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The Hubble Space Telescope: Past, Present, and Future

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Abstract I present and illustrate some of the most recent *HST* results and the plans for future observations, including the current studies of solar system planets, the extensive imaging of the Helix Nebula, the detection of superluminally expanding light echoes around the newly discovered variable star V838 Mon, the repeated measurements of the collision of SN 1987A ejecta with its inner circumstellar ring, that show a marked increase of high energy interactions, the study of M31 halo stellar populations and the puzzle of their origin, and the plans for the *ACS* Ultra-Deep Field observations that will probe the Universe to an unprecedented depth.

Key words: planets and satellites: individual (Mars, Neptune) — planetary nebulae: individual (NGC 7293) — novae, cataclysmic variables — supernovae: individual (1987A) — galaxies: halos — cosmology: early universe

1 INTRODUCTION

At fourteen years of age, the "middle-aged" Hubble Space Telescope (*HST*) is still playing a major role in astronomical research and is undoubtedly one of the most important and most prolific space astronomy missions.

HST is a cooperative program of the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) to operate a long-lived space-based observatory for the benefit of the international astronomical community. *HST* is an observatory first conceived in the 1940s, designed and built in the 1970s and 80s, and become operational in the 1990s. *HST* was designed to be a different type of mission – a long term space-based observatory, whose instrumentation and equipment were planned to be serviced at a regular three year cycle.

HST was deployed in low-Earth orbit (~ 600 km) by the crew of the space shuttle Discovery (STS-31) on 25 April 1990. Although at the beginning the mission looked severely faulted because the spherical aberration, the first maintenance mission STS-61 Endeavour, December 1993) fully restored the functionality of *HST*. In fact, all *HST* servicing missions so far, *i.e.* SM1 in December 1993, SM2 in 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 - Planetary Camera 2 (*WFPC2*), the new Advanced Camera for Surveys (*ACS*), which with its tenfold

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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 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). Another servicing mission is planned for May 2005 (SM4), which includes the installation of the Cosmic Origins Spectrograph (*COS*, a high-resolution UV spectrograph) and the Wide Field Camera 3 (*WFC3*, with imaging capabilities extending from the near-UV to the near-IR). Because of the extraordinary scientific results obtained so far and expected in the years to come, in late 1997 the length of the *HST* mission was extended five more years with respect to the original 15-year design life, so that in the current plan *HST* is to be operated until the year 2010.

That extension was decided when the James Webb Space Telescope (*JWST*), the near/mid-infrared successor of *HST* (Panagia 2003, this volume), was expected to be launched in 2007, while currently the launch of *JWST* is planned for late 2011. It follows that, if now one wants to assure a substantial overlap of the two missions, a further *HST* extension should be envisaged which would require an additional servicing mission. However, servicing missions by the shuttle are expensive and inherently dangerous, and, therefore, NASA decided to assess the scientific impact of its current plan for effecting the transition from *HST* to *JWST* in the context of its overall space science program, and to determine if there are modifications to this plan that may better address key scientific issues within the constraints provided by the agency's strategic plan and budget. To this end in mid-2003 NASA Office of Space Science chartered a panel of senior community members, with John Bahcall serving as chair, to review agency plans and to receive community input on the *HST*-*JWST* transition topic.

After a broad consultation with the astronomical community at large, extensive discussions with scientific and engineering experts, and following a meeting with selected representatives of the *HST* and *JWST* projects, the panel issued their report [1] which is very positive about *HST*, its contributions, and the desirability of keeping it functioning as a scientific facility as long as possible. Actually the report, while favoring an extension of *HST* lifetime past 2010 in view of a partial, at least, overlap with the *JWST* mission, considers a number of possible of different scenarios, from having two missions (a SM4 in 2005 and a SM5 in about 2010) to dismissing any further maintenance mission altogether, and for all of them recommends actions to maximize the scientific outcome of the *HST* mission, whatever the decision, mostly dictated by budgetary and safety considerations, could be. Therefore, with a dose of cautious optimism and a grain of realism, we could expect that, *budget permitting*, the *HST* mission may be extended even past 2010.

In the following sections I shall review some of the telescope's most recent results and outline some of the planned observations for the near future. Summaries of previous years most exciting *HST* results can be found in Panagia (1999, 2002).

2 MARS'S CLOSE ENCOUNTER WITH EARTH

On August 27, 2003, the third and fourth planets from the Sun, namely the Earth and Mars, were at their closest encounter in recorded human history.

