↑

Hubble seen from Space Shuttle *Discovery*, STS-103, during Servicing Mission 3A in 1999 (two ESA astronauts were on this flight, Jean-François Clervoy and Claude Nicollier)

→ SEEING WITH HUBBLE-VISION

20 years of science with the Hubble Space Telescope

Antonella Nota
Directorate of Science and Robotic Exploration, ESA/Space Telescope Science Institute, Baltimore, USA

Mark McCaughrean
Directorate of Science and Robotic Exploration, ESTEC, Noordwijk, The Netherlands

Bob Fosbury and Colleen Sharkey
Space Telescope European Coordinating Facility, Garching, Germany

Carl Walker
Directorate of Legal Affairs and External Relations, ESTEC, Noordwijk, The Netherlands

The NASA/ESA Hubble Space Telescope is one of the greatest scientific projects of all time. For 20 years, Hubble has opened our eyes to the wonders of our 'planetary' backyard and beyond, and has made a number of fundamental discoveries in astronomy and physics.

Named after the renowned astronomer Edwin P. Hubble, this space-based observatory has revolutionised astronomy by providing unprecedented deep and clear views of the Universe, ranging from our own Solar System to extremely remote fledgling galaxies that formed not long after the 'Big Bang', billions of years ago.

Launched on 24 April 1990, Hubble has been greatly extended in its scientific powers through new instrumentation installed during five servicing missions with the Space Shuttle. Its primary mirror is 2.4 m in diameter, not large by ground-based standards, but giving amazing performance in space.

The Universe is transparent to visible light over journeys lasting thousands of millions of years. However, just before this light arrives at telescope mirrors on Earth, it must travel through our turbulent atmosphere and the fine cosmic details become blurred.

→ Edwin Powell Hubble (1889–1953) was first to show that the Universe is expanding and is considered by many to be the father of observational cosmology

Putting a telescope in space is one way of avoiding this problem. From its vantage point 575 km above Earth, Hubble can detect light with 'eyes' five times sharper than the best ground-based telescopes under normal conditions. As well as collecting visible light from its orbit high above the atmosphere, Hubble can also observe the infrared and ultraviolet wavelengths that are filtered out by the atmosphere.

NASA's partner for Hubble

From hardware and astronauts, to groundbreaking science, the European influence in the Hubble project has been vast and vital. ESA has a nominal 15% stake in the mission and has provided, among other things, the Faint Object Camera and the first two sets of solar panels that powered the spacecraft until 2002.

Just as important as ESA's financial and technical contributions is that of the people who support the telescope and use it to investigate the Universe. There are many astronomers in Europe who use Hubble, but the two main centres for Hubble science employ dedicated groups of full-time astronomers.

→ Space Telescope European Coordinating Facility

Based at the headquarters of the European Southern Observatory in Garching, near Munich, ST-ECF developed and maintains the European copy of the full Hubble archive and has worked with the STScI and the Canadian Astronomy Data Centre on many of the archive developments, including the Hubble Legacy Archive that contains a wide range of 'science-ready' data products.

The ST-ECF group has worked on a series of Hubble science instrument projects and, in recent years, has become responsible for the 'slitless spectroscopy' modes offered by most of Hubble's cameras.

→ The Space Telescope Science Institute in Baltimore, USA

A group of 15 European astronomers works at the Space Telescope Science Institute (STScI) in Baltimore, Maryland (USA) while another group runs the Space Telescope European Coordinating Facility (ST-ECF), near Munich, Germany, to provide a direct connection to European astronomers.

ESA's contribution entitles European astronomers to 15% of the telescope's observing time, but this fraction has reached over 25% when robust and scientifically compelling proposals have been made.

ESA's Hubble Space Telescope Project Scientist and Mission Manager at STScI, Antonella Nota, has a long history with Hubble. An astronomer originally from Venice, Italy, she spent ten years supporting Hubble instrument science operations – starting as head of the Faint Object Camera Group, then head of the Observatory Support Group and as head of the NICMOS (Near-Infrared Camera and Multi-Object Spectrometer) Group.

"It is an enormous benefit to ESA and to the European community to have European scientists at STScI. Their unique knowledge has been fundamental for instrument calibration and user support. Their presence at senior levels in the organisation ensures that the views of the European scientific community are well represented. As many of them eventually return to Europe, the expertise they acquire working directly with Hubble is often put to use in Europe at universities and other research institutions, where many of them now hold leading positions," said Antonella.

← Antonella Nota, ESA's Hubble Space Telescope Project Scientist and Mission Manager at STScI

From their orbital vantage point, these modes are extremely sensitive and allow the spectroscopic analysis of objects fainter than can be achieved from the ground, even with much larger telescopes. The measurements of many of the 'high-redshift' supernovae that spawned the idea of an accelerating Universe and the existence of 'dark energy' were made with Hubble's slitless spectrographs.

For Servicing Mission 4, ST-ECF provided much of the processing needed to set up and calibrate the slitless spectroscopic modes of the new Wide Field Camera 3. This camera has two infrared spectroscopic modes that offer a unique and very powerful capability to map the history of star formation over most of the age of the Universe.

Since the late 1990s, the group also has been producing much of the European outreach and public relations products for this joint ESA/NASA mission. It has introduced a number of innovative products, such as the highly popular Hubblecast, available through iTunes, and the FITS Liberator software that enables Photoshop users around the world to process Hubble image data. Many amateur astronomers as well as professionals benefit from this work.

