The Hubble Space Telescope

A Peek Into The Cosmos

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1 Introduction

It is thought that apes evolved into man when we started building tools for hunting. Some of us disagree and propose that it was when they looked up at the night sky and wondered what those flashy lights were. That was the spark of curiosity, the need to want to explore further beyond one's usual basic needs, which differentiated us from other species. Around 2.5 million years later, here we are, progressing the pursuit of knowledge started by our ancestors.

One major step we took in "looking up" is launch the famed Hubble Space Telescope (HST) (named after Edwin Hubble, a pioneer of Modern Cosmology). A joint venture by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), it aims to provide a deeper insight into the cosmos by observing in the ultraviolet, visible, and near infrared regions of the electromagnetic spectrum with its 2.4 meter mirror.

After launch disasters, budget problems and technical delays, the HST finally achieved launch aboard the space shuttle Discovery in 1990 and reached Low Earth Orbit where it still sits. Its lower orbit removes atmospheric aberrations, resulting in higher resolution (only limited by diffraction of light) while also probing the UV and X-ray region of the spectrum, which is conveniently absorbed by the atmosphere (good for us!).

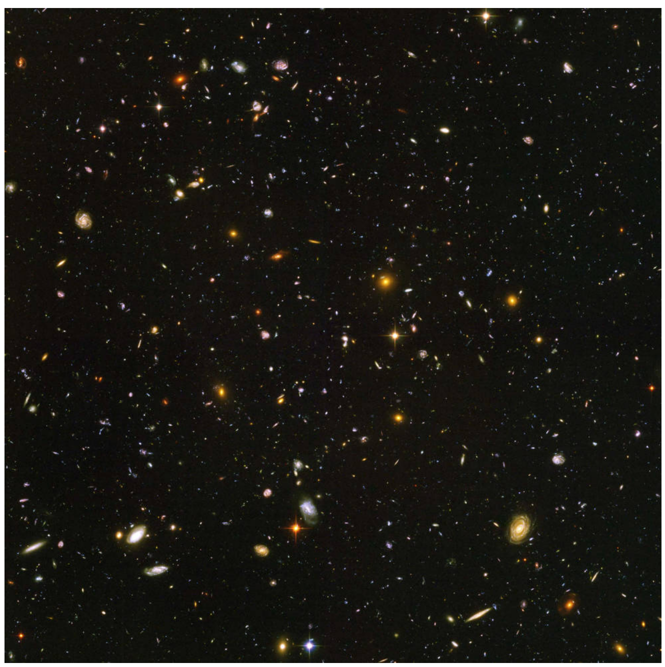

Figure 1: The Hubble deep field, the farthest anyone has ever peeked into the cosmos, each dot here represents a distant galaxy [1].

The instruments which it was launched with (some of which were defective) underwent changes, and were replaced by more sophisticated versions during the multiple servicing missions, all of which were carried out by astronauts (see section 6 for more details).

Though launched in 1990, the HST wasn't the first space telescope to be launched (and hopefully not the last, *looks with hope in direction of JWST*), but it has been by far the most vital research tool for humanity.

Armed with some of the most delicate instruments made by man, HST began taking pretty pictures, providing insights into the amount of dark matter in the universe, detecting gamma ray bursts, discovering black holes and much more. Arguably its most important contribution was providing insight into the expansion of the universe, allowing us to come up with cosmological evolution models.

Hubble's deployment 30 years ago marked one of the most significant advancements in Astronomy, so join us on this wild ride as we pay our respects to this massive project which has forever revolutionized our understanding of the universe.

2 The Birth of Hubble

2.1 Why we need eyes in space

There are many ground based observatories around the world that stretch the limits of what we can see in the night sky, but there are certain things that even the biggest of the telescopes placed on the highest of mountains cannot achieve.

Figure 2: The Pillars of Creation: A breathtaking image of the Eagle Nebula taken by Hubble [2].

In 1923, Hermann Oberth (considered to be the father of modern rocketry) proposed for the first time that telescopes could be placed in Earth's orbit using rockets based on missile technology. 23 years later, the astronomer Lyman Spitzer published an article which outlined two key advantages. The first, was the angular resolution (fancy word for how far apart, in terms of angles, two objects in the night sky must be, so that the telescope can tell them apart) would only be limited by diffraction and the second that we would be able to observe infrared and ultraviolet light, which are usually absorbed by the atmosphere. The turbulence in the earth's atmosphere, though responsible for the magical phenomenon of stars twinkling, is a headache for ground based telescopes as corrections have to be made in the data obtained (Not at all an easy task!).

Figure 3: The Hubble Space Telescope being deployed from the cargo bay of *Discovery* [3].

2.2 From vision to reality

Along with his 1946 article, Spitzer proposed a "realistic" plan for such a space telescope and lobbied for his idea for almost 30 years. But, the reality was that no one had yet managed to get simple man-made satellites into space, let alone complex optical instruments. It wasn't until 1957 when the launch of Sputnik 1 by the Soviets sparked the space race between the United States and Soviet Union, that the art of placing satellites into Earth's orbit was perfected. (Sort of.)

Finally in the 1970s, NASA and the European Space Agency took up the idea and proposed a 3 metre long space telescope which they cleverly decided to name 'The Large Space Telescope' (LST). Funds for the project started flowing in when the United States Congress sanctioned it and the work on the LST officially began (much to the satisfaction of Mr. Spitzer). At this point it was decided that the telescope be named in honour of Edwin Hubble, who had discovered the expansion of the Universe in 1920 and the telescope itself was downsized to 2.4 metres [4].

For such an expensive project it was essential that the telescope have a long service life and for this, it was crucial that it be serviced regularly. This is exactly why the HST was designed to be maintained by astronauts. With the development of the space shuttle technology, said service missions became plausible (along with space-walks!) and after completion of the ground mirrors in 1981, the telescope was set to be launched into space in 1986.

Following the delay caused by Space Shuttle Challenger's disaster, Hubble was finally launched on April 24, 1990 by Space Shuttle Discovery and it 'unfurled its wings' the very next day. A mission that had taken more time to develop than the Moon landings was finally a reality and we were all set to peer into the cosmos like never before.

3 What's inside?

3.1 It's all about the body

Before we dive into the wide array of instruments inside Hubble, we should know what it's made of - from the outside. Hubble is 13.2 m long and 4.2 m wide at the back end, where the instruments are housed. At 11 tonnes, it is approximately the same size and weight as that of a school bus. It is powered by two solar arrays which store their energy in six large batteries. This way, Hubble can operate even when it is not under direct sunlight. Which is nice.

The main optics of Hubble involve a Cassegrain reflector, named after a 15th century French cleric who was among the first to suggest this basic optical design. Light from the main hyperbolic mirror is reflected to a secondary hyperbolic mirror, which in turn reflects light back towards the primary mirror, in a hole in the centre.

