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Ten Years Hubble Space Telescope

Editorial

Give me the material, and I will build a world out of it!

Immanuel Kant (1724–1804), the great German philosopher, began his scientific career on the roof of the Friedrich's College of Königsberg, where a telescope allowed him to take a glance at the Universe inspiring him to his first masterpiece, the "Universal Natural History and Theory of Heaven" (1755). Applying the Newtonian principles of mechanics, it is the result of systematic thinking, "rejecting with the greatest care all arbitrary fictions". In his later Critique of the Pure Reason (1781) Kant maintained that the human intellect does not receive the laws from nature, but rather dictates them upon it, since our mind requires a priori rules in space and time, in cause and in effect, in order to understand nature. And the result of his cosmological studies confirms the strength of his empirical thinking. Sapere aude: "dare use your mind," used he to say to his critics.

In his Universal Natural History he wrote: "Nature, on the immediate edge of creation, was as raw and undeveloped as possible. Only in the essential properties of the elements, which made up the chaos, can we perceive the sign of that perfection, which nature has from its origin, since its being is a consequence arising from the eternal idea of the Divine understanding". Can one better describe the dawn of this world?

The present issue of Spatium is dedicated to a scientist who lived a century after Kant and a telescope built another century later. The Hubble Space Telescope has revolutionised our understanding of the cosmos much the same as Kant's theoretical reflections did. Observing the heavenly processes, so far out of any human reach, gives men the feeling of the cosmos' overwhelming forces and beauties from which Immanuel Kant derived the order for a rational and moral human behaviour: "the starry heavens above me and the moral law within me…".

Who could be better qualified to rate the Hubble Space Telescope's impact on astrophysics and cosmology than Professor Roger M. Bonnet, the former Director of Science at the European Space Agency? It was under his guidance that in the frame of a joint NASA/ESA programme the Hubble Space Telescope was created, leading to one of the many marvellous achievements of the European Space Agency's science programme. R. M. Bonnet, now the International Space Science Institute's Executive Director, gave a fascinating lecture on the Hubble Space Telescope to the Pro ISSI audience on 6 November 2003. We are indebted to Professor Bonnet for his kind permission to publish herewith a slightly revised version of his lecture.

Sapere aude!

Hansjörg Schlaepfer
Zürich, June 2004

Impressum

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Front cover: The beautiful Eskimo Nebula is an intricate structure of shells and streamers of gas around a dying Sun-like star 5000 light-years away. The disc of material is embellished with a ring of comet-shaped objects, their tails streaming away from the central, dying star. The planetary nebula began to form about 10,000 years ago, when the dying star started to expel an intense 'wind' of high-speed material out into space. (Credit: Space Telescope Science Institute, STScI)

Ten Years Hubble Space Telescope *)

Roger M. Bonnet, International Space Science Institute, Bern

The Man…

Edwin Powell Hubble was born in Marshfield, Missouri, USA, on November 29, 1889. In 1898, his family moved to Chicago, where he attended high school. Edwin Hubble was a fine student and an even better athlete, but he also found time to study and earn an undergraduate degree in mathematics and astronomy. He then went to Oxford University, where he did not continue his studies in astronomy, but instead studied law.

In 1913, Hubble returned from England and was called to the barrister, setting up a small practice in Louisville, Kentucky; but it didn't take long for him to realise that he was not happy as a lawyer, and that his real passion was astronomy. He therefore studied at the Yerkes Observatory and received in 1917 the doctorate in astronomy from the University of Chicago. Following a tour of duty in World War I, Hubble was employed at the Mount Wilson Observatory in California, where he devised a classification system for the various galaxies he observed, sorting them by content, distance, shape, and brightness. It was during these studies that he noticed the red shifts in the emission of light from galaxies, which he correctly interpreted as moving away from each other at a rate proportional to their distance. From these observations, he was able to formulate in 1929 the so-called Hubble's Law, allowing astronomers to determine the age of the universe, and proving that the universe was expanding.

It is interesting to note here that as early as 1917, Albert Einstein had already introduced his general theory of relativity, and produced a model of space based on that theory, claiming that space was curved by gravity, therefore that it must be able to expand or contract; but he found this assumption so far fetched, that he revised his theory, stating that the universe was static. Following Hubble's discoveries, he is quoted as having said that second guessing his original findings was the *biggest blunder* of his life, and he even visited Hubble to thank him in 1931.

After World War II, Edwin Hubble returned to the Mount Wilson and Mount Palomar observatories and continued his studies until his death on September 28, 1953. During his life, Hubble had tried to obtain the Nobel Prize, even hiring a publicity agent to promote his cause in the late 1940s, but all the effort was in vain as there was no category for astronomy. With or without a Nobel Prize he will forever be remembered as the father of observational cosmology and as a pioneer of the distant stars.

Figure 1
Edwin Hubble around 1920

*) Pro ISSI lecture, Bern, November 6, 2003

…and the Telescope

Its History

In the 1970s, NASA and ESA took up the idea of a space-based telescope. Funding began to flow in 1977. Later, it was decided to name the telescope after Edwin Hubble. Although the Hubble Space Telescope (HST) was downsized later to a 2.4 m primary mirror diameter from the initial 3 m, the project started to attract significant attention from astronomers.

The precision-ground mirror was finished in 1981 and the assembly of the entire spacecraft was completed in 1985. The plan called for a launch on NASA's Space Shuttle in 1986 but just months before the scheduled launch, the Challenger disaster caused a 2-year delay of the entire Shuttle programme. HST was finally launched on 24 April 1990. Soon after, the tension built up as astronomers examined the first images through the new telescope's eyes. It was soon realised that its mirror had a serious flaw: the mirror edge was too flat by a mere fiftieth of the width of a human hair, enough of focusing defect to prevent it from taking sharp images.

Fortunately, the HST was the first spacecraft ever to be conceived as serviceable. That made it possible for engineers and scientists at the Space Telescope Institute in Baltimore (USA) to come up with a cleverly designed corrective optics package that would restore the telescope's eyesight completely. A crew of astronauts including Claude Nicollier carried out the repairs necessary to restore the telescope to its intended level of performance during the first Hubble Servicing Mission (SM1) in December 1993. This mission captured the attention of both astronomers and the public at large to a very high degree: meticulously planned and brilliantly executed, the mission succeeded on all counts. It will go down in history as one of the great highlights of human space flight. Hubble was back in business!

The European contribution covered a nominal 15% stake in the mission including the Faint Object Camera, the first set of two solar panels that powered the spacecraft as well as a team of space scientists and engineers at the Space Telescope Science Institute (STScI) in Baltimore. Contraves Space of Zurich provided the Primary Deployment Mechanism, assuring the deployment of the solar panels either by a command from the onboard computer or manually by an astronaut.

The Spacecraft

The Hubble Space Telescope is a long-term, space-based observatory. Observations are carried out in the visible, infrared, and ultraviolet light. It circles the Earth in 96 minutes on a circular orbit 600 km above the ground, inclined 28 deg. to the equator. Hubble's orbit above the Earth and its excellent stability allow astronomers to make the high resolution observations that are essential to open new windows to planets, stars, and galaxies. Furthermore, access to the infrared and ultraviolet light window can only be achieved from space, because the atmosphere prevents it from reaching the ground.

At the heart of the HST are a 2.4 m primary mirror, fine guidance sensors and gyroscopes as well as a collection of four science instruments that work from the near infrared through the visible to ultraviolet light. There are two cameras and two combined camera/spectrographs. Power for the computers and the scientific instruments onboard is provided by large solar panels.

The telescope uses an elaborate system of attitude controls to secure its stability during observations. The spacecraft has a pointing stability of 0.007 arcsec, which is equivalent to a 1 € coin in Paris seen from Bern. A system of reaction wheels manoeuvres the telescope into place and its position in space is monitored by gyroscopes. The fine guidance sensors are used to lock onto guide stars to ensure the extremely high pointing accuracy needed to make very accurate observations.

The Hubble Space Telescope Servicing Concept

As stated above, the Hubble Space Telescope was built around a revolutionary servicing concept from the very beginnings. The concept aimed at allowing not only repair missions in case of faulty components, but also to replace subsystems once technologically more advanced instruments or computers have become available. In addition, this concept allowed the mission to be put on track after the repair of the initial flaw of the primary mirror.

Since SM1, three other Servicing Missions have been carried out: during SM2 in 1997 two new instruments were installed. In Service Mission SM3A (1999) many of the spacecraft's crucial technical systems were exchanged. During SM3B in 2002 the telescope was again equipped with new science instruments. In the wake of the Columbia accident, however, and as a first consequence of the strategic redirection of the US science programme, NASA has cancelled the next servicing mission, which was foreseen in 2003. At this moment in time it is not yet clear whether the telescope will be serviced again. This may lead to a much shorter service life as compared to the initial plans, which foresaw an end of mission in 2010.

