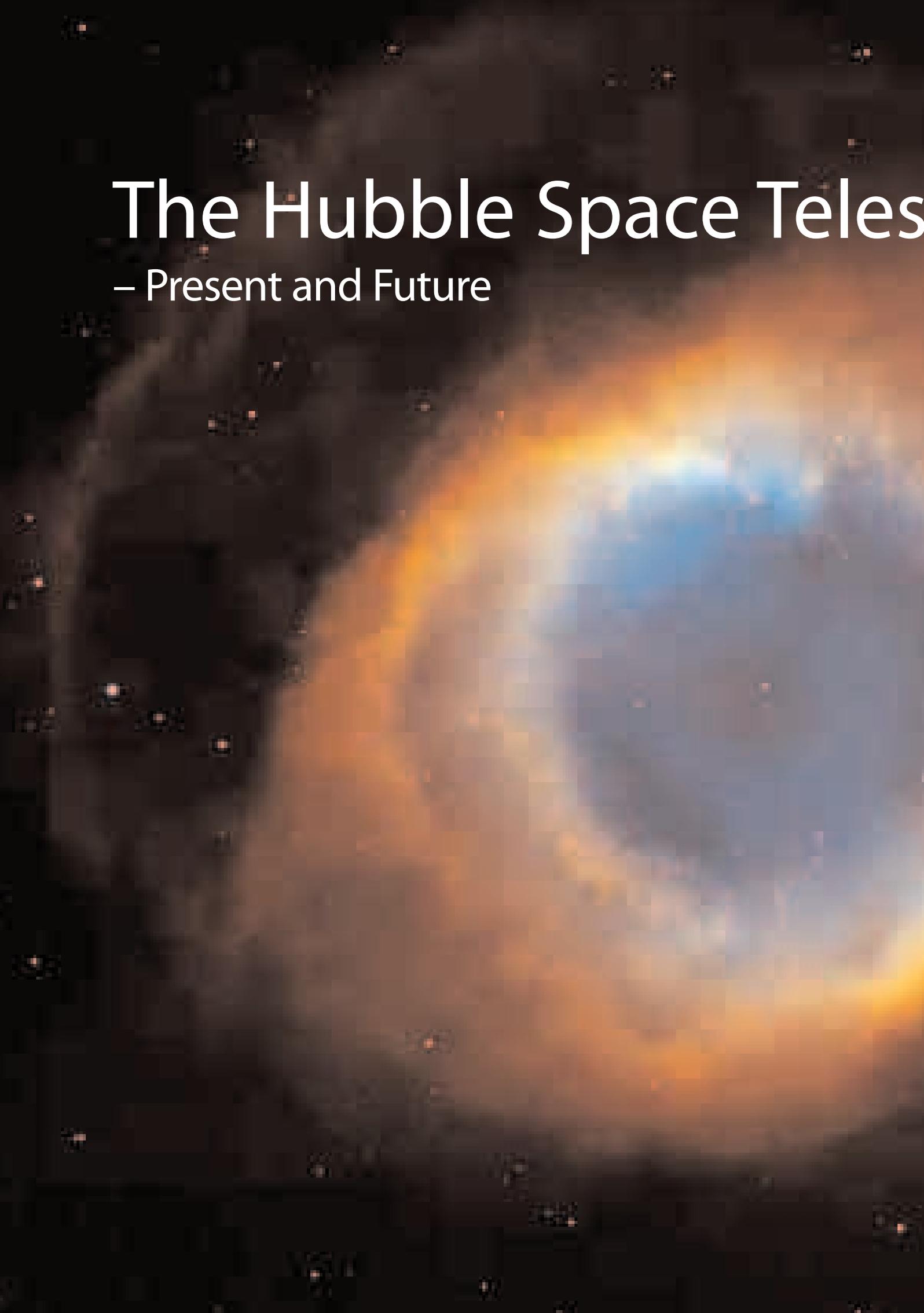


# The Hubble Space Telescope

– Present and Future



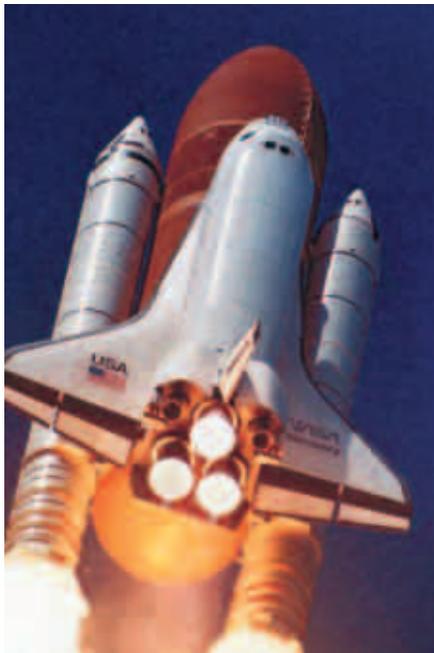
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**A**fter fourteen years in orbit, the 'middle-aged' Hubble Space Telescope continues to play a major role in astronomical research, and is undoubtedly one of the most important and prolific space astronomy missions of all time. To do justice to the many important, exciting and fundamental discoveries made with Hubble, one would have to write a very thick book. This article is therefore intended to illustrate just a small selection of the telescope's results and to outline some of the observations planned for the near future.

The Hubble Space Telescope (HST) is a cooperative NASA/ESA programme conceived in order to operate a long-lived space-based observatory for the benefit of the international astronomical community. Designed and built in the 1970s and 80s, HST was planned to be a different type of mission from its forerunners, namely a long-term observatory facility in space, whose instrumentation and equipment would be serviced and exchanged in a regular three-year cycle.

HST was deployed in low-Earth orbit (about 600 km) by the crew of the Space Shuttle 'Discovery' (STS-31) on 25 April 1990. Although at the beginning the mission looked severely handicapped because of spherical aberration in HST's optics, the first maintenance mission by Space Shuttle 'Endeavour' (STS-61), in December 1993, fully restored Hubble's functionality. In fact, all of the HST servicing missions conducted so far – SM1 in December 1993, SM2 in



Launch of the Hubble Space Telescope (HST) on 23 April 1990



HST with full-Moon and Earth in the background during servicing mission SM3A (Courtesy of NASA)

February 1997, SM3A in December 1999, and SM3B in February/March 2002 – were enormous successes.

HST's current science instruments include three cameras, the Wide Field and Planetary Camera 2 (WFPC2), the new Advanced Camera for Surveys (ACS), which with its tenfold increase in efficiency and its doubled field of view relative to WFPC2 has opened up much-anticipated new capabilities for discovery, the Near Infrared Camera - Multiobject Spectrograph (NICMOS), which was revived in servicing mission 3B with the installation of a mechanical cooling system, one spectrograph, the Space Telescope Imaging Spectrograph (STIS), and the Fine Guidance Sensors (FGS, primarily used for astrometric observations).