The reason why the two planets were unusually close is opposition. Approximately every two years, the Earth's orbit catches up to Mars's orbit, aligning the Sun, Earth, and Mars in a straight line, so that Mars and the Sun are on opposite sides of Earth. The fact that Earth's orbit is nearly circular ($e_{\rm Earth} = 0.0167$) while Mars' is more markedly elliptical ($e_{\rm Mars} = 0.0934$) results in Earth-Mars approaches ranging between 56 and 100 million kilometers. In late August

[1] http://www.nasa.gov/audience/formedia/features/MP_Public_Reports.html

Earth was near aphelion and Mars at perihelion, thus being separated by a distance of a mere 55.8 million kilometers, the shortest in about 60,000 years.

During past oppositions, many famous observations were made of the Red Planet. An opposition in November 1659 made it possible for Christiaan Huygens to see and sketch the first accurate drawings of the Martian surface, which showed a major dark feature on the planet now known as Syrtis Major. Although farther away than usual during the opposition of 1666, Mars offered Gian Domenico Cassini the first view of its polar ice caps. Cassini was also able to determine the rotation period of Mars from his opposition observations. In the late 19th century, Giovanni Schiaparelli made perhaps the most famous observations of Mars, performing detailed studies of those "canals", as Father Angelo Secchi had called them about 14 years earlier, and which, due to a misinterpretation, set the stage for speculation about life on Mars. Following that, during the perihelial opposition of 1877, Mars came close enough to Earth for Asaph Hall to resolve Mars's two small satellites, which he named Phobos and Deimos.

The shorter-than-usual separation of these planets also made summer 2003 the ideal time to launch scientific expeditions to Mars. With such a shorter distance not as much fuel is needed to reach Mars, which leaves more room for valuable scientific instruments. Thus, NASA has launched a pair of Mars Exploration Rovers (MER-A "Spirit" on June 10 and MER-B "Opportunity" on July 7) to land on the planet and investigate the Martian surface. Similarly, the European Space Agency successfully launched the Mars Express probe which will reach the planet in December 2003, starting its studies of the entire surface of the planet and its atmosphere, and will analyze Mars' soil with the Beagle 2 lander.

Taking advantage of such a close opposition, a series of *HST* observations were planned, some of which have already been executed (see *e.g.,* Figure 1). In particular, a team led by Jim Bell is carrying out a coordinated program (GO 9738) of spectroscopy, imaging, and spectropolarimetry of Mars during the August 2003 opposition to study the composition and physical state of surface materials and airborne aerosols. The observations include (a) Moderate spectral resolution 290 to 570 nm *STIS* long-slit push-broom imaging spectroscopy of Mars, to constrain the properties of airborne aerosol particles and to search for and globally map iron-bearing minerals that are diagnostic of specific past climatic conditions; (b) *WFPC2* UV-VIS images designed primarily to quantify the effects of ice and dust aerosols on our *STIS* spectra; (c) *NICMOS* near-IR images to search for and globally map the presence of hydrated surface minerals; and (d) *ACS* multispectral polarizer images to provide critical phase function measurements needed to constrain the physical properties of the Martian surface layer. The observations are timed to take full advantage of the closest approach of Mars to Earth, so that images and spectra are acquired at a spatial scale comparable to existing spacecraft orbital spectroscopy data ($\sim$ 10 km/pixel) and in wavelength regions not sampled by past or current Mars spacecraft instrumentation. These observations also provide complementary scientific and calibration measurements in support of current and future NASA and ESA Mars exploration missions.

Finally, in February 2004, a last observation will be made simultaneously with the Mars Exploration Rover Mission. August 27 *ACS* observations have already provided high-resolution images of Mars (at 7.33 kilometers per pixel). All of these observations also provide complementary scientific and calibration measurements in support of current and future NASA and ESA Mars exploration missions.

3 A CHANGE OF SEASONS IN NEPTUNE

Observations of Neptune made over six years show a distinct increase in the amount and brightness of the banded cloud features located mostly in the planet's southern hemisphere (Sromovsky *et al.* 2003).

Neptune was already known for its violent weather, with winds up to 1500 km/h, but the new Hubble observations are the first to suggest that the 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 with Keck Telescope observations from July 2000 to June 2001 by H. Hammel and co-workers (see *e.g.,* Rages, Hammel & Lockwood 2002). Near-infrared observations at NASA's Infrared Telescope Facility on Mauna Kea, Hawaii are planned for this summer to further characterize changes in the high-altitude cloud structure.

