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April 2000

HUBBLE SPACE TELESCOPE

10 YEARS THAT CHANGED OUR VISION

- EUROPE & HUBBLE

HUBBLE

esa

The Hubble Project

The Hubble Space Telescope is a project of international co-operation between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). The partnership agreement between ESA and NASA was signed on 7 October, 1977.

ESA has provided two pairs of solar panels and one of Hubble's scientific instruments (the Faint Object Camera), as well as a number of other components. In addition, 15 European scientists are working at the Space Telescope Science Institute in Baltimore (STScI), which is responsible for the scientific operation of the Hubble Observatory and is managed by the Association of Universities for Research in Astronomy (AURA) for NASA. In return, European astronomers have guaranteed access to 15% of Hubble's observing time.

The Space Telescope European Coordinating Facility (ST-ECF) hosted at the European Southern Observatory (ESO) in Garching bei München, Germany, supports European Hubble users. ESA and ESO jointly operate the ST-ECF.

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Lockheed Martin Missiles & Space

VLT image on p. 16 and ESO HQ image on p. 10:
European Southern Observatory (ESO)

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NASA

10 Years that Changed our Vision - *Europe & Hubble*

Claude Nicollier
ESA astronaut and astronomer

A large ground based telescope is always surrounded by a massive mount... Hubble is free floating in space, light, slim, apparently fragile, but incredibly capable!

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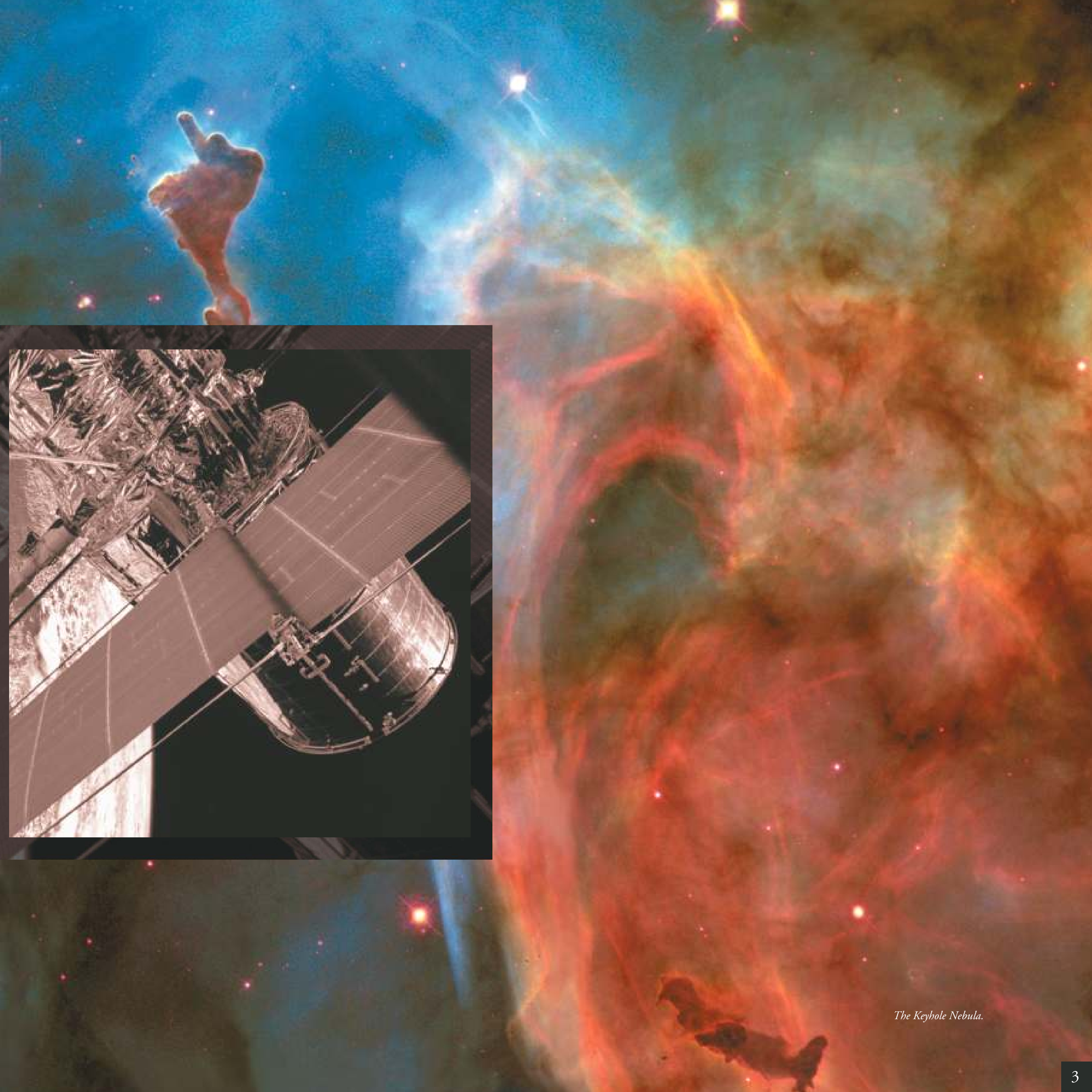


The Keyhole Nebula.

Changing our Vision

The involvement of the European Space Agency in the Hubble Project dates back to 1977 and initially there may have been doubts about its effective return. First, the long delay due to the Challenger disaster, followed by the unexpected discovery of the spherical aberration of the telescope mirror soon after launch, made any prospects for a scientific return seem distant.

Today, after 10 years of operation, we can confidently say that European investment in the Hubble Project has been, and remains a great ESA success!

The impressive impact that the Hubble observations have had on astrophysics and cosmology is, to a not inconsiderable degree, due to the intellectual contribution of European scientists, who, thanks to the ESA participation, have had access to this unique facility. The large fraction of Hubble observing programmes and scientific papers which include European astronomers has confirmed that ESA's decision to participate in Hubble was a wise one.

Together with the scientific success of Hubble, ESA can also be proud of the excellence of its technological and operational contributions: the Faint Object Camera, the Solar Arrays, the scientists working at the Space Telescope Science Institute and at the Space Telescope European Coordinating Facility and last, but not least, the professional job done by its astronauts during the servicing missions to Hubble. In all these areas we have shown ourselves to be reliable partners.

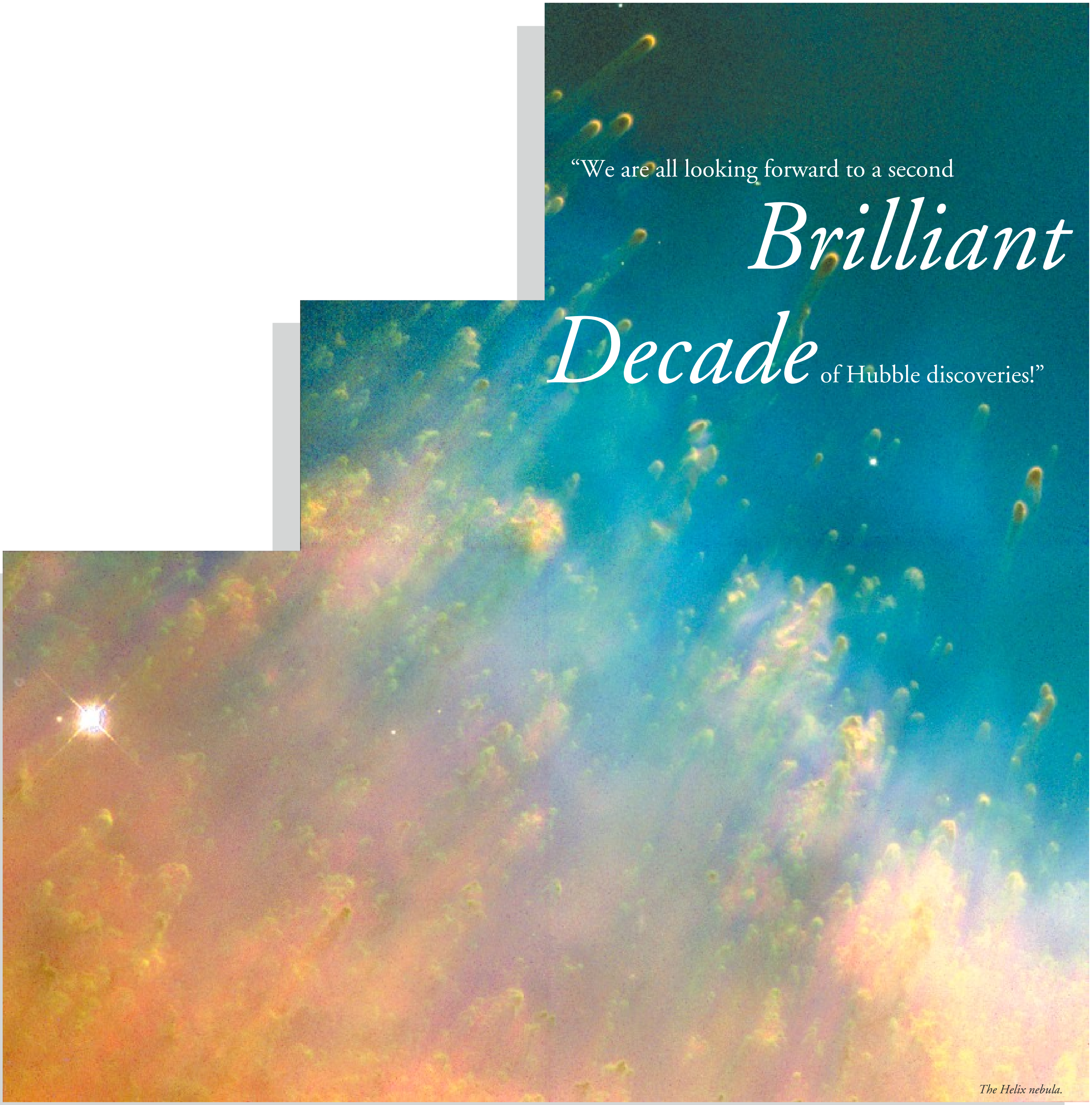
The next decade of Hubble will see an even more effective scientific return for Europe as European astronomers benefit from the synergy of Hubble with large ground-based telescopes that are now becoming available to them. Furthermore, ESA is now in a position to negotiate an important future contribution to the Next Generation Space Telescope with NASA and the Canadian Space Agency.

