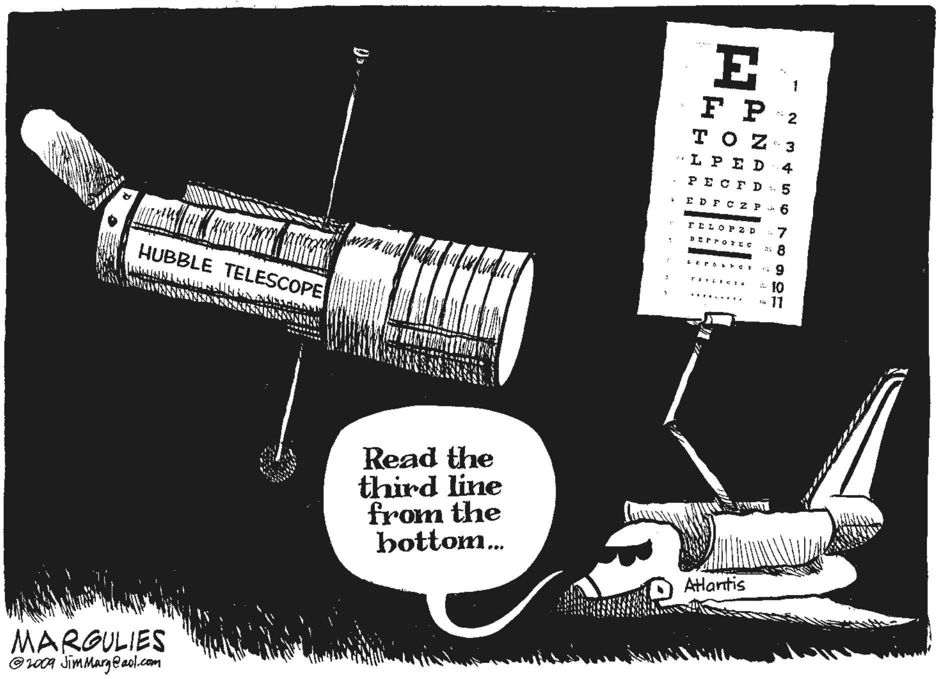
1 The Horsehead Nebula in the Orion Molecular Cloud is roughly 1500 light-years away. The nebula appears transparent and ghostly when seen in the infrared, as imaged here by the high-resolution Wide Field Camera 3. (NASA, ESA and the Hubble Heritage Team [STScI/AURA])

25 years of Hubble

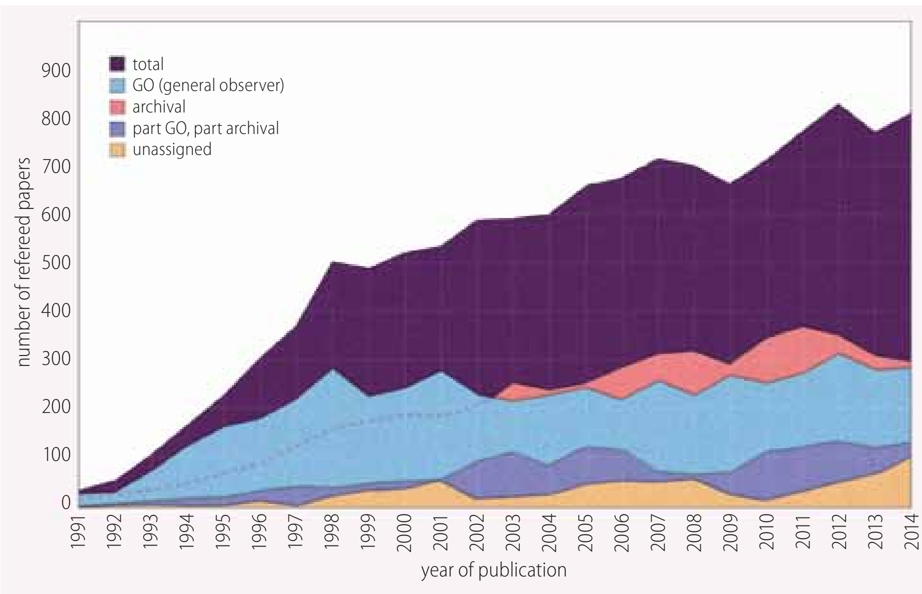
In his Presidential Address for 2015, **Martin Barstow** celebrates the scientific and cultural impact and future legacy of the Hubble Space Telescope.

