VOYAGER 2

THE GRAND TOUR OF THE SOLAR SYSTEM

an essay by

HAMISH LINDSAY





"All I can say is…..Wow!
What a way to leave the solar system!"

Laurence Soderblom, Voyager Imaging Science Lead

VOYAGER 2

THE GRAND TOUR OF THE SOLAR SYSTEM

an essay by
HAMISH LINDSAY



Jupiter
page 27



Saturn
page 42



Uranus
page 71



Neptune
page 96

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 artwork.

Mission Facts

Voyager 2
Launch date/time: 20 August 1977 / 14:29:45 UTC
Launch site: Launch Complex 41, Cape Canaveral
Launch vehicle: Titan IIIE / Centaur D-1T / Star-37E

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

Mission duration
Planetary mission: 12 years, 1 months, 12 days
Interstellar mission: 49+ years (ongoing)
Insufficient power for any instrument: 2030
Out of range of DSN: 2036 (estimated)

Planetary Encounters

Jupiter: Closest approach: 9 July 1979
Distance: 570,000 kilometres

Saturn: Closest approach: 26 August 1981
Distance: 101,000 kilometres

Uranus: Closest approach: 24 January 1986
Distance: 81,500 kilometres

Neptune: Closest approach: 25 August 1989
Distance: 4,951 kilometres

Instruments and Systems
Active and disabled systems as of September 2026

Name	Active	Disabled
Imaging Science System		5 Dec ‘89
Radio Science System	✓	#
Infrared interferometer spectrometer radiometer		1 Feb ‘07
Ultraviolet Spectrometer		12 Nov ‘98
Triaxial Fluxgate Magnetometer	✓	TBD*
Plasma Spectrometer		26 Sep ‘24
Low Energy Charged Particle Instrument		24 Mar ‘25
Cosmic Ray System	✓	TBD*
Planetary Radio Astronomy Investigation		21 Feb ‘08
Photopolarimeter System		3 Apr ‘91
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.





John Casani (Voyager Project Manager 1975-77) with the US flag sewn into Voyager 2's thermal blanket. Voyager 2 is in the background. The Golden Record and cover plate are displayed on the table. Photo taken on 4 August 1977. Image: NASA/KSC

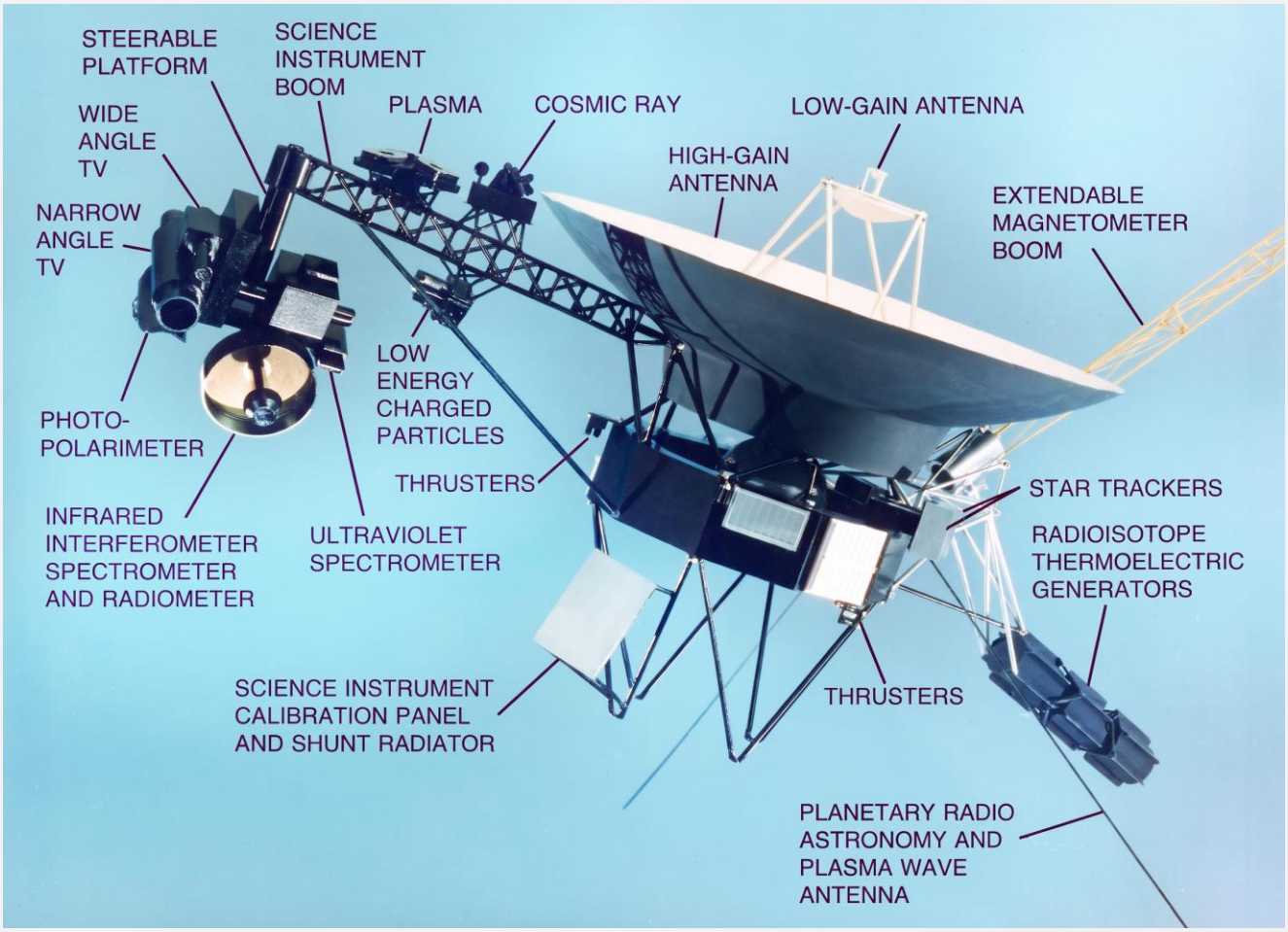


Diagram of Voyager spacecraft components. Graphic: NASA/JPL

VOYAGER 2

SYSTEMS AND INSTRUMENTATION

The two Voyager spacecraft are identical. They use sensors and gyroscopes to stay correctly oriented and keep their high-gain antennas pointed toward Earth. Their main science package includes 10 instruments supporting 11 investigations, including radio science.

The main body of the spacecraft or "bus" carries the engineering systems and science instruments and looks like a large ten-sided box. Its centre line is called the z-axis, and the high-gain antenna points along this axis toward Earth. Small thrusters attached to the bus allow the spacecraft to roll around the z-axis.

High Gain Antenna (HGA)

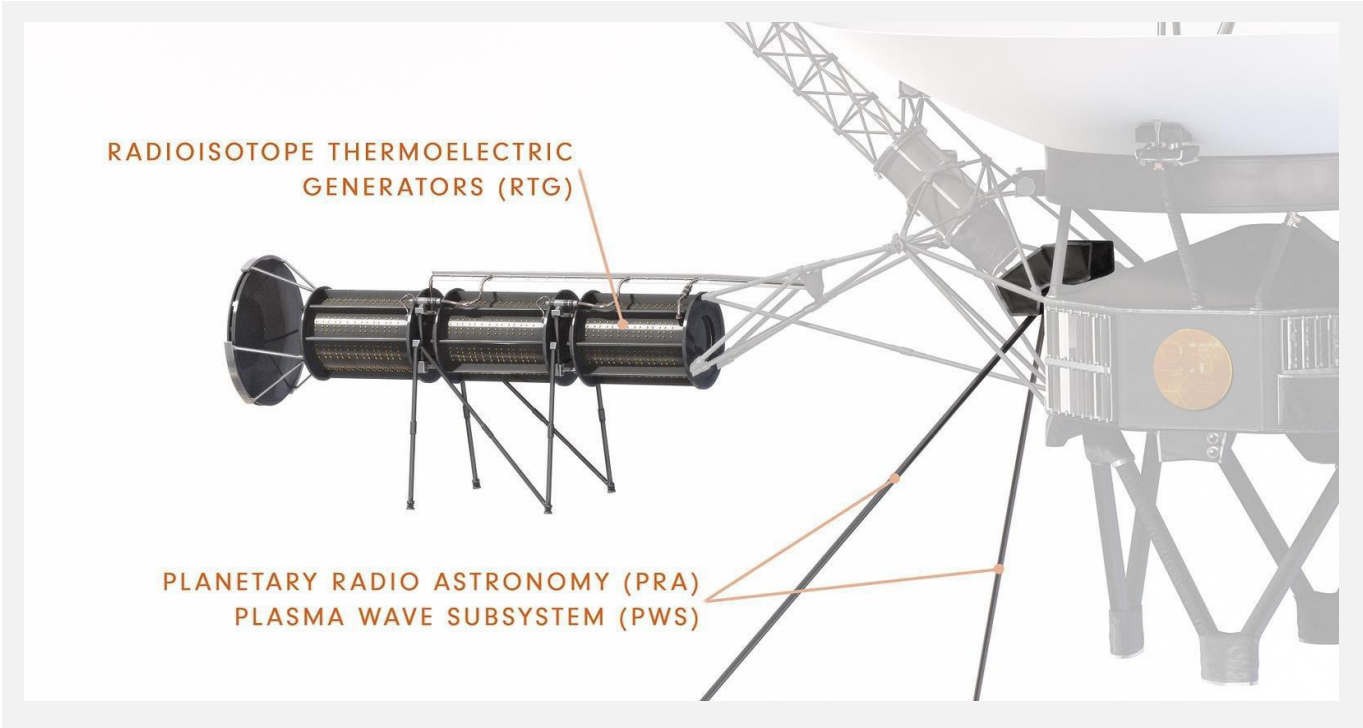
The 3.7 metre diameter HGA sends data to Earth on two frequency channels. The X-band channel, at about 8,450 MHz (megahertz), carries science and engineering data at speeds of up to 7.2 kilobits per second. For comparison, FM radio is around 100 megahertz.

The S-band channel, at about 2,295 MHz, sends basic information about the spacecraft's condition at 40 bits per second. The S-band frequency has not been used since the Voyager's last planetary encounters.

The uplink carrying command and ranging signals transmitted from the ground station is in the S-band range at a frequency of 2,113 MHz.

The Deep Space Network (DSN) ground station antennas can receive the two signals simultaneously through their 64 metre antennas (expanded to 70 metres for the Uranus and Neptune encounters).

The DSN could also use the high efficiency (HEF) 34 metre antennas though only for receiving the X-Band signals. Later, two 34 metre antennas supporting both S- and X-band receivers could be arrayed to receive from Voyager 2 and up to four 34 metre antennas for Voyager 1. [See Ed's note*]



Radioisotope Thermoelectric Generator (RTG)
Three RTGs are the spacecraft's main power source. Each RTG contains a radioactive heat source and a device that turns heat into electricity, along with parts that control pressure, measure temperature, connect components, release extra heat, and support the unit. The three RTGs are mounted end-to-end on an extendable boom.

The heat source uses plutonium-238 fuel in the form of plutonium oxide. As the fuel naturally breaks down, it releases particles that produce heat inside the container. A thermoelectric converter then turns this heat into electricity.

Planetary Radio Astronomy (PRA)
This instrument is really two separate experiments - the Plasma Wave (PWS) and the Planetary Radio Astronomy (PRA) subsystems, sharing the two 10 metre long beryllium antennas forming a "V".

The PRA is a sophisticated radio receiver that listens for any radio signals that are produced by the Sun or planets, their magnetospheres or lightning.

It works in two ways:

1. In the single frequency mode, it listens to a selected frequency
2. In the scanning mode it sweeps across the selected frequency spectrum searching for any signals.

The PRA receiver covers two frequency bands, from 20.4 kHz to 1300 kHz and from 2.3 MHz to 40.5 MHz.

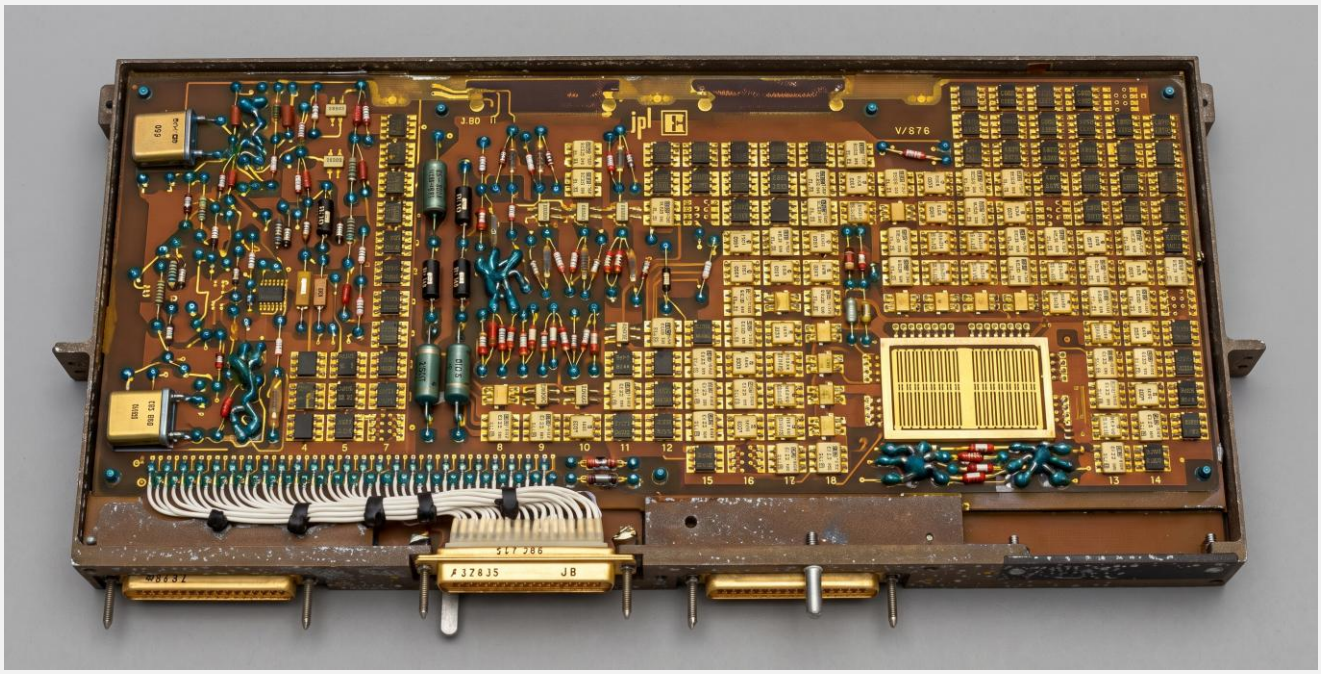
Plasma Wave Subsystem (PWS)
Associated with the PRA system, the PWS was a late addition to Voyager's instrumentation, being added in mid-1974. It shares the 10 metre long "V" antenna with the PRA.

Normally operating in the scanning mode, the PWS is a radio receiver and amplifier listening for signals that humans can hear. Plasma wave signals are processed using a 16-channel spectrum analyser providing frequency sampling from 10Hz to 56 kHz every four seconds during planetary encounters.

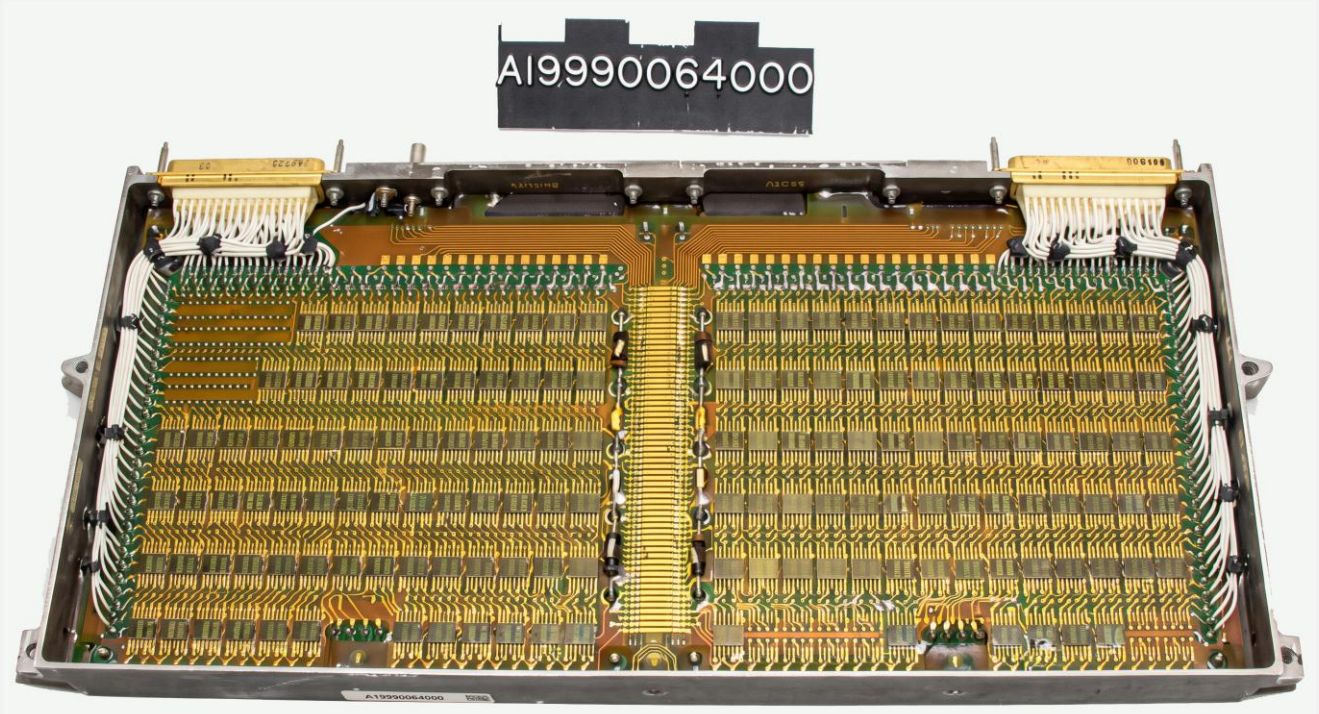
In its second mode of operation, it can simultaneously listen to all the stations in the audio band and can detect the presence of tiny ring particles striking the spacecraft as it passes through planetary rings.

This instrument is so sensitive it can detect electronic switching in other equipment on board the spacecraft, and in the audio tapes it can hear the thrum of the spacecraft's main power supply, the ping as the attitude thrusters fire and ringing as other instruments operate.

Calibration Panel
The calibration target is a flat rectangular plate with a known colour and brightness. Instruments on the movable scan platform, such as the cameras and infrared instrument, can point at it to check and adjust their measurements.



Above: A circuit board that makes up part of the Voyager AACS subsystem.
Image: (above) NASA/JPL, (below) NASA/JPL/NASM
Below: A Data Automation Subsystem Logic subassembly circuit board from the AACS subsystem.

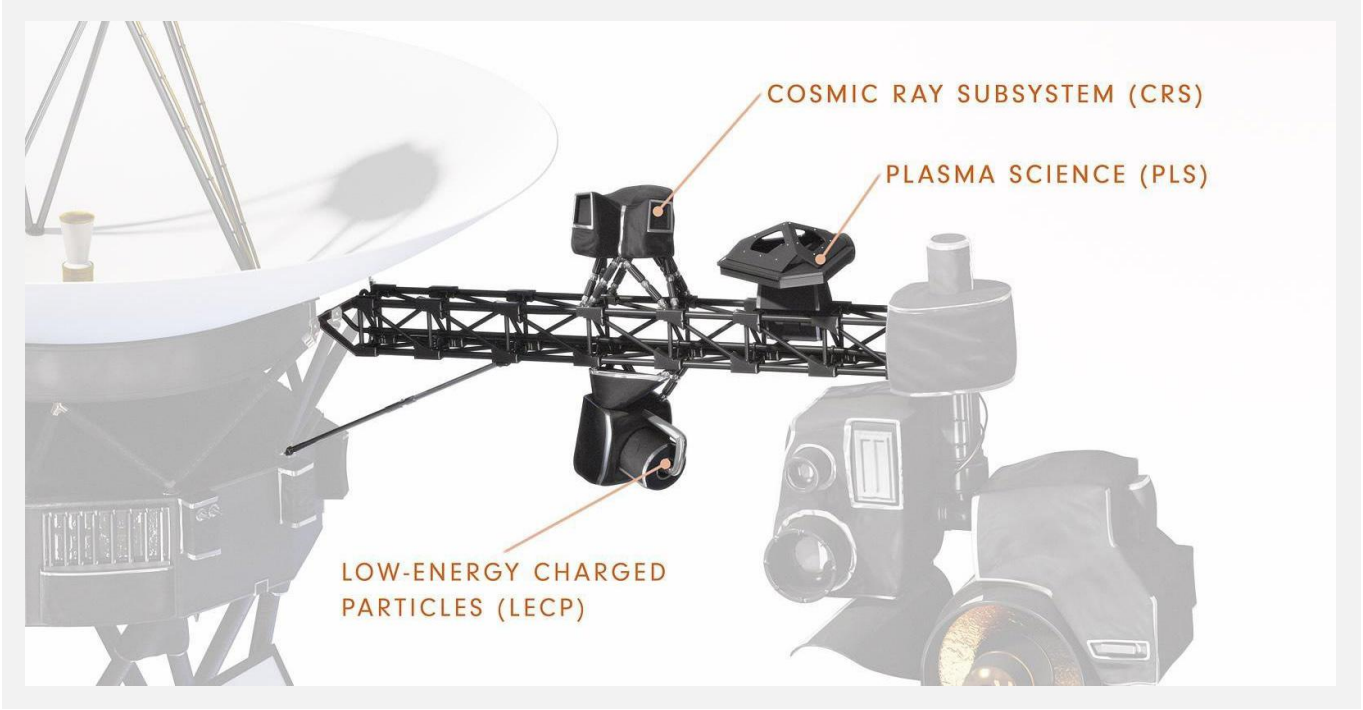


Command Computer Subsystem (CCS)
The CCS provides sequencing and control functions and contains fixed routines such as command decoding, systems fault detection and corrective routines, mission critical antenna pointing information, and spacecraft sequencing information.

Attitude and Articulation Control Subsystem (AACS)
The AACS controls spacecraft orientation maintains the pointing of the high gain antenna towards Earth, controls attitude manoeuvres, and positions the scan platform.

Cosmic Ray Subsystem (CRS)
Cosmic rays are primarily protons and electrons and are the most energetic particles found in nature. They could pose a hazard to future human and robotic space travellers.

The CRS and LECP look for particles of higher energy than the PLS. The LECP has the broadest energy range of Voyager's three particle sensors.



The CRS only looks for very energetic particles, and has the highest sensitivity.

Very energetic particles can often be found in the intense radiation fields surrounding some planets (like Jupiter). Particles with the highest-known energies come from other stars. The CRS looks for both. The CRS makes no attempt to slow or capture the super-energetic particles. They simply pass completely through, leaving signs that they were there.

Mounted about half way up the science boom, the CRS consists of seven fixed mounted telescopes - 4 single-ended low-energy telescopes (LETS); 2 double-ended high–energy telescopes (HETS) and one electron telescope (TET).

All use silicon wafers of varying thicknesses (35 microns to 6 millimetres) cut from carefully grown pure crystals. The areas vary from 2.8 to 9.6 square centimetres.

Electrically conducting metals such as aluminium, gold and lithium are spread on the wafers. The energy, mass and direction of each entering particle is measured by the number of detectors it penetrates, the electrical charge it deposits and which telescope it enters.

Plasma Science (PLS)

A plasma is a gas of charged particles. Voyager's PLS looks for the lowest energy particles. It also has the ability to look for particles moving at particular speeds.

The PLS looks for the lowest-energy particles in plasma. It also has the ability to look for particles moving at particular speeds and, to a limited extent, to determine the direction from which they come.

Measures the properties and radial evolution of the solar wind in the range:

- Ions 10 eV – 6 keV
- Electrons 4 eV – 6 keV.

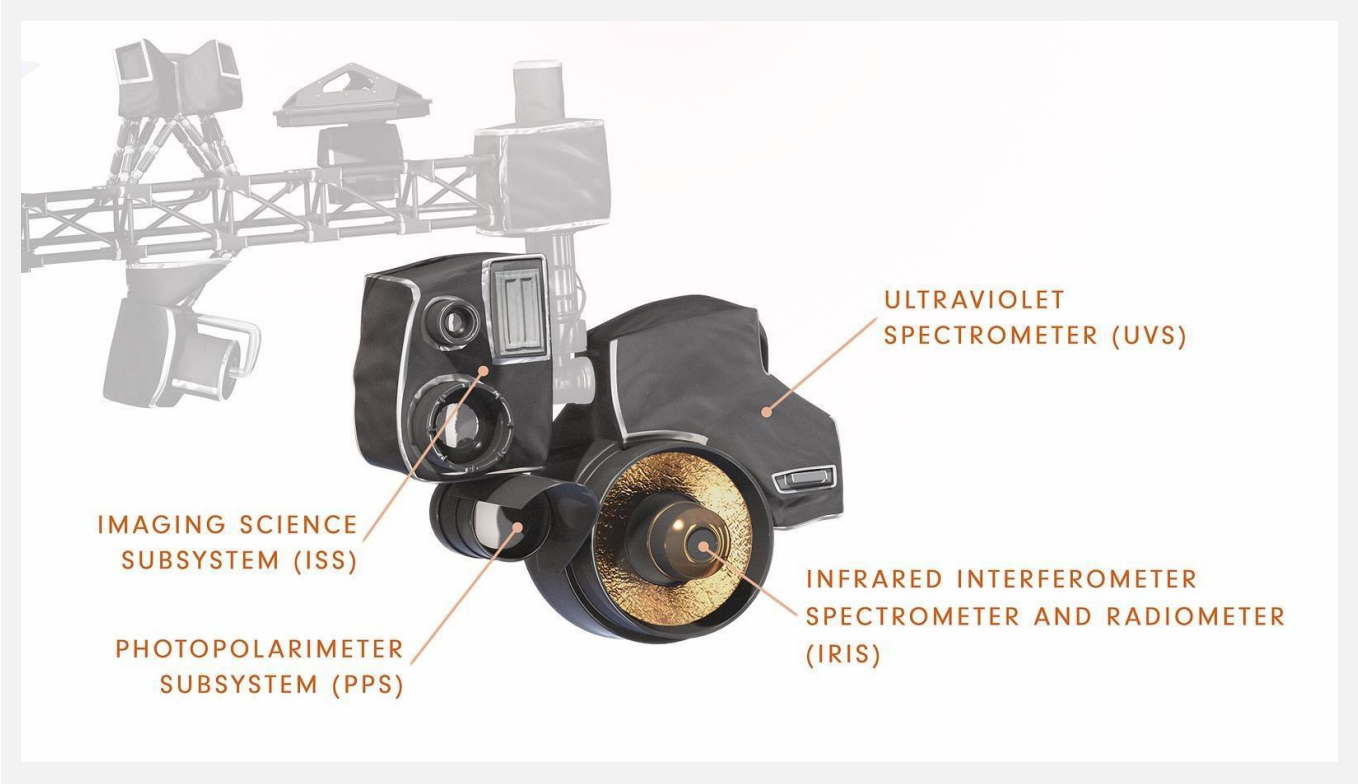
Low Energy Charged Particle Subsystem (LECP)

The LECP looks for particles of higher energy than the PLS, and it overlaps with the Cosmic Ray Subsystem (CRS). It has the broadest energy range of the three sets of particle sensors. Measures the energy spectrum of low-energy particles 10 – 10,000 keV and ions 10 – 150,000 keV/h.

The LECP can be imagined as a piece of wood, with the particles of interest playing the role of bullets. The faster a bullet moves, the deeper it will penetrate the wood. Thus, the depth of penetration measures the speed of the particles. The number of "bullet holes" over time indicates how many particles there are in various places in the solar wind, and at the various outer planets. The orientation of the wood indicates the direction from which the particles came.

The LECP measures the energy spectrum of low energy particles such as electrons in the range:

- Electrons 10 – 10,000 keV
- Ions 10 – 150,000 keV/n



Infrared Interferometer Spectrometer and Radiometer (IRIS)

The IRIS experiment helped determine the vertical structure of a planet's atmosphere. By measuring the infrared and visible radiation emitted and reflected from an object, a lot can be learned about atmospheric gas composition, clouds, hazes, temperatures, dynamics and heat balance.

The IRIS actually acts as three separate instruments. First, it is a very sophisticated thermometer. It can determine the distribution of heat energy a body is emitting, allowing scientists to determine the temperature of that body or substance. Second, it is a device that can determine when certain types of elements or compounds are present in an atmosphere or on a surface. Third, it used a separate radiometer to measure the total amount of sunlight reflected by a body at ultraviolet, visible, and infrared frequencies.

The radiometer responded to radiation in the spectral range from 0.3 to 2 µm, that is, from ultraviolet, through the visible spectrum to near infrared. Two interferometers cover the range 2.5 to 50 µm, or mid to far infrared.

IRIS has a 50 centimetre diameter telescope equipped with a permanent telephoto lens looking for infrared light.

The light strikes a mirror which reflects wavelengths longer than 2.5 µm into the interferometer and transmits wavelengths shorter than 2 µm into the radiometer.

Imaging Science Subsystem (ISS)

Voyager has two science sensors (cameras) designed for visible light operation – the ISS and PPS. The ISS consists of two television cameras, functioning like a pair of 35mm film cameras, except the light is converted into electronic signals for storage on an on-board tape recorder, or direct transmission back to Earth. Both would be considered telephoto lenses to the family photographer, who would regard 55 mm as a normal lens.

The ISS is a modified version of the slow scan vidicon camera designs that were used in the earlier Mariner flights. The ISS consists of two television-type cameras with fixed aperture lenses, each with 8 filters in a commandable filter wheel mounted in front of the vidicons.

One has a low resolution 200 mm wide-angle lens with an aperture of f/3, while the other uses a higher resolution 1500 mm narrow-angle f/8.5 lens, capable of reading a newspaper headline from a distance of a kilometre. The wide angle camera has three filters explicitly designed to detect sodium near Io and methane at Jupiter, Saturn, Uranus and Neptune.

The exposure time can be varied from 0.005 seconds to 15.3 seconds, though long exposures using multiples of 48 seconds are possible.

Each ISS picture is made up of over 5 million bits, transmitting 12 to 17 pictures per hour from Uranus by compressing the 5 million bits into 2 million bits. Each frame consists of 640,000 picture elements (pixels), each of which is expressed as a level of grey on a scale from 0 (black) to 255 (white). Colour scenes are reconstructed on Earth by combining images taken through different filters.

The ISS was used to observe the visible characteristics of planets, satellites, atmospheres, and rings, mapping, and included the sizes, colours, brightness, and surface texture of objects.

The Voyager navigation team used ISS pictures of moons against background stars in known positions to accurately locate where the spacecraft was when a picture was taken.

Photopolarimeter Subsystem (PPS)
The PPS uses a 0.2 metre telescope fitted with filters and polarization analysers. It covers eight wavelengths in the region between 235 µm and 750 µm (µm – micrometre – 0.001mm).

This experiment is designed to determine the physical properties of particulate matter in the atmospheres of Jupiter, Saturn, and the Rings of Saturn by measuring the intensity and linear polarization of scattered sunlight at eight wavelengths in the 2350-7500Å (Angstrom – one ten billionth of a metre) region of the spectrum.

The experiment will also provide information on the texture and probable composition of the surfaces of the satellites of Jupiter and Saturn and the properties of the sodium cloud around Io.

During the planetary encounters a search for optical evidence of electrical discharges (lightning) and auroral activity were also conducted by the instrument.

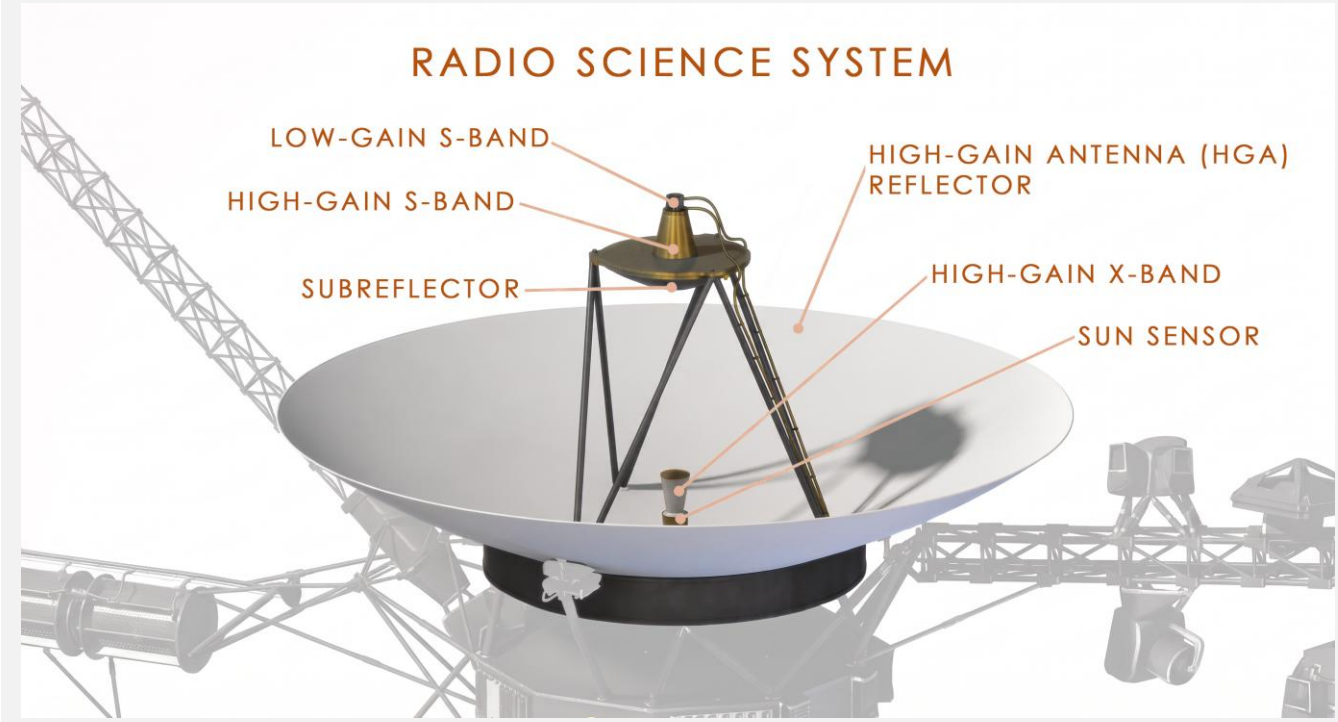
Ultraviolet Spectrometer (UVS)
Mounted on the scan platform, the UVS is a very specialised type of light meter that is sensitive to ultraviolet light. It determines when certain atoms or ions are present, or when certain physical processes are going on. The instrument looks for specific colours of ultraviolet light that certain elements and compounds are known to emit.

The Sun emits a large range of colours of light. If sunlight passes through an atmosphere, certain elements and molecules in the atmosphere will absorb very specific frequencies of light. If the UVS, when looking at filtered sunlight, notices the absence of any of these specific colours, then particular elements and/or compounds have been detected. This process is call identifying elements or compounds by atomic absorption.

Magnetometer (MAG)
Although the MAG can detect some of the effects of the solar wind on the outer planets and moons, its primary job is to measure changes in the Sun's magnetic field with distance and time, to determine if each of the outer planets has a magnetic field, and how the moons and rings of the outer planets interact with those magnetic fields.

Measures low and high magnetic field intensities from 0.02 nT to 2,000,000 nT (nT – nanoteslas).





Radio Science Subsystem (RSS)

All the sensors on Voyager are passive except for the RSS. A passive sensor must wait for the energy or particles to come to it. An active sensor creates its own energy and sends it out to the target.

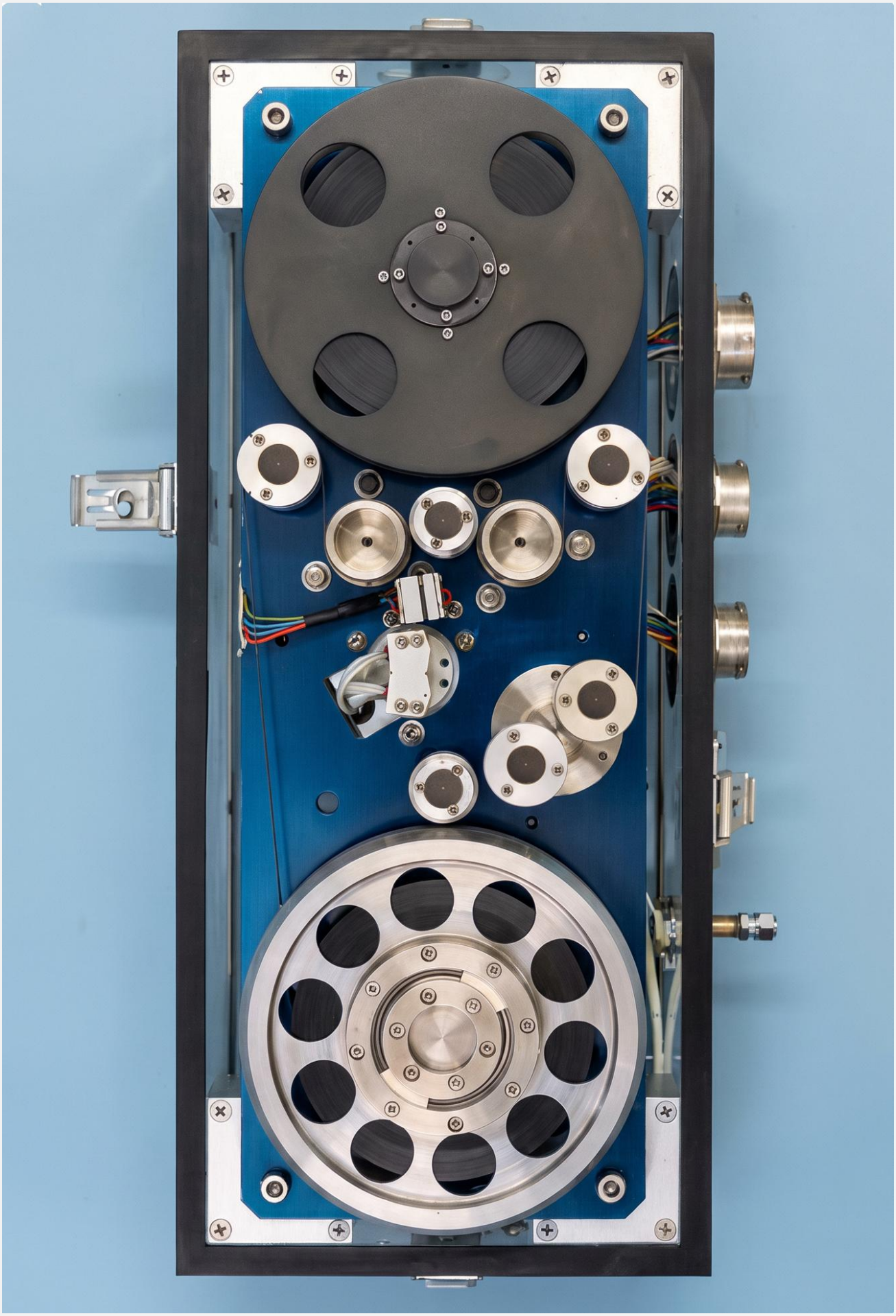
The RSS is the radio transmitter used to communicate with the spacecraft, and the sensors are the tracking stations on Earth. The RSS uses both S and X band frequencies driven by an ultra-stable oscillator. Changes in the frequency, phase, delay, strength and polarisation of the received signal from the spacecraft as it passes behind objects provide a lot of information about planets and satellites and their atmospheres.

The Radio Science Subsystem is used in four totally different experiments:

1. To probe planetary and satellite atmospheres. When the spacecraft is about to pass behind, or emerge from behind a planet or satellite with an atmosphere, the signal will be bent and slowed (refracted) by the atmosphere. From the changes in the X band and S band signals the temperature and pressure of the atmosphere at different altitudes can be calculated. The atmosphere's density can be calculated from the amount the signal is bent.
2. Directing the X band signals through planetary rings. Changes in the X and S band intensities and frequencies are used to estimate the number, size, shape and thickness of the planetary rings.
3. To determine the mass of a planet or satellite using the Doppler principle. Any change in the speed of the spacecraft caused by an object's gravity will change the frequency of the signal received by the tracking stations.
4. A test of General Relativity. The Theory of General Relativity predicts a change in the frequency of a radio signal when the signal's source passes near any massive body. Each time the spacecraft passes close to a planet any change in the spacecraft's carrier frequency is measured and compared to the change predicted by General Relativity.

Editor's note: * The DSN continues to provide two-way communications for both Voyager spacecraft. However, while Goldstone, Madrid and Canberra (Tidbinbilla) can all receive from Voyager 1, only Canberra has the high power transmitter on its 70 metre antenna able to send commands to the spacecraft. Downlink from Voyager 1 can be done using a single 70 metre dish, but can also be achieved by arraying up to four 34 metre antennas.

It is worth noting that since May 2002, Canberra is the only Deep Space Network station that can provide two-way communications for Voyager 2, since the spacecraft is now so far 'south/below' the planetary ecliptic, that the northern hemisphere stations no longer have line of sight, due to Earth being in the way.



Voyager’s 8-track digital tape recorder has 328 metres of ½ inch magnetic tape. Image: NASA/JPL
Storage capacity is a whopping 64 megabytes! Enough to store approximately 100 (800x800 pixel) images.

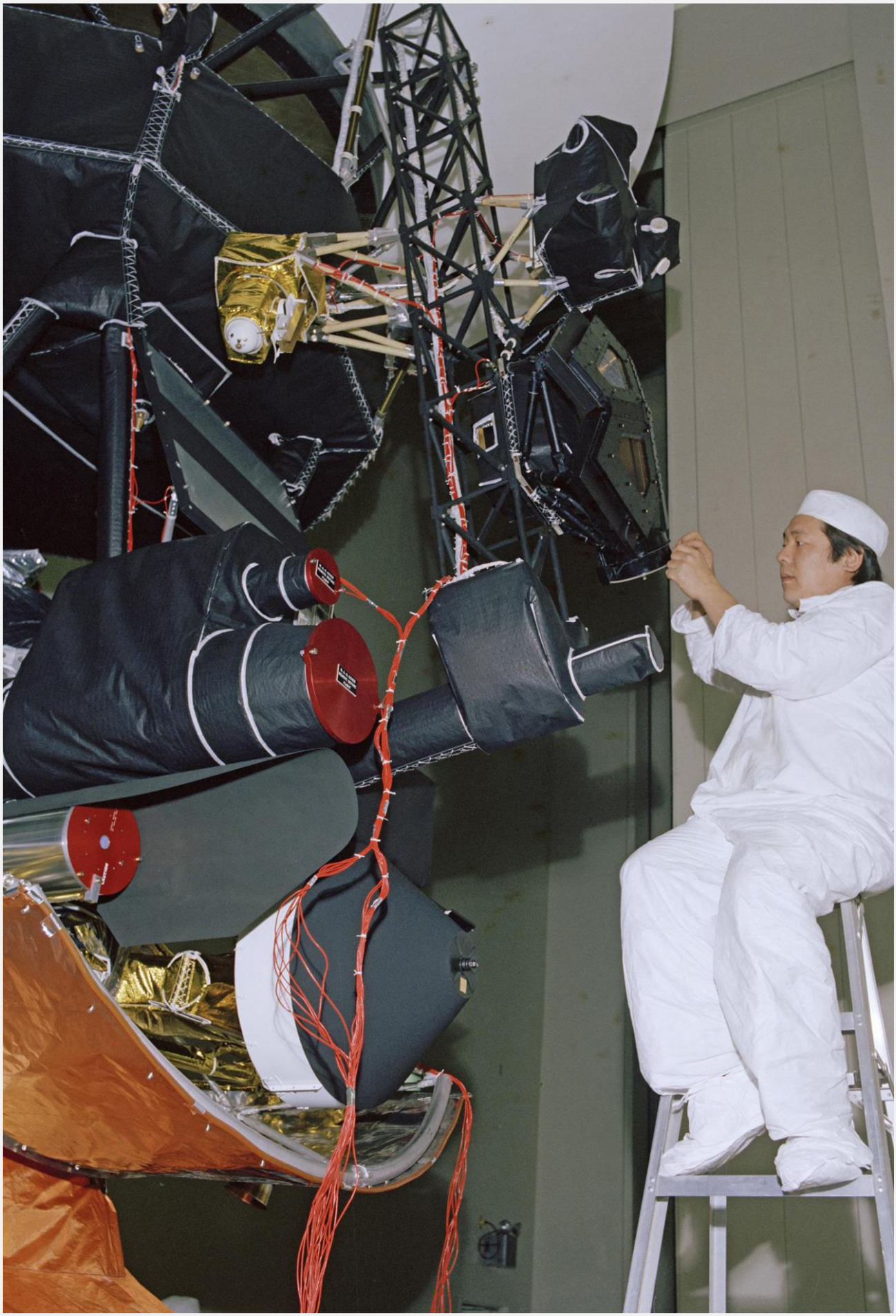


JPL engineers working on the 10-sided central “bus” structure on Voyager 2 on 24 February 1977.

Images: NASA/JPL

JPL engineers working on NASA's Voyager 2 spacecraft on 23 March 1977.





JPL engineer works on vibration acoustics and pyro shock testing, 18 November 1976.
There were extensive tests done on proof test models before work on the actual flight spacecraft.



Voyager 2 is being prepared for encapsulation in its payload fairing at the
Spacecraft Assembly and Encapsulation Facility at NASAs Kennedy Space Center. Image: NASA/KSC



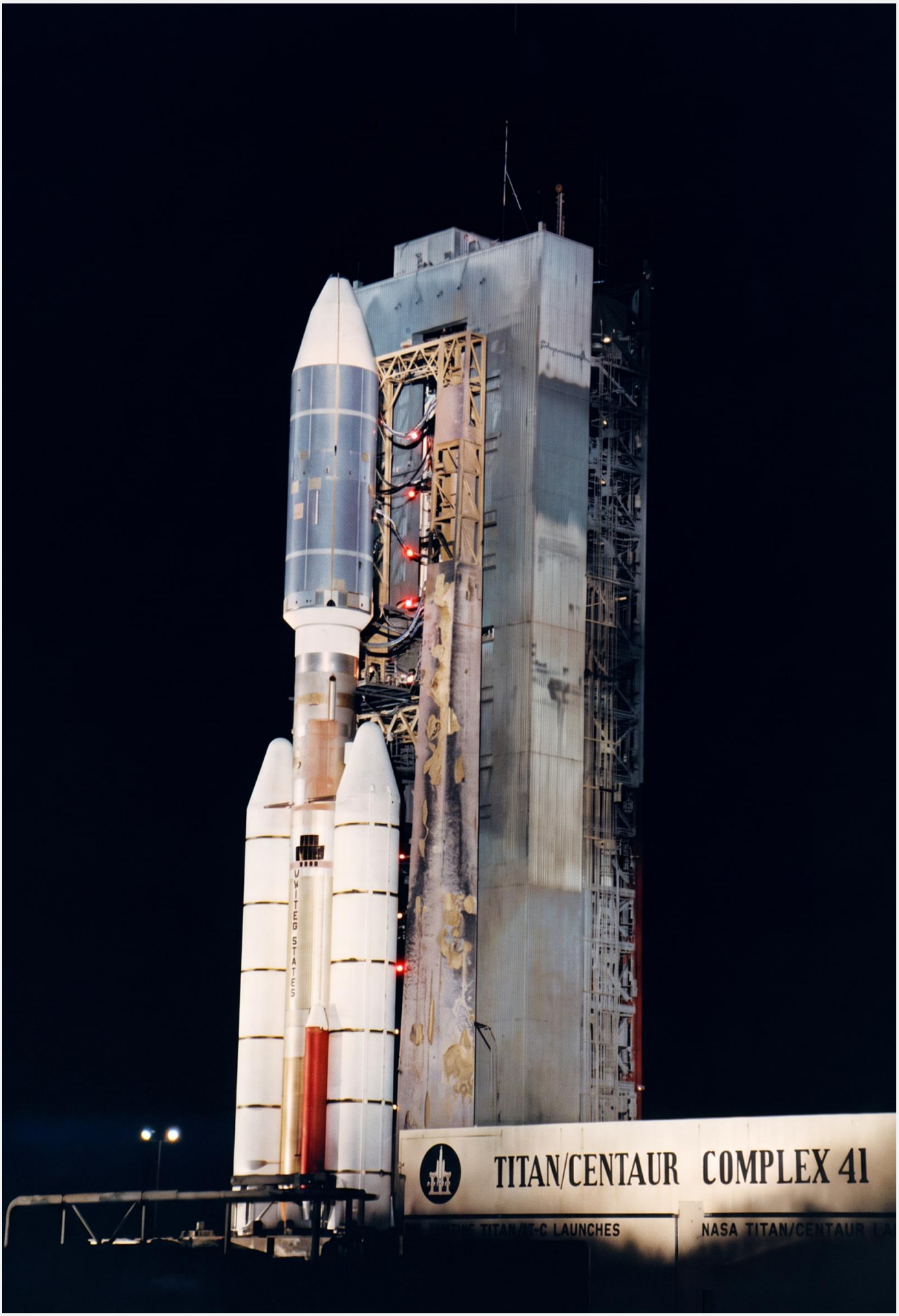
Another view of Voyager 2 being prepared for encapsulation in its payload fairing at the Spacecraft Assembly and Encapsulation Facility at NASAs Kennedy Space Center. Image: NASA/KSC



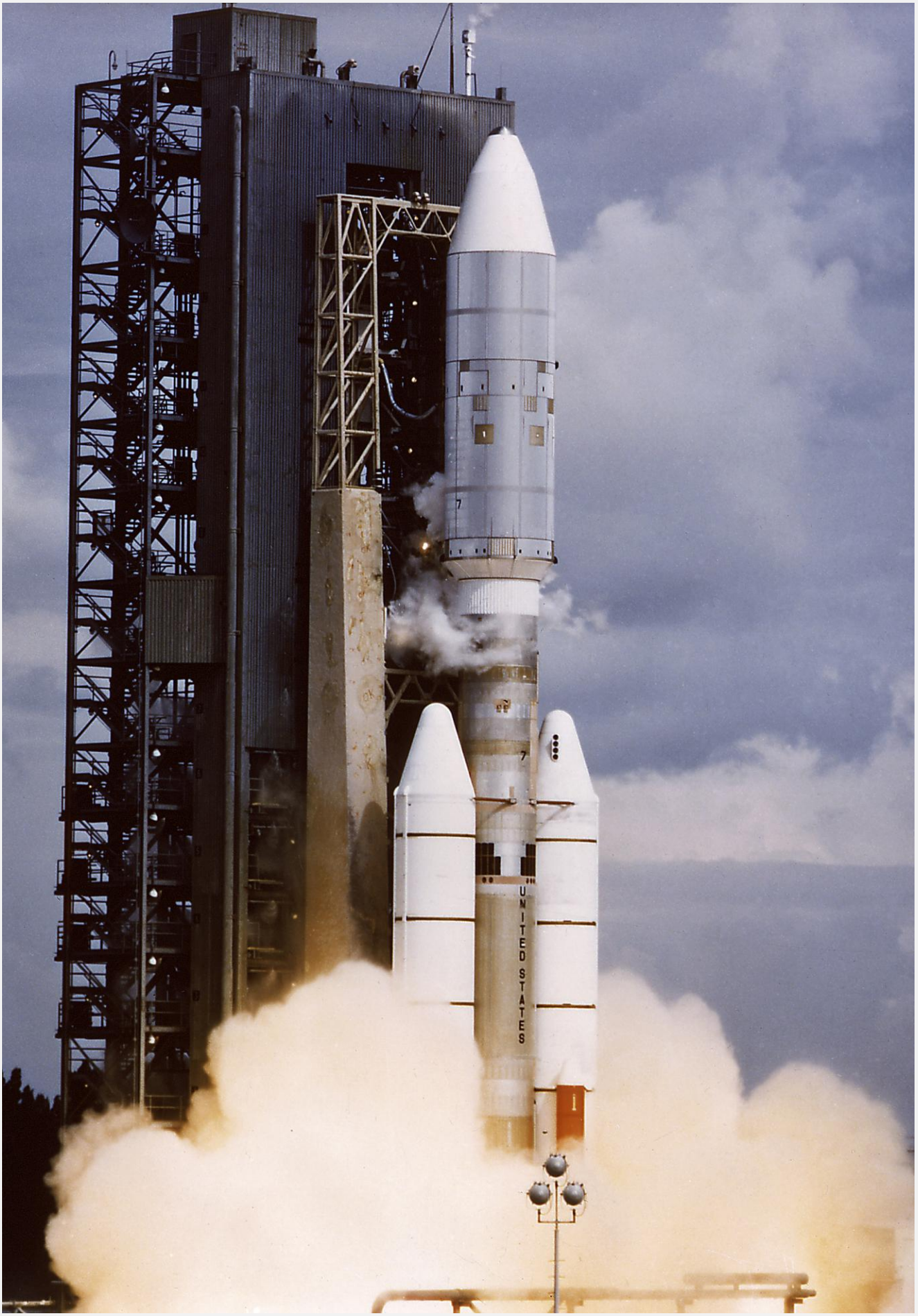
Voyager 2 inside its payload fairing be lifted for mating to the Titan/Centaur (TC-7) launch vehicle at Cape Canaveral Air Force Station in Florida on 5 August 1977. Image: NASA/KSC



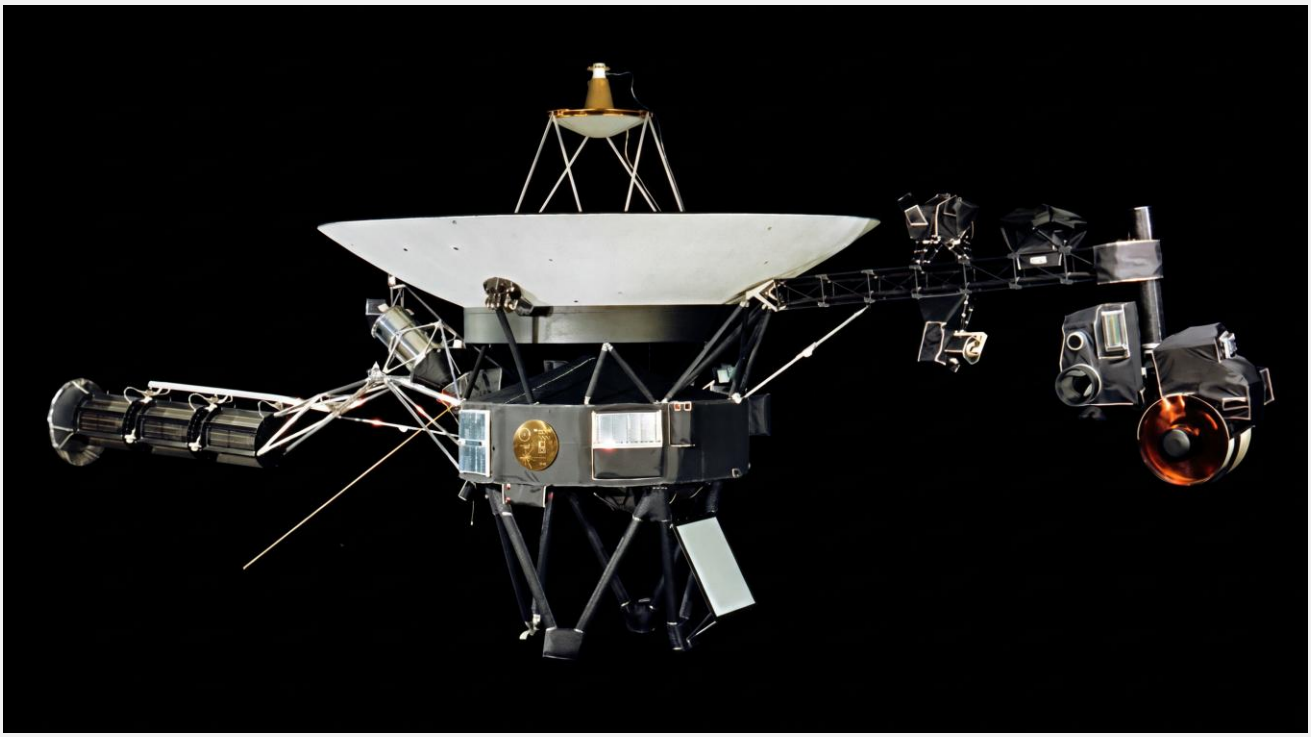
Closeup view of Voyager 2 inside its payload fairing be lifted for mating to the Titan/Centaur (TC-7) launch vehicle at Cape Canaveral Air Force Station in Florida on 5 August 1977. Image: NASA/KSC



The Titan/Centaur (TC-7) launch vehicle sits on the launch pad at Cape Canaveral at Launch Complex 41. Image: NASA/KSC



Titan IIIE / Centaur D-1T / Star-37E vehicle launches with Voyager 2
at 10:29:45am US EDT from Cape Canaveral, Florida on 20 August 1977. Image: NASA/JPL



Replica of the Voyager spacecraft at the Jet Propulsion Laboratory. Image: NASA/JPL

VOYAGER 2

THE GRAND TOUR OF THE SOLAR SYSTEM

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. 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.

So, Voyager 2 was launched first at 0029:45 AEST on 21 August (1029:45 USEDT 20 August) 1977 on another Titan III-E/Centaur rocket. It whipped past the Moon in 10 hours, an hour faster than the Pioneers, and more than two and a half days faster than Apollo. As the Titan/Centaur wasn't quite powerful enough to send the Voyagers on the planned trajectory, a solid propellant booster was added to the stack to produce an additional 68,000 newtons of thrust. After a 43 second burn, the booster dropped off and let Voyager 2 continue its journey.

Voyager 2's problems began right at the start. Project Manager John Casani and his engineers in the control centre watched helplessly as within minutes Voyager 2 suffered two difficulties with the AACS (Attitude and Articulation Control Subsystem). The first, a problem with one of the three stabilising gyroscopes which corrected itself, and the other a computer switching to the back-up computer during the Titan burn, suspected to be spacecraft gyrations caused by the AACS gyroscope problem.

Voyager 2 separated from the final stage of the Titan rocket early. The Centaur upper stage automatically corrected the error before releasing the spacecraft, and Voyager 2 blasted out of earth orbit 71 minutes after launch – next encounter the massive planet Jupiter, two years and 1.2 billion kilometres away.

Only two minutes after leaving the Earth orbit the spacecraft was struggling to stabilise itself, taking one and a half hours to settle down. Then an hour after launch telemetry data indicated the scan platform had not locked into the fully deployed position, but this was traced to a faulty sensor. Next a sticky thruster sprayed the spacecraft with hydrazine fuel and sent it off course before it was detected and corrected.



Titan IIIE / Centaur D-1T / Star-37E vehicle launches with Voyager 2
at 10:29:45am US EDT from Cape Canaveral, Florida on 20 August 1977. Image: NASA/JPL



Titan IIIE / Centaur D-1T / Star-37E vehicle launches with Voyager 2
at 10:29:45am US EDT from Cape Canaveral, Florida on 20 August 1977. Image: NASA/JPL

At this point Voyager 2 was cruising along at 70,920 kilometres per hour, 4,680 kilometres per hour slower than Voyager 1. It was nearly 95 million kilometres from Earth, and the time for the signal to reach Earth was 5 minutes 12 seconds. Voyager 2 passed Mars at a distance of 137 million kilometres.

On 23 September 1977 Voyager 2 experienced a failure in the Flight Data System (FDS), which lost 15 of the 243 engineering measurements normally sent back to Earth. Of the 15, several are duplicated in the remaining 228 measurements, some could be deduced from combinations of other measurements, some were only needed during launch, and the remainder may have had some effect on performance analysis of other subsystems aboard the spacecraft.

An effort to reset the FDS in October failed, so the problem was considered a permanent hardware failure and alternatives to work around the failures were used.

On 31 October 1977 Voyager 2 rolled over so that the star tracker shifted its reference from Canopus to Deneb on the opposite side to minimise the effect of solar pressure, which was contributing to the frequent attitude control thruster firings to steady the spacecraft, and to allow an earlier pointing of the High Gain Antenna to Earth.

Late in November 1977 one of Voyager 2's two duplicate transmitters' performance began to degrade so it was switched to low-power mode to preserve it.

Voyager 2 broke through the Asteroid Belt, a band of rocks and dust 360 million kilometres wide, on 21 October.

Voyager 1 overtook Voyager 2 around 15 December 1977, to arrive at Jupiter 4 months ahead of Voyager 2.

VOYAGER 2 HAS RADIO RECEIVER PROBLEMS

When another crisis developed in Voyager 2 in April 1978, JPL Director Bruce Murray gave Voyager absolute priority over all other projects. He saw this as an emergency situation.

The busy flight controllers, working on the Voyager 1 scan platform problem, forgot to send a routine command to Voyager 2.

If the on-board computer did not receive a command from Earth for a week it was programmed to switch to the back-up receiver.

On 5 April the deadline passed, and the computer did just as it was programmed to do – switched to the back-up receiver. Surprised engineers discovered the back-up receiver was faulty – its tracking loop capacitor was defective. This meant the receiver could not follow a changing frequency from the ground stations, called the doppler effect. Doppler is the variation from the original transmitted frequency due to changes in the relative velocity between the spacecraft and the ground station, mainly due to the Earth's rotation.

After 12 hours and still no commands from Earth, the computer switched back to the prime receiver and commands could be sent again. The controllers breathed a sigh of relief. But not for long.

Thirty minutes later the prime receiver failed completely - permanently. Apparently an unknown failure in the receiver caused an excessive current, which blew the receiver fuses. Shocked engineers now had a dead prime receiver and a back-up unable to continuously follow the signal from Earth. Voyager 2 was in deep trouble.

Unable to send commands, contact with the spacecraft was lost while engineers had to wait seven days for the spacecraft to switch to the back-up receiver, when they had a 12-hour window to try and restore communications with the spacecraft. To do this they had to calculate the exact frequency required by the receiver to lock on to the signal from Earth and make sure the tracking stations sent this signal, constantly correcting for all the doppler effects.

The transmitted frequency from the tracking station had to be within 96 Hertz of the receiver rest frequency or the spacecraft would not lock on to the received signal. Even the temperature changes affected the rest frequency, a change as small as 0.25ºC in the receiver would shift the rest frequency by 96 Hertz.

How do the controllers predict such small changes in the temperature of the spacecraft? A computer model was developed to take into account all the temperature changes caused by the changing

angles of sunlight, the fluctuating electrical power consumption and any other effects they could think of.

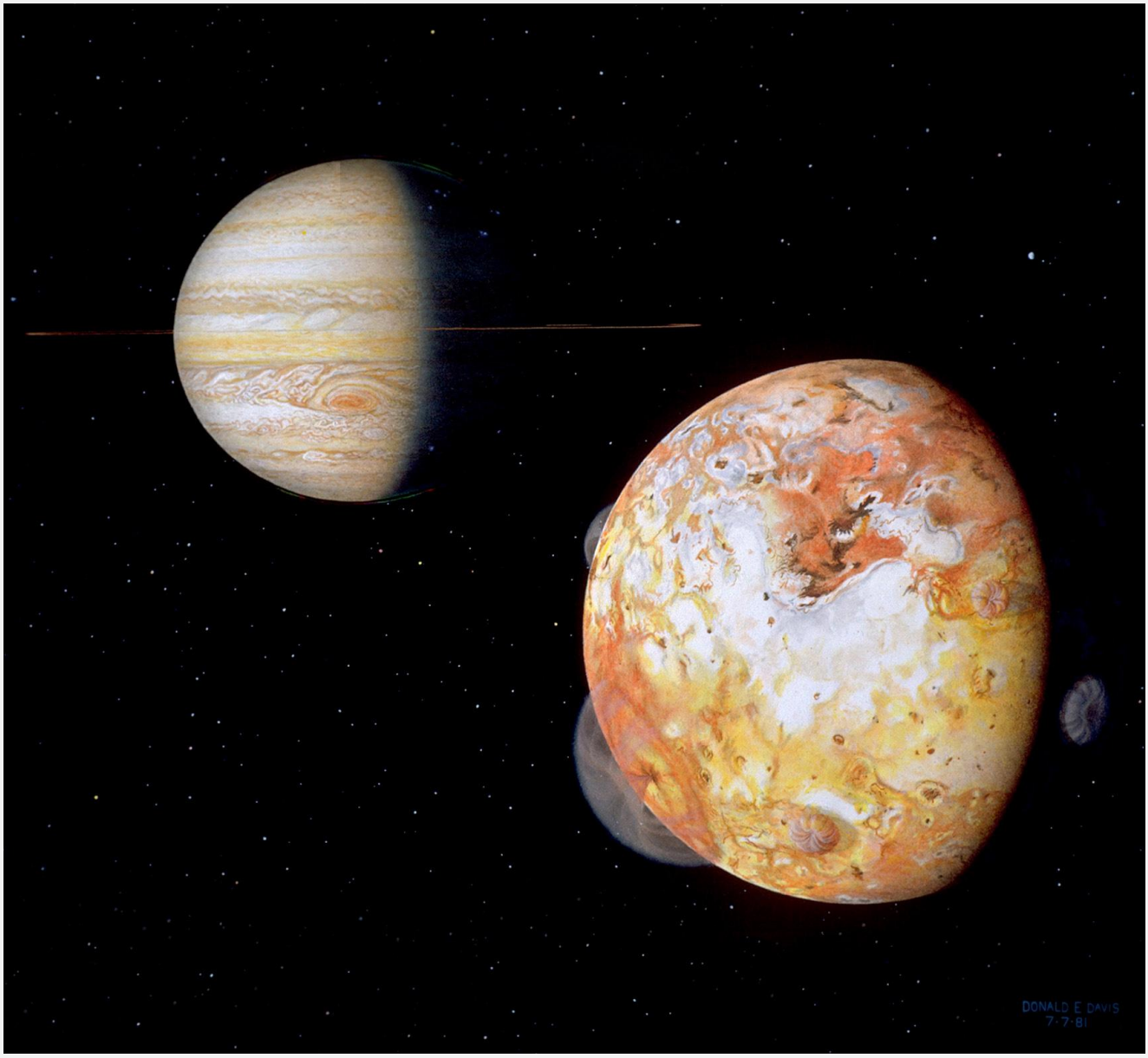
On 13 April 1978 at 20:30 AEST, the DSN station at Madrid transmitted the fateful signal over a distance of 474 million kilometres and to the relief of the engineers and scientists at JPL, 54 minutes later Voyager 2 acknowledged receiving the signal. Relieved flight controllers then went ahead with a solid 9 hours of commands to update the spacecraft.

Still troubled by the faulty receiver, Voyager 2 was following in the wake of Voyager 1. In response to Voyager 1's experiences, changes were incorporated in the sequences of the scientific observations for the upcoming July Jupiter encounter.

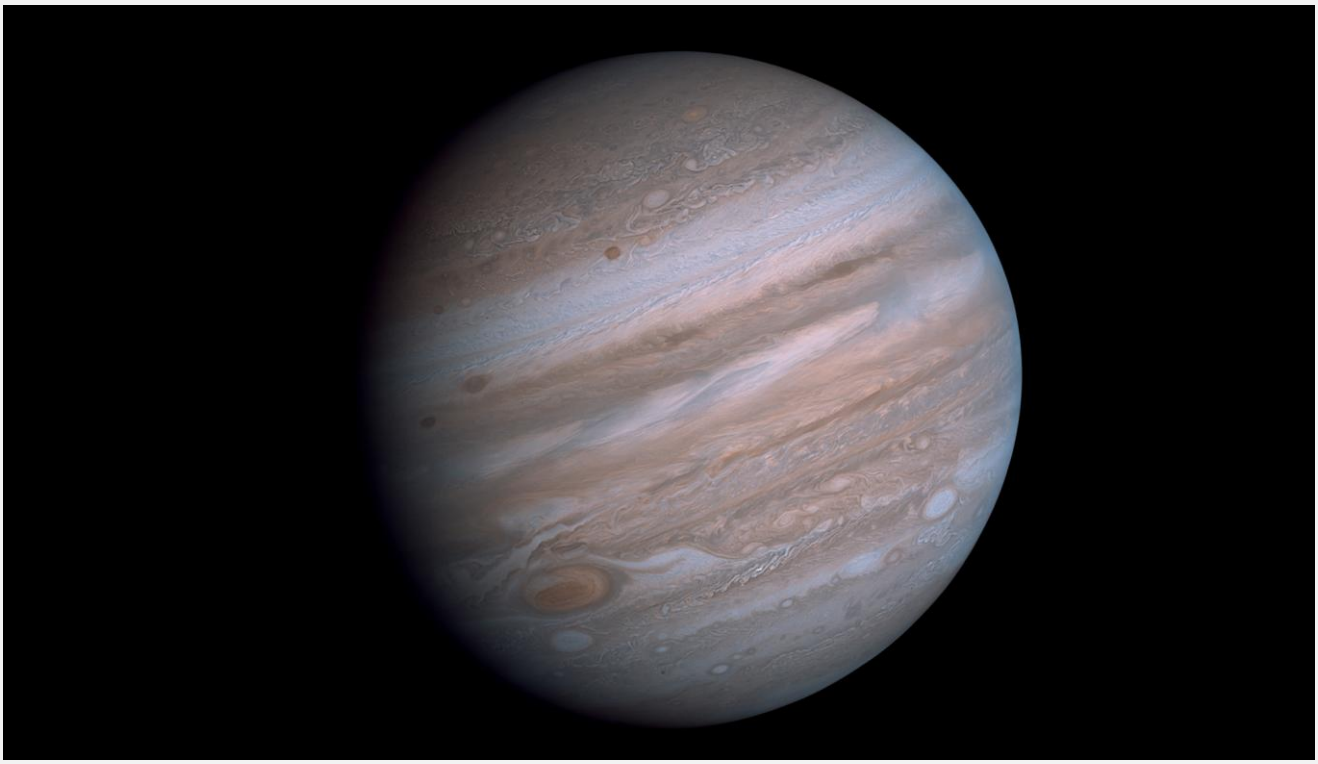
A 10-hour Io volcano watch was added, taking advantage of the fact that shortly after Point of Closest Approach (PCA) at Jupiter the spacecraft would remain within about 1 million kilometres of the moon for a long period, keeping the same face roughly in view. More studies would be made of the dark side of Jupiter to search for more auroral and lightning activity.

