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ÚSTAV JAZYKŮ

THE EVOLUTION OF SPACE TELESCOPES

EVOLUCE VESMÍRNÝCH DALEKOHLEDŮ

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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TITLE OF THESIS:

The Evolution of Space Telescopes

INSTRUCTION:

The aim of the semester project is to describe the evolution of the space telescope. The work will describe the invention of the first telescopes/space telescopes from the beginning the 17th century till the present. The advantages and disadvantage of different types of space telescope will be discussed. Then an overview of the missions in the launch of the most important space telescopes will be outlined. The future thesis will examine these space telescopes in a much deeper way.

RECOMMENDED LITERATURE:

Christopher Gainor, Not Yet Imagined: A Study of Hubble Space Telescope Operations, National Aeronautics Space Administration, Washington, D.C., 2020, ISBN 9781626830615 (hardcover) at https://www.nasa.gov/sites/default/files/atoms/files/not_yet_imagined_tagged.pdf

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Hubble: An Overview of the Space Telescope, at https://www.nasa.gov/sites/default/files/atoms/files/hstoverview-v42021_1.pdf

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Abstract

This thesis focuses on the description of the history of the telescope, starting with the refracting and reflecting versions of the optical telescope and following with a brief outline of the history of the radio telescope and space telescopes in general. Then, basic characteristics of space telescopes are specified and their positive and negative features are compared. Finally, the three most influential space telescopes are described and their contributions to science are discussed.

Key Words

Telescope, space telescope, electromagnetic spectrum, mirror, Hubble, Kepler, Webb

Abstrakt

Tato bakalářská práce se zaměřuje na popis historie dalekohledu, počínaje refrakčními a reflexními verzemi optického dalekohledu a pokračuje stručným nástinem historie radioteleskopu a vesmírných dalekohledů obecně. Poté jsou specifikovány základní vlastnosti kosmických dalekohledů a jejich pozitivní a negativní vlastnosti jsou porovnány. Na závěr jsou popsány tři nejdůležitější vesmírné dalekohledy a jejich přínosy pro vědu jsou objasněny.

Klíčová slova

Dalekohled, vesmírní dalekohled, elektromagnetické spektrum, zrcadlo, Hubble, Kepler, Webb

Rozšířený abstrakt

Tato bakalářská práce na téma Evoluce vesmírných dalekohledů (angl. The Evolution of Space Telescopes) se zaobírá popisem vývoje dalekohledu od jeho úplného počátku až po dnešní nejmodernější vesmírné teleskopy. Cílem této práce je podat stručně a přehledně zpracované informace o daném tématu.

První kapitola se zabývá historickým vývojem tohohle astronomického přístroje. V podkapitole 1.1 je zmíněno objevení dalekohledu Hansem Lippersheyem v roce 1608 a jeho následné vylepšování Galileem Galileim a Johannesem Keplerem. První teleskopy byly sestaveny za pomoci čoček a brzy byla optická teorie refrakčního dalekohledu zdokonalena. Největší limitací těchto dalekohledů byly optické chyby způsobené zakřivením čoček, zejména sférická a chromatická aberace. Tyto chyby byly odstraňovány prodloužením fokální délky teleskopu. Ve druhé polovině sedmnáctého století byly konstruovány enormně dlouhé dalekohledy (několik desítek až stovky metrů), které představovali vrchol veškerého potenciálu čočkových dalekohledů.

Podkapitola 1.2 se zaměřuje na jiný druh optického dalekohledu – zrcadlový. I když byla optická teorie reflexního teleskopu známá už od doby Galilea, výroba a broušení zrcadel byly dlouhou dobu příliš náročné. Z tohoto důvodu byl první funkční zrcadlový dalekohled sestrojen až Isaacem Newtonem v roku 1668. I když byl Newtonův vynález funkční, stále nemohl konkurovat dlouhým refraktorům. To se podařilo až Johnu Hadleymu v roce 1721, když vyrobil reflektor s parabolickými zrcadly. Další významnou osobností ve vývoji dalekohledu byl William Herschel, který mimo jiné objevil planetu Uran v roku 1781.

Následující podkapitola (1.3) se věnuje vzniku radioastronomie a začíná neúmyslným vynálezem radioteleskopu Karlem Janskym v roce 1936. Jansky zkoumal efekt vzdálených bouřek na radiové komunikace a objevil neočekávaný zdroj radiového signálu, který byl nakonec identifikován jakožto střed naší galaxie. Krátce poté se začali radioastronomií zabývat i další astronomové, především Grote Reber a Harold Ewen s Edwardem Purcellem. Po druhé světové válce radioastronomie rychle rozkvétala. Byly odpozorovány přesné vzdálenosti Země od Slunce a dalších planet v Sluneční Soustavě a byli objeveny kvazary a pulsary.

V podkapitole 1.4 jsou zpracovány počátky vesmírných dalekohledů. Po druhé světové válce byly zkonfiskovány německé rakety V-2, které byly předělány pro vědecké účely. Tyto rakety měli dostatečný výkon k výstupu nad atmosféru a s postupem času byly vylepšovány a použity k prvním spektroskopickým pozorováním mimo atmosféru. Po úspěšném vypuštění sovětského satelitu Sputnik v roce 1957, tempo amerického vesmírného programu prudce vzrostlo a NASA začala pracovat na tzv. Orbitálních astronomických observatořích (angl. Orbiting Astronomical Observatories, OAO).

Druhá kapitola se zaobírá popisem vesmírných teleskopů s členěním podle části elektromagnetického spektra, kterou zkoumají, tzn. radiovou, mikrovlnnou, infračervenou, viditelnou, ultrafialovou, rentgenovou a gamma složku. Každé části je věnovaná jedna podkapitola. Radiové vlny jsou zachytávány anténami. Signál je v této části elektromagnetického spektra slabý, a proto i výsledné snímky bývají méně kvalitní. Tomuto problému lze předcházet použitím astronomické interferometrie – použitím více radioteleskopů najednou. Obecně platí, že čím větší je vzdálenost mezi radioteleskopy, tím ostřejší bývá výslední obraz, a pro tenhle účel jsou vesmírné radioteleskopy nejvhodnější. Mikrovlnné dalekohledy jsou podobné radiovým, taky detekují vlny za pomoci antén. Jejich primární využití je při pozorování reliktního záření (angl. Cosmic Microwave Background Radiation), které je pozůstatkem velkého třesku.

Infračervené záření je vyzařováno každým zdrojem tepla. To znamená, že infračervené dalekohledy musí být chlazeny na úroveň blízkou k absolutní nule, aby se zabránilo zkreslení dat samotným dalekohledem. Tyto vlny nepřecházejí zemskou atmosférou, a proto se dají pozorovat pouze vesmírnými teleskopy. Výhodou téhle části spektra je, že se infračervené světlo nesráží s prachovými částečkami tak, jako viditelné světlo. Astronomové mohou skrze tuto spektrální složku vidět přímo do středu galaxií nebo hvězdokup, i když jsou vysoce přesycené viditelným světlem.

Viditelné světlo a jeho sousedící oblasti (infračervené a ultrafialové záření) jsou detekovány optickými dalekohledmi, zejména zrcadlovými. Tato část spektra je vhodná pro studium hvězd, které vyzařují v těchhle vlnových délkách. Další výhodou je možné využití spektroskopie – analýzy optického spektra a mezer v něm, které symbolizují chemické prvky daného kosmického objektu.

Ultrafialová část elektromagnetického spektra je absorbována atmosférou, takže pro pozorování jsou potřebné vesmírné teleskopy. Ty zkoumají primárně mladé hvězdy, které vydávají záření spíš v téhle části spektra. Nejběžnější chemické prvky ve vesmíru mají svůj spektroskopický „podpis" právě v ultrafialovém světle, a následná analýza umožňuje získávat informace o tom, kde se tyto prvky nacházejí.

Rentgenové světlo má vysokou úroveň energie a lze ho zachytit pouze zrcadly se speciálním povrchem a seskupením ve velmi tupých úhlech vzhledem k příchozímu světlu. Daný signál se pak odrazí od povrchu zrcadla do detektoru. Zdroje rentgenových vln jsou většinou žhavá vesmírná tělesa, především černé díry, pozůstatky supernov, nebo vnější atmosféry hvězd.

Gamma záření nelze zachytit běžnými prostředky, tudíž musí být použity speciální detektory s filtry, aby zamezily nežádoucímu záření z okolí. Množství zachycených gamma částic je velmi malé, a z tohoto důvodu bývá výsledný obraz méně detailní. Gamma vlny jsou vyzařovány nejžhavějšími kosmickými objekty – černými dírami a supernovami. V této části spektra jsou také studovány gama záblesky (angl. Gamma Ray Bursts).

