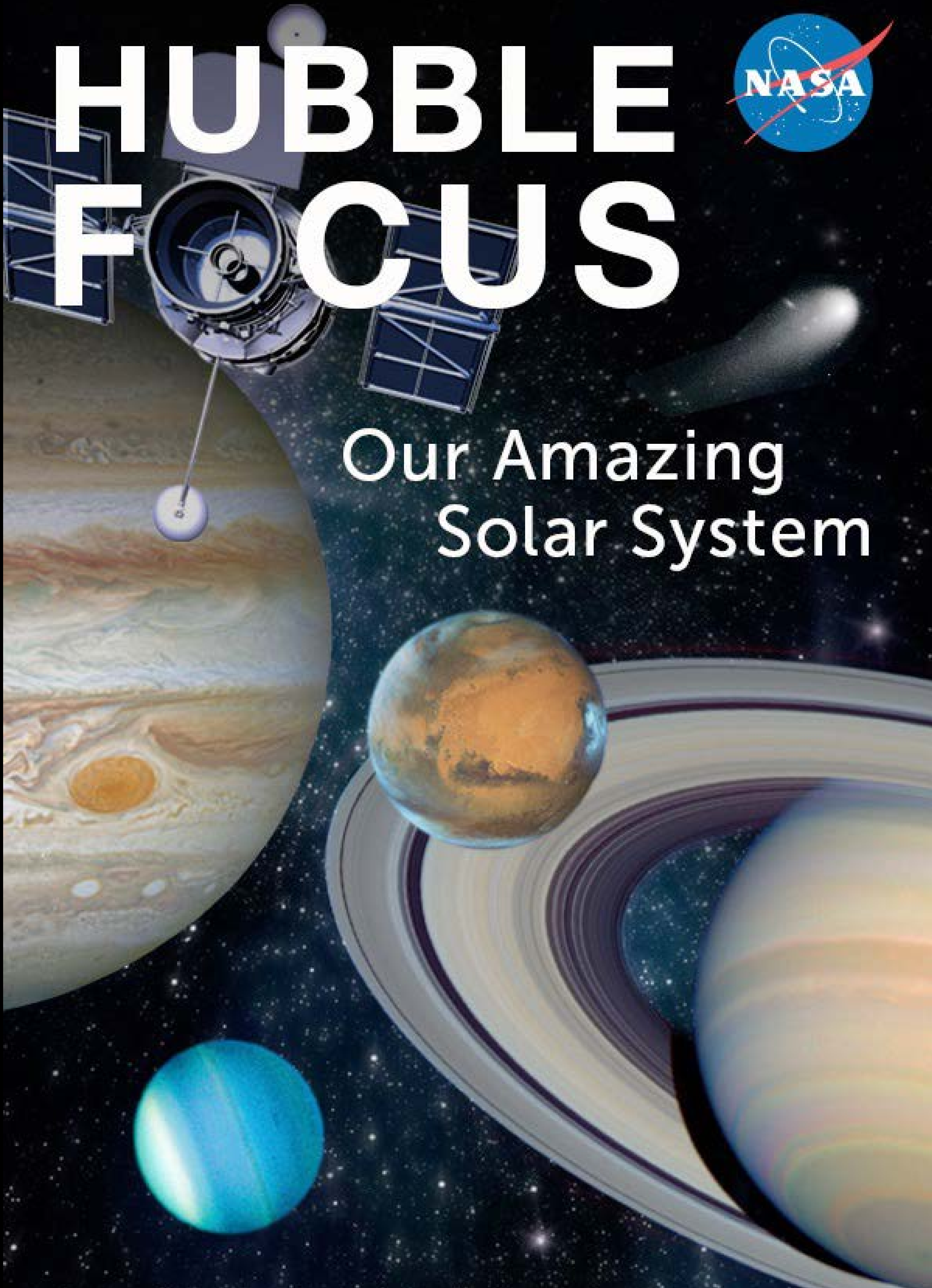
HUBBLE FOCUS

Our Amazing Solar System



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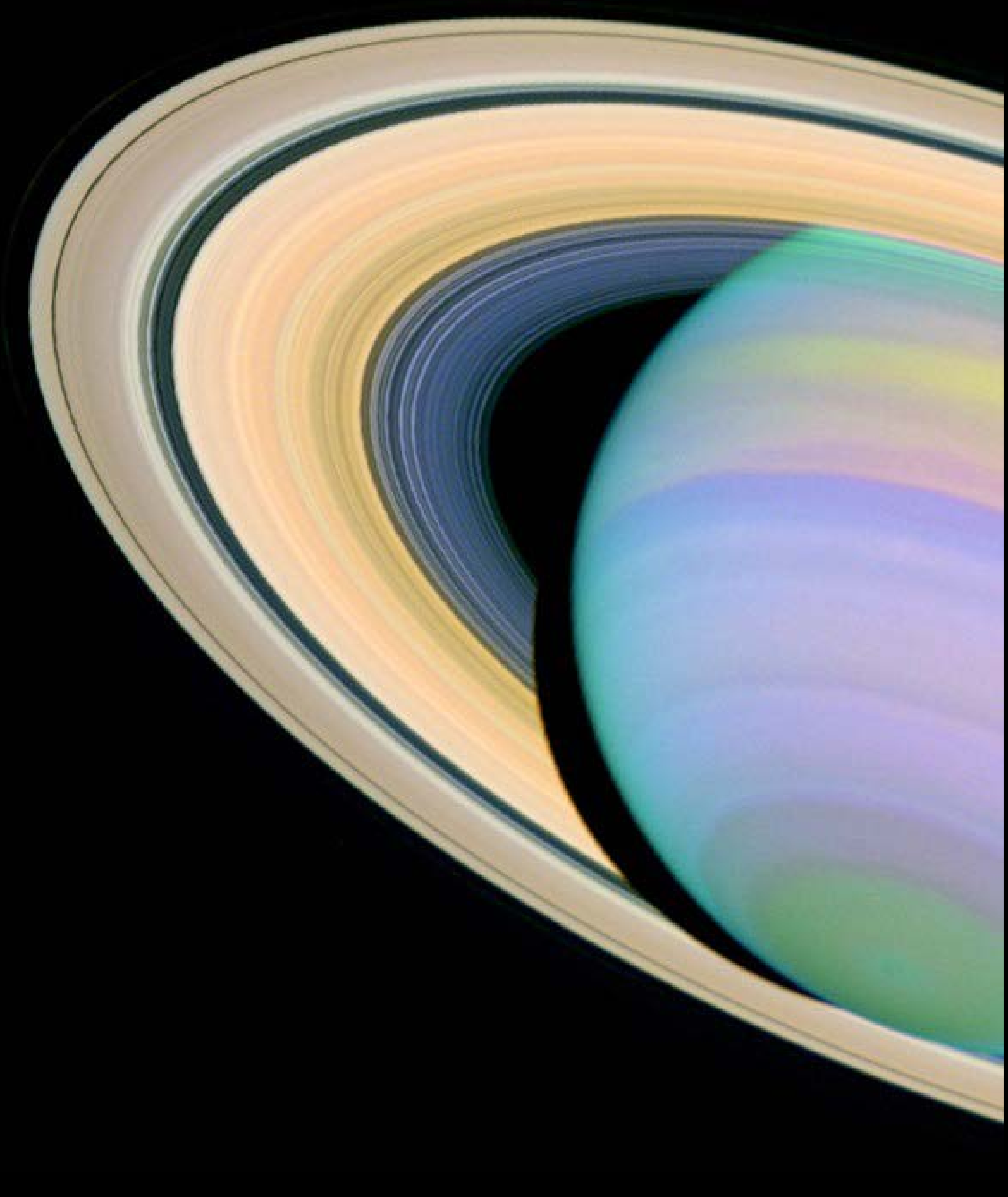


Since its launch in 1990, NASA's *Hubble Space Telescope* has made more than one million observations, amassed a huge archive of scientific findings, and had a profound effect on all areas of observational astronomy. *Hubble* has addressed fundamental cosmic questions and explored far beyond the most ambitious plans of its builders. It has discovered that galaxies evolve from smaller structures, found that supermassive black holes are common at the centers of galaxies, verified that the universe's expansion is accelerating, probed the birthplaces of stars inside colorful nebulas, analyzed the atmospheres of extrasolar planets, and supported interplanetary missions. The rate of discovery with *Hubble* is simply unparalleled for any telescope in the history of astronomy.

Hubble observes the universe from Earth orbit, just outside our planet's atmosphere.

As NASA's first Great Observatory and the first major optical telescope in space, *Hubble* ushered in a new era of precision astronomy. The heart of the telescope is its 94.5-inch-diameter primary mirror. It is the smoothest optical mirror ever polished, with no deviations greater than one-millionth of an inch.

Operating outside Earth's turbulent atmosphere, free from the blurring and filtering effects of that atmosphere, *Hubble* can resolve astronomical objects ten to twenty times better than typically possible with large ground-based telescopes. It also can observe those objects across a range of the electromagnetic spectrum, from ultraviolet light through visible and to near-infrared wavelengths.

Hubble can detect objects as faint as 31st magnitude, which is about 10 billion times fainter than the human eye can see. The telescope can see faint objects near bright objects—an important requirement for studying the regions around stars and close to the glowing nuclei of active galaxies. Astronomers have used *Hubble*'s sharp vision to probe the limits of the visible universe, uncovering never-before-seen objects that existed not long after the birth of the universe in the Big Bang.

Hubble's view is optically stable, meaning the quality of its observing conditions never changes from day to day or even orbit to orbit. *Hubble* can revisit celestial targets with the same acuity and image quality over and over again. This is crucial for precision observations in which astronomers try to detect small changes in the light, motion, or other behavior of a celestial object.

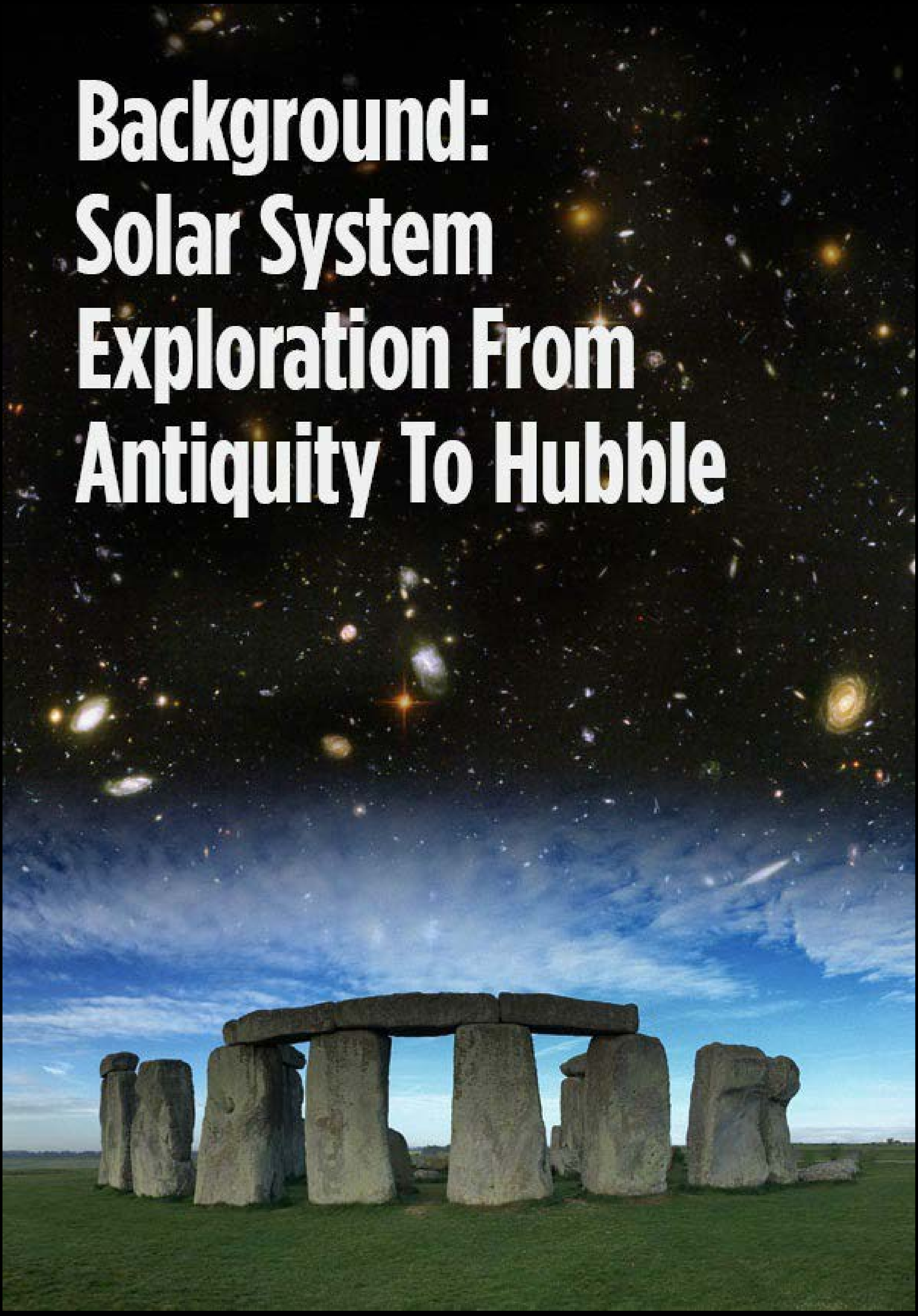
Hubble is more technologically advanced now than it was when launched, thanks to the maintenance and upgrades provided by five space shuttle servicing missions between 1993 and 2009. *Hubble* is expected to continue operating beyond 2020.

Astronauts John Grunsfeld and Andrew Feustel install a new Fine Guidance Sensor on *Hubble* during the last servicing mission in May 2009.

This e-book is the first in a series called *Hubble Focus*. Each book will present some of *Hubble*'s more recent and important observations within a particular topic. The subjects will span from our nearby solar system out to the horizon of *Hubble*'s observable universe.

This book, *Hubble Focus: Our Amazing Solar System*, highlights *Hubble*'s exciting recent discoveries about dynamic planetary atmospheres, minor planets, moons, comets, and asteroids. *Hubble*'s recent contributions build upon the rich history of solar system exploration by flyby spacecraft, orbiters, landers, and rovers to help address some of humanity's fundamental questions about our place in the solar system and in the universe.

Background: Solar System Exploration From Antiquity To Hubble



Long before recorded history, the rhythm of the heavens beckoned early sky watchers. The seasonal changes of the stars helped guide planting and harvesting seasons in early agriculture. Some people interpreted celestial shifts and cycles as signs of divine influence on Earth. Central to making astrological predictions were observations of five starlike objects that moved against the background stellar tapestry. They were called the “wanderers,” or planets. The planets were associated with gods. The names we use today are from Roman mythology.

Planets were logically among the first targets Italian scientist Galileo Galilei observed with the newly invented telescope in the early 1600s. Almost overnight the planets became other worlds. Venus had phases like the moon, Saturn had “appendages” (later resolved as rings), and Jupiter had its own system of satellites that circled the planet like celestial clockwork.

This video, using *Hubble* images recorded on January 24, 2015, shows three of Jupiter’s large moons casting shadows on the giant planet.

The development of larger telescopes led to the discovery of Uranus in the late 1700s and Neptune in the mid-1800s. The solar system’s inventory got more complicated with the discovery of “minor planets” at the beginning of the 1800s. Astronomers quickly recognized that these objects resided between Mars and Jupiter and were a fraction the size of Earth. By 1850, astronomers decided to demote the minor planets to “asteroids” (a Greek term for “starlike”), and the major planet count was reduced to eight.

Increasingly larger telescopes in the 1800s revealed even more details about the planets. Jupiter had an enormous, red-colored storm. Venus was cloaked in eternal cloud cover. Mars had polar caps that grew and shrank with seasonal changes, fueling speculation that the Red Planet might be inhabited.

At about the same time, astronomers largely turned their attention away from the planets and set their gaze farther outward. In the late 1800s, the advent of photography and spectroscopy (the science of dividing light into its component colors, as with a prism) allowed for stars and galaxies to be extensively studied and cataloged. Stellar astrophysics and cosmology dominated astronomy for most of the next century. However, planetary astronomy got a huge and unexpected boost in the 1950s.

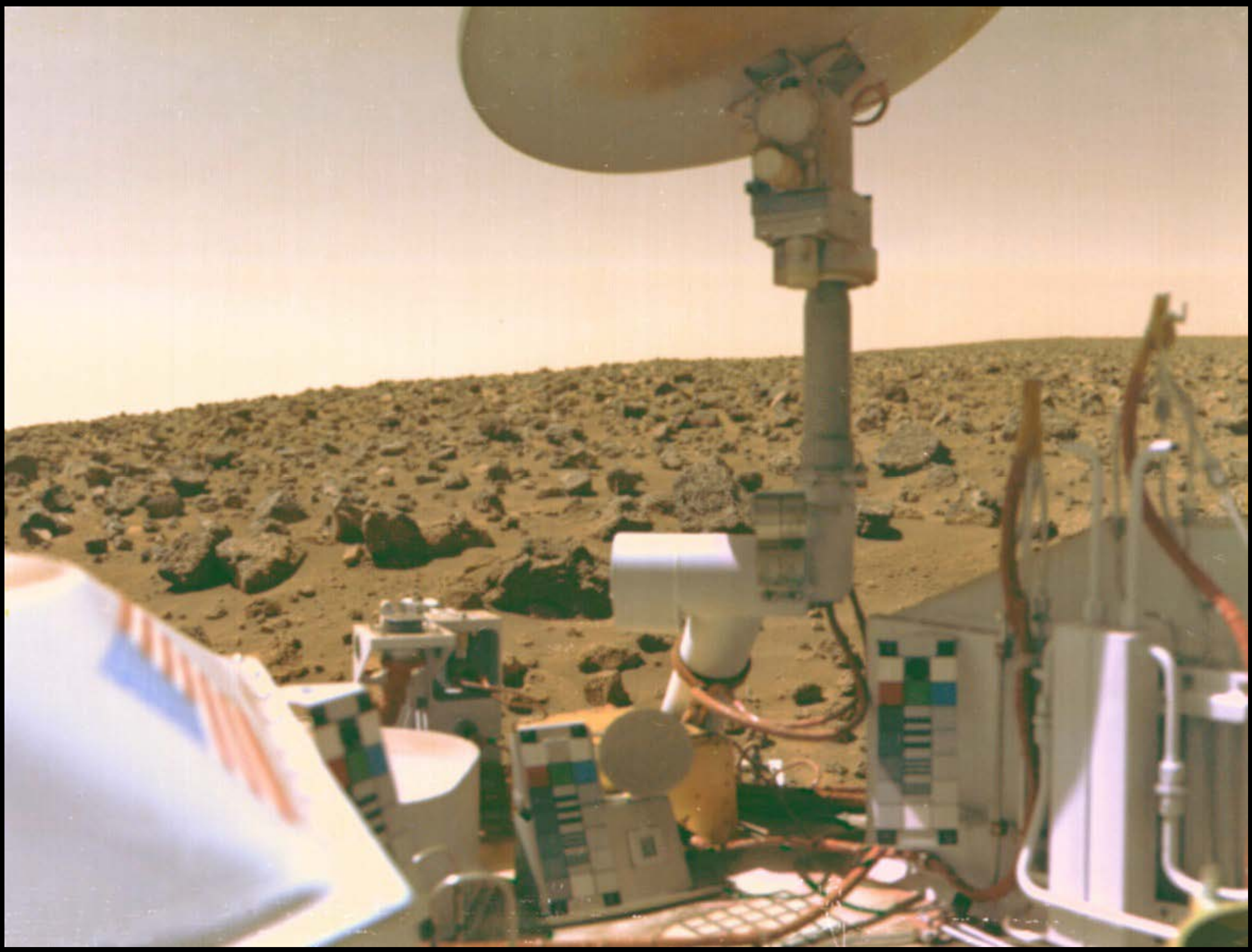
On October 4, 1957, the Soviet Union launched the first artificial satellite into orbit around Earth. The Soviet's technological triumph sent a seismic shockwave across American culture and education. The launch of the basketball-sized Sputnik propelled the world's two superpowers into the Space Race.

In 1958 the National Aeronautics and Space Administration (NASA) was created, and one of its major charters was to send probes to the planets. NASA's exploration strategy was straightforward: First send vehicles to fly by the planets and transmit snapshots back to Earth, then follow up with orbiters to photomap the planets, and where feasible, put down spidery landers onto solid surfaces. This was a natural technological driver for solving the mysteries of the compositions, structures, origins, and evolution of the planets.

In 1962, the *Mariner 2* spacecraft made the first-ever flyby of another planet, Venus, swooping within 10,000 miles of the planet's surface and kicking off a five-decade-long initial reconnaissance of the solar system. Just two years later, the *Mariner 4* spacecraft made the first flyby of the planet Mars. The probe's cameras, much more primitive than what is on a modern smartphone, sent back fleeting glimpses of a bland, pockmarked world. The Red Planet looked dead.

The *Mariner* missions were the first U.S. spacecraft to journey to other planets, specifically Venus and Mars.

In the 1970s, Mars was intensively studied by two *Viking* orbiters and a pair of nuclear-powered landers. The close-up photos revealed that Mars was much more interesting than anyone had imagined. Bird's-eye views taken from Martian orbit revealed a complex geologic history with immense volcanoes, a great rift valley (suggesting a brief attempt at plate tectonics), and evidence for rivers, lakes, and even an ocean in the remote past. Experiments also searched for evidence of life but produced inconclusive results, leaving that question open to this day.



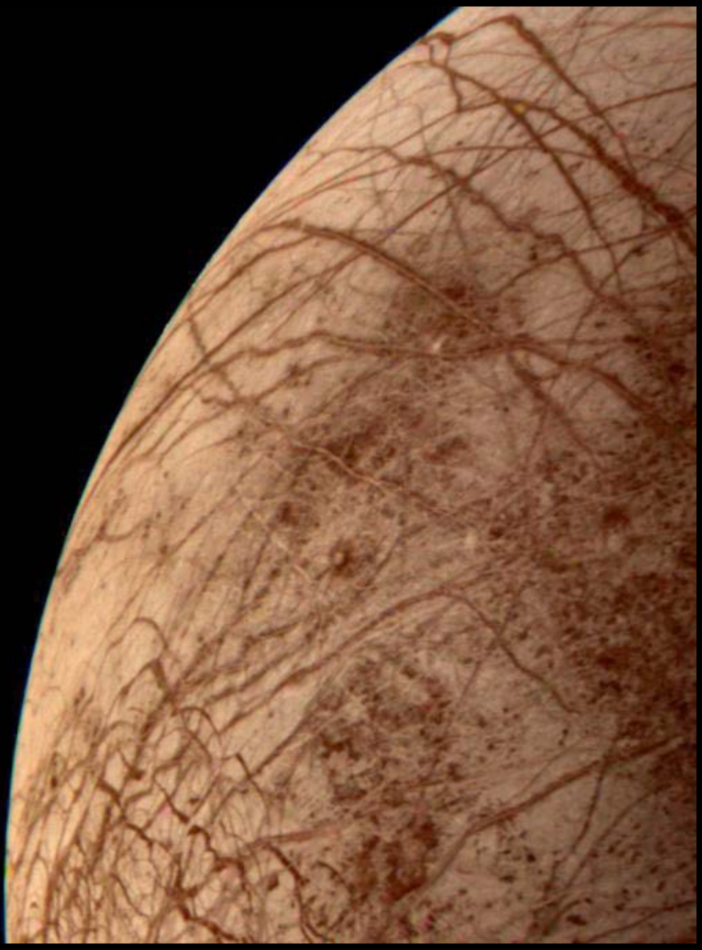
The *Viking* project was the first U.S. mission to land safely on Mars and return images from the planet's surface.

This mosaic of Mars is a compilation of images captured by the *Viking 1* orbiter. The center of the scene shows the entire Valles Marineris canyon system, over 2,500 miles long and up to 6 miles deep.

With the Red Planet completely photomapped and even probed for exobiology, the focus shifted to visiting the four major outer planets. A pair of *Voyager* probes flew by Jupiter in 1979.

This illustration depicts one of the two *Voyager* probes, which took advantage of a rare geometric arrangement of the outer planets in the late 1970s and the 1980s that allowed the spacecraft to conduct a four-planet tour with a minimum of propellant and trip time.

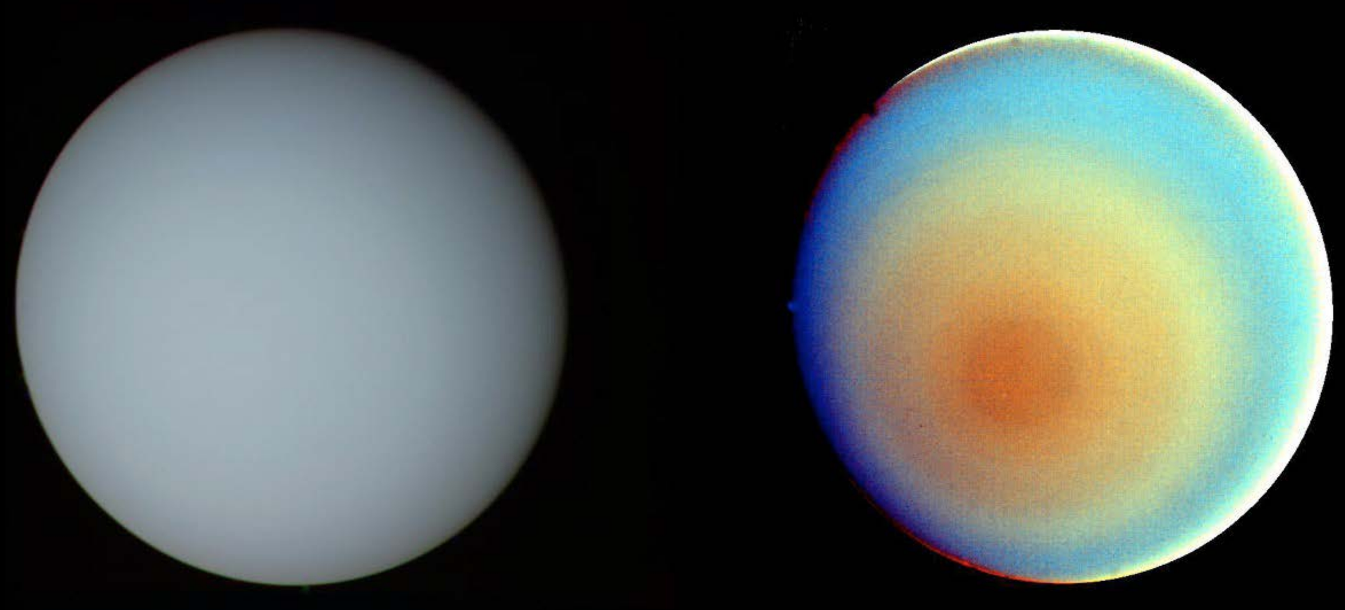
Among the biggest surprises was the complexity and diversity of Jupiter's four largest satellites. Io had active volcanism. Callisto had an ancient, heavily cratered surface. Ganymede was a patchwork of dark and light regions of varying ages. Europa's billiard-ball-smooth surface looked cracked, like an eggshell, which helped lead scientists to speculate that Europa might have a subsurface ocean.