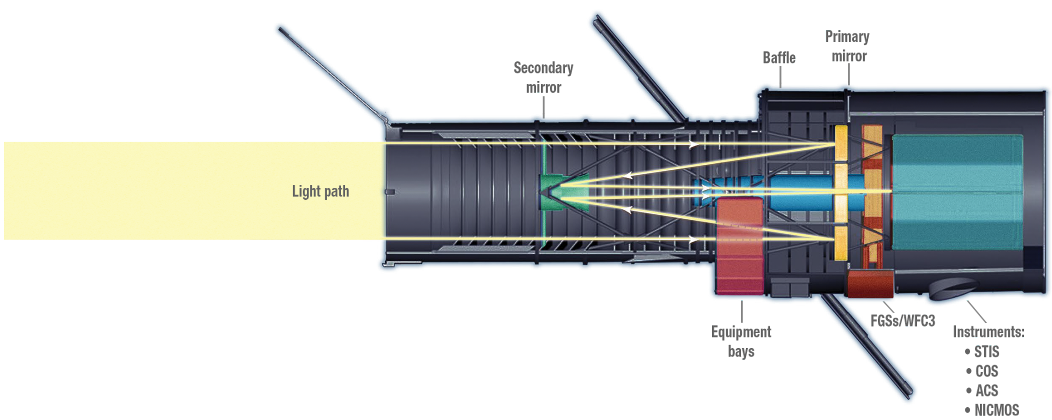

Figure 4: The structure of Hubble, displaying it's Cassegrain reflector [5].

The primary mirror is 2.4 m in diameter, which in the absence of any atmospheric interference lets it detect light 10 billion times fainter than the human eye can perceive and can distinguish astronomical objects with an angular diameter of a mere 0.05 arcseconds. This gives it about 10 times better resolution than even the larger ground based telescopes. However, it was not always so due to the faulty primary mirror (Jump to Section 6).

The optical array and sensors are built to observe light in the visible, ultraviolet and near-infrared regions of the electromagnetic spectrum. However, it was not built keeping infrared observations in mind as some heaters keep the mirrors and instruments relatively warm which create their own heat based infrared noise.

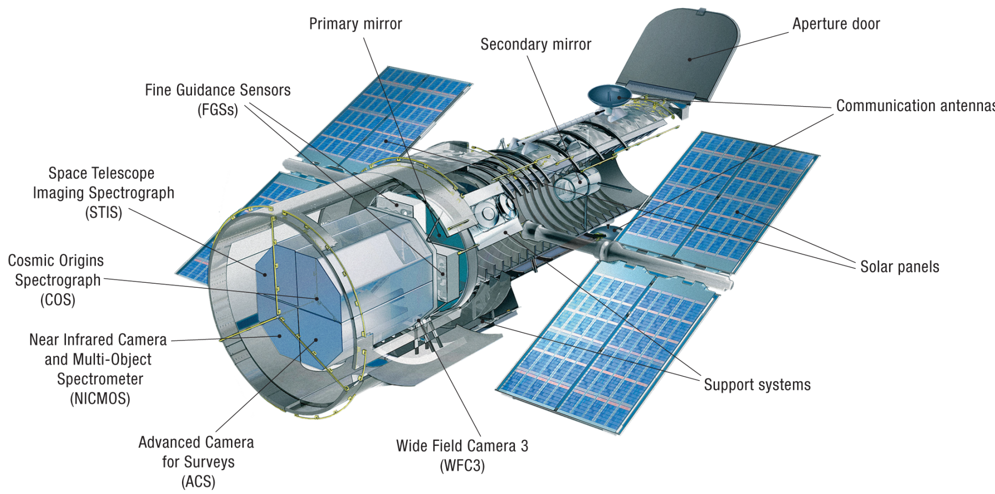

Figure 5: Labeled Diagram of the Instruments. Credit : NASA, ESA [6].

3.2 'bout them sensors

At launch, Hubble had five main instruments. After five upgrade missions though, all five of them have been replaced, ship of Theseus style. Thus follows the list of Hubble instruments, old and new:

- Wide Field Camera, the third (WFC 3) currently residing inside Hubble has replaced the first two Wide Field and Planetary Cameras (WF/PC and WF/PC2) and can capture light in all spectra - UV, visible and near IR. It is high resolution and has a wide field of view, making it the workhorse camera. It not only gives us the beautiful images we all know and love, but it has also imaged many important subjects ranging from nearby star formation to distant galaxies.

- The Cosmic Origins Spectrograph (COS), successor of Corrective Optics Space Telescope Axial Replacement (COSTAR), successor of the High Speed Photometer(HSP)(almost a dynasty!), breaks the spectrum of incoming UV light to study it in detail. It studies points of light like distant stars, quasars and helps study galaxy evolution and planet formation.

- The Advanced Camera for Surveys (ACS) takes surveys of the universe with its wide field of view, sharp and high sensitivity camera. It replaced the Faint Object Camera (FOC) and takes some of the most impressive visible light images. It helps map distribution of dark matter, distant galaxies and their clusters, and looks for massive exoplanets.

- The Space Telescope Imaging Spectrograph (STIS) is the successor of the Faint Object Spectrograph (FOS) and combines a camera with a spectrograph to determine the subject's temperature, composition and more. It studies the hot and the extreme, such as black holes, massive stars and even atmospheres of worlds around other stars.

- The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) is built focused on observing the near IR spectrum. It is the successor of the Goddard high Resolution Spectrograph (GHRS) and sees what is invisible to the visible and UV cameras - details of distant galaxies, planets and sites hidden behind stellar dust, such as sites of stellar formation. It sports three cameras with different fields of view. Unfortunately, it is no longer operational.

The telescope has some additional features which help the main instruments function properly. Some honourable mentions are as follows:

- Aperture Door: Hubble's aperture door can close if needed to protect the instruments from being overexposed by sunlight.

- Communication Antennas: Hubble stores its data in one of its solid state recorders, which relay the data to one of its four High Gain Antennas (HGAs) (last abbreviation of the section, I promise) as radio signals. These signals go through one of NASA's communications satellites and reach the ground.

- Solar Panels: Hubble currently has a set of rigid solar panels based on Gallium Arsenide (GaAs - It's a chemical formula. Can't help it!). Despite being smaller, these generate more power than the previous sets.

- Support Systems: Hubble has many more supporting instruments and sensors such as gyroscopes, reaction wheels and other electronic gizmos which help it stay focused on an object, record and even process some data in the telescope itself.

However, none of these sophisticated instruments are of much use, if they do not relay their data back to us.

4 Hello, Earth?

The operations team at NASA's Goddard Space Flight Centre (GSFC) constantly contacts and monitors Hubble for its good health, safety and performance. This includes checking its subsystems, software development, sustaining engineering of the hardware and data management. A separate contractor team at the Space Telescope Science Institute (STScI) in Baltimore, Maryland, manages scientific operations such as allotting telescope time, scheduling observations and collecting, processing and archiving scientific data.

Together, the GSFC and STScI maintain communication with Hubble 24/7, though most of this is automated monitoring, scheduling and data collection. However, this was not always the case as before May 2011, a team of console operators staffed the missions operation room at all times. As a result of this automation the subsystem engineers now mostly focus on special operations and various tests. Having mentioned the communication with the satellite, how does it really work? The answer is a well set up Tracking and Data Relay Satellite System (TDRSS). If you think it sounds complex or boring, don't worry! This beautiful schematic diagram gives a gist.

