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The Physical Universe:
Clues And Evidence

Term Paper

The Hubble Space Telescope

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Contents Page

Part I – The Conception and Working of the Hubble Space Telescope

The Need For Space Telescopes

Ever since Galileo assembled his first telescope, astronomers have made use of the invention to gather and interpret information that the universe has to offer. Telescopes have evolved from their early days. For example, initially, lens telescopes were used to refract light to produce images. Contemporary telescopes use mirrors instead of lenses to reflect images into a focal point to produce sharp images. Mirrors produce sharper images than lenses, and thus are preferred over lenses in modern telescopes. In general, telescopes have grown larger and more sophisticated in recent times. However, no matter how large and how sophisticated, telescopes based on earth have their limitations.

The main problem that these telescopes had was related to the atmosphere. Light from celestial objects is partly absorbed by the earth's atmosphere. This problem can be ameliorated by building larger telescopes that can gather more light, but that would mean that the amount of background light gathered by the telescope, from artificial sources on earth, or moonlight being dispersed by particles in the atmosphere, or from the airglow in the upper layers of the atmosphere[i] would increase as well[1]. Another problem is that the atmosphere is turbulent, and tends to smear out images of celestial bodies. What should, in theory, appear as point like objects now appear as discs because of the smearing of light. A telescope's theoretical resolution is given roughly by the product of the wavelength of the incident radiation and the focal length, divided by the diameter of the primary mirror or lens[2]. In reality, however, most earth-based telescopes have resolutions that are about a hundred times worse than the theoretical resolution because of the distortion from the atmosphere.

To add on to this problem of distortion, the atmosphere only allows radiation of certain wavelengths to pass through. It shields us from X-ray and ultraviolet radiation, and is largely opaque to radiation that is much longer than that of visible light[3] (most importantly, infrared radiation[ii]). These areas of the spectrum provide important information that cannot be gathered by telescopes here on earth.

To try and counter these problems, several telescopes were constructed on mountaintops, away from populated areas, so as to not be affected by artificial light, and, since the atmosphere is very thin at higher altitudes, to attempt to reduce the amount of distortion by the atmosphere. However, it was obvious that the best way to remove the

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[1] Fischer and Duerbeck (1996), Hubble p. 24
[2] Ibid, p. 26
[3] Fischer and Duerbeck (1998), Hubble Revisited p. 17

problems created by the atmosphere was to make observations in outer space, where there was no atmosphere.

Conception Of Space Telescopes

In 1923, German pioneer of space flight, Hermann Oberth outlined an idea for an orbital space telescope, placed in geosynchronous orbit around the earth to make observations from outer space in his book *Die Rakete zu den Planetraumen* (*The Rocket into Planetary Space*)[4]. At that time, of course, his ideas were considered science fiction, as space travel was not yet established. That is, however, the first time that anyone had an idea of putting a telescope out in space.

In the 1950s and 60s, space exploration began to gain ground. Astronomers made use of this and subsequently some satellites in orbit were fitted with sensors to detect radiation in the ultraviolet, X-Ray and gamma regions. These detectors made some very interesting observations, mostly by accident. An experiment to detect the X-rays originating from the moon resulted in the discovery of X-ray stars. Ultraviolet detectors were able to map the ultraviolet spectra of the sun. Gamma detectors discovered unexplained bursts of gamma radiation of cosmic origin[5]. The very first astronomical observatories were launched into space in the early 1960s but were very small and had very limited capabilities. This was because space travel technology had not developed enough to carry heavy payloads and there were no powerful electronic detectors available to justify the launch of any major space-based observatory[6].

The Hubble Space Telescope had its beginnings in the mind of eminent American scientist Lyman Spitzer in 1946. His idea was to place a telescope in orbit solely for the sake of research. He wrote at that time that "the most important contribution of such a radically new and powerful instrument would not be to supplement our current ideas about the universe in which we live, but to uncover new, hitherto unimaginable problems"[7]. In that same year, however, a five-metre telescope on Palomar mountain was just completed and attention was diverted away from Spitzer's idea[8].

It was only more than a decade later, after the launch of spacecraft into space that Spitzer's ideas were taken seriously. In the 1960s, an idea emerged in NASA for the launch of a Large Space Telescope (LST). In 1966, Lyman Spitzer chaired the first meeting of a committee from the prestigious National Academy of Sciences looking into the possibility of such a telescope. The Ad Hoc Committee on the Large Space Telescope, as it was called published a report titled 'Scientific Uses of the Large Space Telescope' in 1969. This report gathered all the ideas and proposals for the LST into a few major proposals. The most important use of the LST, as outlined by this report was to

[4] Peterson and Brandt (1995), Hubble Vision p. 16
[5] Fischer and Duerbeck (1996), p. 20
[6] Fischer and Duerbeck (1998), p. 15
[7] quoted in Fischer and Duerbeck (1998), p. 23
[8] Fischer and Duerbeck (1998), p. 23

accurately measure astronomical distance, aid in the determination of Hubble's constant and hence, estimate the age of the universe[9] (see page 8).

Initially, there was a lot of scepticism on the viability of such a telescope. However, the success of two observing satellites, the OAO-2 in 1968 and OAO-3 (Copernicus) in 1972, launched under the Orbiting Astronomical Observatory Programme[iii] helped to convince scientists that a space telescope could work. A plan for a 3-m telescope was drawn up, and an effort was made to garner a wide base of support for the telescope[10].

