VOYAGER 1

A VOYAGE TO FOREVER

an essay by

HAMISH LINDSAY

“No one was able to predict all
of the details that Voyager 1 has seen.
So, we expect more surprises.”

Dr Ed Stone, Voyager Project Scientist

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Extracted from content available on the Honeysuckle Creek Tracking Station website, developed by Colin Mackellar

www.honeysucklecreek.net

Click or scan the QR code below to see the website:

Cover illustration: Adapted from a NASA-produced poster.

Mission Facts

Voyager 1
Launch date: 5 September 1977
Launch time: 12:56:01 UTC
Launch site: Launch Complex 41, Cape Canaveral
Launch vehicle: Titan IIIE / Centaur D-1T / Star-37E

Spacecraft
Spacecraft mass: 815 kilograms (at launch)
721.9 kilograms (dry mass)
Manufacturer: Jet Propulsion Laboratory
Power: Radioisotope Thermoelectric Generator
470 watts (at launch)

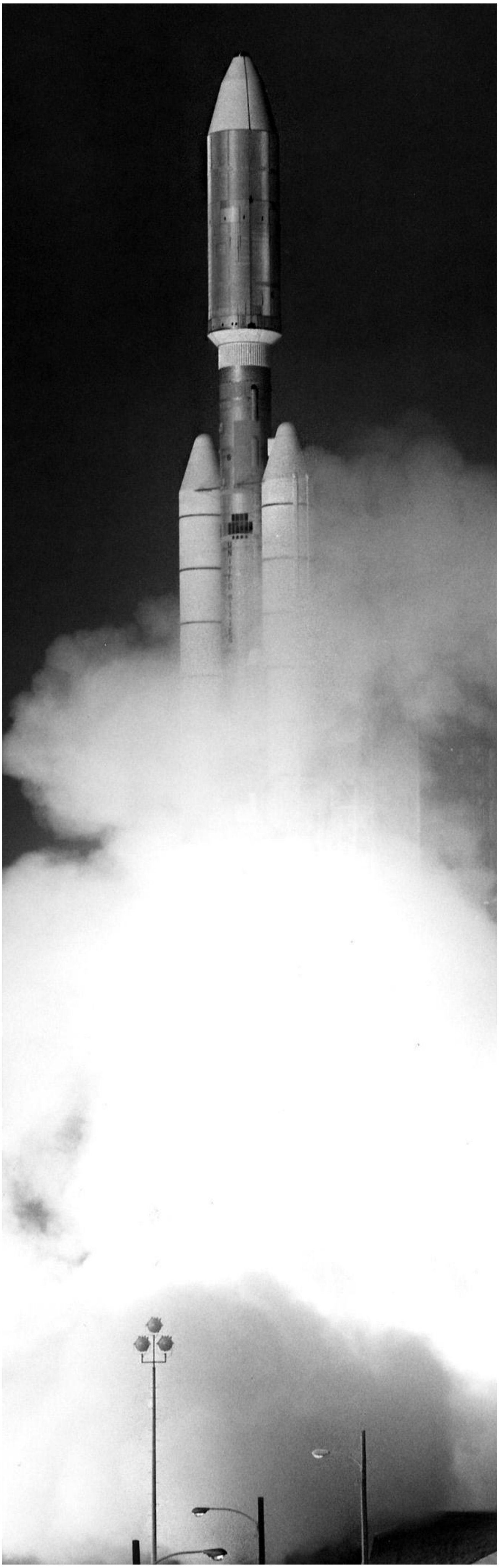
Mission duration
Planetary mission: 3 years, 3 months, 9 days
Interstellar mission: 45+ years (ongoing)
Insufficient power for any instrument: 2027-2036
Out of range of DSN: 2036 (estimated)

Planetary Encounters
Jupiter: flyby
Closest approach: 5 March 1979
Distance: 349,000 kilometres
Saturn: flyby
Closest approach: 12 November 1980
Distance: 124,000 kilometres

Instruments and Systems
Active and disabled systems as at September 2026

Name	Active	Disabled
Imaging Science System		14 Feb '90
Radio Science System	✓	#
Infrared interferometer spectrometer radiometer		3 June '98
Ultraviolet Spectrometer		19 Apr '16
Triaxial Fluxgate Magnetometer	✓	TBD*
Plasma Spectrometer		1 Feb '07
Low Energy Charged Particle Instrument		17 Apr '26
Cosmic Ray System		25 Feb '25
Planetary Radio Astronomy Investigation		15 Jan '08
Photopolarimeter System		29 Jan '80
Plasma Wave Subsystem	✓	TBD*
Data Tape Recorder	✓	TBD*
Gyroscopic operations	✓	TBD*

* Plan to turn off, possibly at the end of 2027.
# System still in use, but no science investigations.



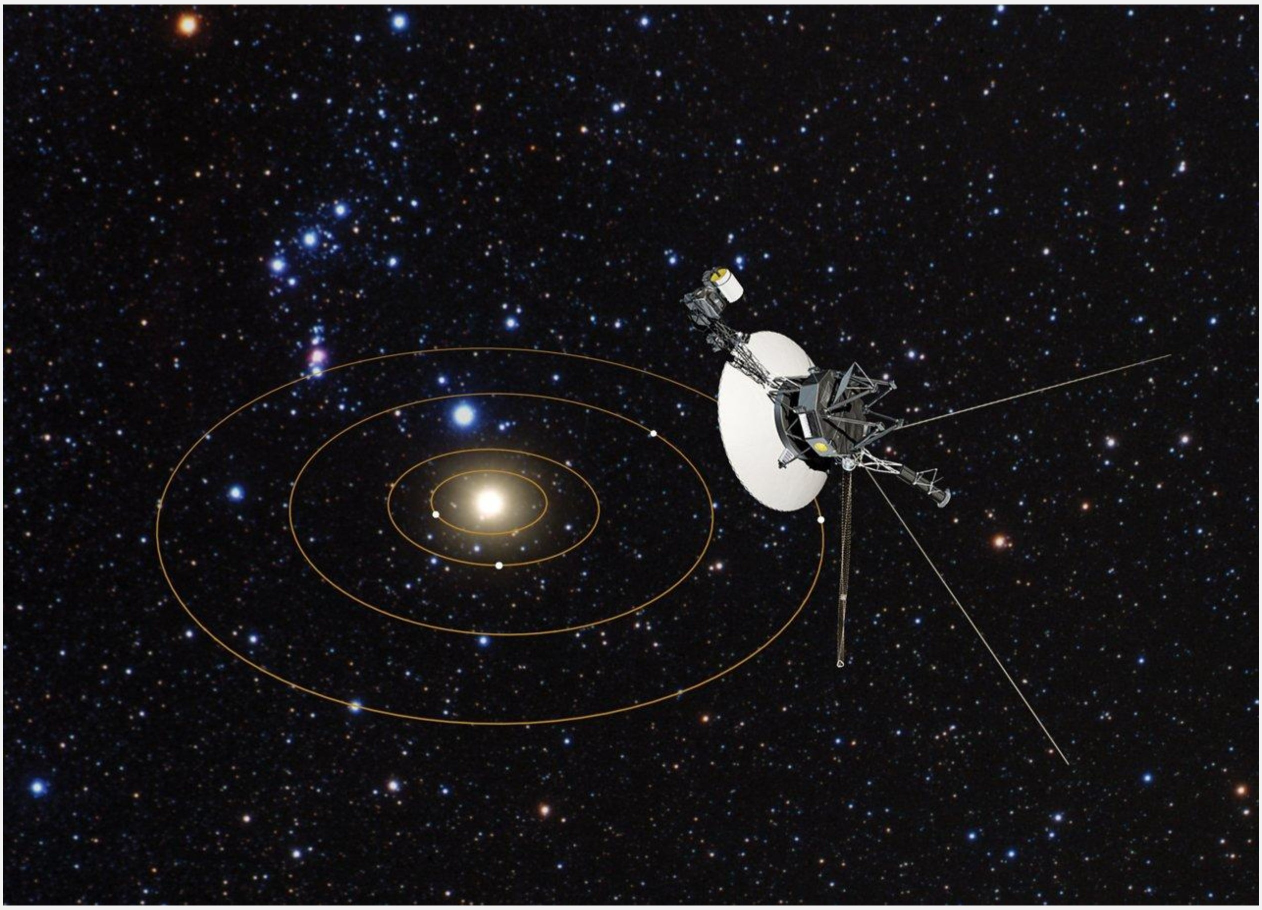


Illustration of a Voyager spacecraft outside the planetary solar system. Image: NASA

VOYAGER 1

A VOYAGE TO FOREVER

My favourite Deep Space projects were the two Voyager missions, which will literally journey on forever, probably still travelling through the galaxy after our Sun has burnt itself out.

A highlight of my space tracking career was Voyager 1's arrival at the planet Saturn when I was operating the receivers at Honeysuckle Creek during the encounter.

I had already spent countless hours tracking the spacecraft over three years on the journey towards Saturn.

This is the story of the two little Voyager spacecraft that against all odds made it to the outer reaches of the solar system, and into the galactic void, all the while keeping in touch with home base back on Earth.

It is not meant to be a source of information on the planets and their moons and satellites, though some of this information is included.

Way back at the beginning of the twentieth century orbital theory scientists began looking at ways of speeding up travel between planets.

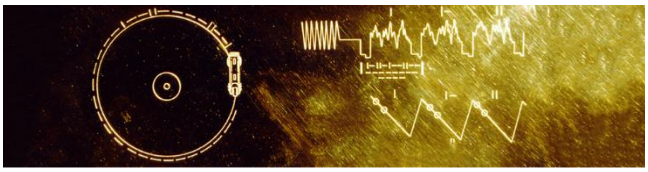
In 1925 German Walter Hohmann (1880–1945) published a book which demonstrated a very fuel-efficient path to move a spacecraft between two different orbits, now called a Hohmann Transfer Orbit. Another visionary was Krafft Ehricke (1917-1984). He arrived in the US with Werner von Braun and was chief designer of the Centaur rocket that launched the Voyager spacecraft.

He was also credited, with English physicist Derek Lawden, with the gravity-assist technique of shortening the travelling time between planets.

In 1961 mathematician Michael Minovich, working for the Jet Propulsion Laboratory (JPL), Pasadena, California, developed a gravity-assisted mission trajectory for a mission to the planets Venus and Mercury.

As a result, Mariner 10 became the first spacecraft to visit two planets using gravity-assist in 1973.

Minovich went on to apply his theories to Jupiter and the outer planets.



The first meeting of the Voyager Science Steering Group on the steps of Building 180 at the Jet Propulsion Laboratory on 31 January 1972. Image: JPL/Caltech

Front row (from left)**:**
Radio Science Subsystem Team Leader – Von Eshleman
Project Scientist – Edward Stone
Project Manager – Harris (Bud) Schurmeier
Mission Analysis and Engineering Manager – Ralph Miles
Magnetometer Principal Investigator – Norman Ness
NASA Planetary Program Office Deputy Director – Ichtiaque Rasool
Robert Soberman – (proposed/not confirmed as PI of the Particulate Matter Investigation)
Unidentified member of the NASA Office of Space Science.

Second row (from left)**:**
Infrared Interferometer Spectrometer Principal Investigator – Rudolf Hanel
Planetary Radio Astronomy Principal Investigator – James Warwick
Ultraviolet and Spectrometer Principal Investigator – A. Lyle Broadfoot.

Third row (from left)**:**
Low-Energy Charged Particles Principal Investigator – Stamatios (Tom) Krimigis
Cosmic Ray Subsystem Principal Investigator – Rochus (Robbie) Vogt
NASA Outer Planets Missions Program Manager – Warren Keller
Imaging Science Subsystem Team Leader – Bradford Smith
Photopolarimeter Principal Investigator – Charles Lillie.

Fourth row (from left)**:**
Plasma Investigation Principal Investigator – Herbert Bridge
Spacecraft Systems Manager – Raymond Heacock
NASA Outer Planets Missions Program Scientist – Milton (Mike) Mitz
Science Manager – James Long.

THE ORIGINAL CONCEPT OF THE GRAND TOUR

In July 1965, Gary Flandro, also working at JPL on a temporary summer job, realised that all the big planets - Jupiter, Saturn, Uranus and Neptune - were going to be all lined up on the same side of the Sun.

He then figured that a spacecraft launched between 1976 and 1978 could utilise Jupiter's gravitational field to reach the other big planets,

> *"I immediately had the idea that we could reach all these planets with a single flight,"* he said.

Even his most experienced colleagues had not spotted this situation.

The four large outer planets of Jupiter, Saturn, Uranus and Neptune constitute 99.8% of the aggregate planetary mass that orbits our Sun.

Only once every 176 years do these giant planets line up to allow a spacecraft to visit them with a minimum use of fuel and time, and if you want to add Pluto it only occurs every 600 years. Using the gravity assist technique, or 'slingshot' effect, the flight time to Neptune was reduced from 30 years to only 12.

Encouraged by his supervisor, Joe Cutting, and one of his professors, Homer Stewart, Flandro approached the mission scientists at JPL with his concept and within days a press release was issued to announce the design phase of a new project to visit the four outer planets.

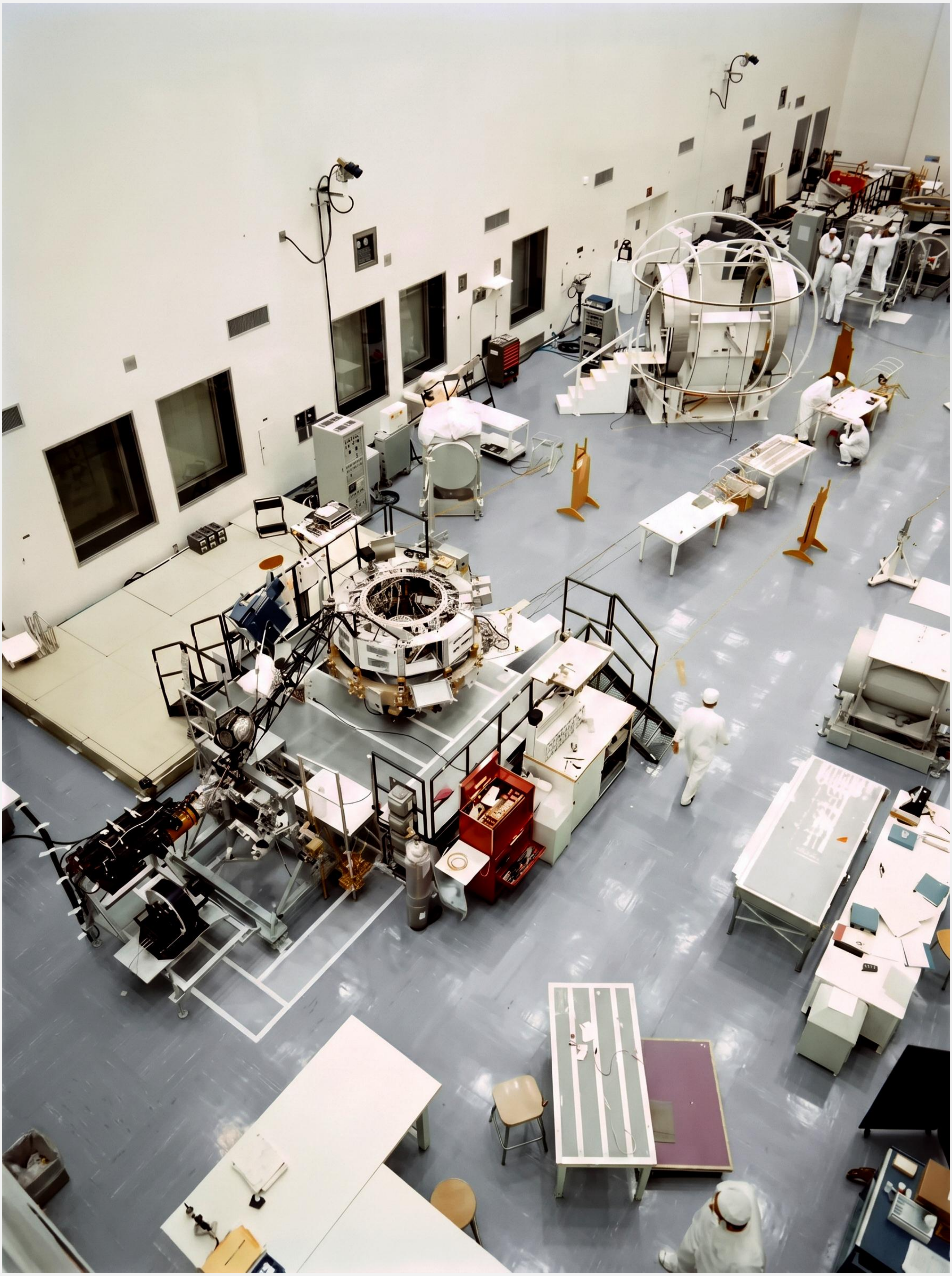
In response to this concept in the northern spring of 1970 James van Allen, one of the world's first space scientists, chaired a scientific group brought together by NASA to explore the scientific opportunities offered by this proposed Grand Tour. Prospects for a healthy budget from Congress looked promising as they could see great scientific promise for physicists, astronomers, meteorologists and geologists; a historic American achievement; keeping America ahead of the Russians; and a project to take up the slack after the expensive Viking missions to Mars.

The small conference room at JPL began to fill with engineering diagrams and plans as the scientists and engineers began to wrestle with the design of a new spacecraft and technical aspects of collecting and transmitting the mass of data expected from these remote outposts.

This was going to be at the cutting edge of technology, breaking new ground in deep space communications.

Two trajectories were looked at:

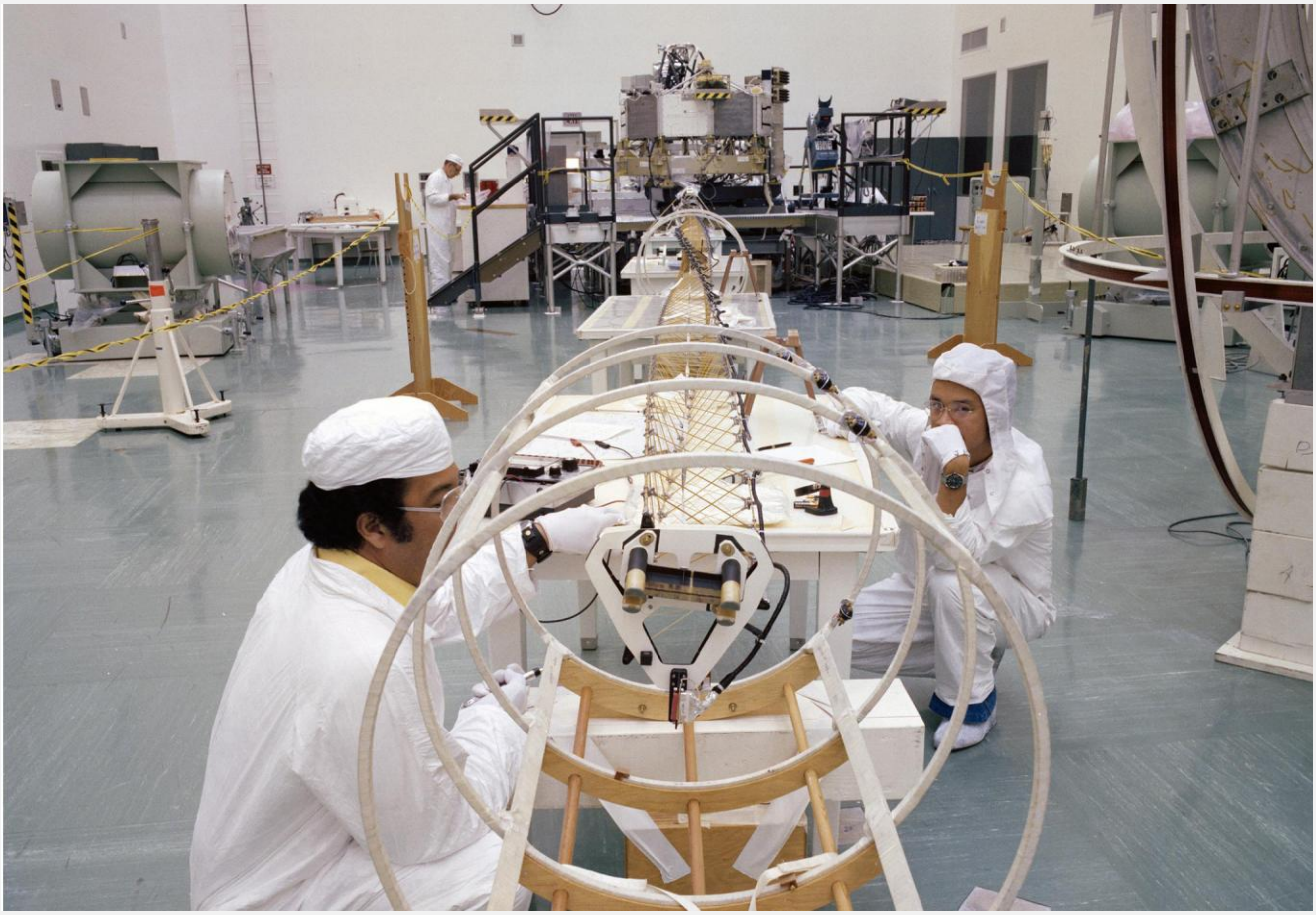
1) An August 1977 launch to Jupiter followed by a 'free' trip to Saturn, Uranus and Neptune.
2) A few weeks later a second spacecraft would head for Jupiter and Saturn, but the gate to Uranus and Neptune would have already closed, so the second spacecraft would fly on to Pluto.



High Bay 1 inside the Spacecraft Assembly Facility at
NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California.

Image: NASA/JPL

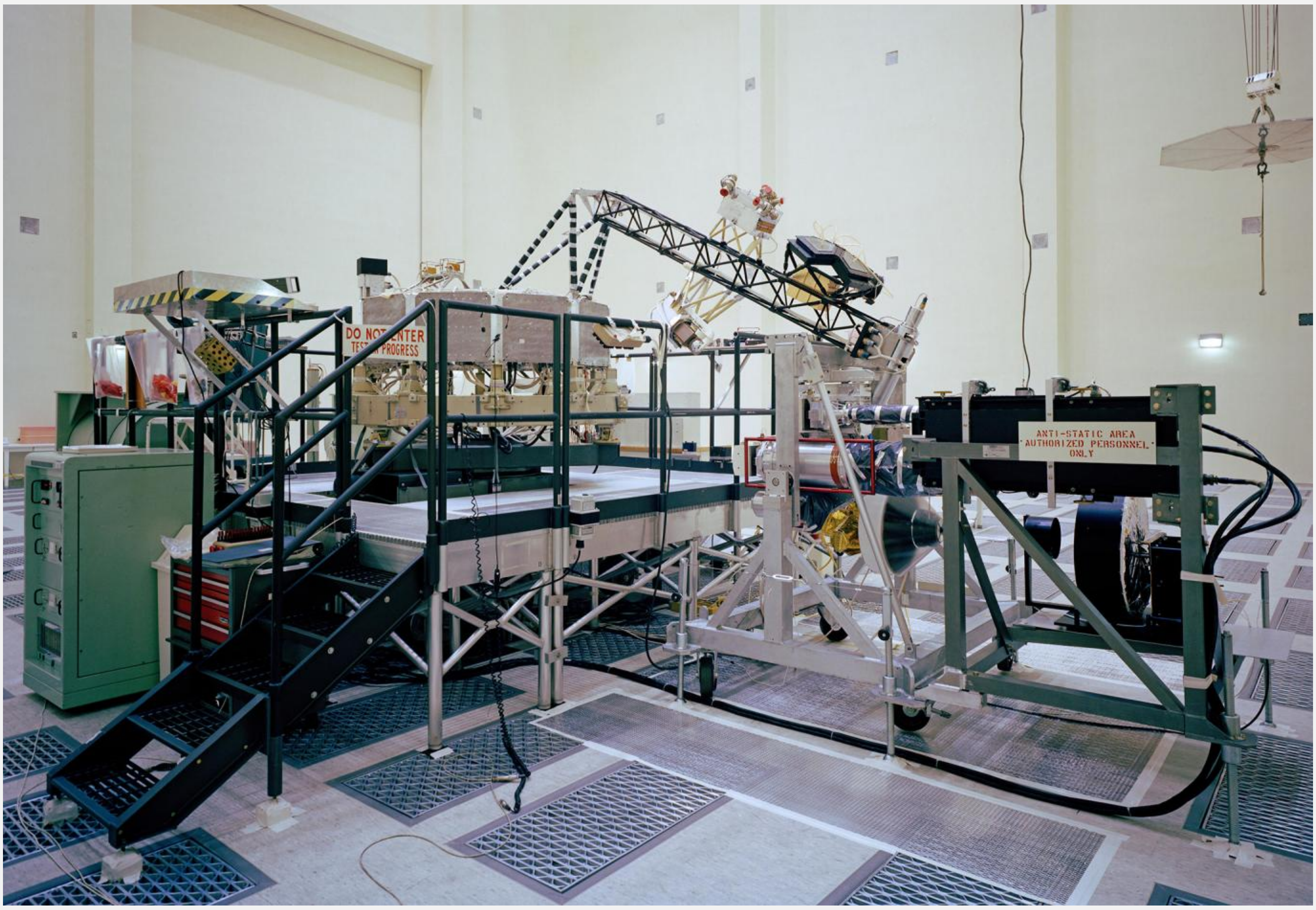
Four workstations where assembly of major components for the Voyager spacecraft were assembled, integrated and tested in clean room conditions.



Above: The Triaxial Fluxgate Magnetometer is fully deployed in special rig.

Images: NASA/JPL

Below: The boom arm carrying a suite of science instruments and the camera platform.



Above: Voyager's antenna is made from a honeycomb aluminium core
covered with a graphite-impregnated epoxy laminate skin.

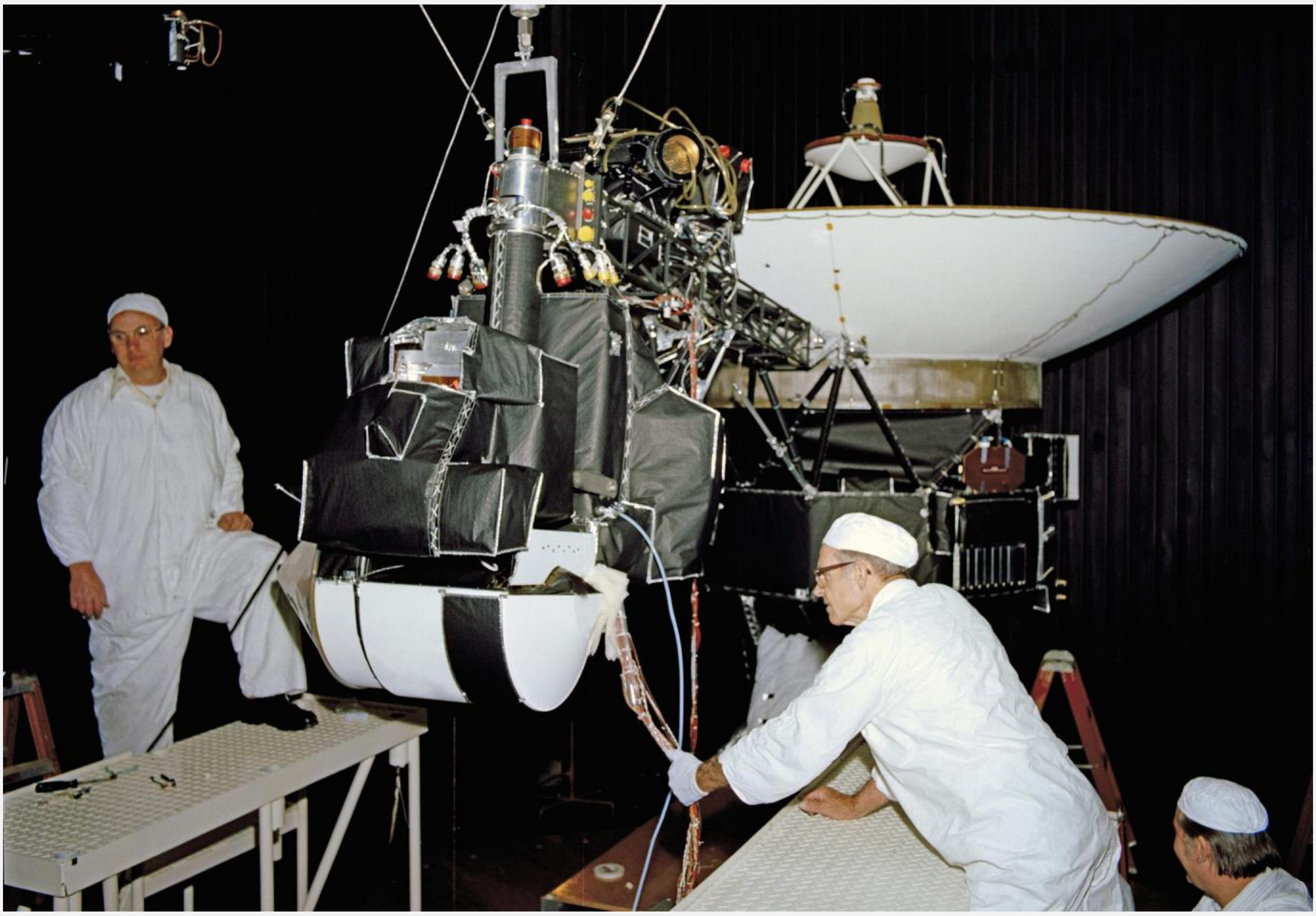
Images: NASA/JPL

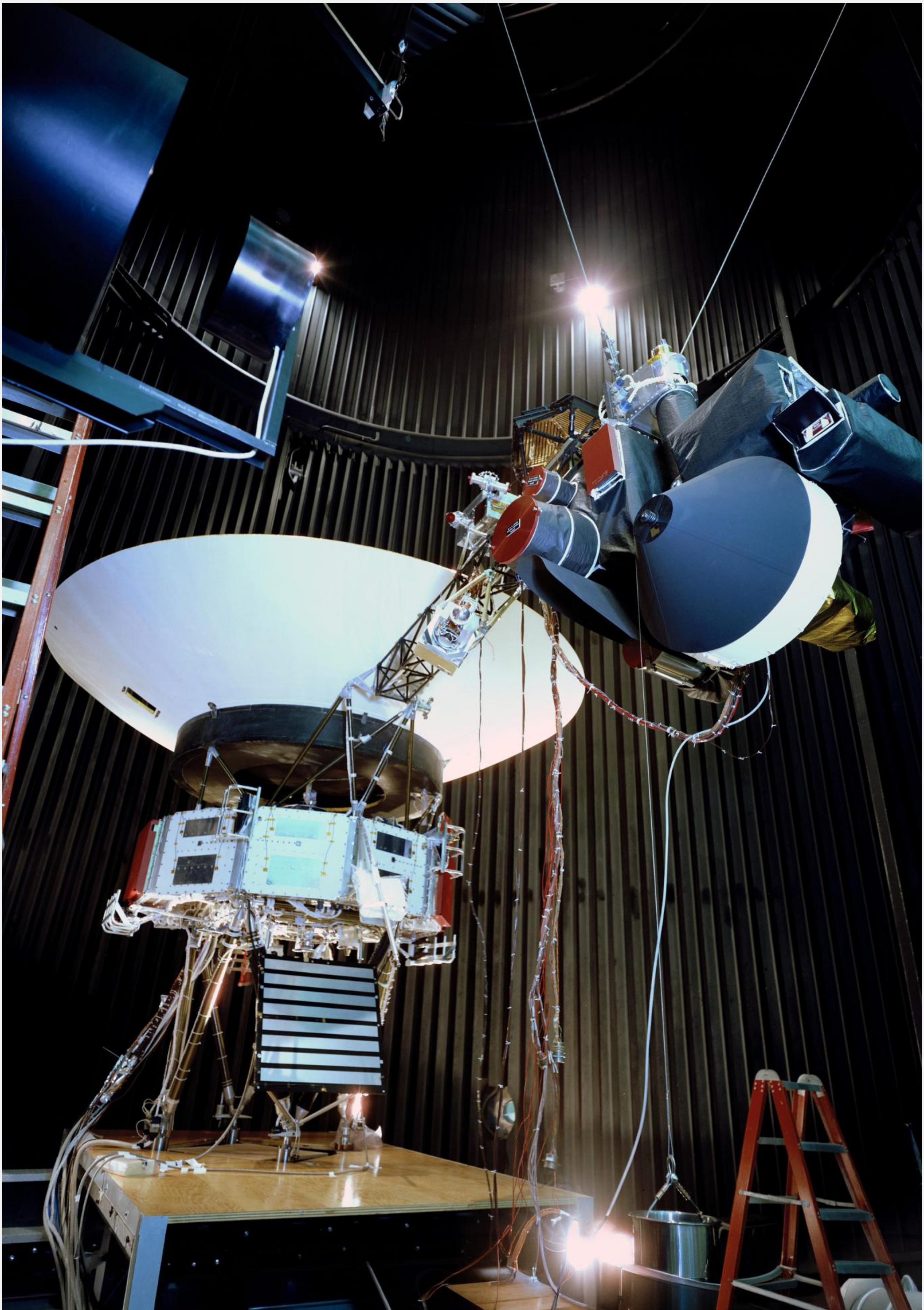
Below: A technician removes the release layer from the Voyager antenna. See the mould form at left.

Above: A view of the deployed magnetometer arm and the nearly completed Voyager in the background.

Images: NASA/JPL

Below: Technicians prepare the Voyager spacecraft for testing.





A Voyager proof test model inside the space simulator chamber at NASA's Jet Propulsion Laboratory in December 1976. Image: NASA/JPL

These Grand Tour missions to Neptune and Pluto were planned and publicly promoted, but only costing $US865 million, half as much as the expensive Viking project to land on Mars. Ed Stone, Project Scientist from the California Institute of Technology, observed when the mission was first proposed,

> *"When this mission was first conceived back in the early 1970s, the best ideas of what the moons of the outer planets would look like were that they would be heavily cratered, ancient objects, much like our own Moon."*

Meanwhile, in the outside world space events were moving along rapidly. In August 1971 Apollo 15 showed earthlings stunning pictures of the mountainous lunar landscape at the Hadley base; in November 1971 Mariner 9 went into orbit around Mars and returned amazing pictures of mountains, canyons, and valleys larger than anything on Earth; and on 5 January 1972 President Nixon announced the development of the Space Shuttle to follow the Apollo/Soyuz and Skylab programs.

Then came the fatal blow - on 11 January 1972 NASA notified JPL that Congress had scrapped the Grand Tour for budget reasons. The heady momentum gathered by the early planetary explorations and Apollo successes was beginning to dissipate.

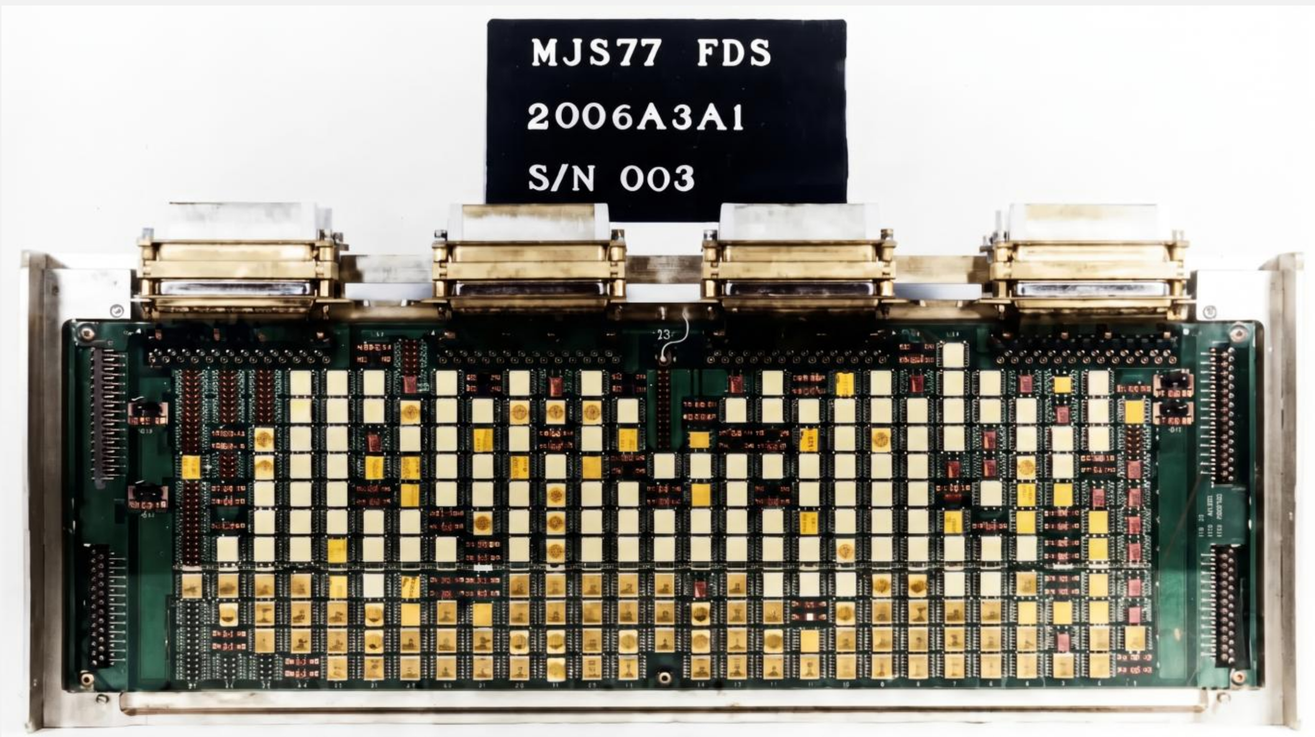
JPL responded by shelving the earlier expensive grandiose ideas, using up to four spacecraft, and replaced them with a more restricted, budget-wise project they called MJS77 (Mariner-Jupiter-Saturn '77) and $10 million was set aside by Congress to fund a mission to Jupiter and Saturn, work to begin in July 1972.

The scientists at JPL hoped that once the spacecraft had proved itself, Congress could be persuaded to add Uranus and Neptune to the project, and planned the trajectories accordingly. JPL still had to justify the reduced cost of the MJS77 project to President Nixon. With strong support from the scientific community NASA finally approved the project on 18 May 1972.

Only a month before, five men were arrested for breaking into the Watergate Office building.

That same year more than a thousand engineers, scientists, and technical managers, led by project manager Harris Bud Schurmeier, looked at the awesome task of designing and building a spacecraft to fly to the furthest reaches of the solar system.

In the beginning neither Uranus nor Neptune figured seriously in the planning. At the time the spacecraft's remote sensing instruments were not expected to yield much from Uranus, let alone Neptune. Sunlight falling on Uranus was only 1/400th the amount at Earth.



1 of 8 printed Flight Data Subsystem (FDS) circuit boards used on Voyager. Note the 'MJS77' tag. Image: JPL

Even so, MJS77 was the most ambitious, complex planetary project ever devised, and they only had five years to deliver an operational spacecraft to Cape Canaveral by the northern summer of 1977.

When I first heard about a mission to the giant planets it was still called Mariner Jupiter Saturn, MJS77 for short, and at Honeysuckle Creek I was given publicity material under that title.

Some of the scientists found this rather a meaningless title so in early 1977 they stuck some names such as Nomad and Antares on a blackboard and voted for one of them. The name Voyager was chosen and announced on 4 March 1977 - with some trepidation, as the original mission to Mars to be launched on top of an Apollo Saturn V was called Voyager and was scrapped.

Pioneers 10 and 11 *(see separate essay)* paved the way to Jupiter and Saturn. Although they were not equipped for sophisticated photography, they returned some amazing, derived images of the two gas giants, and a plethora of data for analysis.

The first thing the Voyager scientists spotted was the radiation at Jupiter was a thousand times stronger than they had anticipated, so had to completely redesign all their circuitry, harden the electronic components, and install radiation shields around all the sensitive equipment.

There was a change for us on the ground with Voyager. Previously the DSN's standard frequency had been in the S-Band spectrum with 2,295 MHz, but Voyager introduced a new higher band frequency of 8,418 MHz in the X-Band to carry more information with the same power transmitters *(see below for more details)*.

The new X-Band frequency was used to carry both scientific and engineering data, but unfortunately is more vulnerable to rain showers, which meant that the weather played an important role during planetary encounters.

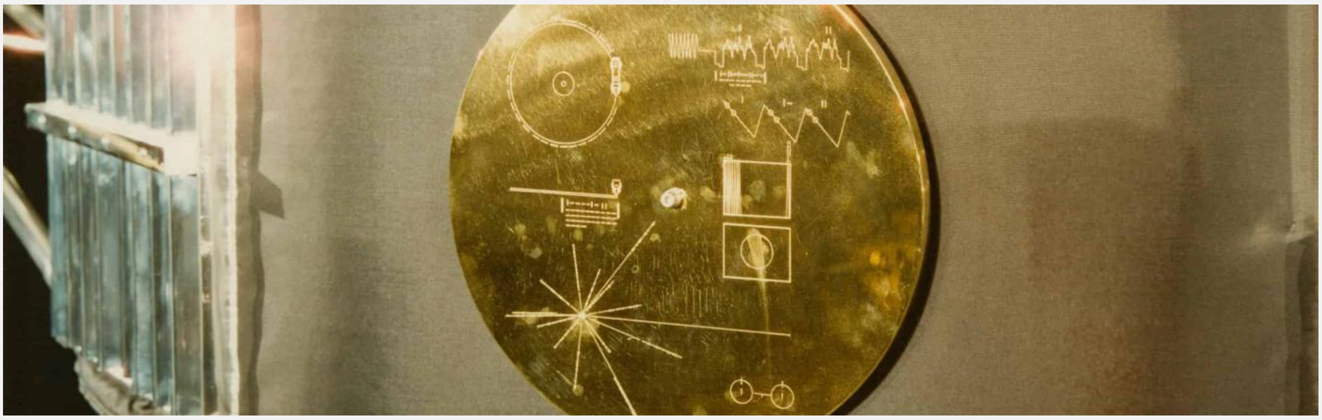
This did become a problem at Madrid when Voyager 1 arrived at Saturn, and some data was lost due to heavy rain storms in the days leading up to the encounter, but the heavy rain managed to miss the station during the really critical moments of the encounter. Luckily in Canberra we have a fairly dry climate, particularly in summer, so rain had never affected our tracking, up to this point, anyway.