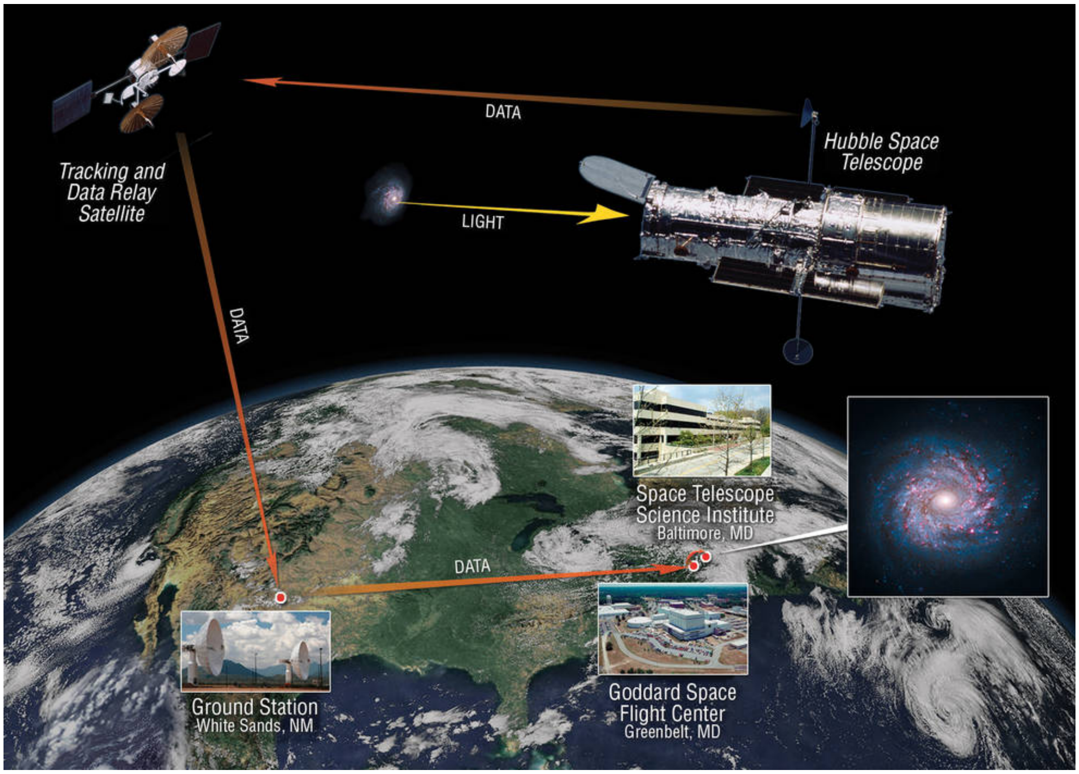

Figure 6: Tracking and Data Relay Satellite System (TDRSS) relaying data for communication. Credits: NASA, ESA [7].

As seen in the diagram, the Space Telescope Operations Control Centre (STOCC) at GSFC relays its data to NASA's White Sands Test Facility (WSTF? Yep, NASA likes to abbreviate everything) where large antennas transmit radio waves to the TDRSS, which forwards them to Hubble. The reverse path is used for receiving scientific data from Hubble's solid state recorders. This scientific data, after being quality checked, is forwarded to the STScI via high speed network links to be processed, distributed and archived.

5 A deluge of discoveries

It is time for us to delve into the details of some of the major discoveries made by the HST and justify why we were hyping this telescope so much, crediting it with opening major doorways to our understanding of the universe.

After being successfully deployed on April 25, 1990, Hubble captured its "first light" image of an 8.2 magnitude (a system of measurement of brightness of a star that astronomers use) star in the Carina constellation, relatively uninteresting, but it showed the stark difference between the HST and ground based images, the former being 50% sharper. After a few fixer-uppers, Hubble was ready to provide us with more beautiful and puzzling observations.

5.1 Shining Light on Dark Matter and Dark Energy

Hubble's uniquely sharp vision allows astronomers to "see" the influence of gravity on galaxies and galaxy clusters. While analyzing Hubble's data, astronomers found the evidence that a stronger gravitational attraction seemed to be present, than the one just provided by visible matter, leading to the realization that the dark forces (dark energy and matter) dominate in our universe.

Galaxy rotation curves, a plot made to analyze the relation between velocities at different radial distances from the centre, show that the velocity becomes fairly constant after a while, instead of reducing as the inverse square of the distance as theories predict, giving strong evidence for a "dark" form of matter, which provided the needed gravitational attraction for the observed plot.

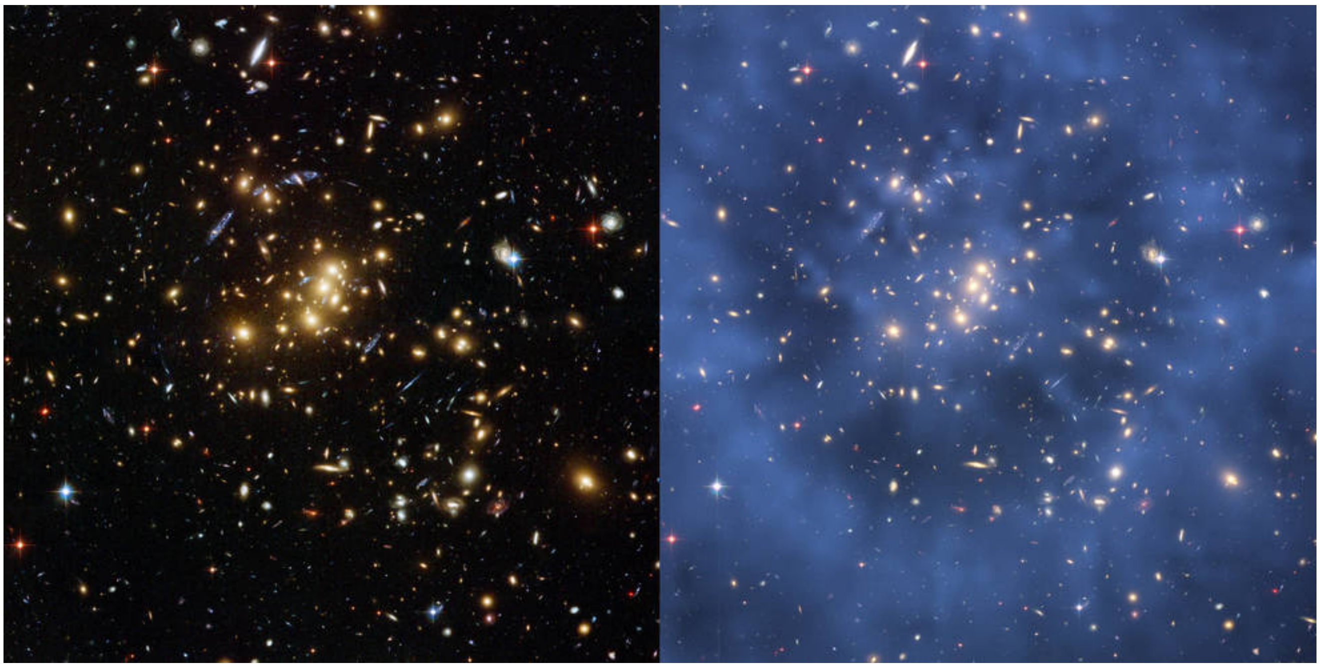

Figure 7: The image on the left shows an image captured by HST. The blue arcs are gravitationally lensed galaxies lying behind the cluster. The image on the right shows the distribution of dark matter hence expected from this observational data [8].