A high priority was given to further observations of the newly discovered rings, which had not figured in the Voyager 2 sequences at all. More extensive measurements of the emission from the glowing torus surrounding Jupiter near the orbit of Io were added.

Voyager 2 would fly much closer to Europa and Ganymede, but further from Io, which would be on the other side of the planet.



Volcanic Io and Jupiter in this artist's commissioned work for JPL. Image: Donald E. Davis (public domain)



Voyager 2 approaches Jupiter. Image: NASA/JPL, Modern processing: Justin Cowart

VOYAGER 2

JUPITER ENCOUNTER

This was the second good look at Jupiter by the Voyagers, but turned out to be no repetitive re-run. Voyager 2 had a different view of each world, and both Jupiter and Io had experienced changes in the four-month period since Voyager 1's visit.

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)*."*

Voyager 2's observatory phase began on 24 April 1979 - 76 days before encounter, and found Jupiter's cloud formations had changed.

The timing offset experienced by Voyager 1 as a result of Jupiter's intense radiation environment was not expected to be a problem on Voyager 2 for two reasons:

1. Even at closest approach Voyager 2 was more than twice as far from Jupiter as Voyager 1.
2. The Voyager 2 computer was programmed to re-synchronise the timing systems automatically every hour. In this way, even if the radiation environment proved to be higher than expected the image smear that might occur from a timing offset would be prevented.

As a result of Voyage 1's visit, scientists modified some of Voyager 2's pre-planned sequences, adding a 10 hour Volcano watch as the spacecraft would remain within a million kilometres of Io for a long period, keeping the moon's same face in view. Further studies of the dark side of Jupiter would look for lightning and auroral activity.

A high priority was given to studying Voyager 1's newly discovered ring. Voyager 2 was expected to see the faces of Callisto and Ganymede not seen by Voyager 1.

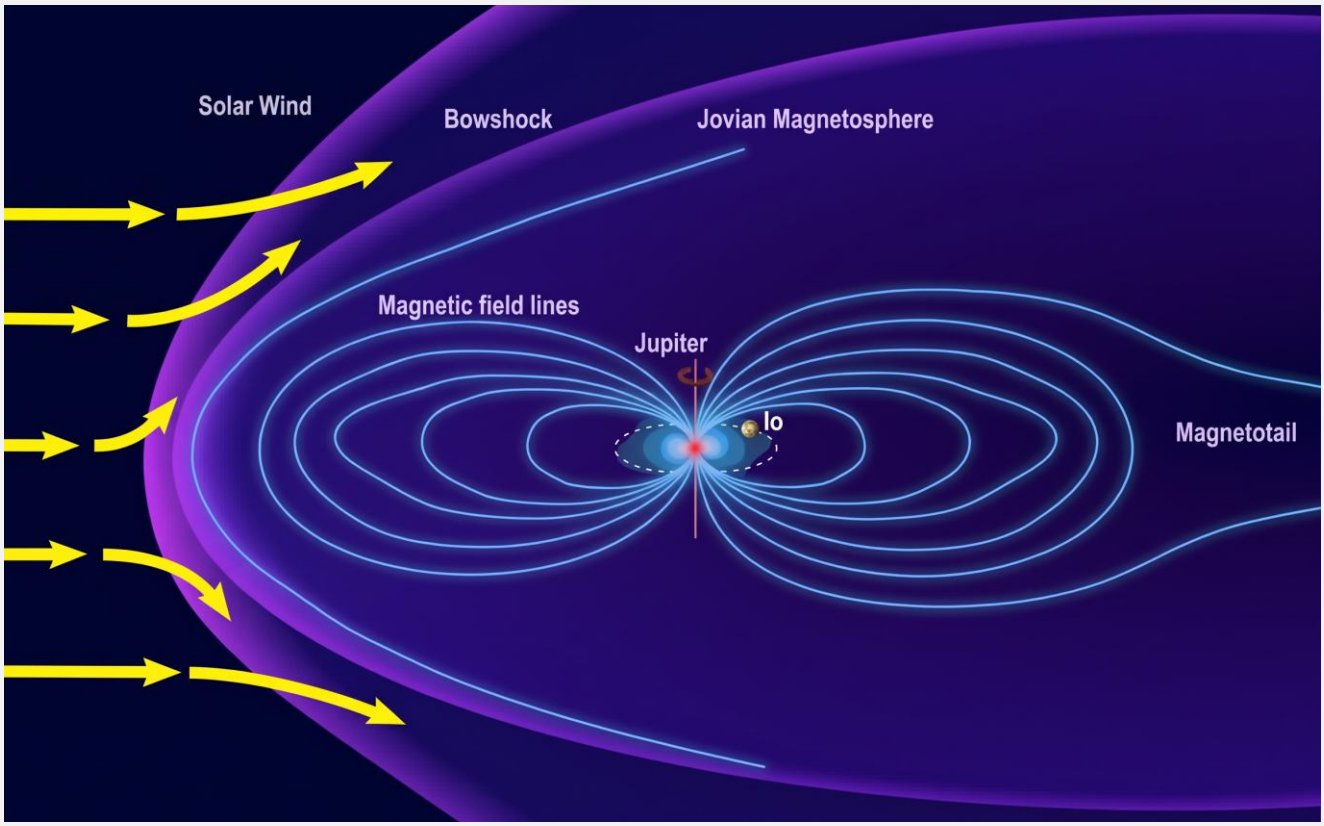


Diagram illustrating the solar wind warping the bowshock and magnetosphere of Jupiter. Graphic: NASA

The most important difference, however, was Voyager 2 would fly much closer to Europa, giving scientists their first good look at mysterious streaks gouged out of the surface, and a closer look at Ganymede to examine strange 'snowmobile' looking tracks.

As Voyager 2 approached Jupiter it took movies to show any changes in the Great Red Spot, and between 27 May and 29 May took 50 hours of nearly continuous picture taking, covering 5 rotations of the planet to supplement Voyager 1's colour movie of 10 rotations taken the previous January.

Voyager 2 had a different trajectory to Voyager 1, and the moons were in different locations, so most of the Galilean moons were encountered on the way in. Voyager 2 made its Jupiter pass deep in the southern hemisphere, unlike Voyager 1, which flew past just south of the equator.

Monday, 9 July began a frenetic period as Voyager 2 had its own adventures at Jupiter.

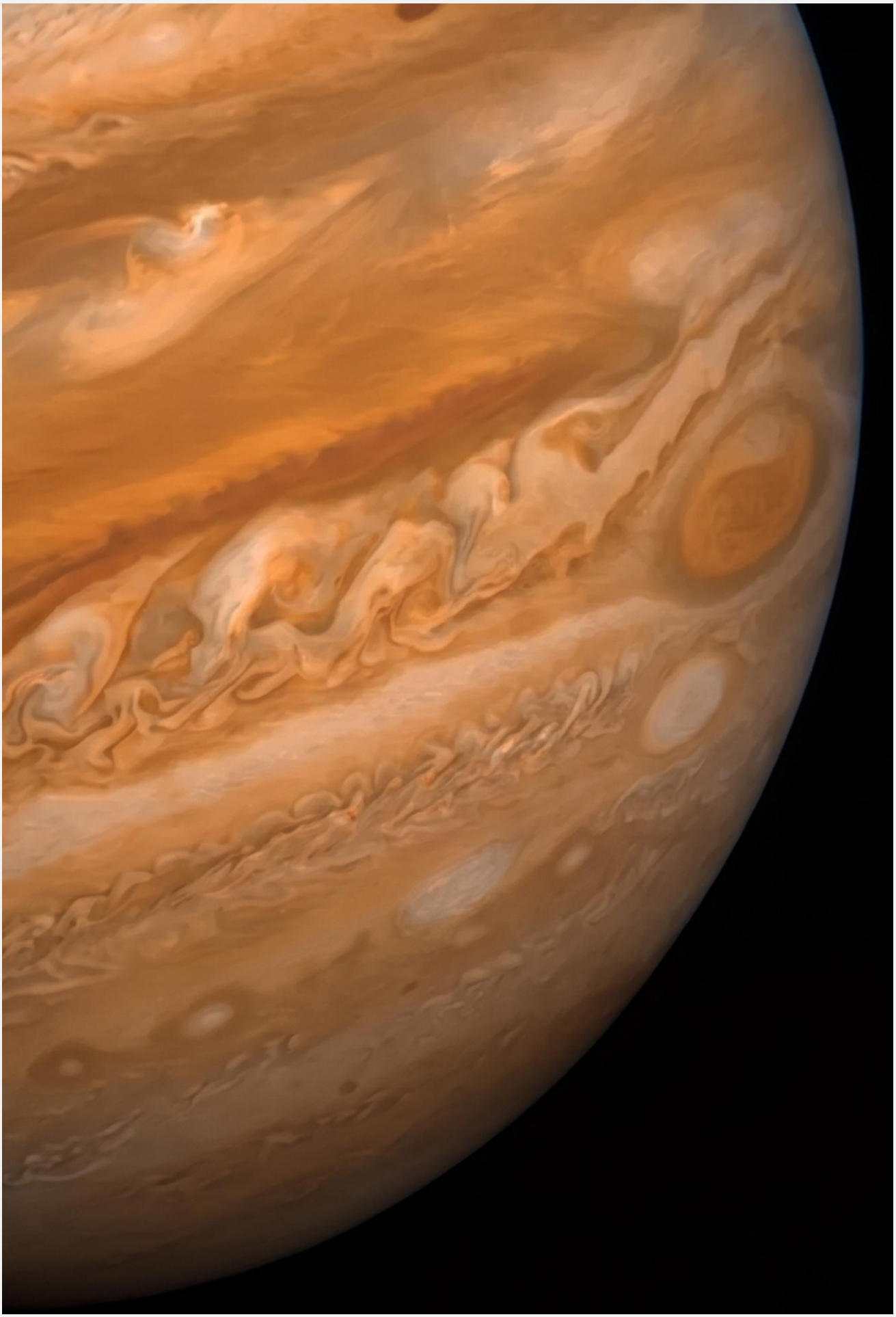
BOWSHOCK AND MAGENTOSPHERE ENCOUNTERS

Date	Distance*	Discovered by
2 July	6,921,189	First Bowshock encounter
	6,781,367	Bowshock multiple crossings
3 July	6,082,257	Bowshock
4 July	5,033,592	Magnetopause multiple crossings
5 July	4,963,681	Magnetopause
	4,823,859	Bowshock return
	4,684,037	Bowshock
	4,334,482	Magnetopause

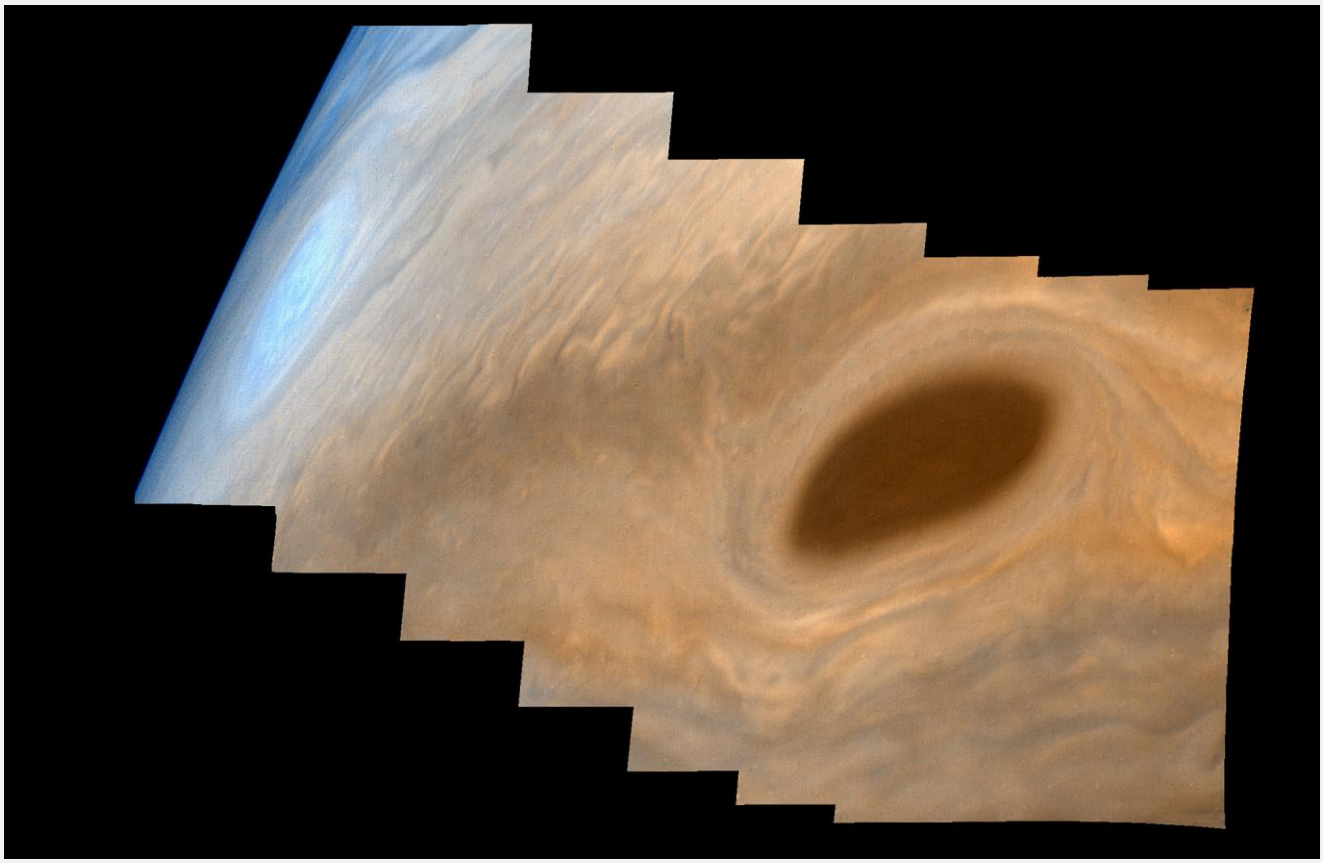
* from Jupiter's centre (kilometres)

CROSSING THE BOW SHOCK – 2 JULY 1979

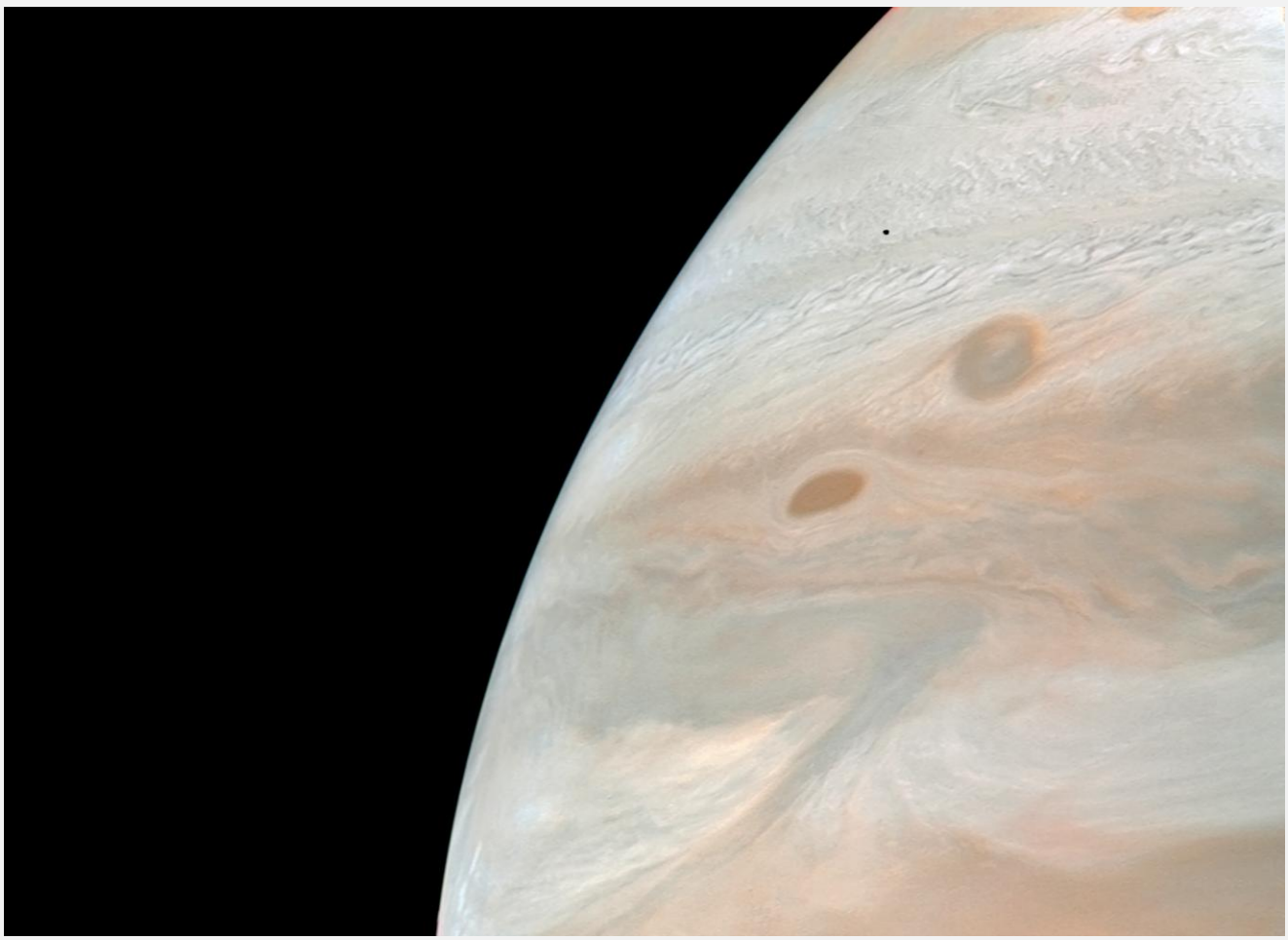
Voyager 2's first crossing of the bow shock was on 2 July at a distance of 6.92 million kilometres from the planet, followed by 11 other crossings measured by the plasma instrument, magnetometers, and plasma wave instrument before 5 July, indicating the magnetosphere had expanded and was more variable since Voyager 1's visit. Also, the bow shock seemed thicker than before, one Voyager 2 crossing took 10 minutes compared to Voyager 1's longest crossing only took one minute.

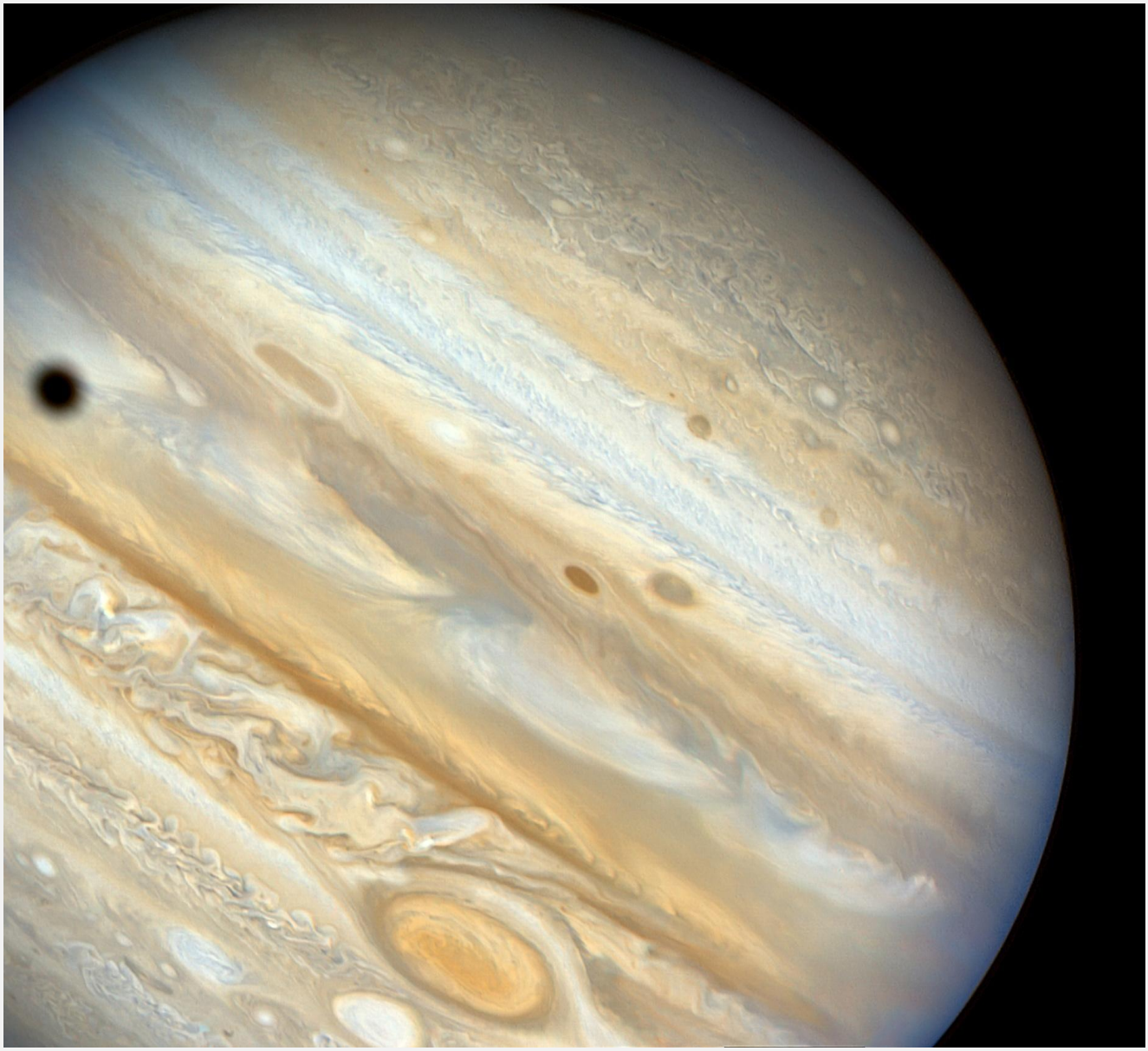


The Great Red Spot, which is many times larger than the Earth, is a massive anti-cyclonic storm on Jupiter, but it is only one of many complex features within the Jovian atmosphere. Image: NASA/JPL

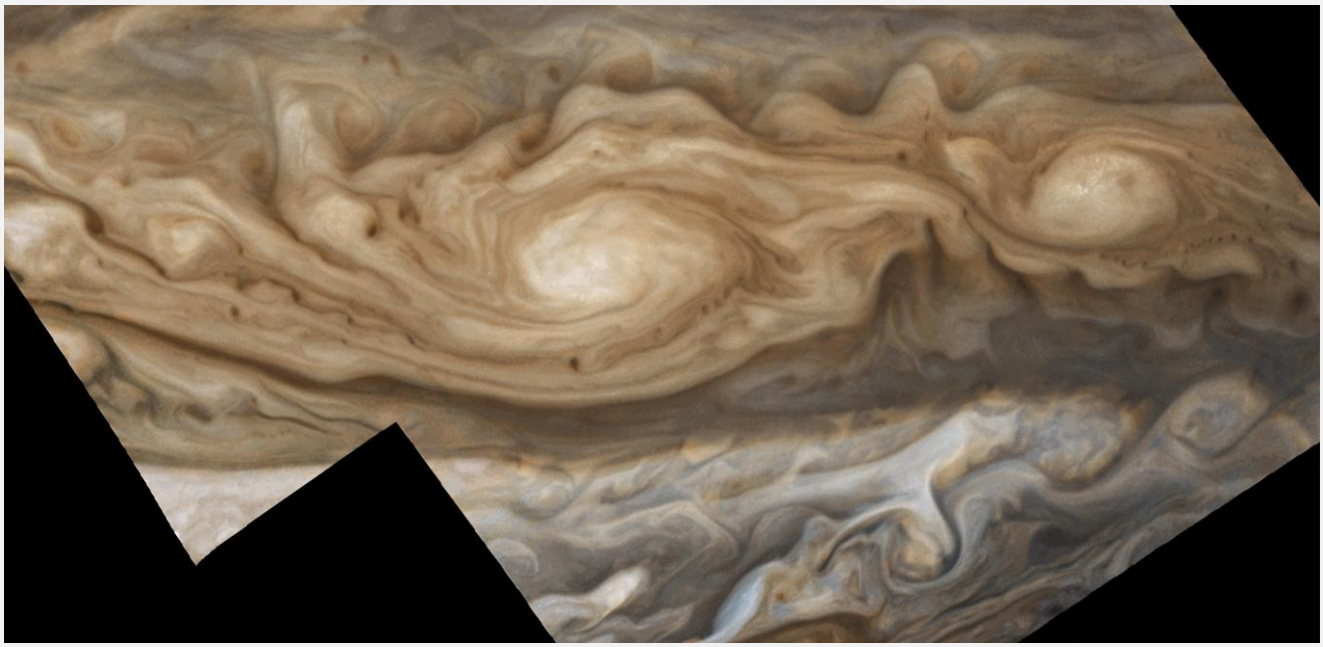


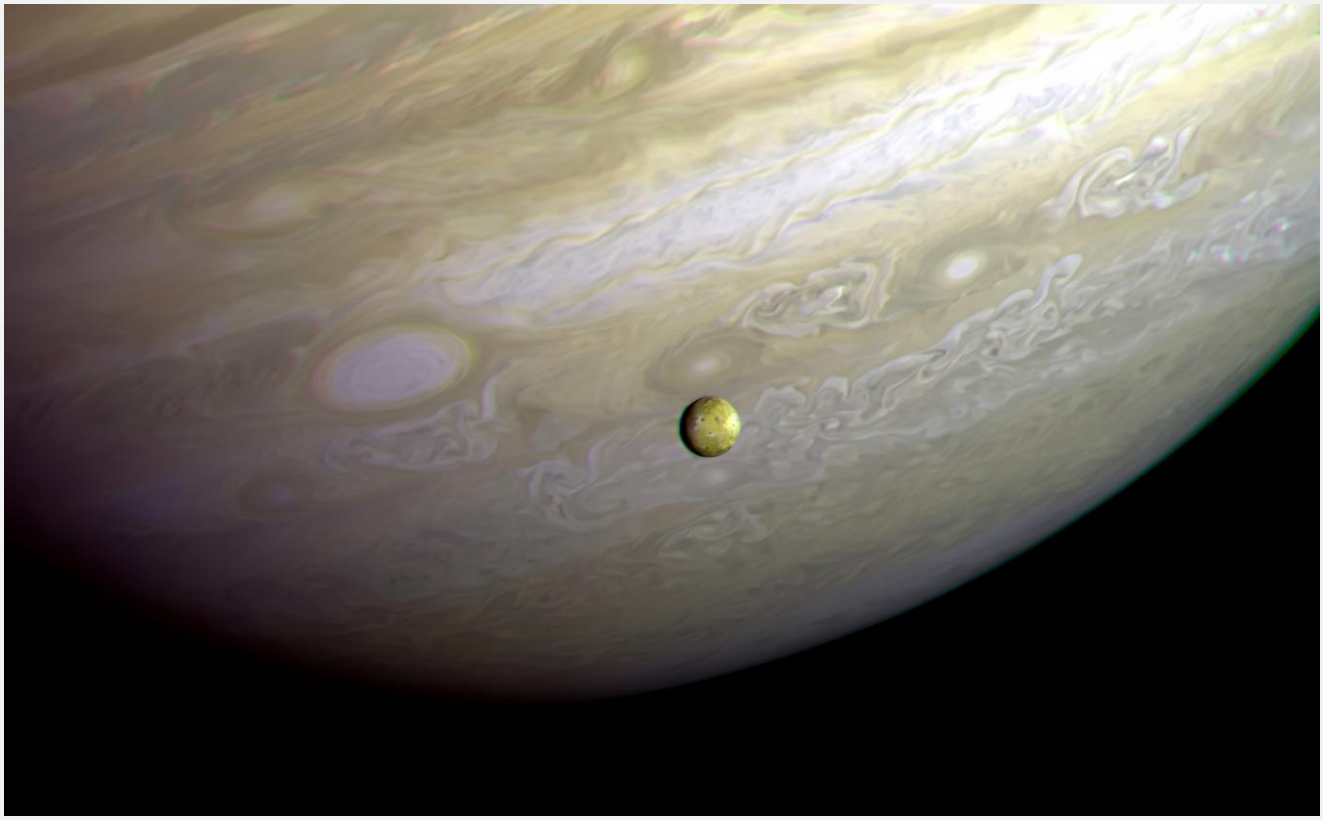
Above: The limb of Jupiter, white ovals and brown barges.
Images: NASA/JPL, Modern processing: (above) Björn Jónsson, (below) Justin Cowart
Below: Jupiter and Amalthea (small black dot above the two ovals)



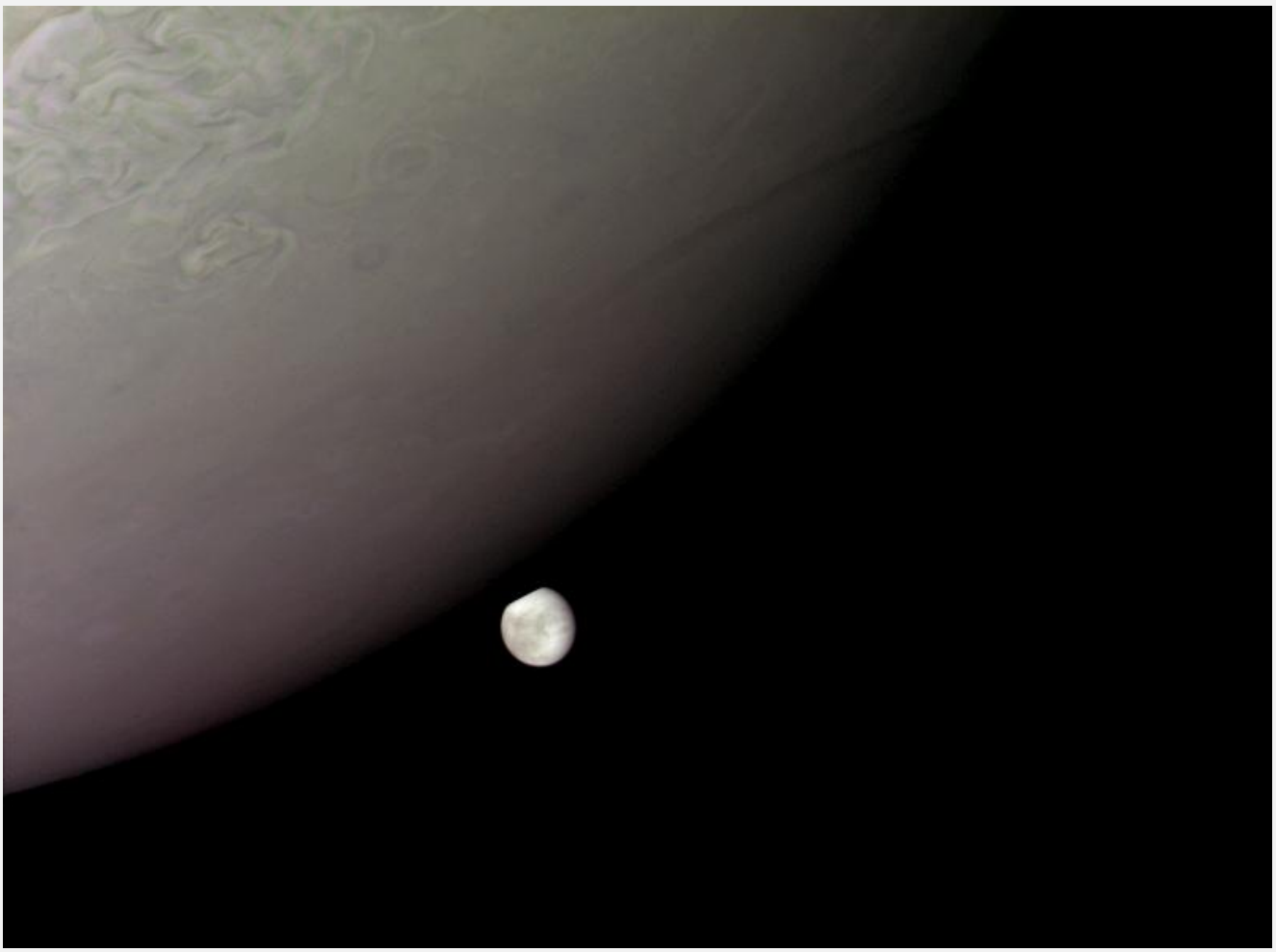


Above: The shadow of the moon Callisto on the surface of Jupiter's atmosphere.
Images: NASA/JPL, Modern processing: (above) Ian Regan, (below) Alexis Tranchandon
Below: Complex 3-dimensional cloud structures with bright peaks and darker troughs.





Above: The volcanic moon Io hovering in front of Jupiter's swirling clouds.
Images: (above) NASA/JPL, (below) NASA/JPL, Modern processing: Daniel Macháček
Below: The icy moon Europa peaks out from behind Jupiter.





Jupiter's Great Red Spot as seen by Voyager 2. Image: NASA/JPL

THAT GREAT RED SPOT AGAIN

The first feature that grabbed everyone's attention was the Great Red Spot (GRS), a Jovian feature known for at least three centuries.

A month before the encounter by Voyager 2 Jupiter was sporting a different face to that seen during Voyager 1's visit. The bright tongue extending upward from the Great Red Spot was interacting with a thin, bright cloud above it that had travelled twice around Jupiter in 4 months. The turbulent region west of the Great Red Spot had begun to break up and separate from it.

The white ovals south of the Great Red Spot had drifted to the east, while the GRS itself had drifted to the west. The white zone just south of the GRS seen by Voyager 1 had become very narrow.

The GRS itself had also changed – it had become a more uniform orange-red, possibly reverting back to the colours seen by Pioneers 10 and 11.

The brown spots in the north temperate region at the same longitude as the Great Red Spot were now on the other side of the planet.

A dark brown spot had developed along the northern edge of the brown equatorial region and some of the white markings that protruded into the equatorial region at the time of the first fly-by were missing in the Voyager 2 pictures.

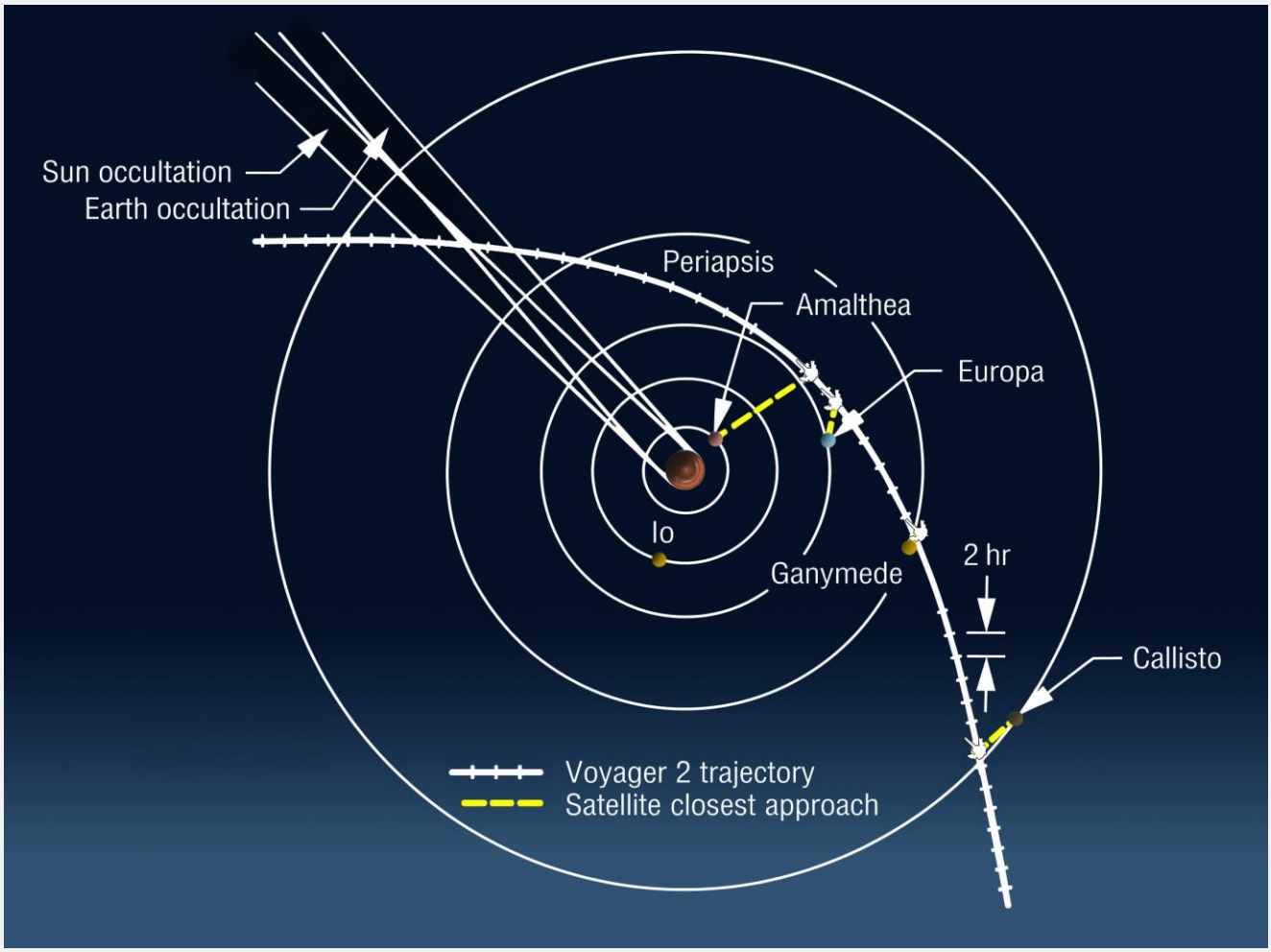
The back-up receiver doppler problem was in hand. Mission controllers discovered that the 'housekeeping' telemetry signals were sensitive to the match between the incoming frequency and the receiver frequency.

By monitoring these signals, they could detect a frequency drift in time to correct the transmitted frequency to keep the signal arriving at the spacecraft's receiver within the limits.

All the commands had been successfully loaded into the spacecraft's computer memory, and no communications difficulties were experienced during the encounter.

SKYLAB'S DEMISE INTERFERES WITH VOYAGER 2's MOMENTS OF GLORY

Just as they were entering their action period the Voyager team were chagrined to hear that the world's media were more interested in the fate of Skylab as it spun in its death throes over Australia during 12 July than their groundbreaking discoveries going on at Jupiter.



Voyager 2's trajectory through the Jovian system and major moon encounters. Graphic: NASA/JPL

VOYAGER 2

ENTERING THE REALM OF JUPITER'S MOONS

The first moon spotted and discovered^ by Voyager 2 was Adrastea on 8 July 1979.

ADRASTEA (S/1979J1)

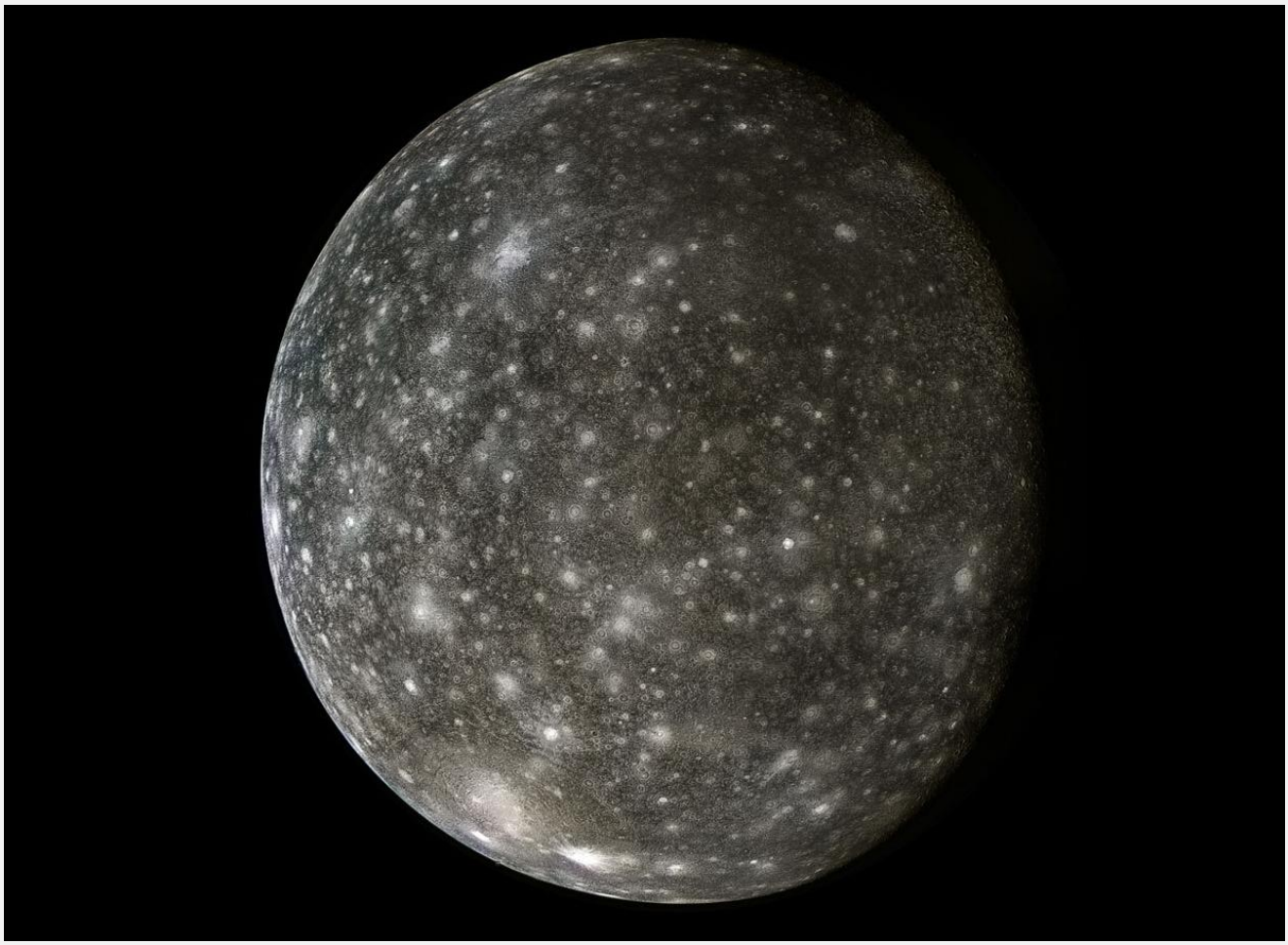
Diameter:	20 x 16 x 14 kilometres
Albedo:	0.1
Mass:	7.4933 x 10^{15} kilograms
Jupiter distance:	128,971 kilometres
Orbital period:	7hrs 9.5min Earth hours
Surface temp:	-151°C
Closest approach:	~ 570,000 kilometres

Voyager 2 discovered 1979J1, a new satellite orbiting 128,971 kilometres from Jupiter, 23 hours before closest approach. On 8 July 1979 Graduate student David Jewitt working with Ed Danielson of the Imaging team, both from Caltech, began a detailed analysis of all the ring photos. Jewett calculated its orbit with optical navigation engineer Stephen Synnott.

In early October 1979 Jewett looked more closely at a short streak in a picture taken on 8 July, previously thought to be a star. But it did not correspond to the position of any known star. A second image was found in another picture, and the differing angles and lengths of trails of the object confirmed it was a new satellite of Jupiter, skimming along the outer edge of the newly found ring.

In 1983 it was officially named Adrastea after the daughter of Jupiter and Ananke. With a mean diameter of 20 kilometres, it travels at 112,961 kilometres per hour along its orbit giving a period of 7 hours 9 minutes 30 seconds.

Editor's note: ^Following the discovery by Voyager 2, scientists went back and re-examined data taken by Voyager 1 during its flyby on 4 March 1979.
The imaging team successfully identified Adrastea as a single, pixelated dot straddling Jupiter's ring system, proving that Voyager 1, even at its extreme distance, had unknowingly imaged the tiny moon first.
One notable processed image from Voyager 1 captures Adrastea alongside the shadow of Io – which can be viewed on pg.34 in the Voyager 1 booklet in this series.



Voyager 2 captured this image of Callisto. Image: NASA/Caltech-JPL. Modern processing by Kevin M. Gill

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:	-193°C min / -108°C max
Closest approach:	214,886 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 -155°C, appears to be flat and very ancient, with signs of heavy bombardment by meteorites.

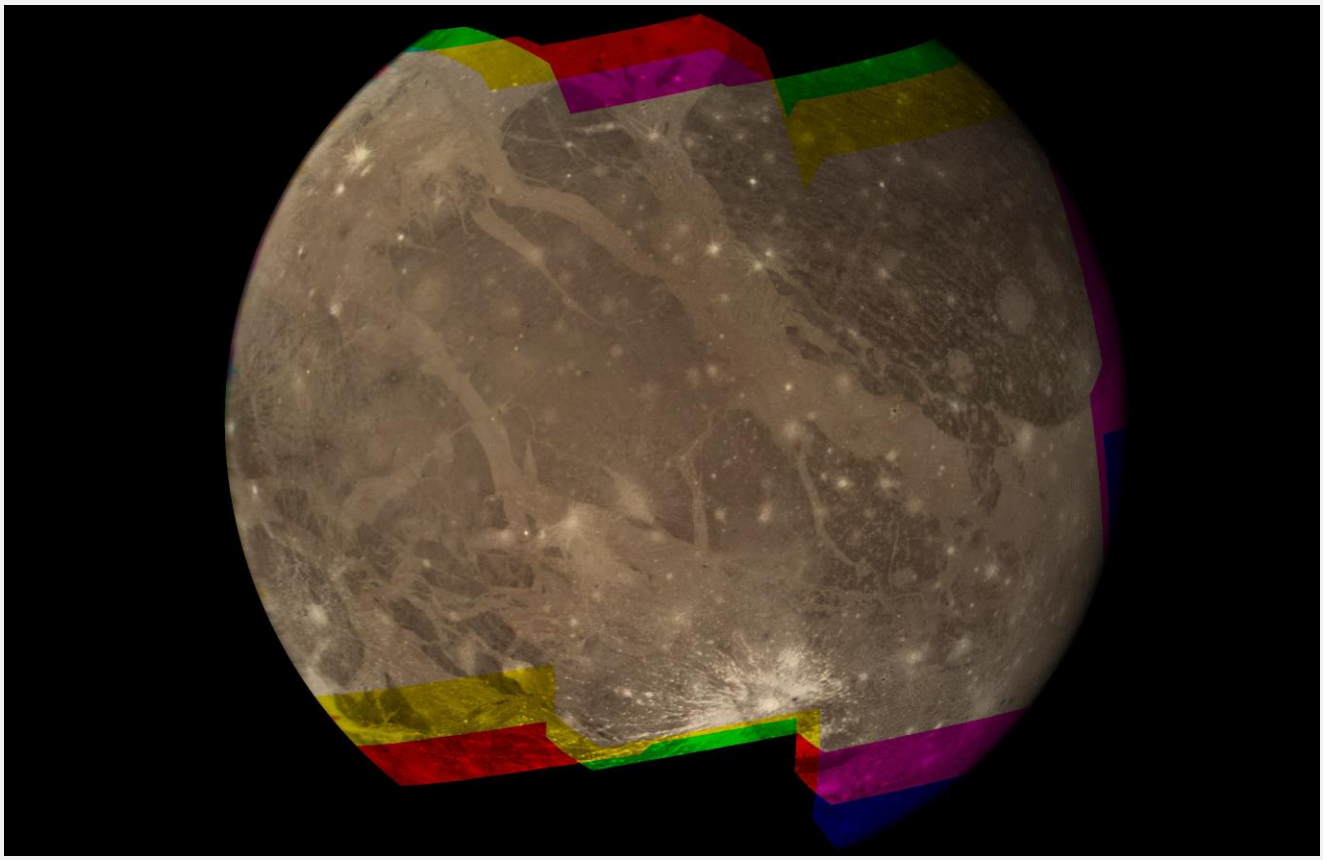
The interior seems to be composed of compressed rock and ice, with the amount of rock increasing with depth.

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 2's first study of Callisto began at 1924 AEST 8 July ending with 80 high resolution pictures that showed features that looked like double-walled craters but no more giant ring features. Closest encounter with Callisto was at 2222 AEST, closing to within 214,886 kilometres.

Scientists thought it was the most heavily cratered object in the solar system. British-born, Garry E. Hunt on the Imaging team commented,

"There's just not room for another crater on that body – it's totally full."



Orthographic projection of Ganymede's anti-Jovian hemisphere. Resolution is 2 kilometres per pixel.
Image: NASA/JPL. Modern processing: Constantine Thomas

GANYMEDE

Diameter:	5,262 kilometres
Albedo:	0.43
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:	62,300 kilometres

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 Callirrhoë, 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.

Ganymede, the largest moon in the solar system, was next on the list with an angle of view not seen by Voyager 1. Voyager 2 met Ganymede at 1730 AEST 9 July at a distance of 62,300 kilometres. Out of a total of 217 pictures, 69 were transmitted back to Earth in real time, the remainder recorded for later playback.

They showed a world of amazing variety – heavily cratered regions; long, parallel mountain ridges; mysterious narrow furrows looking like a grooves made by a giant rake; and white ejecta blankets from impacts that looked like a dazzling snow-covered landscape.

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 a temperature of -160°C.

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.



Europa mosaic from Voyager 2 photos. Image: NASA/JPL. Modern processing: Ted Stryk

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.

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.

EUROPA

Diameter:	3,151.6 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 at equator
Closest approach:	205,850 kilometres

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.

We began receiving close-up pictures of Europa just after midnight on 10 July with closest approach at 0354 AEST at a distance of 205,850 kilometres, closer by Voyager 1's encounter by 526,395 kilometres. With a resolution down to 5 kilometres, pictures of Europa showed a bright, icy crust covered by spectacular dark streaks reminding the observers of the shell of a cracked egg.

The closer high-resolution photos from Voyager 2, however, left scientists puzzled: The features were so lacking in topographic relief that as one scientist described them, they *"might have been painted on with a felt marker."*

There is a possibility that Europa may be internally active due to tidal heating at a level one-tenth or less than that of Io.

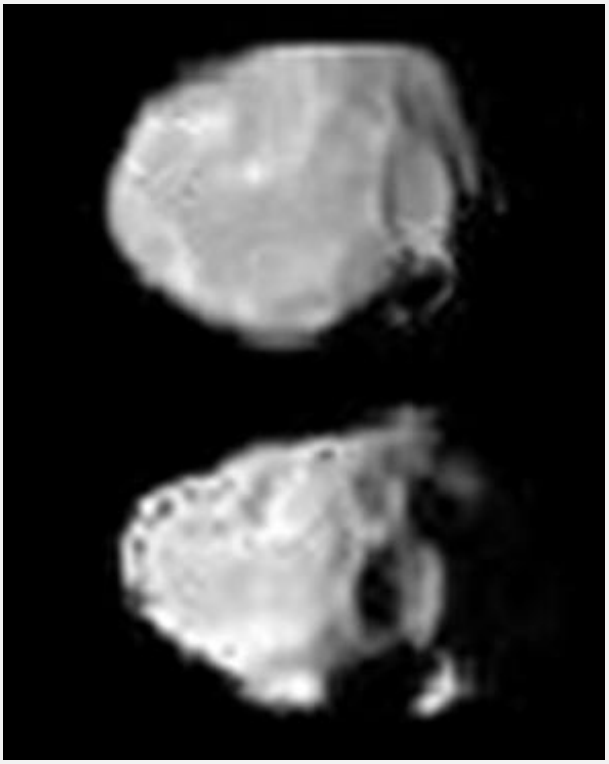
Despite its cracked appearance, Europa showed no topography at all, it was like a billiard ball. Larry Soderblom addressed the media that day with,

> *"Included in this Jovian collection of satellites are the oldest* (Callisto)*; the youngest* (Io)*; the darkest* (Amalthea)*; the brightest* (Europa)*; the reddest* (Amalthea and Io)*; the most active* (Io)*; and the least active* (Callisto)*. Today we found the flattest* (Europa)*."*

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:	558,600 kilometres

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 who nursed the new-born Jupiter. Amalthea is often depicted with a goat, whose milk is said to have fed the infant Jupiter.



Two views of Amalthea from Voyager 2's Wide Angle camera. Image: NASA/JPL

Amalthea is a potato shaped moonlet covered in a red coating. Only 270 by 160 kilometres, Amalthea orbits around Jupiter every 11 hours 57 minutes 23 seconds. 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.

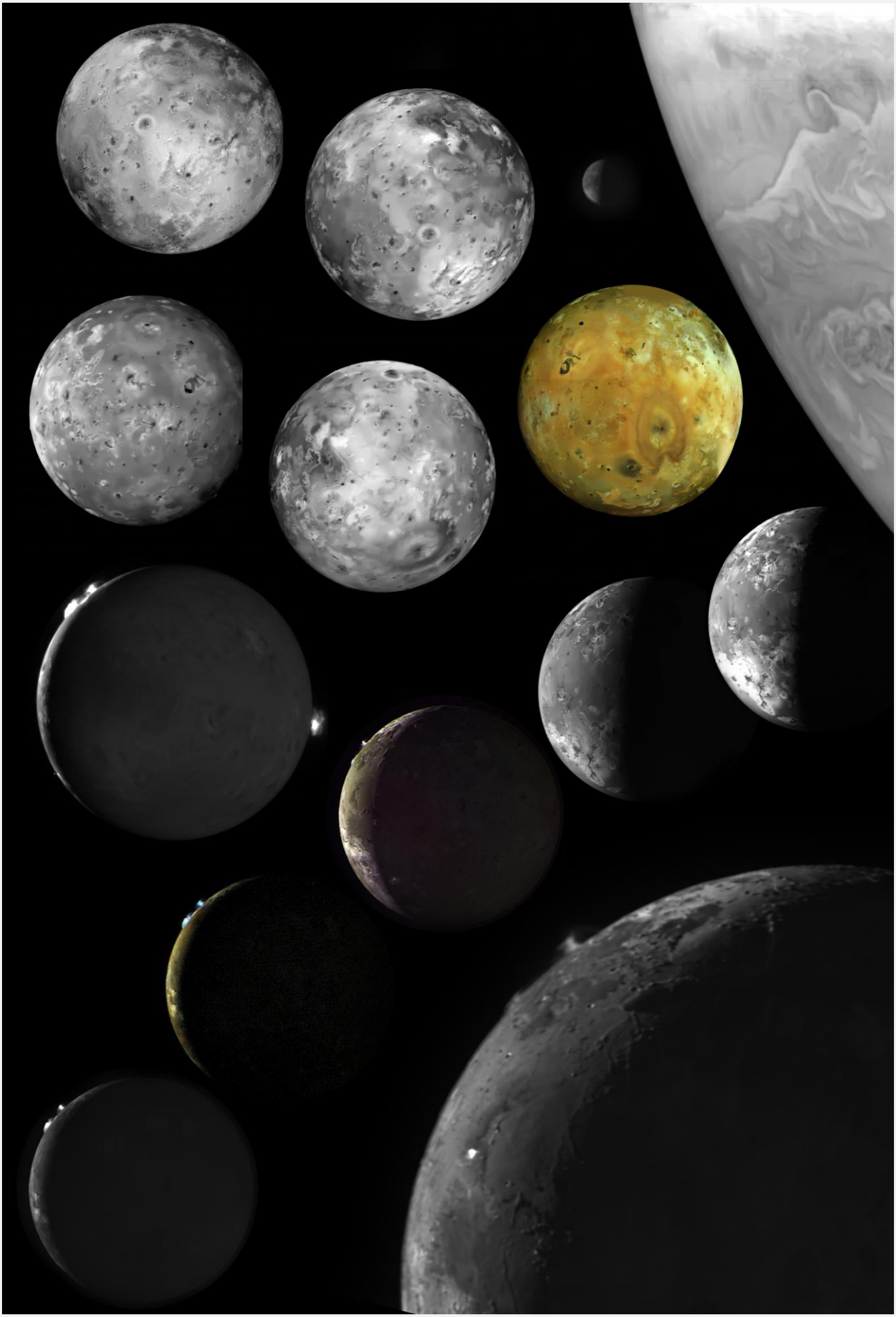
At 0602 AEST 10 July Voyager 2's cameras had their own look at Amalthea from a distance of 558,600 kilometres.

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

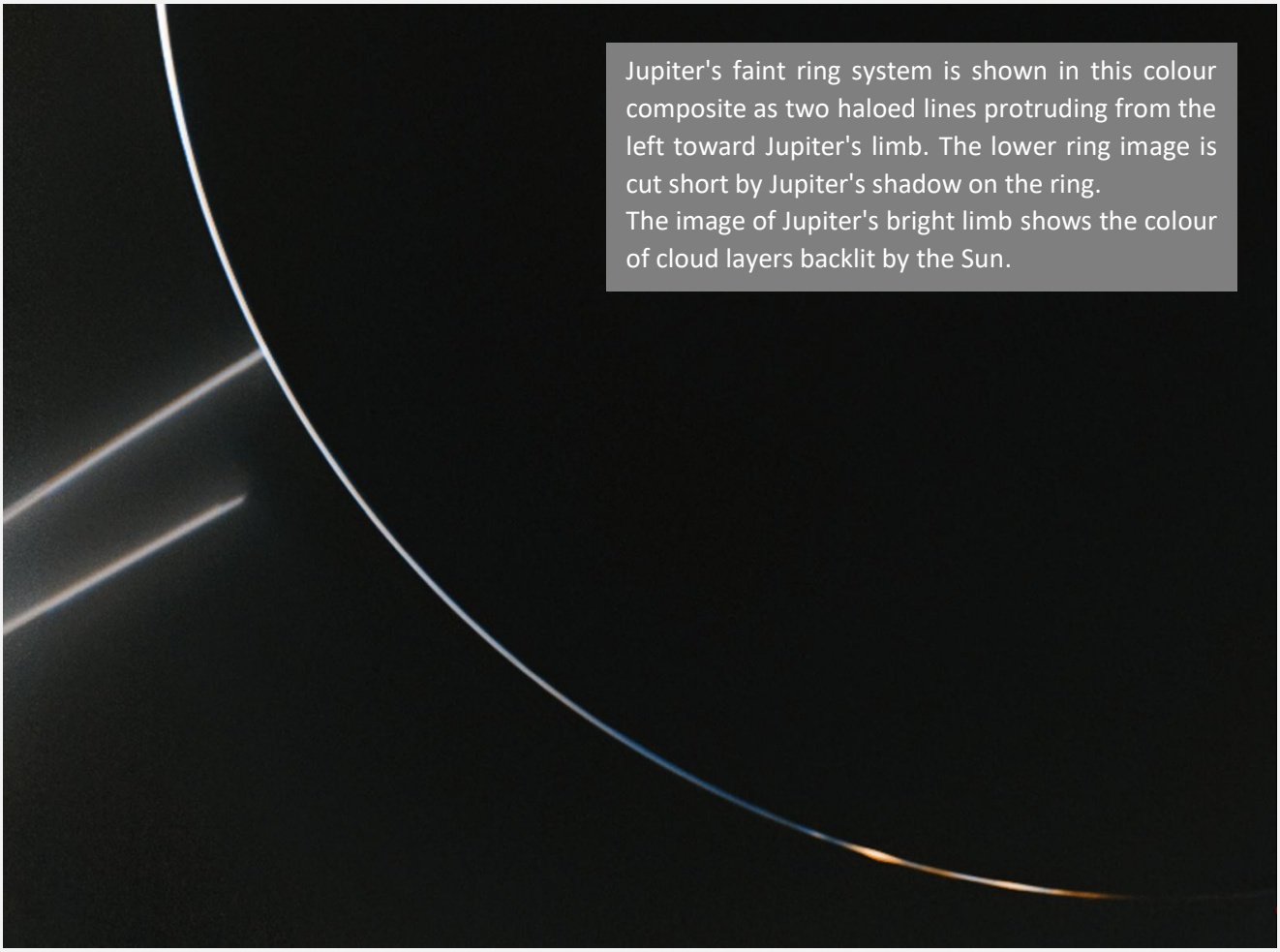
MOONLETS

	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)



Multiple observations of the moon Io (eye-oh) as seen by the Voyager 2 spacecraft. Images: NASA/JPL



Jupiter's faint ring system is shown in this colour composite as two haloed lines protruding from the left toward Jupiter's limb. The lower ring image is cut short by Jupiter's shadow on the ring.
The image of Jupiter's bright limb shows the colour of cloud layers backlit by the Sun.

VOYAGER 2

JUPITER – PCA – POINT OF CLOSEST APPROACH
0829 AEST – Tuesday, 10 July 1079

In the early Australian morning of 10 July at 0829:51 AEST Voyager 2 shot past Jupiter at a distance of 650,180 kilometres from the cloud tops at 73,000 kilometres per hour - not as close or as fast as Voyager 1.

IO - TEN HOUR IO VOLCANO WATCH

At 0839 AEST 10 July a ten-hour Io watch began, mixed with more observations of the rings, and dark side searches for auroras and lightning bolts.

As the 10-hour watch progressed Io rotated in the same direction as the spacecraft, keeping the same side facing the busy cameras. A few volcanoes were observed, but most were missed.

During the sequence the volcanic plumes could be seen on both edges, one in the setting Sun, and on the other side shining in the dawn light.

Plume P2 (Loki) was now the highest volcano on Io as P1 (Pele) seemed to have subsided.

Just after closest approach at Jupiter, Voyager 2 looked past the planet to Io on the other side from a distance of 1,129,850 kilometres at 0933 AEST.

The 10-hour Io watch ended at 1855 AEST.

EARTH AND SUN OCCULTATIONS

Earth occultation occurred from 0645 to 0832 AEST 11 July for 1h 47m followed by a Sun occultation from 0934 to 1212 AEST for 2h 38m

With only ring photography left, some of the team began to head for home and celebrations for another successful encounter. While in the shadow of Jupiter Voyager 2 began ring observations between 1016 and 1040 AEST, taking 6 long-exposure wide-angle pictures of the dark side of the giant planet from a distance of 1,450,000 kilometres, about 2^{o} below the equator. The first of these frames appeared on the TV monitors showing the rings with unexpected brilliance, and the remaining scientists gathered around the monitors with rising excitement. Seen from this new perspective the rings were remarkably clear, showing the outline of Jupiter and protruding from it two

narrow lines – one reaching all the way to Jupiter's rim, and one broken off, apparently hidden by the planet's shadow.

The wide-angle pictures were followed by telephoto shots showing more detail and for the first time a definite width for the rings could be seen, with a hint of additional material inside the main ring.

The two Voyager spacecraft took 33,000 images of the Jovian system, and added 4 new moons to the 12 already known to exist, though that number has since blown out to something like 63# moons and small satellites of which 48 are named (*at the time of writing*). A summary of the 16 main moons of Jupiter, listed at right, from the innermost to the outermost:

Editor's note: # According to NASA, as at August 2026, Jupiter has 115 moons that have been officially recognised by the International Astronomical Union (IAU), but that number doesn't capture the complexity of the Jovian system of moons, rings and asteroids.

The gas giant planet has thousands of small objects in its orbit.

Scientists are getting so good at spotting tiny moons orbiting the giant planets that the IAU has decided the smallest will no longer be given mythological names unless they are of "significant" scientific interest.

SUMMARY OF JUPITER'S MOONS AND SMALLER SATELLITES

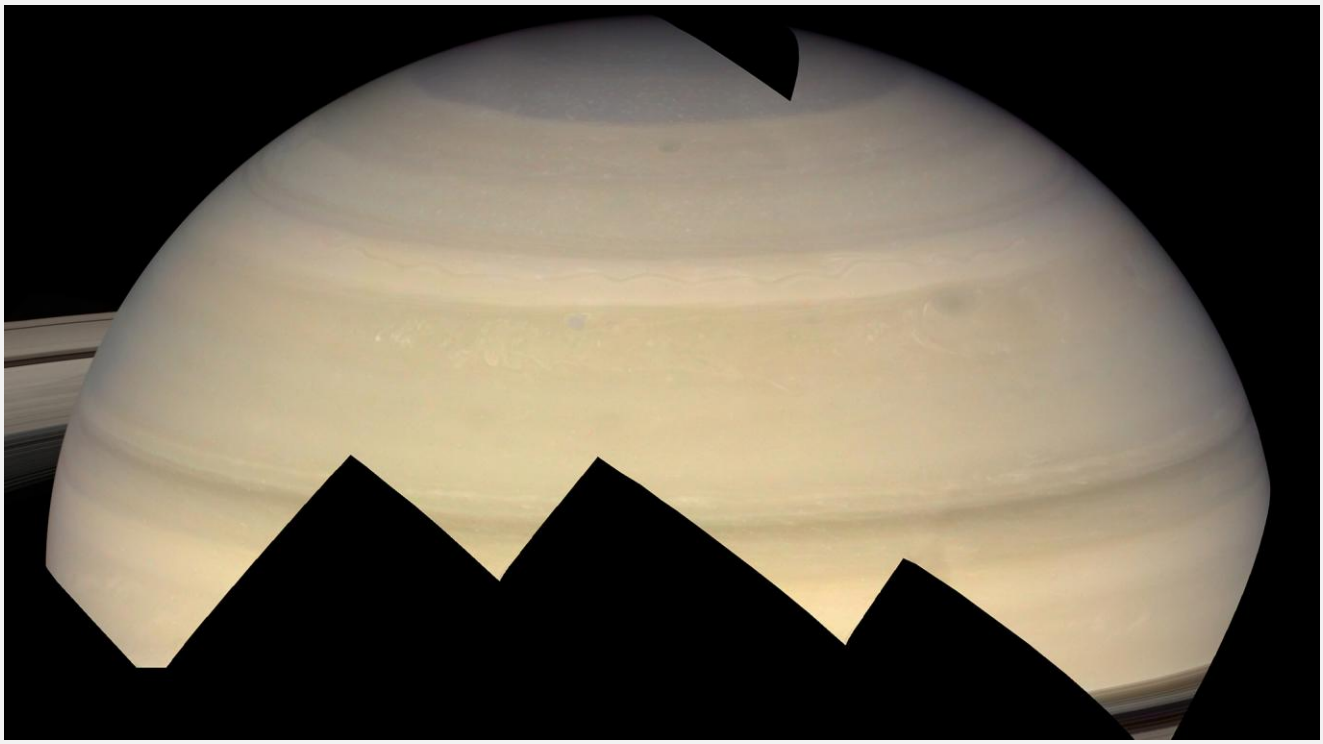
	Diameter kilometres	Kilometres from Jupiter's centre
Metis	43	128,000
Adrastea *	24x20x14	129,000
Amalthea *	270x166x150	181,300
Thebe	110x90	222,000
Io *	3,630	422,000
Europa *	3,138	661,000
Ganymede *	5,262	1,070,000
Callisto *	4,800	1,883,000
Leda	16	11,094,000
Himalia	186	11,480,000
Lysithia	36	11,720,000
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 2 observed the moon.



SUMMARY OF JUPITER ENCOUNTER – 24 APRIL - 11 JULY 1979

Date	AEDT	Distance*	Event/Closest Approach
April 24			Observatory phase began
May 28			Far encounter period began
July 2		6,921,189	First contact with bowshock
July 8	22:22	214,886	Callisto
July 9	17:15	62,300	Ganymede
July 10	03:54	205,850	Europa
	06:02	558,600	Amalthea
	08:51:21	**721,670**	**Jupiter**
	08:39		Begin Io volcano watch
	09:18	1,129,850	Io
	18:55		End Io volcano watch
July 11	06:30		Enter Earth occultation
	08:17		Exit Earth occultation – 1 hour 47 minutes
	09:19		Enter Sun occultation
	11:57		Exit Sun occultation – 2 hours 38 minutes
		One-way signal elapsed time was 51 minutes	
		* from Jupiter's centre (kilometres)	



Saturn's beige but complex atmosphere. Image: NASA/JPL, Modern processing: Björn Jónsson

VOYAGER 2

SATURN ENCOUNTER

The close range views of the clouds of Saturn by Voyager 2 showed jet streams racing along at up to 1,800 kilometres per hour along the equator.

In November 1990 the Hubble Telescope spotted a rare equatorial storm that ran right around the planet in an easterly direction, suspected to go as deep as 2,000 kilometres.

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 there was no real time pictures, the images from the cameras were a string of codes passing by us. Also, all the pictures received had happened 1 hour 26 minutes ago.

Voyager 2 followed roughly the same trajectory as Pioneer 11, crossing the ring plane at approximately the same point. Many of Pioneer's findings influenced the Voyager planning. As a result of Voyager 1's visit mission planners made many changes to the original tasks to be performed by Voyager 2. Voyager 2's emphasis was on the rings, in particular the F Ring.