The Hubble Space Telescope, which celebrated 25 years in space in April 2015, is a panchromatic instrument that can probe difficult-to-reach parts of our galaxy and the distant universe. Having been involved with the HST for most of my scientific career, I am aware of the importance of this iconic observatory to culture as well as science, throughout the 25 years it has been orbiting Earth.

It is interesting to start by considering what 25 years means: four US presidents, five UK prime ministers (and one Queen!), half an astronomy career, a family from birth through to graduation and beyond – not to mention five family cars. But the idea of a visible-band telescope in space has been around for much longer. Lyman Spitzer was one of the earliest proponents in the 1940s (Spitzer 1946) and there was



2 One of many cartoons mocking Hubble's initially impaired vision. (Jimmy Margulies)



3 The scientific impact of Hubble is still increasing, as measured by the number of papers published each year.

active discussion of the idea in the mid-1960s. Hubble is more like 50 years old, from the first detailed concepts until now.

At the time of Hubble's launch on 24 April 1990, I was working on the ROSAT X-ray and extreme ultraviolet (EUV) astronomy mission, which was due for launch a couple of months later, so I didn't have time to pay too much attention. But I did notice the publicity – NASA is a big organization with fast and effective public relations activity. Press coverage was widespread, especially in the US. However, Hubble is actually a joint project between NASA and ESA; key players from the UK included Malcolm Longair, Mike Disney and Alex Boksenberg. ESA contributed the Faint Object Camera, the original solar panels, and the European Coordination Facility in Garching, Germany; there have also been many European staff at the Space Telescope Science Institute in Baltimore. The collaboration made good links for European astronomy and we have been very successful at getting time on the HST.

After the excitement of the launch, the telescope's beginnings were inauspicious, to say the least. I remember the horrible realization, following in-orbit checkout, that the mirror was the wrong shape and the hoped-for leap in resolution could not be achieved. The problem was spherical aberration and there was an atmosphere of gloom and doom, despite, or perhaps because of, the many mocking cartoons.

All was not lost. The HST had been designed and built as an instrument which it was possible to return to and refit, making use of the space shuttle (as not quite shown in figure 2). A plan was developed for a repair mission and in 1993 a set of optical elements (COSTAR: Corrective Optics Space Telescope Axial Replacement) was installed to correct the mirror anomalies, along with a replacement camera (Wide Field Planetary Camera 2). This complex and demanding mission restored Hubble's vision to that originally planned, to considerable relief. It also made the telescope into a media star through the stunning images that made headlines worldwide. The opportunity to refurbish and repair Hubble through a series of servicing missions has led to the HST taking on new instruments and capabilities that could not have been imagined when the telescope was first designed. All the new instruments incorporated their own corrective optics and COSTAR was removed during the last servicing mission in 2009.

Was HST worth it?

The hiatus after Hubble's launch allowed time for many questions about the value of the project: basically, was Hubble worth the money? This question has been

4 Asteroid P/2013 P5 was discovered with the Pan-STARRS survey telescope in Hawaii, but it was Hubble's follow-up images that revealed six comet-like tails of dust. The structures changed dramatically during 13 days, leading to speculation that the asteroid is rotating so rapidly that its surface is flying apart. (NASA, ESA and D Jewitt [Univ. of California, L.A.], J Agarwal [Max Planck Inst. for Solar System Research], H Weaver [Johns Hopkins Univ. Applied Physics Lab.], M Mutchler [STScI] and S Larson [Univ. of Arizona])

firmly put to rest over the past 25 years, in which Hubble has proved itself a scientific workhorse: 140 000 orbits; three initial key projects; 22 proposal cycles; many, many deep fields, from the Hubble Deep Field to today's Frontier Fields with their powerful gravitational lensing of the distant universe; and a million observations. The most recent allocation cycle received more than 1100 proposals from around 25 different countries. This is a successful observatory by any measure. The Hubble Ultra Deep Field revealed a fantastic array of galaxies – the science these data contained has revolutionized our understanding of how galaxies evolved. And, not least, Hubble science resulted in a Nobel Prize in 2011. The unexpected finding that the expansion of the universe is accelerating depended significantly on Hubble data, used by Nobel Laureates Adam Riess, Brian Schmidt and Saul Perlmutter.