→ Helmut Jenkner, Deputy Head of the ESA HST Mission at STScI

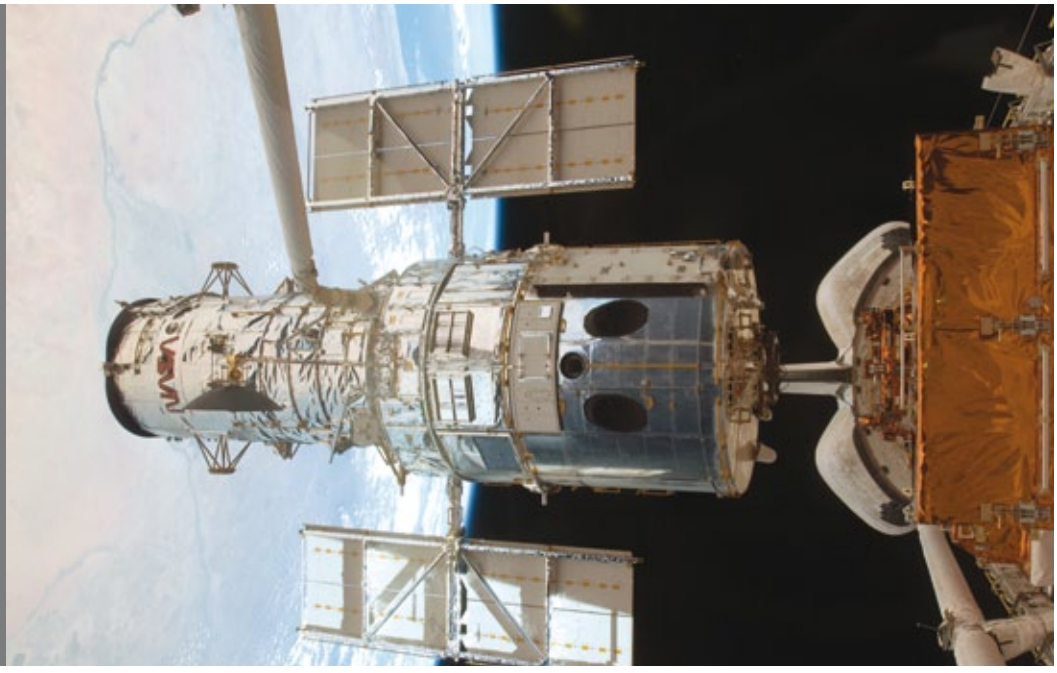
Some of the ESA astronomers at STScI were deeply involved in the design and execution of Servicing Mission 4 in 2009. Helmut Jenkner, the Deputy Head of the HST Mission at STScI, was in the NASA Goddard Space Flight Center control room during the spacewalks. During long shifts, day and night, Helmut represented ESA and the European community when major decisions were made about the observatory.

"For me, Servicing Mission 4 was certainly the most exciting period in my 27 years on the Hubble programme, as its success promises exceptional science for years to come," said Jenkner.

Other ESA astronomers were involved in the commissioning activities of the instruments, such as the optimisation campaign for the Advanced Camera for Surveys (ACS). ESA's Linda Smith, an expert on star clusters and starbursts galaxies, is the team leader at STScI for ACS and the Wide Field Planetary Camera 2 (WFPC2, now 'retired' to the National Air and Space Museum in Washington DC).

During her 15 years as an astronomy professor at University College London, Smith made frequent visits to STScI but decided several years ago to take a leave of absence from teaching to work full-time at the Institute. She liked it so much she gave up her professorship to focus completely on Hubble.

With her team, Linda led the ACS optimisation campaign, preparing calibration files and test runs at NASA's Goddard Space Flight Center. "We had to prepare for the possibility that ACS wouldn't work as well as it used to," said Linda. "You're aware that all of the work could be in vain. I thought people were going to be so disappointed but it was so exciting! Straight 'out of the box', it worked better than we could have even hoped!"



→ Servicing Mission 4: Space Shuttle *Atlantis*'s remote manipulator arm lifts Hubble from the cargo bay before releasing the orbital observatory to resume observations of the Universe

> **I hadn't expected this image for ACS to be so amazing. The large, orangeish arc is incredible and everybody on the team is proud to be working on such a capable instrument.**

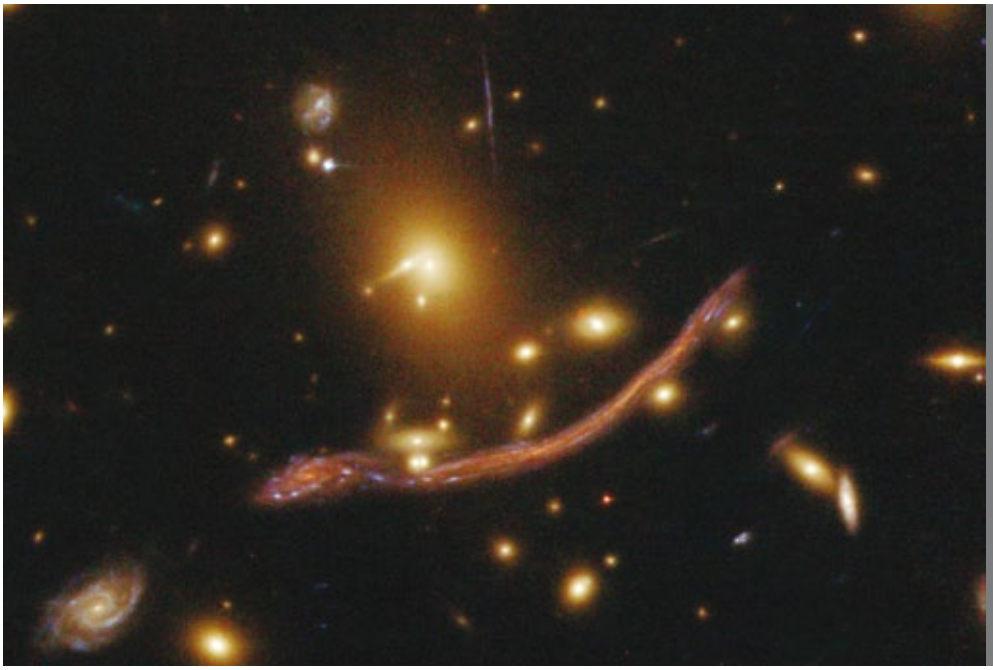
The ACS Early Release Observation (the first Hubble picture released after SM4) was the culmination of months of hard work and preparation, so seeing the image for the first time was exciting and satisfying for Linda. It was a stunning picture of Abell 370, a galaxy cluster that highlights the phenomenon known as 'gravitational lensing'.

"I hadn't expected this image for ACS to be so amazing. The large, orangeish arc is incredible and everybody on the team is proud to be working on such a capable instrument," said Linda.

Now that Hubble is working better than ever, Linda is looking forward to doing more research using this observatory and to making ACS available for other Hubble researchers.

Marco Chiaberge's affiliation with STScI dates back to 2001 when he was an ESA post-doctoral researcher. He returned to his native Italy to work at the Institute of Radio Astronomy in Bologna before rejoining STScI in 2005. Chiaberge led one of the teams that analysed the first data from ACS after SM4, which involved long late-night hours and lots of patience.

Now that the camera is functioning again, Chiaberge and his team have to get to know the 'new' ACS. He serves as the calibration lead, ensuring that the instrument is optimally set up for observers. An expert on so-called 'active galactic nuclei' (galaxies with black holes at their centres), he looks forward to working with the improved Hubble to pursue new research, peering deeper into the Universe to study distant galaxy clusters.