One of the most important evidences come from the analysis of the most gigantic structures in the observable universe - galaxy clusters. These are clusters of around 100-1000 galaxies, which on closer observation, as shown above, contain weird blue arcs. This is due to the presence of large amounts of matter, which due to their collective gravitational attraction, bend light emitted by galaxies behind the cluster, as predicted by the Einstein's General Theory of Relativity. This phenomenon is called Gravitational lensing. Further analysis revealed that the amount of visible matter present was not enough to account for the large amounts of lensing observed, giving a boost to the observational evidence for the existence of dark matter and enabling us to calculate its density.

In the next subsection we will get to know that it was also discovered that the universe is expanding, accelerating in fact, which brought up the discussion of a new form of energy, called Dark Energy, which causes expansion and accounts for around 74% of combined mass energy in the universe.

5.2 The Age-Old question

In one of the most famous classic papers in the annals of science, Edwin Hubble's 1929 article on the observed relation between distance and recession velocity of galaxies (the velocity at which they are moving away from us)—the Hubble Law—unveiled the expanding universe and forever changed our understanding of the cosmos. Hubble showed that galaxies are receding away from us with a velocity that is proportional to their distance from us: more distant galaxies recede faster than nearby galaxies. The proportionality constant is rightly known as Hubble's Constant (H_0), and accurately measuring it could allow us to make a good estimate of the age of the universe, the amount of dark matter in the universe, serve as a test to many theoretical cosmological models, and much more [9].

As if living up to the greatness of the man after whom it was named, the HST further confirmed the fact that galaxies are receding away from us and that the universe is indeed expanding (by studying distant supernovae). The first step came in 1993, when astronomers used the HST to determine distance to the M81 galaxy, providing a more accurate value of H_0.

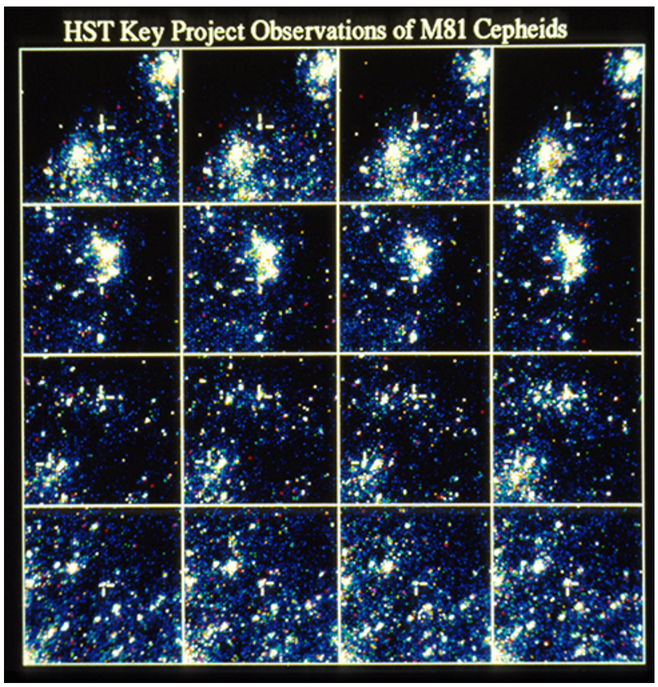

Figure 8: Observations of M81 Cepheid's [10].

They did this by measuring the apparent magnitudes (brightness as visible from earth) of Cepheid variables, which are basically pulsating stars that change their brightness within a fixed period, and astronomers can accurately predict their absolute magnitude (the actual brightness of the star). After this, it was just a matter of simple arithmetic to find out the distance of the galaxy from us. Velocity was determined by measuring the red-shift of the light coming towards us (if the source of light is moving away from us, the light emitted by it stretches and is said to be red-shifted, increasing its wavelength by a phenomenon called the Doppler Effect). These 2 measurements helped in accurately determining H_0 (with around 95% confidence, but hey, that's so much more accurate than the other predictions that we have made so far) and with it, the age of the Universe, was pegged at around 13.75 billion years.

5.3 Once you go black, you never go back

No discussion about space can ever be complete without a short tour of black holes, arguably the most enigmatic structures in the universe. First theoretically predicted in 1915 by Einstein in his General Theory of Relativity, to capturing the first image of a black hole nearly a 100 years later, the journey of our understanding of them has progressed a lot, and of course HST has had a big role to play.

It was first hypothesized in the 1960s that black holes could be found at the centre of only some galaxies, but HST data helped us conclude that they probably exist at the centre of almost all galaxies. These are super-massive black holes, which feed off luminous stars and gas surrounding them.

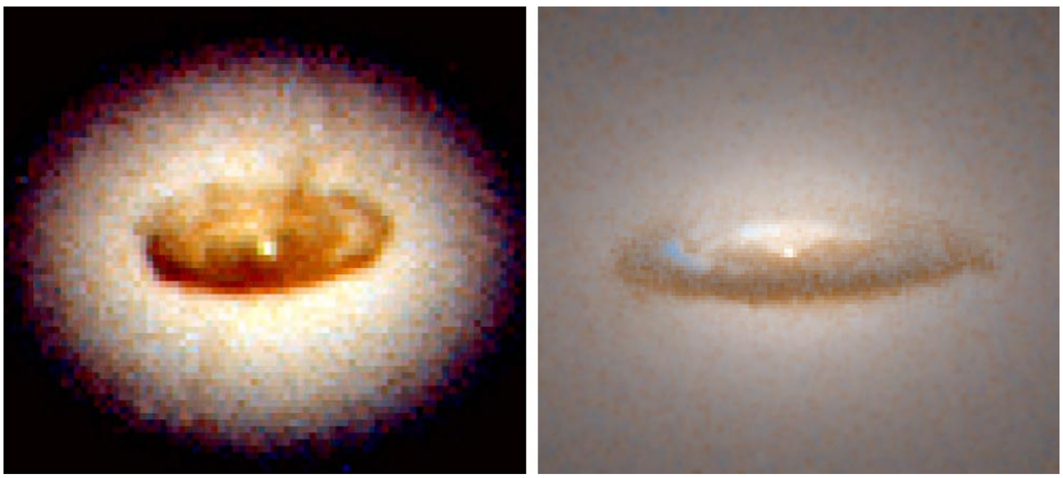

Figure 9: Accretion disks at centres of galaxy NGC 4261 and NGC 7052 [11].

Images captured by the HST also showed a major correspondence between the size of the central black hole and the galaxy itself, strongly indicating that they evolved together. In addition to this, HST also provided the first ever view of accretion disks (a fancy word for the disk-like flow of the matter surrounding a black hole), as well as jets of highly relativistic subatomic particles shooting out of these black holes. This helped us understand the physics of plasma near black holes, and how radio jets are actually produced.

5.4 A Star is Born, and dies

What better way for astronomers to understand how stars are born and the violent processes that take place in young stars, than just taking a peek into regions which are actively forming new stars? So instead of breaking heads to theoretically figure out a model, astronomers once again turned to the HST's infrared detectors for data on turbulent clouds of dust, where gravitational attraction clumps these gases to form stars (these diffused clouds of gas are known as nebulae). Observations show that star birth is a violent process, producing intense ultraviolet radiation and shock fronts. These observations made in 2010, by capturing a small portion of one of the most active star forming regions, the Carina Nebula, showed interstellar dust being eaten up by young stars in the region. The HST also captured the process of star birth in the Eagle Nebula (See figure 2).