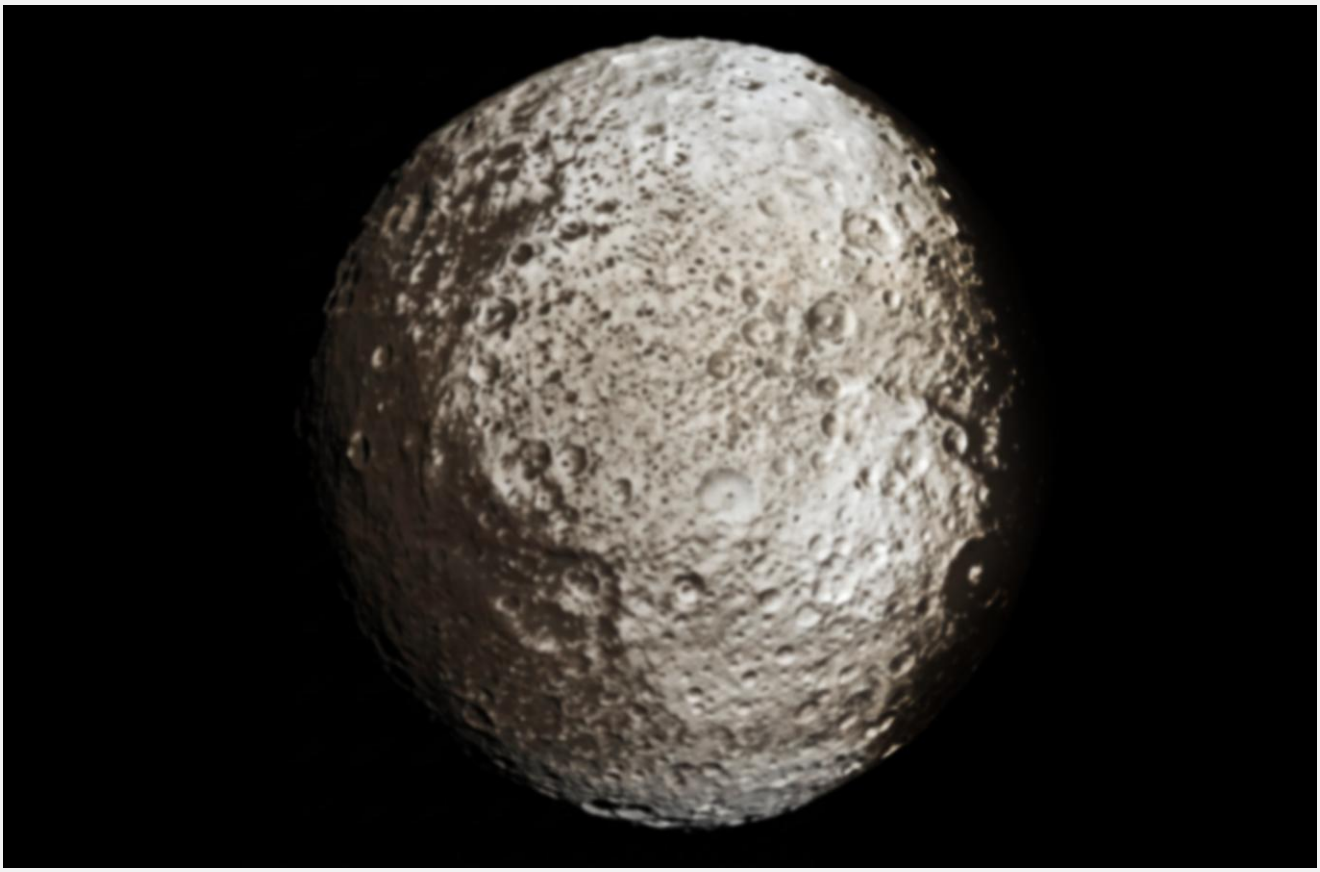
Voyager 2 began its encounter with Saturn on 5 June 1981 with a ten week observatory phase. Project scientist Ed Stone offered that Voyager 2's visit would provide a better look at Saturn than Voyager 1, as the spacecraft would come closer to the planet, would see the lighted side of the rings and its Photopolarimeter experiment was operational (Voyager 1's had failed).

The photopolarimeter enabled the scientists to observe the occultation of a bright star through the rings. By measuring the variations in starlight through the rings the scientists would be able to map the distribution of particles with a resolution up to 20 times better than the best previous images.

> Journalist Jim Loudon lamented, *"With the first encounter by Voyager 1 things that happened were easy to make into news stories, enough to fill a column. Now it's different – you can't write story about that now. This time the pictures are being taken to find out why there are a thousand rings – and we can't answer that instantly."*

Voyager 2 flew closer to Enceladus, Tethys, Hyperion, Iapetus and Phoebe than Voyager 1, but was also able to study Mimas, Dione, Rhea and Titan, though from greater distances.

Travelling at a million kilometres per day, or 11.6 kilometres per second, Voyager 2's visit began with a look at the moon Iapetus, the outermost of the large icy satellites.



Voyager 2 view of Iapetus through its Narrow Angle Camera. Image: NASA/JPL

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:	909,070 kilometres

The first object Voyager 2 met at Saturn was the moon Iapetus, circling the planet at a distance of 3,559,400 kilometres.

Voyager 1 only had a distant view of Iapetus on 14 November 1980, the closest it came was 2,474,000 kilometres. Voyager 2 approached within 909,070 kilometres at 2329 AEST on 22 August 1981, so was able to resolve features down to 20 kilometres across.

Even Cassini had noticed something unusual about the moon – it had a varying albedo.

Voyager 2 confirmed this with pictures showing a striking contrast between the trailing icy surface and the dark leading hemisphere, somewhat like the difference between clean snow and asphalt.

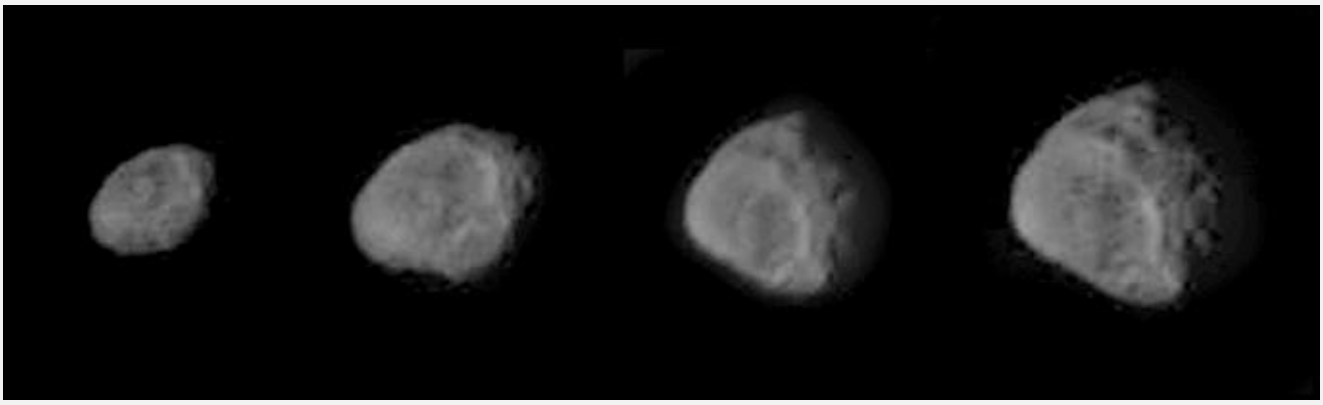
With about a tenth less albedo, the reddish darker surface showed very little detail, whereas the icy part seemed to be heavily scarred with impact craters. Pictures showed white spots in the dark area and vice versa along the border, suggesting the dark coating may be quite thin.

Three days after Iapetus, Voyager 2 passed by Hyperion at 1126 AEST on 25 August at a distance of 470,000 kilometres with a resolution down to 10 kilometres.

The sponge–like object 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. Initially it seemed that the moon's longest axis did not point towards Saturn, which was against all theories and Scientist Ed Stone checked,

"Are you sure you know where Saturn is?"

It turned out Hyperion has a chaotic rotation, in fact, so chaotic that its orientation in space is unpredictable. It is the only moon in the solar system known to have this feature, as well as not to be tidally locked to its planet. It is, however, locked into a relationship with Titan – for every three orbits of Saturn it makes, Titan makes four.



Four views of Hyperion from Voyager 2 at a distance of 470,000 kilometres. Images: NASA/JPL

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:	470,000 kilometres

Voyager 2 could only photograph Hyperion from a distance – it took the Cassini spacecraft to fill in more details in 2005 with a fly-by coming within 500 kilometres, with another pass in 2006.

The Voyager 2 pictures showed a strange looking moon with its irregular shape, almost looking like a potato. Its surface looks like a sponge with one crater 121.6 kilometres in diameter and 10.2 kilometres deep. Dark reddish material fills the bottom of the craters. The moon's low density suggests it is composed mainly of water ice and a small amount of rock, with 46% of the moon's porous volume empty space.

SATURN'S ATMOSPHERE AND AURORAS

While Voyager 2 was behind Saturn, its radio signal penetrated the upper atmosphere, and measured temperature and density. Minimum temperatures of –191.2°C were found at the 70-millibar level (surface pressure on Earth is 1,000 millibars).

The temperature increased to -130.2°C at the deepest levels probed -- about 1,200 millibars. Near the north pole temperatures were about 10°C colder at 100 millibars than at mid-latitudes. It is suspected the difference may be seasonal.

The Voyagers found aurora-like ultraviolet emissions of hydrogen at mid-latitudes in the atmosphere, and auroras at polar latitudes (above 65 degrees). The high-level auroral activity may lead to formation of complex hydrocarbon molecules that are carried toward the equator. The mid-latitude auroras, which occur only in sunlit regions, remain a puzzle, since bombardment by electrons and ions, known to cause auroras on Earth, occurs primarily at high latitudes.

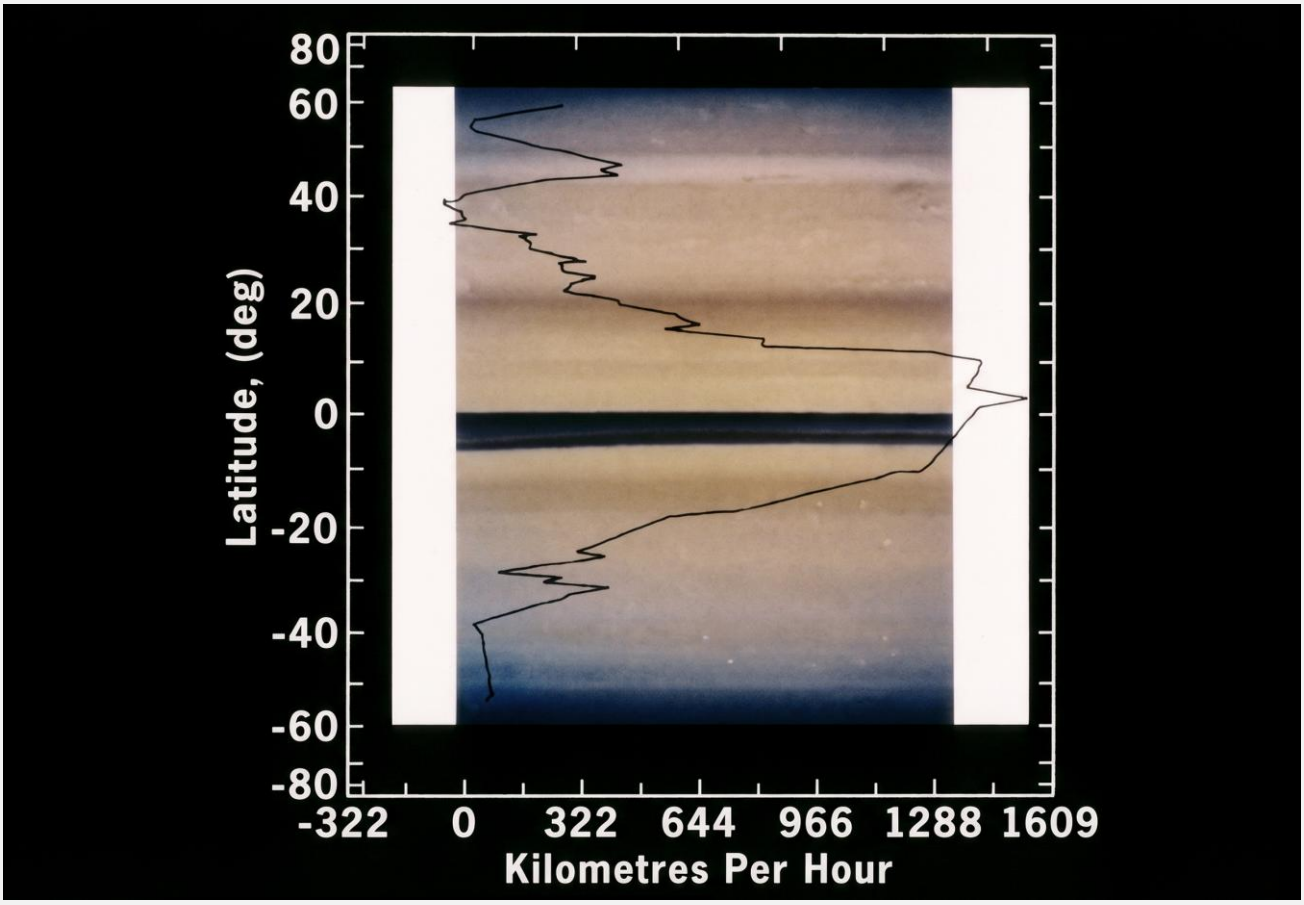
SATURN'S HIGH SPEED WINDS

Saturn's atmosphere turned out to be a bit disappointing after the colourful bands of Jupiter. Although banding did exist, the colour pictures revealed a dull, buff coloured planet with faint darker bands cutting across the planet parallel to the equator. Some oval spots were detected, but none as dramatic as Jupiter's.

Near the equator though, the Voyagers measured winds about 1,800 kilometres per hour (500 meters a second!) to at least a depth of almost 2,000 kilometres below the cloud tops. You wouldn't want to land at Saturn's equator carrying bits of paper!!

The winds blow mostly in an easterly direction. Strongest winds are found near the equator, and velocity falls off uniformly at higher latitudes. At latitudes greater than 35°, winds alternate east and west as latitude increases. Marked dominance of eastward jet streams indicates that winds are not confined to the cloud layer, but must extend inward at least 2,000 kilometres.

Furthermore, measurements by Voyager 2 showed a striking north-south symmetry that leads some scientists to suggest the winds may extend from north to south through the interior of the planet.



Variations in wind speeds measured across Saturn's varying latitudes. Graphic: NASA/JPL

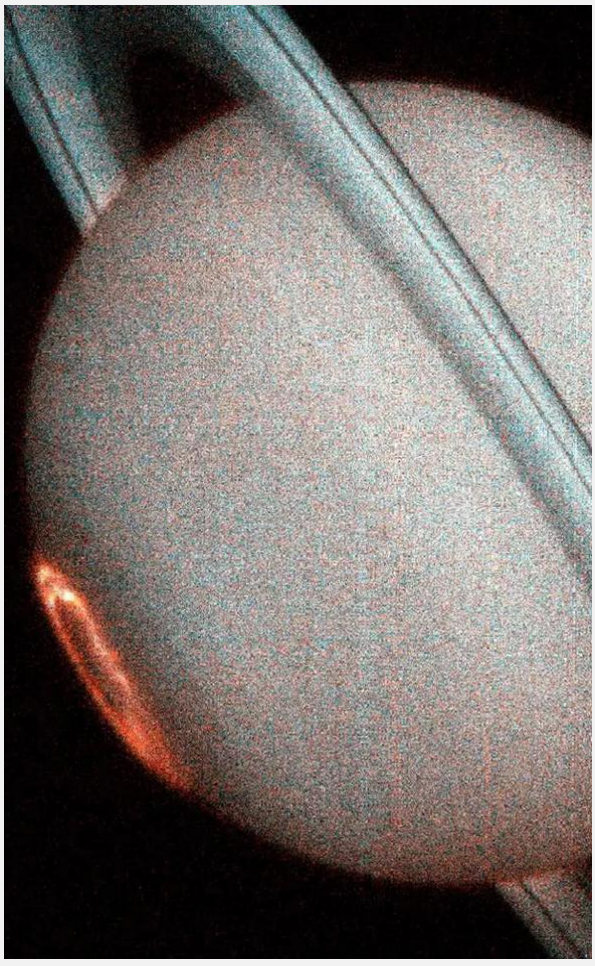
Using radio emissions from the planet, Voyager 2 found that Saturn spins once every 10 hours 39 minutes and 15 seconds, more than twice as fast as the Earth. The winds hurtling around Saturn's equator are three times as fast as Jupiter's, and ten times faster than a hurricane on Earth.

Saturn's density is less than that of water, so if there were an ocean big enough, we would be awed by the sight of the whole planet floating in the sea of water.

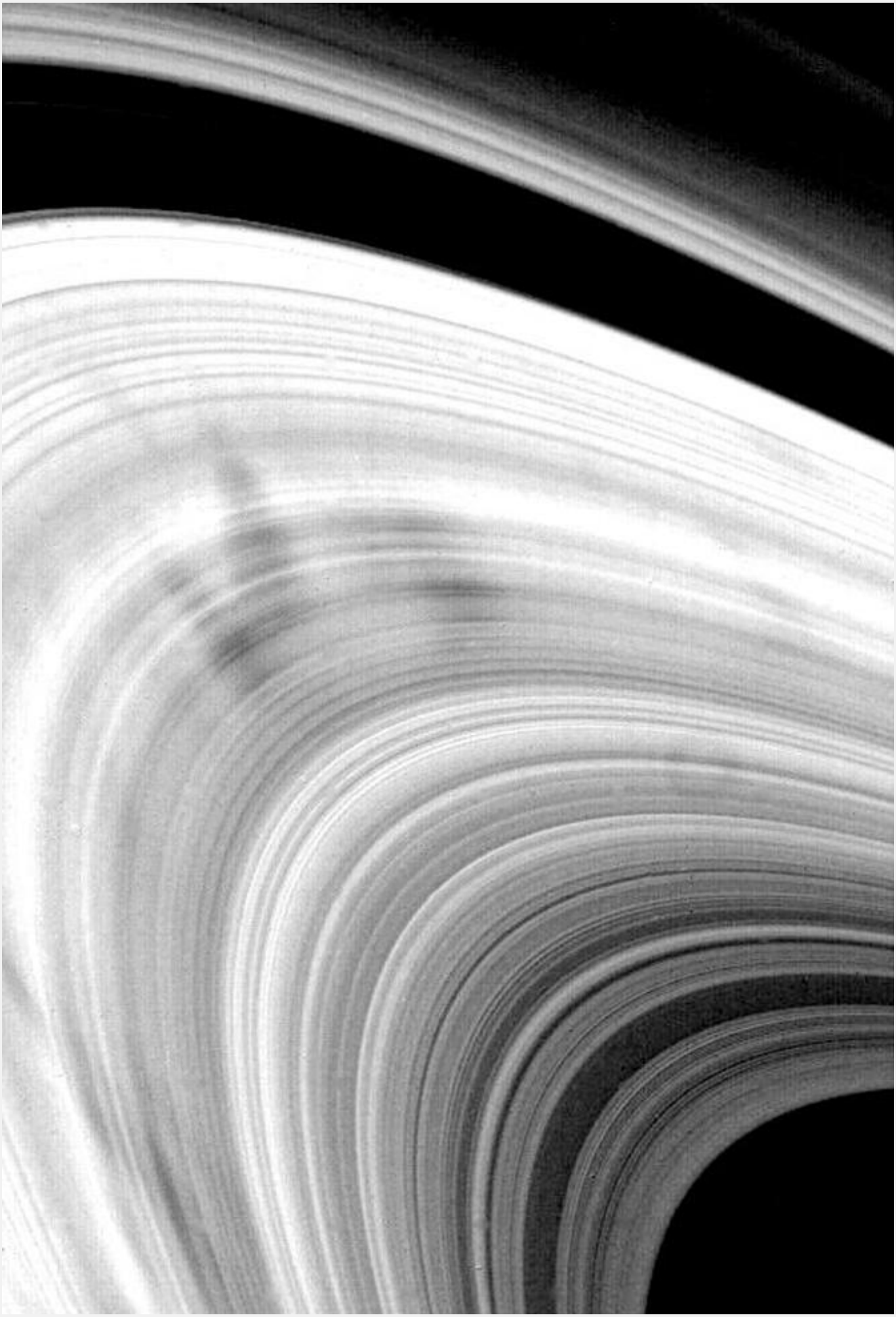
As Voyager 2 homed in on the rings, the six known rings became hundreds, then thousands of thin ringlets. The Cassini Division, previously thought to be empty, was found filled with ringlets. After the spacecraft went behind the rings the ring particles were measured to be 7.6 metres down to 1.8 metres in diameter.

Spokes of dark radial shadows were seen by the Voyager cameras.

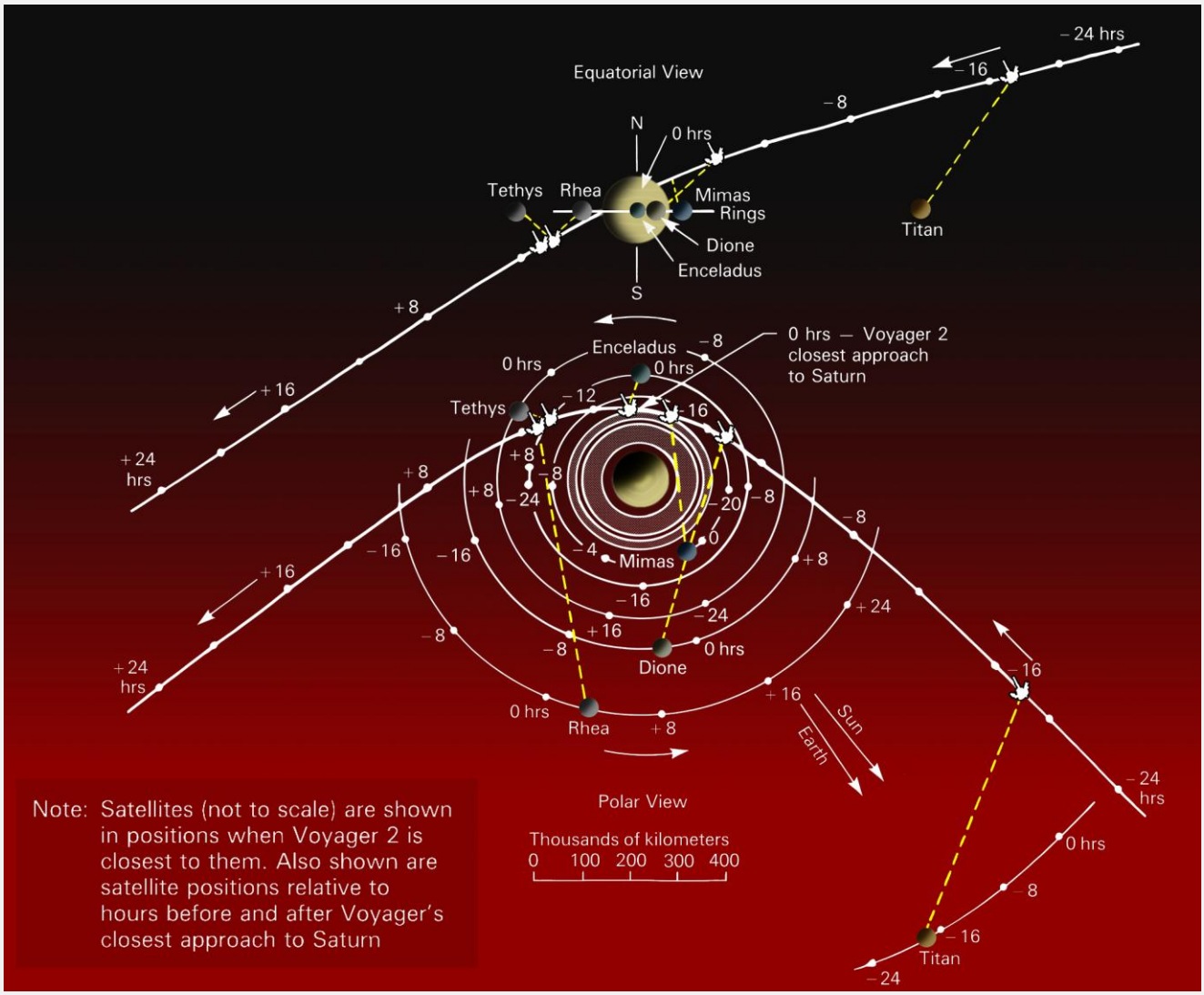
The Voyagers took the moon count from 10 to 18, varying from Atlas, only 137,600 kilometres from the planet to Phoebe way out at 12,874,400 kilometres, though the current count is 31 moons and satellites.



Aurora via Hubble Telescope. Image: NASA/STScI



Voyager 2 provided new data and views of Saturn’s spectacular rings and mysterious spokes. Image: NASA/JPL



Voyager 2's trajectory through the inner Saturnian system. Graphic: NASA/JPL

Following the results of Voyager 1's visit, from August the Deep Space Network began to provide 24 hour support for Voyager 2 to cover all the events coming up.

23 August 1981

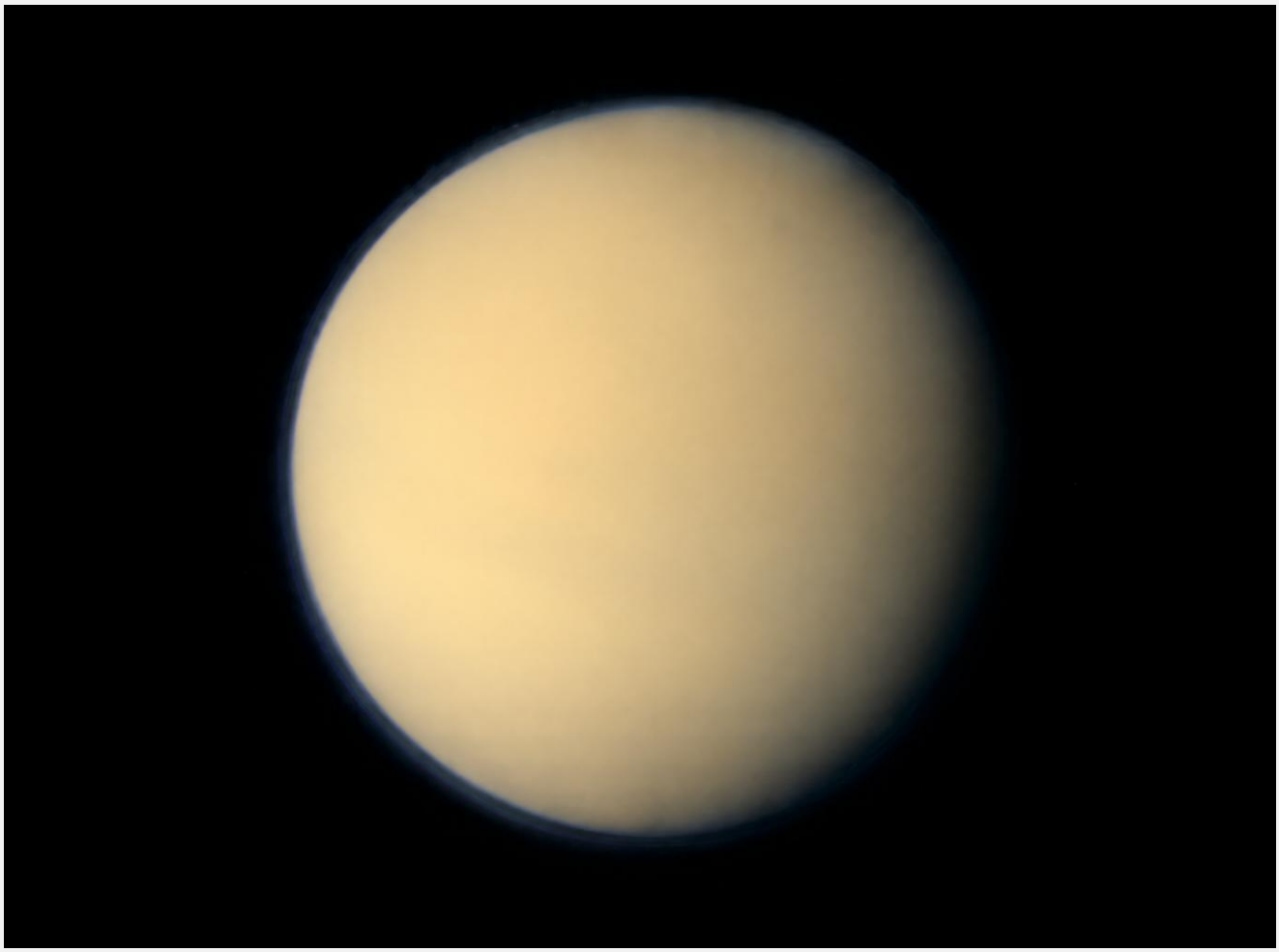
The first object Voyager 2 encountered at Saturn was Iapetus, a small world divided into bright and dark halves. The trailing bright half was peppered with craters. The leading dark side revealed little detail in any of the Voyager pictures. The symmetry of the divide between dark and light may infer that it is caused by material impacting the leading edge of the moon.

The spacecraft passed over the north pole of the icy moon at 1133 AEST at a distance of 910,000 kilometres. The previous best estimate of the moon's mass was from Pioneer 11, but the uncertainty of the data meant a meaningful figure for the density could not be calculated. As the gravitational pull of Iapetus bent the trajectory of Voyager 2 slightly, a more accurate figure was calculated, and a new radius of 744 kilometres was worked out from the images, 20 kilometres larger than the Voyager 1 estimate. The new data indicated that the moon is nearly pure ice.

At this distance the surface of Saturn was still showing a bland, featureless face, and this was not an atmospheric haze, but the clouds were intrinsically less colourful and had less contrast than Jupiter.

It seems that Jupiter has something in its atmosphere to keep the different coloured clouds separate, whereas Saturn either has less intense colours in the first place or the circulation of the atmosphere tends to mix the clouds, producing an almost uniform butterscotch colour.

The last commands for the scan platform were generated and sent to the Voyager 2 spacecraft on 24 August.



Voyager 2's image of Titan and its hazy atmosphere. Image: NASA/JPL, Modern processing: Gordan Ugarkovic

On its in-bound journey Voyager 2 could see as far south as 40°S latitude. Now the entire southern hemisphere from equator to pole were visible, while views of the northern hemisphere were blocked by the rings.

26 August 1981

At 0105 AEST, 1,910,495 kilometres from the planet, the data from the spacecraft indicated it had passed through the planet's bow shock, but it seemed highly unstable, oscillating back and forth. Voyager 2 crossed it again at 0435, at 0556, at 1000 and finally for the last time at 1152 at a closing distance of 1,325,896 kilometres.

Andy Ingersoll, an atmospheric dynamitist, predicted from the Voyager 1 encounter where Saturn's long term storms it saw would be nine months later. The Voyager 2 images coming in confirmed almost all of his predictions.

The scan platform was busy studying the rings and searching for inner satellites. The scientists were particularly interested in images of Enceladus, the moon that had seemed so bright but lacked large craters from the Voyager 1 visit. At 1126 AEST Voyager 2 took some high-resolution images of Hyperion at a distance of 470,000 kilometres.

Just after 0600 AEST of 26 August Voyager 2 reached the magnetopause, which was so compressed by the solar wind pressure that it lay inside Titan's orbit.

TITAN

Diameter:	5,150 kilometres
Albedo:	0.22
Mass:	1.345 x 10^{23} kilograms
Saturn distance:	1,221,850 kilometres
Orbital period:	15.95 Earth days
Surface temp:	-180°C
Atmos. pressure:	1.5 bars (at the surface)
Closest approach:	665,000 kilometres

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 1 flew within 6,490 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.

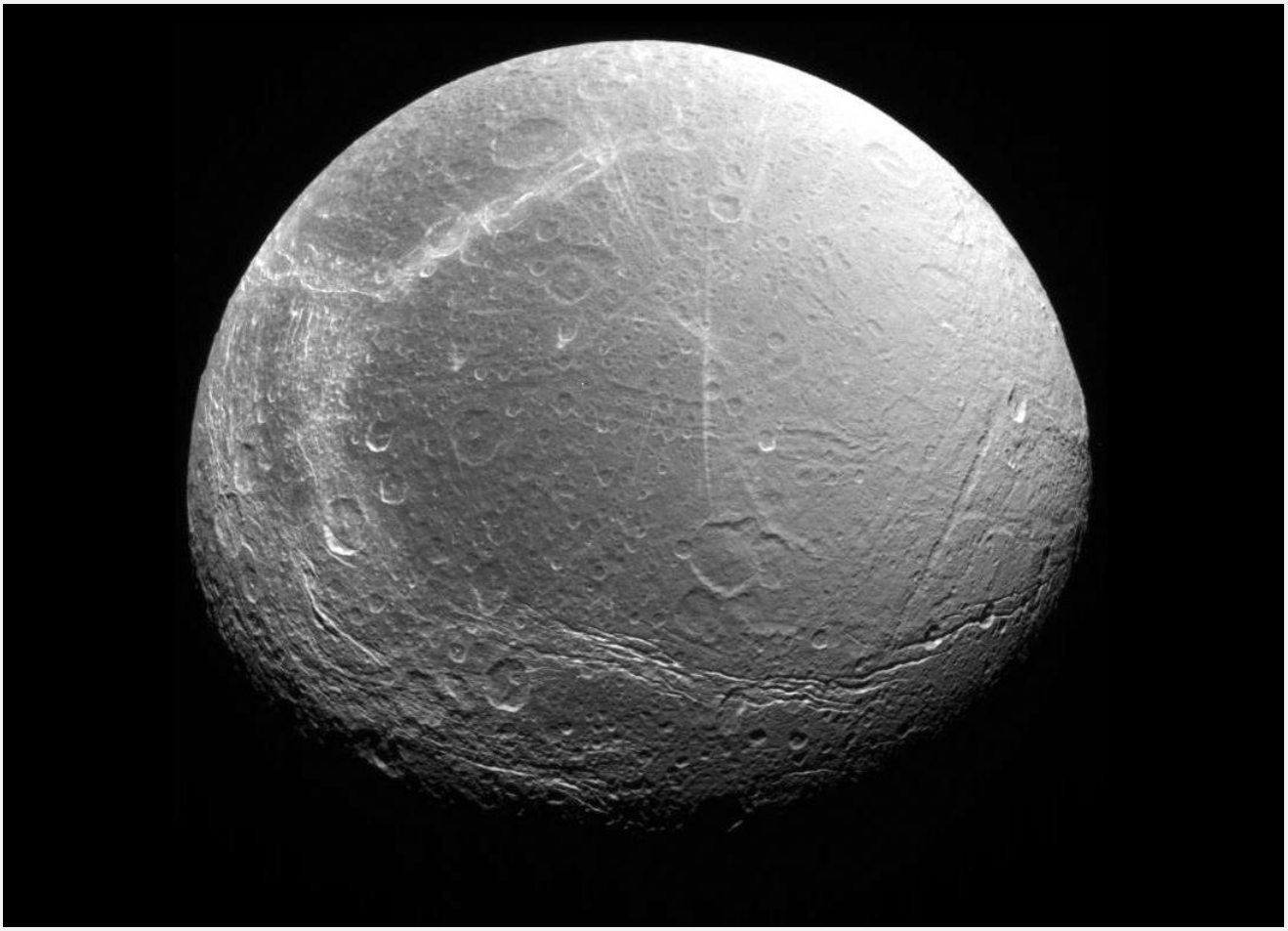
Titan, Saturn's largest moon, is the only Solar System planetary body other than Earth with a thick nitrogen atmosphere. The Voyager spacecraft confirmed that methane was the second-most abundant atmospheric constituent in Titan's atmosphere, and revealed a rich organic chemistry, but its cameras could 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 2 passed Titan at 1937 AEST 25 August at a distance of 665,000 kilometres.





Dione (Dye-Oh-nee). Image: NASA/JPL

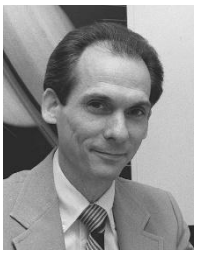
DIONE

Diameter:	1,122 kilometres
Albedo:	0.998
Mass:	1.09545 x 10^{21} kilograms
Saturn distance:	337,400 kilometres
Orbital period:	2.736 Earth days
Surface temp:	-186°C
Closest approach:	502,000 kilometres

Dione is named after the Titaness Dione of Greek mythology, and was first discovered by Giovanni Cassini in 1684 on the same night he first spotted Tethys.

> 1980S6 (Dione B) at 0904 AEST 26 August at a distance of 318,000 kilometres.

At the crowded media briefing on the morning of 23 August at JPL, while Voyager was still 3 million kilometres from the planet, Deputy Project Manager Ek Davis announced that the final navigation analysis showed that Voyager 2 would arrive 3 seconds ahead of schedule and within 50 kilometres of the target point.



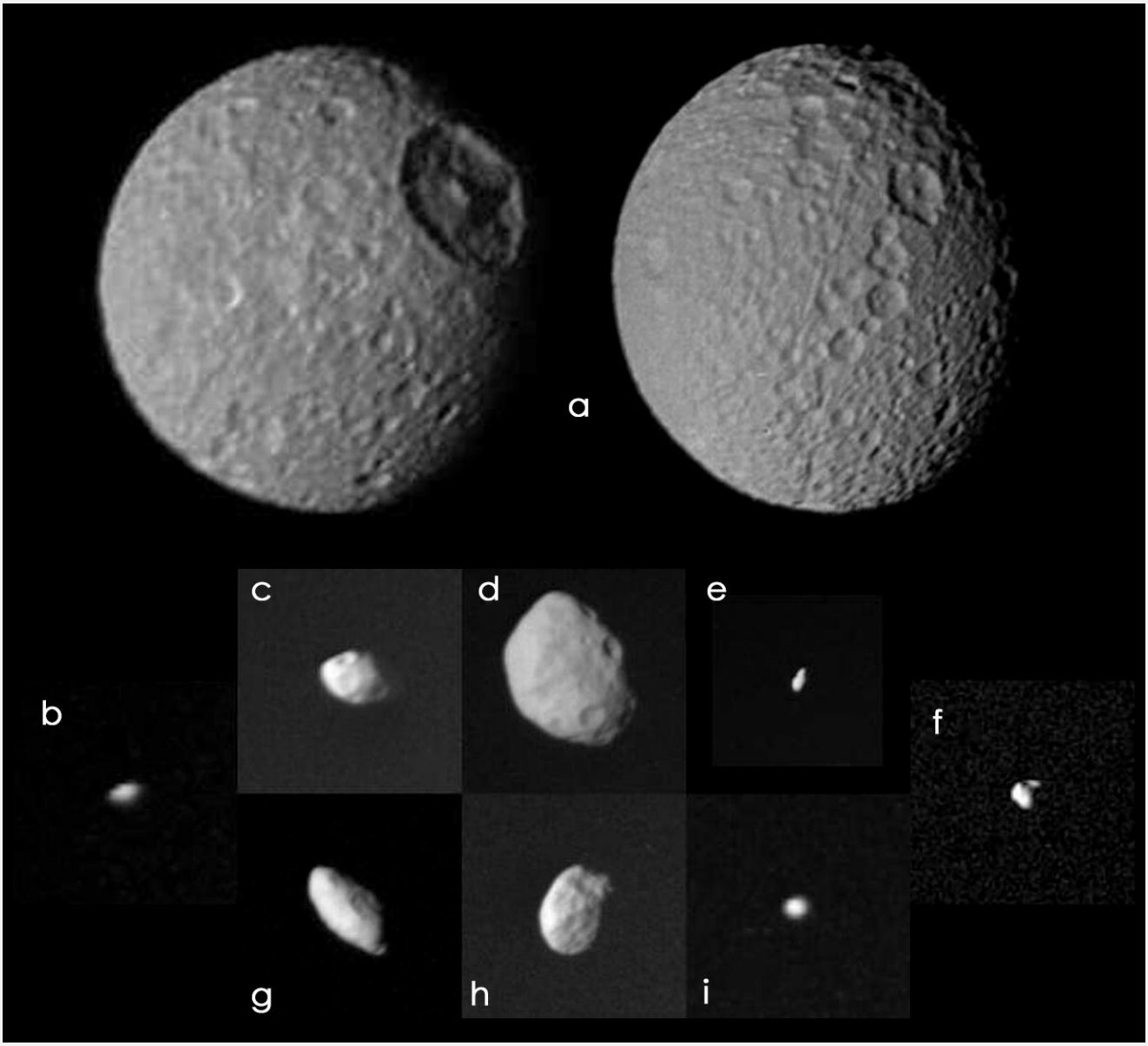
Project scientist from Caltech Ed Stone added,

"The images of the rings we receive today will be of much higher resolution than anything we have ever seen before."

At 1218 AEST, right on schedule, the light from the star Scorpii was received from Voyager and 22 minutes later the star began to dim as it passed behind the C-Ring. By 1340 a profile of 82,000 kilometres of the Rings had been obtained that would require 800 metres of chart paper to document at 10 points per centimetre.

With that experiment completed the cameras were turned on again for a look at the moon Enceladus before occultation and the Ring Plane crossing. At this point nobody had any qualms about the crossing because Pioneer 11 had successfully negotiated it at that distance before.

Ring plane crossing inbound and star Delta Scorpii occultation at 0939 AEST 26 August, and Dione at 1104 AEST 26 August at a distance of 502,000 kilometres.



Moons and moonlets of Saturn. Mimas (a) is not to scale with (b)-(i), which are in scale to each other.
(a) Two views of Mimas; (b) 1980S28 - Atlas; (c) 1980S26 - Pandora; (d) 1980S1 - Janus; (e) 1980S25 - Calypso; (f) 1980S6 - Helene; (g) 1980S27 - Prometheus; (h) 1980S3 - Epimetheus; (i) Hyperion. Images: NASA/JPL

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:	310,000 kilometres

Mimas, only 391 kilometres in diameter, has a 9.97 kilometre high mountain in the centre of a 130 kilometre wide crater called Herschel, 10 kilometres deep, with a mountain 914 metres higher than Mount Everest.

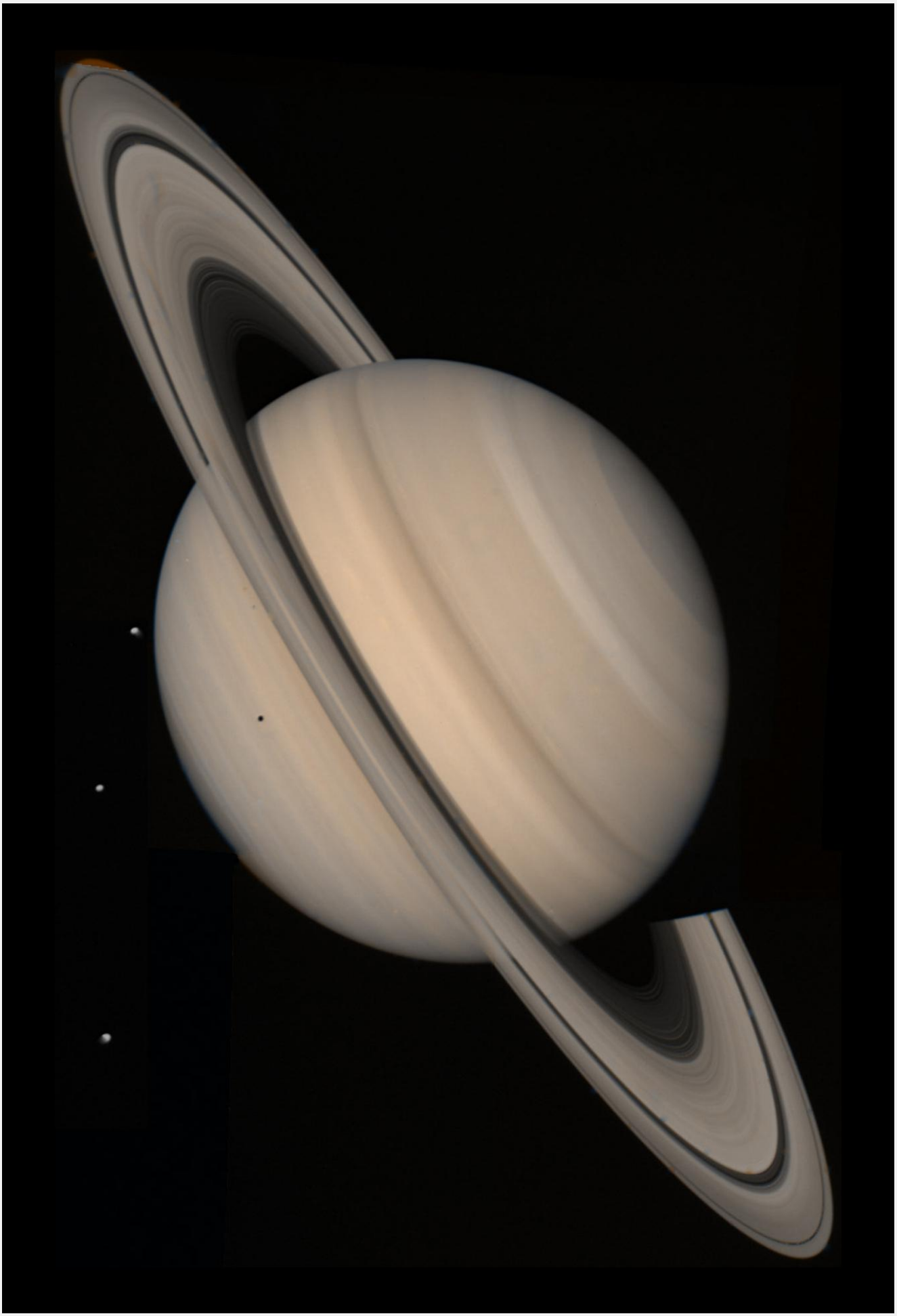
Voyager 2 passed Mimas at 1233 AEST 26 August at a distance of 310,000 kilometres.

1980S25 (Calypso) at 1233 AEST 26 August at a distance of 284,000 kilometres.

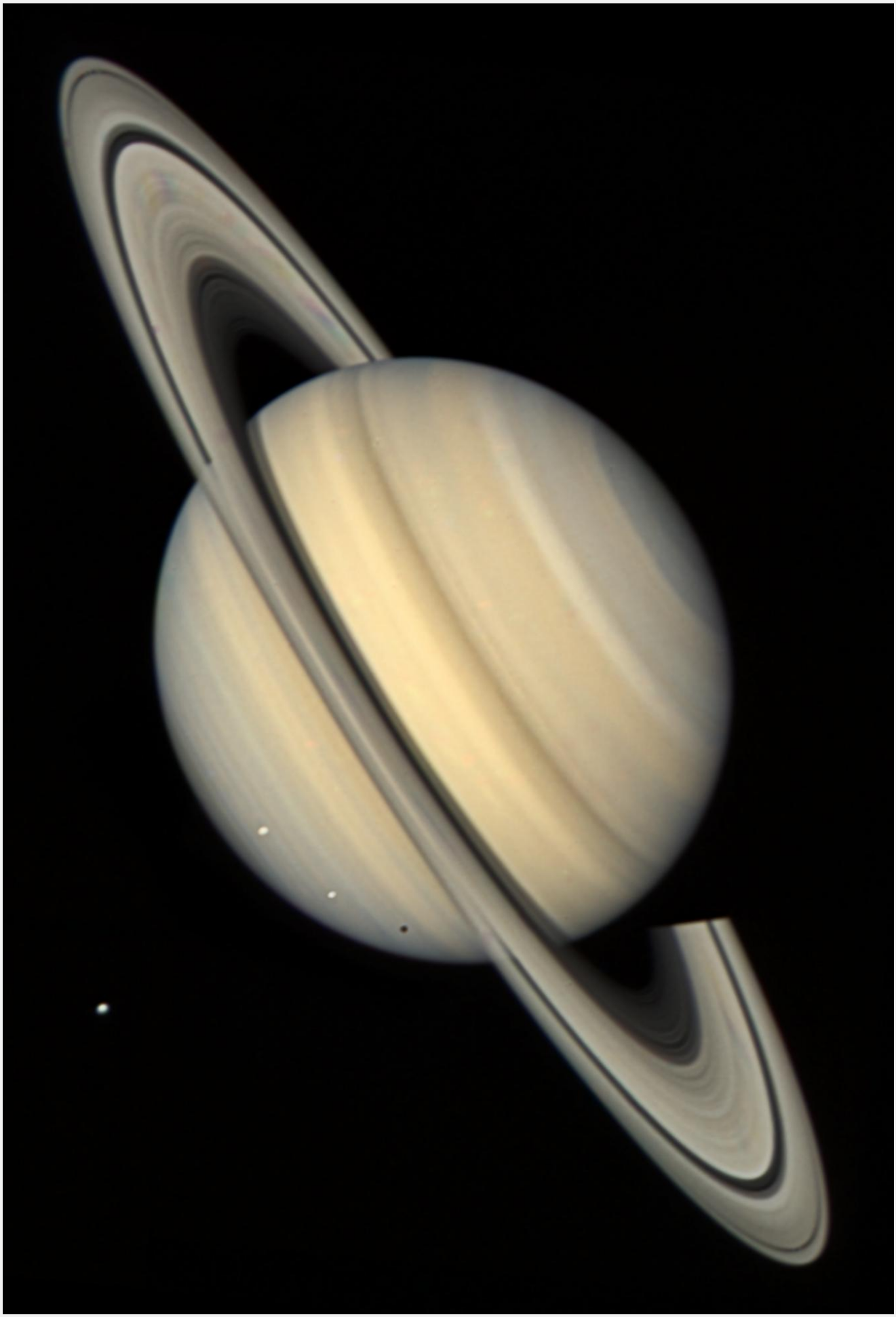
1980S28 (Atlas) at 1308 AEST 26 August at a distance of 287,000 kilometres

1980S26 (Pandora) at 1318 AEST 26 August at a distance of 107,000 kilometres

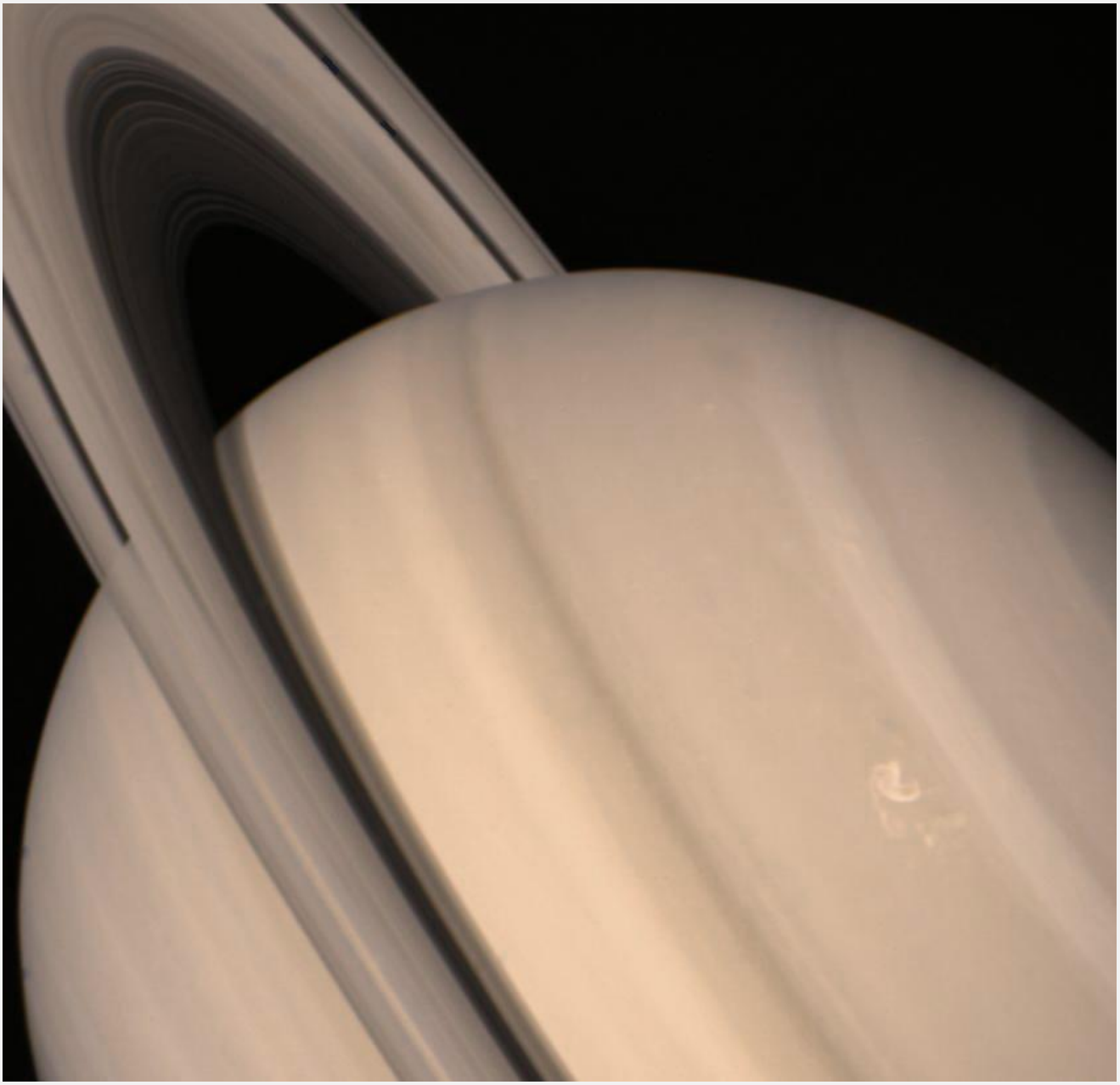
Coming into the closest approach, the scan platform was darting around with increasing emphasis on the moons, particularly Enceladus, the moon that appeared so bright and lacking in large craters as seen from Voyager 1.



Saturn with Tethys (top and shadow), Dione and Rhea. Image: NASA/JPL, Modern processing: Ian Regan



Rhea (left), Tethys (top and shadow) and Enceladus (left). Image: NASA/JPL, Modern processing: Ian Regan



A bright storm is visible in Saturn's northern hemisphere. Image: NASA/JPL

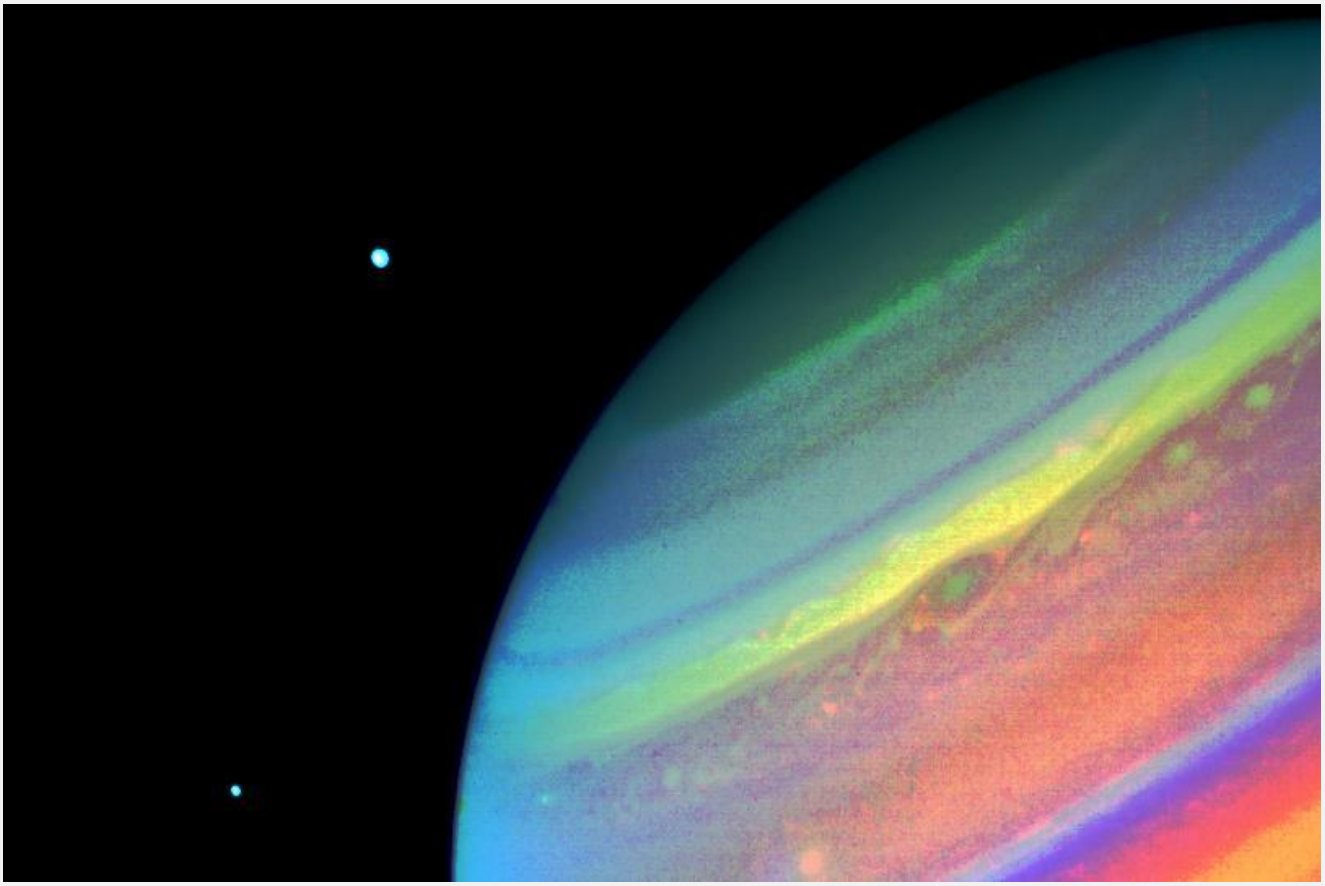
VOYAGER 2

SATURN – PCA – POINT OF CLOSEST APPROACH
1324 AEST – Wednesday, 26 August 1981

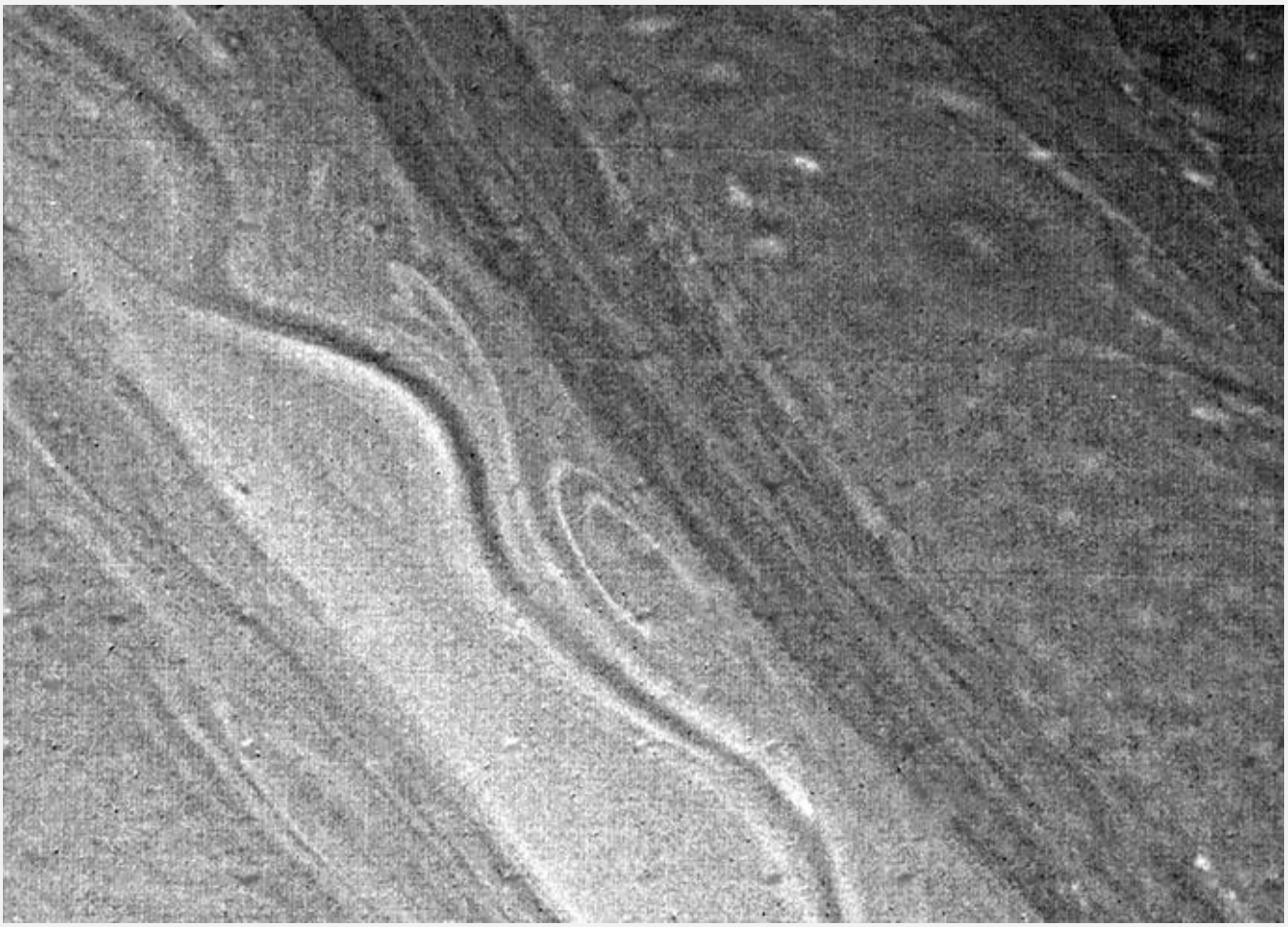
Voyager 2 slipped past Saturn at 1324:57 AEST on 26 August 1981 at a height of 100,830 kilometres above the cloud tops. Two hours later, at 1526 AEST, it disappeared behind the planet's rim and all the links to Earth dropped out for 1 hour and 35 minutes. Out of sight of the anxious watchers on Earth, Voyager 2 shot past the ring plane at 1544 and soon ran into trouble, though the weary flight controllers were quite unaware of the sufferings of their spacecraft as they waited. The VIP's and some of the scientists headed for home, intending to catch up on events the next day…

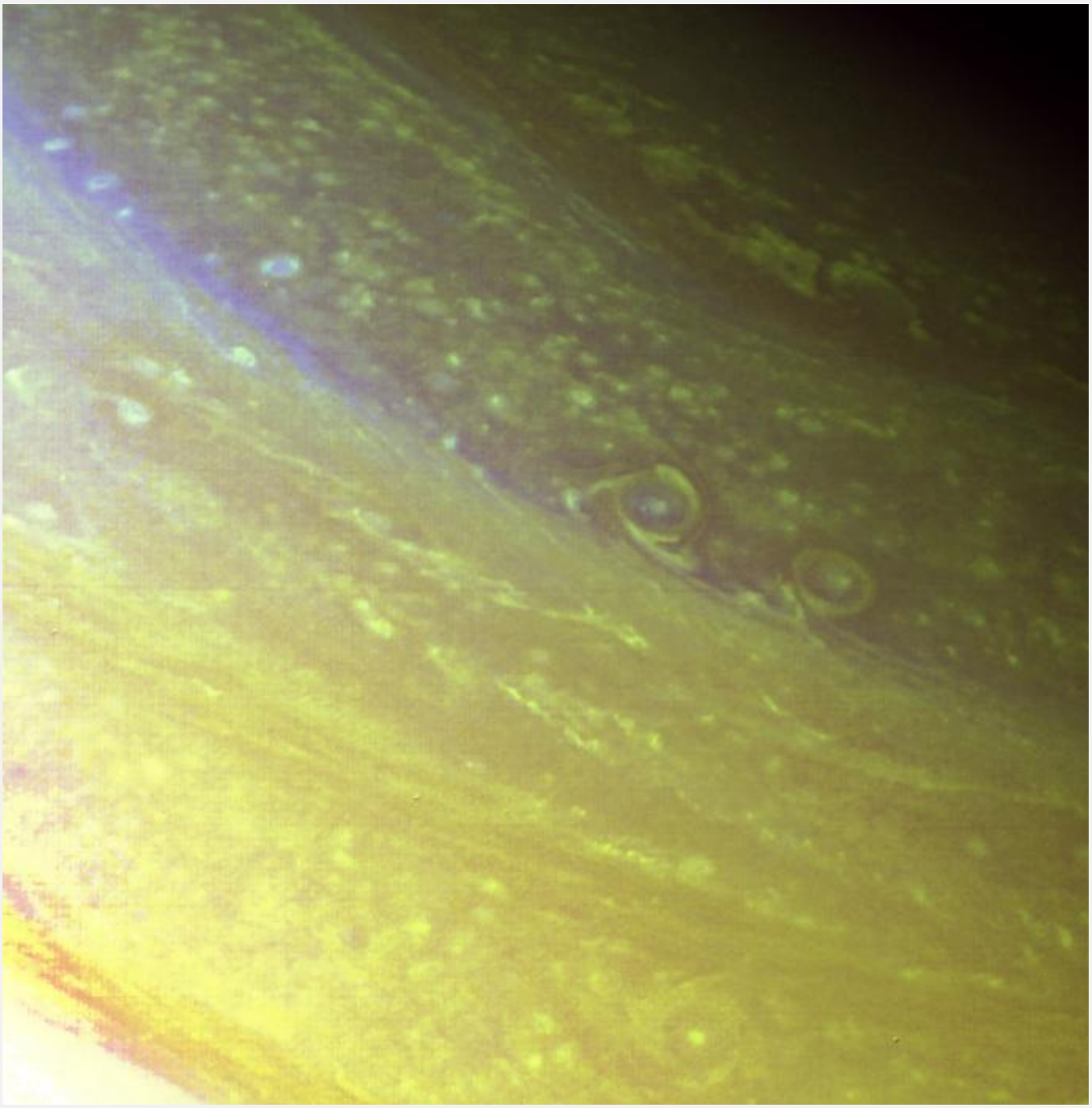
At Tidbinbilla and Honeysuckle Creek, the technicians sat back and waited for the signal to reappear, the big 64 metre dish DSS43 being nudged along by the computer. At 1544 AEST Voyager shot past the ring plane about 3,000 kilometres outside the G Ring. About 45 minutes after the crossing, the plasma wave instrument (PWS) recorded activity a million times above the normal energy level, which indicated its sensor was being peppered by a cloud of tiny particles, which vaporised when they hit the spacecraft. It sounded as though the spacecraft was being pelted by driving rain.

> Prometheus 1980S27 at 1333 AEST 26 August at a distance of 247,000 kilometres.



Above: False colour view of Saturn's atmosphere from 14.7 million kilometres.
The moons Dione (right) and Enceladus (bottom) are visible.
Images: NASA/JPL
Below: Voyager 2 close-up of circulating wind patterns and bands in Saturn's atmosphere.