Nobel Prizes aside, the HST has been highly productive in many scientific areas, with an annual publication rate that continues to increase (figure 3). Hubble has shone new light on objects from our own solar system to the edge of the universe; researchers have spent a lot of time understanding our place in it. Much of this success comes about because Hubble has a very well conceived archive: data remain accessible, together with the data products and expertise that help astronomers to use them. Indeed, publications based mainly on research using the archive are beginning to outstrip those from new observations. The archive is already a treasure trove of data from many interesting objects and continues to grow.

The last shuttle servicing mission to the HST (SM4) took place in 2009. Preparations for it coincided with a period when I was a member of the Space Telescope Users Committee (STUC). The main focus of the meetings I attended was planning for the mission and choreographing of the space walks in terms of science objectives. We had to decide on which changes were essential or non-essential, and the order in which to install upgrades and new instruments, always working within the framework of "what happens if there's not enough time?" We had to work out the scientific priorities, and set out a list of what had to be fixed ahead of which installation. A particular issue that has dogged Hubble (and other missions) has been the failure of the gyros used to point the spacecraft. Much work was carried out on understanding the failure mechanisms, in order to improve their lifetime – as a result, I now know more about failure rates on gyros than I ever wanted to know! However, the current complement of gyros on Hubble are more robust than those flown in the past, helping the longevity of the mission.

One thing I took away from this experience, apart from respect for the astronauts who carried out such complex operations in space, was a detailed appreciation of the amazing array of complementary working instruments that became available throughout such a long working life. The current capabilities of Hubble far exceed those expected at the start of the project and it became possible because of the repeated shuttle servicing missions.

Amazing instruments

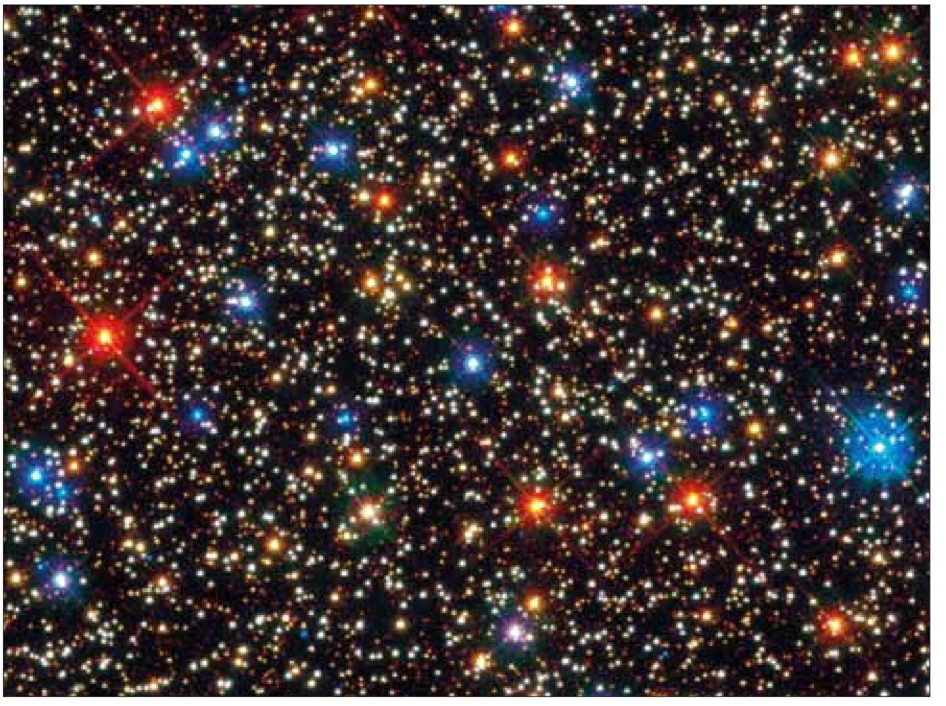
Today we have the Wide Field Camera 3 (WFC3), the Advanced Camera for Surveys (ACS), the Cosmic Origins Spectrograph (COS), the Space Telescope Imaging Spectrograph (STIS) and the Fine Guidance Sensors, together keeping Hubble operating as a valuable tool for research. Hubble has made possible a huge amount of science across the universe. Everyone has their favourites and it is always difficult to single out a particular topic but here I outline a few that stay with me.