Neptune rotation axis is tilted at an angle of about 29 degrees so that the northern and southern hemispheres alternate in their positions relative to the Sun. Therefore, like the Earth, Neptune would have four seasons, but, unlike the Earth, the seasons of Neptune last for decades, not months. Actually, since Neptune obits the Sun in about 165 years, a single season on the planet can last more than 40 years. If what scientists are observing is truly seasonal change, the planet will continue to brighten for another 20 years.

What is remarkable is that Neptune exhibits any evidence of seasonal change at all, 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 can such a small energy input affect the dynamic nature of Neptune's atmosphere.

4 NGC 7293: THE HELIX NEBULA

The Helix Nebula, *a.k.a.* NGC 7293, lies about 200 pc away towards the constellation of Aquarius and has a diameter of about 0.8 pc, thus spanning as much as 14 arcminutes in the sky. Figure 3 shows an image made by combining newly released images from the *HST-ACS* and wide-angle images from the Mosaic Camera on the WIYN 0.9 m Telescope at Kitt Peak National Observatory.

This image of the Helix Nebula is one of the largest and most detailed celestial images ever made. Making these *HST* observations was made possible by the fortuitous combination of events. Among the most prominent of meteor showers is the Leonids each November. The shower in 2002 was predicted to be especially rich and since those meteoroids pose a non-zero risk to the spacecraft, *HST* had to carry out a special procedure to minimize the risk and any consequences. As in the past several years, *HST* was required to be pointed in a particular direction during the meteor shower so as to keep the telescope's aft end toward the stream while minimizing the cross-section of the solar arrays. This "stand down" period was from 0 to 14 hours UT on November 18, 2002. In preparing for this special effort, STScI staff member Ian Jordan noticed that just outside the nominal pointing region lied the Helix Nebula, which had been examined by Hubble many times (see, *e.g.,* the dramatic images of globules shown press release STScI-1996-13). This was too good an opportunity to miss! The *HST* Project at Goddard Space Flight Center was immediately contacted and their concurrence in using *HST* slightly beyond its nominal pointing area was secured.

Then a small group of STScI scientists was set up to design a program that would make effective use of the nine orbits available. This group, led by Margaret Meixner, created a program that imaged a substantial portion of the large Helix in two colors, using both *ACS* and *WFPC2*, with the intent of establishing a first-epoch dataset that is suitable for later work to measure proper motions of the knots. A high-quality public image, which is shown in Figure 3, was also produced, by combining all of the *HST* images and complementing them with images taken with the KPNO 0.9 m WIYN telescope large-field images. More details on these observations can be found at http://archive.stsci.edu/hst/helix/.

5 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 light echoes appeared around the star shortly afterward, as illumination from the outburst propagated into a surrounding, pre-existing circumstellar dust cloud (see Figure 4). This is the first light echo seen in the Milky Way since 1936. The star and its surrounding medium has been studied obtaining a series of high-resolution images and polarimetry of the light echo with the HST-ACS (Bond *et al.* 2003).

The echo exhibits a series of circular arcs, whose angular expansion rates show that the distance is greater than 2 kpc. The polarimetric imaging would imply an even greater lower limit to the distance of as high as 6 kpc. 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. 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 B type companion.

V838 Mon thus appears to represent a new class of stellar outbursts, 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 1980's. The presence of the circumstellar dust implies that previous eruptions have occurred, and spectra show it to be a binary system. When combined with the high luminosity and unusual outburst behavior, these characteristics indicate that V838 Mon represents a hitherto unknown type of stellar outburst, for which we have no completely satisfactory physical explanation.

6 FIREWORKS IN SN 1987A EQUATORIAL RING

Supernova 1987A exploded on 1987 February 23 in the Large Magellanic Cloud. Although *HST* was not yet in orbit when this rare chance to observe a nearby supernova appeared, it took advantage of the opportunity as soon as it became operational. The European Space Agency's Faint Object Camera took the first images of SN 1987A on 1990 August 23–24, which revealed the supernova crowned by a glorious circumstellar ring. Later, two more rings were discovered.

