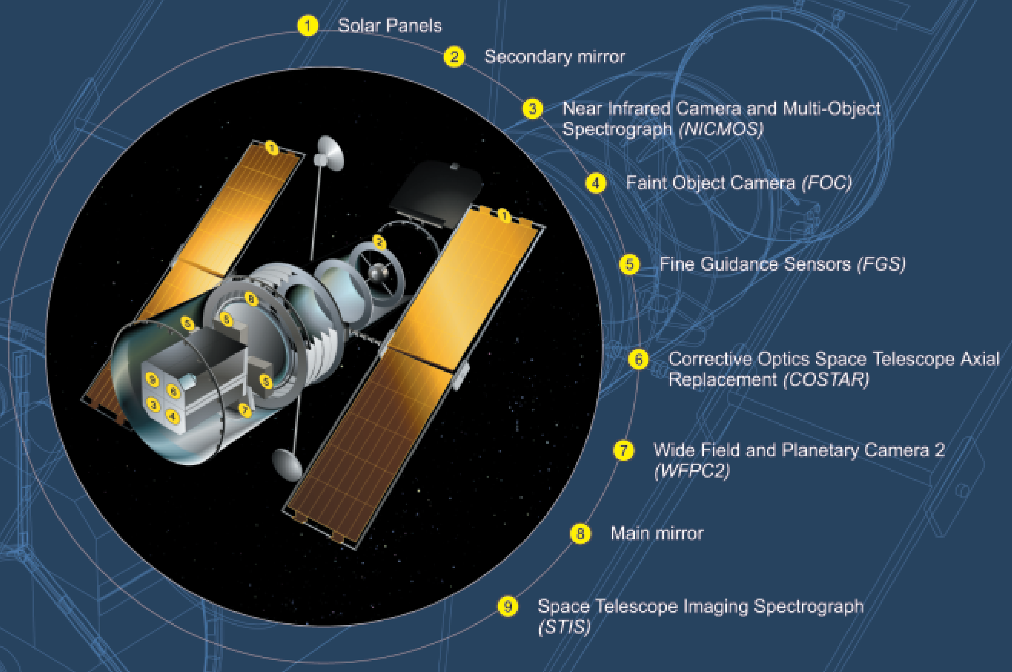
Hubble Space Telescope



The Instruments

The complement of instruments onboard Hubble – 2 cameras, 2 imaging spectrographs and a set of 3 fine guidance sensors – enable a wide variety of observations to be made.
The second Wide Field/Planetary Camera (WFPC2) is the primary camera on Hubble. It is capable of imaging the sky through a wide range of filters extending from a wavelength of 1000 nm in the near infrared to 115 nm in the ultraviolet.

The Spacecraft

Primary mirror — *Ritchey-Chrétien optics*	*2.4 m*
Total length	*15.9 m*
Diameter (solar panels stowed)	*4.2 m*
Solar panel span	*12.1 m*
Weight	*11,110 kg*
Pointing accuracy	*7 milliarcseconds for 24 hrs*

The Orbit

Altitude (original)	*598 km*
Inclination to the equator	*28.5 degrees*
Mission lifetime	*20 years (until 2010)*

More general and technical information about the NASA/ESA Hubble Space Telescope can be found at the
Hubble European Space Agency Information Centre: **http://hubble.esa.int**