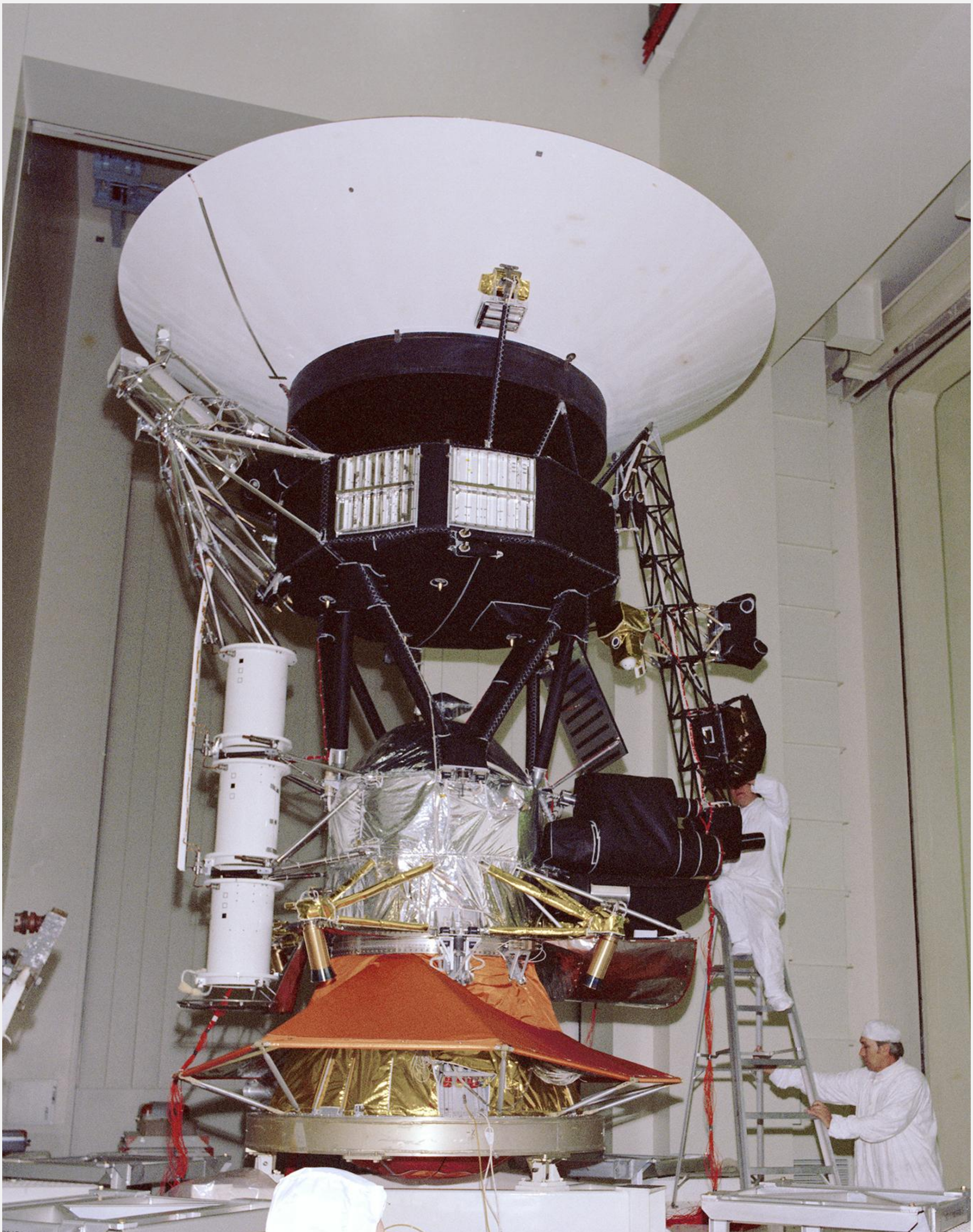
The data rates at X-Band began with 115.2 kilobits per second at Jupiter, dropped to 44.8 kbps at Saturn, 21.6 kbps at Uranus, 14.4 kbps at Neptune, and as low as 7.2 kbps cruising in the outer reaches of the solar system.

It is interesting to note the rapid rate of technological progress. In 1965 Mariner 4 sent back 200 by 200 picture elements, each taking 8½ hours to play back at a data rate of 8⅓ bits per second. 14 years later Voyager returned 800 by 800 picture elements in 48 seconds at 115,200 bits per second.

It is also interesting to compare our life style at the time of the launch. Australia's population was only just over 14 million, and a 3 bedroom home cost $46,000. Our average income was $11,000 a year, and a new car would cost you $6,000 while petrol was 16 cents a litre.

It was primitive days of the personal computer, called microcomputers then. To appreciate the primal nature of the Voyager computers, 1977 saw the Apple II with 48k RAM, Commodore PET with 32k RAM, and Tandy TRS-80 Model 1 with 12k ROM released onto the market. It was four years before IBM would introduce its PC (Personal Computer) to revolutionise the computer world.





Engineers working on vibration acoustics and pyro shock testing of NASA's Voyager on 18 November 1976. Image: NASA/JPL

The Titan-3E, Centaur-D1T and Star-3E stages are stacked and moved to the assembly stand
in preparation for the arrival of the payload fairing containing the Voyager 1 spacecraft. Image: NASA/KSC

Voyager 1 inside its payload fairing is lifted in preparation for mating to the launch vehicle. Image: NASA/KSC

VOYAGER 1
LAUNCH – 5 SEPTEMBER 1977

Using Titan III-E/Centaur rockets, the largest launch vehicle available to NASA at the time *(the mighty Apollo Saturn V had already been retired)*, the Voyagers were launched from Launch Complex 41, Air Force Eastern Test Range, Cape Canaveral, Florida.

Voyager 2 was launched first because if it was boosted by the maximum performance of the Titan/Centaur it would just barely catch the old Grand Tour trajectory to Uranus and Neptune. Launched two weeks later, Voyager 1 could only visit Jupiter and Saturn, with Pluto out of reach.

A Titan-3E Centaur-D1T Star-3E (TC-6) lifts-off from Launch Complex 41 carrying Voyager 1.
Image: NASA/KSC

Following a faster trajectory, it would reach Jupiter four months ahead of Voyager 2 and go on to arrive at Saturn nine months ahead. The nine month separation between arrivals at Saturn meant if Voyager 1 failed in its objectives, Voyager 2 could still be re-targeted to achieve them - but at the expense of the Uranus and Neptune encounters.

Voyager 1's launch was delayed twice to check out the problems experienced by Voyager 2, before it was sent off 16 days after Voyager 2 at 2256:01 AEST on 5 September (0856:01 USEDT). This was the last time the powerful Titan III-E/Centaur rocket combination was used.

Then came the second surprise. Due to a slight error in the mixture ratio of the two liquid fuels, the Titan rocket burned for a shorter time than planned. The next stage, the Centaur rocket, detected the deficiency and used 545 kilograms more fuel to extend its burn time just enough to compensate. That only left 3.4 seconds of fuel – a close call!

Over a social beer in Cocoa Beach the Director of JPL, Bruce Murray, realised that if the two launch rockets had been swapped around, Voyager 2 probably would not have received enough velocity to reach Uranus and Neptune, missing the opportunity of a century.

The final Jupiter trajectory insertion boost of the propulsion module provided a bonus by requiring less than 2 kilograms of hydrazine of an allotted 14 kilograms, leaving 12 extra kilograms for spacecraft attitude control for the rest of the mission.

Ahead lay Jupiter, 998 million kilometres away.

All spacecraft systems checked out as operational within a few hours after launch, and it looked as though Voyager 1 was going to be a successful spacecraft. It passed the Moon ten hours after launch at a distance off the surface of 92,000 kilometres. Two weeks after Voyager 1 set out for Jupiter, on 18 September, it took the first picture of the Earth and Moon in the one frame, from a distance of 11.66 million kilometres from Earth. Eighteen different angles with three different filters were transmitted back for processing.

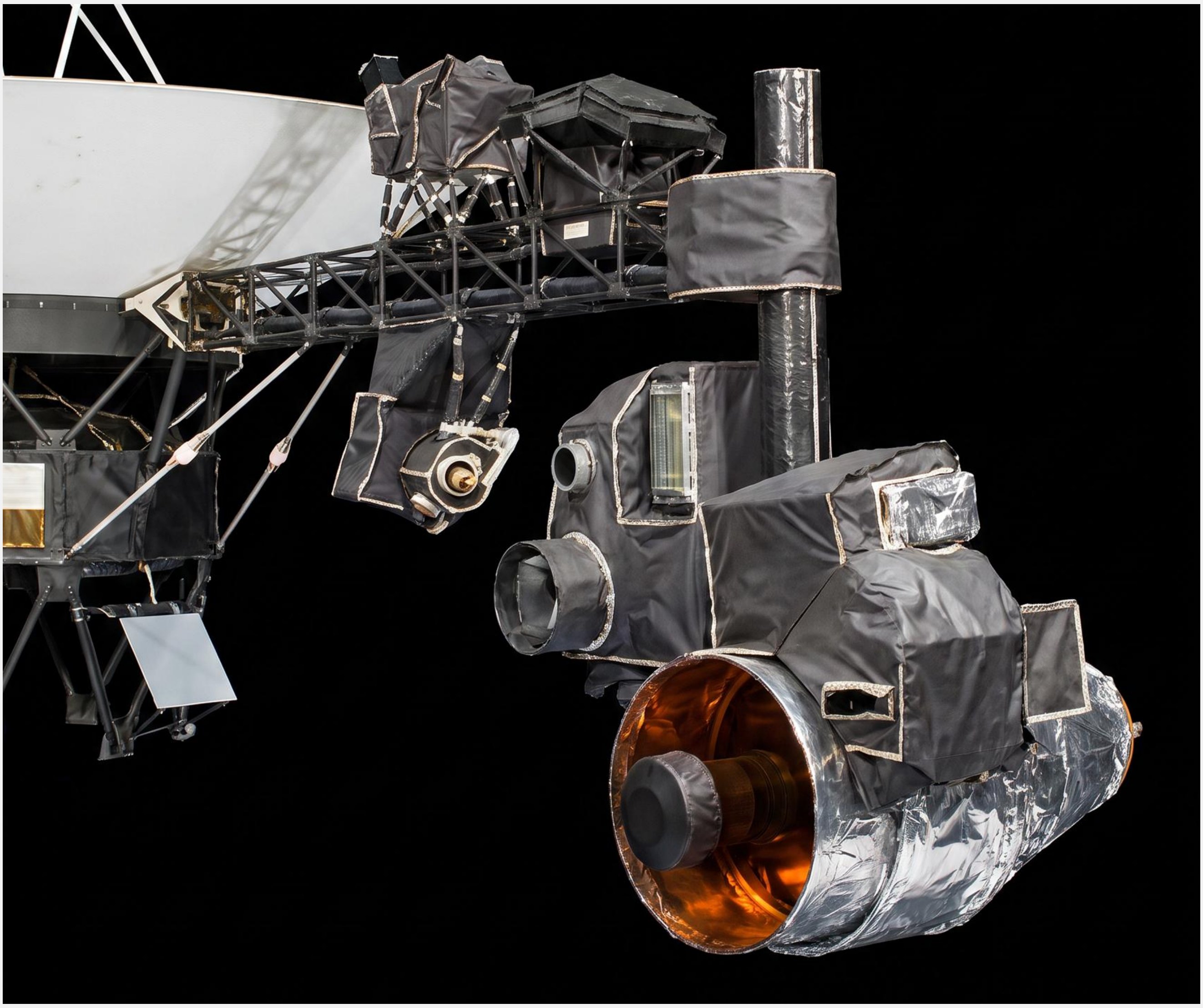
At this point Voyager 1 was cruising along at 75,600 kilometres per hour, 4,680 kilometres per hour faster than Voyager 2. It passed Mars at a distance of 139 million kilometres.

During 11 September the first TCM (Trajectory Correction Manoeuvre) boosted the spacecraft's speed by 8.8 kilometres per hour, and on 13 September another 36.4 kilometres per hour was added. Data received indicated 20% less velocity than planned, suspected to be thruster exhaust impinging on spacecraft structural supports. Compensation was scheduled for the next TCM, which was successfully executed on 29 October.

These periodic adjustments to the flight path were necessary to ensure precise arrival times. In this case Voyager 1's arrival time at Jupiter was critical to study the interaction between Jupiter and Io, as Voyager 2 was not going anywhere near Io during its fly past.

Voyager 1 overtook the Voyager 2 spacecraft around 15 December 1977 and increased its lead to arrive at Jupiter 4 months ahead of Voyager 2.

The Earth and Moon from 11.66 million kilometres captured by Voyager 1 on 18 Sept. 1977. Image: NASA



The scan platform on Voyager 1 faced issues early in the mission. Image: NASA/JPL

VOYAGER 1 HAS SCAN PLATFORM PROBLEMS

Voyager 1's honeymoon ended abruptly on 23 February 1978 when its scan platform slowed and stopped during a manoeuvre.

On 17 March it was commanded to back off -1.5º in azimuth, but stopped short of the target. Two more tries, +9º in azimuth and +3º in elevation were successful.

After a month of careful trials, on 4 April the scan platform was commanded to perform 38 slews, and the next day another 50. On 31 May commands were sent to slew the platform through the faulty section, and it drove through normally.

Engineers suspected that a small piece of plastic from the scan actuator fill screw locking mechanism must have caught in the gears and was crushed or dislodged by all the test slews.

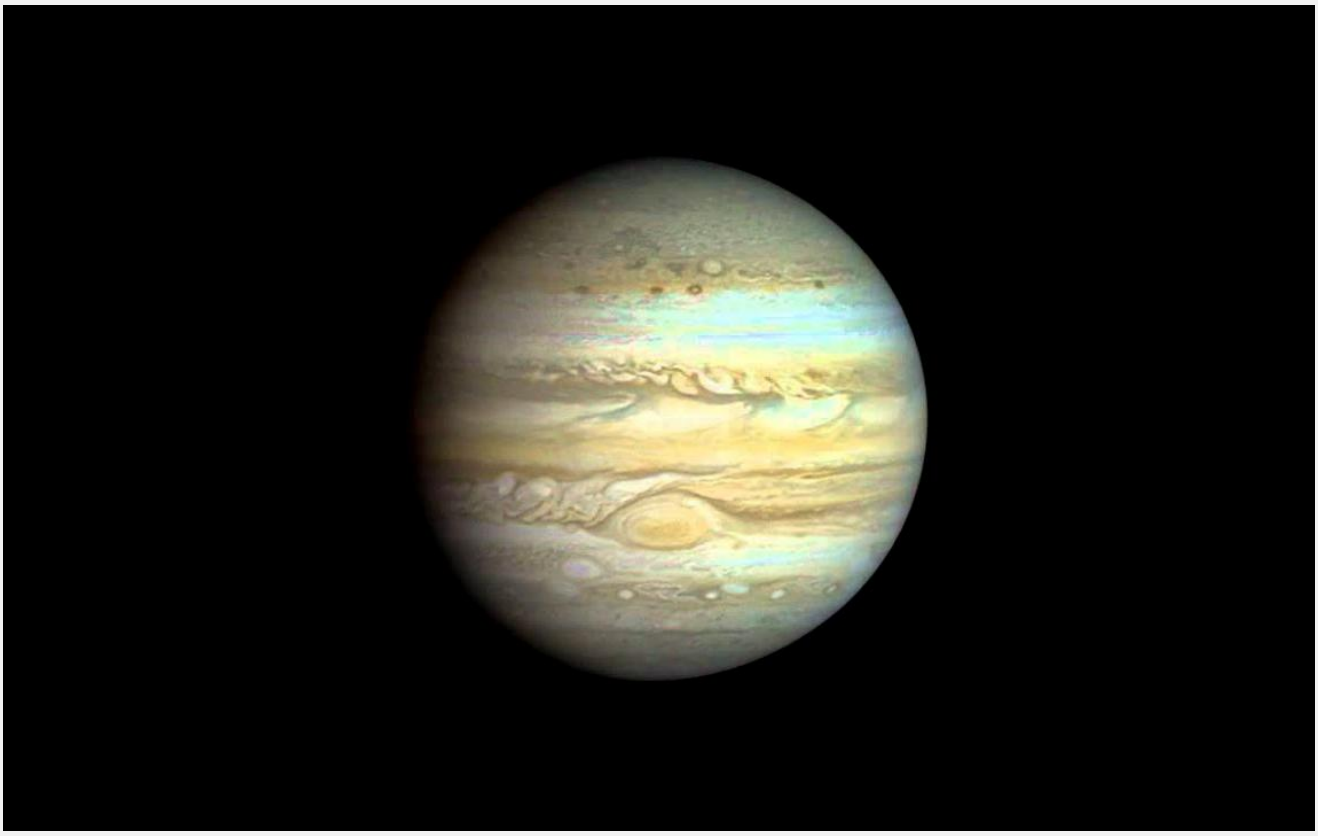
Its maximum slew rate is a degree per second, so it would take 6 minutes to complete a full turn.

THROUGH THE ASTEROID BELT

Voyager 1 burst through the Asteroid Belt on 8 September 1978. It entered the belt, a band of rocks and dust 360 million kilometres wide between the orbits of Mars and Jupiter, with Voyager 2 on 10 December 1977.

Then on 10 December 1978, 83 million kilometres from Jupiter, Voyager 1 took pictures of the planet that surpassed the best photographs ever taken from ground-based telescopes on Earth.

From 12 to 14 December 1978 the Voyager team went through their first Near Encounter Test, a simulation of the 39-hour period before Voyager 1 made its closest approach to Jupiter, and the Flight Teams and Tracking Stations were put through their paces, checking equipment, personnel and procedures.



Voyager 1 took this approach image of Jupiter in January 1979. Image: NASA. Processing: Björn Jónsson

VOYAGER 1

JUPITER ENCOUNTER

Named after the Roman god, Jupiter's discovery date is unknown, as it was known to the ancient civilisations. It has always been regarded as the King of the Planets. It is two and a half times more massive than all the other planets put together. Jupiter is the border between the inner and outer planets. The inner worlds are small and rocky, while beyond Jupiter the worlds are large, with thick gaseous atmospheres, each commanding many moons and rings.

After the Moon and Venus, Jupiter is the third brightest object in our night sky. Orbiting 778.57 million kilometres from the Sun, Jupiter takes 11.86 Earth years to circle the Sun at a speed of 47,052 kilometres per hour. It is the fastest spinning planet in the solar system, spinning on its axis so fast a day only lasts 9 hours 56 minutes as measured by radio emissions from the core.

Its mass (quantity of matter) is 318 times larger than that of Earth. Although Jupiter has a large mass, it has a relatively low density averaging 1.33 grams per cubic centimetre, slightly more than the density of water. Its gravity is 2.4 times the Earth's so 100 kilograms would weigh 240 kilograms on Jupiter.

With no solid surface, the 'surface' of Jupiter is nominally set at a pressure of 1000 bars, with a temperature that varies from -163ºC to -121ºC. The temperature at the cloud tops is -145ºC. Measurements made by ground instruments and spacecraft show that Jupiter's temperature increases with depth below the clouds. The temperature reaches 21ºC – *"comfortable room temperature"* - at a level where the atmospheric pressure is about 10 times as great as it is on Earth. The core temperature may be about 24,000ºC - hotter than the surface of the Sun.

JUPITER ENCOUNTER
MONDAY 5 MARCH 1979
JUPITER FACTS

Diameter:	139,822 kilometres
Distance to Sun:	778,340,821 kilometres
Mass:	1.8986 x 10^{27} kilograms
Orbital period:	11.9 Earth years
Length of day:	9.9 Earth hours
Surface temp:	-148ºC
Closest approach:	348,890 kilometres

The atmosphere consists of 86% hydrogen, 13% helium, 0.1% methane, 0.1% water vapour plus traces of ammonia, ethane, phosphine, and hydrogen sulphide. The outermost layer of the atmosphere contains crystals of frozen ammonia. With a diameter of 142,984 kilometres, Jupiter has 2½ times more mass than all the planets and moons of the whole solar system combined, radiating twice as much energy as it receives from the Sun. As it only has a small tilt of 3.13°, there are no significant seasonal changes on the surface. It has an albedo of 0.52.

There is still some uncertainty regarding the interior structure of Jupiter. One model shows a homogeneous model with no solid surface; the density may simply increase gradually toward the core, the pressure rising up to 10 million bars. Alternatively, Jupiter may possess a dense, rocky core with a mass of up to twelve times the Earth's total mass; roughly 3% of the total mass. The core region is surrounded by dense metallic hydrogen, which extends outward to about 78% of the radius of the planet, and is probably primarily responsible for Jupiter's powerful magnetic field.

On 7 January 1610, when Galileo pointed his telescope at Jupiter for the first time he saw it was a globe surrounded by bright points which he first took to be stars. But then found that these *"stars"* accompanied Jupiter in its motion and crossed over from right to left. He soon realised these were four moons, which he called the Medici stars. These four moons would be visible to the naked eye if they weren't so close to the planet.

When the Voyagers began exploring the realms of Jupiter, there were 15 known moons. The four outer moons – Sinope, Pasiphae, Carme and Ananke circle the planet in retrograde orbits of high inclination, their distances from the planet stretching from 20 to 23.7 million kilometres. These small satellites, none more than 50 kilometres across, take nearly two Earth years to circle Jupiter.

The next four moons are Elara, Lysithea, Himalia (largest of the group at 170 kilometres across), and Leda, the last discovered by Charles Kowal in 1974. They have similar orbits, varying between 11 and 12 million kilometres, also with a high inclination, but rotate in a prograde direction.

Then come the large, or Galilean moons – Callisto, Ganymede (as large as Mars), Europa (just smaller than our Moon), and Io. All are in nearly circular orbits in the same plane as Jupiter's equator, and lie within the inner magnetosphere of Jupiter.

There are 3 additional satellites inside the orbit of Io. The first, designated 1979J2, was discovered by Voyager 1, next is Amalthea, first discovered in 1892, orbits Jupiter in 12 hours at a distance of 181,000 kilometres. A smaller satellite, Adrastea, is closer at 134,000 kilometres.

Scientist Ed Stone commented not much happened scientifically between 1972 to 1979, but when Voyager 1 arrived at Jupiter on 5 March 1979 –

> *"…then the floodgates opened. I mean it just really was a flood. The data was coming in huge, overwhelming deluges, faster than we could comprehend what we were seeing."*

Imaging scientist from the US Geological Survey, Lawrence Soderblom,

> *"When the Voyager spacecraft arrived at Jupiter, we examined Io, Europa, Ganymede, and Callisto. Two of them we knew to be roughly the size and density of our own Moon; the other two we knew to be the size of Mercury, but to consist roughly of half water or water ice. In this cold setting, we expected lifeless, plain, simple, geologic styles and histories that would interest only the most esoteric planetary geologists. To our surprise we discovered an intensely volcanically active moon laced with sulphur and sulphur dioxide driven volcanoes* (Io)*; a moon with a complex, intricate, interwoven network of stretch marks and cycloidal ridges* (Europa)*; and a moon with a bizarre jumble of forms driven by a process of ice-raft tectonics that resembles in some aspects Earth's own process of continental drift* (Ganymede)*."*

As Voyager 1 began its observatory phase of Jupiter on 4 January 1979, 61 days before encounter, the Earth had reached perihelion, its closest approach to the Sun at a distance of 147 million kilometres. Jupiter also reached opposition, i.e. directly opposite the Sun from Earth on 24 January 1979. It took signals from the tracking stations on Earth 63 minutes 20 seconds to reach Voyager and return at the speed of light.

From 30 January Voyager 1 took a photograph every 96 seconds over a 100-hour period, including a movie covering ten Jovian days.

CROSSING THE BOWSHOCK – 28 FEBRUARY 1979

The bow shock is the line of interaction between the particles trapped by a planet's magnetic field and the particles of the solar wind streaming past. It is the outermost layer of the magnetosphere. The magnetosphere is the charged particles controlled by a planet's magnetic field.

The outer regions contain hot plasma consisting mainly of hydrogen, oxygen and sulphur ions.

The stronger the magnetic field the larger the magnetosphere. Jupiter's magnetosphere is 20,000 times stronger than the Earth's magnetic field. Many of the charged particles trapped in a planet's magnetosphere originate from the solar wind, but in Jupiter's case Io's volcanoes provide a substantial portion of Jupiter's magnetosphere.

The magnetopause is the area of the magnetosphere where the pressure from the magnetic field is balanced with the pressure from the solar wind, and changes size and shape as the pressure from the solar wind fluctuates.

Voyager 1 crossed Jupiter's bow shock 5 times. The first crossing was at 0056 AEDT on 1 March at a distance of 6 million kilometres from Jupiter. When the solar wind increased the magnetopause was pushed back and at 0651 crossed the spacecraft in the opposite direction, only to return at midnight AEDT.

The last crossing was at a distance of 3.3 million kilometres. Voyager 1 entered the magnetopause, the boundary of the magnetosphere, at 0623 on 2 March 4.7 million kilometres out.

Scientists noticed that the solar wind pressure was two to five times greater than its level during the Pioneer 10 and 11 encounters.

At 4.12 million kilometres from the planet the magnetopause collapsed again, followed by the bow shock and Voyager 1 found itself back in the interplanetary medium.

The bow shock expanded out for the final time at 3.9 million kilometres as the magnetospheric boundary bounced in and out.

The following table lays out the antics of the Bowshock and Magnetosphere boundaries from 0056 AEDT 1 March as Voyager 1 approached the planet:

BOWSHOCK AND MAGENTOSPHERE ENCOUNTERS

Date	Distance*	Discovered by
28 Feb	6,012,346	First Bowshock encounter
	5,732,702	Bowshock return crossing
1 March	5,033,592	Bowshock expansion
	4,684,037	Magnetopause first encounter
2 March	4,124,749	Magnetopause return
	4,054,838	Bowshock return
	3,915,016	Final Bowshock expansion
3 March	3,285,817	Final Magnetopause crossing
	* from Jupiter's centre (kilometres)	

During 2 March reception of the X-Band signal by DSS43 at Tidbinbilla was interrupted for about 14 minutes by heavy rain, so Goldstone hung on for as long as possible and only three minutes of data was lost during the hand-over.

By now the signal from the spacecraft was taking 36 minutes 41 seconds to reach the Earth.

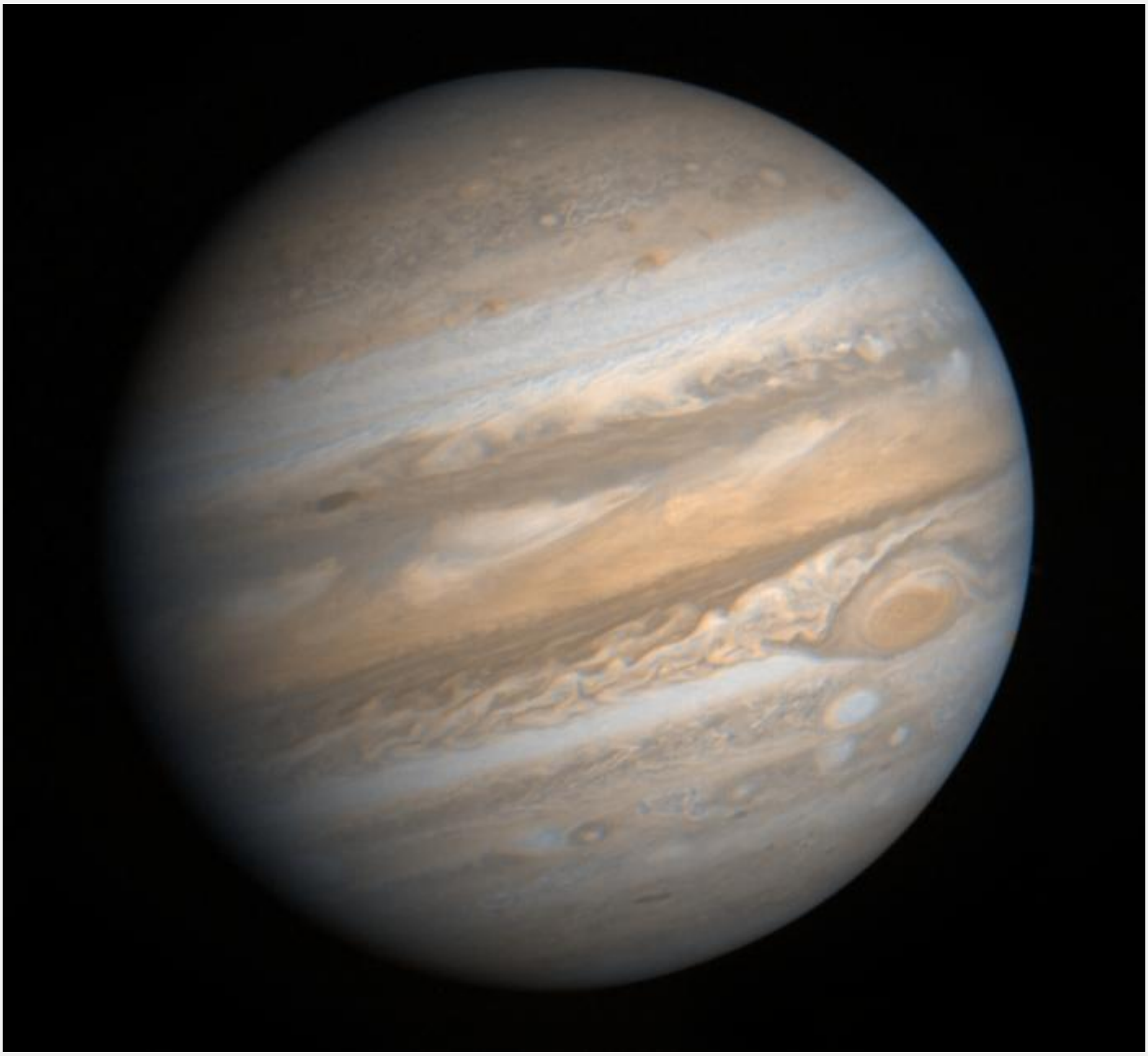
THE JOVIAN ATMOSPHERE

Leader of the imaging team from the University of Arizona, Brad Smith, announced to the media,

> *"Jupiter is far more complex in its atmospheric motions than we had ever imagined. We are seeing a much more complicated flow of cyclonic and anticyclonic vorticity circulation. We see currents which flow along and seem to interact with an obstacle and turn around and flow back."*

It seems that under the ever-changing weather patterns of cyclonic and anticyclonic flows, of storms and eddies, of ovals and filaments, of reds, browns and whites seen on the surface there is an underlying pattern. Jupiter seems to be one of the most active places in the solar system.

Scientists have labelled the dark bands belts and the light bands zones.

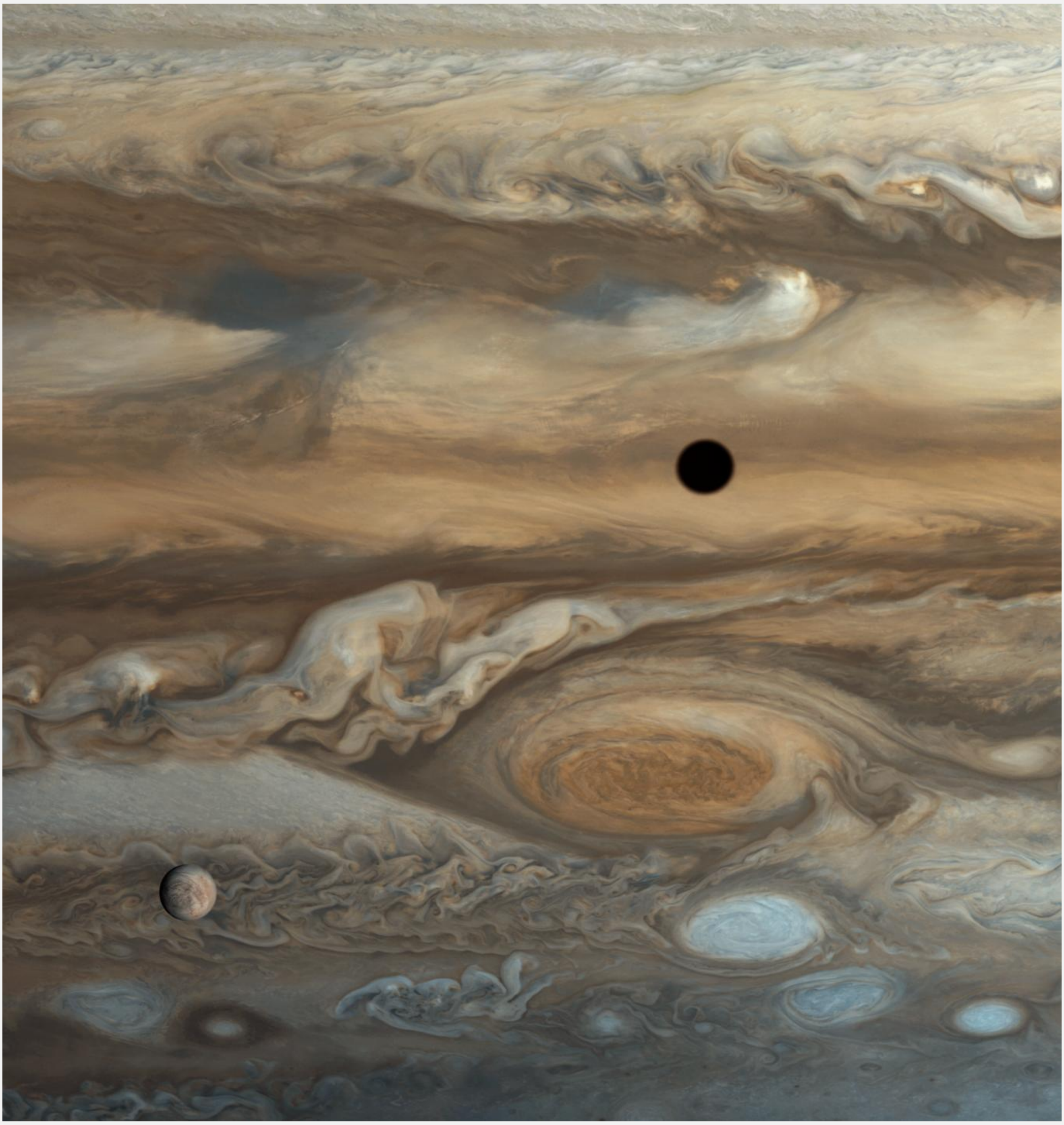


King of the Planets – The gas giant Jupiter reveals its majesty in this Voyager 1 image.
Composite of Voyager images processed using modern techniques by Björn Jónsson

These belts and zones seem to be the Earth's equivalent of jet streams, with winds extending at least 150 kilometres down into the atmosphere.

Comments from the NASA website on the atmosphere of Jupiter:

- Atmospheric features of broadly different sizes appear to move with uniform velocities. That suggests that mass motion (movement of material) and not wave motion (movement of energy through a relatively stationary mass) was being observed.
- Rapid brightening of features in the atmosphere was followed by spreading of cloud material. That is probably the result of disturbances that trigger convective (upwelling and downwelling) activity.
- A pattern of east-to-west winds extends as far pole ward as 60º north and south, roughly similar to the pattern seen in more temperate areas where belts and zones are visible.
  Previous investigations led scientists to believe the near-polar regions (above 45º latitude) are dominated by convective upwelling and downwelling.
  Voyager showed they apparently are not, at least up to 60° latitude, and probably up to 75°.
- Material associated with the Great Red Spot, Jupiter's most prominent atmospheric feature, moves in a counter-clockwise (anticyclonic) direction.

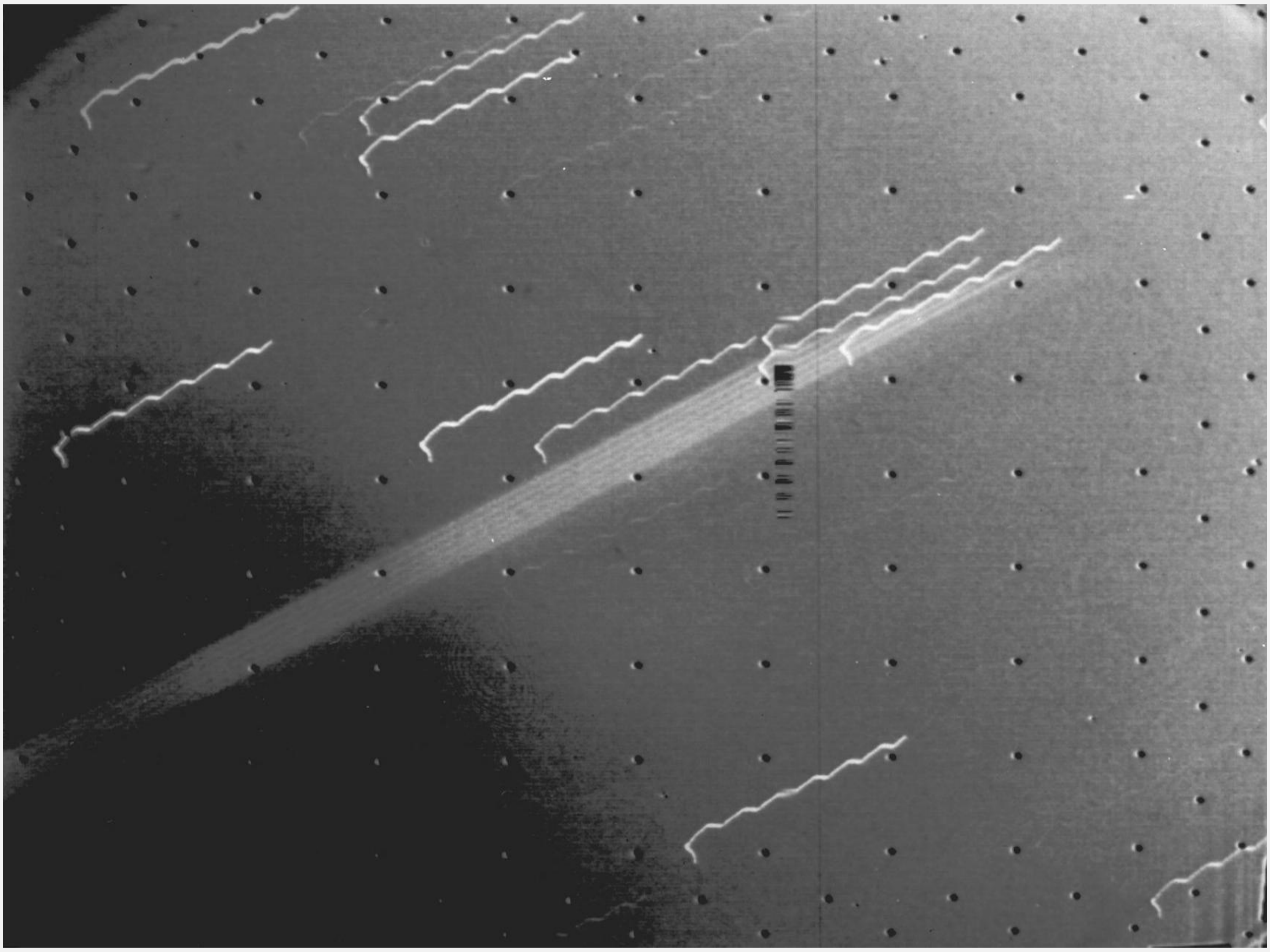


Europa and the Great Red Spot (GRS) as seen by Voyager 1. The shadow of Io is above the GRS.
Composite of Voyager 1 images processed using modern techniques by Alexis Tranchandon

At the outer edge, material appears to rotate in four to six days; near the centre, motions are small and nearly random in direction.

- Small spots appear to interact with the Great Red Spot and with each other.
- Voyager instruments observed auroral emissions, similar to Earth's northern lights, in the polar regions, in ultraviolet and visible light.

  Pioneer 10 and 11 didn't see the ultraviolet emissions during their encounters. The auroral emissions appear to be related to material from Io that spirals along magnetic field lines to fall into Jupiter's atmosphere.
- Voyager also saw cloud-top lightning bolts, similar to superbolts in Earth's high atmosphere.
- Atmospheric temperature at 5 to 10 millibars (1/200th to 1/100th Earth's surface atmospheric pressure) is about 160 Kelvin (–113.2°C). An inversion layer - a warm region above a cold layer - exists near the 150-millibar level. (Pressure at Earth's surface is about 1,000 millibars.)



A long exposure reveals Jupiter's rings. The background stars are wavy due to oscillations by Voyage 1. The black dots are geometric calibration points within the camera. Image: NASA/JPL

- The Voyagers observed ionospheric temperatures that changed with altitude, reaching about 1,100 Kelvin (826.8°C). That was also not observed by Pioneers 10 and 11, and Voyager scientists believe they are witnessing large temporal or spatial changes in the ionosphere of Jupiter.

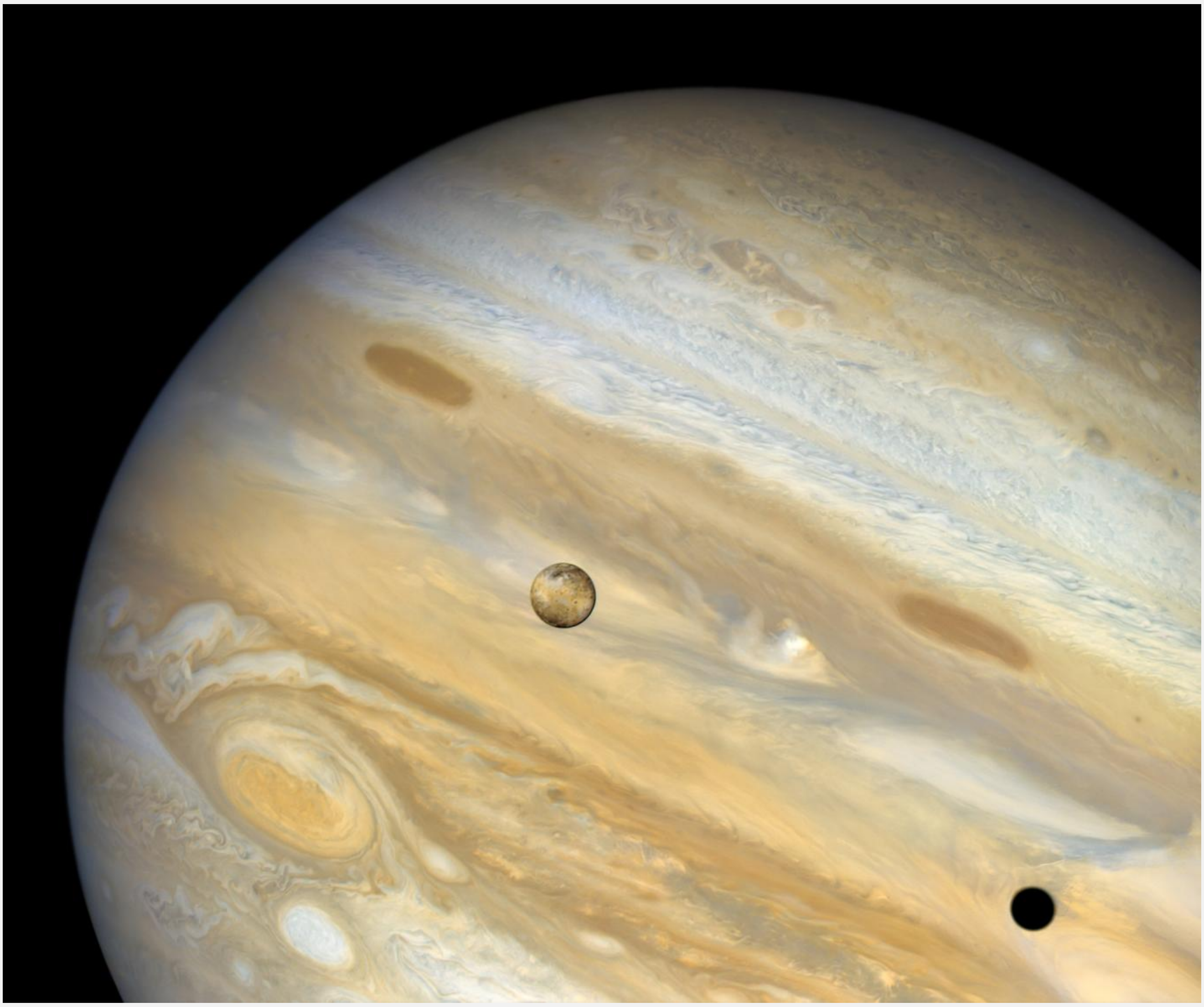
The Voyagers measured helium in the upper atmosphere; its percentage compared to hydrogen is important to understand composition and history of the atmosphere - and the primordial cloud of which the Sun and planets formed. Relative abundance of helium to hydrogen is about 11 percent by volume.