← Part of one of the first images returned by Hubble's newly repaired Advanced Camera for Surveys, peering nearly five billion light-years away to resolve intricate details in the galaxy cluster Abell 370 (NASA/ESA/SM4 ERO team/ST-ECF)

← Space Shuttle *Discovery* lifts off on 24 April 1990, carrying the STS-31 crew of five and the Hubble Space Telescope into space

Danny Lennon, the Deputy Head of the STScI Instrument Division, was also very busy orchestrating the instrument commissioning activities during SM4, while at the same time closely following the first in-flight tests of the Cosmic Origin Spectrograph. An ultraviolet spectroscopy expert by training and scientific interests, Lennon joined the STScI staff in 2009, just in time to dive into and enjoy the most exciting moments.

→ History of Hubble

The idea of sending a telescope into space was first proposed long before the first satellites were launched. German rocket scientist Herman Oberth suggested a space-bound telescope as early as 1923 in his book *Die Rakete zu den Planetenräumen*.

It took many years before technology caught up with Oberth's idea. The American scientist Lyman Spitzer proposed a more realistic plan for a space telescope in 1946 and lobbied for his idea for almost 30 years. In the 1970s, NASA and ESA took up the idea and proposed a 3-m space telescope. The NASA/ESA Memorandum of Understanding was signed in October 1977. After funding began to flow in 1977, Hubble was downsized to 2.4 metres, but still started to attract significant attention from astronomers.

The precision-polished 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 delay of the entire Shuttle programme.

Hubble was finally launched in 1990 and the tension built up as astronomers examined the first images through Hubble's eyes. It was soon realised that Hubble's mirror had a serious flaw. A focusing defect prevented Hubble from taking sharp images – the mirror edge was too flat by a mere fiftieth of the width of a human hair.

1977
NASA/ESA Memorandum of Understanding signed

1981
Precision-polished mirror completed

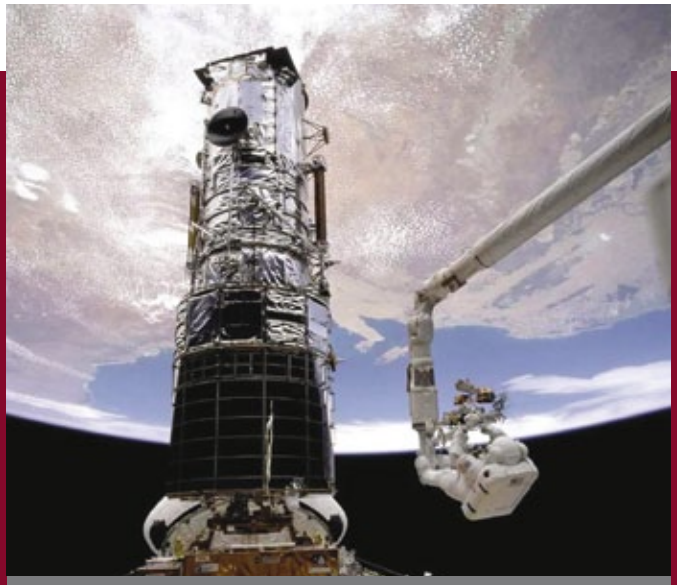
1985
Assembly of complete spacecraft finished

1986
Challenger disaster caused a delay in Shuttle programme

1990
Hubble was launched but its mirror had a serious flaw: a focusing defect

"During SM4 we had to carry out 'aliveness tests' of each instrument immediately following its installation or repair by the astronauts. Our elation and excitement grew as, one after another, the aliveness tests were declared successful. The catchphrase of SM4 became 'It's alive!', heralding the emergence of a new and improved Hubble," said Lennon.

Although floating silently above us, Hubble depends on its teams on both sides of the Atlantic Ocean. A great deal of public relations effort goes into the promotion of Hubble, but the beauty of its images alone is enough to lure people into a fascination with space. Hubble's new lease on life is set to provide even more amazing images and data, increasing our knowledge of the Universe. ■



↑ During Hubble's first servicing mission STS-61, astronaut Story Musgrave is anchored on the end of the Remote Manipulator System arm, ready to install protective covers on the magnetometers

Over the following months, scientists and engineers from NASA and ESA worked together and came up with a superb corrective optics package that would restore Hubble's eyesight completely. A Shuttle crew 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.

SM1 captured the attention of both astronomers and the public at large to a degree that no other Shuttle mission since has achieved. Meticulously planned and brilliantly executed, the mission succeeded on all counts. It will go down in history as one of the highlights of human spaceflight. Hubble was back in business.

Since SM1, four other Servicing Missions have been carried out: during SM2 in 1997, two new instruments were installed; in SM3A in 1999, many of Hubble's crucial technical systems were exchanged; and in 2002 came SM3B when Hubble again was fitted with new science instruments. Following SM4, Hubble is now expected to work long into the new decade, with strong hopes for an overlap with its successor, the James Webb Space Telescope, which is currently under construction by NASA, ESA and the Canadian Space Agency, and due for launch in 2014.

→ ESA astronaut Claude Nicollier using one of the Hubble power tools, during the second of three STS-103 extravehicular activities in 1999