Voyager 2 acquired this color image of the Jovian moon Europa during the spacecraft's close encounter on July 9, 1979. The complex array of streaks indicates that Europa's icy crust has been fractured and filled by material from the moon's interior.

During their flybys of Saturn, *Voyager 1* and *2* found previously unseen moons orbiting the planet and confirmed that Saturn's moons are icy. The flybys revealed that Titan has a thick, nitrogen-dominated atmosphere, which hides the moon's surface from visible-light cameras. *Voyager* also determined that Saturn radiates more heat than it receives from the Sun.

Though *Voyager 1* completed its mission after flying by Saturn, *Voyager 2* continued on a long trek to Uranus and then Neptune. Scientists discovered that Uranus has a tilted magnetic field, and during *Voyager* 2's flyby of Neptune observed giant storms on what was thought to be a quiescent planet. They also found geysers of nitrogen gas and dust on Neptune's frozen moon Triton.



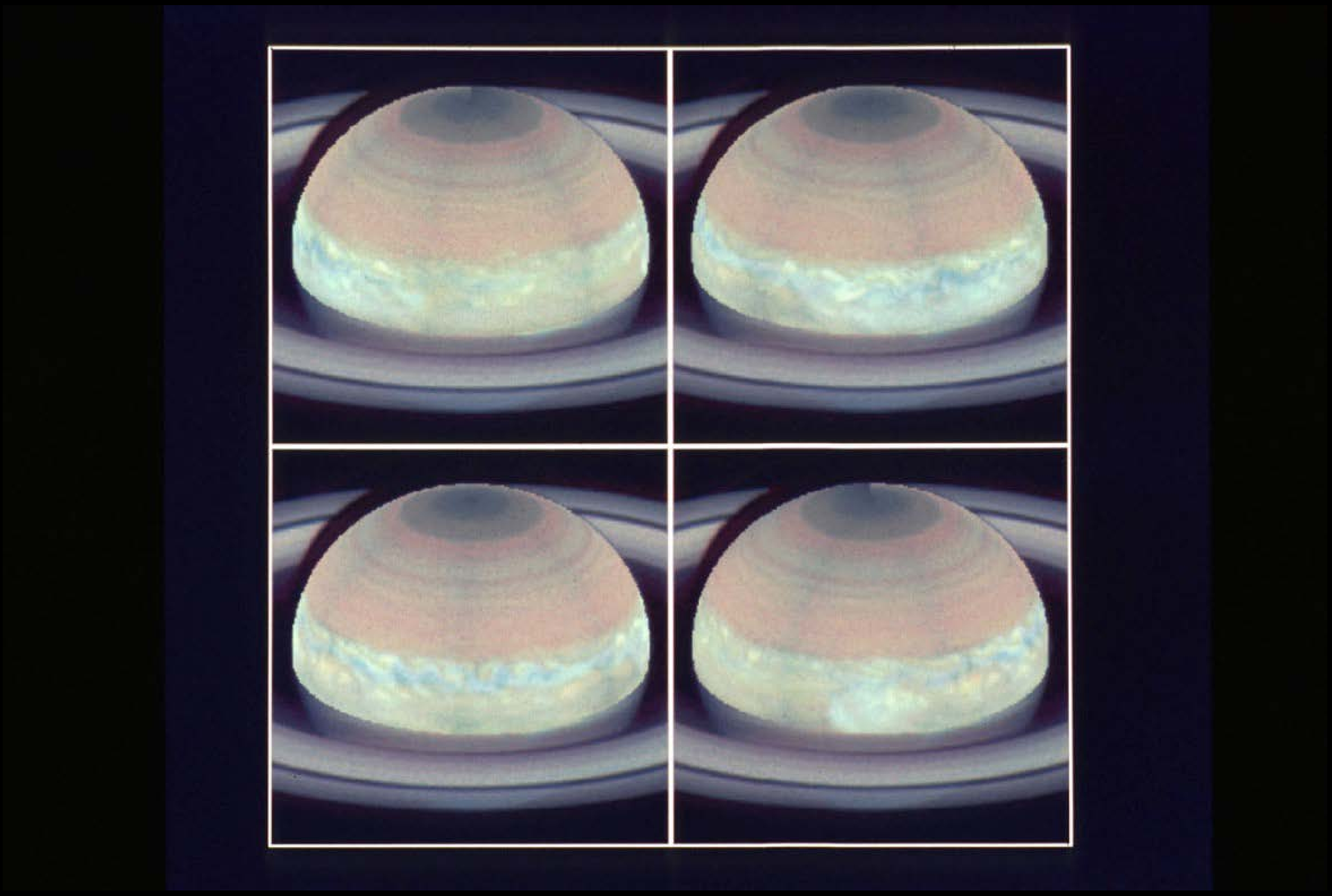
Voyager 2 captured these true-color (left) and false-color (right) views of Uranus on January 17, 1986, revealing subtle details in the planet's atmosphere.

Voyager 2 captured this image of Triton's south polar terrain. About 50 dark plumes mark what might be geysers.

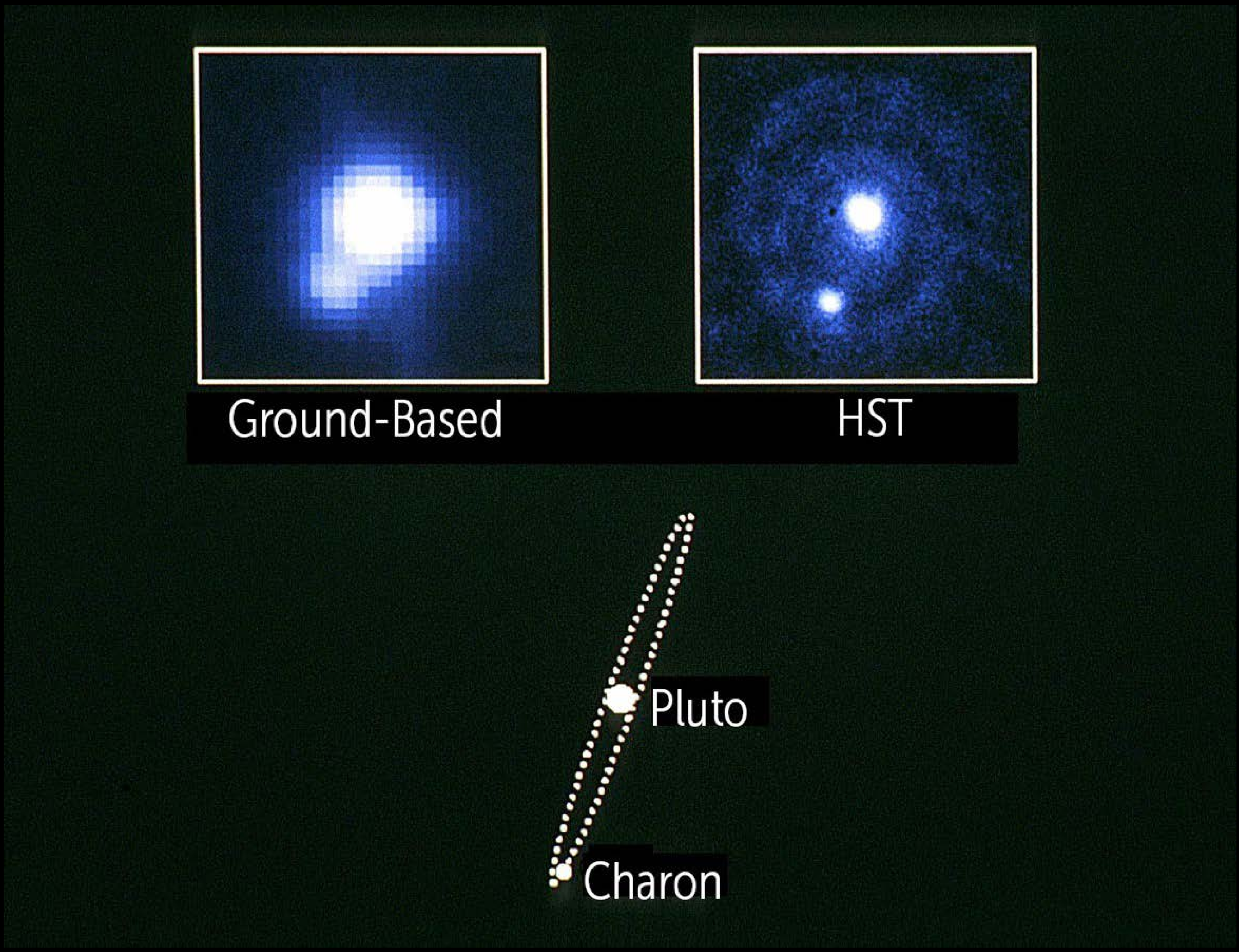
As the *Voyagers* were sprinting across the outer solar system, the *Hubble Space Telescope* was under construction. The telescope was launched just a year after *Voyager 2* flew past Neptune. With its unprecedented clarity and sensitivity across a broad swath of the electromagnetic spectrum, *Hubble* was designed to look into the farthest regions of the universe, but its design also included the ability to track planets like a sports photographer would track a fleet-footed athlete.

The timing was perfect because NASA's planetary missions revealed there was significant follow-up research for *Hubble* to do. *Hubble* could obtain high-resolution images in colors from the ultraviolet (bluer than the eye can see) to the near-infrared (redder than the eye can see). Though not as crisp as spacecraft close-ups, the observations could span years and be compared and contrasted to the flyby photos.

Even before the spherical aberration in *Hubble*'s primary mirror was corrected, scientists used the space telescope to make observations of a new storm on Saturn. *Hubble* also provided the first photograph that clearly resolved Pluto from its binary companion, Charon, which was discovered only 12 years earlier as a moving "bulge" on Pluto in ground-based images.



Hubble captured images of a planet-encircling storm system on Saturn in November 1990.



Soon after its launch in 1990, *Hubble* obtained the first picture that clearly separated Pluto and its largest companion, Charon. (The blurry rings in the *Hubble* image are artificial effects caused by the primary mirror's spherical aberration, which was corrected in 1993.) The ground-based image was taken by the Canada-France-Hawaii Telescope.

Besides comparing contemporary views of the planets to those of previous space missions, *Hubble* has supported many of NASA's planetary missions in the 1990s and beyond, including the *Galileo* and *Juno* orbiters to Jupiter, the *Cassini* orbiter to Saturn, the *New Horizons* spacecraft to the Pluto system, and the *Dawn* mission to Vesta and Ceres in the asteroid belt. *Hubble* also monitored the weather on Mars as a series of NASA orbiters and landers returned to the Red Planet after a two-decade hiatus.

Hubble was the only space resource that could distinctly watch a planet before, during, and after a spacecraft flyby. It also allowed scientists to take that flyby data and put it into a broader context.

Just six months after the space telescope's optical clarity was restored during *Hubble*'s first servicing mission, *Hubble* was in the right place at the right time to photograph a never-before-seen event: The collision of a comet with the planet Jupiter. With images ten times sharper than those available from ground-based telescopes of the time, *Hubble* chronicled the sequential string of Comet Shoemaker–Levy 9 fragments as they impacted the gas-giant world—each impact unleashing more energy than that of the United States' nuclear arsenal at the peak of the Cold War.

This *Hubble* image of a "bruised" Jupiter shows several impact sites from Comet Shoemaker–Levy 9, which had broken up as it approached Jupiter.

To the delight and amazement of astronomers, *Hubble* discovered a number of minor bodies undetected by other spacecraft or ground observatories, such as chaotic moons orbiting distant worlds and even a few moons that the *Voyager* missions had missed. *Hubble* also made remarkable discoveries in the asteroid belt, where collisions among these primitive bodies continue to this day.

Hubble came along at just the right time to bolster NASA's ambitious planetary program. Working symbiotically with other planetary missions and observatories, *Hubble* has helped unveil a much more intriguing and dynamic solar system than ever imagined before.

Chapter 1: Weather on the Planets

If Earth were the size of an apple, its atmosphere would be no thicker than the apple's skin. Yet Earth's atmosphere has profound effects on our everyday lives. It's a churning hydrodynamic engine fueled by solar energy, driving our weather. Extreme weather, such as droughts, heat waves, and hurricanes, can disrupt or threaten the lives of millions. However, predicting weather precisely remains a challenge.

Fortunately, Earth is not alone in space. Planetary scientists look to weather on other planets to develop a holistic picture of meteorology, gaining context and insight into weather on our own planet. How would Earth's weather be different if we had no oceans? Take a look at arid Mars. What if Earth rotated much slower? Examine Venus. What if Earth had no solid surface? Consider the outer gas giant planets: Jupiter, Saturn, Uranus, and Neptune.

As on Earth, weather is ever-changing in the solar system at large. Imagine space aliens trying to understand the dynamics of Earth's atmosphere by analyzing a few snapshots from an interstellar probe. Scientists face the same challenge when perusing photos from planetary flybys of other planets—especially photos of the outer planets that have deep atmospheres and no solid surfaces. Confounding this picture is the fact that most planets also go through seasonal changes, driven not only by the planet's axial tilt, but in some cases, internal heating.

Hubble's longevity, combined with its high resolution, has given astronomers an unprecedented opportunity to monitor planetary atmospheric changes in detail for nearly three decades. Ongoing observations of Mars and those from the long-term Outer Planet Atmospheres Legacy (OPAL) program, which is using *Hubble* to create global maps of the outer planets every year, are continuing to build that trove of information about planetary weather.

Mars

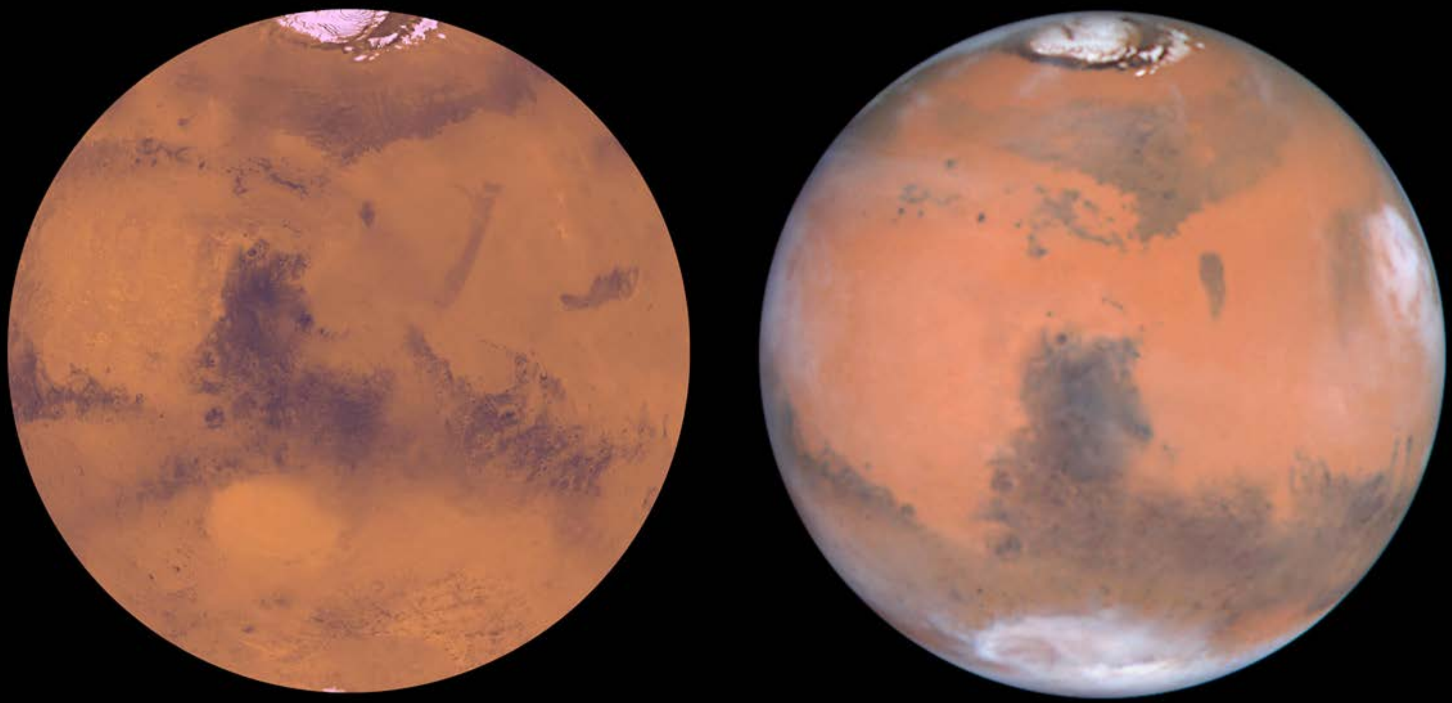
At an average distance of 142 million miles from the Sun, Mars takes 687 days to complete one orbit, making its seasons about twice as long as Earth's. The axis of Mars is tilted about 25 degrees, similar to Earth's tilt. But the planet's orbit is more elliptical than Earth's, so its seasons are more extreme.

This *Hubble* image was taken on May 12, 2016, when Mars was only 50 million miles from Earth. Bright, frosty polar caps and clouds are signs that Mars has dynamic seasons.

The atmosphere on Mars is extremely thin, so winds are anemic. (Yet Martian winds can reach high speeds and can still sculpt dunes and stir up dust devils.) The average atmospheric pressure on Mars is roughly 135 times lower than on Earth, or equal to Earth's atmospheric pressure at an altitude of 20 miles (just 7.5 millibars on Mars as compared to 1,013 millibars on Earth's surface). The Martian atmosphere is 95 percent carbon dioxide.

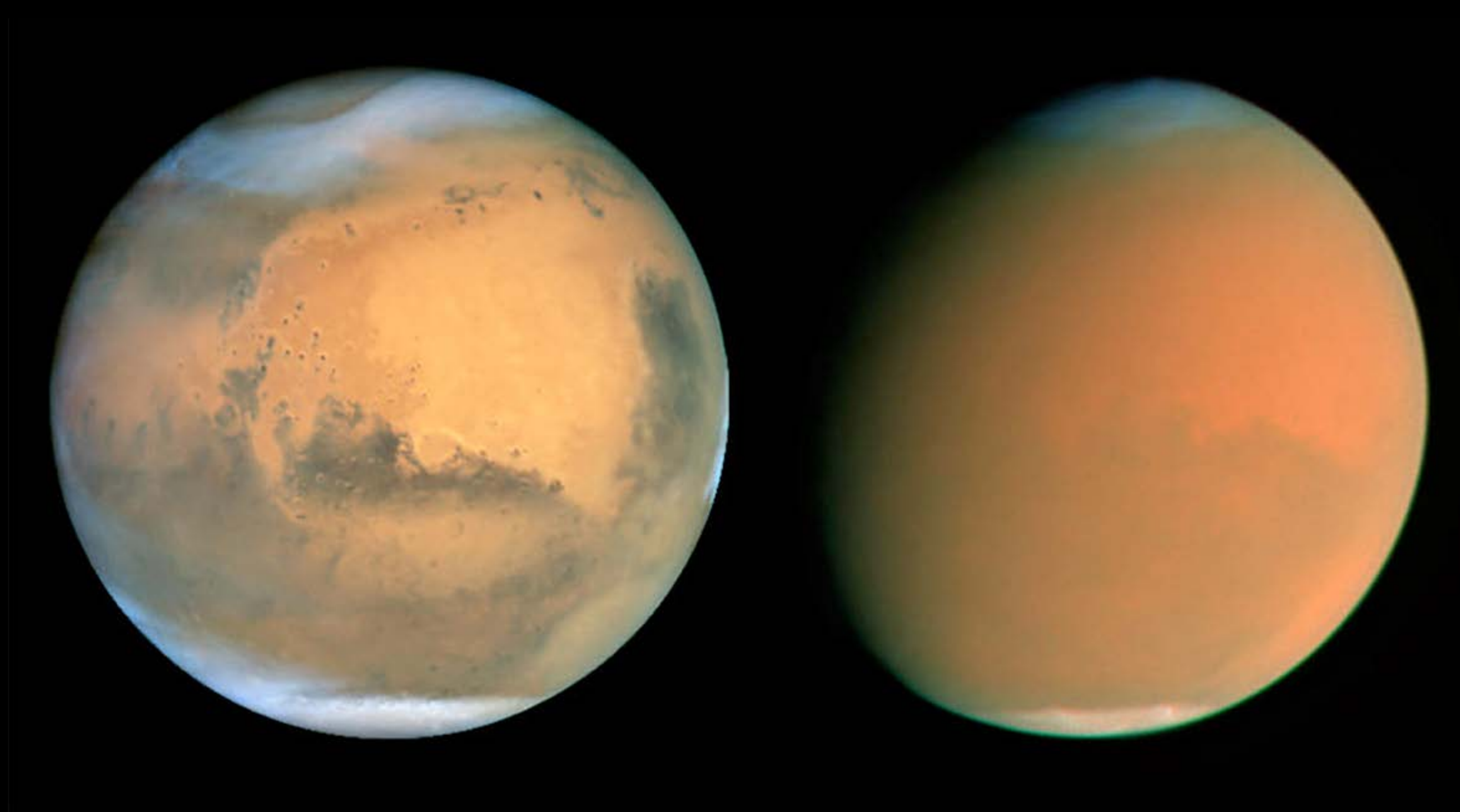
Mars is a cold planet with an average temperature around –80˚F. Summertime highs at the equator peak at 70˚F but can plummet to around –100˚F overnight. Even though there are only trace amounts of water vapor, clouds do form at high altitude around the Red Planet's extinct volcanoes. Morning haze and fog form as well.

When comparing *Hubble* observations of Mars with close-up photos taken in the 1970s by NASA's twin *Viking* orbiters, it becomes evident that the Martian surface is dynamic and ever changing. Some regions that were dark in *Viking* images are bright red in *Hubble*'s views; some areas that were bright red are now dark. Winds move sand and dust from region to region, often in spectacular dust storms. Over long timescales many of the larger bright and dark markings remain stable, but smaller details come and go as they are covered and then uncovered by sand and dust. While probes and rovers continue to explore the Martian environment on local scales, *Hubble* has the ability to monitor the activity on the planet as a whole.



These images, showing the Syrtis Major region of Mars, were taken two decades apart by *Viking 1* (left) and by *Hubble* (right). The images show changes in some of the planet's bright and dark markings.

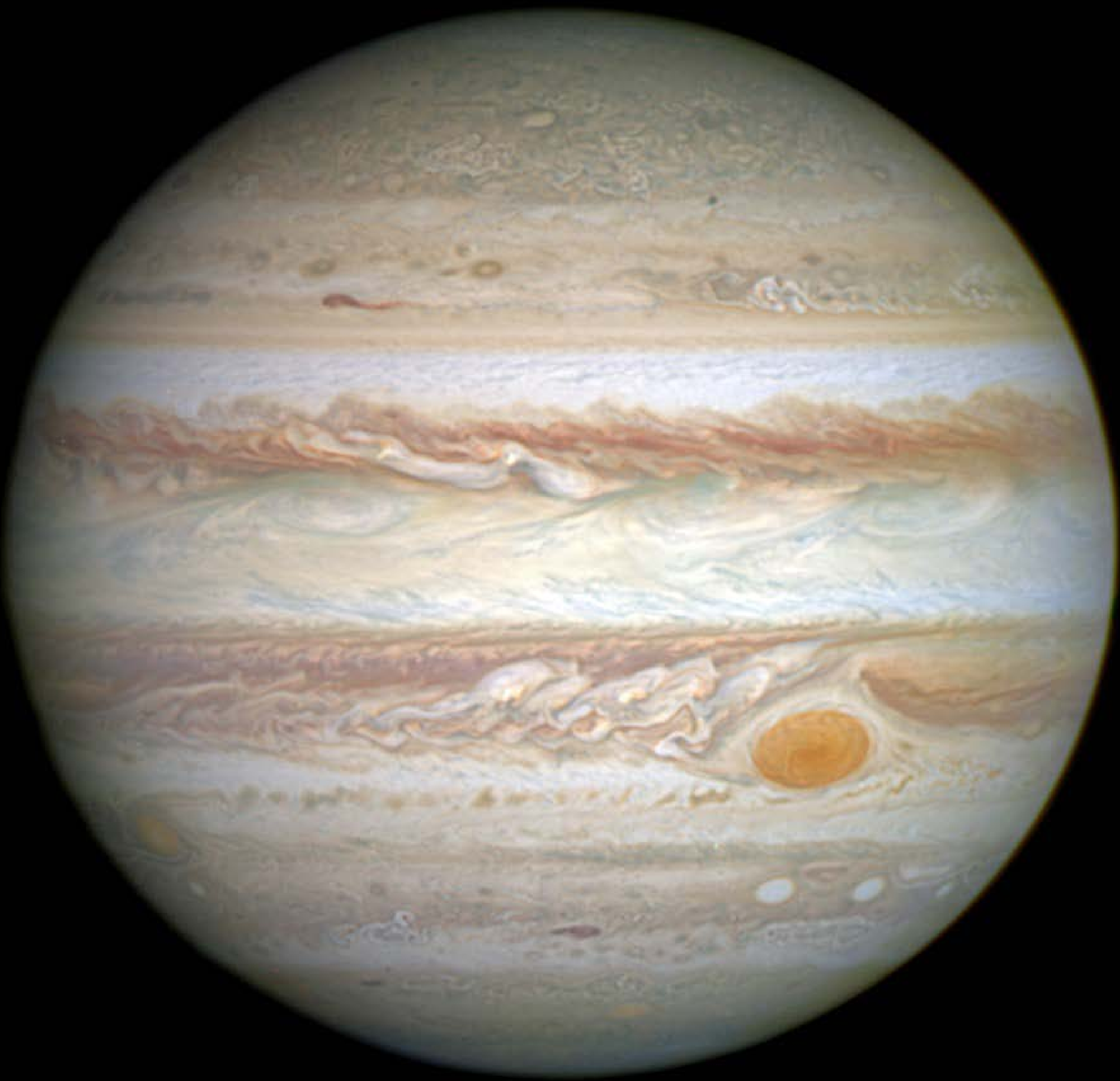
Global dust storms on Mars typically happen when it is summer in the Martian southern hemisphere. In 2001, *Hubble* tracked the growth of one such storm after it was born within the giant asteroid impact crater, the Hellas basin. *Hubble* watched as, in just two months, the storm raged across the planet, obscuring all surface features. During such storms, the fine airborne dust blocks a significant amount of sunlight from reaching the Martian surface. Because the airborne dust is absorbing this sunlight, it heats the upper atmosphere.