VOYAGER 1 DISCOVERS JUPITER HAS RINGS

No one was expecting rings around Jupiter, the tidal forces from the big moons made it theoretically impossible. But at 16 hours 52 minutes before encounter, at 0613 AEDT, Ed Danielson, an imaging scientist from Caltech, insisted the Voyager cameras were pointed off to the right of the limb of Jupiter in the planet's equatorial plane at the exact moment the spacecraft would be crossing the equatorial plane, and the shutters commanded for an 11.2 minute exposure. Brad Smith explained,

> *"We weren't certain of the exact moment that we would cross the equatorial plane, so we planned to open our shutter and leave it open as we went through."*

To everyone's surprise a single, very faint ring appeared on the television screens back on Earth. Starting at about 20,509 kilometres above the surface and extending out to 178,500 kilometres, the brightest part of the ring turned out to be only 5,150 kilometres wide and 32 kilometres thick. Two days later two Hawaiian astronomers, Eric Becklin and Gareth Wynn-Williams, at the Manua Kea Observatory succeeded in detecting the rings by their reflected sunlight, confirming Voyager 1's discovery. The way the sunlight was scattered indicated the rings were made of fine dust-like particles, which is suspected to come mainly from the inner moonlets of Metis and Adrastea.



The volcanic moon Io (eye-oh) and its shadow transit the face of Jupiter. Image: NASA/JPL

VOYAGER 1 ENTERS THE REALM OF JUPITER'S MOONS

On 10 February Voyager 1 crossed the orbit of Sinope, Jupiter's outermost moon, but still had 23.7 million kilometres to go to reach the planet itself. During 13 February, twenty days before Jupiter's closest approach, the disc of Jupiter exceeded the field of view of the telephoto camera, and the wide-angle camera took over full disc imaging.

A severe thunderstorm at DSS 43 Tidbinbilla in Canberra during the afternoon of 3 March again interrupted the X Band science data flow for 3 hours and 20 minutes. Close-ups of the Great Red Spot and an extended series of observations of the glowing sodium cloud around Io were lost.

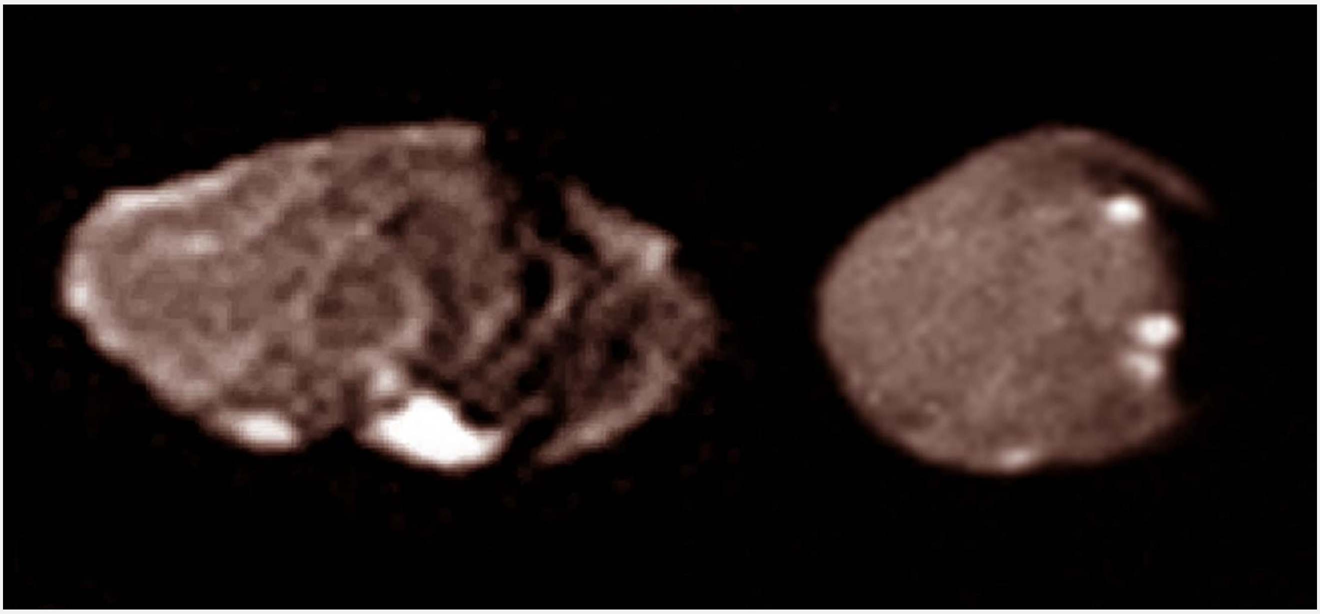
For this historic occasion a special television monitor was set up in the White House for the President and his family, and the Governor of California visited JPL in Pasadena for the night.

JPL was now host to scientists from around the country and abroad, with staff in the operational areas burning lights around the clock. Special computer controlled locks were installed on the doors, and security guards patrolled the halls.

During the early morning in Los Angeles on Monday 5 March images of Jupiter flashed across the television screens every 48 seconds and the project scientists prepared for action. Garry Hunt, a member of the imaging team said,

> *"It seems far more photogenic now than it did during the Pioneer encounters. There are infinitely more details than we ever imagined."*

At 0823 AEDT 5 March Voyager 1 crossed the orbit of Ganymede and a few hours later Europa's orbit before taking a look at the first moon to be studied, Amalthea.



Two views of Amalthea taken by Voyager 1. Images: NASA/JPL

AMALTHEA

Diameter:	166.9 kilometres (mean)
Albedo:	0.09
Mass:	2.0682 x 10^{18} kilograms
Jupiter distance:	181,365 kilometres
Orbital period:	11h 57m 23s Earth hours
Surface temp:	-153.2°C
Closest approach:	416,912 kilometres

First in the cavalcade of Jupiter's moons to come under the scrutiny of Voyager 1's camera lenses and instruments was Amalthea.

Discovered by Edward Barnard on 9 September 1892, at Lick Observatory, Amalthea was originally designated Jupiter V, then the French astronomer Camille Flammarion suggested the name Amalthea for this moon, but it wasn't formally adopted until 1976. Amalthea is named for a naiad (a female water nymph in mythology) who nursed the new-born Jupiter. Amalthea is often depicted with a goat, whose milk is said to have fed the infant Jupiter.

Amalthea is a potato shaped moonlet covered in a red coating. Only 270 by 160 kilometres in size, Amalthea orbits around Jupiter every 11 hours 57 minutes 23 seconds at a speed of 95,652 kilometres per hour.

Always keeping its same side facing Jupiter, it is the reddest object in the solar system, and appears to give out more heat than it receives from the Sun.

Voyager 1 came within 416,912 kilometres of Amalthea at 1728 AEDT 5 March 1979.

Amalthea is one of a group of four satellites, or moonlets, that orbits Jupiter inside Io. From the closest to the furthest they are:

MOONLETS

	Distance*	Discovered by
Metis	128,000	Voyager 1
Adrastea	129,000	Voyager 2
Amalthea	181,300	Edward Barnard 1892
Thebe	221,900	Voyager 1
	* from Jupiter's centre (kilometres)	

Voyager 1 was responsible for the discovery Thebe, one of Jupiter's inner moons, when a member of the optical navigation team, Stephen Synnott, spotted the moonlet and its shadow in some of Voyager 1's pictures of the surface of Jupiter on 5 March 1979 while verifying the existence of Adastra (1979J1).

THEBE 1979J2

Diameter:	98.6 kilometres
Albedo:	0.047
Mass:	1.4987 x 10^{18} kilograms
Jupiter distance:	221,900 kilometres
Orbital period:	16h 11m 18s Earth hours
Surface temp:	-149°C
Closest approach:	280,000 kilometres

Left: Discovery image of Thebe (dark spot above swirling clouds). **Right:** Galileo image of Thebe. Images: NASA

The first of these pictures was originally taken at 1839 AEDT, 4 hours 26 minutes before the point of closest approach (PCA) to Jupiter.

Originally called S/1979J2, this satellite was ultimately named *"Thebe"*, after the daughter of the river god Asopus, and Metope. Names associated with Jupiter - or his Greek equivalent, Zeus - in a variety of ways in different myths. In one, Thebe was a nymph who was a love of Zeus. In another, she was an Egyptian king's daughter and a love of Jupiter.

Along with its sister inner moon, Metis, Thebe was exempted from the International Astronomical Union's requirement that prograde satellites (not counting the Galilean moons) receive names ending in *"a"*.

Tidally locked so the same side always faces Jupiter, Thebe travels around its orbit at 86,148 kilometres per hour, giving it an orbital period of 16 hours 11 minutes 18 seconds.

Jupiter's innermost moon Metis was discovered by Stephen Synnott of the Voyager science team on 4 March 1979. He first thought it was 1979J1 Adrastea but when checking Voyager 1 pictures from March 1979 he discovered Thebe.

Further cross checking between Voyager 1 and Voyager 2 pictures showed this object would have been on the opposite side of Jupiter from Thebe's position. This led to the discovery of Metis.

METIS 1979J3

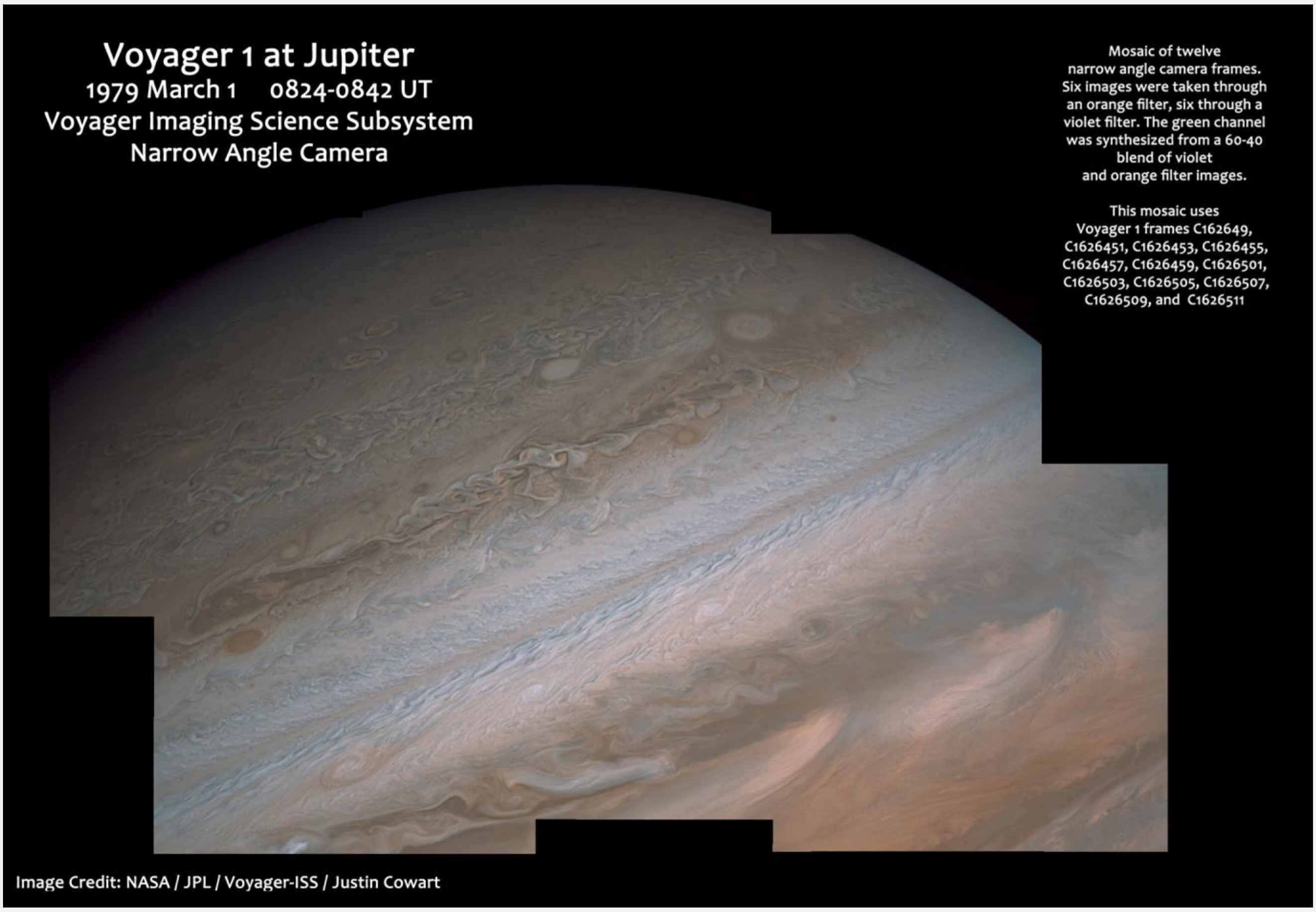
Diameter:	43 kilometres
Albedo:	0.061
Mass:	1.1989 x 10^{17} kilograms
Jupiter distance:	128,000 kilometres
Orbital period:	7h 5m 0s Earth hours
Surface temp:	-150°C
Closest approach:	- kilometres

Metis (wisdom, or skill) was a Titaness who was the first wife of Zeus (Jupiter) and mother of Athena. Zeus tricked Metis into a fly and swallowed her while pregnant with their first child because he feared the power of the baby, but he was too late. The baby became Athena and leapt fully grown and armed from Zeus' head.

Metis has a mean diameter of 43 kilometres with the longest dimension of 60 kilometres. Travelling around its orbit at 113,652 kilometres per hour Metis would be the fastest satellite in the solar system with an orbital period of 7 hours 4 minutes 30 seconds.

Ring specialist of Cornell University, Joe Burns, suggested that if it were not for the small moonlets, which includes Metis, orbiting so close to Jupiter, none of the rings would exist.

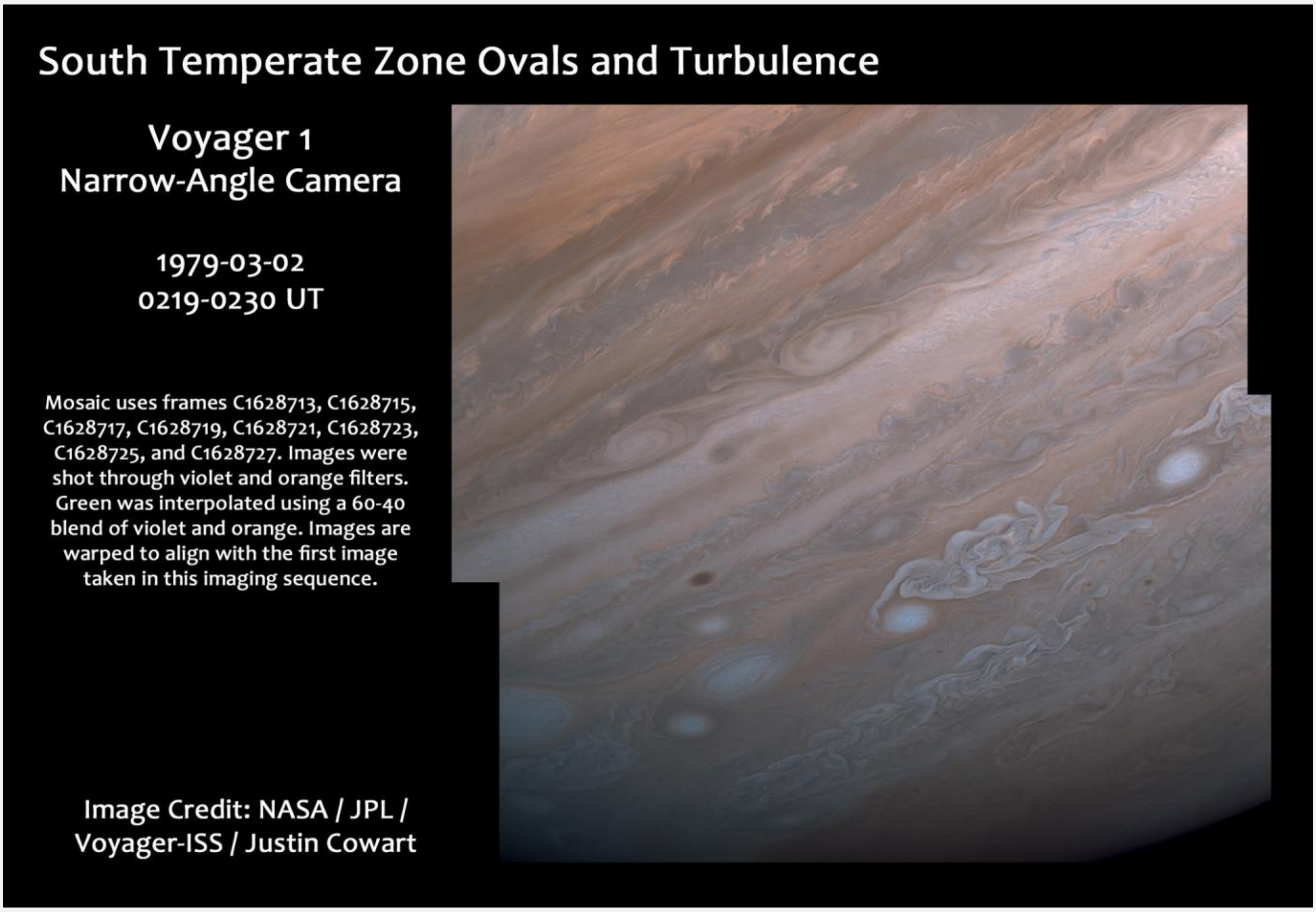
He thinks that the main rings probably come from Adrastea and Metis.



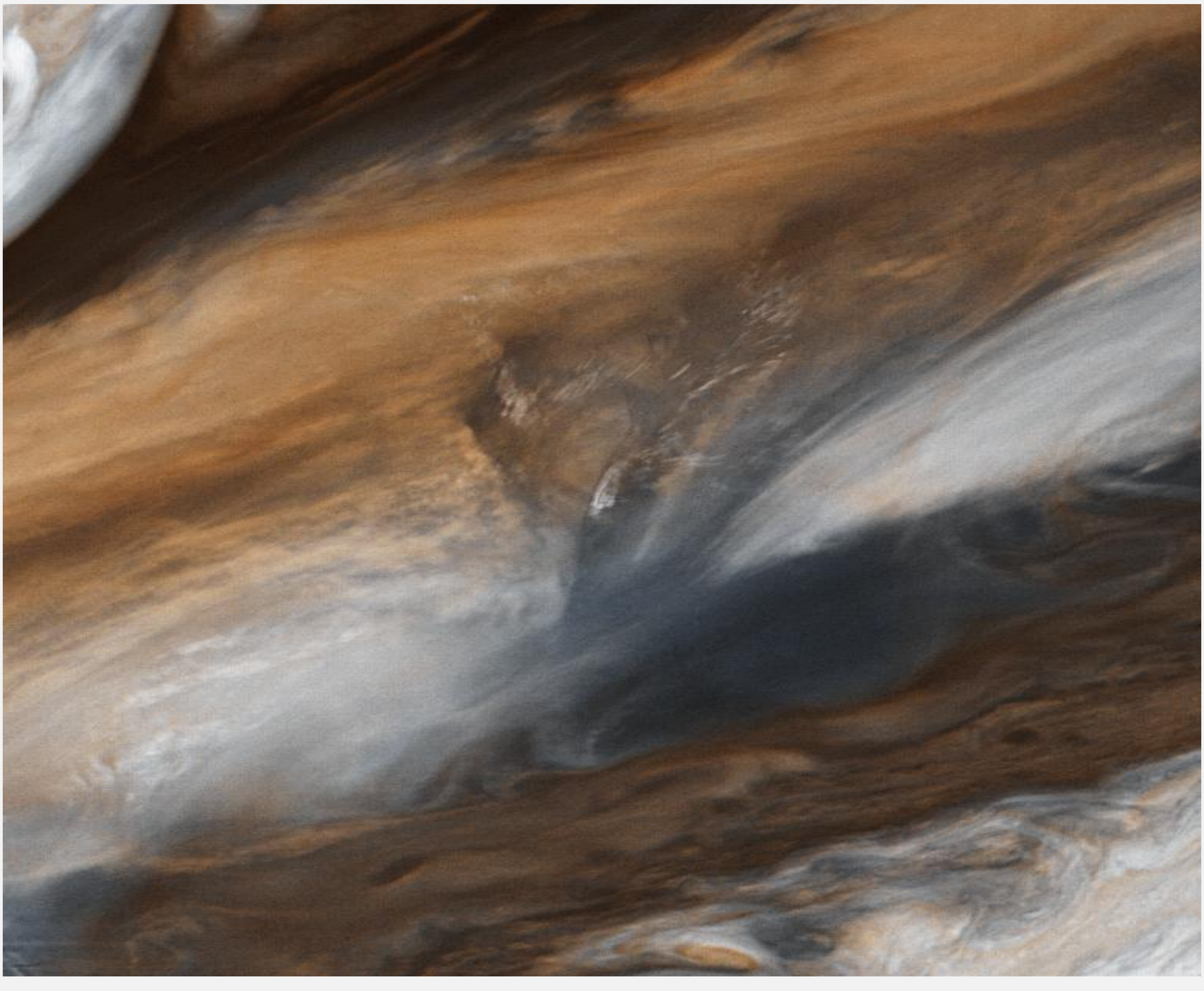
Above: Mosaic of Voyager 1 images showing northern latitudes,

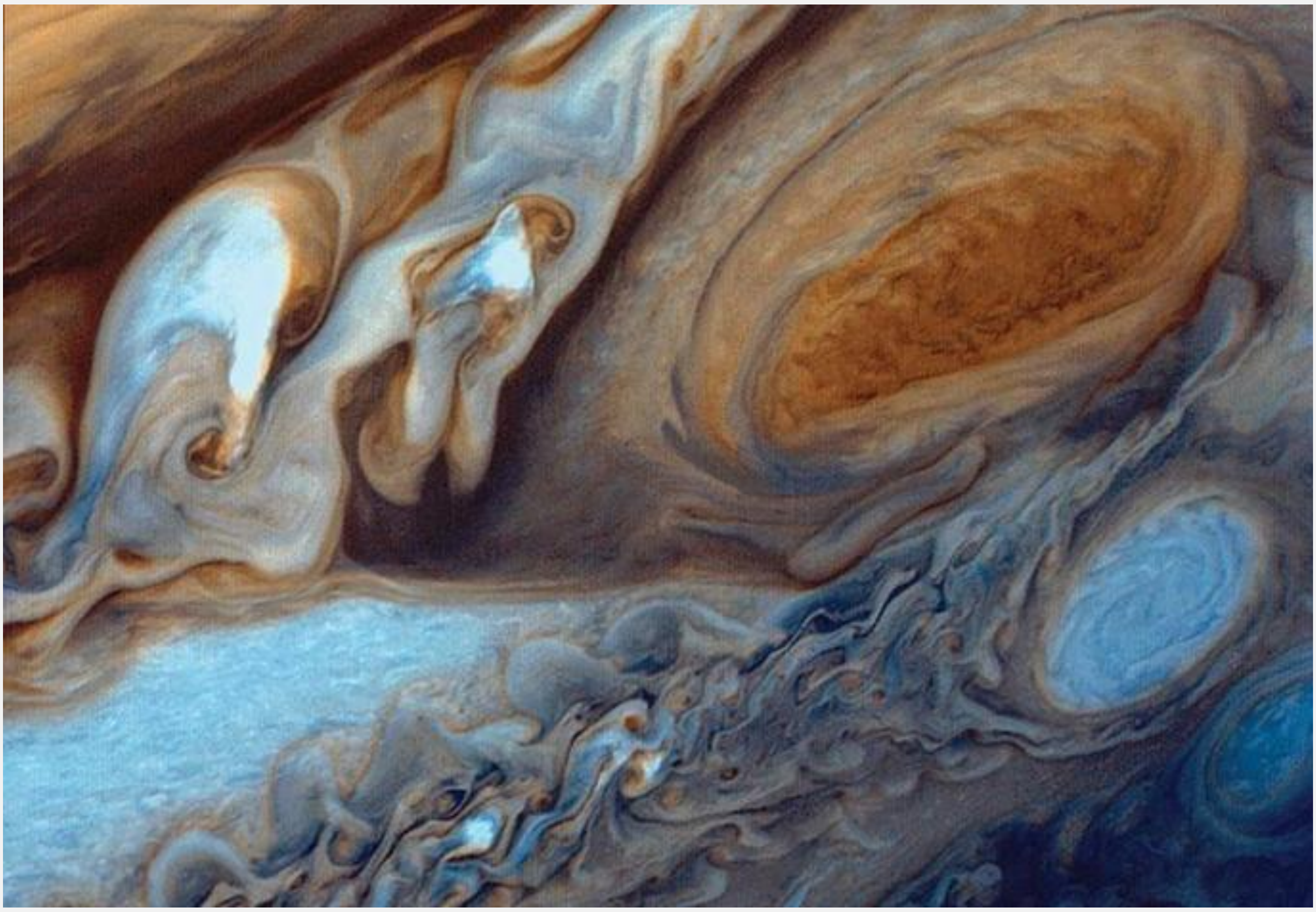
Images: NASA/JPL. Modern processing by Justin Cowart

Below: Mosaic of Voyager 1 images showing Jupiter's south temperate zone.



Above: Mosaic of Voyager 1 images showing clouds in the northern polar region of Jupiter.
Images: NASA/JPL. Modern processing by (above) Justin Cowart and (below) Alexis Tranchandon
Below: Complex cloud layers in Jupiter's atmosphere.

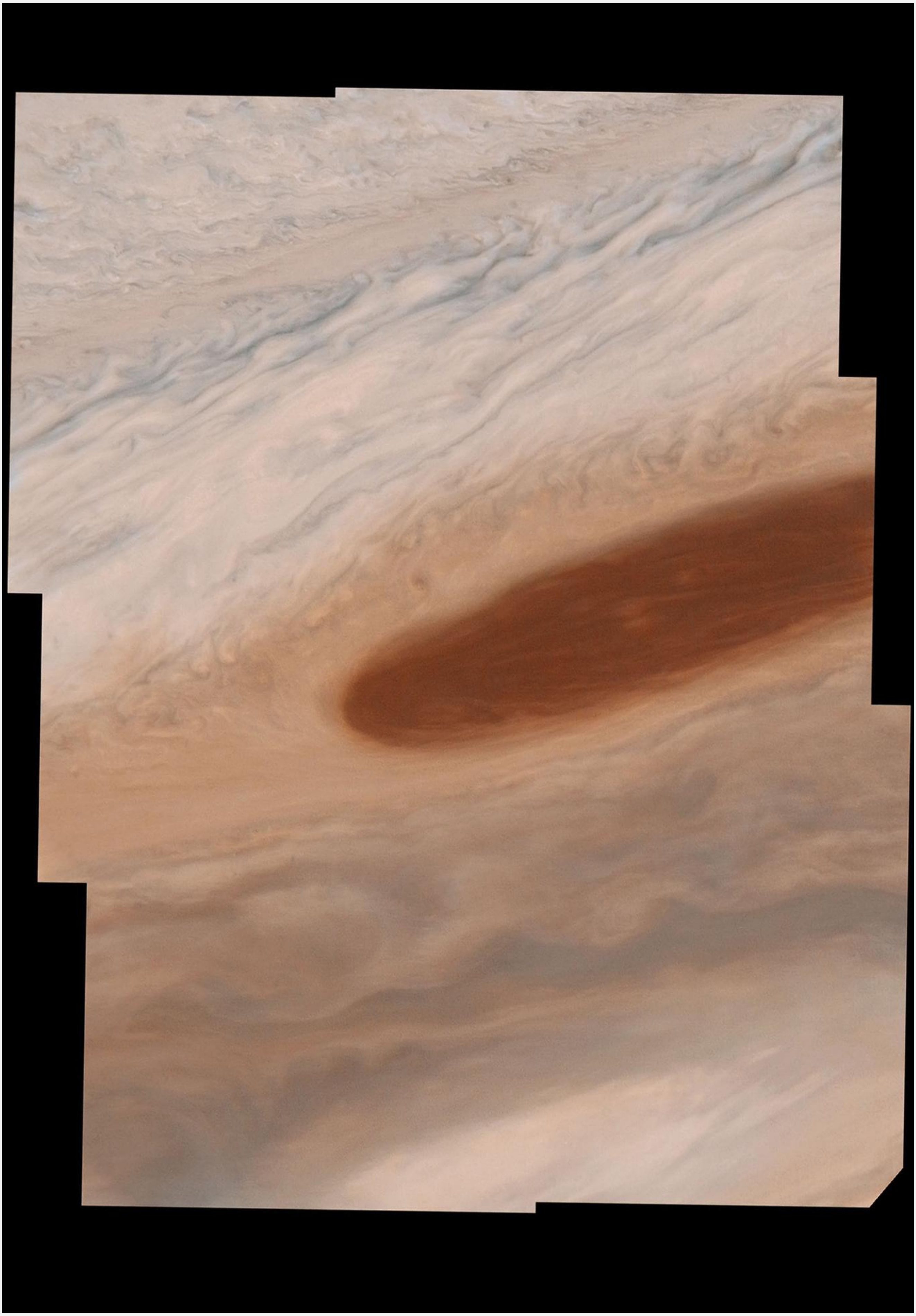




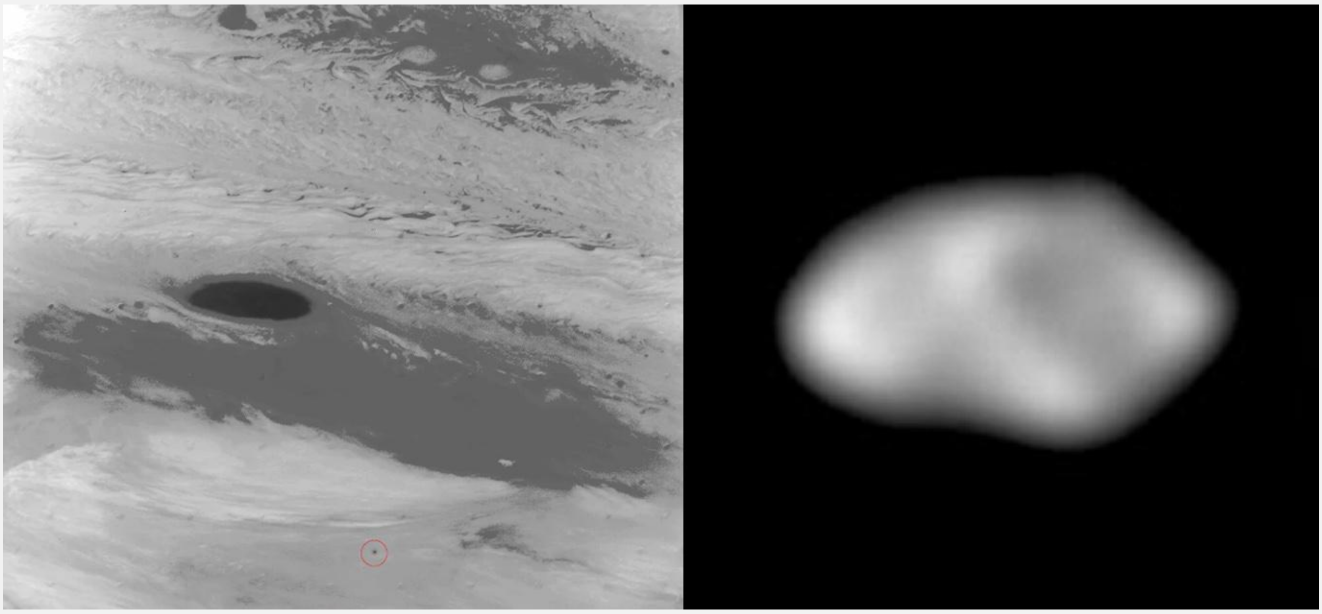
Above: Colour enhanced image of the complex cloud structures near the Great Red Spot.

Images: (above) NASA/JPL. Modern processing (below) by Björn Jónsson

Below: Big enough to swallow two Earths, Jupiter's Great Red Spot.

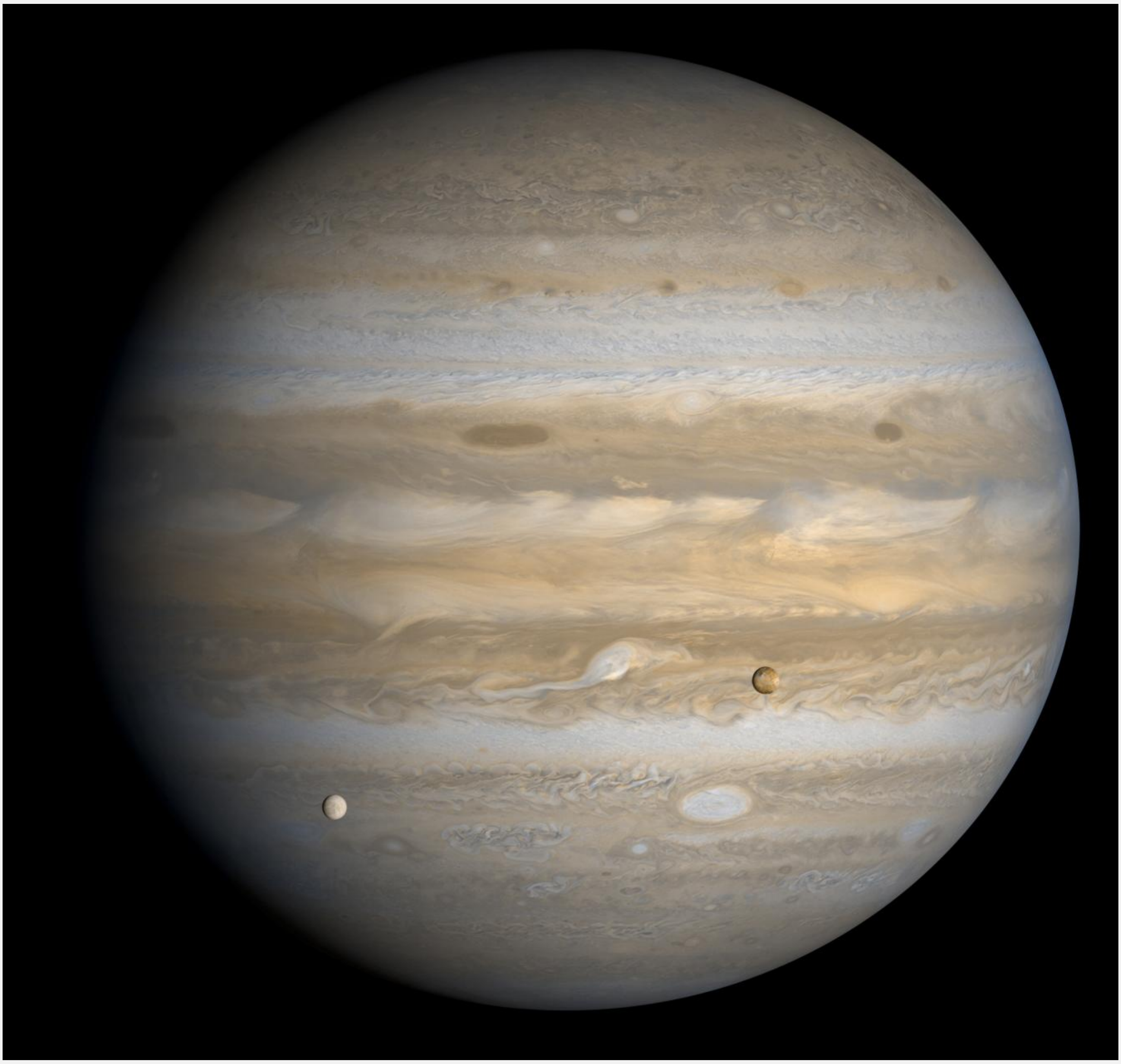


‘The Barge’ is a cyclonic storm similar to the much larger Great Red Spot.
Image: NASA/JPL. Processed by Justin Cowart



Left: Metis (circled) seen by Voyager 1 against Jupiter's clouds. **Right:** Metis seen by Galileo. Images: NASA

The moonlet Adrastea (circled) as seen by Voyager 1 on 4 March 1979.
The shadow of Io is on the left. Wave cloud formation in Jupiter's atmosphere are seen below.
Image: NASA/JPL. Image processed using modern techniques by Justin Cowart



The Galilean moons Europa (left) and Io (right) transit the face of Jupiter in this Voyager 1 image.
Composite of Voyager images processed using modern techniques by Björn Jónsson

VOYAGER 1 AT JUPITER
PCA – POINT OF CLOSEST APPROACH
23:05 AEDT – MONDAY 5 MARCH 1979

Voyager 1 raced past Jupiter at 130,305 kilometres per hour, coming to within 277,400 kilometres of the cloud tops at 2305:26 AEDT 5 March 1979.

The first moon Voyager 1 saw after passing Jupiter was the enigmatic Io.

Discovered by Galileo Galilei on 7 January 1610, though Simon Marius claimed to have discovered it a week before. Io was named after an unfortunate princess who was loved by Zeus and changed into a heifer by the god Jupiter and given by Juno into the charge of Argus and driven all the way to Egypt. There she regained her human form and was transformed into the Egyptian goddess Isis.

While most Australians were asleep, Voyager 1 swept past Io's south pole at the closest range of 20,253 kilometres at 0220 AEDT on 6 March 1979, just before disappearing behind Jupiter.

IO

Diameter:	3,643 kilometres
Albedo:	0.63
Mass:	8.93×10^{22} kilograms
Jupiter distance:	421,700 kilometres
Orbital period:	1.77 Earth days
Surface temp:	-135°C (hot spots 27°C)
Closest approach:	20,253 kilometres

Jupiter's limb is visible in the background, with the volcanic moon Io dominating the scene.
Image: NASA/JPL. Voyager 1 image processed using modern techniques by Ted Stryk

DSS43 at Tidbinbilla and DSS44 Honeysuckle Creek were tracking the spacecraft at the time.

Io turned out to be a very active moon, different to any other known body in the solar system - it was a shock to the scientists, expecting it to be riddled with impact craters.

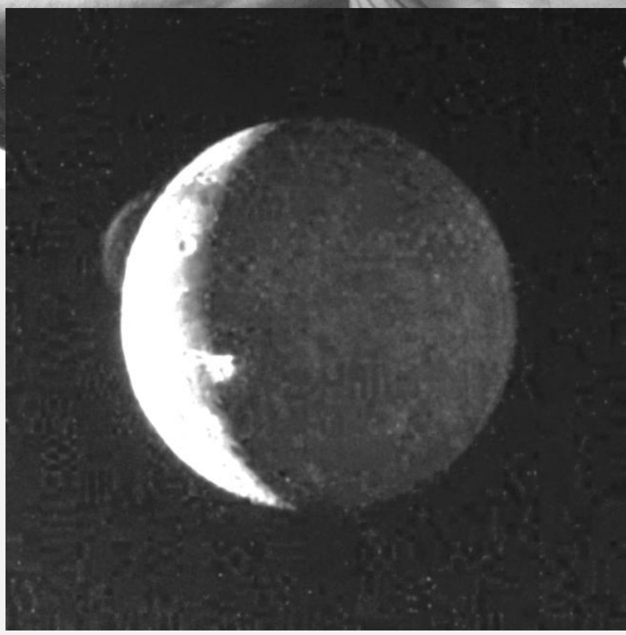
Linda Morabito, a 26-year-old optical navigation engineer, was checking Voyager's line of departure from Jupiter by measuring the positions of stars off the limb of Io using a picture taken at 0500 USPST on 8 March. When she spotted a bluish crescent cloud sprouting from the edge of the moon she was puzzled. As Io has no atmosphere, a cloud rising hundreds of kilometres above the surface did not make sense.

The next day she eliminated all the possibilities and concluded it must be a volcano – a volcano of incredible violence rising 280 kilometres above the surface. The lava had to be gushing out at more than 3,700 kilometres per hour.

As it was a Friday, most senior members of the team had left for their homes to get some rest, so it was two days before she could show and discuss her find with her colleagues. It was Monday

morning before the other Imaging Team scientists saw her picture, and Joseph Veverka and Robert Strom promptly began looking for other signs of volcanic activity.

By mid-morning several additional volcanic plumes had been found.



Top: Joe Donegan, Ed Travers, Linda Morabito and Steve Synnott in the navigation team's image processing room, where the discovery of active volcanism on Io took place.
Right: Volcanic plume and hot spot on Io.
Left: Linda Morabito with her Io discovery image.

Jupiter with icy Europa (right) and volcanic Io (left). Image: NASA/JPL

Io has the highest density of all the moons in the solar system. Primarily composed of molten silicate rock it probably has a core of iron (perhaps mixed with iron sulphide), the core's radius being at least 900 kilometres.

Unlike the other Galilean satellites, Io has little or no water. Io's terrain consists mostly of flat plains rising to less than 1 kilometre with some mountains up to 13 kilometres high. Numerous lakes of molten sulphur and calderas up to several kilometres deep appear on the surface.

The original volcano P1, which became known as Pele, after the Hawaiian goddess of volcanoes, was the first direct observation of active volcanism in a world besides the Earth. Io has become the most active volcanic place we have yet found, with no impact craters of any kind.

A later volcano called Loki (P2) was more powerful than all of the Earth's volcanoes combined. Ra Patera is Io's largest shield volcano with a diameter of 450 kilometres, but its peak only rises 1 kilometre above the terrain. Shield volcanoes have relatively gentle slopes, usually produced by successive outpourings of fluid lava.

Strictly speaking, scientists now regard Io's volcanoes more as huge geysers of lava. Voyager 1's cameras spotted a total of 8 volcanoes.

As Europa and Ganymede are adjacent to Io, the gravitational attraction of these moons pulls it out of its orbit, but when Io speeds ahead and the two moons lose their influence, Jupiter pulls Io back into its regular orbit. This causes huge tidal bulges, as high as 100 metres, on Io's surface.

This constant movement generates a lot of internal heat, which melts sulphur compounds and ejects them violently from the moon through volcanoes.

As the magnetosphere rotates with Jupiter, it sweeps around Io and strips away about a tonne of material per second. The material forms a torus, a doughnut-shaped cloud of ions that glow in the ultraviolet. The torus's heavy ions migrate outward, and their pressure inflates the Jovian environment with more energetic sulphur and oxygen ions falling along the magnetic field into the planet's atmosphere, resulting in auroras.

Io acts as an electrical generator as it moves through Jupiter's magnetic field, developing 400,000 volts across its diameter, and generating an electric current of 3 million amperes that flows along the magnetic field to the planet's ionosphere.