When the new ACS was installed, it replaced the ESA Faint Object Camera (FOC), which had spent a record-breaking 4340 days – almost 12 years – in space. During its time on HST, the FOC had many celebrated successes. Its very high angular resolution, which meant it could produce extremely sharp images, was used to great effect in providing unique close-up views of nearly every class of astronomical object. Among many other firsts, the FOC

revealed the first surface details on the planet Pluto, made the first direct images of the atmospheres of giant stars like Betelgeuse, took the first image of an 'exposed' black hole, and showed the circumstellar material around exploding stars like Nova Cygni 1991 and around supernovae like SN 1987A. Its sharp eye penetrated the inner enigmatic cores of

active galaxies, where black holes with masses up to several billion times that of our Sun are hiding. Its special ability to detect the very faintest ultraviolet light was extensively used to make spectra of very distant quasars. This effort ultimately resulted in a breakthrough in cosmology - the first detection of singly ionised helium in the medium between the galaxies.



ESA/STScI representatives in front of the retrieved Faint Object Camera (FOC) in the clean room at Goddard Space Flight Center on 25 April 2002

Peter Jakobsen, the current ESA Project Scientist for the FOC, comments:

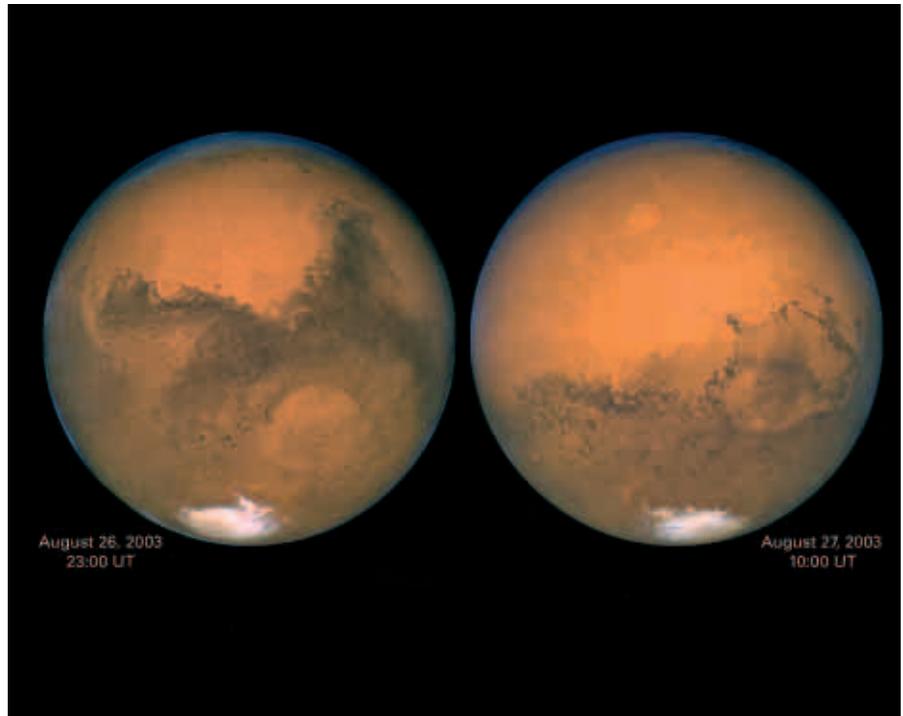
*"Although the images obtained with the FOC have only rarely been as photogenic as the famous images from the Wide Field and Planetary Camera 2, the FOC has served the astronomical community well and brought home its fair share of scientific firsts."*

Observations made with the HST have both solved problems that had been under debate for many years, and revealed quite unexpected and exciting new phenomena. The crop of high-impact science from Hubble includes the definitive measurement of the expansion rate of the Universe (the so-called 'Hubble constant'), the confirmation and characterisation of massive black holes at the centre of galaxies, the detection of the host galaxies of Quasi Stellar Objects (QSOs) and the exhaustive study of the properties of the intergalactic medium, telling us a great deal about the chemical evolution of the Universe.

Even more exciting are the discoveries that were totally unanticipated and that have opened new avenues to our knowledge of the cosmos, such as the discovery of the acceleration of the Universe, which implies the existence of the so-called 'dark energy' that has dominated its expansion over the last 8 billion years, the properties of extremely distant galaxies as shown by the Hubble Deep Field observations that have provided us the direct view at thousands of galaxies formed just a few billion years after the Big Bang, clues to the nature of the gamma-ray burst sources that are possibly the most energetic explosions in the Universe, the formation of planets in disks around young stars, the full characterisation of planets orbiting other stars, and the dramatic collision of fragments from comet Shoemaker-Levy 9 with Jupiter's atmosphere.

### Mars' Close Encounter with Earth

On 27 August 2003, the third and fourth planets from the Sun, namely the Earth and Mars, were at their closest for 60 000 years. Approximately every two years, the Earth's orbit catches up with that of Mars, aligning the Sun, Earth and Mars in a straight line, with Mars and the Sun on opposite sides of the Earth. The fact that Earth's orbit is



*HST images (WFPC2) of Mars taken during its closest approach to the Earth (Courtesy of NASA, J. Bell (Cornell University) and M. Wolff (Space Science Institute))*

nearly circular while that of Mars is more markedly elliptical results in Earth-Mars approaches ranging between 56 and 100 million kilometres. In late August 2003, Earth was near aphelion and Mars at perihelion, putting them a mere 55.8 million kilometres apart!

Taking advantage of such a close 'opposition' of the planets, a series of HST observations were planned to study the composition and physical state of surface materials and airborne aerosols. Timed to take full advantage of the closest approach of Mars to Earth, images and spectra were acquired at spatial scales comparable to existing spacecraft orbital spectroscopy data (about 10 km/pixel) and in wavelength regions not sampled by past or current Mars spacecraft instrumentation. These observations have therefore provided complementary scientific and calibration measurements in support of current and future NASA and ESA Mars exploration missions.