I am not a solar system expert in my research life, but I have been impressed by Hubble's views of our local corner of the universe. I liked the intriguing asteroid that seems to behave like a comet with a tail and a coma (P/2013 P5, figure 4); I also enjoy the great views we've had of the giant planets, especially using Hubble's multiwavelength capability, such as the images showing Saturn's ultraviolet aurora.

Hubble has revealed a lot about star formation in our galaxy – the wide wavelength range from ultraviolet to infrared far surpasses anything available from the ground and produces an almost three-dimensional effect that has often made headlines worldwide. The science value of these images is evident from the image of the Omega Centauri cluster taken with the WFC3 after the 2009 shuttle mission upgrade (figure 5). The combination of the three wavebands – UV, optical, IR – picks out the diversity of objects in the cluster, showing red giants, white dwarfs and normal stars, and their interactions. This beautiful image contains a huge amount of scientific information, including measurements of the age of the cluster from the cooling of the white dwarfs within it, acting also as a test of other measures of the age of our own galaxy. Using COS, it is possible to examine the interstellar medium, using the light from quasars passing through this gas along the line of sight to probe the spectra of this gas in UV. This is the only way to measure and understand the temperature and density of the intracluster medium.

I work on white dwarfs, so I am a fan of dead and dying stars. Planetary nebulae such as NGC 6203 and the Ring Nebula (figure 6) are beautiful objects, but they need to be viewed in a wide-field image, which is very difficult to achieve using adaptive optics on ground-based telescopes. They usually look smooth and uniform in ground-based observations, but the higher-resolution Hubble data show that they are actually very complex – and anything but smooth, posing challenges for understanding their formation.

One of the key aims of the HST at its launch was to extend the distance scale in the universe and pin down the value of the Hubble constant (H_0), a project led by Wendy Freedman. This built on the ideas of Edwin Hubble himself, who used Cepheid variables to develop a cosmic distance scale. While Hubble's original distance–velocity plot was a triumph, bearing in mind the errors in the data, Freedman's project took the distance scale out to 100 Mpc and improved the precision of H_0 from a factor of 2 in uncertainty to 10% – a considerable achievement. The light curves of Type Ia supernovae were instrumental in pushing out the distance scale even further and establishing the acceleration of the expansion of the universe, led by Adam Reiss among others. Hubble really improved the precision with which we can measure the universe; the supernova distance scale has calibrated the value of H_0 to within 4%. New deep-field data from Hubble and the other great observatories will push the scale out further by finding supernovae at greater distances using lensed supernovae in the Frontier Fields.



5 One of the first images taken by the Wide Field Camera 3 (WFC3), this shows a small region inside the massive globular cluster Omega Centauri, home to nearly 10 million stars. The UV/visible light photograph reveals a variety of stars in key stages of their life cycles and, although the stars are close together, WFC3's sharpness can resolve each of them as individual stars. (NASA, ESA and the Hubble SM4 ERO Team)

Other worlds

When the HST was launched in 1990, nobody knew exoplanets existed. They were not included in any Hubble projects or proposals for more than a decade. However, once these objects were discovered and new instruments came on stream improving the capabilities of the telescope, Hubble has been able to study them. For example, studies of Fomalhaut, combining coronagraphic and direct images of the system to reveal the dust disc, produced a direct image of an exoplanet within the disc. Repeated observations allow its orbit to be followed. A key method of discovering planets is the detection of their transits as they pass in front of their host stars, one that has been applied extensively by NASA's Kepler observatory. Once stars with planets have been identified, it is possible to use Hubble to observe stars with planets in and out of transit and obtain the spectrum of the planet itself. The technique can reveal the presence of gases such as methane, and establish the existence of planetary winds and other features.