At the press conference that morning Brad Smith happily announced,

> *"The Io pictures this morning were truly spectacular and the atmosphere up in the imaging area was punctuated by whoops of joy or amazement – or both."*

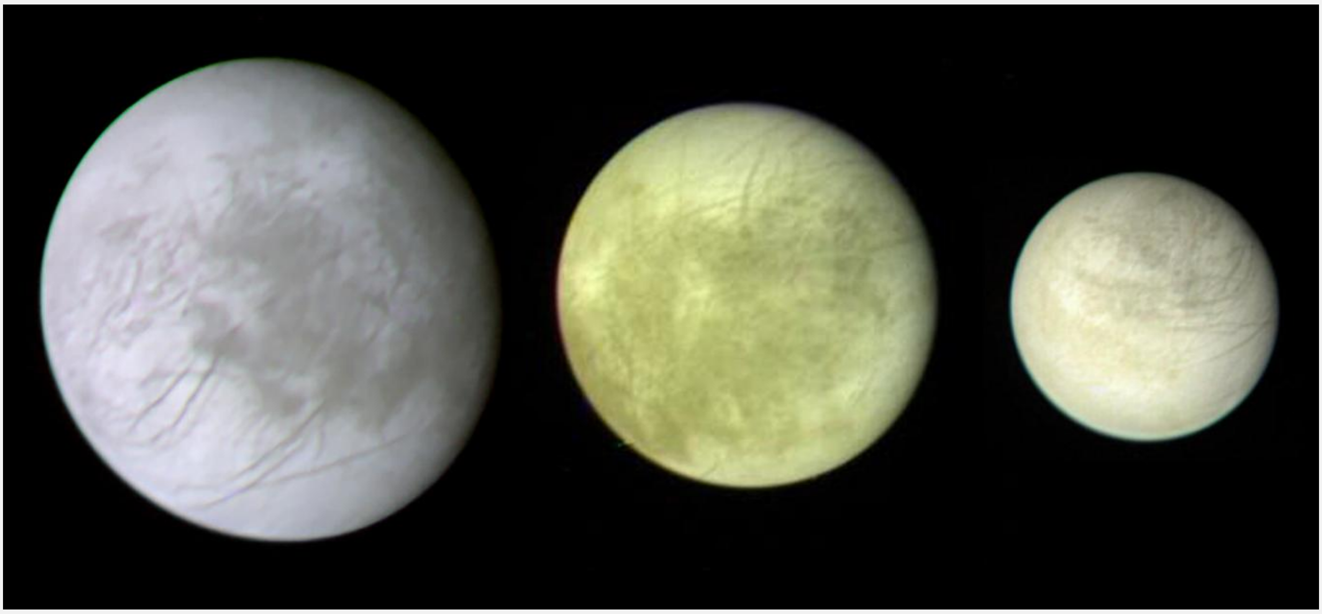
Europa orbits above Jupiter's dynamic and intricate cloudscape.
Image: NASA/JPL. Voyager 1 image processed using modern techniques by Kevin M. Gill

VOYAGER 1
OCCULTATION BEHIND JUPITER

Then at 0251 AEDT on 6 March Voyager 1 slipped behind the rim of Jupiter and all its signals dropped out. As Voyager 1 pressed on, 53 minutes later it plunged into darkness as the sun set on the spacecraft.

During this signal *"blackout"* period of 1 hours 57 minutes all the data being sensed was being stored in the on-board magnetic tape recorders for dumping back through the tracking stations to Earth later. Looking down onto the dark surface of the planet below, the infrared IRIS (see below for details of this instrument) measured the night temperatures of the planet and long-exposure pictures were taken to look for aurora, lightning and fireballs in the Jovian atmosphere.

One 3 minute 12 second exposure taken with the wide-angle camera showed a long white streak – the largest aurora ever seen, almost 29,000 kilometres long. In the same frame 19 smaller bright spots showed Jupiter had 'superbolts' of lightning active in the clouds, the plasma experiment (PWS) detecting 'whistling' radio emissions from them.



Three views of Europa from Voyager 1. Images: NASA/JPL

These superbolts are suspected to be triggered by the torus material from Io, spiralling down magnetic field lines into the planet's ionosphere.

Communication with Voyager 1 was restored on the other side at 0448 AEDT, and it was back in sunlight at 0556.

The first thing the flight controllers noticed was the spacecraft's main clock had slowed down by about 6.3 seconds, and the next day it was 8 seconds slow, believed to be caused by the powerful radiation belts of Jupiter. Then the two central computers lost synch with each other and the flight data subsystem, with the result that pictures were being taken 40 seconds early. This timing error resulted in the camera taking some pictures while the scan platform was still moving, causing some images to be blurred.

EUROPA

Diameter:	3,121.6 kilometres
Albedo:	0.67
Mass:	4.8 x 10^{22} kilograms
Jupiter distance:	671,034 kilometres
Orbital period:	3.55 Earth days
Surface temp:	-163°C
Closest approach:	732,245 kilometres

Next in the cavalcade of moons was Europa. Discovered by Galileo Galilei on 7 January 1610, though Simon Marius claimed to have discovered it a week before. Europa, the beautiful daughter of Agenor, son of Poseidon and King of Phoenicia, and his wife Telephassa, was seduced by Zeus disguised as a white bull and carried her off to Crete where he fathered her three sons, Minos, Rhadamanthus and Sarpedon.

Frigid Europa is the opposite to Io – a smooth, ice-coated ball, with a surface temperature of -163°C at the equator and -223°C at the poles. It is proposed that the surface is a crust of frozen water, about 29 kilometres thick, floating on a 100 kilometre deep ocean of salt water below. A new crust welling up under the ice plates was most probably slushy ice, or even liquid water that has since frozen and fractured.

If this is true, Europa has the only known reservoir of water outside the Earth, and may support some sort of primitive life. Europa seems to have a tenuous atmosphere of pure oxygen of 1µPa, though it may not be of biologic origin. It is most likely generated by ultraviolet sunlight and charged particles hitting Europa's icy surface, splitting water into hydrogen and oxygen. The hydrogen escapes Europa's gravity due to its low atomic mass, leaving the oxygen behind.

While still in Jupiter's shadow Voyager 1 passed within 732,245 kilometres of Europa at 0425 AEDT. Voyager 1 only had a distant, tantalising look at Europa, Voyager 2 was to go 526,395 kilometres closer. Europa displayed a large number of intersecting linear features in the low-resolution photos from Voyager 1.

At first, scientists believed the features might be deep cracks, caused by crustal rifting or tectonic processes.

Ganymede as seen by Voyager 1. Image: NASA. Modern processing: Ted Stryk

Next came Ganymede – the largest moon in the solar system. Voyager 1 closed in on it at 1321 AEDT on 6 March, passing 114,600 kilometres from its centre.

Discovered by Galileo Galilei on 11 January 1610, though Simon Marius claimed to have discovered it a week before. Ganymede, the most beautiful youth alive, son of King Tros and Callirrhoö, is a Trojan prince abducted to Olympus by Zeus and appointed as the immortal cupbearer to Zeus. He was carried off by Zeus, who had changed into an eagle for the occasion.

Just 18 minutes before closest approach the ultraviolet instrument watched as a bright star disappeared behind Ganymede and appeared ten minutes later.

No dimming caused by an atmosphere was observed though scientists later set an upper limit for any gas at 1 billionth of the atmospheric pressure on the surface of the Earth, or just a trace of oxygen.

GANYMEDE

Diameter:	5,262 kilometres
Albedo:	0.431
Mass:	14.8 x 10^{22} kilograms
Jupiter distance:	1,070,412 kilometres
Orbital period:	7.15 Earth days
Surface temp:	-203°C min / -121°C max
Closest approach:	114,600 kilometres

Larger than the planet Mercury, Ganymede is composed of silicate rock and water ice, with an ice crust floating over a warmer ice mantle that may contain a layer of liquid water. It has a heavily cratered, icy surface with an average temperature of -160ºC. To show how wrong scientists can be when guessing, David Morrison said at a briefing,

> *"While I am delighted to see craters, it is just the opposite of what I would have expected. I thought Io would have had plenty of craters, and that Ganymede, because of the icy surface, simply would not be able to hold large craters over geological time."*

The orbits of Io, Europa, and Ganymede form a pattern known as a Laplace Resonance; for every four orbits that Io makes around Jupiter, Europa makes exactly two orbits and Ganymede makes exactly one, making a 1:2:4 resonance. This resonance causes the gravitational effects of the three moons to distort their orbits into elliptical shapes, since each moon receives an extra tug from its neighbours at the same point in every orbit it makes.

The tidal force from Jupiter, on the other hand, works to circularize their orbits. This constant tug of war causes regular flexing of the three moons' shapes; Jupiter's gravity stretches the moons more strongly during the portion of their orbits that are closest to it and allowing them to spring back to more spherical shapes when they're farther away. This flexing causes tidal heating of the three moons' cores. This is seen most dramatically in Io's extraordinary volcanic activity, and to a somewhat less dramatic extent in the geologically young surface of Europa indicating recent resurfacing.

CALLISTO

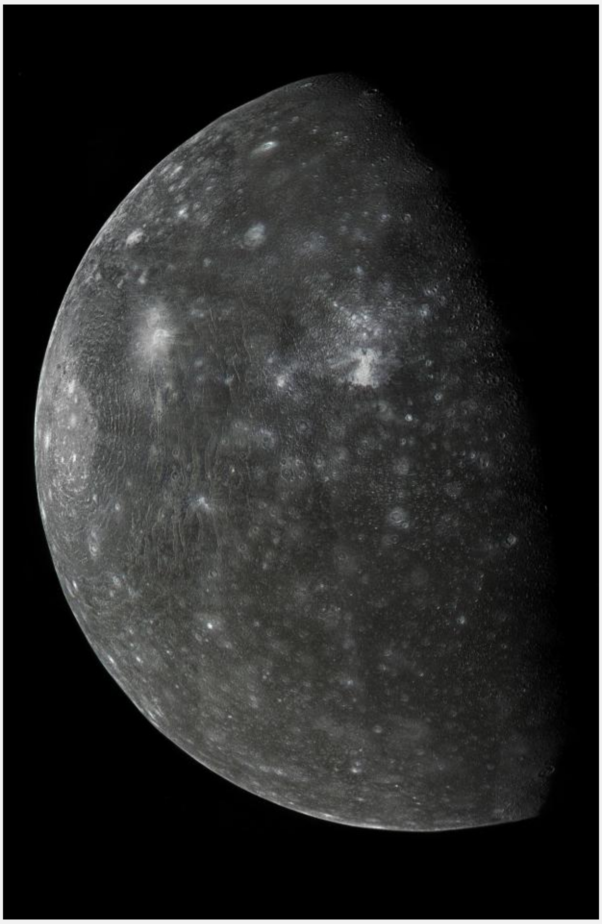
Diameter:	4,821 kilometres
Albedo:	0.17
Mass:	10.8 x 10^{22} kilograms
Jupiter distance:	1,882,709 kilometres
Orbital period:	16.9 Earth days
Surface temp:	-193ºC min -108ºC max
Closest approach:	125,108 kilometres

Discovered by Galileo Galilei on 7 January 1610, though Simon Marius claimed to have discovered it a week before. Callisto, in Greek mythology is a nymph, daughter of Lycaon and one of Artemis' huntresses. Zeus wanted to woo her, and so disguised himself as Artemis and seduced her. To hide her from his jealous wife Hera, Zeus changed Callisto into a bear.

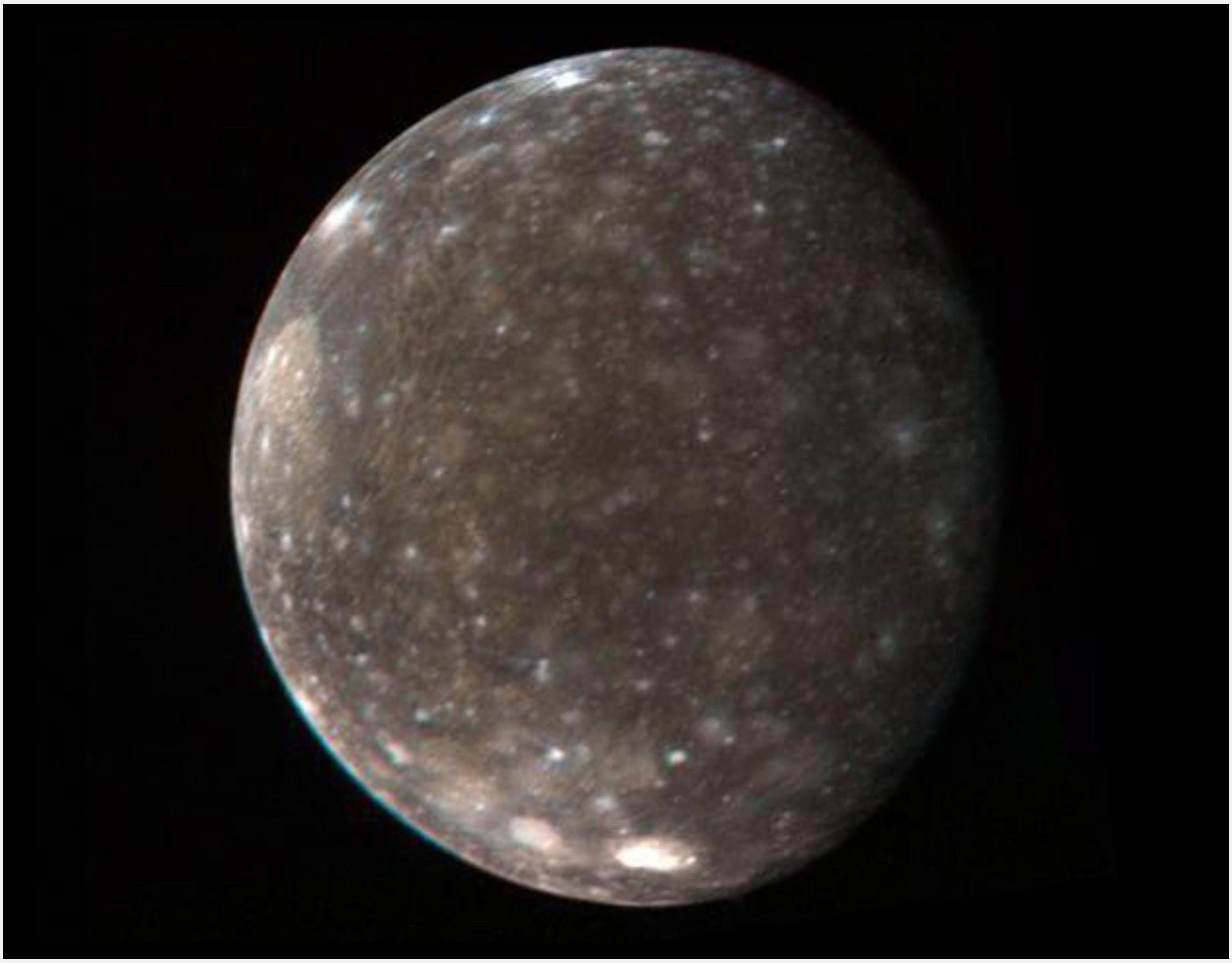
One of the most cratered moons in the solar system, Callisto's icy surface, with an average temperature of -155ºC, appears to be flat and very ancient, with signs of heavy bombardment by meteorites. The interior seems to be composed of compressed rock and ice, with the amount of rock increasing with depth.

Callisto has a very old, heavily cratered crust showing remnant rings of enormous impact craters. The largest craters have apparently been erased by the flow of the icy crust over geologic time. Almost no topographic relief is apparent in the ghost remnants of the immense impact basins, identifiable only by their light colour and the surrounding subdued rings of concentric ridges.

Voyager 1 came within 125,108 kilometres of Callisto at 0414 AEDT on 6 March.



Callisto from Voyager 1. Image: NASA/JPL
Modern processing by Daniel Macháček



Callisto is one of the most cratered moons in the Solar System. Image: NASA/JPL

Scientists were beside themselves with excitement with the images and data coming in, Garry Hunt announcing,

"The activity around the monitors now is quite incredible with people caught breathless by the pictures coming in. Every satellite we've seen has been a different world.

I'm delighted Voyager 2 is not far behind, since I'm convinced that we'll see yet another face of Jupiter by then. The weather will have changed by July."

Ed Stone, Cosmic Ray scientist from Caltech, summed the Voyager 1 encounter with,

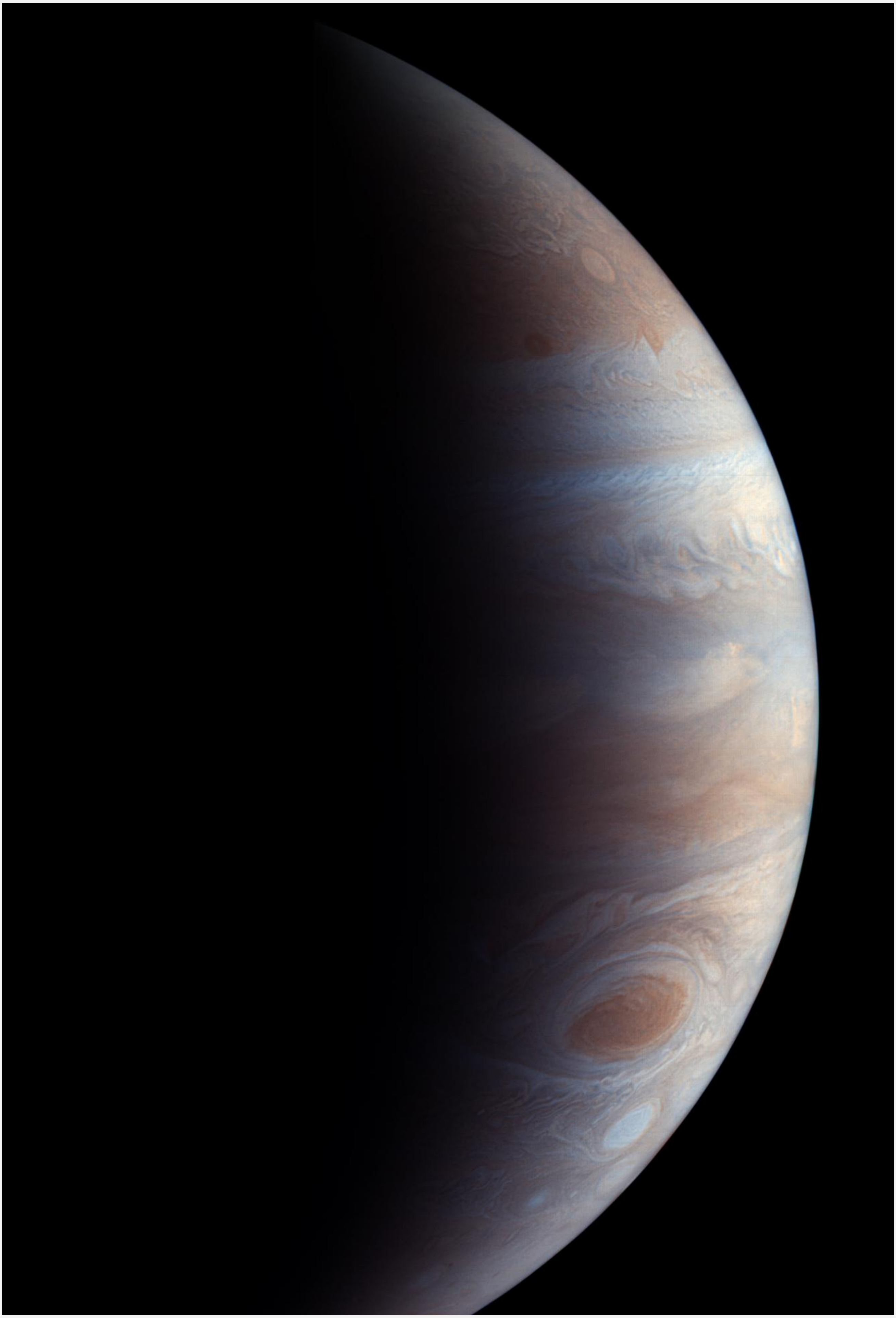
> *"I think we have almost a decade's worth of discovery in this two week period, and I think that all of the people* (the Voyager scientists) *feel the same saturation of new information which has occurred. We will probably be studying it in great detail for at least five years."*

Voyager 1 sent back over 15,000 photographs of Jupiter and its moons and mountains of data from the science experiments.

SUMMARY OF JUPITER'S MOONS AND SMALLER SATELLITES

	Diameter kilometres	Kilometres from object's centre
Metis	43	128,000
Adrastea	24x20x14	129,000
Amalthea *	270x166x150	181,300
Thebe	110x90	222,000
Io *	3,630	422,000
Europa *	3,138	661,000
Ganymede *	5,262	1,070,000
Callisto *	4,800	1,883,000
Leda	16	11,094,000
Himalia	186	11,480,000
Lysithia	36	11,720,000
Elara	76	11,737,000
Ananke	30	21,200,000
Carme	40	22,600,000
Pasiphae	50	23,500,000
Sinope	36	23,700,000

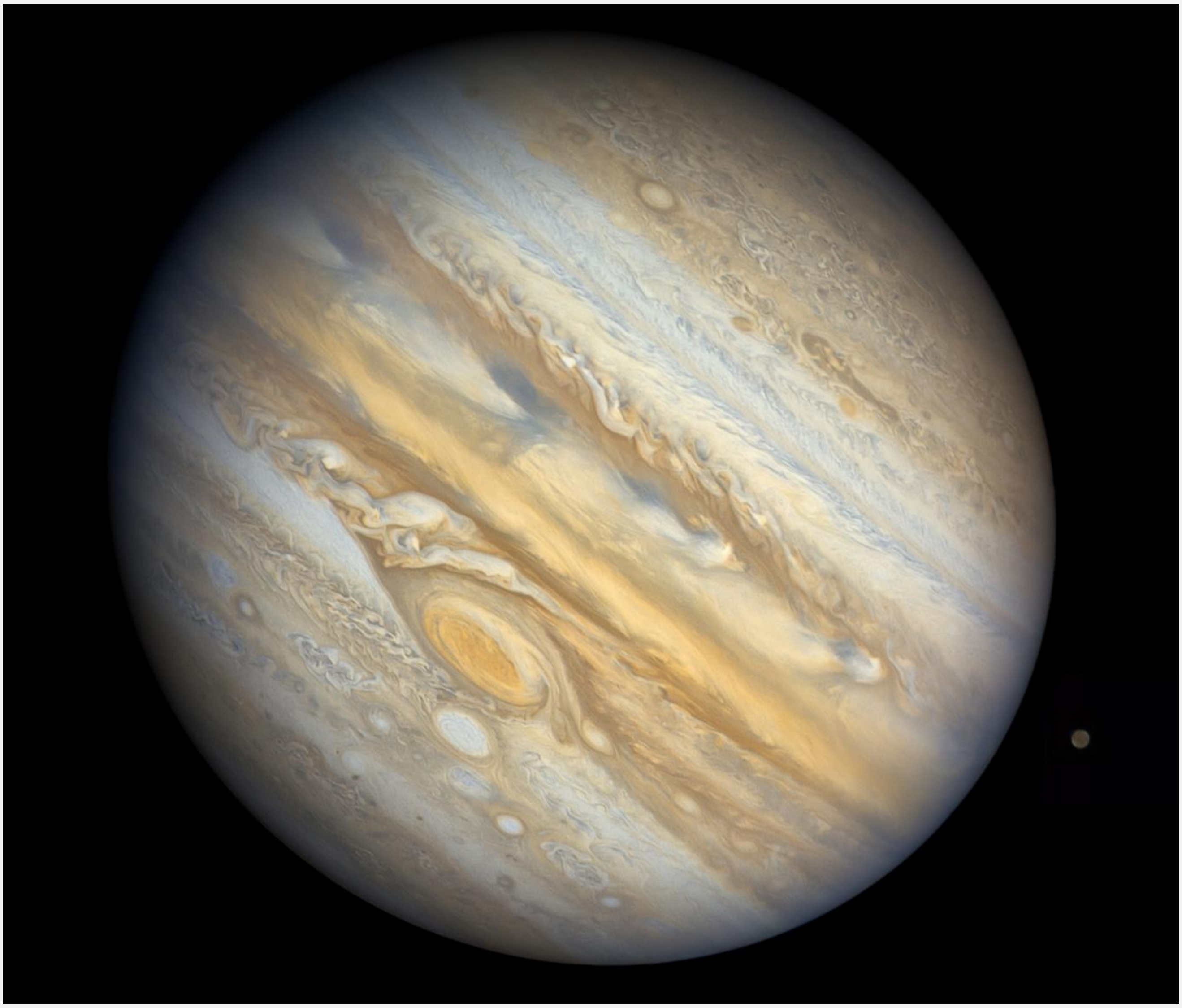
* asterisk indicates Voyager 1 observed the moon.



A composite of 8 images taken 5 days after closest approach as Voyager 1 departs Jovian space.
Images: NASA/JPL. Modern processing by Justin Cowart.

SUMMARY OF JUPITER ENCOUNTER – 4 JANUARY - 7 MARCH 1979

Date	AEDT	Distance*	Event/Closest Approach
January 4		60 million	Observation phase begins
January 30			Far encounter period begins
March 1	01:10	6.15 million	First contact with bow shock
March 4	22:08		Begin Jupiter encounter activities
March 5	17:28	416,912	Amalthea
	23:05	**348,890**	**Jupiter**
March 6	02:20	20,253	Io
	02:51		Enter Earth occultation
	03:44		Enter Sun occultation
	04:25	732,245	Europa
	04:48		Exit Earth occultation (1 hour 57 minutes)
	05:56		Exit Sun occultation (2 hours 12 minutes)
	13:21	114,600	Ganymede
	01:59		End Jupiter encounter activities
March 7	04:14:20	125,108	Callisto
		One-way signal elapsed time was 31 minutes 40 seconds	
		* from Jupiter's centre (kilometres)	



Jupiter and Callisto (right). Image: NASA/JPL. Modern processing by Ian Regan

Next stop Saturn! Artwork by David A. Harding. Source: NASA/JPL

VOYAGER 1
HEADS FOR SATURN

With the Jupiter encounter successfully accomplished, Voyager 1 used the massive planet's orbital energy, like a sling-shot, to accelerate to 84,500 kilometres per hour and altered its flight path to encounter Saturn. Without using Jupiter's aid, Voyager 1 would have needed nearly 1.5 million kilograms of fuel, instead of the miserly 5 kilograms it ended up using.

VOYAGER 1
LOSS OF SIGNAL

On 16 October 1979 Voyager was commanded to perform a 22 hour science manoeuvre to allow the fields and particles instruments to study the entire sky with a series of 10 yaw and 25 roll turns. The computer was then supposed to re-align the high gain antenna with Earth. The flight controllers had a fright when the manoeuvre was carried out but no signal was received because the star tracker locked on to Alpha Centauri instead of Canopus.

DSS43 Tidbinbilla's powerful 100 kilowatt transmitter was used to force commands through the spacecraft antenna sidelobes into the computer. The commands told the spacecraft to roll 56.8º to bring it back to look at Earth, and the star sensor within 1o of Canopus. Once it had locked onto Canopus the mission returned back to normal operations.

VOYAGER 1
PHOTOPOLARIMETER (PPS) EXPERIMENT DECLARED UNSERVICEABLE

During December 1979 Voyager 1's photopolarimeter (PPS) was declared to be of no further use after tests revealed its photomultiplier tube, which converts weak light signals to electrical currents had almost no sensitivity left.

Combined with the problem in the motor drive circuit, which turns the light analysis wheels, scientists declared there would be no scientific value in any data this instrument would return. It would now be up to Voyager 2's PPS for any data from Saturn.

Deep Space Station 43 at Tidbinbilla in its original 64-metre (210 foot) configuration. Image: CDSCC Archive

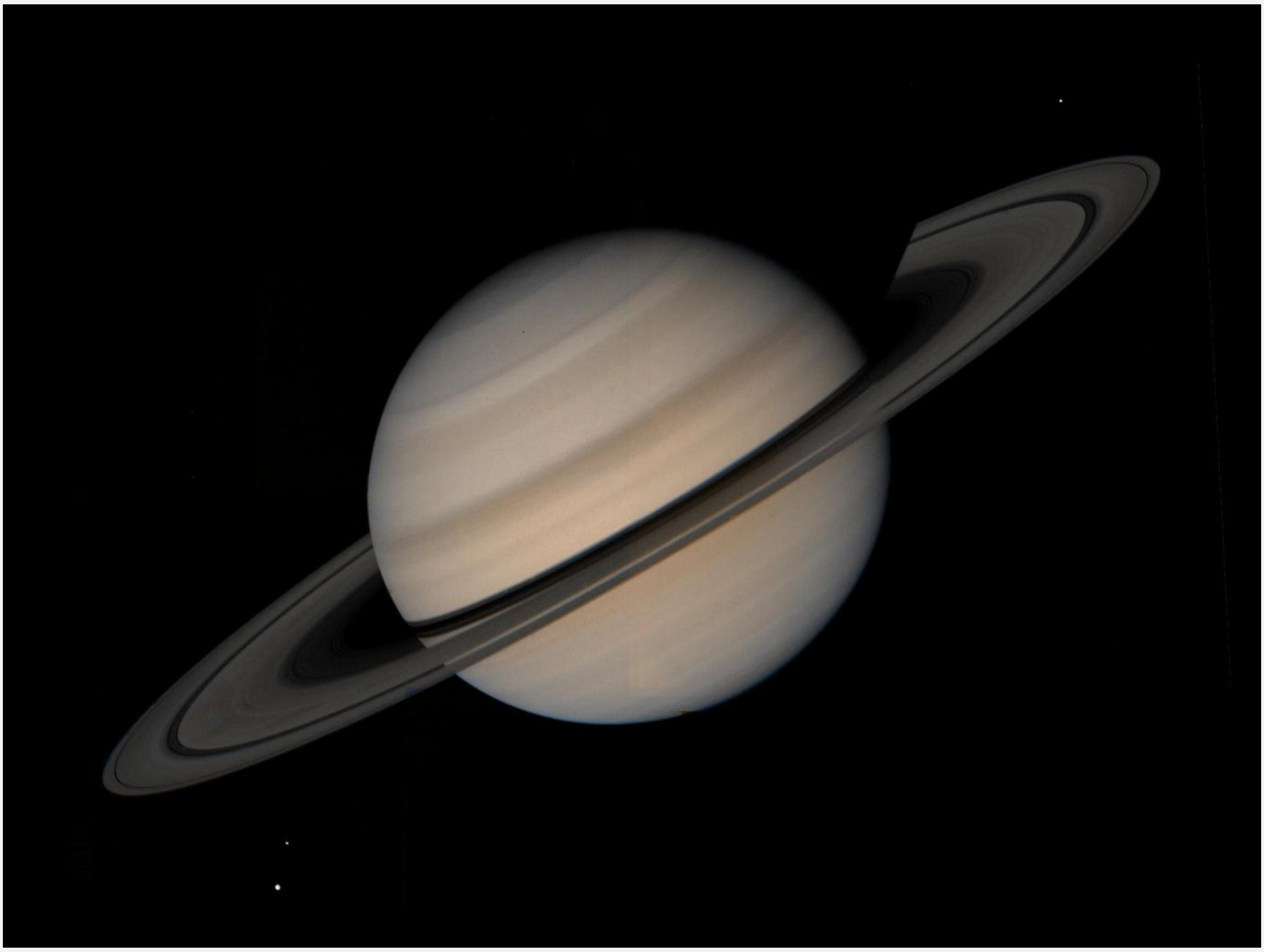
VOYAGER 1
ANOTHER TEMPORARY LOSS OF SIGNAL

Voyager 1 gave everyone another fright at 0915 AEDT on 14 December 1979 when the DSN Tracking Stations could not find its signal after a trajectory course correction. The spacecraft had to turn its high gain antenna away from Earth while performing these manoeuvres, then the on-board computers had to restore the alignment with Earth after the manoeuvre was completed. After the sequence abort the spacecraft was stabilised by its internal gyros and was Sun pointed only.

On 16 December commands were sent to perform a Sun cone, searching for Earth by rotating the antenna around the Sun with an 8^{o} offset, stopping at 16 different points.

At the third point ground stations picked up a strong signal as the high gain beam swept across the Earth. Six minutes of data was received before the spacecraft moved on to the next point. At the completion of the search sequence Voyager 1 was commanded back to the third point, and DSS 43 at Tidbinbilla then received a good signal.

The spacecraft was commanded to return to the reference star Canopus on 19 December and by 0700 21 December Voyager 1 was back to normal.



Saturn and the moons Mimas (upper right) and Tethys (bottom left) and Enceladus. Image: NASA/JPL

VOYAGER 1

SATURN ENCOUNTER

Saturn comes from Roman mythology, though the Greeks called it Kronos after Zeus's father. Mesopotamian astronomers called it *"the Old Sheep"*. The first explanation of the famous rings came from Christiaan Huygens in 1659.

Saturn orbits the Sun at a speed of 34,700 kilometres per hour, taking 29.4 Earth years to orbit the Sun once. As measured by Voyager a day lasted 10 hours 39 minutes 24 seconds, though later measurements by Cassini in 2004 made it 10 hours 45 minutes 45 seconds It has an albedo of 0.7 and a gravity comparison with Earth means 100 kilograms would weigh 106 kilograms near the poles on Saturn. With a tilt of 25.33º, to date it supports 53 moons and small satellites.

Saturn's interior is similar to Jupiter's, having a rocky core at the center, a liquid metallic hydrogen layer above that, and a molecular hydrogen layer above that. Traces of various ices are also present.

Saturn has a very hot interior, reaching 11,700ºC at the core, and, like Jupiter, it radiates more energy into space than it receives from the Sun.

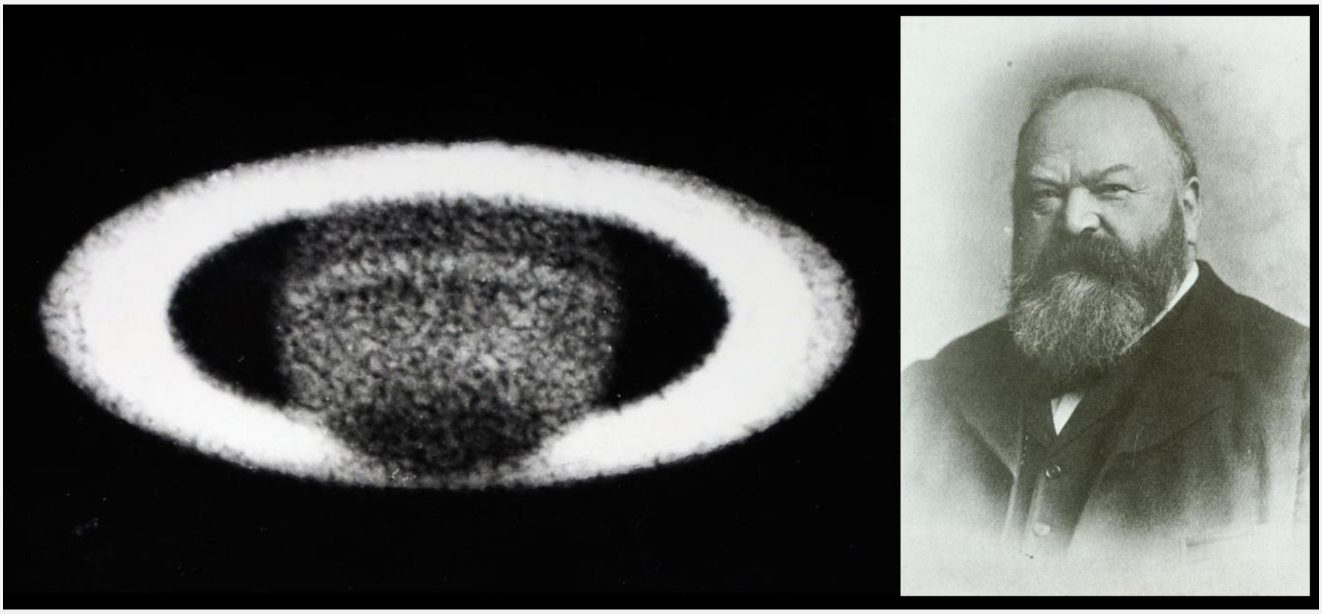
Early astronomers were awed by Saturn, and called it the *"Wonder of the Solar System"*. Noted French astronomer Camille Flammarion wrote,

> *"The balancing of shapes and the niceness of the proportions make it a perfect work of art."*

Until the end of the 18th century Saturn marked the frontier of the Solar System.

SATURN ENCOUNTER
WEDNESDAY 12 NOVEMBER 1980
SATURN FACTS

Diameter:	116,464 kilometres
Distance to Sun:	1,426,666,422 kilometres
Mass:	5.6846 x 10^{26} kilograms
Orbital period:	29.4 Earth years
Length of day:	10 hrs 39 mins 24 secs
Surface temp:	-178°C
Closest approach:	126,000 kilometres



English astronomer, Andrew Ainslie Common captured this image of Saturn in 1883.

Galileo first focussed his telescope on Saturn in 1610, and was puzzled by what he thought were three orbs, which seemed to slowly change over time. His crude, low-power telescope could not define the rings.

Christiaan Huygens (1629-1695) studied the planet for years, and it wasn't until 1655 that he realised that he had been watching flat rings circling the planet.

Then, in 1675 Cassini discovered the rings were divided into two parts by a dark line, now called the Cassini Division. Later he discovered some of Saturn's bigger moons.

The first successful photograph of Saturn was taken by English astronomer Andrew Common (1841-1903) in 1883. In 1895 American James Keeler (1857-1900) agreed with Scot James Maxwell's (1831-1879) theory the rings were swarms of small meteoric particles. Until Voyager detected the rings around Jupiter and Uranus, these rings were considered to be unique in our solar system.

Saturn's magnetic field is smaller than Jupiter's, extending only one or two million kilometres. The axis of the field is almost perfectly aligned with the rotation axis of the planet.

When Gary Flandro began his work at JPL in 1964, he originally suggested Voyager fly in between the planet and its rings. Fortunately, this proposal was not put into action; it might have meant a premature end to the Voyager 1 mission.

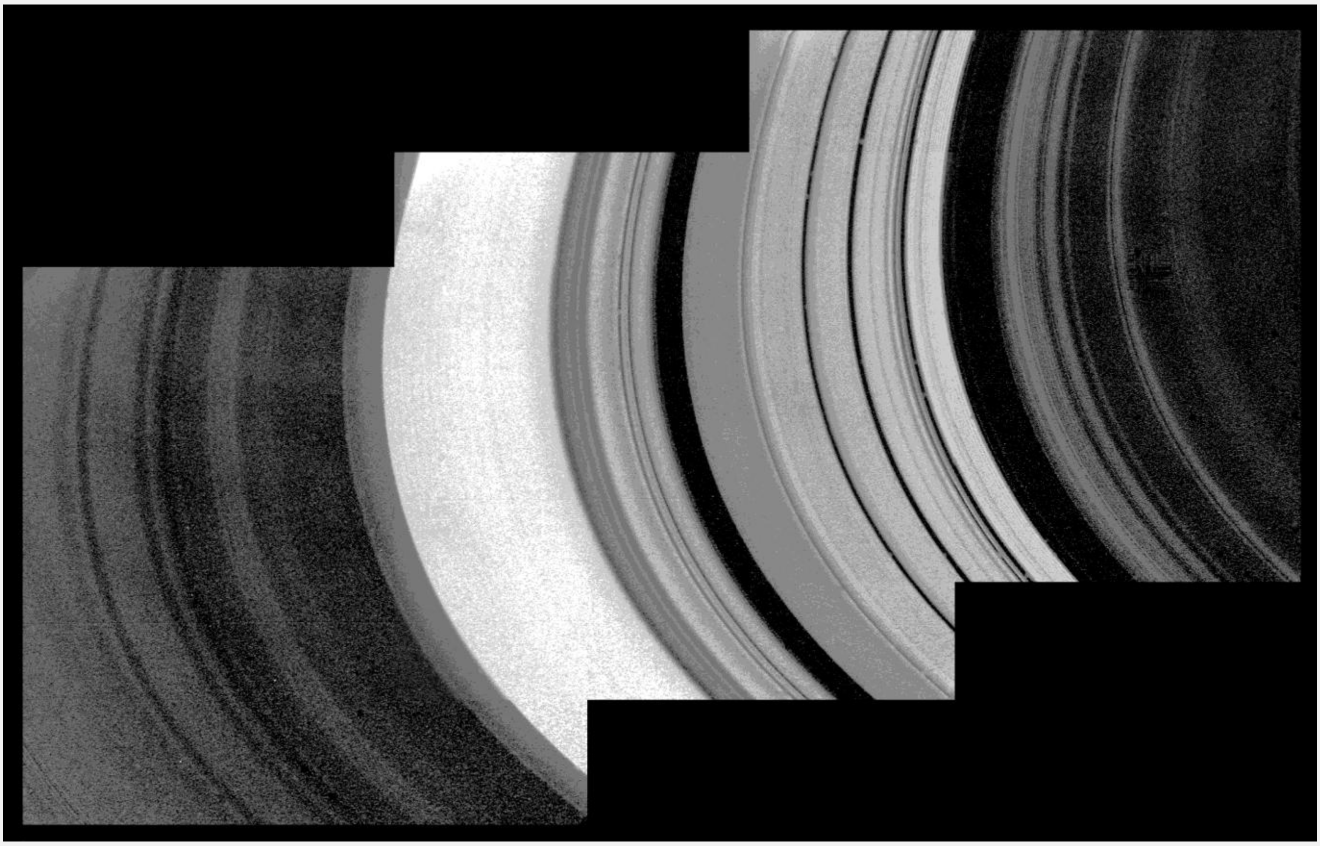
At the beginning of October 1980, just as scientists were preparing for Voyager 1 to meet Saturn, there was a pre-dawn planetary show for sky watchers. Jupiter and Saturn were close together and Venus was nearby in the morning sky, just before sunrise, while Mars and Mercury were also visible. When Saturn and Jupiter are next to each other astronomers call this event the 'Great Conjunction' and in this case the actual conjunction was on 14 January 1981. The Great Conjunction occurs every 18-20 years.

THE SATURNIAN ATMOSPHERE

The temperature on the 'surface,' nominally set at 1000 bars, varies from –190ºC to -130ºC. At the cloud tops it is -180ºC. The atmosphere consists mainly of 93% Hydrogen, 5% Helium, 0.2% Methane and 0.1% water vapour plus traces of ammonia, ethane and phosphine.

Saturn's atmosphere exhibits a banded pattern similar to Jupiter's, but Saturn's bands are much fainter and are also much wider near the equator. Saturn's winds are among the Solar System's fastest. Voyager data indicated peak easterly winds of 1,800 kilometres per hour. Strongest winds are near the equator. Saturn's finer cloud patterns were not observed until the Voyager flybys. Since then, however, Earth-based observations have improved to the point where regular observations can be made.

Saturn's usually bland atmosphere occasionally exhibits long-lived ovals and other features common on Jupiter.



Composite of Voyager 1 images of Saturn’s rings. Images: NASA/JPL

In 1990 the Hubble Space Telescope observed an enormous white cloud near Saturn's equator, which was not present during the Voyager encounters and in 1994 another, smaller storm was observed. The 1990 storm was an example of a Great White Spot, a unique but short-lived Saturnian phenomenon with a roughly 30-year periodicity. Previous Great White Spots were observed in 1876, 1903, 1933, and 1960, with the 1933 storm being the most famous.

VOYAGER 1
RINGS OF SATURN

With the arrival of the Voyagers at Saturn the estimate of the numbers of rings had gone from tens to hundreds to thousands.

Saturn's ring particles range in size from microscopic dust to barn-sized boulders. If you assembled them all in one place you would have enough material to make an icy satellite one or two hundred kilometres wide - much like Saturn's present-day moon Mimas.

The debris layer is extraordinarily thin. Saturn's rings are 250,000 km wide, but only a few tens of meters thick. A sheet of paper the size of San Francisco would have about the same ratio of width to depth.

Indeed, if you made a 1-meter-wide scale model of Saturn, the rings would be 10,000 times thinner than a razor blade.