V poslední kapitole této práce jsou probrány tři nejvýznamnější vesmírné dalekohledy vůbec: Hubbleův a Keplerův vesmírný dalekohled a Vesmírný dalekohled Jamese Webba. První podkapitola (3.1) popisuje přelomové přínosy Hubbleova vesmírného dalekohledu, který byl prvním velkým vesmírným teleskopem ve vesmíru. Hubbleův teleskop byl vypuštěn na oběžnou dráhu kolem Země v roku 1990 a dodnes zůstává v provozu. Tenhle dalekohled je opravdu revoluční – s jeho pomocí se podařilo zjistit přesný věk vesmíru a způsob jeho rozpínání, a taky zachytit vysoce detailní snímky Hubble Deep Fields.

Předmětem podkapitoly 3.2 je Keplerův vesmírný dalekohled, který byl aktivní v letech 2009 až 2018. Jeho primární misí bylo hledání exoplanet, konkrétně analýza jejich frekvence v obyvatelných zónách kolem jejich mateřských hvězd. Z tohohle výzkumu bylo následně objeveno více než 2 600 exoplanet. Třetí podkapitola 3.3 se zaměřuje na nově vypuštěný Vesmírný dalekohled Jamese Webba. Tenhle dalekohled byl vyslán do vesmíru v roce 2021 a za tu dobu provedl množství astronomických pozorování. Je navržen tak, aby pokračoval v misi Hubbleova teleskopu, tj. zkoumání počátků vesmíru, hledání a spektroskopická analýza exoplanet a pozorování vzniku hvězd a galaxií. V závěru práce je krátké shrnutí, kde jsou všechny informace zrekapitulovány.

BÁTOROVÁ, Silvia. *Evoluce vesmírných dalekohledů.* Brno, 2023. Dostupné také z: https://www.vut.cz/studenti/zav-prace/detail/151497. Bakalářská práce. Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, Ústav jazyků. Vedoucí práce Kenneth Froehling.

Prohlášení

Prohlašuji, že bakalářskou práci na téma *Evoluce vesmírných dalekohledů* jsem vypracovala samostatně pod vedením vedoucího bakalářské práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne ....

Silvia Bátorová

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CONTENTS

INTRODUCTION

A telescope is a tool that focuses light, and, as a result, it produces a bigger and brighter image than what is possible to be observed by a naked eye. The first telescope was made in the year 1608, and its beginnings have been slow. The progress of the telescope's development was hindered by the level of skill the lens manufacturers possessed (the more perfect the lens, the better the image produced) and the theory of optics available at that time. The refracting telescope was mostly limited by its optical theory – or lack there of. No advancements in optical theory had been made for a long time after Galileo's and Kepler's forms. The issues with aberrations (at that time unknown) were worked around by increasing the focal length of the lenses. The next advancement in its optical theory was made by René Descartes, who theoretically solved spherical aberration and by Isaac Newton, who explained chromatic aberration.

In stark contrast is the reflecting telescope, where the theory had been available since Galileo and kept steadily advancing with the work of Descartes, Mersenne, Gregory and others. The major limitation in its development had been the manufacturing process, since a reflecting surface was even harder to make than a refracting one. This is why the first usable reflector was made in 1668, many years after its theoretical advent. Even then, the reflecting telescope could not compare to the long refracting telescope. It was only in 1721, when John Hadley created a parabolic mirror telescope that the reflector became a popular astronomical instrument.

The next phase in the telescope's evolution came with the rise of radio astronomy in the 20th century. By detecting waves outside of the visible spectrum, astronomers could gather new information from cosmic sources. Since radio waves cannot be seen by human eyes, computer programs are used to transfer the collected data into images.

Most parts of the electromagnetic spectrum are absorbed by the Earth's atmosphere. In order to make use out of all parts of this spectrum, humankind had to reach past this barrier and deploy space telescopes. This has caused an astronomical revolution. The images unimpeded by the negative effects of the atmosphere, such as the scattering of light or differing air density, were of much higher quality than ever before. Observations of much further parts of the universe could as of then be performed. The subsequent utilization of the entire electromagnetic spectrum revealed the universe in a whole new light. And with each new space telescope launched, more information about the universe was revealed.

The beginnings of the space telescope occurred after the second World War. The initial attempts involved sending sounding rockets with spectroscopic instruments above the atmosphere, where they gathered data from the Sun. The dawn of space telescopes culminated with the launch of NASA's Orbiting Astronomical Observatories. After these events, a new era for the telescope emerged – with the launch of the Hubble Space Telescope in 1990. Hubble was the largest, most ambitious astronomic endeavor up to that point, carrying on board many revolutionary scientific instruments.

Remarkably, it is still active more than 30 years later and keeps collecting data from all corners of the universe, from our own Solar System to the very beginning of time. Its primary mission has a very broad scope due to the fact that so much of the universe was still unknown at the time of its development. Hubble has exposed our universe in way never imagined before. It has confirmed the existence of exoplanets, studied black holes and determined the age of the universe with unparalleled accuracy. It has also revealed surprising information about the expansion of the universe and observed the distant parts of the cosmos with the use of gravity lenses and deep field images.

Over the years, many space telescope have been deployed into space. Among the most distinguished ones is the Kepler Space Telescope. Operating between 2009 to 2018, it performed innovative photometric observations of exoplanets in our galaxy and analyzed their prevalence in the habitable zones of their respective star systems. The planets Kepler discovered offered fascinating insights into the way star systems are formed and the characteristics of exoplanets. It has laid foundations for further search for extraterrestrial life.

Continuing the work of both Hubble and Kepler is the James Webb Space Telescope. Webb was launched in 2021 and its mission is to observe the early stages of the universe, study the formation of galaxies and star systems and analyze exoplanets. As the largest, most advanced space telescope as of now, it is able to capture images with an unprecedented amount of detail. Webb is currently performing observations, which are already producing extraordinary results. It has taken images of nebulae, galaxies and stars and detected exoplanets, while also spectroscopically analyzing their atmospheres.

This thesis is divided into three chapters. The first chapter presents the brief history of the telescope. The second chapter focuses on the categorization of space telescopes in accordance with the spectral band that they study, as well as introducing their strengths and weaknesses. The third chapter takes a closer look at the Hubble, Kepler and James Webb Space Telescopes and describes the impacts they have had on modern-day astronomy. At the end of the thesis there is a conclusion in which the contents of the thesis are briefly summarized.

1. THE FIRST TELESCOPES AND SPACE TELESCOPES

For thousands of years people have gazed at the sky and wondered what those tiny specks of light could be. Throughout the centuries many discoveries have been made about the universe we live in. The early civilizations gave us the notion of stars and planets, that the Earth is round and rotates around its axis and that the planets and the Moon do not emit light of their own, but merely reflect light from the Sun. They developed calendars and star catalogues, observed many astronomical phenomena such as comets and supernovae and built sun-clocks and observatories. (Cook, 2018)

But there is only so much to learn from something so minuscule and so out of our reach. Up until a few hundred years ago, people were limited by their eyesight and the distance of the cosmic objects. The invention of the telescope was revolutionary, changing almost everything people knew about the universe and forever altering the course of astronomy. Finally, the star-gazers had a tool that brought the night sky closer.

1.1 Lens telescopes – refractors

The first mention of a telescope came from the Netherlands in the year 1608. Though it is unclear who precisely is the official inventor of the telescope, most historians agree that it was Hans Lippershey, who specialized in making glasses. He appears to be the first person, who put two lenses together and had them form a clear, enlarged image. He made a prototype of his discovery and the news of the groundbreaking apparatus soon spread to the rest of Europe.

A year later, Galileo Galilei had heard about Lippershey's telescope and adapted it to make his own version, which was to be used for astronomical purposes. It consisted of two lenses – one concave and one convex – held together by a metal tube. He kept refining his design in order to increase magnification and made numerous discoveries and observations. He discovered four of Jupiter's largest satellites and observed the surface of the Moon, the phases of the planet Venus and dark spots on the surface of the Sun.

