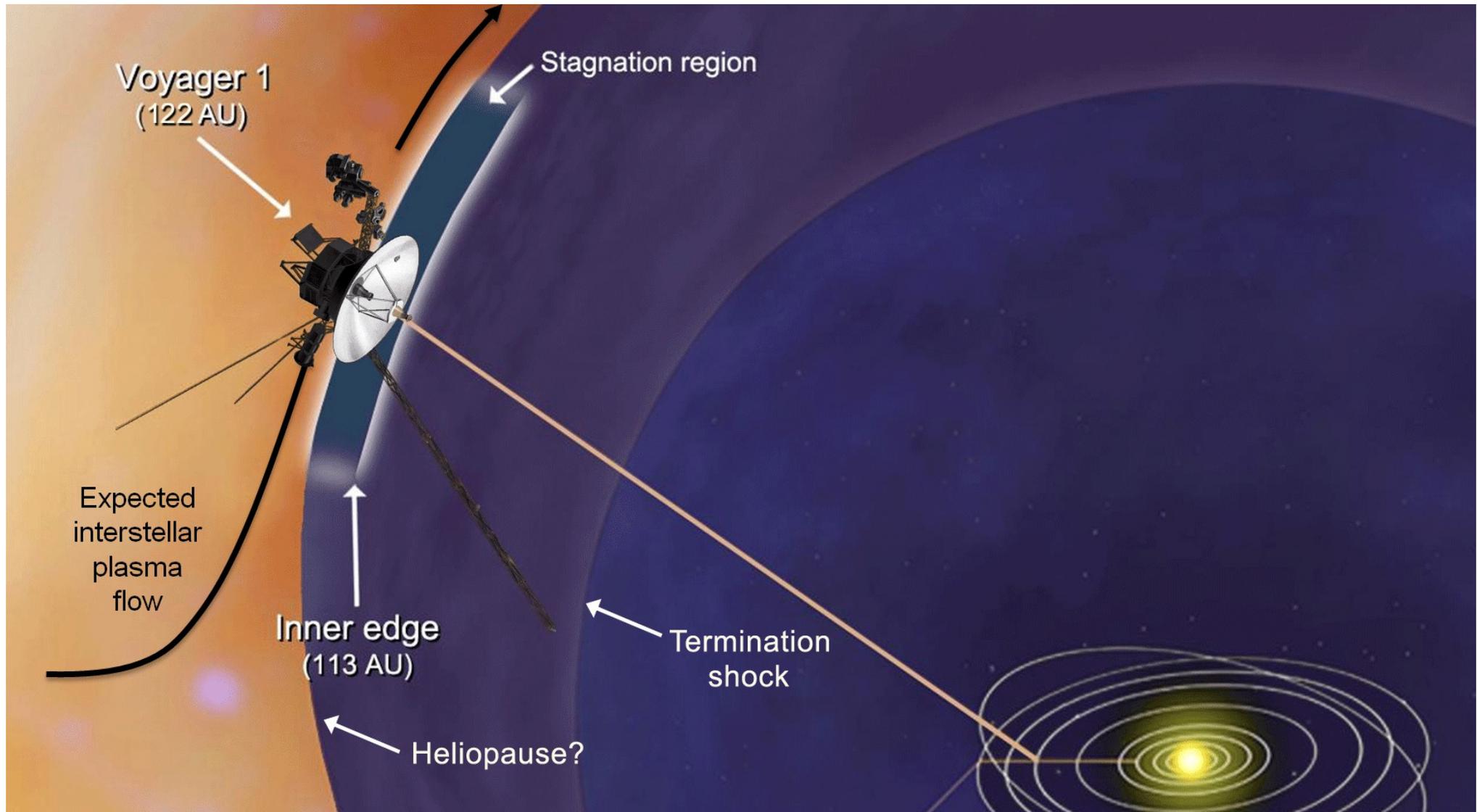
What Are They Discovering Now?