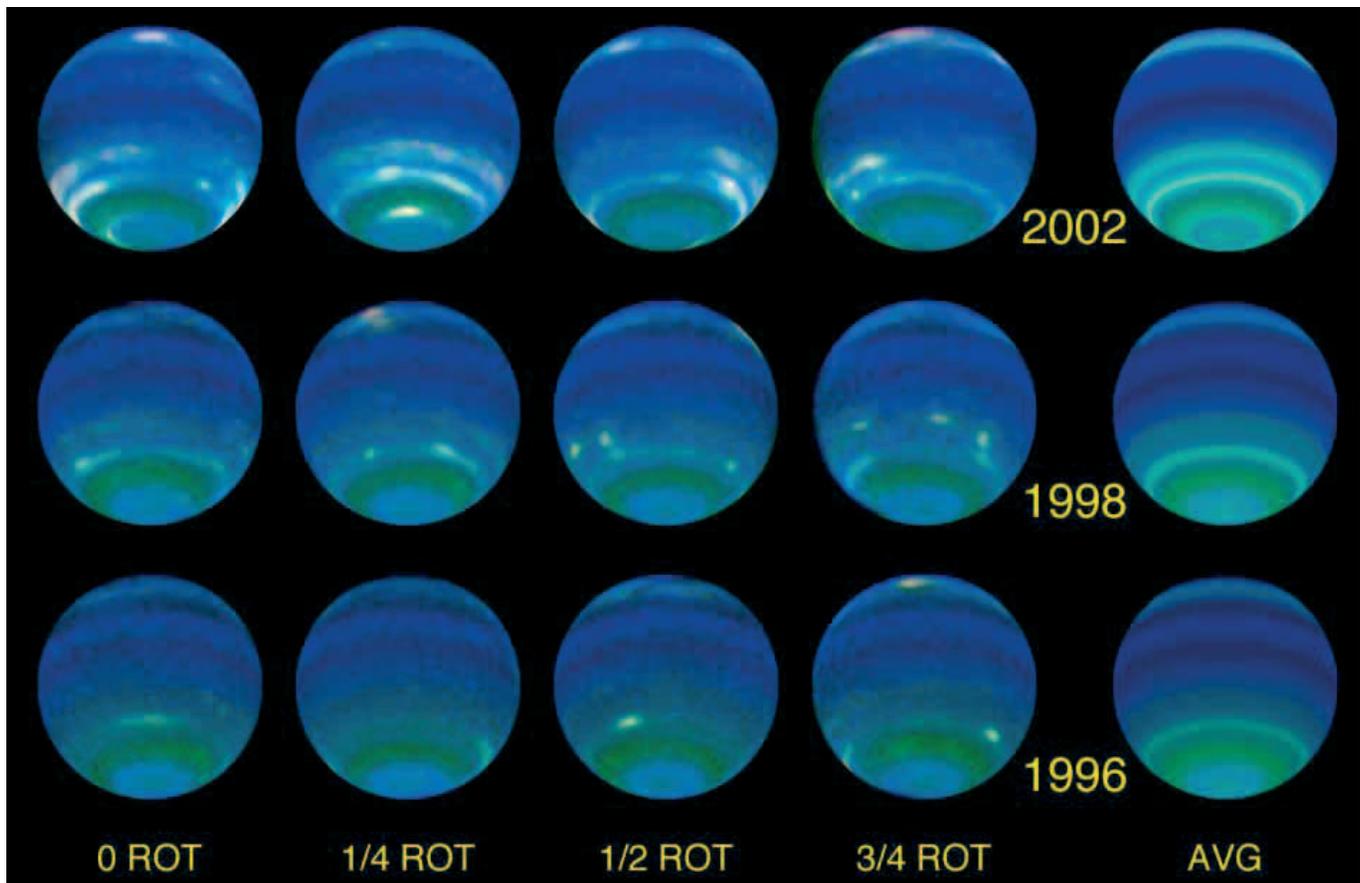
The unusually small separation of the planets also made summer 2003 the ideal time to launch scientific expeditions to Mars, as less fuel was then needed to reach the Red Planet, leaving more room

onboard the spacecraft for valuable scientific instruments. Hence ESA's summer 2003 launch of its Mars Express probe, which reached the planet in December.

### A Change of Seasons on Neptune

Observations of Neptune made by Hubble over a six-year period show a distinct increase in the amount and brightness of the banded cloud features located mostly in the planet's southern hemisphere. Neptune was already known for its violent weather, with winds of up to 1500 km/h, but the new HST observations are the first to suggest that this planet undergoes a change of seasons. Using Hubble, three sets of observations of Neptune were made, in 1996, 1998, and 2002, each covering a full rotation of the planet. The images showed progressively brighter bands of clouds encircling the planet's southern hemisphere.

The recent trend of increasing cloud activity on Neptune has been qualitatively confirmed at near-infrared wavelengths by Keck Telescope observations between July 2000 and June 2001 (by H. Hammel and co-workers). Additional near-infrared



Images of Neptune taken between 1996 (bottom) and 2002 (top) during different rotation phases (Courtesy of NASA)

observations were made last summer with NASA's Infrared Telescope Facility on Mauna Kea, in Hawaii, to further characterise the changes in the high-altitude cloud structure.

Neptune's rotation axis is tilted at an angle of about 29 degrees, so that the planet's northern and southern hemispheres alternate in their positions relative to the Sun. Therefore, like the Earth, Neptune should have four seasons, but unlike Earth they should last for decades rather than months. What is remarkable is that Neptune exhibits any evidence at all of seasonal change given that the Sun, as viewed from the planet, is 900 times dimmer than it is from Earth. Since the amount of solar energy intercepted is what should determine the seasons, it is still a mystery how such a small energy input can affect the dynamic nature of Neptune's atmosphere.

### Extrasolar Planets: A Giant Planet around the Star HD209458

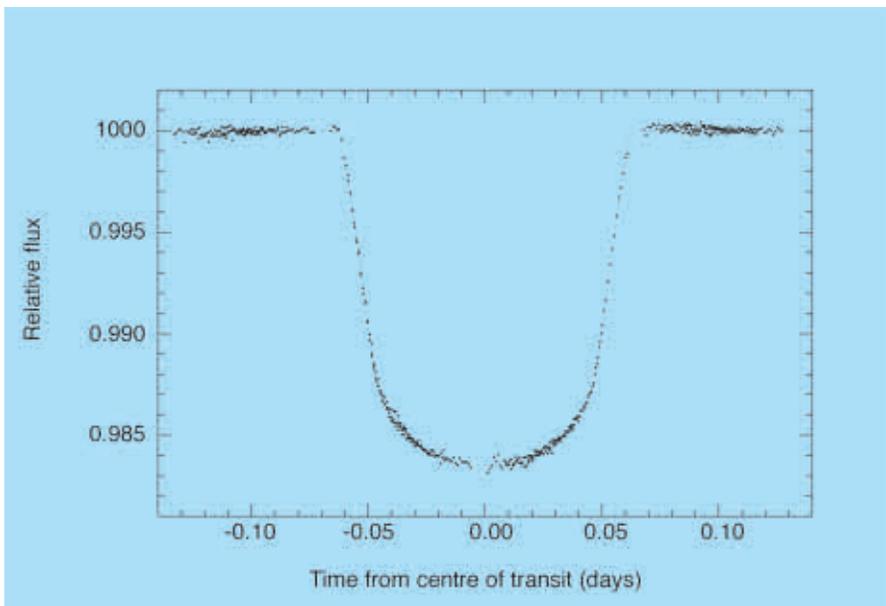
One of the most important questions in science and philosophy is: 'Are we alone in the Universe?' Answering it is quite hard, but we can approach the problem by first addressing other questions such as: 'Are there planets around other stars', and 'if so, are they suitable for the development of life as we know it?'

It is now almost ten years since the first unambiguous detection of an extra-solar planet, and by now we can count more than a hundred of them around stars in the solar neighbourhood. Still, characterising those planets, i.e. determining all of their properties, is a much harder task that requires special tools and techniques. Fortunately, HST is equipped with the high sensitivity and high-angular-resolution tools needed to do the job.