Jeff Cuzzi, planetary systems scientist, said there are two reasons to believe the rings are young:

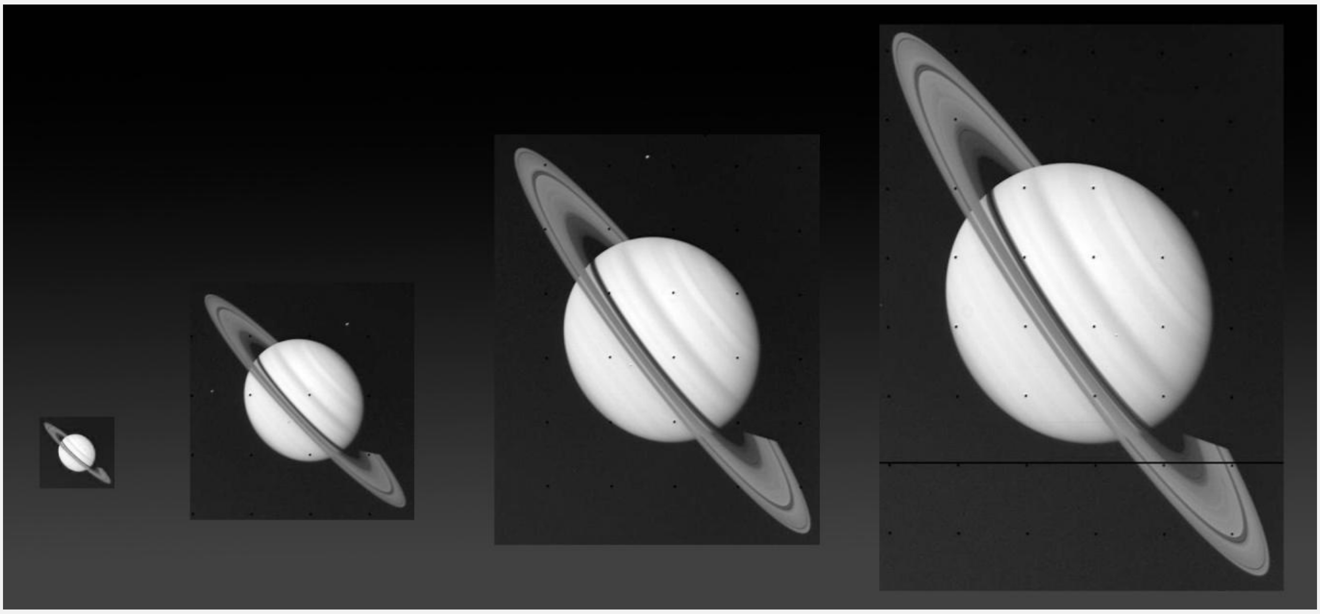
First, they are bright and shiny like something new. It's no joke, he assures. The wide-spanning rings sweep up space dust (bits of debris from comets and asteroids) as Saturn orbits the Sun. Rings much older than a few hundred million years would be darkened by accumulated dust.

> *"The fact that they're bright suggests they're young,"* he says.

Second, small moons that orbit through the outermost regions of the ring system are gaining angular momentum at the expense of the rings.

> *"During the next few hundred million years,"* explains Cuzzi, *"the outer half of the rings will fall toward the planet, and the little moons – called shepherd satellites - will be flung away. This is a young dynamical system."*

By 1 October 1980, Voyager 1 was 56 million kilometres from Saturn, and its cameras could resolve ring details 1,000 kilometres across.


Saturn approach from Voyager 1. Black dots are calibration marks within the camera. Images: NASA/JPL

Closing the planet at 1.3 million kilometres per day (54,167 kilometres per hour), details of the rings and cloud structure began to appear.

On 6 October a new structure could be seen in the B Ring, dark lines spreading out radially like spokes in a cartwheel, and plans were made to make a movie sequence of them.

On 24 October Voyager 1 entered the Far Encounter phase and the next day a new satellite was spotted weaving along the outer edge of the F Ring, followed by another in the inner edge of the F Ring – the first new Saturnian satellites discovered by the Voyagers.

On 3 November Voyager 1 was 12 million kilometres from Saturn, and the large moon Titan began to reveal features to the camera. On 6 November, the spacecraft was 8 million kilometres from the planet and travelling at 55,440 kilometres per hour. Observations concentrated on the rings and Titan every six hours. The resolution of the telephoto camera on Titan was now 150 kilometres.

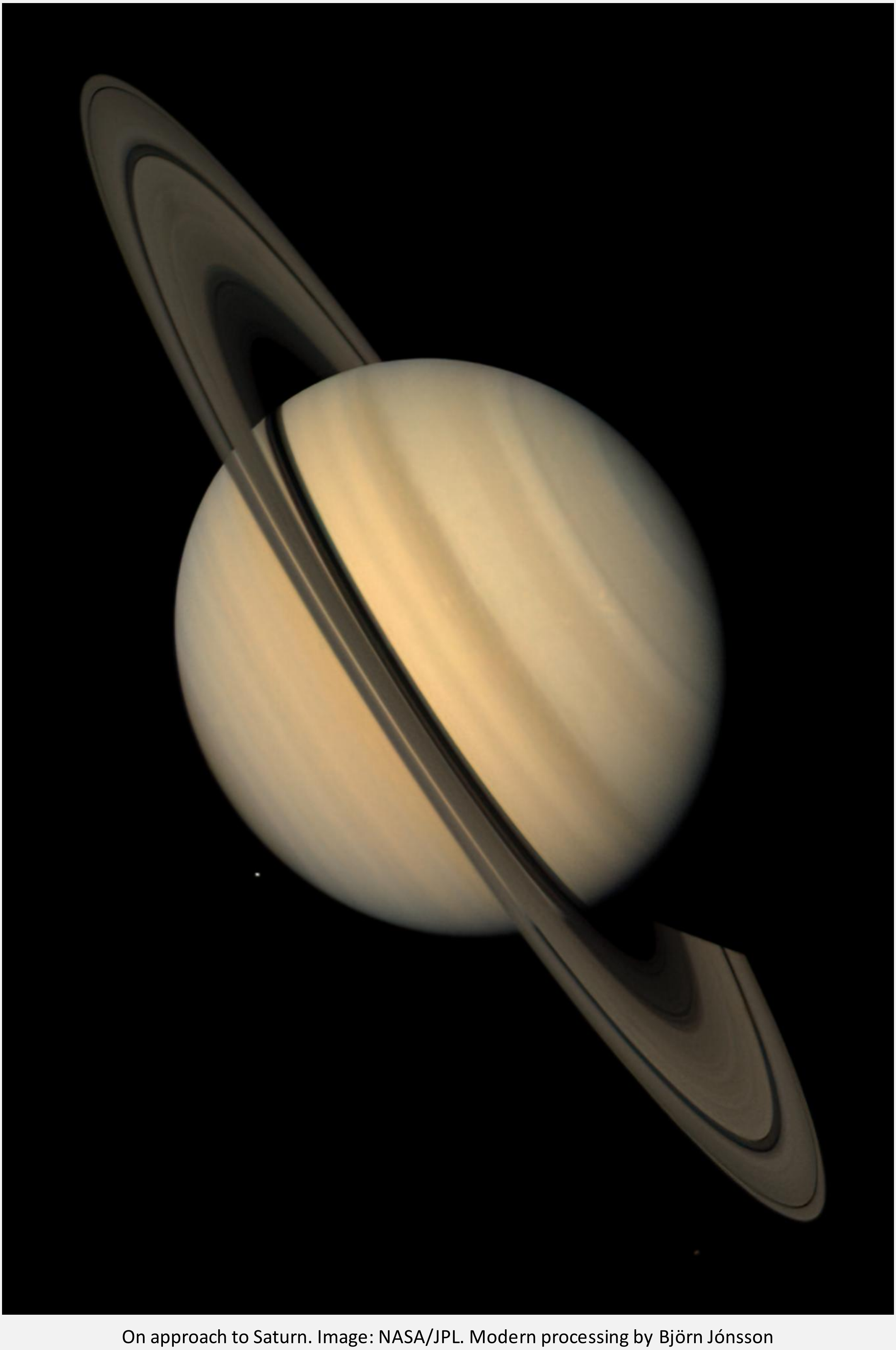
At the 1030 PST media conference on 6 November Project Manager Ray Heacock announced that all the spacecraft systems were in excellent condition except the Canopus star tracker, which was misbehaving, but was not expected to cause any problems during the encounter.

After the planet Saturn, Voyager 1's prime target was to study Titan. On 7 November Ray Heacock, Voyager Project manager at the time, planned a trajectory correction manoeuvre to bring the spacecraft 650 kilometres closer to Titan for the radio occultation experiment.

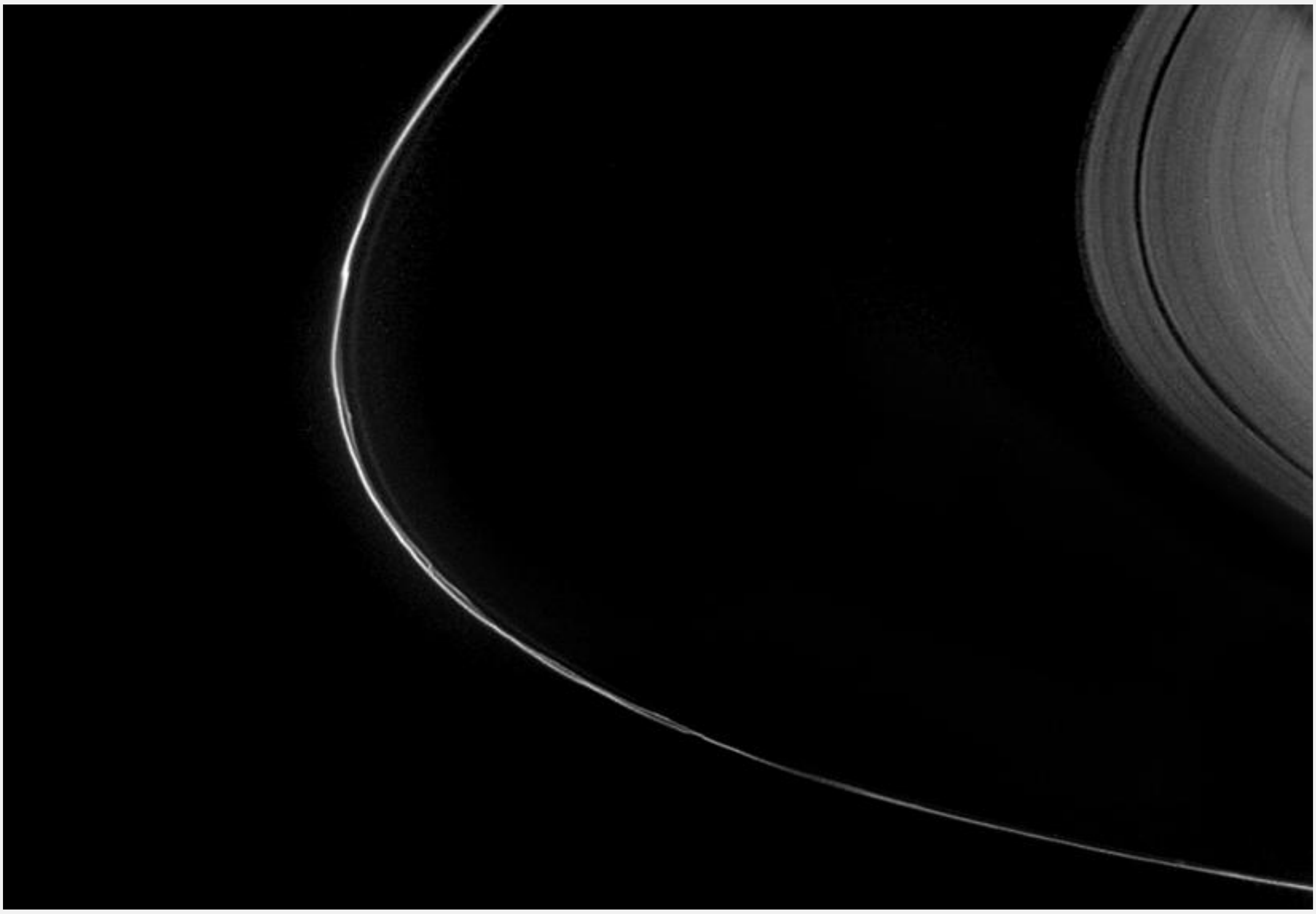
This meant the spacecraft turning away from Earth and breaking the link with the tracking stations and then relying on its computer to bring it back in alignment. Some of the scientists were nervous that the whole Voyager 1 mission would be jeopardised if anything went wrong. It was so close to encounter – why tempt fate?

The commands were transmitted from Goldstone's 64 metre dish at 1523 AEDT on 7 November and Voyager 1 rotated a quarter of a turn away from the Earth's direction. All radio communications were severed, and everyone held their breath. The whole Voyager 1 mission relied on the commands being correct and the spacecraft's systems working perfectly, or the spacecraft would be lost forever. The hydrazine thrusters gassed for 11 minutes and 45 seconds to smoothly adjust the spacecraft onto the new course. Then at 1808 AEDT on 8 November the signal from Voyager 1, 1.6 billion kilometres away, reappeared at Goldstone and the ninth manoeuvre had been successful.

On 10 November, now 3 million kilometres from Saturn, Voyager 1 saw the first detailed views of the moons Tethys and Dione. The sensing instruments were busy with Titan, the camera resolution better than 35 kilometres as the moon



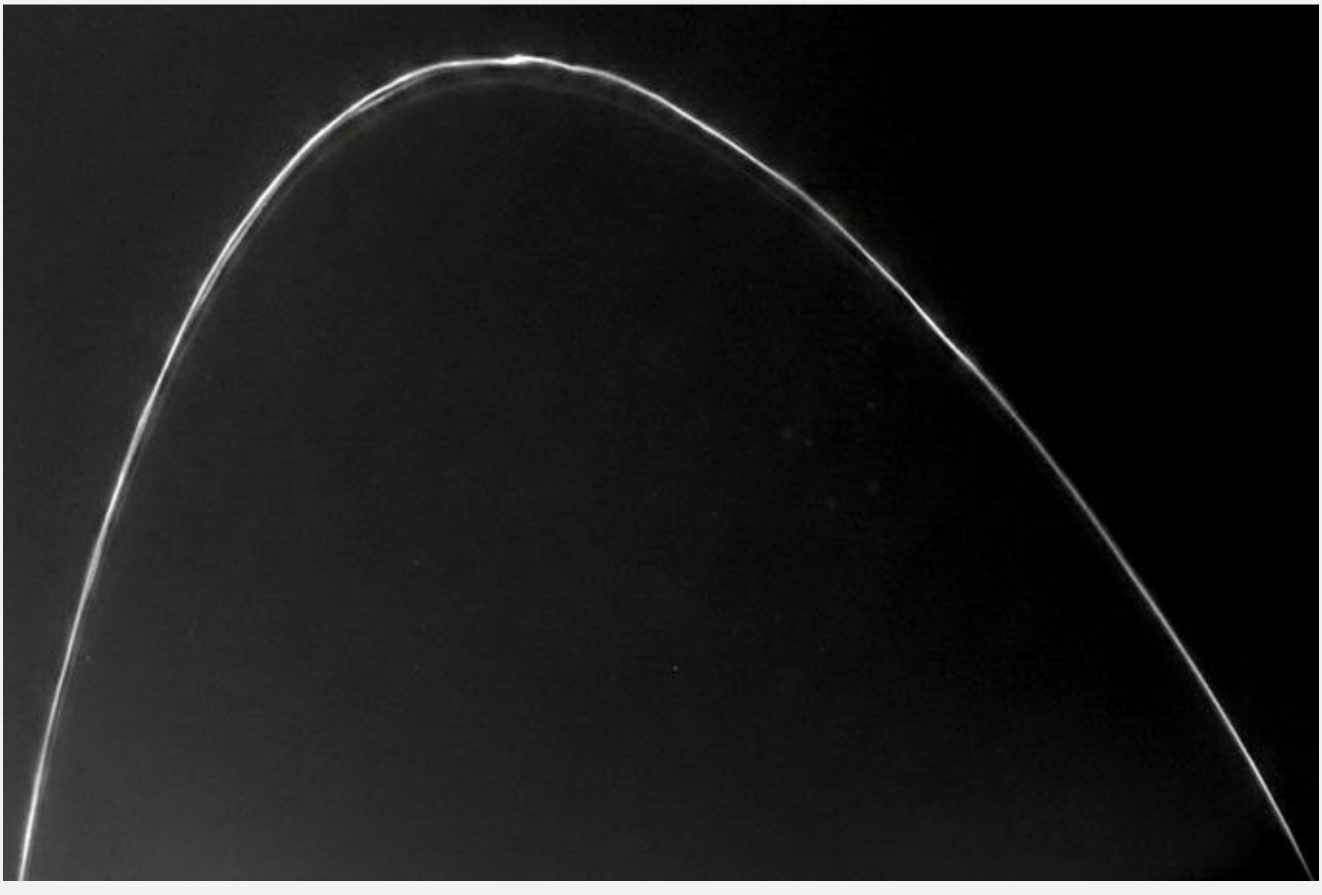
On approach to Saturn. Image: NASA/JPL. Modern processing by Björn Jónsson

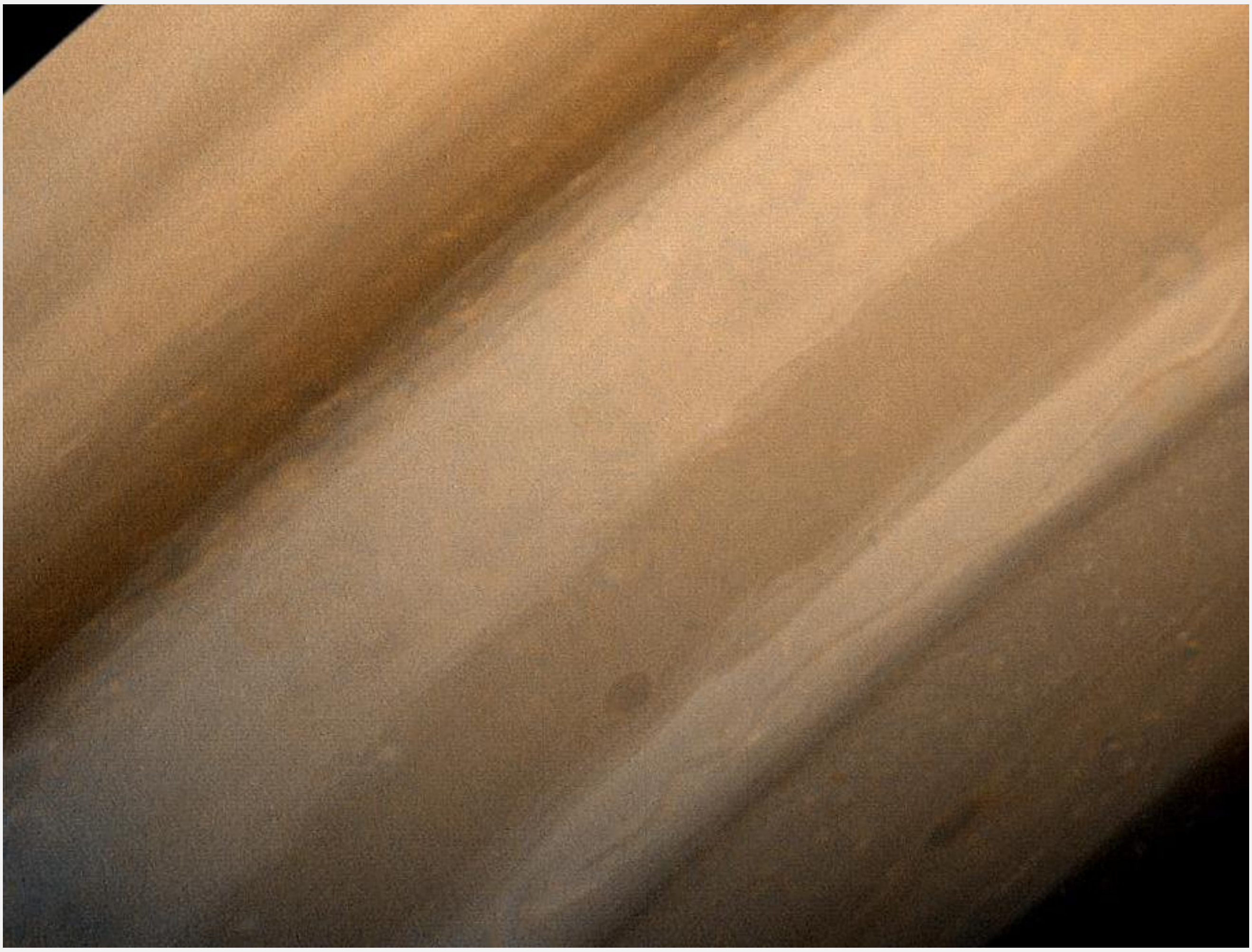


Above: Voyager 1 images revealed the F-ring which has a braided appearance.

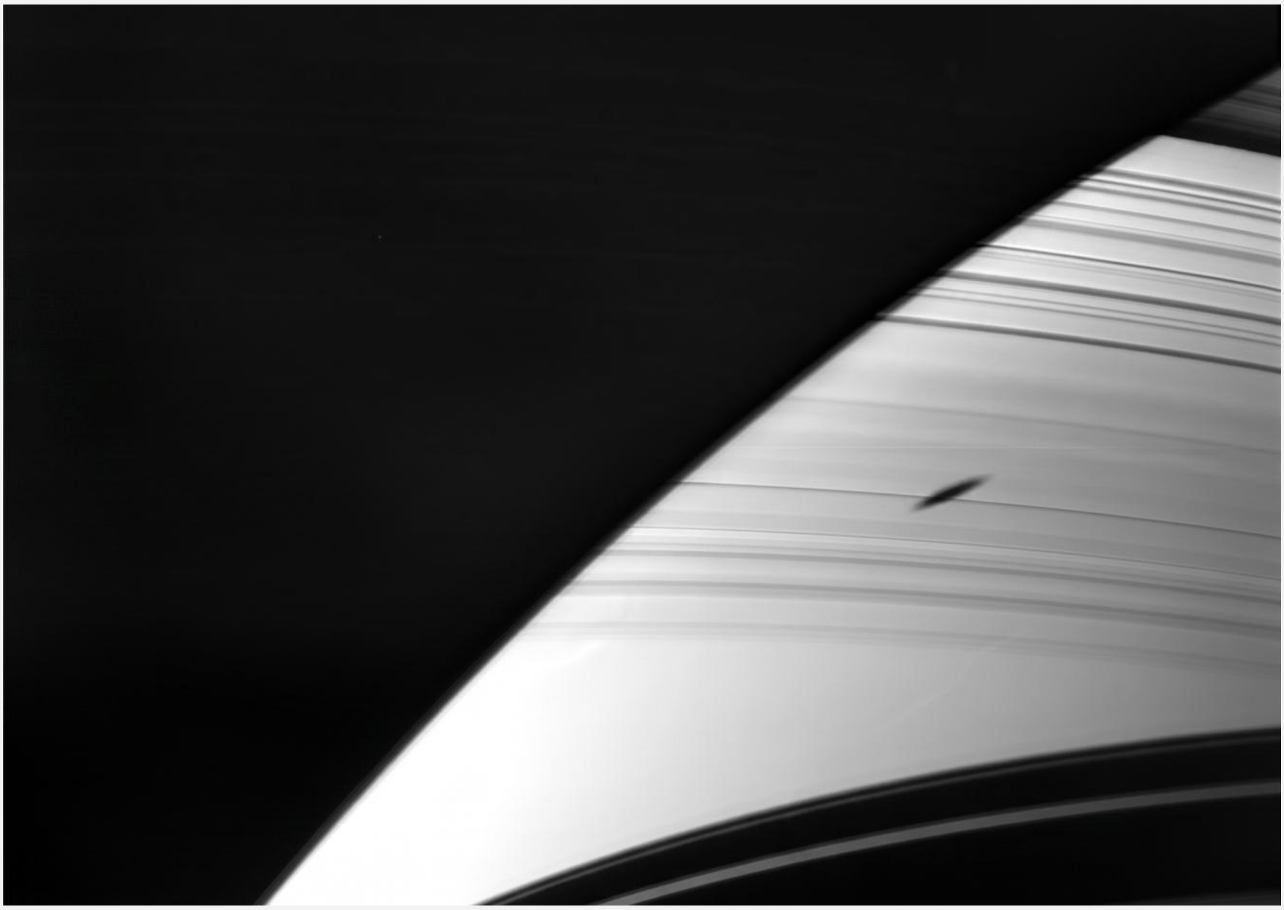
Images: NASA/JPL

Below: Waves and distortions in the F-ring were discovered to be from the gravitational influence of two small “shepherd moons”, Prometheus on the inside and Pandora on the outside.

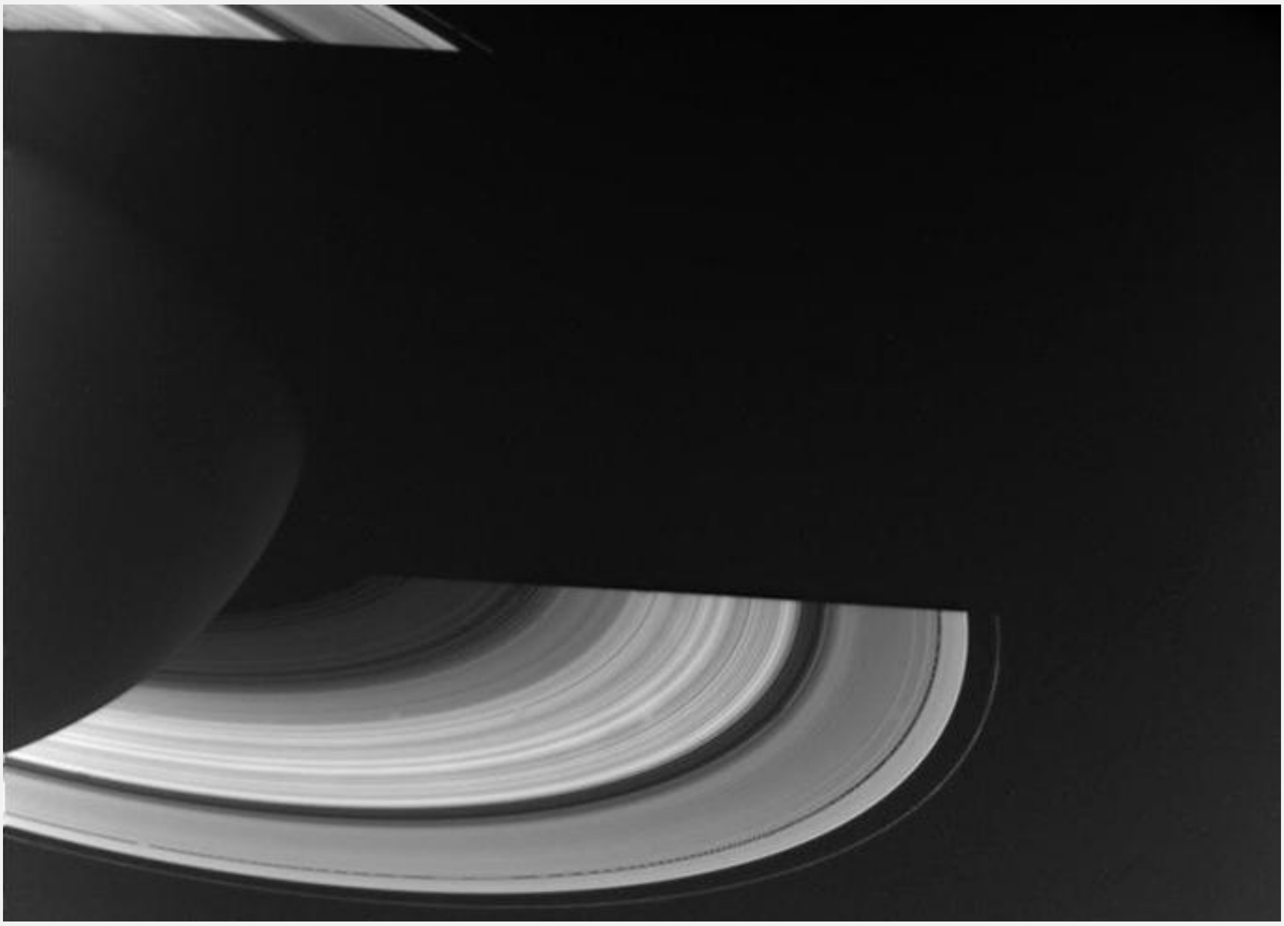


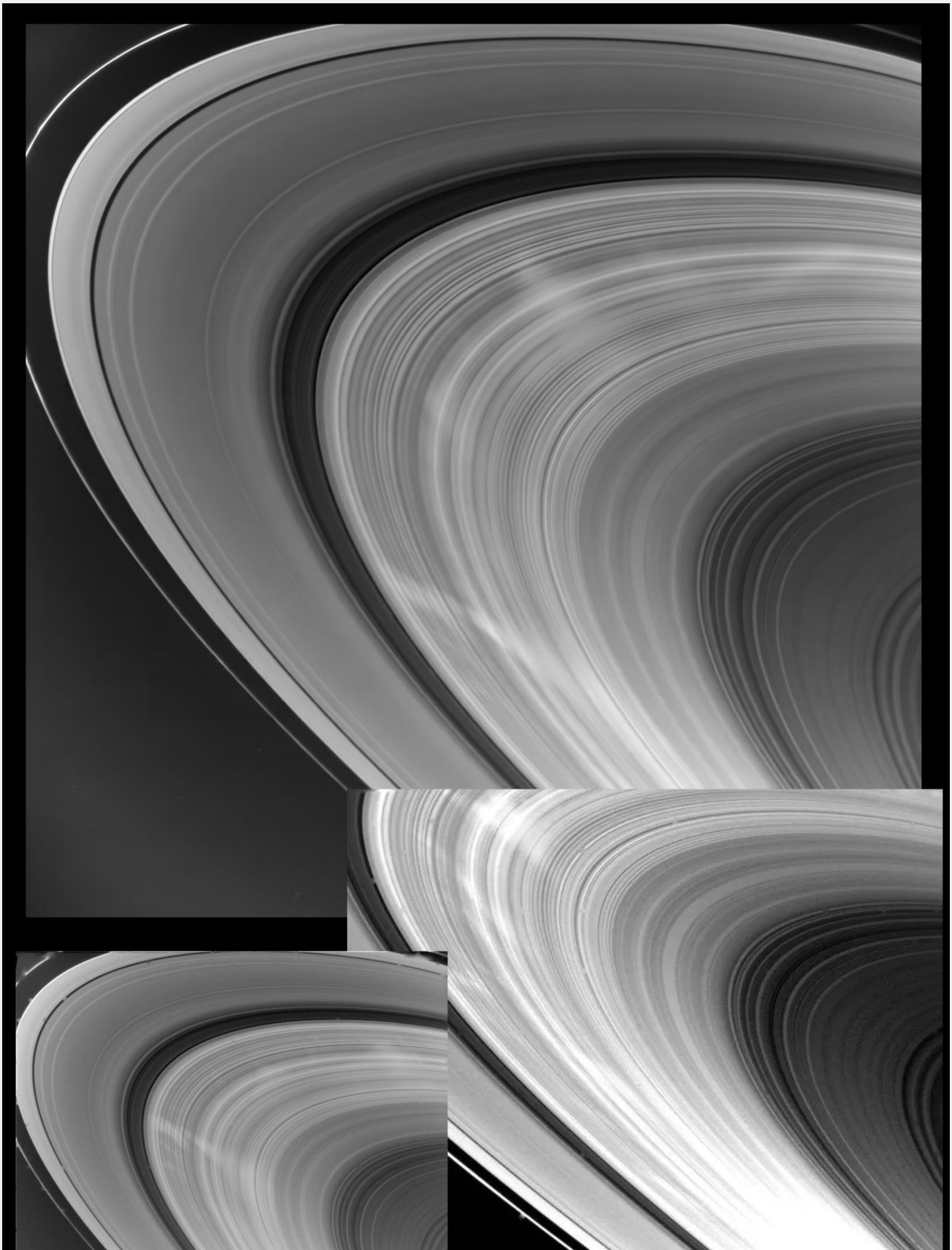


Above and Below: Closeup views of cloud bands and brown ovals in Saturn's atmosphere. Images: NASA/JPL



Above: The inner rings of Saturn are seen as gossamer strands against the planet's atmosphere. The ring's shadow cuts across, along with the elongated shadow of either Mimas or Tethys.
Images: NASA/JPL
Below: Saturn's shadow cuts across the rings. Note the farside of Saturn is being lit by ring-shine.





Three views of the “spokes” which scientists believe are electrostatically-charged dust particles above Saturn’s B-ring caused by interactions with Saturn’s magnetic field and solar winds. Images: NASA/JPL loomed larger and larger in the camera lenses. The scientists were hoping for some holes in the clouds to see the surface.

The spacecraft was expected to cross the magnetosphere bow shock at 1000 AEDT on 12 November to begin the Near Encounter period. But there was no bow shock at the expected time. Titan was now 493,000 kilometres away, but scientists were disappointed that no features were showing in the bland atmosphere...... and no signs of any holes to see the surface beneath.

As Voyager 1 homed in on Saturn, nearly two years after its encounter with Jupiter, excitement rose to fever pitch around the corridors and science labs at the Jet Propulsion Laboratory.

At Honeysuckle and Tidbinbilla, we began to concentrate on the encounter procedures. From our point of view, it was the same as any other track except for the signal dropping out when the spacecraft went behind the planet. All the action was in the spacecraft controlled from JPL in Pasadena. In these deep space missions, we could not see what was going on in real time, as we could not see any pictures. We had to wait for them to come out in the popular media such as Time Magazine, like anybody else.

In contrast to fiery, massive Jupiter with its violent storm-tossed atmosphere, volcanic pizza-like moon Io, and gigantic lightning bolts, Saturn looked cool and ethereal as Voyager approached it on 10 November 1980. As a JPL scientist said,

> *"After Jupiter we were afraid Voyager's Saturn encounter was going to be a bust."*

But to their surprise many more reporters arrived at JPL for the Saturn encounter than the Jupiter event. Voyager's encounter with Saturn probably created more interest than the Jupiter fly-by because the stunning results from the first encounter whetted the appetites of the media, there were the unique rings to look and marvel at, and the moon Titan with its atmosphere and nitrogen seas roused the media's interest, hoping for a possible breakthrough story about a new world. Larger than the planet Mercury, Titan has a nitrogen atmosphere similar to the Earth, but with perpetual clouds which scientists think could drop fine methane sleet into liquid oceans of methane. Titan is so far away from the Sun, full daylight on Titan is probably the same brightness as moonlight on Earth. To Earthly humans, it would seem a bizarre world indeed. It is interesting to speculate on the experiences of Earthlings when they land on the surface of Titan one day and stand on a frozen coast to look out at a sea of methane ruffled by nitrogen breezes under a dull, glowing red sky.

Then at 1150 AEDT at a distance of 1,579,021 kilometres from Saturn Voyager 1 suddenly plunged through the first bow shock. As predicted, the magnetosphere of Saturn was larger than when Pioneer 11 flew past. During that Los Angeles evening Voyager 1 experienced five separate encounters with the magnetopause as it pulsed to the Sun's solar wind pressure changes. The first crossing took place at 1319 AEDT at a distance of 1,428,352 kilometres and the last at 1413 at a distance of 1,380,137 kilometres.

On 7 November commands were transmitted from the Goldstone station for a trajectory correction burn of the attitude control thrusters to spin the spacecraft a quarter of a turn on its axis to maximise the fly by Titan.

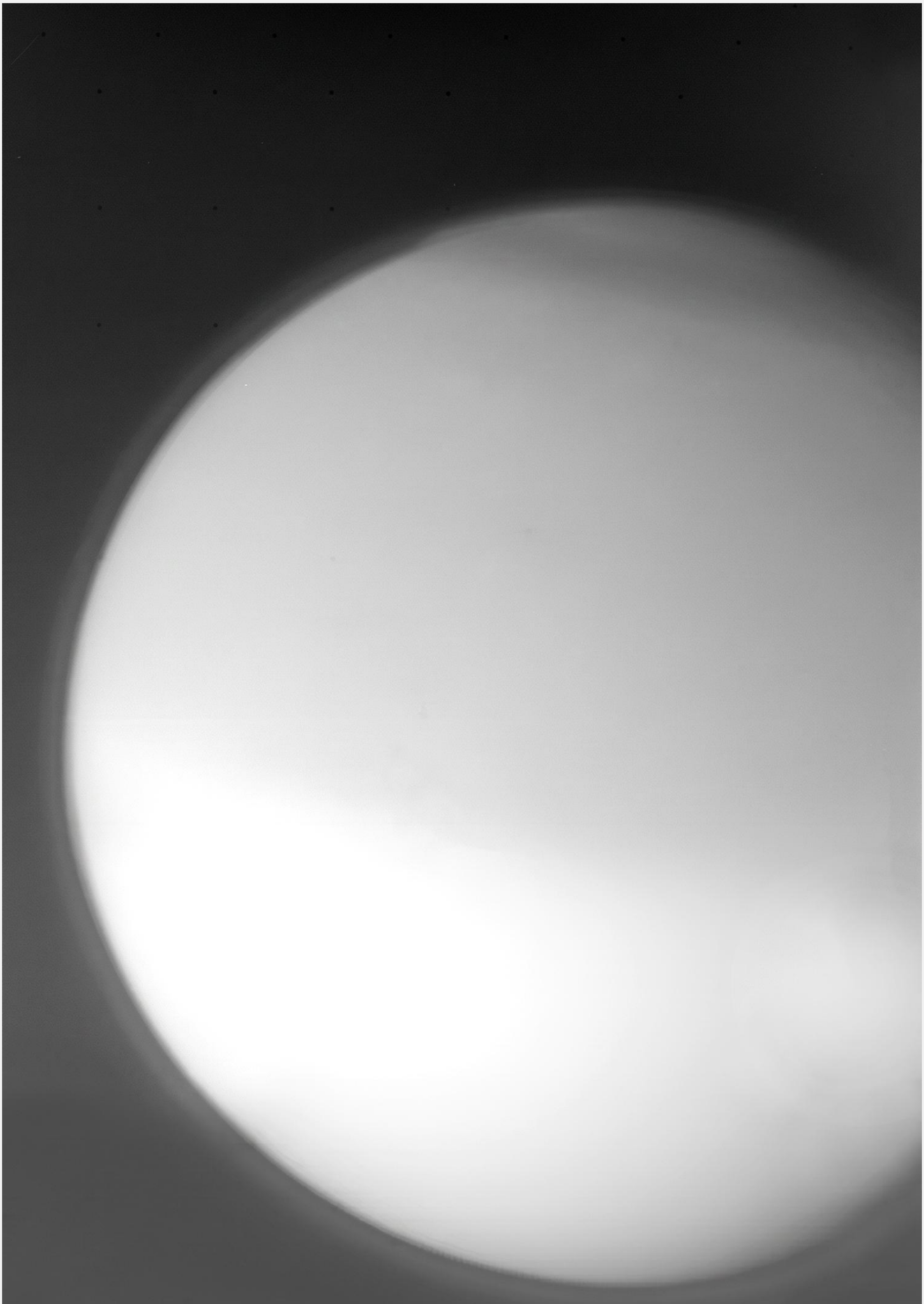
The atmospheric scientists were keen to develop vertical, temperature and pressure profiles of its atmosphere using the RSS instrument.

Designed to send the spacecraft on a path to shave past Titan, this manoeuvre broke the radio link with Earth, and it was up to the programmers to send the commands to realign the spacecraft back to point the high gain antenna back to the Earth.

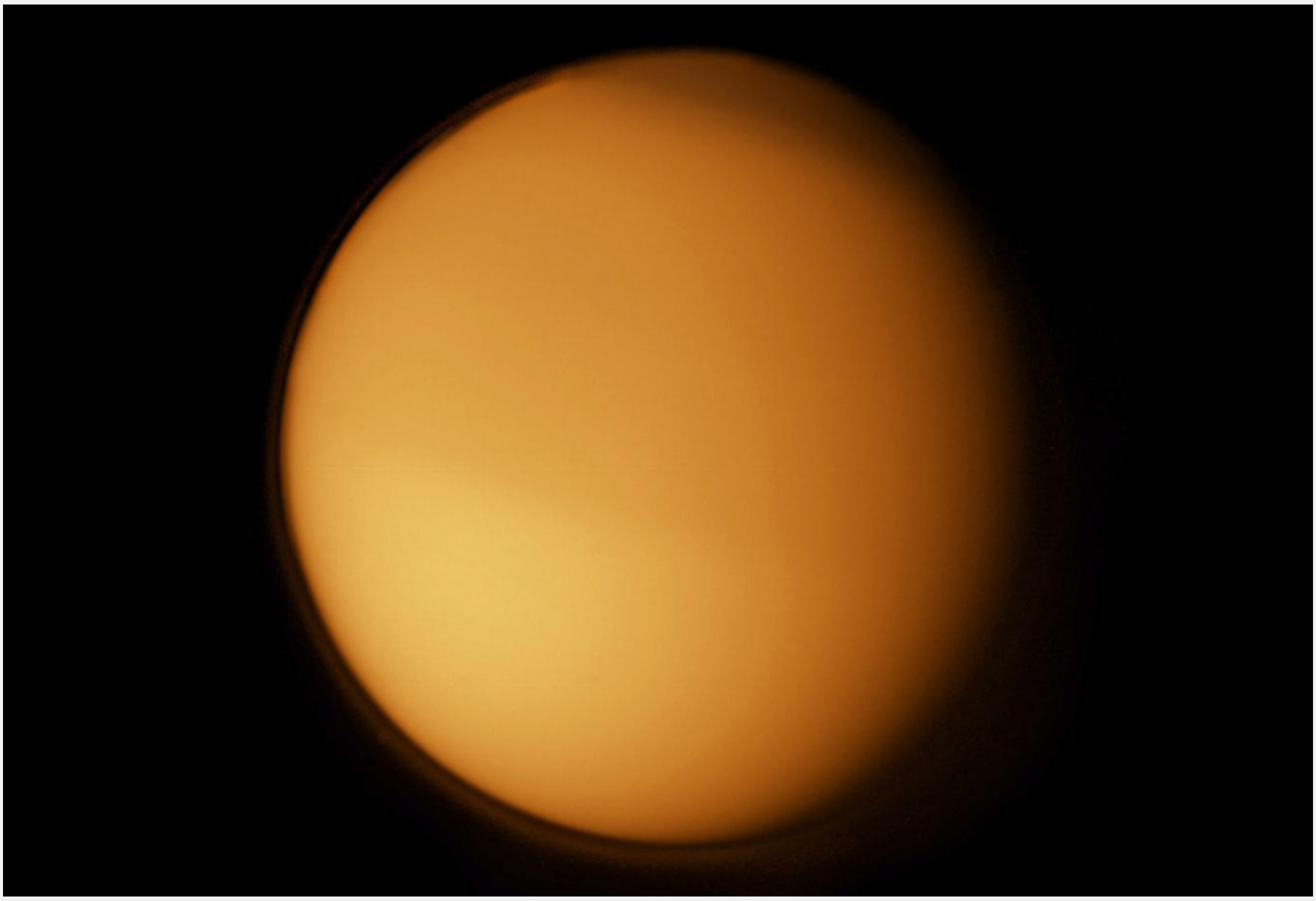
Scientists held their breath and crossed their fingers until the signal reappeared after the manoeuvre, and the data confirmed the procedure had been executed perfectly.