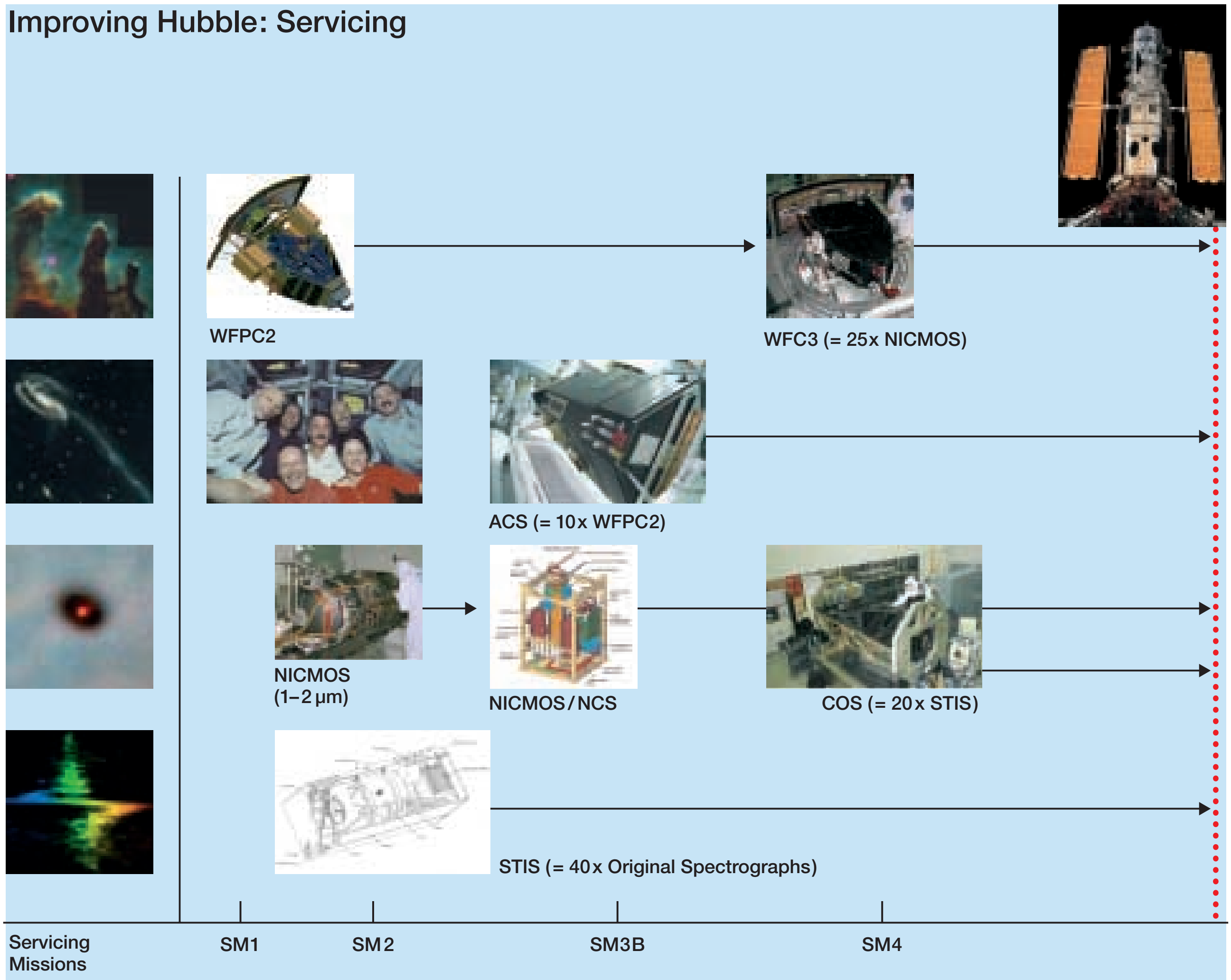


Figure 2 shows the servicing mission planning

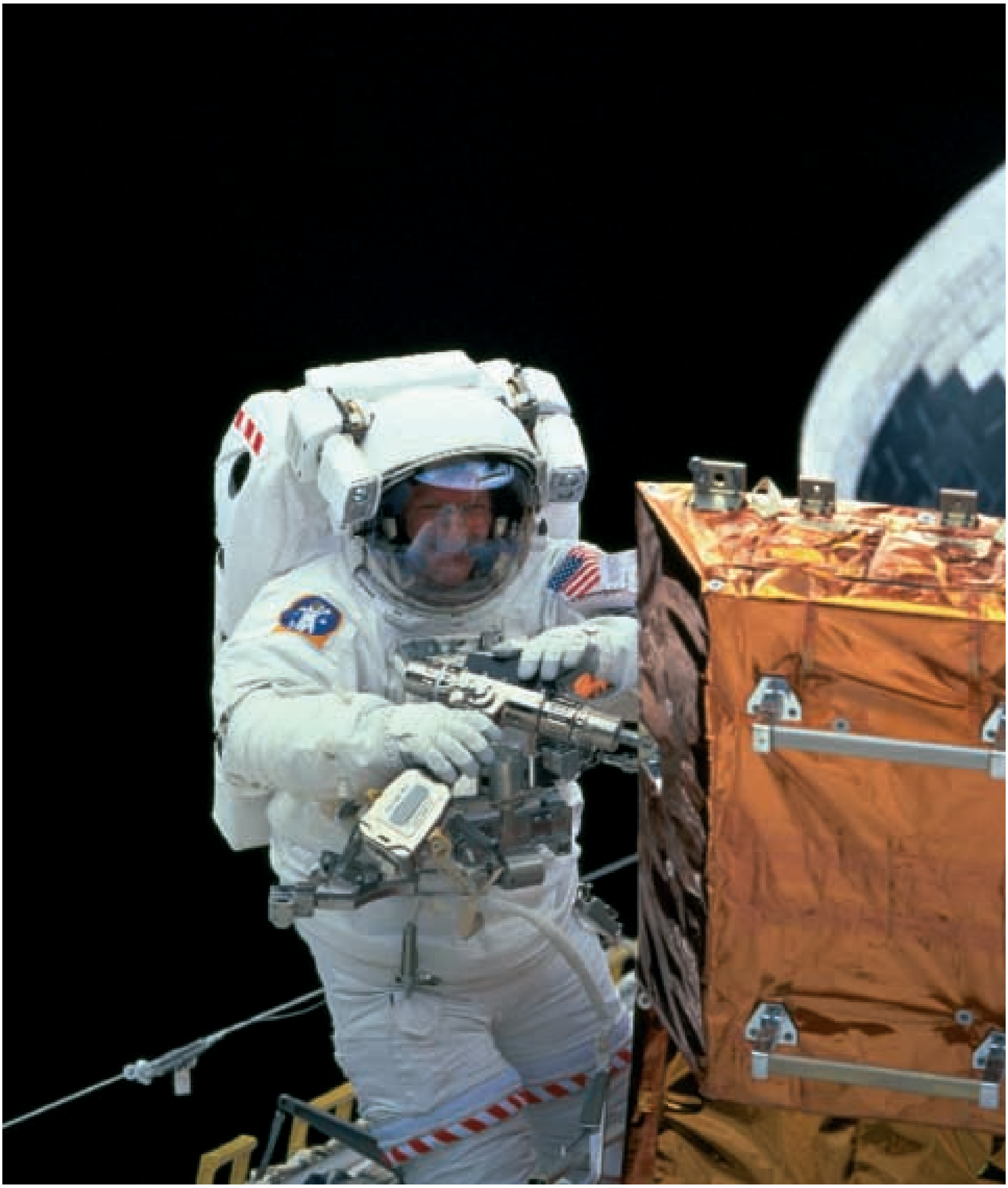


Figure 3: The famous photograph of Claude Nicollier as a happy space worker on the first Hubble Space Telescope Servicing Mission (Credit: NASA)

The Instruments

Hubble's science instruments currently include two cameras, two imaging spectrographs and a suite of fine guidance sensors:

The Wide-Field Planetary Camera 2 (WFPC-2)

The WFPC-2 is Hubble's workhorse camera. It records images through selection of 48 colour filters covering a spectral range from the far ultraviolet to visible and near-infrared wavelengths. It has produced most of the pictures that have been released as public outreach images over the years. Its resolution and excellent quality have made it the most used instrument in the first ten years of Hubble's life.

The Space Telescope Imaging Spectrograph (STIS)

The STIS is a versatile dual-purpose instrument consisting of a camera and a spectrograph operating over a wide range of wavelengths from near infrared to the ultraviolet.

The Near Infrared Camera and Multi-Object Spectrometer (NICMOS)

The NICMOS can take images and make spectroscopic observations of astronomical targets. It detects infrared light between 0.8 µm to 25 µm.

The Advanced Camera for Surveys

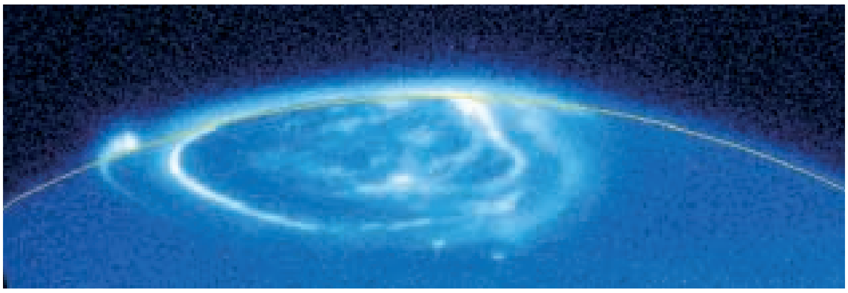
This camera replaced the initial Faint Object Camera built by the European Space Agency, which was returned to ESA after the Servicing Mission S3B.

The Fine Guidance Sensors (FGS)

The HST has three Fine Guidance Sensors on board. Two of them are used to point and lock the telescope onto the target and the third can be used for astrometry, making very precise position measurements to establish stellar distances and investigate stellar binary systems.

Figure 4 shows the Hubble Space Telescope after release from its first servicing mission.

Scientific Highlights



From Solar System Science…

Thanks to its unrivalled optical resolution power, HST provides visual information about the Solar System on a near continuous basis (as opposed to planetary fly-by's). The following examples show some of the most striking results in the field of Solar System research.