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

Recently, Hubble has observed the high-velocity material from the supernova explosion starting to overtake and crash into the slower-moving inner ring. Figure 5 shows the dramatic evidence of these collisions. The circumstellar ring, which until 1996 was relatively quiescent, started to develop bright spots in 1997, and in May 2001 one can identify almost a dozen bright spots. These bright spots are the result of the fast moving component of the ejecta colliding with the stationary equatorial ring. The fastest debris, moving at 15,000 km s^{-1} or 1/20 the speed of light, are now colliding with the slower moving gas which was ejected when the progenitor was a red supergiant (*e.g.,* Sonneborn *et al.* 1998).

Over the next decades, as "slower" ejecta layers 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 explosion.

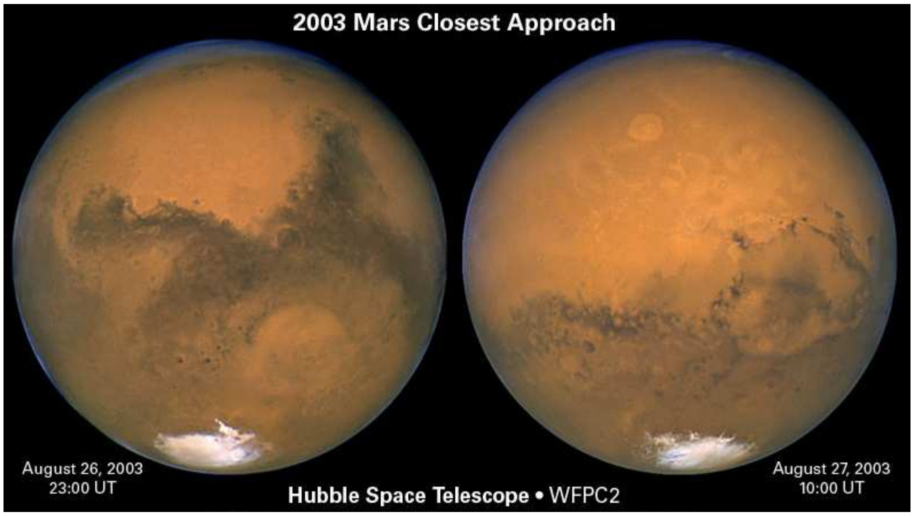

Fig. 1 Mars' images taken at its closest approach to the Earth. [Credit: NASA]

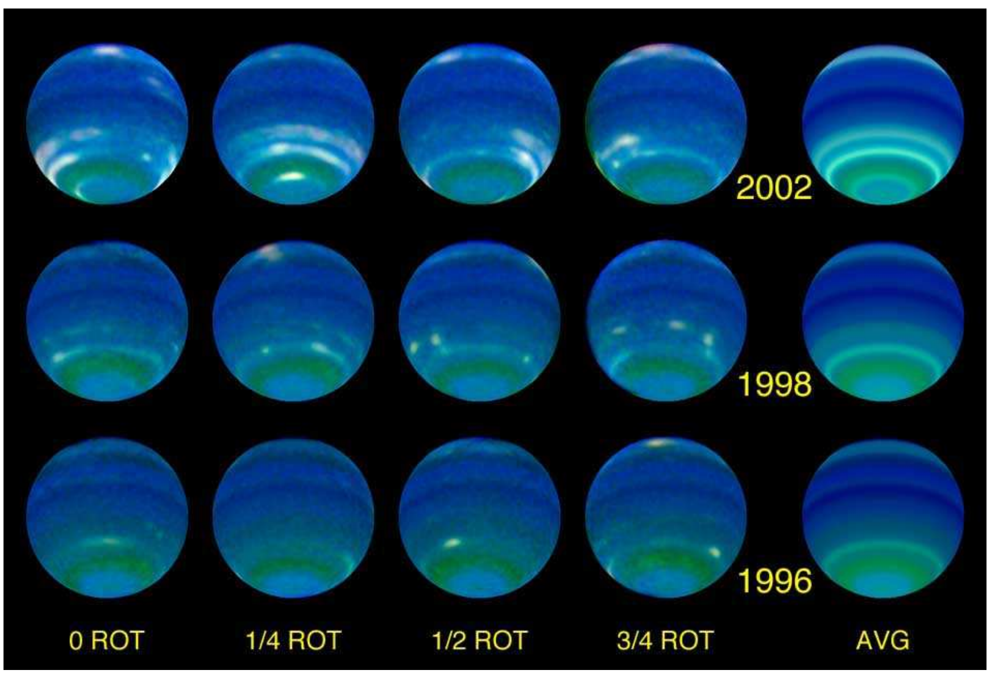

Fig. 2 Images of Neptune taken between 1996 (bottom) and 2002 (top) at different rotation phases. [Credit: NASA]