With such exciting prospects, it is important that the European community, particularly its younger generation, is regularly and effectively informed about the progress and the successes that Europe is achieving in this field. For this reason we have established the Hubble ESA Information Centre to maintain effective communication channels between the Hubble and NGST projects and the European media.

Hubble has already changed our vision of the Universe. We are looking forward to a second brilliant decade of Hubble discoveries!

R.M. Bonnet
ESA Director of Science

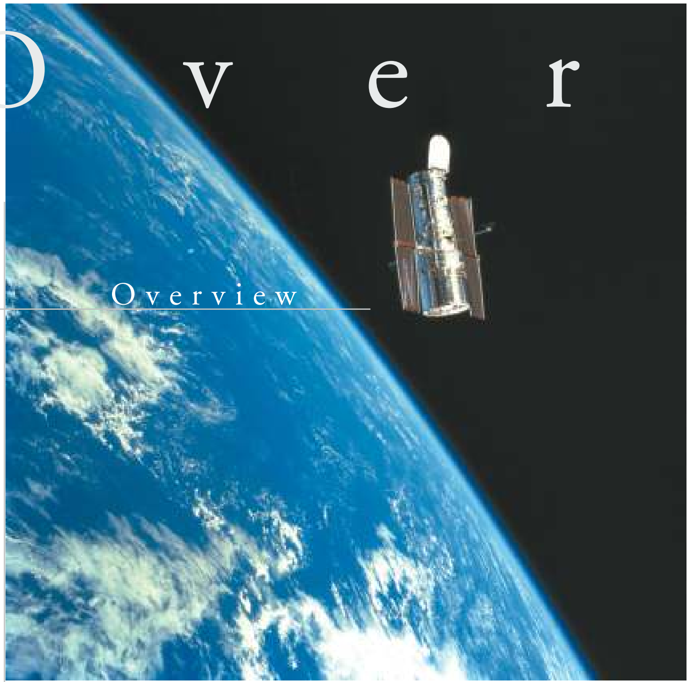
“...the Hubble Project has been, and remains a great ESA success!”



The Helix nebula.

About Hubble

Overview



Hubble just after release, SM3A.

The Universe is gloriously transparent. Visible light can travel across it unchanged for billions of years, but in the last few microseconds before the light arrives at telescope mirrors on Earth it passes through our turbulent atmosphere and the fine cosmic details are blurred. We see the same effect with the naked eye when we watch stars twinkling in the dark night sky.

Putting a telescope into space is one way of evading this problem. The Hubble Space Telescope, a joint NASA/ESA project, has already made some of the most dramatic discoveries in the history of astronomy. Named after the American scientist Edwin Hubble, Hubble looks deep into space where some of the most profound mysteries are waiting to be unravelled. From its vantage point 600 km above the Earth, Hubble can detect light before it is distorted by the atmosphere with 'eyes' 10 times sharper than the largest ground-based telescopes. Hubble also carries the biggest ultra-violet instrument ever flown in space, so that it can detect wavelengths that are completely filtered out before they reach the ground. High above the atmosphere, Hubble gives astronomers a clear view out into the furthest reaches of space and time.

Facts

Launch date – 24 *April, 1990*

Launch mass – *11 110 kg*

Dimensions – *15.9 m long, 4.2 m diameter*

Solar panels – *Each 2.4m x 12.1m*

Current instruments – *WFPC2, STIS, NICMOS, FOC, and Fine Guidance Sensors*

Orbit – *Circular, 593 km above the Earth and inclined at 28.5° to the Equator*

Expected operational lifetime – *20 years*

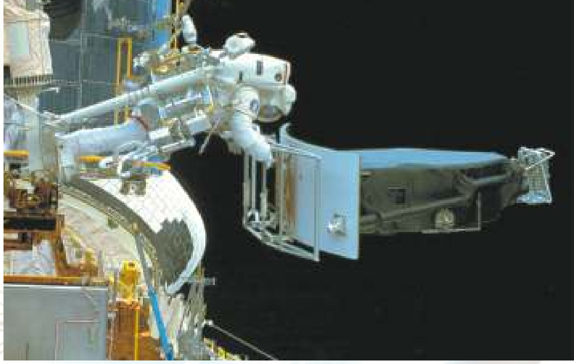
Costs – *ESA's financial contribution to Hubble is 593 million Euros (in 1999 terms)* e w

Instruments

From its earliest days Hubble has been designed as a permanent space-based observatory that can be serviced by the Space Shuttle. These Servicing Missions allow astronauts to replace and update the science instruments on board.
Hubble's complement of science instruments currently includes two cameras, two imaging spectrographs and fine guidance sensors (used for astrometric observations).
Hubble's position outside the Earth's atmosphere enables these science instruments to produce high resolution images of astronomical objects. Ground-based telescopes can seldom provide resolution better than 0.5-1.0 arc-seconds, except briefly, under the very best observing conditions. Hubble's resolution is about 10 times better, or 0.05 arc-seconds.

Wide Field Planetary Camera 2
WFPC2 is Hubble's workhorse camera. It records images through a selection of 48 colour filters covering a spectral range from the far-ultraviolet to visible and near-infrared wavelengths. WFPC2 has produced most of the stunning 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 10 years of Hubble's life.

Space Telescope Imaging Spectrograph
STIS is a versatile 'dual purpose' instrument using the most modern technology. It consists of a camera and a spectrograph operating over a wide range of wavelengths from the near-infrared region to the ultraviolet.



Exchanging WFPC1 (here) with WFPC2, SM1.

The Near Infrared Camera and Multi-Object Spectrometer
NICMOS can take infrared images and make spectroscopic observations of astronomical targets. NICMOS detects infrared light invisible to human eyes with wavelengths between 8000 to 25000 Ångstroms. NICMOS is currently not in use and awaiting a new cooling system to be installed on the next Servicing Mission (3B).

The Faint Object Camera
FOC was built by the European Space Agency. It is an optical and ultraviolet camera able to count individual photons (light particles) as they arrive. The sharpness of the images obtained by FOC is the highest achievable with the Hubble instruments and greater than that of the WFPC2 camera.

The Fine Guidance Sensors
Hubble has three Fine Guidance Sensors (FGS) 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 accurate position measurements to establish stellar distances and investigate binary star systems.

Exchanging FGS, SM2.

Hubble with its instrument bay open, SM3A.

Initial Problems

Installation of COSTAR to fix Hubble's vision, SM1.

Spherical aberration

We have come to take the excellent performance of the Hubble Space Telescope for granted. However, immediately after launch people were reminded that Hubble was not just an ordinary satellite, but a complex piece of innovative engineering and as such, liable to teething problems.

The most serious and notorious problem was an optical defect called spherical aberration, which was caused by the malfunction of a measuring device used during the polishing of the mirror. As a result, Hubble could not achieve the best possible image quality, although still outperforming ground-based telescopes in many ways. Analysing the problem and developing an optical correction was a masterpiece of optical engineering and an outstanding example of the valuable collaboration between engineers and scientists from both America and Europe.

Solar Panels

A less complex, but annoying problem was a small but unacceptable jitter in the position of the entire spacecraft introduced by Hubble's solar panels whenever it moved from the sunlit to the dark part of the orbit, and vice versa. A mechanism holding the solar arrays in place was sensitive to tiny motions caused by the temperature difference of some 200 degrees Centigrade between the two parts of the orbit.

The Repair

During the first HST Servicing Mission in December 1993 a crew of astronauts carried out the repairs necessary to restore the telescope to its intended level of performance. Although the two other servicing missions which have since been performed were at least as demanding in terms of complexity and work load, the first servicing mission captured the attention of both the professional community and the public at large to a degree that no other Shuttle mission 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.

Before correction

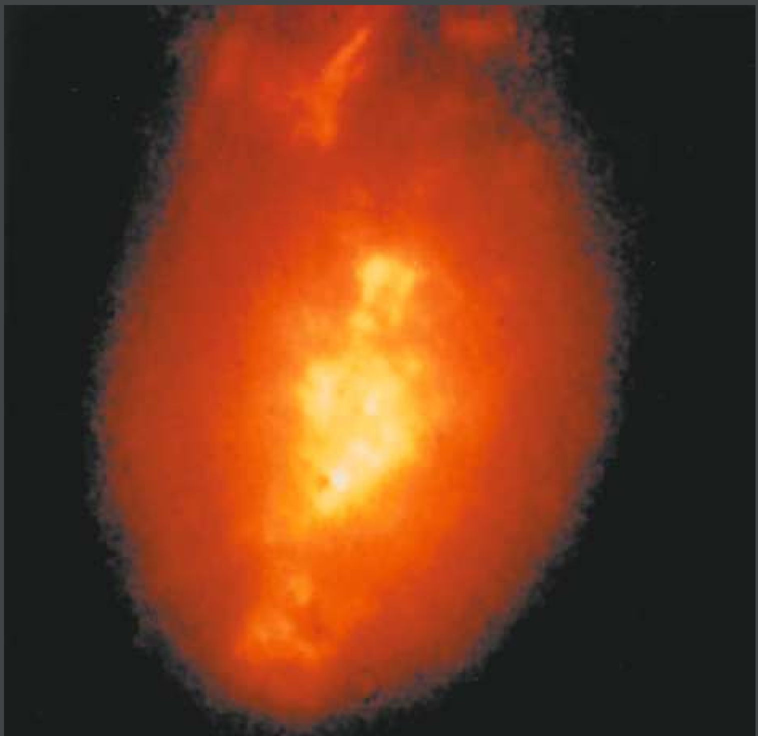
Spiral galaxy M100 before and after the correction of Hubble's vision.