The Hubble Space Telescope – 10 Years On

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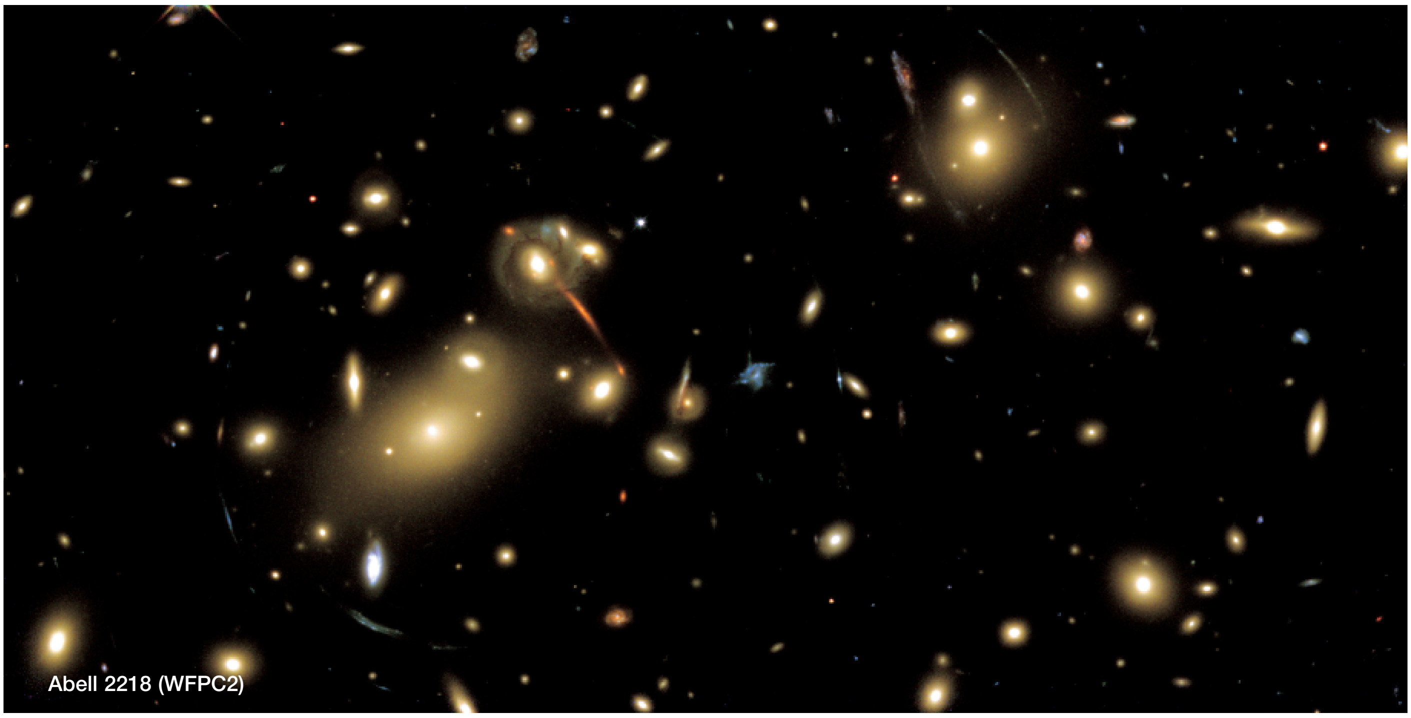
Last Christmas Eve was very special one for ESA astronauts Claude Nicollier and Jean-François Clervoy: together with their American colleagues, they spent it aboard the Space Shuttle 'Discovery', after concluding the latest scheduled repair mission to the orbiting Hubble Space Telescope (HST). This third Shuttle refurbishment mission to HST was, like its two predecessors, a resounding success. Only days later, as Hubble entered the new millennium, came the first beautiful images of a complex gravitationally lensing cluster of galaxies.

The astronauts' visit took place shortly before the 10th Anniversary of the launch of Hubble, which was first placed in orbit on 26 April 1990. Since then, HST has become the leading tool in ultraviolet, optical and near-infrared astronomy and is now looking forward to another decade of exciting discoveries and sharp views of the Universe.

Introduction

ESA is NASA's partner in the Hubble Space Telescope Project. ESA built the Faint Object Camera (the HST instrument that delivers images with the highest spatial resolution), provided the solar panels that power the spacecraft, and supports a team of 15 scientists at the Space Telescope Science Institute in Baltimore (STScI), USA. In return, a minimum of 15% of the Telescope's observing time is guaranteed for projects and research submitted by European astronomers from ESA's Member States. In reality, the high standard of projects from European astronomers has, so far, won them some 20% of the total observing time.

The initial ESA/NASA Memorandum of Understanding on HST expires 11 years after its launch, i.e. in April 2001. Both ESA and NASA are convinced that the collaboration on HST has been very successful, not merely in the development and initial operation of the Telescope, but also, more significantly, during its scientific operation. ESA astronomers have had access to a unique facility and the project as a whole has benefitted from the European intellectual contribution. A 'concept agreement' for the continuation of the collaboration, including a possible participation in the Next-Generation Space Telescope, has already been signed.



Abell 2218 (WFPC2)

European astronomers receive assistance from the Space Telescope European Coordinating Facility (ST-ECF) in Garching, near Munich, Germany. The ST-ECF, jointly operated by ESA and ESO, the European Southern Observatory, provides support in the calibration and analysis of HST data, and maintains and offers to the community the scientific archive of HST images and data.

The Servicing Missions

Servicing Missions that continuously keep the observatory and its instruments in prime scientific condition are one of the innovative ideas behind Hubble. Initially, telescope maintenance visits were planned for every 2.5 years and a larger overhaul was envisaged every five years, when HST would have been brought back to the ground. This plan has changed somewhat over time and a servicing scheme that includes Space Shuttle Servicing Missions every three years was finally decided upon.

The first two Servicing Missions – in December 1993 (STS-61) and February 1997 (STS-82) – were very successful. In the first three years of operation, HST was not able to meet expectations because its primary mirror is 2 microns too flat at the edge. This defect was discovered only after launch and initially caused severe consternation amongst the scientific community and the general public. However, the first Servicing Mission in 1993 (on which the European astronaut Claude Nicollier flew)

STS-103 Servicing Mission

corrected for this problem by installing a new instrument with corrective optics (COSTAR - Corrective Optics Space Telescope Axial Replacement). This pair of 'glasses' opened the way to HST's golden age. The images were at last as sharp as originally hoped for, and new, astonishing results started to emerge on a regular basis. On the first Servicing Mission, the solar panels were also replaced and a new camera was installed (Wide Field and Planetary Camera 2 - WFPC2). The High-Speed Photometer (HSP) was replaced by COSTAR.