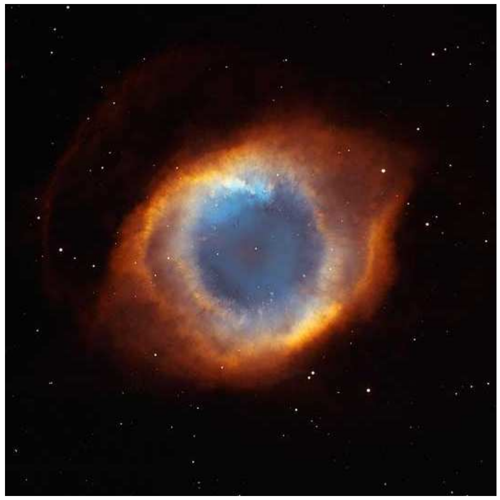

Fig. 3 The composite picture of the Helix Nebula from *ACS* images wide-angle images from the Mosaic Camera on the NSF 0.9 m telescope at KPNO. [Credit: NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner (STScI), and T.A. Rector (NRAO)]

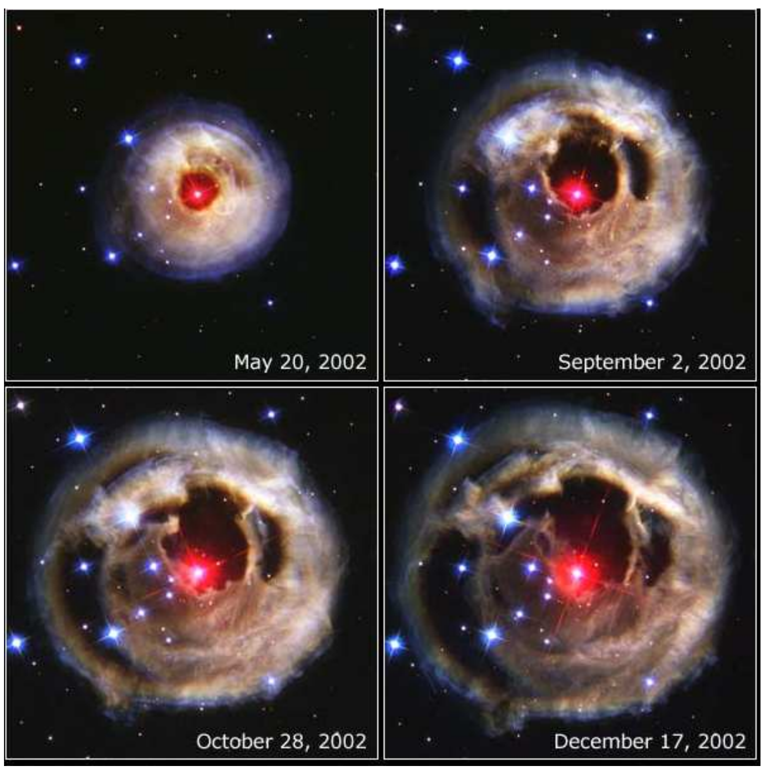

Fig. 4 Comparison of *ACS* images of V838 Mon obtained between May 20, 2002, and December 17, 2002. The structure is dominated by a series of nearly circular arcs and rings, centered on the variable star, but there are cavities that become progressively more asymmetric with time. [Credit: NASA, ESA and H.E. Bond (STScI)]