One of the techniques that can be used with Hubble is to study the transit of a

planet in front of its parent star. As the transit occurs, a small fraction of the stellar surface is covered by the planet, producing a 'partial eclipse' and causing the observed luminosity of the star to be somewhat lower than normal, the more so the larger the planet involved. In this way, one can directly determine the size of the planet relative to the star. Since the star's radius is known from other independent measurements, one can obtain an accurate measure of the absolute size of the planet. Moreover, from measurements of the parent star's motion, which trace its 'wobble' due to the presence of the planet, one can unambiguously determine the planet's mass. Knowing the mass and the size of the orbiting planet, one can derive its average density, thereby providing stringent constraints for theoretical models of planet formation.

The low-mass companion to the star HD 209458, denoted as HD 209458b, is the



The HST-STIS light curve of HD209458 provides evidence for a planet transit (Courtesy of T. Brown et al.)

first extra-solar planet found to transit the disk of its parent. Hubble Space Telescope Imaging Spectrograph (STIS) observations of the HD 209458 system (see figure) indicated the presence of a companion planet with an orbital period of 3.52 days, a mass at least 70% of that of Jupiter, a radius about 35% larger than Jupiter's, and orbiting at a distance from its parent star of only 1/200th of the Sun – Earth distance. These properties suggest a planet rather similar to Jupiter, but orbiting closer around its star than Mercury does around the Sun. As a consequence, it is estimated that the planet's upper atmosphere is so hot that it boils hydrogen off into space.

A detailed analysis of the transit light curve led to the conclusion that the planet had no rings (which would have appreciably altered the curve's shape), nor an orbiting satellite with mass greater than 3 times the mass of the Earth (whose presence would have affected the curve's symmetry).

On the other hand, spectrophotometric observations made at the times of four transits revealed that a neutral sodium absorption line was becoming detectably stronger (about 2 parts in 10 000), providing clear evidence for the presence of a sodium-rich atmosphere on the planet. This represents the first detection of an atmosphere on an extra-solar planet,

marking the beginning of a new and exciting era in which such planets begin to be fully characterised, rather than just being merely detected gravitationally as point sources with mysterious properties.

Recently, an international team using the STIS, led by Alfred Vidal-Madjar (CNRS/Institut d'Astrophysique de Paris), has detected, for the first time ever, the presence of oxygen and carbon in the extra-

solar planet's atmosphere's evaporating envelope. Analysis of the starlight passing through the envelope shows that it is being torn off by the extreme 'hydrodynamic drag' created by its evaporating hydrogen atmosphere. The astronomers believe that the oxygen present exists naturally, and is not being produced by any sort of life on the gaseous hot world. Nevertheless, it is a promising demonstration that the chemical composition of atmospheres on planets many light-years away can be measured, as this could someday lead to the discovery of the atmospheric biomarkers of life on such extra-solar planets.

Because the oxygen and carbon are bleeding off the gas-giant extra-solar planet, it has been dubbed 'Osiris', after the Egyptian god who lost part of his body – like HD209458b – after having been killed and cut into pieces by his brother to prevent his return to life.

### The Helix Nebula: When Opportunity Knocks

The Helix Nebula, also known as NGC 7293, lies about 600 light-years away from Earth, towards the constellation of Aquarius. It has a diameter of about 2.4 light-years, thus spanning as much as 14 arcminutes in the sky. The image shown here was made by combining newly



Composite picture of the Helix Nebula produced by combining Hubble ACS images with wide-angle images from the Kitt Peak Mosaic Camera (Credit NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner (STScI) and T.A. Rector (NRAO))

released images from Hubble's ACS instrument and wide-angle images from the Mosaic Camera on the NSF 0.9 m Telescope at Kitt Peak National Observatory (USA). It is one of the largest and most detailed celestial images ever made.

These Hubble observations were made possible by a fortuitous combination of events. One of the most prominent of the meteor showers is the Leonids each November. The shower in 2002 was predicted to be especially heavy, and so to minimise the risk to the telescope its aft end was pointed towards the incoming stream, whilst also minimising the cross-section presented by the solar arrays. The 'stand down' period was to last from 0 to 14 hours UT on 18 November, but in preparing for it STScI staff member Ian Jordan noticed that just outside the nominal planned safe pointing direction lay the Helix Nebula, which had been examined by Hubble many times before. This was too good an opportunity to miss and so, having secured the agreement of the HST Project at Goddard Space Flight Centre (GSFC), a small group of STScI scientists, led by Margaret Meixner, and including ESA astronomers Letizia Stanghellini and the author, created a programme that would use the nine available HST orbits to image a substantial portion of the large Helix in two colours, using both Hubble's ACS and WFPC2 instruments. The intention was to establish a first-epoch dataset suitable for later work to measure the motions of the tight knots immersed in the nebula.

### The Mysterious Outburst of the Star V838 Monocerotis

The previously unknown variable star V838 Monocerotis erupted in early 2002, brightening suddenly by a factor of almost 10 000 at visual wavelengths. Unlike a supernova or nova, V838 Mon did not explosively eject its outer layers; rather, it simply expanded to become a cool supergiant with a moderate-velocity stellar wind. A series of superluminally expanding ring-like structures appeared around the star shortly afterwards, as illumination from the outburst propagated into a surrounding, pre-

