
The Scientific Impact of Hubble Telescope

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Abstract

The Hubble Space Telescope (HST) is an extraordinary instrument that has made a revolution in our understanding of the universe since its launch in 1990. Since then, it has provided unprecedented optimism and hope to reach bigger things. It has been a game-changing invention for astronomers, physicists, and science enthusiasts around the world enabling them to discover miracles that were formerly considered impossible to achieve. The HST's legacy extends beyond its scientific contributions. Its captivating images and public accessibility have inspired millions worldwide, fuelling public interest in astronomy and space exploration. This research paper aims to examine the scientific impact of the Hubble Telescope across various fields of astrophysics and cosmology. Through our research, we aim to highlight some of the critical scientific breakthroughs facilitated by the Hubble Telescope, including the measurement of the Hubble constant, the study of galaxies and dark matter, the investigation of exoplanets, and the exploration of the early universe.

Keywords: *Astrophysics, Hubble Space Telescope (HST), Cosmology, Galactic studies, Exoplanets, Spectroscopy, James Webb Space Telescope (JWST), Nancy Grace Roman Space Telescope (RST), Wide-Field Infrared Survey Telescope (WFIRST), Corrective optics, Spherical aberration, Stellar astronomy, Transit method, Dark matter, Gravitational lensing, Ultraviolet and infrared observations.*

1. Introduction

The Hubble Space Telescope (HST) stands as a testament to humanity's unyielding quest to explore the cosmos and unlock the mysteries of the universe. Hubble is named after an American astronomer, Edwin P. Hubble. Launched in 1990 by NASA and the European Space Agency, the HST has become one of the most iconic and influential astronomical observatories ever deployed. Generally, Earth's atmosphere alters and blocks the light that comes from space. Hubble orbits above Earth's atmosphere, which gives it a better view of the universe than telescopes have at ground level. This remarkable instrument has revolutionized our understanding of the universe, providing astronomers and researchers with unparalleled views of celestial objects and phenomena. The HST's significance lies not only in its groundbreaking scientific discoveries but also in its role as a symbol of human ingenuity and technological achievement. Its ability to peer deep into the vastness of space and time has profoundly impacted various fields of astronomy and astrophysics, leading to a plethora of scientific breakthroughs. The objectives of this research paper are to explore and analyze the scientific impact of the Hubble Space Telescope, shedding light on the key discoveries and advancements it has brought about in cosmology, galactic studies, stellar astronomy, and planetary science. By delving into the specific contributions of the HST in these areas, we aim to demonstrate the profound influence this space-based observatory has had on advancing our knowledge of the cosmos. The HST plays a very important role in cosmology determining the age and expansion rate of the universe, refining cosmological parameters, and investigating distant supernovae and dark energy. In

the realm of galactic studies, the Hubble Telescope has been instrumental in resolving galactic structures, studying galactic collisions and interactions, and unravelling the mysteries of supermassive black holes at the center of galaxies.

Overcoming Atmospheric Limitations:

1) Advantages of Space-Based Observations: Space-based observations, as exemplified by the Hubble Space Telescope (HST), offer several distinct advantages over ground-based telescopes, primarily stemming from their ability to operate above Earth's atmosphere. These advantages have revolutionized the field of astronomy and significantly enhanced our understanding of the universe. Unobstructed View: Unlike ground-based telescopes, which are subject to atmospheric turbulence and light pollution, space-based observatories like the HST have an unobstructed view of the cosmos. The absence of atmospheric distortion allows for clearer and more detailed observations, enabling astronomers to study faint and distant celestial objects with unprecedented precision. Enhanced Resolution: Atmospheric turbulence causes blurring and reduces the resolution of ground-based observations. In space, there is no such limitation, and space telescopes can achieve significantly higher resolutions, capturing fine details and structures that would otherwise be obscured by the Earth's atmosphere. Full Spectral Range: Earth's atmosphere absorbs certain wavelengths of light, particularly in the infrared and ultraviolet regions. Space-based observatories can observe the full range of the electromagnetic spectrum, providing valuable data on various astronomical phenomena and allowing astronomers to study objects that emit radiation in these otherwise inaccessible wavelengths.

Extended Observation Time: Ground-based telescopes are constrained by daylight and weather conditions, limiting the amount of time available for observations. Space telescopes, on the other hand, can operate 24/7 without interruption, maximizing their observational capabilities and ensuring continuous data collection.