- The solar wind ends, not with a bang, but with a whimper
- Solar and Galactic magnetic fields interact in ways we didn't know before
- Solar wind stagnation zone contains magnetic foam (each bubble the size of Earth's orbit)
- The termination shock looks as expected
- The bow shock does not
- The heliosheath is not symmetrical, but not elongated as much as previously thought

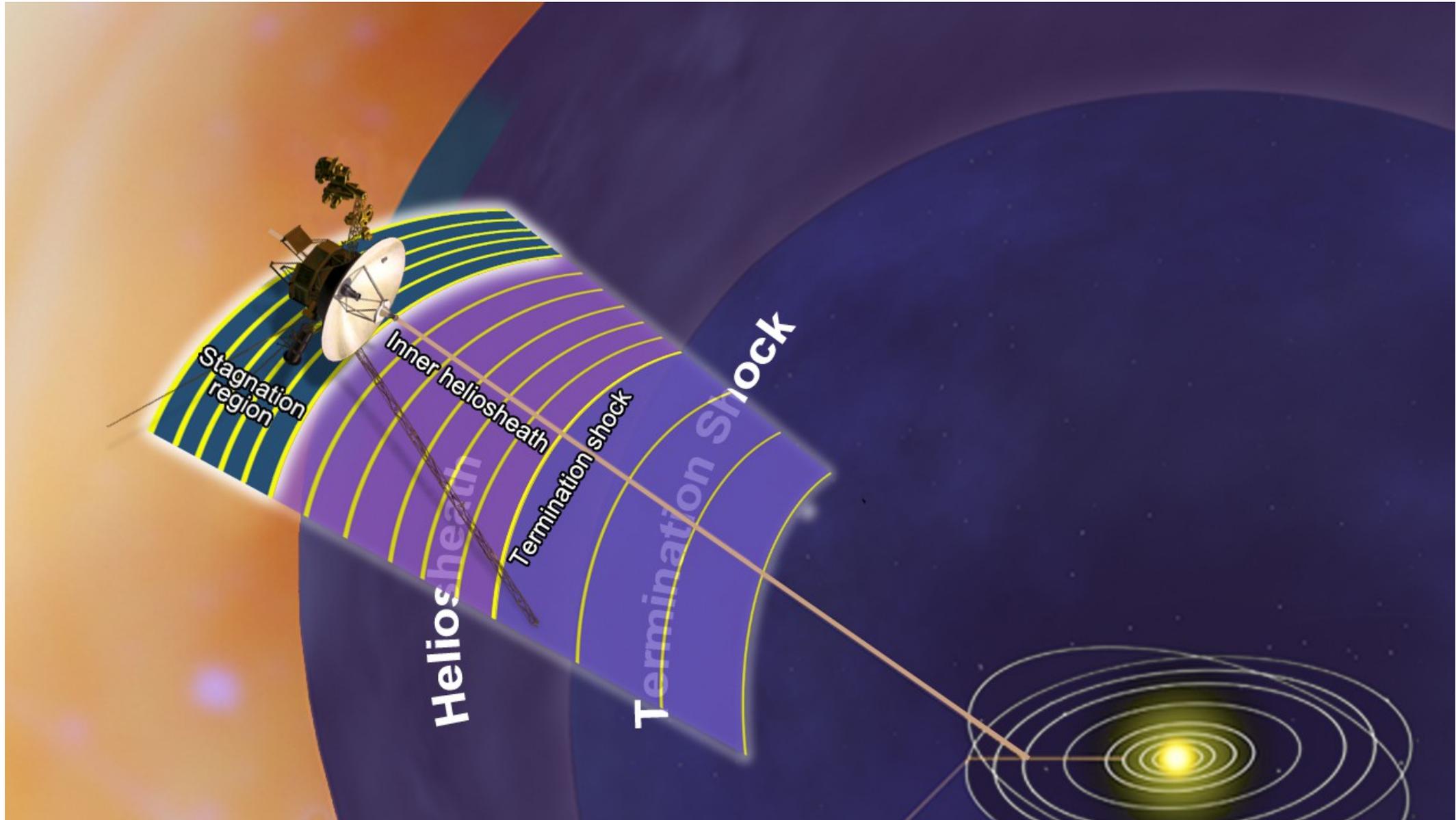
Interaction of Magnetic Fields and Wind

- Solar wind is composed of charged particles
- Charged particles follow magnetic fields
- The solar magnetic field is not like the simple field of a bar magnet, but the sum of many fluid magnetic volumes in the Sun.
- At the heliopause, the solar magnetic field is not well-defined force lines, but a magnetic foam
- There is no longer a magnetic force driving the solar wind
- Solar wind becomes stagnant eddy of particles