During the second Servicing Mission, instruments and other equipment were repaired and updated. The Space Telescope Imaging Spectrograph (STIS) replaced the Goddard High-Resolution Spectrograph (GHRS), and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) replaced the Faint-Object Spectrograph (FOS).

The third Servicing Mission was initially intended to replace the ESA Faint-Object Camera (FOC) with the new Advanced Camera for Surveys (ACS) and to install a cryocooler on the infrared instrument NICMOS in order to extend its operational lifetime. Furthermore, the solar arrays, as well as many other subsystems, were scheduled for replacement. As the mission schedule filled with ever more tasks, the gyroscope system that Hubble uses to maintain its orientation began to show signs of failure. Without the help of the gyroscopes, HST would have to be kept in a fixed, safe orientation and scientific operation would have to be suspended. It was therefore decided to split the third Servicing Mission into two parts (SM3A and SM3B), with the first mission aimed at replacing the gyroscopes as soon as possible, thus postponing the installation of the new instruments to SM3B. This was a wise decision, since the gyroscopes did indeed fail just a month before SM3A.

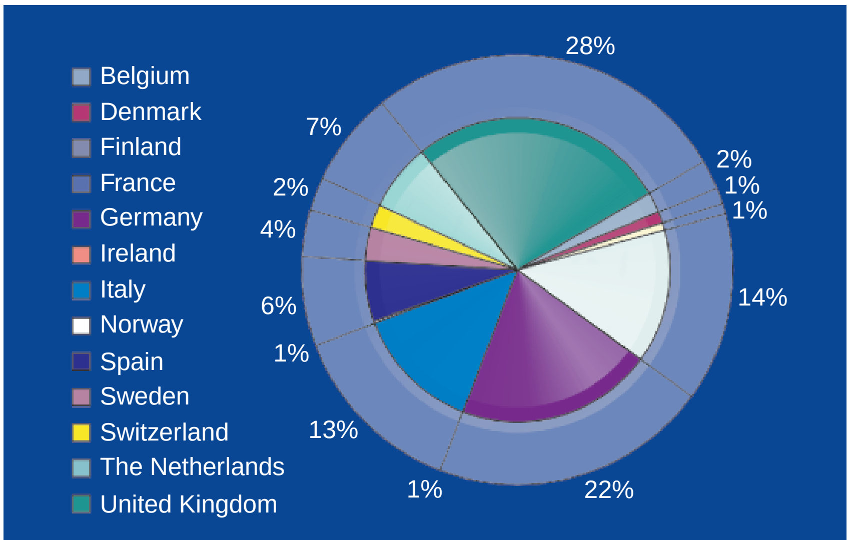
SM3B is now scheduled for late 2001 and a 4th, final servicing visit is planned around 2004, during which a new UV spectrograph (COS - Cosmic Origins Spectrograph) will be installed, together with a refurbished Wide-Field Camera (WFC3). After this, HST will continue to be operated, but on a reduced-cost basis, for as long as it continues to produce useful scientific results, possibly up to and beyond 2010 when its successor, the Next-Generation Space Telescope, should be ready to pick up the HST legacy.

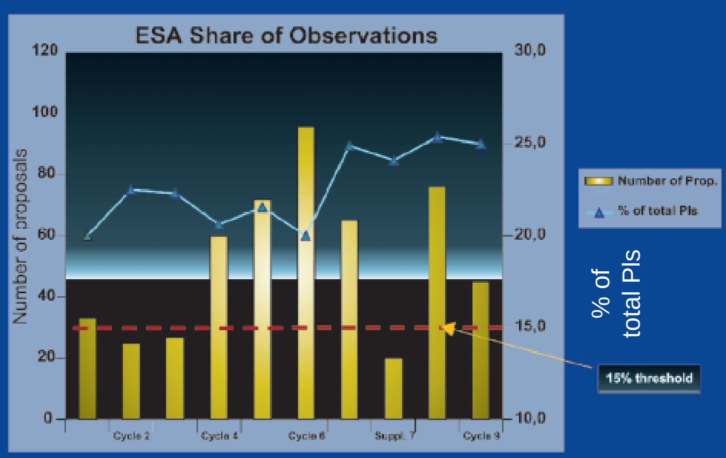
The first 10 years of HST have demonstrated how significant the concept of Servicing Missions has been for the continued efficient operation of such a sophisticated telescope.

Not only was the initial mirror problem, which would otherwise have meant the 'sudden infant death' of HST, promptly corrected, but new and continuously improved instruments were installed, ensuring that HST has remained competitive with the fast-evolving arena of ground-based astronomy.