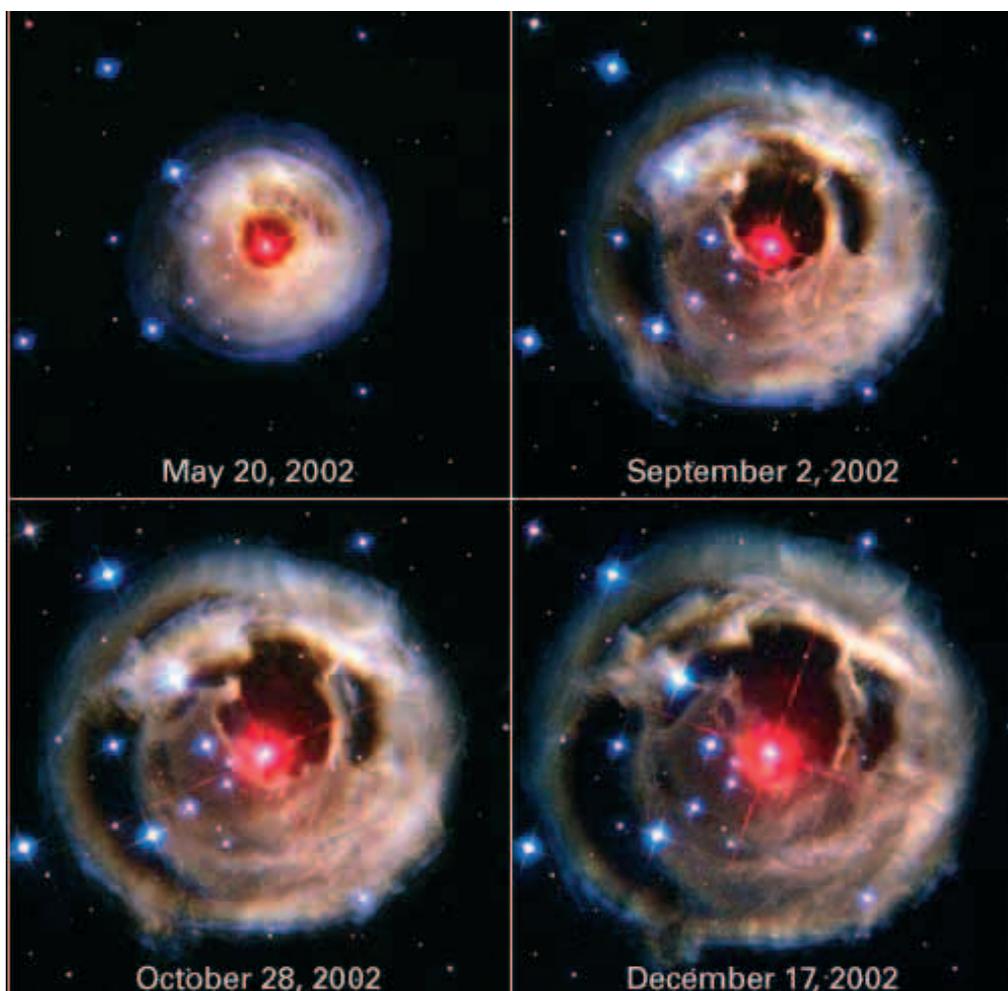
existing circumstellar dust cloud (see figure). They are produced by simple reflection of light from the star by dust particles that are present in the circumstellar medium and, therefore, they are called 'light echoes'. This was the first light echo seen in the Milky Way since 1936.

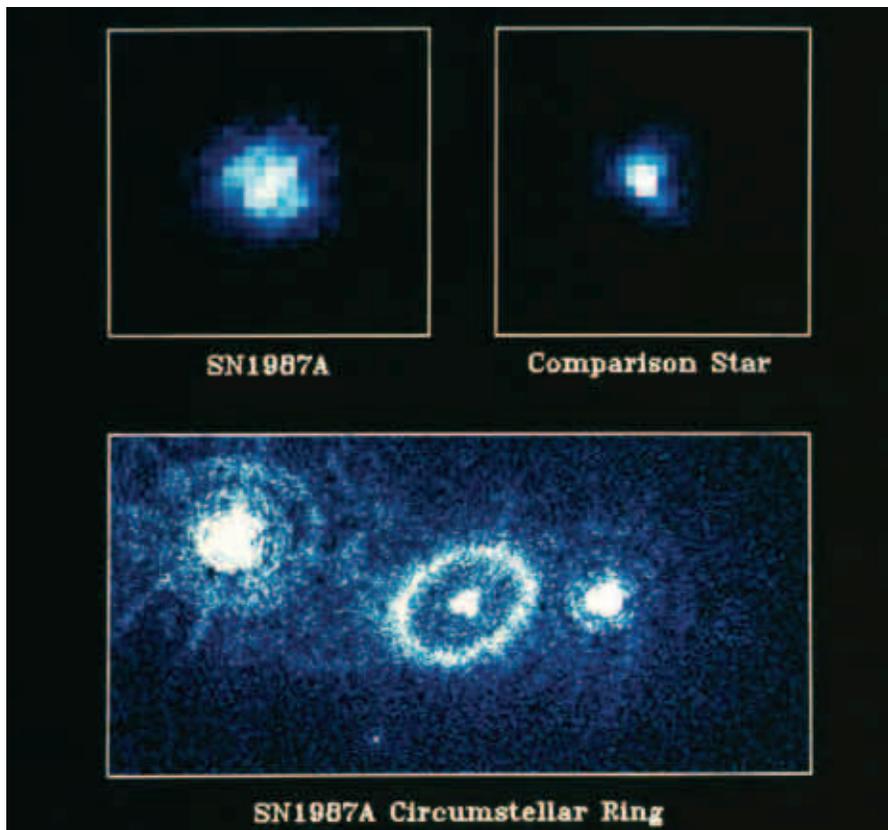
The star and its surrounding medium has been studied by an international team led by Howard Bond (STScI) and including Romano Corradi (Isaac Newton Group of Telescopes, La Palma), Ulisse Munari (Observatory of Padua) and the author. They obtained a series of high-resolution images and polarimetry of the light echo with Hubble's ACS instrument.

The echo exhibits a series of circular arcs, whose angular expansion rates show that the star is more than 6000 light-years away. The polarimetric imaging would imply an even greater lower limit to the distance, as

high as 19 000 light-years. Both of these limits mark the first times that these phenomena have been used to constrain an astronomical distance in the Milky Way. At maximum light, the object was extremely luminous, at least as bright as visual absolute magnitude 9.6, which is about a million times brighter than the Sun. The spectrum of the star during the outburst remained that of a cool stellar photosphere, but as the outburst subsided a composite spectrum appeared, which revealed the presence of a hot-star companion.

V838 Mon thus appears to represent a new class of stellar outburst, occurring in binary systems containing a relatively hot Main Sequence star and a companion that erupts to become a cool supergiant. A remarkably similar event was seen in the Andromeda Galaxy in the late 1980s. The presence of the circumstellar dust implies





*Historic image of SN 1987A and its equatorial circumstellar ring taken on 24 August 1990 with the ESA Faint Object Camera (FOC)*

that previous eruptions have occurred, and spectra show it to be a binary system. When combined with the high luminosity and unusual outburst behaviour, these characteristics indicate that V838 Mon represents a hitherto unknown type of stellar outburst, for which we have no completely satisfactory physical explanation.