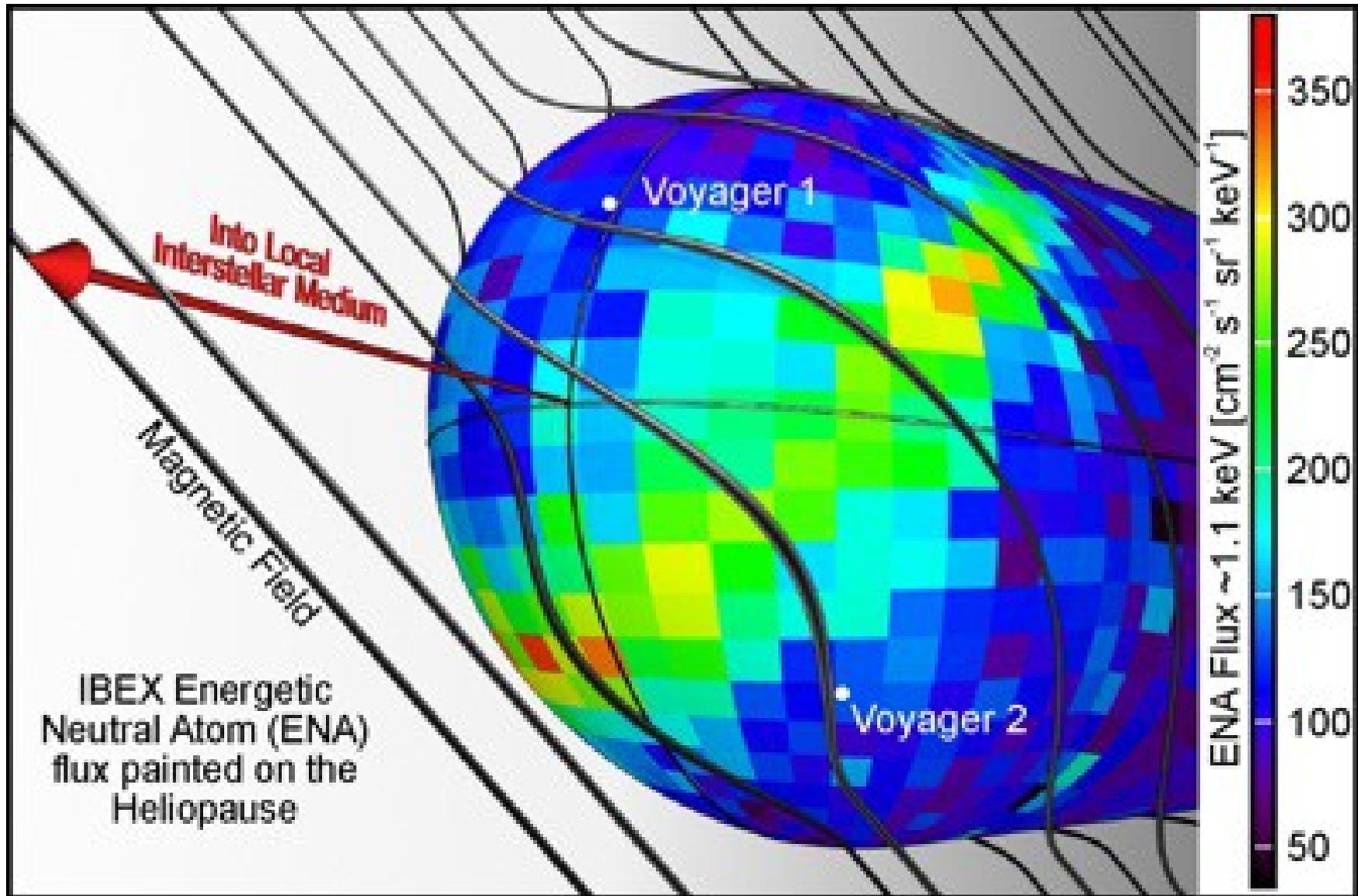
What Voyager found there (plasma)



What Voyager found there (magnetism)