In 1972, the idea of building the LST fell on fertile ground, and NASA decided to take the project up, and entrusted Robert O' Dell to be the project scientist for the LST. When the American Congress was approached for funding, however, they were reluctant to provide funding. After initially cutting off all funding to the programme, they later agreed to provide $300 million dollars to the project, on condition that NASA found a way to make the project cheaper, and sought the substantial participation of other nations. Subsequently, to cut costs, new plans were drawn up for a 2.4 metre telescope, and the European Space Agency (ESA) was recruited[11]. A memorandum of understanding was signed between NASA and ESA in 1977. ESA would provide 15% of the cost of the telescope, through providing for the Faint Object Camera and the solar panels that would provide energy. In addition, they would also provide some staff members for the yet-to-be-formed Space Telescope Science Institute. In return, ESA was promised about 15% of the observation time[12]. The foundations for the LST were laid and the project began as a collaboration between NASA and ESA.

Building And Launching The Telescope

After the project was approved in early 1977, NASA took up the task of co-ordinating the entire project. The NASA Marshall Space Flight Centre in Huntsville, Alabama was selected to be the lead management for the project. The NASA Goddard Space Flight Centre in Greenbelt, Maryland was chosen to be the 'operational nerve centre' for the telescope, and was given the task of developing the scientific instruments to be mounted in the telescope. A list of instruments that would be placed in the telescope was drawn up and are as follows:

- The Wide Field and Planetary Camera (WF/PC-1)
- The Faint Object Camera (FOC) to be developed by the ESA
- The Faint Object Spectograph (FOS)
- The High Resolution Spectograph (now called the Goddard High Resolution Spectograph or GHRS)
- The High Speed Photometer (HSP)

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[9] Peterson and Brandt pp. 19-21
[10] Ibid, p. 22
[11] Fischer and Duerbeck (1996) pp. 28-29
[12] Peterson and Brandt p23

The construction of the telescope and these instruments began in 1979[13]. The proposed layout is shown in Figure 1.

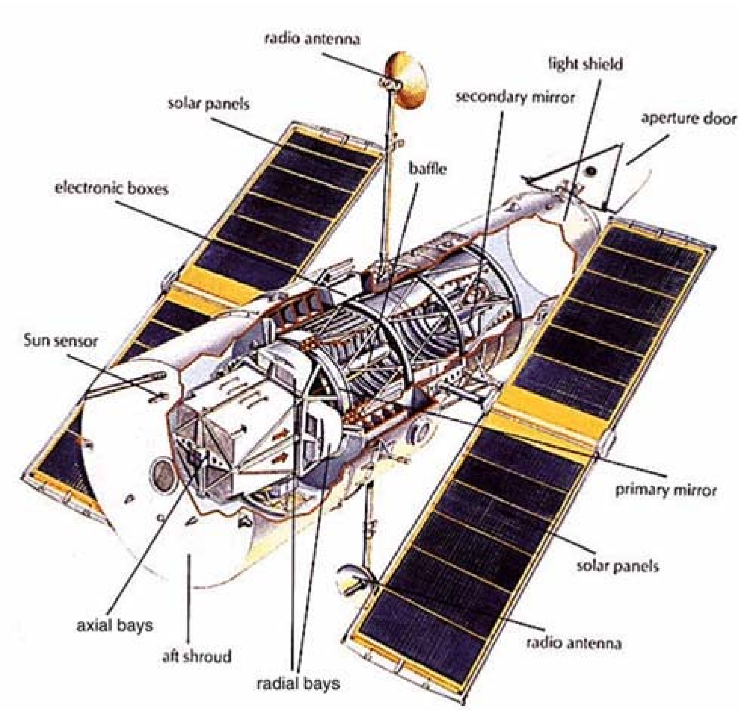

Figure 1 – The proposed schematic of the LST. Picture taken from The Hubble Project

The most important consideration in building a telescope is, of course, the set of mirrors that will be used to focus images. In the case of the LST, on top of being built to precision, the mirrors also had to be built to withstand the rigours of launch and orbit in space. A firm called Perkin-Elmer won the contract to build the primary mirror with a diameter of 2.4 metres[14]. The mirror was of the Ritchey-Chretien type, which provided a larger field of view, and less optical distortion. The setback was that the mirror was not spherical, but had the shape of a hyperboloid, which was difficult to achieve. The mirror was constructed of titanium silicate glass and had a focal length of 57.6 metres[15].

The LST went through a line of name changes, and eventually, in 1983, it was officially named the Edwin P. Hubble Space Telescope[16]. The expected launch of the telescope was delayed several times, due to unexpected complications. At the same time, the cost of the project had more than quadrupled. In 1986, when construction of the telescope was finally completed, it had cost a total of US$1.6 billion just to design and develop[17]. The Hubble Space Telescope weighed a total of 11,000kg, had a length of 13.2 metres and a maximum diameter of 4.2 metres[18].

The Hubble Space telescope was months away from launch when the space shuttle Challenger exploded, resulting in NASA suspending all space shuttle flights for two and a half years. This delayed the launch of the telescope yet again. In 1990, after

[13] Peterson and Brandt pp. 24-25
[14] Fischer and Duerbeck (1996) p. 44
[15] Ibid, p. 38
[16] Peterson and Brandt p. 23
[17] Ibid, p. 29
[18] The Hubble Project

going through yet another aborted launch on April 10th, the Hubble Space Telescope was finally launched as a payload of the space shuttle Discovery on the 24th of April[19].