### Fireworks in SN 1987A's Equatorial Ring

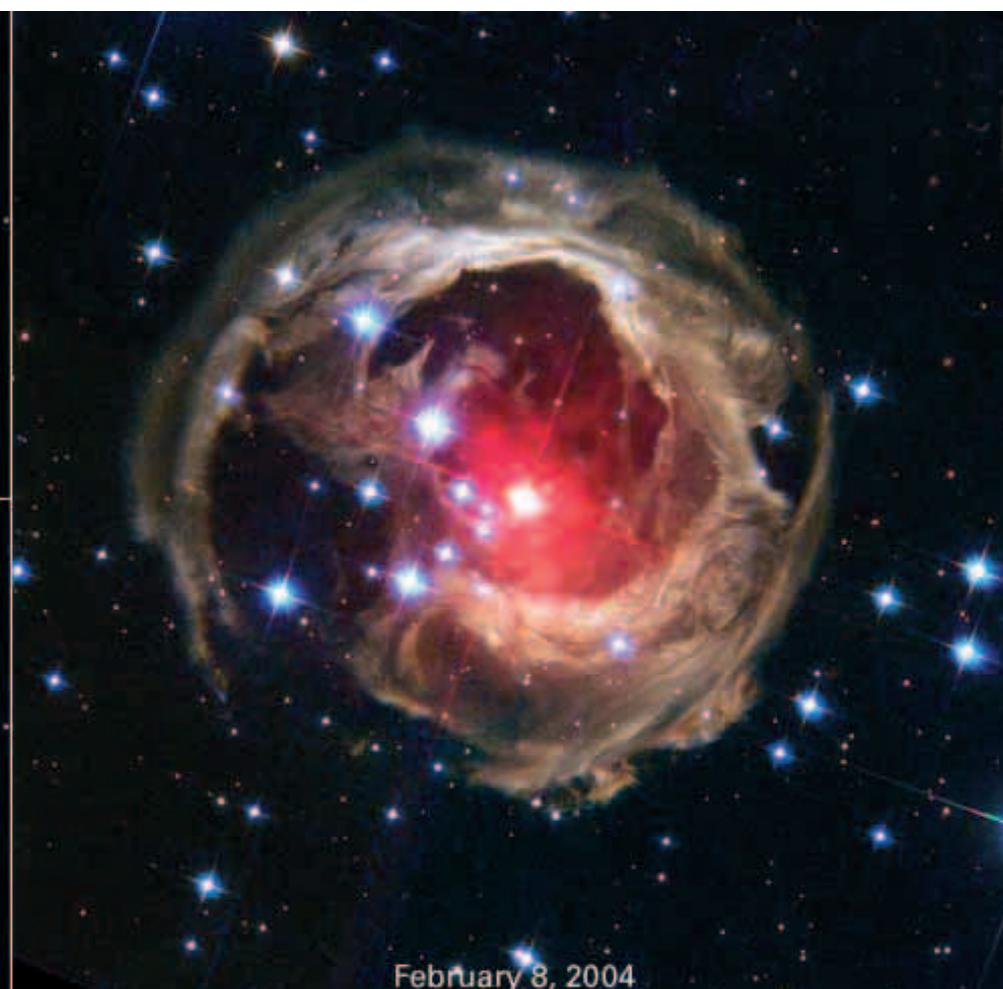
SN 1987A exploded on 23 February 1987 in the Large Magellanic Cloud. Hubble was not yet in orbit when this rare chance to observe a nearby supernova appeared, but it took advantage of the opportunity as soon as it became operational. ESA's Faint Object Camera took the first images on 23/24 August 1990, which revealed SN1987A to be crowned by a glorious circumstellar ring (see figure). Later, two more rings were discovered with WFPC2.

Since then, HST has kept an attentive eye on SN 1987A, and its observations have provided many fundamental results, including a direct measure of the supernova's expansion, the detailed properties of its surrounding rings, the accurate measurement of the distance to the supernova, and the origin of the stars associated with it.

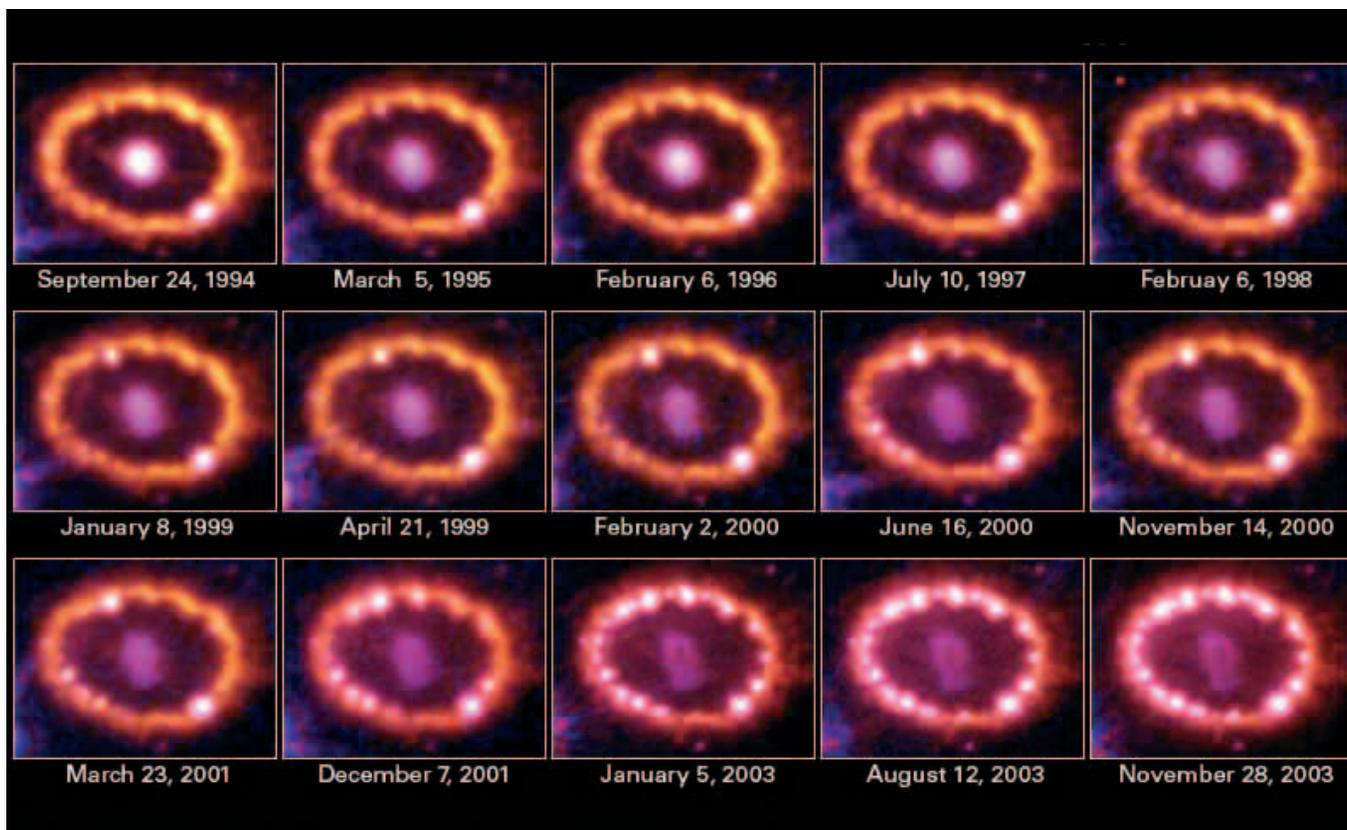
Recently, Hubble has provided dramatic evidence of high-velocity material from the supernova explosion starting to overtake and crash into the slower-moving inner ring (see figure). Relatively quiescent until 1996, in 1997 the circumstellar ring started to develop bright spots, and now one can identify more than a dozen. They are the result of the fast-moving component of the ejecta, travelling at 15 000 km/s or 1/20th the speed of light, colliding with the stationary equatorial ring.