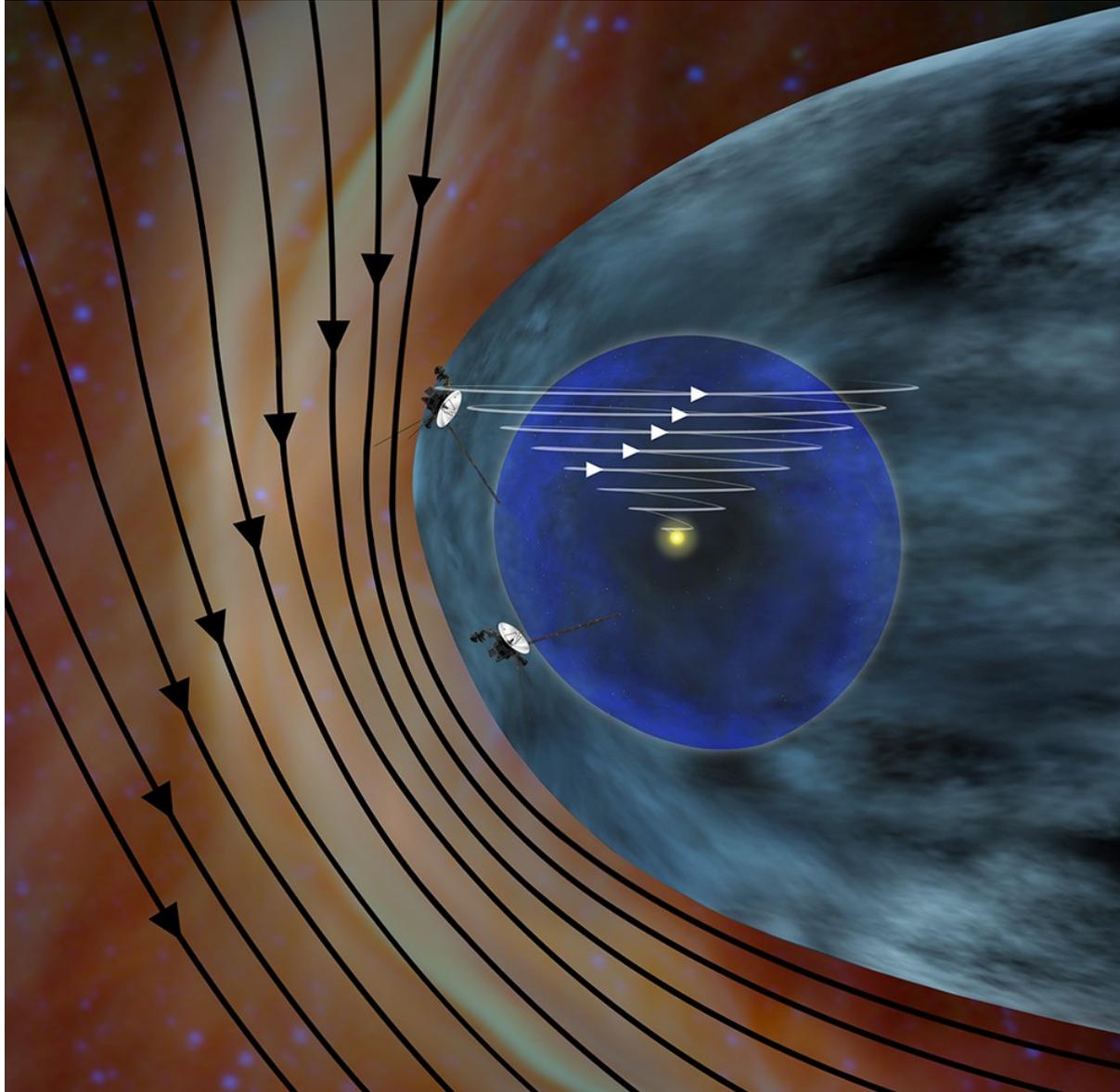
New model of the heliosphere



The Magnetic Highway

- August 2012: After passing through the stagnation zone, Voyager 1 entered a new, unexpected part of the heliopause.
- The magnetic field once again has well-defined force lines. End of the magnetic foam.
- Rotating the craft for careful measurements of magnetic direction suggests this is still the Sun's magnetic field, not yet the galactic magnetic field.
- May be caused by pressure of nearby, differently-aligned galactic magnetic field.

Voyager 1 on the Magnetic Highway



Took the on ramp August 2012

Image: NASA
Animation: NASA

Is Voyager Leaving the Solar System?

- NASA announced they had left the Solar System when they were farther from the Sun than Neptune
- Voyager 1 is now where the Solar Wind ends



Is Voyager Leaving the Solar System?

- 1989 Voyager 1 passed Neptune's orbit
- 2004 Voyager 1 found the Termination Shock (speed of solar wind drops to subsonic)
- 2010 Voyager 1 found unexpected region with no solar wind
- 2012 Voyager 1 found sudden increase in cosmic rays
- 2012 Voyager 1 found magnetic highway

When do we call “Voyager has left the building”?

- March 2013 first formal papers published describing the December 2012 Voyager 1 data
- American Geophysical Union called Voyager 1 “out of the Solar System”
- Voyager team at NASA said they are still waiting for the magnetic field to change from solar to galactic
- AGU backed off their claim

What marks the end of the Solar System?