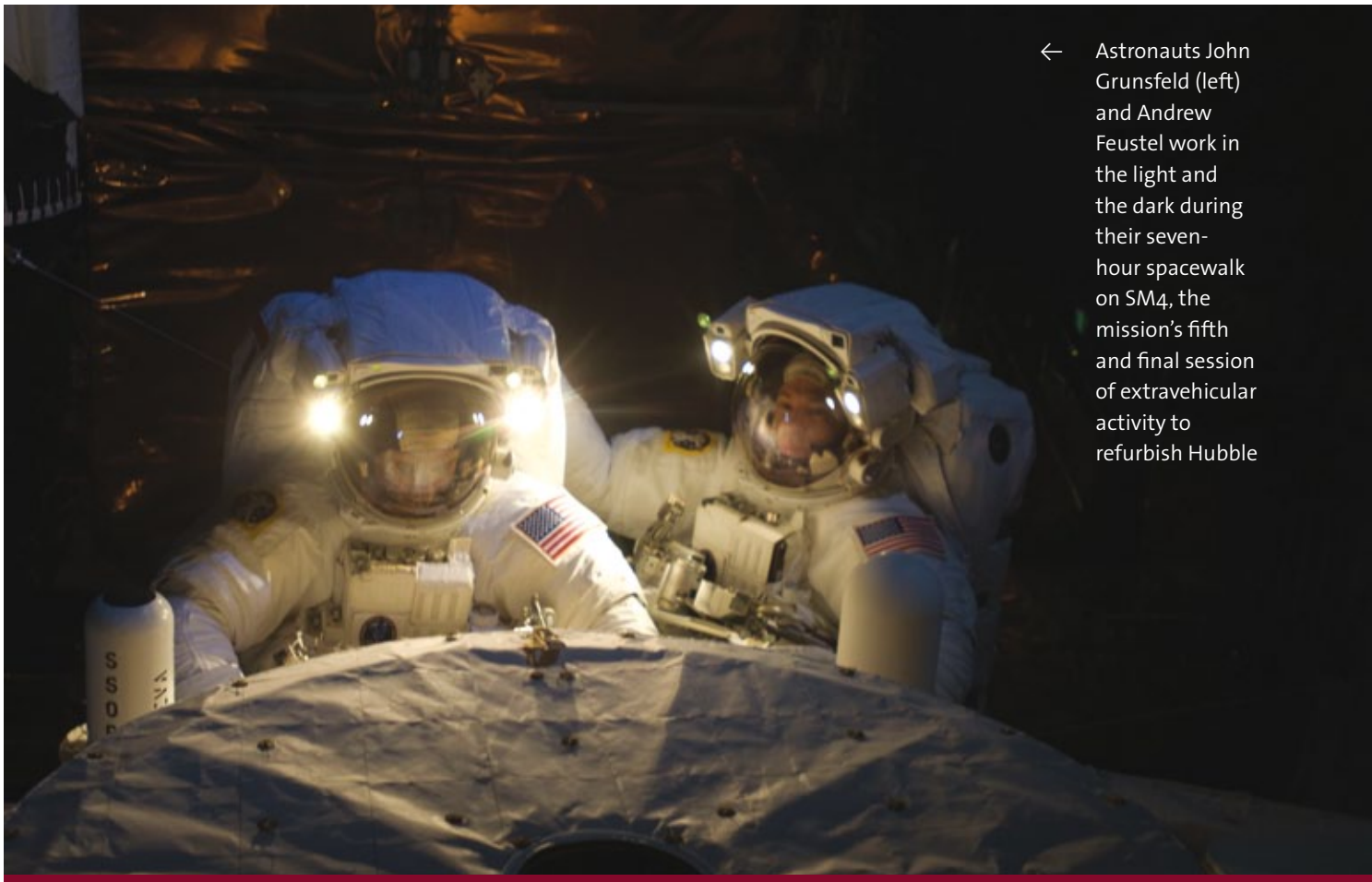
1993
First Hubble Servicing Mission (SM1) in December 1993

1997
During SM2 two new instruments were installed

1999
SM3A: Many of Hubble's crucial technical systems were exchanged

2002
SM3B: Hubble again was fitted with new science instruments

2009
SM4: Fifth and last Shuttle Servicing Mission



← Astronauts John Grunsfeld (left) and Andrew Feustel work in the light and the dark during their seven-hour spacewalk on SM4, the mission's fifth and final session of extravehicular activity to refurbish Hubble

→ Servicing Mission 4

During the ambitious NASA Servicing Mission 4 in May 2009, the Space Shuttle *Atlantis* STS-125 rendezvoused with Hubble, captured it with the Shuttle's robot arm and placed it in its payload bay. The STS-125 astronauts performed on-orbit repairs on two important science instruments.

With the Space Telescope Imaging Spectrograph (STIS) and Advanced Camera for Surveys (ACS) still in place on Hubble, the STS-125 spacewalkers attempted – for the first time ever – to repair instruments in orbit. These instruments were never designed to be fixed in space.

Astronomers the world over watched anxiously as the astronauts performed 'space surgery' on their treasured telescope, knowing that the period following the mission would be critical to the future success of Hubble.

A team of ESA engineers kept a watchful eye on Hubble's large solar panels – the lifeblood of the spacecraft – as they turned and made way for spacewalking astronauts. Although the ESA-supplied solar panels were replaced in 2002, the new ones are still connected to European solar array drive mechanisms.

Led by Michael Eiden, ESA HST Project Manager for the Science and Robotic Exploration Directorate, the team of four worked 12-hour shifts to provide 24-hour coverage for the entire mission, supervising the positioning of the panels and ensuring the integrity of the solar array hardware.

"We were elated with the performance of ESA's Solar Array Drive Electronics and Solar Array Drive Mechanisms – they performed flawlessly," said Eiden. "I have worked on all of the servicing missions, but to be able to support the last mission to this extraordinary telescope was particularly gratifying."

↑ ESA HST Project Manager for the Science and Robotic Exploration Directorate Michael Eiden shares a handshake with NASA Goddard Mission Operations Manager Keith Walyus

← The ESA Hubble team during shift handover. Michael Eiden (far left) and Udo Rapp (far right) work the orbit shift, while Lothar Gerlach (second from left) and Manfred Schmid (middle) work the planning shift

← The ESA HST team with ESA HST Project Scientist & Mission Manager Antonella Nota

During the spacewalks, the astronauts delivered two new instruments, a camera and a spectrograph. The Wide Field Camera 3 (WFC3), which replaced the workhorse WFPC2, is the first single instrument on Hubble to be able to image across infrared, visible and ultraviolet wavelengths.

The Cosmic Origins Spectrograph (COS) will help astronomers to determine the chemical composition and evolution of the Universe. Both instruments use advanced technology to improve Hubble's potential for discovery dramatically and to enable observations of the faint light from the young stars and galaxies in the Universe.

The astronauts were also able to repair the Advanced Camera for Surveys (ACS) and the Space Telescope Imaging Spectrograph (STIS), both affected by power failures. A dramatic moment occurred when the astronauts had to conquer a stubborn bolt on a handrail attached to STIS before taking on the task of removing 111 screws to access the instrument's power supply card. After trying multiple options without success, managers on the ground advised astronaut Mike Massimino to use 'brute force' to break off the handrail, so he could proceed with the removal of the cover plate.