The Hubble Space Telescope In Orbit

After launch, the space shuttle Discovery went into orbit between 613 and 615 kilometres above sea level. Five hours later, the Hubble Space Telescope began relaying information, although power was still being supplied by the shuttle. One day later, the umbilical cord attached between the shuttle and the telescope was disconnected and the solar arrays were unfurled. These solar arrays produced about 4.4 kiloWatts of energy and provided the power necessary to operate the telescope. Soon, the telescope was released from the shuttle and went into orbit[20].

"First Light" for the Hubble Space Telescope was on May 20th 1990. This was the day when the first pictures taken by the WF/PC-1 camera on board were relayed to the ground station. This event was covered extensively by the press. The commands to capture two images of a star cluster NGC 3532 using the WF/PC-1 were sent to the telescope. Later, the information was recorded on tape and relayed through satellites to the Goddard Space Flight Station. Pictures at first glance confirmed that the Hubble Space Telescope was indeed functional[21]. This news was greatly welcomed by the scientific community.

However, right from the time the telescope was released into orbit, it faced several problems. Initially, the front cover of the telescope would not open due to communication problems. The huge solar panels were warped and deformed every time the telescope crossed the day-night boundary in its orbit. This caused major disturbances, and compromised the telescope's ability to lock onto a specific target. It took several weeks before the Hubble Space Telescope (HST) could be calibrated to bring images into focus, delayed by an error in calculations[22]. All these problems, however, could be fixed. There was another problem that was discovered which not quite as correctable.

After First Light, on May 20th, the Wide Field and Planetary Camera Team studying the first pictures sent down from the space telescope realised that there was something strange about the pictures. The images were not as clear as they were supposed to be. A normal image should have focused light from the stars into a bright spot. The HST's first images, however, showed a central bright spot, surrounded by a halo of light, with tendrils of light extending outwards from the centre. At first, most of the team thought it was a focusing problem. However, as time wore on, and more tests were conducted, it increasingly seemed as though the problem was not the focusing. When the Faint Object Camera (FOC) had its first light in June of the same year, the same problem appeared. This ruled out the possibility that the problem lay with the

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[19] Fischer and Duerbeck (1996) p. 32
[20] Fischer and Duerbeck (1998) p. 26
[21] Fischer and Duerbeck (1996) pp. 36-37
[22] Ibid, p. 35

WF/PC-1 and set the stage for Primary Mirror tests. After many tests and simulations, it was discovered that the problem was with the optical system of the HST. The primary mirror had been ground too much, such that it was too flat by two microns[iv]. Although this was merely half the thickness of a strand of hair, it was severe enough to throw the success of the project into question[23].

Immediately, NASA began to study feasible options to correct the defect. Since the defect was a regular defect, it was possible, theoretically to fix the problem with a complicated set of mirrors to focus the light passing through the primary mirror. The task was subcontracted to Ball Aerospace. The instrument that would save the HST was called the Corrective Optics Space Telescope Axial Replacement (COSTAR)[24]. This would be installed in the telescope in its first servicing mission.

The Servicing Missions

Right from the start, the HST was planned to allow for in-orbit servicing. It was built to be "astronaut-friendly" with many hand rails and foot holds built all around its structure. The servicing would allow the telescope to survive for much longer under the harsh conditions, and also allow for replacement of the on board detectors by more up to date instruments. It is this aspect of the HST which allowed the spherical aberration in the primary mirror to be corrected successfully.

Figure 2 - HST pictures of the M100 Galactic Nucleus before and after COSTAR. Picture Taken from Barbree and Caidin p. xxi

NASA had to prepare for the first servicing mission more quickly than planned to correct the problems that the HST had been facing. On December 2nd 1993, space shuttle Endeavour lifted off to start Servicing Mission 1 (SM-1). After the shuttle was parked in orbit, and had captured the telescope in its payload bay, the servicing began. First, two malfunctioning gyros[v] were replaced. Next, the two solar panels were replaced to correct the vibrations that were produced every time the telescope moved past the day-night border. After this, the old WF/PC-1 was replaced by a new camera, the WF/PC-2. On the fifth day of SM-1, the High Speed Photometer (HSP) was replaced by the COSTAR. A few other minor repairs were carried out after

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[23] Peterson and Brandt pp. 6-9
[24] Ball Aerospace

this, and on December 10th, the telescope was once again released from the shuttle and into orbit[25].

On January 13th 1994, a press conference was held to demonstrate the effectiveness of COSTAR. Pictures taken before and after COSTAR was installed showed clearly demonstrated this (see figure 2). The other problems that the satellite had been facing were also mostly solved. Hubble now fulfilled all original optical specifications, and the first servicing mission was considered a resounding success. The entire project had been saved from failure and embarrassment[26].