Galileo's findings greatly intrigued Johannes Kepler, who studied optics and the effect of refraction and was the first to correctly describe how a human eye perceives images. In 1611, he proposed a refined version of the Galilean telescope, which used two convex lenses. (King, 1955)

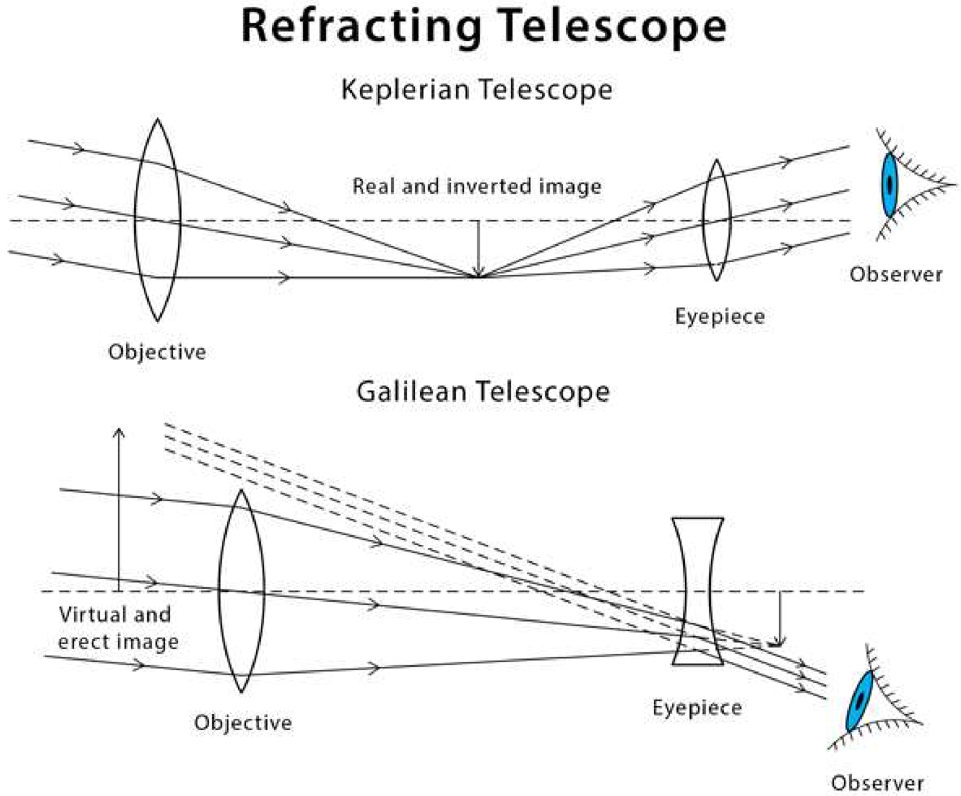

Fig. 1. Refracting Telescope ("Refracting Telescope," 2020)

The Galilean telescope was limited by a small field of view and magnification of up to only 20 times. The Keplerian telescope offered increased magnification and brighter and sharper image. But the convex lens Kepler proposed as an eyepiece exacerbated the optical distortions known as spherical and chromatic aberration. (Van Helden, 2009) Spherical aberration means the rays of light passing through a spherical lens cannot converge into a single point, resulting in a blurred image. Chromatic aberration is created by the dispersion of full-spectrum light, causing the image to have colorful, blurry edges. (Kumar, 2006)

Many astronomers had worked on ways of reducing these errors, such as increasing the focal length of lenses. In order to achieve this, telescopes had to increase in length. One of these astronomers was Johannes Hevelius. He made numerous telescopes in the 1640s, the biggest one being 46 meters long. Another pioneer of this era was Christiaan

Huygens, who with his high-quality telescopes of considerable length discovered Saturn's moon Titan in 1655.

These long telescopes were not limited by the laws of optics, but rather by practical constraints. There came a point where the sheer size of the instrument became impractical. The aligning of the lenses turned out to be a tedious complication, the heavy instrument needed to be operated with the help of ropes and pulleys and its weight made it prone to swaying and shaking, which blurred the perceived image. With this in mind, Huygens opted for making a telescope without the heavy tube. He created an aerial telescope, with the two lenses mounted on a pole, a design of which he described in one of his publications in 1684. (Wall, 2018)

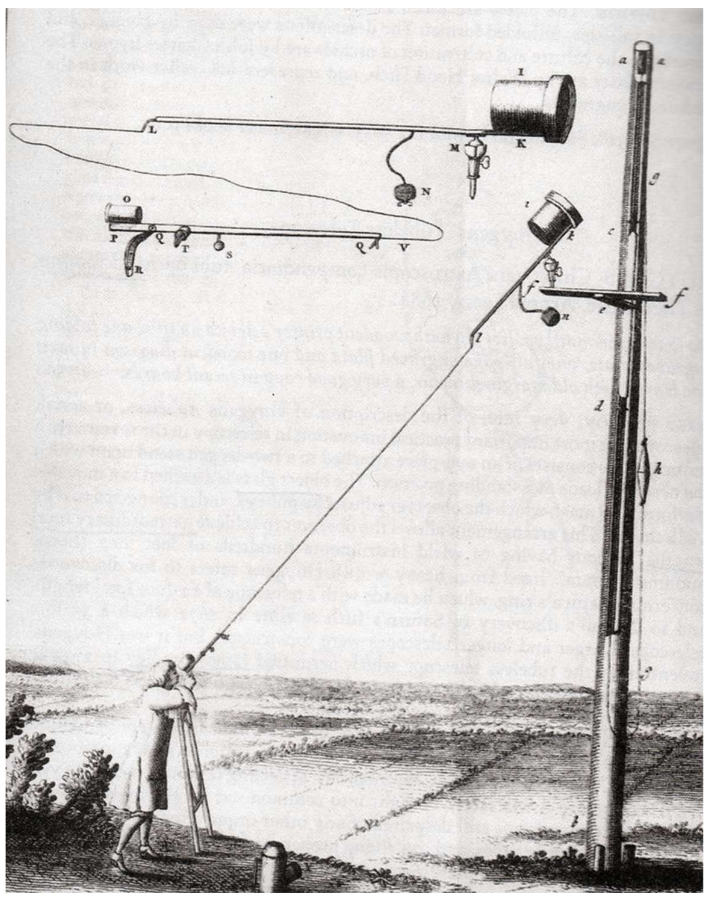

Fig. 2. Aerial Telescope (Ptak, n.d.)

The potential of the refracting telescope had been fulfilled for a while. It took a few decades for the next improvement to it be made – the creation of the achromatic lens. In the meantime, some astronomers had their minds set on an entirely new design of the telescope altogether: the reflector.

1.2 Mirror telescopes – reflectors

After Kepler, the next important advancement to the theory of optics came with the work of René Descartes. He studied the nature of light and colors, the effects of refraction and reflection and described a way of fixing spherical aberration – using aspherical lenses and mirrors. He also confirmed the need of using parabolic mirrors in reflecting telescopes.

The concept of the reflecting telescope had been thought of by even Galileo himself; he recognized that replacing refracting lenses for reflecting mirrors would produce a similar magnifying effect. Though the attempts at making such telescopes were unsuccessful for some time. The first reflecting telescope was made by Niccolò Zucchi in 1616, but the quality of the image was too insufficient to be considered usable. Other forms of the reflecting telescope were proposed independently of each other by Marin Mersenne in 1636 and by James Gregory in 1663. (Wilson, 2007)

The difficulty of making a curved reflecting surface proved to be the major limiting factor in the invention of a working reflecting telescope. In 1668, a new design for the reflector had been created by Isaac Newton. He constructed a telescope with a primary plano-concave mirror and a secondary plane mirror angled at 45°, which reflected the light into an eyepiece. (Cottrell, 2016) The curved mirror was made from a bronze alloy, with arsenic added as a way of increasing reflectivity.

The reason why Newton was the first to succeed lies probably in the fact that while his colleagues relied on artisans to make the pieces used for their telescopes, Newton built his tools and the entire telescope by himself.[1] He also brought into the field two considerable improvements: one being the way of polishing the telescope mirrors (pitch

[1] According to Westfall (1993), Newton mentioned to the husband of his half-niece “if I had staid for other people to make my tools & things for me, I had never made anything of it ….” (p. 81).

polishing) and the other being the theory of chromatic aberration, which he derived from his famous study of light.