Figure 5 shows Jupiter's aurora with the footprints of its moons Io, Ganymede and Europa. Since Jupiter possesses a strong magnetic field, the footprints of its moons become visible. Io produces particles from volcanic eruptions. The ionised gas becomes trapped by Jupiter's magnetic field. As the particles spiral along the magnetic field lines, they hit Jupiter's atmosphere near the poles (the magnetic field threads the north and south poles similar to Earth's magnetic field). Generally, the particles follow the moon's field lines to the poles with some straggling particles providing the lagging lines. HST discovered this phenomenon because, unlike the earlier Voyager flybys, it can observe the planets continuously on timescales ranging from minutes to years. (Credit: STScI, John Clarke)

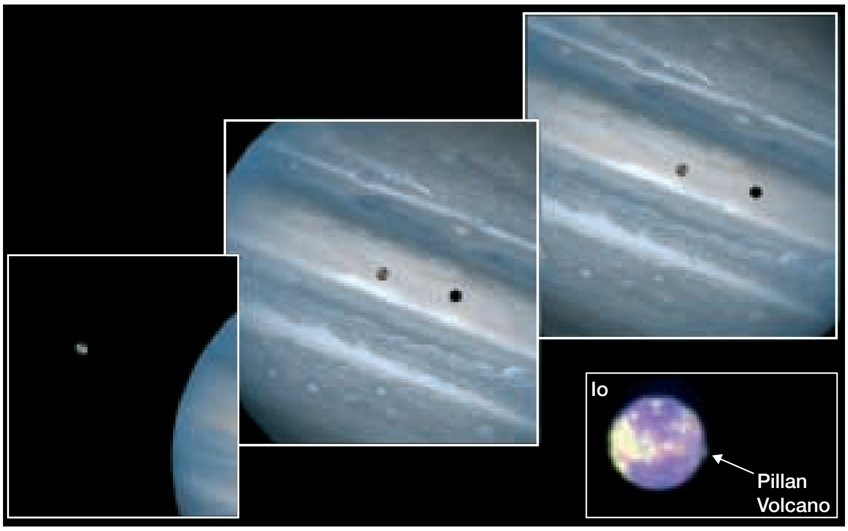


Figure 6: Transit of Io above Jupiter. HST is not only able to show the Jupiter moons, but also the shadows they cast onto the surface of Jupiter. On the left image, Jupiter's moon Io is seen on the left from Jupiter. In the centre and the right images Io, together with its shadow is seen before the planet. Even Io's volcanic activity can be identified with the 400 km high gas and dust plume emerging from its silhouette (right, bottom image). (Credit: STScI, J. Spencer)

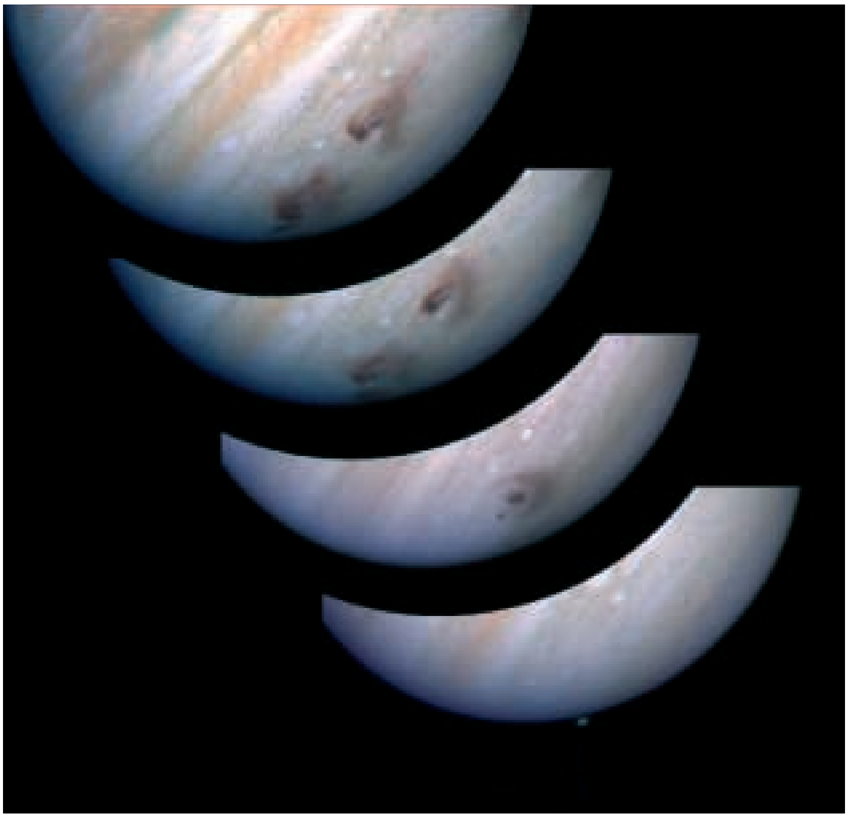


Figure 7 captures a cosmic catastrophe, when in 1994 the comet Levy-Shoemaker came near Jupiter, which by virtue of its giant gravitational field not only attracted the comet but also broke it into parts. This figure shows Jupiter being hit by two of Levy-Shoemaker's comet fragments and the subsequent disturbances in its atmosphere (from bottom to top). (Credit: STScI)

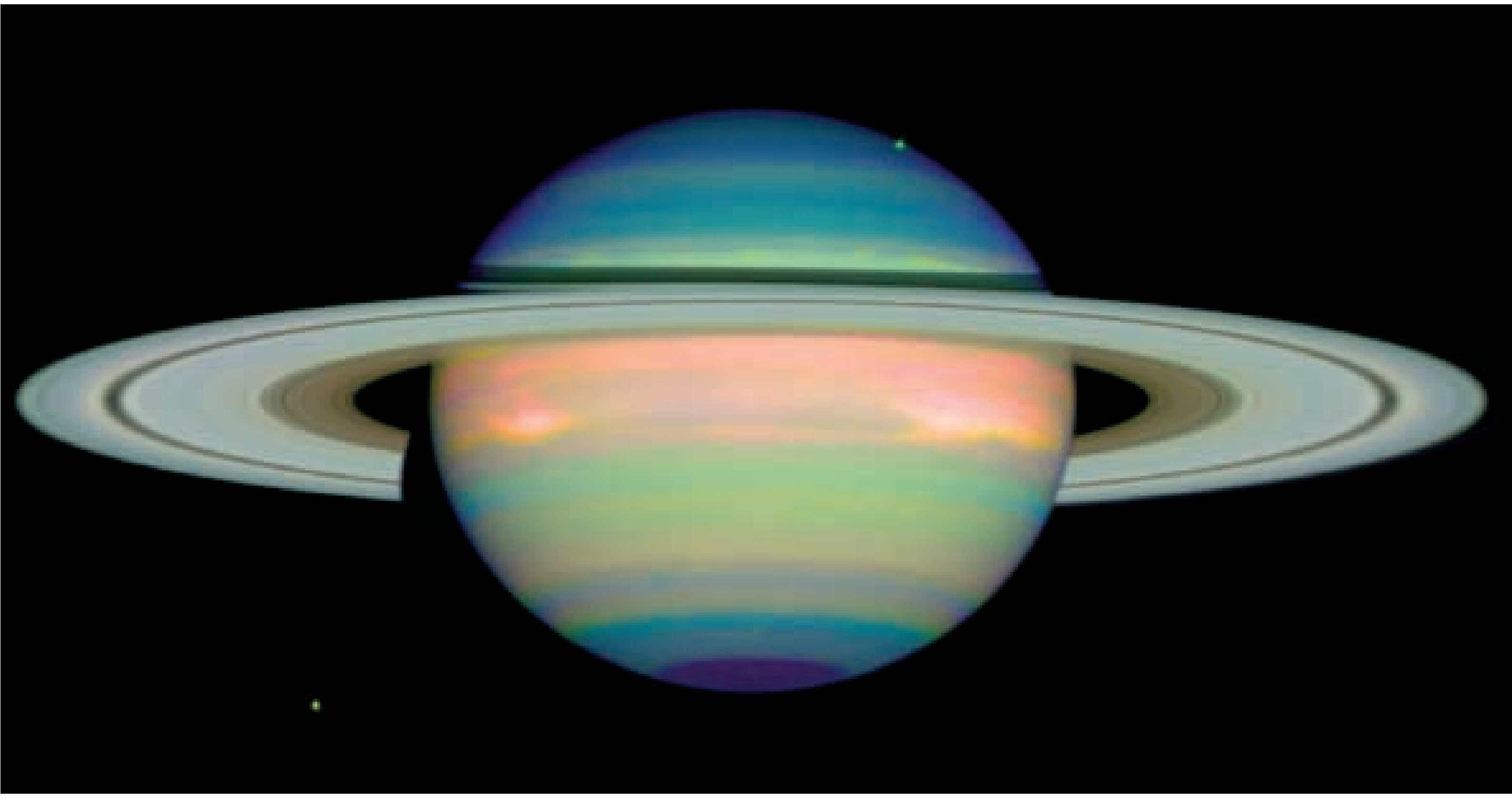
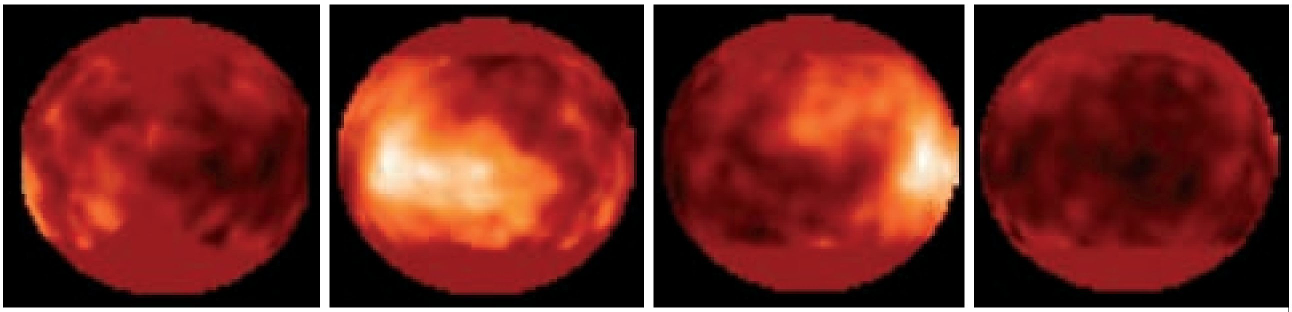