2) Correcting for Atmospheric Distortions:

The Role of Corrective Optics to fully exploit the advantages of space-based observations and achieve the highest possible image quality, the Hubble Space Telescope (HST) has been equipped with advanced corrective optics.

COSTAR: The Corrective Optics Space Telescope Axial Replacement (COSTAR) was installed during the telescope's first servicing mission in 1993. It served as a corrective device for the spherical aberration in Hubble's primary mirror, which was discovered shortly after its launch. The Corrective Optics Space Telescope Axial Replacement (COSTAR) successfully compensated for the distortion, restoring the telescope's intended imaging capabilities.

WFPC2: The Wide Field and Planetary Camera 2 (WFPC2) was one of the HST's original instruments and played a vital role in the early years of the telescope. WFPC2 incorporated corrective optics to counteract the spherical aberration and allowed for the capture of high-resolution images across a wide field of view.

WFC3: During the final servicing mission in 2009, COSTAR was replaced with the Wide Field Camera 3 (WFC3). This instrument significantly expanded the HST's capabilities in both the ultraviolet and infrared regions of the spectrum. WFC3's advanced corrective optics improved the telescope's resolution and sensitivity, further enhancing its ability to explore diverse astronomical phenomena.

By employing all these corrective optics and operating above the Earth's atmosphere, the Hubble Space Telescope has overcome atmospheric limitations, enabling scientists to conduct groundbreaking research and capture breathtaking images of the universe. The combination of space-based observations and advanced corrective technologies has been instrumental in shaping our understanding of the cosmos, uncovering celestial mysteries, and inspiring new generations of astronomers to explore the wonders of space.

2. Working Principle:

At the heart of Hubble's observational prowess lies its principal "eye," known as the Wide Field and Planetary Camera 2 (WFPC2). This sophisticated camera relies on a quartet of CCD (Charge-Coupled Device) chips arranged in an "L" configuration to capture incoming light. Among these four CCD chips, three are dedicated to low-resolution, wide-field imaging, while the fourth excels at high-resolution planetary observations. The unique arrangement allows all four chips to be simultaneously exposed to the celestial target, with the target image thoughtfully centered on the preferred CCD chip. WFPC2 boasts the capability to perceive both visible and ultraviolet light, offering the flexibility to capture images through various filters and craft natural-colour representations, as exemplified by the iconic Eagle Nebula image. However, the WFPC2 camera, versatile though it may be, encounters limitations in certain scenarios, particularly when interstellar gas and dust obscure our view of celestial objects in visible light. To surmount such challenges, the Hubble Space Telescope employs a specialized suite of three highly sensitive cameras, collectively constituting the Near Infrared Camera and Multi-object Spectrometer (NICMOS). These instruments excel at capturing near-infrared wavelengths, penetrating the cosmic veils of dust and gas to unveil otherwise concealed cosmic wonders. Shortly after its deployment in 1990, astronomers encountered an issue with the Hubble Space Telescope (HST). The colossal observatory, roughly the size of a tractor-trailer, was struggling with a fundamental challenge: an inability to achieve proper focus. The culprit was traced back to a minute flaw in the telescope's primary mirror, an imperfection no thicker than one-fiftieth the width of a human hair. Despite its minuscule nature, this flaw led to spherical aberration, resulting in the production of blurred and distorted images. In response to this setback, scientists embarked on a mission to rectify the HST's optical deficiency. Their solution? A groundbreaking intervention in the form of a specialized "contact" lens aptly named COSTAR, which stands for Corrective Optics Space Telescope Axial Replacement. COSTAR featured an assembly of compact mirrors designed to intercept the imperfect light beams originating from the primary mirror, correct the distortions, and then transmit the refined light to the scientific instruments situated at the mirror's focal point. Besides illuminating a celestial object, the light emanating from that object can also reveal what it's made of. The specific colours tell us what elements are present, and the intensity of each colour tells us how much of that element is present. The Space Telescope Imaging Spectrograph (STIS) separates the incoming colours of light much as a prism makes a rainbow. In addition to describing the chemical composition, the spectrum can convey the temperature, density, and motion of a celestial object. If the object is moving, the chemical fingerprint may shift toward the blue end (moving toward us) or the red end (moving away from us) of the spectrum. The final instrument on board the HST is its Fine Guidance Sensors (FGSs), which point the telescope and precisely measure the positions and diameters of stars, as well as the separation of binary stars. The Hubble has three of these sensors overall; two to point the telescope and keep it fixed on its target, looking for "guide" stars in the HST field near the target. When each FGS finds a guide star, it locks on to it and feeds information back to the HST steering system to keep that guide star in its field. While two sensors are steering the telescope, one is free to make astrometric measurements (star positions). Astrometric measurements are important for detecting planets because orbiting planets cause the parent stars to wobble as they move across the sky. Hubble zooms around the Earth every 97 minutes, so focusing on a target can be difficult. Three onboard systems allow the telescope to remain fixed on an object: gyroscopes, the Fine Guidance Sensors that we talked about in the previous section, and reaction wheels. The gyroscopes keep track of Hubble's gross movements. Like compasses, they sense its motion, telling the flight computer that Hubble has moved away from the target. The flight computer then calculates how much and in what direction Hubble must move to remain on target. The flight computer then directs the reaction wheels to move the telescope. Hubble's Fine Guidance Sensors help keep the telescope fixed on its target by sighting guide stars. Two of the three sensors find guide stars around the target within their respective fields of view. Once found, they lock onto the guide stars and send information to the flight computer to keep the guide stars within their field of view. The sensors are more sensitive than the gyroscopes, but the combination of