*Comparison of Hubble ACS images of V838 Mon obtained between 20 May 2002 and 8 February 2004. The structure is dominated by a series of nearly circular arcs and rings, centered on the variable star, but there are cavities that become progressively more asymmetric with time*

*(Credit: H.E. Bond (STScI), Hubble Heritage Team, NASA, ESA)*



February 8, 2004



Images of SN 1987A and its inner circumstellar ring obtained with HST's WFPC2 instrument between September 1994 and November 2003. It appears that the quiescent ring has developed at least thirty hot spots in the last five years (Courtesy of R.P. Kirshner (Harvard) & NASA)

Over the next decades, as 'slower' ejecta layers (keeping in mind that they still have velocities of several thousand km/s!) reach the ring, more and more spots will light up and the whole ring will shine as it did in the first several months after the explosion. Eventually, the bulk of the ejecta will completely sweep the ring up, clearing the circumstellar space of that remnant of the pre-supernova wind activity.

### Supernovae and Cosmology: Clues to the Acceleration of the Universe

Since supernovae are very bright objects and relatively common, they are prime candidates for probing the distances to galaxies. A particular type, denoted as Type Ia supernovae (SNIa, characterised by the absence of hydrogen in their envelopes) are perhaps the best 'standard candles'. They are so similar to each other that their brightness provides a dependable gauge of their distance, and so bright that they are visible billions of light years away. However, one needs also to determine the

exact value of their luminosity before using them as 'proper' standard candles and most progress in this field has been made over the last decade.

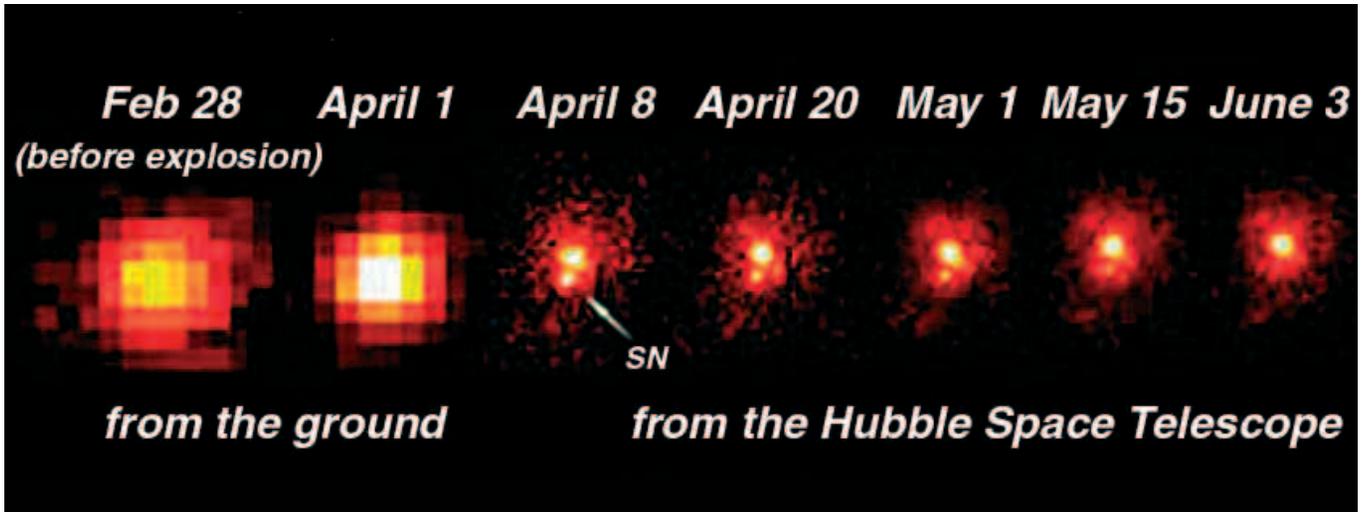
Using Hubble, an international team led by Allan Sandage, and including Gustav Tamman (Univ. of Basle), Abi Saha (STScI), and ESA's Duccio Macchetto and the author, has conducted an extensive programme to determine the absolute brightness of a selected sample of supernovae. This has allowed the placing of SNIa on an absolute scale, and the expansion rate of the Universe, the so-called 'Hubble Constant', to be determined as 63 km/s/Mpc, with a precision of 10%. This implies possible ages of the Universe in the range 11-17 billion years, depending on the acceleration/deceleration history of the Universe itself.

When researchers initially set out to measure the Universe's expansion rate, they expected to find that distant supernovae appeared brighter than their redshifts would suggest, indicating a slowing rate of expansion with time due to

the gravitational attraction of all masses in the Universe. Instead they found the opposite: at a given redshift, distant supernovae were dimmer than expected (see accompanying figure). So in fact, expansion was accelerating.

Not only did this discovery mean that the Universe would never come to an end, more fundamentally it implied that 70% or more of the Universe is made of something mysterious that we know nothing about - namely the so-called 'dark energy' that approximately 7 billion years ago overcame gravity and started pushing the Universe into an accelerated expansion.

Currently, there are two leading interpretations for the 'dark energy', as well as many more exotic possibilities. It could be an energy percolating from empty space as Einstein's theorised 'cosmological constant', an interpretation which predicts that 'dark energy' is unchanging and has a prescribed strength. An alternative possibility is that dark energy is associated with a changing energy field dubbed



Sequence of observations of supernova SN 1998ay (Courtesy of the Supernova Cosmology Project Team)

‘quintessence’. This field would be causing the current acceleration, in a milder version of the inflationary episode from which the early Universe emerged.

When astronomers first realised that the Universe was accelerating, the conventional wisdom was that it would expand forever. However, until we understand the nature of ‘dark energy’ and its properties better, other scenarios for the

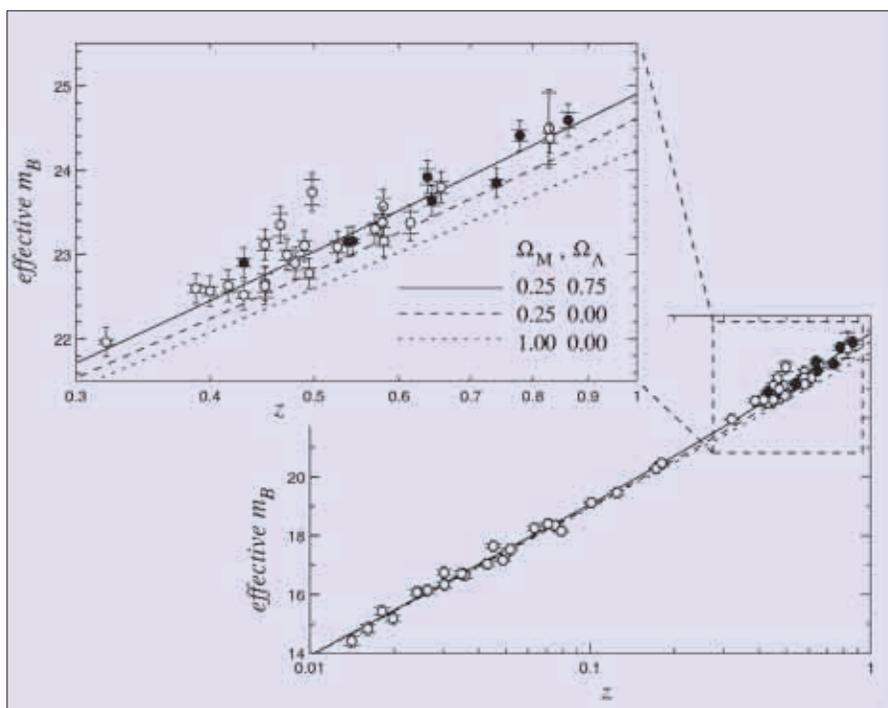
fate of the Universe are possible. If the repulsion from ‘dark energy’ is or becomes stronger than Einstein’s prediction, the Universe may be torn apart by a future ‘Big Rip’, during which it expands so violently that first the galaxies, then the stars, then the planets, and finally atoms come ‘unglued’ in a catastrophic end of time. Currently, this idea is very speculative, but one being pursued by the