TITAN

Diameter:	5,150 kilometres
Albedo:	0.22
Mass:	1.345 x 10^{23} kilograms
Saturn distance:	1,221,870 kilometres
Orbital period:	15.95 Earth days
Surface temp:	-178°C
Surface pressure:	146.7 kPa (kilopascals)
Closest approach:	3,800 kilometres



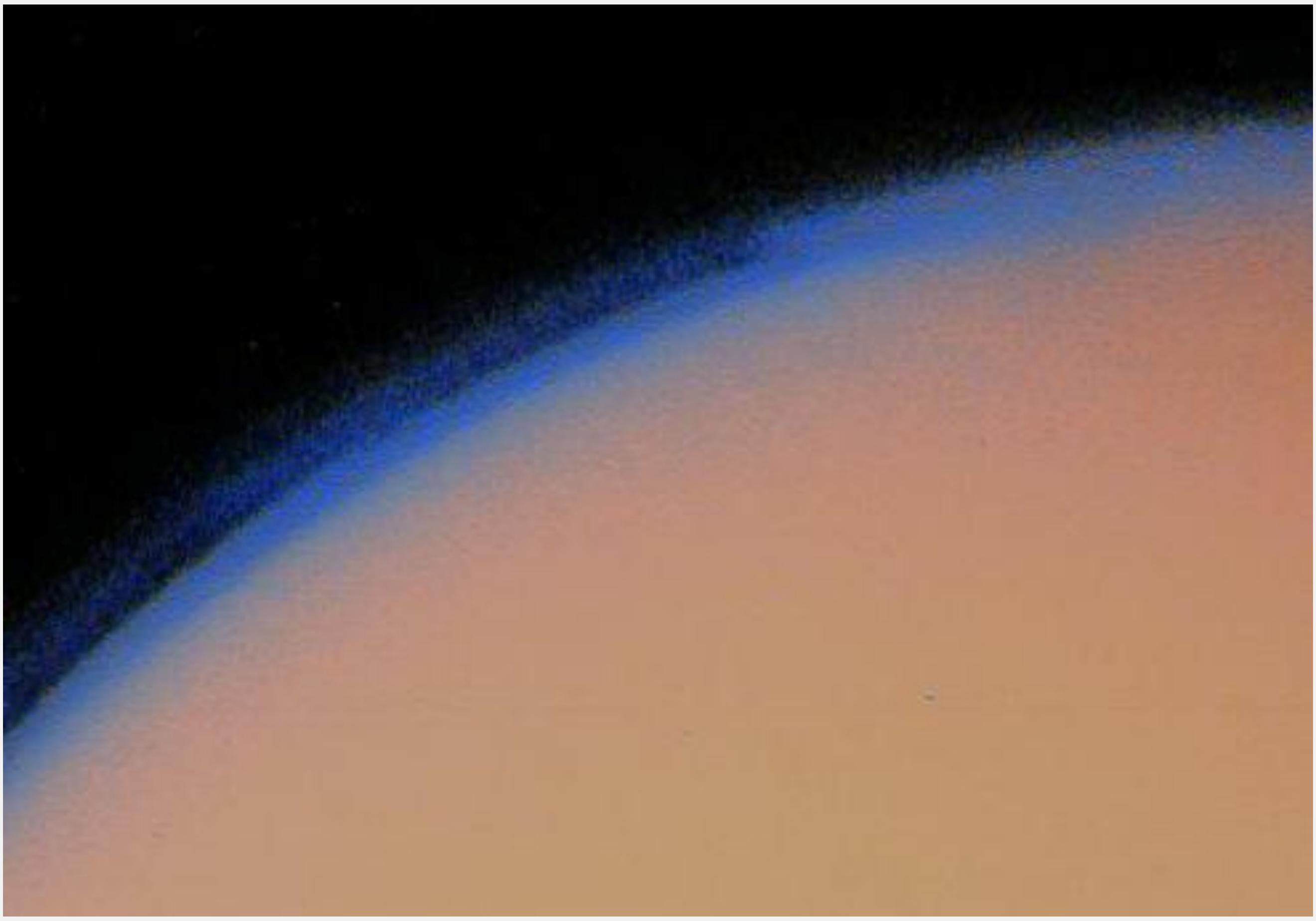
Composite of Voyager 1 narrow-angle camera raw images of Titan.
Images: NASA/JPL. Composite: Glen Nagle



Above: Colour composite of Titan using multiple wavelengths captured by Voyager 1's cameras.

Image: NASA/JPL

Below: Colour-enhanced close-up of Titan's hazy cloud layers.



Discovered by Christiaan Huygens on 25 March 1655, he originally named his discovery simply *Saturni Luna* (Latin for Saturn's moon).

In 1847 the name Titan and the names of all seven satellites of Saturn then known came from John Herschel, discoverer of Mimas and Enceladus. He suggested the names of the Titans, sisters and brothers of Cronos (the Greek Saturn), be used.

Titan's atmosphere is 98.4% nitrogen, the remaining 1.6% being methane, with traces of other gases such as hydrocarbons. The bulk composition of the moon is half water ice and half rocky material. Its interior is thought to be a dense, rocky core, overlaid by a mantle of ice with a liquid layer consisting of water and ammonia between the ice crust and rocky core.

Titan is the most interesting of all the moons, so much so that the Cassini spacecraft sent a robot messenger down to the surface in January 2005. Voyager 1flew within 3,800 kilometres of it, giving a resolution of 1.3 kilometres but could not penetrate the atmospheric haze. Scientists visualise the surface consists of methane as a solid, liquid, and gas, so methane clouds may drizzle methane rain or methane snow, and there may be methane rivers and lakes.

Voyager measured its surface temperature as –180ºC, too cold for living things as we know them, but it could be like studying prehistoric Earth. With a lifetime of just 20 million years, methane must be regularly resupplied to the atmosphere to be as abundant as it is today.

Titan is larger than the planet Mercury, though Mercury has twice its mass. It is the second largest moon in the solar system after Jupiter's Ganymede. Its surface pressure is greater than Earth at 1.467 bars. Titan's air is predominantly made up of nitrogen with other hydrocarbon elements, which gives Titan its orange hue. These hydrocarbon rich elements are the building blocks for amino acids necessary for the formation of life. Scientists believe that Titan's environment may be similar to that of the Earth's before life began putting oxygen into the atmosphere.

Titan, Saturn's largest moon, is the only Solar System planetary body other than Earth with a thick nitrogen atmosphere.

The Voyager spacecraft confirmed that methane was the second-most abundant atmospheric constituent in Titan's atmosphere, and revealed a rich organic chemistry, but its cameras could not see through the thick organic haze.

After a seven-year interplanetary journey on board the Cassini orbiter, the Huygens probe was released on 25 December 2004. It reached the upper layer of Titan's atmosphere on 14 January and landed softly after a parachute descent of almost 2.5 hours.

An exciting scientific data set was returned by the Huygens probe, offering a new view of Titan, which appears to have an extraordinarily Earth-like meteorology, geology, and fluvial activity (in which methane would play the role of water on Earth).

While many of Earth's familiar geophysical processes appear to occur on Titan, the chemistry involved is quite different. Instead of liquid water, Titan has liquid methane. Instead of silicate rocks, Titan has frozen water ice. Instead of dirt, Titan has hydrocarbon particles settling out of the atmosphere. Titan is an extraordinary world having Earth-like geophysical processes operating on exotic materials under very alien conditions.

A seasonally varying haze, which appears to be the main source of heating and cooling that drives atmospheric circulation, shrouds the moon. The haze has numerous features that have remained unexplained. There are several layers, including a *"polar hood"*, and a pronounced hemispheric asymmetry. The upper atmosphere rotates much faster than the surface of the moon, and there is a significant latitudinal temperature asymmetry at the equinoxes.

Voyager 1 flew within 3,800 kilometres of Titan at 14:42 on 12 November AEDT, passing behind the moon for an analysis of its atmosphere. It was early spring in the northern hemisphere, and early autumn in the south.

Unfortunately, the moon just appeared as a featureless orange ball to the Voyagers' cameras, unable to peer under the haze. The RSS occultations and IRIS measurements found that the temperature decreased with altitude from the surface until a height of 42 kilometres .

Three views of Tethys – (left and centre) from Voyager 1's narrow-angle camera, (right) wide-angle camera view of Saturn with Dione (bottom) and Tethys and its shadow just below the rings. Image: NASA/JPL

TETHYS	
Diameter:	1,048 kilometres
Albedo:	0.8
Mass:	6.1755 x 10^{20} kilograms
Saturn distance:	294,672 kilometres
Orbital period:	45.76 Earth hours
Surface temp:	-187°C
Closest approach:	415,320 kilometres

Giovanni Cassini discovered Tethys on 21 March 1684. He referred to Tethys as one of the four Sidera Lodoicea (Stars of Louis) after King Louis XIV (the other three were Iapetus, Dione and Rhea). Other astronomers called the Saturn moons by number in terms of their distance from Saturn. Thus, Tethys was Saturn III. John Herschel suggested that the moons of Saturn be associated with the Greek mythical brothers and sisters of Kronus. (Kronus is the equivalent of the Roman god Saturn in Greek mythology.)

The name comes from the Greek goddess (or Titan) Tethys, who was the daughter of Uranus and Gaea, a sister to Kronus and the wife of Oceanus. She was said to be the mother of the chief rivers, the mother of three thousand daughters called the Oceanids and the embodiment of the waters of the world. Geological features on Tethys generally get their names from *"The Odyssey"* by Homer.

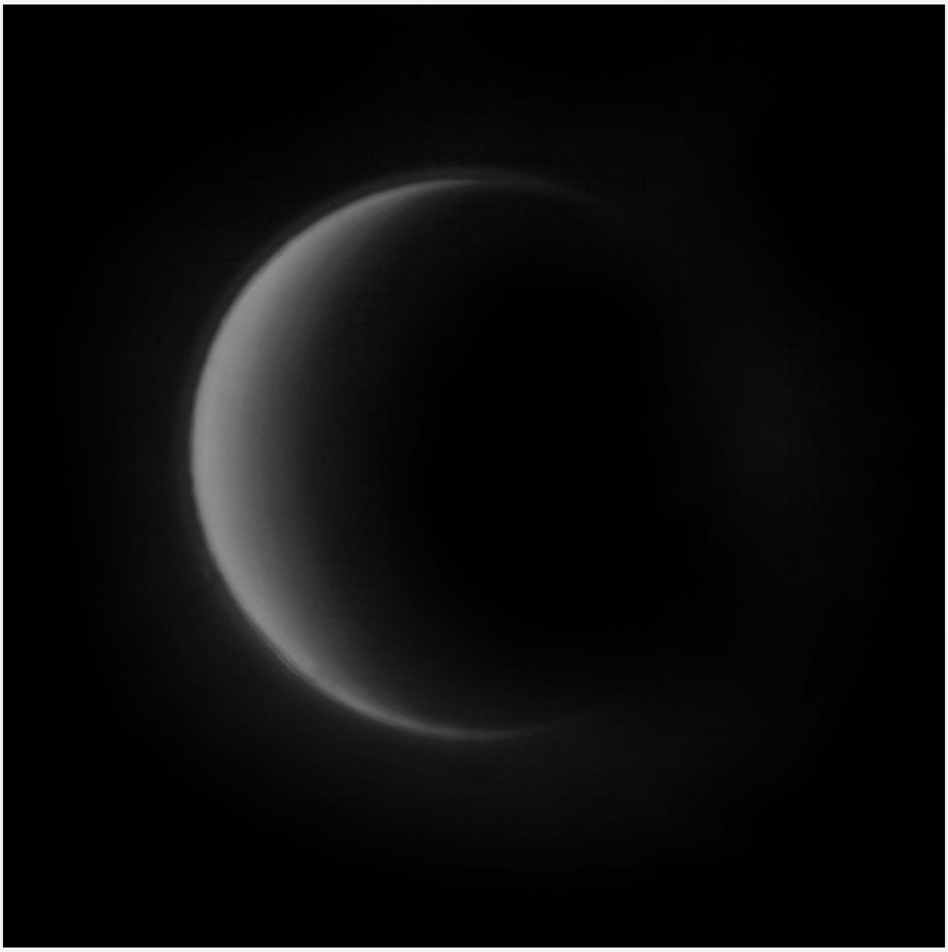
Slightly less than one third the size of Earth's moon, Tethys has the lowest density of all the major moons of the solar system, suggesting it is made of water ice with a small fraction of rock.

Its heavily cratered, highly reflective surface showed our little spacecraft a large canyon, later named Ithaca Chasma, more than 2,000 kilometres long, reaching from the north pole all the way down to the south pole. Another enormous feature is a 400 kilometre wide crater with the biggest central peak yet found in the solar system to be called Odysseus, four times larger than the crater Herschel on Mimas. Tethys is accompanied by two small satellites called Telesto and Calypso

Although Voyager 1 images showed features down to 24 kilometres across, it remained for Voyager 2 to come much closer and reveal more details about Tethys.

Now it was 2 hours 28 minutes to Voyager 1's closest approach to Titan. There was a bad scare at Madrid tracking station when heavy thunderstorms passed over the area, and a 30 minute heavy shower began just before the Titan occultation. There was also a 43 second deviation from the planned exit, which meant the spacecraft was about 200 kilometres off target.

At 1542 AEDT 12 November Voyager 1 passed 6,490 kilometres from Titan – less than the distance from New York to Rome – the IRIS



Voyager 1 image after its flyby of Titan. Image: NASA/JPL

instrument busy taking spectra of infrared emissions from the high upper atmosphere.

At 1620 the modulation was turned off, leaving only the carrier signal for the occultation experiment to determine the depth and composition of Titan's atmosphere.

At 1646 the Sun set behind the edge of Titan as seen from the spacecraft and a minute later the signal dropped out as Voyager 1 went behind the moon. Ten minutes later, at 1635, Voyager emerged and at the same time passed through the plane of the rings of Saturn, and for the next 24 hours would be looking at the outer side of Saturn, which is from the opposite side from the Sun, the dark side.

As the mission progressed, the planners wrestled with many possibilities and doubts as they aimed the spacecraft at the ringed planet.

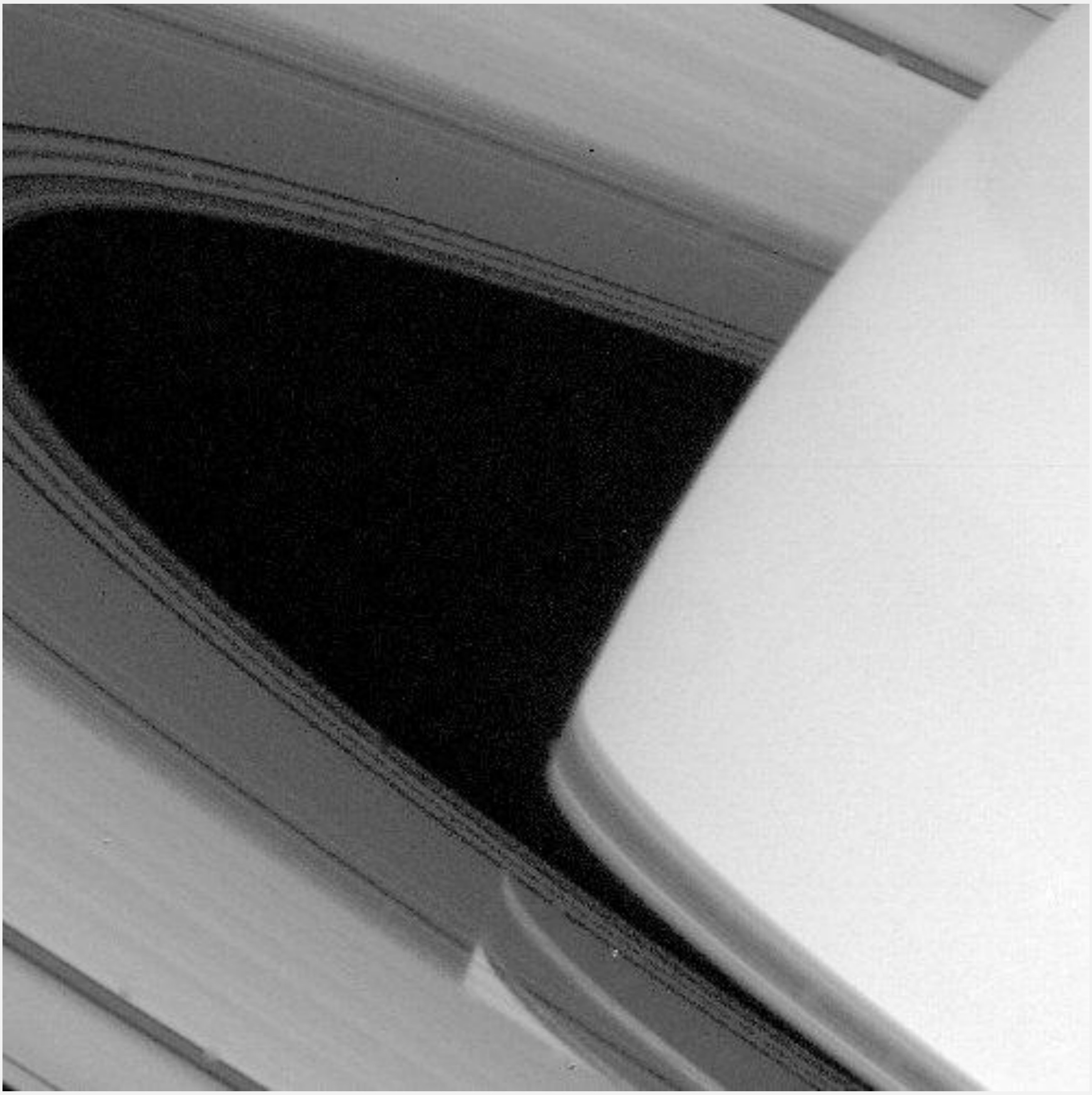
Originally there were 10,000 possible paths past Saturn for Voyager 1 to fly down. A team of ten scientists responsible for the mission navigation had to boil it down to just one - one that had to be right.

The moon Titan was a prime target, but if the spacecraft flew by Titan it couldn't continue on to Uranus and Neptune, so Voyager 2 was planned to follow the second route to continue on to Uranus and Neptune. If Voyager 1 failed to cover Titan, then Voyager 2 would have to be redirected to cover it, and miss out on the outer planets.

So, Voyager 1 had to be successful - which it was. Voyager 2 could then follow a trajectory to take it on to Uranus and Neptune. How close to the rings can you go without damaging the spacecraft? What would happen if there was something there?

Of course we weren't involved in all these politics at Honeysuckle, we were busy following Revision D of the 618-700 NOP, or Network Operations Plan for Voyager.

I was lucky enough to be working on the servo system and receivers on day shift when Voyager 1 had its encounter with Saturn. In the USB area there were four of us - Tony Gerada, the Shift Supervisor, me the servo and receiver operator, Terry Hearn, the Receiver and RF operator, and a Data operator.



Voyager 1's narrow-angle camera captured this close-up view of Saturn and its rings. Image: NASA/JPL

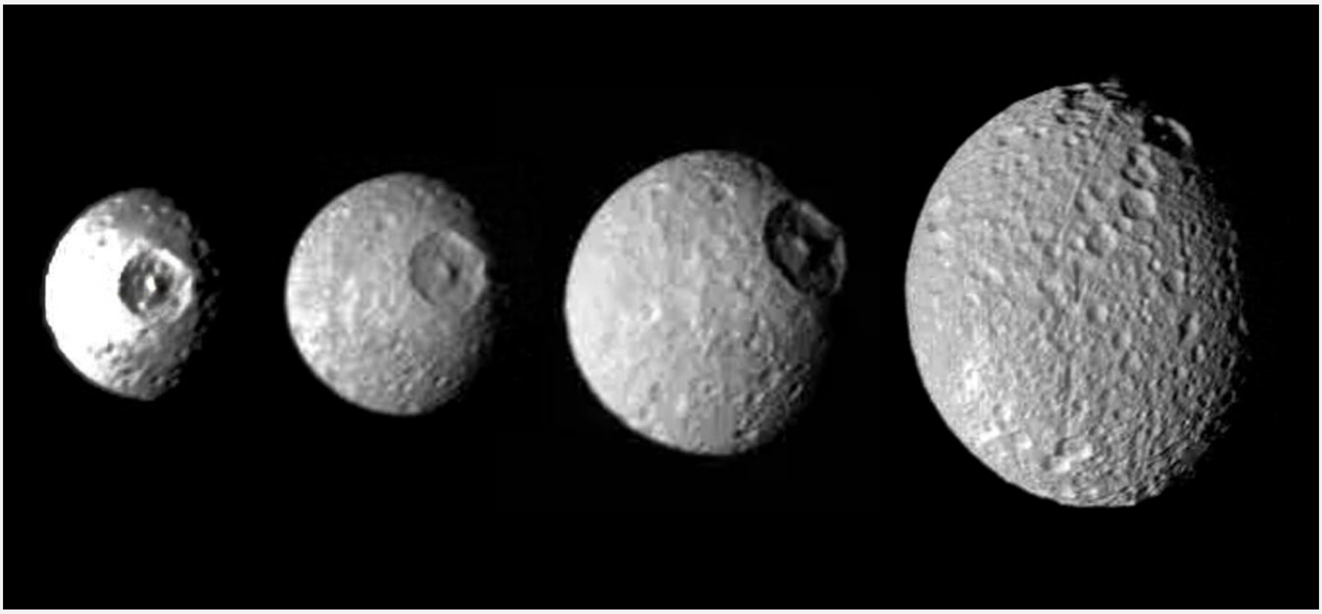
VOYAGER 1 AT SATURN
PCA – POINT OF CLOSEST APPROACH
10:46 AEDT – Thursday 13 November 1980

For years we had been tracking the Pioneers and Voyagers, nursing them through the Jupiter encounters, and suddenly here was Voyager 1 about to approach the ringed planet.

It was the morning of our day shift on 13 November 1980 (still the 12th in the USA). Earlier in the day I had already been up the antenna and jotted down the transmitter meter readings after checking the servos were running sweetly. It was always a nightmare that something would fail and immobilise the antenna just when the Americans were depending on us.

Back in the USB room I loaded the predicts (instructions to point the antenna at the spacecraft) into the computer; Terry Hearn had set up the receivers and calculated the System Temperature before Tony Gerada contacted Track, the worldwide operations centre at JPL at Pasadena in California, and passed on our system configuration and performance figures. They checked us out before I sent the antenna off to the horizon to meet Voyager 1, being tracked by Goldstone, in California.

Exactly at the scheduled time the signal from the spacecraft filled our receivers and telemetry channels, and we checked all the readings and data were as they should be.



Four views of Mimas from Voyager 1, including the 130 kilometre-wide Herschel crater. Images: NASA/JPL

They always were - those spacecraft were as regular as the stars themselves.

With Apollo we knew what was happening because we had real-time television, and the events on the moon were only happening a second or so away.

Here we had no real time pictures, the images from the cameras were a string of codes passing by. Also, all the pictures we received had happened two hours ago. So, sitting at the console, all I could use was a diagram from the NOP to try and visualise what was happening to our little spacecraft so far from home.

Voyager 1 encountered Saturn at 1046:30 on 13 November 1980 Eastern Australian daylight savings time, skimming 123,910 kilometres above the cloud tops. At 1243 AEDT Voyager 1 slipped behind Saturn's rings, its signal appearing briefly as it passed successively behind rings C, B and A.

Voyager 1's signal appeared again at 1435 AEDT from behind the A Ring. Forty-five minutes later the spacecraft crossed the ring plane for the second time, and the spacecraft began looking for the moon Mimas.

Mimas, named after the giant Greek god who was killed by Hephaestus and now said to lie beneath Mount Mimas in Erythres in Turkey, was first discovered by William Herschel in 1789.

The innermost of Saturn's major moons, it's only 394 kilometres in diameter with a huge 130 kilometre wide crater called Herschel, 10 kilometres deep, with a peak rising 6 kilometres from the centre of its floor.

MIMAS

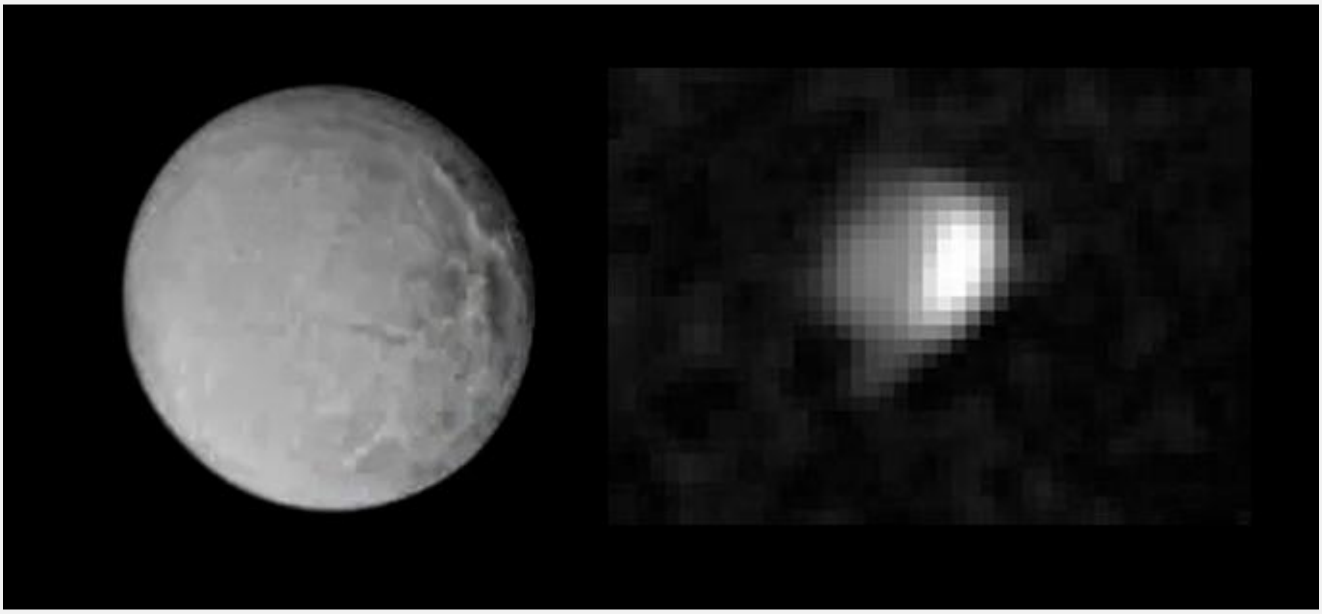
Diameter:	394 kilometres
Albedo:	0.6
Mass:	3.7493 x 10^{19} kilograms
Saturn distance:	188,224 kilometres
Orbital period:	23.14 Earth hours
Surface temp:	-209°C
Closest approach:	88,820 kilometres

ENCELADUS

Diameter:	502 kilometres
Albedo:	1.0
Mass:	1.08022 x 10^{20} kilograms
Saturn distance:	240,192 kilometres
Orbital period:	33.36 Earth hours
Surface temp:	-240°C min / -128°C max
Closest approach:	202,251 kilometres

Enceladus seems to be almost pure water ice, making it the most reflective object in the solar system. Enceladus appears to have by far the most active surface of any satellite in the system (with the possible exception of Titan, whose surface was not photographed).

At least five types of terrain have been identified on Enceladus.



Later missions would reveal more detail of the surface of Enceladus. Modern processing did show that Voyager 1 had glimpsed the plumes/geysers (right) of the icy moon. Images: NASA/JPL. Processed by Ted Stryk

OCCULTATION AT SATURN

I was on the receivers at Honeysuckle Creek when Voyager 1 went behind the ringed planet. The signal cut out at exactly the moment predicted, the white *"In Lock"* light on my receiver blinking out and the two-tone alarm started singing.

After Voyager 1's signal vanished as it went behind Saturn, at 12:45 AEDT on 13 November, we waited for the signal to reappear on the other side of the planet. We all feared something might happen to our spacecraft as it whipped past the rings. I was trying to imagine the little spacecraft speeding past the giant planet and its moons and scraping past the rings, aware it had all happened 1 hour 23 minutes ago.

It really had to be pure imagination, because we had no real time television, and it was a week or so before we saw any close up pictures of the planet and its rings. Those pictures came out in newspapers and magazines later.

Then at the predicted time I went through the acquisition procedure, tuning steadily until we reached Track Syn Frequency and there it was, as though nothing had happened. All the excitement was stored in the spacecraft's recorders. In parallel with the Prime Site, DSS43, the big dish at Tidbinbilla, it was our job to collect it and pass it on to the scientists at JPL.

Voyager 1 sent back 15,000 images from Saturn. If we had been using the television system used in Mariner 4 to Mars in 1965 it would have taken a whole year to send one picture!!

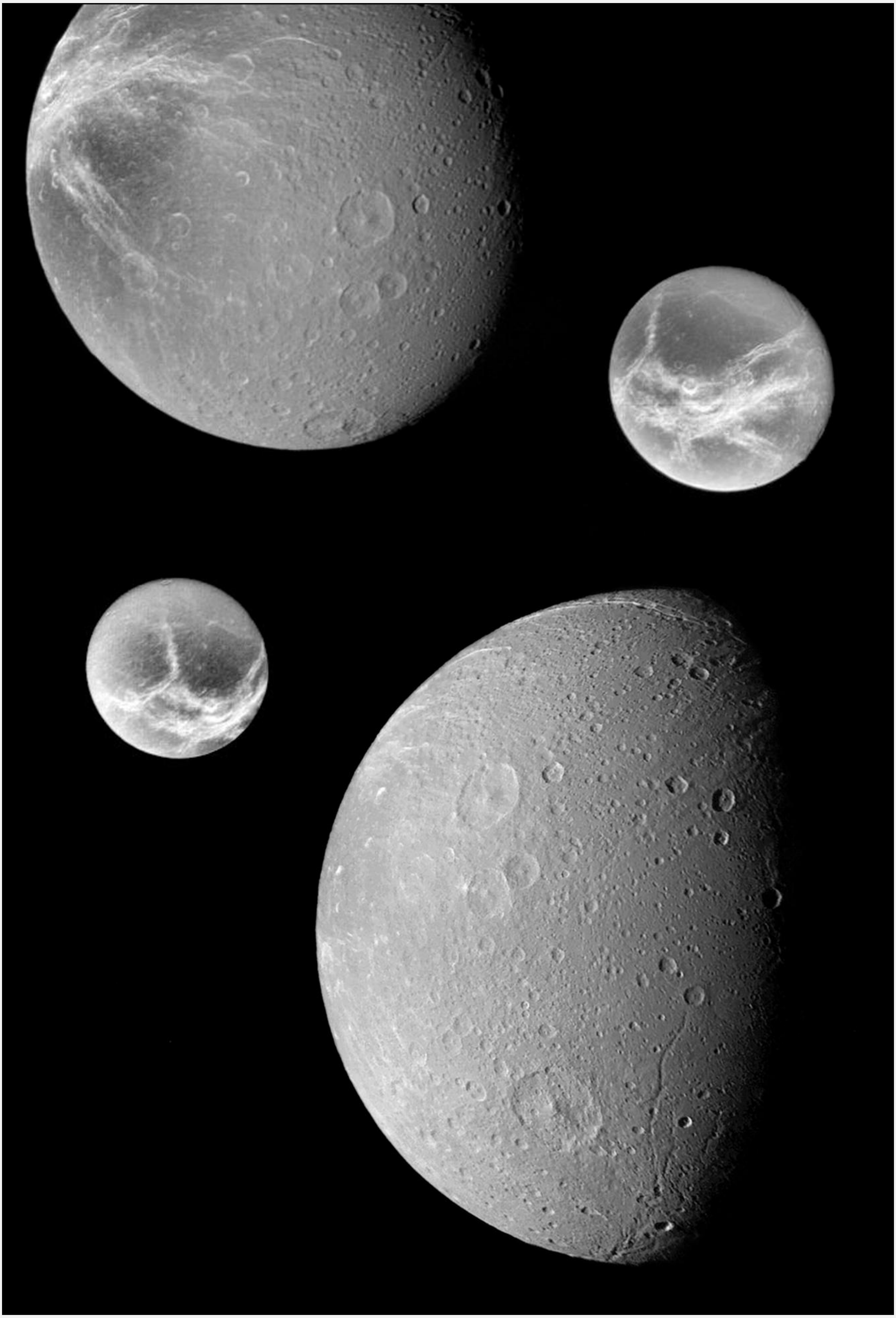
Mariner took 22 frames of Mars, 200 by 200 pixels, each requiring 8½ hours of playback at a data rate of 8⅓ bits per second. Voyager returned pictures each of 800 by 800 pixels in 48 seconds at a data rate of 115,200 bits per second.

The day after the encounter, 13 November, Voyager 1 had safely passed Saturn and its rings, and headed off on a trajectory to take it out of the solar system into interstellar space. During the day the official encounter period ended, and Voyager 1 entered the Post encounter phase. Now the views looking back at Saturn were from a perspective that had never been seen by mankind before – views from the other side of the ringed planet.

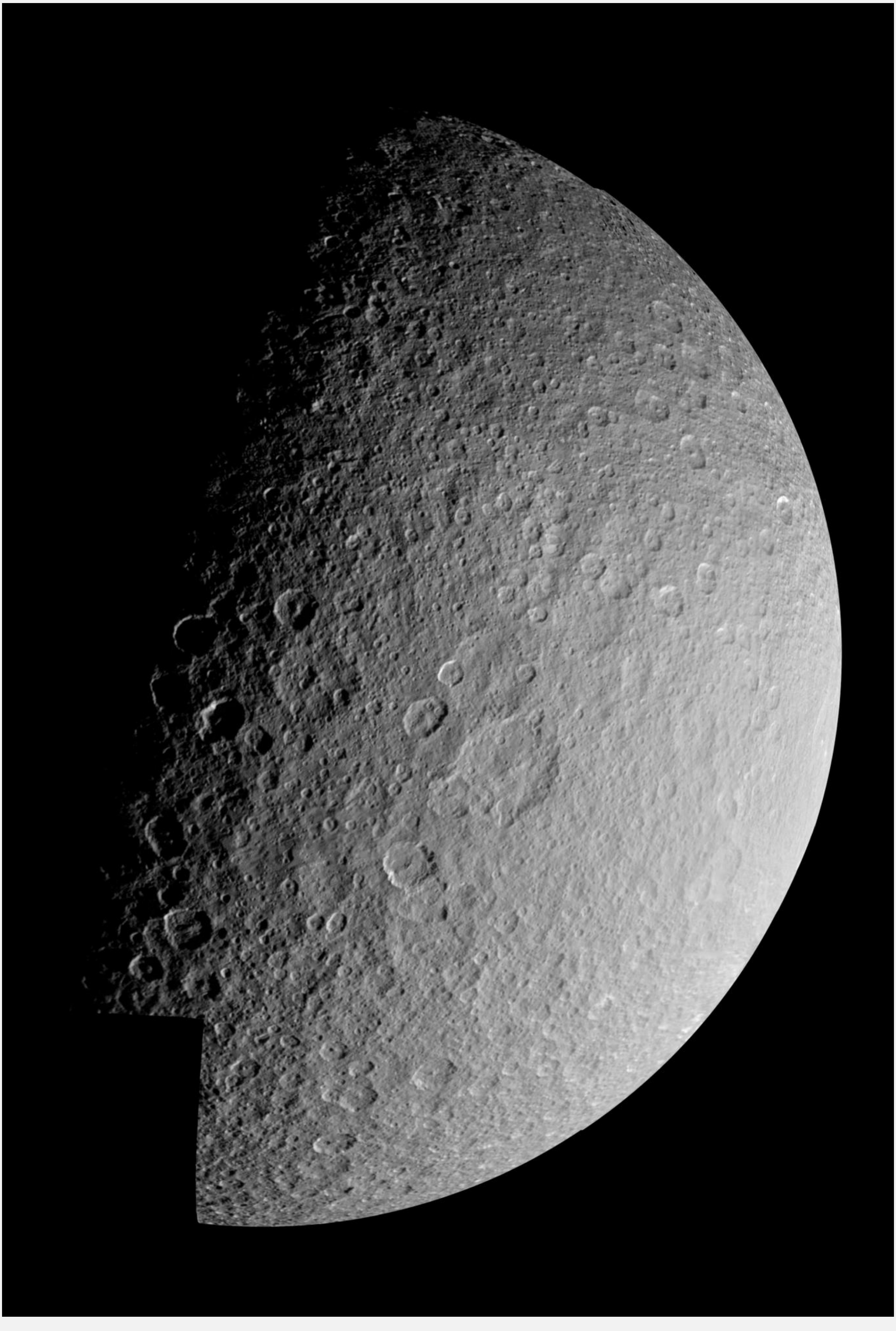
DIONE

Diameter:	1,122 kilometres
Albedo:	0.998
Mass:	1.09545 x 10^{21} kilograms
Saturn distance:	377,400 kilometres
Orbital period:	2.7369 Earth days
Surface temp:	-186^{o}C
Closest approach:	161,131 kilometres

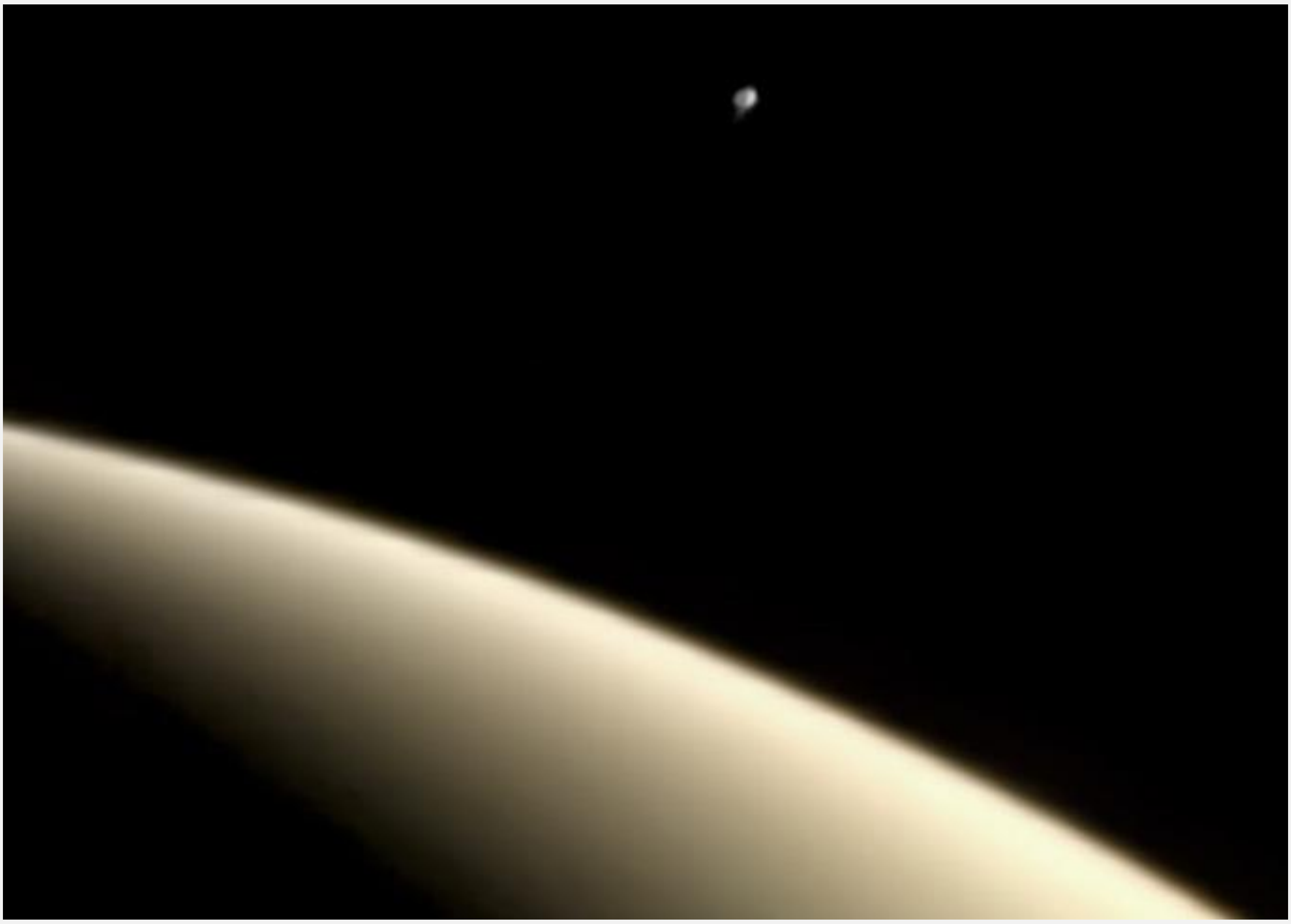
Dione is named after the Titaness Dione of Greek mythology, and was first discovered by Giovanni Cassini in 1684.



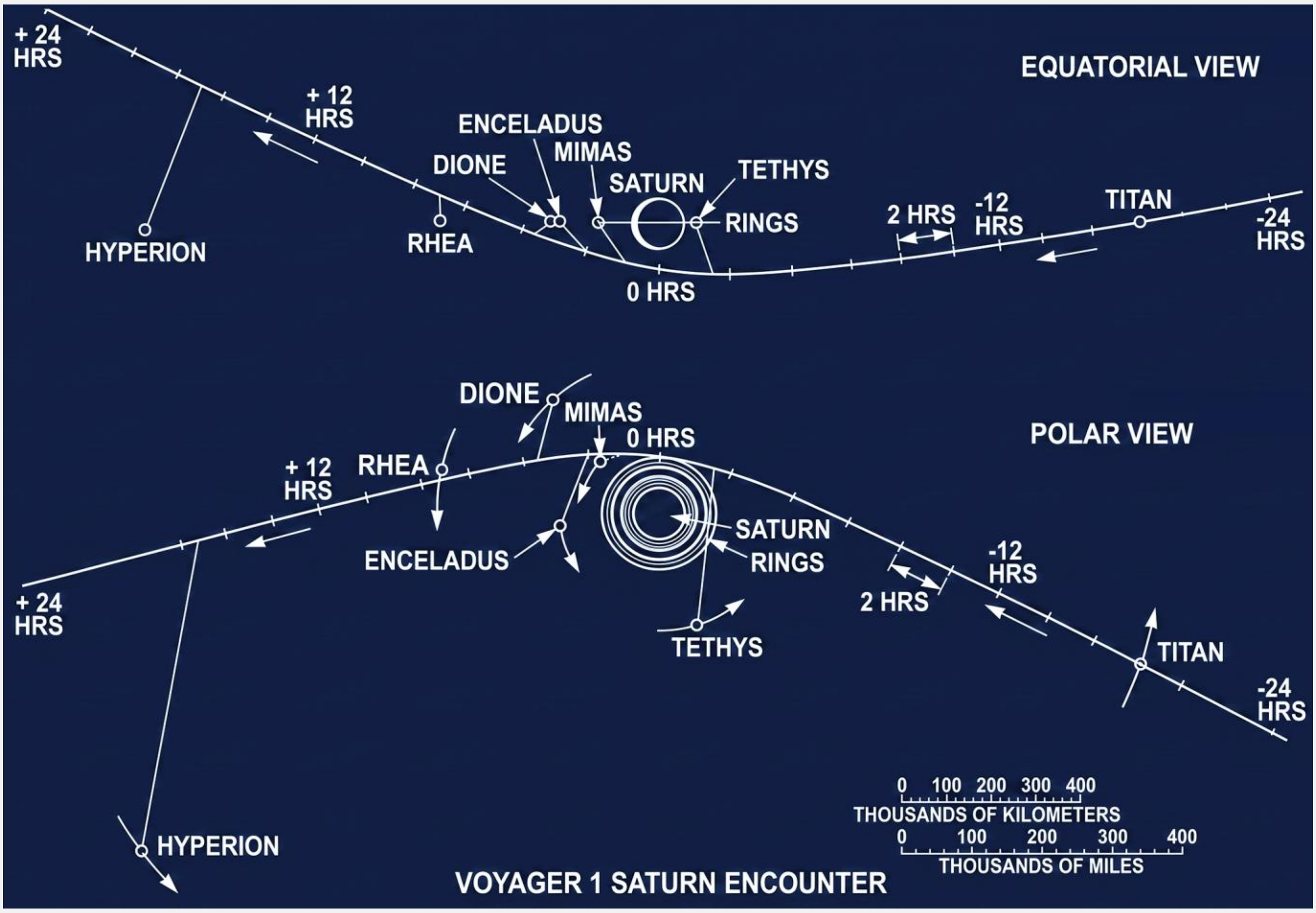
Various Voyager 1 views of Dione's complex surface features. Images: NASA/JPL and (bottom) Ted Stryk

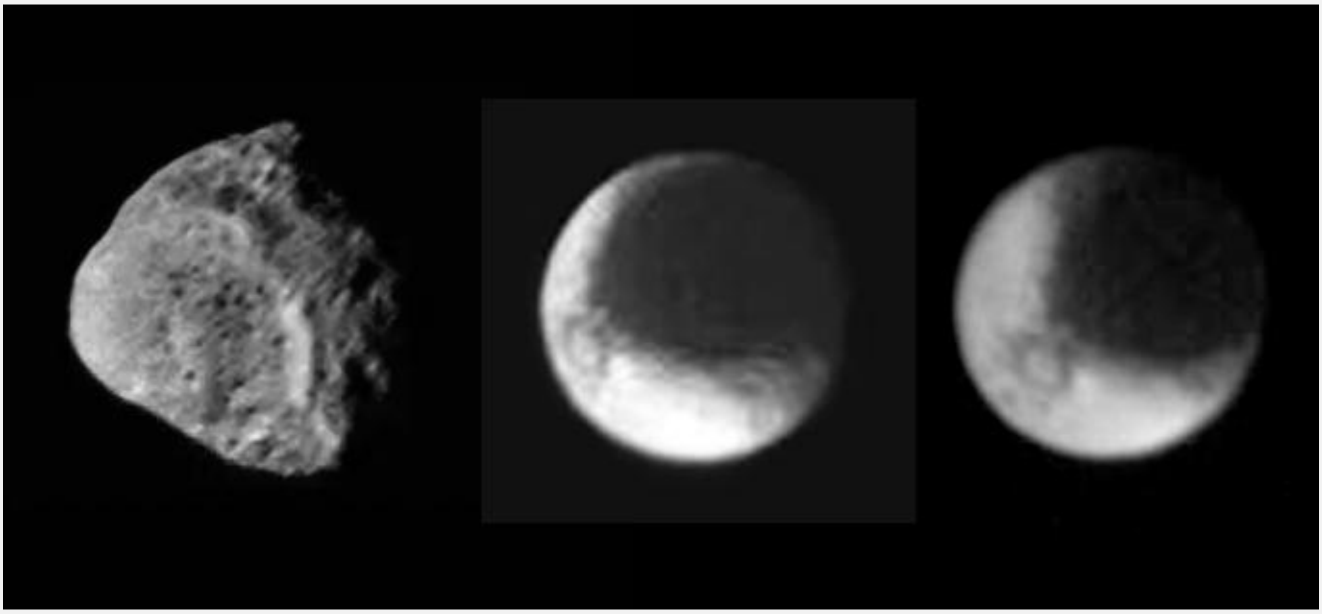


A view of Rhea looking from its northern hemisphere. Images: NASA/JPL. Processed by Björn Jónsson



Above: Colour view of the moon Enceladus above Saturn. Note the plume/geysers are visible.
Image: NASA/JPL and processed (above) by Ted Stryk
Below: Diagram of Voyager 1's trajectory through the Saturnian system.