Two dramatically different faces of Mars appear in these *Hubble* comparison images, which show the development of a global dust storm. In June 2001 (left image), the seeds of the dust storm were brewing in the giant Hellas Basin (oval at lower right) and at the northern polar cap. By early September 2001 (right image), the storm engulfed the planet, obscuring all surface features.

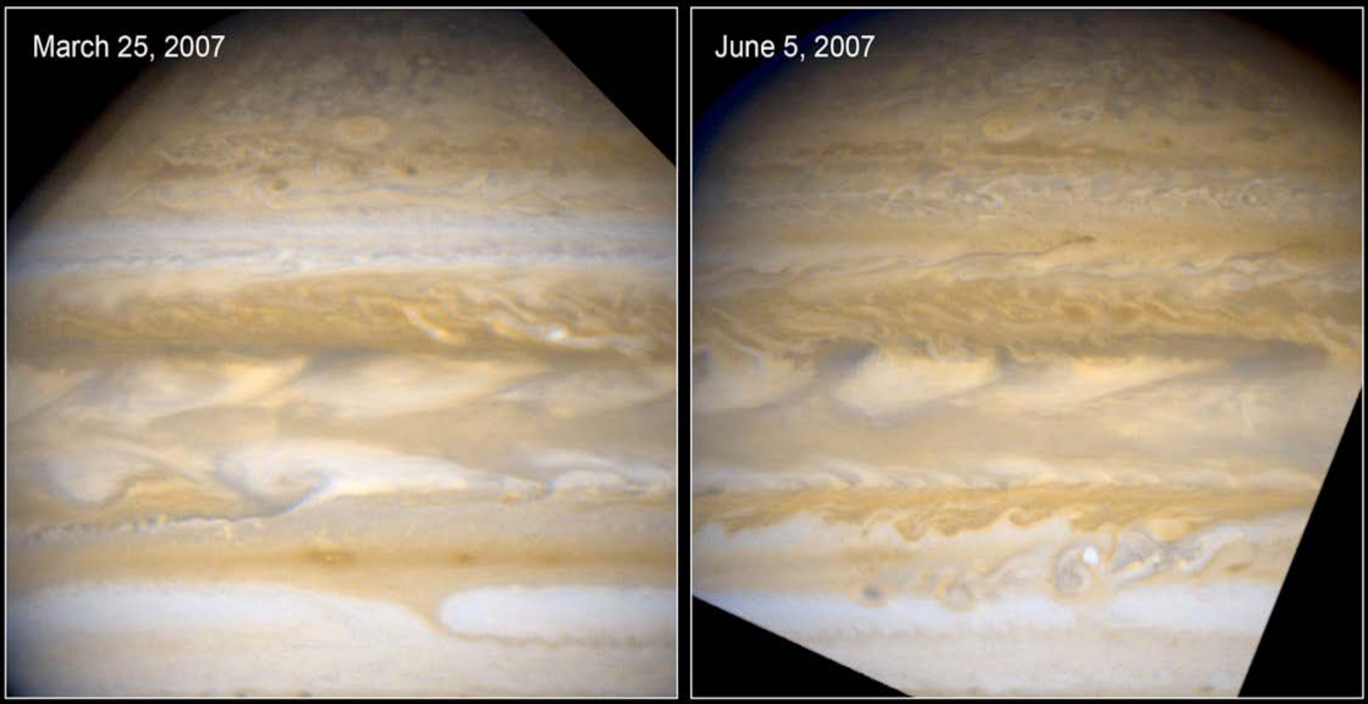
Jupiter

Jupiter is wrapped in clouds of ammonia crystals that form a striped appearance with yellow, brown, and white hues. The clouds are arranged into bands of different latitudes, known as tropical regions. These bands are produced by air flowing in different directions at various latitudes. Lighter colored areas, called zones, are high-altitude regions where the air rises. Darker, low-altitude regions where air falls are called belts. Constantly stormy weather occurs where these opposing east-to-west and west-to-east flows interact and cause turbulence.



Hubble captured this image of Jupiter in 2014. Distinctive Jovian features such as belts, zones, and storms—including the Great Red Spot—are clearly visible in this picture.

With a meager axial tilt of just 3 degrees, Jupiter has practically no seasonal changes. Instead, the planet's weather is driven by a combination of heat bubbling up from its interior —which may be several times hotter than the Sun's surface—and a feeble amount of radiation from the Sun (which is just 1/25th the brightness as seen from Earth). Still, *Hubble* has uncovered dynamic variations and tracked ever-changing cloud patterns on the giant planet.



These *Hubble* images reveal a rapid transformation in the shape and color of Jupiter's clouds near the equator. The image on the left was taken on March 25, 2007, and the one on the right is from June 5, 2007.

Hubble has studied in detail how Jupiter's turbulent clouds are constantly changing as they encounter atmospheric disturbances while sweeping around the planet at hundreds of miles per hour. The observations capture a broad range of features, including winds, clouds, storms, and changes in atmospheric chemistry. *Hubble*'s repeated observations of Jupiter will help current and future scientists see how the clouds change over many years.

The movement of Jupiter's clouds can be seen when comparing these two global maps, in which Jupiter's cloud bands are laid out as a flat projection. Scientists produced these maps of Jupiter using *Hubble* observations for the Outer Planet Atmospheres Legacy program taken on January 19, 2015, from 2:00 UT to 12:30 UT and from 15:00 UT to 23:40 UT.

In Jupiter's North Equatorial Belt, *Hubble* imaged an elusive wave that had been spotted on the planet only once before, decades earlier, by *Voyager 2*. In *Voyager*'s images, the wave is barely visible, and nothing like it was seen again until the recent *Hubble* observations. In the *Hubble* images above, the wave appears as nearly vertical lines passing through the top of the dark, central cloud belt. The wave was found traveling in a region dotted with cyclones and anticyclones. Similar waves—called baroclinic waves—sometimes appear in Earth's atmosphere where cyclones are forming. The wave may originate in a clear layer beneath the clouds, only becoming visible when it propagates up into the cloud deck.

The Great Red Spot

The Great Red Spot on Jupiter is the planet's trademark. This giant storm is located 22 degrees south of Jupiter's equator and is larger than Earth. Possibly seen since the 1600s, the storm rotates counterclockwise and has drifted several times around the planet. Much smaller storms appear as white or brown ovals. Such storms can last only a few hours or carry on for centuries.

Historic observations from the late 1800s gauged the Great Red Spot to be as big as 25,500 miles on its long axis. The NASA *Voyager 1* and *Voyager 2* flybys of Jupiter in 1979 measured its width at 14,500 miles across.

Images from *Hubble*, taken over two decades, confirm that the spot continues to shrink and is becoming more circular than oval. The long axis of this characteristic storm was about 150 miles shorter in 2015 than it was in 2014. The storm had been shrinking at an even faster rate in recent years, but the change from 2014 to 2015 is more consistent with the long-term trend. Still, the cause behind the shrinking has yet to be fully explained.

Today, the Great Red Spot is more orange than red, and the spot's core, which typically has more intense color, is less distinct than it used to be. An unusual wispy filament is seen, spanning almost the entire width of the vortex. This filamentary streamer rotates and twists within the spot, circumnavigating the spot roughly every three days and getting distorted by winds that reach speeds of up to 500 miles per hour.

In this movie, a series of *Hubble* images shows Jupiter's Great Red Spot shrinking from 1995 to 2014. In 1995 the spot's long axis was estimated to be 13,020 miles across; in 2009, it was measured at 11,130 miles across; and in 2014, it was approximately 10,250 miles across.

Jupiter's Magnetosphere

Jupiter has the largest and most powerful magnetic field of any planet in the solar system. Magnetic fields are invisible, but if Jupiter's could be seen by an observer on Earth, it would appear as big as the full moon.

Charged particles that get trapped in Jupiter's magnetic field are channeled toward the planet's poles, where they can cause atmospheric gases to heat up and fluoresce, producing vibrant auroras. Such auroras can be seen on Earth as well, where they are more commonly known as the Northern and Southern Lights.

Hubble made a series of far-ultraviolet observations of Jupiter's auroras in the spring of 2016. The disk of Jupiter in this video was imaged at a different time by the Outer Planet Atmospheres Legacy (OPAL) program.

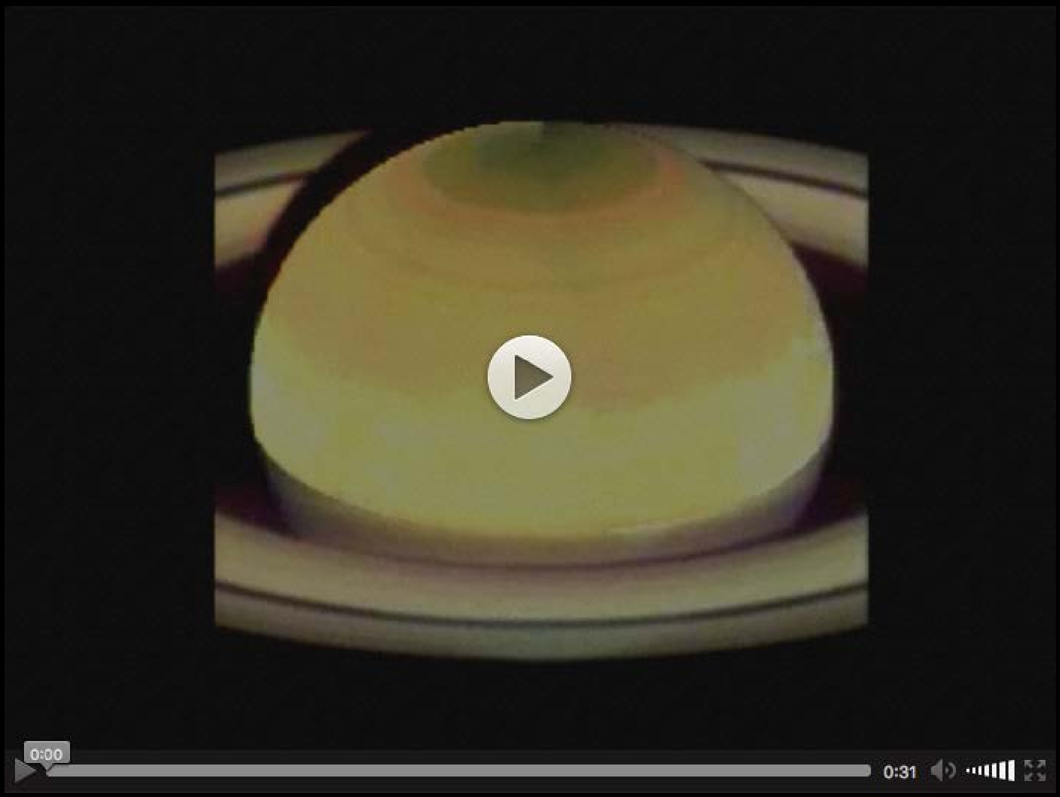
Hubble is able to capture the ultraviolet glow of Jupiter's auroras. Besides producing a vivid light show, Jupiter's auroras can help scientists determine how various components of the planet's magnetosphere respond to different conditions in the solar wind, a stream of charged particles ejected from the Sun. The auroras on Jupiter are hundreds of times more energetic than auroras on Earth, cover areas bigger than Earth, and never cease.

In 2016, a set of *Hubble* observations was perfectly timed as NASA's *Juno* spacecraft entered into orbit around Jupiter. As *Hubble* measured the auroras on Jupiter, *Juno* measured the properties of the solar wind itself. This was an ideal collaboration between a telescope and a space probe. Using this series of far-ultraviolet images from *Hubble*'s Space Telescope Imaging Spectrograph, it was possible for scientists to create videos that demonstrate the movement of the auroras.

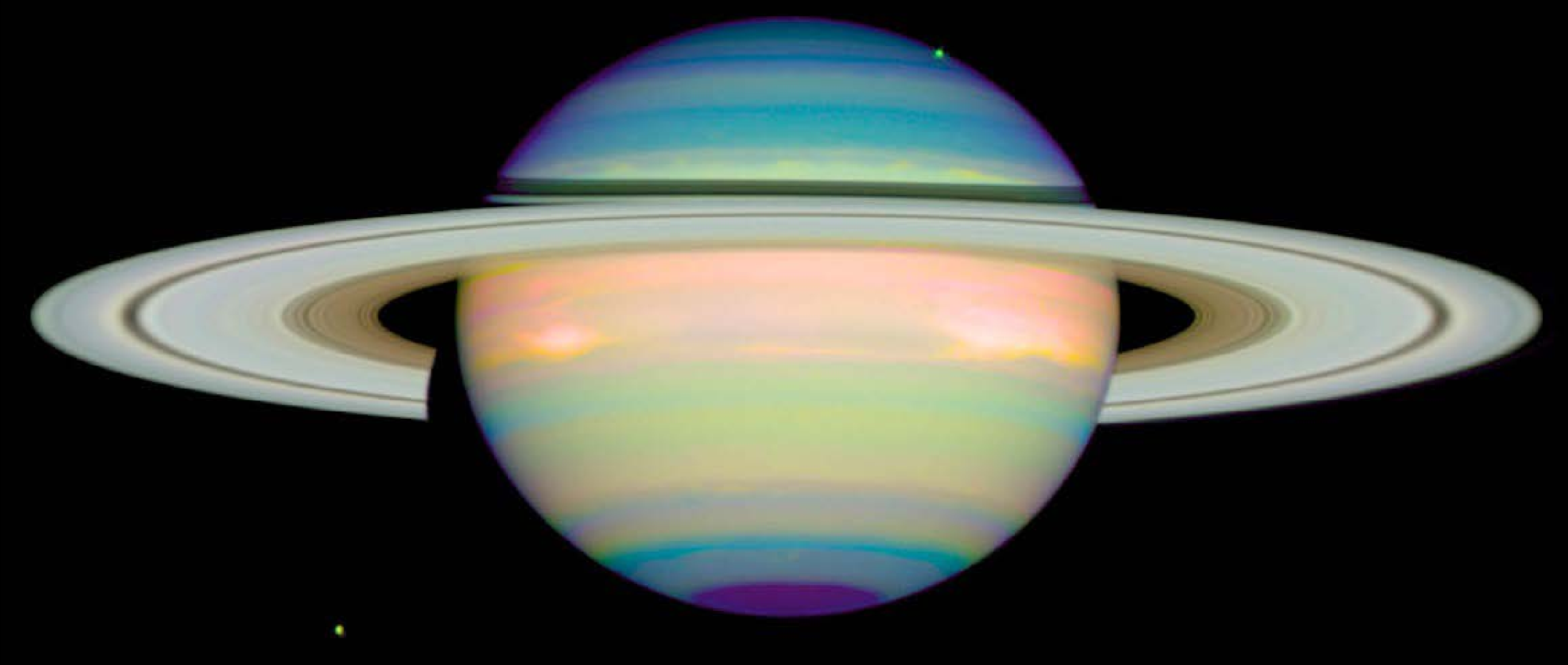
Saturn

Like Jupiter, Saturn has banded cloud patterns and alternating wind directions at different latitudes. Saturn's colors are more subdued, though, and its bands are under a deeper layer of high-altitude methane haze. Unlike Jupiter, Saturn has an axial tilt similar to that of Earth. This means the planet experiences seasonal changes, some of which have been observed. But like Jupiter, Saturn's internal heat keeps temperatures about the same year-round and planet-wide.

A seasonal storm emerged on Saturn in September 1990 as a white spot the size of Texas. When *Hubble* imaged it a couple months later it had grown and extended completely around the planet. In some places the storm appeared as great masses of clouds, and in others as an organized turbulence.



In November 1990, *Hubble* observed a storm that wrapped all the way around Saturn. The observations provided a better understanding of wind speeds in Saturn's atmosphere, as well as the composition and altitude of the clouds.



Hubble provided high-resolution images of Saturn's deeper cloud structure by photographing the planet at near-infrared wavelengths. The blue colors in this infrared image indicate a clear atmosphere down to a main cloud layer. The shadings of blue relate to variations in the cloud particles, either in size or chemical composition. The cloud particles are believed to be ammonia ice crystals. The dark region around the south pole (bottom) is likely a big hole in the main cloud layer.

The green and yellow colors signify a haze above the main cloud layer. The haze is thin where the colors are green but thick where they are yellow. Most of the southern hemisphere is quite hazy. These layers are aligned with latitude lines because of Saturn's east-west winds.

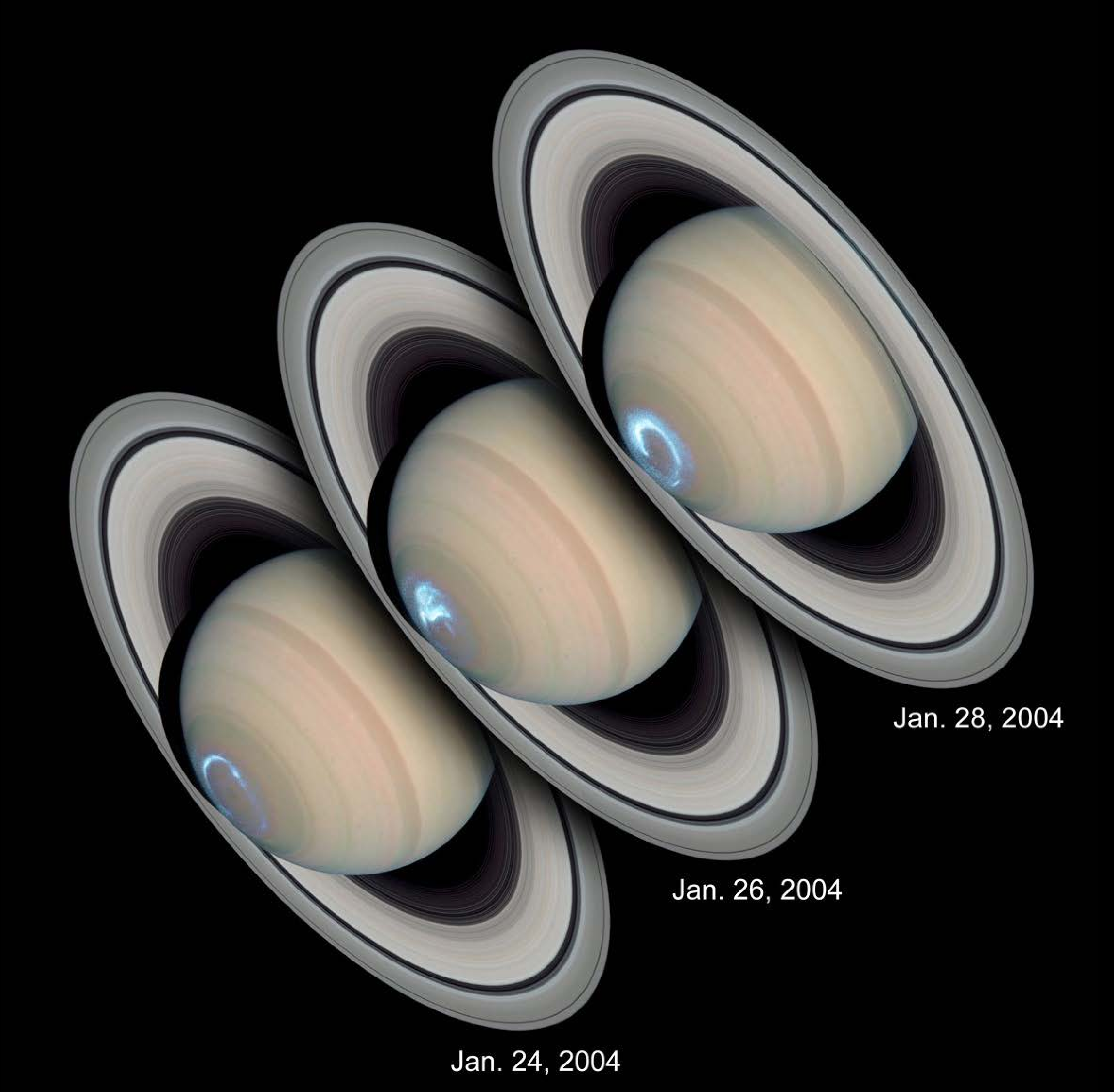
The red and orange colors depict clouds reaching high into the atmosphere. Red clouds are even higher than orange clouds. Two storms near Saturn's equator appear white. The smaller storm on the left is about as large as Earth.

Saturn's Auroras

Saturn's auroras glow in wavelengths of ultraviolet light that are absorbed by Earth's atmosphere, so they can only be observed from space.

The first investigations of Saturn's auroras came from NASA's *Pioneer 11* spacecraft, which recorded a far-ultraviolet brightening at Saturn's poles in 1979. During their Saturn flybys in the early 1980s, the *Voyager 1* and *2* spacecraft studied the auroras and mapped the planet's enormous magnetic field for the first time.

Hubble made the first detailed images of Saturn's auroras in the mid-1990s. The ultraviolet sensitivity of *Hubble*'s Space Telescope Imaging Spectrograph, installed in 1997, allowed scientists to study the workings of Saturn's magnetosphere and upper atmosphere in much greater detail.



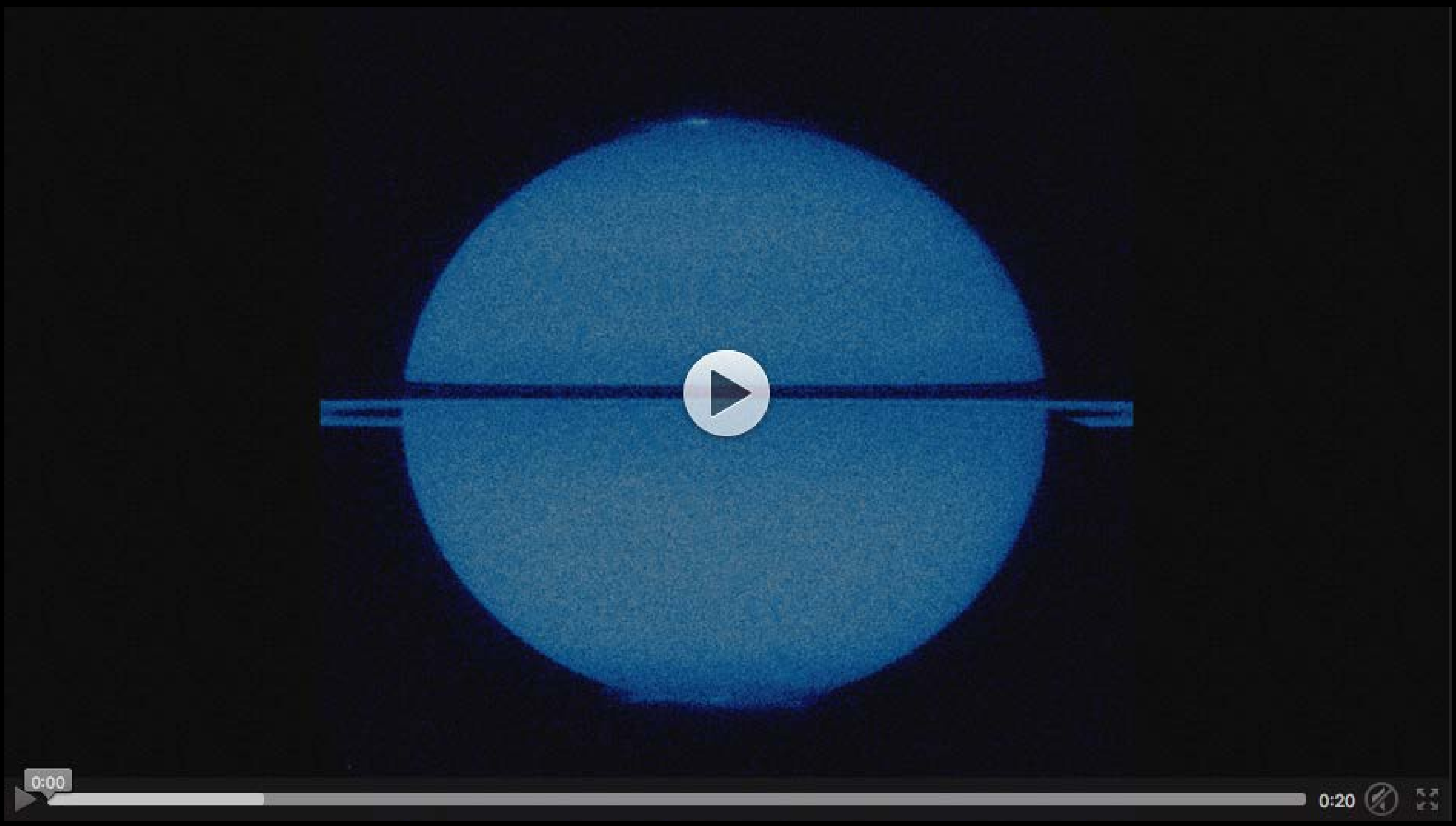
Hubble snapped a series of photographs of auroras dancing around Saturn's southern pole over several days in 2004. The images reveal the dynamic nature of Saturn's auroras, which differ from day to day.

Hubble images reveal ripples and overall patterns that evolve slowly, appearing generally fixed and independent of the planet's rotation. At the same time, the auroras show local brightening that often follows the rotation of the planet and exhibits rapid variations on timescales of minutes. These variations and regularities indicate that the auroras are primarily shaped and powered by a continual interplay between Saturn's magnetic field and the flow of charged particles from the Sun.

Hubble observations show that Saturn's auroras differ in character from day to day, moving around on some days and remaining stationary on others. But compared with Earth, where auroral storms develop in about 10 minutes and may last for a few hours, Saturn's auroral displays can last for several days.