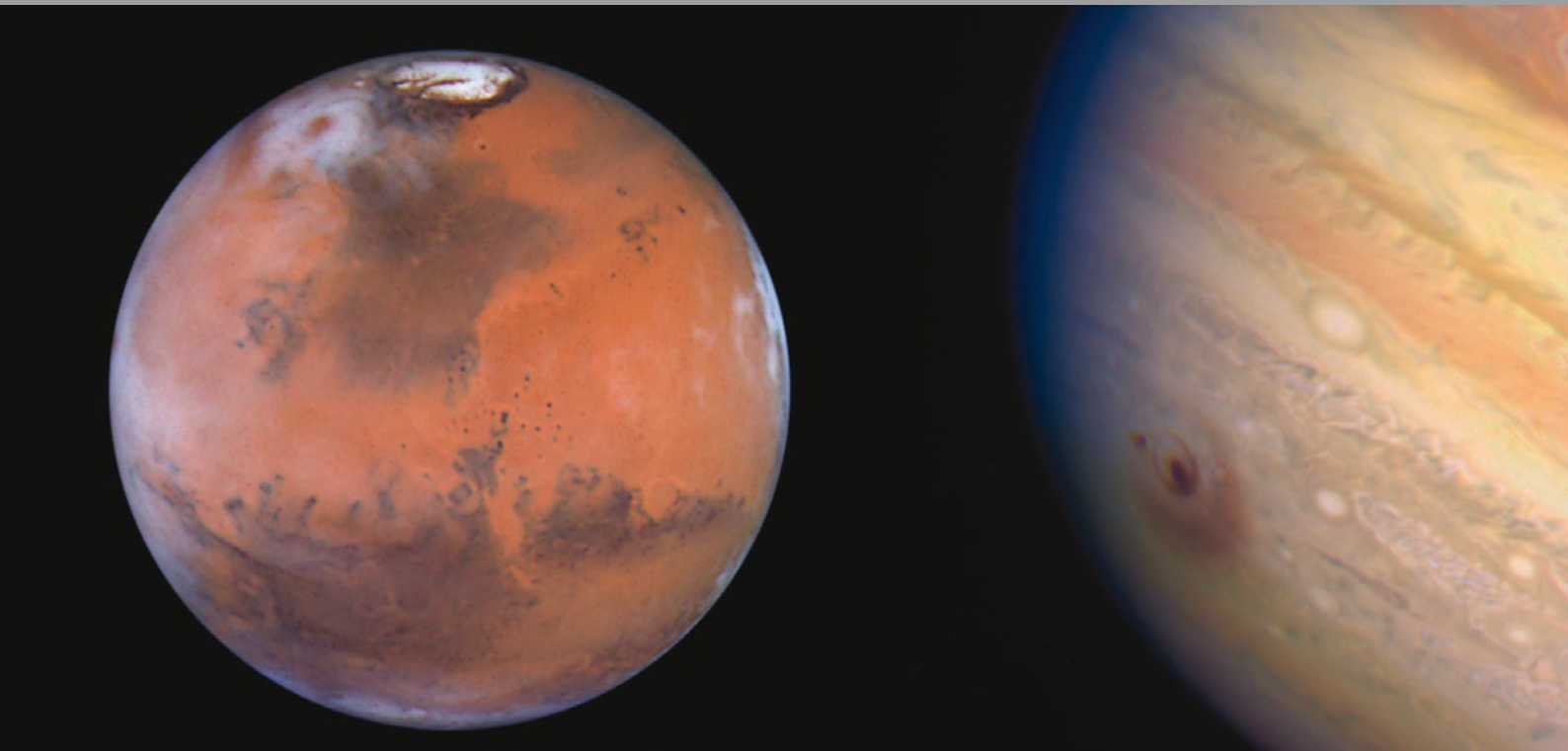
ACS's powerful imaging capabilities at both ultraviolet and optical wavelengths are now both available again, although its High Resolution Channel could not be fixed. ACS provides the perfect complement to the powerful new WFC3, and the duo will be vital for the study of dark energy and dark matter.

After a 13-day mission, all mission objectives were accomplished during five spacewalks that totalled 36 hours, 56 minutes. Hubble was revitalised, now more capable than ever. ■

→ TOP 20 OF SOME OF THE MOST AMAZING HUBBLE IMAGES

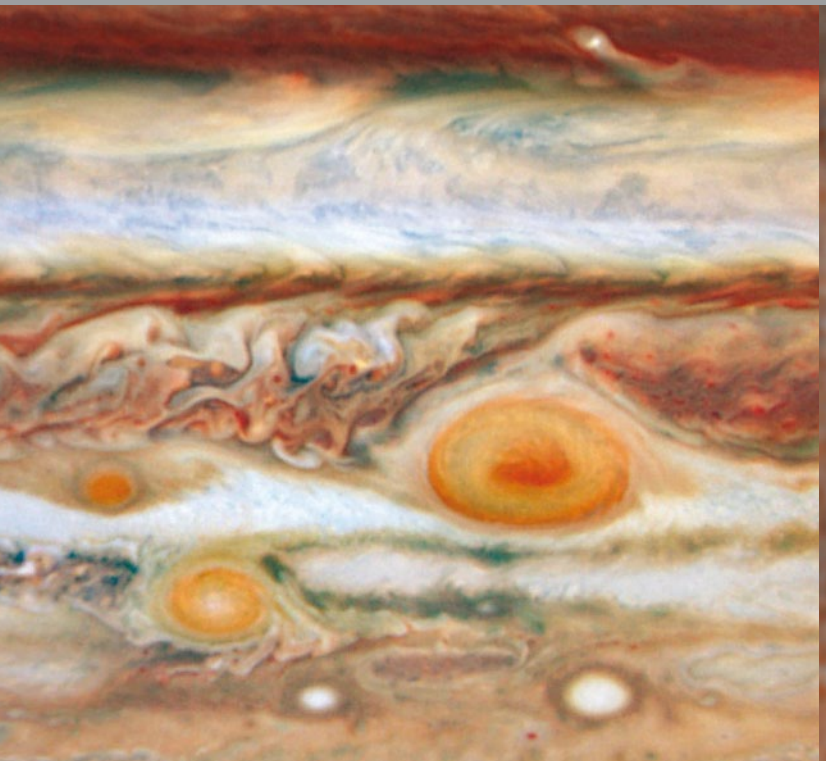
↓ **20.** Mars seen in 1999, with dark sand dunes around the polar ice cap, and a large cyclonic storm churning nearby. Early morning clouds can be seen along the left limb of the planet (Univ. Colorado/Cornell/SSI/NASA/ESA)

↓ **19.** A true colour image of Jupiter reveals the impact sites of fragments 'D' and 'G' from Comet Shoemaker-Levy 9 (MIT/NASA/ESA)