Figure 8 shows the planet Saturn in the infrared light. The picture is a combination of three images from Hubble's NICMOS instrument and shows the planet in reflected infrared sunlight. Different colours indicate varying heights and compositions of cloud layers generally thought to consist of ammonia ice crystals. The eye-catching rings cast a shadow on Saturn's upper hemisphere. The bright stripe seen within the left portion of the shadow is infrared sunlight streaming through the large gap in the rings known as the Cassini Division. Two of Saturn's many moons have also put in an appearance, Thetys just beyond the planet's disk at the upper right, and Dione at the lower left. (Credit STScI, E. Karkoschka)



Figures 9 (top) and 10 (bottom): HST renders invaluable services to mission planners when it comes to exploring planets and moons in the frame of future landing missions. In the case of the joint NASA / ESA mission Cassini / Huygens it was of primordial importance to get as much information on Titan and its atmosphere in order to design properly the details of the lander mission for Huygens. The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) was best suited to penetrate Titan's opaque atmosphere containing nitrogen and carbon compounds and to provide information about its surface. Figure 9 above shows Titan seen by the NICMOS from four different directions in a distance of approx 1.5 billion km. This is approximately equivalent to observing a football in Zurich from Berne. The brighter areas are believed to be icy continents in oceans of methane and ethane, and of course scientists are eager to place Huygens on a beautiful site along one of Titan's beaches in January 2005, as sketched in Figure 10. (Credits: Figure 9: STScI, Figure 10: ESA)

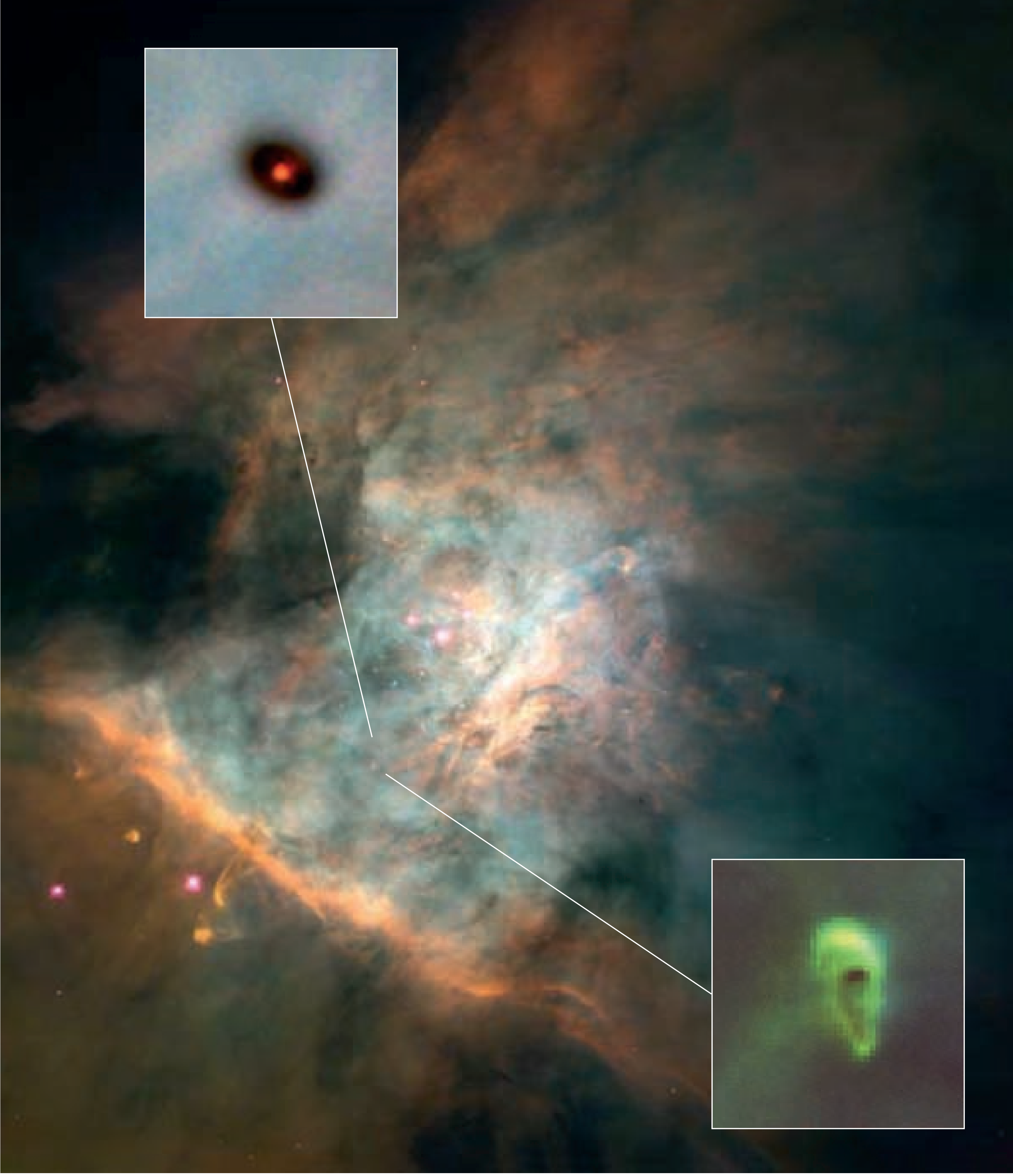


Figure 11 depicts one of the close-by cradles of formation of stellar systems in the Orion nebula. The two disk images show the two distinct disk types: a disk silhouetted against the background nebula (top left) and a disk inside the nebula whose outer parts are also ionised creating a glowing, teardrop-shaped bubble of ionised gas around it. These disks are the precursors of new planetary systems. Hubble Space Telescope's images of these disks were the first direct pictures confirming the general planet-creation scenario that has been stipulated by Immanuel Kant in 1755 and Pierre-Simon Laplace some years later. (Credit: STScI, C. Robert O'Dell)

...to Future Solar Systems...

Of course, the Hubble Space Telescope is instrumental not only in discovering the secrets of the Solar System but of other solar systems that exist around other stars. In the interstellar space, where dust and gas is extremely thinly distributed, irregularities of the density of matter eventually cause the higher densities to generate slightly increased gravitational fields, which in turn slowly attract additional matter from the ambient space, leading to a further increase of the gravitational forces. An avalanche process is initiated whereby more and more mass is concentrated in time spans of 10,000 of years. After around 1 million year a protoplanetary disk is formed, which, due to the angular momentum of the former dust cloud, rotates around an axis perpendicular to the future solar system's ecliptic plane. After a further 100 million years, when the mass of the new star has exceeded a certain critical threshold, the nuclear fusion process in its core is ignited, burning hydrogen into helium thereby releasing enormous amounts of energy, causing the new star to shine. From the debris remaining in the disk, planetesimals of increasing mass are formed and after another 1 billion years the planets have gathered the majority of matter circling around the central star. If there is a planet not too close to the central star and not too far away it may contain liquid water on its surface that may become a new shelter of life in the cosmic void. (See also Spatium 6 for further details).