Hyperion (left) and two views of Iapetus. Images: NASA/JPL

While out of sight of Earth behind Saturn, Voyager 1 encountered the tidally locked moon Dione at a distance of 161,131 kilometres. Dione has two small co-orbital satellites called Helene, orbiting the planet ahead of it, and Polydeuces, trailing behind.

Only slightly larger than Tethys, Dione is largely made of water ice with a dense core of silicate rock. The surface is strewn with impact craters ranging in size from a few hundred metres to over 100 kilometres. The brighter leading hemisphere seems to be less littered with craters than the darker trailing side.

Voyager 1 pictures showed wispy Tethys' most striking feature is the Amata Crater, with a diameter of 240 kilometres.

RHEA

Diameter:	1,528 kilometres
Albedo:	0.949
Mass:	2.306 x 10^{21} kilograms
Saturn distance:	527,040 kilometres
Orbital period:	4.5 Earth days
Surface temp:	-220°C
Closest approach:	73,980 kilometres

Rhea is Saturn's second largest moon, and ninth largest moon in the solar system. Rhea is named after the god Titan Rhea of Greek mythology, 'Mother of Gods.' It was first discovered by Giovanni Cassini in December 1672.

The final event of an exciting day in Pasadena was a very close approach of 73,980 kilometres to Rhea at 1556 AEDT, where the pictures could resolve features as small as 1.3 kilometres across.

It had been necessary to rotate the whole spacecraft during the exposures to compensate for the speed of the spacecraft past the moon.

Voyager 1 took some good pictures of the surface, which showed it was relatively uniformly covered in craters, the majority around 20 kilometres in diameter. One exception is Izanagi, with a diameter of 250 kilometres.

HYPERION

Diameter:	270 kilometres
Albedo:	0.3
Mass:	5.62 x 10^{18} kilograms
Saturn distance:	1,500,934 kilometres
Orbital period:	21.3 Earth hours
Surface temp:	-180°C
Closest approach:	879,127 kilometres

Named after the Greek god of watchfulness and observation, the tumbling, potato shaped moon Hyperion was first discovered by William Bond on 16 September 1848, followed two days later by William Lassell.

The distinctive sponge –like moon has bright 10 kilometre high crater walls, indicating a lot of water ice. It is surmised that Hyperion had probably been a larger object shattered by a number of devastating collisions, as it does not revolve on its axis but tumbles along rotating every 13 days. It has a 193 kilometre long scarp called Bond Lassell Dorsum.

IAPETUS

Diameter:	1,472 kilometres
Albedo:	0.04 – 0.5
Mass:	1.805 x 10^{21} kilograms
Saturn distance:	3,559,400 kilometres
Orbital period:	79.3 Earth days
Surface temp:	-183°C min / -143°C max
Closest approach:	2,474,000 kilometres

Iapetus, the third largest moon of Saturn, was the first of Saturn's moons discovered by Giovanni Cassini on 25 October 1671.

With Tethys, Dione, and Rhea, Iapetus was originally named The Stars of Louis in honour of King Louis XIV until the name Iapetus was suggested by astronomer John Herschel in 1847.

Iapetus is a Titan from Greek mythology. He was son of Uranus and Gaia, and father by an Oceanid named Clymene or Asia of Atlas, Prometheus, Epimetheus, and Menoetius.

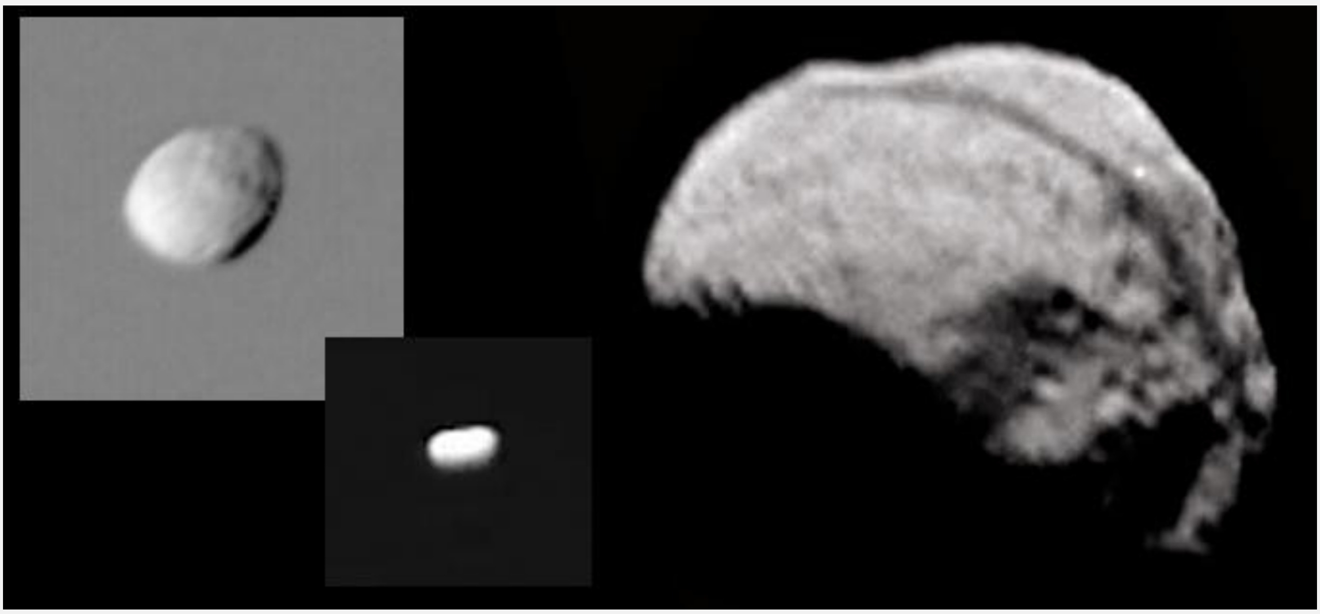
Through Prometheus and Epimetheus and Atlas, he is an ancestor of the human race.

Unlike the other planetary bodies in the solar system, Iapetus has a dark leading hemisphere with an albedo of 0.05 while the trailing hemisphere is ten times brighter. Cassini himself said he could see Iapetus on one side of Saturn, but not on the other.

SUMMARY OF SATURN'S MOONS AND SMALLER SATELLITES

	Diameter kilometres	Kilometres from object's centre
Atlas	40x20	137,670
Prometheus	140x100x80	139,353
Pandora	110x90x80	141,700
Epimetheus*	140x120x100	151,472
Janus*	220x200x160	151,422
Mimas *	392	185,520
Enceladus *	520	238,020
Tethys*	1,060	294,660
Telesto	34x28x26	294,660
Calypso	34x22x22	294,660
Dione *	1,120	377,400
Helene*	36x32x30	377,400
Rhea *	1,530	527,040
Titan *	5,150	1,221,860
Hyperion*	410x260x220	1,481,000
Iapetus *	1,460	3,560,830
Phoebe	213	12,947,913

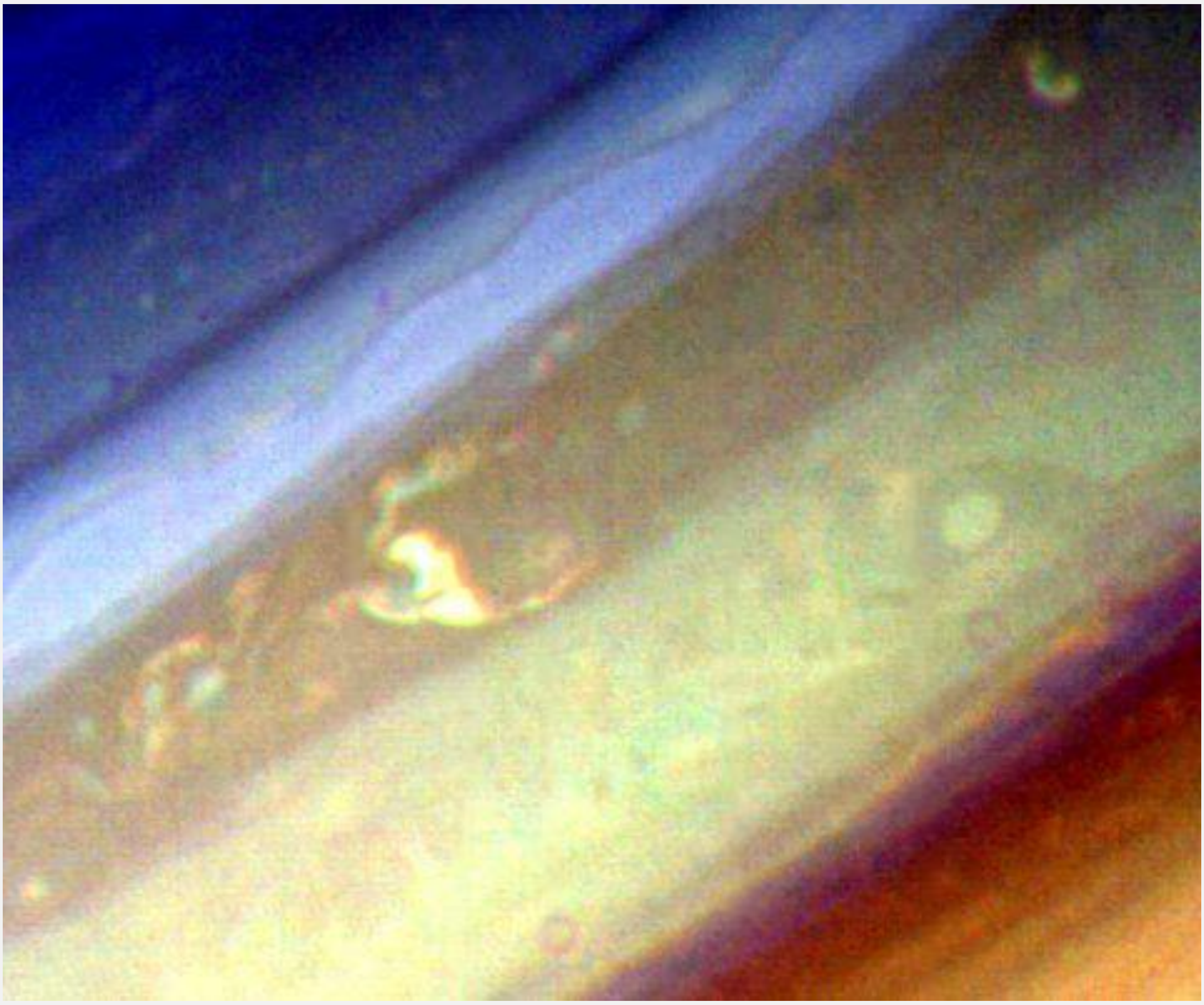
* asterisk indicates Voyager 1 observed the moon.



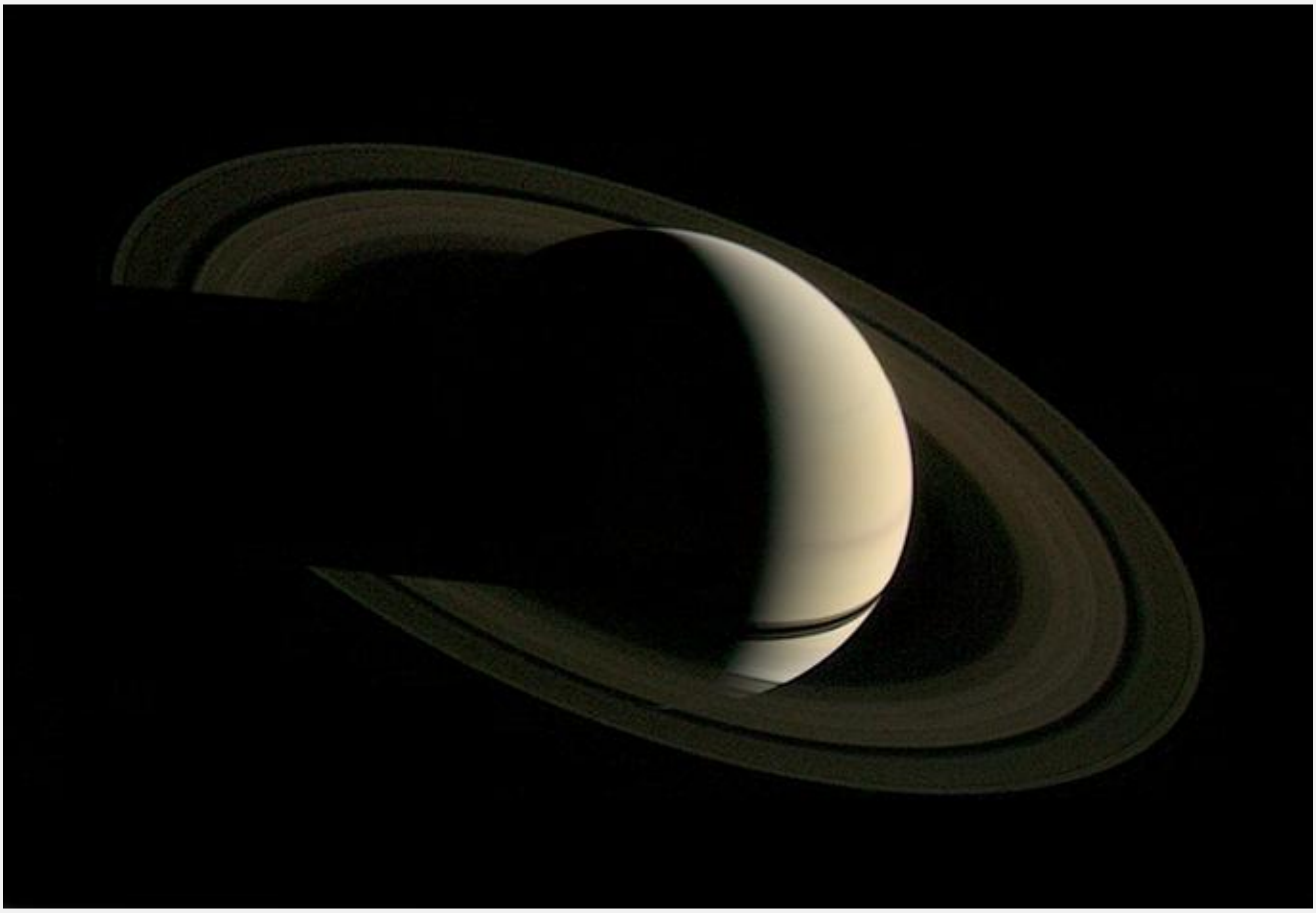
Voyager 1 made observations of the moons Janus (left), Helene (centre) and Epimetheus. Images: NASA/JPL

SUMMARY OF SATURN ENCOUNTER – 12-14 NOVEMBER 1980

Date	AEDT	Distance*	Event/Closest Approach
Nov. 12	14:42	3,800	Titan
	16:59		Saturn inbound ring plane crossing
Nov. 13	09:18	415,320	Tethys
	10:46:30	**182,142**	**Saturn**
	12:44	88,820	Mimas
	12:45		Saturn occultation
	12:52	202,251	Enceladus
	12:59		Sun occultation
	14:21		Enter Earth/Ring occultation
	14:37		Exit Earth/Ring occultation (16 minutes)
	14:40	161,131	Dione
	16:45		Outbound ring plane crossing
	17:23	73,980	Rhea
Nov. 14	03:46	879,127	Hyperion
	18:27	2,474,000	Iapetus
		One-way signal elapsed time was 1 hour 23 minutes	
		* from Saturn's centre (kilometres)	



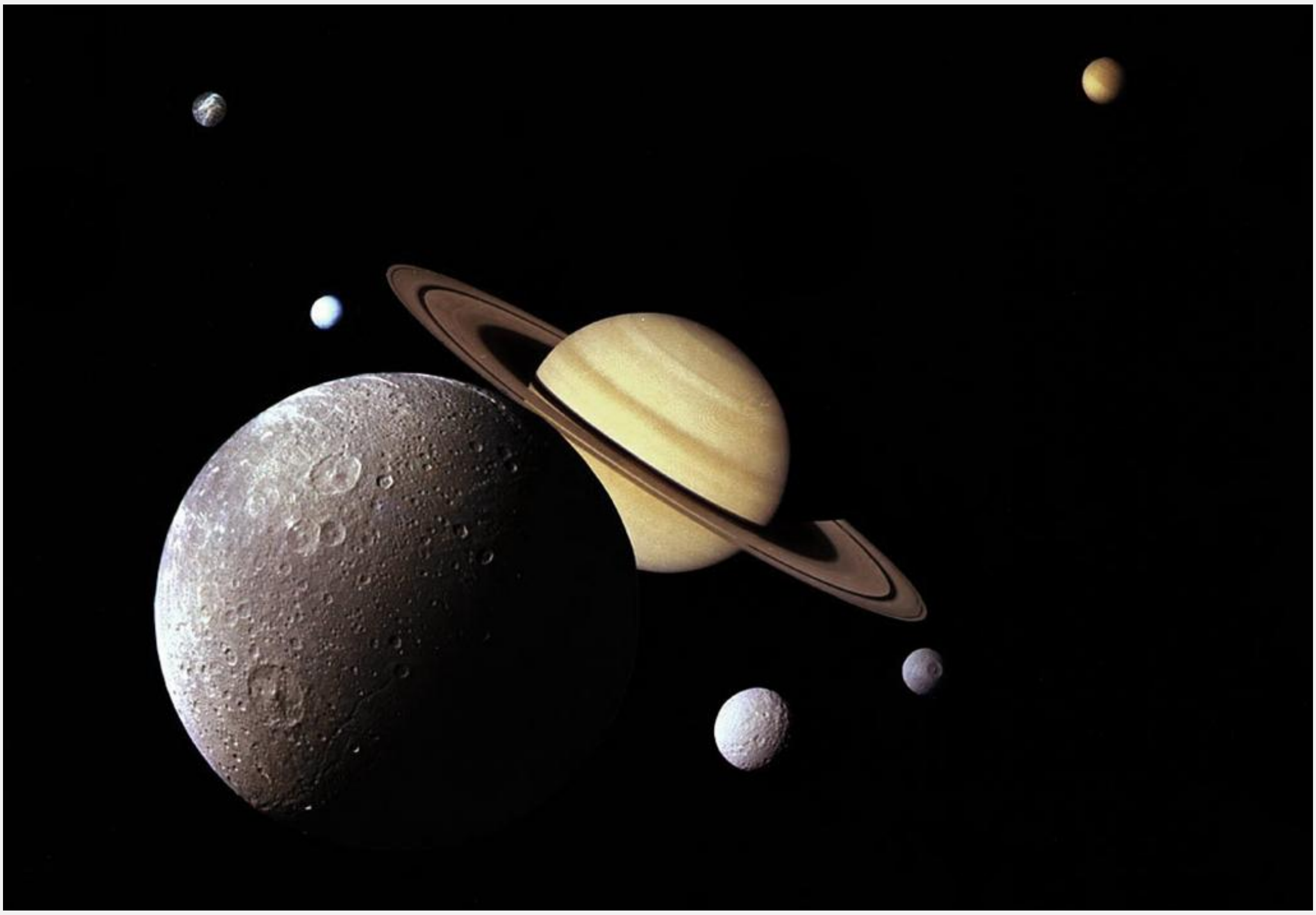
False colour view of small-scale convective cloud features and longitudinal waves in Saturn's northern hemisphere. Images: NASA/JPL

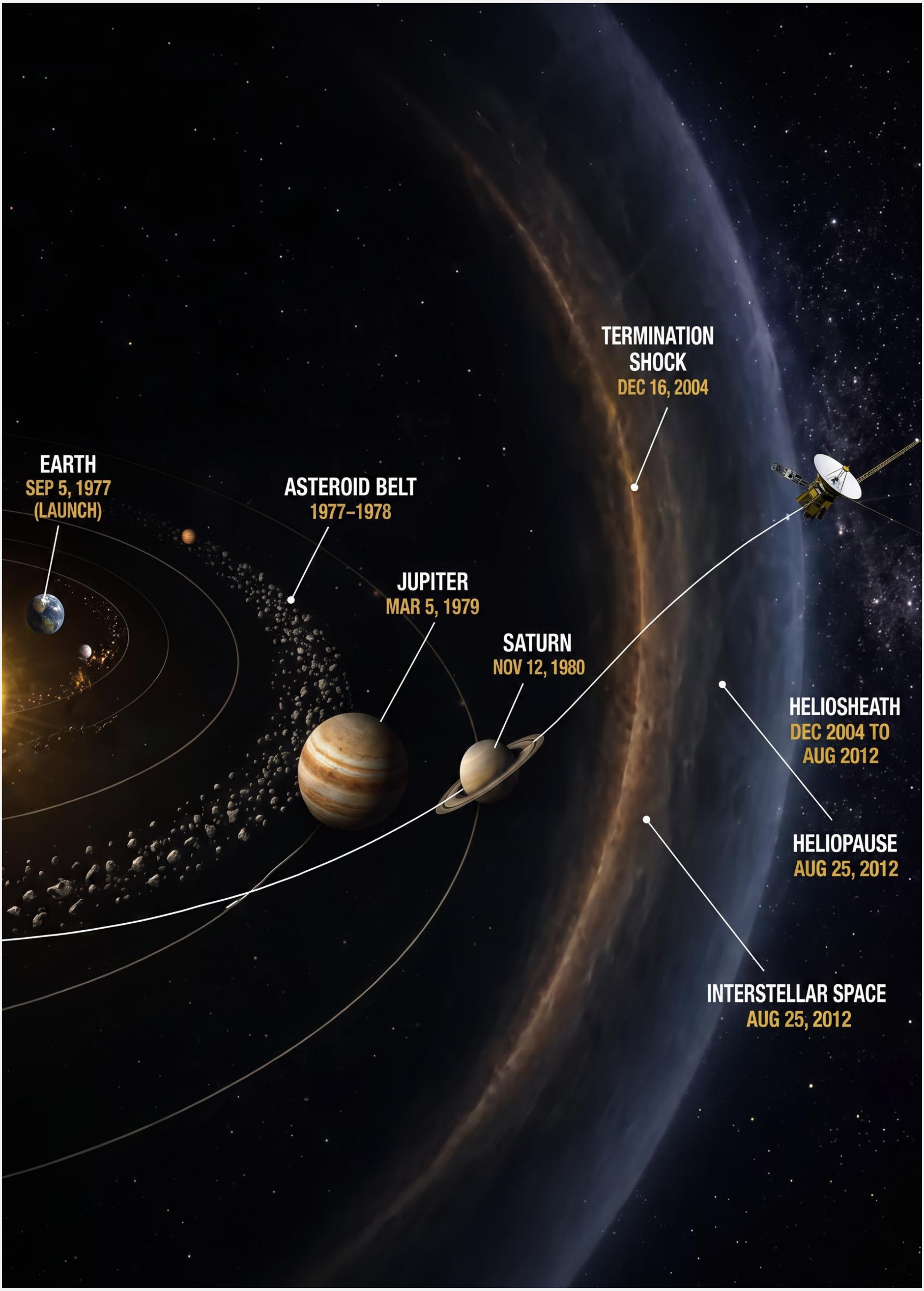


Above: Voyager 1's departure image of Saturn.

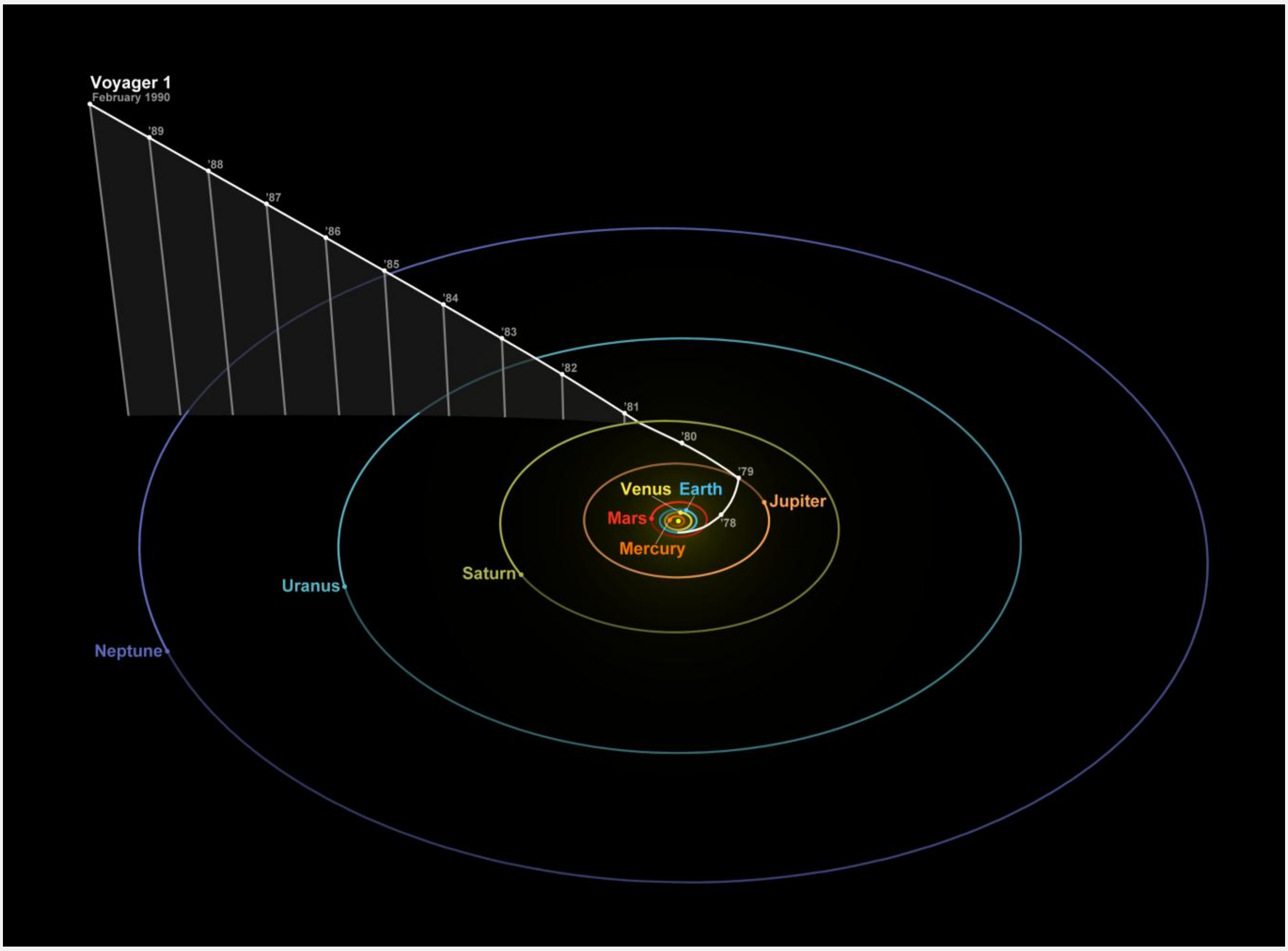
Image: NASA/JPL and processed (above) Gordan Ugarkovic

Below: A montage of Saturn and some of the moons Voyager 1 observed during the encounter.





The journey beyond Jupiter and Saturn. Graphic: NASA/JPL
Voyager 1's trajectory put the spacecraft on a path 'above' the ecliptic plain and to eventually reach the outer boundary of the planetary solar system – the heliosphere – the magnetosphere created by the Sun's outward flow of energy colliding with the interstellar wind.



Nearly 10 years after leaving Saturn behind, Voyager 1 was ready for a final photograph. Graphic: NASA/JPL

VOYAGER 1

THE INTERSTELLAR MISSION

So, Voyager 1 had successfully completed its primary task – no other planets lay in its path, and its course could not be re-directed to any other planet. It left the solar system, rising above the ecliptic plane at an angle of about 35 degrees at a rate of about 520 million kilometres a year.

Voyager 1 continued to study ultraviolet sources among the stars, and the fields and particles instruments aboard the Voyagers will continue to search for the boundary between the Sun's influence and interstellar space.

By this time 11,000 person years had been devoted to the project. The spacecraft had travelled 7.1 billion kilometres from Earth and, ignoring the launch vehicle, had a staggering fuel economy of 13,000 kilometres per litre. Between planets its speed was 81,900 kph relative to Earth, or 80,970 kilometres per hour relative to the Sun, (the heliocentric velocity).

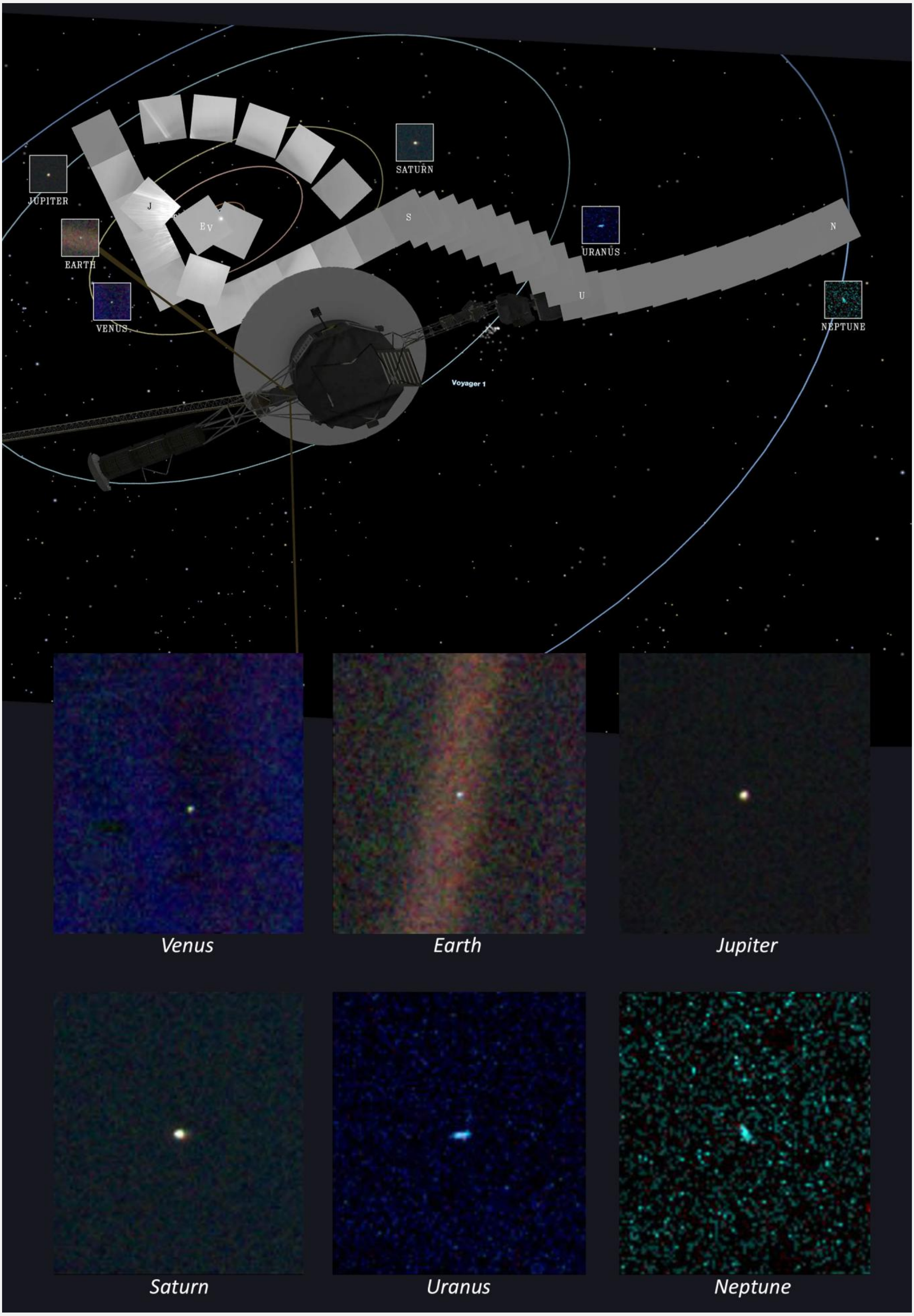
The Voyager scientists liken sending a signal to the Voyager spacecraft to throwing a tennis ball across the Pacific Ocean to enter a selected porthole of a moving cruise liner.

A PALE BLUE DOT

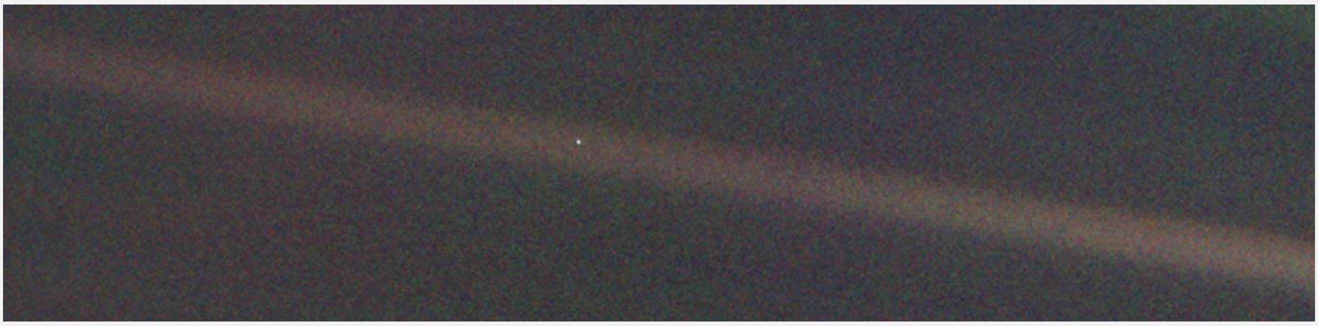
While Voyager 2 was busy shooting past Neptune, Voyager 1, by now 32º above the ecliptic 6 billion kilometres from Earth, was able to look back at a view of the whole solar system – a view never seen by Earthlings before.

On 14 February 1990 the Voyager scientists programmed the cameras to take pictures of all the planets as well as individual narrow angle frames centred on the individual planets.

The mosaic was created by starting at Neptune, working in to Uranus and Saturn, passing horizontally below and vertically to the left of the Sun, arcing above and to the right of the Sun, finally jumping to the frames containing Mars, Jupiter, Earth and Venus – a total of 60 frames; 39 wide angle and 21 telephoto.



Voyager 1's "family portrait" of the Solar System. Images: NASA/JPL
This was the last sequence of images taken on Valentine's Day 1990.



“A mote of dust suspended in a sunbeam.” – Carl Sagan

Neptune, Uranus, Saturn, Jupiter, Earth, Venus and the Sun were clearly visible in the set of images, but Mercury was masked by the Sun’s glare, while the light level in the Mars narrow angle image was so low it was very hard to identify. The images of Uranus and Neptune were smeared due to the spacecraft’s motion during the 15 second exposure. These images were recorded on board the spacecraft and relayed back to Earth in a series of playbacks in March, April and early May.

In the course of taking this mosaic consisting of a total of 60 frames, Voyager 1 made several images of the inner Solar System from a distance of 40 astronomical units (1 AU = 150 million km) and about 32 degrees above the ecliptic plane. 39 wide-angle frames link together six of the planets of our Solar System in this mosaic.
Our Sun is seen as the bright object in the center of the circle of frames. Outermost Neptune is 30 times further from the Sun than Earth.

The wide-angle image of the Sun was taken with the camera’s darkest filter and the shortest possible exposure to avoid saturating the camera’s vidicon tube with scattered sunlight.

The Sun is not large as seen from Voyager 1, only about 1/14 of the diameter as seen from our planet, but is still almost 8 million times brighter than the brightest star in Earth’s sky, Sirius.

The result of this great brightness is an image with multiple reflections from the optics in the camera. Wide-angle images surrounding the Sun also show many artifacts attributable to scattered light in the optics. These were taken through the clear filter with one second exposures.

Narrow-angle images of Earth, Venus, Jupiter, Saturn, Uranus and Neptune were acquired as the spacecraft built the wide-angle mosaic.

Jupiter is larger than a narrow-angle pixel and is clearly resolved, as is Saturn with its rings. Uranus and Neptune appear larger than they really are because of image smear due to spacecraft motion during the long exposures.

From Voyager’s great distance Earth and Venus are mere points of light, less than the size of a picture element even in the narrow angle camera.

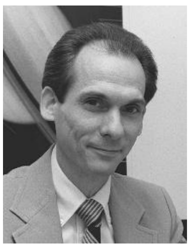
Earth was a crescent only 0.12 pixel in size.

Coincidentally, Earth lies right in the center of one of the scattered light rays resulting from taking the image so close to the Sun.

A few key members did not make it in: Mars had little sunlight, Mercury was too close to the Sun, and dwarf planet Pluto turned out too dim.

Taking these images was not part of the original plan, but the late Carl Sagan, a member of the Voyager imaging team at the time, had the idea of pointing the spacecraft back toward its home for a last look.

The title of his 1994 book Pale Blue Dot he refers to the image of Earth in this series.



“25 years ago, Voyager 1 looked back toward Earth and saw a pale blue dot, an image that continues to inspire wonderment about the spot we call home,” said Dr Ed Stone from the California Institute of Technology in Pasadena, who is a project scientist for the Voyager mission.

These images are the last that Voyager 1, which launched in 1977, returned to Earth.

NASA scientists subsequently turned the camera off so that the computer controlling it could be repurposed.

Voyager 1 ventures into the interstellar darkness. Graphic: NASA/JPL

THE INTERSTELLAR MISSION BEGINS

As this essay is written, Voyager 1 is still operating, but no longer has the capability to take pictures.

> *"After taking these images in 1990, we began our interstellar mission. We had no idea how long the spacecraft would last,"* Dr Stone said.

Today, Voyager 1, at a distance of 130 astronomical units, is the farthest human-made object from Earth, and it still regularly communicates with our planet.

In August 2012, the spacecraft entered interstellar space – the space between the stars – and has been delivering data about this uncharted territory ever since.

Its twin, Voyager 2, also launched in 1977, is also journeying toward interstellar space.

These pictures were the last of roughly 67,000 images taken by both Voyagers over the previous 12½ years.

In July 2003 these four spacecraft were pushing their way out into our Milky Way Galaxy, beyond the orbit of Pluto. Voyager 1 was the farthest from Earth, travelling at a speed of 62,763 kilometres per hour relative to the Sun, and leaving us at 3.5 AU's per year. It was over 13.122 billion kilometres from the Earth, and the signals from the Earth-based tracking stations took 24 hours 39 minutes to get to the spacecraft and back at the speed of light. Voyager 2 was 10.474 billion kilometres away from us, travelling at 3.1 AU's per year and it took 19 hours 24 minutes for the signal to get there and back.

Voyager scientists predict that it is possible we may first lose the signals from the spacecraft when the Sun's light will become so feeble the Sun sensor will not be able to lock on to it, and the spacecraft will begin to tumble, sweeping its transmitted signal all over the cosmos. No tracking station would be able to find the signal.

If the sun sensor can manage to keep locked on the Sun, the knock out failure is expected to be the thermal power generators will cool down for lack of Plutonium fuel in 2020 and drop below the minimum working power of 230 watts; the spacecraft electronics would freeze, and the transmitted signal will disappear. That's when the spacecraft would really shut down.

Finally, around 2023 the hydrazine attitude propellant to keep the spacecraft's antenna pointing at Earth will run out, and the spacecraft will tumble out of control in drift mode for the rest of galactic time.

NASA's Associate Administrator for Space Science in Washington, Dr Thomas Mutch, made the following statement just after Voyager 2 had passed Jupiter,

"What we have been witnessing is a truly revolutionary journey of exploration. We have gone beyond the familiar part of the solar system to objects that are so exotic that their very existence, at least as far as I am concerned, was something I'd accepted intellectually, but didn't really accept in an immediate sense.

We're starting out in our own space program on a new stage of space exploration – on our own long journeys beyond the solar system to distant lands.

We never like to think, or rather, it's statistically unlikely, that we are at a turning point in history. But if you look back at history books, such events are clearly read into the record.

And I submit to you that when the history books are written a hundred years from now, two hundred years from now, the historians are going to cite this particular period of exploration as a turning point in our cultural, our scientific, and intellectual development."