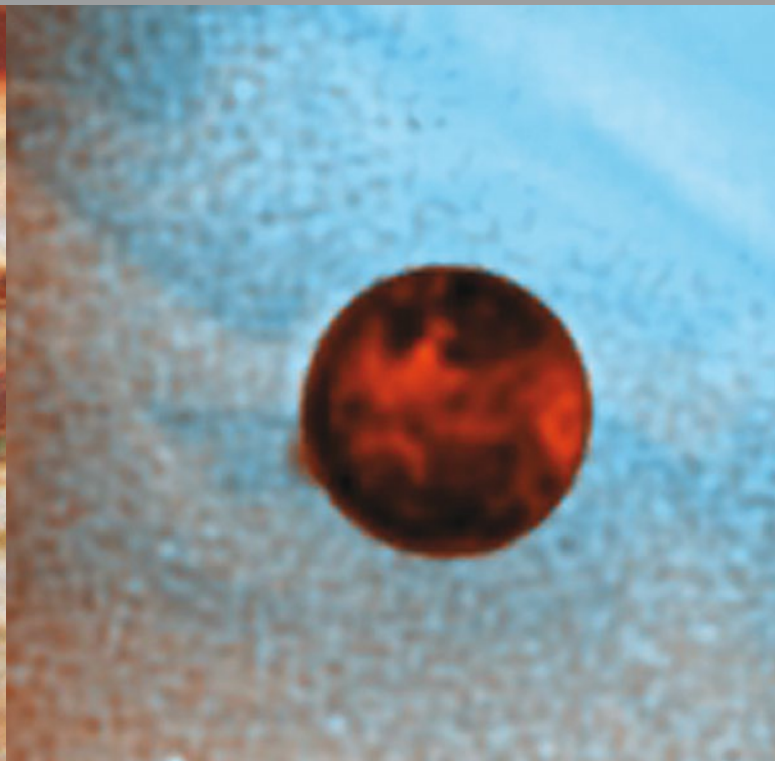


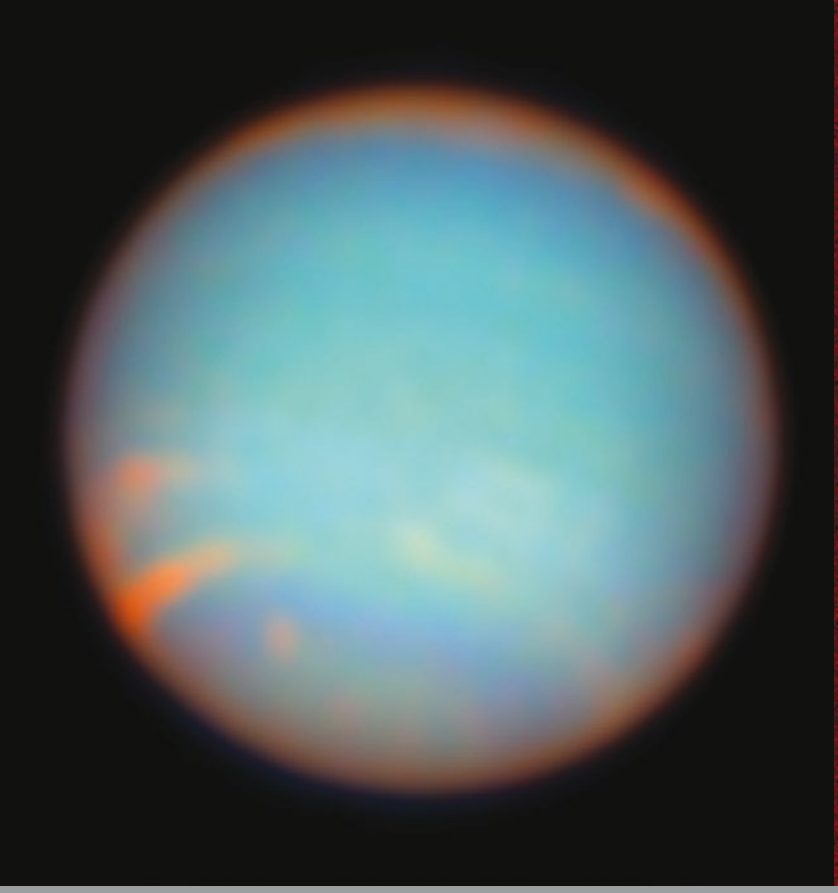
↓ One of the Universe's most stately and photogenic galaxies, the Sombrero galaxy, M104 (NASA/ESA/STScI/AURA)

↓ **18.** A third red spot has appeared alongside its cousins, the Great Red Spot and Red Spot Jr., in the turbulent atmosphere of Jupiter (NASA/ESA/Univ. Calif., Berkeley)

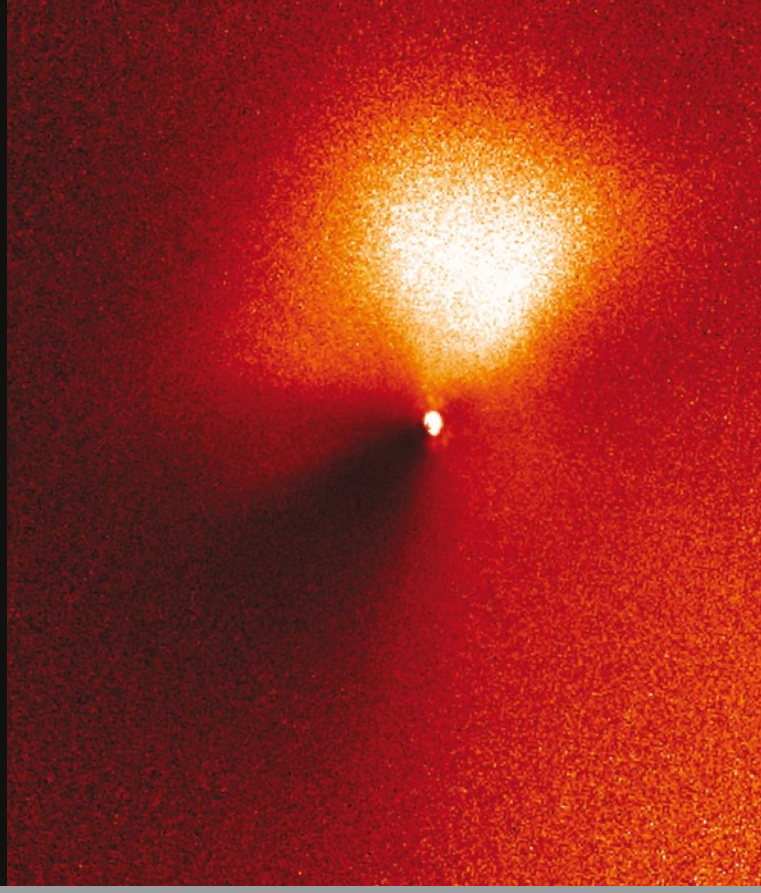


↓ **17.** A 400-km-high plume of gas and dust from a volcanic eruption on Io, Jupiter's large innermost moon, taken by the Hubble WFPC2 in 1996 (NASA/ESA/Lowell Obs.)