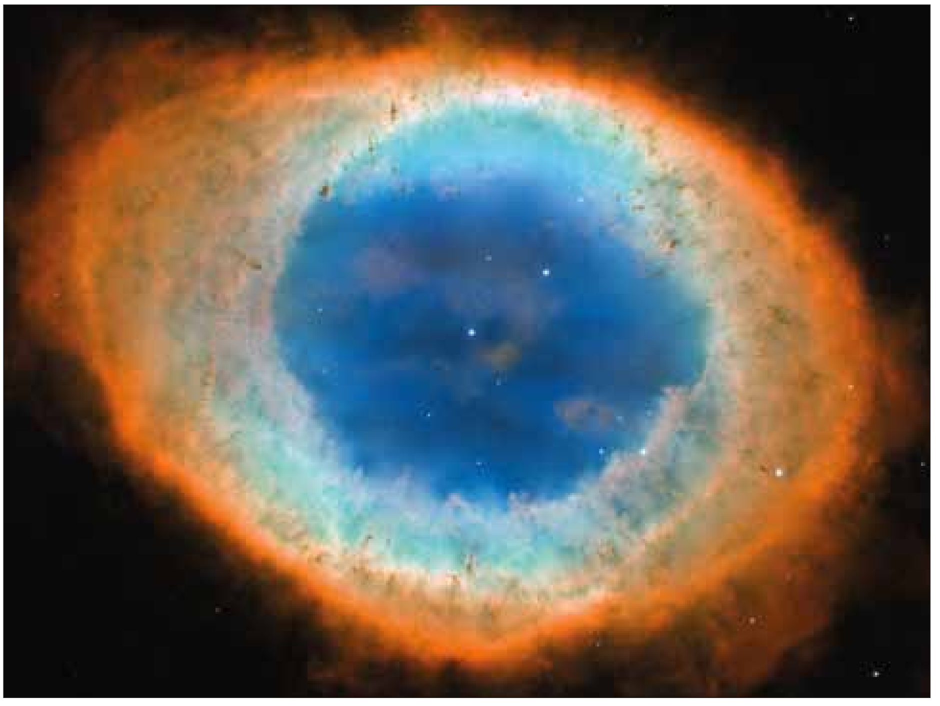
Hubble has also allowed observation of something rather unexpected in the study of white dwarfs, through its UV capability. These dead stars are not simply sitting there cooling down – they are also swallowing exoplanet debris. Many white dwarfs have atmospheres of pure hydrogen, as heavier elements eventually sink as a result of their high gravitational field. However, many objects contain surprising levels of heavy elements – pollution, if you like. Hubble can measure the abundances of this material through UV observations made by COS and STIS. Abundance ratios indicate that the material must have come from outside the star – a result of bombardment – and that it is rocky debris left over from planetary systems. It is possible to measure the composition of these rocky leftovers, leading to the make-up of the planets that once existed around stars now long dead.

Cultural impact

It would be easy to think, on the basis of newspaper coverage, that Hubble is the world's only telescope, such is its iconic status. If you stopped someone in the street and asked if they had heard of, say, XMM-Newton, you would get a blank look; if you said Hubble, they might well stop and chat. Hubble images have featured in the national press and made the front pages many times; they have shaped the public vision of the universe and, in turn, made the telescope itself very highly regarded, even loved.

That public recognition and affection showed itself after the loss of the space shuttle Columbia in 2003. The fifth mission to the HST (SM4) was initially cancelled, but a public outcry forced its reinstatement. That mission installed WFC3 and COS, repaired STIS and ACS, and replaced one of the FGS units and six gyroscopes, allowing the telescope to continue as the valuable scientific and cultural asset it is today.

Hubble has featured in many scientific publications and in unnumbered websites and blogs. It has also inspired more formal cultural events, such as the exhibition mounted in Venice for the 2011 Hubble scientific meeting that drew an immense footfall for a science exhibition – I was astounded that so many people came through that gallery in a back street



6 This visible-light image (from WFC3 in 2011) of the Ring Nebula revealed that its shape is more complicated than astronomers thought, with dark, irregular knots of dense gas embedded along the inner rim of the ring. The white dot in the centre of this planetary nebula is the star's hot core, a white dwarf. (NASA, ESA and the Hubble Heritage [STScI/AURA]–ESA/Hubble Collaboration)

in Venice, especially future generations. NASA has a vast and very active public relations team and ESA does a lot of work, through its coordination facility in Garching until its closure and now through ESO. Much of the outreach takes place online. The Hubble Heritage Site (http://heritage.stsci.edu) has spectacular images and excellent documentation, including online brochures and booklets. A European innovation has been the *Hubblecast with Dr J* (http://bit.ly/1AZyatJ), which has had an important impact on science education – it has helped young people in particular to become engaged in science in ways that the more traditional science lecture cannot do.