Europe and Hubble

As already mentioned, the contribution of ESA to the Hubble project guarantees European scientists access to 15% of Hubble observing time. This time is allocated on pure scientific merit by an international panel that includes European experts. Ever since HST scientific operations began, European astronomers have been allocated more than the guaranteed 15% threshold, and in recent years the fraction of time allocated 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 Principal Investigators (PIs) or Co-Investigators (CoIs) in at least one successful Hubble observing programme, and many were investigators in many cycles.





NGC 4038-9B

The ESA participation in the Hubble project has an importance for European astronomy over and above the numbers and statistics: it provides the opportunity to use a World-class observatory of a kind that Europe alone would not have been able to build and operate. Thus, it has enabled scientists in Europe to continue to be competitive and even to lead in several areas of astrophysics and cosmology.

Hubble science

Ten years of exciting Hubble observations are not easy to summarise in a short article. We can only give a small sample of the science from HST here, highlighting, perhaps, areas where Hubble has influenced the research development most dramatically.

Firstly, Hubble is unique because of its unprecedented high resolution over the entire field of view. It has been debated recently that the best placed ground telescopes – some of which have much larger collecting areas than HST, such as the Very Large Telescope or the Keck Telescopes – can reach diffraction-limited PSFs (Point Spread Functions) using a technique called active optics. Active-optics systems rely on a fast-reacting optoelectronic surface to correct for the wavefront distortion introduced as light passes through the atmosphere to reconstruct the original wavefront and thus produce diffraction-limited images. However, this technique works only for a very limited field of view – a few seconds of arc in radius – while a space telescope like HST is only limited by its own optical aberrations. To give an example, the new Advanced Camera for Surveys on HST has a field of view of 202 $arcsec^2$. HST is still the only telescope able to render images of extended objects, such as galaxies and nebulae, with the same superb resolution of 0.05 arcsec over the whole field.

Secondly, HST has the ability to extend its observations to wavelength ranges that are either inaccessible from the ground – like the UV region from 330 to 115 nm – or are heavily disturbed by the atmosphere – like the near-IR range from 0.8 to 2.5 micron.

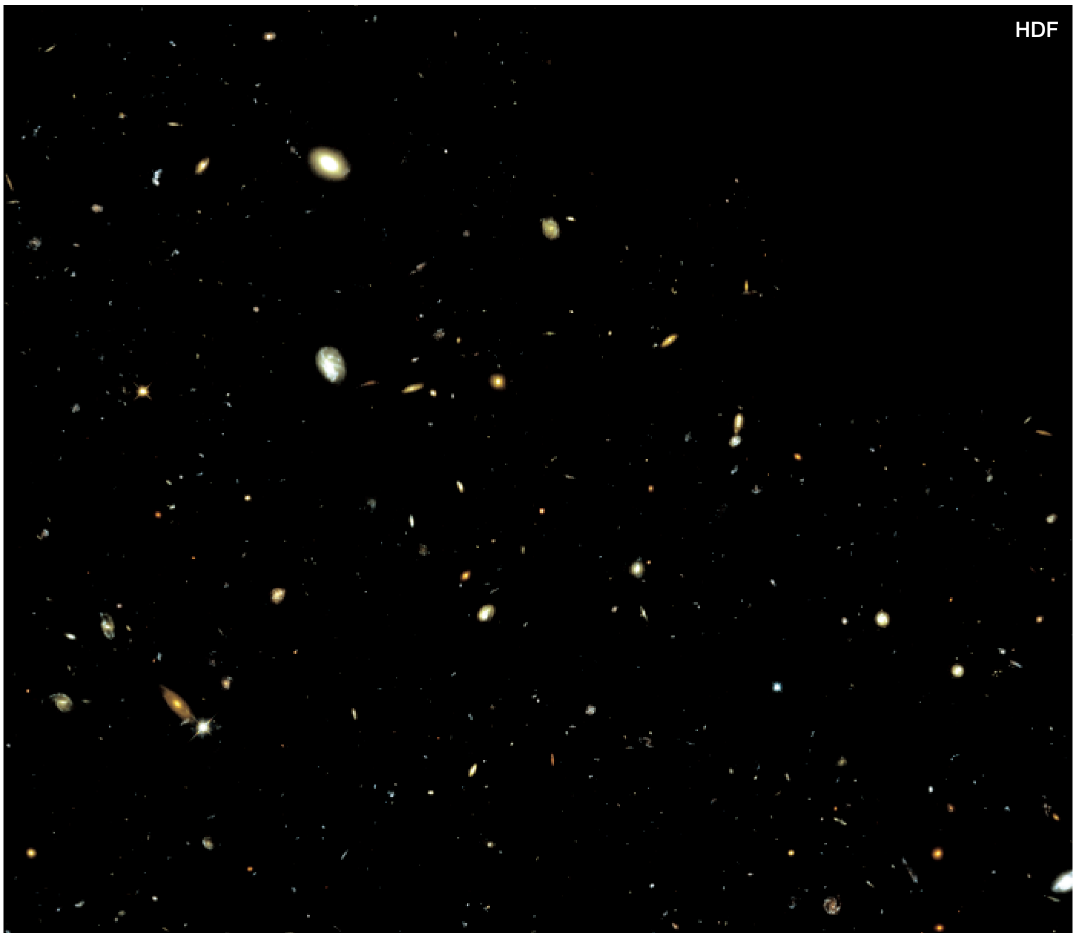
These two fundamental properties of Hubble, together with the lower sky background noise that is achievable above the Earth's atmosphere, make it a unique instrument. HST is not only able to make its own discoveries and pursue its own lines of research independently, it is also capable of stimulating follow-up observations from complementary instruments, both in space and from the ground. This is possibly the most important of Hubble's advantages: by imaging celestial objects with unprecedented clarity, HST has forced astronomers to look at these objects and their physical properties with different eyes.