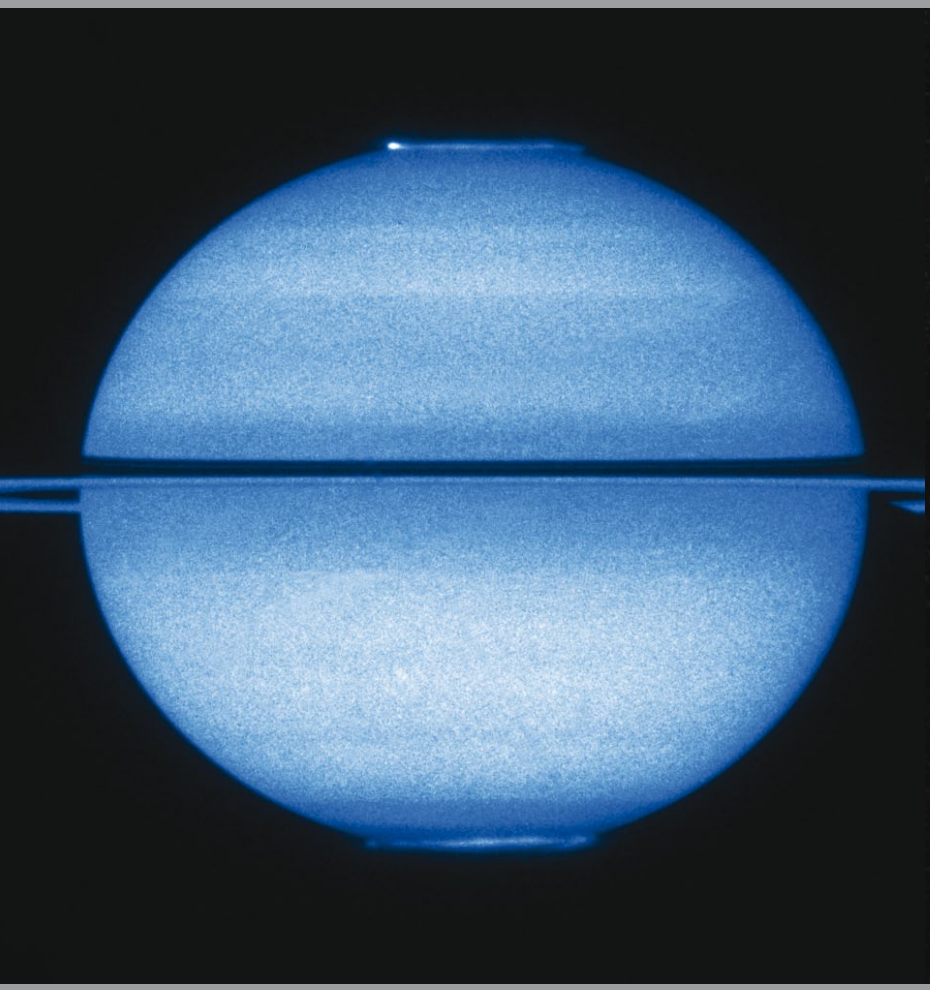




↑ **16.** Atmospheric features seen on Neptune taken through colour filters on the Advanced Camera for Surveys in 2003 (NASA/ESA/Univ. Ariz.)



↑ **15.** Hubble captures the gaseous outburst from Comet 9P/Tempel 1, after being hit by the Deep Impact spaceprobe (NASA/ESA/Johns Hopkins Univ./App. Phys. Lab)



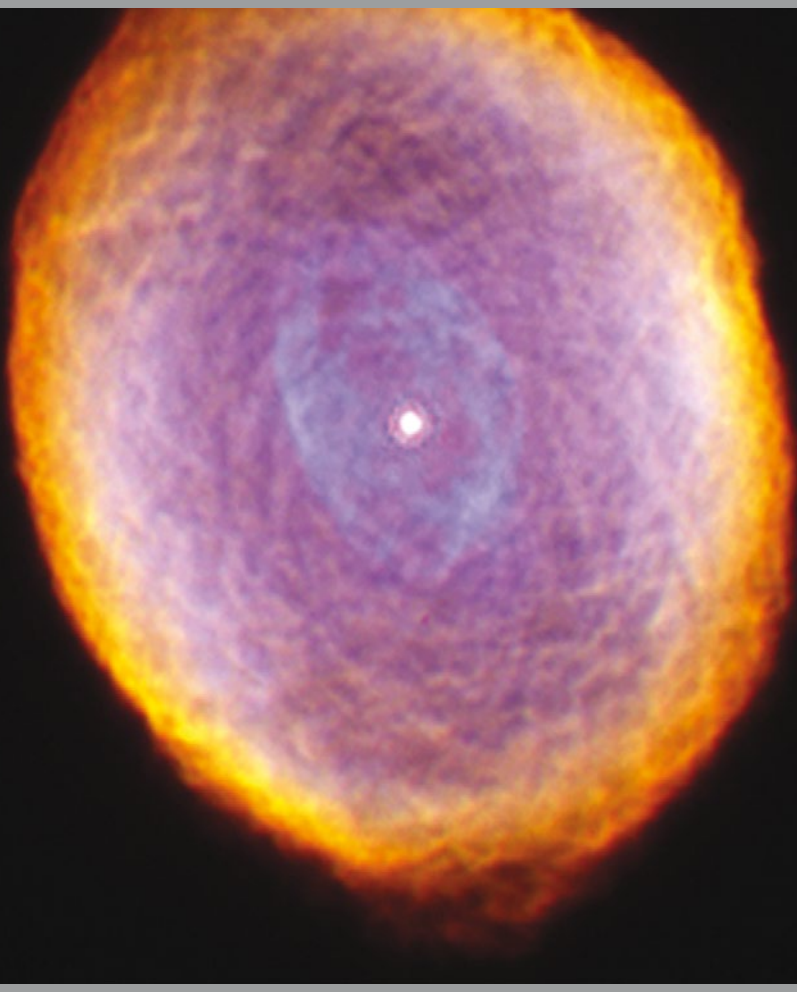
↑ **12.** A unique image from 2009 features Saturn with its rings edge-on and both poles in view, offering a stunning view of its almost symmetrical aurorae, Saturn's own 'northern' and 'southern lights' (ESA/Univ. Leics.)