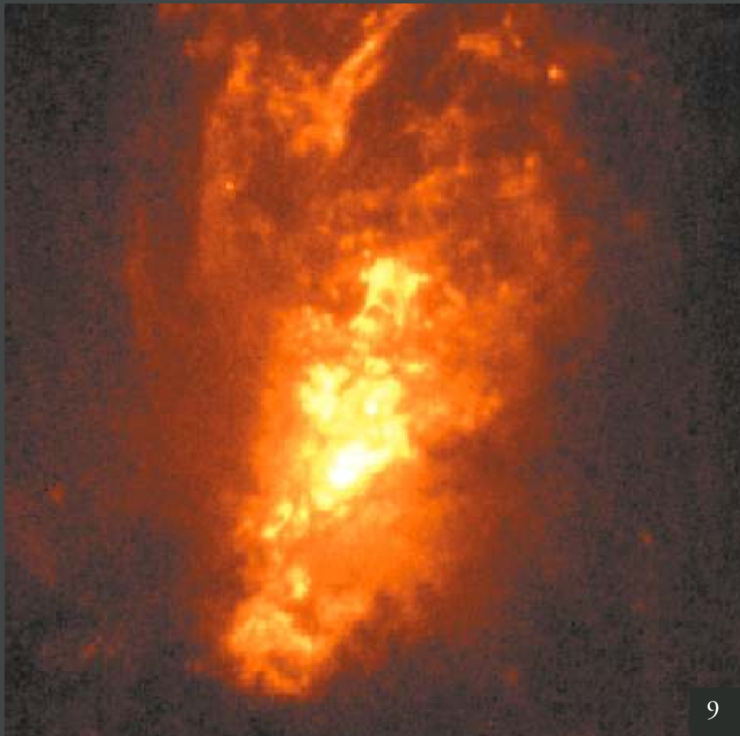
After correction

Before correction

The core of active galaxy NGC 1068 before and after the correction of Hubble's vision.

After correction





Europe & Hubble

Science and Operations

ESO HQ in Garching near Munich.

Piero Benvenuti
ESA Hubble Project Scientist, Head of ST-ECF

Hubble is of paramount importance to European astronomy. It gives European scientists the opportunity to use a world class observatory of a kind that Europe alone would not have been able to build and operate, enabling scientists in Europe to continue to be competitive and even lead in several areas of astrophysics and cosmology. Today the European astronomical community is in a good position to apply its experience with Hubble and exploit effectively the large observing facilities currently under construction or discussion, such as the ESO Very Large Telescope (VLT), the Gemini Telescopes and the Next Generation Space Telescope (NGST).

Duccio Macchetto
ESA astronomer, Head of the Science Policies Division, STScI

ESA has 15 European scientists working at STScI in Baltimore as part of its contribution to the science operations of Hubble. This European contingent has not only played a significant part in the successful operation of the Hubble Observatory, but has also often consisted of young European astronomers taking the opportunity to work in a highly stimulating environment. Many European Hubble Observers have spent periods of research time at STScI and several European students have completed their Ph.D. studies there. It is an excellent return for the investment.

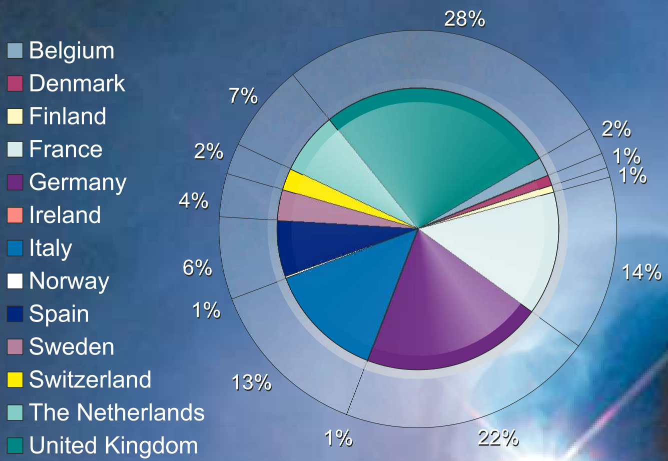
European use of Hubble

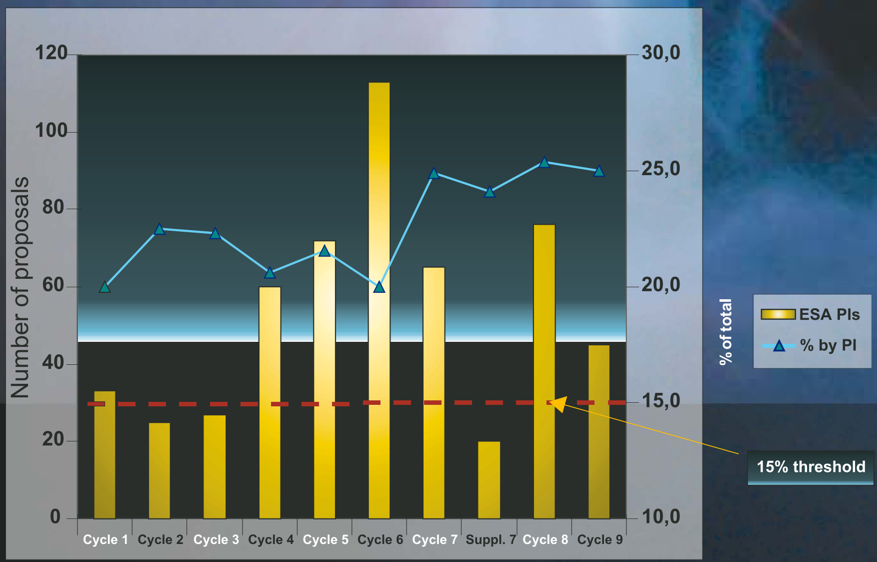
ESA's contribution to the Hubble Project guarantees European scientists access to 15% of Hubble observing time. Hubble time is allocated on pure scientific merit by an international panel that includes European experts. During the past 9 cycles of Hubble observations (approximately 9 years), European astronomers have always been allocated more than the guaranteed 15% threshold and in recent years the fraction of allocated time to European scientists has been close to a quarter.

Scientists from most ESA Member States have had an opportunity to observe with Hubble. During the first 9 cycles, more than 850 European astronomers were so-called Principal Investigators (PIs) or Co-Investigators (CoIs) in at least one successful Hubble observing programme and many were investigators in several cycles.

The success of a scientific mission can be measured by the number and quality of scientific papers that are published in the specialised press. The number of papers based on Hubble observations published each year has been increasing continuously since the telescope's launch. There is at least one European author or co-author on about 30% of these papers, indicating the importance of Hubble to European astronomy.

European PIs and CoIs by Country (total number = 864)





Space Telescope-European Coordinating Facility (ST-ECF)

The ST-ECF supports European Hubble users and is jointly operated by ESA and ESO. The ST-ECF offers support for the preparation of Hubble observing proposals and the scientific analysis of observations. It also operates the Hubble Science Archive, which makes data available to the astronomical community via the Internet.

When an observation is made with Hubble the data are the exclusive property of the observers for one year, after which all scientific data are made available to the public. In ten years of successful operation the Hubble Archive has accumulated more than 130,000 unique astronomical images and is a real gold mine to be exploited by astronomers for many years to come.

STScI

The Space Telescope Science Institute (STScI) is responsible for the scientific operation of Hubble as an international observatory. The STScI is housed on the Johns Hopkins Homewood campus in Baltimore and it is operated by AURA (the Association of Universities for Research in Astronomy) for NASA. The STScI currently has a combined staff of approximately 500, of whom approximately 100 are Ph.D. astronomers and scientists, including 15 ESA staff members.

Among the prime tasks of the STScI are the selection of the Hubble observing proposals, their execution, the scientific monitoring of the telescope and its instruments and the archiving and distribution of the Hubble observations.

The STScI has been recently selected by NASA as the responsible institute for the scientific operations of the Next Generation Space Telescope, NGST.

Reflection nebula NGC 1999 in Orion.