- With Voyager, we have accomplished something few had ever imagined possible: the exploration of the four largest planets in our solar system.
- For our generation, the Voyager mission data transformed Jupiter, Saturn, Uranus, and Neptune from astronomical oddities into familiar neighbours, each with its own distinct characteristics. In 12 years these two spacecraft rewrote the books on the giant planets.
- Voyager discovered three of the eight known regular satellites (moons in near-equatorial, prograde, nearly circular orbits) of Jupiter, four of the eighteen known regular satellites of Saturn, ten of the fifteen known regular satellites of Uranus, and six of the eight known satellites of Neptune, as well as divulged the amazingly complex geologies of the satellites we already knew.
- Voyager found rings around Jupiter and revealed the startling complexity of Saturn's fabled rings. The ring systems of Uranus and Neptune are barely detectable from Earth, but Voyager revealed details that showed us the distinct characteristics possessed by each system.
- Voyager gave us our first detailed look at the magnetic fields and charged particle environments of the giant planets, following up on the first glimpses of Jupiter's by Pioneers 10 and 11 in 1973 and 1974 and of Saturn's by Pioneer 11 in 1979.
- Voyager data forced us to revise our earlier, simpler notions of the processes that formed and altered the solar system, giving birth to the science of comparative planetology.
- Voyagers 1 and 2 continue to operate, now at the greatest distances ever achieved by human-made objects, and may soon reach the outer limits of the Sun's magnetic influence, becoming the first spacecraft to enter the interstellar environment.

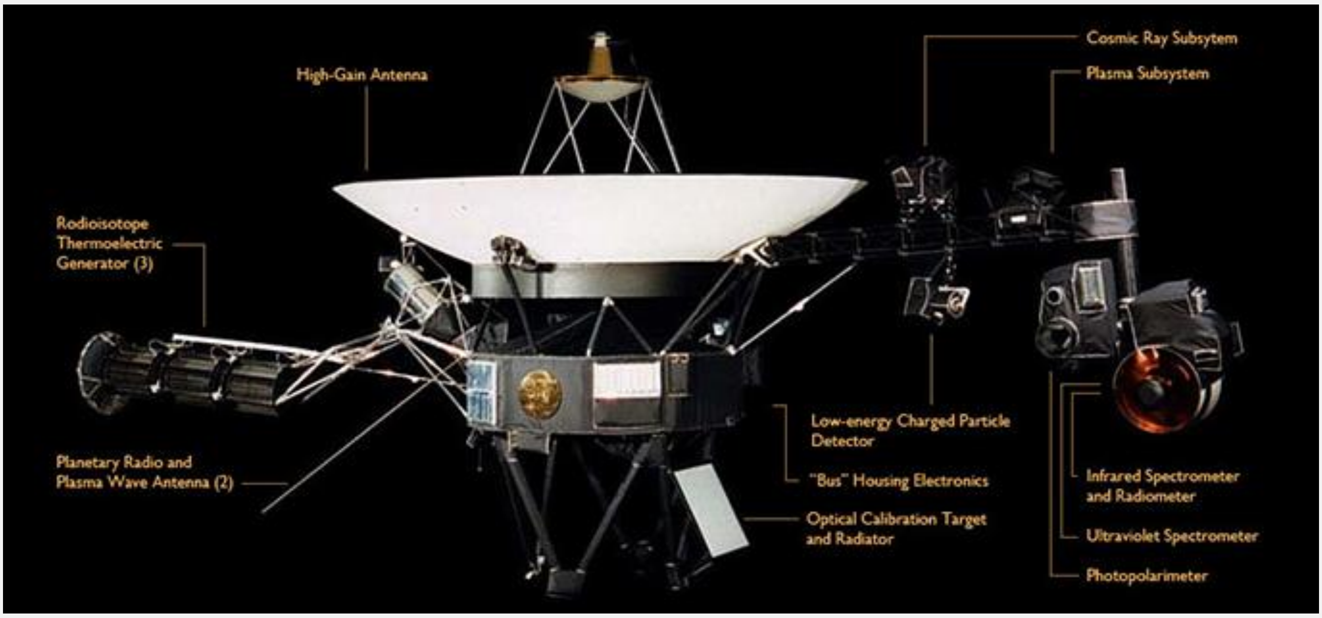
As I write this, we say farewell to our four little spacecraft as they approach the heliopause and leave the solar system to enter the vast, unimaginable distances of the intragalactic void, travelling on excruciating lonely journeys - four specks from Earth. As they don't have the velocity to escape the galaxy, all four will wander around the vast, empty spiral arms of the Milky Way, leaving our sun and its planets to become just another dim star in the heavens.

One wonders if they are the only spacecraft travelling in our galaxy – or any galaxy?

Pioneer 10 is going back along the tail of the solar system's heliosphere heading for Taurus, which it should reach in 2 million years, while Pioneer 11 is going out ahead of us towards the Constellation of Aquila, which it should reach in 4 million years.

Voyager 1 is climbing above the ecliptic at an angle of 35° and a speed of 60,000 kilometres per hour relative to the Earth heading for the Constellation Ophiuchus which it should reach in the year 40,272 AD, while Voyager 2 is plummeting down at an angle of 47°, travelling at a speed of 58,000 kilometres per hour from Earth, heading for Sagittarius and Pavo.

In about 40,000 years it will pass within 1.7 light years of the small star of Ross 248 in the Constellation of Andromeda.



REPAIRS OUT IN SPACE

In March 2002 the Voyager engineering team led by flight engineer Tim Hogle executed some repairs to the Voyager 1 spacecraft.

> *"The original attitude-control system showed slowly increasing signs of trouble in the past two years,"* said Hogle.

Diagnostics pointed to an electronic component that takes analogue signals from position-sensing devices and converts them into digital values for an onboard computer. Because of the system's design, switching to that component's backup also meant activating the backup Sun sensor and star tracker, which provide the reference points for the spacecraft's orientation in space.

> *"We had to plan this switch very carefully,"* Hogle said. *"This backup equipment hadn't been tested since Voyager 1 was approaching Saturn in 1980. If it didn't work right, switching to it could confuse the onboard computer about the spacecraft's orientation, which could lead to faulty pointing of the antenna and loss of communications with Earth."*

Among other precautions, the team programmed a temporary changeover with an automatic reversion to the original system, allowing just enough time to evaluate the backup. The planning effort identified potential trouble points in advance and made provisions to be able to correct them, if necessary, before the final changeover, nine days after the temporary one. The cautious approach paid off.

The system made an unexpected lock onto the Sun during the temporary switch, so the spacecraft was instructed to keep itself steady with gyroscopes during the final switch. The spacecraft had been carrying those components and other spare parts since it was launched in 1977 on what was then slated as a four-year mission.

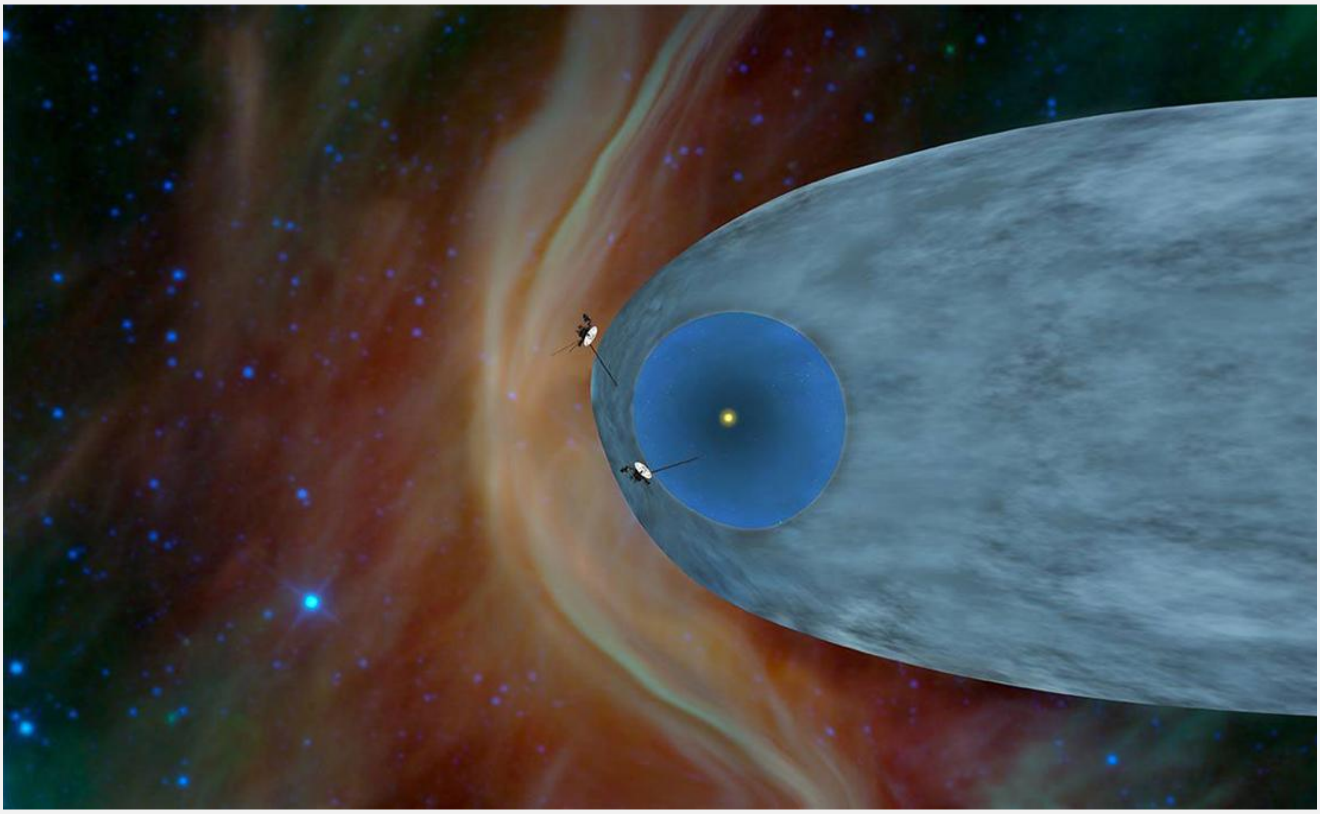
> *"After sitting on the shelf for 25 years, it's like using new equipment,"* said Ed Massey, Voyager project manager.

Calibration of the backup system was completed 1 April 2002.

The original designers' foresight in building backup systems into the Voyagers helps, but making changeovers aboard a spacecraft more than 12.5 billion kilometres away presents enormous challenges. Anything that could go wrong needs to be anticipated, because reaction time is unforgivingly slow.

In 2007 the signals from the tracking stations had a round trip light time of 28 hours for Voyager 1 and 24 hours for Voyager 2 while the signal strengths received at the tracking stations of both spacecraft were down to –159 dbm at the 70 metre dishes, and –162 dbm at the 34 metre dishes. The spacecraft were covering 1.6 million kilometres per day on their way out of the solar system.

The task of supervising the two Voyager missions now fell to a flight team of just 14 people. Miniscule compared with a team of more than 300 in the 1980s.



The Voyager spacecraft have both crossed into interstellar space, beyond our solar system. Graphic: NASA/JPL

VOYAGER 1

THE OUTER EDGE OF OUR SOLAR SYSTEM

Solar System Termination Shock:
Blowing outward billions of kilometres from the Sun is the solar wind, a thin stream of electrically charged gas.

This wind travels at an average speed ranging from 300 to 700 kilometres per second (700,000 - 1,500,000 miles per hour) until it reaches the termination shock.

At this point, the speed of the solar wind drops abruptly as it begins to feel the effects of interstellar wind.

Heliosphere:
The solar wind, emanating from the Sun, creates a bubble that extends far past the orbits of the planets. This bubble is the heliosphere, shaped like a long wind sock as it moves with the Sun through interstellar space.

Heliosheath:
The heliosheath is the outer region of the heliosphere. Voyager entered the heliosheath about 14 billion kilometres from the Sun.

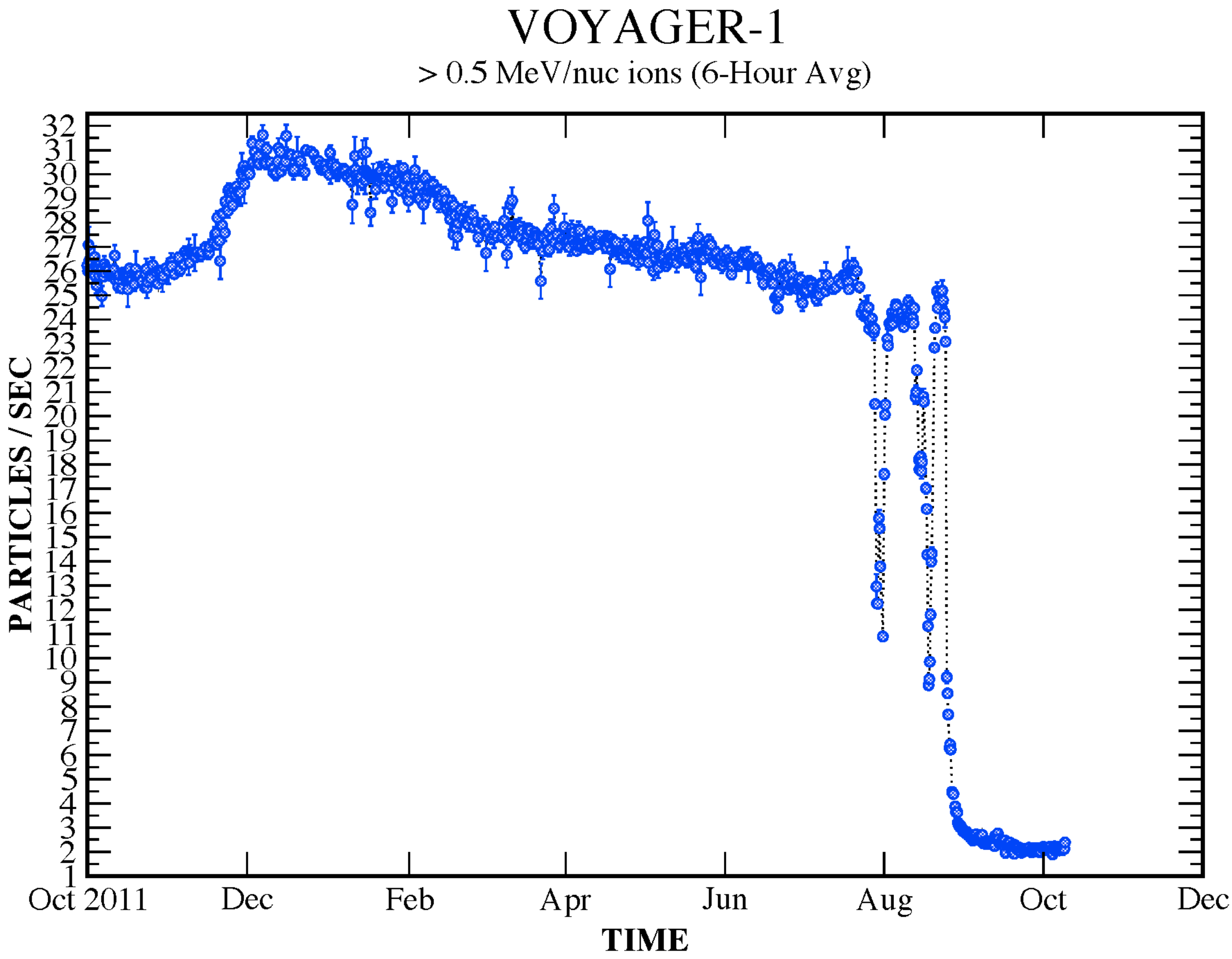
This is about 94 times the distance from the Sun to Earth.

The heliosheath is just beyond the termination shock, the point where the solar wind slows abruptly, becoming denser and hotter. The solar wind piles up as it presses outward against the approaching wind in interstellar space.

Heliopause:
The boundary between solar wind and interstellar wind is the heliopause, where the pressure of the two winds are in balance. This balance in pressure causes the solar wind to turn back and flow down the tail of the heliosphere. Once Voyager passes the heliopause, it will be in interstellar space.

Bow shock:
As the heliosphere ploughs through interstellar space, a bow shock forms, much as forms in front of a boulder in a stream of water.

Currently Voyager 1 is the fastest interstellar spacecraft, leaving our solar system at a rate of 62,100 kilometres per hour. It has already passed the termination shock at a distance of 14,062,199,845 kilometres and entered the heliosheath in December 2004, and is expected to reach the heliopause in 2012, where the 1,600,000 kilometre per hour solar wind abruptly slows and becomes denser and hotter as it presses against interstellar gas.



The drop in the solar wind showed that Voyager 1 had crossed the interstellar boundary. Graphic: NASA/JPL

It was expected the wind beyond the shock would slow to a few hundred thousand kilometres per hour. But the Voyager scientists were surprised to find that the speed was much less, and at times the wind appeared to be flowing back inward toward the sun.

"This could mean that the outward pressure of wind was decreasing as the sun entered the less active phase of its 11-year cycle of sunspot activity," said project scientist Ed Stone.

Another surprise: the direction of the interplanetary magnetic field in the outer solar system varied more slowly beyond the termination shock.

As the sun rotates every 26 days, the direction of the field alternates every 13 days. That field is carried out by the solar wind, with the alternating directions forming a pattern of zebra stripes moving outward past the spacecraft.

One could imagine a zebra with giant *"magnetic stripes"* running past the spacecraft and Voyager 1 *"observing"* an alternating stripe every 13 days. After the shock, the *"zebra"* with its stripe pattern was moving at nearly the same speed as Voyager, so that it took more than 100 days for the stripe to pass the spacecraft and for the magnetic field to switch directions.

Perhaps the most puzzling surprise is what Voyager 1 did not find at the shock. It had been predicted that interstellar ions would bounce back and forth across the shock, slowly gaining energy with each bounce to become high speed cosmic rays. Because of this, scientists expected those cosmic ray ions would become most intense at the shock.

However, the intensity did not reach a maximum at the shock, but has been steadily increasing as Voyager 1 has been moving farther beyond the shock boundary.

This means that the source of those cosmic rays is in a region of the outer solar system yet to be discovered.

Both spacecraft have adequate electrical power and attitude control propellant to continue operating until around 2020, when the available electrical power will no longer support science instrument operation. If there is some way to keep all the spacecraft systems going, the signal from Voyager 2's 10 watt transmitter would be expected to fade out completely around 2160.

At that point Voyager will be 92,774,940,000 kilometres from Earth. To grasp the size of that number, it would take you 131,440 years to travel to it at 80 kilometres per hour in a car!!

On Earth we will still be on our first trip around the galaxy, still only 2% of the first time around!! After we lose their signals, the Pioneer and Voyagers' journeys will then go on forever, possibly still travelling somewhere in the galaxy when our sun has long burned itself out, and the human race has either moved elsewhere, or become extinct. In August 2006 they were 15 billion kilometres (9.3 billion statute miles) from the sun and still on the job 24/7 12 months of the year.

If you are wondering where they are now, the diagram below shows you where to look:

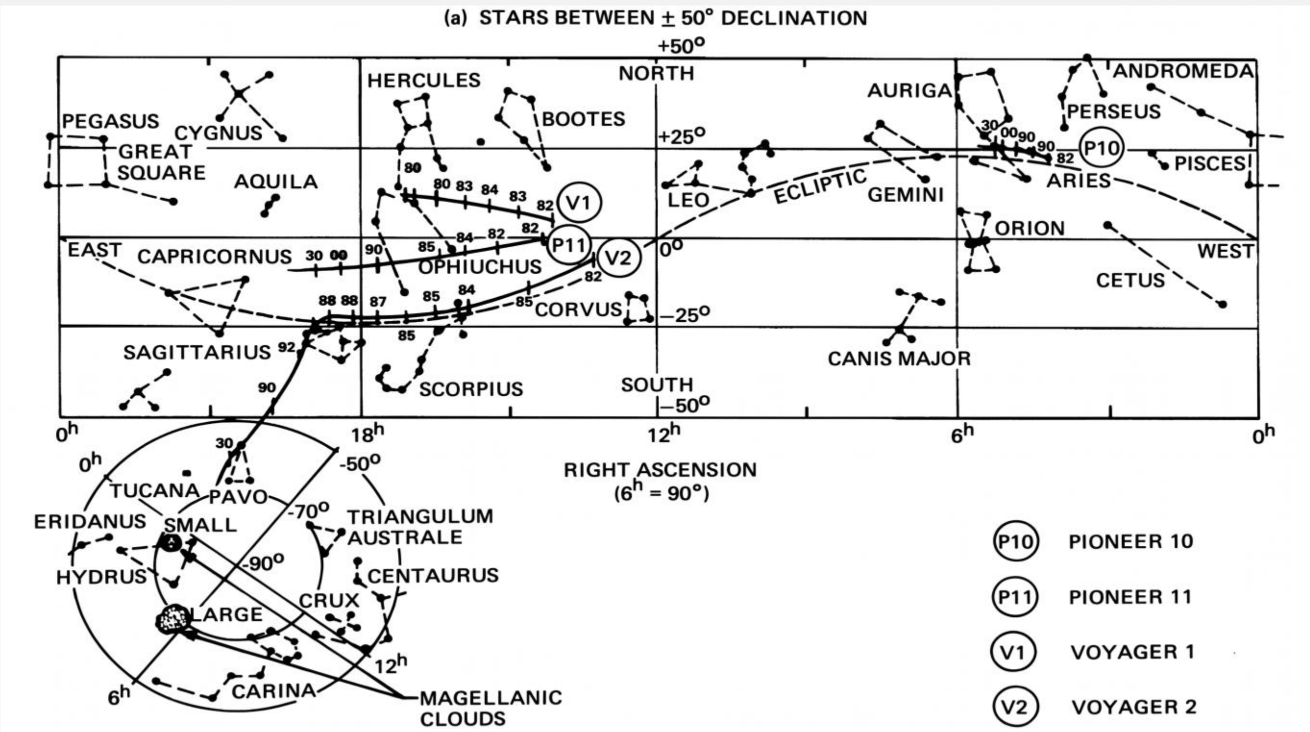
In December 2012 the Voyagers entered a new region of the outer reaches of our solar system, expected to be the final area the spacecraft will have to cross before reaching interstellar space.

The Voyager scientists think this region is still inside the solar bubble because the direction of the magnetic field lines has not changed. Their direction is predicted to change when the Voyagers break through into interstellar space.

> *"Although Voyager 1 is still is inside the sun's environment, we now can taste what it's like on the outside because the particles are zipping in and out on this magnetic highway,"* said Edward Stone, Voyager project scientist based at the California Institute of Technology, in Pasadena. *"We believe this is the last leg of our journey to interstellar space. The new region isn't what we expected, but we've come to expect the unexpected from Voyager."*

Voyager data from two onboard instruments that measure charged particles showed the spacecraft first entered this magnetic highway region on 28 July 2012.

The region ebbed away and flowed toward Voyager 1 several times. The spacecraft entered the region again in 25 August and the environment has been stable since.



The approximate positions of the Pioneer and Voyager spacecraft. Graphic: NASA/JPL

"If we were judging by the charged particle data alone, I would have thought we were outside the heliosphere," said Stamatios Krimigis, principal investigator of the low-energy charged particle instrument, based at the Johns Hopkins Applied Physics Laboratory, Laurel, Maryland. "But we need to look at what all the instruments are telling us and only time will tell whether our interpretations about this frontier are correct."

Spacecraft data revealed the magnetic field became stronger each time Voyager entered the highway region; however, the direction of the magnetic field lines did not change.

"We are in a magnetic region unlike any we've been in before - about 10 times more intense than before the termination shock - but the magnetic field data show no indication we're in interstellar space," said Leonard Burlaga, a Voyager magnetometer team member based at NASA's Goddard Space Flight Center in Greenbelt, Md. *"The magnetic field data turned out to be the key to pinpointing when we crossed the termination shock. And we expect these data will tell us when we first reach interstellar space."*

Basically, the team needed more data on plasma, which is ionized gas, the densest and slowest moving of charged particles in space. Plasma is the most important marker that distinguishes whether Voyager 1 is inside the solar bubble, known as the heliosphere, which is inflated by plasma that streams outward from our sun, or in interstellar space and surrounded by material ejected by the explosion of nearby giant stars millions of years ago.

Adding to the challenge: they didn't know how they'd be able to detect it.

On 12 September 2013, NASA finally agreed that Voyager 1 was outside the Sun's heliosphere. Ed Stone, Project Scientist, announced,

"We have been cautious because we're dealing with one of the most important milestones in the history of exploration – only now do we have the data – and the analysis – we needed. We looked for signs predicted by the models that use the best available data, but until now we had no measurements of the plasma from Voyager 1."

Voyager 1's plasma instrument, which measures the density, temperature and speed of plasma, stopped working in 1980, right after its last planetary flyby. When Voyager 1 detected the pressure of interstellar space on our heliosphere in 2004, the science team didn't have the instrument that would provide the most direct measurements of plasma. Instead, they focused on the direction of the magnetic field as a proxy for source of the plasma.

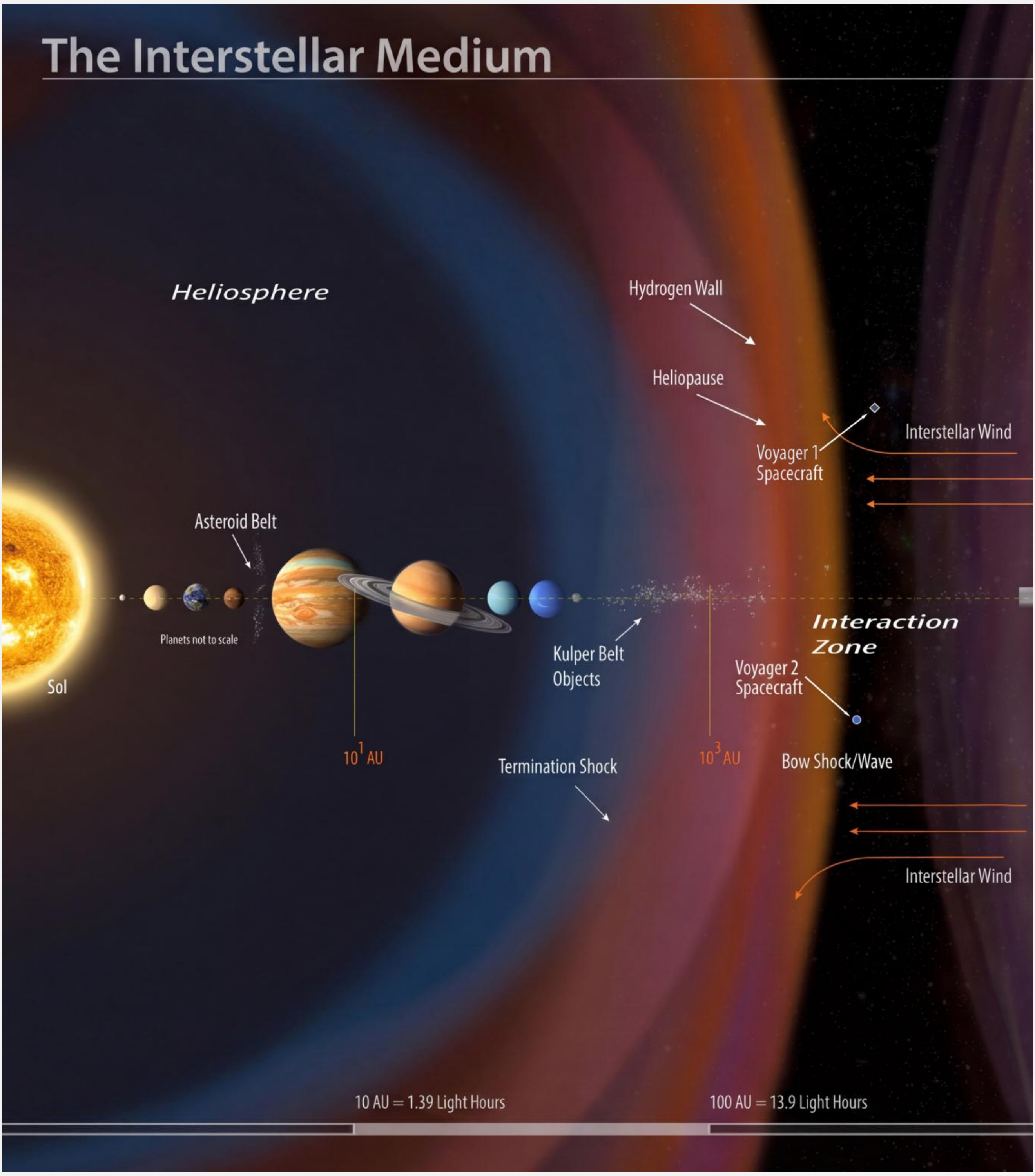
Since solar plasma carries the magnetic field lines emanating from the sun and interstellar plasma carries interstellar magnetic field lines, the directions of the solar and interstellar magnetic fields were expected to differ.

Most models told the Voyager science team to expect an abrupt change in the magnetic field direction as Voyager switched from the solar magnetic field lines inside our solar bubble to those in interstellar space. The models also said to expect the levels of charged particles originating from inside the heliosphere to drop and the levels of galactic cosmic rays, which originate outside the heliosphere, to jump.

In May 2012, the number of galactic cosmic rays made its first significant jump, while some of the inside particles made their first significant dip. The pace of change quickened dramatically on 28 July 2012. After five days, the intensities returned to what they had been. This was the first taste of a new region, and at the time Voyager scientists thought the spacecraft might have briefly touched the edge of interstellar space.

By 25 August, when Voyager 1 entered this new region for good, all the lower-energy particles from inside zipped away. Some inside particles dropped by more than a factor of 1,000 compared to 2004. The levels of galactic cosmic rays jumped to the highest of the entire mission. These would be the expected changes if Voyager 1 had crossed the heliopause, which is the boundary between the heliosphere and interstellar space.

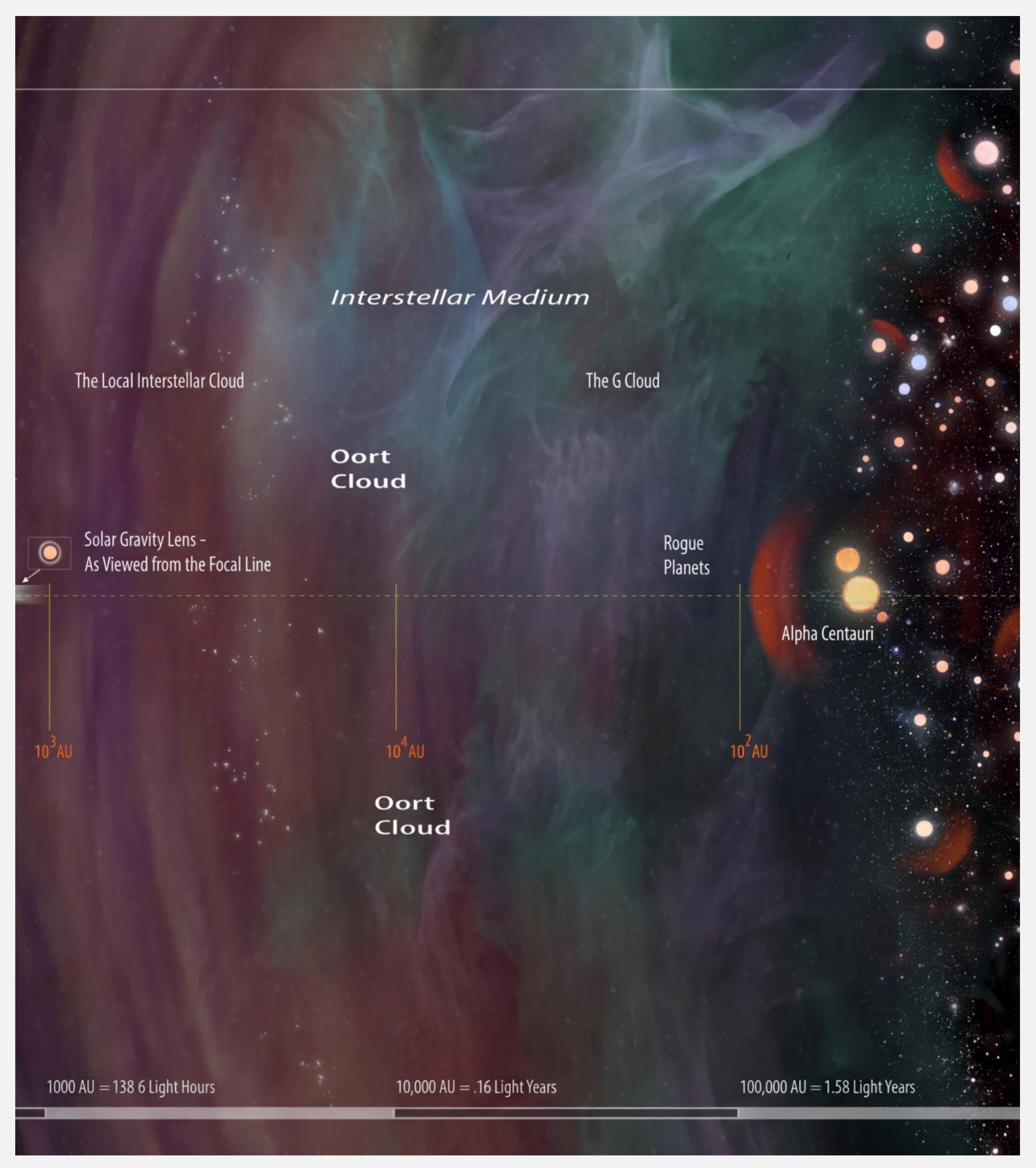
However, subsequent analysis of the magnetic field data revealed that even though the magnetic field strength jumped by 60 percent at the boundary, the direction changed less than two degrees.



This suggested that Voyager 1 had not left the solar magnetic field and had only entered a new region, still inside our solar bubble, which had been depleted of inside particles.

Then, in April 2013, scientists got another piece of the puzzle by chance. For the first eight years of exploring the heliosheath, which is the outer layer of the heliosphere, Voyager's plasma wave instrument had heard nothing. But the plasma wave science team, led by Don Gurnett and Bill Kurth at the University of Iowa, Iowa City, had observed bursts of radio waves in 1983 to 1984 and again in 1992 to 1993. They deduced these bursts were produced by the interstellar plasma when a large outburst of solar material would plow into it and cause it to oscillate.

It took about 400 days for such solar outbursts to reach interstellar space, leading to an estimated distance of 117 to 177 AU (117 to 177 times the distance from the sun to the Earth) to the heliopause. They knew, though, that they would be able to observe plasma oscillations



directly once Voyager 1 was surrounded by interstellar plasma.

Then on 9 April 2013, it happened: Voyager 1's plasma wave instrument picked up local plasma oscillations. Scientists think they probably stemmed from a burst of solar activity from a year before, a burst that has become known as the St. Patrick's Day Solar Storms.

The oscillations increased in pitch through 22 May and indicated that Voyager was moving into an increasingly dense region of plasma.

This plasma had the signatures of interstellar plasma, with a density more than 40 times that observed by Voyager 2 in the heliosheath.

Gurnett and Kurth began going through the recent data and found a fainter, lower-frequency set of oscillations from 23 October to 27 November 2012.

When they extrapolated back, they deduced that Voyager had first encountered this dense interstellar plasma in August 2012, consistent with the sharp boundaries in the charged particle and magnetic field data on August 25.

Stone called three meetings of the Voyager team. They had to decide how to define the boundary between our solar bubble and interstellar space and how to interpret all the data Voyager 1 had been sending back. There was general agreement Voyager 1 was seeing interstellar plasma, based on the results from Gurnett and Kurth, but the sun still had influence. One persisting sign of solar influence, for example, was the detection of outside particles hitting Voyager from some directions more than others. In interstellar space, these particles would be expected to hit Voyager uniformly from all directions.

> *"Now that we had actual measurements of the plasma environment - by way of an unexpected outburst from the sun - we had to reconsider why there was still solar influence on the magnetic field and plasma in interstellar space,"* Stone said. *"The path to interstellar space has been a lot more complicated than we imagined."*

Stone discussed with the Voyager science group whether they thought Voyager 1 had crossed the heliopause. What should they call the region were Voyager 1 is?

> *"In the end, there was general agreement that Voyager 1 was indeed outside in interstellar space,"* Stone said. *"But that location comes with some disclaimers - we're in a mixed, transitional region of interstellar space. We don't know when we'll reach interstellar space free from the influence of our solar bubble."*

So, would the team say Voyager 1 has left the solar system? Not exactly - and that's part of the confusion. Since the 1960s, most scientists have defined our solar system as going out to the Oort Cloud, where the comets that swing by our sun on long timescales originate. That area is where the gravity of other stars begins to dominate that of the sun.

It will take about 300 years for Voyager 1 to reach the inner edge of the Oort Cloud and possibly about 30,000 years to fly beyond it.

Informally, of course, *"solar system"* typically means the planetary neighbourhood around our sun. Because of this ambiguity, the Voyager team has lately favoured talking about interstellar space, which is specifically the space between each star's realm of plasma influence.

> *"What we can say is Voyager 1 is bathed in matter from other stars,"* Stone said. *"What we can't say is what exact discoveries await Voyager's continued journey. No one was able to predict all of the details that Voyager 1 has seen. So, we expect more surprises."*

Voyager 1, which is working with a finite power supply, has enough electrical power to keep operating the fields and particles science instruments through at least 2020, which will mark 43 years of continual operation. At that point, mission managers will have to start turning off these instruments one by one to conserve power, with the last one turning off around 2025.

Voyager 1 will continue sending engineering data for a few more years after the last science instrument is turned off, but after that it will be sailing on as a silent ambassador.

In about 40,000 years, it will be closer to the star AC +79 3888 than our own sun. (AC +79 3888 is travelling toward us faster than we are travelling towards it, so while Alpha Centauri is the next closest star now, it won't be in 40,000 years.)

And for the rest of time, Voyager 1 will continue orbiting around the heart of the Milky Way galaxy, with our sun but a tiny point of light among many, until even that winks out when our Sun burns itself out.

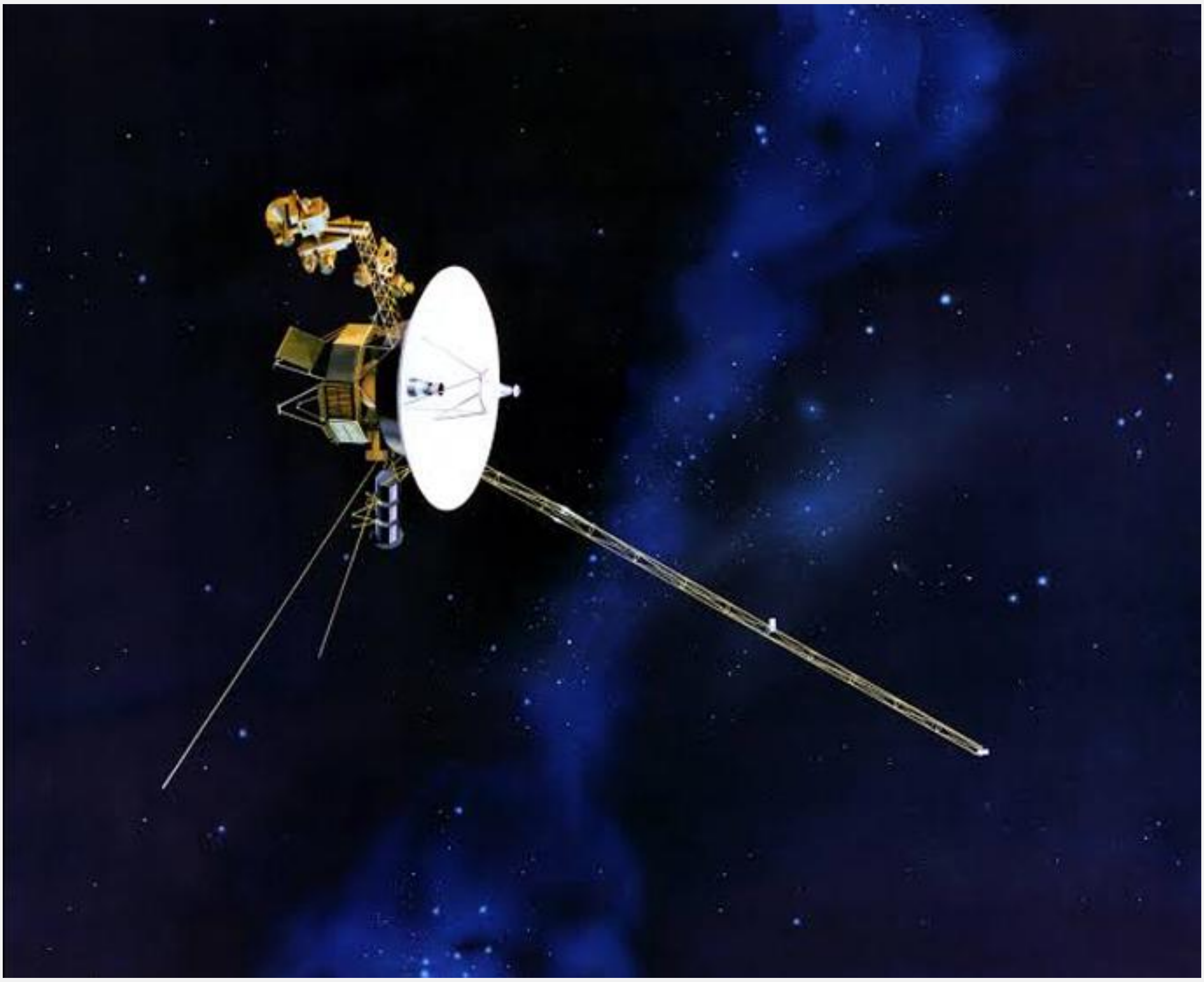
As this was written there were five science investigation teams participating in the Interstellar Mission. They were:

1. Magnetic field investigation
2. Low energy charged particle investigation
3. Cosmic ray investigation
4. Plasma Investigation (Voyager 2 only)
5. Plasma wave investigation

Five instruments onboard the Voyagers directly supported the five science investigations. The five instruments were:

1. Magnetic field instrument (MAG)
2. Low energy charged particle instrument (LECP)
3. Cosmic ray instrument (CRS)
4. Plasma instrument (PLS)
5. Plasma wave instrument (PWS)

Editor's note: *See the current list of active instruments in the Mission Facts list on page 4.*



It takes 245 million years for our Solar System to travel around the Galaxy once. Looking back to that time the Earth was in the Permian era, with all today's continents still clumped together in the supercontinent called Pangaea – long before the dinosaurs appeared. All these changes to the planet to bring it to where we are today have happened in one revolution of the galaxy!!

Humanity, even before the cave dwellers, has been around for two to three million years at the very most. So, we have hardly begun our first orbit of the Galaxy. Even the Dinosaurs only made it a quarter of the way around.

In that short space of time, we have left the planet Earth - surely a remarkable achievement.

Will there ever be such a gigantic leap forward in so short a time by any form of life in the evolution of the Earth?

This is our new playground, and our Pioneer and Voyager spacecraft have begun to play in it.

Images, illustration and captions by Glen Nagle.
Some content from the honeysucklecreek.net created and developed by Colin Mackellar.
Unless specified, illustrations and captions by Hamish Lindsay, Colin Mackellar, and Glen Nagle.
Thanks to: Bruce Murray Space Image Archive.
Some images in this booklet have been digitally cleaned using AI tools and Photoshop, with great care taken to not change important details.
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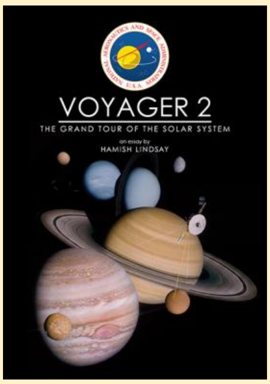

Hamish Lindsay's essay
Voyager 2 –
The Grand Tour of the Solar System
is available at the honeysucklecreek.net website. Click the image (left) to access.

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Hamish Lindsay (1937-2022) worked at the Muchea, Carnarvon and Honeysuckle Creek space tracking stations between 1963 and 1981.

He wrote many essays on the history of human spaceflight and was the author of the book, Tracking Apollo to the Moon.