In 2004, *Hubble* captured auroras around Saturn's south pole brightening significantly. This corresponded to the arrival of a large disturbance in the solar wind. *Hubble*'s images showed that when Saturn's auroras become brighter, and thus more powerful, the ring of light encircling the pole shrinks in diameter. *Hubble*'s observations, along with those from NASA's *Cassini* spacecraft, which was on its way to Saturn at the time, also provided clues that Saturn's auroras might be generated differently than those on Earth and Jupiter.

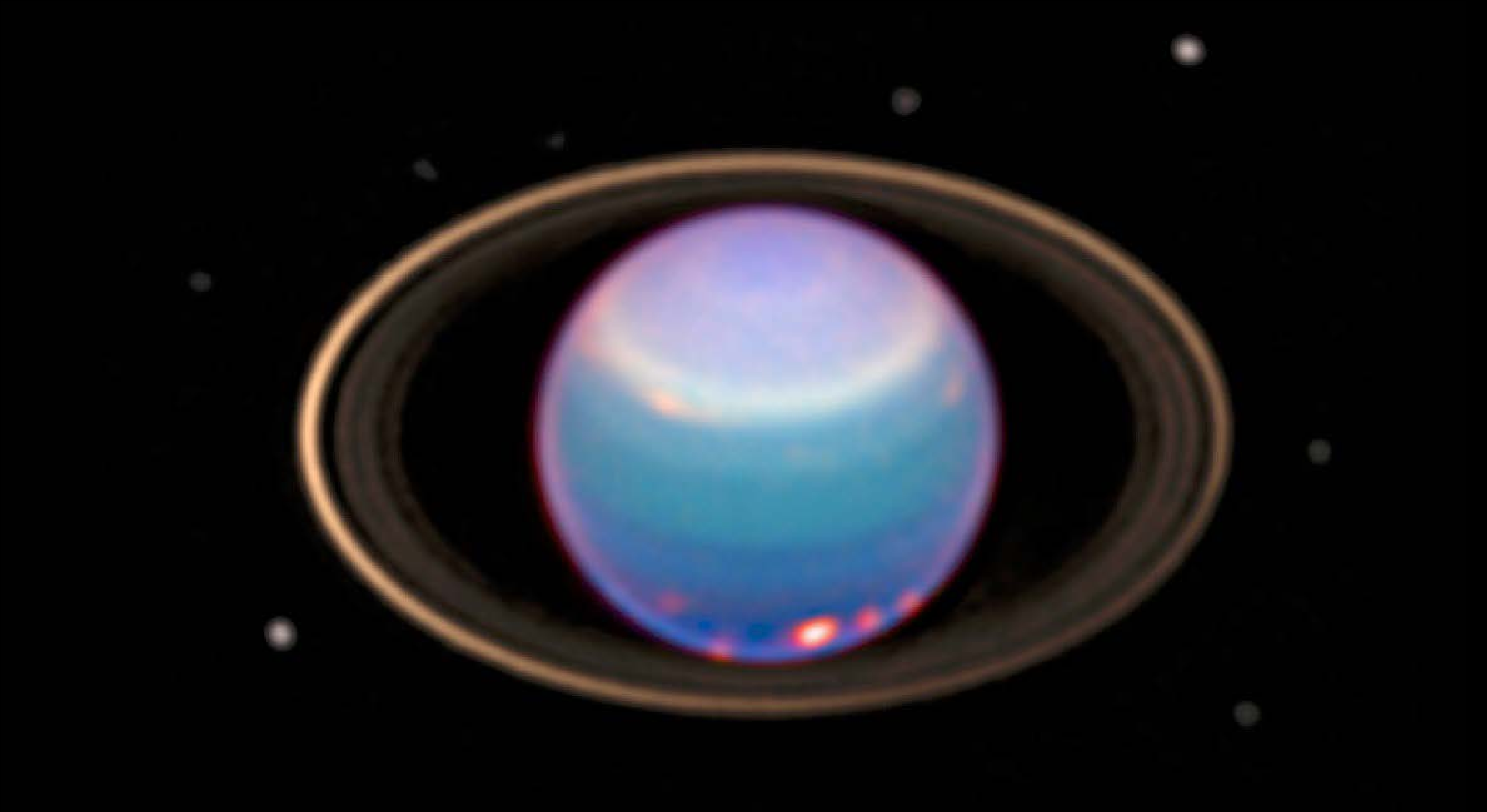
In January and March 2009, astronomers used *Hubble* to take advantage of a rare opportunity only available every 15 years to photograph Saturn when its rings were tilted edge-on to Earth. This allowed for a perspective where both poles could be viewed simultaneously. The observations showed the northern auroral oval to be slightly smaller and more intense than the southern one, implying that Saturn's magnetic field is not equally distributed across the planet.



This unique movie features *Hubble* images of the auroral light show at both of Saturn's poles. The opportunity to simultaneously image both of Saturn's poles occurs only twice during the planet's 30-year orbit.

Uranus

Uranus is tipped on its side relative to the other planets in our solar system. As a consequence, during its 84-year orbit around the Sun, Uranus experiences the most extreme seasonal changes among the planets. When *Voyager 2* flew past Uranus in 1986, the planet's northern hemisphere was facing almost directly toward the Sun, and its southern hemisphere was in total darkness. However, *Voyager*'s close-up images failed to find clouds or any banded structures like those found on the other large planets.



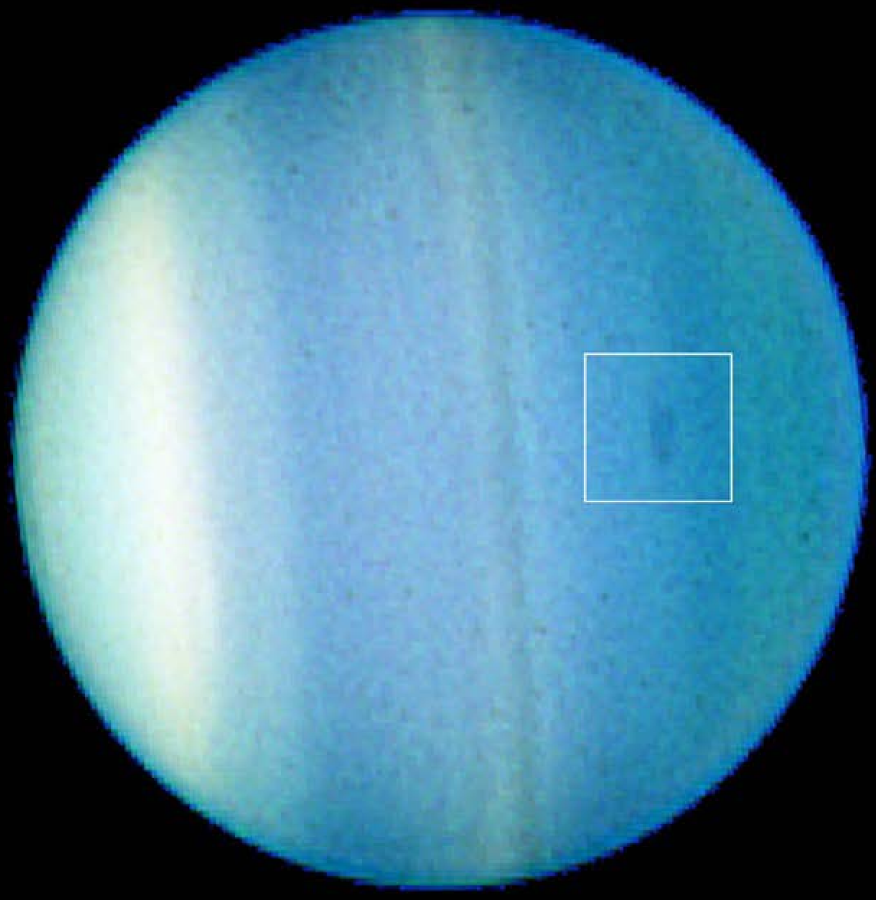
Hubble's infrared view of Uranus shows the planet surrounded by its four major rings and by 10 of its 27 known moons. In 1998, the space telescope found about 20 clouds on Uranus—nearly as many clouds as had been observed in total up to that point.

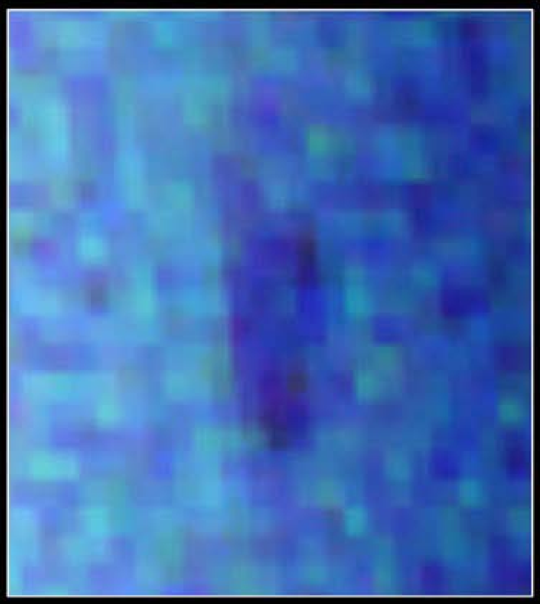
When *Hubble* looked at Uranus in 1994, it saw clouds over the southern hemisphere as early spring was arriving there. By observing Uranus in infrared wavelengths, *Hubble* could probe deeper into the planet's atmosphere to study its structure. It identified two high, hazy layers of atmosphere above a lower, clearer layer. *Hubble*'s infrared views also revealed banded structure and clouds that were almost as large as continents on Earth.

Using these images, astronomers measured wind speeds in the northern hemisphere of Uranus for the first time. Velocities there approached 600 miles per hour. The extreme winds on Uranus may only persist in the outer layers of the atmosphere, perhaps driven by moisture condensing and evaporating in the atmosphere.

Uranus is similar to Neptune in size and atmospheric composition, but its atmosphere does not appear to be as active as Neptune's. There have been unconfirmed sightings of dark spots on Uranus in the past, including in sketches made in the early 1900s. However, while dark spots have been frequently observed on Neptune, they have been rare on Uranus.

In 2006 *Hubble* photographed a dark vortex on Uranus large enough to engulf two-thirds of the United States. The elongated feature measured 1,100 miles by 1,900 miles and appeared at a latitude of 27 degrees in the planet's northern hemisphere. It signaled the approach of spring in the northern hemisphere, which was becoming fully illuminated by sunlight after many years of being in shadow.



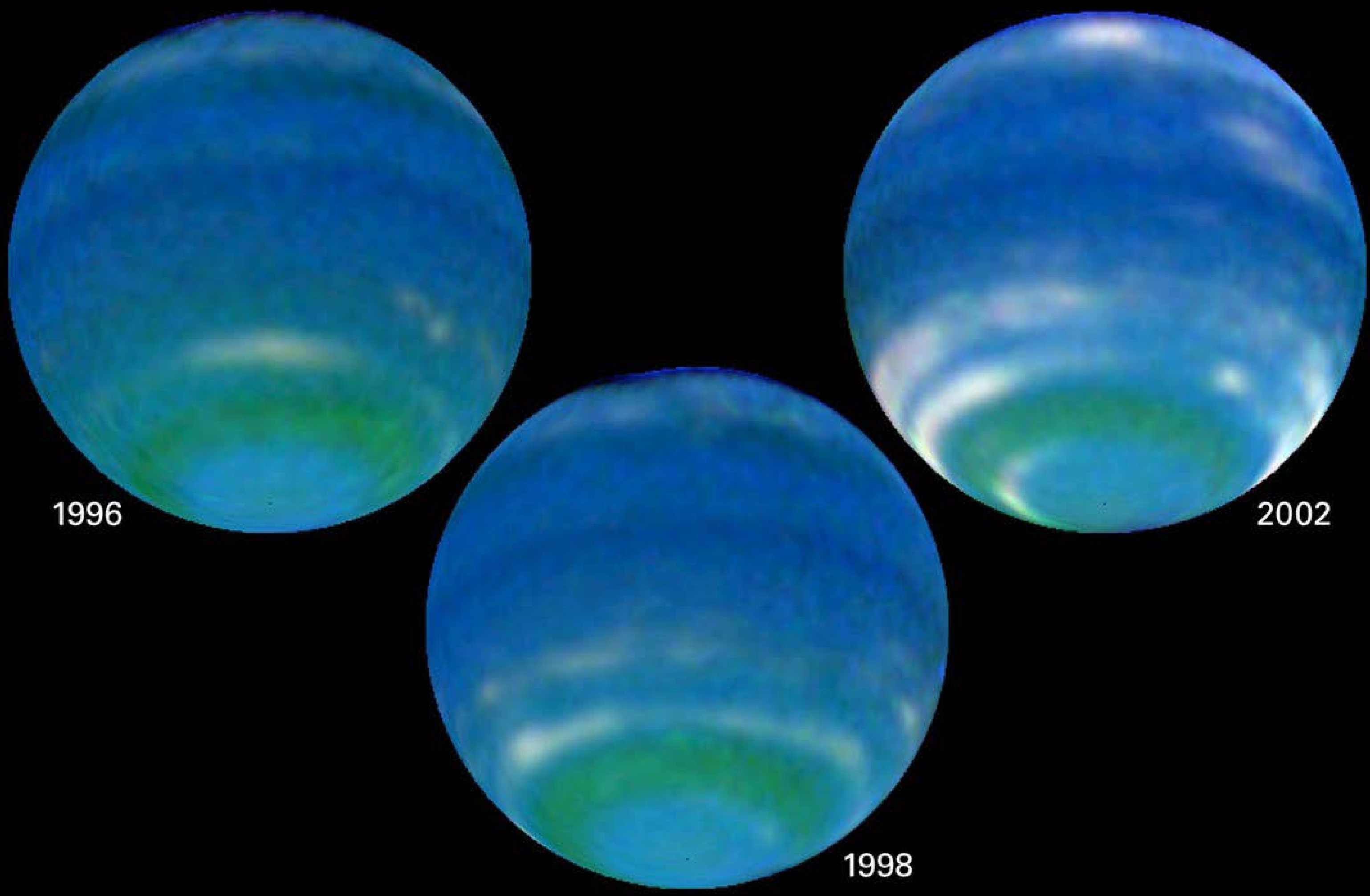


In 2006, *Hubble* took the first definitive images of a dark spot on Uranus. The elongated feature measured 1,100 miles by 1,900 miles.

Neptune

Very little was known about Neptune and its atmosphere until *Voyager 2* arrived at the planet in 1989. *Voyager* revealed a banded cloud structure and a storm that was called the Great Dark Spot.

Neptune's axis is tilted similar to Earth's. Neptune therefore exhibits seasonal changes. However, the seasons on Neptune last for decades, not months as on Earth. In fact, Neptune has only completed one orbit of the Sun since its discovery in 1843. It is remarkable that Neptune exhibits any evidence of seasonal change at all, given that the Sun, as viewed from the planet, is 900 times dimmer than it is from Earth. Still, *Hubble* has been able to observe such changes.



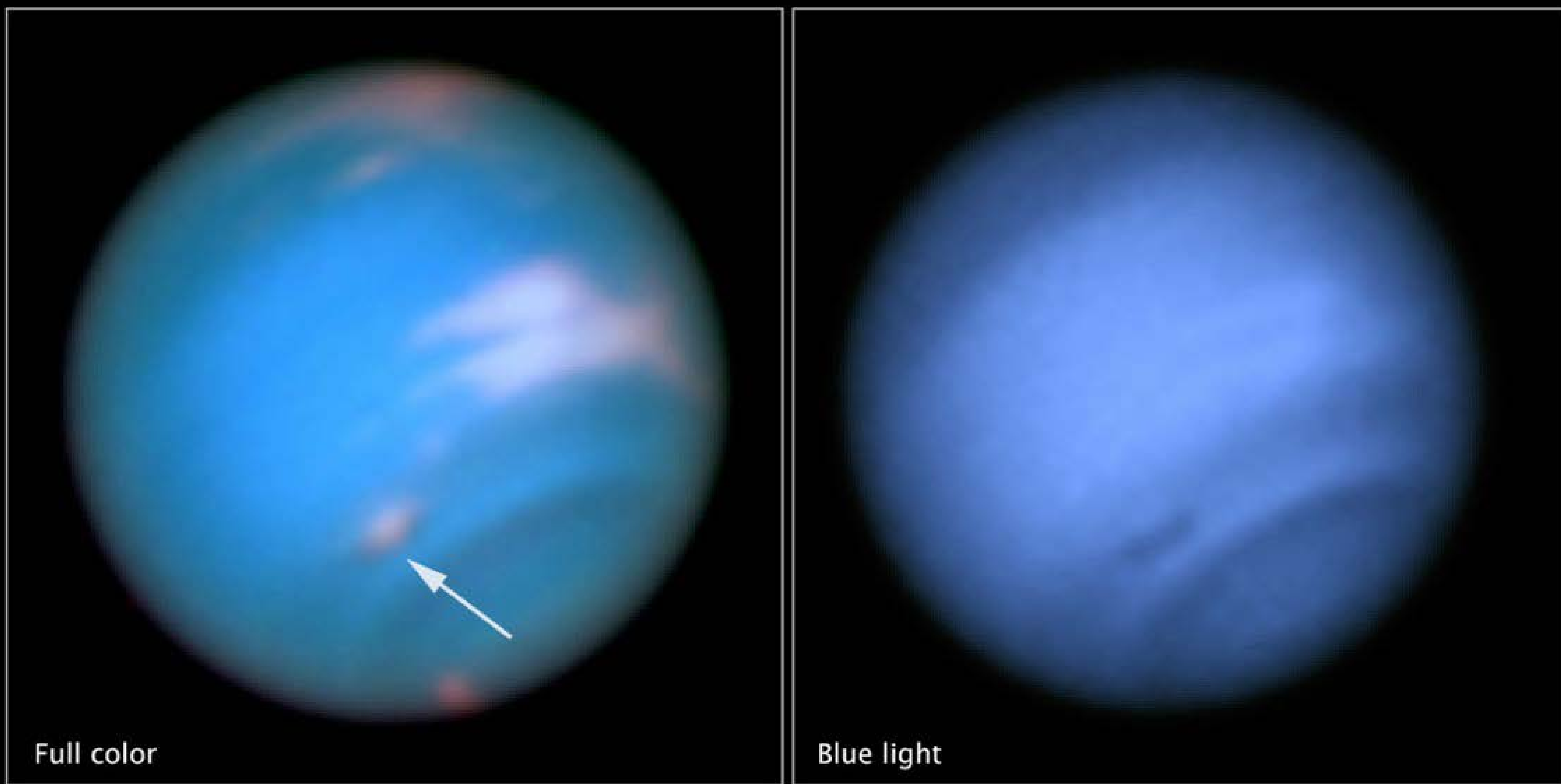
Hubble observations revealed an increase in Neptune's brightness in the southern hemisphere due to an increase in the amount of clouds there. Astronomers consider this brightness increase a harbinger of seasonal change.

Hubble's near-infrared capabilities allow the telescope to observe high-altitude clouds on Neptune that are useful for tracking seasonal changes. In fact, *Hubble* images taken in the late 1990s showing that cloud bands on Neptune were getting wider and brighter were considered the first observational evidence that the planet undergoes a change of seasons. In 2002 astronomers using *Hubble* noted that the abundance of high-altitude clouds increased the planet's brightness from observations made in the late 1990s.

Hubble studies show that Neptune has a nearly constant brightness at low latitudes (near the equator). This bolsters the idea that the observed changes are seasonal in nature, because seasonal effects would be minimal near the equator and most evident at high latitudes.

Neptune's Dark Spots

Neptune's Great Dark Spot, discovered by *Voyager 2* in 1989, had disappeared by 1994 when *Hubble* turned its gaze toward the planet. However, *Hubble* found four similar spots that appeared sequentially in subsequent years. In observations taken on May 16, 2016, *Hubble* identified a new dark vortex, the first to be observed in the 21st century.



In May 2016, *Hubble* spotted a new dark vortex on Neptune.

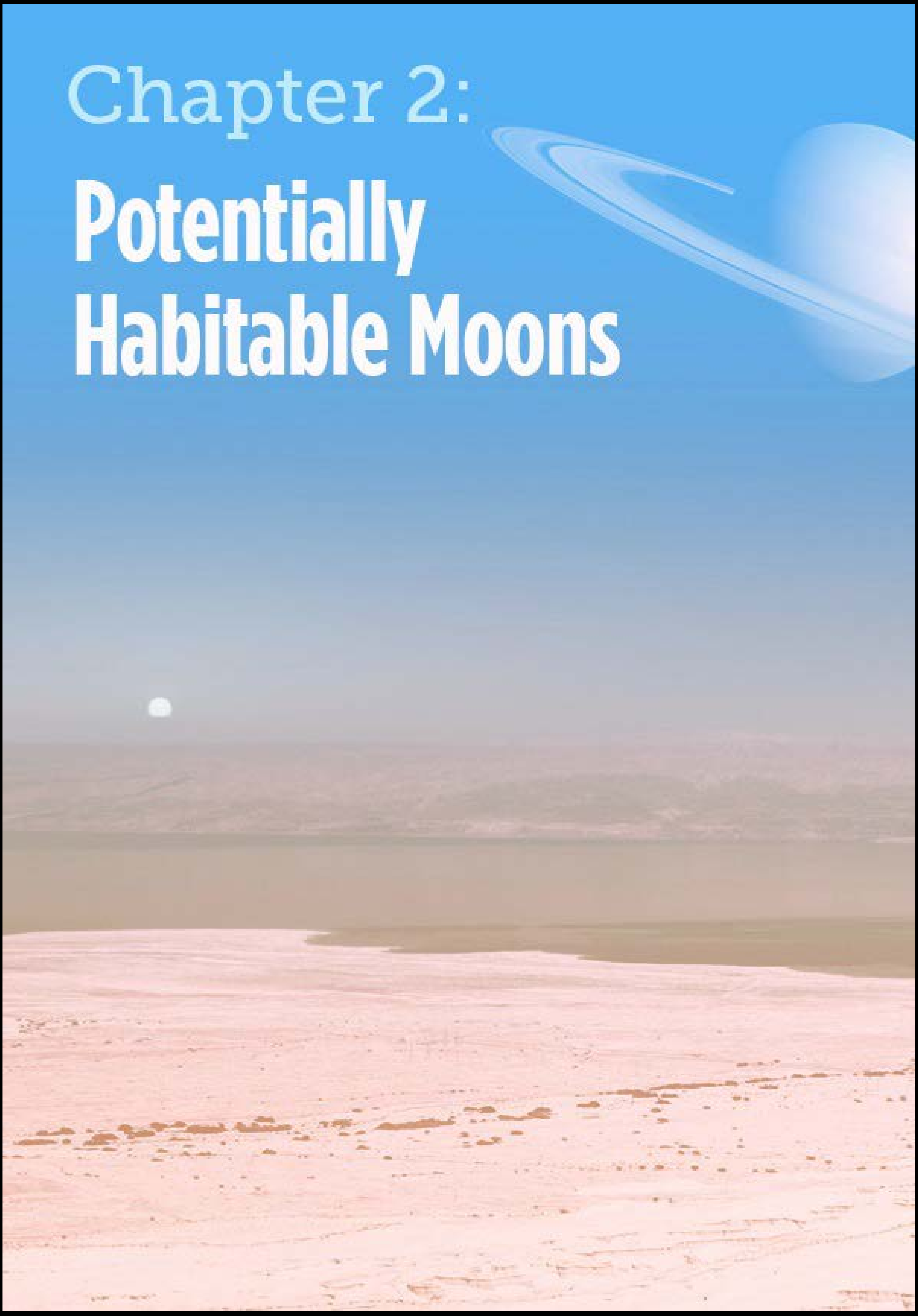
Observations by *Voyager 2* and *Hubble* have shown that dark vortices are high-pressure systems and are usually accompanied by bright companion clouds. The bright clouds form when the flow of ambient air is perturbed and diverted upward over the dark vortex, causing gases to freeze into methane ice crystals. The dark vortices coast through the atmosphere like huge, lens-shaped, gaseous mountains. The companion clouds are similar to so-called orographic clouds that appear as pancake-shaped features lingering over mountains on Earth. Neptune's dark vortices are typically only seen at blue wavelengths, and only *Hubble* has the high resolution required for seeing them on distant Neptune.

Neptune's dark vortices have exhibited surprising diversity over the years, in terms of size, shape, and stability (they meander in latitude, and sometimes speed up or slow down). They also come and go on much shorter timescales compared to similar anticyclones seen on Jupiter, which evolve over decades.

Planetary astronomers hope to better understand how dark vortices originate, what controls their drifts and oscillations, how they interact with the environment, and how they eventually dissipate. Measuring the evolution of the dark vortex on Neptune will extend the knowledge of both the dark vortices themselves, as well as the structure and dynamics of the surrounding atmosphere.

Chapter 2:

Potentially Habitable Moons



At the latest count, there are more than 150 moons orbiting the eight major planets in our solar system, while additional moons are known to orbit dwarf planets and asteroids. These natural satellites come in a wide variety of shapes, sizes, and types.

Some moons—including the smallest ones—were likely captured by the gravitational pull of their parent bodies. Other moons may have been born out of a collision between two terrestrial planet-sized objects. Many of the larger moons probably formed from the disks of gas and dust circulating around planets in the early solar system. The largest moons are geologically complex, each with a dense core, surrounded by a mantle and crust.

This photo illustration presents images (not taken by *Hubble*) of selected moons of our solar system. It shows the moons at their relative sizes to each other and to Earth, and exhibits the wide diversity among the moons.

Earth's own moon is the most intensively studied satellite in the solar system. It is the only extraterrestrial body on which humans have walked, and a variety of handpicked rock samples from the Moon were brought back to Earth by NASA's *Apollo* astronauts. Some date back to the origin of the Earth-Moon system.

The Moon lies alongside Earth within the solar system's habitable zone, where temperatures are just right for liquid water to exist on a planet's surface. However, while watery Earth teems with life, the Moon is bone-dry, airless, and lifeless.

The Sun's habitable zone is not the only factor for finding abodes of life in the solar system, though. Astrobiologists are looking to the frozen moons of giant planets as potential habitats for at least simple life forms. Some of these worlds may have subsurface oceans of liquid water kept warm by internal radioactivity or gravitational tidal forces from their parent planet. And, where there is water, there could be life.