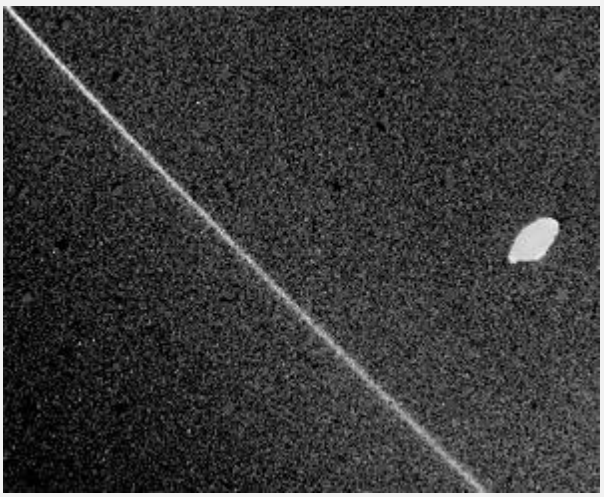


False-colour view of Saturn’s atmosphere. The oval storms are 250 kilometres in diameter. Image: NASA/JPL

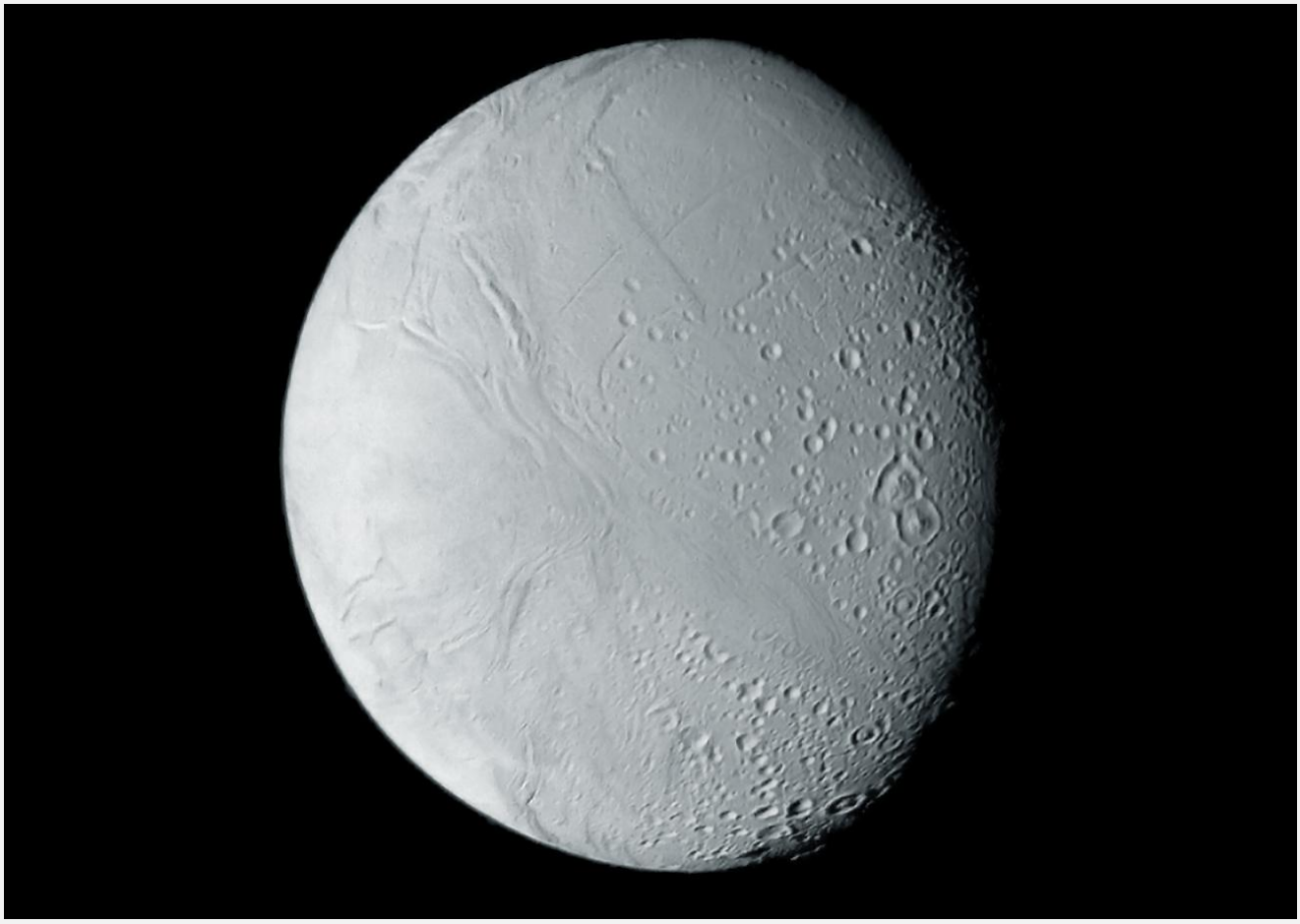
Prometheus is the third of Saturn's known satellites. S. Collins and others discovered it from photographs taken by Voyager during its encounter with Saturn. Prometheus acts as a shepherd satellite for the inner edge of Saturn's F-Ring.

The moon is extremely elongated about 145 by 85 by 62 kilometres in diameter. It has a number of ridges and valleys on its northern side.

Several craters about 20 kilometres in diameter are visible, but it appears to be less cratered than its nearby neighbours Pandora, Janus and Epimetheus.



Saturn’s F-ring and Prometheus. Image: NASA/JPL



Enceladus. Image: NASA/JPL, Modern processing: Ted Stryk

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:	310,000 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.

Voyager 2 passed Enceladus at 1344 AEST 26 August at a distance of 87,140 kilometres, its pictures able to resolve features down to 2 kilometres.

Janus 1980S1 at 1354 AEST 26 August at a distance of 223,000 kilometres

Earth occultation at 1400 AEST 26 August

Epimetheus, 1980S3 at 1406 AEST 26 August at a distance of 147,000 kilometres

Sun occultation at 1406 AEST 26 August

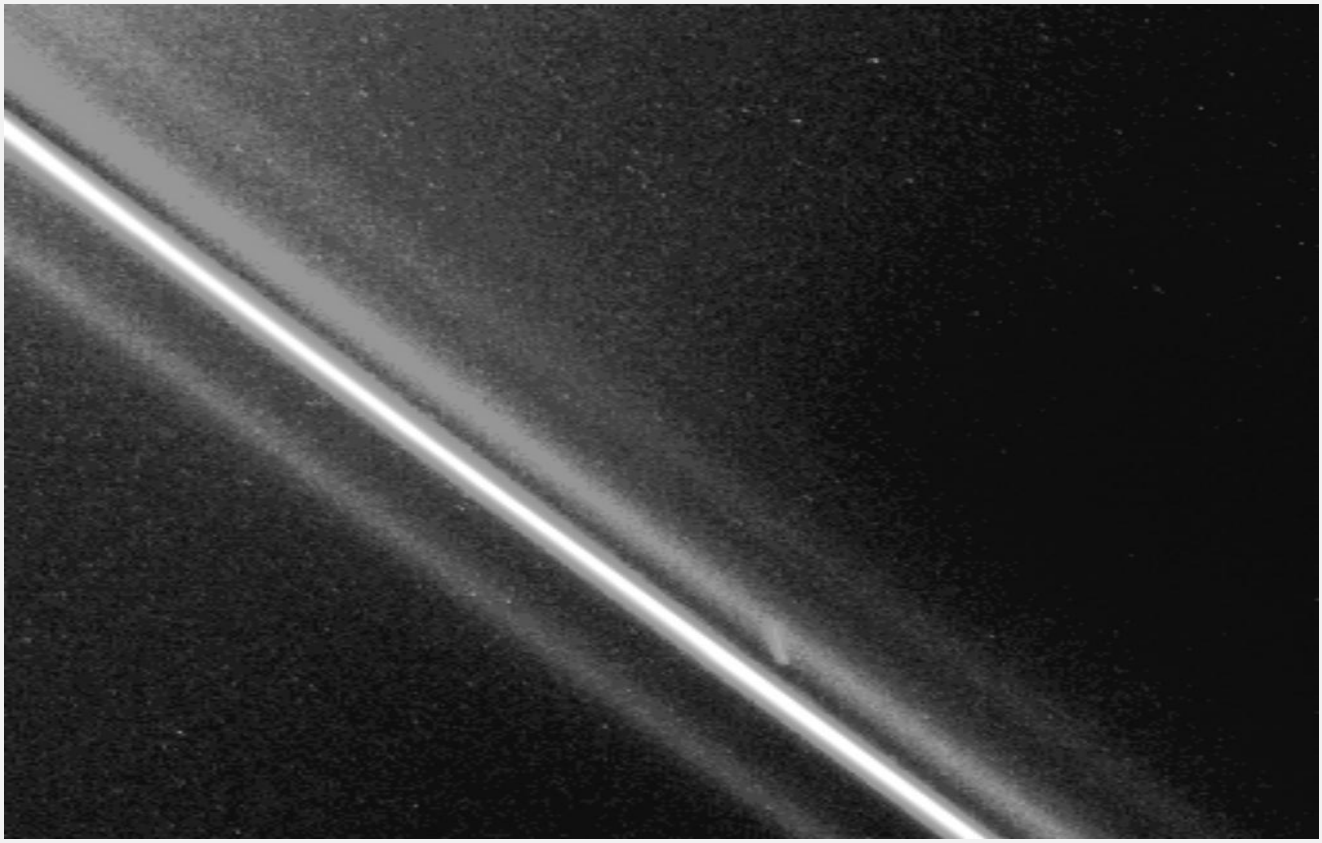
Ring plane crossing outbound at 1418 AEST 26 August

Out of Earth occultation at 1535 AEST 27 August

As Voyager 2 emerged from behind the planet at 1535 AEST on 27 August, Tidbinbilla pounced on the signal, and everyone breathed a sigh of relief - the spacecraft had survived.

Some of the mission personnel at JPL began heading for home believing all was well. This initial relief turned to concern then despair when the telemetry indicated that some of the thrusters had fired independently and then there was consternation when it was found the scan platform was pointing straight at the Sun.

The scientists and members of the media became aware there were no high-resolution pictures coming through on their monitors.



Saturn's F-ring from 51,500 kilometres. The small dash in the rings is a background star trail. Image: NASA/JPL

What was worse - this had all happened 1½ hours earlier and it would take another 1½ hours to send corrective commands to the spacecraft.

As the engineering data flowed in it seemed that the scan platform had seized in azimuth and the computer had sensed a major problem and automatically tried to slew the platform to a safe position from the Sun, but this move was not completed either. The scan platform carried the wide and narrow angle cameras (ISS), the infrared interferometer (IRIS), the ultraviolet spectrometer (UVS) and the photopolarimeter (PPS). The other experiments were unaffected.

At about 1900 AEST the first urgent instructions were sent to command the platform to slew to a safe position pointing away from the Sun and put the instruments into the stand-by mode. By about 2300 it was apparent that the spacecraft had responded to the commands and most of the problems had fixed themselves – now it was just the scan platform.

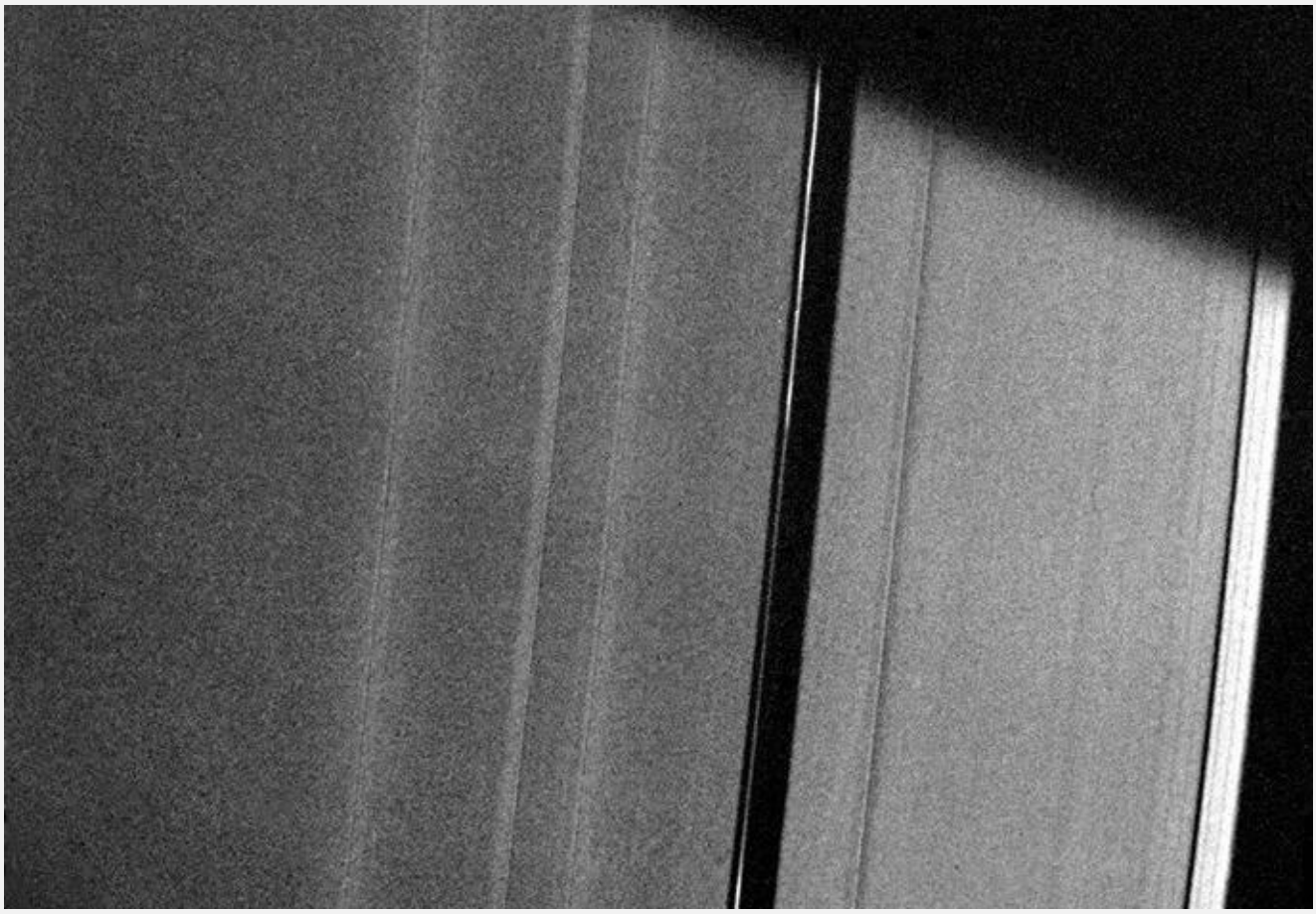
It was found the platform would work only slowly in azimuth between 180 ^{o} and 270^{o}, but the elevation was unaffected. The digital tape recorder would have to be played to find out what had happened.

When the tape data was replayed at 0200 on 27 August a despondent band of engineers and scientists gathered around the displays and monitors. The first pictures were of the F Ring, superb high-resolution views, better than any from Voyager 1. Next came a crescent image of one of the F Ring shepherding satellites.

Then the highest-resolution views of Enceladus should have appeared – but only a blank screen stared back at the grim faces. With the Tethys views every frame was blank except one that had a sliver of the moon. After this only the wide-angle pictures of the rings appeared anywhere close to the target. At 55 minutes after the ring plane crossing the azimuth froze completely. One more accidental frame showed an inner ring in the Keeler Gap. That was all.

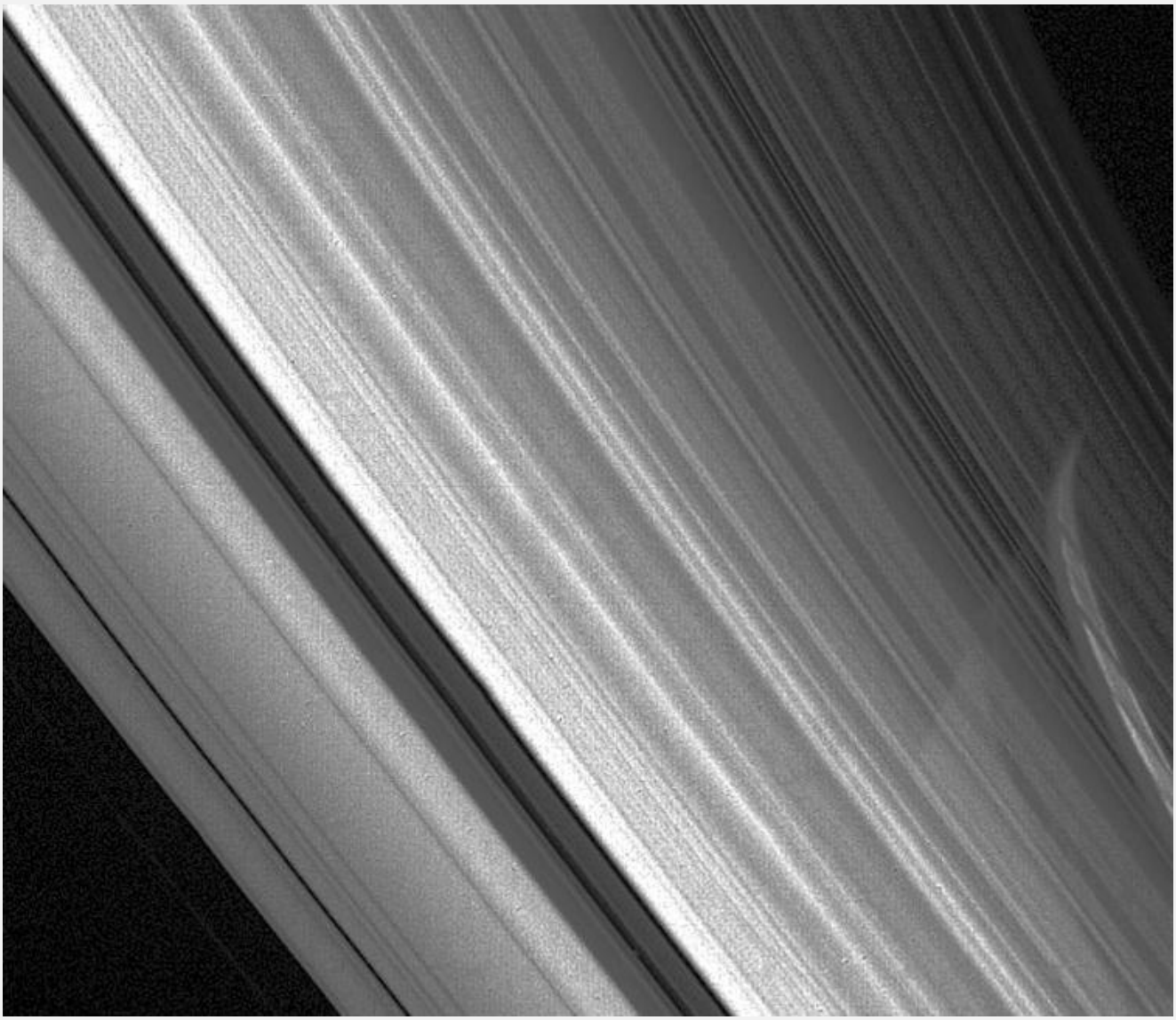
Lost were pictures of the close encounters with Enceladus and Tethys, stereo pictures of the F Ring, close-up views of the rings from the dark side and another photopolarimeter ring occultation that would have yielded an even higher resolution analysis of the A and F Rings.

As the 75 scientists gathered around the monitors listened to the plasma wave instrument they suspected the high readings were more than likely



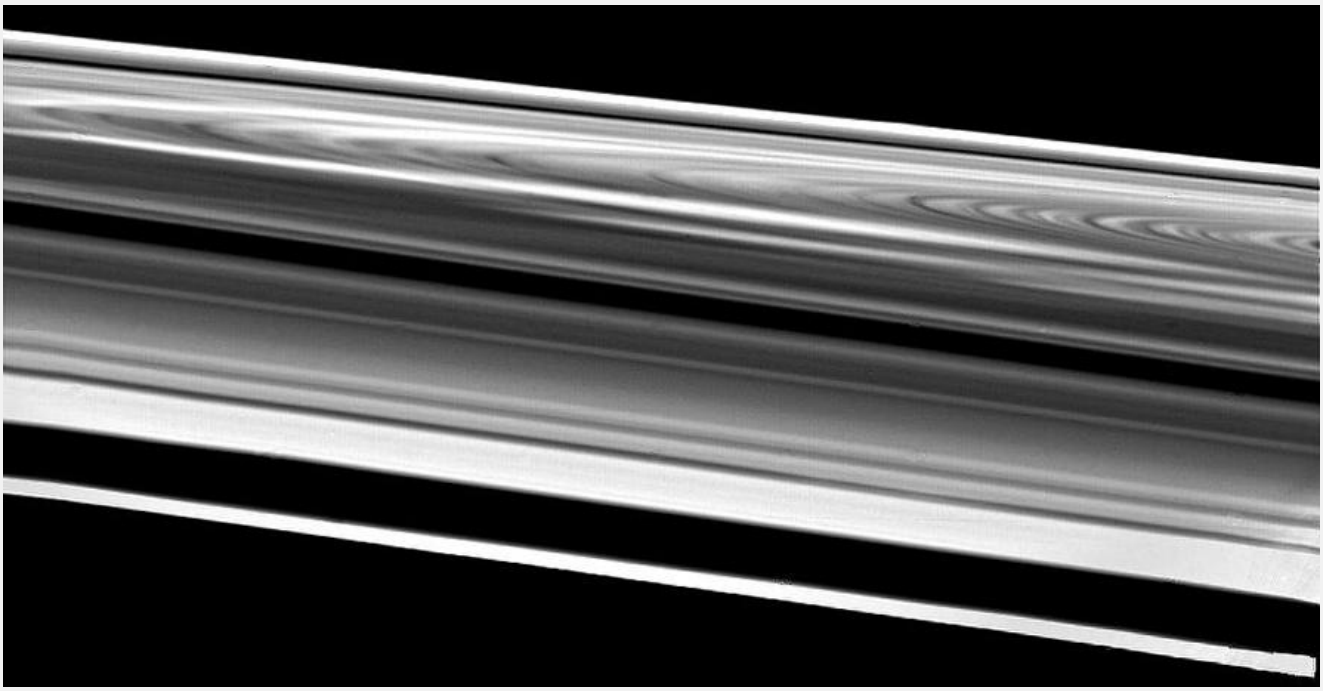
Above: Taken from 227,800 kilometres, Saturn's A-Ring and Encke Gap.
Images: NASA/JPL
Below: Taken from 743,000 kilometres, a 6,600 kilometre wide section of Saturn's B-Ring.

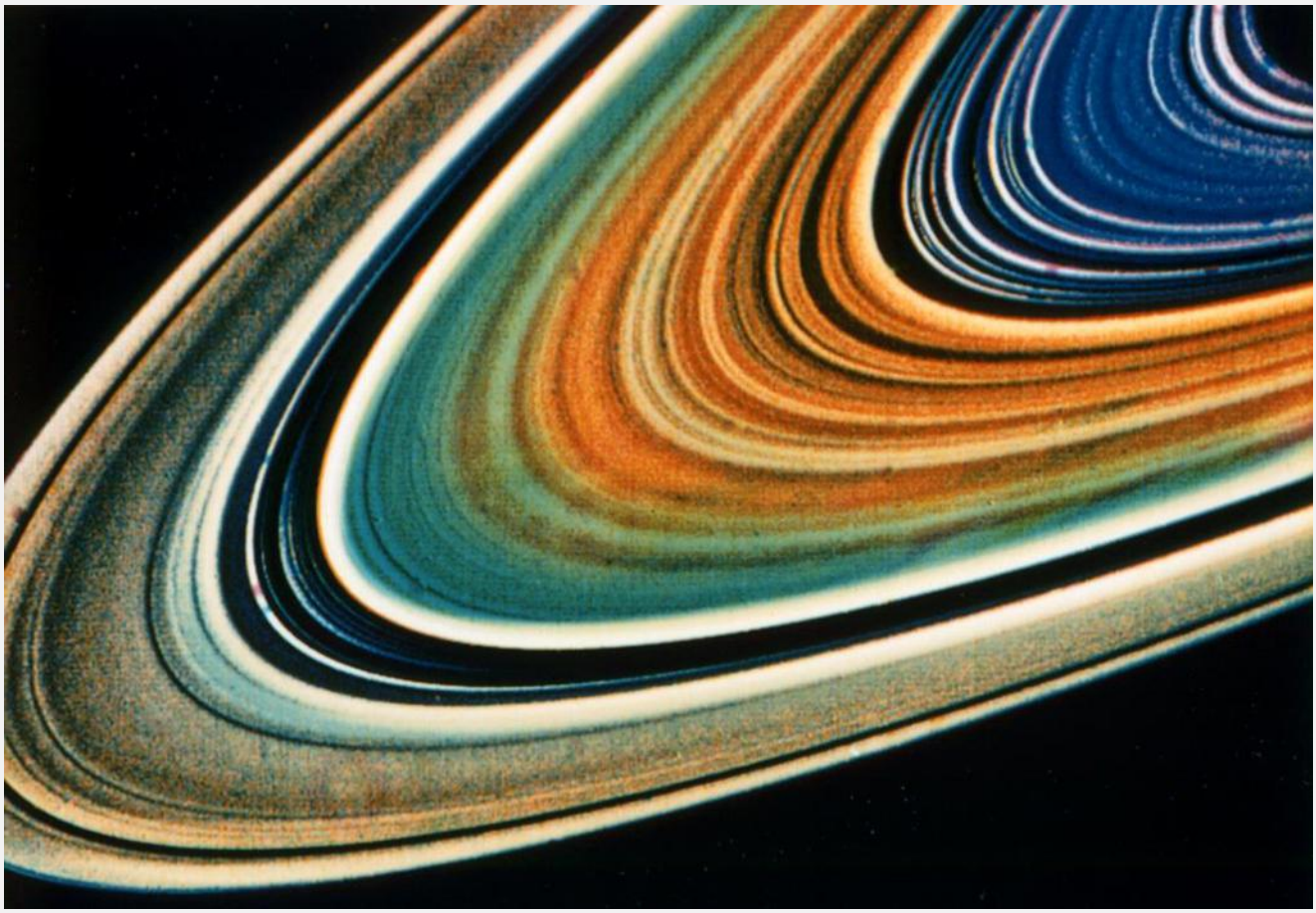




Above: Saturn's limb is visible through part of the C-Ring and the inner part of the B-ring
Images: NASA/JPL

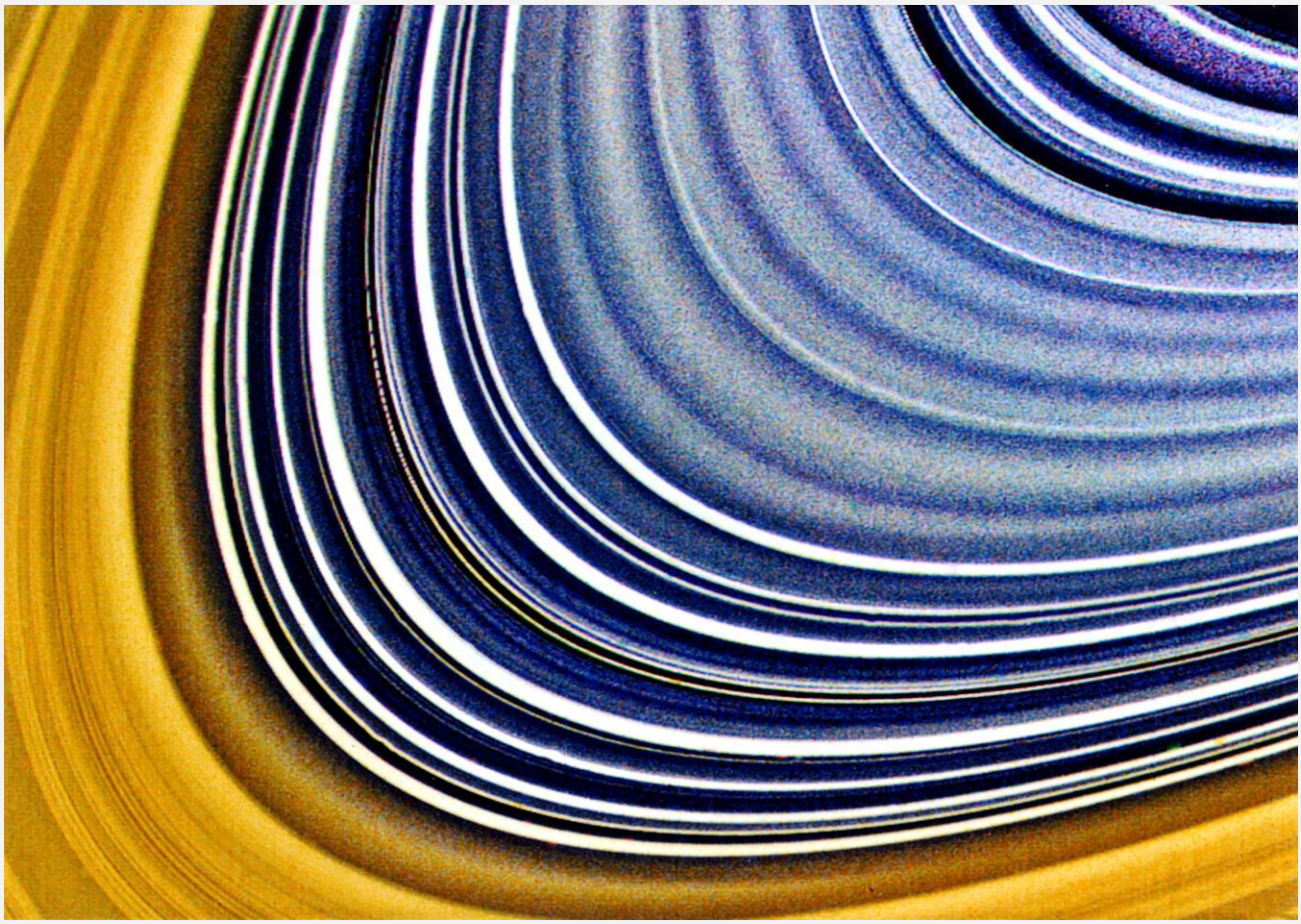
Below: Taken from 103,000 kilometres just before the ring plane crossing. F-Ring (nearest), then A-Ring with the Encke Gap, the Cassini Division (the narrow dark band at centre), then the B- and C- Rings.

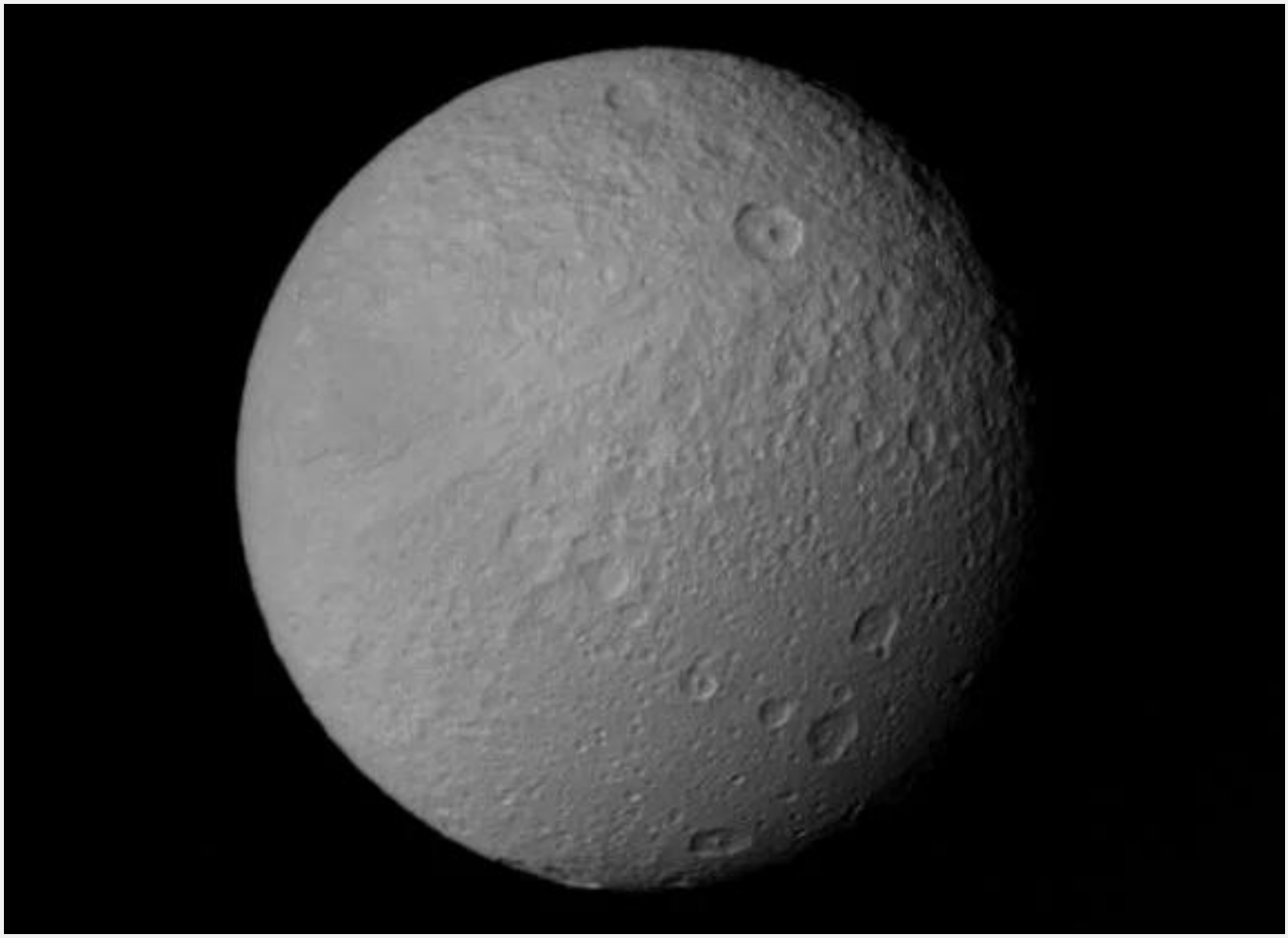




Above: Orange and ultraviolet filters and enhanced colour depict possible chemical composition variations. Images: NASA/JPL

Below: Ultraviolet, clear and green filters reveal the colour of ‘dirty ice’ (blues) in Saturn’s C-Ring.





Tethys. Image: NASA/JPL, Modern processing: Emily Lakdawalla

an electrical phenomenon caused by bursts of plasma generated by impact at 10 kilometres per second with thousands upon thousands of very small dust grains.

Listening to the tape they were astonished to hear the roaring sound of these impacts sounded like a hailstorm striking a tin roof.

But did this dust storm have anything to do with the jammed scan platform? Engineers had to admit the tape replay had not solved the riddle. Pressure was mounting to try and get the scan platform moving again.

Meanwhile the spacecraft continued to transmit endless blank frames, complete with the exposure time, aperture and filter used – all that Los Angeles day.

> Calypso, 1980S13 at 1601 AEST 27 August at a distance of 154,000 kilometres

Giovanni Cassini discovered Tethys on 21 March 1664. He referred to Tethys as one of the four *Sidera Lodoicea* (Stars of Louis) after King Louis XIV (the others were Iapetus, Dione and Rhea).

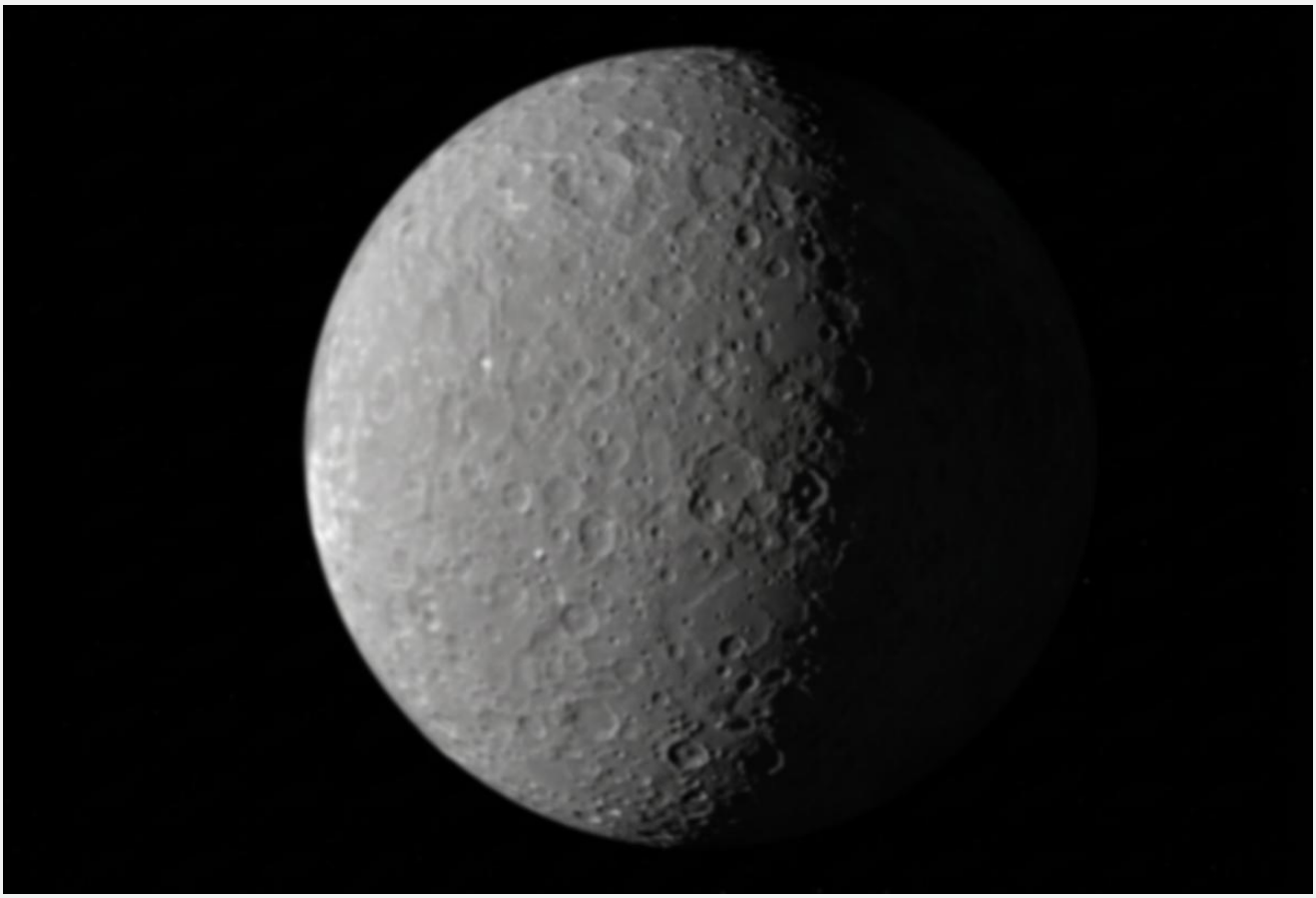
TETHYS

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^{o}C
Closest approach:	93,000 kilometres

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



Rhea from Voyager 2. Image: NASA/JPL

embodiment of the waters of the world. Geological features on Tethys generally get their names from "The Odyssey" by Homer.

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:	645,000 kilometres

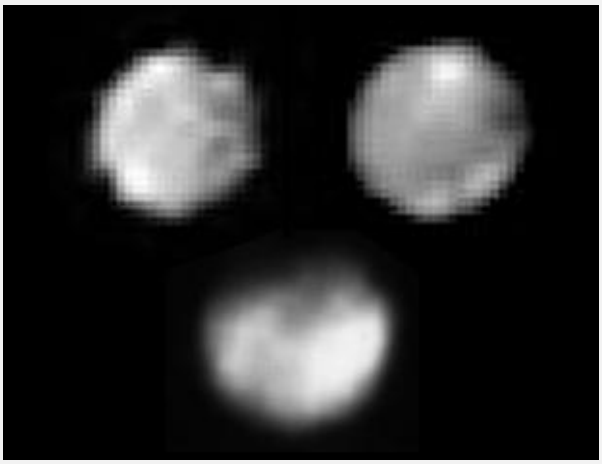
Voyager 2 passed by Tethys at 1611 AEST 27 August at a distance of 93,000 kilometres, 322,320 kilometres closer than Voyager 1.

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. Already spotted by Voyager 1, its heavily cratered, highly reflective surface showed 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.

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.

Voyager passed by Rhea a few minutes after Tethys at 1628 AEST 27 August at a distance of 645,000 kilometres.



Voyager 2 views of Phoebe. Images: NASA/JPL

PHOEBE

Diameter:	213 kilometres
Albedo:	0.06
Mass:	0.8292 x 10^{19} kilograms
Saturn distance:	12,947,913 kilometres
Orbital period:	550.3 Earth days
Surface temp:	-198ºC
Closest approach:	2,080,000 kilometres

Phoebe was discovered by American astronomer William Pickering in August 1898.

The Moons' of Saturn were originally named for Greco-Roman Titans and descendants of the Titans. But as many new moons were discovered scientists began selecting names from more mythologies, including Gallic, Inuit and Norse stories. Phoebe is another name for the goddess the Greeks called Artemis and the Romans called Diana. She was the youthful goddess of Earth's Moon, forests, wild animals, and hunting.

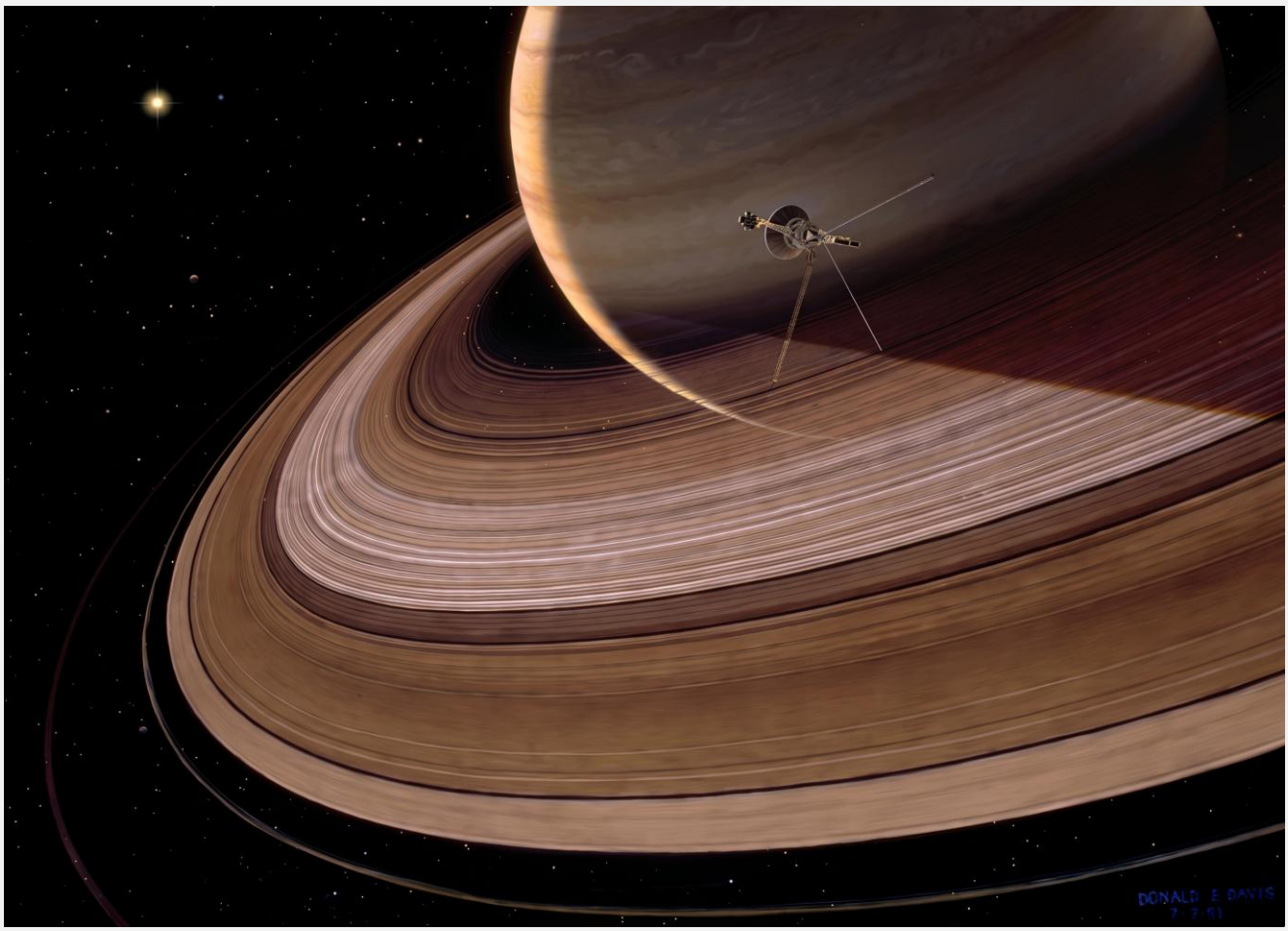
Sworn to chastity and independence, she never married and was closely identified with her brother Apollo.

The moon Phoebe travels in the opposite direction to all the other moons, so is probably a later arrival captured by Saturn's gravity.

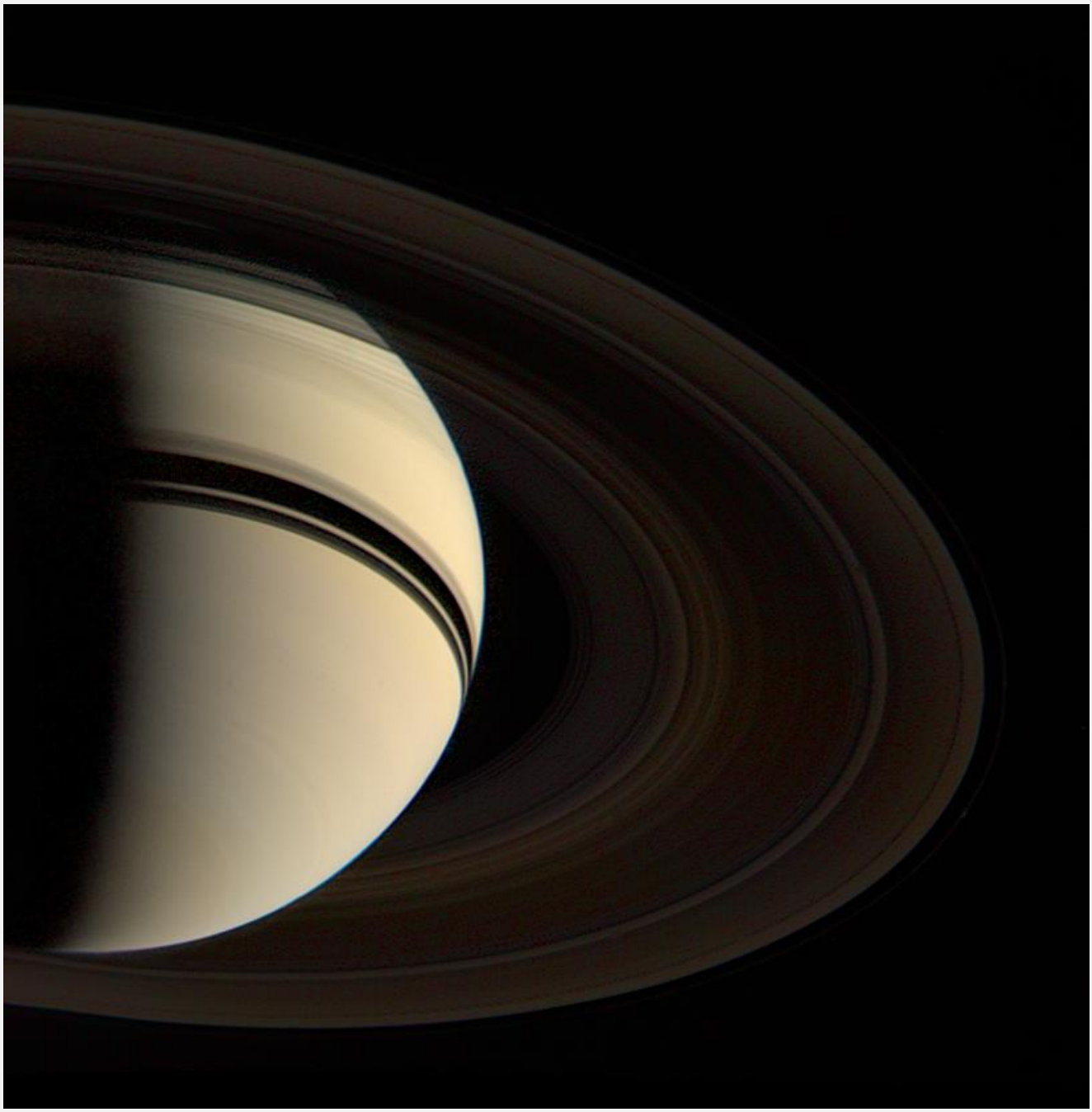
Voyager 2 photographed Phoebe after passing Saturn. Phoebe orbits Saturn in a retrograde direction (opposite to the direction of the other satellites' orbits) in a plane much closer to the ecliptic than to Saturn's equatorial plane. Voyager 2 found that Phoebe has a roughly circular shape, and reflects about 6 percent of the sunlight. It also is quite red. Phoebe rotates on its axis about once in nine hours. Thus, unlike the other Saturnian satellites (except Hyperion), it does not always show the same face to the planet.

If, as scientists believe, Phoebe is a captured asteroid with its composition unmodified since its formation in the outer solar system, it is the first such object that has been photographed at close enough range to show shape and surface brightness.

Voyager 1 passed too far from Phoebe to photograph it, but Voyager 2 passed Phoebe at 13:33 AEDT 5 September at a distance of 2,080,000 kilometres and ended its visit to Saturn.



Voyager 2 departing Saturn by renowned space artist Don Davis. Image: Donald E. Davis (public domain)



Departure image from Voyager 2 taken 29 August, 0345UTC, after its successful flyby of Saturn.
Images: NASA/JPL, Modern processing: Gordan Ugarkovic

On 28 August the platform responded to a command to move in azimuth by 10^{o}. A second command produced a jerky movement.

By the 29th, Deputy Project Manager and Mission Director Dick Laeser announced at the media briefing that the scan platform was operational again with limitations, and at 1038 AEST on 30 August all personnel gathered around the monitors to look for the first picture since the ring plane crossing.

Slowly, line by line, the frame was displayed on the screens and line by line a picture of Saturn and its rings appeared on the monitors.

Though not centred properly, for the first time a picture of the dark side of the rings was displayed. A sharp dark shadow of the planet lay across the rings.

JPL astronomer and assistant Project Scientist for Saturn Dr Ellis Miner remembers,

"At first none of us could make out what it was. Then it dawned on me that looking back in that direction, Saturn was upside down in the monitor because of the direction things were pointed, so I ran up to the screen and said, 'Look! Here's the ring, and here's Saturn, and here's a shadow.'"

SUMMARY OF SATURN ENCOUNTER – 5 JUNE - 28 SEPTEMBER 1981

Date	AEDT	Distance*	Event/Closest Approach
June 5			Observatory phase began
July 31			Far encounter period began
Aug. 22	23:29	909,700	Iapetus
Aug. 25	11:26	470,000	Hyperion
	19:37	665,000	Titan
Aug. 26	09:04	318,000	1980S6 (Helene)
	11:04	502,000	Dione
	12:33	310,000	Mimas
	12:33	284,000	1980S25 (Calypso)
	13:08	287,000	1980S28 (Atlas)
	13:18	107,000	1980S26 (Pandora)
	13:23:25	**161,094**	**Saturn**
	13:32	247,000	1980S27 (Prometheus)
	13:44	87,140	Enceladus
	13:53	223,000	1980S1 (Janus)
	13:59		Enter Earth occultation
	14:05	147,000	1980S3 (Epimetheus)
	14:05		Enter Sun occultation
	14:17		Ring plane crossing outbound & descending
	15:34		Exit Earth occultation (1 hour 35 minutes)
	15:43		Exit Sun occultation (1 hour 38 minutes)
	16:01	154,000	1980S13 (Telesto)
	16:11	93,000	Tethys
	16:28	645,000	Rhea
Sept. 5	11:32	2,080,000	Phoebe
Sept. 28			End post encounter period
		One-way signal elapsed time was 1 hour 26 mins 35 secs	
		* from Saturn's centre (kilometres)	

Voyager 2 imaging was back in business.

Tests were set up in a workshop under mechanical engineer Carl Marchetto focussing on three areas:

- Using the prototype actuator to determine the cause of failure
- trying to recover motion in the spare flight actuator once it was purposely failed
- and operating vital parts under a variety of conditions.

First they tried to duplicate the failure. The prototype failed after 348 revolutions – four less than the actuator on the spacecraft.

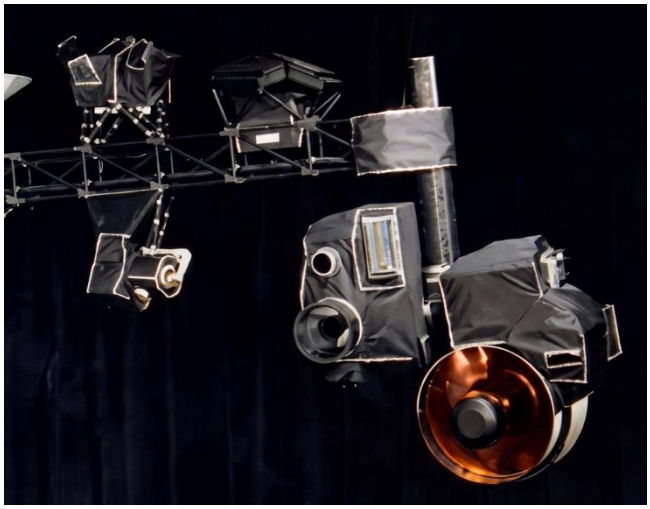
An examination found that the first gear cluster had seized due to a lubrication failure, which led to galling of the shaft. Material removed during the galling process was redistributed, eventually reducing the clearance between moving parts ultimately causing the gear cluster to seize.

The next step was to try and find a way to restore the gear cluster back to life. The most effective way was to vary the actuator's temperature from +10°C to -35°C. The normal operating temperature was -7°C.

The temperature of the on-board actuator can be controlled by turning instruments on and off and turning the actuator heater and motor coils on in different combinations.

These temperature changes caused the actuator parts to expand at different rates, crushing any material that might accumulate from the galling process.

"We found that slew rates were a big factor in the failure. The flight spare never failed at low rates – almost always at high rates, and sometimes at medium rates," the manager of Voyager's Flight Engineering Office, Bill McLaughlin, explained.



The final analysis for the azimuth seizure favoured a lubrication problem, worn gears and the close tolerances between the gear teeth in the azimuth actuator. Frictional heat build-up caused the lubricant to become less viscous, migrate from the bearing area and allow metal-to-metal contact. Then a complex chain of chemical reactions between the lubricants and materials contributed to the manufacture of debris.

After a rest it seems enough had crept back to free the gears. Astronomer and Assistant Project scientist Ellis Miner admitted,

> *"We found so many things to do with Voyager 2 after the Voyager 1 flyby, that may have led to the scan-platform problem, because we had the thing swinging back and forth in the sky so fast and so furiously that we think that's what drove the lubricant out of the gears and caused the gear train to seize."*

To determine the operational status, or health, of the actuators, the engineers tried to vary the power-on pulse width to the drive stepper motor. A normal pulse width was 120 milliseconds when slewing at the low rate. Tests showed that pulse widths of 5 and 6 milliseconds would produce a normal slew rate, but if an 8 millisecond pulse produced erratic slew rates it would be an indication the actuator was going to fail again. Tests on Voyager 1 during August and Voyager 2 in September 1983 showed the actuators were behaving normally.

As Voyager 2 departed from Saturn it had a completely different aspect from Voyager 1. Now it was looking back at the dark southern side of the rings whereas Voyager 1 had looked at the sunny northern face.

The Voyager cameras were finding quite unexpected phenomena in this ring system. Two small moons playing tag; two moons of ice speeding around Saturn seemed to be shepherding trillions of particles to hold the whole ring system together. They appeared be herding escaping particles back into the system.

During a press conference at the end of Voyager 2's Saturn flyby, a reporter asked JPL's Dr. Ed Stone, project scientist for the mission, what percentage of the expected science had been obtained during the flyby.

Without hesitating Ed Stone answered, *"Two hundred percent."*

After the excitement of the Saturn encounters, we returned to housekeeping tracking the two spacecraft, but heard the good news that Congress had funded Uranus and Neptune flybys by Voyager 2.

Saturn (*at the time of writing*) has 56^ moons and small satellites, 35 of them named. A summary of the 17 main moons of Saturn follows:

SUMMARY OF SATURN'S MOONS AND SMALLER SATELLITES

	Diameter kilometres	Kilometres from Saturn'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 2 observed the moon.



Members of the Voyager Imaging Team at the Jet Propulsion Laboratory. Image: NASA/JPL
From left: Ed Danielson, Garry E Hunt, Carl Sagan, Brad Smith, Toby Owen,
Allan Cook III, Verner Suomi, Merton Davies, and Larry Soderblom (from USGS).

Laurence Soderblom, Deputy Team Leader from the US Geological Survey, summed up,

"Examination of three of the smallest classical Saturnian moons, Mimas, Enceladus, and Hyperion, reveals a diversity many times broader than the narrow terrestrial view we had held prior to the Voyager missions.

Mimas is close to what we expected; a frozen, pockmarked ball of cold rubble. Hyperion is about the same size as Mimas but shows a highly irregular shape indicating that it is a fragment torn from a much larger, rigid object.

On Enceladus, the greatest surprise, regions of cratered plains suggest great antiquity, yet other regions are free of craters, at least to the limit of resolution. Our best models indicate that this tiny body must have been active in the geologically recent past and is probably, at least from time to time, geologically active today.

The lesson we learned is that wherever we look, we will find energy sources that will drive the geologic engines of planets: some radiogenic, some accretional heat, some gravitational, and, probably, some chemical and some electromagnetic. We have also learned that no matter how cold the ambient environment, materials are available to serve as lubricants to mobilize the interiors of the planets. On the Saturnian satellites, the likely lubricants are methane and ammonia.

How limited were our expectations of the Saturnian moons compared to what we found."

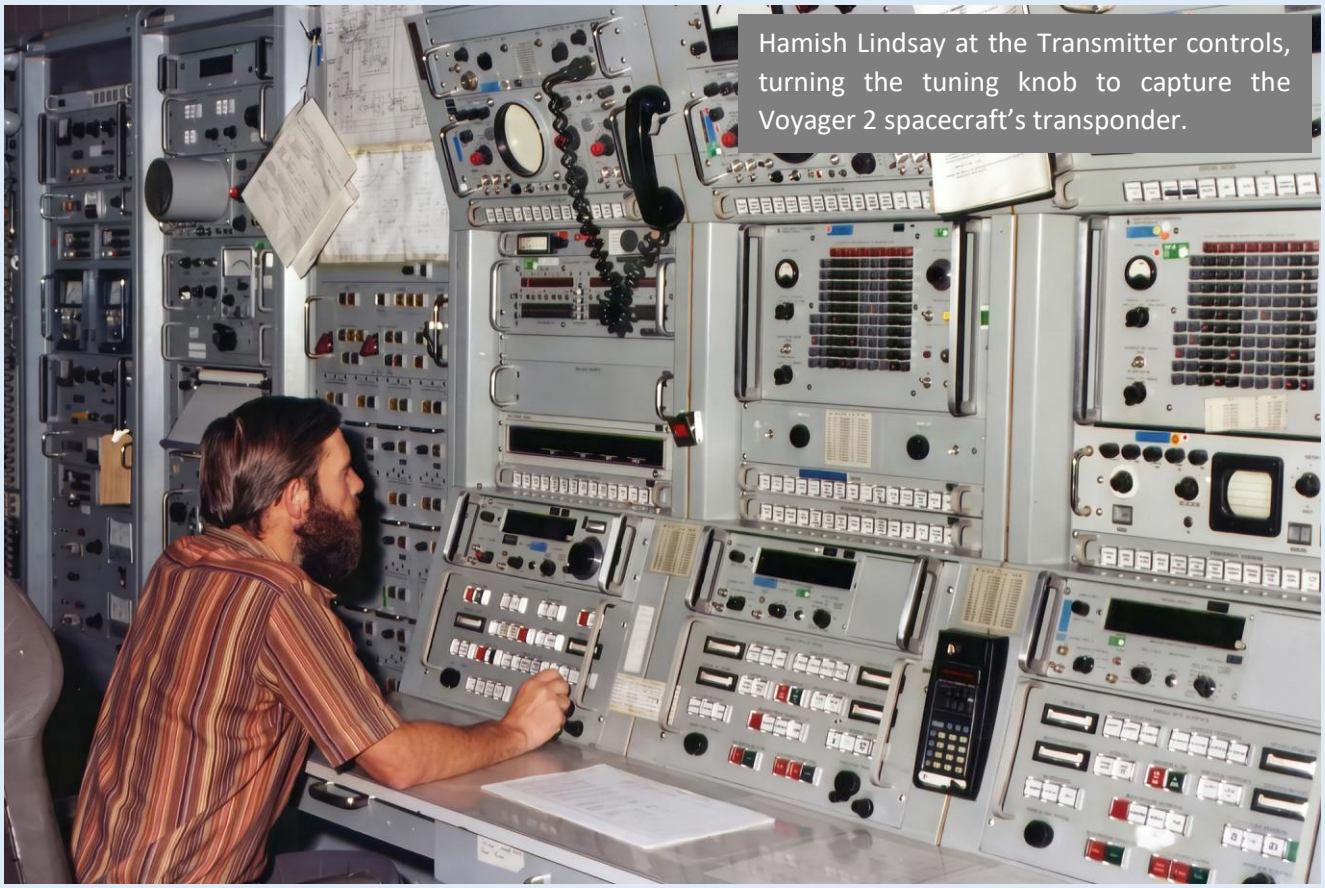
After its encounter with Saturn, Voyager 1 had accomplished its mission, it was flung out of the plane in which all planets move, and flew on to the limits of our solar system. Meanwhile, its sister probe Voyager 2 flew on to the next planet.

Even at a speed of more than 80,000 km per hour, the trip to Uranus took five years.

The engineers on Earth needed this time to prepare themselves for a difficult task - out there, far away from the Sun, there is very little light for the cameras. This requires much longer exposure times. But if the probe is moving very rapidly at the same time, the images become fuzzy.

The researchers had to program the cameras to swivel around at the speed of the probe, in order to compensate for its movements.

All this had to be fully automated, as Voyager 2 had travelled too far away from Earth to be controlled directly by radio signal.



Hamish Lindsay at the Transmitter controls, turning the tuning knob to capture the Voyager 2 spacecraft's transponder.

When the MJS77 project was originally developing, $US7 million was added to the budget to enhance the spacecrafts' capabilities. Among these enhancements was the ability to reprogram the back-up computers out in space.

With the bit rate dropping rapidly as the spacecraft ventured further and further out, this far-sighted facility was used to compress the TV signals from the cameras.

Thus, instead of transmitting every pixel state each time, a program was developed for the back-up computer to only transmit the state of a pixel if there was a change from the previous one. This reduced the communications rate by a factor of two and half.

Another facility attributed to the extra $7 million 'gift' was a system to transmit error-free data back to Earth using a Reed-Solomon coding system. The code groups data into chunks called symbols instead of single bits.

The basic error coding used from the beginning of the mission was enhanced for the Uranus encounter, and the engineers were satisfied that all that could be done had been done to achieve a successful encounter.

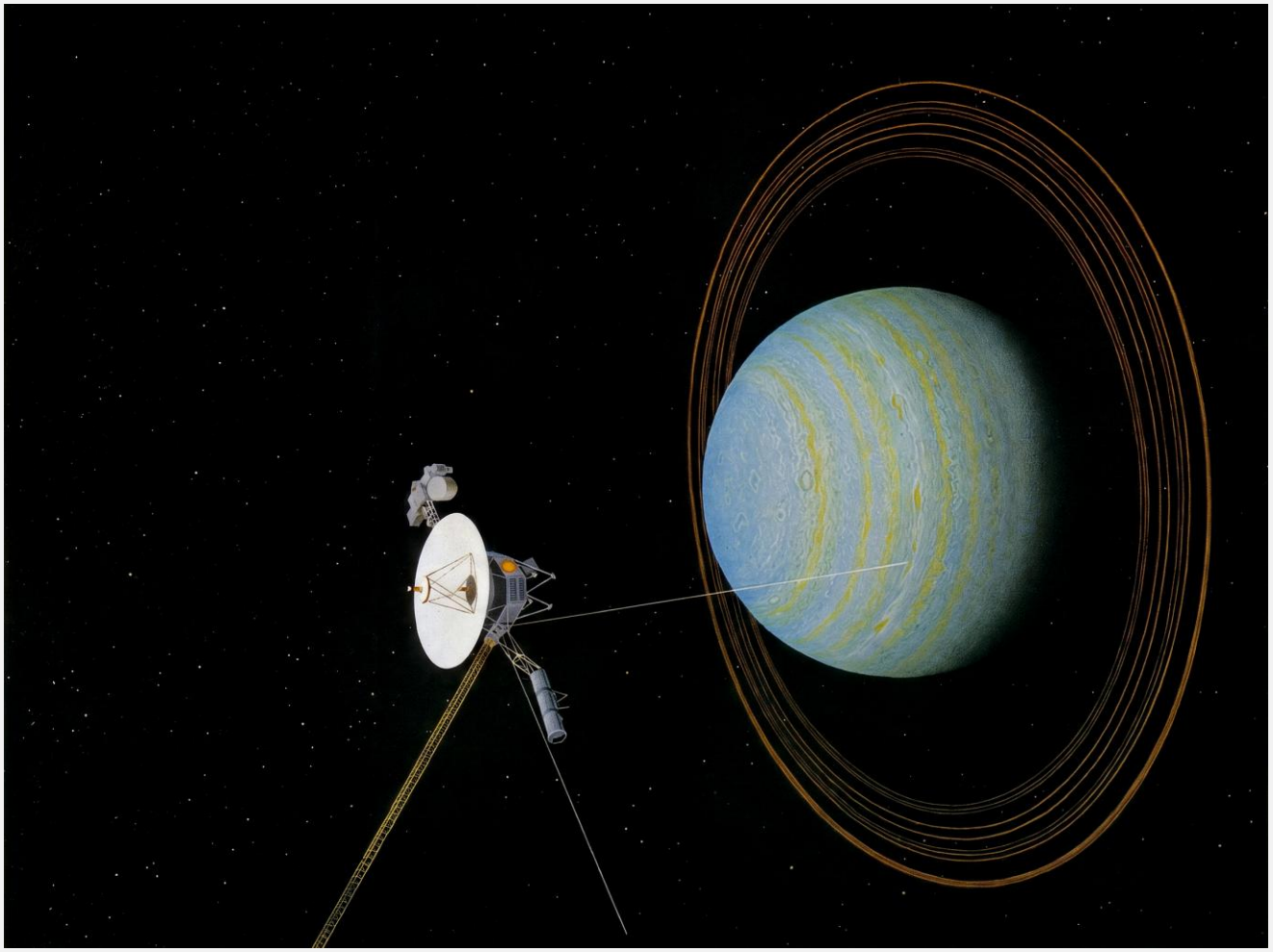
On the ground communication engineers were putting together everything they could to pick up the faint whispers from Voyager 2 to extract the precious data. In a quiet valley near Socorro, New Mexico, twenty-seven identical radio telescopes, each 24.7 metres in diameter, had been built well after the Voyagers were launched. In August 1989 this VLA (Very Large Array) set of dishes were hooked up by microwave links with the big dishes at the Goldstone complex.

It is interesting to note if it had been Voyager 1 instead of Voyager 2 at Uranus these brilliant engineering feats could not have been done, because the back-up computer on Voyager 1 had failed early in its voyage. Combined with the inferior performance of the Voyager 1 launch vehicle it seems that fate was smiling on this mission.

Editor's note: ^ According to NASA, as at August 2026, Saturn has 293 confirmed moons in its orbit, far more than any other planet in our solar system. Saturn's moons range in size, from one that is larger than the planet Mercury - Titan - to others as small as a sports arena. The small moon Enceladus has a global ocean under a thick, icy shell. Scientists have identified both moons as high-priority science destinations for future deep-space missions.



Artist’s depiction of Voyager 2’s next destination, the Uranus system. Image: Rick Guidice



Voyager 2 approaching Uranus by space artist Don Davis. Image: Donald E Davis (public domain)

VOYAGER 2

URANUS ENCOUNTER

The third largest planet in the solar system, was discovered on 13 March 1781 by Sir William Herschel. The very dark rings were seen in 1977.

It orbits the Sun at a speed of 24,480 kilometres per hour at a distance of 2.872 billion kilometres and completes one orbit every 84 Earth years.

Compared to Earth's gravity, 100 kilograms would weigh 86 kilograms on Uranus. With a diameter of 51,118 kilometres, the length of a day on Uranus is 17 hours 12 minutes, measured by Voyager 2 reading the radio emissions from the planet. The surface temperature at 1 bar is -197°C while at the cloud tops it is -220°C. Its albedo is 0.51.

The interior of Uranus is richer in heavier elements, most likely compounds of oxygen, carbon, and nitrogen, as well as rocky materials. This is in contrast to Jupiter and Saturn, which are mostly hydrogen and helium. Uranus (like Neptune) is similar to the cores of Jupiter and Saturn without the massive fluid metallic hydrogen envelope. The internal heat of Uranus is lower than that of Jupiter and Saturn. Both Jupiter and Saturn radiate more energy than they receive from the Sun. This causes many powerful convection currents to form in the atmosphere.

On Uranus that heat source is much lower due to its lower mass, with the temperature of its core roughly 6,727°C compared to 29,727°C at Jupiter's core and 17,727°C at Saturn. Uranus supports 27+ moons and small satellites.

URANUS ENCOUNTER
SATURDAY 25 JANUARY 1986
URANUS FACTS

Diameter:	51,118 kilometres
Distance to Sun:	2,870,658,186 kilometres
Mass:	8.681 x 10^{25} kilograms
Orbital period:	84.0 Earth years
Length of day:	17 hrs 12 mins Earth hours
Surface temp:	-220°C min / -197°C max
Closest approach:	81,440 kilometres



The south pole of Uranus greeted Voyager 2 as it approached. Image: NASA/JPL

Uranus is distinguished by the fact that it is tipped on its side at an angle of 97.77^{o}, so then the question arises which is the north pole? The governing body for astronomical nomenclature, the International Astronomical Union, established a convention using the Earth as a reference – all poles above the ecliptic are north poles and all below south poles. Since one of the Uranian poles was tilted about 8^{o} below the ecliptic it was designated the South Pole, and that was the pole facing the Sun when Voyager arrived at Uranus.

The Sun shines on the northern hemisphere for 42 Earth years and on the southern hemisphere for the other 42 years, while the equator remains in constant twilight.

This vertical target, with Uranus the bullseye to spacecraft approaching from Earth, means that the significant events of an encounter will be compressed into 6 hours compared to 35 hours for Jupiter and 13 days for the satellites out to Phoebe's orbit at Saturn.

GROUND TRACKING SUPPORT

By the time Voyager 2 had arrived at Uranus DSS44 Honeysuckle Creek had closed. Of all the tracking stations Tidbinbilla was in the best position to track Voyager 2. To cope with the weakening signal as the distance increased, the DSN 'arrayed' antennas. DSS43 at Tidbinbilla was arrayed with the 64-metre antenna at Parkes, which allowed a bit rate of 21,600 bits per second.