"If we want a new space telescope – and I think we do – we should start now"

Education has been one of the greatest legacies of this project. The impact on schools has been enormous. For example, the National Space Academy programme, led by the National Space Centre in Leicester, makes much use of the inspirational value of Hubble. There are also projects involving unconventional audiences, such as the *Touch the Universe* tactile astronomy guide, a braille guide to astronomy.

We know that we are engaging teachers and young people across the world through Hubble. In the UK our outreach is excellent but the evidence base supporting this is not as good as we would like. Perhaps the best data currently available are in the impact statements prepared by universities for the 2014 Research Excellence Framework, but perhaps we could and should make more of the undoubted scientific and educational impact of Hubble on people in the UK.

2020 vision

Hubble continues to work well, with a suite of great instruments and, so far, every sign that it will continue to be a valuable scientific tool for a good number of years. We hope these instruments will last – without the shuttles there is now no option to go up there and service them – but they are a scarce scientific resource of which we should make the best use. Hubble is expected to continue to operate through to 2020, although there are no guarantees. If all works out, we can hope for some overlap with the James Webb Space Telescope, scheduled for launch in 2018 – offering the potential for really interesting science.

While the launch of the JWST, including its UK instrument MIRI and the significant European contributions, is an exciting prospect that is going to change our view of the universe again, I have to admit to some personal sadness. JWST will have incredible capabilities, but its wavelength coverage is more restricted and will not access the UV and most of the visible spectrum, which means that it will not be so useful for some areas of astronomy that have come to depend on Hubble. Therefore, when Hubble eventually fails it will leave a hole in our coverage of the spectrum.

Hubble has been in space for 25 years and it was about 25 years in the making, before that. The JWST was developed on the same timescales. So if we want a new space telescope for the UV and visible part of the spectrum – and I think we do – we should be planning it now. Even so, it is a distant prospect – a 2030 launch would be an optimistic launch date.

Why do I think we need a new telescope? There's an argument that we could do a lot with what we have already got, which makes it hard to propose a new general space observatory – like Hubble – now, with such a long time horizon. Also, within the space agencies, there is a trend away from accepting the case for a general-purpose observatory. It is necessary to have a "killer app" – a major scientific goal that requires an instrument transcending current capabilities by a large margin. I think that a UV and optical space observatory has just such a unique capability: the direct study of Earth-like extrasolar planets and the search for biosignatures, an instrument to image such planets and obtain diagnostic spectra.

Detectable biosignatures are probably rare. Therefore, it is essential to maximize the number of potentially observable targets. Ultraviolet radiation has one tremendous advantage: the shorter the wavelength of the radiation, the better the resolution. With a large 12–16 m UV/optical space telescope it will be possible to resolve habitable zones around nearby stars out to a few tens of parsecs, giving access to an estimated 10–100 Earth-like planets. In the infrared, the accessible volume will be limited to only a few objects.

As well as exoplanet studies, there are a whole host of other things that a high-definition space telescope could do. But such a telescope will be expensive. It will need to be an international project, probably on a larger scale than JWST, and will take many years of planning and preparation. Therefore, we need to start the process now in order to deliver the project on a timescale that will be useful for the next generation of scientists. There will be many technical challenges, although the JWST will solve some of those involving mirror deployment. If we get moving, we could hope for launch in 15–20 years. And I can hope to come to a later Presidential Address and, perhaps, hear about the first extrasolar Earth. ●

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MORE INFORMATION
Hubble Heritage Site http://heritage.stsci.edu
Hubblecast with Dr J http://bit.ly/1AZyatJ
HubbleSite (NASA outreach) http://hubblesite.org
ESA's Hubble portal https://www.spacetelescope.org
NASA mission pages http://www.nasa.gov/mission_pages/hubble

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