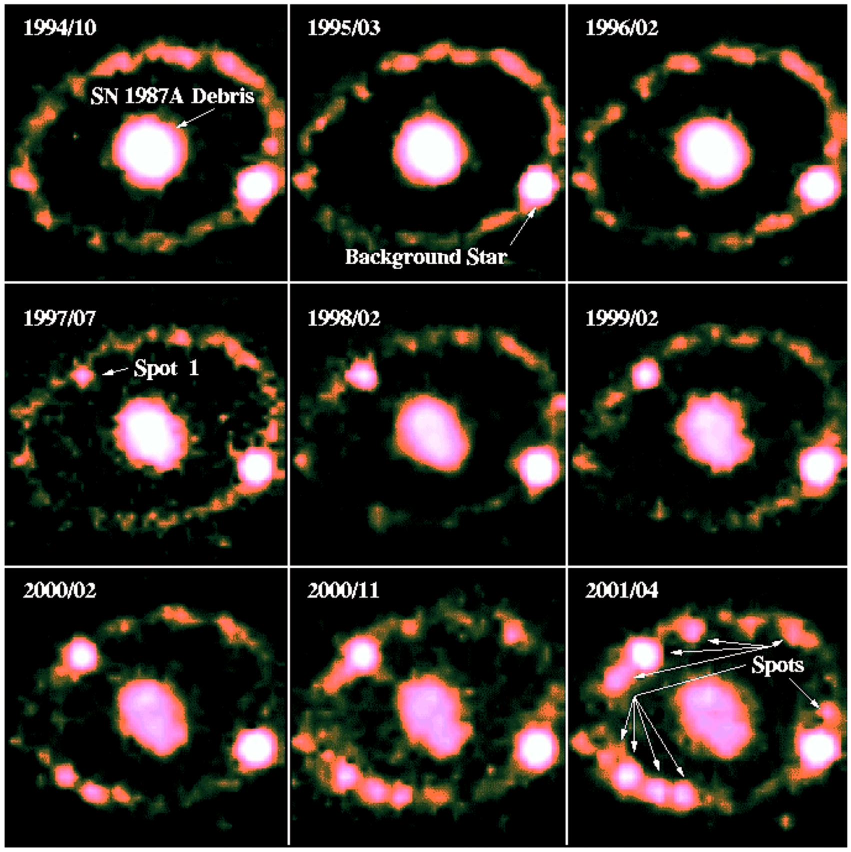

Fig. 5 Series of images of SN 1987A and its inner circumstellar ring obtained with *HST-WFPC2* between October 1994 and May 2001. It appears that the quiescent ring has developed at least nine hot spots in the last five years. [Courtesy of Peter Challis (CfA), on behalf of the SINS project (Supernova INtensive Study, PI: R.P Kirshner)]

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.

7 YOUNG STARS IN THE ANDROMEDA HALO?

With an investment of 120 orbits of *HST* observing time, a team led by Tom Brown has obtained a color-magnitude diagram (CMD) for a minor-axis field in the halo of the Andromeda galaxy (M31), 51 arcmin (11 kpc) from the nucleus (Brown *et al.* 2003). These observations, taken with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope, are the deepest optical images yet obtained (but not for long! see Section 8), attaining 50% completeness at V = 30.7 mag (see Figures 6 and 7). The CMD, constructed from approximately 300,000 stars, reaches more than 1.5 mag fainter than the old main-sequence turnoff. Brown *et al.* analysis is based on direct comparisons to *ACS* observations of four globular clusters through the same filters,