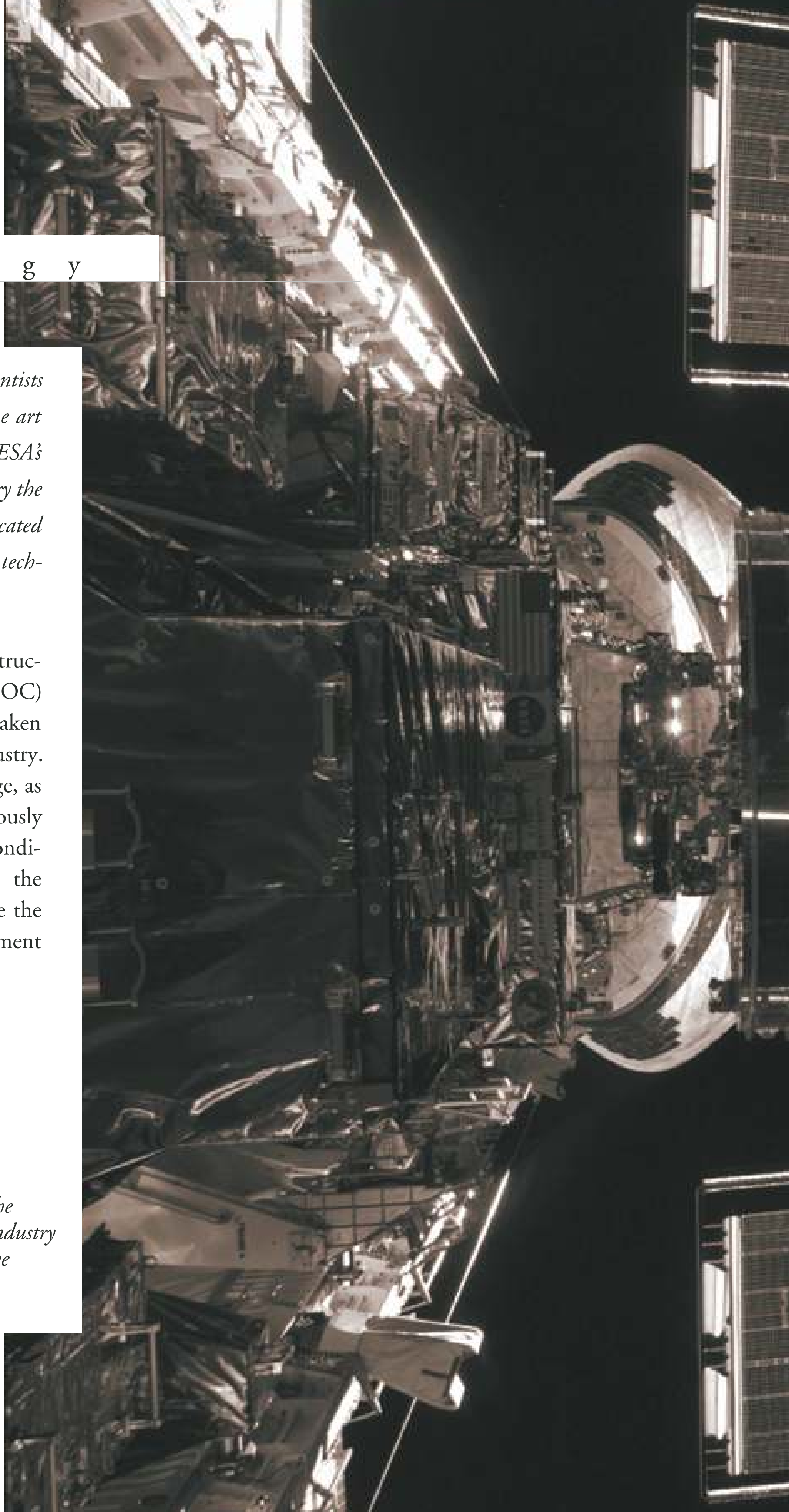
Hubble & Europe

T e c h n o l o g y

FOC

Hubble not only gives European scientists the opportunity to carry out state of the art investigations, it also fulfils one of ESA's major goals by giving European industry the chance to develop and build sophisticated space hardware using the most modern technology.

The design, development and construction of the Faint Object Camera (FOC) formed an ambitious project undertaken jointly by ESA and European industry. FOC presented a significant challenge, as it required technology that had previously only been used under laboratory conditions to be operated remotely in the extreme conditions of space. Despite the difficulty of the project the instrument has achieved wonderful results.



A. Linssen
Head of Project Management Support Office, ESA Science

Apart from the scientific return, the team spirit built up over the years between ESA/European Industry and NASA/American Industry by working on Hubble has created many friendships which have already outlasted some professional careers.

Hubble's solar panels.

Solar Panels

Power for the entire observatory is generated by two huge solar panels, which were also designed, developed and built by European industry under ESA's leadership. These panels are delicate, flimsy structures, which would collapse under their own weight if unfurled on Earth. They had to be packed in such a way that they survived the extreme loads of launch and the ascent into orbit. Once deployed the solar panels must always face the Sun to keep the batteries of the telescope charged. There was no margin for error in this design since, if Hubble lost power completely due to a malfunction of the arrays, Hubble's mission could not have continued.

European industry, together with ESA, has contributed to the overall success of Hubble Space Telescope, a truly international collaboration between Europe and the United States. Today this is perhaps not so very remarkable, but it must be remembered that when the initial ESA activities on Hubble began in the mid-seventies Europe was not as united as it is now. Large scale projects such as the NASA/ESA Hubble Space Telescope and other ESA space projects have worked as a catalyst in the development of the European Union as we know it today.

Hubble during SM2.

The launch on 24 April 1990.

The Launch and the Servicing Missions

The Hubble Space Telescope was launched on the shuttle Discovery (STS-31) on 24 April 1990 at 12:33:51 UT. The Space Shuttle took Hubble up to its highest possible orbit, where the telescope was released at 19:38 UT on 26 April at an altitude of more than 600 km.

The Servicing Missions

Servicing Missions keep the observatory and its instruments in prime scientific condition and are one of the innovative ideas behind Hubble. Early plans envisaged maintenance visits to the telescope every 2.5 years and that every five years Hubble would return to Earth for a larger overhaul. This plan has been modified and the servicing scheme now includes Shuttle Servicing Missions roughly every three years, but no interim return to Earth for Hubble.

First Hubble Servicing Mission

The primary mirror aberration described elsewhere in this brochure meant that Hubble did not live up to expectations during its first three years. On the First Servicing Mission in December 1993 (STS-61) astronauts, including the Swiss Claude Nicollier, installed COSTAR (Corrective Optics Space Telescope Axial Replacement), a new instrument with corrective optics to act as Hubble's 'spectacles'. Hubble's golden age began, the images were as sharp as originally hoped and new, astonishing results started to emerge on a regular basis. COSTAR replaced the High Speed Photometer (HSP) and the older Wide Field/Planetary Camera (WFPC) was replaced with WFPC2. The solar panels were replaced to overcome the problem of excessive flexure. This first Servicing Mission is seen as the turning point in the

Claude Nicollier
ESA astronaut and astronomer

During both Hubble Servicing Missions 1 and 3A, I could not stop thinking about how beautiful the orbiting instrument is, especially when seen against the blackness of space, its solar arrays illuminated by the Sun... A large ground based telescope is always surrounded by a massive mount... Hubble is free floating, light, slim, apparently fragile, but incredibly capable!

1993

Installation of COSTAR.

Servicing Mission 1

1997

Astronauts on duty.

Servicing Mission 2

1999

Inserting FGS.

Servicing Mission 3A

Future

Hubble's third set of solar panels (SM3B)

SM3B SM4 SM5

Hubble project by many of the people involved. The extremely complex operations carried out in space by the astronauts succeeded in transforming Hubble into the most powerful scientific tool ever made.

Second Hubble Servicing Mission

The Second Servicing Mission (STS-82) took place in February 1997 and included five spacewalks. The primary goal was the replacement of two first generation scientific instruments, the Faint Object Spectrograph (FOS) and the Goddard High Resolution Spectrograph (GHRS), with two new ones, the Near Infrared Camera and Multi-Object Spectrograph (NICMOS) and the Space Telescope Imaging Spectrograph (STIS).

Servicing Mission 3A

In November 1999 a fourth gyroscope in Hubble's original complement of six failed. A minimum of three working gyros is required to control where Hubble points in space, so this latest failure automatically sent the telescope into a protective safe mode and prevented any further observations. This made the replacement of the gyros vital. NASA had anticipated this problem and divided the original Mission 3 into two parts, bringing 3A forward to meet the situation. Discovery was launched in December 1999 and the astronauts – including ESA astronauts Claude Nicollier and Jean-François Clervoy – successfully completed the repairs and other scheduled upgrades so that Hubble is now back in top working condition, delivering superb images.

Future Servicing Missions

During SM3B (currently scheduled for 2001) the astronauts will replace the Faint Object Camera with the Advanced Camera for Surveys (ACS), install a new set of solar panels and a cooling system for NICMOS, enabling it to resume operation. Work on the replacement of the thermal insulation will also continue and the telescope will be moved to a higher orbit. Plans for a fourth Servicing Mission are at an early stage, but two new science instruments are already being developed for this mission: the Cosmic Origins Spectrograph (COS), which will replace COSTAR, and the Wide Field Camera 3 (WFC3), which will replace WFPC2. There are plans to retrieve Hubble at the end of its life (around 2010) and bring it back down to the ground, since it is thought that the size of the telescope will make it unsafe to allow it just to fall to Earth.

The Future

The ground – space synergy

Sunset over ESO's Very Large Telescope (VLT).

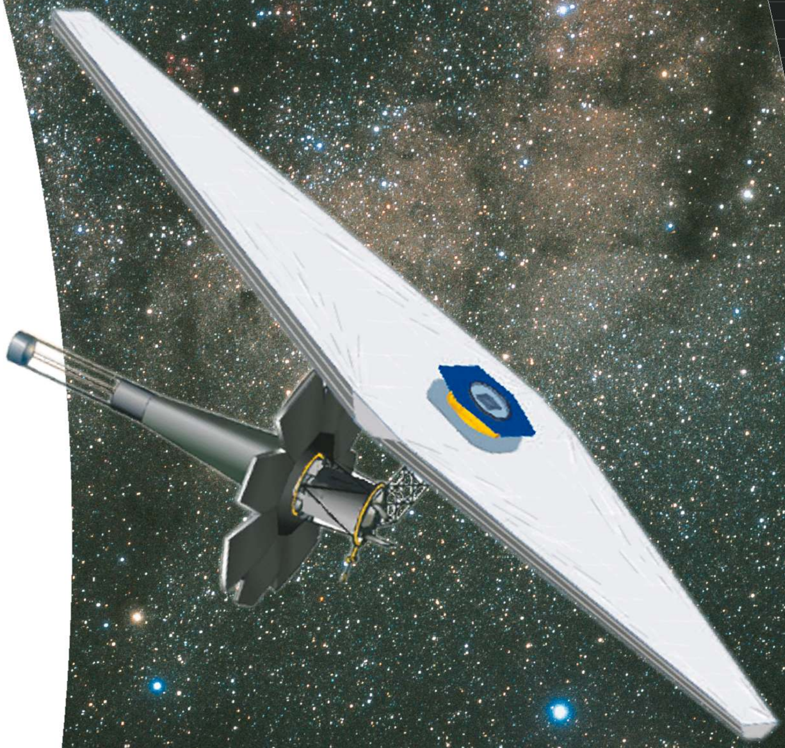
Catherine Cesarsky
Director General, European Southern Observatory (ESO)

Advances in astrophysics and cosmology are based more and more on the combined use of ground- and space-based observations. Organisations that are running the large observatories should make a special effort to facilitate the synergy between space and ground facilities, both in their scientific usage and in their operations, where mutual sharing of technology and procedures can result in substantial savings. ESA and ESO are already combining their efforts in several strategic areas and are looking forward to even more fruitful collaborations in the future.