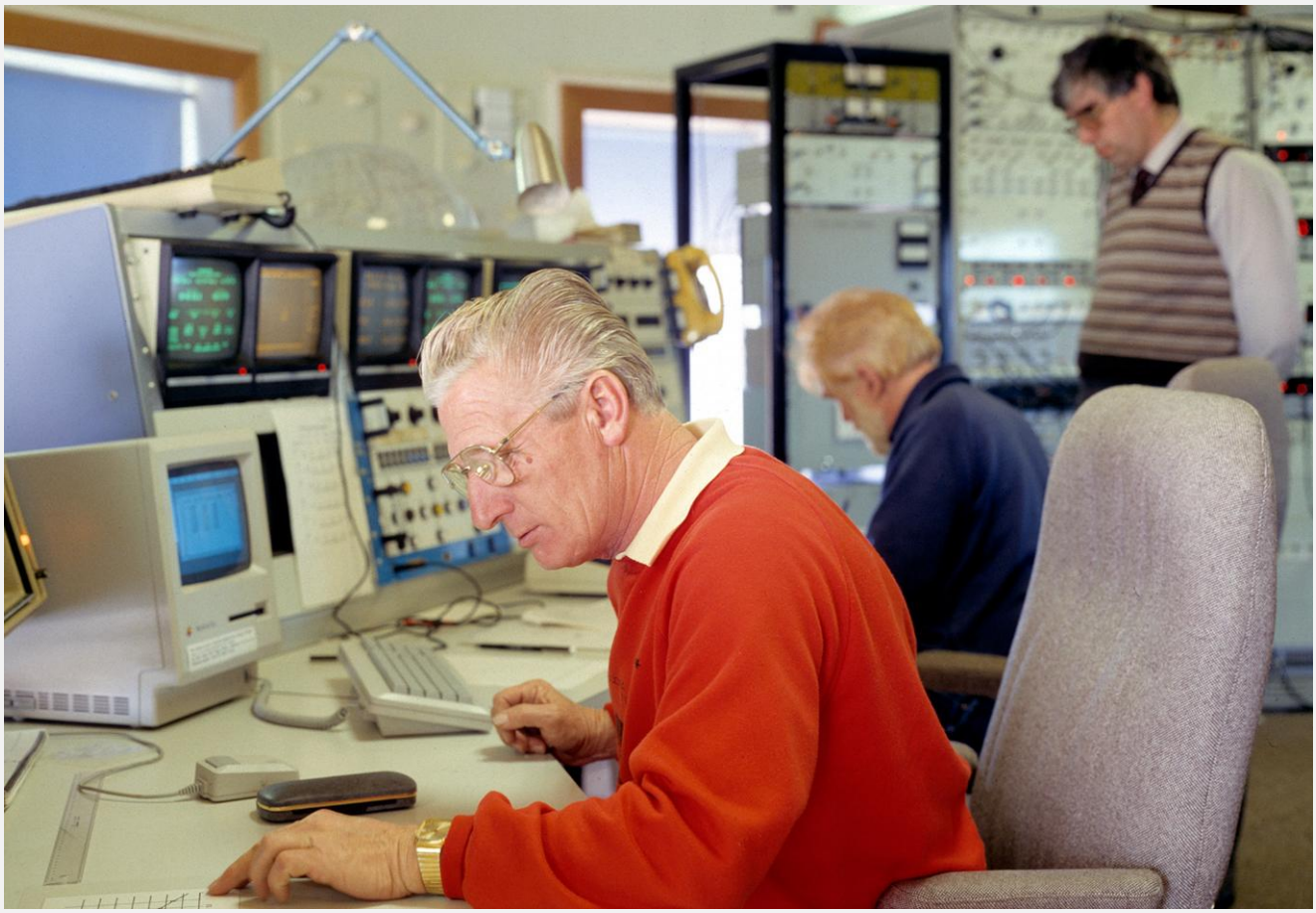


Above: The 64 metre radio telescope located at Parkes in central New South Wales.
Images: (above) © CSIRO Radio Astronomy Image Archive, (below) Tidbinbilla Archives
Below: The 64 metre receiver/transmitter antenna Deep Space Station 43 – DSS43 (right), and the 34 metre DSS42 (foreground), located at the Deep Space Network station at Tidbinbilla near Canberra.



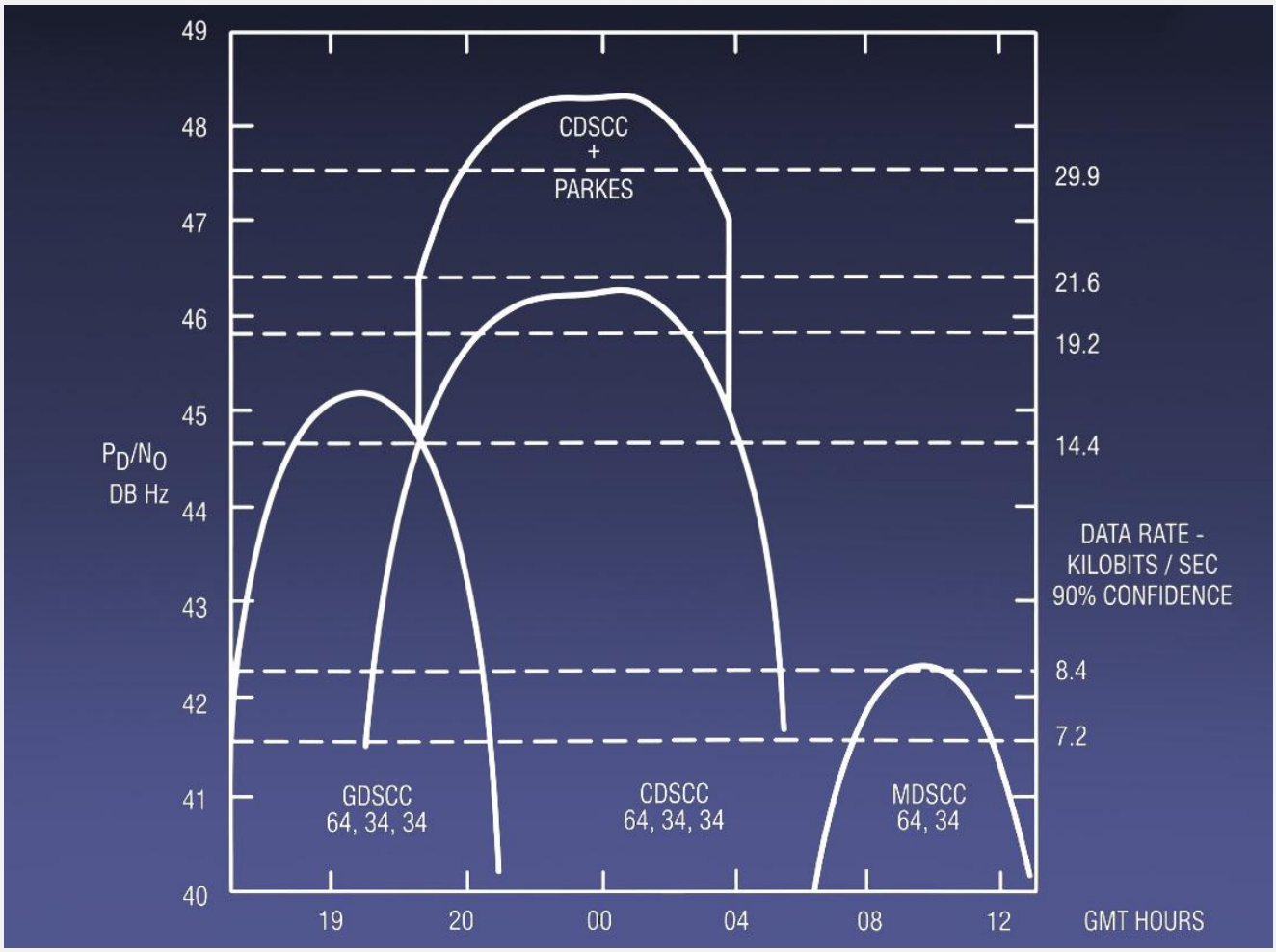


Above: Part of the Tidbinbilla crew working from Parkes (from left) unidentified, Dwight Holmes, Mike Dinn, Peter Churchill, and Paul Mullen. **Images:** (above) HSK.net, (below) © CSIRO Radio Astronomy Image Archive
Below: In the Parkes control room - Ben Lam (front), Alan Wright (centre) and Andrew Hunt (back).





The “Voyager Containers” setup under the Parkes dish where Tidbinbilla crews operated NASA equipment.
Image: © CSIRO Radio Astronomy Image Archive



Plot of the expected data rates from Voyager 2 shows the impact of arraying Tidbinbilla and Parkes.
Graphic: 'Uplink - Downlink' by Doug Mudgway

Another development to help reduce the transmission time of pictures was configuring the second of the two computer processors in the spacecraft's Flight Data System (FDS) to compress image data, allowing transmission of the same amount of information using less than half the number of bits.

This was done by transmitting the brightness of the first pixel in each line of an imaged scene, then only transmitting the relative difference between adjacent pixels in the remainder of the line. Each image contains 640,000 pixels.

Before, each pixel required 8 bits to describe it and its grey level from 0 to 255. The data compression reduced this requirement to about 3 bits per pixel, cutting the bits per image from 5.12 million to less than 2 million.

At Jupiter the Voyagers could handle 115,200 bits per second, at Saturn it had dropped to 44,800 bits per second, and at Uranus, even with arraying, it was down to 21,600 bits per second.

At Jupiter Voyager 2 could send back as many as 75 pictures per hour. At Uranus Voyager 2 would only be able to send a maximum of 12 to 17 pictures per hour.

Initially Uranus appeared to be a huge scientific disappointment. Its atmosphere is composed of various gases, mostly methane and ammonia.

For some reason, the source of heat inside Uranus has dried up. Therefore, no turbulences arise in the planet's atmosphere, and it can hide behind an amorphous veil.

The planet's moons turned out to be more interesting for the researchers. They showed geological structures that continue to baffle scientists to this day.

By using the gravity of Jupiter and Saturn to increase its speed, it took Voyager 2 only 12 years to get to Neptune, instead of 20 years. Uranus is twice as far from the Sun as Saturn. Jupiter images could be relayed back to Earth at 115,200 bits per second, Saturn at 44,800 bits per second - but Uranus?

Voyager had proved an extremely stable platform at Jupiter and Saturn, but would need to do even better at Uranus as only1/400th of the light with corresponding longer exposures for taking pictures. Engineers set up a rig to control the Voyager attitude 60 times steadier than the hour hand of an analogue clock.

The tasks set out for Voyager 2 it approached Uranus were:

1. Determine the rotation rate of the planet
2. Determine the composition of the planet's atmosphere
3. Measure how much sunlight is absorbed by the atmosphere
4. Measure how much energy is emitted from the deep interior
5. Map the location of clouds and any hazes.
6. Measure wind speeds
7. Search for auroral activity
8. Determine the size, composition, and distribution of ring particles
9. Profile the positions and eccentricities of the rings
10. Search for new rings
11. Look for shepherding satellites
12. Measure the sizes and shapes of the moons
13. Map the surface features and composition of the moons
14. Measure the strength, orientation and charged particle population of the magnetic field
15. Attempt to measure the rotation rate of the magnetic field
16. Attempt to measure the rotation rate of the planet's interior.

THE OBSERVATORY PHASE

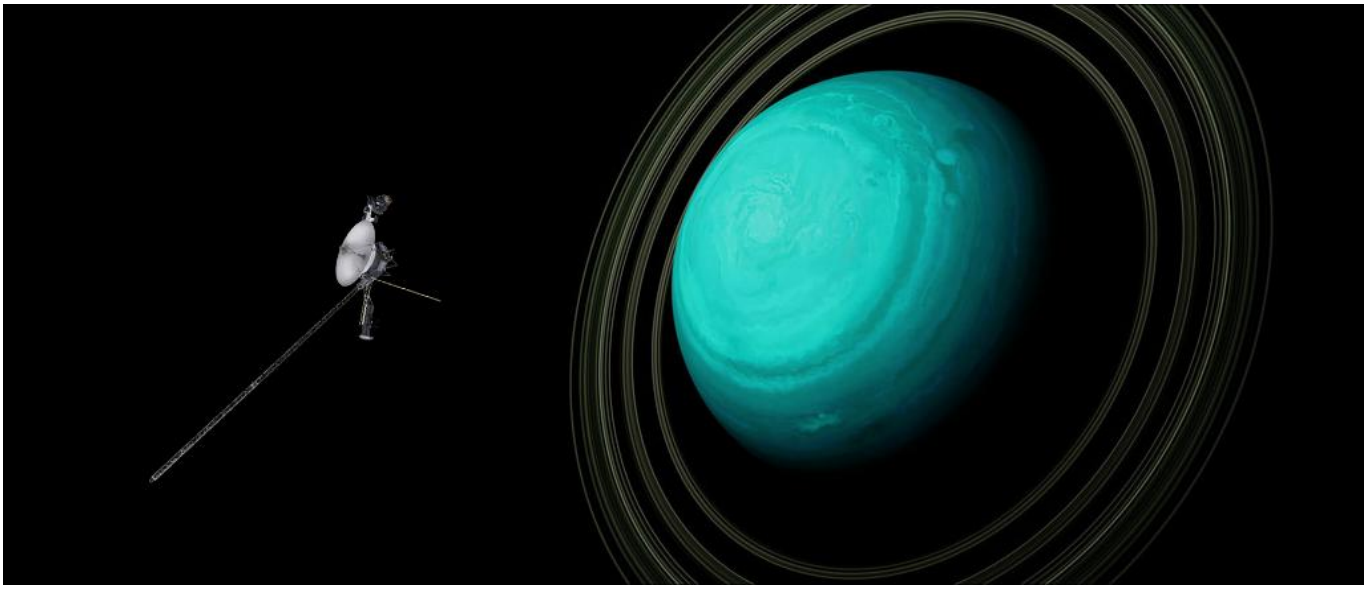
Voyager 2 began the Observatory phase on 4 November 1985. The first event on 23 January 1986 was the magnetosphere's interaction with the solar wind, 17,000 kilometres from the planet's centre – the Bow Shock.

It took Voyager 2 three hours to pass through the turbulent area of the magnetosheath and then enter the magnetosphere proper. In the outer magnetosphere the particles are mostly ionised hydrogen, quite different from Earth, Jupiter and Saturn.

About 100 hours before closest approach, a critical test took place. The scan platform's actuators for elevation and azimuth needed to be checked out. Should any actuator have a down-graded performance the whole spacecraft would have to be used to align the science instruments with the target.

The azimuth axis and the spacecraft roll axis are nearly parallel so a roll motion of the whole spacecraft, including the scan platform, could be used to point the science instruments, including the cameras. However, the pitch and yaw axes would take the high gain antenna away from the Earth so any data would have to be recorded for later playback.

On 20 January a patch was transmitted to the secondary Flight Data System (FDS) to bypass a discrete bit in memory that was inverting one bit in one word causing streaking of the images. The cause was apparently a single word failure, but all imaging information was expected to be recovered.



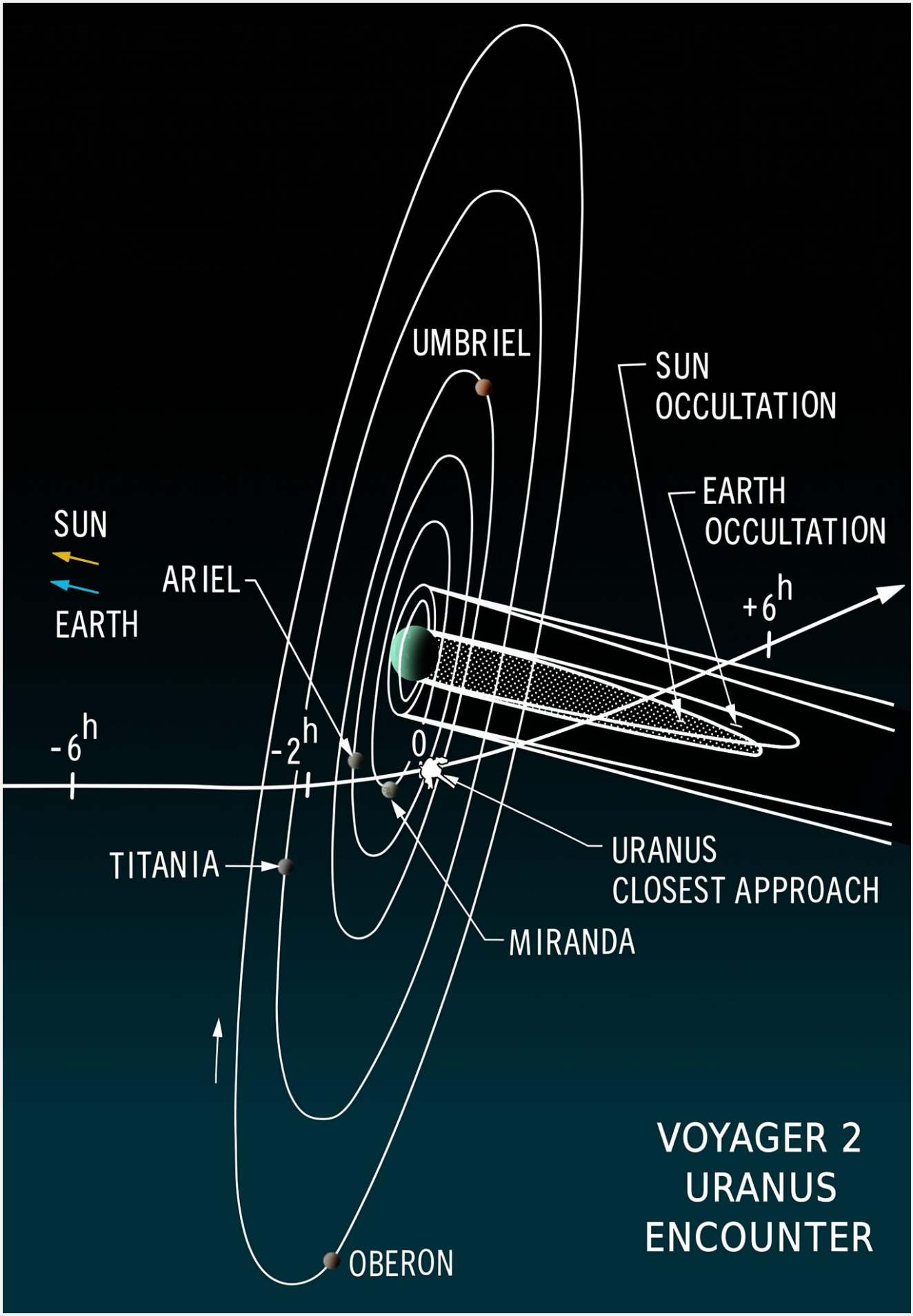
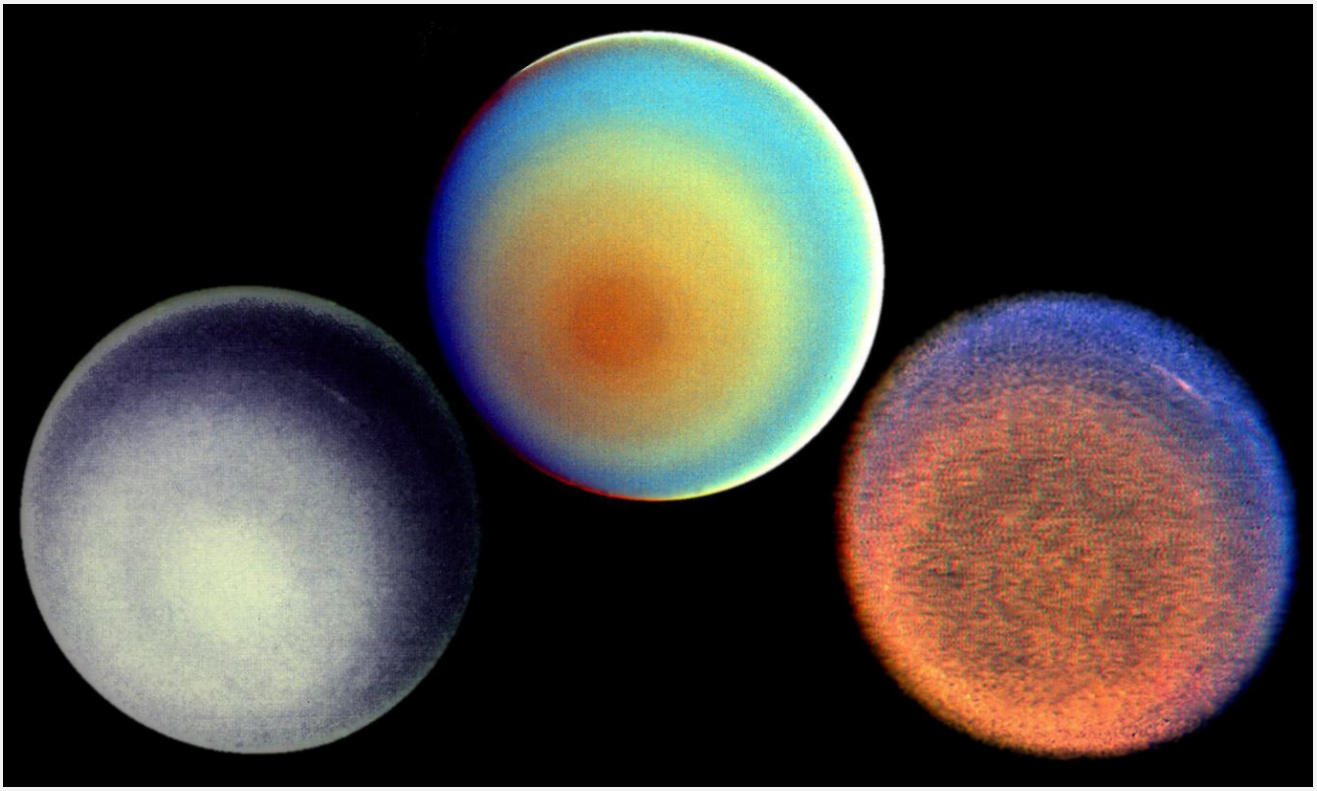


Diagram of Voyager 2's trajectory through the Uranian system.
Graphic: NASA/JPL



False colour images revealed subtle cloud streaks and different atmospheric bandings. Images: NASA/JPL

VOYAGER 2

URANUS – PCA – POINT OF CLOSEST APPROACH
04:59 AEDT – Saturday, 25 January 1986

Voyager passed through the vertical Uranus system beside the moon Miranda on 25 January 1986 at a speed of 53,000 kilometres per hour, seeing the planet from a distance of 81,440 kilometres above the cloud tops at 0459:47 AEDT, taking a mere six hours to pass through the aquamarine planet's environment.

As Voyager 2 crossed the ring plane, but well away from them, the plasma wave experiment detected a large number of dust impacts on the spacecraft. This diffuse dust cloud may be several thousand kilometres thick. Voyager 2 crossed the ring plane about 115,000 kilometres from the centre of the planet, inside the orbit of Miranda.

Excitement at JPL rose to fever pitch as the data from the spacecraft arrived from 2.9 billion kilometres away through DSS43 Tidbinbilla and Parkes 2¾ hours after the actual encounter.

Six hours of intense work revealed that this appeared to be a bland world with no Great Blue Spots, no violent atmospheric storms or colourful eddies. It was disappointing to face a hungry media with this flat news.

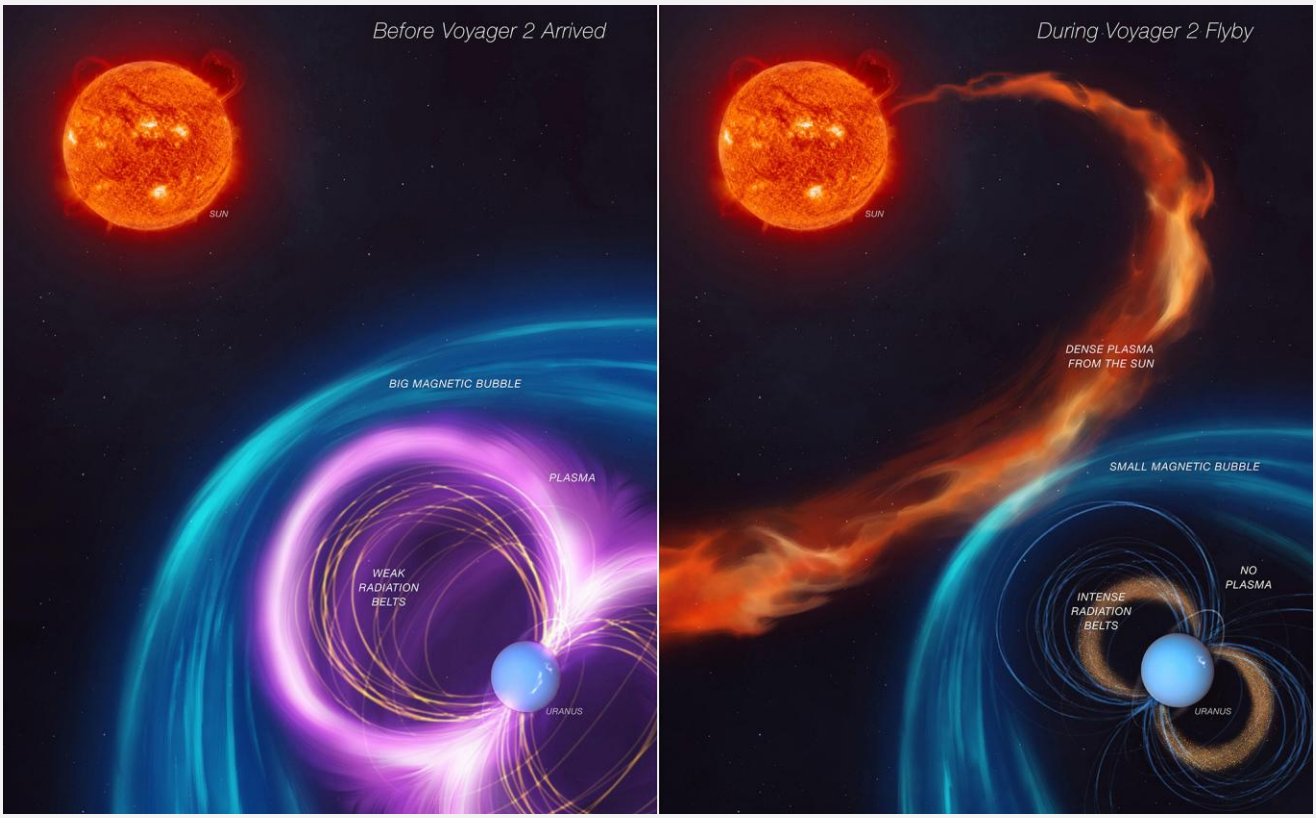
ATMOSPHERE

However, false colour images helped raise some interest by revealing some of the environment. The atmosphere consists of 83% hydrogen, 15% helium, 1.99% methane, 0.01% ammonia plus traces of ethane, acetylene, carbon monoxide, and hydrogen sulphide.

Voyager 2 found the atmospheric winds, their speeds ranging from 145 to 580 kilometres per hour, blow in the same direction as the planet rotates. The average temperature is about -215^{o}C. Surprisingly, the illuminated and dark poles, and most of the planet, show nearly the same temperature at the cloud tops. A high layer of haze was detected around the sunlit pole, which was also found to radiate large amounts of ultraviolet light, a phenomenon dubbed "dayglow."

MAGNETIC FIELD

The presence of a magnetic field at Uranus was unknown until Voyager's arrival. The intensity of the field is roughly comparable to that of Earth's, though it varies much more from point to point because of the large offset of 58.6^{o} of its axis to the planet's rotational axis. The peculiar orientation of the magnetic field suggests that the



Voyager 2's encounter with Uranus coincided with an unusual space weather event which helped scientists understand the intense radiation belts observed by the spacecraft. Graphic: NASA/JPL

field is generated at an intermediate depth in the interior where the pressure is high enough for water to become electrically conducting.

Voyager 2 found there is a magnetic field pushing 600,000 kilometres head of the planet and extending at least 10 million kilometres behind. The extreme tilt of the magnetic axis combined with the tilt of the planet's rotational axis causes this cylindrical magnetotail to rotate about its own axis in a corkscrew shape.

The radiation belts were found to be so intense that irradiation would quickly darken any methane trapped in the icy surfaces of the moons and possibly explain their dark surfaces.

THE RINGS

All nine previously known rings of Uranus were photographed and measured, as were other new rings and ringlets. These observations showed that Uranus's rings are distinctly different from those at Jupiter and Saturn.

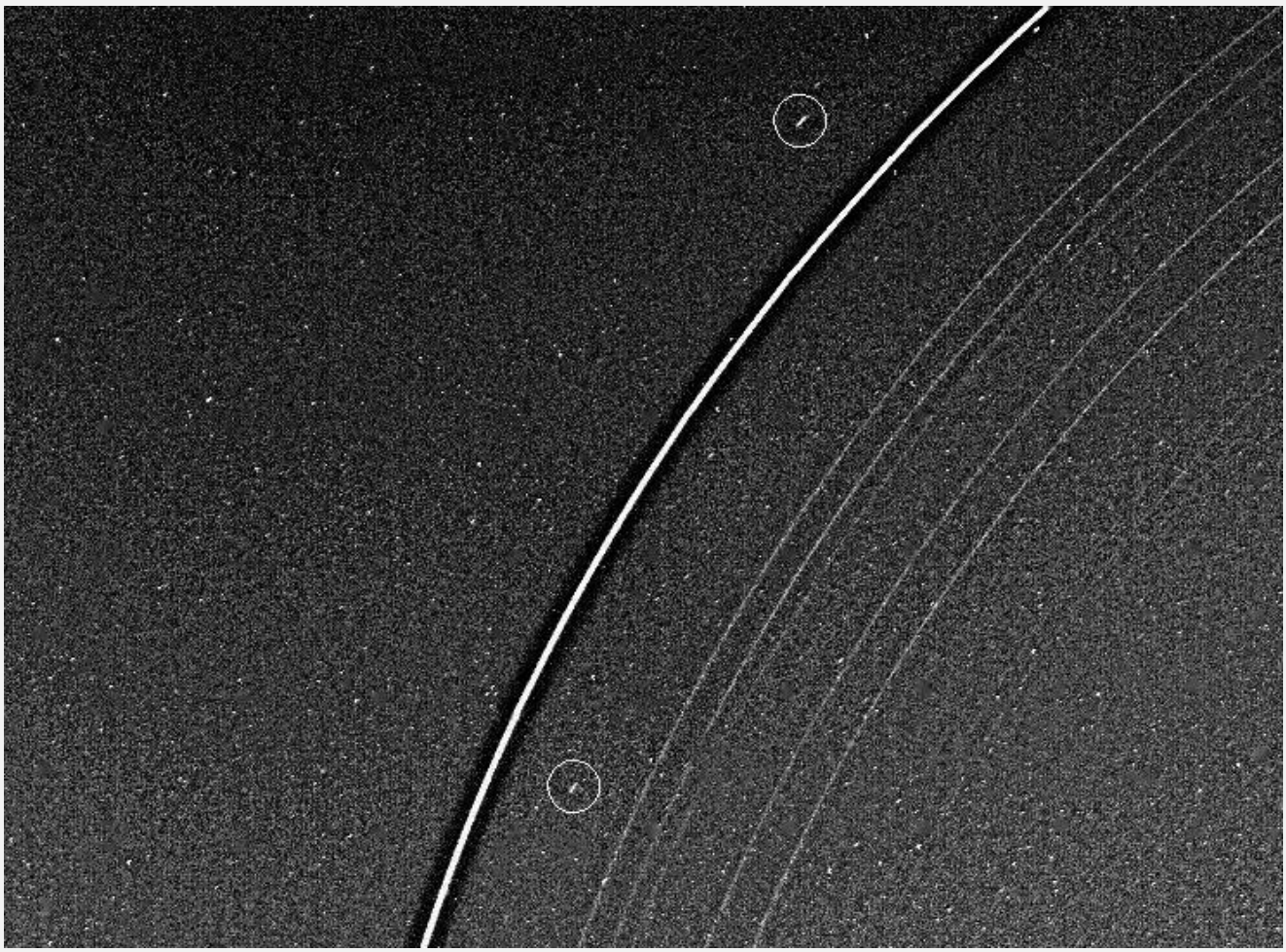
Radio measurements showed the outermost ring, the epsilon, to be composed mostly of ice boulders up to a metre across. However, a very tenuous distribution of fine dust also seems to be spread throughout the ring system.

Incomplete rings and the varying opacity in several of the main rings led scientists to believe that the ring system may be relatively young and did not form at the same time as Uranus. The particles that make up the rings may be remnants of a moon that was broken by a high-velocity impact or torn up by gravitational effects.

To date, two new rings have been positively identified. The first, 1986 U1R, was detected between the outermost of the previously known rings -- Epsilon and Delta -- at a distance of 50,000 kilometres from Uranus's centre. It is a narrow ring like the others. The second, designated 1986 U2R, is a broad region of material perhaps 3,000 kilometres across and just 39,000 kilometres from the planet's centre.

The number of known rings may eventually grow as a result of observations by the Voyager 2 photopolarimeter instrument. The sensor revealed what may be a large number of narrow rings -- or possibly incomplete rings or ring arcs -- as small as 50 metres in width.

The individual ring particles were found to be of low reflectivity. At least one ring, the Epsilon, was found to be grey in colour. Important clues to



The Epsilon ring with shepherd moons 1986U7 Cordelia (bottom) and 1986U8 Ophelia (top). Image: NASA/JPL

Uranus's ring structure may come from the discovery that two small moons -- Cordelia and Ophelia -- straddle the Epsilon ring. This finding lends credence to theories that small moonlets may be responsible for confining or deflecting material into rings and keeping it from escaping into space. Eighteen such satellites were expected to have been found, but only two were photographed.

The sharp edge of the Epsilon ring indicates that the ring is less than 150 metres thick and that particles near the outer edge are less than 30 metres in diameter.

The Epsilon ring is surprisingly deficient in particles smaller than about the size of a beach ball. This may be due to atmospheric drag from the planet's extended hydrogen atmosphere, which probably siphons smaller particles and dust from the ring.

THE MOONS

Voyager 2 obtained clear, high-resolution images of each of the five large moons of Uranus known before its visit, and discovered 10 new moons.

All the observations occurred within a span of 8 hours due to the horizontal tilt of the planet and satellite orbits.

The moons and features on the moon's surfaces were all named after characters from the works of William Shakespeare.

TITANIA

Diameter:	1,577 kilometres
Albedo:	0.35
Mass:	3.4550 x 10^{21} kilograms
Uranus distance:	435,910 kilometres
Orbital period:	8.7 Earth days
Surface temp:	-203°C
Closest approach:	365,200 kilometres

Titania, Uranus' largest moon, was discovered by William Herschel on 11 January 1787 and is named after the queen of fairies in Shakespeare's A Midsummer Night's Dream.

With a mean surface temperature of -203°C, it is likely made up of a rocky core and an icy mantle.



Titania is Uranus' largest moon and features canyons several kilometres deep. Image: NASA/JPL

It is marked by huge fault systems and canyons that indicate some degree of intense geologic activity in its history, possibly due to tidal heating from Uranus. Canyons, the most prominent being Messina Chasmata, are up to 1,500 kilometres long and 2-5 kilometres deep.

OBERON

Diameter:	1,523 kilometres
Albedo:	0.31
Mass:	3.1104 x 10^{21} kilograms
Uranus distance:	583,520 kilometres
Orbital period:	13.5 Earth days
Surface temp:	-203°C
Closest approach:	470,600 kilometres

Oberon, the outermost and second largest of the moons of Uranus, was discovered by William Herschel on the same day as Titania in 1787, and was named after the mythical king of the fairies in Shakespeare's A Midsummer Night's Dream.

With a surface temperature of -203°C Oberon has an old, heavily cratered surface with little evidence of internal activity other than some unknown dark material apparently covering the floors of many craters.

ARIEL

Diameter:	1,162 x 1156 x 1155 kms
Albedo:	0.31
Mass:	1.2331 x 10^{21} kilograms
Uranus distance:	190,900 kilometres
Orbital period:	2.52 Earth days
Surface temp:	-213°C
Closest approach:	127,000 kilometres

Ariel was discovered by William Lassell on 24 October 1851 and is named after a spirit in Shakespeare's The Tempest.

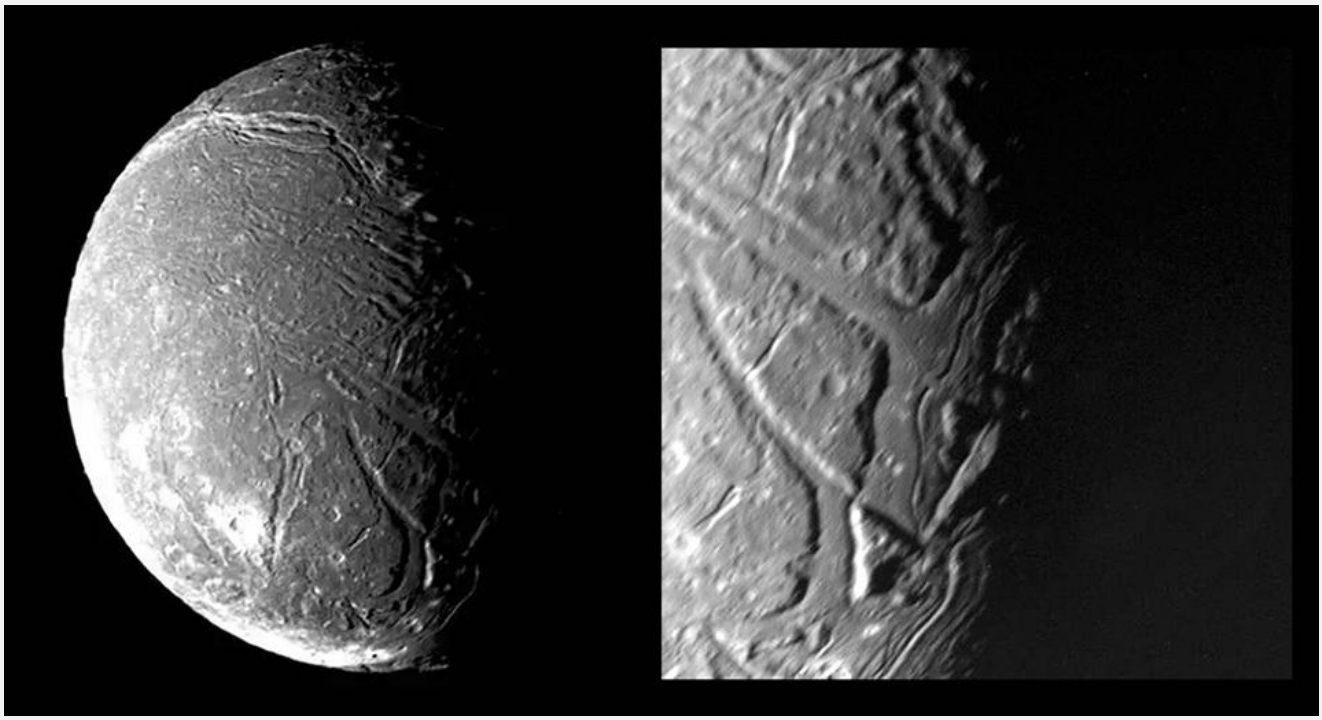
It has the brightest and possibly the geologically youngest surface in the Uranian moon system, suffering a mean temperature of -213°C.

As Voyager 2 flew closer to Ariel than Titania, it was able to distinguish three types of terrain.

The first was heavily cratered, inferring age, the second parallel ridges roughly 20 kilometres apart, while the third a series of rolling plains. Largely devoid of craters greater than about 50 kilometres, indicates that low-velocity material within the Uranian system itself peppered the surface, helping to obliterate larger, older craters.



A montage of Oberon images taken by Voyager 2 during its flyby of this heavily cratered moon.
Images: NASA/JPL, Modern processing: Ted Stryk



Ariel (left) and a closeup of it surface terrain. Images: NASA/JPL

Ariel also appears to have undergone a period of even more intense activity leading to many fault valleys and what appear to be extensive flows of icy material. Where many of the larger valleys intersect, their surfaces are smooth; this could indicate that the valley floors have been covered with younger icy flows.

MIRANDA

Diameter:	480 x 468 x 466 kms
Albedo:	0.32
Mass:	6.293 x 10^{19} kilograms
Uranus distance:	129,390 kilometres
Orbital period:	34 Earth hours
Surface temp:	-187^{o}C
Closest approach:	29,000 kilometres

Miranda, innermost of the five large moons, was discovered by American astronomer Gerard Kuiper on 16 February 1948, and named after Miranda, a principal character in Shakespeare's The Tempest.

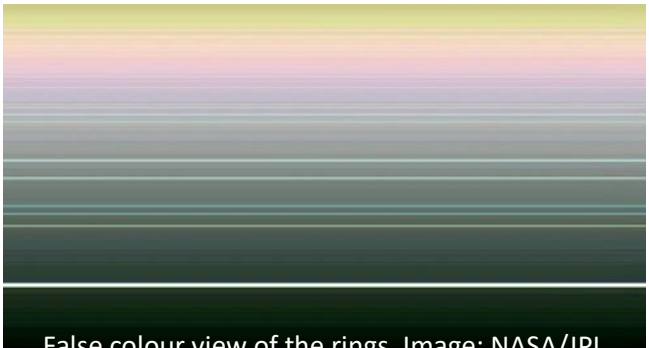
Voyager 2's path to Neptune took it close to Miranda's orbital distance from Uranus, resulting in good high-resolution images of the moon. It is one of the strangest bodies yet observed in the solar system. Voyager 2 flew within 29,000 kilometres of the moon, returning images that showed some areas of the moon at resolutions down to 600 metres.

The reddish surface showed scarps, sawtooth terraces, extensional and compressional faults, cratering, slabs, trenches, huge fault canyons as deep as 20 kilometres, terraced layers and a mixture of old and young surfaces.

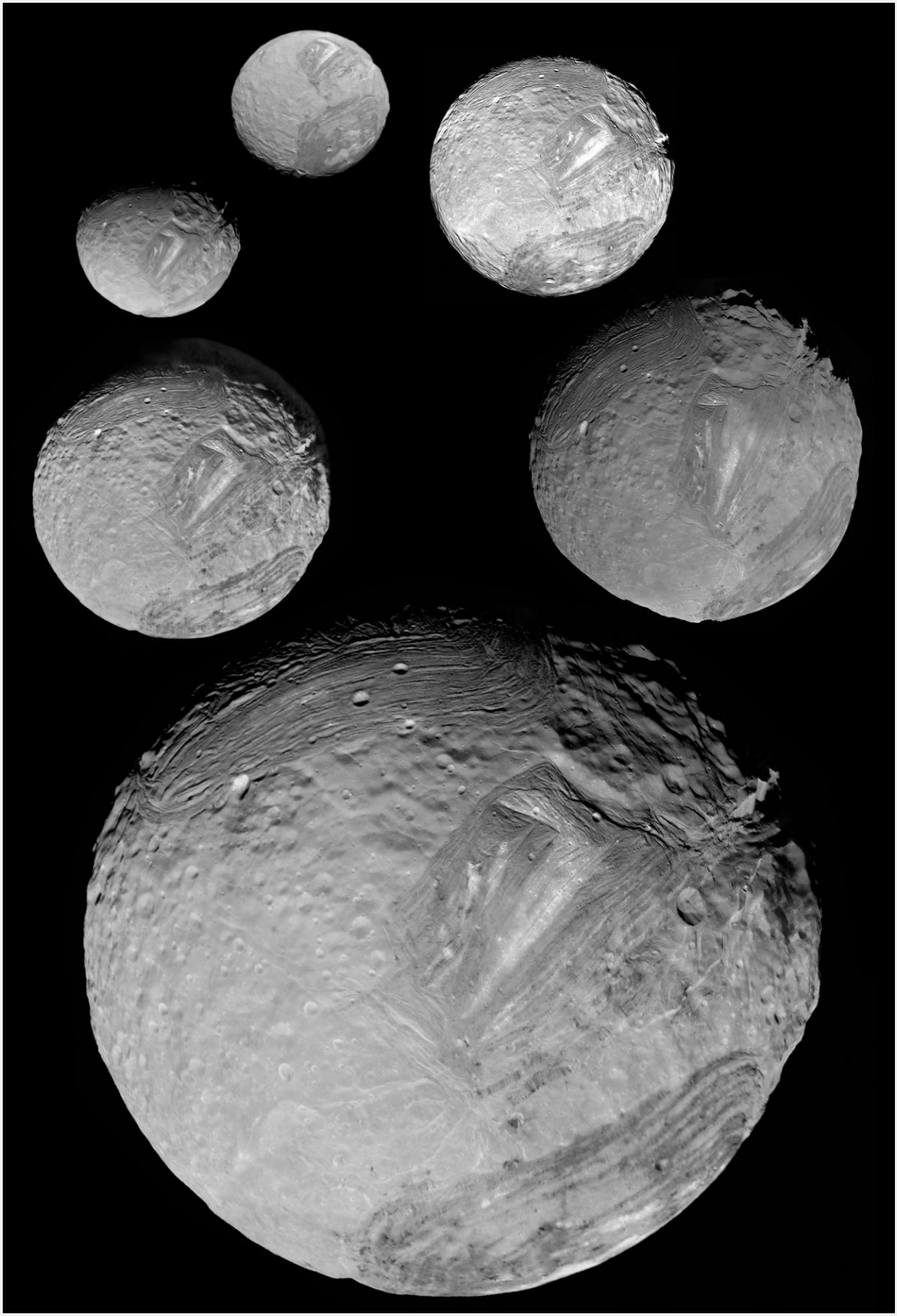
The younger regions may have been produced by incomplete differentiation of the moon, a process in which up-welling of lighter material surfaced in limited areas.

Alternatively, Miranda may be a re-aggregation of material from an earlier time when the moon was fractured into pieces by a violent impact.

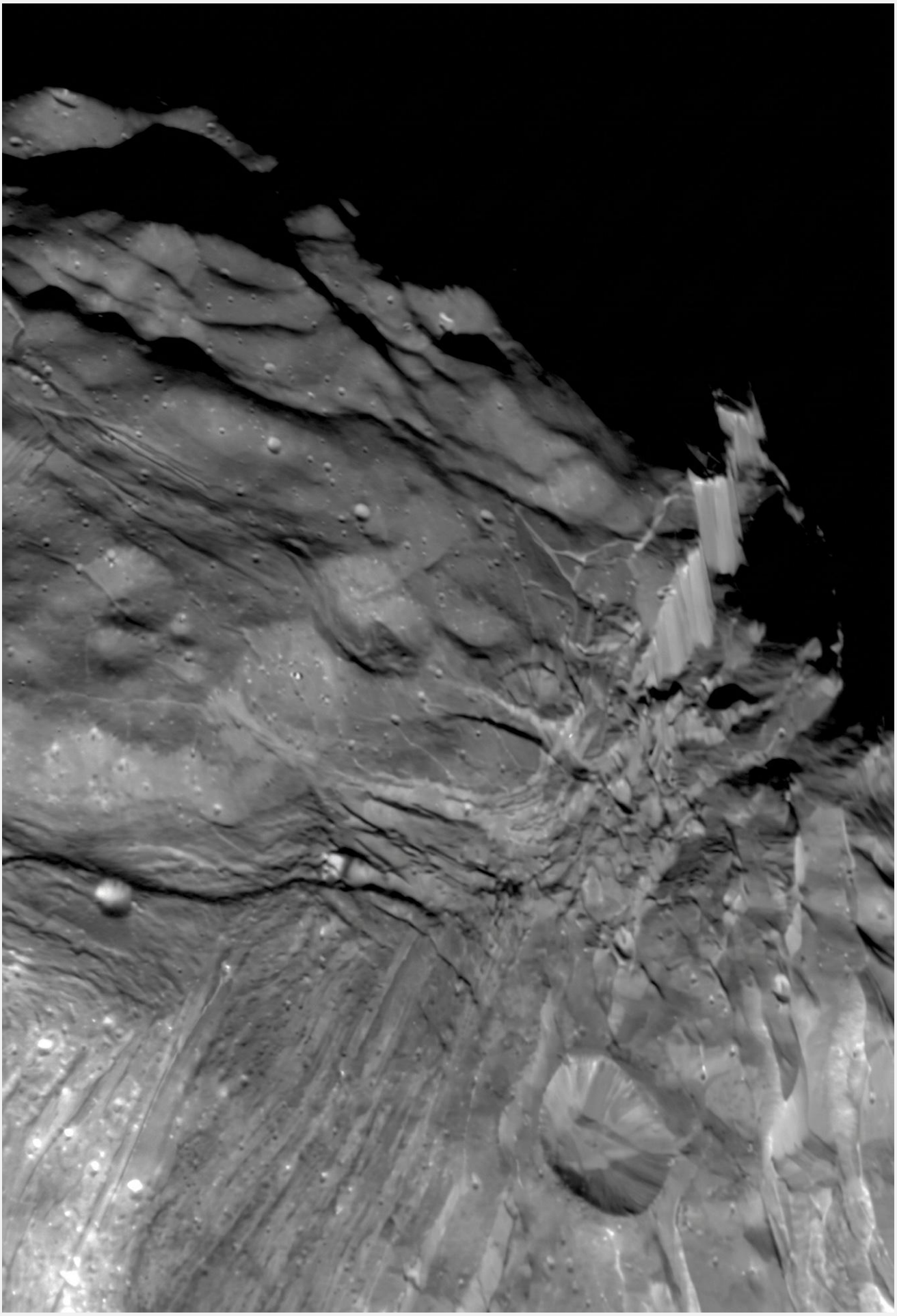
Given Miranda's small size and low temperature of -187^{o}C, the degree and diversity of the tectonic activity on this moon has surprised scientists. It is believed that an additional heat source such as tidal heating caused by the gravitational tug of Uranus must have been involved. In addition, some means must have mobilized the flow of icy material at low temperatures.



False colour view of the rings. Image: NASA/JPL



A montage of Miranda images taken by Voyager 2 during its flyby of this
rugged moon shaped by dynamic forces. Images: NASA/JPL, (largest image) Modern processing: Ted Stryk



The rugged topography was probably produced by compressional tectonics.
The fault scarp or ‘cliff’ (upper right) is estimated to be 5 kilometres high. Image: NASA/JPL



Dark and 'dusty' Umbriel. Image: NASA/JPL, Modern processing: Ted Stryk

UMBRIEL

Diameter:	1,165 kilometres
Albedo:	0.26
Mass:	1.2331 x 10^{21} kilograms
Uranus distance:	266,000 kilometres
Orbital period:	4.144 Earth days
Surface temp:	-198°C
Closest approach:	325,000 kilometres

Umbriel is ancient and dark, apparently having undergone little geologic activity. Large craters pockmark its surface. The darkness of Umbriel's surface may be due to a coating of dust and small debris somehow created nearby and confined to the vicinity of that moon's orbit.

DSS43 – ANTENNA SYSTEM FAILURES

A series of antenna system failures during the Uranus encounter affected the quality of the radio science data during occultation. In particular, at Tidbinbilla, on the big dish – Deep Space Station 43 - an antenna elevation angle encoder failed and was disconnected. This failure, in turn, caused the subreflector controller to command the subreflector to move as though it was operating in its normal gain-peaking mode, but at a faster rate.

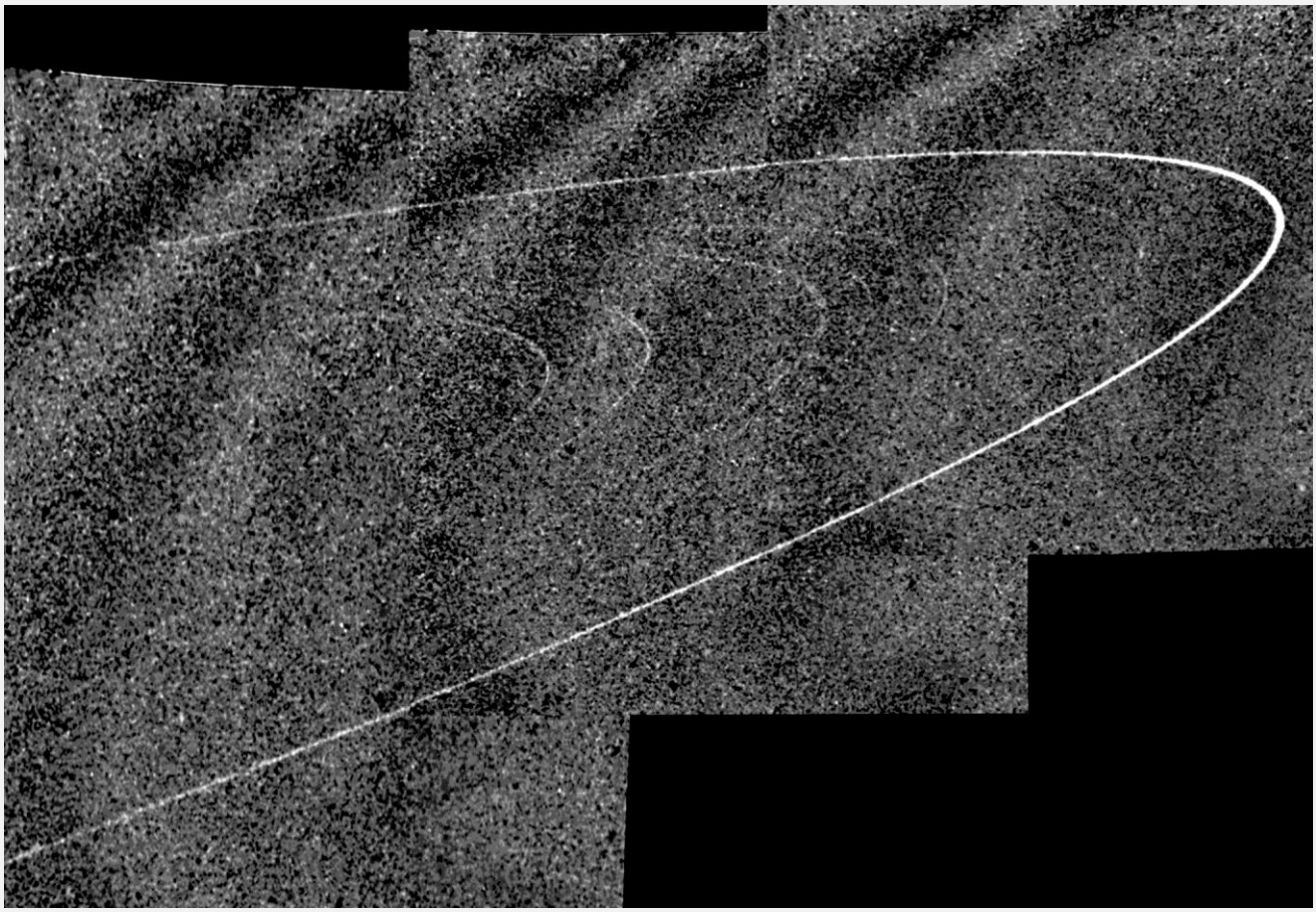
After about 12 minutes the subreflector movement was automatically stopped because of a previously planned decision to turn off the subreflector controller. The antenna continued to track the spacecraft for the rest of the pass with a mispositioned subreflector, which affected both antenna gain and pointing.

Voyager 2 obtained clear, high-resolution images of each of the five large moons of Uranus known before the encounter: Miranda, Ariel, Umbriel, Titania and Oberon.

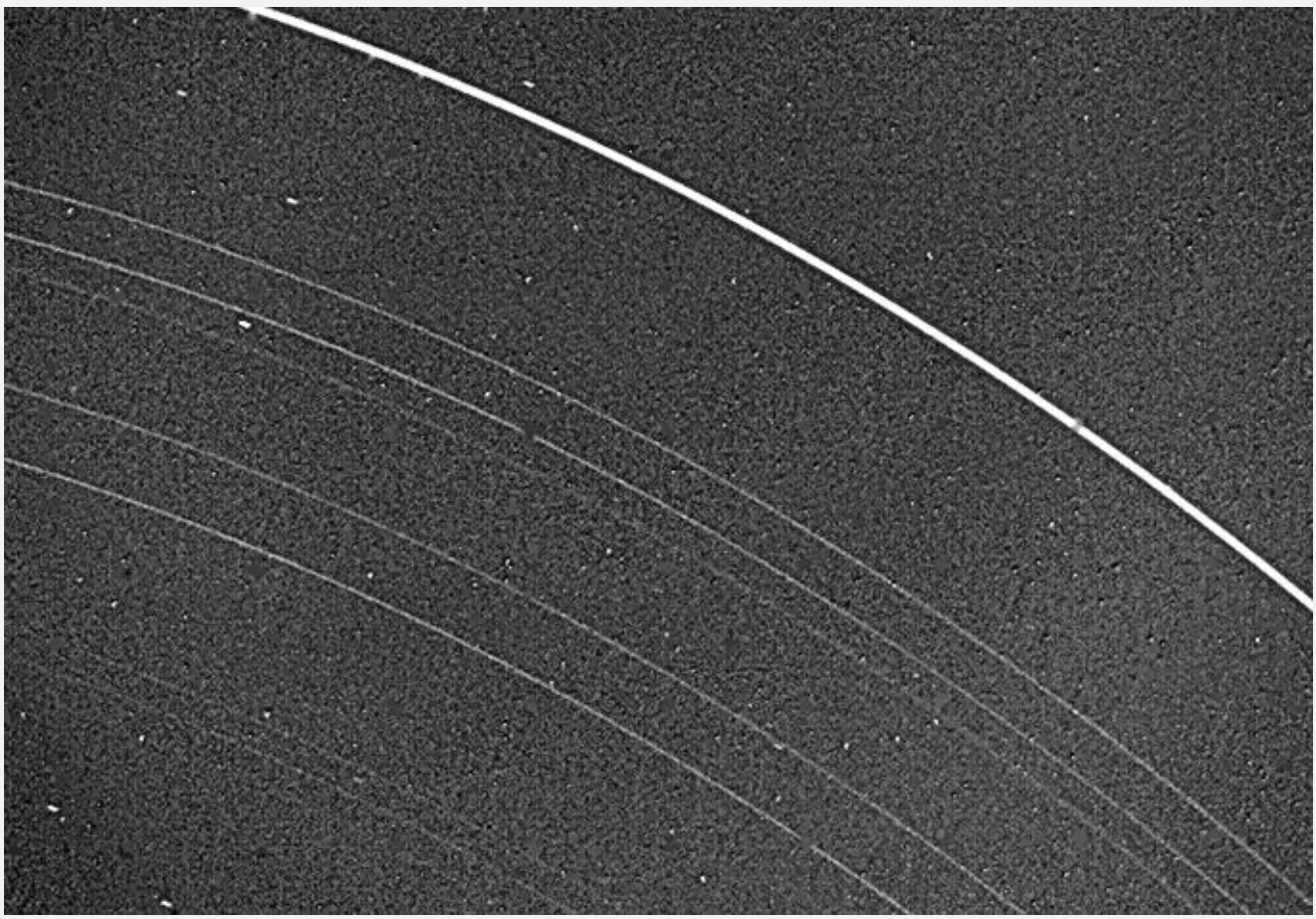
PUCK - 1985U1

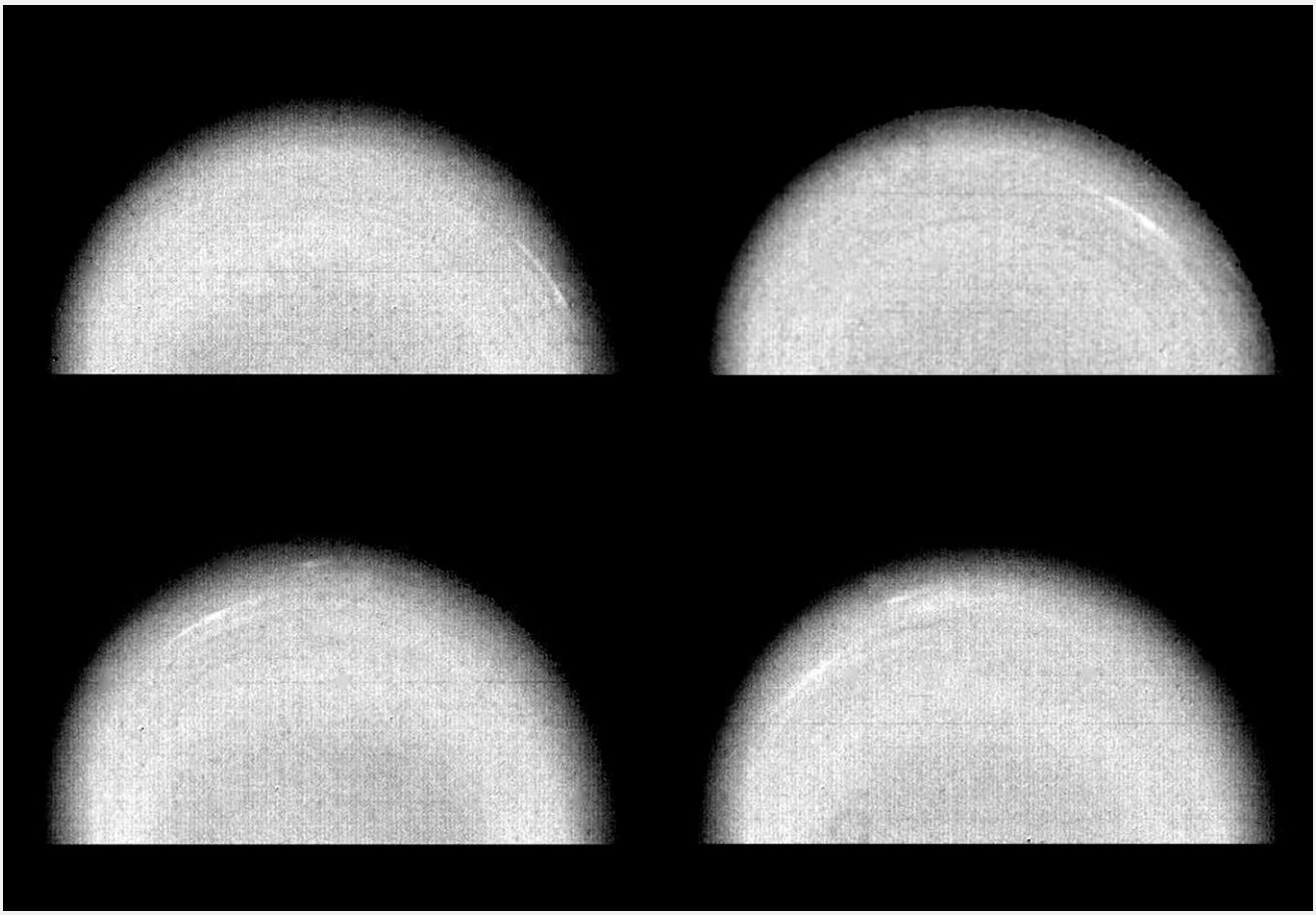
Diameter:	162 kilometres
Albedo:	0.104
Mass:	2.0035 x 10^{18} kilograms
Uranus distance:	86,007 kilometres
Orbital period:	18 hrs 17 mins Earth hours
Surface temp:	-208°C
Closest approach:	86,010 kilometres

The 10 new moons discovered by Voyager 2 bring the total number of known Uranian satellites to 15^{+}. The largest of the newly detected moons, named Puck, is 162 kilometres in diameter, larger than most asteroids.

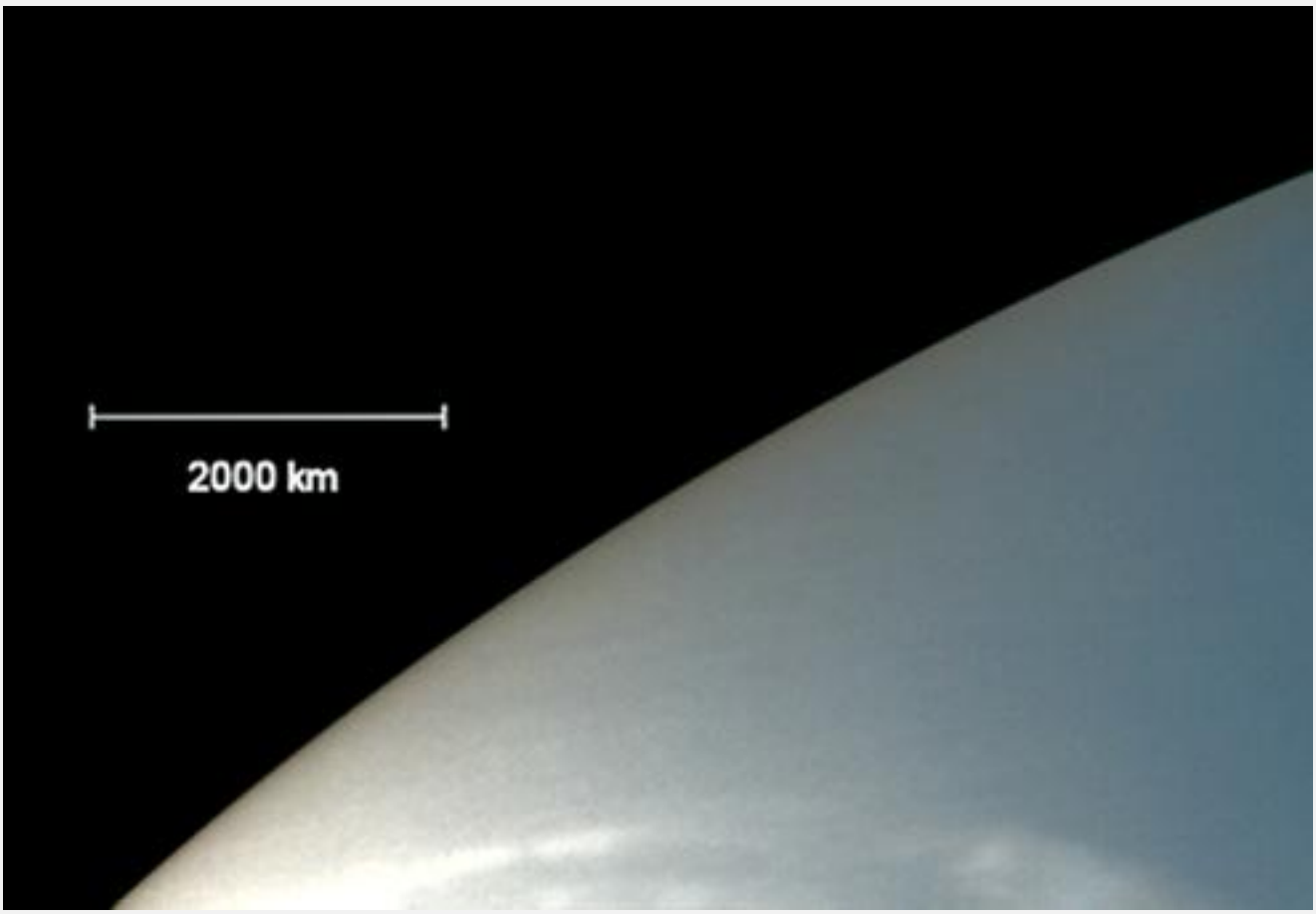


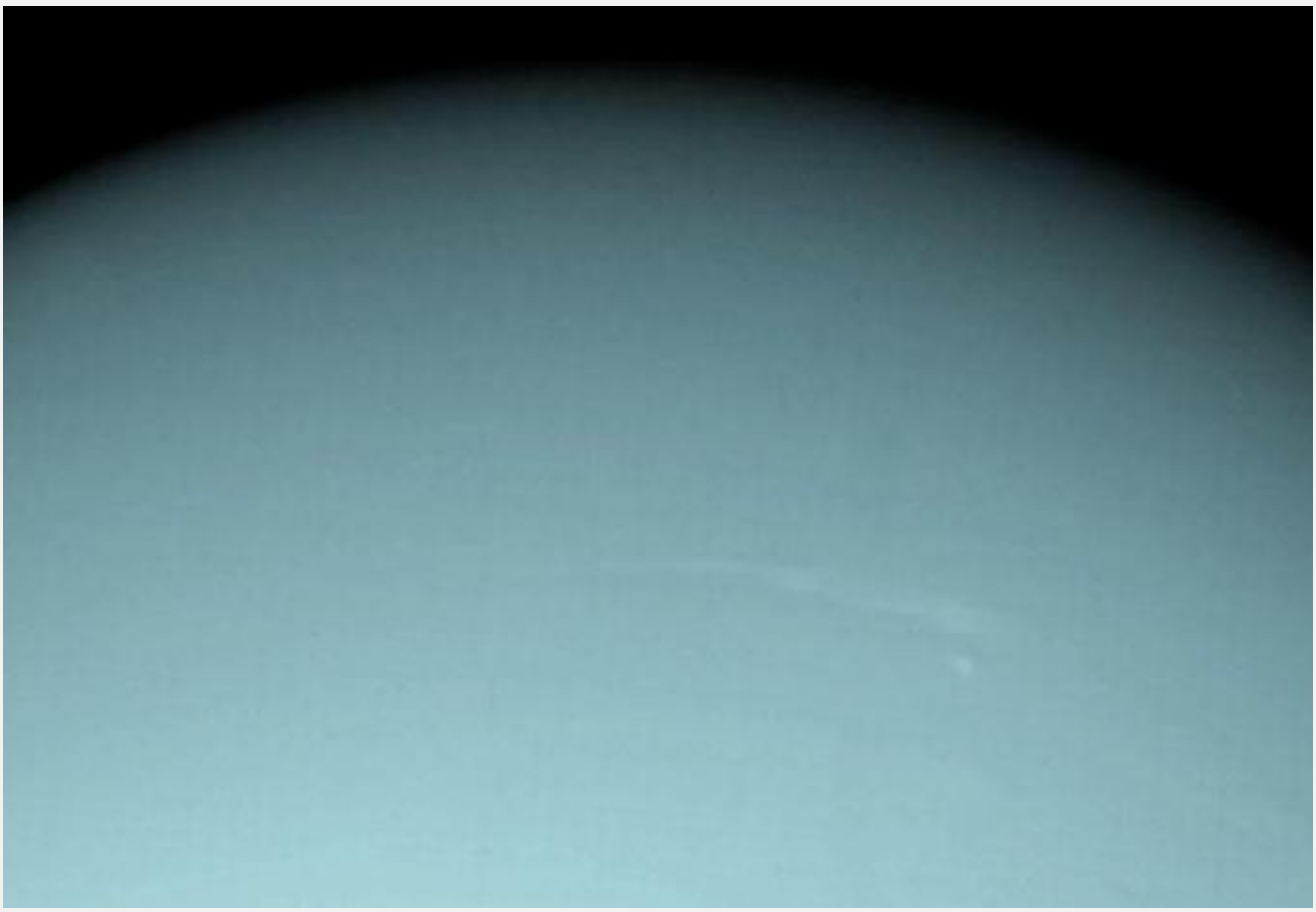
Above: Voyager 2 took this image as it approached the plane of the Uranian ring system.
Images: NASA/JPL
Below: Epsilon ring (top), then Delta, Gamma and Eta, followed by Beta and Alpha,
and lastly the faint rings closest to the planet, simply known as four, five and six.