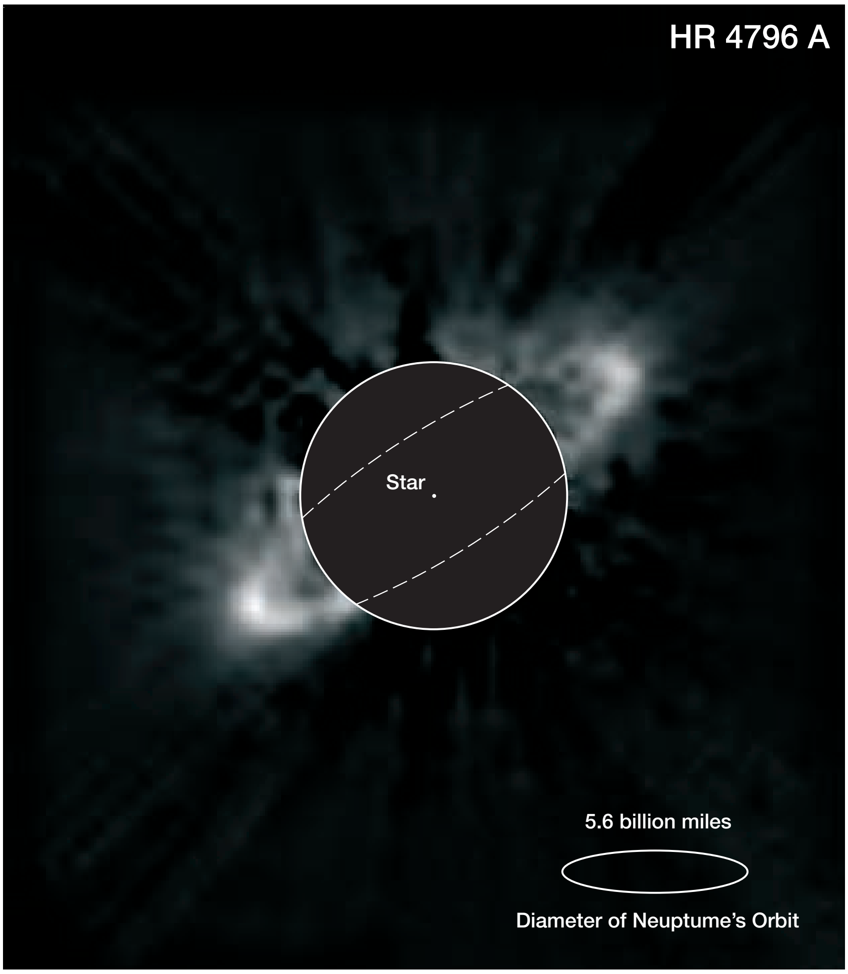
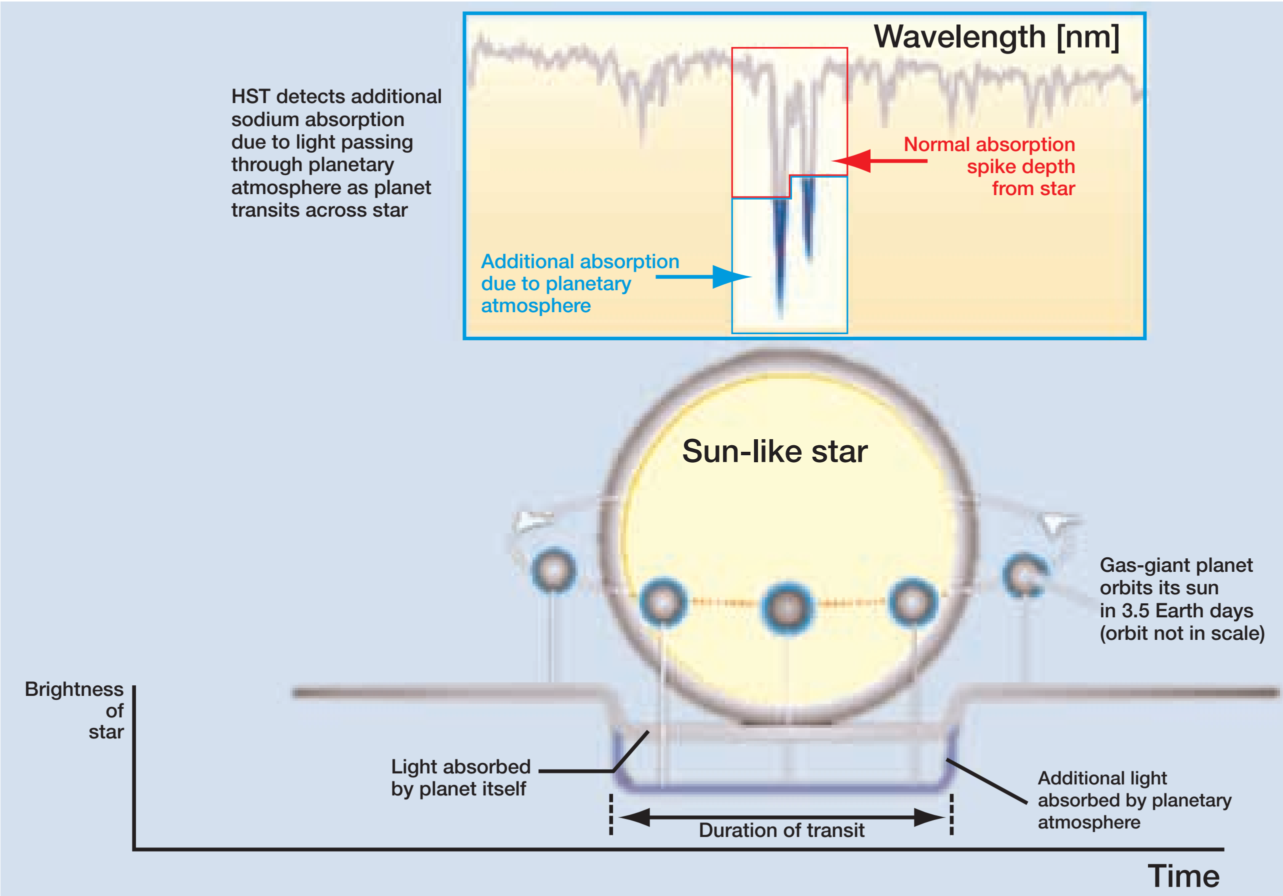


Figure 12 shows the capability of central obscuring of the NICMOS Instrument. By eclipsing the light of the central star like a solar eclipse but with an opaque mask, the faint light of rings of matter around HR 4796A becomes visible. This is the very place where planets will form. Note the dimension of this protoplanetary disk being in the order of 20 billion km, about twice the diameter of the Solar System. Rings seen in disks around main sequence stars are most easily interpreted as gravitational sweeping by small companions to the stars i.e. planets. The only way that we know how to produce rings is to have gravitational sweeping of the matter by companion bodies. (Credit STScI)



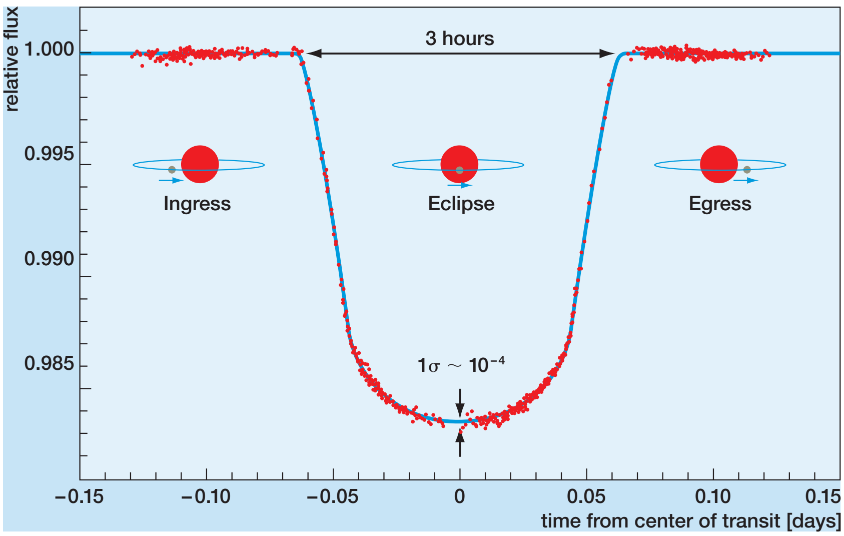


Figure 13: The STIS aboard HST is a powerful spectrograph. This figure shows schematically how the sodium abundance in the atmosphere of the planet HD 209458b was detected. The STIS was used to observe the star before, during, and after the planet partially eclipsed the star. Astronomers compared the depth of the eclipse at the wavelengths of two absorption lines of sodium with the depth at adjacent wavelengths free of absorption. Since the sodium in the atmosphere absorbed more starlight, the eclipse depth at those wavelengths was slightly greater than in the adjacent wavelengths. The versatility and power of HST made it possible to perform such pioneering measurements. (Credit: STScI)

… and the Death of Stars

While the birth of stars is a slow process their death is a spectacular show. A star with sufficient mass content shines thanks to the nuclear fusion of its light elements. When this fusion process comes to an end, no heat generating fusion process keeps the star shining anymore, it will, therefore, collapse under its own gravitational field and release thereby a lot of gravitational energy causing its relics partially to be merged to heavier elements, which are then scattered into space. Together with fresh hydrogen these heavier atoms may become the seeds of new generations of stars whose planets eventually may support life. When our Solar System formed around 4 600 million years ago it also collected the relics of such former generations of stars, that at the end of their lives had produced heavy elements, which today are found on Earth and in our own bodies. (see also Spatium 3 for further information).

Figure 14: The shapes of planetary nebulae may become extremely complex like in the case of the Red Spider Nebula. It is still not understood how such complex structures may evolve. But in any case, nature is beautiful, when it explodes. (Credit: STScI)

Figure 15 shows the hourglass nebula through the light scattered by the gas expelled by the dying star at an earlier epoch. The shapes of dying stars show an astonishing variety of colours and forms depending on the properties of the former star. This HST snapshot of MyCn18, a young planetary nebula, reveals that the object has intricate patterns of "etchings" in its walls. A planetary nebula is the glowing relic of a dying, Sun-like star. The results are of great interest because they shed new light on the poorly understood ejection of stellar matter that accompanies the death of these stars. According to one theory on the formation of planetary nebulae, the hourglass shape is produced by the expansion of a fast stellar wind within a slowly expanding cloud, which is denser near its equator than near its poles. (Credits: Raghvendra Sahai and John Trauger, JPL)