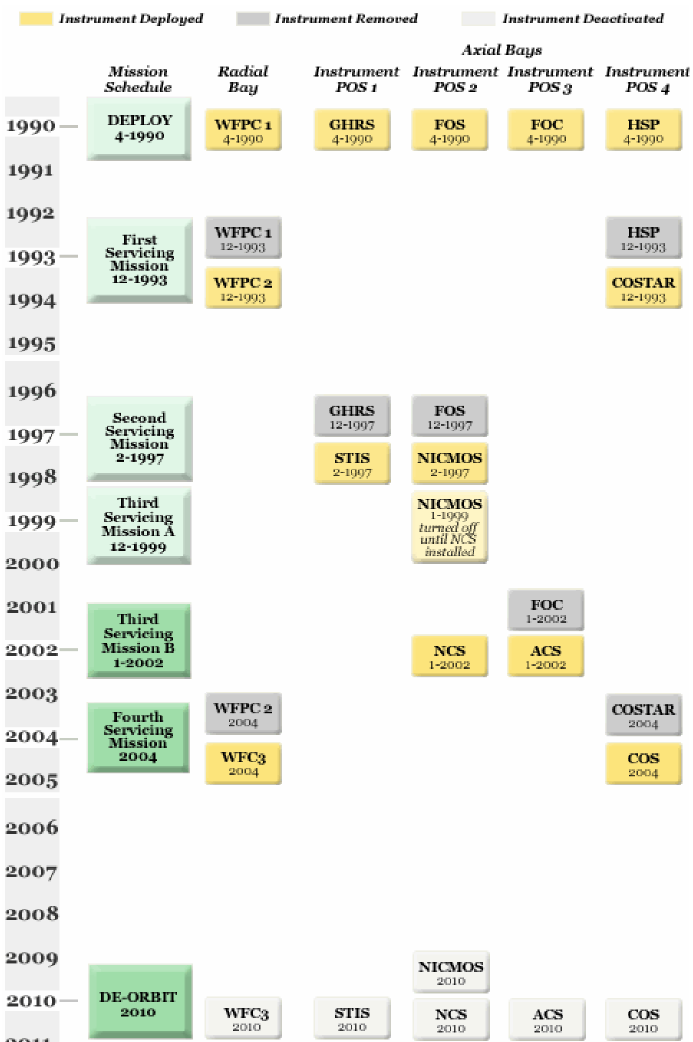

Figure 3 - Instruments aboard the Hubble and changes made during the Service Missions. Taken from The Hubble Project

Building on the success of SM-1, more servicing missions were carried out in February 1997 (SM-2), October 1998 (HOST), December 1999 (SM-3A) and March 2002 (SM-3B). Another mission has been scheduled for 2004[27]. A brief explanation of the changes made during the missions is given in Figure 3 (Refer to Appendix 1 for a short description of each instrument). These missions have enabled the HST to remain up-to-date and provide better data than it was originally capable of. It has also extended the telescope's life by 5 years, and it is now expected to stay in service till 2010.

[25] Fischer and Duerbeck (1998) pp. 30-32
[26] Ibid, p. 32
[27] The Hubble Project

Part II – The Hubble Space Telescope and Its Contributions to Science

The Age Of The Universe

In the field of Cosmology, the origin of our universe has always been a very debated topic. The most widely accepted model is the Big Bang Model. According to this model, the universe started out as a point of infinite density – a singularity – and expanded into the universe that we see today. This gained ground after astronomer Edwin Hubble showed in 1929 that other galaxies are moving away from the Milky Way. In fact, he found that there existed a linear relationship between the distance of other galaxies from the Milky Way and the speed at which they moved away from it. He was able to determine the relative speeds of these galaxies by looking at their redshifts.

Edwin Hubble then put this relationship in the form $\mathbf{v = H_0 d}$ where v is the speed in kilometres per second, d is the distance in Megaparsecs[vi] and H_0 is the Hubble constant. The Hubble constant is an important quantity because it measures the rate of expansion of the universe[28].

If we were to turn the wheels of time backwards, then galaxies which are now moving apart from one another would instead move towards one another. Eventually, all galaxies would eventually collide at a single point, and this is the singularity that the universe first originated from. Using this logic, we can find out how much time has elapsed since the galaxies were at a point. Since the galaxies are moving apart with velocity v, and are a distance d from us, the time taken to travel that distance would be $\mathbf{d/v = 1/H_0}$[vii]. This means that if we were able to find the Hubble constant, it's inverse would in fact give an estimate of the age of our universe!

One of the primary objectives of the Hubble Space Telescope was to help determine the value of the Hubble constant more accurately. The way to do this was to firstly, measure the redshift of distant galaxies which would enable us to derive its relative velocity, and accurately measure the distance to the galaxy. The HST was able to perform both these tasks better than any ground-based telescope.

The redshift of galaxies can be measured by looking at their emission spectra. Well-known spectral lines caused by various elements such as hydrogen, calcium and iron do not appear at the wavelength at which we measure them in a terrestrial laboratory. They are, instead, shifted towards the red part of the spectrum. The difference can be compared to obtain the redshift of a celestial body, and hence its relative velocity[29]. The HST was able to do this much better than any ground-based telescope because the

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[28] Fischer and Duerbeck (!996) p. 63
[29] Fischer and Duerbeck (1998) p. 45

atmosphere was not permeable to many wavelengths of radiation, especially ultraviolet. This mean that emission spectra could only be obtained for high redshifts, when the radiation was shifted towards the red end of the spectrum[30] The HST, however, faced no such problem, and was able to measure the redshifts of both nearby and distant galaxies accurately.

There are several methods to measure the distance to celestial bodies that were far away. One of the most popular ways is to use a special class of stars known as Cepheid variable stars. Certain conditions in the outer layer of these stars cause them to pulsate in size with a regular frequency. At the beginning of the last century, a correlation between the period of pulsation and their luminosity was discovered[31]. What this meant was that if a Cepheid variable star could be found in distant galaxy, it could be observed to determine its period of pulsation. This would give the actual or 'intrinsic' luminosity of the star. By comparing the actual luminosity with the apparent luminosity (the brightness at which it is seen by telescopes), the distance to the galaxy can be calculated.