In 1672, independently of Newton, a new design had been proposed by Laurent Cassegrain. His version was similar to the designs of Mersenne and Gregory, so Newton, seeing as all of these versions were not ready to be put into practice quite yet, heavily and unjustly criticized Cassegrain's form and his work soon fell into obscurity. It was only later that his work was uncovered and used again – and nowadays it is the most commonly used layout in modern telescopes. (Watson, 2007)

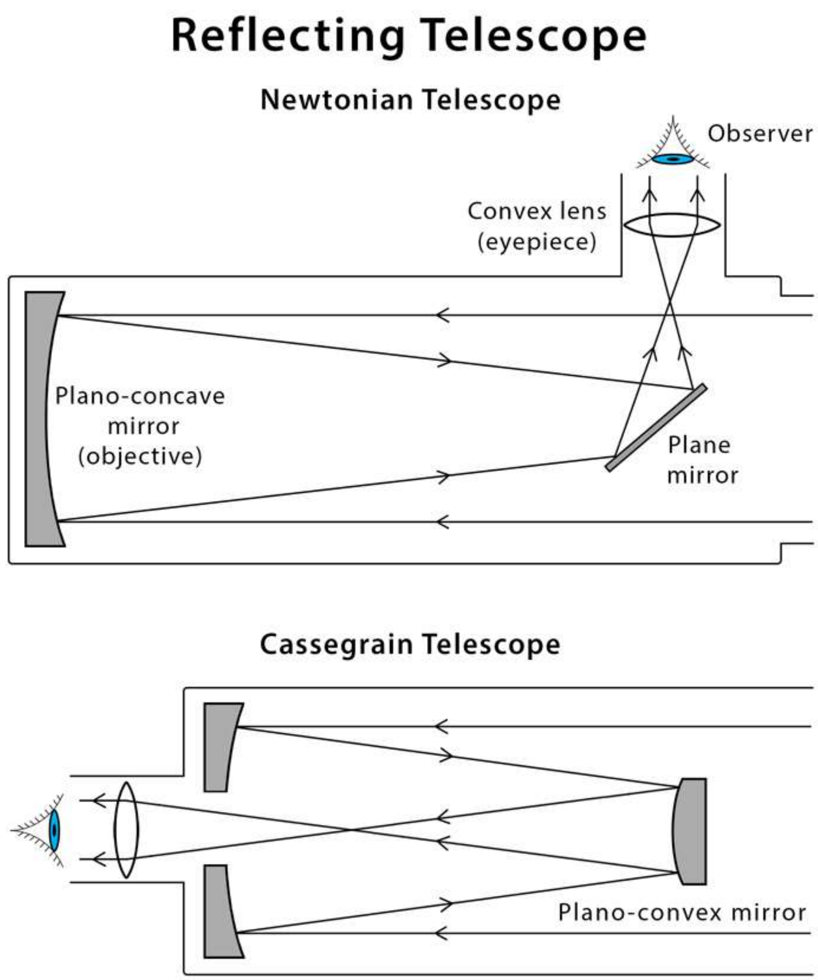

Fig. 3. Reflecting Telescope ("Reflecting Telescope," 2020)

Though Newton's telescope was the first and only successful version for some time, it still had a lot of drawbacks. The metal from the telescope's mirror had low reflectivity and was prone to tarnish and had to be repolished regularly. (Cotrell, 2016) For these reasons, it still could not compare to the long aerial telescopes of that time and was regarded merely as a scientific toy. (King, 1955) Newton's invention had been a major step forward in the telescope's evolution, but in order for the reflector to surpass the refractor, more improvement in the fabrication of telescope mirrors needed to be done.

In 1721, these improvements were achieved by John Hadley, who made a Newtonian reflector with parabolic mirrors. His craftsmanship was so remarkable that it could compete with the aerial telescope and it is thanks to Hadley that the reflector became a tool usable in praxis. Another big breakthrough for the telescope (this time for the refractor) was the invention of the achromatic lens by Chester Moore Hall in 1729. But its usefulness was not recognized until John Dollond expanded the research and patented it in 1750. An achromatic lens, as its name would suggest, reduces chromatic and even spherical aberration. (Wilson, 2007)

In the second half of the 18^{th} century, the work of William Herschel improved the reflector even further. He kept refining his skill of mirror polishing and bore great results, eventually discovering Uranus with one of his telescopes in 1781. (Wall, 2018) A great leap forward was made by Jean Foucault, who invented a new way of making mirrors and made the first silver-on-glass telescope in 1857, greatly easing the difficulty of manufacturing the reflector. (Bell, 1922)

Over the following years many more discoveries and improvements had been made to the telescope. The telescopes kept getting bigger and bigger and the quality of their image had been improving drastically. But the direction of the telescope's development would soon take a completely unexpected turn – with the creation of radio astronomy.

1.3 Radio telescopes

In the 20^{th} century, radar and radio communication was on the rise. In order to achieve a clear signal, disturbances acting onto the signal had to be studied and prevented. In 1936, Karl Jansky studied the effect distant thunderstorms had on communications. He assembled an antenna and placed it onto a rotating stand so it could be aimed at the direction of the interference. He soon found an unusual amount of noise coming from a certain point in the azimuth.[2] It was coming from the center of our galaxy. Jansky's work was picked up by Grote Reber, who built his own radio telescope in 1937. It was a parabolic reflector antenna and with it he made a series of observations and published the first maps of galactic radio emission.

The radio and radar technology saw a lot of development during the Second World War. After the war, many of the German radar antennas were utilized by radio astronomers. (Baars and Kärcher, 2018) In 1951, the 21-cm radiation of neutral hydrogen atoms in our galaxy was measured by Harold Ewen and Edward Purcell. It helped expose the shape of our Milky Way. During that same year, the galaxy Cygnus A was discovered by radio astronomy.

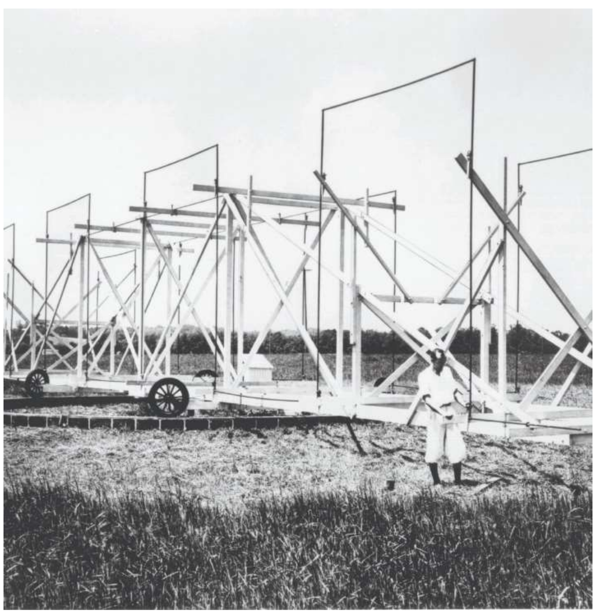

Fig. 4. Jansky's Antenna (National Radio Astronomy Observatory [NRAO], n.d.-b)

Fig. 5. Reber's Radio Telescope (NRAO, n.d.-a)

Over the upcoming years, more and more discoveries had been made with larger and larger telescopes. The range of the measured frequencies kept also increasing, allowing

[2] Azimuth: a horizontal angle measured clockwise in degrees from a reference direction

for precise evaluation of distances to nearby planets. As a result, the astronomical unit (the average distance from the Earth to the Sun) could be accurately determined, enabling the calculation of the distances of all Solar System planets from the Sun. Surfaces and temperatures of planets were also possible to be identified. Other important footnotes in the radio astronomy's history were the discoveries of quasars (1963), cosmic microwave background radiation left after the Big Bang (1964) and pulsars (1967). The most recent breakthrough has been the first ever picture of a black hole, which was taken in 2020. (Lauterbach, 2022)

1.4 Space telescopes

A telescope in space, e.g., in Earth‘s orbit, is not hindered by the effects of the Earth's atmosphere. These effects occur in multiple ways; the first being the scattering of light coming from space. Scattering of light occurs most commonly with wavelengths similar to the size of particles the light hits. Hence, visible light scatters when coming into contact with mist or dust, all the while radio waves pass through them with no issue. The second effect of the atmosphere is its diverse density, which causes the stars to 'twinkle' – to change their position and brightness level. This negatively influences the sharpness of the telescope's image. The third effect is the absorption of most of the wavelengths of the electromagnetic spectrum. As a consequence, observations of the absorbed parts of the electromagnetic spectrum have to either take place in space or in specific areas on Earth, though the quality in those places is still subpar. (Australia Telescope National Facility [ATNF], n.d.)

The advantages of space telescopes were widely recognized by scientists, though the difficulties of launching cargo into orbit proved very challenging and stalled the launch of space telescopes for quite a while. The first steps in space astronomy were taken with the launching of V-2 rockets after the Second World War. The V-2 rockets were originally made by the German military with the purpose of bombarding enemy cities. After the war ended, these rockets were confiscated by the USA and USSR and repurposed for space exploration. The rockets used by the USA were equipped with spectrometers and took measurements during their short flights above most of the Earth's atmosphere.

After the V-2's, more advanced rockets were built and in 1946, the first map of the ultraviolet spectrum of the Sun was obtained. In addition to rockets, astronomical balloons were often used to take more precise measurements and images due to their smoother motion. Balloons were used to, for instance, study the surface of the Sun. The pace of the American space exploration gained rapid traction after the USSR successfully launched their first space satellite, Sputnik, in 1957. In the following year, NASA began working on Orbiting Astronomical Observatories (OAO). (Spitzer, 1979)

OAO 2, NASA's first successful space telescope, studied the universe within the ultraviolet spectrum. It was launched in 1968 and provided the scientists with new information about the true temperature of hot stars (which was higher than previously believed) and proved that comets hold clouds of hydrogen around them. (Reddy, 2018) The launch of OAO 2 marked the starting point of a new era – the era of space exploration, accompanied with the deployment of a great number of space telescopes, each outdoing the last. With the image capturing technology always improving and continually better deployment methods becoming available, humankind keeps reaching further for the stars than it ever has before.