Europa

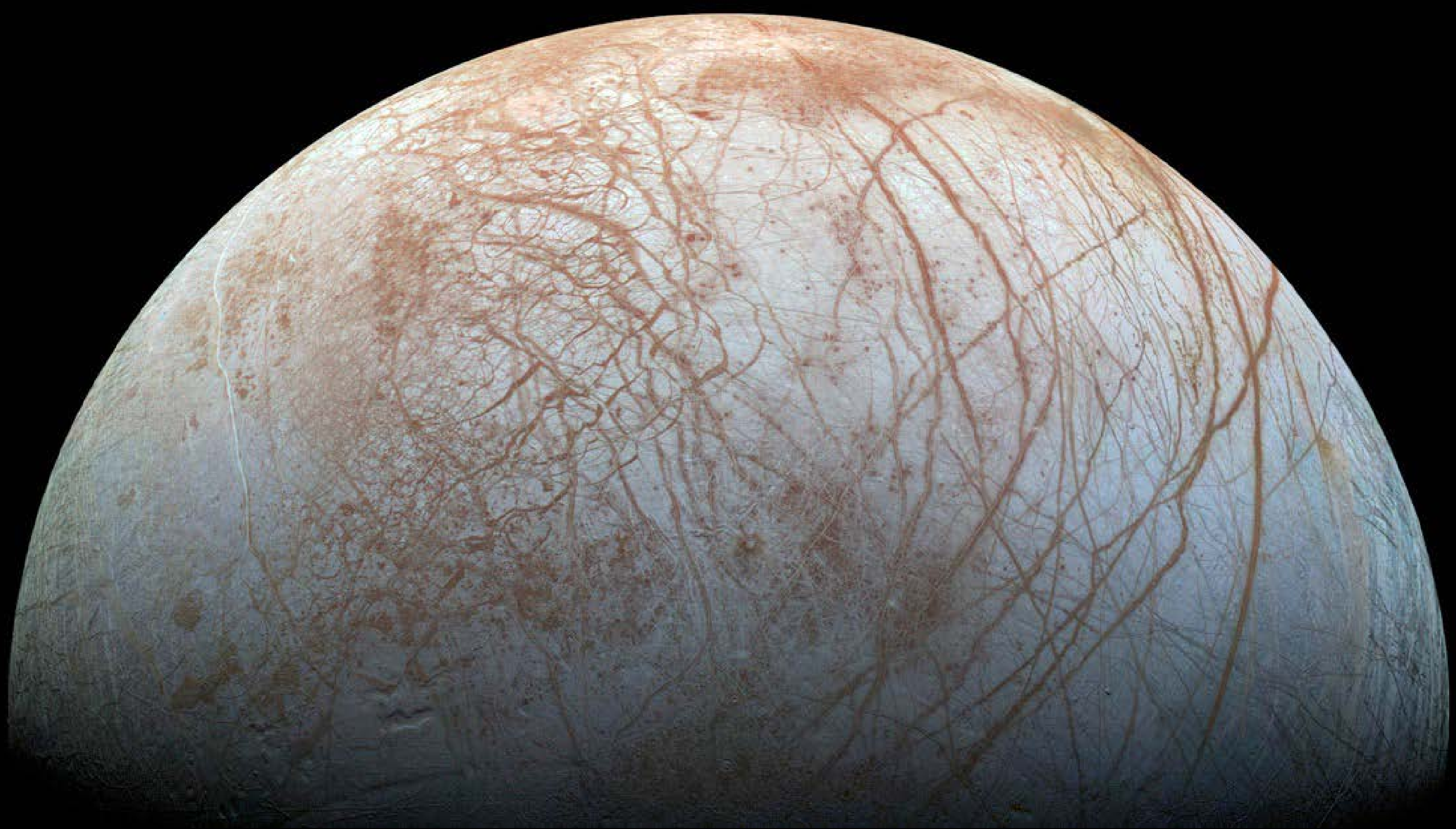
Before the dawn of interplanetary travel, Jupiter's four largest moons—Io, Europa, Ganymede, and Callisto—were suspected to be covered in water ice. When NASA's *Pioneer 10* and *11* flew by the Jovian system in the early 1970s, they found that Europa, Ganymede, and Callisto were indeed ice-rich.

In this *Voyager 1* image, Europa appears at upper left and Io at lower right, above Jupiter's cloud tops. Credit: NASA/Justin Cowart (processing)

In contrast, when NASA's *Voyager 1* and *2* flew by Jupiter in 1979, they found that Io was covered by volcanoes. This meant that Io's interior was kept warm over billions of years.

The only plausible mechanism was gravitational tidal forces that flexed the moon's interior—like squeezing a rubber ball—generating heat. Scientists realized that if this "tidal pumping" kept Io's interior warm, then the same process might be happening on Jupiter's icy moons to heat subsurface oceans of liquid water.

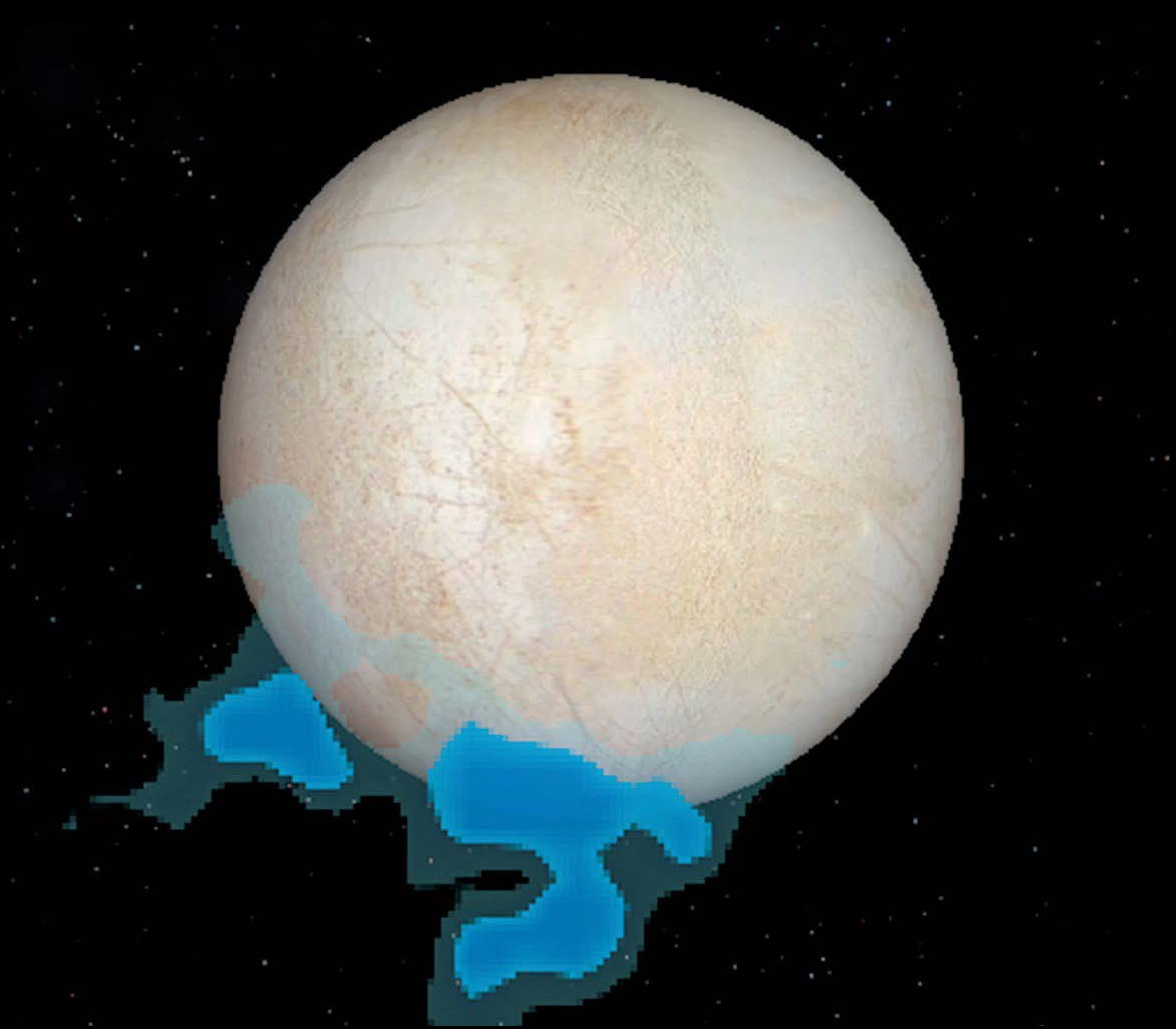
This hypothesis was bolstered by the *Voyager* images of Europa, which showed a smooth surface that was cracked like an eggshell. Geologists thought that these cracks might have been caused by expansion of the icy crust due to the freezing of an early ocean. This process created fractures in the ice that brownish fluids filled from below the surface and which are now visible as dark markings.



Jupiter's icy moon Europa looms large in this color view, made from images taken by NASA's *Galileo* spacecraft in the late 1990s.

Voyager scientists even speculated that Europa might be venting liquid water that would immediately "flash freeze" into ice-crystal geysers. *Voyager 2* saw no geysers—but three decades later, the first tantalizing evidence for geysers was found. And it was not from another Jupiter probe, but from *Hubble*, peering at the moon across 500 million miles of space.

The recent evidence for geysers came in an unusual way—from auroras that *Hubble* observed on Europa in December 2012. *Hubble*'s Space Telescope Imaging Spectrograph (STIS) detected faint ultraviolet light from an aurora, powered by Jupiter's intense magnetic field, near the moon's south pole. The spectral signature of the aurora indicated the presence of atomic oxygen and hydrogen. This was a telltale sign that water molecules were being broken apart by electrons traveling along magnetic field lines.



This graphic shows the location of water vapor observed by *Hubble* over Europa's south pole. *Hubble* didn't photograph the plumes, but spectroscopically detected auroral emissions from oxygen and hydrogen in the regions depicted in blue.

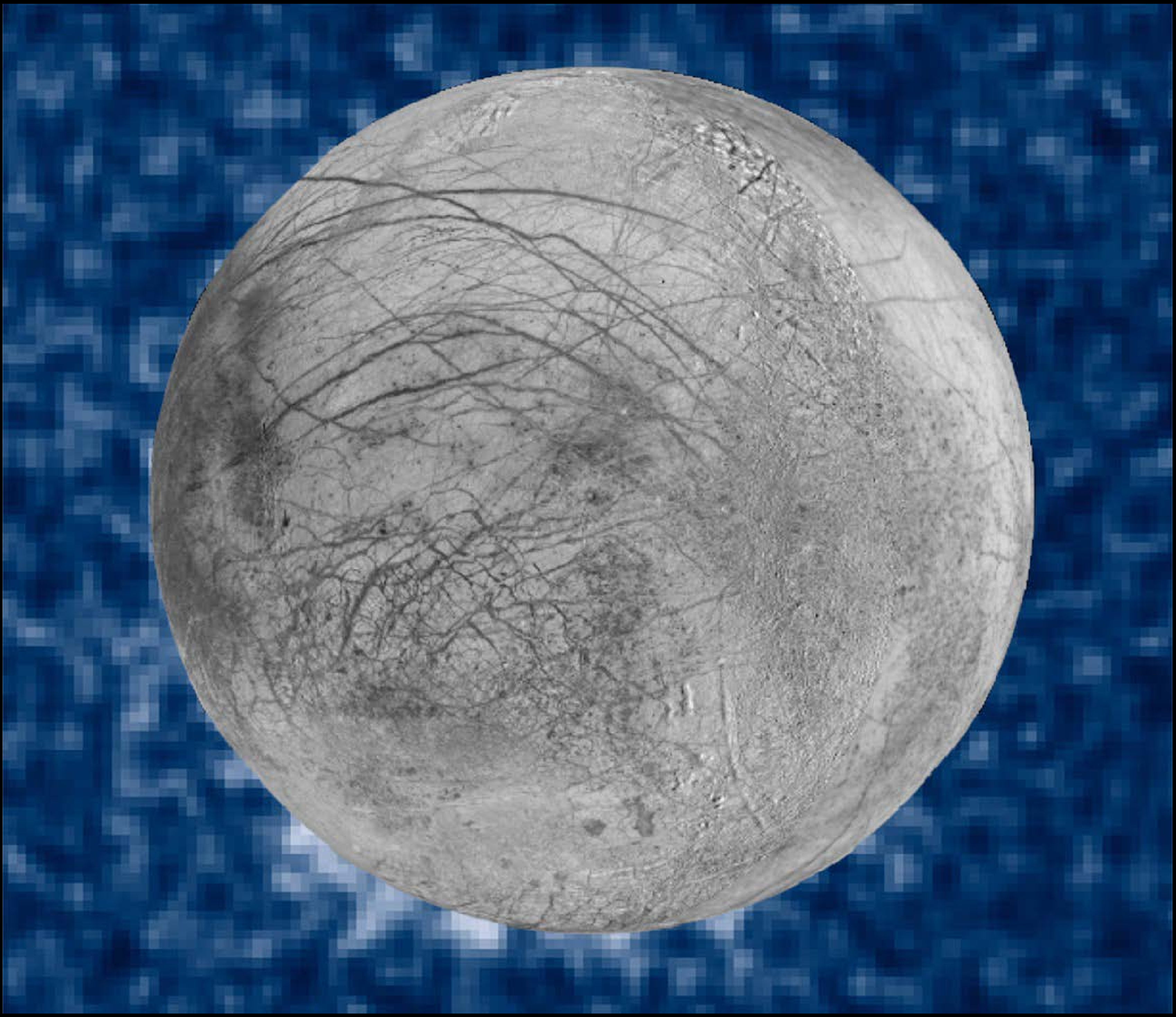
The researchers suggested that the water molecules came from water being vented into space. This phenomenon seems similar to what NASA's *Cassini* orbiter discovered in 2005 when it photographed geysers on Saturn's moon Enceladus. However, Europa is much larger and more geologically complex than Enceladus, so the mechanism behind the ejecting plumes could be quite different.

Another *Hubble* team tried a different approach to look for plumes on Europa. These scientists were inspired by *Hubble* observations of extrasolar planets that pass in front of their parent stars. In those observations the planet cannot be resolved, but the composition of the planet's atmosphere can be deduced by its influence on starlight passing through the atmosphere.

The scientists wondered whether features of an extended atmosphere on Europa might be opaque enough to be seen in silhouette against the reflected sunlight from Jupiter. *Hubble*'s ultraviolet sensitivity was ideal for the experiment because there is an ultraviolet haze on

Jupiter that makes the planet look featureless when viewed at those wavelengths. This made it easier to distinguish any features above Europa seen in silhouette.

In three separate observations in 2014 and once again in 2016, *Hubble* spotted plume-like features on the limb of Europa. Two of the finger-like structures seen in 2014 were at approximately the same latitude where hydrogen and oxygen were detected in the auroral observations from 2012. The locations of the other plumes, one observed in 2014 and the other in 2016, not only matched up with each other but also corresponded to the position of a warm spot on the moon's icy crust, as detected in the late 1990s by NASA's *Galileo* spacecraft. This provided another hint that water could be erupting from Europa's subsurface.



This composite image shows suspected plumes of water vapor erupting at the 7 o'clock position off the limb of Europa. *Hubble* observed the plumes in silhouette as the moon passed in front of Jupiter. The image of Europa (in gray), superimposed on the *Hubble* image (in blue), is assembled from observations made by the *Galileo* and *Voyager* missions.

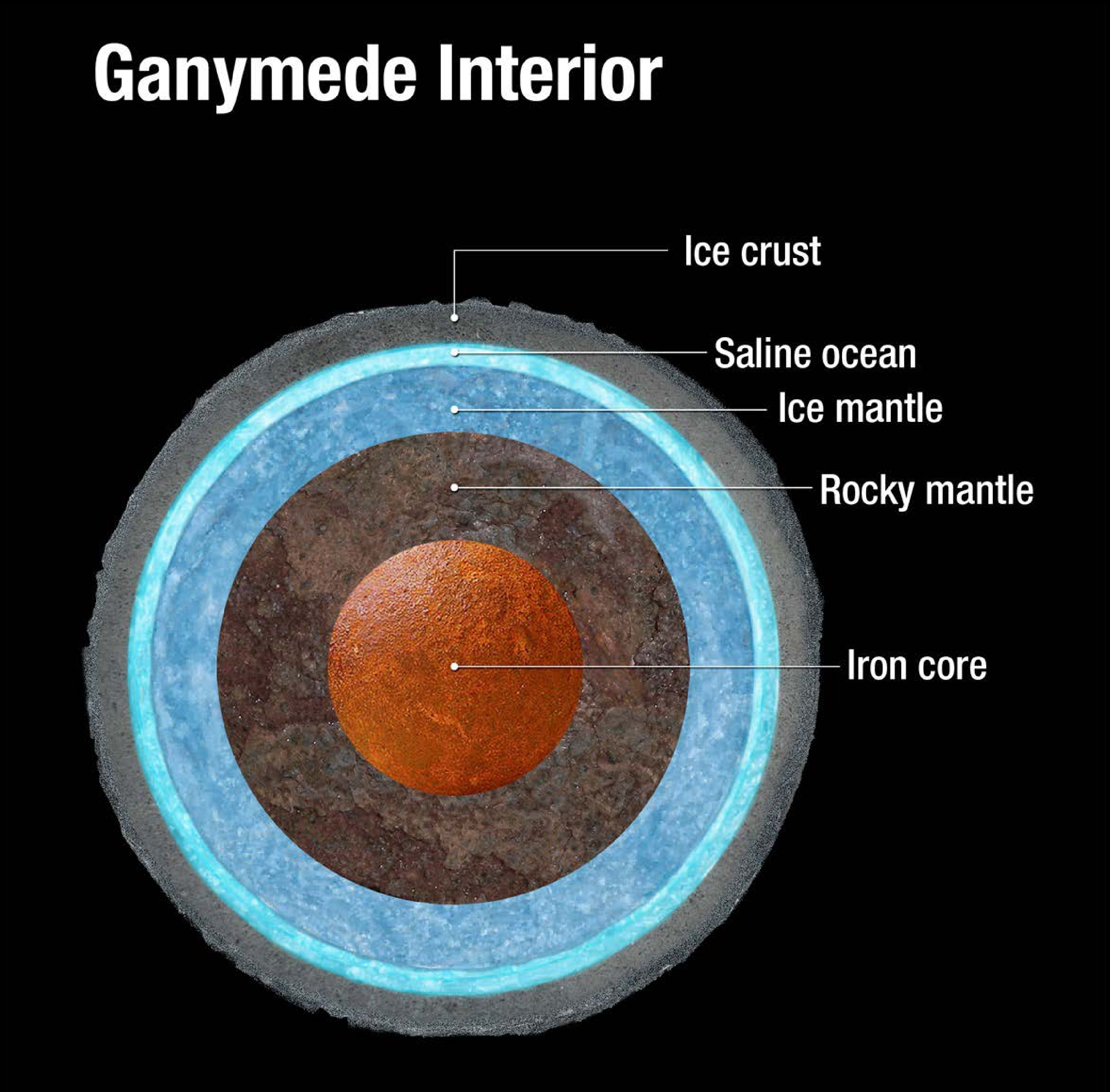
The two types of observations that offer evidence for plumes on Europa are markedly different, but the results largely agree about the amount of material needed to create plumes as well as the height of the plumes—about 125 miles.

If the venting plumes originate in a subsurface ocean, they could act as an elevator to bring deep-sea water (and possibly life, if it exists) above Europa's surface, where it could be sampled by visiting spacecraft. This offers an opportune way to access the chemistry of the ocean without drilling through miles of ice.

This is an artist's concept of a plume of water vapor being ejected from the frigid, icy surface of Europa. Scientists calculated that such a plume observed by *Hubble* rose to an altitude of 125 miles and then probably rained frost back onto the moon's surface. Credit: K. Retherford (Southwest Research Institute)

Ganymede

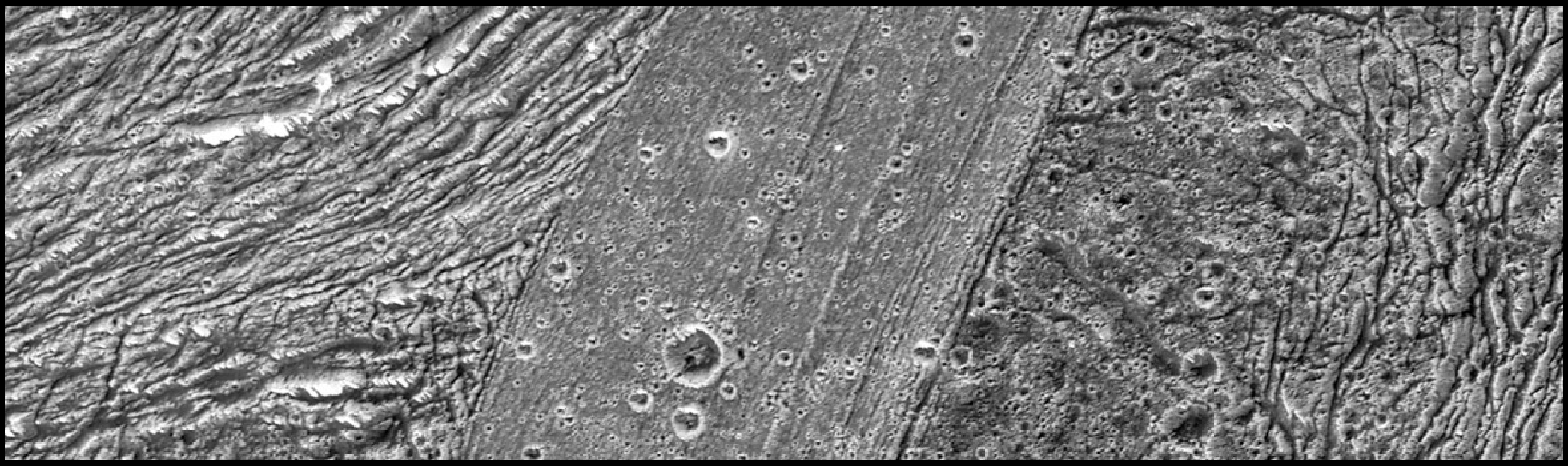
Ganymede, another Jovian moon, is the largest satellite in our solar system, bigger than Mercury and nearly three-quarters the size of Mars. Like a planet, Ganymede has structural layers beneath its surface. It has a magnetic-field-generating, metallic iron core, which is wrapped in a spherical shell of rock. There may be a salty ocean sandwiched between an ice mantle and the moon's thick, icy crust.



This illustration depicts the interior structure of Ganymede, based on theoretical models combined with observations by *Hubble* and NASA's *Galileo* spacecraft. Ices and a saline ocean dominate the outer layers, while a denser rock mantle and iron core lie deeper inside the moon.

In 1996 astronomers using *Hubble* found evidence of a tenuous oxygen atmosphere on Ganymede. Charged particles trapped in Jupiter's powerful magnetic field rain down onto Ganymede's surface. This breaks up water molecules on the surface into oxygen and hydrogen atoms, which form the thin atmosphere.

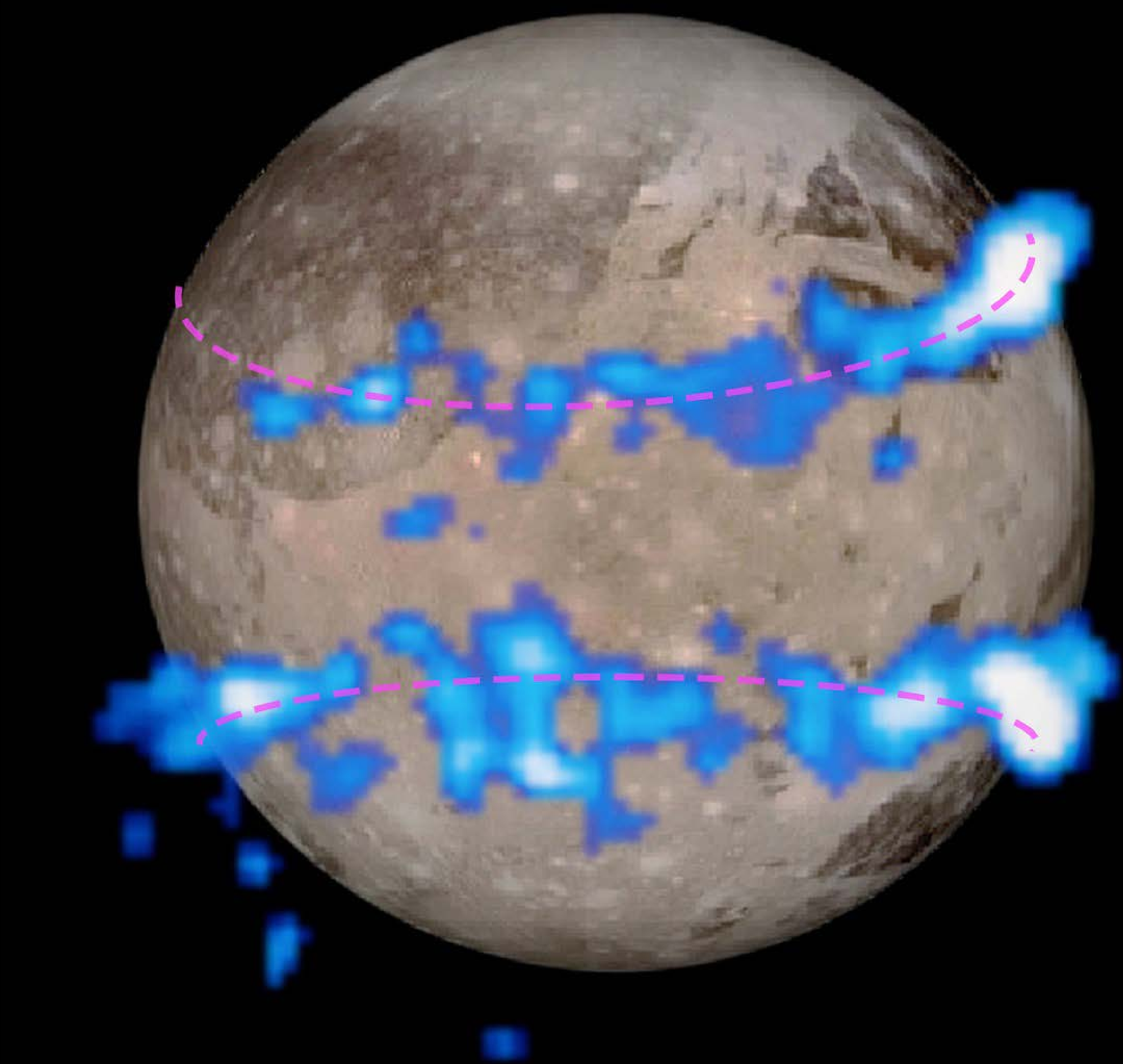
Around the same time, photos from NASA's Jupiter-orbiting *Galileo* spacecraft yielded surprising new information about Ganymede's geological past: ancient, cratered ice fields overlain by younger, ice volcanic plains; ridged ice mountains; deep furrows; and smooth, broad basins that are products of tectonic forces. About half of Ganymede's old, cratered surface appears to have been resurfaced by younger volcanic and tectonic activity. This would imply the actions of a liquid beneath the icy crust.