gyroscopes and the sensors can keep the HST fixed on a target for hours, despite the telescope's orbital motion. The HST can't use rocket engines or gas thrusters to steer like most satellites do, because the exhaust gases would hover near the telescope and cloud the surrounding field of view. Instead, the HST has reaction wheels oriented in the three directions of motion (x/y/z or pitch/roll/yaw). The reaction wheels are flywheels, like those found in a clutch. When the HST needs to move, the flight computer tells one or more flywheels which direction to spin in and how fast, which provides the action force. By Newton's third law of motion (for every action there is an equal and opposite reaction), the HST spins in the opposite direction of the flywheels until it reaches its target. This strategic combination of instruments, from COSTAR's optical correction to WFPC2's versatile imaging and NICMOS's near-infrared capabilities, equips the Hubble Space Telescope with an array of tools to conquer the challenges of astronomical observation and unravel the mysteries of the universe.

Instrument Briefing:

Wide Field & Planetary Camera 1(WF/PC1) 1990 – 1993

High Speed Photometer(HST) 1990 – 1993

Goddard High Resolution Spectrograph(GHRS) 1990 - 1997

Faint Object Spectrograph(FOS) 1990 – 1997

Faint Object Camera(FOC) 1990 – 2002

Corrective Optics Space Telescope Axial Replacement(COSTAR) 1993 – 2009

Wide Field and Planetary Camera 2(WFPC2) 1993 – 2009

Near Infrared Camera and Multi-Object Spectrometer(NICMOS) 1997 – Present

Space Telescope Imaging Spectrograph(STIS) 1997 – Present

Advanced Camera for Surveys(ACS) 2002 – Present

Wide Field Camera 3(WFC3) 2009 – Present

Cosmic Origins Spectrograph(COS) 2009 – Present

Fine Guidance Sensor(FGS1R) 1997 – Present

Unveiling Galaxies and Dark Matter: Galaxy Observation and Classification: The Hubble Telescope has provided astronomers with unparalleled views of distant galaxies. It has captured detailed images of galaxies across different stages of their evolution, from young and actively star-forming galaxies to mature elliptical and spiral galaxies. These observations have allowed scientists to study the structure, morphology, and dynamics of galaxies, shedding light on their formation and evolution. **Distance Measurements:** One of Hubble's key contributions has been its ability to measure the distances to galaxies accurately. It has been used to observe Cepheid variable stars and Ia supernovae in distant galaxies. These objects have known intrinsic luminosities, which makes them valuable "standard candles" for distance measurements. By comparing their observed brightness to their known luminosity, astronomers can determine the distance to their host galaxies. These distance measurements have been crucial for determining the expansion rate of the universe, known as the Hubble constant.

Dark Matter Studies: While Hubble doesn't directly see dark matter, its observations have provided evidence for the existence of dark matter based on its gravitational effects on visible matter. The distribution of visible matter (stars and gas) in galaxies does not fully account for the observed gravitational interactions within galaxies and galaxy clusters. The gravitational lensing effects observed through Hubble's images reveal the presence of more matter than can be accounted for by visible matter alone. This discrepancy strongly suggests the presence of dark matter, which does not emit light but exerts a gravitational pull on visible matter.