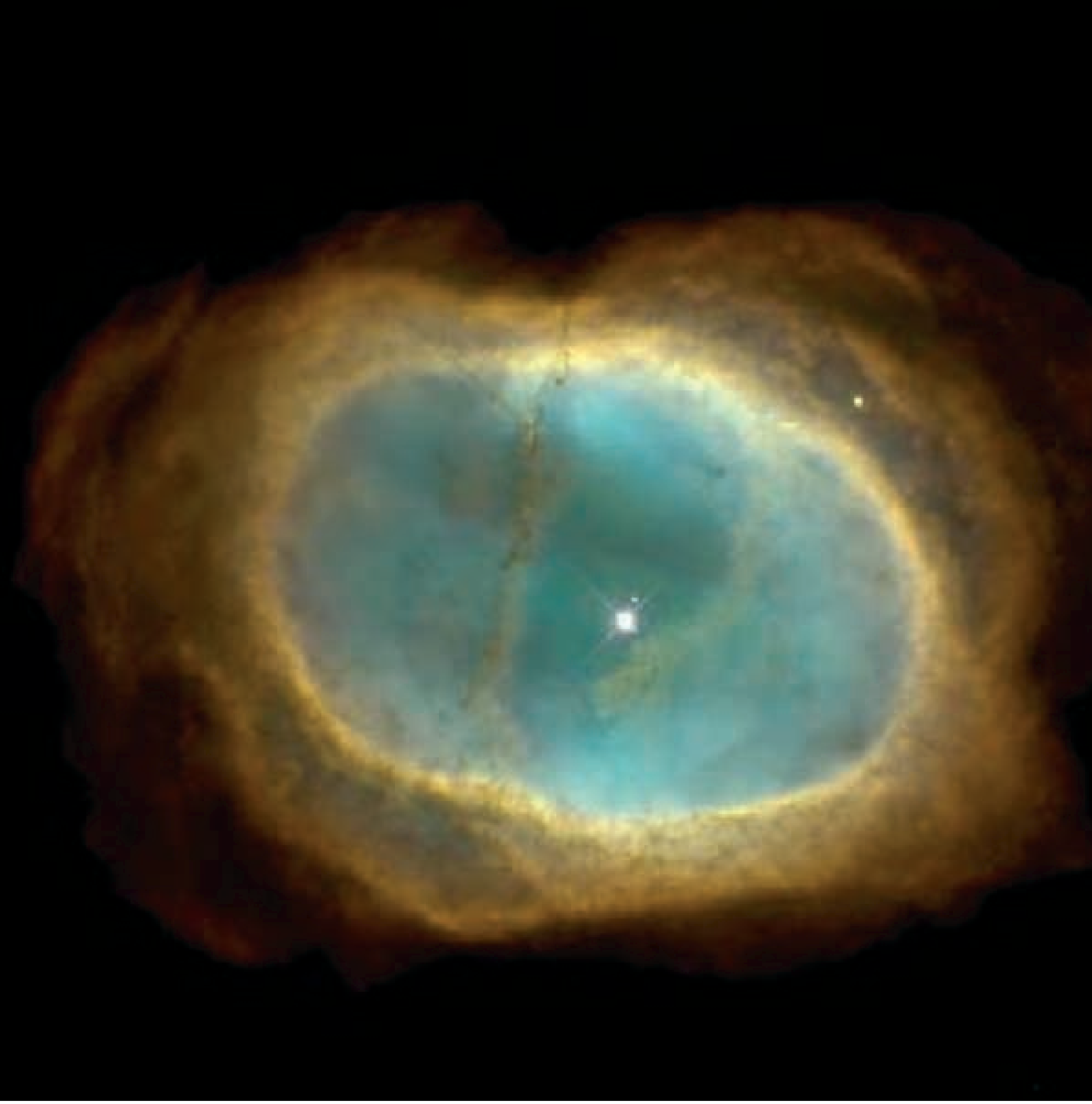


Figure 16: The Eight-Burst Nebula NGC 3132 is another striking example of a planetary nebula. This expanding cloud of gas, surrounding a dying star, is known to amateur astronomers in the southern hemisphere as the "Eight-Burst" or the "Southern Ring" Nebula. The name "planetary nebula" refers only to the round shape that many of these objects show when examined through a small visual telescope. In reality, these nebulae have little or nothing to do with planets, but are instead huge shells of gas ejected by stars as they near the ends of their lifetimes in fact probably ingesting any planet which they might have around them. NGC 3132 is nearly half a light year in diameter, and at a distance of about 2000 light years it is one of the nearer known planetary nebulae. The gases are expanding away from the central star at a speed of 15 km/s. This image clearly shows two stars near the centre of the nebula, a bright white one, and an adjacent, fainter companion to its upper right. (A third, unrelated star lies near the edge of the nebula.) The faint partner is actually the star that has ejected the nebula. This star is now smaller than our Sun, but extremely hot. The flow of ultraviolet radiation from its surface makes the surrounding gases glow through fluorescence. The brighter star is in an earlier stage of stellar evolution, but in the future it will probably eject its own planetary nebula. (Credit: STScI)

Figure 17: While the nebula of Figure 14 was from a single star, this figure shows a binary system consisting of two near-by stars. In this case, the explosion becomes very complex albeit symmetrical in shape. This figure shows the so-called "ant nebula" (Mz 3) resembling the head and thorax of a garden-variety ant. This HST image reveals the "ant's" body as a pair of fiery lobes protruding from the dying star. Scientists using Hubble would like to understand how a spherical star can produce such prominent, non-spherical symmetries in the gas that it ejects. One possibility is that the central star of Mz 3 has a closely orbiting companion that exerts strong gravitational tidal forces, which shape the outflowing gas. For this to work, the orbiting companion star would have to be close to the dying star, about the distance of the Earth from the Sun. At that distance, the orbiting companion star would not be far outside the hugely bloated hulk of the dying star. It is even possible that the dying star has consumed its companion, which now orbits inside it. A second possibility is that, as the dying star spins, its strong magnetic fields are wound up into complex shapes. Charged winds moving at speeds up to 1000 km per second from the star, much like those in our Sun's solar wind but millions of times denser, are able to follow the twisted field lines on their way out into space. These dense winds can be rendered visible by ultraviolet light from the hot central star or from highly supersonic collisions with the ambient gas that excites the material and make it to fluoresce. (Credit: STScI)

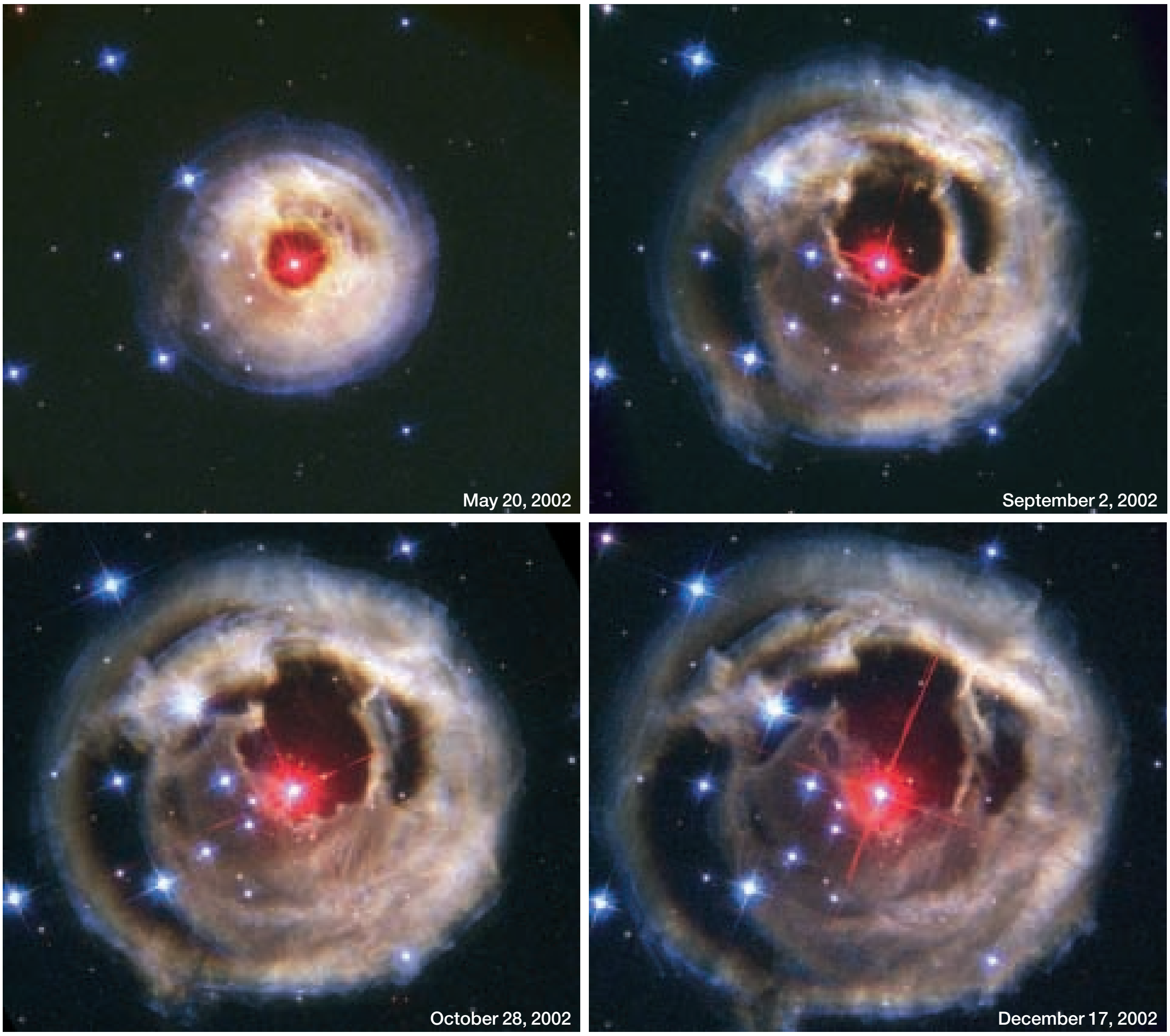


Figure 18: One of the most spectacular images obtained by the HST is this sequence of the V838 Monocerotis collected over a time span of about six months. Calculations of the speed of the shells showed that they move with the speed of light. This is obviously an illusion. The visible shells are in fact different parts of dust clouds released by the central dying star in the course of its life. They are illuminated by short bursts of light released by the star and spreading with the velocity of light. This effect is called a "light echo." The red star at the centre of the eyeball-like feature is an unusual erupting super giant called V838 Monocerotis, located about 20,000 light-years away in the winter constellation Monoceros (the Unicorn). During its outburst the star brightened to more than 600,000 times our Sun's luminosity. The outer circular feature is slightly larger than the angular size of Jupiter on the sky. For several more years its diameter will increase as reflected light is scattered from more distant portions of the nebula. Eventually, when light starts to be released from the backside of the nebula, the light echo will give the illusion of contraction, and finally it will disappear probably by the end of this decade. The black gaps around the red star are regions of space where there are holes in the dust cloud. (Credit: STScI)