Hubble has not only made many breakthroughs in astrophysics and cosmology, but has also paved the way for a more efficient use of large ground-based telescopes, as well as driven the design of new observing instruments.

For example, Hubble's superior resolution is unique in pinpointing faint, distant galaxies, but its relatively small primary mirror is not large enough to analyse the light from these remote objects in depth. Once the galaxies have been identified the 8-10 metre diameter ground-based telescopes, such as the European Southern Observatorys Very Large Telescope (VLT), the Keck Telescopes and the Gemini Telescopes, can observe them and use advanced instruments to analyse these faint signals and reveal the nature and composition of these very remote galaxies. It is the combined use of Hubble and these ground-based facilities that allow astronomers not only to know *where* the objects are, but also *what* they consist of and *how old* they are.

Many other planned observatories, both on the ground – such as ESO's ALMA, the Atacama Large Millimetre Array, or the 40-100 metre optical telescopes – and in space – such as ESA's Planck, First, NASA's Map and others – will start their explorations influenced heavily by the solid base of knowledge and experience gained from Hubble.



NGST

Hubble's crisp images of the depths of our galaxy and of the remote Universe have stimulated the design of new, even more ambitious observatories. The expansion of the Universe means that the further back astronomers look in time, the more light gets shifted to longer wavelengths. To actually 'see' further than Hubble, back to the time when galaxies were formed, we must observe in infrared light. The Next Generation Space Telescope (NGST), an 8-metre deployable telescope, capable of gathering ten times more light than Hubble and with an extraordinary sensitivity to infrared light is planned to be deployed in 2009 and will be Hubble's heir.

NGST is currently being studied by the NASA (National Aeronautics and Space Administration), CSA (Canadian Space Agency) and ESA.

Sergio Volonté
ESA, Astronomy Missions Coordinator

The successful participation of ESA in the Hubble project has proved to be extremely beneficial to the European scientific community. Quite logically, ESA is now actively involved with NASA, joined by the Canadian Space Agency, in the preparation of Hubble's successor, the Next Generation Space Telescope (NGST). NGST is a large aperture infrared mission that will peer through the remote universe back in time to the epoch of "First Light" when the first stars and galaxies ignited.

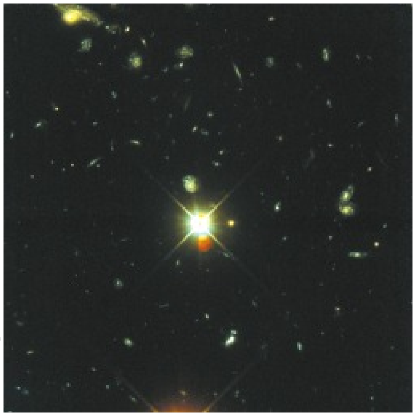
The Deep Fields

One of the main scientific justifications for building Hubble was to measure the size and age of the Universe and test theories about its origin. Images of faint galaxies give 'fossil' clues as to how the Universe looked in the remote past and how it may have evolved with time. The Deep Fields gave astronomers the first really clear look back to the time when galaxies were forming.

Hubble Deep Field North (WFPC2).

Stefano Cristiani
Space Telescope-European Coordinating Facility (ST-ECF)

In my view the Hubble Deep Fields are some of the images that have made the greatest impact on observational cosmology so far. These impressive dips into the depths of space and time have allowed astronomers to glimpse the first steps of galaxy formation more than 10 billion years ago and are without doubt some of the great legacies of the Hubble Space Telescope.



Hubble Deep Field South (STIS).

The idea for the Hubble Deep Fields originated in results from the first deep images taken after the repair in 1993. These images showed many galaxies, which were often quite unlike those we see in the local Universe and could not otherwise be studied using conventional ground-based telescopes.

The first Deep Field, the Hubble Deep Field North (HDF-N), was observed over 10 consecutive days during Christmas 1995. The resulting image consisted of 342 separate exposures, with a total exposure time of more than 100 hours, compared with typical Hubble exposures of a few hours. The observed region of sky in Ursa Major was carefully selected to be as empty as possible so that Hubble would look far beyond the stars of our own Milky Way and out past nearby galaxies.

The results were astonishing! Almost 3000 galaxies were seen in the image. Scientists analysed the image statistically and found that the HDF had seen back to the very young Universe where the bulk of the galaxies had not, as yet, had time to form stars. Or, as the popular press dramatically reported, “Hubble sees back to Big Bang”...

These very remote galaxies also seemed to be smaller and more irregular than those nearby. This was taken as a clear indication that galaxies form by gravitational coalescence of smaller parts.

In 1996 it was decided to observe a second Deep Field, the Hubble Deep Field South (HDF-S), to assess whether the HDF-N was indeed a special area and thus not representative of the Universe as a whole. This time the field also contained a quasar, which was used as a cosmological lighthouse and provided valuable information about the matter between the quasar and the Earth.

After the Hubble observations of HDF-N and -S, other ground and space-based instruments targeted the same patches of sky for long periods. Some of the most interesting results seem to emerge from these fruitful synergies between instruments of different sizes, in different environments and with sensitivity to different wavelengths.

The Age and Size of the Universe

Cepheids

The top ranked scientific justification for building Hubble was to determine the size and age of the Universe through observations of Cepheid variables in distant galaxies. This scientific goal was so important that it put constraints on the lower limit of the size of Hubble's primary mirror.

Cepheids are a special type of variable star with very stable and predictable brightness variations. The period of these variations depends on physical properties of the stars such as their mass and true brightness. This means that astronomers, just by looking at the variability of their light, can find out about the Cepheids' physical nature, which then can be used very effectively to determine their distance. For this reason cosmologists call Cepheids 'standard candles'.
Several groups of astronomers have used Hubble to observe Cepheids with extraordinary results. The Cepheids have then been used as stepping-stones to make distance measurements for supernovæ, which have, in turn, given a measure for the scale of the Universe. Today we know the age of the Universe to a much higher precision than before Hubble: around 15 billion years.

Spiral galaxy NGC 4603 containing Cepheids being used for distance measurements.

Gustav A. Tammann
Astronomer, University of Basel

We certainly live in exciting times. Hubble has made enormous progress possible within cosmology. Today we have a much more unified cosmological picture than was possible even five years ago when people were talking of 'The Cosmology in Crisis'. We have seen a dramatic change from misery to glory!

Supernova 1994D (lower left).

Supernovæ

Hubble's sharp vision means that it can see exploding stars, supernovæ that are billions of light years away and difficult for other telescopes to study.

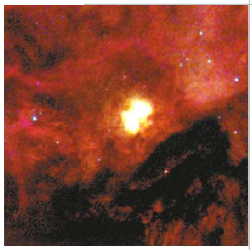
Most scientists today believe that the expansion of the Universe is accelerating. This result came from combined measurements of remote supernovæ with most of the world's top-class telescopes, including Hubble, and it was a very surprising one. For many years cosmologists have discussed whether the expansion of the Universe would stop in some distant future or continue ever more slowly. From the new results it seems clear that the expansion is nowhere near slowing down. In fact, due to some mysterious property of space itself (called vacuum energy), the expansion is accelerating and will continue forever.

Hubble has given these supernovæ measurements an added precision, mostly due to its high resolution. From the ground an image of the supernova usually blends in with the image of its host galaxy. Hubble can distinguish the light from the two sources and thus measure the supernova directly.

Bruno Leibundgut
Astronomer, European Southern Observatory (ESO)

Hubble gave us the distance measurements of the first four supernovæ that made us realise something was wrong with our present understanding of the Universe. Even though the definite proof that the Universe is accelerating came later, we could not reconcile our Hubble observations with a Universe where the expansion is slowing down.

Stellar *Evolution*



Newly born massive stars in the Papillon Nebula.

Most of the light and radiation we can observe in the Universe originates in stars – individual stars, clusters of stars, nebulae lit by stars and galaxies composed of billions of stars. Stars are spheres of glowing hydrogen and other chemical elements which produce their prodigious energy output by converting lighter elements to heavier ones through nuclear processes similar to those in hydrogen bombs. Like human beings they are born, mature and eventually die but their lifetimes are vastly longer than our own.

Hubble has gone beyond what can be achieved by other observatories by linking together studies of the births, lives and deaths of individual stars with theories of stellar evolution. In particular Hubble's ability to probe stars in other galaxies enables scientists to investigate the influence of different environments on the lives of stars. This is crucial in order to be able to complement our understanding of the Milky Way galaxy with that of other galaxies.

Hubble was the first telescope to directly observe white dwarfs in globular star clusters. White dwarfs are stellar remnants and provide a 'fossil' record of their progenitor stars which shone so brightly that they long ago exhausted their nuclear fuel. Through these measurements it is possible to determine the ages of these ancient clusters which is an important cosmological tool.