This close-up image from NASA's *Galileo* spacecraft shows Arbela Sulcus, a long, flat feature on Ganymede. Liquid water may have flowed from within Ganymede, filled a depression, and then cooled to create a smooth surface.

Galileo measured Ganymede's magnetic field in 2002, providing the first evidence that supported suspicions of an underground ocean. A thick layer of melted, salty water somewhere beneath Ganymede's icy crust would be the best way to explain some of the magnetic readings. In addition, infrared observations by *Galileo* revealed minerals on parts of Ganymede's surface that suggest that salty water may have emerged from below or melted at the surface in the past. However, the infrared evidence did not indicate whether or not an ocean persists on Ganymede today.

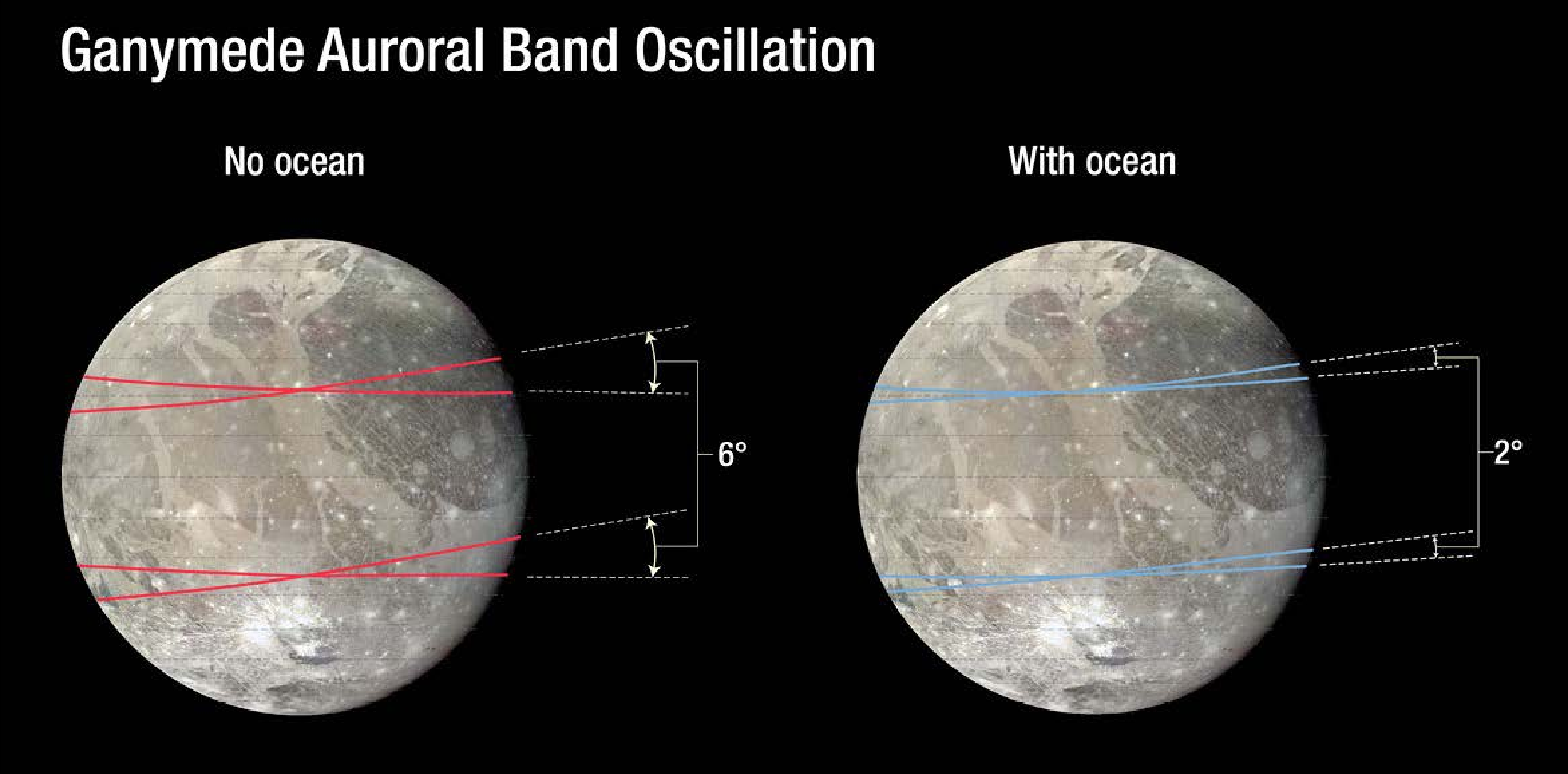
Hubble observations made in 2015 provided the best evidence yet that Ganymede currently possesses an underground saltwater ocean, which may have more water than all the water on Earth's surface. The evidence came from studying auroras on Ganymede. Because Ganymede is close to Jupiter, it is embedded in Jupiter's magnetic field. When Jupiter's magnetic field changes over a roughly five-hour period (believed to be tied to Jupiter's rotation), the auroras on Ganymede also change, "rocking" back and forth.



Hubble observations in ultraviolet light reveal a pair of auroral belts encircling Ganymede. In this illustration, the belts are colored blue and are overlaid on a visible-light image of Ganymede taken by NASA's *Galileo* orbiter.

If a saltwater ocean were present, Jupiter's magnetic field would induce a secondary magnetic field in the ocean that would counter Jupiter's field. This "magnetic friction" would suppress the rocking of the auroras. Indeed, *Hubble*'s observations revealed that the rocking of Ganymede's auroras is limited to 2 degrees, instead of the 6 degrees expected if the ocean were not present.

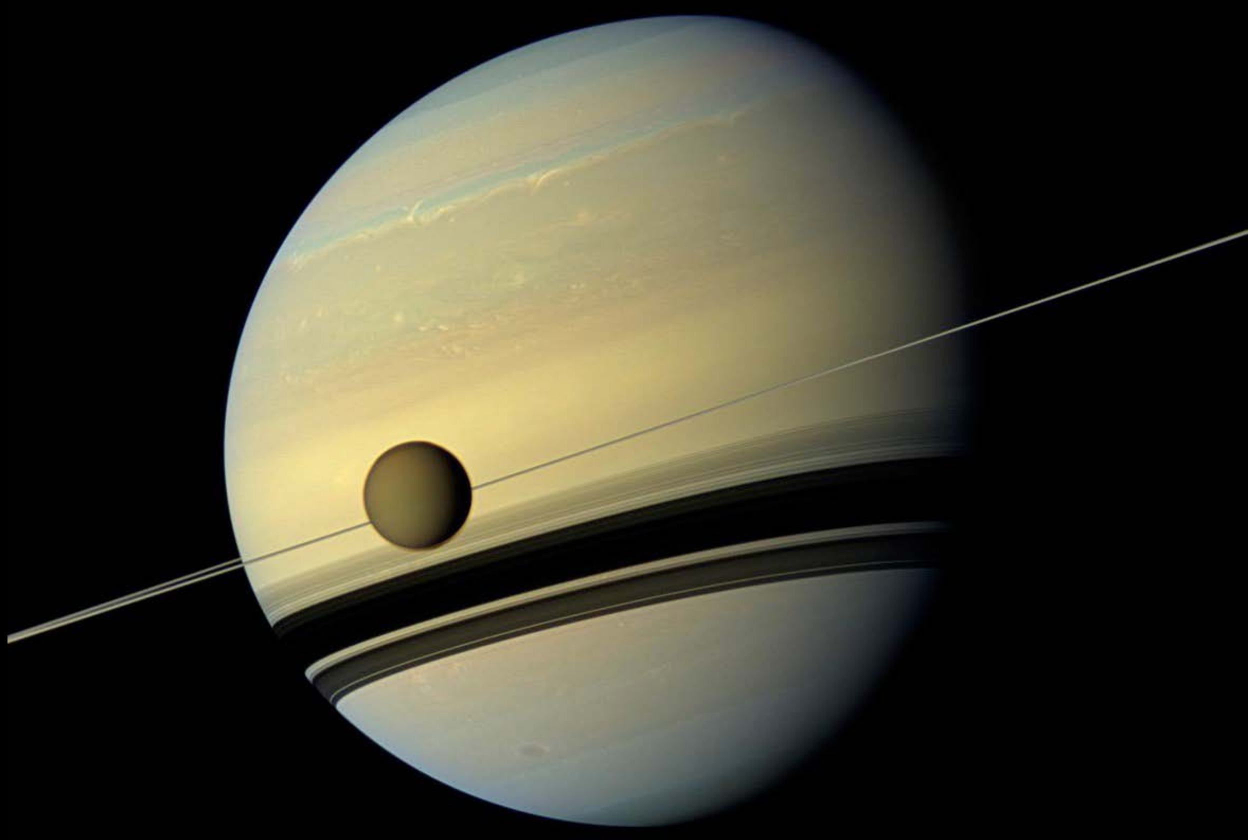
Scientists estimate that Ganymede's ocean is 60 miles deep—10 times deeper than Earth's oceans—and is buried under a crust of ice that could be at least 100 miles thick.



The auroras on Jupiter's moon Ganymede oscillate or "rock" back and forth. *Hubble* observations showed that the rocking of Ganymede's auroral belts are restricted to just 2 degrees, which is expected if Ganymede had a subsurface ocean. If Ganymede had no subsurface ocean, scientists would expect the angle of the auroral belts to vary by 6 degrees.

Titan

There is only one world in the solar system other than Earth that has lakes on its surface: the giant moon Titan, which orbits Saturn. Additionally, Titan has an atmosphere that is thicker than Earth's. It also rains on Titan, and there are thunderstorms. But at a surface temperate of –290˚F, this is no place for a relaxing beach vacation. Water there freezes as hard as granite. The lakes are filled not with water but with liquid methane, while the beaches are made of a hydrocarbon goo. The rain is methane as well, and after it falls it flows across the surface in narrow channels.

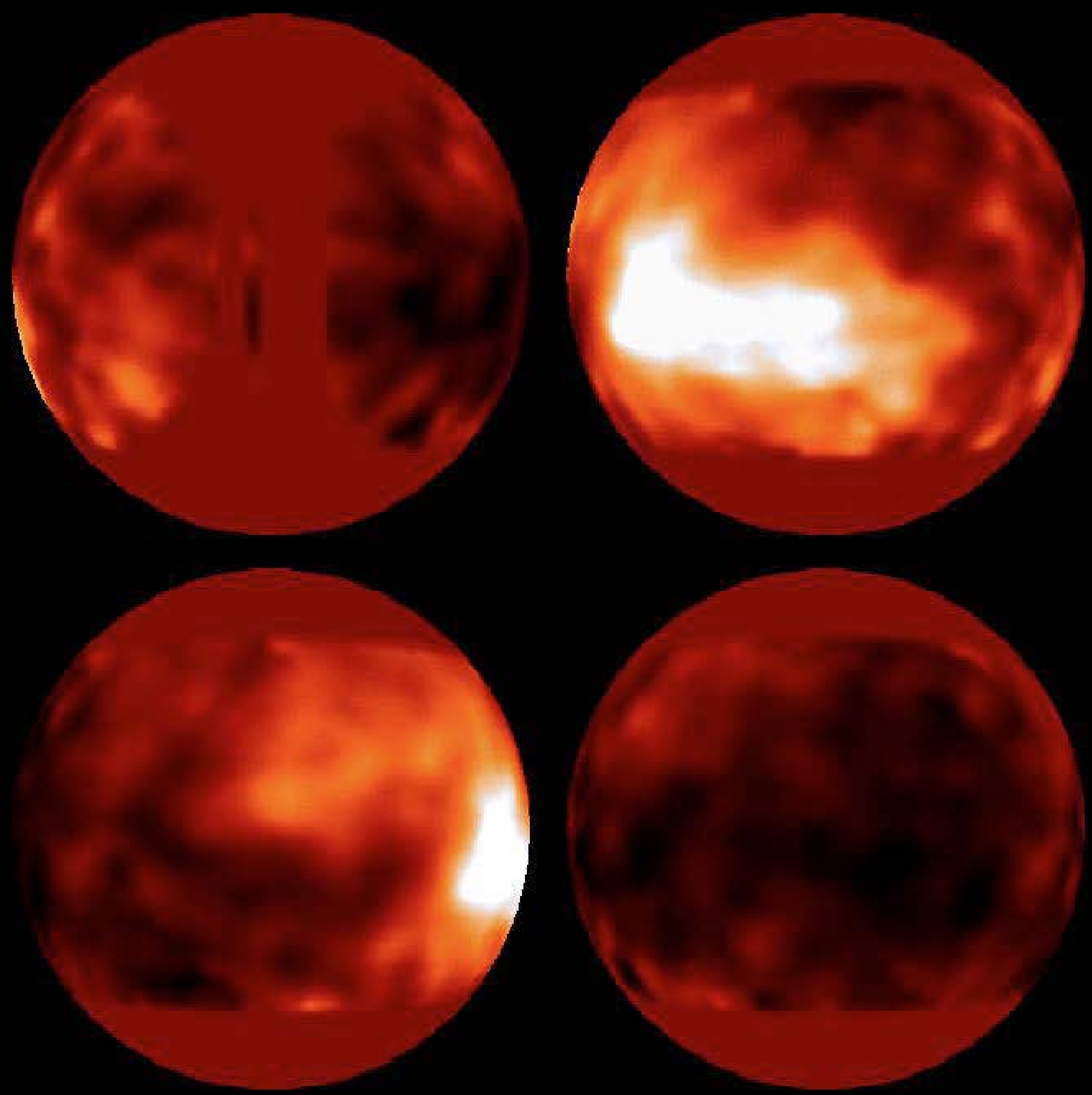


Titan appears in front of Saturn and its thin rings in this photograph from NASA's *Cassini* spacecraft. Larger than the planet Mercury, Titan is completely featureless when viewed in visible light because it is covered in an orange, hydrocarbon smog.

These are very recent discoveries, because Titan is veiled in clouds. Titan's atmosphere, about four times as dense as Earth's, is primarily nitrogen laced with methane and ethane. Sunlight breaks up nitrogen and methane molecules in the atmosphere, which recombine to form more complex hydrocarbon molecules. These hydrocarbons form a smog similar to that found over large cities on Earth, but much thicker. This orange haze is impenetrable to visible-light observations.

Four moons of Saturn pass in front of the planet in this visualization made from *Hubble* images taken on February 24, 2009. The largest moon is Titan. The smaller moons are (from left to right) Enceladus, Dione, and Mimas.

In 1994 astronomers used *Hubble* to obtain the first images of Titan's surface. At near-infrared wavelengths, Titan's haze is transparent enough for *Hubble* to map surface features according to their reflectivity. *Hubble* mapped light and dark features over the surface of the moon during one 16-day rotation of Titan. One prominent feature was a bright area 2,500 miles across, about the size of the continental United States.

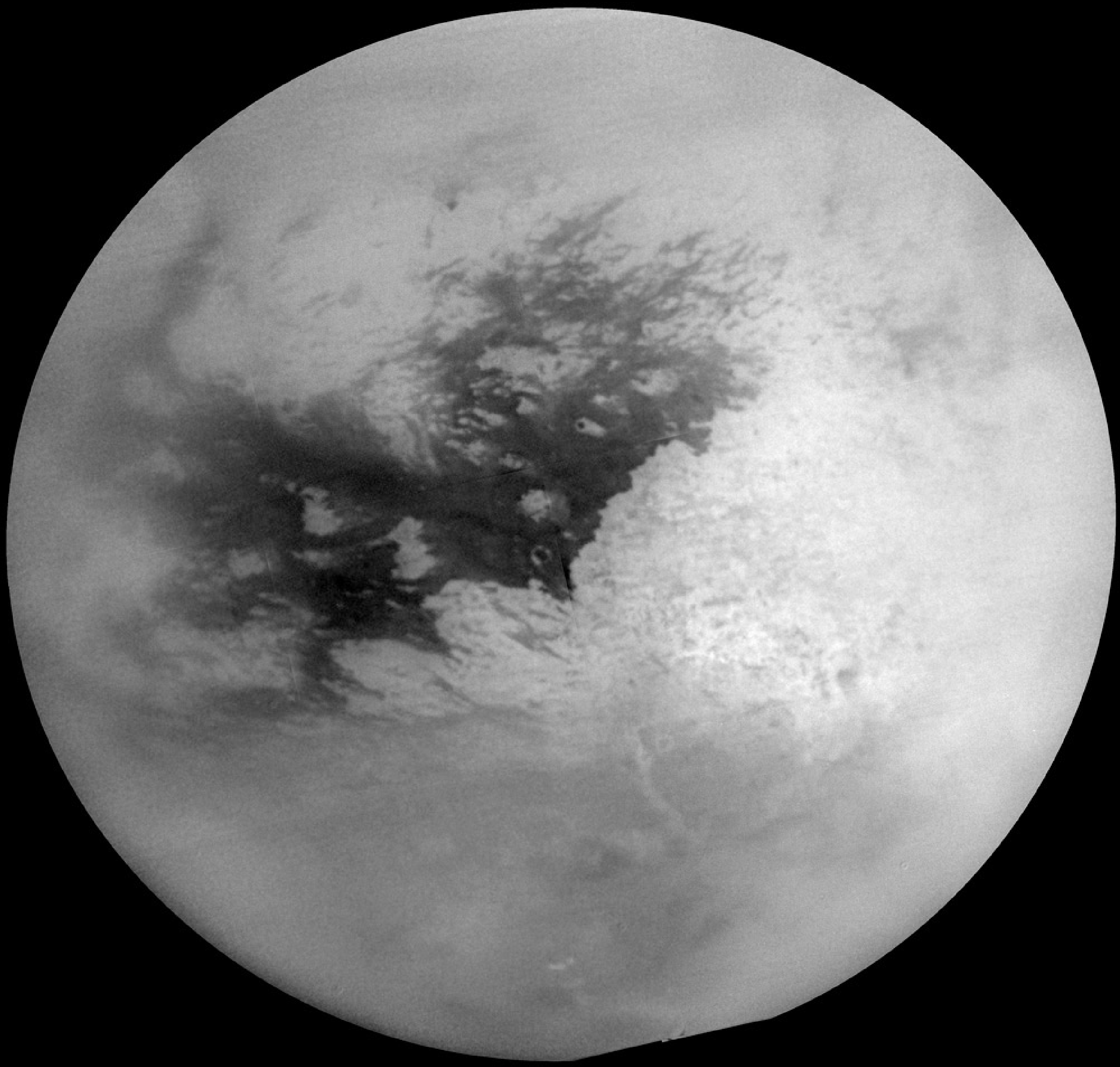


These near-infrared images of Titan, taken by *Hubble* in 1994, provided humanity's first glimpse at the surface of the cloud-covered moon. The observations were the first to map bright and dark features on the surface. The four global projections are separated in longitude by 90 degrees.

Planetary scientists were puzzled over the dark and bright areas in the *Hubble* images. Were they continents, impact craters, or other features? Scientists had long suspected that Titan's surface was covered with a global ethane-methane ocean. The *Hubble* images were the first to show that there was at least some solid surface.

In 1997 and 1998, scientists used *Hubble's* Near Infrared Camera and Multi-Object Spectrometer (NICMOS) to identify two brightness peaks in the prominent, continent-sized bright feature on Titan. Many smaller landmarks could also be mapped, including distinct surface structures on the darker side of Titan.

Arriving at Saturn in 2004, NASA's *Cassini* mission made multiple close passes of Titan, allowing scientists to map the surface with radar and infrared imaging. *Cassini* provided detailed observations of the bright and dark features discovered by *Hubble*. Cassini also revealed vast seas several hundred miles across and up to several hundred feet deep, fed by river-like channels, as well as numerous smaller, shallower lakes. A lander called *Huygens*, which arrived with *Cassini*, returned detailed, close-up images of surface features such as hills, dunes, channels, dry river beds, and even frozen cobblestones.

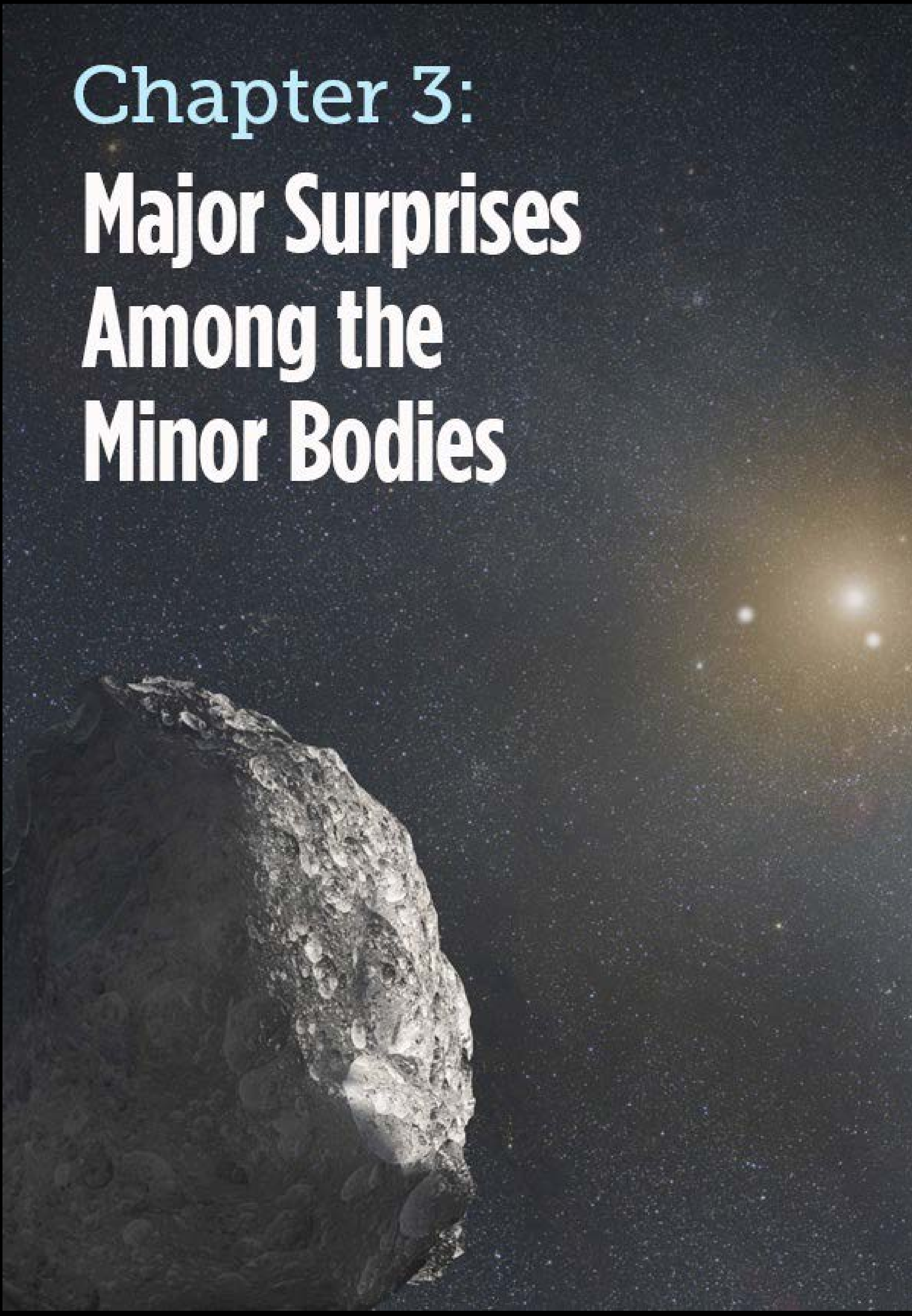


NASA's *Cassini* spacecraft provided closer views of bright and dark regions on Titan first observed by *Hubble*. The dark region seen here is now named Shangri-La, while the bright area to the right is called Xanadu.

The methane cycle, frigid climate, and lack of liquid water on Titan's surface makes one wonder what life might be like on a world radically different from Earth. Instead of being water-based, any life on Titan might use liquid hydrocarbons as a solvent. Titan microorganisms might breathe hydrogen and eat acetylene as an energy source for metabolism. What strange creatures those would be.

Chapter 3:

Major Surprises Among the Minor Bodies



If there are nearby extraterrestrial civilizations with the curiosity to explore the universe, they may have our Sun on their target list. If they have technical capabilities similar to ours, the first thing they might notice is the Sun's 12-year wobble due to the gravitational tug of Jupiter, the most massive planet in our solar system. If they have space telescopes comparable to *Hubble*, they would detect the faint glow of the Kuiper belt, a vast ring of icy debris encircling the Sun beyond the orbit of Neptune. Using space telescopes much bigger than *Hubble*, they would eventually image the feeble glow of Earth.

But far below the telescopes' detection limits are other denizens of the solar system. Except for Venus and Mercury, all of the planets are orbited by moons, with the moons becoming more abundant the smaller they are. Vastly more numerous are the asteroids and comets that ply the space between the planets. We know today that these minor bodies not only have potentially profound effects on the planets but also are invaluable relics that tell us about planet formation in the earliest days of the solar system.

Hubble has studied several comets as they approached the Sun, such as Comet C/2012 S1 (ISON), seen here against a field of stars and galaxies.

Comets are generally seen as small, fragile bodies composed of a mixture of ice, grains, and frozen gases. As a comet approaches the Sun, its surface warms up and its ices sublimate, creating a tail millions of miles long, which is a comet's trademark. In contrast, asteroids are mostly composed of rock, some ices, and traces of iron, nickel, and other metals. However, *Hubble*'s high-resolution images have begun to blur the classical definitions between comets and asteroids, showing that these minor bodies are more dynamic and complicated than once thought.