Figure 19 shows the Whirlpool Galaxy perpendicular to its galactic plane. We clearly see the spiral arms, where billions of stars that build up this galaxy are concentrated. The red stars are young starting stars, while the blue dots are large massive stars. New pictures from Hubble are giving astronomers a detailed view of the Whirlpool galaxy's spiral arms and dust clouds, which are the birth sites of massive and luminous stars. This galaxy, also called M51 or NGC 5194, is having a close encounter with a nearby companion galaxy, NGC 5195, just off the upper edge of this image. The companion's gravitational influence is triggering star formation in the Whirlpool, as seen by the numerous clusters of bright, young stars, highlighted in red. (Credit: STScI)

Figure 20 shows Gomez's Hamburger, a Sun-like star nearing the end of its life. The hamburger buns are light scattered from the central star, which itself is obscured by a large band of dust in the middle. (Credit STScI)

Beyond the Milky Way

One of the major contributions of Edwin Hubble was the observation of galaxies beyond the Milky Way. Our galaxy is a flat disk with a diameter of approx. 100,000 light years. We find ourselves in one of several spiral arms far outside its centre. The large aperture of the HST as well as its (now) nearly perfect optical quality allows observations of distant objects out to regions, which have never been observed before. Since light travels with a limited speed of 300,000 km/s we observe distant objects not in their present state, but at an earlier state in the past. The further they are the earlier can we look into the past. In addition it allows us to observe galaxies like ours but from very different angles.

Figure 21 shows the ESO 510-G13 galaxy, whose galactic plane seems to be bent. HST has captured an image of this unusual edge-on galaxy, revealing remarkable details of its warped dusty disk. In contrast, the dust and spiral arms of normal spiral galaxies, like our own Milky Way, appear flat when viewed edge-on. (Credit: STScI)

Figure 22 shows a ring galaxy called the Hoag's Object. It is a young galaxy, which has not yet developed its spiral arms. A nearly perfect ring of hot, blue stars pinwheels about the yellow nucleus. The entire galaxy is about 120,000 light-years wide, which is slightly larger than our Milky Way. The blue ring, which is dominated by clusters of young, massive stars, contrasts sharply with the yellow nucleus of mostly older stars. What appears to be a "gap" separating the two stellar populations may actually contain some star clusters that are almost too faint to see. Curiously, an object that bears an uncanny resemblance to Hoag's Object can be seen in the gap at the one o'clock position. The object is probably another ring galaxy.

Ring-shaped galaxies can form in several different ways. One possible scenario is through a collision with another galaxy. Sometimes the second galaxy speeds through the first, leaving a "splash" of star formation. But in Hoag's Object there is no sign of a second galaxy, which leads to the suspicion that the blue ring of stars may be the shredded remains of a galaxy that passed nearby. Some astronomers estimate that the encounter occurred about 2 to 3 billion years ago. The galaxy is 600 million light years away in the constellation Serpens. (Credit: STScI)

Figure 23 shows a cosmic catastrophe. This impressive image shows two colliding galaxies called NGC 3314, which lie about 140 million light years from Earth, in the direction of the southern hemisphere constellation Hydra. The bright blue stars forming a pinwheel shape near the centre of the front galaxy have formed recently from interstellar gas and dust. In many galaxies, interstellar dust lies only in the same regions as recently formed blue stars. However, in the foreground galaxy, NGC 3314a, there are numerous additional dark dust lanes that are not associated with any bright young stars. A small, red patch near the centre of the image is the bright nucleus of the background galaxy, NGC 3314b. It is reddened for the same reason the setting Sun looks red. When light passes through a volume containing small particles (molecules in the Earth's atmosphere or interstellar dust particles in galaxies), its colour becomes redder.

Collision does not mean that the single stars physically touch each other, since the distances between them are so large. But due to their gravitational fields collisions of galaxies may lead to collisions of stars caught by the gravitational field of large stars in one of the galaxies. Through an extraordinary chance alignment, a face-on spiral galaxy lies precisely in front of another larger spiral. This line-up provides us with the rare chance to visualise dark material within the front galaxy, seen only because it is silhouetted against the object behind it. Dust lying in the spiral arms of the foreground galaxy stands out where it absorbs light from the more distant galaxy. This silhouetting shows us where the interstellar dust clouds are located, and how much light they absorb. The outer spiral arms of the front galaxy appear to change from bright to dark, as they are projected first against deep space, and then against the bright background of the other galaxy. (Credit: STScI)

Figure 24 shows the Black Hole in the galaxy M84. HST has strongly contributed to the understanding of the mechanics of galaxies. Thanks to HST and new observations conducted in large ground based observatories such as the Very Large Telescope of the European Southern Observatory in Chile, we know that galaxies are powered by black holes in their centre. Their mass density is so high, that no matter, not even light can escape, hence their name. Due to their high mass they generate strong gravitational fields, the binding force of galaxies preventing the individual stars from escaping the common centre. In the case of M84, HST was able to provide pictures of the core of the galaxy. (Credit: STScI).

The Early Universe

HST's nearly perfect optical system combined with its excellent long-term stability allows to investigate regions of the universe which have never been reached before. Some 15 billion years ago, the universe started to expand and cooled over the next half million years. The glowing plasma of which it was composed, recombined into atoms of neutral gas, mostly hydrogen and some helium. The glow from this era of recombination has been observed as the cosmic microwave background radiation, and is used to study the large-scale geometry of the universe. Over the following half billion years or so, termed the Dark Age, the cold gas began to assemble into what we think are the first galaxies. The Dark Age ended when the light from the stars and the newly formed galaxies and quasars reionised the surrounding neutral gas.

Figure 25 shows the deepest portrait of the visible universe ever achieved. This historic new view is actually based on a million-second exposure of two separate images taken by the Advanced Camera for Surveys and the Near Infrared Camera and Multi-Object Spectrometer. Both images reveal some galaxies emerging from the Dark Age, a mere 500 million years after the Big Bang. These galaxies are too faint to be seen in Hubble's previous faraway looks. The HUDF field contains an estimated 10,000 galaxies in a patch of sky just one-tenth the diameter of the full Moon. Besides the rich harvest of classic spiral and elliptical galaxies, there are many strange galaxies littering the field telling about a period when the Universe was more chaotic than today and when order and structure were just beginning to emerge.

Getting better with Age

The Hubble Space Telescope started to be designed in 1975 and was supposed to be launched in the early 1980s. Due to the loss of the Challenger Shuttle it was launched in 1990 only. Its technology therefore is nearly 25 years old now. During these 25 years technological progress was impressive and it continues probably to be so. Any non-serviceable spacecraft would already be outdated at the beginning of its lifetime in orbit. The ingenious concept to update the scientific instruments as well as elements like onboard computers, tape recorders, solar panels, etc. kept HST abreast of technological progress. In other words rather than becoming obsolete HST gets better with increasing age. **Figure 26** gives an impression of the importance of the concept of serviceability for the ambitious increase in sensitivity.

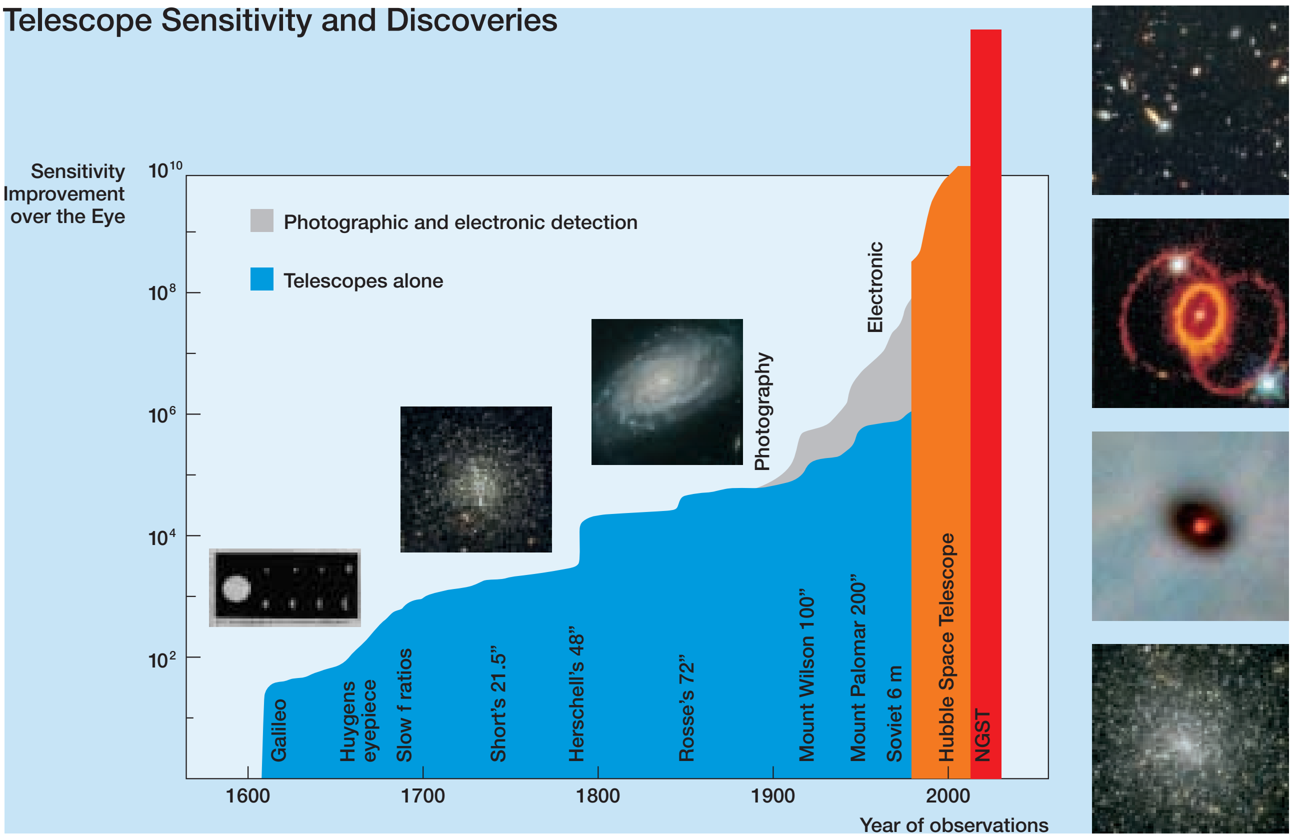


Figure 26 shows the evolution of observation sensitivity as compared to the naked human eye since Galileo Galilei's first astronomical observations in 1609. The striking result here is that since Galilei's initial advance, no other advance in technology has been proportionately as great as when HST became operational. It advances the state of the art by nearly two orders of magnitude.