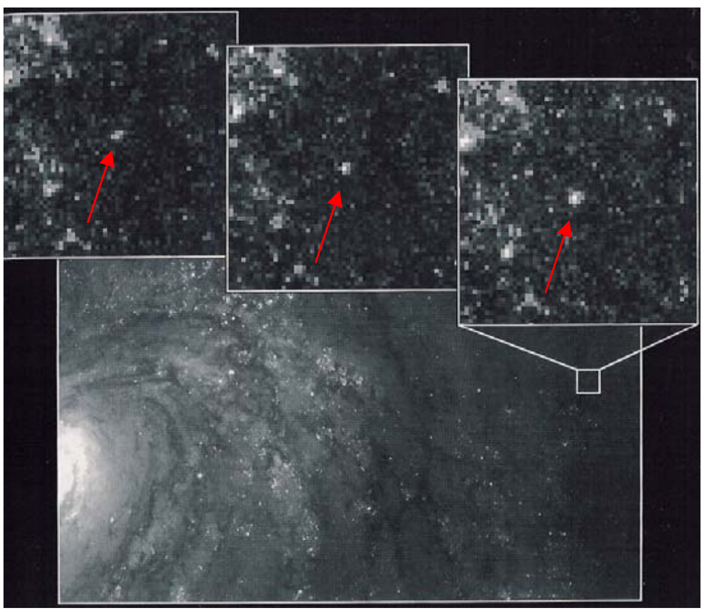

Figure 4 - Cepheid variable star in M100 seen to vary in brightness. Picture taken from Fischer and Duerbeck (1996) p. 67

The Hubble Space Telescope is extremely useful in picking out and observing Cepheid variable stars in distant galaxies. Figure 4 shows three enlargements showing such a star in the spiral galaxy M100 and the variation of its brightness with time. The Cepheid could not be observed as a single star by any ground-based telescopes. Using the instruments on the HST, the period of the star was calculated to be 51.3 days, giving a distance of about 56 million light years. Such an accurate calculation would not have been possible with ground-based telescopes, especially for galaxies further away than M100[32].

Using measurements of redshifts and distances from observations made by the HST, astronomers have managed to reduce the error in the Hubble constant to between 55 km/sMpc and 85 km/sMpc. The difference is partly due to the fact that there are other ways to calculate the distance to other galaxies which seem to give a slightly different

[30] Peterson and Brandt p. 215
[31] Fischer and Duerbeck (1996) p. 67
[32] Ibid, p. 68

value of the Hubble constant. It is hoped, however, that the HST will enable us to narrow the error in the Hubble constant to within 10%[33].

Intergalactic Gases

Quasars are celestial bodies that serve as excellent 'standard candles' to help us figure out what lies between them and us. They are the brightest objects known, and thus their line of sight can cover a much higher fraction of the universe than any other celestial body. The spectra of quasars can be studied, to make observations as to which wavelengths of radiation have been absorbed before reaching the earth[34].

The Hubble Space Telescope was used to study the absorption spectra of radiation emitted by quasars. What was observed is that there are numerous absorption lines known as the 'Lyman-alpha forest' in the ultraviolet spectrum[35]. This must mean that there is some matter between the quasars and us which absorbs this radiation. The absorption spectra were produced by hydrogen gas found in galaxies. Strangely, however, the quasars that were being observed did not have any galaxies in the direct line of sight. However, it was noted after more analysis that galaxies close to the line of sight of the quasars produced absorption spectra as well. This led scientists to conclude that many normal galaxies are surrounded by extended hydrogen clouds, which can reach a diameter up to fifteen times the diameter of the optical image of the galaxy[36].

The absorption line of Hydrogen gas is at a wavelength of 1216 angstroms when measured in a laboratory. However, the earth's atmosphere does not allow any radiation with a wavelength less than 3200 angstroms, which is in the visible light region, to pass through it. Thus, ground based telescopes cannot be used to study these absorption spectra unless they have a large enough redshift to move into the visible light region. A space-based telescope would not have this problem, and can measure the absorption spectra at low redshifts as well[37].

Although the origins of these hydrogen gas clouds, and how they are maintained at such distances from the galaxies are not yet fully understood, the Hubble Space Telescope has helped uncover this great mystery which may enhance our understanding about the formation and composition of galaxies.

Formation Of Galaxies

The search for the origins of our universe and how it came to be the way it is today has been one of the central tasks of astrophysics. One way to get a clearer picture

[33] Fischer and Duerbeck (1996) p. 70
[34] Peterson and Brandt p. 214
[35] Ibid, p. 215
[36] Fischer and Duerbeck (1996) p. 22
[37] Peterson and Brandt p. 215

of the beginnings of our universe would be look back in time, if possible, and compare what the universe was like then to what it looks like now. That is what the Hubble Space Telescope was used to do in 1995.