Another area where Hubble's work has been widely acknowledged is the linking of star formation (also see page 28-29) with stellar evolution. Hubble's infrared instrument, NICMOS, is capable of looking through the dust surrounding newly born stars. Some of the most surprising discoveries so far have come about by peering through the clouds of dust surrounding the centre of our Milky Way. Astronomers found that this centre, which was thought to be a calm and almost 'dead' region, is in fact populated with massive infant stars gathered into clusters.

Gerard Gilmore
Astronomer, University of Cambridge

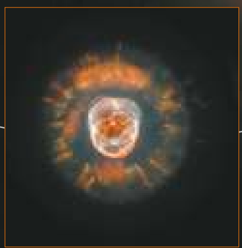
Hubble has in my view revolutionised the study of globular clusters – especially those in other galaxies. These objects are so dense and the stars so tightly packed together that it is almost impossible to separate the stars from each other with ground-based telescopes. We have been able to measure what kind of stars they are composed of, how they evolve and how gravity works in these complex systems.

The last phases of solar-like stars have been investigated through observations of planetary nebulae and proto-planetary nebulae. These are colourful shells of gas expelled into space by dying stars. The varying shapes and colours of these intricate structures with different colours tracing different, often newly created, chemical elements, have shown that the final stages of the lives of stars are more complex than once thought.

The Ring Nebula, M57. A planetary nebula.

Old star cluster Hodge 301 surrounded by supernova remnants.

The rings surrounding supernova 1987A.



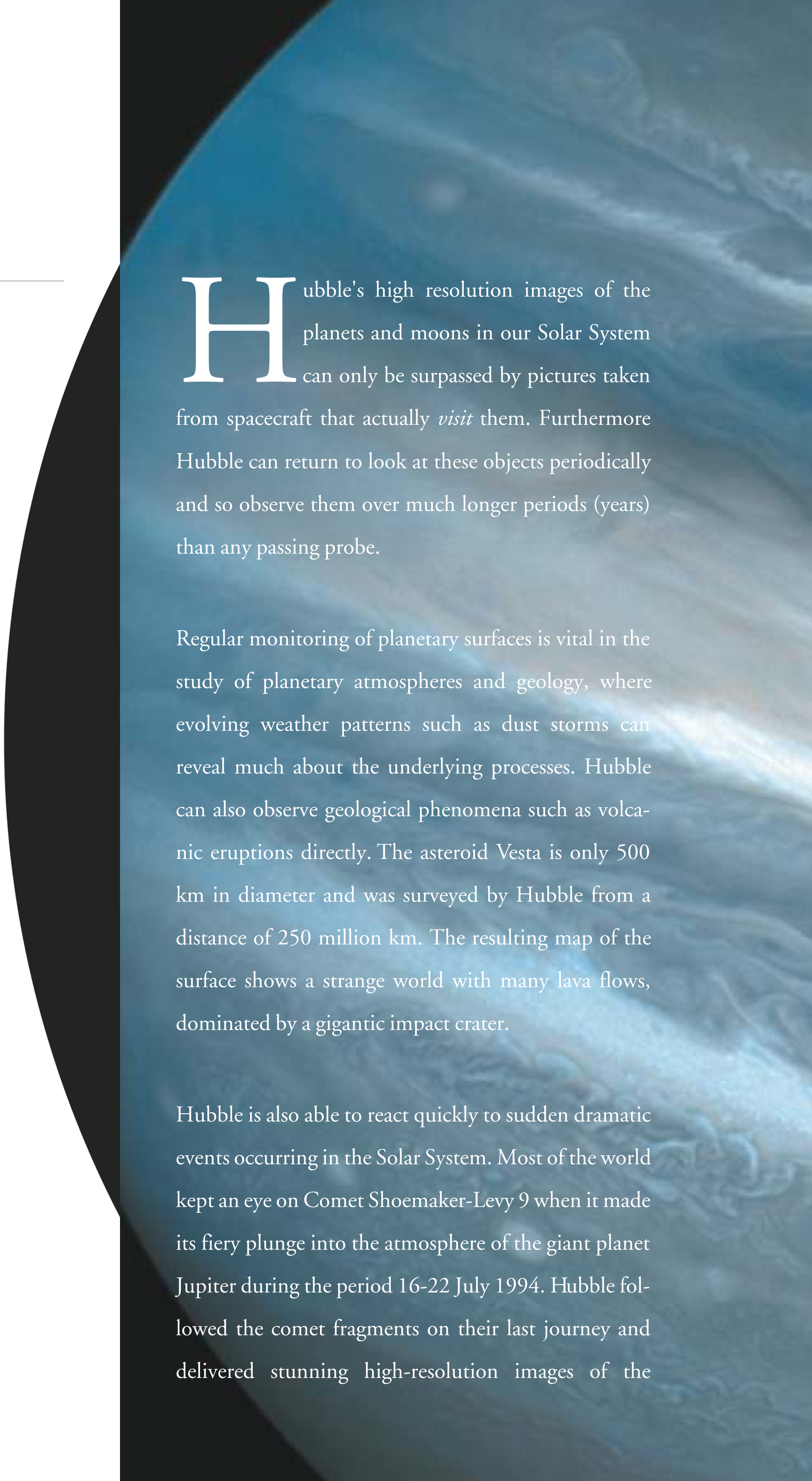
The Eskimo nebula, a planetary.

Supernova 1987A

When the first nearby supernova for centuries exploded in the Large Magellanic Cloud in 1987 it was scrutinised with every available telescope on Earth. On many occasions since its launch in 1990 Hubble has turned its gaze to the site of this unique event 150,000 light years away, and thanks to its very high resolution, it has been possible to monitor in detail the progress of the cataclysmic explosion. Hubble has seen two rings of gas on each side of the exploding star which were expelled by the dying star in its last death throes several thousand years before the final explosion. In recent years astronomers have watched as different parts of these rings are hit by the blast wave from the explosion as it expands through space.

Our Solar System

Pluto and its moon Charon.



Hubble's high resolution images of the planets and moons in our Solar System can only be surpassed by pictures taken from spacecraft that actually *visit* them. Furthermore Hubble can return to look at these objects periodically and so observe them over much longer periods (years) than any passing probe.

Regular monitoring of planetary surfaces is vital in the study of planetary atmospheres and geology, where evolving weather patterns such as dust storms can reveal much about the underlying processes. Hubble can also observe geological phenomena such as volcanic eruptions directly. The asteroid Vesta is only 500 km in diameter and was surveyed by Hubble from a distance of 250 million km. The resulting map of the surface shows a strange world with many lava flows, dominated by a gigantic impact crater.

Hubble is also able to react quickly to sudden dramatic events occurring in the Solar System. Most of the world kept an eye on Comet Shoemaker-Levy 9 when it made its fiery plunge into the atmosphere of the giant planet Jupiter during the period 16-22 July 1994. Hubble followed the comet fragments on their last journey and delivered stunning high-resolution images of the

Rudi Albrecht
Space Telescope-European Coordinating Facility (ST-ECF)

We conducted an intensive series of observations of Pluto with Hubble followed by advanced data processing on the ground. We saw surface features emerge for the first time in history on our screens. For me, personally, it was a memorable experience to be able to show this image to the original discoverer of Pluto, Clyde Tombaugh, and in this way let Hubble pay a tribute to his great discovery.

Jupiter's cloudbands with moon Io passing high above and casting a shadow.

Impact site of one of the fragments of Comet Shoemaker-Levy 9.

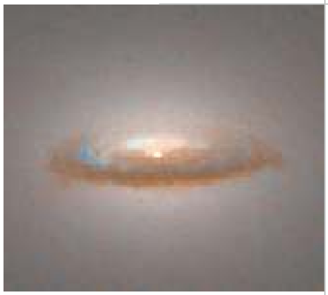
impact scars, from which important new information on conditions in the Jovian atmosphere was obtained.

On their fly-bys past Jupiter and Saturn the Voyager probes showed that these gas giants had auroræ similar to the northern lights here on Earth. However, Hubble's images of the auroræ were the first to reveal the delicate structure that so impressed many scientists. Hubble carries cameras that are sensitive to ultraviolet light, which is absorbed by the atmosphere and hence not seen by ground based observatories.

Pluto is the only planet not yet visited by space probes, but in 1994 Hubble made the first clear images showing Pluto and its moon Charon as separate objects from a distance of 4.4 billion kilometres.

Mars with cyclone clouds.

Black Holes, *Quasars, and Active Galaxies*



300 million solar-mass black hole in galaxy NGC 7052.

In the 1950s and 1960s astronomers had found objects, such as quasars and radio sources, whose energy output was so immense that it could not be explained by traditional sources of energy such as that produced by normal stars. It was suggested that their vast energy output could best be explained if massive black holes were at the centres of these objects.

Prior to the launch of Hubble a handful of black hole candidates had been studied but the limitations of ground based astronomy were such that irrefutable evidence for their existence could not be obtained.

Black holes themselves, by definition, cannot be observed, since no light can escape from them. However, astronomers can study the effects of black holes on their surroundings. These include powerful jets of electrons that travel huge distances, many thousands of light years from the centres of the galaxies. Matter falling towards the black hole can also be seen emitting bright light and if the speed of this falling matter can be measured, it is possible to determine the mass of the black hole itself. This is not an easy task and it requires the extraordinary capabilities of Hubble to carry out these sophisticated measurements.

Hubble observations have been fundamental in the study of the jets and discs of matter around a number of black holes. Accurate measurements of the masses have been possible for the first time. Hubble has found black holes 3 billion times as massive as our Sun at the centre of some galaxies.