Figure 10: A 3-light year tall pillar of the Carina Nebula, an active star formation region [12].

Hubble has also captured images of energetic jets of glowing gas from young stars in unprecedented detail. These jets are a byproduct of gas swirling into newly forming stars, some of which get channeled by magnetic fields and shot from the poles of the spinning stars at supersonic speeds in opposing directions [12]. Multiple observations of different regions in various stages of star formations are invaluable in understanding the processes leading to formation of stars and their evolution, early (in astronomical terms!) in their life stages. Analysis of the Orion Nebula images also showed protoplanetary disks of gases and dust around young stars, leading to further discussion about Alien Worlds being common around such areas. (dID sOMeOne sAY ALIENS?)

In January 2002, an unexplained flash of light from a red super giant star left what looked like an expanding bubble of debris. In fact, the light was simply illuminating clouds that were already in place around the star. The sudden burst was supposed to be triggered by the star swallowing a companion star or planet which revealed the dust clouds surrounding the star.

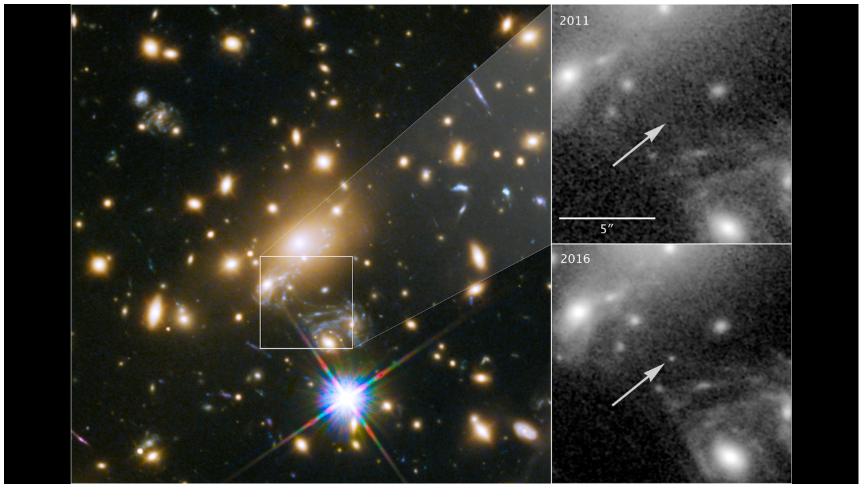

Figure 11: Icarus- The farthest individual star we have ever seen, when its intensity increased by 2000 times due to gravitational lensing [13].

Remember gravitational lensing (in subsection 5.1)? This brilliant phenomenon came handy to astronomers once again in April 2018, when a galaxy cluster - MACS J1149+2223 located around 5 billion light years away from earth, lensed the light from a distant galaxy, and allowed us to see the farthest star ever. This star, accurately dubbed 'Icarus' (a blue super giant star), is around 9 billion light years away from us, and is 100 times farther than any other individual star we have yet seen, giving us more incentive to keep looking up, lest any such coincidences happen again!

The first supernova explosion was captured by the HST in 2015 (once again gravitationally lensed by another galaxy due to which 4 images of the same supernova were captured in an arrangement known as Einstein's Cross-a known consequence of lensing) and also provided information on the amount of dark matter in the intervening galaxy!! Hubble has revealed in unprecedented detail the appearance of Sun-like stars that have entered the death throes of their lives. These beautiful images (do visit the NASA website for more beautiful images) yield insights into the complex dynamics that accompany a star's release of its outer gaseous layers before it collapses. Analysis of the Crab Nebula, arguably one of the most famous nebulae out there, revealed many details about the rapidly spinning pulsar at the core of this nebula. Figure 12 shows some of the many beautiful images captured by Hubble, laying bare the death throes of gigantic stars.

5.5 From humble asteroids, to galactic mergers, and everything in between

Not only has Hubble helped us explore farther than we have ever gone into the cosmos, but has also opened up our own backyard (the Solar System), with its own range of exotic objects.

Observations by the HST of asteroids in the Asteroid Belt between the orbits of Mars and Jupiter show the end products of powerful collisions between them, which are slowly eroding the belt. Observations also show structures of some unique asteroids with comet-like tails of dust radiating from them resembling rotating lawn sprinklers, probably formed from dust ejection events.