theorists. At the other extreme, a variable ‘dark energy’ might fade away and then flip in force such that it pulls the Universe back together rather than pushing it apart. This would lead to a ‘Big Crunch’, in which the Universe ultimately implodes.

### The Hubble Ultra-Deep Field: A Journey to the Frontiers of the Universe

One of the most ambitious and successful HST projects has been the study of the so-called ‘Hubble Deep Field’ (HDF). For 12 consecutive days in December 1995, the telescope was pointed at an area of the sky in the constellation Ursa Major, selected for being most devoid of nearby objects, so as to probe the distant Universe, and thus the distant past.

The WFPC2 was used to image the field in four broad bands, spanning the spectrum from the near-ultraviolet to the near-infrared. The HDF images showed that nearly a third of very distant galaxies, which existed early in the history of the Universe, appear to be interacting galaxies. In particular, the Hubble Deep Field survey has uncovered quite a number of odd-shaped, disrupted-



Observed magnitudes of SNIa supernovae as a function of redshift shows that distant supernovae become dimmer than expected (Courtesy of the Supernova Cosmology Project Team)



*A composite image of the Hubble Ultra-Deep field (Courtesy of S.W.S. Beckwith, the HUDF Team and NASA)*

exposure reveals the first galaxies to emerge from the so-called 'dark ages', the time about half billion years after the Big Bang when the first stars reheated the cold, dark Universe. The final ACS image (see figure) is studded with a wide range of galaxies of various sizes, shapes, and colours. In vibrant contrast to the image's rich harvest of classic spiral and elliptical galaxies, there is a zoo of oddball galaxies littering the field. Some look like toothpicks, others like links on a bracelet. A few appear to be interacting. Their strange shapes are a far cry from the majestic spiral and elliptical galaxies we see today. These oddball galaxies chronicle a period when the Universe was more chaotic. Order and structure were only just beginning to emerge!

### The Future

Because of the extraordinary scientific results obtained so far with Hubble and the many more expected in the years to come, in late 1997 the length of the HST mission was extended by five more years with respect to the original 15-year design lifetime. The plan was to continue operating the telescope until the year 2010, with the hope of providing continuity for astronomers by then having the James Webb Space Telescope (JWST), Hubble's near/mid-infrared successor, in full operation. The next Hubble servicing mission (SM4), planned for mid-2006, was to include the installation of the Cosmic Origins Spectrograph (COS, a high-resolution ultraviolet spectrograph) and the Wide Field Camera 3 (WFC3, with imaging capabilities extending from the near-ultraviolet to the near-infrared).

This is not to be: to the dismay of most astronomers, on 16 January NASA announced that there would be no further Hubble servicing missions, with future Space Shuttle flights going exclusively to the International Space Station (ISS). The decision was based on a complex mix of factors, including crew safety, budget constraints and a commitment to complete

looking galaxies. They offer direct visual evidence that collisions between galaxies were more the rule than the exception in the early days of the Universe.

This analysis has led to the conclusion that the Big Bang may have been followed by a stellar 'baby boom'. The early Universe may have had an active, dynamic youth in which stars formed out of clouds of dust and gas at incredible rates. Consequently, most of the stars that the Universe will ever make may have already been formed, and so it now contains largely 'mid-life' stars.

The installation on HST in 2002 of the new Advanced Camera for Surveys (ACS), with its tenfold increase in sensitivity, opened new possibilities for exploring the Universe and so an even more ambitious project has been implemented to reach out to its ultimate frontiers, namely the Hubble Ultra-Deep Field (HUDF) project. The main science drivers are to study galaxy evolution and cosmology, including probing the epoch of re-ionisation up to

redshifts of about 6.5 and characterising not only the colours, but also the morphologies of faint sources. The ACS is the primary instrument for these surveys, but WFPC2, NICMOS and STIS are also being used in parallel.

The HUDF survey is being carried out using 'Director's Discretionary Time', based on the consensus recommendation of a Scientific Advisory Committee to the STScI Director Steven Beckwith. A local Working Group, composed of STScI astronomers, led by Massimo Stiavelli, and including ESA's Massimo Robberto and the author, has assisted in the definition of the project and has been looking in detail at the implementation of the survey. The HUDF observations began on 24 September 2003, and continued until 15 January 2004. The reduced ACS images and source catalogues were released on 9 March, just seven weeks after the completion of the observations.

The composite picture that has emerged from the million-second-long HUDF

the ISS before the Shuttle is phased out at the end of the decade, with crew safety being a primary factor following the tragic loss of 'Columbia' in February 2003. The US National Academy of Science has formed a panel to assess the viability of Space Shuttle or robotic servicing options as well as benefit and risk assessments, and we hope that plans will proceed expeditiously to save this premier scientific mission.

While these studies are underway, the present plan is to exploit the current instruments and capabilities of Hubble until it becomes impractical to continue to do so. The gyroscopes, for example, are known to have a finite lifetime, so there is a high probability that HST will have to be operated in a two-gyro mode relatively soon, which may imply substantial restrictions on

the sky coverage and on the spatial resolution of the science observations. Eventually, a controlled de-orbiting of Hubble will have to take place, using a special robotic mission.

Astronomers are renowned for being creative and unconventional. Their ingenuity saved the HST mission from failure when the spherical-aberration problem with its primary mirror was discovered shortly after its launch, and was brilliantly fixed by installing corrective optics for all instruments. Now again, astronomy's best creative minds are hard at work to find ways to extend Hubble's lifetime without violating safety and budgetary constraints. Among the many innovative ideas put forward during a series of brain-storming sessions at STScI, one that has been pursued in earnest is to add a

complement of gyroscopes and a power supply to the robotic device that is being designed to de-orbit HST. When that device locks onto the ailing telescope, not only could it guarantee a controlled atmospheric reentry, but it could also ensure several more years of fully functional lifetime for Hubble. The idea of an innovative servicing mission which, if successful, will allow continuity of the science from the observatory, has now been further developed and although much more work will be needed it is encouraging to know that, when presented with such difficult problems, scientists can be inventive enough to devise and pursue 'seemingly impossible' solutions that may eventually come to the rescue against all odds!



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