While this might have been expected, Hubble has surprised everyone by providing strong evidence that black holes exist at the centres of all galaxies. Furthermore, as it appears that larger galaxies are the hosts of larger black holes. There must be some mechanism that links the formation of the galaxy to that of its black hole and vice versa. This has profound implications for theories of galaxy formation and evolution and will certainly be the subject of considerable additional research with Hubble during the next decade.

Quasars

In the 1980s observations made with different ground-based telescopes showed that some quasars were surrounded by fuzzy light. It was suspected that the quasars reside in galaxies and that the fuzzy patches of light could be those host galaxies. Hubble's high-resolution Faint Object Camera images showed with clarity that this is indeed the case. More importantly the hosts of quasars appear to be galaxies of all types, contrary to earlier predictions that favoured the idea that quasars were to be found only in elliptical galaxies. This is important since the light from quasars is believed to be produced by black holes at the centres of their host galaxies. Astronomers can now show that this is indeed the case and that quasar host galaxies are the same types of galaxies found in our neighbourhood. This realisation also leads to the question of why most of the nearby galaxies, including our own Milky Way have 'dormant' black holes, namely black holes which are inactive at this time. This will be the subject of new studies with Hubble.

Quasar PG 0052+251 and its host galaxy.

Unified model

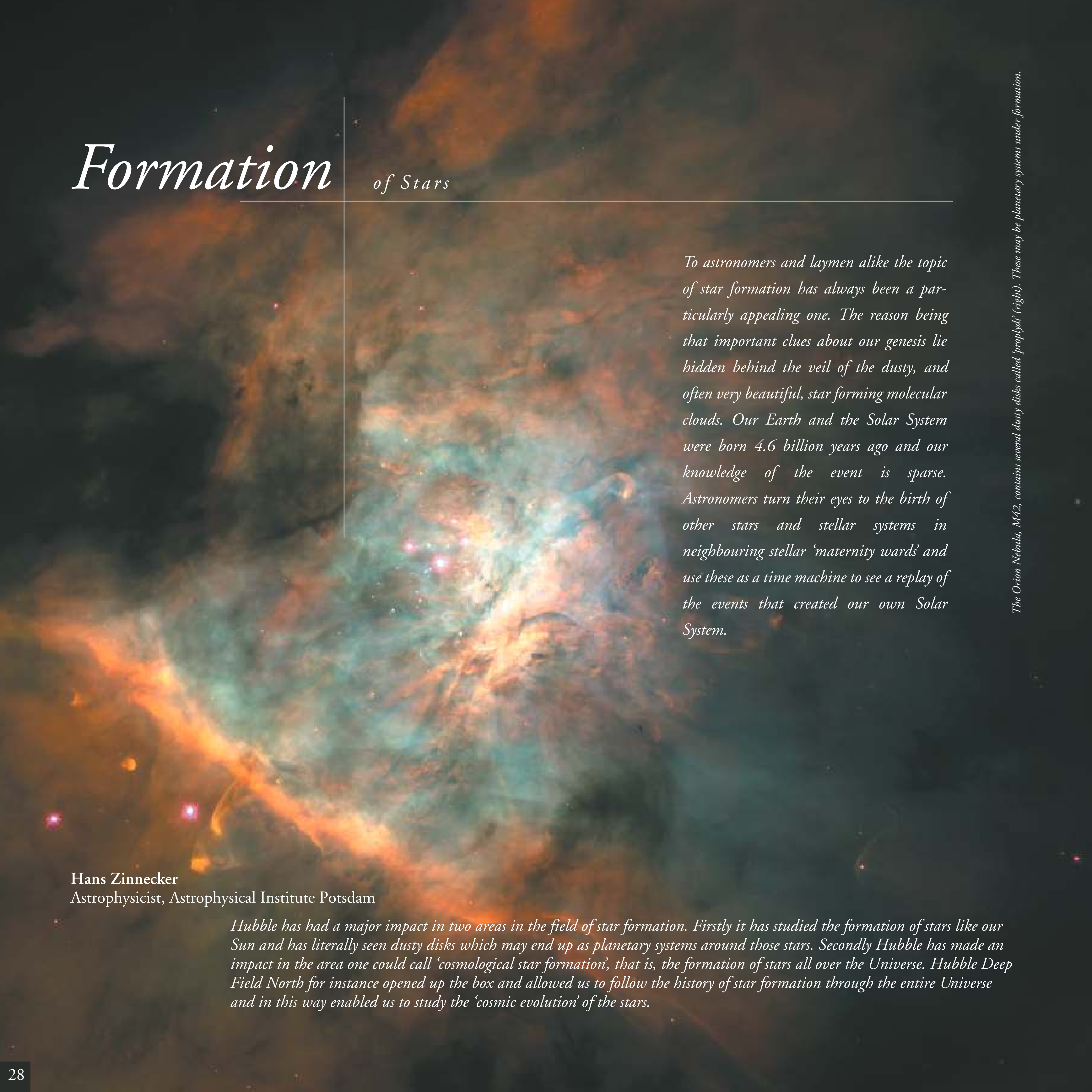
Today most astronomers believe that quasars, radio galaxies and the centres of so-called active galaxies just are different views of more or less the same phenomenon: a black hole with energetic jets beaming out from two sides. When the beam is directed towards us we see the bright lighthouse of a quasar. When the orientation of the system is different we observe it as an active galaxy or a radio galaxy. This 'unified model' has gained considerable support through a number of Hubble observational programs. The simplistic early ideas have however been replaced by a more complex view of this phenomenon – a view that will continue to evolve in the years to come.

Duccio Macchetto
ESA astronomer, Head of the Science Policies Division, STScI

Hubble provided strong evidence that all galaxies contain black holes millions or billions of times heavier than our sun. This has quite dramatically changed our view of galaxies. I am convinced that Hubble over the next ten years will find that black holes play a much more important role in the formation and evolution of galaxies than we believe today. Who knows, it may even influence our picture of the whole structure of the Universe...?

Formation *of Stars*

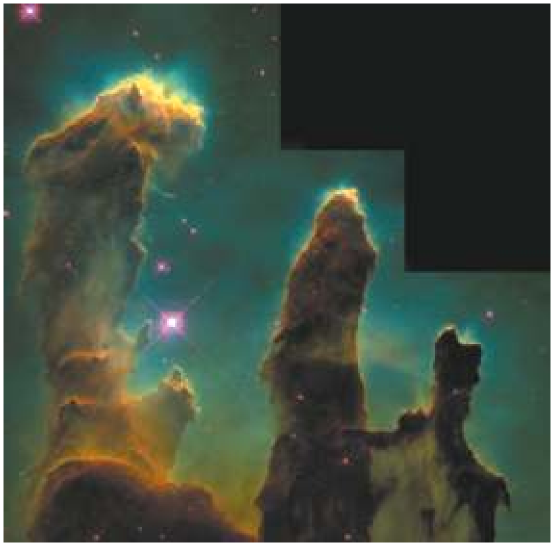
To astronomers and laymen alike the topic of star formation has always been a particularly appealing one. The reason being that important clues about our genesis lie hidden behind the veil of the dusty, and often very beautiful, star forming molecular clouds. Our Earth and the Solar System were born 4.6 billion years ago and our knowledge of the event is sparse. Astronomers turn their eyes to the birth of other stars and stellar systems in neighbouring stellar 'maternity wards' and use these as a time machine to see a replay of the events that created our own Solar System.



The Orion Nebula, M42, contains several dusty disks called 'proplyds' (right). These may be planetary systems under formation.

Hans Zinnecker
Astrophysicist, Astrophysical Institute Potsdam

Hubble has had a major impact in two areas in the field of star formation. Firstly it has studied the formation of stars like our Sun and has literally seen dusty disks which may end up as planetary systems around those stars. Secondly Hubble has made an impact in the area one could call 'cosmological star formation', that is, the formation of stars all over the Universe. Hubble Deep Field North for instance opened up the box and allowed us to follow the history of star formation through the entire Universe and in this way enabled us to study the 'cosmic evolution' of the stars.



The Eagle Nebula, M16.

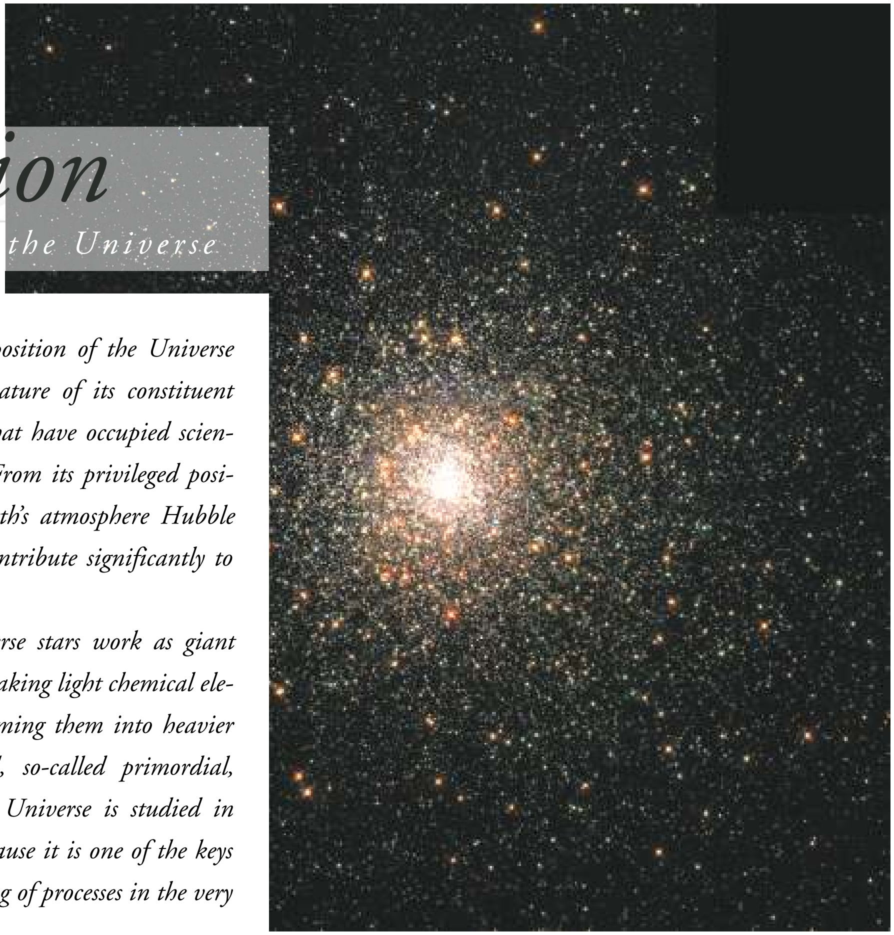
The large mosaic of 15 Hubble images showing the central part of the Orion complex is one of the most detailed images of a star forming region ever made. It shows a very young star cluster blowing a 'bubble' in its remnant parent cloud of glowing gas so that the stars start to be seen in visible light – like the smoke in a forest fire being driven away by the heat.