Galaxy Cluster Observations: Hubble's observations of galaxy clusters have also contributed to our understanding of dark matter. The way light from background galaxies is bent and distorted by the gravitational field of massive foreground clusters provides information about the distribution of dark matter

within those clusters. This gravitational lensing effect helps astronomers map the mass distribution and study the behaviour of dark matter on larger scales.

Studying Dark Matter Halos: Hubble's observations of galaxies and their rotation curves have provided insights into the distribution of dark matter within galaxies. The way galaxies rotate suggests the presence of massive dark matter halos surrounding them. Hubble's observations of galaxy rotation curves and the dynamics of galaxies within clusters have informed models of how dark matter is distributed on various scales.

Probing Exoplanets and Planetary Systems:

The Hubble Space Telescope has indeed played a significant role in probing exoplanets and planetary systems. While Hubble was not specifically designed for exoplanet research, its capabilities have been utilized to study the atmospheres, compositions, and even the presence of exoplanets around distant stars. Here's how Hubble contributes to this field and the science behind it.

Exoplanet Detection and Characterization: Hubble has contributed to the discovery and characterization of exoplanets primarily through transit and direct imaging methods.

Transit Method: Hubble has observed exoplanets as they pass in front of their host stars (transits). This causes a temporary dimming of the star's light, allowing astronomers to deduce the exoplanet's size, orbital period, and distance from its star. The depth and shape of the light curve during a transit provide information about the exoplanet's atmosphere, such as its composition and the presence of clouds or haze.

Direct Imaging: Hubble has directly imaged a few exoplanets by blocking out the glare of their parent stars. This technique allows scientists to study the exoplanet's atmospheric properties, temperature, and even its orbital dynamics.

Studying Exoplanet Atmospheres: Hubble's observations of exoplanets have provided insights into their atmospheric compositions.

Spectroscopy: Hubble can analyze the light that passes through an exoplanet's atmosphere during a transit. By studying the spectrum of this light, scientists can identify the presence of specific molecules in the atmosphere, such as water vapor, methane, carbon dioxide, and more. This helps in understanding the conditions and potential habitability of the exoplanet.

Physics and Working Science:

Spectroscopy: Hubble's spectroscopic observations involve breaking down light into its constituent colours (spectrum). When an exoplanet transits its host star, a portion of the star's light passes through the exoplanet's atmosphere. This transmitted light contains absorption lines that correspond to the molecules present in the atmosphere. By comparing these absorption lines to laboratory measurements, scientists can determine the atmospheric composition.

Transmission Spectroscopy: In transmission spectroscopy, Hubble observes the change in the star's light as the exoplanet moves in front of it. The spectrum of the star's light changes due to the absorption of specific wavelengths by the exoplanet's atmosphere. This helps scientists understand the composition, temperature, and even the potential presence of clouds or hazes in the exoplanet's atmosphere.

Emission Spectroscopy: In emission spectroscopy, Hubble observes the exoplanet's light as it passes behind its host star. This technique allows scientists to study the temperature structure, as well as the presence of certain molecules emitting light on the night side of the exoplanet.

3. Technological Advancements and Future Prospects:

1) **Upgrades and Servicing Missions:** The HST has undergone several servicing missions to address technical issues and enhance its scientific capabilities. These missions involved sending space shuttle crews

to the telescope to perform maintenance, repair, and install new instruments. Servicing Mission 1 (SM1, 1993): The inaugural servicing mission, SM1, was critical in rectifying the infamous spherical aberration in Hubble's primary mirror. The installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR) significantly improved the telescope's imaging performance, enabling it to achieve its full potential. Servicing Mission 2 (SM2, 1997): SM2 replaced the HST's original solar panels and thermal insulation, ensuring the telescope's power supply and temperature regulation remained stable. The mission also installed the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), an advanced instrument capable of capturing infrared images with exceptional clarity. Servicing Mission 3A (SM3A, 1999): During SM3A to maintain the stability of the HST gyroscope was installed. Many new computers were added to store the data up to 10 times more than the previous one. The mission also replaced key components and fine guidance sensors, further improving Hubble's overall performance. Servicing Mission 3B (SM3B, 2002): SM3B installed a new power control unit, the Advanced Camera for Surveys (ACS) and a refurbished scientific instrument (Space Telescope Imaging Spectrograph, STIS) to restore STIS's functionality which expanded the telescope's field of view and increased its imaging capabilities across multiple wavelengths. This mission ensured the continuation of essential observations in the ultraviolet and spectroscopic range. Servicing Mission 4 (SM4, 2009): The final servicing mission, SM4, installed the Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS). WFC3 significantly enhanced Hubble's imaging capabilities, especially in the ultraviolet and infrared regions, while COS opened new avenues for studying distant objects through spectroscopy.