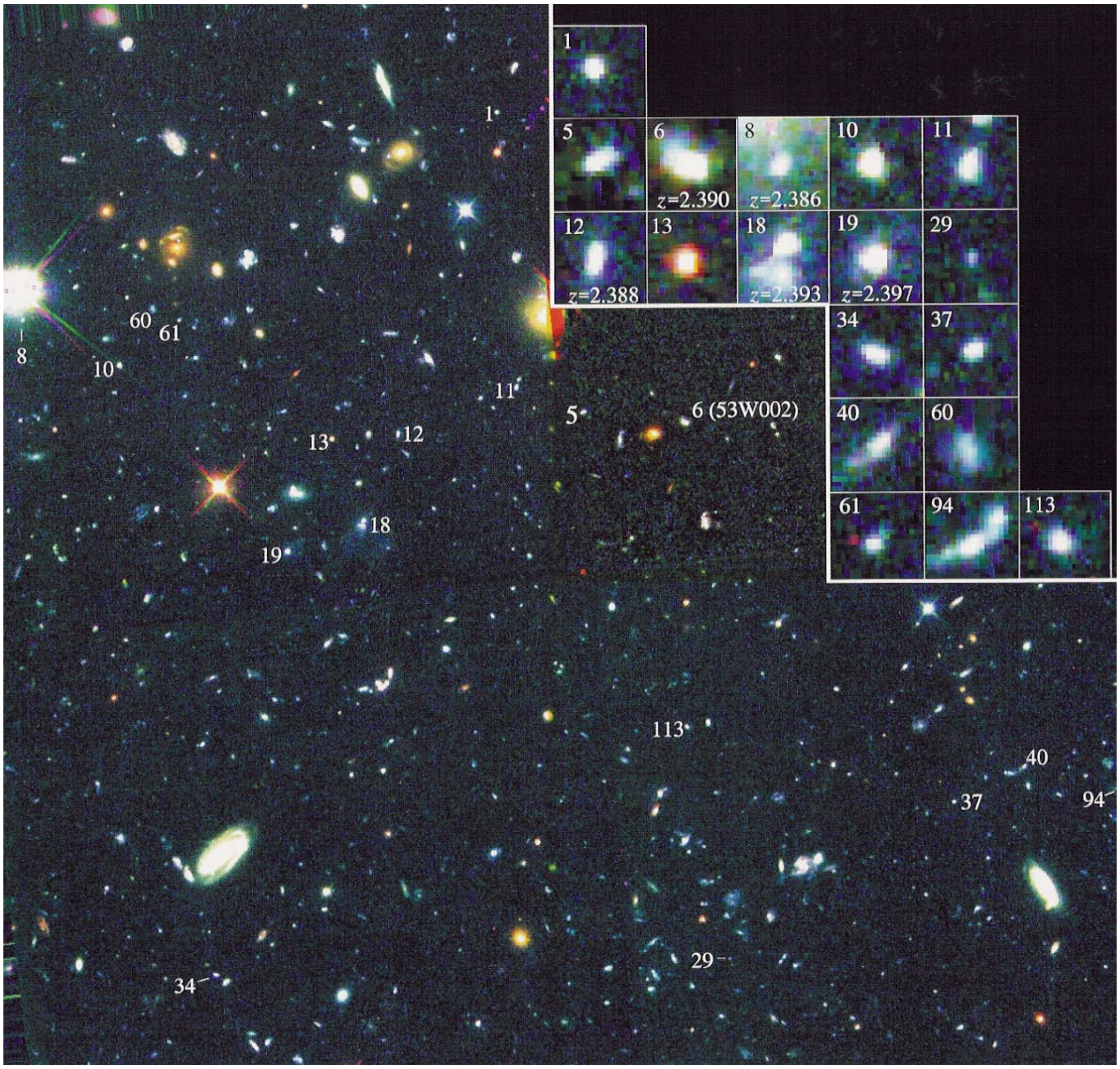

Figure 5 - The Hubble Deep Field, showing the 18 bodies that have been identified as early galaxies in formation. Picture taken from Fischer and Duerbeck p. 66

The director of the HST made use of the discretionary time allocated to point the telescope to an area, one thirtieth the size of the full moon, that contained "nothing" – no star, quasar, or conspicuous radio or infrared source. The observation was carried out from December 18th to December 28th 1995. A total of 342 exposures were taken in four colours and combined to give a single colour image. The resulting image showed several objects, almost all of them distant galaxies, which were at least 3 to 15 times fainter than any other celestial bodies observed till then. This part of the sky, located in the constellation Ursa Major, has come to be known as the Hubble Deep Field[38].

[38] Fischer and Duerbeck (1998) p. 46

The faintest object that had been captured had reached the 30th astronomical magnitude[viii]. This is two and a half billion times fainter than the faintest star visible to the naked eye on a dark night. Correspondingly, these objects also had very high redshifts, four of them even had a redshift greater than 6[39]. This indicated that they are moving away from us at extreme velocity. Using Hubble's law, which says that the further away a galaxy is from us, the faster it moves away from us, astronomers could deduce that these galaxies were extremely far away from us.

Since light has a finite speed, looking at extremely distant galaxies meant that we were literally looking into the past. Since the light that reaches us now, must have left the distant celestial body many billions of years ago. In fact, if the redshift values are correct, we are probably looking back in time about 12 billion years. Luminosity of these distant bodies have been calculated to be around 10^9 to 10^{10} solar luminosities. These are moderate when compared to galaxies but are comparable to starburst galaxies which undergo a phase of strong star formation. the beginnings of galaxy formation. What we must be looking at, therefore, are the beginnings of galaxy formation in our universe[40]. In fact, 18 such bodies have been identified in an area only 2 million light years in diameter. Each body has a diameter of 2000 to 3000 light years and probably contains about a billion stars[41]. Figure 5 shows an image of the Hubble Deep Field (HDF) and the 18 galaxies that have been identified. A study of these galaxies could provide us valuable insight into the evolution of the universe.