Hubble's high resolution has been crucial in the investigation of the dust disks, dubbed proplyds, around the newly born stars in the Orion Nebula. The 'proplyds' may very well be young planetary systems in the early phases of their creation. The details that are revealed are better than what has been achieved with ground-based instruments, and thanks to Hubble we have today visual proof that dusty disks around young stars are common.

Since star birth always seems to take place in dusty environments, Hubble's infrared capabilities have been a very important factor. The infrared instrument NICMOS can peer through large parts of the dust and reveal the complex processes taking place in the star forming regions. Otherwise invisible close double and multiple stars were discovered, as well as faint substellar brown dwarf companions. With NICMOS and its visual counterpart WFPC2, Hubble has observed giant jets of material spewing out from infant stars surrounded by large disks of dust. A fantastic view into the dramatic first steps in the lives of newly born stars.

The Composition

of the Universe



Globular cluster M80.

The chemical composition of the Universe and the physical nature of its constituent matter are topics that have occupied scientists for centuries. From its privileged position above the Earth's atmosphere Hubble has been able to contribute significantly to this area of research.

All over the Universe stars work as giant reprocessing plants taking light chemical elements and transforming them into heavier ones. The original, so-called primordial, composition of the Universe is studied in such fine detail because it is one of the keys to our understanding of processes in the very early Universe.

Helium in the early Universe

Shortly after the First Servicing Mission successfully corrected the spherical aberration in Hubble's mirror a team led by European astronomer Peter Jakobsen investigated the nature of the gaseous matter that fills the vast volume of intergalactic space. By observing ultraviolet light from a distant quasar, which would otherwise have been absorbed by the Earth's atmosphere, they found the long-sought signature of helium in the early Universe. This was an important piece of supporting evidence for the Big Bang theory. It also confirmed scientists' expectation that, in the very early Universe, matter not yet locked up in stars and galaxies was nearly completely ionised (the atoms were stripped of their electrons). This was an important step forward for cosmology.

Quasar lighthouses

This investigation of helium in the early Universe is one of many ways that Hubble has used distant quasars as lighthouses. As light from the quasars passes through the intervening intergalactic matter, the light signal is changed in such a way as to reveal the composition of the gas. The results

Peter Jakobsen
ESA astronomer, NGST Study Scientist

I believe that we now have a good understanding of the amount and composition of 'normal' matter of the Universe. By looking further and further back in time we are now beginning to piece together the history of this matter since it emerged from the Big Bang and eventually collapsed to form the stars and galaxies that we see in the present day Universe. Hubble has played a very important part in unravelling this history. With the Next Generation Space Telescope we hope to reach back to even earlier times and see the very first stars turn on.

have filled in important pieces of the puzzle of the total composition of the universe now and in the past.

Dark Matter

Today astronomers believe that close to 95% of the mass of the Universe consists of dark matter, a substance quite different from the normal matter that makes up atoms and the familiar world around us. Hubble has played an important part in work intended to establish the amount of dark matter in the Universe and to determine its composition. The riddle of the ghostly dark matter is still far from solved, but Hubble's incredibly sharp observations of, for instance, gravitational lenses (see page 32-33) have provided stepping stones for future work in this area.

Sagittarius Star Cloud.

Matter

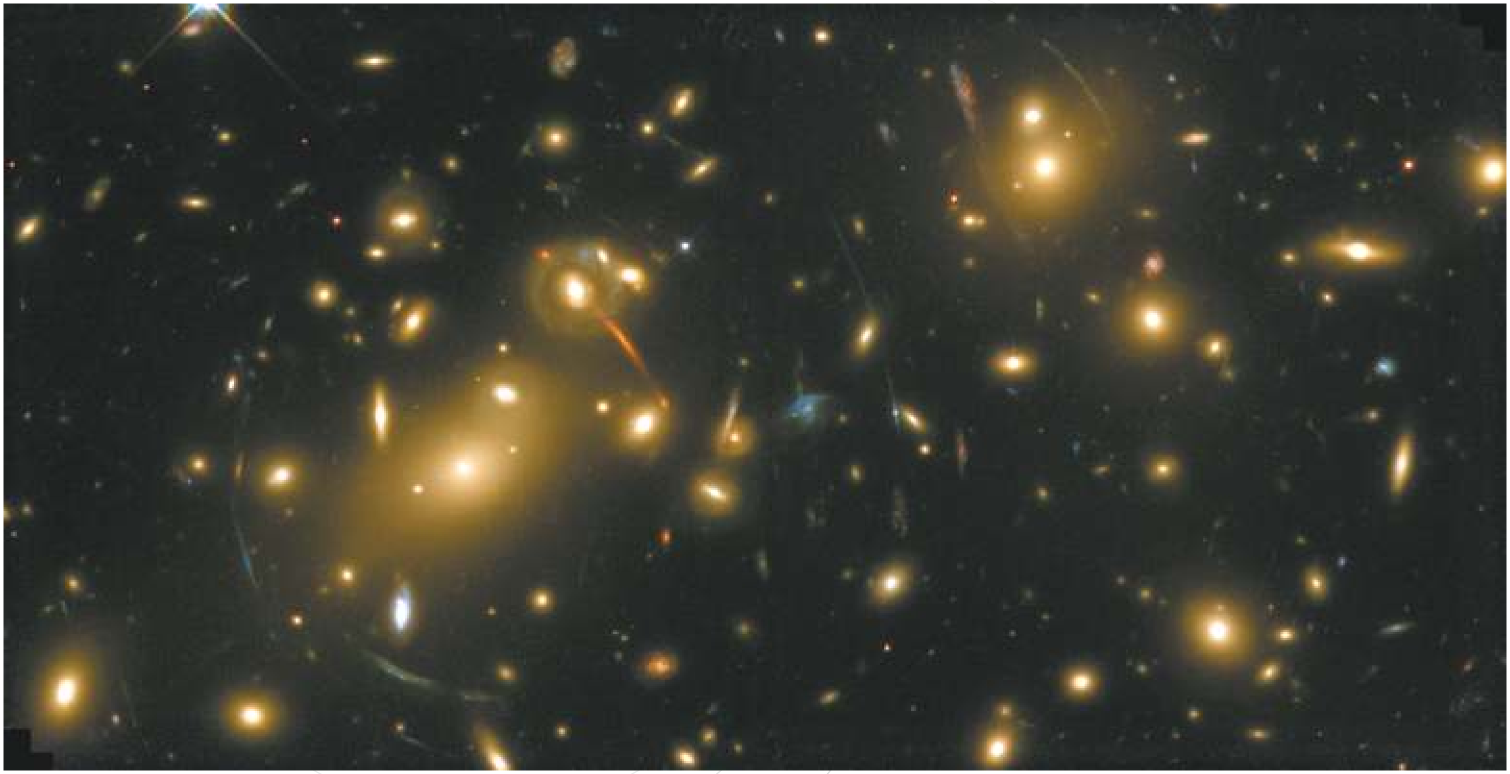
Gravitational *Lensing*

Light does not always travel in straight lines. Einstein predicted in his Theory of General Relativity that massive objects will deform the fabric of space itself. When light passes one of these objects, such as a cluster of galaxies, its path is changed slightly. This effect, called gravitational lensing, is only visible in rare cases and only the best telescopes can observe the related phenomena.

Hubble’s sensitivity and high resolution allow it to see faint and distant gravitational lenses that cannot be detected with ground-based telescopes whose images are blurred by the Earth's atmosphere. The gravitational lensing results in multiple images of the original galaxy each with a characteristically distorted banana-like shape.

Hubble was the first telescope to resolve details within these multiple banana-shaped arcs. Its sharp vision can reveal the shape and internal structure of the lensed background galaxies directly and in this way one can easily match the different arcs coming from the same background galaxy by eye.

Since the amount of lensing depends on the total mass of the cluster, gravitational lensing can be used to ‘weigh’ clusters. This has considerably improved our understanding of the distribution of the ‘hidden’ dark matter in galaxy clusters and hence in the Universe as a whole.



Recent image of the gravitationally lensed cluster Abell 2218.

Richard Ellis
Astronomer, University of Cambridge and California Institute of Technology

When we first observed the galaxy cluster Abell 2218 with Hubble in 1995 we mainly aimed at studying the cluster and its galaxies. But we got a surprise. The images showed dozens and dozens of gravitationally lensed arcs. When we showed these ultrasharp images to our colleagues they could immediately see the importance of using gravitational lensing as a cosmological tool.

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