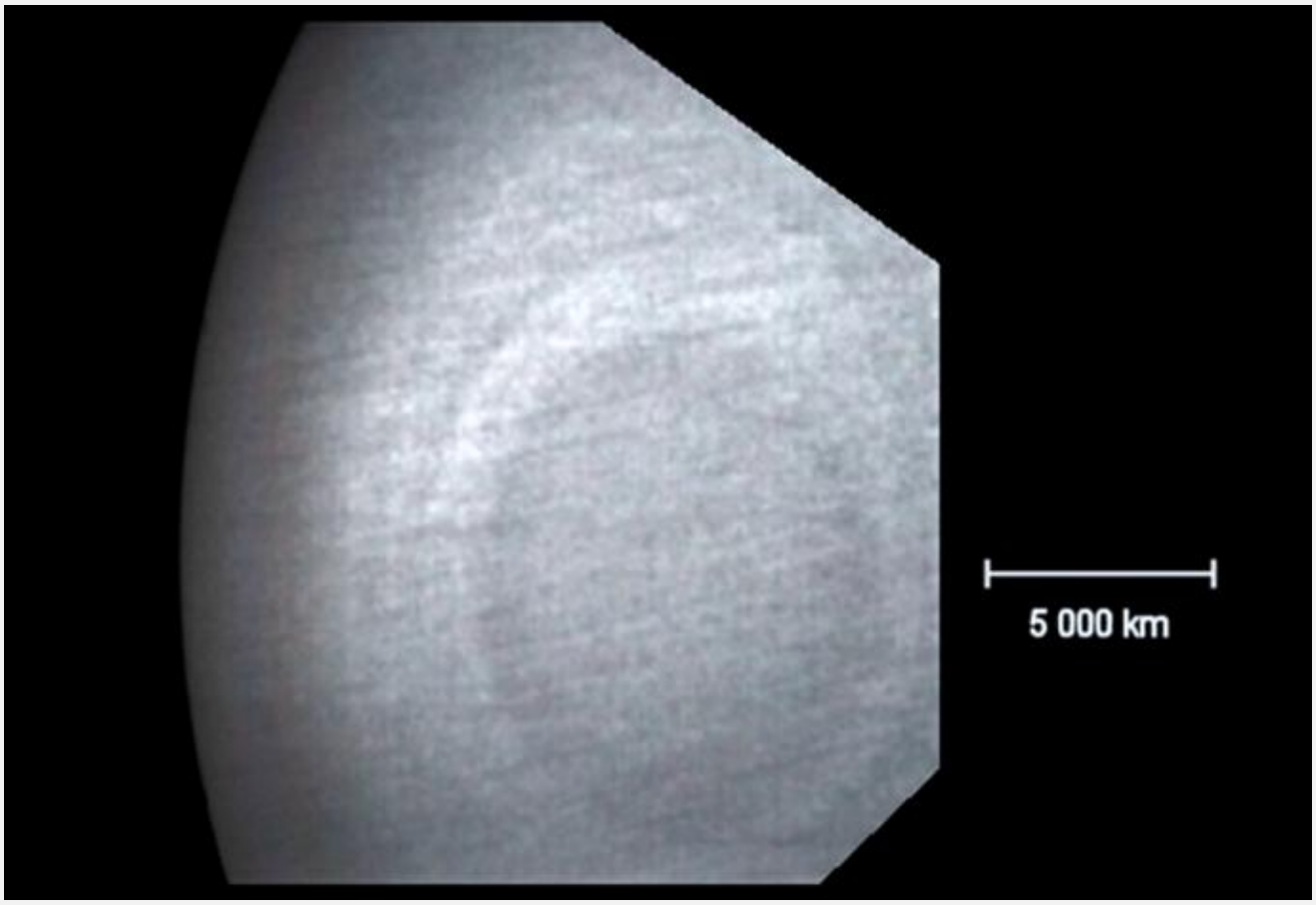


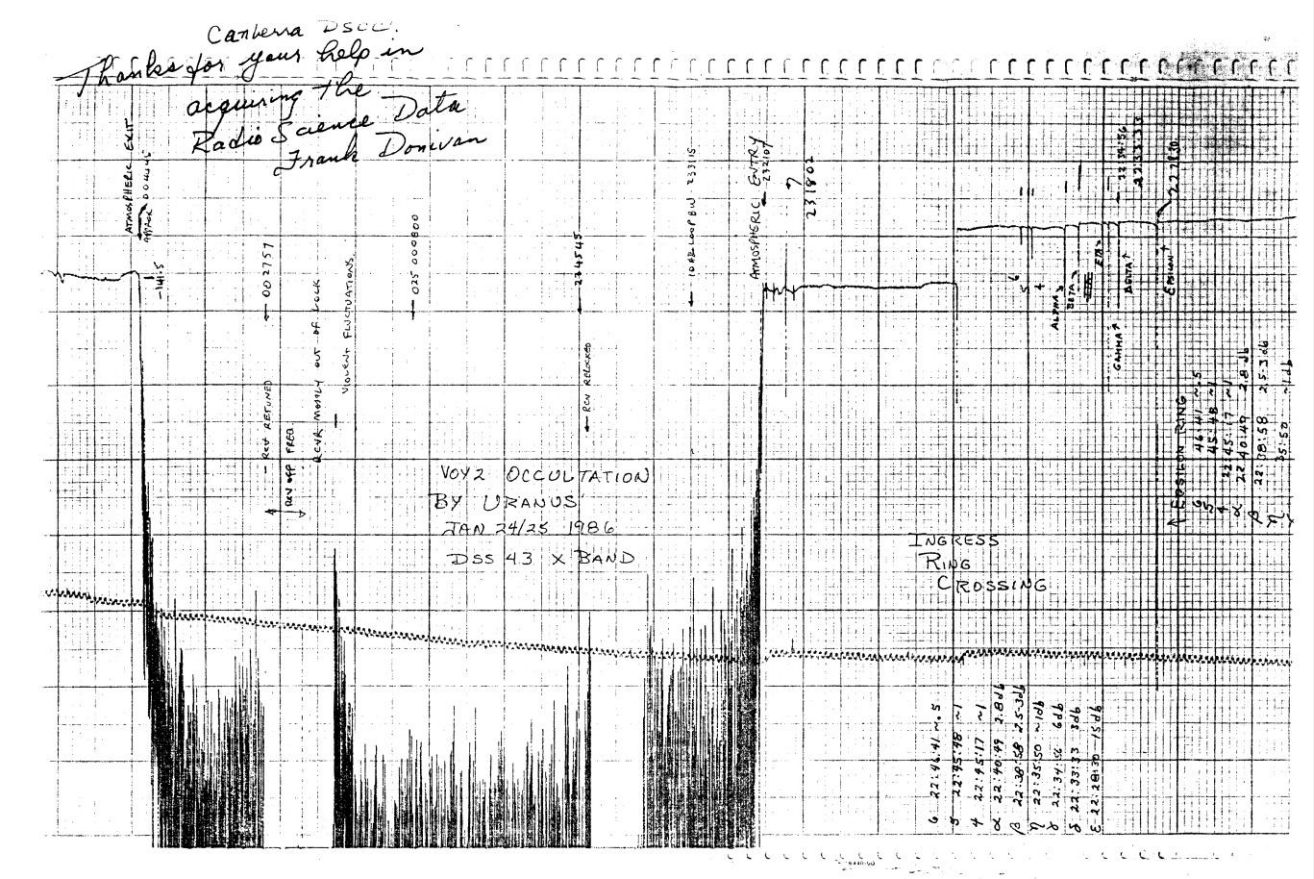
Above: Four images showing the motion of cloud streaks moving with the atmosphere.
Images: (above) NASA/JPL, (below) NASA/JPL, Modern processing: Daniel Macháček
Below: Contrast enhanced image of clouds in the atmosphere of Uranus.





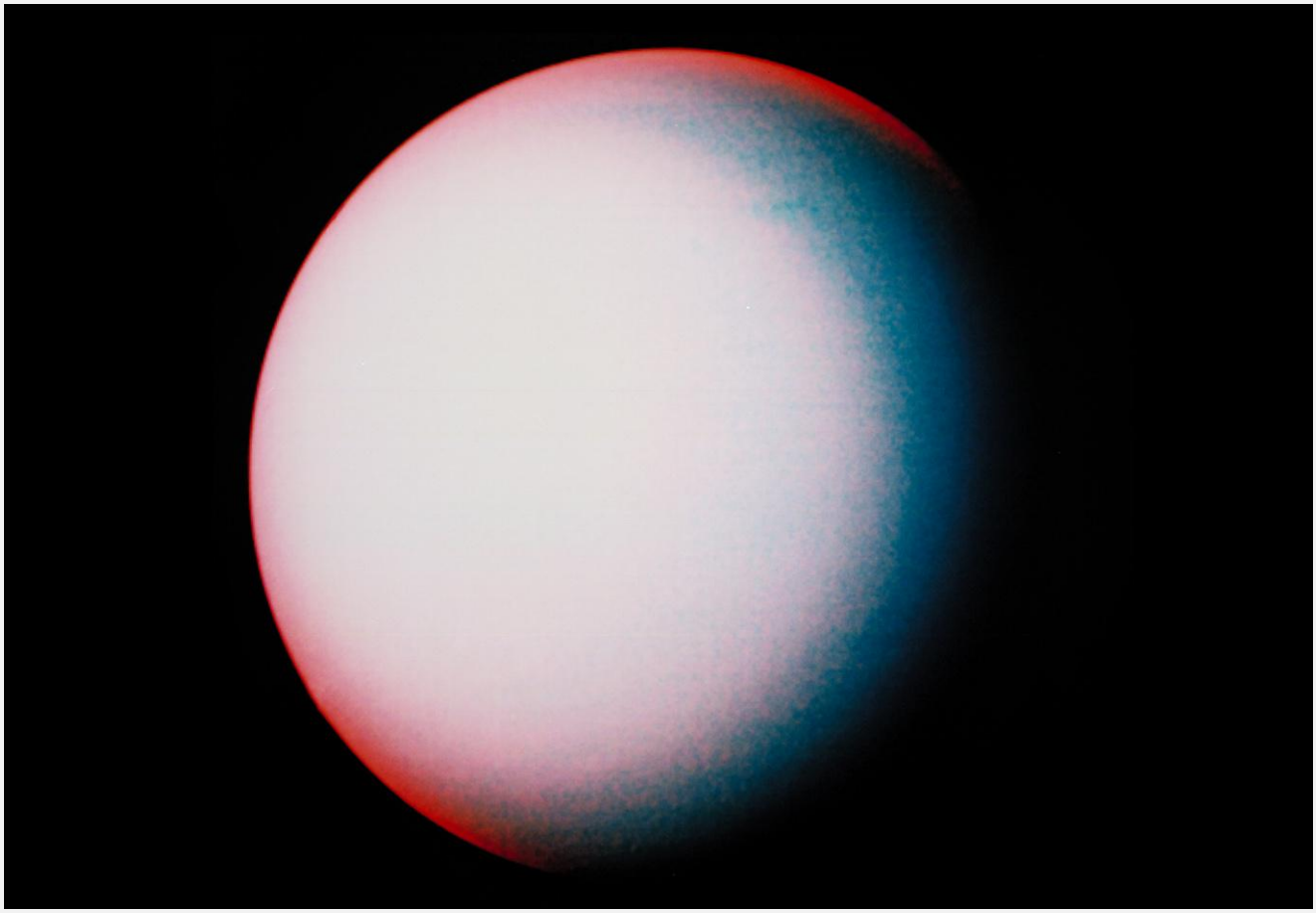
Above: Mid-latitude clouds are barely visible in this colour image from Voyager 2.
Images: (above) NASA/JPL, (below) NASA/JPL, Modern processing: Daniel Macháček
Below: South polar atmospheric structure seen by Voyager 2 in this enhanced image.



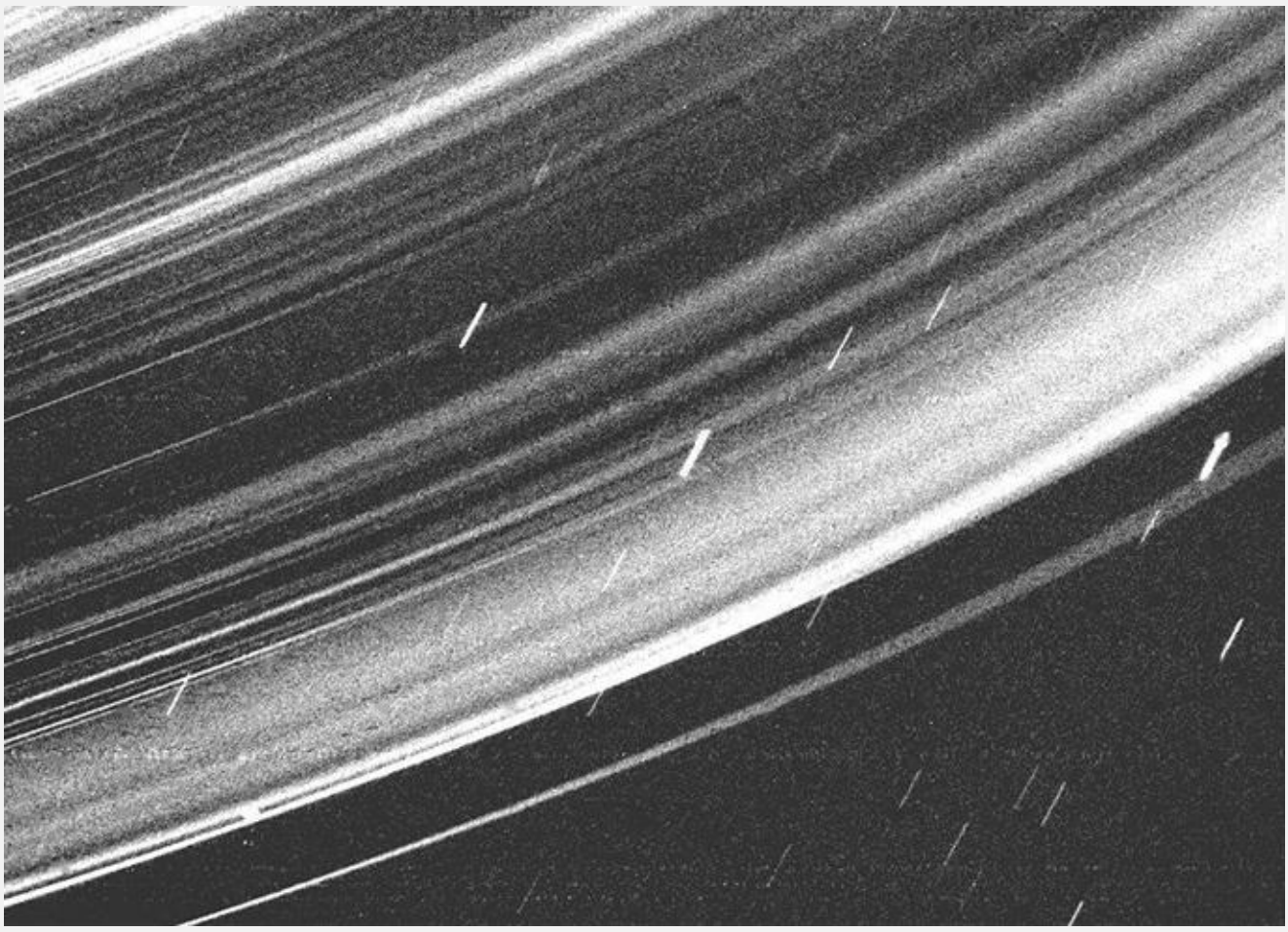


Above: Recording of data collected through DSS43 at Tidbinbilla from Voyager 2 during its occultation at Uranus. It is signed with a note of thanks by Voyager Radio Science Investigator, Frank Donivan.
Images: (above) Scan by John Saxon, (below) Preserved by Mike Dinn, Scan: Colin Mackellar
Below: (from left) Dwight Holmes, Frank Donivan (from JPL), and Mike Dinn at Tidbinbilla





Above: High altitude hazes (red and pinks) in the upper atmosphere over the pole and limb.
Images: NASA/JPL. (Note: *In the image below, white streaks are background stars)*
Below: A long exposure image reveals a continuous distribution of small particles within the ring system.



A summary of the 16 main Uranian moons and satellites from the inner-most to the outer-most up to the time of Voyager 2's visit:

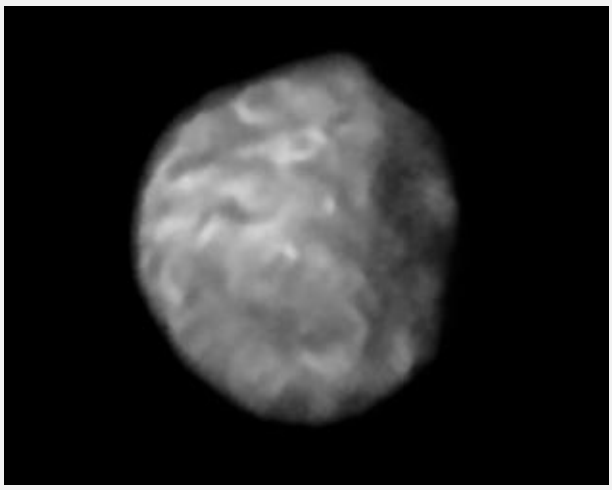
SUMMARY OF URANUS' MOONS AND SMALLER SATELLITES

	Diameter kms	Kms from Uranus' centre
1986U7 Cordelia	26	49,800
1986U8 Ophelia	32	53,800
1986U9 Bianca	44	59,200
1986U2 Juliet	62	61,800
1986U6 Desdemona	54	62,660
1986U4 Rosalind	84	64,400
1986U1 Portia	108	66,100
1986U3 Cressida	54	69,900
1986U5 Belinda	66	75,260
1986U10 Perdita	30	76,417
1985U1 Puck *	162	86,010
Miranda *	483	129,780
Ariel *	1,158	190,900
Umbriel *	1,172	265,970
Titania *	1,577	435,840
Oberon *	1,523	583,400

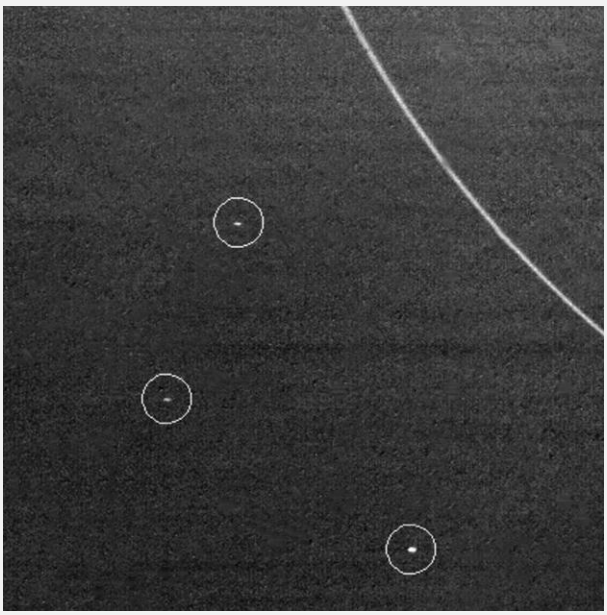
* asterisk indicates Voyager 2 observed the moon.

Editor's note: ^ According to NASA, as at August 2026, Uranus has 29 officially recognised moons. The moons are sometimes called the "literary moons" because they are named for Shakespearean characters, along with a couple of the moons being named for characters from the works of Alexander Pope. The most recently discovered moon was first spotted in November 2023 – S/2023U1 is estimated to be 8-12 kms in diameter.

Voyager 2 left the Uranian system on 26 February 1986 and headed for Neptune, the last planetary outpost of the solar system, as at the time Pluto was inside Neptune's orbit.



Voyager 2 image of Puck. Image: NASA/JPL



1986U3 Cressida (top), 1986U4 Rosalind (middle), and 1986U1 Portia (bottom). Image: NASA/JPL

SUMMARY OF URANUS ENCOUNTER – 5 NOVEMBER 1986 - 25 JANUARY 1986

Date	AEDT	Distance	Event/Closest Approach
Nov. 5 '85	00:02	103,542,000	Observatory phase begins
Jan. 25 '86	02:31	365,000	Titania
	03:33	471,000	Oberon
	03:42	127,000	Ariel
	04:25	29,000	Miranda
	04:59	**106,862**	**Uranus ***
	08:14	325,000	Umbriel

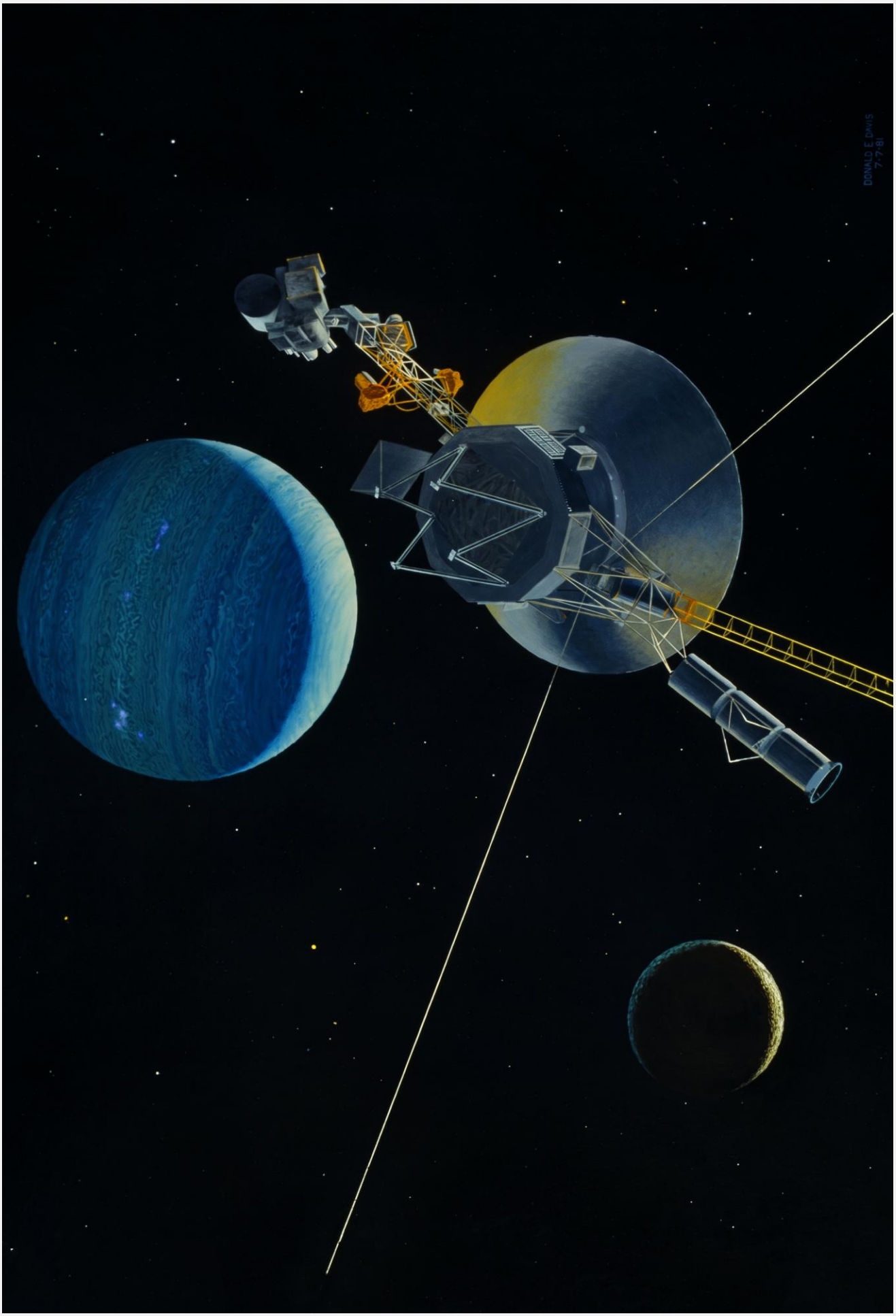
One-way signal elapsed time was 2 hour 45 minutes

* from Uranus' centre (kilometres)

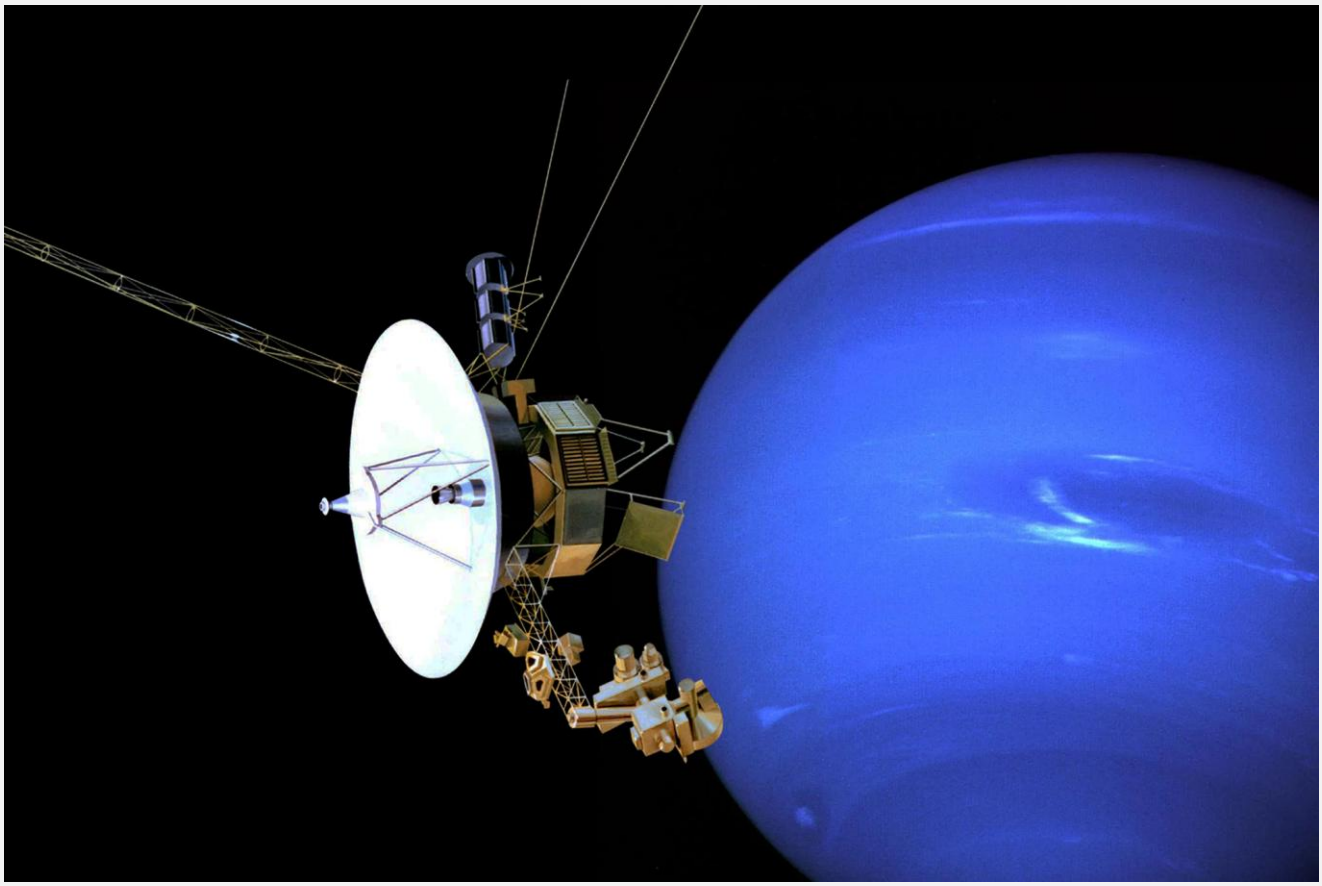


Voyager 2’s departure view of Uranus. Image: NASA/JPL, Modern processing: Emily Lakdawalla

Uranus’ blueish hues were just a hint of what was to come at the next destination!



Artist’s depiction of Voyager 2’s encounter with Neptune and Triton. Image: Donald E. Davis (public domain)



The Grand Finale of the Grand Tour – Voyager 2 approaches Neptune. Image: (composition) NASA/JPL

VOYAGER 2

NEPTUNE ENCOUNTER

Unable to be seen by the naked eye, astronomers have studied Neptune since 23 September 1846 when Johann Gottfried Galle, of the Berlin Observatory, and Louis d'Arrest, an astronomy student, discovered the eighth planet on the basis of mathematical predictions by Urbain Jean Joseph Le Verrier in 1846. John Couch Adams made similar predictions independently in England, but did not publish his predictions.

Galileo Galilei is supposed to have seen Neptune during several nights of observing Jupiter, in January 1613, but didn't realize he was seeing a new planet.

Named after the Roman god of the sea due to its ocean-like blueness, Neptune orbits nearly 4.498 billion kilometres from the Sun. It's so far away it takes sunlight 4 hours and 40 minutes to reach Neptune.

Pluto moves inside Neptune's orbit for about a 20 year period, during which it is closer to the sun than Neptune. Pluto last crossed Neptune's orbit on 23 January 1979, and remained within it until 11 February 1999.

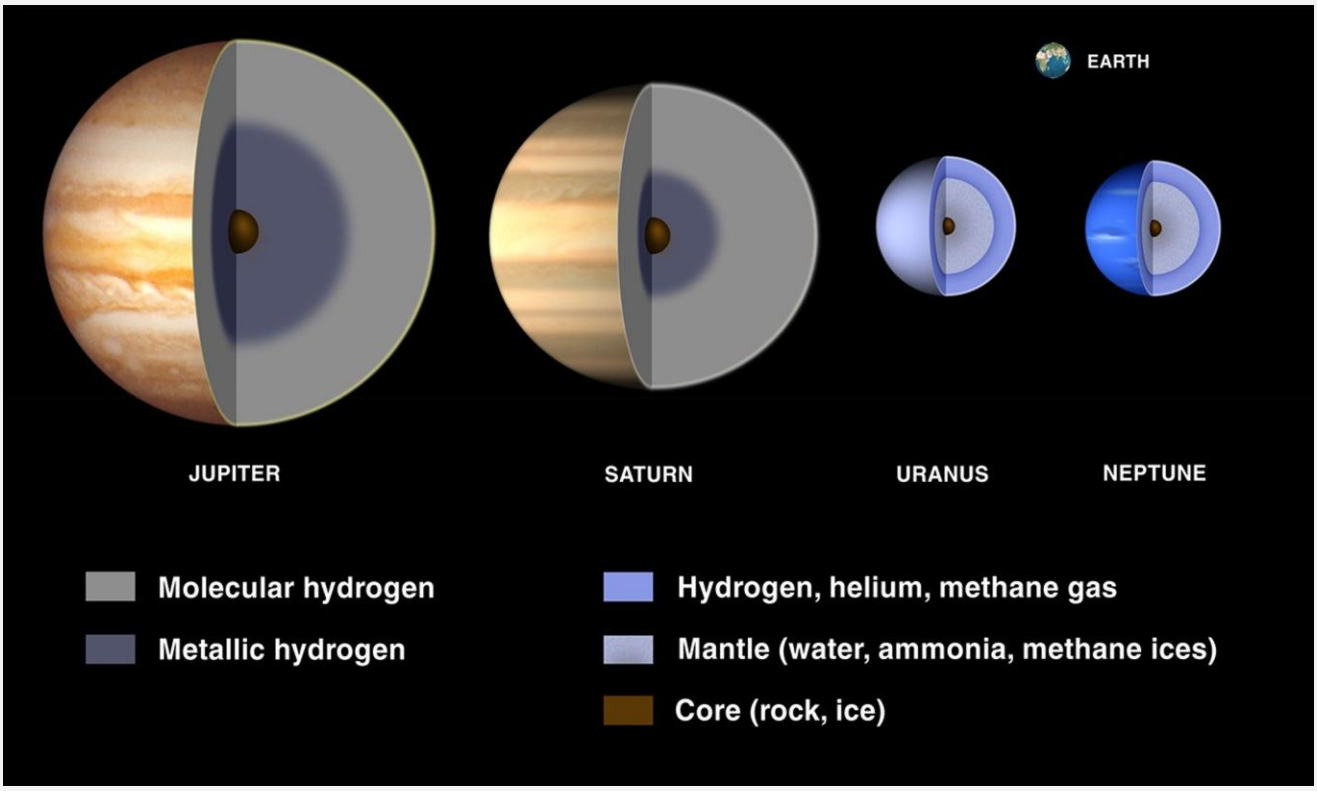
NEPTUNE ENCOUNTER
FRIDAY 25 AUGUST 1989
NEPTUNE FACTS

Diameter:	49,244 kilometres
Distance to Sun:	4,498,396,441 kilometres
Mass:	1.0243 x 10^{26} kilograms
Orbital period:	164.8 Earth years
Length of day:	16 hrs 6 mins 42 secs
Surface temp:	-223°C min / -214°C max
Closest approach:	4,850 kilometres

A diameter of 49,244 kilometres makes Neptune the smallest of the gas giants, but is still able to hold 60 Earths within its sphere. Gravity wise 100 Earth kilograms would weigh 110 kilograms on Neptune.

It orbits the Sun once in 165 years at a speed of 19,555 kilometres per hour, which means it has not quite made a full circle around the Sun since it was discovered.

Neptune is the densest of the four giant planets, about 64% heavier than if it were composed entirely of water. It has an albedo of 0.41.



The interior structures of the gas giant planets. Graphic: NASA

Neptune's internal structure resembles that of Uranus. There is likely to be a core consisting of molten rock and metal, surrounded by a mixture of rock, water, ammonia, and methane.

The atmosphere, extending perhaps 10 to 20 percent of the way towards the centre, is mostly hydrogen and helium at high altitudes. Increasing concentrations of methane, ammonia, and water are found in the lower regions of the atmosphere.

As this is written Neptune supports 13~ moons and small satellites.

Observers on Earth found it difficult to determine the length of a Neptunian day as the cloud motions did not indicate the rotation of the bulk of the planet, estimating it at 18 hours. With the arrival of Voyager 2, the planetary radio astronomy instrument measured the periodic radio waves generated by the magnetic field as 16 hours 6 minutes 42 seconds.

Neptune is tilted by almost 28.32^{o} to the ecliptic so has seasons like the Earth. Voyager 2 arrived during winter in the northern hemisphere.

The Voyager Flight Team faced several challenges at Neptune, including very low light levels, long communication distances and an ageing (*12 years in flight*) spacecraft.

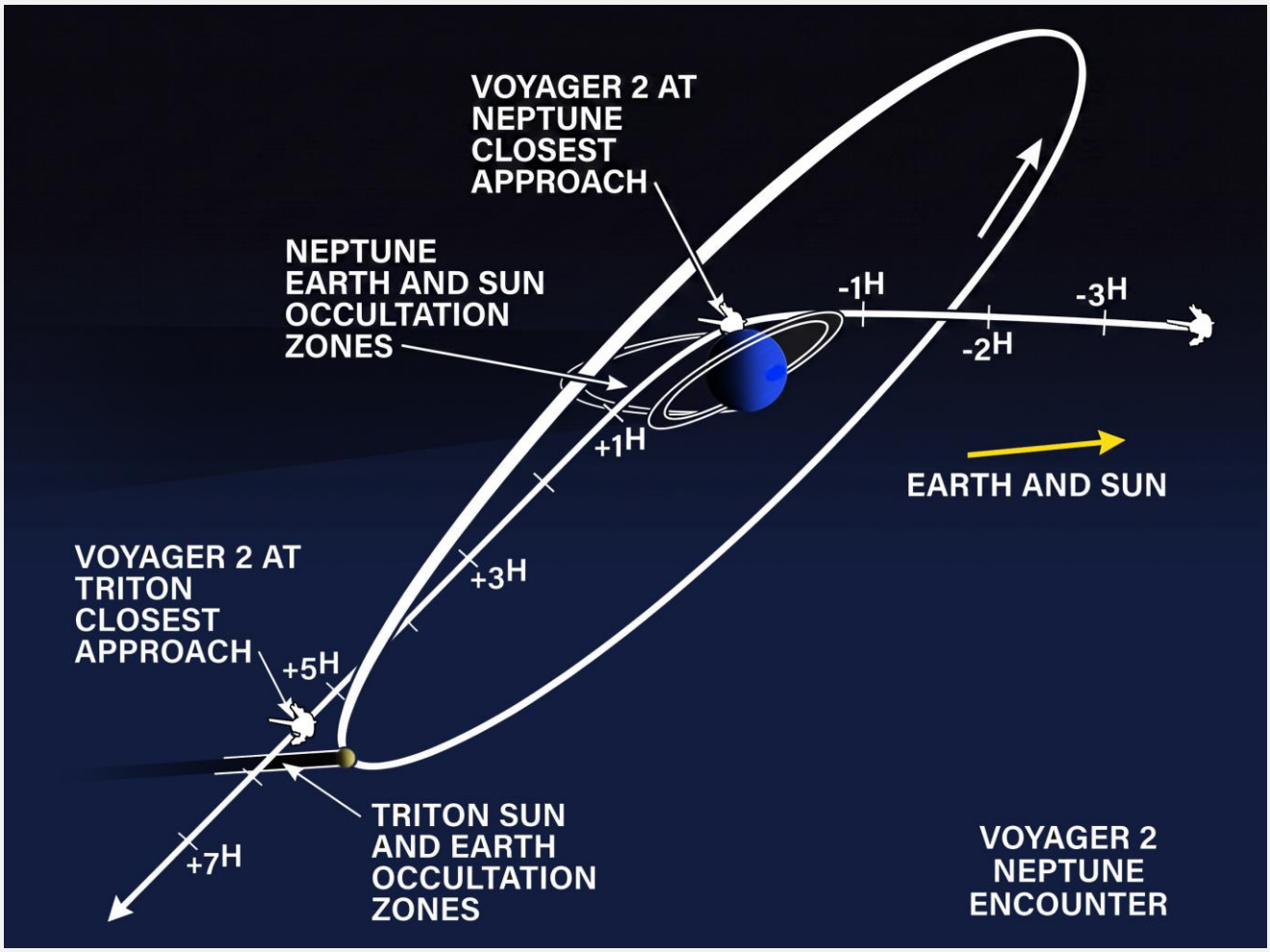
The scientists had chosen a flight path that took Voyager 2 directly over the planet's north pole. While this flight path guaranteed the best view of Neptune, the researchers had only a few seconds to take the critical pictures. If the manoeuvre failed, there would be no second chance.

As this was the last planet of the Solar System that Voyager 2 would be visiting, the Chief Project Scientist, his staff members, and the flight controllers decided to also perform a close fly-by of Triton, the larger of Neptune's two originally known moons, so as to gather as much information on Neptune and Triton as possible, regardless of Voyager 2's departure angle from the planet.

DSS43 Tidbinbilla's support was critical to the Neptune meeting as the close encounter action took place almost directly over eastern Australia.

To gain maximum sensitivity, the CSIRO's radio telescope at Parkes was again brought in, and to further increase the ground sensitivity the 64 metre diameter station at Usuda on Honshu Island in Japan extended the array in order to pick up the "billionth of a billionth" watt signal.

The main action for this encounter occurred during a 53-hour period spanning the 24, 25 and 26 of August.



Voyager 2's trajectory through the Neptune system. Graphic: NASA/JPL

After twelve years of travelling, Voyager 2 finally approached the last planet of its long journey.

Although Brad Smith at JPL and his team celebrated their navigational triumph, they secretly worried that this giant might prove as unspectacular as Uranus. An unfounded worry, as it turned out.

> *"No one had anticipated this: ahead of us lay a planet that looked like Earth, of a beautiful deep blue, with white clouds in its atmosphere!"*

PICTURE TAKING PROBLEMS

Due to the extremely low light levels at Neptune longer exposures were needed to capture good pictures, but with the high relative velocities the result would be blurred images.

Voyager 2 used three techniques for motion compensation. The normal compensation turned the spacecraft to follow the target, but this turned the main antenna away from Earth, so all the data had to be recorded until it was realigned. This *"nodding image motion compensation"* briefly *"nodded"* the spacecraft off the Earth while the exposure was being made. These slew rates were slow, 10 times slower than the hour hand of an analogue clock.

As Bill McLaughlin of the Flight Engineering Office at JPL noted,

> *"The 800 kilogram Voyager spacecraft is being manipulated with jewellers precision from a distance of 3 billion miles."*

The second technique was *"manoeuvre-less image-motion compensation"* using the scan platform to follow the target. The spacecraft had to be kept steady during these exposures. The tape recorder switching on and off could nudge the cameras off target and smear close-up shots.

Normally the spacecraft is steadied by short 10 millisecond bursts of hydrazine propellant by its attitude control thrusters whenever it senses it has drifted off alignment by a few tenths of a degree. For Neptune, five minutes before encounter, the hydrazine bursts were reduced to 4 milliseconds for a quicker response and greater accuracy, programmed to last for an hour.

There were also changes in computer software on the ground and in the spacecraft. Previously exposures longer than 15 seconds had to be recorded for later playback. While typical exposures at Neptune were 15 seconds long, the new software allowed non-recorded images with exposures as long as 96 seconds, to help searching for diffuse ring material. After an exposure it would point the high gain antenna towards Earth and transmit the image data without using the tape recorder, before aligning itself for the next picture.

During 24 August, DSS43 Tidbinbilla in Canberra, Australia transmitted a precise tone in the X-Band frequency (8.400 GHz) and the Deep Space Stations in Madrid in Spain tuned in to the return signal more than 8 hours later over a distance of 4.5 billion kilometres.

With Neptune's gravity tugging away on the spacecraft there was a measurable change in the Doppler, which was used to measure the strength of Neptune's gravity.

NEREID

Diameter:	340 kilometres
Albedo:	0.155
Mass:	3.0873 x 10^{19} kilograms
Neptune distance:	5,513,818 kilometres
Orbital period:	360 Earth days
Surface temp:	-223°C
Closest approach:	4,655,000 kilometres

Nereid was discovered by American astronomer Gerard Kuiper on 1 May 1949. He named it after the Nereids, the sea nymphs of Greek mythology, attendants to the god Neptune.

It is the second largest of Neptune's moons. Kuiper named Nereid after the sea nymphs in Greek mythology.

Nereid is only 340 kilometres in diameter and is so far from Neptune that it requires 360 days to make one orbit -- only five days less than Earth takes to travel once around the Sun. Even after 12 days of observation Voyager 2 only saw Nereid as a faraway blurred blob, and was unable to resolve any details.

Nereid's origins are only speculation. Voyager 2 passed by Nereid 4 hours 1 minute before encountering Neptune, but after 12 days of observations it only saw Nereid as a faint, faraway blob, and was unable to resolve much detail. Recent spectroscopic measurements indicate it has dirty water ice on its surface.

Along with Nereid and last of all Triton, Voyager 2 either discovered or observed a number of smaller moons and moonlets varying in size between 54 to 400 kilometres, close to Neptune's equatorial plane. These tiny companions of Neptune are cratered and irregularly shaped -- they are not round -- and show no signs of any geologic modifications.

Names for the new moons were selected from mythology's water deities by the International Astronomical Union, they are:

1989N6 - Naiad
Naiad, the last satellite Voyager discovered, orbits Neptune in 7 hours 6 minutes. The Naiads were nymphs who lived in and presided over brooks, springs, and fountains.

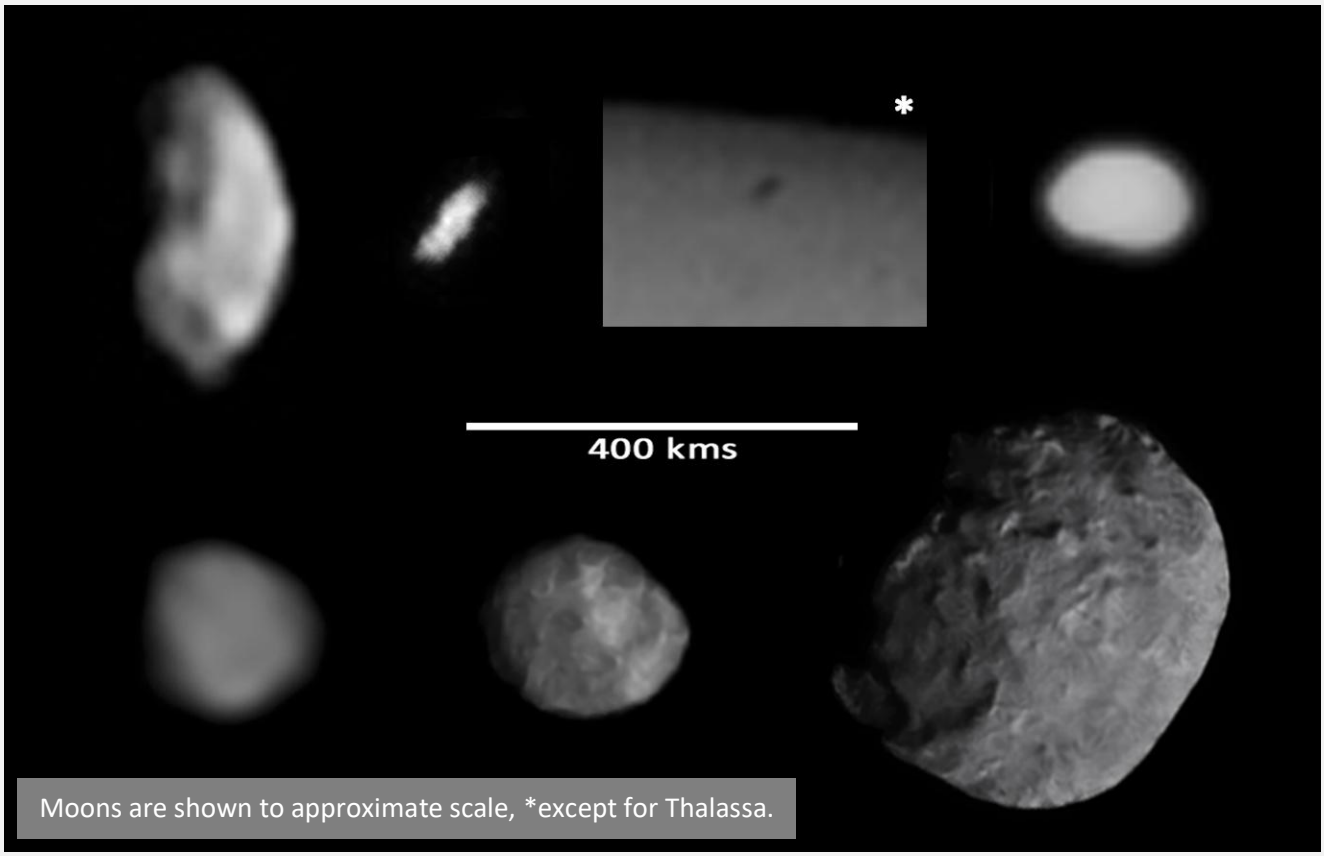
1989N5 - Thalassa
Thalassa orbits Neptune in 7 hours 30 minutes. Thalassa was a daughter of Aether and Hemera. "Thalassa" is also the Greek word for "sea".

1989N3 - Despina
Despina orbits Neptune every 8 hours. Despina was a nymph, the daughter of Poseidon (Neptune) and Demeter.

1989N4 - Galatea
Galatea completes an orbit in 10 hours 18 minutes. Galatea was a Sicilian Nereid loved by the Cyclops Polyphemus.

1989N2 - Larissa
Larissa circles the planet in 13 hours, 18 minutes. Larissa is irregular in shape and appears to be heavily cratered. Larissa was a daughter of Pelasgus. It was first observed by astronomers Harold Reitsema, William Hubbard, Larry Lebofsky and David Tholen on 24 May 1981. It was found by accident while searching for rings around Neptune.

1989N1 - Proteus
Proteus was a sea god who could change his shape at will. Like all six of Neptune's newly discovered small satellites, Proteus is one of the darkest objects in the solar system -- "as dark as soot."



(Top row from left) Nereid, Naiad, Thalassa (seen against the limb of Neptune), Despina;
(second row from left) Galatea, Larissa, and Proteus. Images: NASA/JPL, Processing: Ted Stryk, Justin Cowart

The heavily cratered surface shows no signs of geologic activity. Like Saturn's satellite, Phoebe, it reflects only 6 percent of the sunlight that strikes it. It wasn't discovered from Earth because it is so close to Neptune that it is lost in the glare of reflected sunlight. It completes one orbit in 26 hours 54 minutes.

Other moons were discovered by later telescope observations from Earth (*as tiny points of light*).

2002N1 – Halimede
Discovered by a group including Matthew Holman on 14 August 2002, it was named after one of the Nereids. Halimede is one of three tiny moons (the others are Laomedeia and Sao) in a distant eccentric orbit around Neptune.

2002N2 - Sao
Another moon discovered by Matthew Holman in August 2002. Also named after one of the 50 Nereids, Sao is one of three tiny moons that orbit in a distant eccentric orbit.

2002N3 - Laomedeia
Orbiting 23.571 million kilometres from Neptune, this 42 kilometre diameter moon was discovered by Matthew Holman in August 2002.

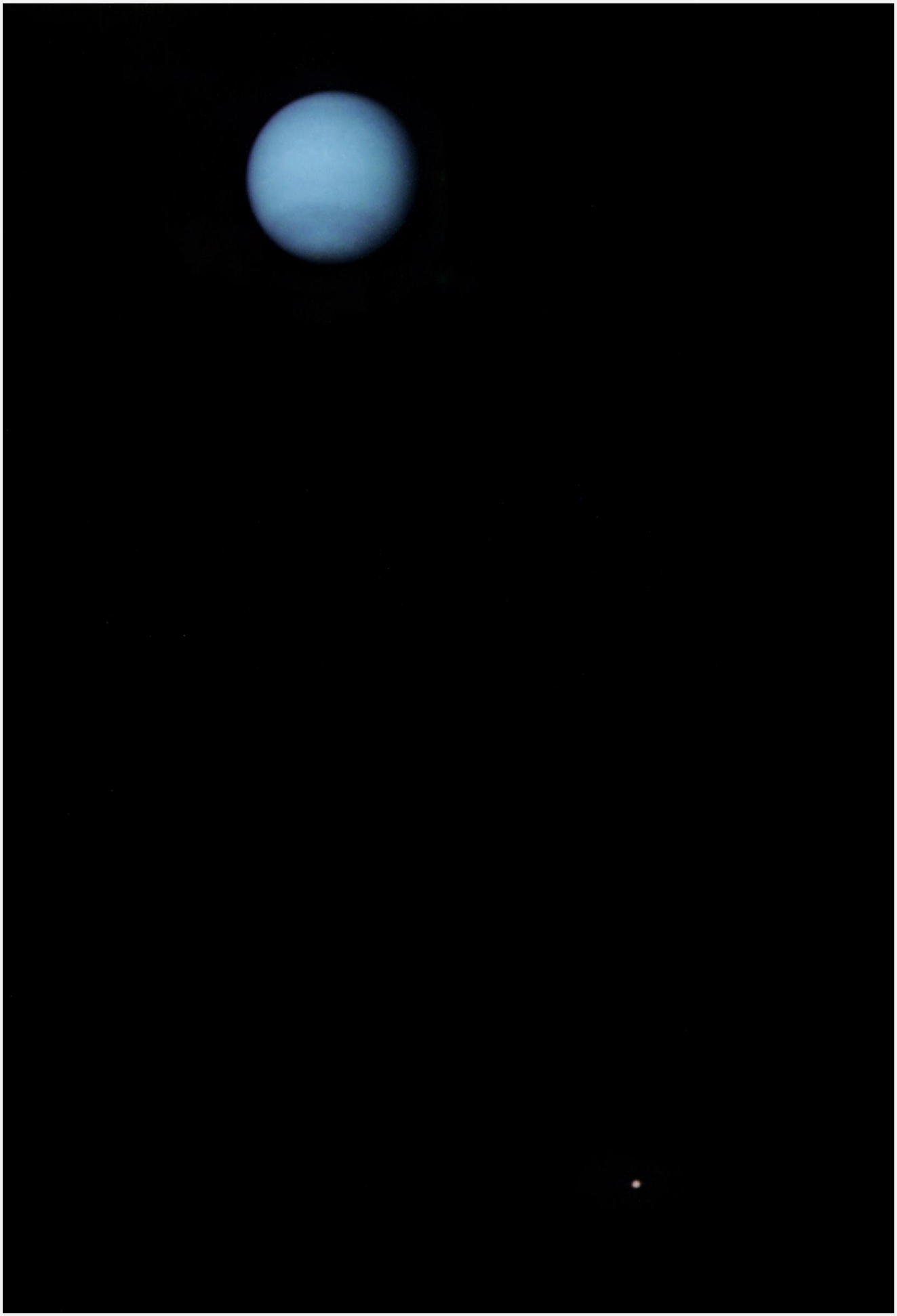
The three moons listed above were discovered on 13 August 2002 by teams at Bianco telescope at the Cerro Tololo Observatory in Chile and the Canada/France/Hawaii Telescope in Hawaii using multiple images digitally combined.

Voyager 2 missed them as they were too faint and far away from Neptune. Laomedeia and Sao have prograde orbits, spinning in the same direction as Neptune, while Halimede orbits in the opposite direction.

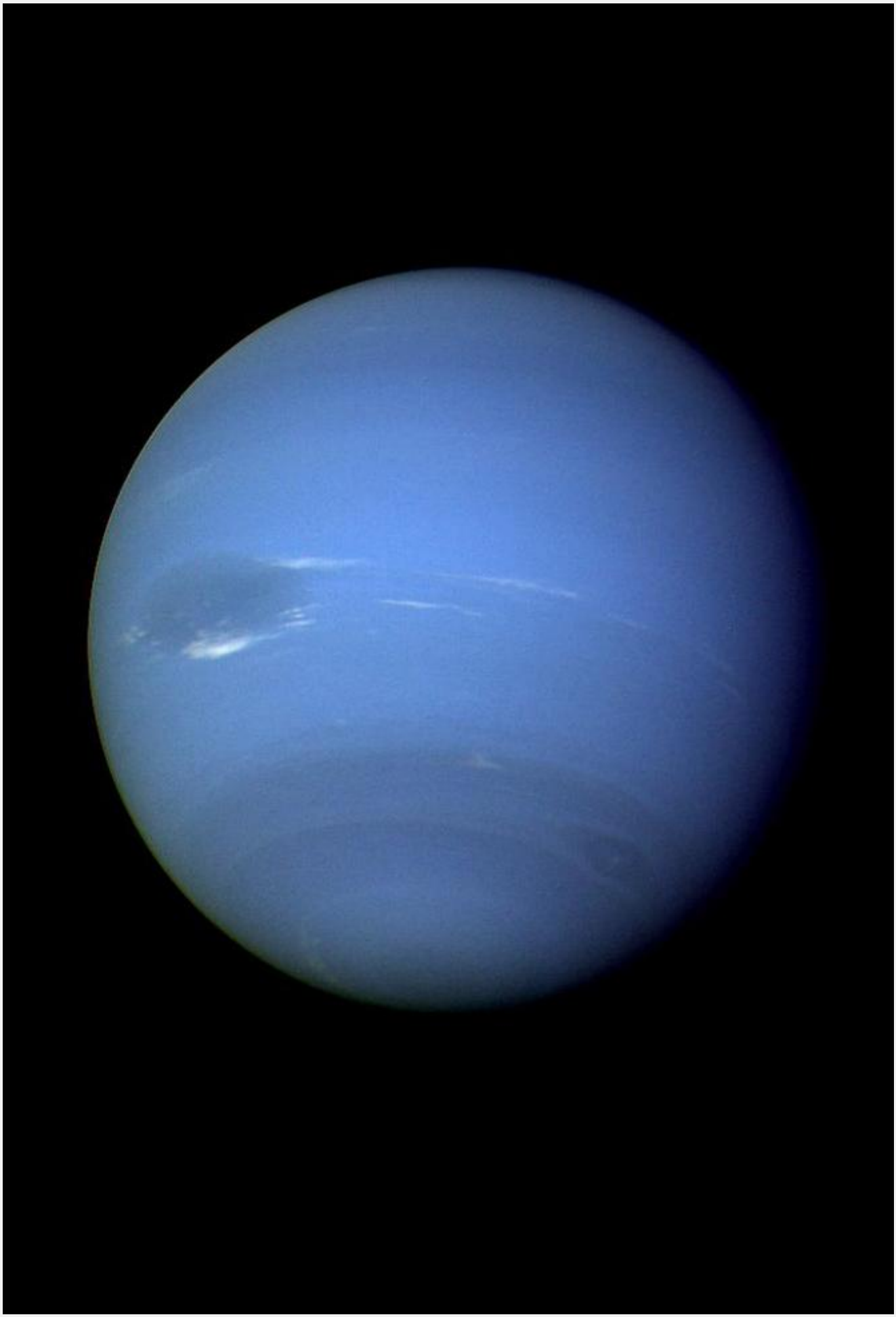
2003N1 - Psamathe
This moon was discovered by Scott Sheppard and David Jewitt in February 2003. This moon is close to the theoretical stable separation from its planet for a body in a retrograde orbit.

2002N4 - Neso
Discovered on 14 August 2002 by Matthew Holman and Brett Gladman, this little retrograde moon is the farthest known object from its planet than any other, and takes 26.67 years to orbit Neptune.





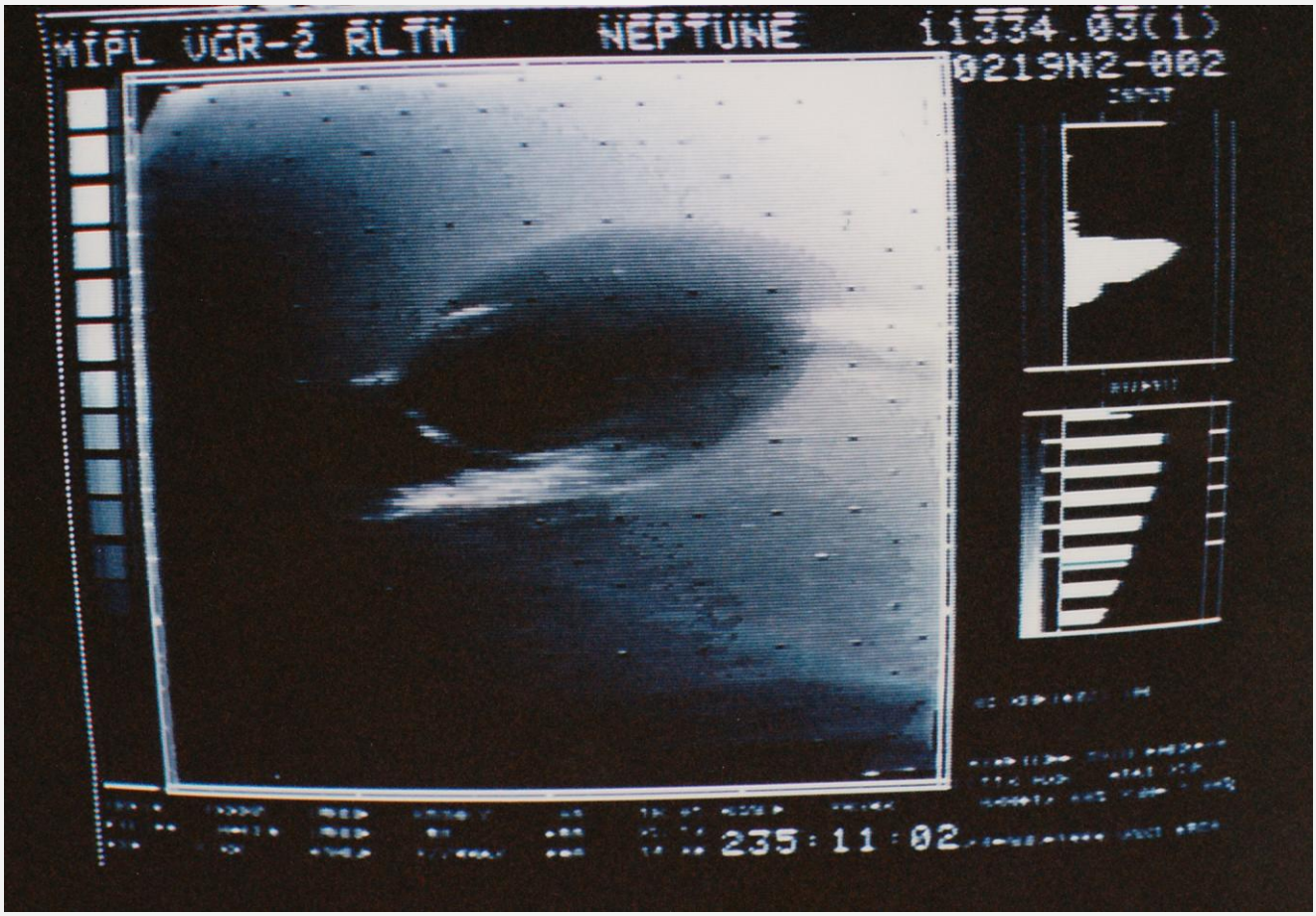
Neptune and Triton from a distance of 76 million kilometres taken 3 July 1989. Image: NASA/JPL

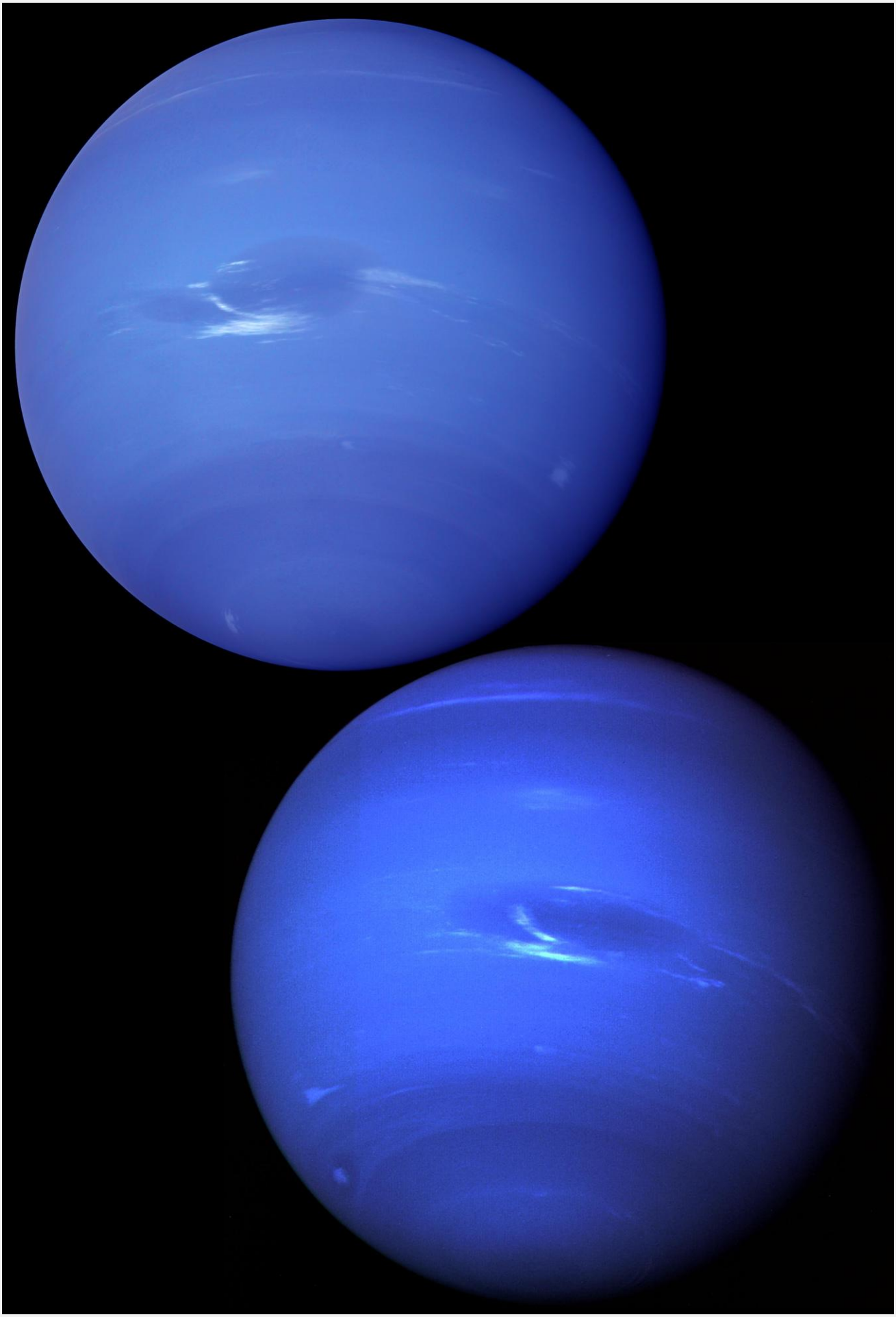


Voyager 2 image compiled from photos taken the 16-17 August 1989. Image: NASA/JPL

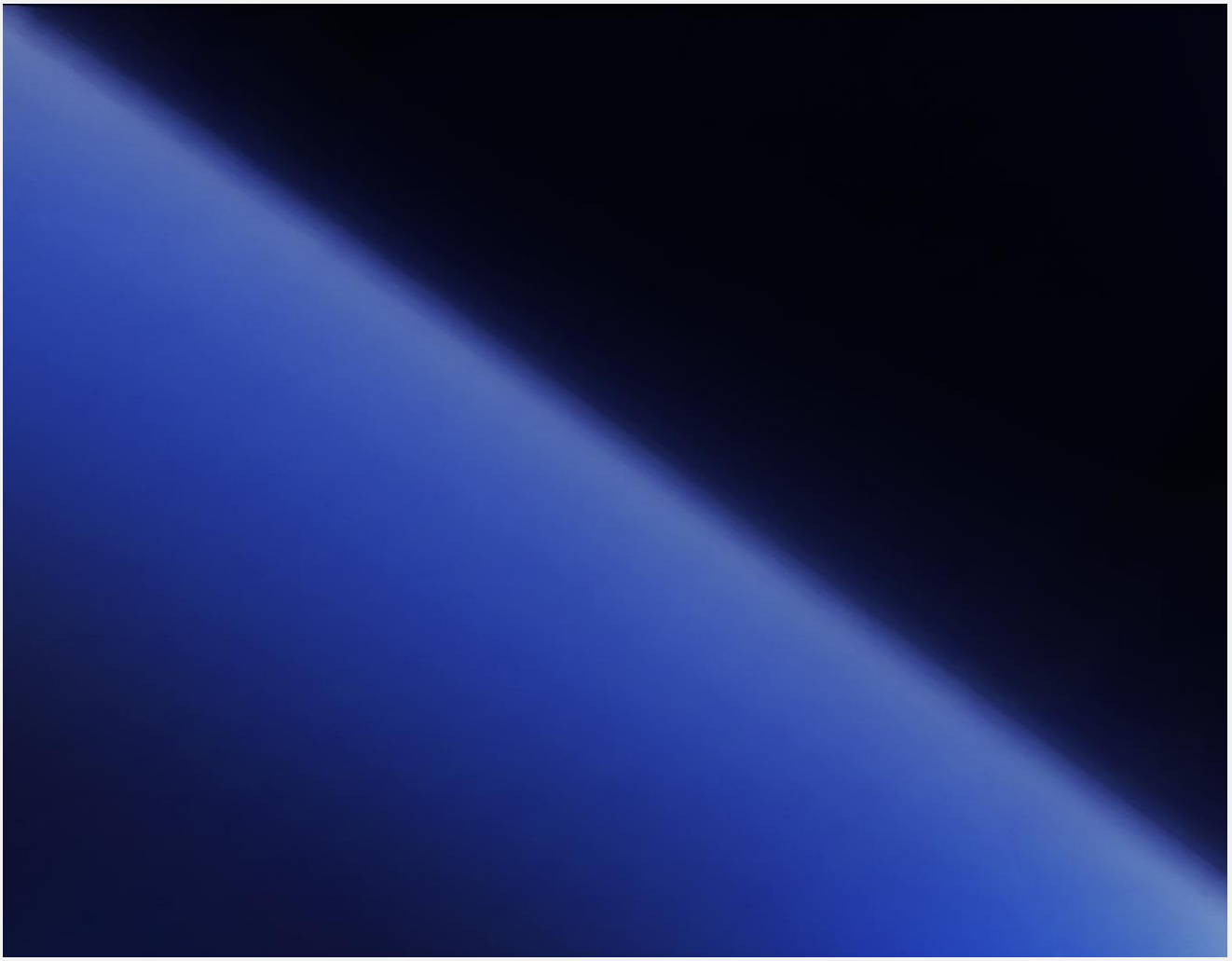


Above: Dr Robina Otrupcek at the control room at Parkes looking at Neptune on the top right screen.
Images: (above) © CSIRO Radio Astronomy Image Archive, (below) Tidbinbilla Archive
Below: Photo of the slow scan monitor at Tidbinbilla showing Neptune's Great Dark Spot.