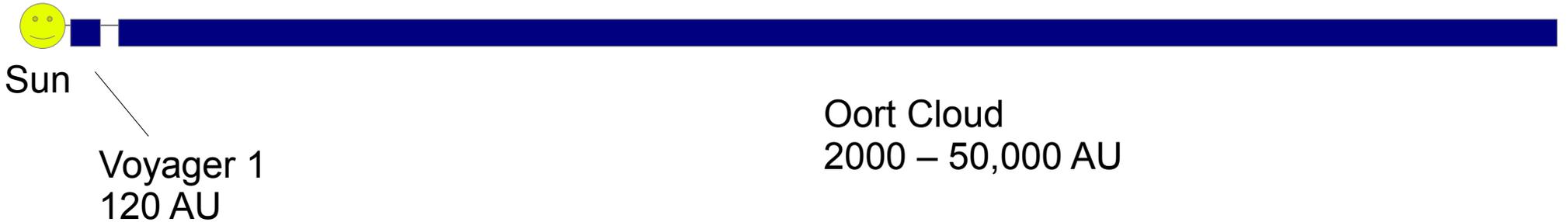
- So far we have looked at
 - Solar wind
 - Solar magnetic field
- What about solar gravity?

Gravitational Edge of Solar System

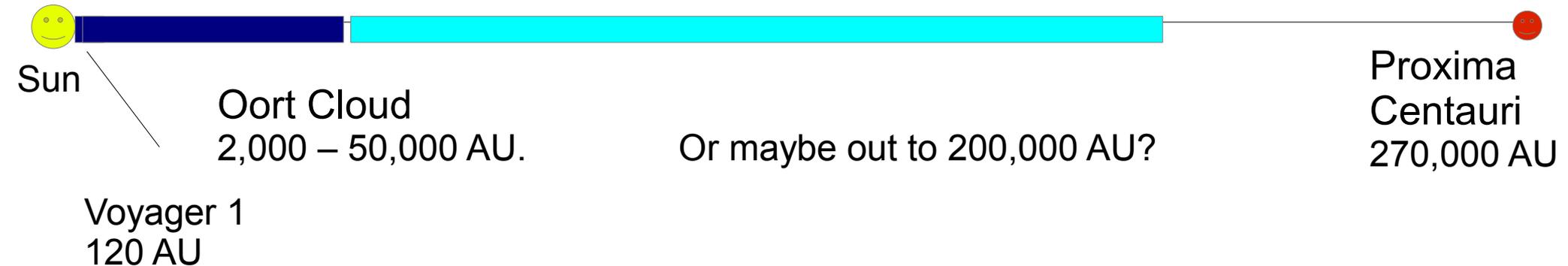


Where is the end of the Oort Cloud?

Is that the end of the Solar System?