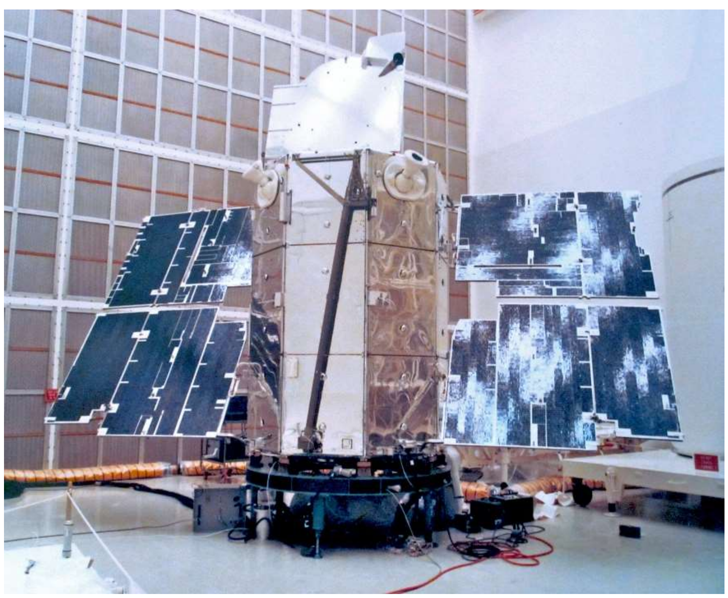

Fig. 6. OAO 2 before launch (Reddy, 2018)

2. TYPES OF SPACE TELESCOPES AND THEIR ADVANTAGES AND DISADVANTAGES

Space telescopes are most commonly categorized according to the part of the EM spectrum they observe. Of course, the same telescope may carry on board multiple measurement devices all designed for different wavelengths. Nonetheless, the telescope usually has one major EM band it focuses on the most. The technology used for data capture varies across the EM spectrum and the advantages and disadvantages of each such measuring method are going to be described in this chapter.

Radio waves and microwaves are able to be picked up by antennas. The part of the EM spectrum around visible light is similar enough in wavelength that it may be collected using the same kind of instruments as are present in optical telescopes – lenses and mirrors. This part of the spectrum contains infrared, visible and ultraviolet radiation. Going further down the spectrum we find waves with such small wavelengths that they pass right through regular mirrors. The X-ray telescopes use mirrors with special surfaces and have them placed at very shallow angles to the incoming waves. The most energy-filled band, the gamma radiation, is not focused like the rest, but is collected by particle detectors. (English, 2017)

2.1 Radio telescopes

Radio waves have the longest wavelength of the EM spectrum. Along with visible light, they are the only two parts of the EM spectrum not absorbed by the Earth's atmosphere. That means observations can be carried out on the Earth's surface. Unlike optical telescopes, radio telescopes can operate during the day and in various weather conditions. Certain ranges of the radio spectrum have been reserved for astronomical observation, with the majority of the spectrum being taken up by communications. This may cause problems with signal interference and noise during observations, especially if the ranges being used by astronomers are close to those used for communications. To reduce interference of the signal, telescopes are situated in areas with low radio traffic, such as mountain ranges. (Lauterbach, 2022)

Radio telescopes are used in a number of ways, one of them being the measurement of the distance the cosmic objects are from us. The mapping of galaxies is also possible with the detection of hydrogen gases, which are commonly found in galaxies. (Commonwealth Scientific and Industrial Research Organisation [CSIRO], 2021) Radio telescopes are also used for studying distant cosmic objects, which emit radio waves, such as quasars or pulsars. These celestial bodies cannot be seen by optical telescopes, because their light is obstructed by dust in neighboring galaxies. (National Aeronautics and Space Administration [NASA], 2016b)

A drawback of radio telescopes is the low quality of image when compared to the same-size optical telescopes. This issue stems from the long wavelength of radio waves. In order for a radio telescope to produce an image of the same quality as an optical telescope would, its size would need to be a million times bigger. During the development of radio astronomy, the challenge of increasing the image sharpness had been the main goal of many astronomers. (Christiansen & Högbom, 1969)

One way of achieving higher resolution is with the use of radio interferometry, which combines the data from multiple radio telescopes. Very Long Baseline Interferometry (VLBI) is a special type of interferometry, where the area of the interferometer spans across thousands of kilometers. These telescopes act the same way as a single large radar dish. (Center for Astrophysics [CFA], n.d.-c)

While the majority of radio telescopes is on the ground, there have been multiple space missions equipped with radar telescopes. The most important ones are HALCA, launched by the Japan Aerospace Exploration Agency (JAXA) and Spektr-R, launched by the Russian Space Agency, Roscosmos. They were both designed for VLBI and provided considerably larger resolution of images than ground-based interferometers. (Krebs, 2017, 2022)

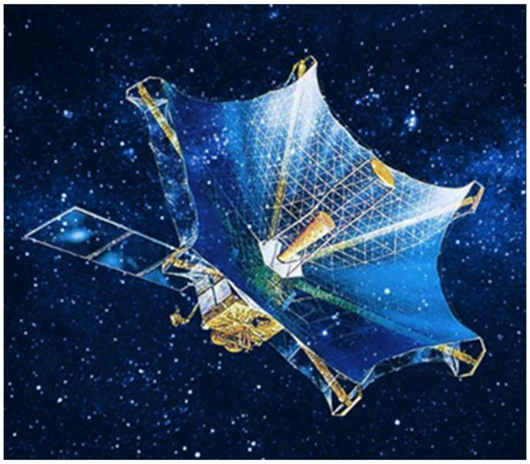

Fig. 7. HALCA (Japan Aerospace Exploration Agency [JAXA], n.d.)

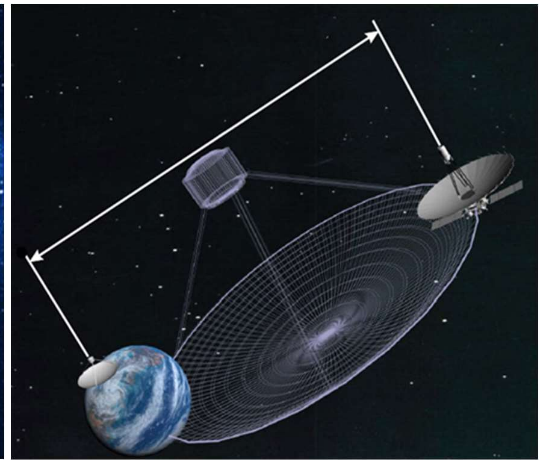

Fig. 8. Spektr-R used as part of VLBI (NASA, 2013)

2.2 Microwave telescopes

Microwaves are often considered to be a subset of radio waves. Microwaves have a higher frequency and thus higher energy than radio waves. They can still partly pass through the atmosphere, but most of them are absorbed by it. Therefore, for most observations in the microwave range, space telescopes need to be deployed. The instruments we use to detect microwaves are the same as those in radio telescopes – antennas. Since microwaves share similar properties to radio waves, their advantages and disadvantages are similar as well. They can see dim celestial objects from very far away, but their resolution is weaker than that of other telescopes.

Microwave telescopes detect objects and phenomena that radiate microwaves, such as black holes, pulsars and, most importantly, cosmic microwave background radiation. CMB radiation was discovered in 1964 by Arno Penzias and Robert Wilson with their horn antenna. (Millis, 2019) The signal they picked up came from all parts of the sky with no variation in intensity. They ascribed it to left-over radiation after the Big Bang and it serves as one of the key proofs of the Big Bang theory. By observing CMB radiation, we can look into the origins of our universe – farthest into the past any telescope can see. (European Space Agency [ESA], n.d.-a)

The most notable microwave space telescopes were COBE and WMAP, both deployed by NASA in the years 1989-1993 and 2001-2010, respectively. (NASA, 2013) Their work was picked up by Planck, a microwave space telescope operated by the European Space Agency, ESA, from 2009 to 2013. The telescopes all primarily studied the CMB radiation and each telescope improved the quality of the maps made by the previous one. (ESA, 2019) The comparison of the image quality of these three telescopes is shown in the figure below.