Two views of Neptune. Note the changes in the clouds near the Great Dark Spot and nearer the poles.
Images: NASA/JPL, (top) Modern processing: Björn Jónsson, (below) NASA/JPL



Colourised view of the limb of Neptune (appearing almost flat) during closest approach. Image: NASA/JPL

VOYAGER 2

NEPTUNE – PCA – POINT OF CLOSEST APPROACH
13:57 AEST – Friday, 25 August 1989

Voyager 2 flew within 4,850 kilometres of the cloud-tops of Neptune's North Pole at 13:57 AEST on 25 August 1989. Speeding along at 60,000 kilometres per hour above Latitude 76°N, this was its closest encounter with any planet since Earth.

At the time Neptune was the furthest planet from the Sun, as the now downgraded Pluto didn't cross Neptune's orbit until 1999.

The spacecraft then arced south towards the moon Triton, and crossed the ring plane thirty minutes later.

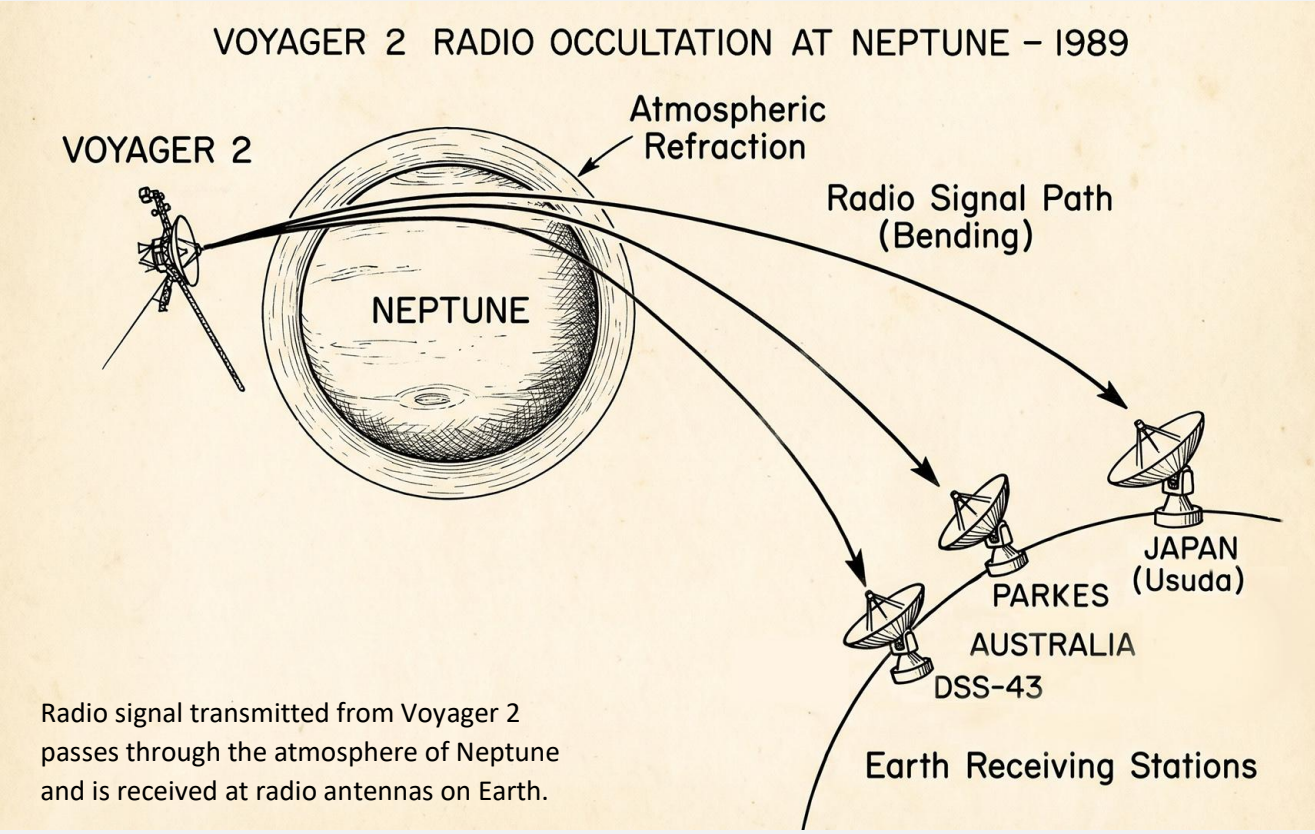
OCCULTATION AND
ATMOSPHERIC MEASUREMENTS

This beautiful blue planet was hiding some unexpected secrets beneath its bland blue surface – violent storms, bizarre weather and the fastest winds in the solar system.

Six minutes after closest approach Voyager 2 went behind the planet.

To analyse Neptune's atmosphere, while out of view of Earth behind the planet, the automated spacecraft performed 24 manoeuvres known as Limbtrack - pointing the high-gain antenna along Neptune's limb, starting with the ingress point in the northern hemisphere, then around the left limb, and ending with the egress point at Latitude 40.4°S. The radio signal from the 20-watt transmitter was bent after passing through the planet's atmosphere, the Limbtrack manoeuvre controlling the pointing of the high-gain antenna to make sure the signal was bent so it arrived at the Earth, and the waiting tracking stations at DSS43 Tidbinbilla and Parkes in Australia, and Usuda, Japan.

At the same time Voyager 2 was collecting fields and particle data, receiving a peak of 300 hits per second from particles as it passed through the rings.



Radio signal transmitted from Voyager 2 passes through the atmosphere of Neptune and is received at radio antennas on Earth.

The spacecraft also took infrared and ultraviolet measurements of the polar region, and a series of three wide-angle images of the ring system. As it passed by the rings it took edge-on views.

Then, as the spacecraft emerged from behind the planet, it saw the Earth first, followed by the Sun 49 seconds later. Voyager 2 kept the high-gain antenna pointed at Earth for the outbound ring occultation.

Neptune's atmosphere consists of 80% hydrogen, 19% helium, 1.5% methane plus traces of hydrogen deuteride and ethane. The most obvious feature of the planet is its blue colour, the result of methane in the upper atmosphere. Methane preferentially absorbs the longer wavelengths of sunlight (those near the red end of the spectrum). What's left to be reflected, are colours at the blue end of the spectrum, which is why Neptune looks so blue.

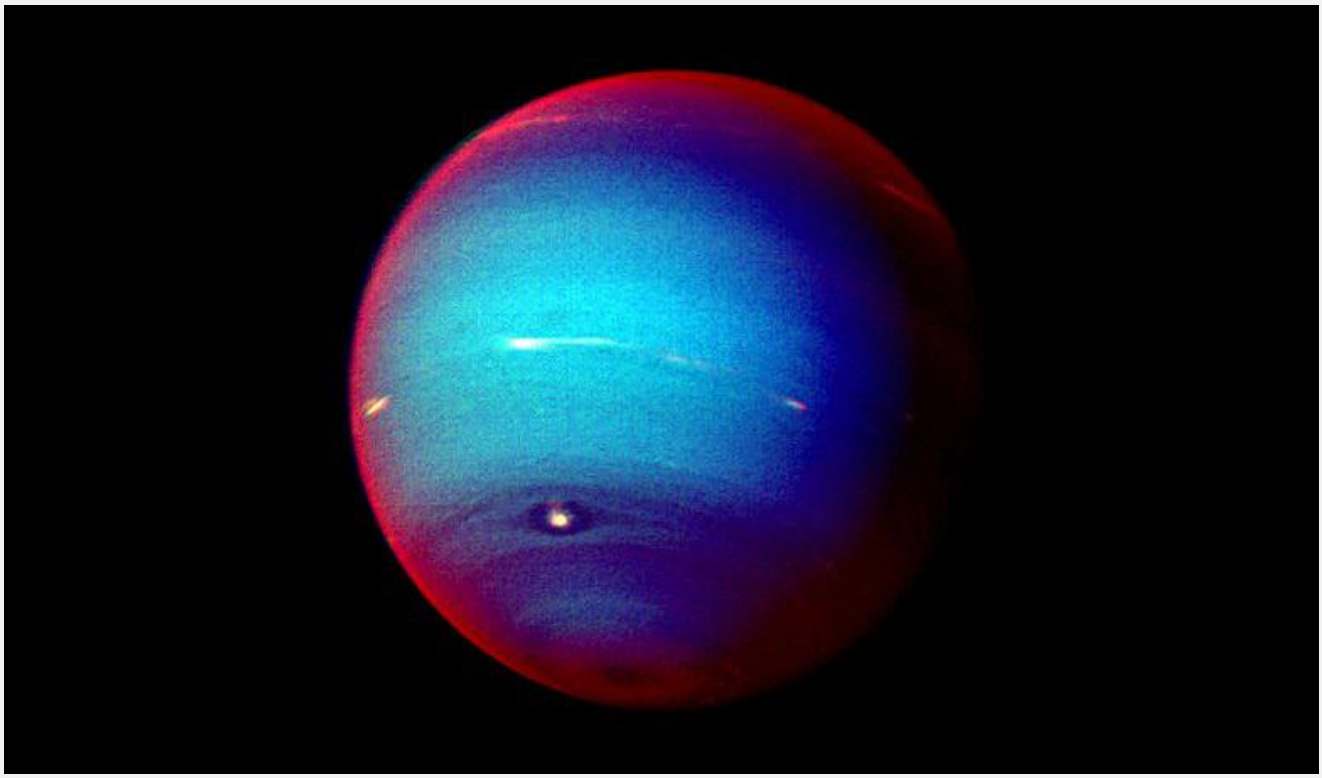
Voyager 1 also measured heat radiated by Neptune's atmosphere. The atmosphere above the clouds is hotter near the equator, cooler in the mid-latitudes and warm again at the South Pole. Temperatures in the stratosphere were measured to be 750 Kelvin (477°C), while at the 100 millibar pressure level, they were measured to be 55 Kelvin (-218°C). The heat appears to be caused, at least in part, by convection in the atmosphere that results in compressional heating: Gases rise in the mid-latitudes where they cool, then drift toward the equator and the pole, where they sink and are warmed.

Neptune has something weird and uncanny about it. Voyager 2 found tremendous storms raging on the planet. Most of these turbulent winds were blowing in a westward direction, which is retrograde, or opposite to the rotation of the planet.

Near the Great Dark Spot, there are retrograde winds blowing up to 2,016 kilometres per hour -- the strongest winds measured on any planet, including windy Saturn, where the Voyagers measured up to 1,800 kilometres per hour.

This came as a great surprise to the astronomers, as normally solar energy drives atmospheric activity, and at Neptune the sun's energy barely penetrates to this place at the edge of the solar system.

So, what could be the engine driving these tremendous storms that rush through the atmosphere of this distant world at ten times the speed of those on Jupiter? By now scientists think they know the cause: on Neptune - unlike Jupiter and Saturn - there are no turbulences to strip the storms of their energy. So once a storm develops, it simply keeps going.

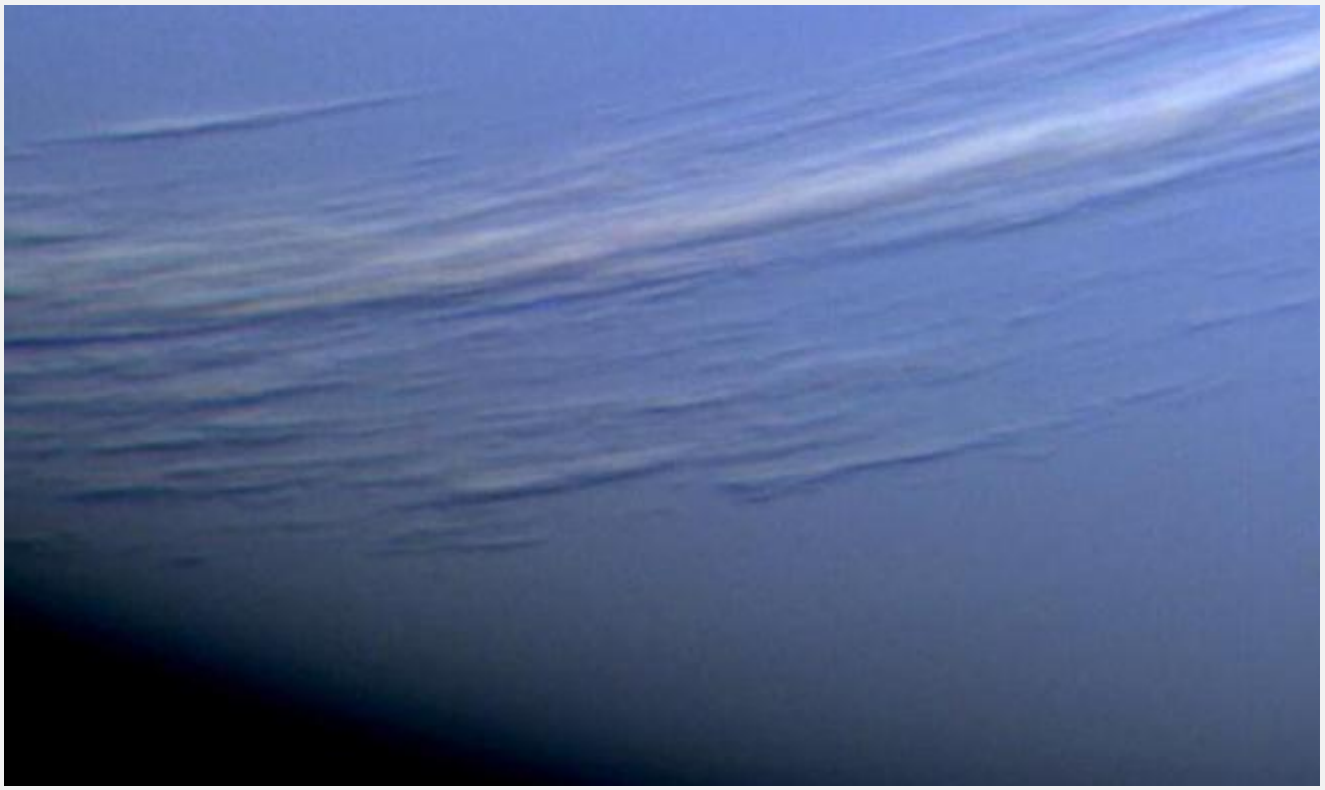


Sunlight passes through the haze and deeper into the atmosphere, where some wavelengths are absorbed by methane gas, causing the center of the image to appear less red. Near the edge, the haze scatters sunlight at higher altitude, above most of the methane, causing the bright red edge around the planet. Image: NASA/JPL

CLOUD SHADOWS

For the first time Voyager 2 found feathery methane cirrus clouds forming and dissipating every few hours, casting long shadows on the main cloud deck about 50-70 kilometres below.

Around Latitude 27°N, the clouds appeared to be 50-200 kilometres across, but did not obstruct Voyager 2 peering down to the main cloud deck below. Streaks of these clouds were also seen in the southern polar regions at 70°S.



High cirrus clouds casting shadows on the surface of Neptune's blueish atmosphere. Image: NASA/JPL



Neptune’s Great Dark Spot. Image: NASA/JPL

THE GREAT DARK SPOT

Even though Neptune receives only 1/900th of the sunlight that falls on Earth, it is a dynamic planet and surprisingly showed several large, dark spots reminiscent of Jupiter's hurricane-like storms.

The largest spot, dubbed the Great Dark Spot, located at Latitude 22^{o}S is about the size of Earth.

Spinning counterclockwise, it is similar to the Great Red Spot on Jupiter and circles Neptune in about 17 hours, travelling westward at 1,207 kilometres per hour.

It has since disappeared, according to Hubble Space Telescope observations. Originally thought to be a large cloud itself, it was later thought to be a hole in the visible cloud deck.

Another spot, designated D2 by Voyager's mission scientists, was located far to the south of the Great Dark Spot, at 55^{o} south. It was almond-shaped, with a bright central core, and also moved eastward around the planet in about 16 hours.

THE SCOOTER

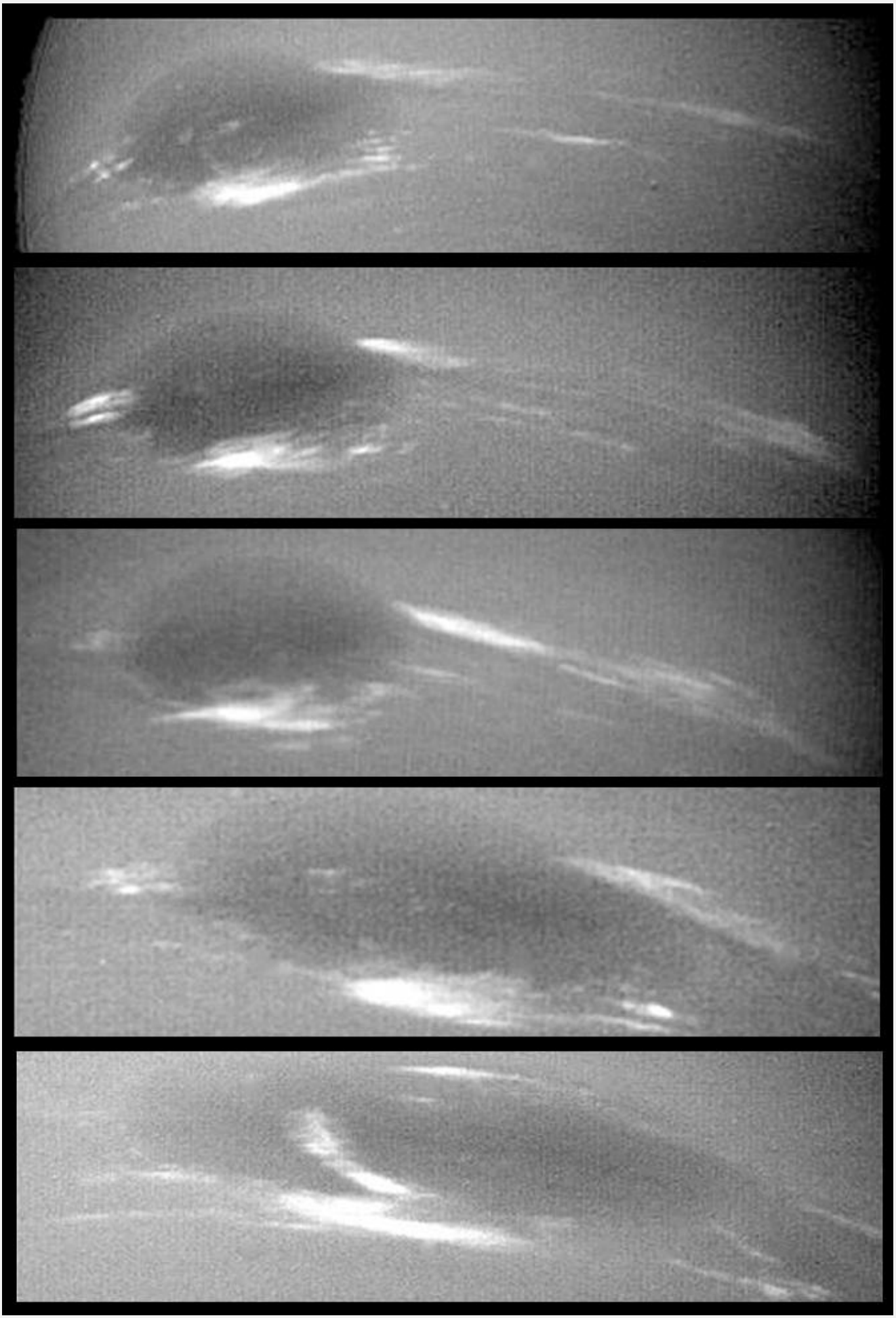
At about Latitude 42^{o}S, a small, irregularly shaped, westward-moving cloud was observed speeding around Neptune every 16 hours or so; this "scooter," as Voyager scientists called it, could be a cloud plume rising above a deeper cloud deck.

MAGNETIC FIELD

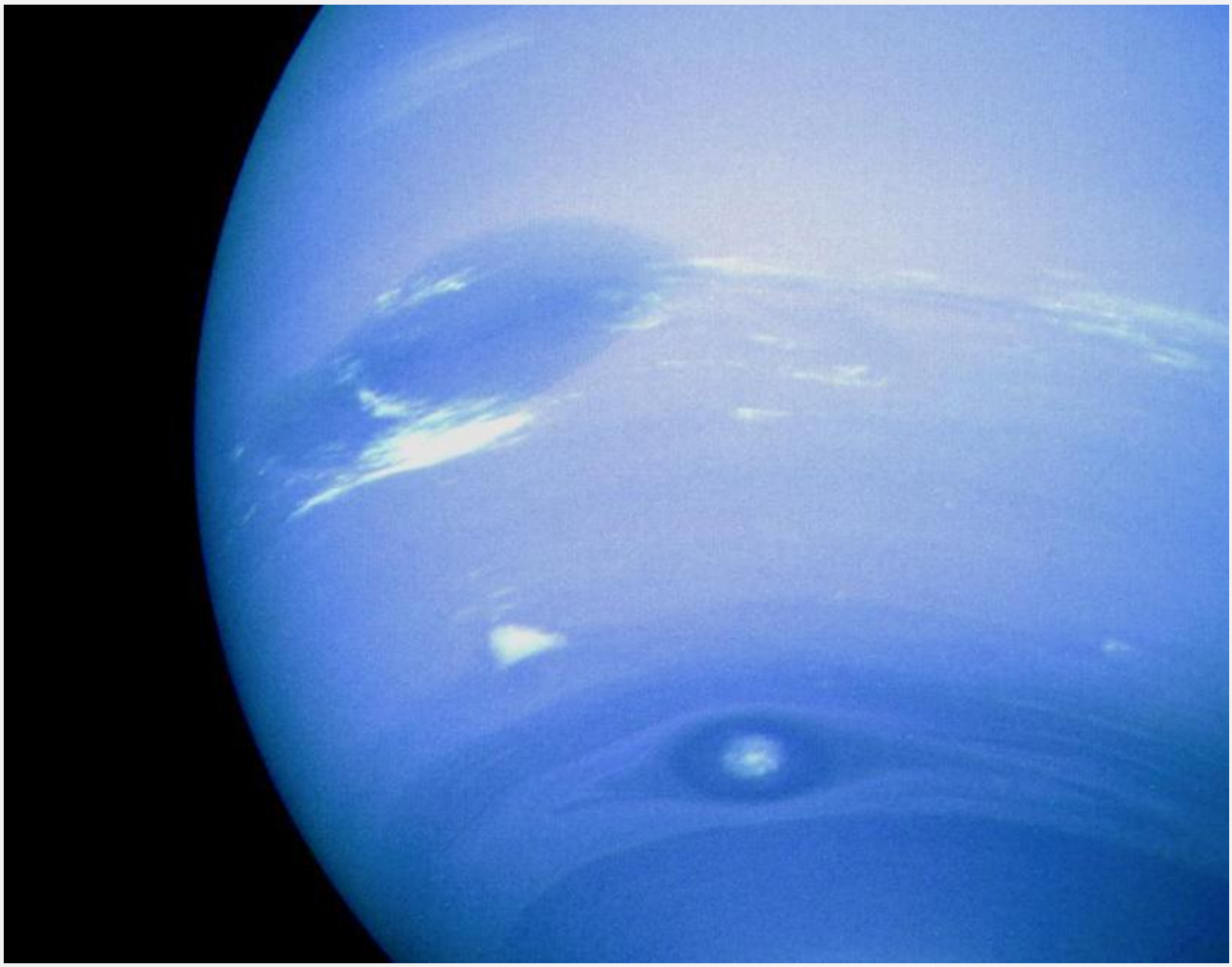
The magnetic field of Neptune, like that of Uranus, turned out to be highly tilted; 47^{o} from the rotating axis and offset at least 13,500 kilometres from the physical centre.

Comparing the magnetic fields of the two planets, scientists think the extreme orientation may be characteristic of flows in the interiors of both Uranus and Neptune and not the result in Uranus's case of that planet's sideways orientation, or of any possible field reversals at either planet.

The spacecraft also detected auroras, but much weaker than those found on Earth and other planets.

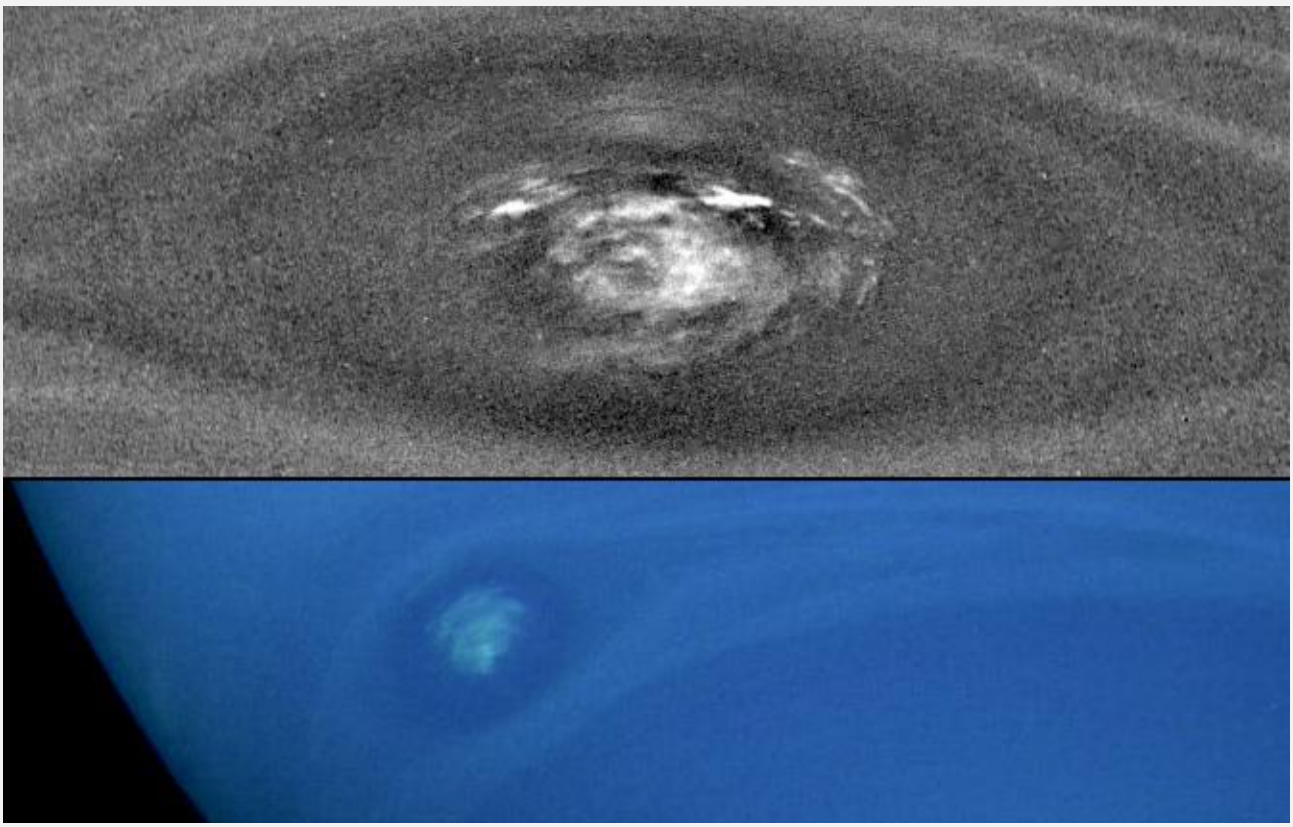


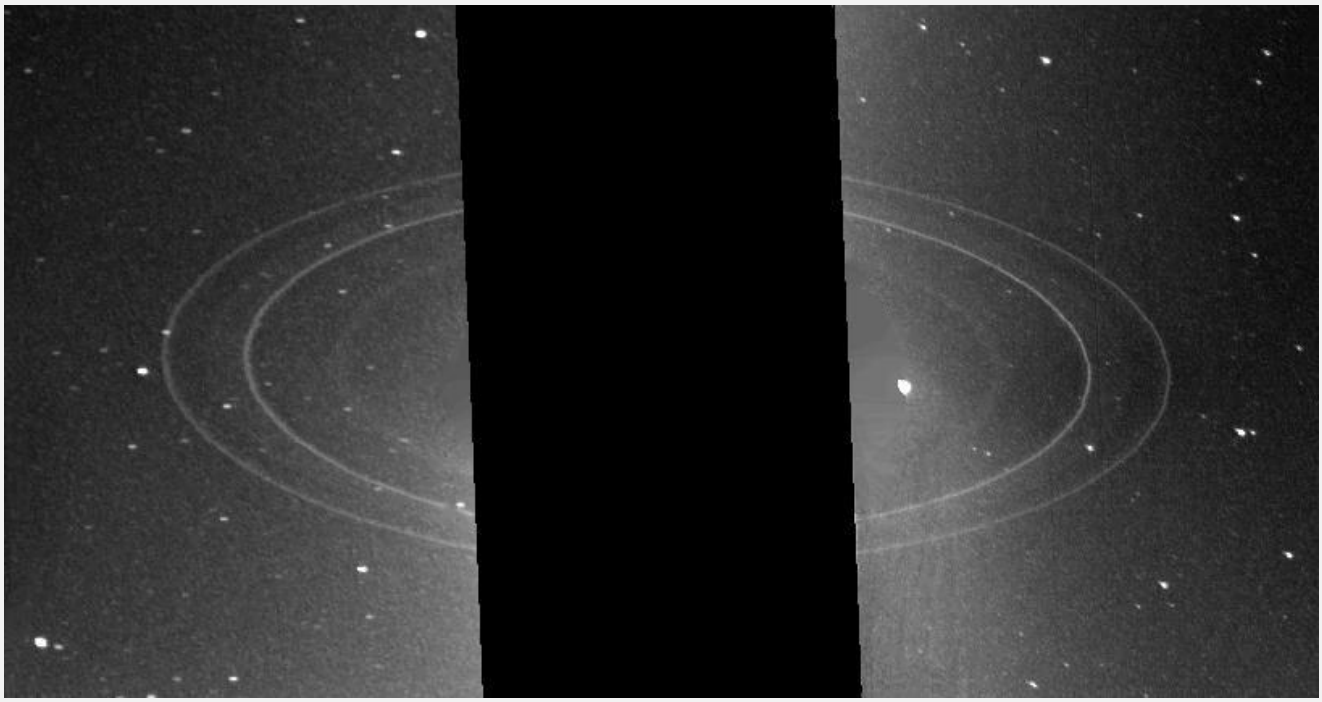
Great Dark Spot showing variations in its shape and changes in the white clouds. Images: NASA/JPL



Above: Below the Great Dark Spot is the bright feature called “Scooter” and then the dark oval “D2”. Images: NASA/JPL

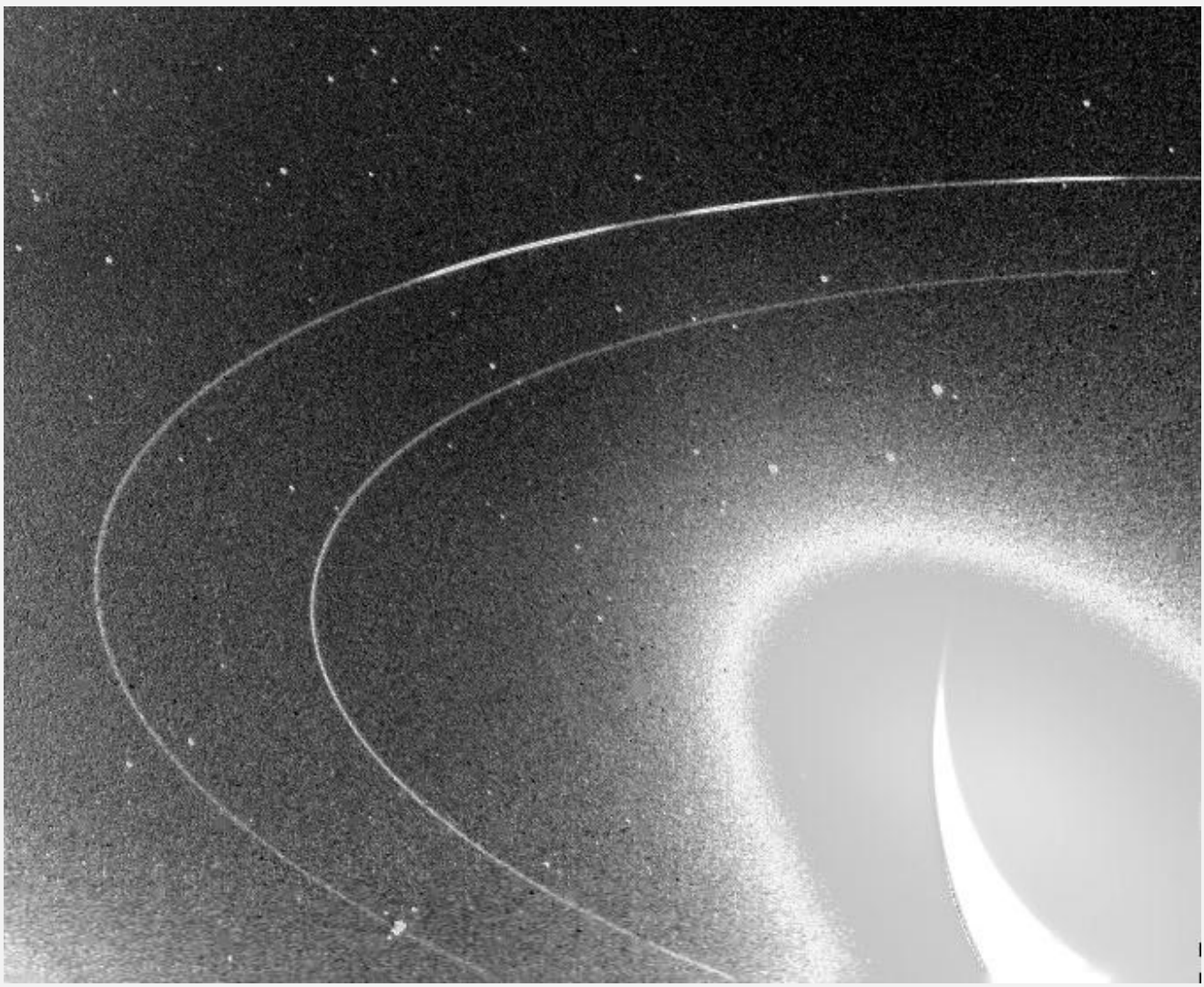
Below: Neptune’s ‘small dark spot’ “D2”. The bright centre indicates an upwelling and rotation of clouds.

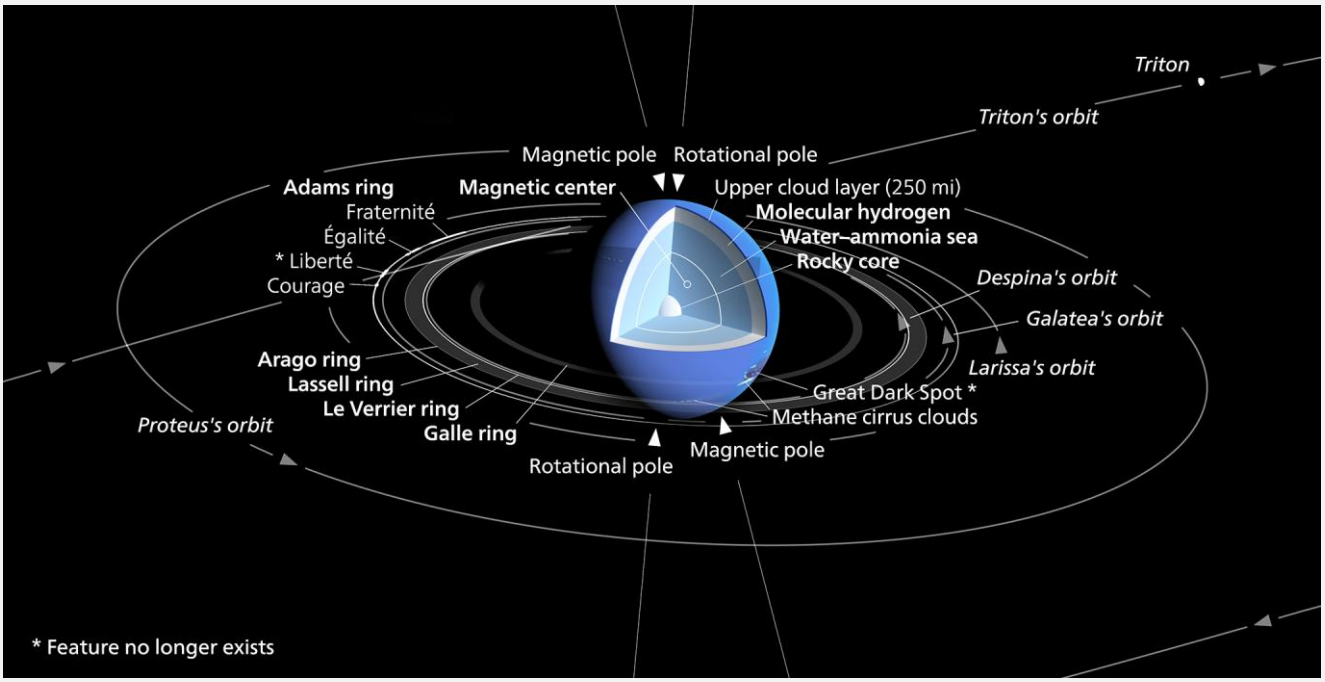




Above: Neptune's main rings (from the outmost) Adams, Arago, Lassell, Le Verrier and Galle.
Images: NASA/JPL

Below: The bright arcs in the Adam's Ring were dubbed (from left) "Liberté, Égalité, Fraternité". Unseen in this image was another arc called "Courage" to the left of Liberté. Physics would suggest that the material in the arcs should spread out, but may be stablised by the gravity of the moon Galatea.





RINGS AND RING ARCS

In 1981, astronomers leaped at an infrequent opportunity: A star would pass behind Neptune so that observers could measure the starlight and how it changed as it passed through the upper layer of Neptune's atmosphere. That would provide clues to its structure.

But the star's light winked off and on before Neptune passed in front of it. Similar measurements were obtained during the mid-1980s. Astronomers concluded that some material (perhaps like that of the rings of Saturn) orbits Neptune, and was responsible for occasional blockage of the star's light. In each observed event, astronomers saw that the ring or rings did not appear to completely encircle the planet -- rather, each appeared to be a segment of a ring – a ring arc.

So, astronomers were convinced that Neptune, too, should have rings - or at least arc-shaped parts of rings. Carolyn Porco was one of them, and she was determined to find these arcs:

> *"Some of the people at the control centre thought we were nuts and were only wasting the probes precious time!"*

But Porco had the luck that often comes with hard work: her Voyager images showed that Neptune was indeed surrounded not just by a vague ring-shaped arc, but also by two additional, small but very sharply outlined ring arcs.

As Voyager 2 approached Neptune, scientists had been working on theories of how partial rings, or "ring arcs," could exist. Most settled for the concept of shepherding satellites that "herd" ring particles between them, keeping the particles from either escaping to space or falling into the planet's atmosphere. This theory had explained some new phenomena observed in the rings of Jupiter, Saturn and Uranus.

When Voyager 2 was close enough, its cameras photographed three bright patches that looked like ring arcs. But closer approach, higher resolution and more computer enhancement of the images showed that the rings do, in fact, go all the way around the planet.

The rings are so diffuse, and the material in them so fine, that earthbound astronomers simply hadn’t been able to detect the full rings.

Based on Voyager 2's findings, one Earth-based observation of the ring arcs is now attributed to the passage of a small satellite/moonlet through the ring area.

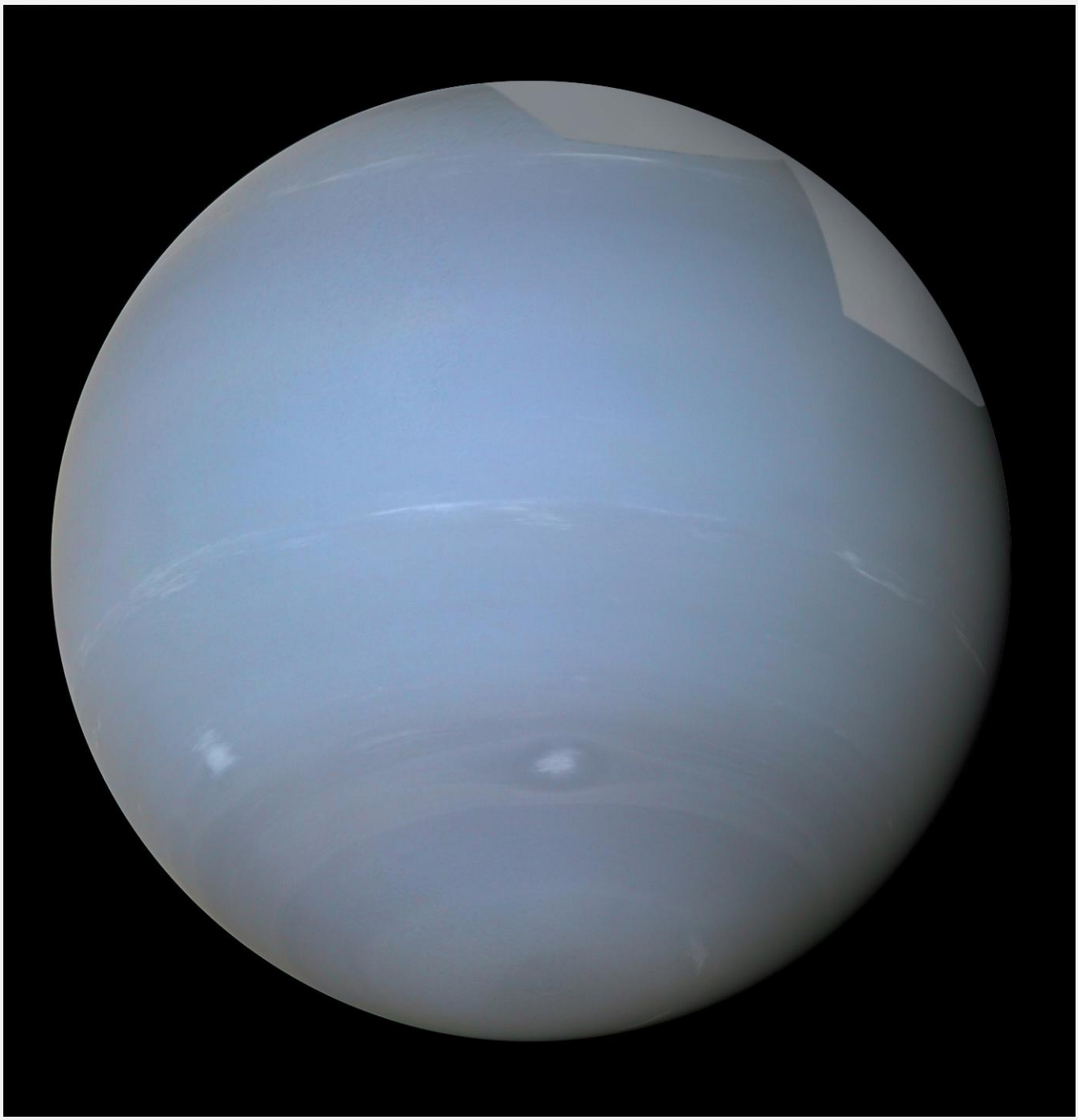
Late in the encounter, the scientists were able to sort out the number of rings :

- The Main Ring, called Adams (officially known as 1989N1R, following the IAU convention) orbits Neptune about 38,100 kilometres above the cloud tops. The main ring contains three separate regions, now named Liberty,

Equality, and Fraternity, where the material is brighter and denser, and explains most of the sightings or "ring arcs." Several Voyager photographs show what appear to be clumps embedded in the rings.

- An area called the Plateau, a broad, diffuse sheet of fine material just outside the Inner Ring.
- The Inner Ring (1989N2R) – known as Le Verrier, about 28,400 kilometres above the cloud tops.
- An Inside Diffuse Ring called Galle (1989N3R) -- a complete ring located about 17,100 kilometres from Neptune's cloud tops. Some scientists suspect that this ring may extend all the way down to Neptune's cloud tops.

The material varies considerably in size from ring to ring. The largest proportion of fine material -- approximately the size of smoke particles -- is in the Plateau. All other rings contain a greater proportion of larger material.

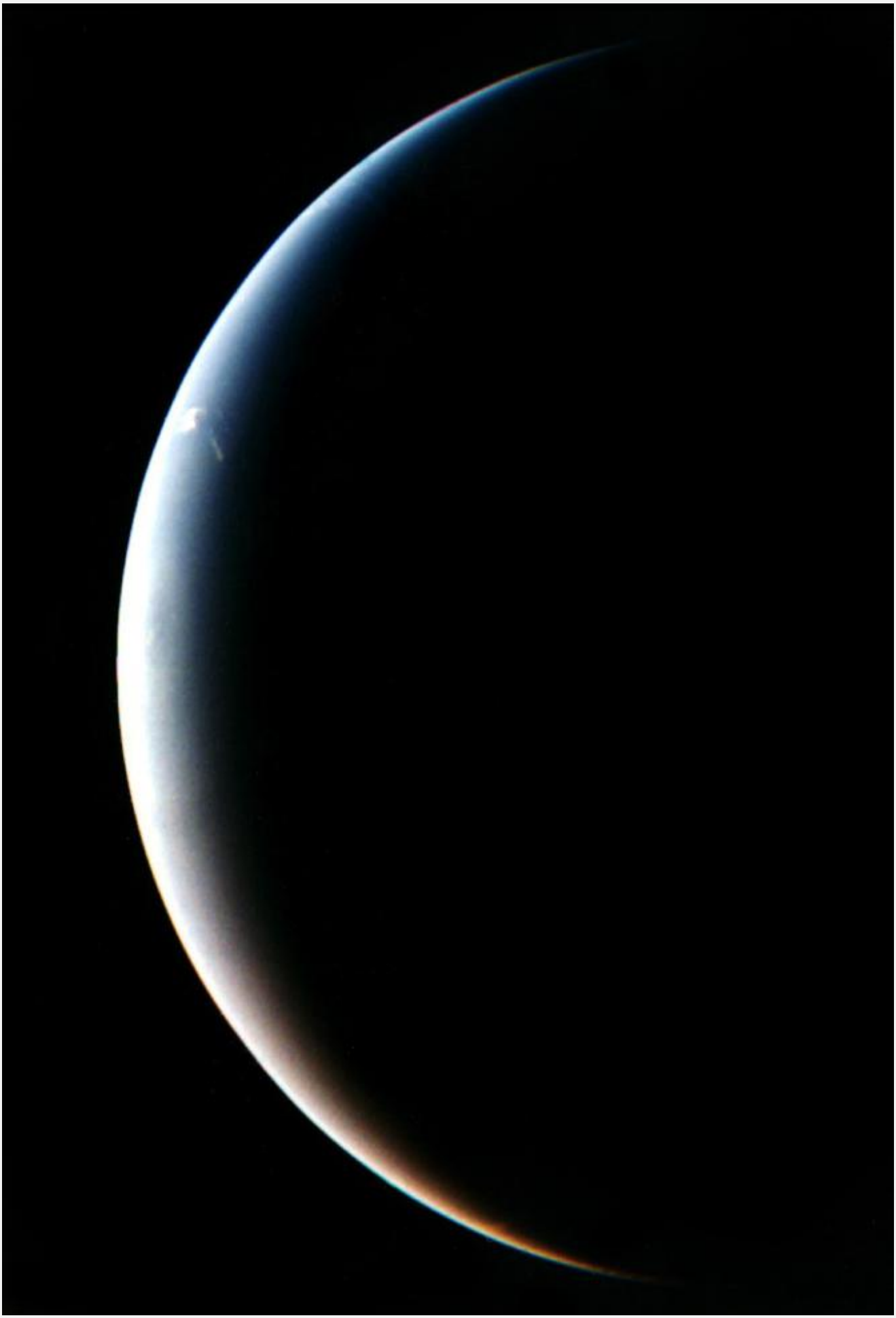


Calibrated image of Neptune. Image: NASA/JPL (data), Modern processing: Björn Jónsson.

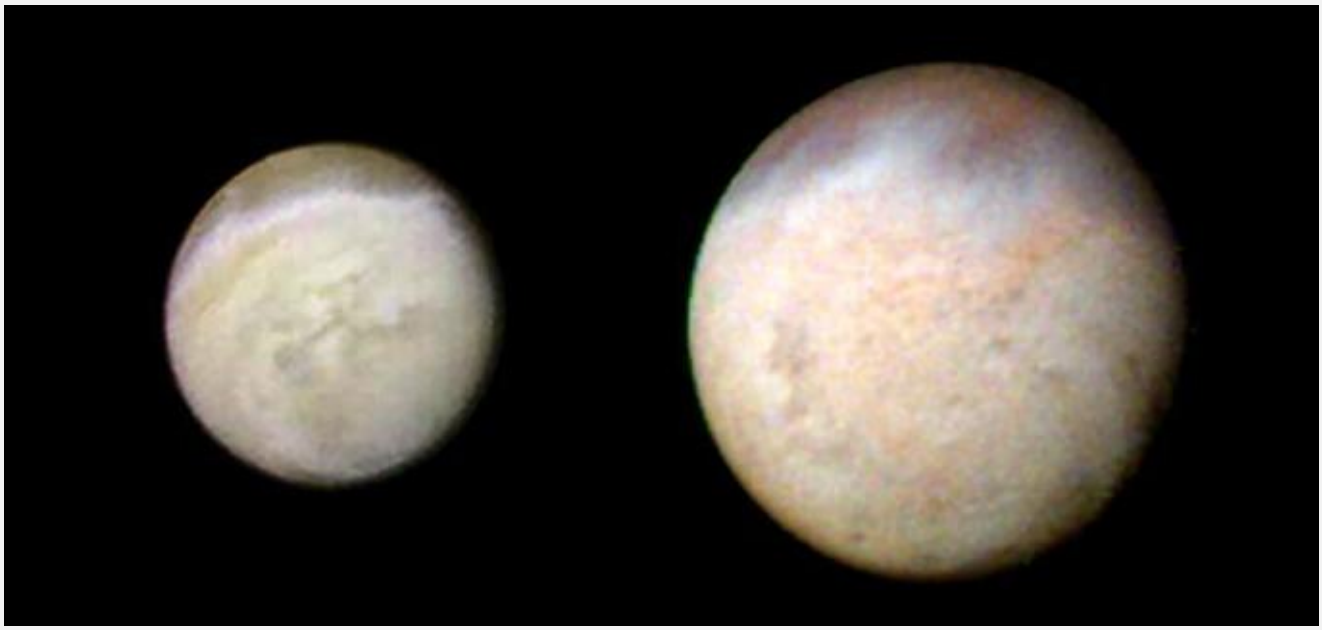
The original releases of Neptune images were purposely ‘enhanced’ and JPL noted as such, but that ‘note’ disappeared through decades of different publications. Today, data from the Hubble Space Telescope and the European Southern Observatory's Very Large Telescope, reveals a new, ‘less-blue’, more accurate view.



This view from Voyager 2 was taken as the spacecraft headed over the northern polar region of Neptune and began its path towards an encounter with Triton, which is seen here as a crescent. Image: NASA/JPL



Voyager 2 looks back to a receding crescent Neptune. It’s south pole is visible on the left. Image: NASA/JPL



Views of Triton taken on the 21st (left) and 23rd (right) August. Images: NASA/JPL, (left) Processing: Ted Stryk

TRITON	
Diameter:	2,706.8 kilometres
Albedo:	0.76
Mass:	2.1395 x 10^{22} kilograms
Neptune distance:	354,759 kilometres
Orbital period:	5.9 Earth days
Surface pressure:	14 microbars
Surface temp:	-236.2°C min/-178°C max
Closest approach:	39,800 kilometres

On 10 October 1846, just 17 days after Galle and d'Arrest first saw Neptune, English astronomer William Lassell discovered a satellite orbiting the planet and dubbed it Triton. Triton is named after the son of Poseidon (the Greek god comparable to the Roman god Neptune).

Triton, almost the size of Earth's Moon, completes an orbit in 5.875 days. Triton shows evidence of a remarkable geologic history, and Voyager 2 images show active geyser-like eruptions spewing invisible nitrogen gas and dark dust particles several kilometres into the tenuous atmosphere.

Triton is the largest moon circling Neptune. In fact, it is larger than Pluto. It is the only large moon in the solar system with a retrograde orbit. The relatively high density and the retrograde orbit offer strong evidence that Triton did not originate near Neptune, but is a captured object.

If that is the case, tidal heating could have melted Triton in its originally eccentric orbit, and the moon might even have been liquid for as long as one billion years after its capture by Neptune.

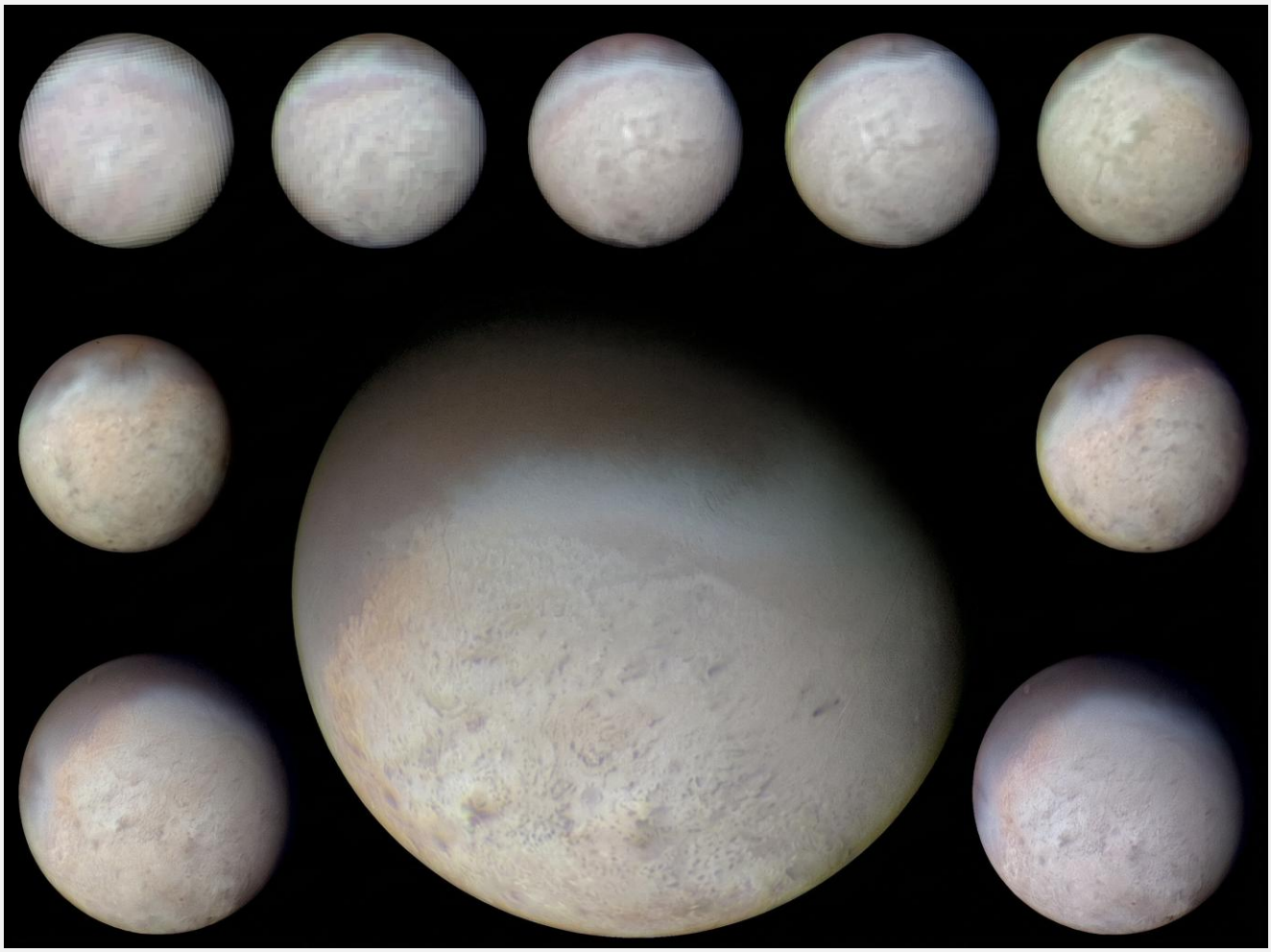
While scientists are unsure of the details of Triton's history, icy volcanism is undoubtedly an important ingredient.

To understand what is happening on Triton, one must ask, 'How cold is cold? How soft is soft? How young is young?' The melting point of water ice is 0°C (at sea level), it deforms more easily and rapidly on Earth than rock does, but becomes almost as rigid as rock at the extremely cold temperatures found on Triton, more than 4.5 billion kilometres from the Sun.

Most of the geologic structures on Triton's surface are likely formed of water ice, because nitrogen and methane ice are too soft to support much of their own weight.

On the other hand, nitrogen and methane, which form a thin veneer on Triton, turn from ice to gas at less than 100° above absolute zero. Most of the geologically recent eruptions at those low cryogenic temperatures are due to the nitrogen and methane on Triton.

The atmospheric pressure at Triton's surface is about 14 microbars, a mere 1/70,000th the surface pressure on Earth. The thin atmosphere of tiny nitrogen ice particles extends about 800 kilometres above the surface, which might form thin clouds a few kilometres above the surface.



A montage of image of Triton as seen by Voyager 2 during its flyby. Images: NASA/JPL

Temperature at the surface is about 37 Kelvin (-236.2°C), the coldest surface of any celestial body yet visited in the solar system. At 800 kilometres above the surface, the temperature rises to 95 Kelvin (-178°C).

Triton is very bright, reflecting 60 to 95% of the sunlight that strikes it (by comparison, Earth's Moon reflects 11%). The surface is mostly frozen nitrogen with a water ice crust.

Titan is one of the coldest objects in our solar system, so cold that the nitrogen is condensed as frost, giving the surface an icy sheen that reflects 70% of the light it receives. It has a tenuous atmosphere of nitrogen with small amounts of methane, and traces of carbon monoxide, barely able to support thin clouds and haze. The atmosphere is probably from volcanic activity driven by seasonal heating by the Sun.

GEYSERS

During the August flyby, Voyager 2 discovered an 8 kilometre high geyser-like plume of dark material erupting from the surface of Triton.

The pictures showed large quantities of the dark material scattered up to 150 kilometres across the surface by westerly winds.

One possibility for such eruptions is that the weak solar energy penetrating the almost transparent ice cap, results in heat building up enough pressure in the gas, possibly nitrogen, to rise from beneath the surface carrying dark particles or ice crystals high into the atmosphere to form clouds.

More geysers were spotted, with isolated dark streaks across the south polar cap, suggesting this feature may be common.

Triton and Io are the only moons known to be volcanically active, Voyager 2 spotting active nitrogen geysers as it flew past. Like our own moon, it is locked into a synchronous orbit with one side always facing Neptune.

The 40% of Triton's surface surveyed at high resolution revealed a greenish terrain of rocky outcrops, ridges, troughs, furrows, hollows, plateaus, icy plains, a few craters and no features above a kilometre high.



Artistic depiction of geysers lofting dark material high into Triton’s atmosphere. Image: Editor

Impact craters are relatively rare due to the ongoing geological activity. Nicknamed cantaloupe by the Voyager team because of a similarity to the melon, the surface appears to be relatively young, estimated at 6 million to 50 million years old.

Before going behind Triton, Voyager 2 trained its Photopolarimetric and Ultraviolet sensors on the star Beta Canis Majoris for about 20 minutes, watching for its brightness to change as it first passed through Triton’s wispy atmosphere, then behind the moon, then back out again.

Just 5 hours and 14 minutes after passing by Neptune, Voyager 2 zipped past Triton at a speed of 63,730 kilometres per hour, at a distance of 39,800 kilometres from its centre.

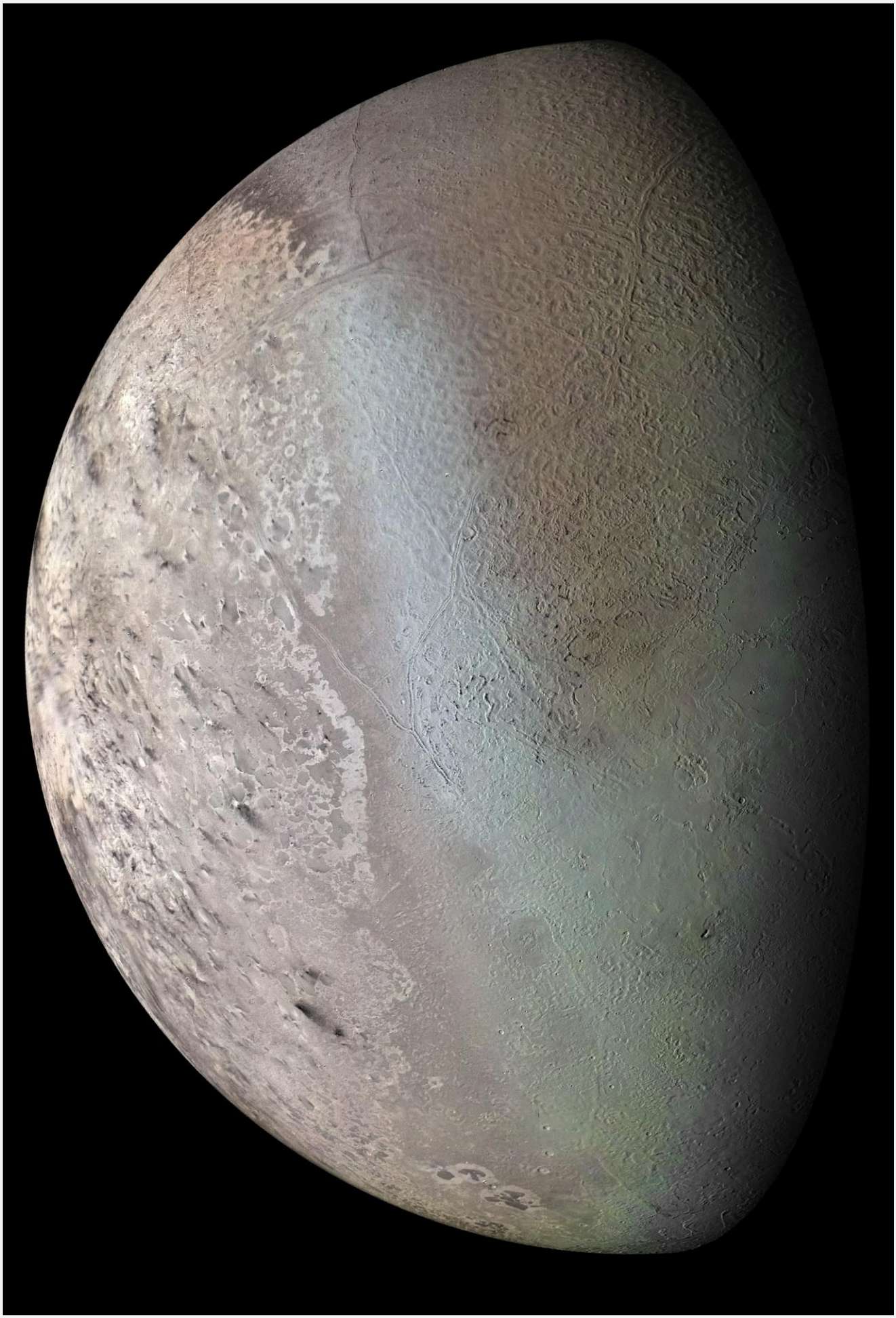
Despite remarkable differences between Triton and the other icy satellites in the solar system, photographs reveal terrain that is reminiscent of Ariel (a satellite of Uranus), Enceladus (a satellite of Saturn), and Europa and Ganymede (satellites of Jupiter).

Even a few reminders of Mars, such as polar caps and wind streaks, can be seen on Triton's surface.

As Voyager 2 left the Neptune environment it was busy sending all the stored data collected back to Earth, but on 28 August found time to change its lock star from Canopus to Spica to allow the LECP (Charged Particle Instrument) to collect samples of the down-stream solar wind and its interaction with particles in Neptune’s nearby magneto tail.



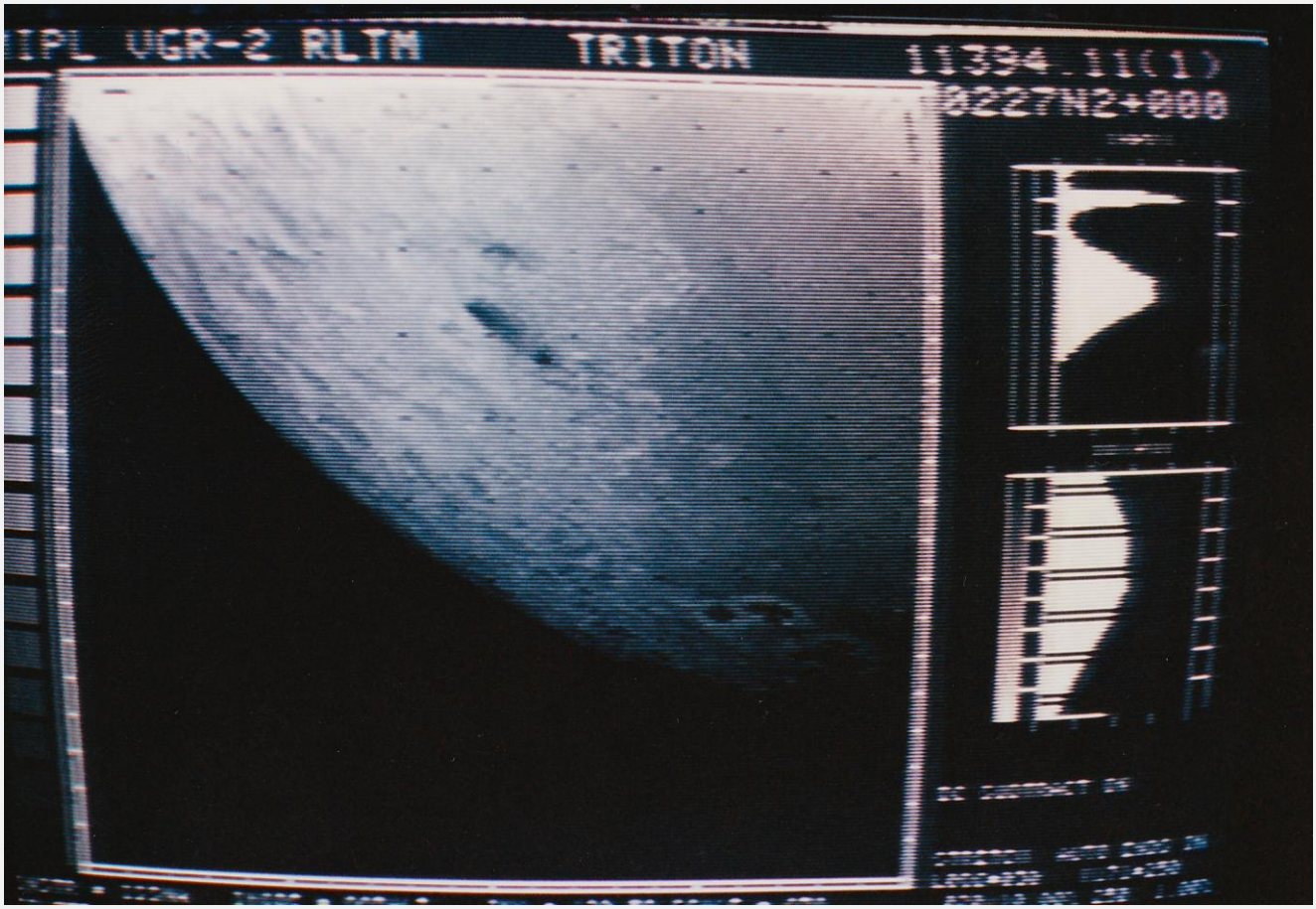
Dark streaks revealing geysers.