It is important to note that the HST line in this figure is sloped upward. Each time the spacecraft is upgraded with new instruments its observing capabilities are increased, making HST a continuously improving facility. The right hand bar shows the expected gains to come from the James Webb Telescope (NGST), the successor of Hubble due to launch around 2011. (Credit: STScI)

After the Hubble Space Telescope

In sharp contrast to the spectacular images HST gathered from dying stars, its own end will be far from spectacular. Unlike most spacecraft Hubble has no onboard propulsion system, relying instead on gyroscopes and flywheels to maintain stability. Thus, at the end of its lifetime, special measures will have to be taken to prevent it from entering the Earth atmosphere in an uncontrolled way. Initially it was foreseen to be retrieved through a dedicated Shuttle mission, but, in the wake of the Columbia disaster, NASA is now forced to concentrate the Shuttle missions on the construction of the International Space Station. Therefore, plans have been presented lately to de-orbit the HST by means of a dedicated autonomous space tug. This spacecraft is intended to launch on a Delta 2 rocket, to grapple the HST and to guide it safely into the Earth's atmosphere over an unpopulated region. That will be the end of one of mankind's greatest achievements…

Several years ago NASA initiated a competition for the design of the successor instrument, which at that time was called the Next Generation Space Telescope. In 2003 the design by TRW Inc was chosen **(Figure 27)** and the mission was baptised James Webb Space Telescope in honour of NASA's second administrator. Unlike the HST, this instrument will not be serviceable, as it will be placed at the Lagrange L2 point that is 1.5 million km from the Earth leeward to the Sun. While this position is attractive, because it is in the Earth's shadow, hence less disturbed by solar radiation, it lacks servicing capabilities at least for the time being, since it is around 5 times farther from the Earth than the current Space Shuttle's reach.

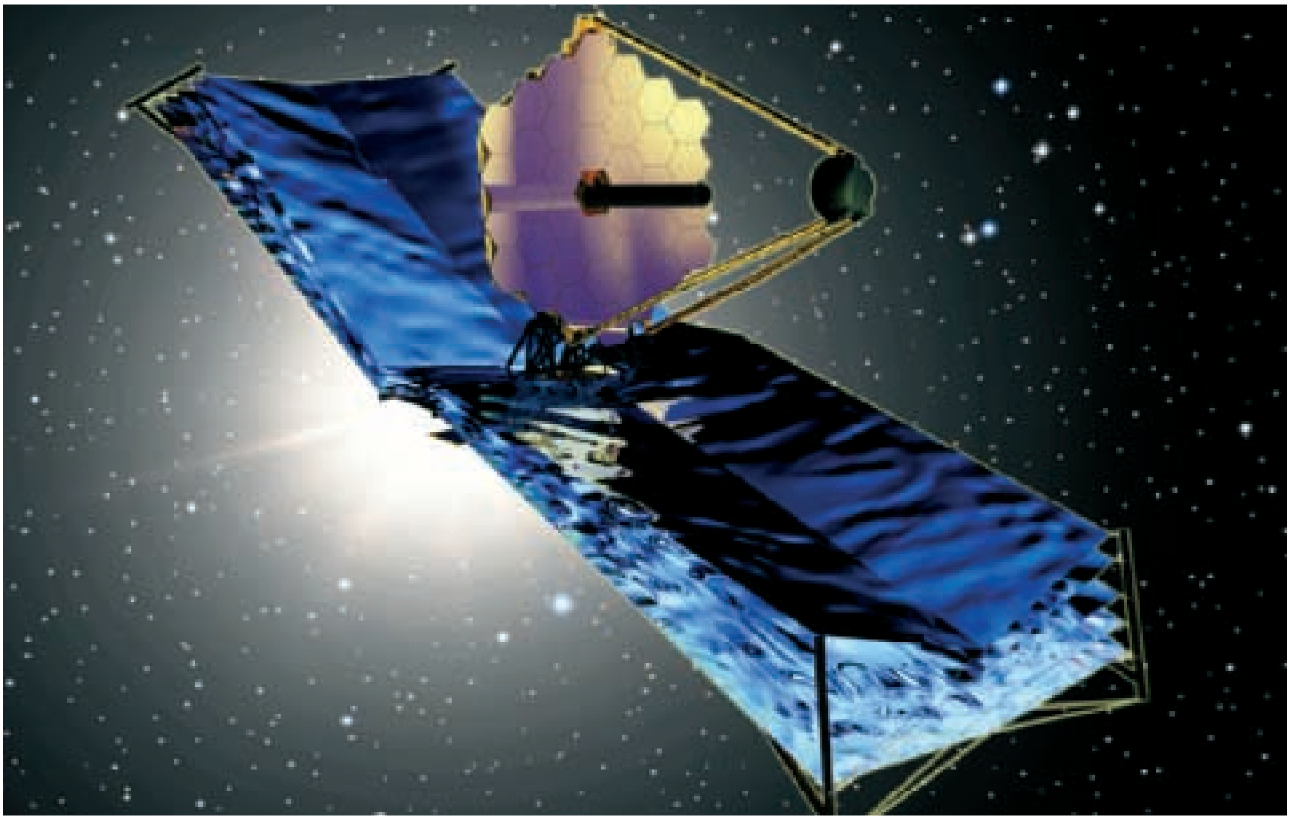


Figure 27: Artists view of the James Webb Telescope, the successor mission to the Hubble Space Telescope (Credit: TRW).

Conclusion

The unique advance permitted by HST amply sustains the European and American investment in this programme. The Hubble Space Telescope has truly revolutionised our knowledge of:

- the creation of galaxies,
- the distance scale of the universe,
- giant black holes in galaxies,
- the intergalactic medium,
- interstellar medium chemistry,
- extra solar planets,

and it is hoped that in the future years of its planned operation, the HST will bring us additional scientific surprises. It is an old wisdom that leading discoveries are often accidental: they follow the ability to observe, not necessarily the originally planned observation. Hubble has dramatically contributed to the modern revolution of astronomy permitted by space techniques and to our understanding of the universe.

Figure 28 shows another ring galaxy (AM 0644-741). The Hubble Space Telescope not only rendered invaluable services to scientists but made us also aware of the beauties of our world, much like that simple telescope, which stimulated Immanuel Kant some 250 years ago.

The author

Roger Maurice Bonnet received his diploma in physics and astronomy in 1968 from the University of Paris. He dedicated his doctorate to the imagery and spectroscopy of the Sun. He was involved in the development of new telescopes and cameras that were flown on balloons, rockets and satellites. In 1969 he founded the Laboratoire de Physique Stellaire et Planetaire of CNRS. There he was engaged in the development of the telescope for the Halley Multicolour Camera of the Giotto Mission under the responsibility of the Max Planck Institute at Lindau (Germany), which took the first high-resolution images of a cometary nucleus. R. M. Bonnet entered the field of international science policy in 1983, when the Council of the European Space Agency appointed him Director of the Science Programme. One of his most prominent achievements of that time was the formulation of the Horizon 2000 Plan. This programme consists of four large cornerstone missions and some smaller missions, amongst which is the European contribution to the Hubble Space Telescope. The transparent long term planning philosophy allowed the academic and the industrial communities to timely build up the required skills thereby placing ESA at the second most important space science agency in the world after NASA. Later, R. M. Bonnet adopted the same concept for the definition of the new Earth observation programme of ESA, known as the Living Planet Programme.

After his departure from ESA in April 2001 he served as Directeur General Adjoint Science at the French Centre National Etudes Spatiales (CNES). There he was asked by the French government to chair a National Commission to analyse and formulate the French space policy. In 2001, he was called by the Director General of ESA to advise him on how to formulate its Aurora programme, setting the goal of landing humans on Mars by 2030.

At the International Space Science Institute R. M. Bonnet succeeded Prof. J. Geiss as Executive Director in 2003. In the same year he was appointed President of the International Committee on Space Research (COSPAR). He is the author of over 150 scientific papers and textbooks and he holds the highest scientific and public service awards like for example the French Légion d'Honneur or the NASA Award for Public Service.

For R. M. Bonnet adventures like the Hubble Space Telescope are the convergence of many scientific and engineering talents in response to questions, which always have challenged the human mind. They realise missions thought impossible before, which open the brain of the young and less young children to the marvellous discovery of the universe.