The Deep Fields

The project known as the 'Hubble Deep Fields' is the most striking example of HST driving other areas of astrophysics research. The Hubble Deep Fields are observations of small areas of the sky obtained by adding together about 350 individual exposures of the same field, with a total exposure time of more than 100 hours, compared with typical Hubble exposures of a few hours. Two Deep Fields, one in each of the Northern and Southern Hemispheres, were carefully selected to be in as empty a patch of sky as possible so that Hubble would look out far beyond the stars of our own Milky Way and out past nearby galaxies. In the case of the Deep Field South, the field also contained a quasar, which has been used as a cosmological light beacon to detect intergalactic clouds lying between the quasar and the observer.

The results were astonishing: almost 3000 galaxies were seen in each image. A statistical analysis of the angular distribution of the galaxies indicated that many of them belonged to a very young Universe, at a time when star

formation had just started. The Deep Fields were immediately used by large ground-based observatories, in particular by the 10 m Keck Telescope and more recently by the ESO Very Large Telescope, as a finding chart for follow-up spectroscopic observations. Indeed, it is only large collecting mirrors, 8–10 m in diameter, that can gather enough light to obtain a spectrum of these faintest galaxies and so determine their cosmological redshift. The problem for Earth-bound telescopes is to know where to point them, since the smearing by the Earth's atmosphere makes the images of the faintest galaxies almost indistinguishable from the background noise. The Hubble Deep Fields solved the problem by providing a highly accurate map of these objects, and here the synergy between space- and ground-based telescopes produced a giant step in our understanding of the history of the early Universe. Many of these galaxies showed the highest redshifts ever observed – more than 5 in some cases. Subsequent statistical analysis, based on these spectroscopic redshifts, allowed astronomers to obtain a relationship between the photometric colours of the galaxies and their redshifts. The resulting cosmological map indicates that remote galaxies are smaller and more irregular that those nearby, supporting the idea that galaxies form by the gravitational coalescence of smaller parts.



The age and size of the Universe

The top-ranked scientific justification for building Hubble was to determine the age and size of the Universe through observations of Cepheid variables in distant galaxies. Cepheids are a special type of variable star with very stable brightness variations. The period of these variations depends on physical properties of the stars such as their mass, age and therefore true brightness. By detecting Cepheid variables in a galaxy and measuring the period of their brightness variation, astronomers can effectively derive the distance of the parent galaxy. The high angular resolution of the HST cameras can distinguish individual stars in distant galaxies where a ground-based telescope, powerful though it may be, would see only a blurred patch of light. Advanced automated techniques for the detection of point-like objects were used to extract and compare the information obtained by Hubble at carefully planned time intervals, and a number of Cepheids were discovered and measured. This fundamental work, which is still in progress, is building a new solid rung on the cosmological distance ladder.