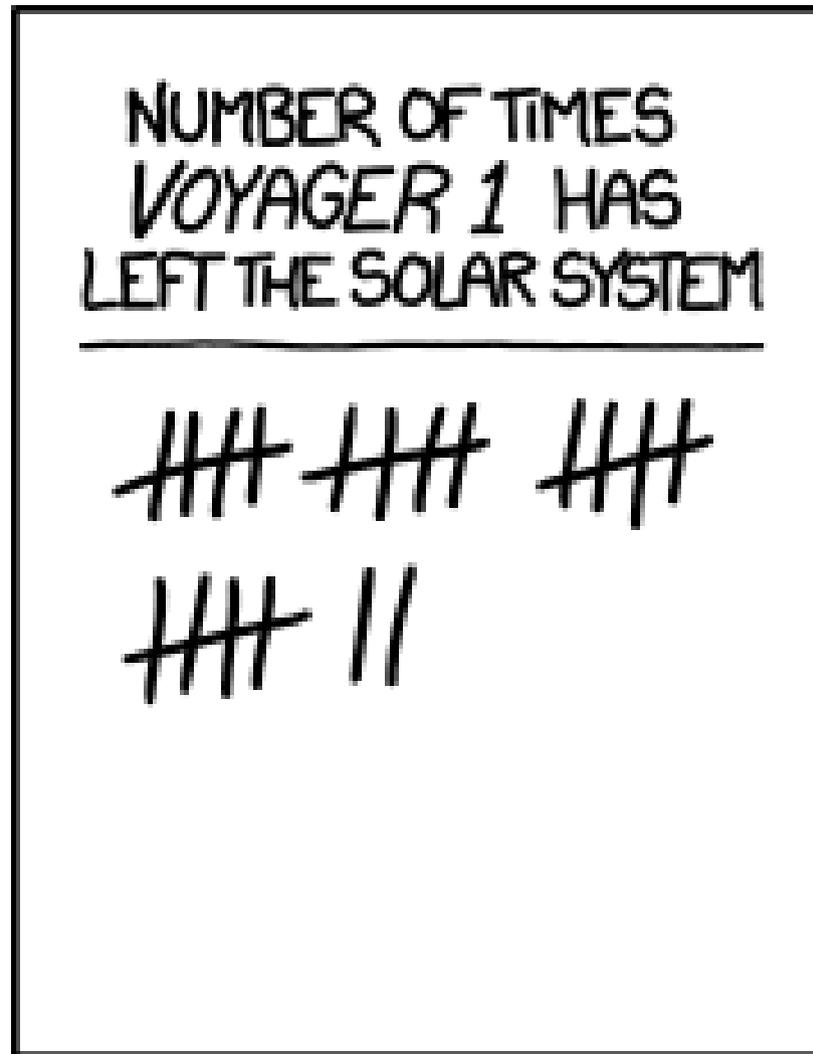


What is beyond the Oort Cloud?



- How far out is still influenced by our Sun's gravity?
- Where is Proxima Centauri's Oort Cloud?
 - Does it mingle with ours?
- Is that the end of our Solar System?
- Is it where the gravity of the two stars balance?
- Voyager 1 is still a long way from that end of the Solar System

Or, as xkcd put it,



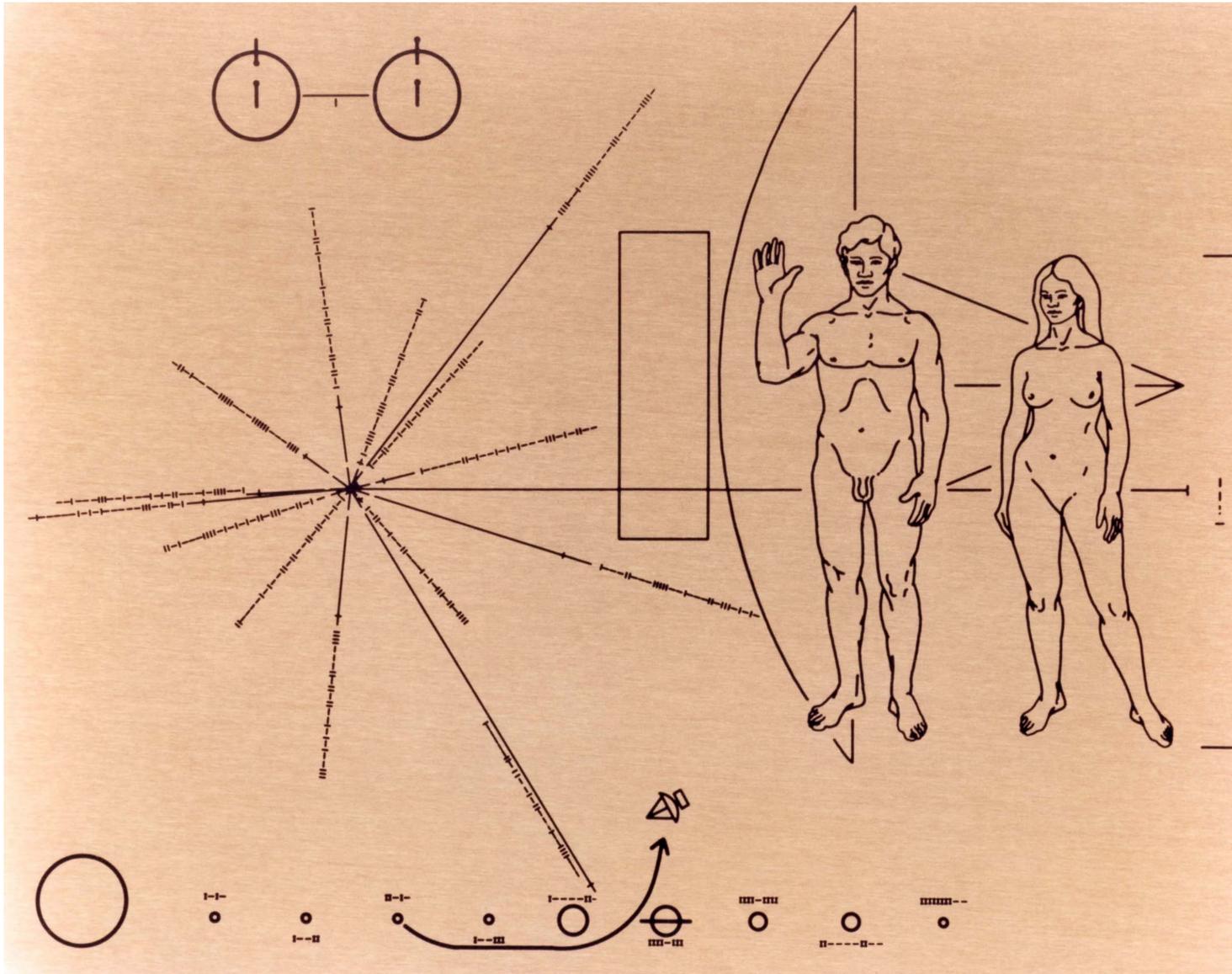
What next?