Two Asteroids Colliding

Though the asteroid belt between Mars and Jupiter has been around for several billion years, *Hubble* has provided evidence that it continues to be a dynamic place.

In late January 2010 *Hubble* observed an odd-looking asteroid discovered by the Lincoln Near-Earth Asteroid Research (LINEAR) sky survey just a couple weeks earlier. *Hubble*'s high-resolution view of the asteroid, called P/2010 A2, revealed a mysterious X-shaped debris pattern and long streamers of dust. The most plausible explanation was that two previously unknown asteroids had collided head-on.

This mysterious X-shaped debris pattern and trailing streamers of dust suggest a head-on collision between two asteroids.

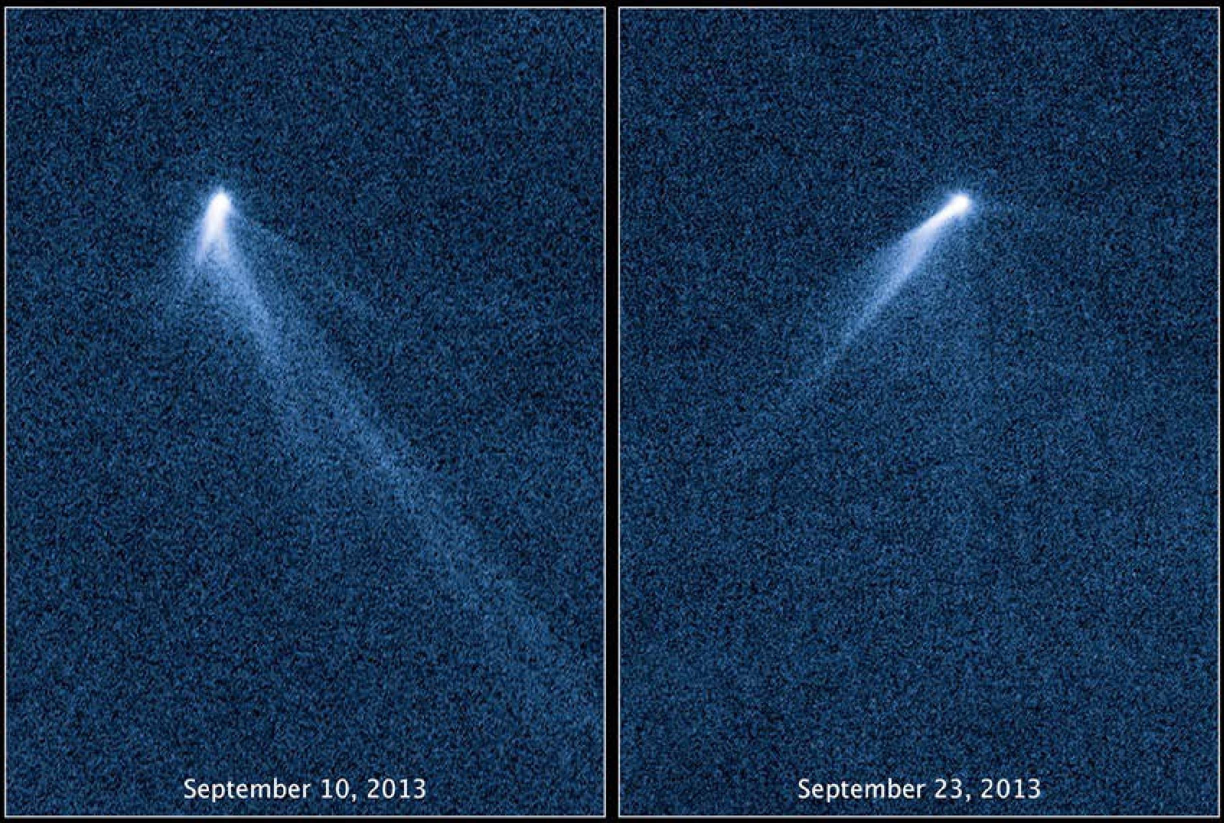
The main body of P/2010 A2 is the surviving remnant of the high-speed collision. The X-shaped filaments are made of dust and gravel, presumably thrown from the asteroid during the collision. Radiation pressure from sunlight likely swept back some of the debris to create the long, straight dust streaks. Ground-based telescopes detected no comet-like gas in the tail, which also supports the impact scenario.

This artist's conception shows a collision between two asteroids where debris plumes are ejected.

Astronomers had long suspected that asteroids are colliding and producing dust, some of which falls into Earth's atmosphere and burns up as luminescent meteors. However, before *Hubble*'s observations of P/2010 A2, no such smashup had been caught in the act.

Disintegrating Asteroids

Hubble astronomers were surprised again in 2013 when they found an asteroid, designated P/2013 P5, with six comet-like tails of dust radiating from it like spokes on a wheel. The multiple tails were discovered in *Hubble* images taken on September 10, 2013. When *Hubble* observed P/2013 P5 again on September 23, 2013, the asteroid's appearance had totally changed. It looked as if the entire structure had rotated.



Hubble first spotted multiple comet-like tails from the asteroid P/2013 P5 on September 10, 2013. The tails had changed by the time *Hubble* observed the asteroid two weeks later.

P/2013 P5 was not a comet because a comet would not eject material in this manner, especially at such a distance from the Sun. Comets experience breakups as their elliptical orbits carry them close to the Sun. However, this object's orbit keeps it farther out, within the asteroid belt.

Astronomers suspected an asteroid collision was to blame. However, the tails could not simply be attributed to an asteroid collision, either. In an asteroid impact, lots of dust would be ejected into space all at once. P/2013 P5 ejected dust for at least five months. Also, the tail structures changed dramatically in a matter of days. The most reasonable interpretation is that the asteroid's rotation rate increased to the point where its surface started flying apart, ejecting dust in episodic eruptions.

Astronomers think that the asteroid was spun up by the pressure of sunlight. The asteroid's spin rate eventually became fast enough that the asteroid's weak gravity could no longer hold it together. Dust avalanching downslope toward the equator, where the rotation rate is fastest, fell off and drifted into space to make a tail. A series of such events produced the multiple tails.

Just a short time later, astronomers were similarly surprised to discover an asteroid that was falling apart. Ground-based telescopes first noticed the asteroid, called P/2013 R3, as a strangely fuzzy-looking object. *Hubble* images revealed that the asteroid was composed of as many as 10 fragments slowly drifting away from each other. The leisurely separation made it unlikely that the asteroid's breakup was caused by a collision, which would be quick and violent. P/2013 R3's disintegration also couldn't be blamed on its ice warming up and vaporizing, because the asteroid was too far from the Sun and therefore too cold. The best explanation was that sunlight was causing the asteroid's rotation rate to increase so much that its weakly bound structure began to pull apart. This was the first time scientists had seen an asteroid crumble into pieces.

A sequence of four *Hubble* images shows the slow breakup of the asteroid P/2013 R3 over three months (October 2013 to January 2014).

Comet Breakups

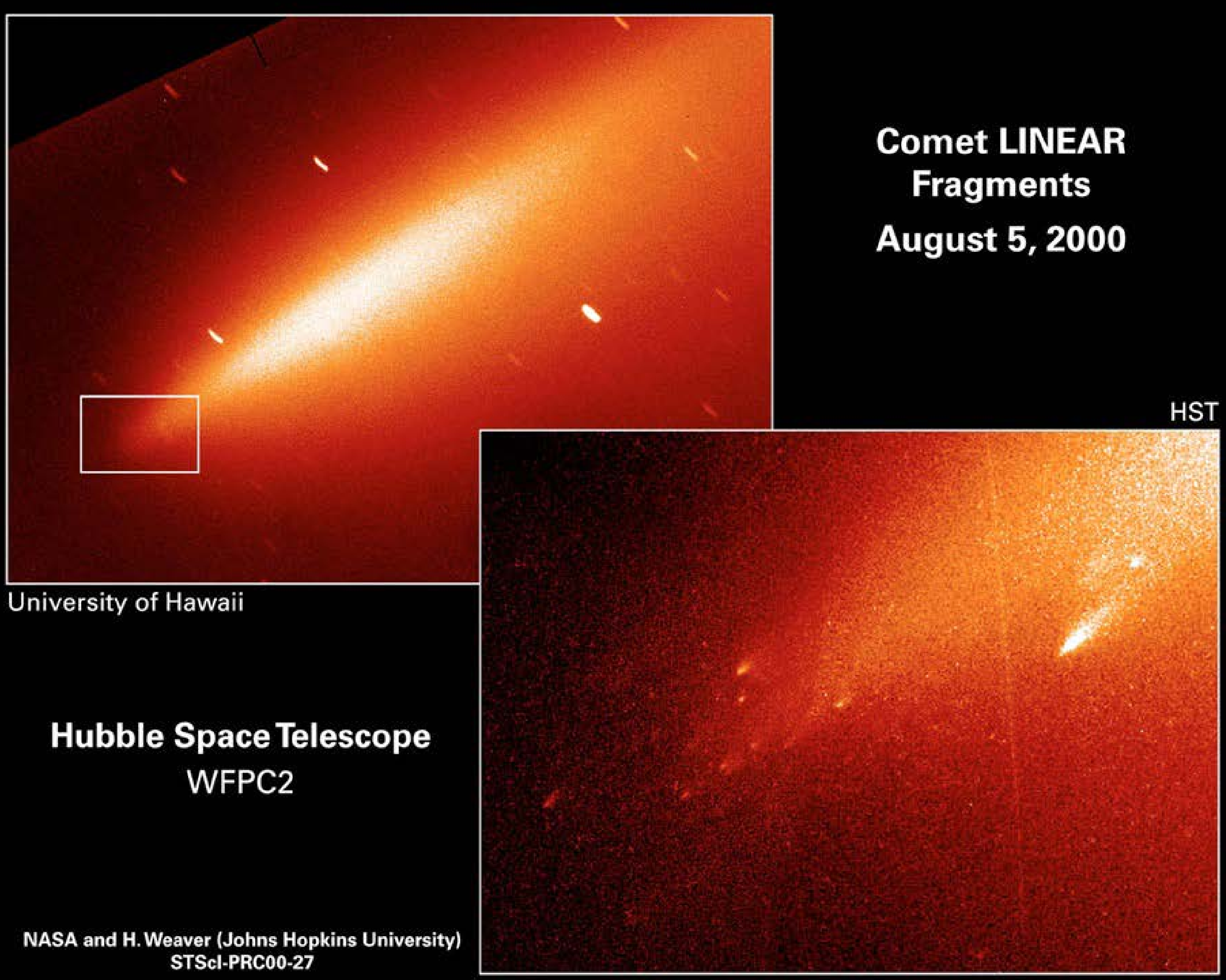
Unlike asteroids, comets have long been known to break apart. Their highly elliptical orbits can carry them very close to the Sun, where they disintegrate under the Sun's blistering heat and strong gravitational forces.

This video, composed of observations by *Hubble* and a ground-based telescope, shows several chunks breaking off of Comet 73P/Schwassmann–Wachmann 3's fragment B.

Hubble's sharp view caught the details of one such comet breakup in early 2006. Ground-based images had revealed that Comet 73P/Schwassmann–Wachmann 3 had splintered into about three dozen icy fragments. *Hubble*'s observations showed that several dozen additional "mini-fragments" trailed behind some of the main fragments and provided unprecedented details about a hierarchical destruction process in which fragments continued to break into smaller chunks.

The "mini-fragments" seen in the *Hubble* images were interpreted as house-sized chunks of the comet's nucleus being pushed down the tail by outgassing from the nucleus. The smaller chunks had the lowest mass and were accelerated away from the parent nucleus faster than the larger chunks. *Hubble* revealed that some of the pieces seemed to dissipate completely over the course of several days.

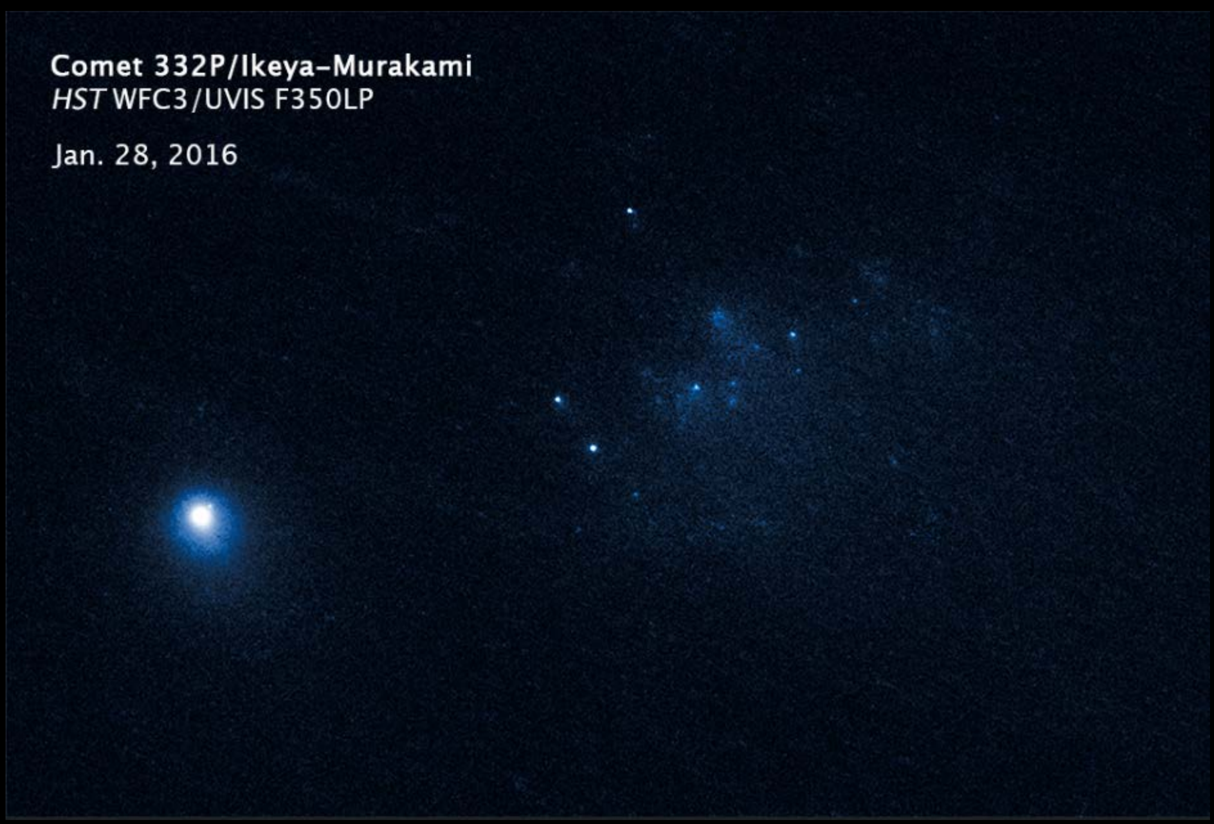
Hubble had observed a similar breakup in 2000. As Comet C/1999 S4 (LINEAR) approached the Sun that year, it disintegrated into a shower of variously sized pieces. An armada of observatories, including *Hubble*, witnessed the comet's dazzling end. *Hubble* was the first to spy a small chunk of the nucleus moving down the comet's tail in early July of that year. By the end of the month, the comet had disintegrated completely. In the debris, *Hubble* resolved at least 16 fragments that resembled "mini-comets"—each roughly the size of a football field and each with a tail.



Ground-based images of Comet C/1994 S4 (LINEAR), such as the one in the upper left taken on August 5, 2000, suggested that the comet's nucleus had vaporized after passing near the Sun. However, a high-resolution *Hubble* image taken about the same time, shown in the lower right, revealed that the nucleus had broken into a shower of "mini-comets." The inset box in the ground-based image shows the area observed in the *Hubble* image. (The faint streak in the *Hubble* image was created by a background star that passed through the exposure as *Hubble* tracked the comet.)

Interestingly, astronomers could only account for about one percent of the total estimated mass of the comet prior to its breakup. Astronomers believe that most of the comet broke into pieces between about 0.1 inch and 160 feet across. Such pebble-sized to house-sized fragments were too small to reflect enough sunlight to be seen in visible light.

More recently, in January 2016, *Hubble* captured some of the most detailed observations of a comet breaking apart as it watched 25 building-sized fragments fall away from Comet 332P/Ikeya–Murakami. For 4.5 billion years the comet had survived in the cold and remote Kuiper belt, but within the last few million years the outer planets gravitationally pulled Ikeya–Murakami into the inner solar system, closer to the Sun. Sunlight heated up the comet's surface, causing jets of gas and dust to erupt, which like rocket engines, spun up the comet's rotation. The faster rotation loosened chunks of material in the comet's nucleus, which began to drift apart in late 2015.



This video, made from *Hubble* images taken over a three-day period in January 2016, shows building-sized fragments drifting away from the nucleus of Comet 332P/Ikeya–Murakami as the comet neared the Sun.

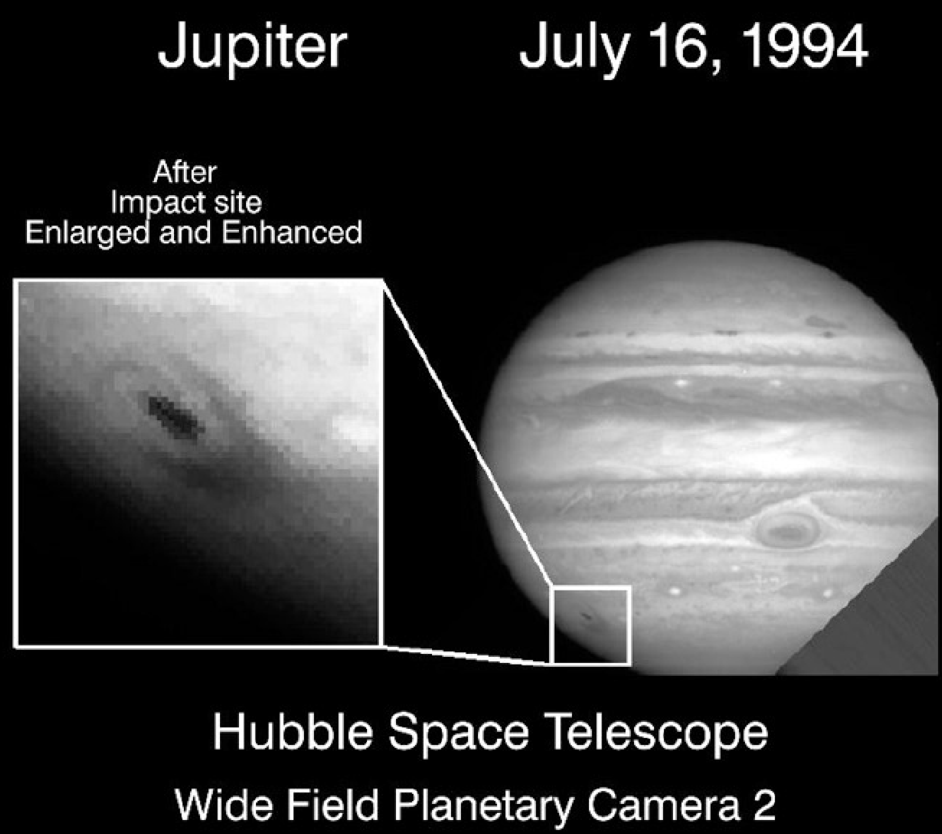
Hubble's observations of Comet Ikeya–Murakami showed that the parent comet changed brightness cyclically, completing a rotation every two to four hours. *Hubble* also revealed that the cometary shards changed shape as they broke apart and changed brightness as icy patches on their surfaces rotated into and out of sunlight.

Collison of the Century

Comet hunters Carolyn Shoemaker, Gene Shoemaker, and David Levy discovered Comet Shoemaker–Levy 9 on March 24, 1993, in a photograph taken with the Schmidt telescope at the Palomar Observatory in California. The discovery image suggested that the comet was unusual because it showed multiple nuclei arranged in a line. Astronomers soon realized the comet was really made up of large fragments of a single cometary nucleus torn apart by gravitational tidal forces as the comet made a close approach to Jupiter in July 1992. Once the orbit was plotted, astronomers realized that the comet was going to collide with Jupiter. This provided a historic opportunity to see a comet impact a planet.

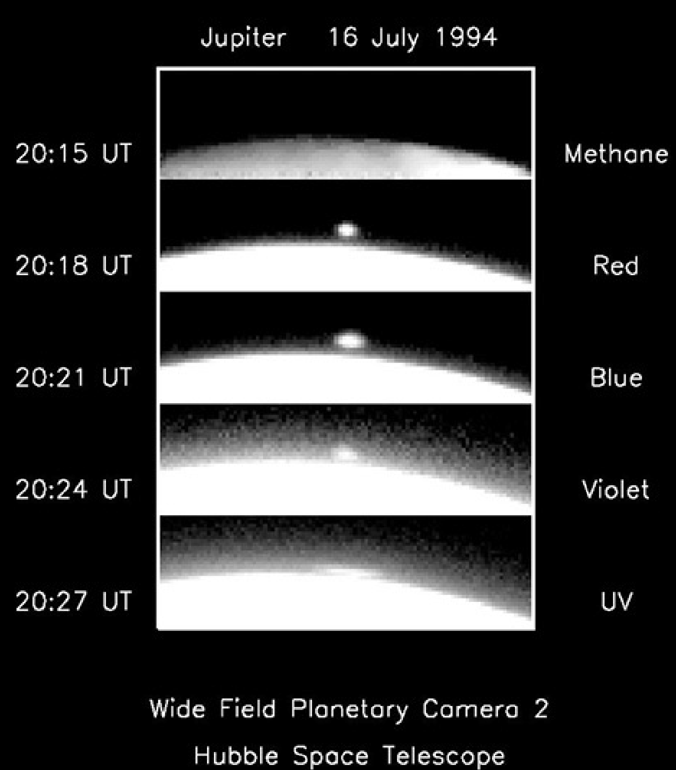
This *Hubble* composite image shows a train of 21 icy fragments from the shattered Comet Shoemaker–Levy 9 heading toward Jupiter.

This "comet train" collided with Jupiter during the third week of July 1994. Each cometary fragment smashed into Jupiter at a velocity of 134,000 mph (fast enough to travel from Earth to the Moon in under two hours). The kinetic energy of each of these impacts unleashed more energy into Jupiter's atmosphere than that of the world's combined nuclear arsenal at the peak of the Cold War. Because the impacts occurred on the nighttime side of Jupiter, the resulting explosions were not directly observable from Earth. But the debris from the impacts made temporary Earth-sized dark spots in Jupiter's upper atmosphere that rotated with Jupiter into *Hubble*'s view.



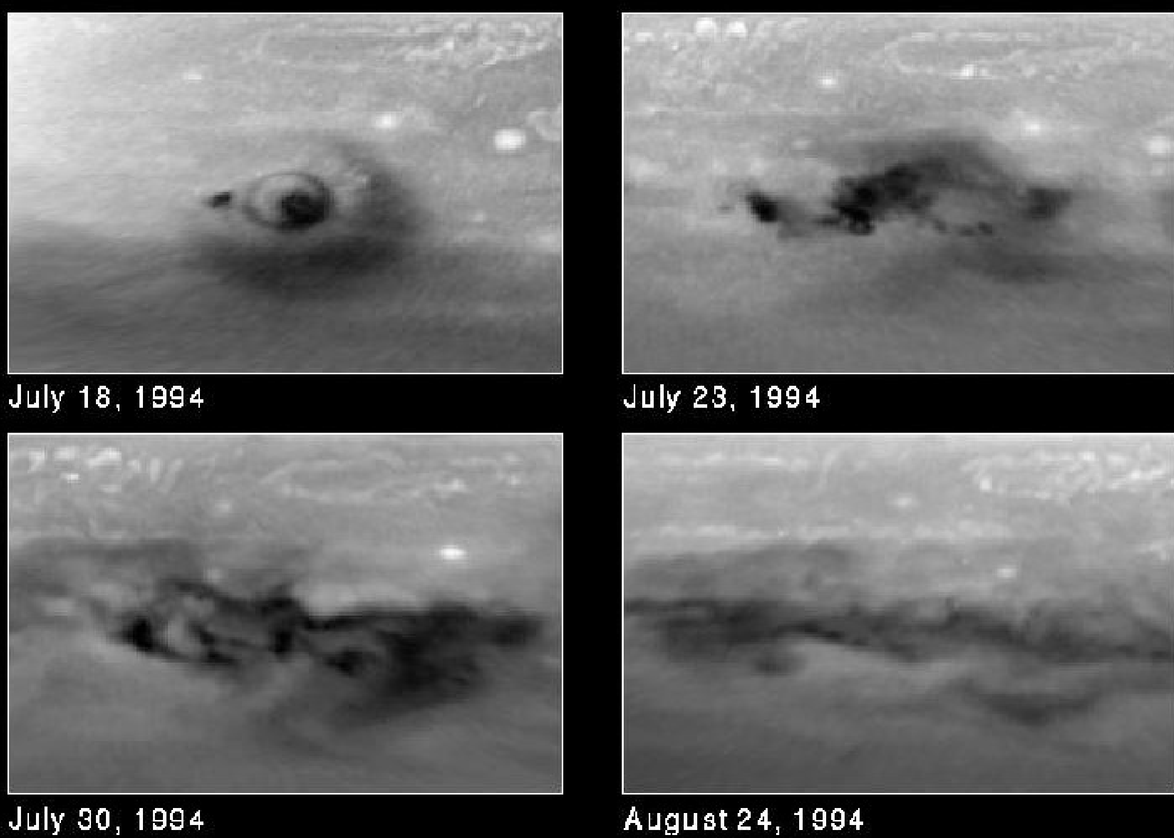
Hubble took this image of Jupiter shortly after the first fragment of Comet Shoemaker–Levy 9 impacted Jupiter. The impact site is visible as a dark smudge, several thousand miles across, in the lower left region of the planet. A close-up view of the impact site is at left.

Before the comet impact, scientists speculated whether the 21 fragments would survive before reaching Jupiter. They were so fragile that gravitational forces might pull them apart into thousands of smaller pieces. *Hubble* answered this question by watching the fragments until about 10 hours before impact. *Hubble*'s high-resolution images showed that the fragments did not break up catastrophically before plunging into Jupiter's atmosphere.



This sequence of *Hubble* images shows a plume appearing over the limb of Jupiter after the first fragment of Comet Shoemaker–Levy 9 struck the planet.