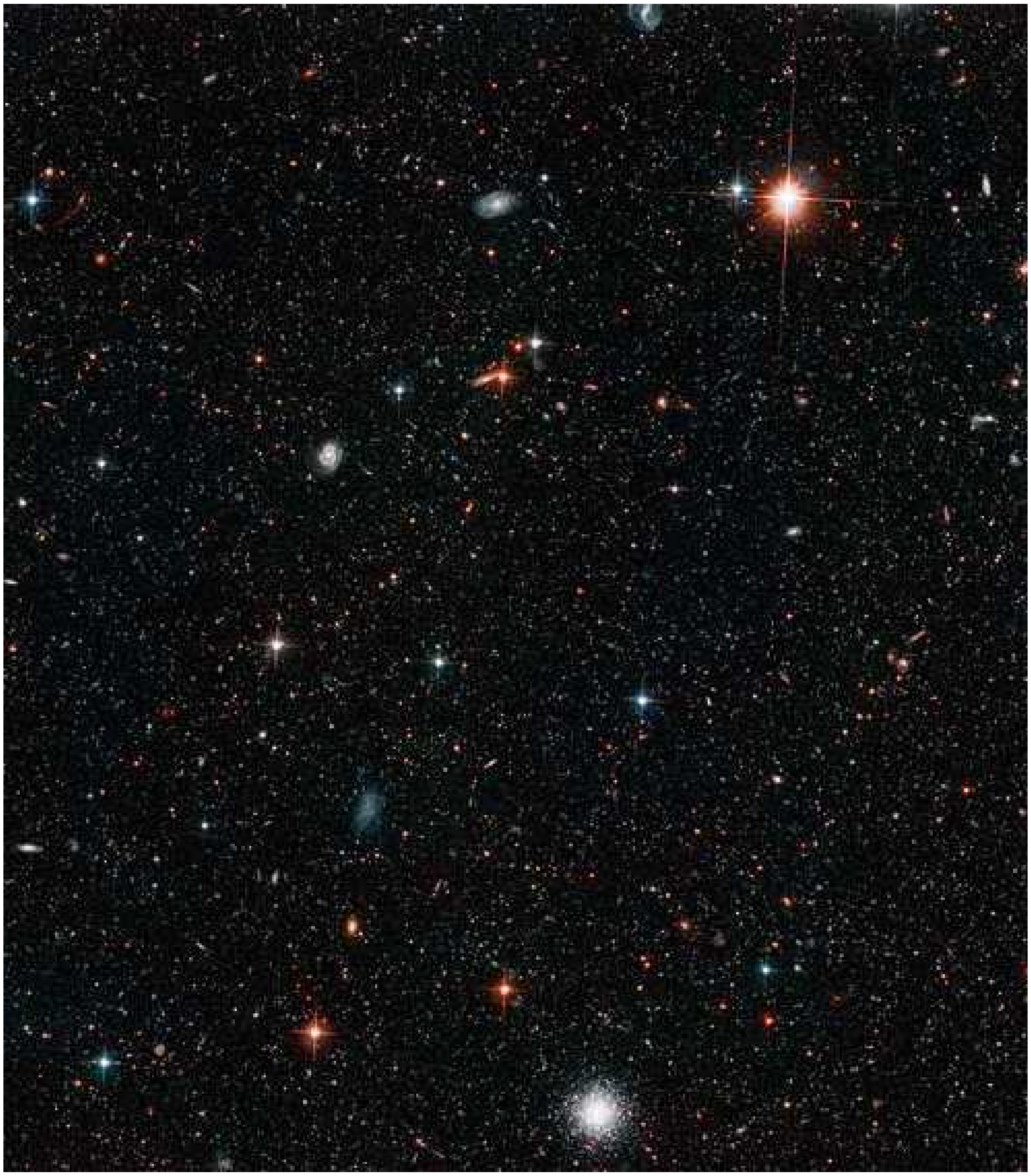

Fig. 6 A $180'' \times 200''$ region of M31 halo, the deepest visible-light image so far taken in space, observed with the *HST-ACS*. [Credit: NASA, ESA and T.M. Brown (STScI)]

as well as chi-squared fitting to a finely-spaced grid of calibrated stellar-population models. They find that the M31 halo contains a major (approximately 30% by mass) intermediate-age (6–8 Gyr) metal-rich ([Fe/H]> -0.5) population, as well as a significant globular-cluster age (11–13.5 Gyr) metal-poor population.