The Hubble Deep Field also provides evidence for the "bottom up model of galaxy formation and the theory of cold dark matter cosmology. In this model, the universe is initially full of "cold" dark matter, moving much slower than the speed of light. Structure emerges from small to large, instead of the other way around. This would mean that first, small stellar systems, such as star clusters and small galaxies form. They then combine into larger galaxies that we see today. These larger galaxies then form clusters and superclusters. If the initial dark matter were 'hot', and had speeds close to that of light, then large structures would emerge first, fragmenting into galaxies only later. Thus, evidence from the HDF showing small galaxies going through star formation is evidence for the cold dark matter model[42].

The Solar System

The Hubble Space Telescope does not only capture images of distant celestial bodies. It has made significant contributions to giving us a better understanding of our own solar system. It has captured images of planets, their moons and asteroids and comets in astounding detail, giving us a clearer picture than what we could have obtained with ground-based telescopes.

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[39] Fischer and Duerbeck (1998) pp. 46-48
[40] Ibid, pp. 48-50
[41] Ibid, p. 65
[42] Ibid.

The least understood planet, and the one that is furthest away from the Sun is Pluto. For a long time, Pluto was considered to be a single entity. It was only in 1978 that a satellite, Charon, was discovered. However, due to its distance from the earth, about 5 billion kilometres, ground-based telescopes could not obtain a clear picture of the two bodies. It was only after the Hubble Space Telescope was used to look at Pluto to obtain clearer pictures as shown in Figure 6 that it was discovered that Pluto and Charon formed a "double planet" pair. Detailed observations enabled scientists to discover that Charon's diameter was about of Pluto's it consisted mostly of ice. On the other hand, about 60% of Pluto was rock[43].

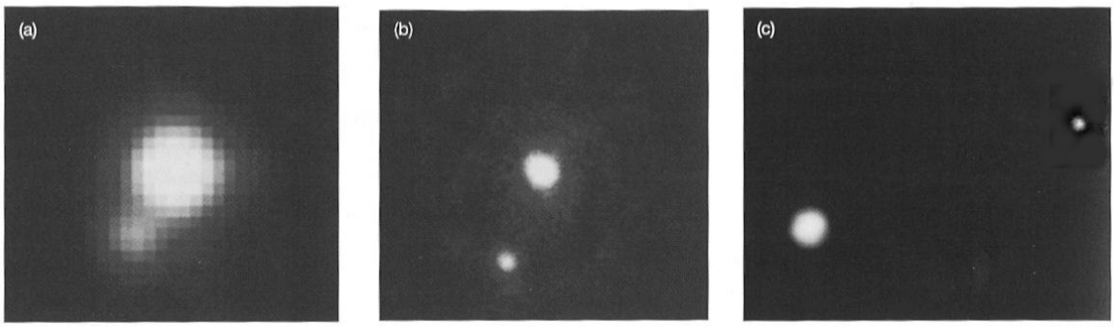

Figure 6 - a) The clearest picture of Pluto and Charon taken using a ground-based telescope. b) Same picture taken with the HST before COSTAR c) Same picture with COSTAR. Picture taken from Peterson and Brandt p. 114 Figure 3.25

The HST has also been used complementarily to other space missions. This is especially so of NASA missions to Mars. Mars has a very dynamic atmosphere and climate. The surface of the red planet is often engulfed storms, some of which are large, while some are local. It was necessary, however, to have a clear picture as to the locations of these storms and the current atmospheric conditions to be able to successfully land probes such as the Mars Pathfinder and Mars Global Surveyor. Unfortunately, ground-based telescopes were not capable of spotting such storms, and thus would not have been able to provide this crucial information[44].

The HST, on the other hand, is able to serve as an excellent "weather satellite" to forewarn astronomers and mission control personnel. For example, a week prior to the Pathfinder landing on Mars, the HST spotted a storm forming about 1000 kilometres south of the landing site. The telescope was used to monitor this storm, and once it was established that the storm would not move into the landing site, the mission was allowed to continue as planned.

Conclusion

There have been a myriad of questions plaguing the minds of cosmologists and astronomers since humans first started the study of celestial bodies. When Galileo

[43] Peterson and Brandt pp. 113-114
[44] Fischer and Duerbeck (1998) p. 178

assembled the first telescope around 400 years ago, it was a great leap forward in our ability to observe and understand our universe. After close to four centuries, we have once again managed to take a similar leap forward.

The Hubble Space Telescope has provided much insight into areas that were previously not understood, from our solar system to the universe as a whole. Although it had its fair share of problems, and it is very expensive to maintain, it is today dubbed as one of the most cost efficient NASA projects simply due to the wealth of information it has provided.

This by no means implies that we have even come close to answering all the questions that lie open before us. Perhaps these questions will never be answered with any certainty. But as creatures who crave to understand our place in the universe, we will have to continually make the effort to observe and comprehend the world around us, both near and far. The Hubble Space Telescope has helped us to do that. However, it does have a limited life span and will be de-activated in 2010, 20 years after its launch[45]. Due to the success of the HST, there are plans to launch yet another space telescope, called the Next Generation Space Telescope (NGST). It is scheduled for operation towards the end of the decade, and will orbit the earth at 1.5 million kilometres – four times the distance to the moon. It will be more powerful than the HST, and will see deeper and further back in time than the HST can, with much greater clarity[46].

There is no doubt that we will continue to improve on space telescope technology to make it cheaper, more efficient and more powerful, and continue to decode the invaluable information that they provide. The Hubble Space Telescope is the platform from which this technology will be built. It will go down in history as a very important step forward towards understanding the universe.