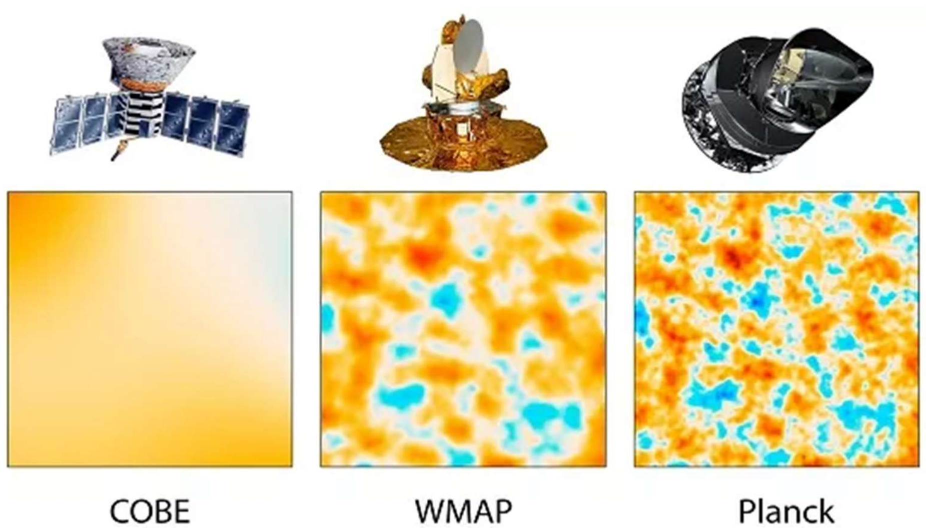

Fig. 9. Comparison of the image quality of telescopes observing CMB radiation (Levesque, 2022)

2.3 Infrared telescopes

Infrared radiation is given off by all warm objects. With higher temperatures comes more infrared radiation. This characteristic is quite problematic for astronomers, since the telescope and its sensors also emit infrared waves. To get around this issue, space telescopes are cooled by liquid nitrogen and helium to temperatures nearing absolute zero. The telescopes are also placed on a special kind of heliocentric orbit, where they are unaffected by the heat coming from Earth. (Ogilvie, 2017)

Infrared waves are mostly absorbed by the atmosphere, thus the use of space telescopes is preferred for this range. The infrared telescopes on the Earth's surface are placed in dry and high-altitude areas in order to limit the effect of water vapor in the atmosphere on the data. Nonetheless, the heat coming from the Earth's atmosphere still needs to be taken into consideration in the measurements. This is done by simultaneously measuring the infrared radiation of both the sky and the celestial bodies and then removing the atmospheric influence from the picture. (NASA, 2013)

Infrared telescopes can detect cosmic objects, which are too cold and dim to be picked up by the optical telescopes, such as planets or cool stars. Just like radio waves and microwaves, infrared waves can also pass through dust in space without being dispersed. (NASA, 2016a) The advantage of using the infrared spectrum is that it can show us in great detail areas, which are heavily saturated by visible light and therefore difficult to discern with optical telescopes. Such areas are, for example, the centers of galaxies or hot parts of the universe, where new stars are born, the so-called ‘star nurseries‘ or nebulae. (NASA, n.d.-b)

The most noteworthy infrared space telescopes were the Spitzer Space Telescope and the Herschel Space Observatory. The Spitzer Space Telescope was the final of NASA’s four Great Observatories, which all studied different parts of the EM spectrum. During its operation between 2003 and 2020, it studied the formation of stars and planets, analyzed atmospheres of exoplanets and identified supermassive black holes. (CFA, n.d.-b) The Herschel Space Observatory was launched in 2009 by ESA and remained in service until 2013. Its unique spectral range reaching from far-infrared to submillimeter wavelengths allowed it to capture signals, which were as of then unobserved by other infrared telescopes. It surveyed in great detail the regions of forming stars. (ESA, n.d.-b)

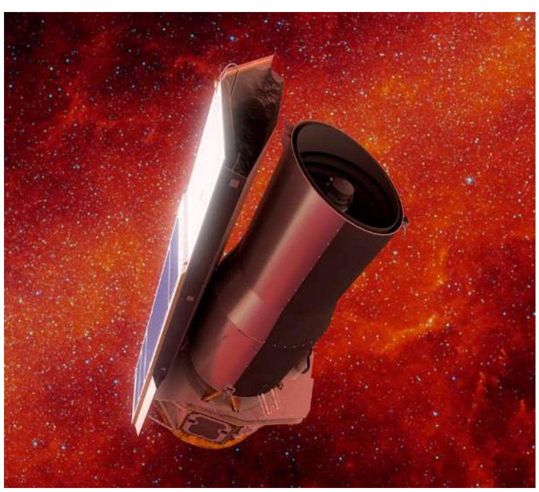

Fig. 10. Spitzer Space Telescope (Urrutia, 2020)

Fig. 11. Herschel Space Observatory (Howell, 2014)

2.4 Visible light telescopes

The visible light is the part of the EM spectrum detectable by the human eye. Hence, it represents the appearance of the universe most people are familiar with. Visible light passes through the atmosphere and as a result it has been the only way of observing the night sky for most of history. Even with the rise of technology detecting other wavebands, the visible light still has its important role in the never-ending study of our universe.

Stars emit a lot of their energy in the form of visible light and their temperature is easily recognized through their color – hot stars are blue, whereas cold stars are red. (Space Telescope Science Institute [STScI], 2019) Another way astronomers use visible light is by studying spectral signatures of atoms present in cosmic objects. Different elements absorb different parts of the EM spectrum, resulting in gaps in the spectrum. By studying the placement of these gaps in the visible light spectrum, astronomers can determine the exact elements the celestial bodies consist of. (NASA, 2010b)

The drawback of visible light is that it scatters upon impact with dust particles. This results in lesser visibility of distant cosmic objects, as with increasing distance rises the possibility of the light hitting dust clouds on its way to the telescope. Another constraint is the amount of light the telescope can gather. If a celestial object is too faint, it will not be visible. The amount of light collected can be increased by making the telescope's mirror bigger, but there is a limit to which degree this is possible. As a consequence, visible light telescopes are able to view only bright celestial bodies, such as stars or galaxies.

The most well-known visible light space telescopes are the Hubble Space Telescope and the Kepler Space Telescope. The Hubble Space Telescope is perhaps the most famous space telescope in the world. Its spectral range extends from the infrared, through the visible and to the ultraviolet radiation and for this reason it is capable of viewing a wider number of space objects and even to compare and combine the data from these different bands. It has been in commission since the year 1990 and during this time it has observed our solar system and galaxy as well as distant planets and black holes. (Belleville, 2022) The Kepler Space Telescope's main objective was to find and study potentially habitable planets in our galaxy. Working from 2009 to 2018, it had discovered more than 2,300 exoplanets. (Bartlett, 2022)

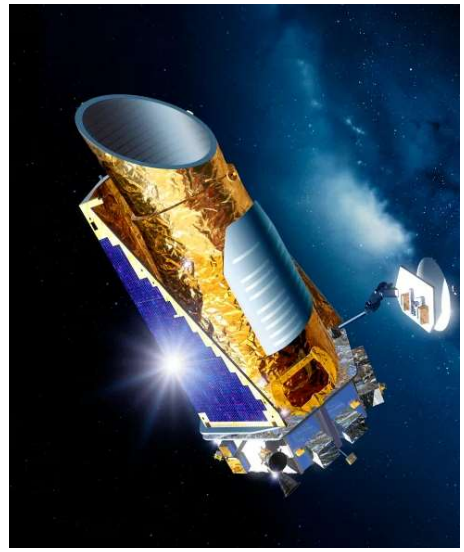

Fig. 12. The Hubble Space Telescope (Ashkenaz, 2022)

Fig. 13. The Kepler Space Telescope (Lemonick, 2014)

2.5 Ultraviolet telescopes

Ultraviolet radiation cannot penetrate the Earth's atmosphere and therefore only space telescopes are capable of detecting it. It is emitted by hot young stars, which radiate mostly in this part of the EM spectrum. In contrast are the older stars, like our Sun, which primarily emit visible light. When comparing data from these two parts of the EM spectrum, astronomers can determine the development and structure of galaxies. (NASA, 2010a) In the ultraviolet band, spectral signatures of the most common elements in the universe occur. Stars and giant gas planets are made up mostly of hydrogen and helium, and so studying them in this part of the EM spectrum reveals significant information about them. Our Sun, as well as Jupiter and Saturn are all analyzed in this way. (Carruthers, 2001)

Ultraviolet radiation is captured the same way as visible light – with the use of mirrors. Although, mirrors in ultraviolet telescopes differ from those used in visible light telescopes. This is due to the difference in wavelengths between these two parts of the EM spectrum. The material used for one type of telescope mirror may not be usable for the other. Ultraviolet telescopes are more restricted when it comes to the choice of mirror material. An additional limiting factor is that the quality of the ultraviolet mirror's surface needs to be greater than that of the mirror used in visible light telescopes. (Fluder, 2020)