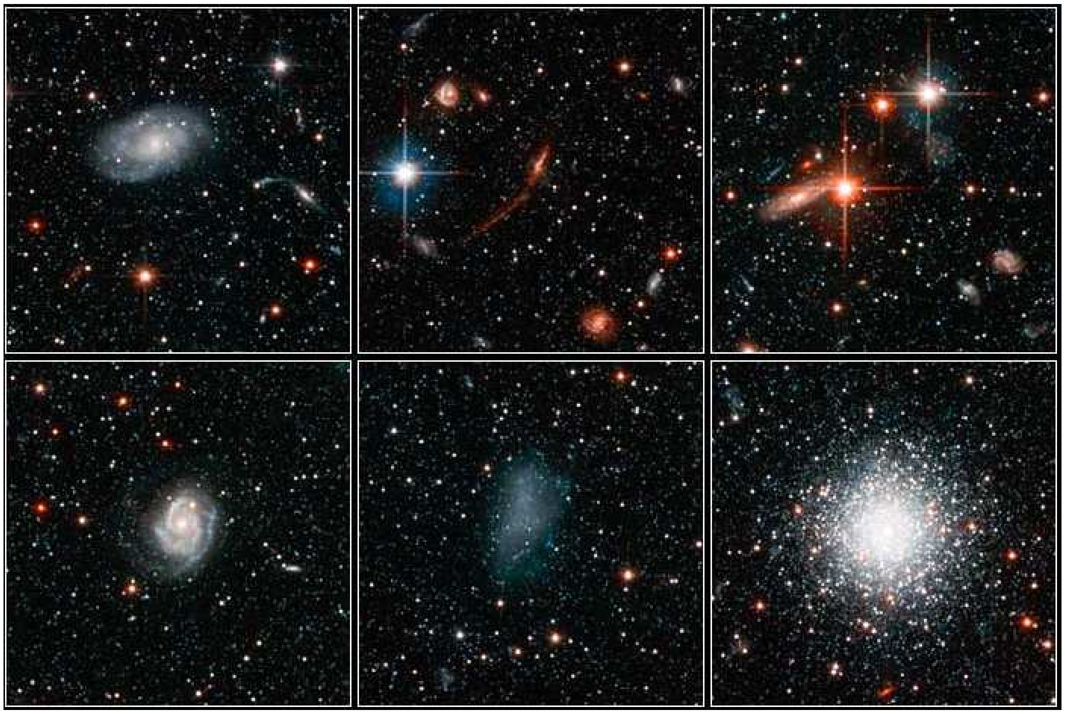

Fig. 7 A sampler of extended objects detected in the M31 halo *ACS* images. [Credit: NASA, ESA and T.M. Brown (STScI)]

The newly discovered younger stars in Andromeda's halo are richer in heavier elements than the stars in our Milky Way's halo, or in most of the small dwarf galaxies that surround the Milky Way. Indeed the level of chemical enrichment seen in these younger stars is characteristic of relatively massive galaxies, containing at least a billion stars. On the other hand, since the gas in a young giant galaxy rapidly falls into the disk, it is unlikely that the newly revealed intermediate-age population could be explained by star formation continuing in the halo for more than 6 Gyrs.

Brown *et al.* argue that a more plausible explanation is a merger with a large satellite galaxy when the Universe was approximately half of its present age, or a series of mergers with smaller satellites. Thus, the resulting halo appears be a mix of stars originally formed in the halo, disrupted-disk stars, disrupted-satellite stars, and stars formed during one or more mergers. These results open a number of interesting new possibilities, but leave us with the new question "what is the typical halo formation process?" Is it a "violent" one like that we see occurring in Andromeda, or is it as quiescent as found in the halo of our Milky Way galaxy? Only further studies on more galaxies will be able to answer this question properly.

8 AS DEEP AS EVER: THE *ACS* ULTRA-DEEP FIELD

The *ACS* Ultra Deep Field (UDF) is a public survey carried out by using Director's Discretionary time. The main science driver are galaxy evolution and cosmology, including probing the epoch of reionization up to $z \sim 6.5$ and characterizing not only the colors but also the morphologies of faint sources. The primary instrument is the Advanced Camera for Surveys but *WFPC2*, *NICMOS* and *STIS* will also be used in parallel.

The UDF consists of a single ultra-deep field (412 orbits in total) within the Chandra Deep Field South (Giacconi *et al.* 2002) in the GOODS area (Giavalisco *et al.* 2003). The pointing will be RA(J2000)=3^{h} 32^{m} $39^{s}.0$ and Decl.(J2000)=$-27°47'$ $29''.1$. This pointing avoids the gaps with the lowest effective exposure on the Chandra ACIS image of CDFS, and is designed to include in the field both a spectroscopically confirmed $z = 5.8$ galaxy and a spectroscopically confirmed type Ia SN at $z = 1.3$. The selected UDF field will be accessible to most major observatories in both Northern and Southern hemispheres.

The survey will use four filters: F435W (56 orbits), F606W (56 orbits), F775W (150 orbits), and F850LP (150 orbits). The F435W (B) and F606W (V) exposures will be one magnitude deeper, and the F775W (I) exposure 1.5 magnitude deeper than the equivalent HDF exposures. The depth in F775W and F850LP is optimized for searching very red objects - like $z = 6$ galaxies - at the detection limit of the F850LP image.

This basic structure of the survey represents a consensus recommendation of a Scientific Advisory Committee to the STScI Director Steven Beckwith. A local Working Group is looking in detail at the implementation of the survey. The Phase II plan for the UDF set of observations is accessible on the web as DD proposal 9978. The *HST* observations will begin on September 24, 2003, and continue through January 16, 2004. The current plan is to release the reduced *ACS* images and source catalogs by February 7, 2004, *i.e.* three weeks after the completion of all *HST* observations.

Further details and updates can be found at http://www.stsci.edu/science/udf/.

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