- Voyager will be the first craft to encounter whatever is beyond our Solar System
- But it will be inert by that time
 - Unfortunately, it will send us no data on interstellar objects

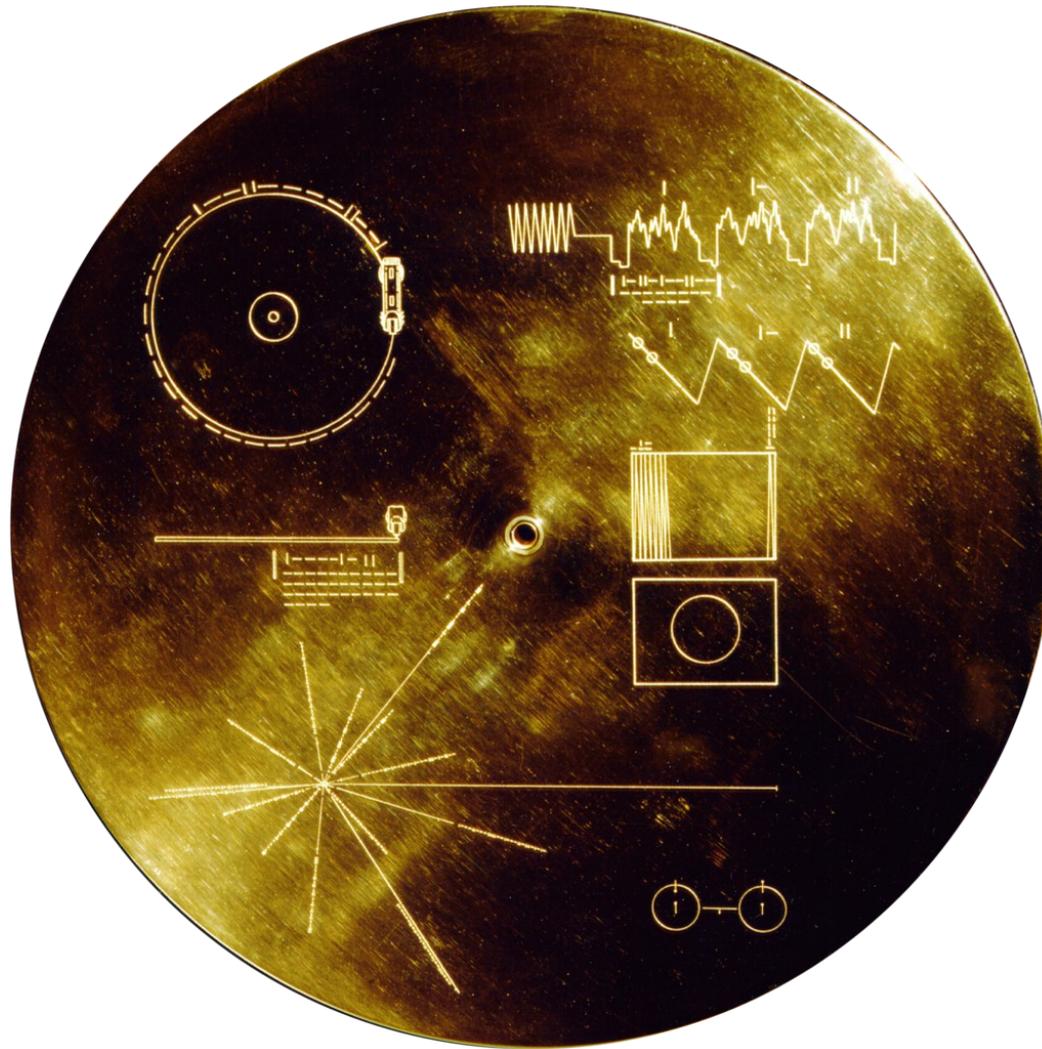
There and Back Again

- Voyager will orbit the galaxy
- Galactic Year is 240,000,000 years
- Unless a star captures it
 - Voyager could enter a transfer orbit to another star
- Or it encounters life that adopts it
- All four craft carry messages to other civilizations

The Pioneer Greeting Plaques



The Voyager Golden Records



What If They Find New Life?