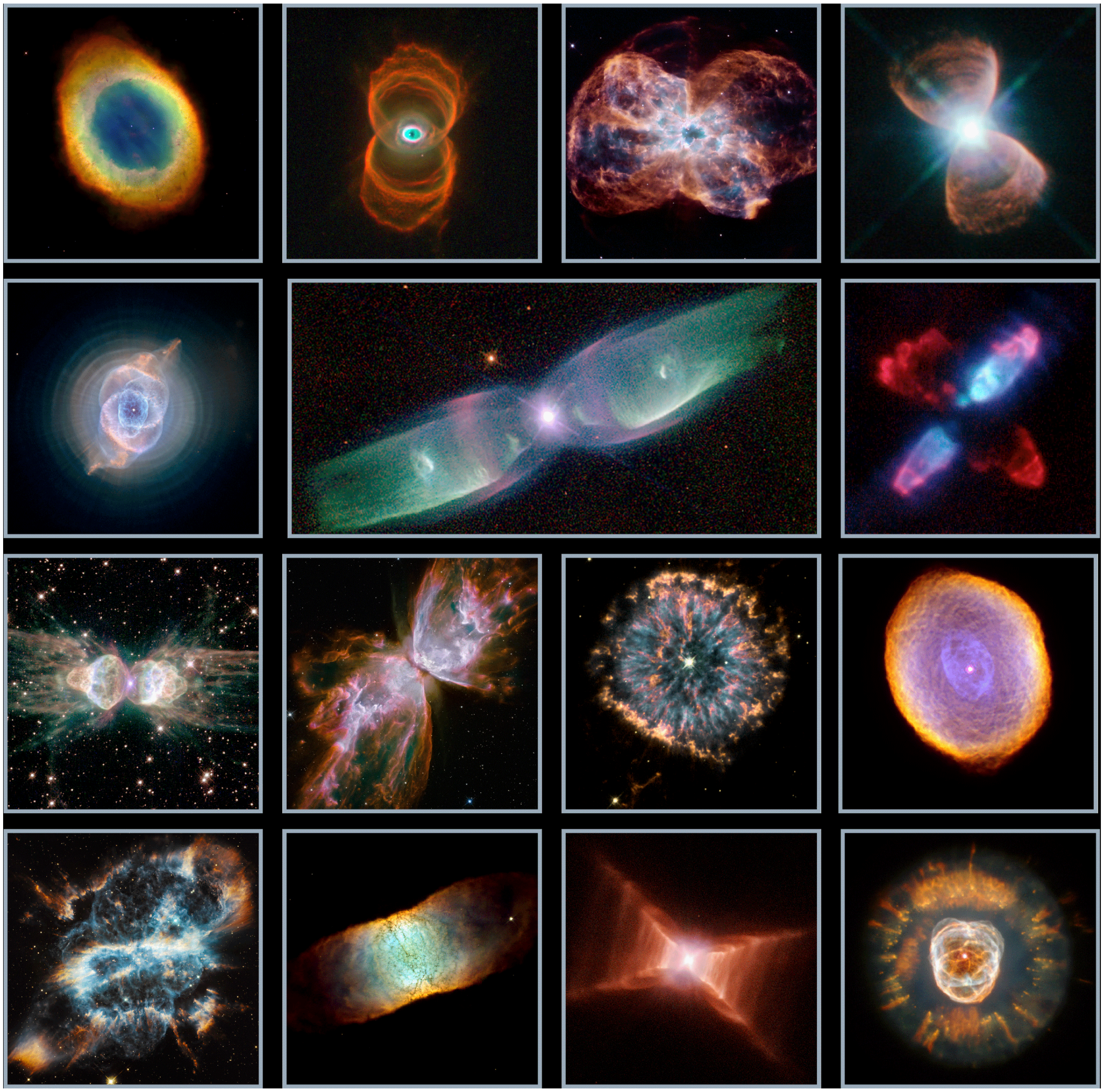

Figure 12: The complex variety of Planetary Nebulae in our universe [14].

While probing the dwarf planet Pluto on the outskirts of our solar system, Hubble spied four previously unknown moons orbiting the icy world. The tiny moons- Nix and Hydra were the first to be spotted, followed by the even tinier Kerberos and Styx [16]. It also helped the New Horizons spacecraft rendezvous with the planet and reveal more details about its surface. Peeking further beyond into the Kuiper Belt (the region of the Solar System that exists beyond the eight major planets, extending from the orbit of Neptune-at 30 AU-to approximately 50 AU from the Sun), it uncovered more objects and dwarf planets, helping astronomers understand the evolution of the Solar System, and was also partly the reason for demoting Pluto to a dwarf planet (Sorry Pluto! There are just too many of you out there :( ).

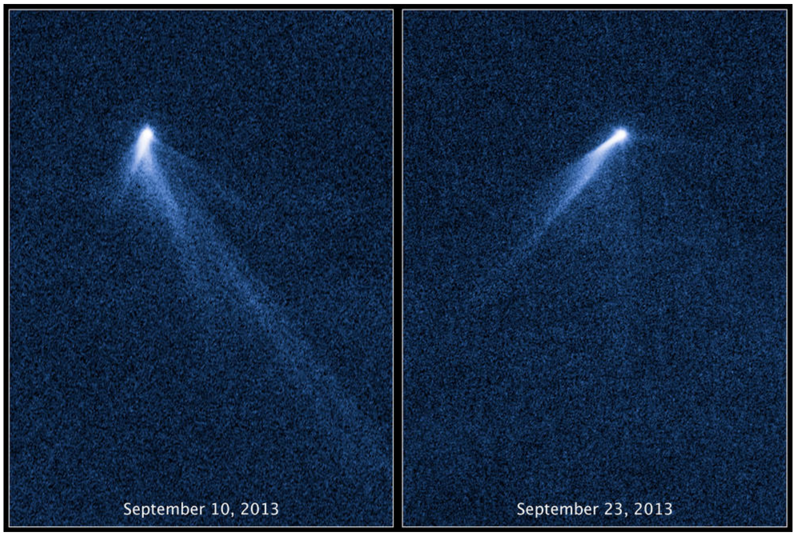

Figure 13: Images of asteroid P/2013 P5 revealed it to be like none other, with various dust trails radiating in multiple directions and changing in appearance with time. [15].

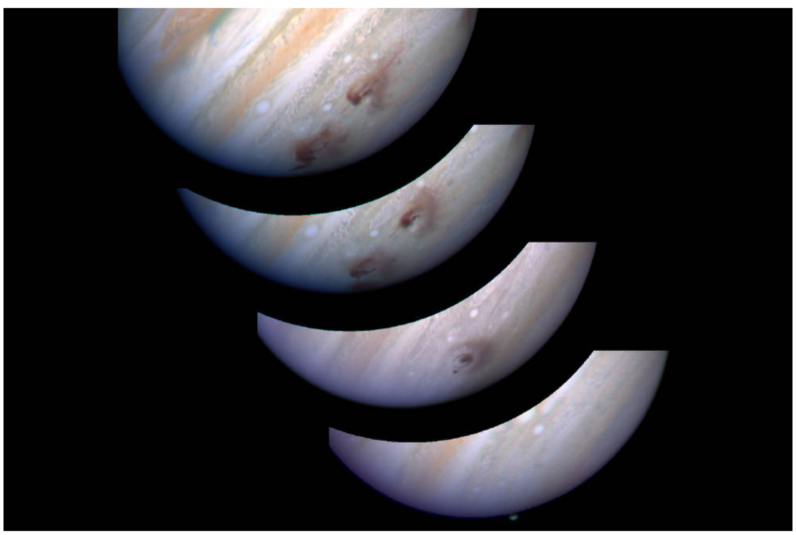

Figure 14: Shown here, beginning at the lower right and ending in the upper left, is a series of four images documenting the spectacular blackened impact sites as they rotated into view from behind the planet. [17].

Hubble has witnessed impacts on Jupiter that were produced by minor bodies in the solar system. The latest collision observed by Hubble occurred in 2009, when a suspected asteroid plunged into Jupiter's atmosphere and left a temporary dark feature the size of the Pacific Ocean. In 1994, Hubble watched 21 fragments of Comet Shoemaker-Levy 9 bombard the giant planet sequentially and was the first time astronomers witnessed such an event. Each impact left a temporary black, sooty scar within Jupiter's clouds, which also shed light on Jupiter's atmosphere [17]. It also helped in analysing the reducing diameter of the Red Spot on Jupiter, taking images of auroras (the lights that appear in the atmosphere of a planet when the charged particles from the sun interact with particles in the atmosphere) on Saturn and Jupiter, and studying the underground saltwater oceans on Ganymede.

Finally moving out of our Solar System, and into similar systems and alien worlds, astronomers used Hubble to make the first measurements of the atmospheric composition of extra-solar planets. Hubble observations have identified atmospheres that contain sodium, oxygen, carbon, hydrogen, carbon dioxide, methane and water vapor. Most of the planetary bodies studied to date are too hot for life as we know it (aLIeNS?!). This is done by the spectral analysis of light which is scattered from the planet's atmosphere (a procedure which splits the light into its constituent components, which helps us understand the composition of the atmospheres of planets). It also discovered many different types of star-planet systems (hot super-Earths, one planet two star systems and so on) which helped in advancing research on alien worlds.

Figure 15: Long streamers of stars and gas appear as tails in this Hubble image of the gravitationally interacting galaxies NGC 4676, nicknamed "The Mice." [18].

Last, but not the least, we move into one of the most violent and catastrophic events of the universe: the collision of galaxies. For all their violence, galactic collisions take place at glacial rates by human standards — timescales on the order of several hundred million years. Hubble's images, therefore, capture snapshots of galaxies at various stages of interaction. The merging of galaxies produces turbulence and tides that can induce new vigorous bursts of star formation within their interstellar gas clouds. Hubble (the man, not the telescope) had proposed the categorization of galaxy shapes into spiral, elliptical and irregular, however, the farther we look (looking back in time!) we see more and more irregular galaxy shapes, since at that stage of the universe, the galaxies were closer together, and hence more likely to interact. Fun fact- The Andromeda and the Milky Way galaxy are going to collide in around 4 billion years from now, which will lead to spectacular skies, assuming humans survive that long. Unlikely (*looks at climate change*).