The most significant ultraviolet space telescopes were GALEX and the Extreme Ultraviolet Observer. GALEX, or Galaxy Evolution Explorer, was launched in 2003 and remained in commission until 2013. Its primary mission was to study the early life of stars, as well as to gather more information about black holes and dark matter. (Jet Propulsion Laboratory [JPL], n.d.) The Extreme Ultraviolet Observer (EUVE) lasted from 1992 to 2001 and was the first telescope assigned to explore the extreme part of the ultraviolet spectrum. It performed an all-sky observation in the extreme ultraviolet band and analyzed the celestial sources of this radiation, such as hot white dwarfs or coronas of stars cooler than the Sun. (NASA, 2012)

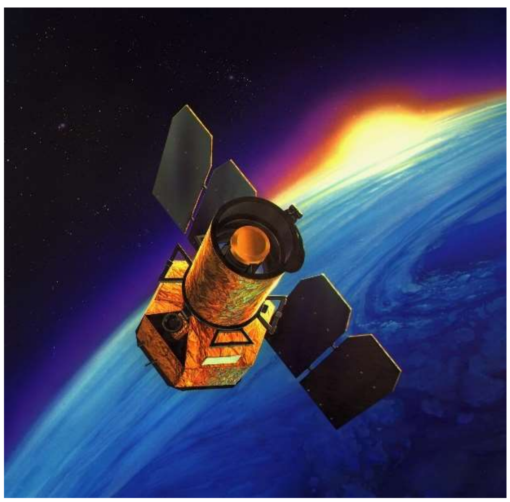

Fig. 14. GALEX (JPL, n.d.)

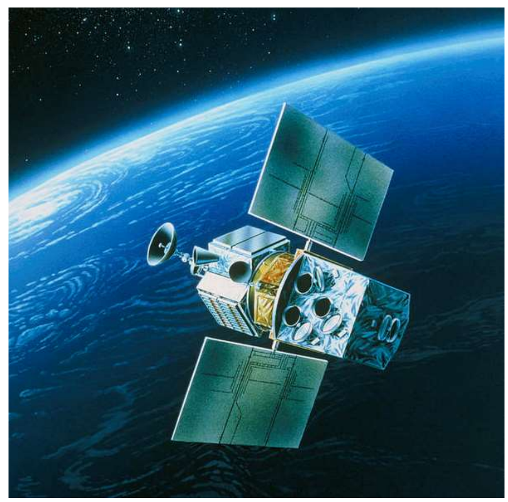

Fig. 15. Extreme Ultraviolet Explorer ("Artist's Impression of Extreme," n.d.)

2.6 X-ray telescopes

X-rays are emitted by hot cosmic objects with temperatures of more than a million degrees Celsius. Such a temperature may be found in the Sun's outer atmosphere – the corona. Other sources of X-rays are located outside of our solar system in the form of supernova remnants, black holes and a special kind of binary stars, where one of the stars is a neutron star collecting gas from a regular star, resulting in X-ray radiation. Hot gas between galaxy clusters is yet another source of X-ray signals, helping with their discovery. (ESA, n.d.-e)

Since the atmosphere is opaque to X-ray radiation, only space telescopes are viable for their detection. X-rays have a shorter wavelength and carry more energy than ultraviolet light. This property makes them pass right through regular mirrors. To mitigate this effect, the mirrors in X-ray telescopes are aligned at very shallow angles to the incoming X-ray signals and focus the waves into the telescope's detector this way. These shallow angles are called the 'grazing incidence'. (NASA, 2018b) A common way of placing these mirrors is to layer them into each other, resembling the composition of an onion. This increases the amount of light the telescope can collect, and thus raises its resolution.

This layering, though, adds to the weight of the telescope and increases the cost of launch. X-ray telescopes also require long focal lengths to focus the signal. To achieve long focal lengths and keep costs low, the NuSTAR telescope was launched with its mast folded, and then extended it upon reaching the orbit. (NASA, 2013) Operating since 2012, it is the first telescope to explore the high-energy part of the X-ray spectrum. It observed black holes, collapsed stars and supernova remnants. (California Institute of Technology [Caltech], n.d.) Another famous X-ray space telescope is the Chandra X-ray Observatory, one of NASA's Great Observatories. It has been in commission since 1999 and during this time studied collapsed stars, black holes and dark matter. (CFA, n.d.-a)

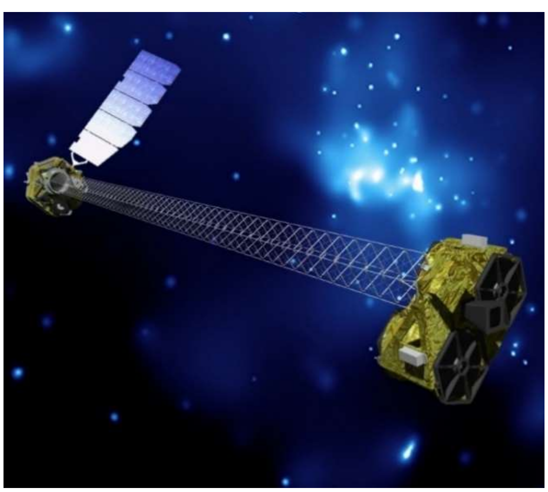

Fig. 16. NuSTAR (Moskowitz, 2012)

Fig. 17. Chandra X-Ray Observatory (NASA, 2019)

2.7 Gamma ray telescopes

Gamma rays are mostly blocked out by Earth's atmosphere and are usually captured by space telescopes. Due to their high energies and short wavelengths, gamma rays are very difficult to detect. Unlike other forms of EM radiation, they cannot be focused by mirrors and different detection techniques need to be used instead. The biggest challenge of this band is the low resolution of images produced. Gamma ray telescope apertures are small, and so is the amount of gamma rays captured. There usually needs to be a long exposure time to properly capture cosmic objects, especially, if they are faint. The accuracy of gamma telescopes is also hindered by the presence of cosmic rays in the background. There are several different filters and shields to mitigate this effect. (Weekes, 2000)

One is a filter (called collimator) that only lets the gamma rays through certain angles, reducing the amount of background noise. Another way of eliminating unwanted signals is with the use of anti-coincidence shields, which shield the detector from undesirable particles coming from the sides. A third way is a coded aperture mask, which lets the detector know from which side the radiation came by partially covering the detector. It acts in a way similar to a skylight letting in a beam of light. (NASA, 2018a)

Gamma rays are emitted by the most energetic sources in the universe. These sources include black holes and supernovae. One telescope that studies these high-energetic phenomena is the Neil Gehrels Swift Observatory. In commission since 2004, its primary mission has been to observe gamma ray bursts. Gamma ray bursts are very strong explosions happening in space approximately once per day. Their origin is currently unknown, but scientists think their sources might be either the explosions of massive supernovae or the collisions of two neutron stars. By collecting data from these bursts, more information about the life of stars is revealed. (Howell, 2018)

Fig. 18. Neil Gehrels Swift Observatory (Howell, 2018)

3. THE HUBBLE, KEPLER AND JAMES WEBB SPACE TELESCOPES

3.1 Hubble Space Telescope

The Hubble Space Telescope is one of the most influential telescopes ever created. As the first large space telescope equipped with many cutting-edge scientific instruments, its innumerable discoveries have provided a deeper than ever before understanding of our universe. While its development was challenging, it laid the foundations of space telescope exploration of the cosmos. The telescope's contributions to modern-day astronomy are of great significance, with more than 19,000 scientific papers published about its observations.

The original mission of Hubble was to study the depths of the universe for the duration of approximately 15 years. As of now, the telescope has been active for more than 30 years, doubly exceeding this plan. Due to the old age of its components, NASA is not planning any further servicing missions to repair or replace them. However, the team of scientists responsible for the HST's operation work diligently to keep the telescope running for as long as possible. (NASA, 2022b)

3.1.1 Development and operation

Following the success of NASA's Orbiting Astronomical Observatories, planning began for a telescope in space, originally named the Large Space Telescope. The concept of a space telescope was proposed in 1946 by Lyman Spitzer, an American scientist and astronomer, in his famous paper *Astronomical advantages of an extra-terrestrial observatory*. In this paper Spitzer argues that a space telescope would "uncover new phenomena not yet imagined, and perhaps to modify profoundly our basic concepts of space and time." In 1977, after many setbacks (including budget cuts and skepticism from his peers and politicians), Spitzer's lobbying for the LST came into fruition when he acquired government funding for his project. The telescope was officially named the Hubble Space Telescope in the year 1983. It got its name after a famous American astronomer, Edwin Hubble, who confirmed the existence of galaxies beyond our Milky Way and determined that the universe is expanding. The HST was launched after multiple delays in 1990 on board of the Space Shuttle Discovery. (American Museum of Natural History [AMNH], n.d.; NASA, 2022a)