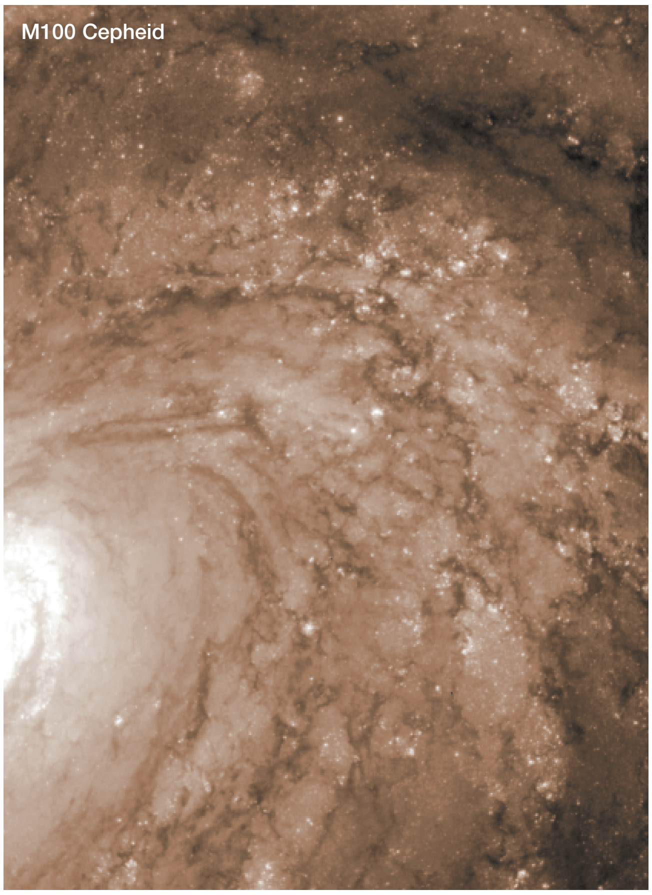
In the past, several of these galaxies for which Hubble has measured their distance using the Cepheid method, have hosted one or more supernovæ. A supernova is a massive star that, towards the end of its life, when it has exhausted most of the available fuel, explodes almost completely. During the outburst, the star brightens by a factor of a billion or more and up to 10^{51} ergs of energy are generated. For a given class of supernova, the maximum brightness reached during the explosion is believed to be almost constant, making them ideal extragalactic distance indicators. The new accurate Cepheid measurements of the distance of the host galaxies combined with the observational data from the supernovæ, provide an excellent tool for calibrating the absolute magnitude that these objects attain at their maximum brightness. These data not only improve the map of the Universe and of the expansion that the competing cosmological models have to account for, they are also preparing a toolbox that will be invaluable when new instruments, such as the Next-Generation Space Telescope, detect even more distant supernovæ.

The formation and evolution of stars

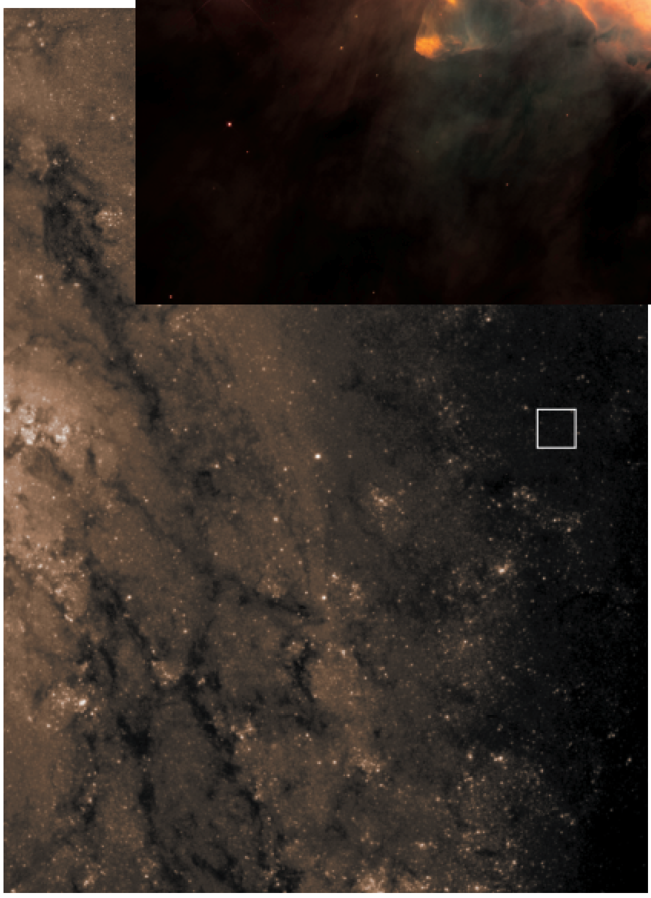
Hubble has also greatly improved our knowledge of stars in their different stages of evolution. The fields in which HST has excelled most are those requiring its high resolution or its sensitivity in the UV and IR wavelength ranges. For example, important progress has been made in the study of globular clusters, especially those in other galaxies. These objects are very densely populated and the stars are so packed together that only Hubble could observe them as distinct objects. HST was the first telescope to observe white dwarfs in globular clusters directly: white dwarfs are stellar remnants and provide a fossil record of their progenitor stars. Through these measurements, it is possible to estimate the age of these ancient clusters – an important test for any cosmological model.

The near-IR NICMOS combined camera and spectrograph was used to look through the dusty clouds that usually surround and hide the star-formation regions in our Galaxy. It was found that newborn stars are grouped into clusters and their environment is far from being a quiet one, crossed as it is by jets and shock waves.