After this whole section on the discoveries made by HST (whew, you made it!), there seems to be no doubt that HST has helped further our understanding of the cosmos, but nothing comes without a price, and as the next section details, Hubble is pretty high maintenance.

6 Hubble trouble

This "deluge" of discoveries and stunning images didn't come easy. Almost the entire duration of Hubble's mission till now has been beset with difficulties, with new hurdles appearing at every corner. Here, we look at some of these challenges and how they were overcome.

Within a week of Hubble's deployment, a major problem soon became apparent. Though the first few photographs taken by it appeared far sharper than those taken by terrestrial telescopes, they were of drastically lower resolution than expected. To top it off, images of point sources of light were "diffused" instead of appearing a few pixels in diameter (as they should be). This meant Hubble was as good as blind when it came to making observations of very faint objects or creating high contrast images (a must for cosmological studies).

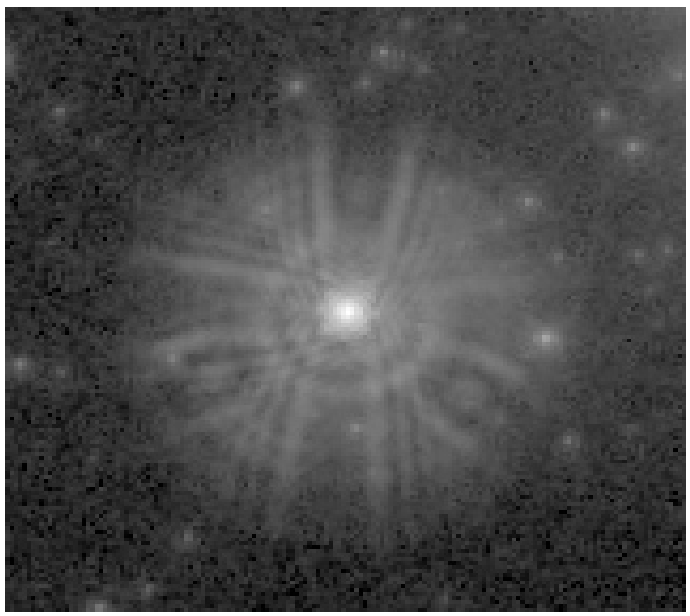

Figure 16: This image taken by the WF/PC shows the light from a star spread out over several pixels instead of a few [19].

6.1 Errors and inverse errors

The root of the problem was traced back to the lens of the mirror testing equipment which was off by 1.3mm. The outcome was a mirror with a spherical aberration (loss of definition in an image because of a flawed surface) of one-fiftieth the thickness of a human hair(!) in the grinding process [20].

Now, some of these diffused images were still usable after running them through some advanced image processing and reconstruction to reverse the effect but, there is only so much a computer can do with what it's given. NASA and the company that created the mirrors were beginning to come under heavy fire for letting such a glaring mistake happen in such an expensive mission. A solution to this problem simply had to be found.

Replacing the mirror, either by launching another mirror into space or by bringing Hubble back to Earth for repairs, was out of the question as it was simply too expensive. The solution to this problem lay in re calibrating the other smaller mirrors and adding mirrors in such a way that they had the inverse of this error, very much the same way the eyesight of a near-sighted or far-sighted person is corrected with spectacles. The WF/PC2 (Wide Field Planetary Camera 2 from subsection 3.2) that was planned to replace the existing WF/PC in the first service mission had a surface that could be configured with the inverse error, but the other devices did not have any intermediate surfaces that could be configured this way. An external correction device was required.

The first service mission launched in 1993 saw the installation of instruments and corrective instruments over the span of 10 days (with five long spacewalks!). The Corrective Optics Space Telescope Axial Replacement (COSTAR) instrument, about the size of a telephone booth, placed into Hubble five pairs of corrective mirrors that countered the effects of the spherical aberration. This was the external correction device that brought Hubble's eyesight back on track. Apart from putting spectacles on Hubble, the first service mission also upgraded Hubble's computers and boosted it's orbit (took it higher up).

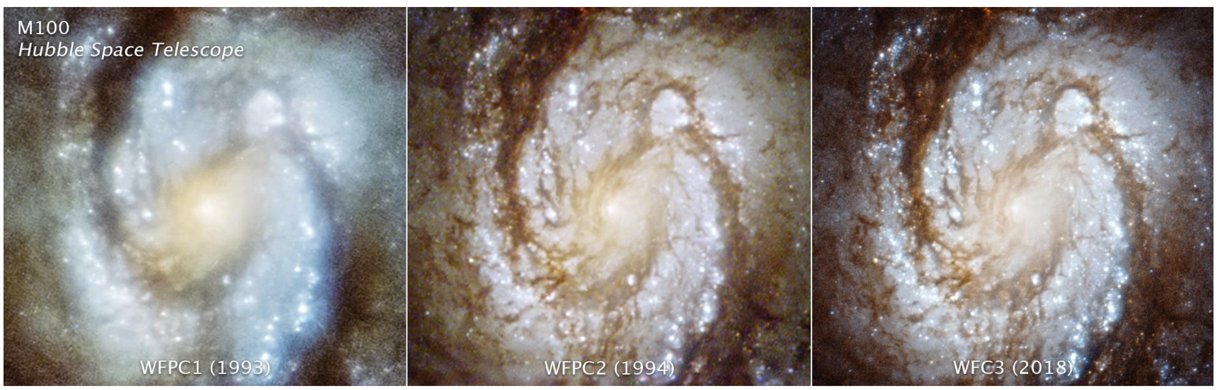

Figure 17: Three images of the M100 galaxy taken by three generations of cameras that were sequentially swapped out. WF/PC(left), WF/PC2(centre) and WF/PC3(right) [21].

6.2 In service of the Lord Hubble

The second service mission which flew in 1997, replaced the Goddard High Resolution Spectrograph (GHRS) and the Faint Object Spectrograph (FOS) with the Near Infrared Camera and Multi- Object Spectrometer (NICMOS) and the Space Telescope Imaging Spectrograph (STIS) respectively (Here's a link to Subsection 3.2). But, some problems in NICMOS's heat sink reduced its life to 2 years from an expected life of 4-5 years. By the time of the third servicing mission (called Service Mission 3A- 1999), four of Hubble's six gyroscopes had failed and the telescope had entered 'safe mode' (hibernation mode). So, this mission was split off from the main mission which was supposed to happen later on as there was an urgent need to awaken Hubble. Service Mission 3A ended up replacing all six of Hubble's gyroscopes, computer and Fine Guidance Sensor.

The fourth service mission (Service mission 3B) saw the replacement of the Faint Object Camera (FOC) with the Advanced Camera for Surveys (ACS) and for the first time since it's deployment, Hubble was completely powered down to change out its Power Control Unit. New solar panels were installed and minor repairs in its insulation were carried out. At this point, all of the original, major instruments were replaced and with the newer instruments already calibrated for the mirror flaw, there was no need for the COSTAR.

Figure 18: Astronauts installing corrective optics during Service Mission 1 [22].