↑ **11.** M2-9, the 'Twin Jet Nebula', is a striking example of a 'butterfly' or a bipolar planetary nebula (Univ. Wash./Leiden Univ./Stockholm Univ./NASA/ESA)

↑ **14.** NGC 6826's eye-like appearance is marred by two sets of red 'fliers' that lie horizontally across the image. Taken in 1996 with Hubble WFPC2 (Univ. Wash./USNO/Cornell/Univ. Florence/Arcetri Obs./NASA/ESA)

↑ **13.** The 'Eskimo' Nebula, NGC 2392 (NASA/ESA/STScI/ST-ECF)

↑ **10.** The glowing eye of planetary nebula NGC 6751 (NASA/ESA/STScI/AURA)

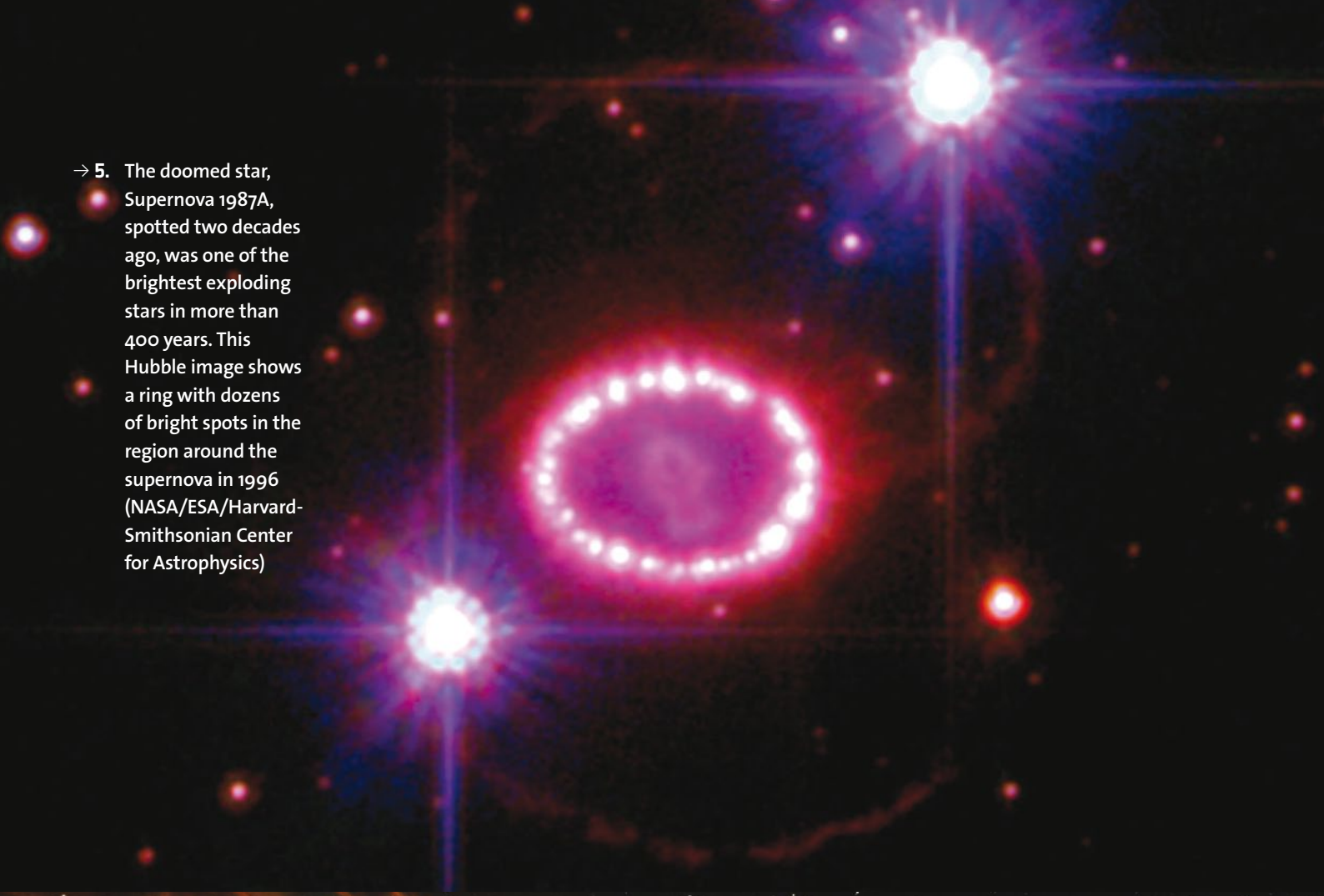


↑ **9.** The 'Spirograph' Nebula, planetary nebula IC 418 (NASA/ESA/STScI/AURA)

→ **8.** Hourglass' 'Nebula, the young planetary nebula MyCn18 (JPL/ NASA/ESA

→ **7.** Supernova 1994D shining just to the left of galaxy NGC 4526 (NASA/ESA/ Key Project/ High-Z Supernova Search)

→ **6.** Blobs of cold cosmic dust lie around the giant elliptical galaxy NGC 1316 (NASA/ ESA/STScI/ AURA)



→ **5.** The doomed star, Supernova 1987A, spotted two decades ago, was one of the brightest exploding stars in more than 400 years. This Hubble image shows a ring with dozens of bright spots in the region around the supernova in 1996 (NASA/ESA/Harvard-Smithsonian Center for Astrophysics)

→ **4.** The planetary nebula NGC 6302 taken by Hubble WFC3 after Servicing Mission 4 (NASA/ESA/ERO)

↑ **3.** The massive group of young stars is only a few million years old and resides in 30 Doradus, the 'Tarantula' Nebula, the largest stellar nursery in our local galactic neighbourhood. Taken by Hubble WFC3 after Servicing Mission 4 (NASA/ESA/ERO)

↑ **2.** In January 2002, a moderately dim star called V838 Monocerotis in the constellation Unicorn suddenly became 600 000 times more luminous than our Sun. This made it temporarily the brightest star in our Milky Way. The light from this eruption created a unique phenomenon, known as a 'light echo', when it reflected off dust shells around the star, and it may represent a stage in a star's evolution that is rarely seen (NASA/ESA/STScI)

↖ **1.** And finally, possibly one of the most fascinating images ever taken: more than 12 billion years of cosmic history are shown in this unprecedented, panoramic, full-colour view of thousands of galaxies in various stages of evolution.

This mosaic is made of images taken in September and October 2009 with WFC3 after Servicing Mission 4 (and 2004 with ACS) and covers a portion of the southern field of a deep-sky study (GOODS) by several observatories to trace the formation and evolution of galaxies (a slice of space that is equal to about a third of the diameter of the full Moon). Such a detailed view of the Universe has never before been assembled in such a combination of colour, clarity, accuracy and depth. It shows over 7500 galaxies stretching back through most of the Universe's history (NASA/ESA/ Ariz. State Univ./Univ. Virginia/Carnegie Obs./Univ. Calif., Riverside/Univ. Calif., Davis/Ohio State Univ./STScI)