Hubble continued observing Jupiter for several weeks after the impacts to track changes in the dark debris caught up in the high-speed winds at Jupiter's cloud tops. The high-speed easterly and westerly jets turned the dark "blobs" at the impact sites into arc-shaped features. This debris was a natural tracer of wind patterns and gave astronomers a better understanding of the physics of the Jovian atmosphere.

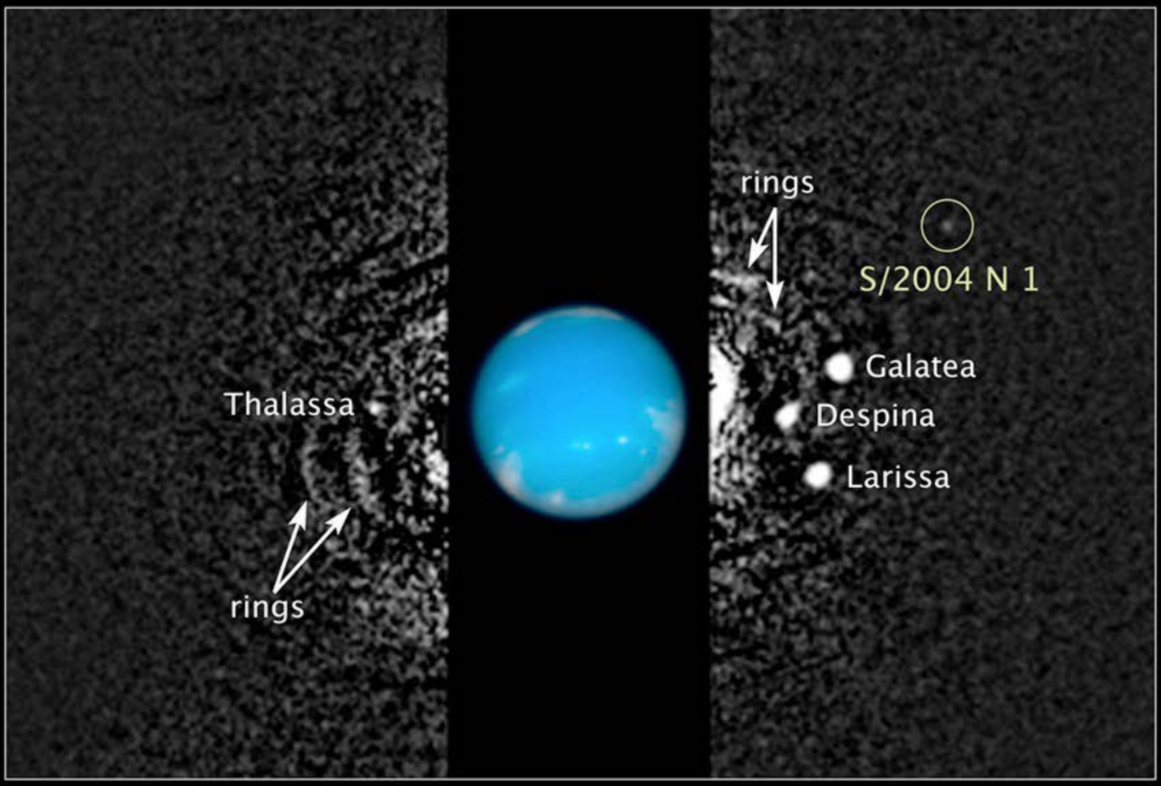


These *Hubble* images reveal the evolution of the Comet Shoemaker–Levy 9 impact region called the D/G complex. This feature was originally produced by two fragments of Comet Shoemaker–Levy 9 that collided with Jupiter on July 17 and 18, 1994. Another fragment hit the site on July 21, further distorting the area.

New Moons

Though there are only eight major planets known to be circling the Sun, there are hundreds of known moons. A large inventory of moons was made by NASA's interplanetary missions of the 1970s and 1980s. For example, when NASA's *Voyager 2* spacecraft flew past Neptune in 1989, it discovered six previously unknown moons orbiting the planet.

Surprisingly, *Hubble* discovered yet another moon that *Voyager*'s cameras apparently missed because it is so small. The moon was uncovered in 2013 during an analysis of faint "ring arcs" of debris that encircle Neptune. The photo captured an unidentified dot about 65,400 miles from Neptune, between the orbits of the moons Larissa and Proteus.



This composite *Hubble* picture shows the location of a newly discovered moon, designated S/2004 N 1, orbiting Neptune. Several other moons that were discovered by the *Voyager* spacecraft appear in the image, along with structures known as ring arcs, which encircle the planet.

After this discovery, astronomers reviewed 150 archival Neptune photographs taken by *Hubble* from 2004 to 2009. The same dot appeared over and over again. The archival images provided enough information for astronomers to plot a circular orbit for the moon, which completes one revolution around Neptune every 23 hours. The moon, provisionally designated S/2004 N 1, is likely no more than 12 miles across. It is so small and dim that it is roughly 100 million times fainter than the faintest star that can be seen with the naked eye.

Similarly, *Hubble* discovered two tiny moons of Uranus in 2003 that had eluded detection during *Voyager 2*'s flyby of the planet in 1986. The two dim moons, now named Cupid and Mab, are only about 10 miles wide apiece. Mab shares an orbit with a giant ring around Uranus that *Hubble* uncovered in 2004, and scientists suspect that material in the ring is being supplied by dust blasted off Mab's surface from meteoroid impacts.

Hubble spotted two small moons around Uranus in 2003 This sequence of *Hubble* exposures shows one of the moons, called Mab (circled).

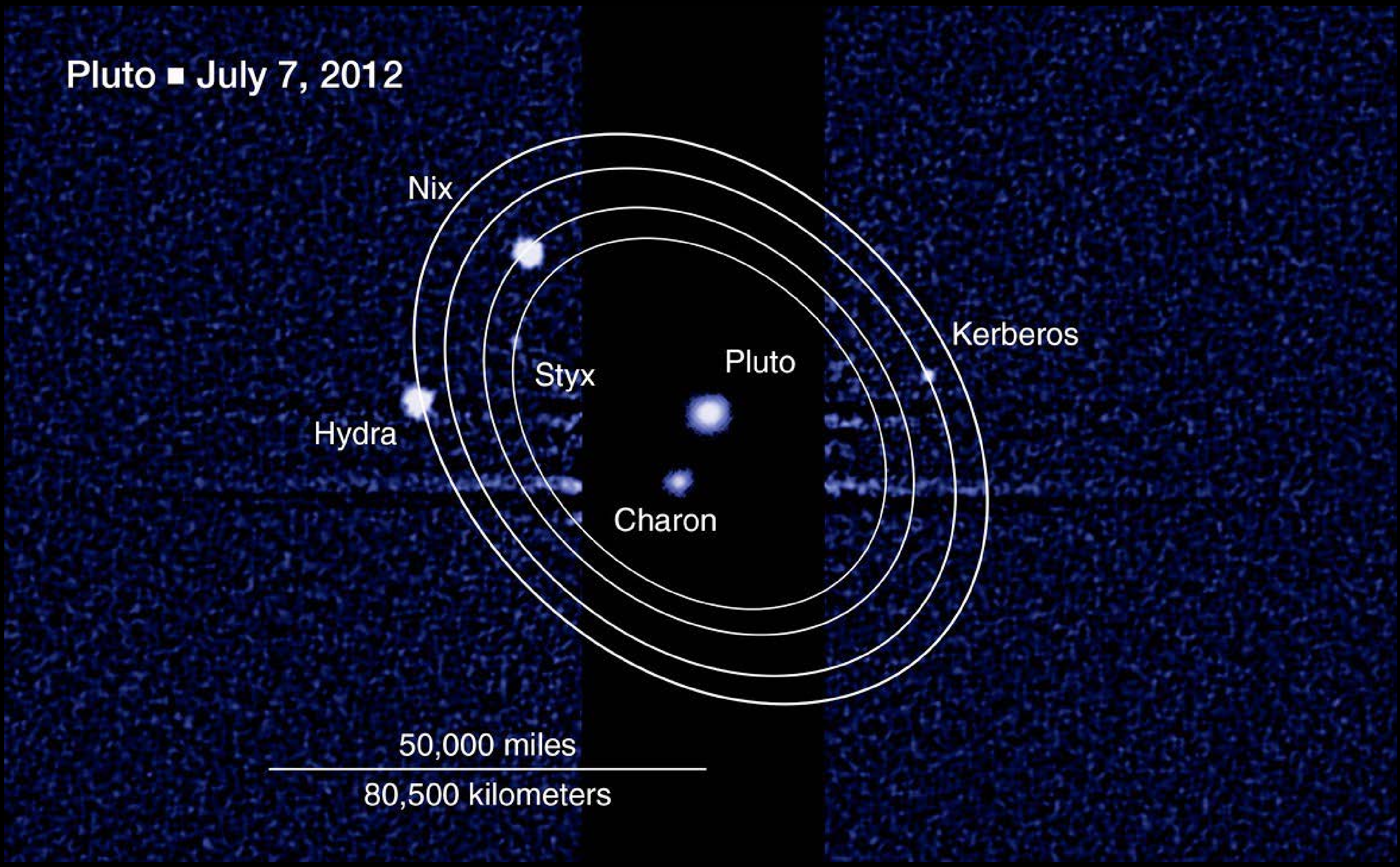
Pluto’s Satellite System

Though Pluto was discovered in 1930, a companion body called Charon wasn’t discovered until 1978, in observations made at the United States Naval Observatory in Washington, D.C. Charon is such a relatively massive companion relative to Pluto (12 percent of Pluto’s mass) that the Pluto-Charon system can be regarded as a binary system, where the two worlds orbit a common center of gravity, or barycenter, located in the space between the two objects. This is analogous to binary stars, which dynamically behave in a similar manner.

Hubble recorded this image of Pluto (lower left) and Charon (upper right) in 1994 when they were 2.6 billion miles from Earth. The two objects appear clearly as separate, sharp disks.

While surveying the Pluto system to uncover potential hazards to NASA’s *New Horizons* spacecraft, *Hubble* discovered four additional moons orbiting both Pluto and Charon. Astronomers were intrigued to find that a binary dwarf planet can have such a complex collection of satellites.

The chain of discoveries started in 2005 when *Hubble* uncovered two very small moons, named Nix and Hydra, that are much farther from Pluto than Charon is. In 2011 *Hubble* spotted another tiny moon, Kerberos. And a year later, in 2012, *Hubble* images revealed the moon now known as Styx.



Hubble discovered two small moons orbiting Pluto and Charon, named Nix and Hydra, in 2005 and later found two even smaller moons, Kerberos and Styx, in 2011 and 2012. Pluto's moons are named for mythological figures associated with the underworld.

The *Hubble* observations show that the satellites' orbits are all co-planar. This discovery offers important clues to the moons' origins and to how the Pluto system formed and evolved. The favored theory is that the four small moons are relics of the same collision that formed Charon.

In 2014, a comprehensive analysis of *Hubble* data showed that two of the moons, Nix and Hydra, are wobbling unpredictably. The moons are too small for *Hubble* to resolve in detail. However, *Hubble*'s first clues to the moons' dynamical chaos came when astronomers measured variations in the light reflected off of Nix and Hydra. Their brightness changed unpredictably. Researchers analyzed these brightness changes using dynamical models of spinning bodies in complex gravitational fields.

Nix and Hydra's motions are chaotic because the moons are embedded inside a dynamically shifting gravitational field, caused by the system's two central bodies, Pluto and Charon, orbiting each other. The variable gravitational field induces torques (twisting forces) that send the smaller moons tumbling in unpredictable ways. This torque is amplified by the moons' elongated shapes.

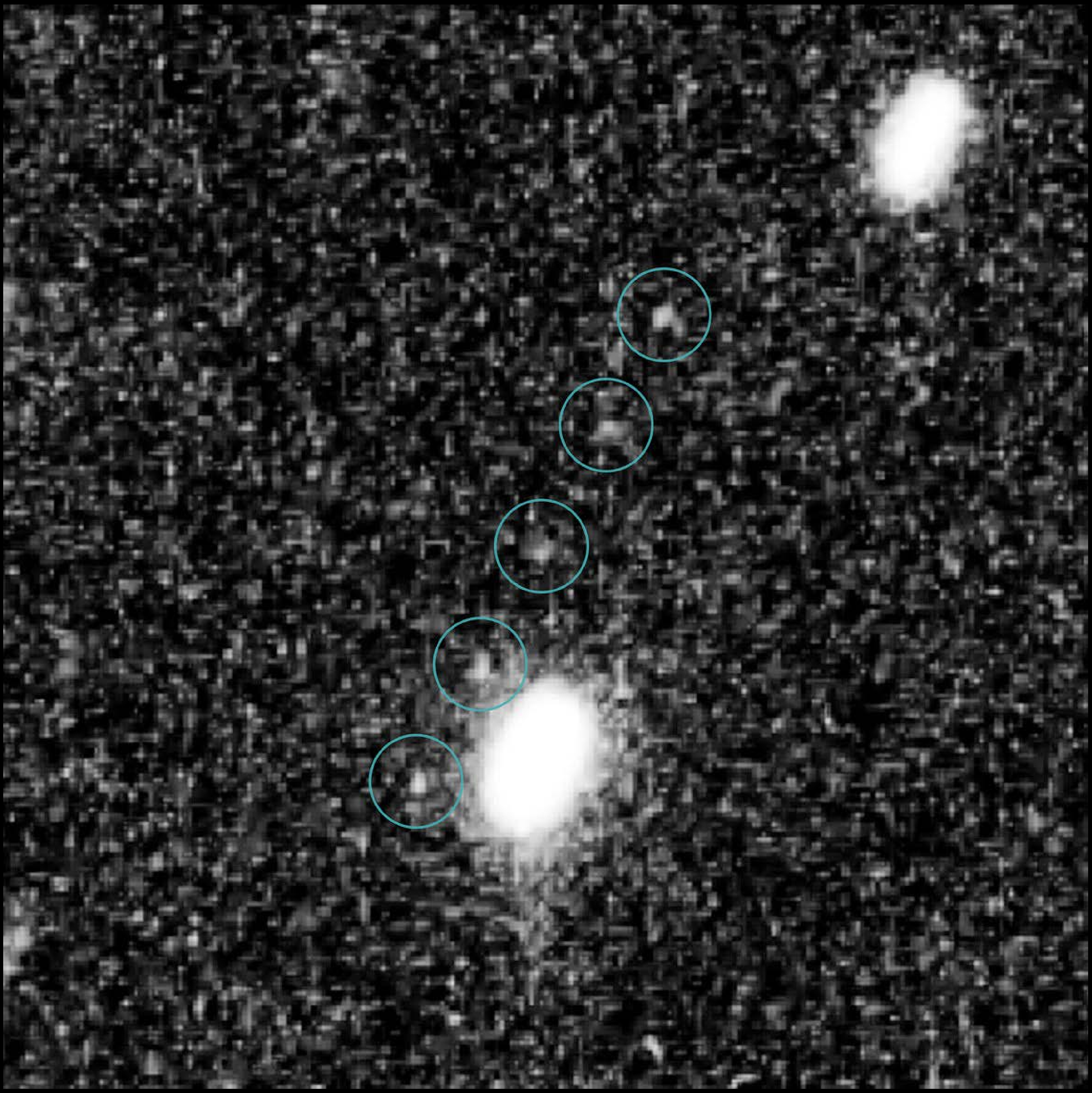
This computer animation shows how the moon Nix wobbles as it orbits Pluto and Charon. The animation compresses two years of motion into two minutes, with one complete orbit of Pluto and Charon every two seconds. Nix appears as it would be seen from the surface of Pluto.

Prior to the *Hubble* observations, astronomers did not anticipate such intricate dynamics in the Pluto system. Virtually all large moons, as well as small moons in close-in orbits, keep one hemisphere facing their parent planet. This means that the satellite's rotation is perfectly matched to the orbital period. Hyperion, which orbits Saturn, is the only other solar-system example of chaotic rotation. (Its unusual rotation is due to the combined gravitational tugs of Saturn and it largest moon, Titan.) Further studies may reveal that Pluto's two other small moons, Kerberos and Styx, wobble chaotically as well.

A Flyby Target in the Kuiper Belt

Members of the *New Horizons* mission team knew that after the spacecraft flew past Pluto in 2015, it would have the ability to study other objects in the Kuiper belt. However, for years after *New Horizons* was launched, there remained no known objects that the spacecraft would be able to reach with the amount of fuel remaining onboard.

In 2014, *Hubble* took up the case. *Hubble* found two strong flyby candidates for *New Horizons*, both about a billion miles beyond Pluto. The mission team eventually settled on one called 2014 MU_{69}, estimated to be just under 30 miles across. In late 2015, after completing its study of the Pluto system, *New Horizons* changed course for an encounter with 2014 MU_{69} on January 1, 2019.



On January 1, 2019, NASA's *New Horizons* spacecraft will fly past a small object in the Kuiper belt named 2014 MU_{69}. The object was discovered by *Hubble* in 2014 during a search for potential flyby targets. This composite image shows the faint object moving (circled) against a field of brighter background stars.

Makemake Moon

In addition to the small moons orbiting Pluto and Charon, *Hubble* has discovered companions around dozens of other members of the Kuiper belt—some nearly equal in size to the primary object and others that are much smaller satellites. Such binary systems provide valuable clues to the nature of these distant worlds. By tracking the orbits of these companions, scientists can calculate the masses of the objects, estimate their densities, and figure out what they might be made of.

In 2016 *Hubble* found that the second brightest Kuiper belt object after Pluto, named Makemake after a creation deity of the Rapa Nui people of Easter Island, has a satellite. The moon—provisionally designated S/2015 (136472) 1 and nicknamed MK 2—is more than 1,300 times fainter than Makemake. MK 2 was seen approximately 13,000 miles from the dwarf planet, and is estimated to be 100 miles across. Makemake is 870 miles wide.

This *Hubble* image reveals the first moon discovered around the dwarf planet Makemake. The tiny moon (arrowed) is almost lost in the glare of the dwarf planet.

Hubble's sharp resolution and ability to see faint objects near bright ones allowed astronomers to pick out Makemake's moon. Yet, previous *Hubble* searches for a moon around Makemake had turned up empty. Astronomers attribute the moon's elusiveness to an edge-on orbit. This orientation means that more often than not *Hubble* cannot spot the moon because the object is lost in Makemake's glare.

Astronomers still need to determine the shape of the moon's orbit, however. This will help settle the question of MK 2's origin. A tight circular orbit means that the moon is probably the product of a collision between Makemake and another Kuiper belt object. If the moon is in a wide, elongated orbit, chances are it is a captured object from the Kuiper belt. Either event would have likely occurred several billion years ago.

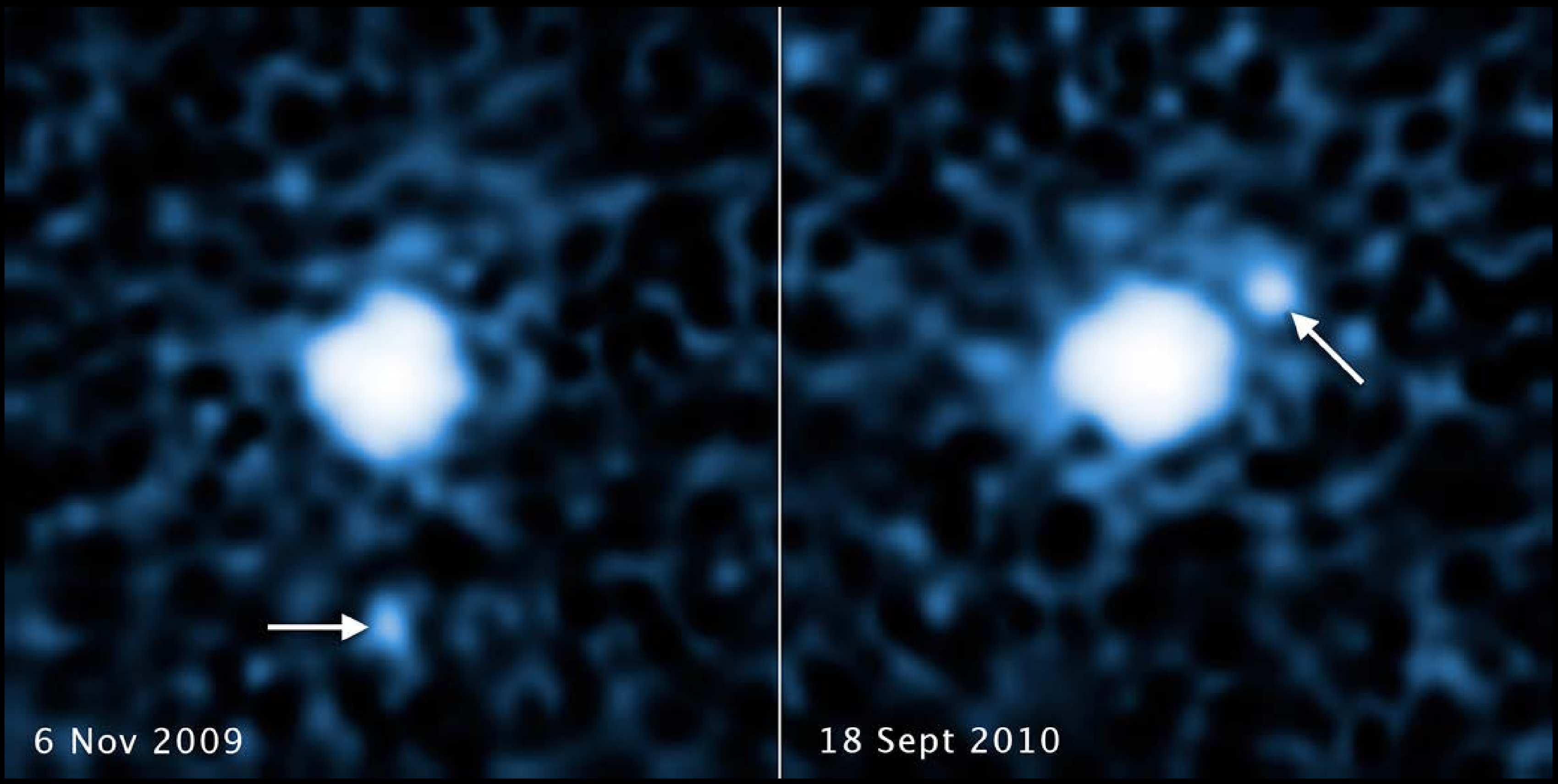
Additionally, by measuring the moon's orbit, astronomers can calculate a mass for the system and determine the density of Makemake.

This artist's concept shows the distant dwarf planet Makemake and its moon, MK 2, with the dim Sun in the background.

MK 2 is unique in that it has a charcoal-black surface, even though Makemake is as bright as snow due to methane frost. One possible explanation is that, unlike larger objects such as Makemake, MK 2 is small enough that it cannot gravitationally hold on to a bright, icy crust, which sublimates (or changes from solid to gas) under sunlight. This would make the moon similar to many comets and Kuiper belt objects that are small and covered with very dark material.

Another Kuiper Belt Moon

When NASA's *Kepler Space Telescope*, operating during its extended K2 mission, observed a Kuiper belt object called 2007 OR_{10} in late 2014, *Kepler* revealed that the object had an unusually slow rotation rate. Suspecting that a moon could be gravitationally pulling on the object and slowing down its rotation, astronomers examined archived *Hubble* images of 2007 OR_{10} taken in 2009 and 2010 and discovered a faint moon in both sets of images. While 2007 OR_{10} is about 950 miles wide, its moon is estimated to be only about 200 miles across.



Archived *Hubble* images from 2009 and 2010 revealed the presence of a moon (arrowed) orbiting the distant Kuiper belt object 2007 OR_{10}.

Identifying the moon was no easy feat, as 2007 OR_{10} is one of the most distant objects ever observed in the solar system. At the time of the moon's discovery, 2007 OR_{10} was three times farther than Pluto is from the Sun.

In addition, 2007 OR_{10} is currently ranked as the third largest solar system object known to exist beyond Neptune. With the discovery of this moon, most of the large objects in the Kuiper belt are now known to have satellites. Astronomers have not yet found a companion to distant Sedna, but it is so far away that any companion would be extremely hard to detect, even with *Hubble*.

Summary

Hubble's precision, wavelength range, and longevity have helped astronomers discover new dynamics in the solar system, provide support to interplanetary probes, and monitor changes on the planets over decades.

Hubble has revealed atmospheric variations, weather patterns, and seasonal shifts on the planets, and it will continue to do so with its Outer Planet Atmospheres Legacy (OPAL) program. Future *Hubble* observations of plume activity on Europa could help guide future missions to study and collect samples of subsurface water from the Jovian moon. And *Hubble*'s ongoing investigations of the smaller bodies orbiting the Sun will help astronomers better understand how our solar system came to be and how it continues to evolve.

Years of *Hubble* observations will also lay the groundwork for NASA's *James Webb Space Telescope* (*JWST*). With its infrared capabilities, *JWST* will investigate planetary atmospheric dynamics in new ways, it will peer through Titan's hazy atmosphere to track surface brightness changes due to rainfall, geologic activity, or sea shrinkage, and it will study the dim, far-off Kuiper belt objects at the outskirts of our solar system. *JWST* will both complement and extend *Hubble*'s long legacy of exploring our amazing solar system.

Further Reading

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More Information

For more information about the *Hubble Space Telescope* mission and its discoveries, visit NASA's *Hubble* website at http://www.nasa.gov/hubble. For additional details and resources, visit HubbleSite.org at http://hubblesite.org.

To learn more about NASA's exploration of the solar system, visit the NASA Solar System Exploration website at https://solarsystem.nasa.gov.

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Credits

The *Hubble Space Telescope* is a cooperative project between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The Space Telescope Science Institute (STScI), operated by the Association of Universities for Research in Astronomy (AURA), conducts the science operations for the *Hubble Space Telescope* under contract NAS5-26555.

Hubble Focus: Our Amazing Solar System was produced by NASA Goddard Space Flight Center and STScI. It was published in September 2017.

The production team for this book included Ken Carpenter, Pat Crouse, Kevin Hartnett, James Jeletic, Vanessa Thomas, and Jennifer Wiseman at NASA Goddard Space Flight Center, as well as Pam Jeffries, Ann Jenkins, and Ray Villard at STScI. Special thanks to Keith Noll (NASA GSFC) for additional science review.