The fifth service mission (aptly named Service Mission 4- 2009) involved the installation of the WF/PC3 and the Cosmic Origins Spectrograph (COS). It also featured the first-ever in-space repair of science instruments (the Advanced Camera for Surveys and the Space Telescope Imaging Spectrograph). The crew removed the now redundant COSTAR and swapped out its batteries and gyroscopes so that Hubble would continue to operate at peak condition for many more years [23].

For all the trouble Hubble gave us, it never once disappointed. The unique perspectives it shared with us more than compensate for the difficulties faced in achieving said perspectives. Read on to find out about what the future holds for Hubble!

7 Farewell?

7.1 Beginning of the “end”

30 years and five service missions later, Hubble is supposedly coming to the end of a commendable career. With the space shuttle program pushed into the history books, the 2009 service mission was its final. It was forecast that Hubble would continue to function at its peak till 2021 and in anticipation of this, the final service mission included the installation of a Soft Capture and Rendezvous System (SCRS) which would allow spacecrafts (likely robotic) to dock with it and safely de-orbit it. Meanwhile, a space telescope, brimming with cutting edge technology and in the works since 1996 was fast being developed to join Hubble and see it off.

7.2 A successor, but not really

The James Webb Space Telescope (JWST), an infrared space observatory (scheduled to launch in March 2021), is meant to complement and extend the discoveries of the HST. It will be the largest, most powerful and complex space telescope ever built and launched into space. With improved sensitivity and coverage in the longer wavelength region, it is expected to look farther into the cosmos like never before (getting repetitive, we know), nearing the beginning of time itself. With this capability, the JWST can observe the formation of the first galaxies and pierce through the dust clouds to observe the formation of stars and planetary systems [24].

Though the launch date of the JWST is set to be overlapped with supposedly the "last year of Hubble functioning", it is not exactly a successor as it does not have the same functionality as Hubble. The HST is well suited to observe in the ultraviolet and visible regions but it falls short in the far infrared region. This is where the JWST will really shine. The two telescopes, Hubble and JWST, were made for each other but unfortunately they might not get to spend much time together.

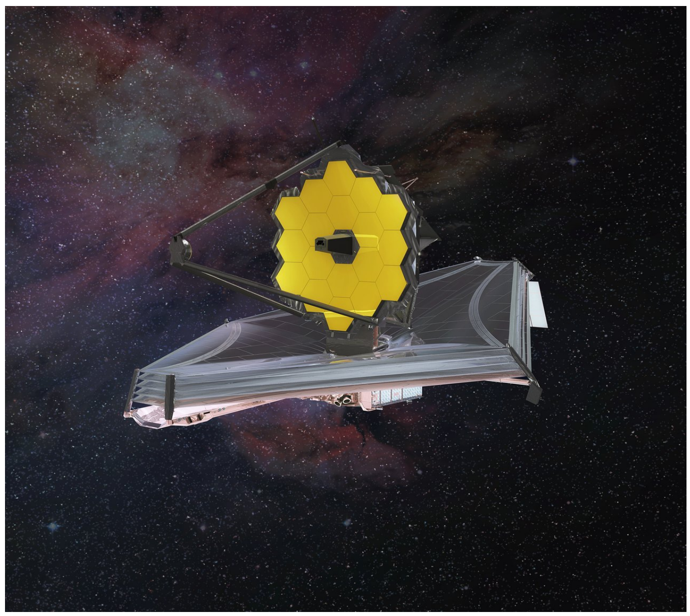

Figure 19: The James Webb Space Telescope [25].

7.3 More "successors"

The European Space Agency(ESA)'s Herschel Space observatory, launched in 2009, was a complementary telescope that was designed to gaze at even longer wavelengths than Hubble or JWST. With a larger-than-Hubble primary mirror it was a true beast that could observe in the far-infrared and sub millimeter ranges of the spectrum. But, it was a short lived beast at that as it was designed for a short mission duration and it ran out of helium, its primary coolant in 2013.

Another advanced concept telescope in the making is the Large Ultraviolet Optical Infrared Surveyor (LUVOIR), a gargantuan, 8-16.8 metre optical space telescope that can serve as a more direct replacement for Hubble. If realised, it will be capable of observing and photographing celestial objects in the ultraviolet, visible and infrared wavelengths (what more do we want?) with substantially better resolution compared to Hubble [26]. The LUVOIR mission is set in the 2025-2035 time frame but considering the punctuality of space missions, it is safe to assume a delay of 10-15 years.

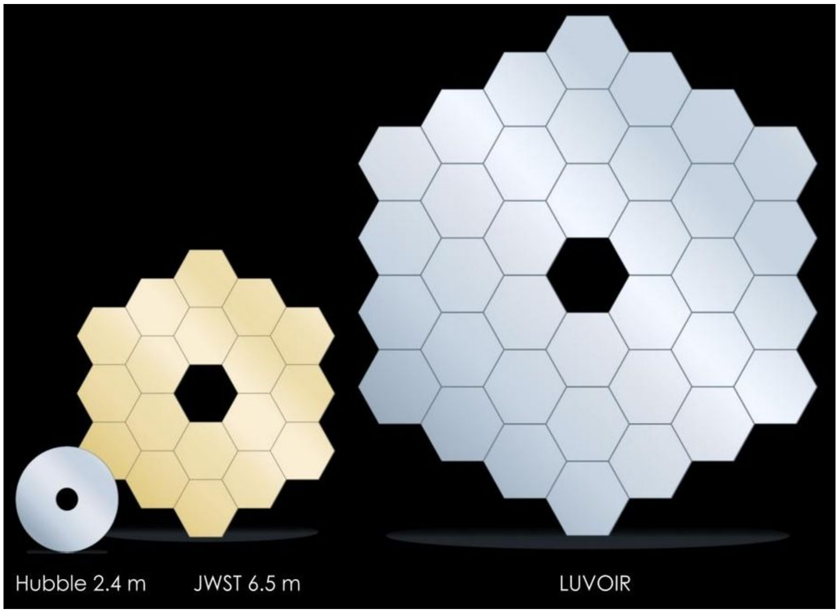

Figure 20: Size comparison of the primary mirrors of Hubble, JWST and LUVOIR [27].

7.4 A matter of life and death

As things stand now, Hubble is in low Earth orbit and as it faces atmospheric drag, it will lose altitude and uncontrollably crash into the Earth's surface sometime in the 2030s (a problem for us mortals). The optical instruments aboard Hubble, though not all of them, may as well last into 2030s. Even with reduced capabilities, there are things that Hubble can see that terrestrial observatories or even JWST for that matter cannot see. Which means that as long as the instruments aboard Hubble function, it is a priceless asset to the scientific community.

In 2017, there was a proposal to use the Sierra Nevada Corp.'s Dream Chaser Space System to service Hubble and boost it to a higher altitude, which much to the dismay of astronomers didn't play out [28]. As of now the plan stands to de-orbit it in a controlled manner, but 'when?' is the next big question. The doors are not yet closed as NASA remains open to proposals like the one mentioned above to keep Hubble on life support.

If they do prolong Hubble's life span, then Hubble and JWST can work in unison like never before, but if they go ahead and decommission it, the entire astronomical community will bid a fond farewell to the titan that opened the doorway to the cosmos. It is only a matter of time before the fate of the world's most beloved telescope is revealed to the entire world.

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