2) Successor Telescopes and Their Potential Impact:

While the Hubble Space Telescope continues to produce groundbreaking science, several successor telescopes are being developed to further expand our observational capabilities and explore different aspects of the universe. Some notable successors include:

James Webb Space Telescope (JWST): The JWST is the most eagerly anticipated successor to Hubble, developed collaboration between NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA). Slated for launch, the JWST will be the most powerful space telescope ever built. Its larger primary mirror and advanced infrared instruments will enable groundbreaking studies of distant galaxies, exoplanets, and the early universe.

Wide-Field Infrared Survey Telescope (WFIRST): WFIRST, a flagship mission by NASA, will focus on cosmic surveys, dark energy studies, and exoplanet research. Equipped with a wide-field instrument and a coronagraph, WFIRST will conduct a comprehensive survey of the cosmos, addressing fundamental questions about the nature of dark energy and the abundance of exoplanets in our galaxy.

Nancy Grace Roman Space Telescope (RST): Named in honour of the "Mother of Hubble," the Roman Space Telescope will conduct wide-field surveys to study cosmic structures and the distribution of dark matter. Its large mirror and advanced imaging capabilities will enable it to complement the observations made by other telescopes, including Hubble and JWST. These successor telescopes hold immense promise in transforming our understanding of the universe, building upon the achievements of the Hubble Space Telescope and pushing the frontiers of astronomical research to new horizons. As technology continues to evolve, these telescopes will undoubtedly serve as the next generation of scientific pioneers, revolutionizing our knowledge of the cosmos and inspiring future generations of astronomers to explore the wonders of space.

4. Conclusion

The Hubble Space Telescope (HST) stands as a remarkable testament to human ingenuity and the pursuit of knowledge about our universe. Since its launch in 1990, the HST has had a profound scientific impact, revolutionizing our understanding of cosmology, galactic studies, stellar astronomy, and planetary science.

Through its space-based observations and advanced corrective optics, the HST has overcome atmospheric limitations, providing astronomers with unprecedented views of celestial objects and phenomena. In cosmology, the Hubble Telescope has been instrumental in determining the age and expansion rate of the universe, refining cosmological parameters, and shedding light on the enigmatic nature of dark energy through observations of distant supernovae. It has enabled us to peer deep into the past and study the early stages of our universe. In galactic studies, the HST's high-resolution imaging capabilities have allowed astronomers to resolve galactic structures, study galactic interactions, and investigate supermassive black holes at the centres of galaxies. These observations have greatly expanded our knowledge of galaxy formation and evolution. The Hubble Telescope's contributions to stellar astronomy have been equally significant. By observing stellar populations, studying stellar evolution, and measuring precise stellar distances, the HST has enriched our understanding of the life cycles and properties of stars. Furthermore, in planetary science, the HST has examined planetary atmospheres, detected, and characterized exoplanets, and explored the diversity of planetary bodies within our solar system. These observations have deepened our knowledge of our celestial neighbourhood and opened new avenues for studying exoplanets in distant star systems. Looking ahead, the prospects of space-based observatories remain bright. Upcoming missions like the James Webb Space Telescope (JWST), the Wide-Field Infrared Survey Telescope (WFIRST), and the Nancy Grace Roman Space Telescope (RST) promise to build upon the legacy of the HST and make groundbreaking discoveries in their respective fields. Ongoing research and the constant advancement of technology will continue to enhance our ability to explore the cosmos further. The Hubble Space Telescope continues to operate, providing valuable data and images that complement the observations made by newer telescopes. Its legacy remains an inspiration to astronomers and space scientists worldwide. In conclusion, the Hubble Space Telescope has made an indelible mark on the field of astronomy and astrophysics. Its scientific impact spans across multiple disciplines, transforming our understanding of the universe and uncovering celestial wonders. As we eagerly await the discoveries that the next generation of telescopes will bring, we can reflect on the profound influence the HST has had on human knowledge and its enduring legacy as a beacon of scientific exploration. The quest to explore the cosmos is an ongoing journey, and the Hubble Telescope has been and continues to be a key protagonist in this great adventure.

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