On many occasions since its launch, Hubble has observed the site of the explosion of the Supernova 1987A in the Large Magellanic Cloud. Again, thanks to its very high resolution, it has been possible to monitor the progress of the cataclysmic explosion in detail. Images clearly show two rings of gas on each side of the exploding star that were expelled by the progenitor star several thousands of years before the final explosion. In recent years, astronomers have watched as different parts of



Orion Nebula, M42



these rings light up as they are hit by the expanding blast wave from the explosion. The expansion of the exploded material, which will eventually form a supernova remnant similar to that of the Crab Nebula, has also been monitored.

Some of the most impressive images obtained by Hubble are those of the star-forming regions in our Galaxy, such as the Orion and the Eagle Nebulæ. These images show in great detail the complex interaction between the radiation generated by the new-born stars and the molecules and dust of the cloud from which they were formed. It is clear now that the existing simplified models – for instance those that assume spherical symmetry and smooth matter density variations – are completely inadequate to describe the actual picture. Since chemical-abundance estimates in other galaxies are based on these models, it is now realised how important is to use the new detailed information on these H II regions to improve other predictive models. In the same H II regions, Hubble also detected dust discs, dubbed proplyds, around the newly-born stars. These discs may well be young proto-planetary systems in the early phases of their evolution.

Our Solar System

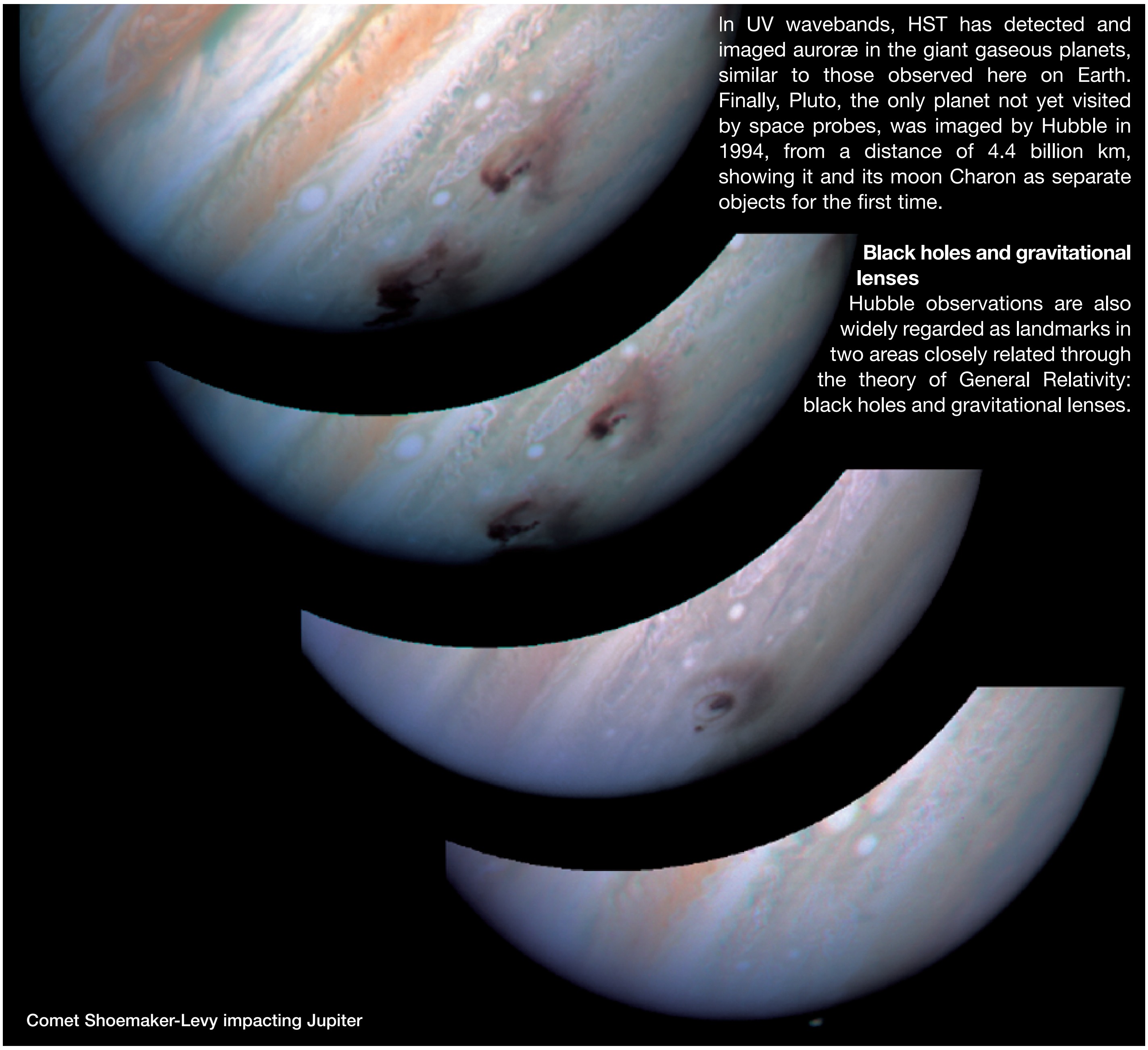
HST's high-resolution images of the planets and moons in our Solar System can only be surpassed by pictures taken from spacecraft that actually fly by the planets. However, Hubble has the big advantage that it can return to look at these objects periodically and so observe them over much longer periods than any passing probe. Regular monitoring of planetary surfaces is vital to the study of planetary atmospheres and geology, where evolving patterns such as dust storms can reveal much about the underlying processes. Hubble can also observe phenomena such as volcanic eruptions directly. The asteroid Vesta is only 500 km in diameter, but has been surveyed by Hubble from a distance of 250 million km. The resulting map of its surface shows many lava flows, dominated by a huge impact crater.