[45] The Hubble Project
[46] Hubble : European Space Agency Information Centre

Appendix 1 – Glossary of Instruments in the Hubble Space Telescope

1990 Initial complement at deployment:

- **WFPC (1)** - Wide Field/Planetary Camera I - First Generation Imaging camera. WFPC (1) operated in either Wide Field mode, capturing the largest images, or Planetary mode with higher resolution.
- **GHRS** - Goddard High Resolution Spectrograph - First Generation Spectrograph. GHRS was used to obtain high resolution spectra of bright targets.
- **FOS** - Faint Object Spectrometer - First Generation Spectrometer. FOS was used to obtain spectra of very faint or far away sources. FOS also had a polarimeter for the study of the polarized light from these sources.
- **FOC** - Faint Object Camera - First Generation Imaging camera. FOC is used to image very small field of view, very faint targets. This is the final, first generation instrument still on Hubble.
- **HSP** - High Speed Photometer - First Generation Photometer. This instrument was used to measure very fast brightness changes in diverse objects, such as pulsars.
- **FGS** - Fine Guidance Sensors - Science/Guidance instruments. The FGS's are used in a "dual-purpose" mode serving to lock on to "guide stars" which help the telescope obtain the exceedingly accurate pointing necessary for observation of astronomical targets. These instruments can also be used to obtain highly accurate measurements of stellar positions

1993 Servicing Mission 1:

- **WFPC2** - Wide Field Planetary Camera II - Second Generation Imaging camera. WFPC2 is an upgraded version of WF/PC (1) which includes corrective optics and improved detectors.
- **COSTAR -** Corrective Optics Space Telescope Axial Replacement - Second Generation Corrective Optics. COSTAR is not an actual instrument, it consists of mirrors which refocus the abbreviated light from Hubble's optical system for first generation instruments. Only FOC utilizes its services today.

1997 Servicing Mission 2:

- **STIS** - Space Telescope Imaging Spectrograph - Second Generation Imager/Spectrograph. STIS is used to obtain high resolution spectra of resolved objects. STIS has the special ability to simultaneously obtain spectra from many different points along a target.
- **NICMOS** - Near Infrared Camera/Multi-Object Spectrometer- Second

Generation Imager/Spectrograph. NICMOS is Hubble's only Near Infrared (NIR) instrument. To be sensitive in the NIR, NICMOS must operate at a very low temperature, requiring sophisticated coolers. Problems with the solid Nitrogen refrigerant have necessitated the installation of the NICMOS Cryocooler (NCC) on SM3B to continue operations.

2002 Servicing Mission 3B:

- **NCS** - NICMOS Cooling System - Like COSTAR, NCS is not a separate instrument but rather a device which will allow NICMOS to continue operations by providing mechanical cooling for the NICMOS detectors. Results from the HOST mission indicate that the NCS will allow NICMOS to operate for up to 5 years beyond SM3B.
- **ACS** - Advanced Camera for Surveys - The Advanced Camera for Surveys (ACS) is a third-generation Imaging Camera. This camera is optimized to perform surveys or broad imaging campaigns.

2003 Servicing Mission 4:

- **WFC3** - Wide Field Camera 3- Fourth Generation Imaging camera. This camera will supplement ACS and guarantee imaging capability for Hubble after the Fourth Servicing Mission.
- **COS** - Cosmic Origins Spectrograph - Fourth Generation Spectrometer. COS is an ultraviolet spectrograph optimized for observing faint point sources with moderate spectral resolution.

Taken from “The Hubble Project”
http://hubble.gsfc.nasa.gov/technology/science-instruments/

Endnotes

[i] In the uppermost layers of the atmosphere, the ionosphere, electrically charged atoms combine with electrons and thereby emit certain spectral lines. The strength of this airglow depends on solar activity (Fischer and Duerbeck : 1996 p. 24).

[ii] Very young and very old stars are comparatively cool, and the dust that envelops them radiates at these longer wavelengths. Thus, to learn about the birth and death of these stars, we must study infrared radiation (Fischer and Duerbeck : 1998 p. 17).

[iii] OAO-2 was an ultraviolet observing satellite, equipped with several photometers to measure the incoming radiation, and spectrographs to separate the radiation into its component wavelengths. OAO-3 carried a high resolution spectroscope and various smaller X-Ray telescopes to explore interstellar matter (Fischer and Duerbeck : 1996 p. 20).

[iv] Perkin-Elmer, the firm responsible to construct the primary mirror, made a mistake in the grinding process. To make sure that mirror was ground and polished to the correct specifications, they built a special device called the “reflective null corrector”. The fault was with one of the components of this device, which was never itself checked, which led to the mirror being ground 2 microns too thin (Peterson and Brandt pp. 12-13)

[v] There are 6 gyros in the HST which are used to control its orientation in space. They were designed for easy exchange in space (Fischer and Duerbeck : 1998 p. 30)

[vi] 1 Megaparsec = 3,260,000 light years

[vii] This is assuming that the universe has been expanding at a uniform rate through time. However, this is not necessarily true. An alternative model which is gaining in popularity is one with a postive ‘cosmological constant’ which implies that the rate of expansion of the universe has been increasing with time. This could would allow for a higher Hubble constant, even though that would give us an estimate of the age of the universe which is less than some of the oldest stars known. This is because, the universe would have gone through a period of much slower expansion, and thus is probably older than the estimation that the Hubble constant gives (Fischer and Duerbeck : 1996 pp. 64-65).

[viii] Astronomical magnitude is a measure of how bright a body appears in the sky. The higher the magnitude, the fainter the object.

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