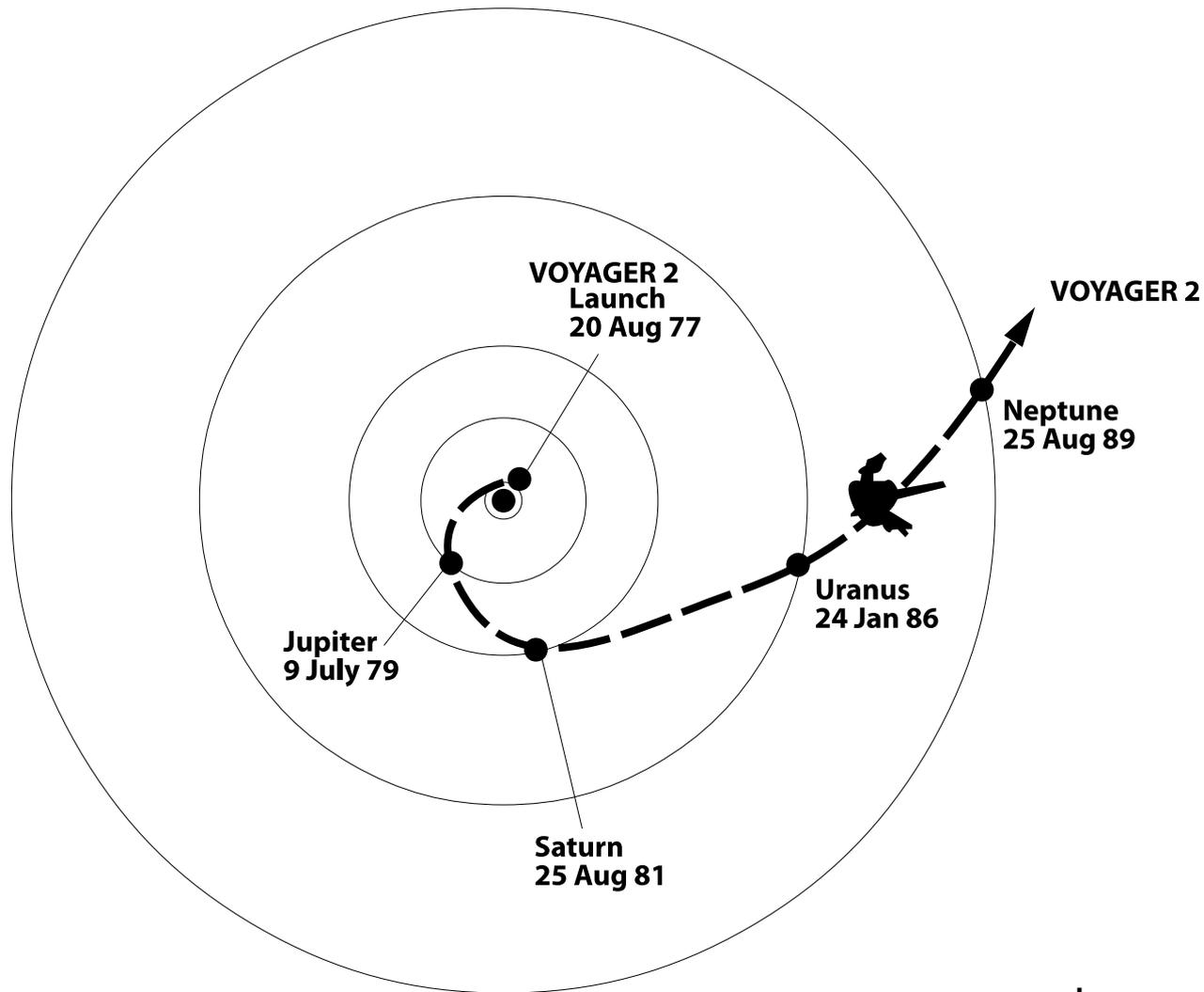


Image: NASA
Movie clip: Paramount

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Pioneer NASA mission site

<http://www.nasa.gov/centers/ames/missions/archive/pioneer.html>

Pioneer 10 on Star Trek V: The Final Frontier. Paramount Pictures

<http://www.youtube.com/watch?v=LOqoljJ0ees>

Voyager NASA mission site <http://voyager.jpl.nasa.gov/>

Voyager 1 http://en.wikipedia.org/wiki/Voyager_1

Voyager 2 http://en.wikipedia.org/wiki/Voyager_2

Voyager 1 on xkcd <http://xkcd.com/1189/>

Voyager golden record http://en.wikipedia.org/wiki/Voyager_Golden_Record