Hubble is also able to react quickly to sudden events occurring in the Solar System. In 1994 it followed fragments of Comet Shoemaker-Levy on their last journey to Jupiter and delivered stunning high-resolution images of the impact scars and of their temporal evolution, from which much new information on conditions in the Jovian atmosphere could be deduced.

In UV wavebands, HST has detected and imaged auroræ in the giant gaseous planets, similar to those observed here on Earth. Finally, Pluto, the only planet not yet visited by space probes, was imaged by Hubble in 1994, from a distance of 4.4 billion km, showing it and its moon Charon as separate objects for the first time.

Black holes and gravitational lenses

Hubble observations are also widely regarded as landmarks in two areas closely related through the theory of General Relativity: black holes and gravitational lenses.



Comet Shoemaker-Levy impacting Jupiter

In the 1950s and 1960s astronomers 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 energy output could best be explained if massive black holes were at the centres of these objects.

Before Hubble was launched, a handful of black-hole candidates had been studied, but the limitations of ground-based observations were such that irrefutable evidence for their existence could not be obtained. Black holes themselves, by definition, cannot be observed directly, but their presence can be inferred from their effects on their close surroundings. These include powerful jets of electrons that travel many thousands of light years from the centres of the galaxies, and matter that falls towards the black hole with an increasing spiralling speed. Accurate measurements of this infall velocity, once again made possible only by the high resolution of Hubble, allow the mass of the black hole itself to be determined. In some galaxies, Hubble found black holes as massive as 3 billion solar masses.

While this might have been expected, Hubble has also provided the strong and unexpected evidence that black holes may exist in the centre of all galaxies. Furthermore, it appears that larger galaxies harbour larger black holes. There must be some mechanism that links the formation of the galaxy to that of its black hole and vice versa – an observation that has profound implications in the theory of the formation and evolution of galaxies.

The bending of light by gravity was the first experimental proof of the validity of the Theory of General Relativity. The effect is very small and, before Hubble, only a few gravitational lens candidates were known. Taking advantage of its sensitivity and resolution, Hubble has now demonstrated how large massive clusters of galaxies can act as powerful cosmic telescopes, imaging distant galaxies and quasars that lie beyond the clusters as characteristically distorted multiple arcs. The importance of these cosmic mirages is that, from the detailed measurements of the distorted arcs, the total mass of the cluster can be derived, regardless of whether the mass is luminous, as are stars, or dark, as is dust, diffuse gas or even exotic massive particles. These mass estimates, directly derived from a gravitational effect, have profound implications for cosmological models. The proven possibility of measuring these gravitational distortions on a large scale, albeit in a statistical sense, has stimulated a new and important research line for which an significant fraction of observing time, both with Hubble and with large ground-based telescopes, is being invested.

The future

Hubble is now half-way through its operational lifetime. Its observations have opened up many vigorous research lines, setting the scene for more ambitious projects. While Hubble will continue to operate in a similar manner through its second decade, with improved capabilities as new instruments are installed, a change in its scientific use can be expected. The huge success of the Deep Fields experiment, in which a large amount of observing time was allocated to a single well-focussed programme, has already modified the HST time-allocation policy. Astronomers are now encouraged to propose large, survey-type observing programmes which, as the Deep Fields experience shows, provide a precious mine of uniform data, out of which hundreds of research groups can extract different scientific aspects, and complementary observations with other space and ground-based observatories can be planned.

Hubble has also paved the way for its natural successor, the Next-Generation Space Telescope (NGST). Hubble's ability to map the distant Universe ends abruptly when the light of the most distant galaxies, heavily redshifted by the cosmic expansion, falls beyond the wavelength range that Hubble can observe. In order to observe the galaxies in their making and light from the first stars in the Universe, it is necessary to observe further out into the infrared region. This is one of the main reasons why NGST has been selected as an IR telescope with a large collecting area. The observatory will be effectively protected against the radiation from Sun and Earth, to allow instruments to cool down and operate at about 40 K. NGST is currently being studied by NASA, ESA and CSA (Canadian Space Agency) for a possible launch around 2010.