Composite of images from Voyager 2 used to create this hemisphere view. Images: NASA/JPL



Triton's limb cuts obliquely across the middle of the image. The field of view is about 1,000 km across. Three irregular dark areas, surrounded by brighter material, dominate the image. Low-lying material with intermediate albedo occupies the central area, and fresh craters occur along the right margin. Sub-parallel alignment of linear patches of dark material shown in the lower and left part of the image suggests that the patches are structurally controlled. Image: NASA/JPL



Above: Slow-scan monitor at Tidbinbilla showing a similar view to the image on the previous page.
Images: Tidbinbilla Archives

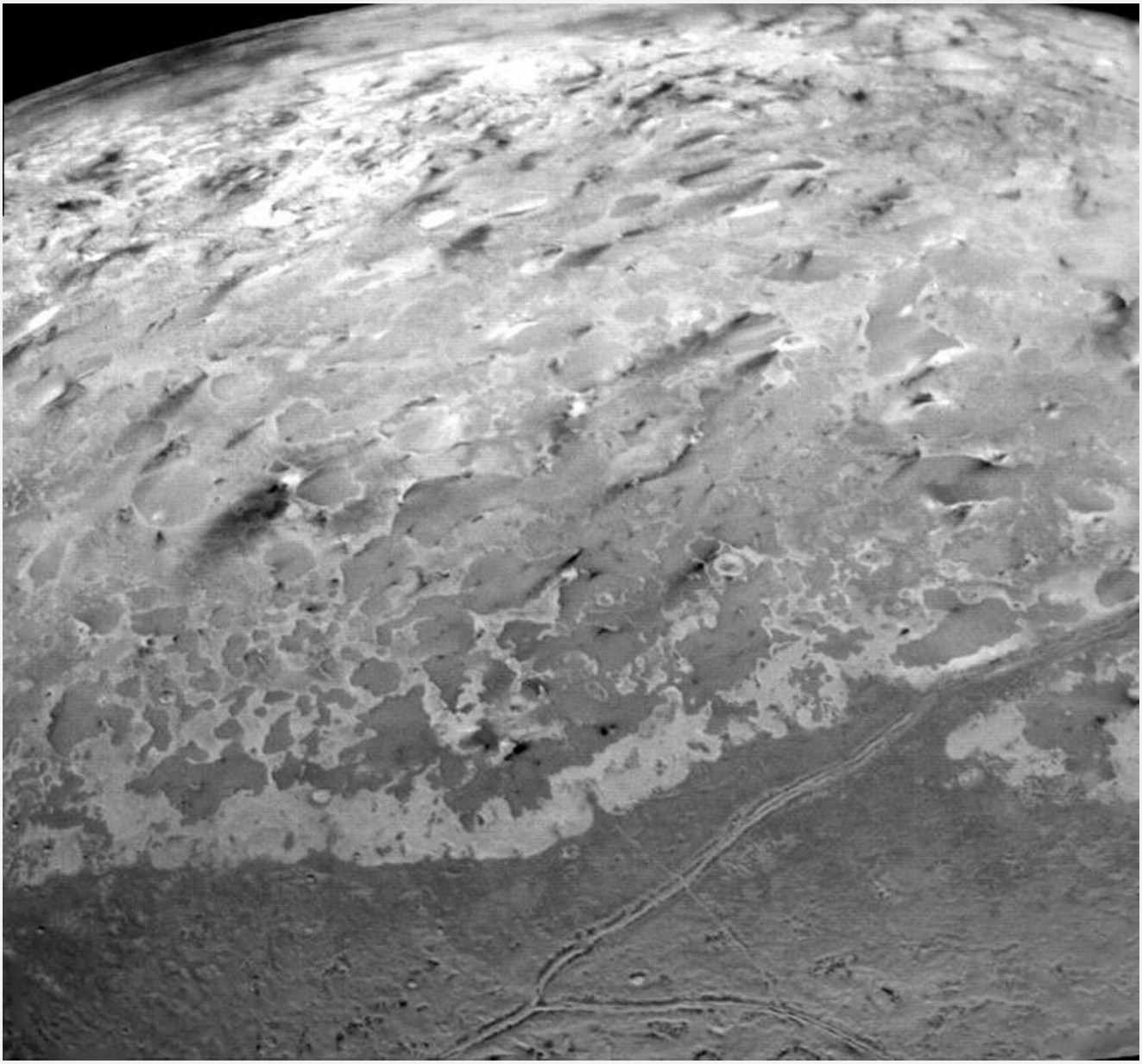
Below: Link Control Operator Richard Stephenson at Tidbinbilla during the Neptune encounter in 1989. Voyager 2 was one of Richard's first missions and in 2026 he's still working at the station. Experience counts!





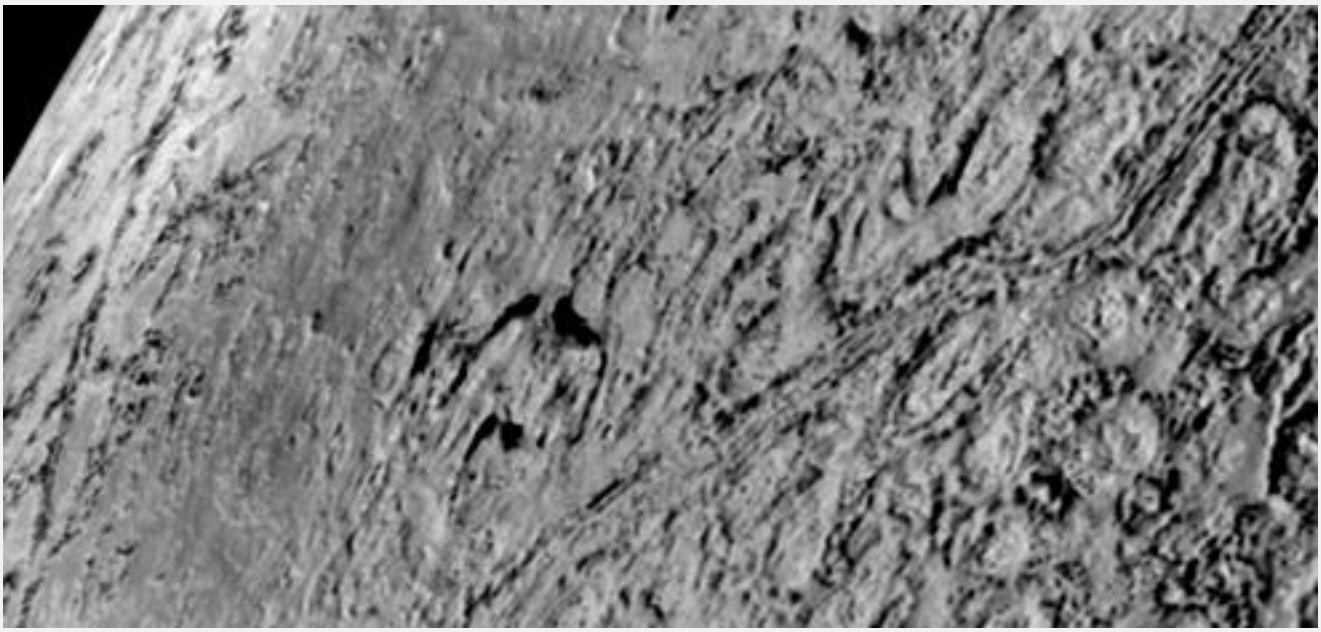
Above: * Staff from Tidbinbilla/CDSCC and support personnel stationed at Parkes for the encounter. **Front row** (from left) Neil McVicar*, Mr Orlandi (Parkes local and casual operator), Peter Churchill*, and Paul Mullen*. **Back row** (from left) Bob Jenkins* (RF engineer), Frank Donivan (JPL), John McCaffery*, Bob Beard*, and Richard Jacobsen* (CDSCC Deputy Director at the time).
Images: © CSIRO Radio Astronomy Image Archive. Personnel names thanks to Mike Dinn/Peter Churchill
Below: Parkes' locals in the Visitor Discovery Centre watch as images from Voyager 2 start to come in.

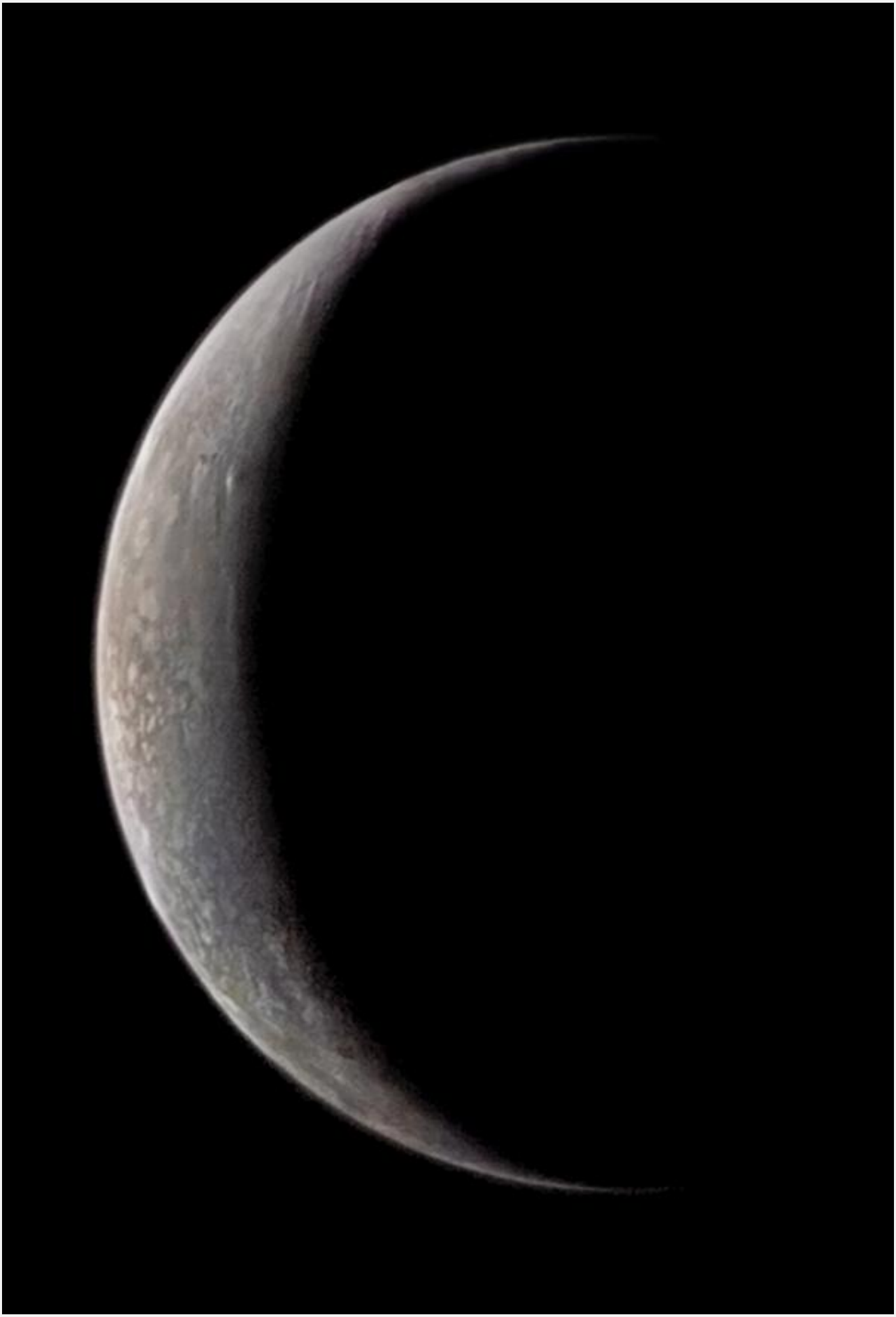




Above: Close-up view of the surface of Triton showing numerous dark streaks from geysers.
Images: NASA/JPL

Below: Some of the rough 'cantaloupe' terrain on Triton.





Triton in crescent in this departure view from Voyager 2. Image: NASA/JPL, Modern processing: Ted Stryk

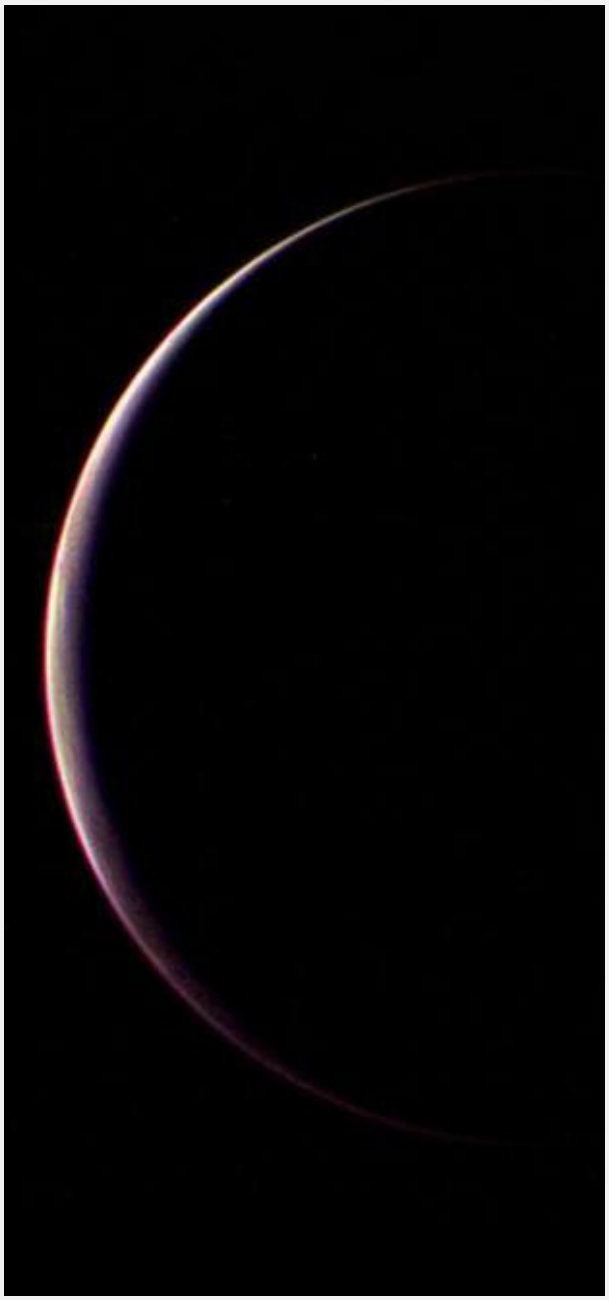
Neptune (*at the time of writing*) has 13~ known moons, six of which were found by Voyager. A summary of the 17 main moons of Saturn follows:

SUMMARY OF NEPTUNE'S MOONS AND SMALLER SATELLITES

	Diameter kilometres	Kms from Neptune's centre
1989N6 Naiad *	26	49,800
1989N5 Thalassa *	32	53,800
1989N3 Despina *	44	59,200
1989N4 Galatea *	62	61,800
1989N2 Larissa *	54	62,660
1989N1 Proteus *	84	64,400
Triton *	108	66,100
Nereid *	54	69,900
2002N1 Halimede	66	75,260
2002N2 Sao	30	76,417
2002N3 Laomedia	154	86,010
2003N1 Psamathe	483	129,780
2002N4 Neso	1,158	190,900

* asterisk indicates Voyager 2 observed the moon.

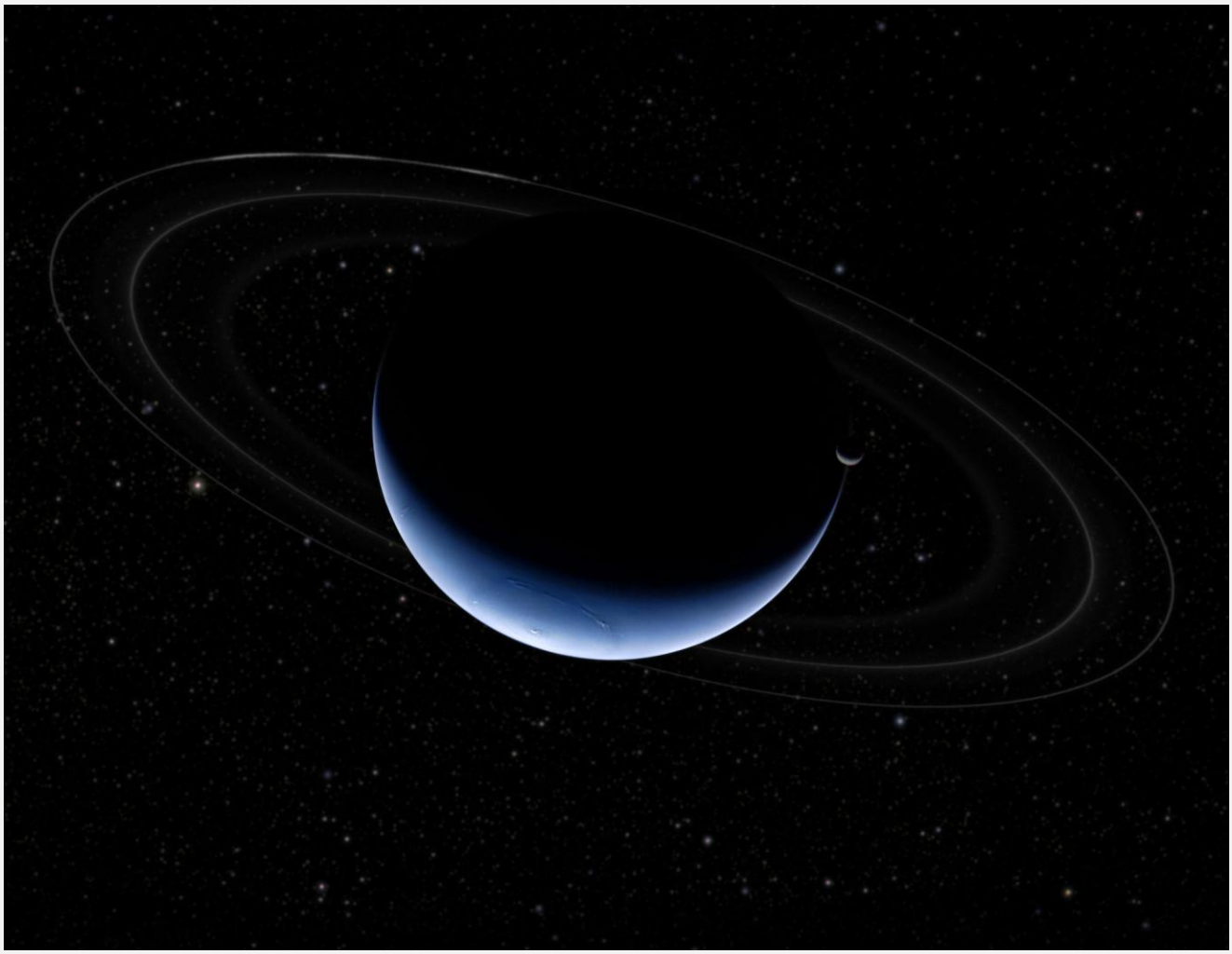
Editor's note: ~ According to NASA, as at August 2026, Neptune has 16 known moons.
All but two of Neptune's 16 moons have been named. Since Neptune is named for the Roman god of the sea, its moons are named for various lesser sea gods and nymphs in Greek mythology.



Thinning crescent of Triton. Image: NASA/JPL

SUMMARY OF NEPTUNE ENCOUNTER – 5 JUNE - 2 OCTOBER 1989

Date	AEDT	Distance	Event/Closest Approach
June 5	16:42		Observatory phase begins
Aug. 6	18:42		Start far encounter phase
Aug. 25	09:56	4,655,000	Nereid
	12:55	78,376	In-bound ring plane crossing
	13:57	**29,183**	**Neptune**
	14:03		Enter Earth and Sun occultation
	14:52		Exit Earth occultation (49 minutes)
	14:53		Exit Sun occultation (50 minutes)
	15:18		Out-bound ring plane crossing (2 hr 23 mins)
	19:11	39,800	Triton
Oct. 2			End Neptune encounter period
		One-way signal elapsed time was 4 hours 06 minutes	
		* from Neptune's centre (kilometres)	



Composition of the southern pole of Neptune, its rings and Triton as Voyager 2 begins its interstellar journey.
Image: (data) NASA/JPL, (artist's composition) Rolf Wahl Olsen - rolfolsenastrophotography.com

VOYAGER 2

LEAVING NEPTUNE –
THE END OF THE PLANETARY MISSION

Millions of people around the world had watched live broadcasts of atmospheric storms, cloud shadows, six new moons, several new rings and the icy moon Triton.

Voyager Project Manager Norman Haynes happily announced,

"Everything went exceedingly well and we couldn't be happier."

Ed Stone summarised the Voyager 2 flight with,

"Voyager 2 will be regarded as the quintessential mission of exploration; there has been no other mission that has explored so many new worlds, and there can be no other mission. Only Voyager has had the opportunity of visiting, in sequence, four giant planets with literally dozens of new worlds in orbit around them."

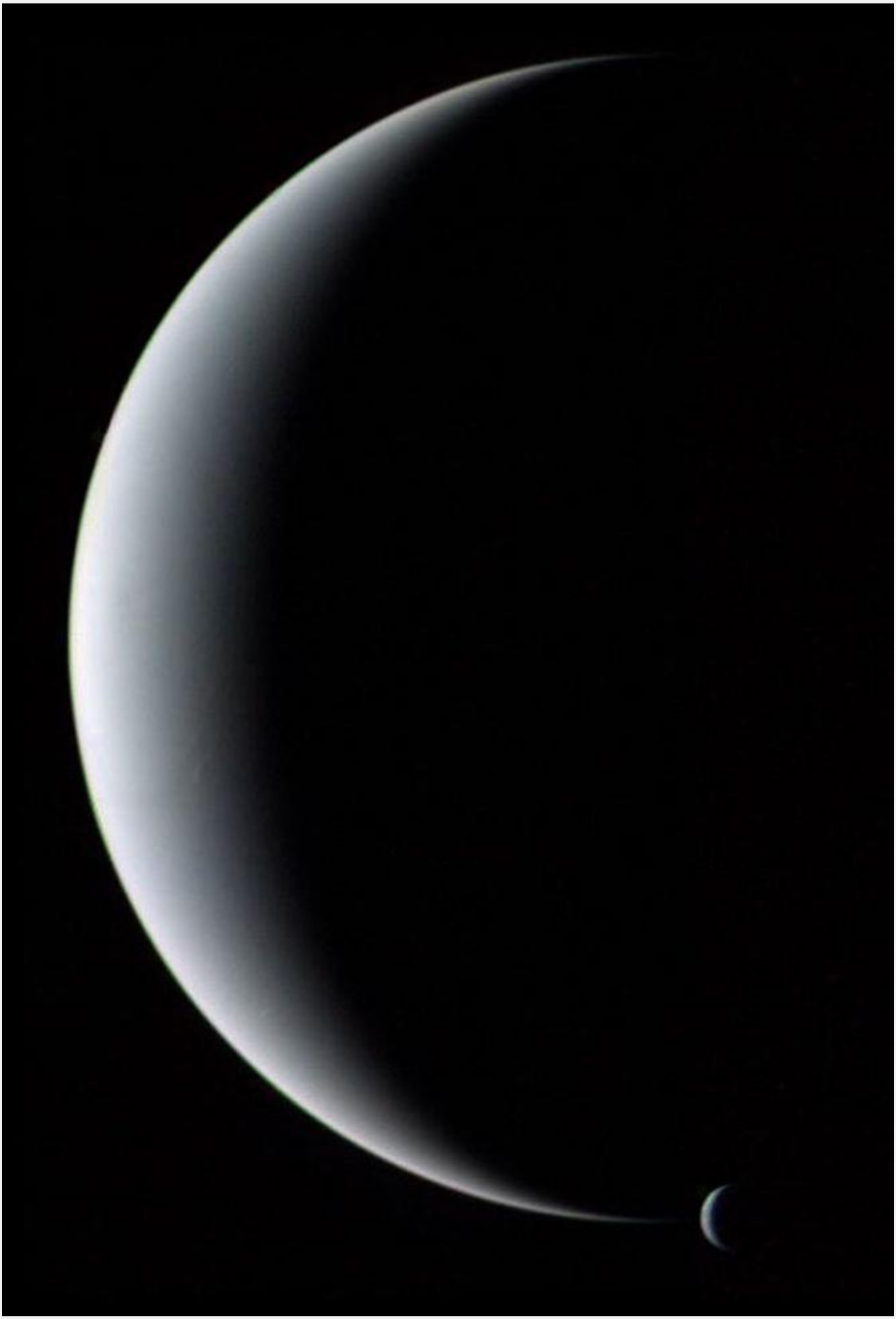
He later commented,

"The Triton flyby was my favourite moment partly because it was a bookend. The journey really started with the discovery of volcanoes on Io with Voyager 1, 10 years earlier -- the first bookend. We finished the planetary part of the mission with another bookend, the flyby of Triton, where we discovered a much colder, smaller world that was also geologically active."

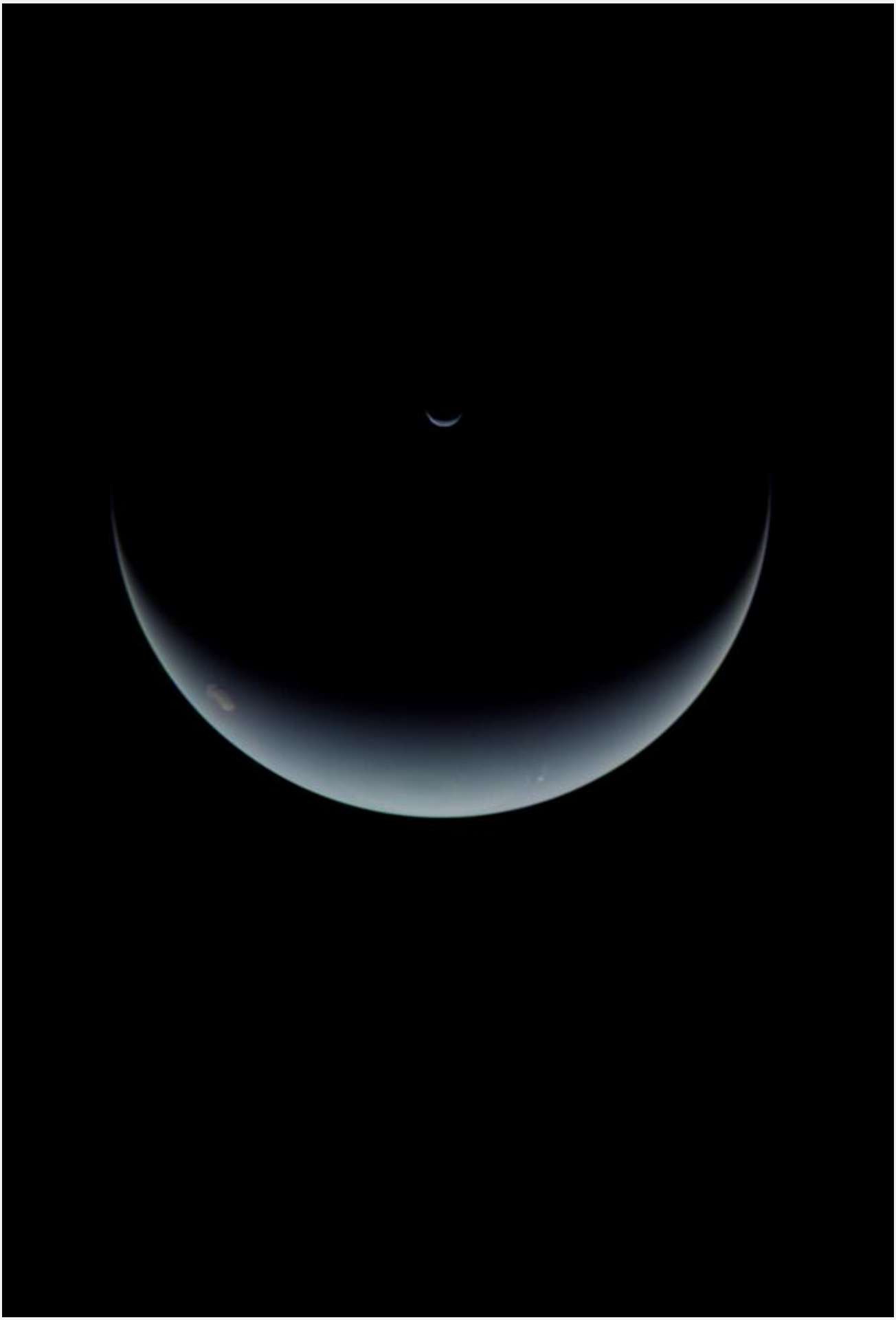
Perhaps the best farewell comment was from scientist Laurence Soderblom at the post-encounter press conference,

"All I can say is…..Wow! What a way to leave the solar system!'

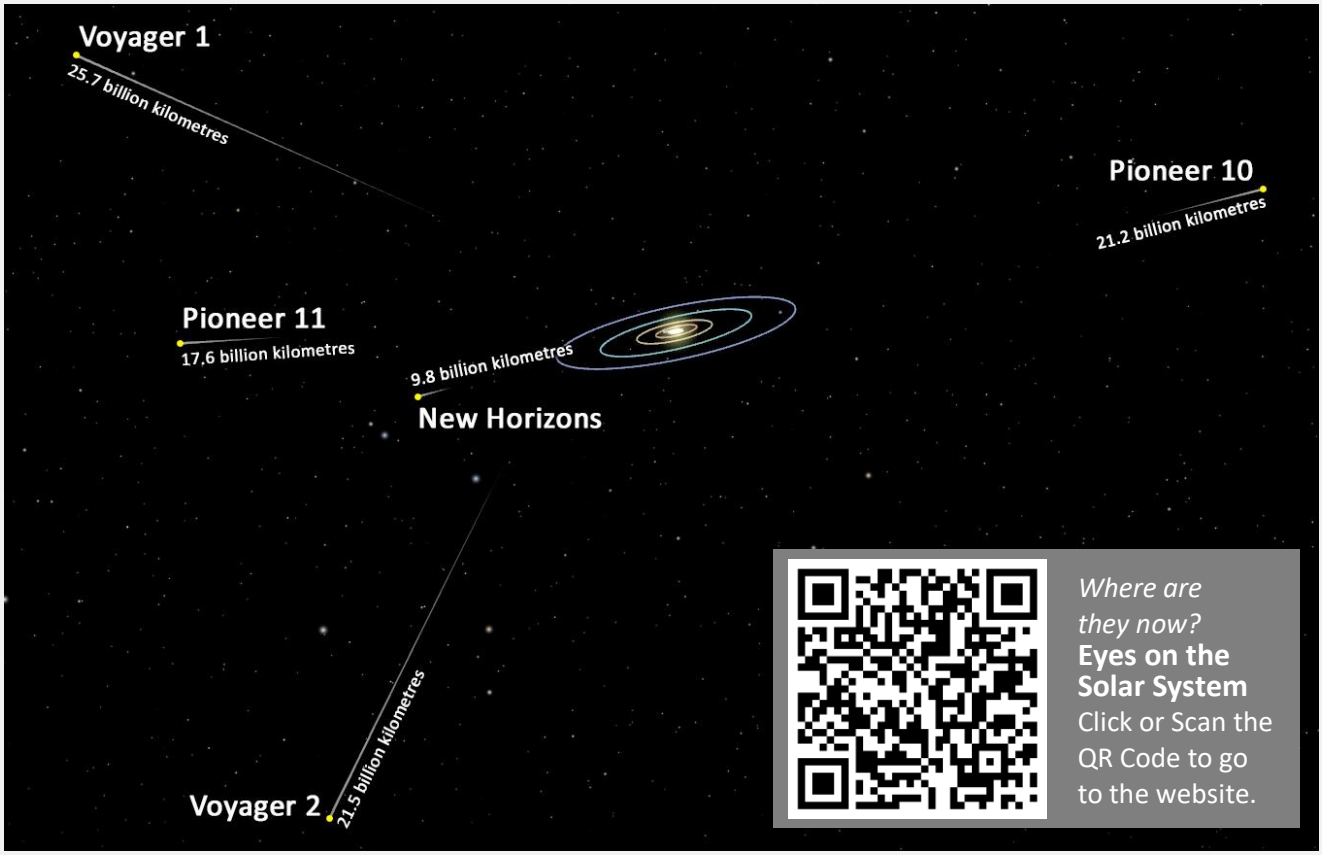
The Neptune fly-by officially ended on 2 October 1989. From now on this incredible trip became known as the Voyager Interstellar Mission.



Crescent Neptune (background) and crescent Triton (lower right). Image: NASA/JPL



Farewell – one of the final images of Neptune and Triton as Voyager 2 departs.
Image: NASA/JPL. Modern processing: Justin Cowart



Continuing their outward journeys, the relative positions and distances as at October 2026, for the Voyager, Pioneer, and New Horizons spacecraft. Graphic: NASA – Eyes on the Solar System

VOYAGERS 1&2

THE INTERSTELLAR MISSIONS

The twin Voyager probes had reached the end of their spectacular planetary missions. Uranus and Neptune have since moved on along their respective orbits and will not be accessible from Earth for the next 150 years - or at least not with present-day technology.

Between them, Voyager 1 and 2 explored all the giant outer planets of our solar system, 48 of their moons, and the unique systems of rings and magnetic fields these planets possess.

Voyager 1 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 2 is also headed out of the solar system, diving below the ecliptic plane at an angle of about 48 degrees and a rate of about 470 million kilometres a year.

Both spacecraft will continue 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 Voyager project.

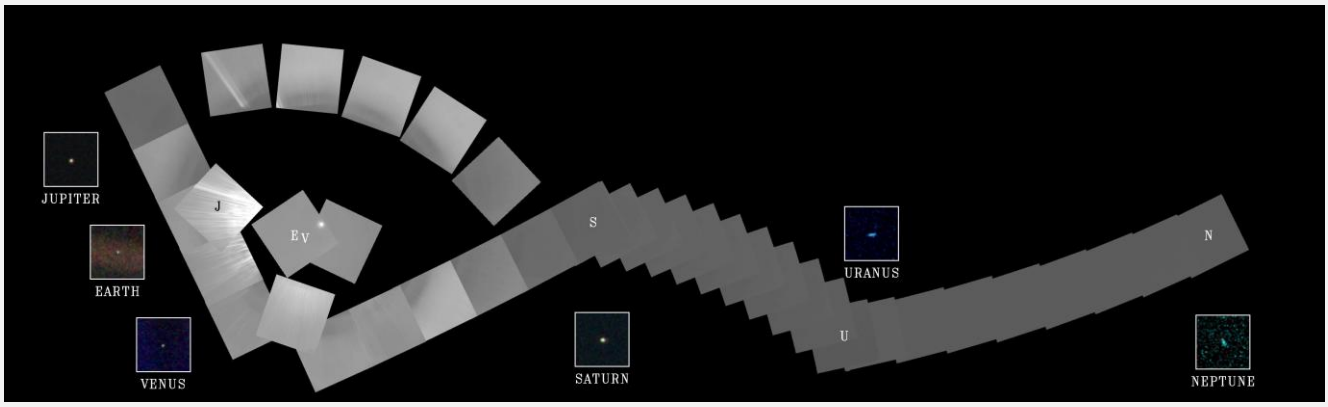
The spacecraft had travelled 7.1 billion kilometres from Earth and, ignoring the launch vehicle, had a staggering fuel economy of 13,000 kilometres per litre. Between planets its speed was 81,900 kph relative to Earth, or 80,970 kilometres per hour relative to the Sun, (the heliocentric velocity).

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.

THE SOLAR SYSTEM FAMILY PORTRAIT

While Voyager 2 was busy shooting past Neptune, Voyager 1, by now 32^{o} 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



Solar System Family Portrait. See the Voyager 1 essay, pages 74-76, for more information. Graphic: NASA/JPL

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.

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.

These pictures were the last of roughly 67,000 images taken between the two 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, 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 gas 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?

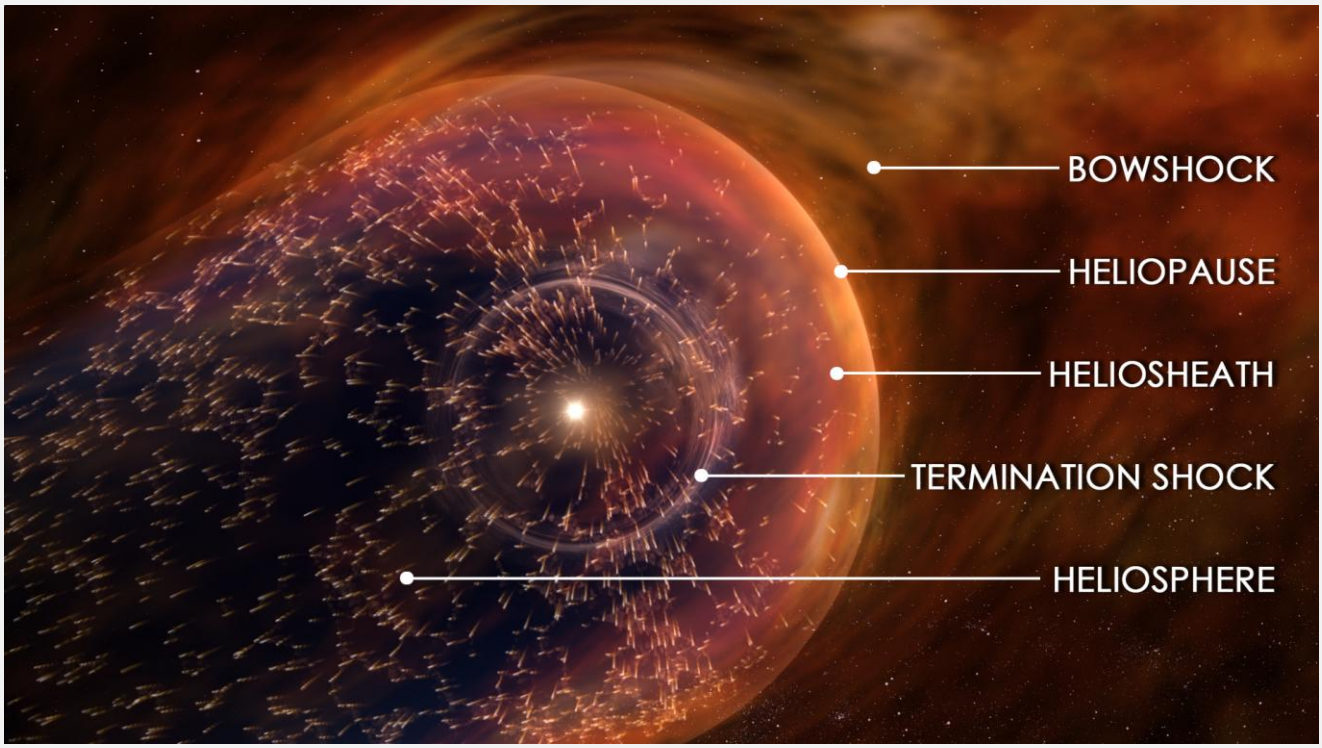
Pioneer 10 is going back along the tail of the solar system's heliosphere heading for Taurus, which it should reach in 2 million years, while Pioneer 11 is going out ahead of us towards the Constellation of Aquila, which it should reach in 4 million years.

Voyager 1 is climbing above the ecliptic at an angle of 35^{o} 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.

Voyager 2 is plummeting down at an angle of 47^{o}, 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.

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





The structure of the Heliosphere surrounding our solar system. Image: NASA/GSFC-Space Visualization Studio
The Sun's magnetosphere and outward rushing solar wind collides with the inward flowing interstellar wind.

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.

BOWSHOCK

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

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 2015, where the 1,600,000 kilometre per hour solar wind abruptly slows and becomes denser and hotter as it presses against interstellar gas.

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.

Voyager 2 should cross the termination shock between 2008 and 2010 and reach the heliopause about 10 years later.

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. 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 were 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 from the sun and still on the job 24/7 12 months of the year.

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 Ed Stone, Voyager project scientist based at the California Institute of Technology, 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.

"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."

There are currently five science investigation teams participating in the Interstellar Mission. They are:

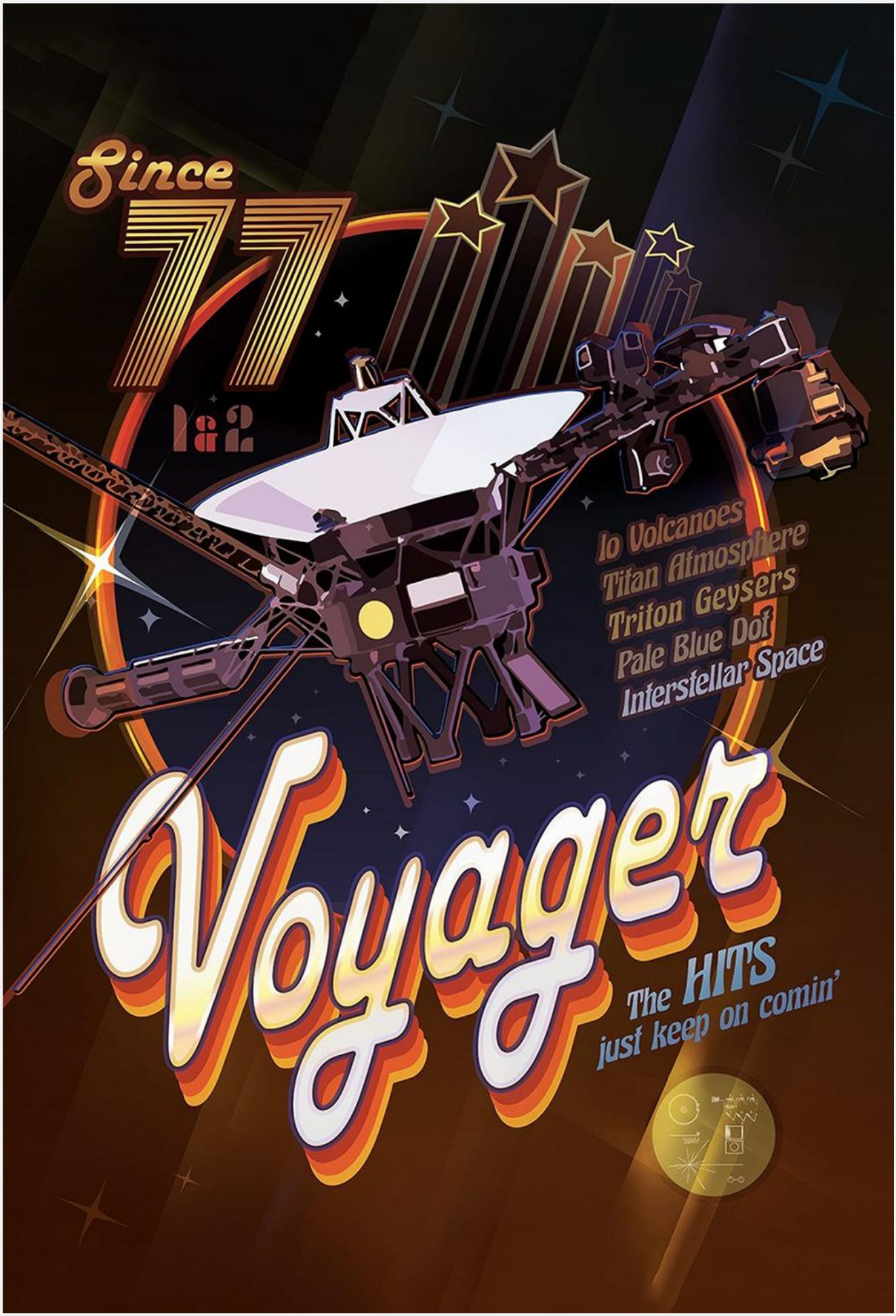
1. Magnetic field investigation
2. Low energy charged particle investigation
3. Cosmic ray investigation
4. Plasma Investigation (Voyager 2 only)
5. Plasma wave investigation

Five instruments onboard the Voyagers directly support the five science investigations. The five instruments are:

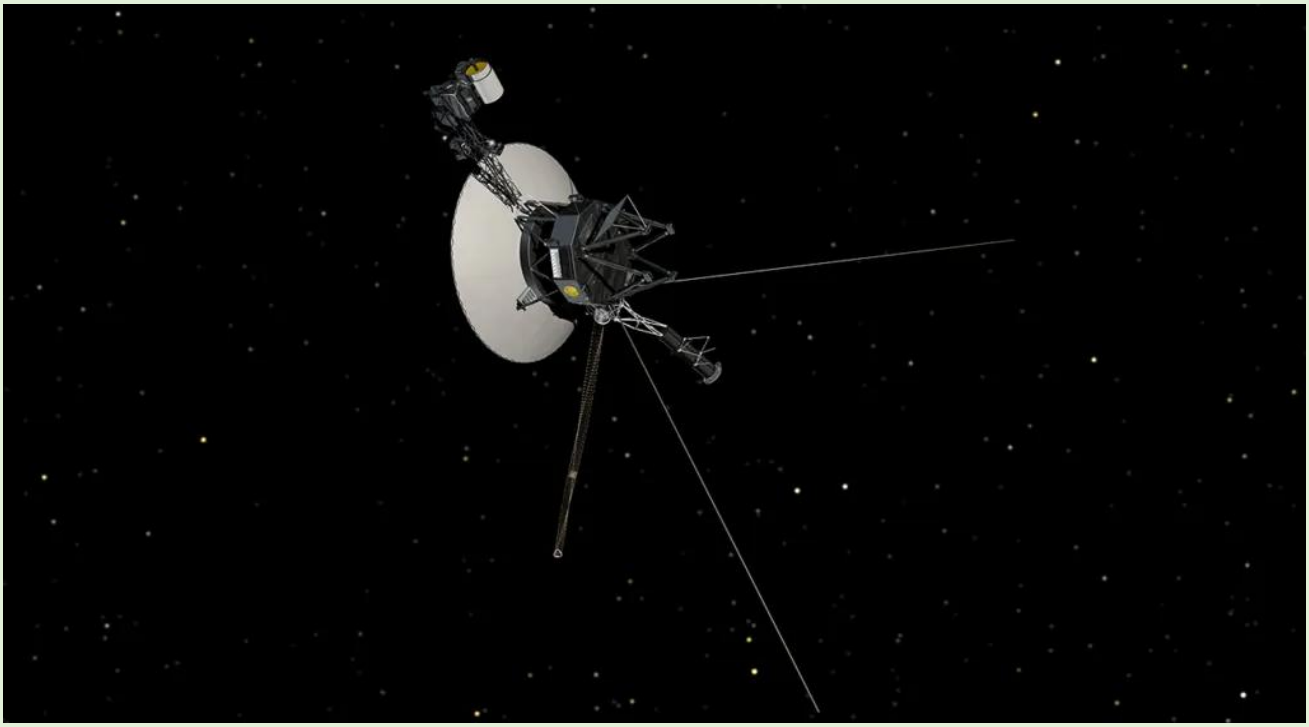
1. Magnetic field instrument (MAG)
2. Low-energy charged-particle (LECP) instrument
3. Cosmic ray instrument (CRS)
4. Plasma instrument (PLS)
5. Plasma wave instrument (PWS)



Dr Edward Stone, Voyager Project Scientist (1972-2002) and JPL Director (1991-2002). Image: NASA/JPL



Retro-disco poster celebrating the Voyager missions. Poster: NASA/JPL



VOYAGERS 1&2

EDITOR'S NOTE – MISSION UPDATE (2026)

Since Hamish Lindsay completed these essays a decade ago, the Voyager missions, those two venerable JPL-built spacecraft, have continued their expeditions into interstellar space.

After nearly 50 years in space, both spacecraft remain in "good health" through the efforts of the very small but dedicated team who are still based in Los Angeles but not always on the lab at JPL.

Some work from home and at other times working out of a rental office in the San Gabriel Valley. The office is wedged directly next door to a dog training school and a McDonald's restaurant. The team of engineers -- many of whom are in their 70s and 80s -- are eligible for the seniors' discount right next door while managing humanity's most distant interstellar spacecraft.

However, even though their journey continues, both spacecraft have faced their share of small "aches and pains" along the way.

INSTRUMENTS

The original 10 instruments on the Voyager spacecraft have now been reduced to:

- Voyager 1 – two instruments (MAG, PWS)
- Voyager 2 – 3 instruments (CRS, MAG, PWS)

Others have been turned off to conserve power.

INTERSTELLAR SHOUT and GIBBERISH

Both Voyager spacecraft have had issues over the years, from failed instruments shortly after launch, to jammed camera platforms, computer glitches, stuck thrusters, and more.

For example, on 21 July 2023, an error in commands transmitted to the spacecraft resulted in Voyager 2 turning its antenna about 2^{o} away from Earth. For the Tidbinbilla team, their "exclusive" spacecraft had suddenly gone silent.

The big dish at Tidbinbilla listened intently for any signal to determine what had happened. Meanwhile, the Voyager team in the US was combing through their computer coding to see what might have possibly happened.

After two weeks of silence, a faint signal was captured by DSS43 in Canberra. The mission team had also found the line of code that was erroneously sent to the vehicle.

It was decided to transmit a new code and try an "interstellar shout" – transmitting at DSS43's maximum output of 100kW – and "hope" that some of that signal makes it was into the spacecraft antenna's side lobes and that it would turn to face back home again.

After a 35 hour round trip time for the 'shout' and then waiting for a possible signal return, Tidbinbilla received a call from Voyager 2, basically saying, *"where have you been?"*, like nothing had happened at all.

GIBBERISH

On 14 November 2023, Voyager 1 started transmitting an unreadable, repeating pattern of binary 1s and 0s.

A DSN engineer determined that even though the spacecraft was sending gibberish, there was in fact some spacecraft telemetry could be read and that the problem was a single computer chip in the Flight Data System had stopped working for reasons unknown – it could have been anything from age, physical wear and tear or being hit by an interstellar particle.

The plan was to tell the spacecraft to take all the functions of that chip and move it over to other chips on the board in hopes that Voyager 1 would start making sense again.

In April 2024, the command was sent and after a 46 hour round trip, and a few tense moments in the Operations Centre at Tidbinbilla, their screens lit up with little green icons noting that they were "in lock" with the spacecraft and that it was indeed sending clean data back to Earth.

An interstellar software patch and repairs at a distance of 24 billion kilometres.

There have been dozens of other incidents over the decades, but the engineers and scientists have managed to nurse and coddle the mission back to operational status time after time.

THE BIG BANG

In July 2026, engineers began freeing up power on Voyager 1 and 2, extending how long the spacecraft can continue to do science.

Nicknamed the "Big Bang," the effort involved simultaneously turning off certain powered devices and substituting them with lower-power alternatives while ensuring the two spacecraft remained warm enough to operate.

The Voyagers' RTGs convert heat from decaying plutonium into electricity. The depleting plutonium, loses about 4 watts each year, making power margins razor thin.

Without the Big Bang activity, the missions would have had to turn off another instrument on the Voyagers before the end of 2026.

The savings should provide power to keep their instruments operating for an extra year.

ENTERING INTERSTELLAR SPACE

Both spacecraft are now travelling through interstellar space, having crossed the Heliopause boundary on:

- Voyager 1 – 25 August 2012
- Voyager 2 – 5 November 2018

DISTANCE

As at October 2026, the Voyager spacecraft are travelling at a speed relative to the Sun of:

- Voyager 1 – 60,904.8 kilometres per hour
- Voyager 2 – 54,950.4 kilometres per hour

They have reach a distance of:

- Voyager 1 – 25.7 billion kilometres
- Voyager 2 – 21.5 billion kilometres

Both are extending that number by ~1.4 million kilometres per day.

ONE LIGHT DAY FROM EARTH

On 18 November 2026 at 10:16 UTC (21:16 AEDT), Voyager 1 will be ~25.902 billion kilometres (173 AU) from Earth, or to put it another way, 'one light day' from home.

At that moment, travelling at the speed of light, radio signals to or from the spacecraft would take 24 hours to cover that distance one-way.

The milestone is not significant in cosmic terms, but for humanity it symbolises our furthest footsteps into the endless void.

WHEN WILL VOYAGER BE GONE?

In some ways, there really is no "end" to the mission. Both Voyagers will continue to head out into the Milky Way Galaxy ahead of us. Steadily leaving our solar system far behind them.

However, Earth will lose contact with them, when the last data is returned, the last instruments will have been turned off, the carrier tone of the radio transmitter being the only evidence that they are still there. But one day, sometime in the mid-2030s, that signal will be at such a low level that it becomes undetectable by the antennas of the Deep Space Network.

From that day forward, whenever it comes, the great silence will be the only thing left.

Editor's note: The best way to stay in touch with the Voyager mission is to visit its website:

https://voyager.jpl.nasa.gov



Hamish Lindsay with his trusty Linhof Super Technika 4x5 camera. Portrait: © William Hall, 2014.

VOYAGERS 1&2

MY FINAL THOUGHTS – HAMISH LINDSAY

The Apollo Project is over, and is now part of our history. Because it involved people, Apollo was very exciting, and I suspect the media will always make a bigger deal of it. But to me JPL's Voyager Project is really much more mind bending than Apollo, because it was so much more expansive, outrageously successful, and is an ongoing project with no end - we are talking in millions of years; possibly outlasting the existence of our solar system.

Even in my youth we had a pretty good idea of what the Moon had in store for us from our earth-based telescopes, but until Voyager the outer planets were mysterious worlds beyond our vision and comprehension.

The discoveries of the Voyager spacecraft instantly outdated and changed all of the astronomy and science books about our solar system and its planets.

What about our Milky Way Galaxy and its Super Massive Black Hole lurking in the centre? What is going happen to it, the Voyager spacecraft and us?

First named by American physicist John Wheeler in 1967, Black Holes were offered as a theory to explain where a lot of missing matter was hiding, and why light bent around certain areas.

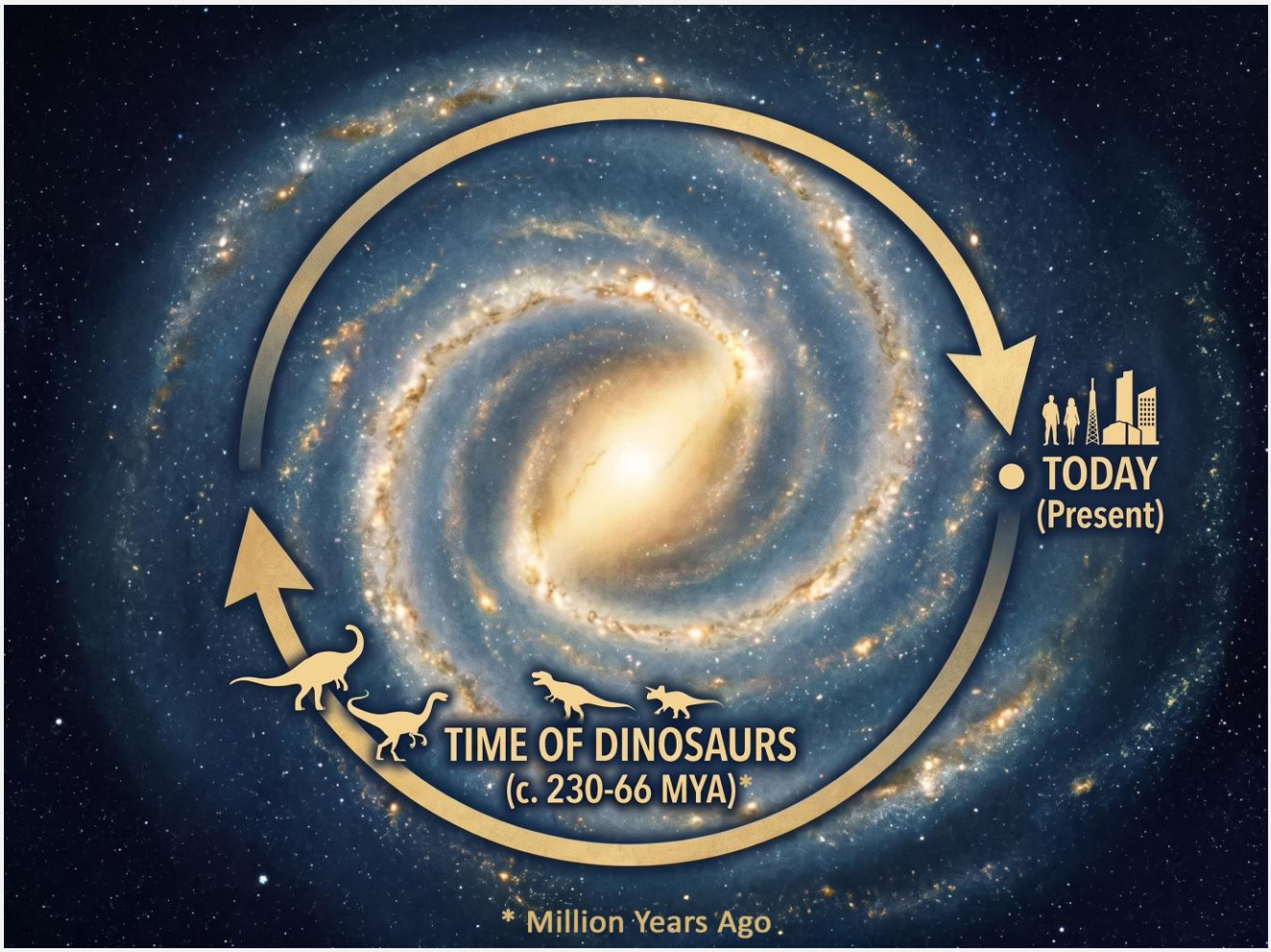
By 2003 research by astronomers using the Hubble Telescope, NASA's Chandra X Ray Observatory, and VLBI arrays on Earth, have determined there are Black Holes and Super Massive Black Holes in the centre of just about every galaxy.

There are two kinds of Super Massive Black Holes, the Feeding and the Quiet. We have a quiet SMBH at the core of our Galaxy, but it has been observed to be having snacks of stray gases, but astronomers believe it is not going to develop into a feeding Black Hole again just yet.

Our SMBH has been measured as 4.3 million times the mass of the Sun crammed into a space 52 million kilometres wide, 26,000 light years away from our Solar System.

Our nearest neighbour, the Andromeda Galaxy 2.3 million light years away, is much bigger, with a SMBH 140 million times the mass of the Sun.

It takes 245 million years for our Solar System to travel around the Galaxy once.



From the time of the earliest dinosaurs to today, the Milky Way has turned only once. Graphic: Editor

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 only 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?

We have talked a lot about the Universe, which for a lot of my life was the whole of our environment, but now we are talking about the Multiverse, where there are many universes, with a whole lot of wild theories about their interactions.

One theory is that a collision of two of these Multiverses created the Big Bang, which has resulted in us being here.

This is our new playground, and our Voyagers have begun to play in it.

THE END OF THE BEGINNING

So, my tale about the Voyagers ends with our minds blown out by the future and its possibilities and the awesomeness of our solar system and the galaxies and super massive black holes of the Universe, as well as marvelling at the ability of the human race to be so successful at exploring the solar system and galactic environment at our first attempt.

The Pioneer and Voyager spacecraft are spreading out into our galaxy on a trip that will last forever, the first human-made objects to leave the solar system, the first to carry the message of our existence out into the Milky Way Galaxy.

They will become lost in the spiral arms of the galaxy, split from our Earthly history and

completely isolated from the events lying in our future and the future of the solar system. Their voyages will continue long after the human race has become extinct; they will probably still be drifting alone along unknown reaches of the galaxy when our sun eventually burns out and becomes a cold, lifeless White Dwarf star.

Are these spacecraft the vanguard of other spacecraft to follow? Will spacecraft carrying humans ever follow them, seeking other worlds? Will we ever leave our solar system…?

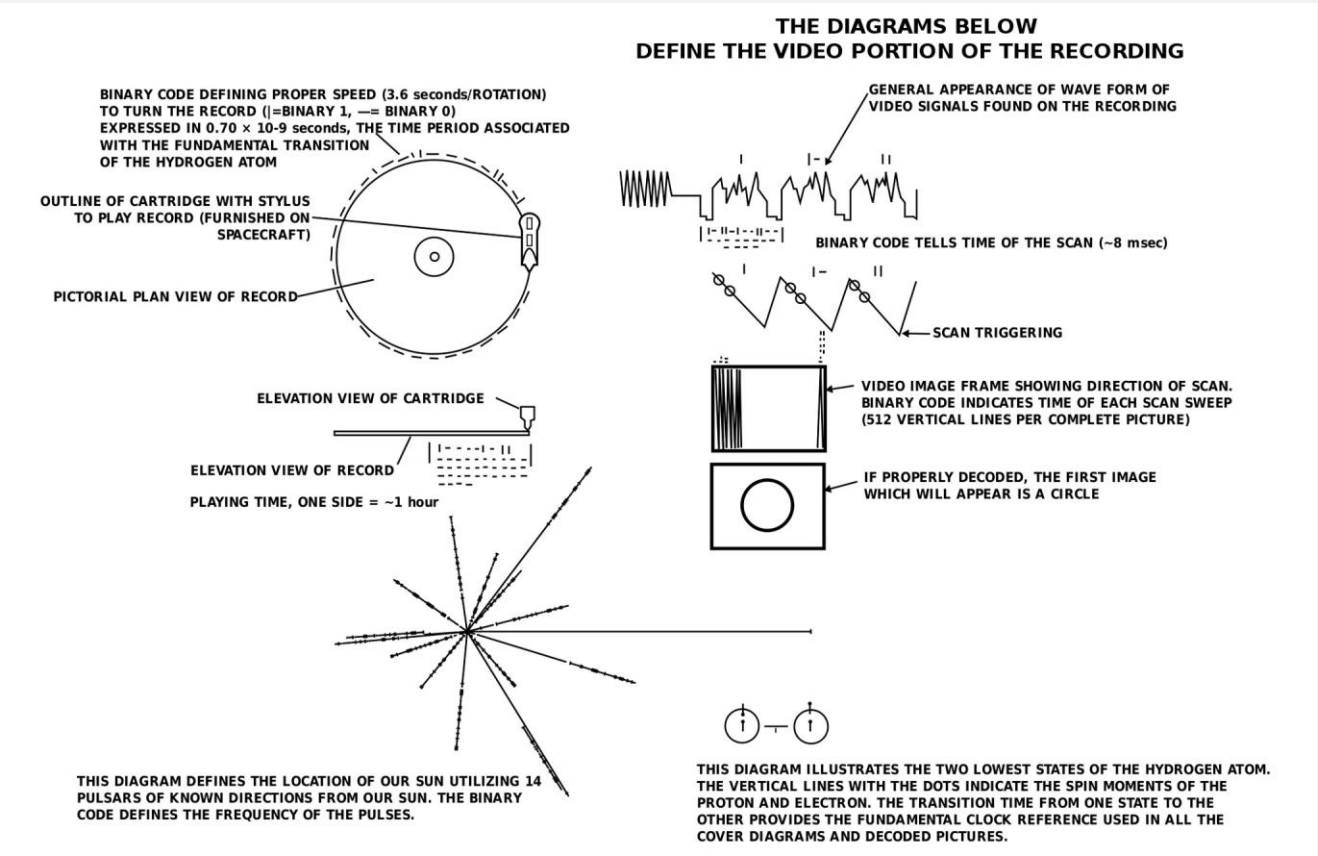
Is there a form of life out there to discover the two Pioneers and the two Voyagers, and thus become aware of our Earth and its existence?

Perhaps a form of life will evolve and discover our spacecraft in the future. Some are frightened that a belligerent form of life will find one of our spacecraft, follow the directions on them to Earth and come to attack us.

The chances are low; there's a lot of empty space out there… but you can never say it's zero.



Installation of the Golden Record on the Voyager 2 spacecraft. Image: NASA/JPL



THE GOLDEN RECORD

Past NASA missions had included plaques with information about Earth, in case an intelligent alien race intercepted the probes.

This spurred, John Casani, Voyager's first project manager, to appoint astronomer and author Carl Sagan to head a committee to come up with a message for Voyager.

Physicist Frank Drake suggested the idea of a record that would have pictures on one side and sounds on the other side. The group had less than six weeks to come up with a record that would represent the entire population of Earth -- in addition to the planet itself -- if it were ever discovered by an intelligent alien race.

Carl Sagan's son Nick was six years old in 1977 when the Voyager records were being assembled. The records feature a recording of him as a child saying, *"Hello from the children of planet Earth."*

> *"It's the classic message in a bottle. The likelihood of finding it is small, but the payoff is huge if it is found,"* said Ann Druyan, a science media producer and author.

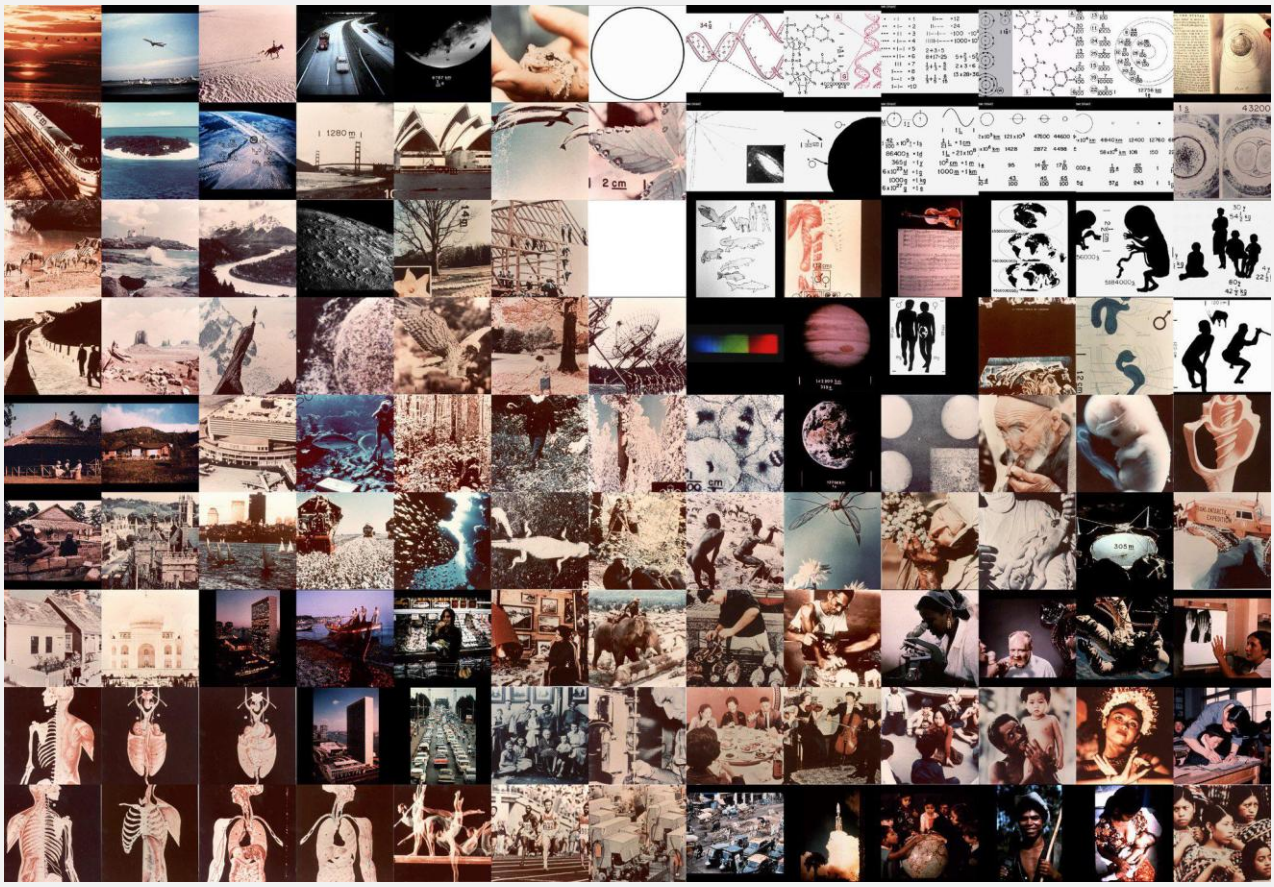
Druyan was appointed creative director of the record project and later married Sagan.

Ed Stone, Voyager's project scientist and former JPL director, explained that although there is almost no chance of the record being found, the record is important as a message to us.

> *"In a sense it's a unifying message,"* he said. *"It's a message from Earth. It contains greetings in many languages, music from many cultures and images that portray our home planet. It's our attempt to say what is Earth, and it's a record of who we think we are."*

Druyan also explained that the coupling of music and science was an especially compelling reason to devote so much energy to the record.

> *"The record represented the idea that science and technology could come together with art," said Druyan, who also designed the sound essay. "It's one of the few totally great stories that we have about humans. It cost the taxpayers virtually nothing, nobody got killed. It was a way to celebrate the glory of being alive on this tiny blue dot in 1977.*
>
> *"This was the most romantic and beautiful project ever attempted by NASA. It had the sounds of a kiss, a mother saying hello to her newborn baby for the first time, all that glorious music.*



The Voyager Golden Record contains 116 images representing our world. Graphic: NASA/JPL

It includes images of Earth, Mars, Mercury, Jupiter, the solar system, solar spectrum, and a galactic location map. Mathematical and physical unit definitions, DNA structures, human anatomy, a developing foetus, and continental drift. Diagrams of male and female anatomy, a nursing mother, people eating and drinking, children, schoolrooms, supermarkets, and architecture from around the world. Landscapes, weather phenomena (thunder, rain), oceans, and diverse animals ranging from elephants and birds to marine life.

Remember, this was during the Cold War. Everyone was living with the knowledge that 50,000 nuclear weapons could go off at any time, and there was a lot of angst about the future. This was something positive -- a way to represent Earth and put our best foot forward. That was irresistible."

If any of these spacecraft are ever found, and it could be thousands, perhaps millions of years in the future, the aliens will find the messages and sounds of the Planet Earth around the Galaxy on a gold disc Carl Sagan called *"Murmurs of Earth"* – sounds from **'our time'** in the second half of the twentieth century.

Editor's note: This is the last essay in Hamish Lindsay's epic series of works on the people, missions and places that placed Australia on the map as a crucial partner in the exploration of the Solar System and beyond. As editor on these essays and producing these booklets, I hope I have honoured what Hamish started.

Essay by Hamish Lindsay © 2014-2016, 2026
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.
PDF formatted by Glen Nagle.

© www.honeysucklecreek.net 2026

Hamish Lindsay's essay **Voyager 1 – A Voyager to Forever** is available at the honeysucklecreek.net website. Click or Scan the QR ode (left) to access.



The Voyager Golden Records carries spoken greetings in 55 languages, natural and human environmental sounds, and about 90 minutes of diverse global music. Image: NASA/JPL



ABOUT THE AUTHOR



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.