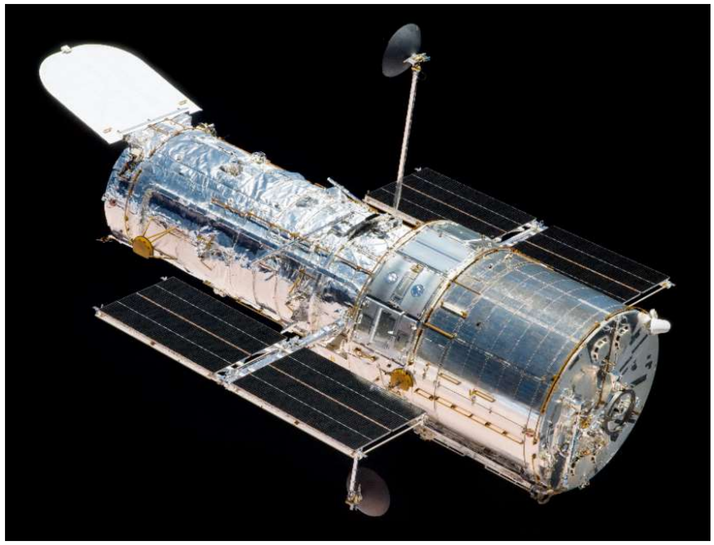

Fig. 19. The Hubble Space Telescope (NASA, 2022f)

But the joy from this long-awaited feat was short-lived. While the images taken by the telescope were much sharper than those from Earth, they were originally expected to be even clearer. It was soon found out that the telescope's mirror had a spherical aberration, since the equipment used for grinding the mirror was improperly calibrated. The surface deviation was only the size of a millionth of a meter, but it still caused the image to be blurry and distorted. Fortunately, the telescope was designed to be maintained by astronauts performing spacewalks, so this issue was possible to be resolved. Since replacing the mirror would be too impractical, the Corrective Optics Space Telescope Axial Replacement (COSTAR) instrument was instead placed over the mirror to rectify the flaw. (NASA, 2019b)

3.1.2 Instruments

The HST is a Cassegrain-type reflector, with the primary mirror's diameter being 2.4 meters. The entire telescope is 13.2 meters long and 4.2 meters wide and contains lots of instruments designed to capture data in the near infrared, visible light and ultraviolet parts of the EM spectrum. (NASA, 2022e) The telescope gets its power from two solar arrays, which can be rotated to face the Sun. During the time when direct sunlight cannot hit the arrays, the telescope's power is sustained by nickel-hydrogen batteries. Its position is maintained by gyroscopes and interferometers. Communications with Earth are established by two high gain antennae. The Support Systems Module (SSM) provides the communications, power and control functions. (STScI, 2010)

The equipment on board of Hubble has undergone several changes over the years of its operation, getting updated as the technology advanced. At this time, 6 scientific instruments are installed, one of them inactive. The two camera systems, the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3), are used for capturing stunning wide-field images of the universe. The ACS is primarily used for taking pictures in the visible light spectrum, but it can also pick up ultraviolet and near infrared radiation. It consists of three channels which all take different kinds of images. The WFC3's purpose is to complement the ACS, thus it operates mostly in the infrared and ultraviolet ranges. The synergy of these two instruments is what makes the telescope's images encompass this entire specific part of the EM spectrum. (NASA, 2022g)

Other than cameras, HST also utilizes two spectrographs, the Space Telescope Imaging Spectrograph (STIS) and the Cosmic Origins Spectrograph (COS). The STIS analyzes the infrared, visible light and ultraviolet bands and gathers information about the elemental make-up of cosmic bodies as well as their temperature, rotational velocity and magnetic fields. (ESA, n.d.-d) The COS, as its name suggests, probes the depths of the universe, investigating the early stages of its formation. It specifically searches for elements such as iron or carbon, which are deemed as being crucial for the development of life. (ESA, n.d.-c)

Another kind of instrument the HST is equipped with is a set of three interferometers called the Fine Guidance Sensors (FGS). These sensors have two functions: to perform astronomical observations and to make sure the telescope is in the right position. The latter function is achieved by two of the sensors locking onto the same cosmic object, such as a star, while the third sensor can analyze it. The last of the currently installed instruments is the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). Its task was to acquire images and perform spectroscopic measurements in the near infrared waveband. It was rendered inactive after a cryocooler malfunction and its functions were taken over by other instruments, namely the WFC3. (NASA, 2022g)

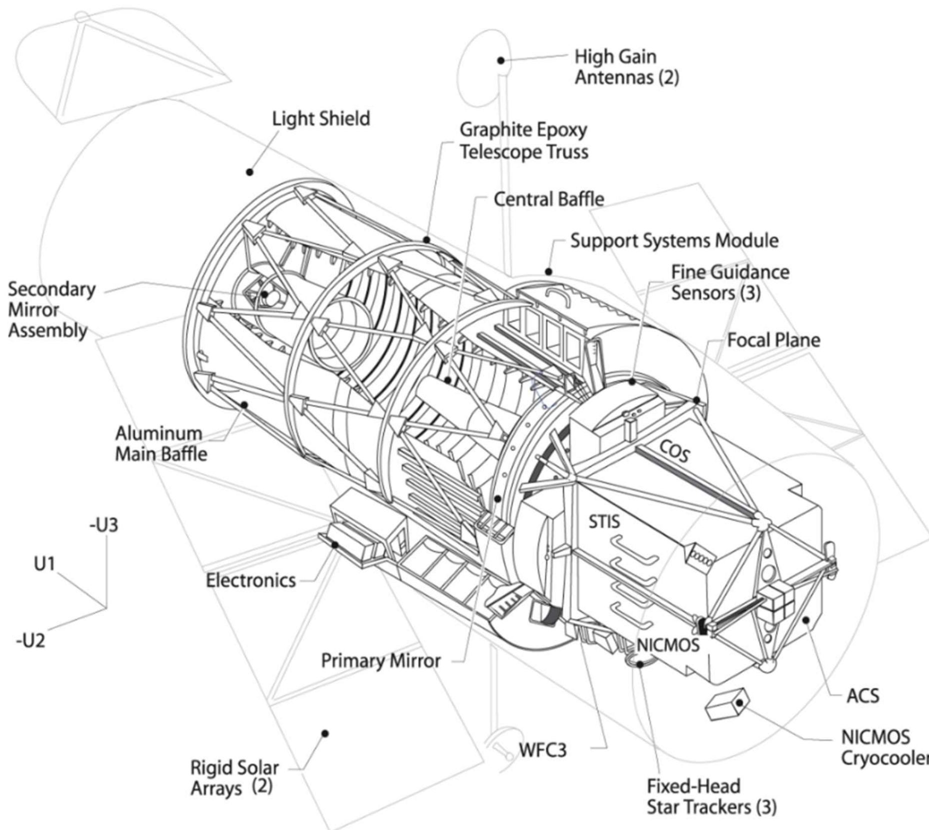

Fig. 20. HST Major Instruments Diagram (STScI, 2010)

3.1.3 Discoveries

The Hubble Space Telescope is quite unique, since no other telescope have had such a wide range of observational objectives, which range from uncovering the mysteries of our Solar System to surveying the beginnings of our universe. This is due to the fact that as the most powerful telescope up to then, the HST could uncover new findings everywhere, even in our own Solar System. The HST has been a crucial asset in discovering more information about our planetary neighbors and their moons. In fact, the only way this telescope could be outperformed is by sending space probes to the planets directly. The advantage of the HST lies in its ability to observe these cosmic objects for longer time periods than the passing space probes. (ESA, n.d.-f) However, it also has its limitations. The Sun is too bright for the telescope’s sensitive instruments, so observing celestial bodies in its close vicinity would damage them. This means that the telescope cannot study the planet Mercury and is very restricted when it comes to studying the planet Venus.[3]

The closest planet the HST has studied in great detail is the planet Mars. Its long-term observations help scientists understand the planet's meteorology, which is vital for planning future crewed missions. The telescope has also surveyed the asteroid belt between the planets Mars and Jupiter. It has performed detailed observations of some of the biggest dwarf planets, in particular Vesta, of which it assisted in creating a surface map.

One of the most intriguing phenomena the HST has captured in our Solar Neighborhood was the encounter of the comet P/Shoemaker-Levy 9 with the planet Jupiter. In 1992, the comet broke apart into 21 pieces as a result of the planet's strong gravitational field while it was passing the gas giant. A year later, the telescope provided images of the comet's fragments and it soon became apparent that all of the pieces would impact the planet in 1994. The HST captured the impacts perfectly. (Fischer & Duerbeck, 1996)

The telescope also studied Jupiter's and Saturn's atmospheres and aurorae. The aurorae are only visible in the ultraviolet band and Hubble is the perfect apparatus for their analysis, since UV rays cannot penetrate the Earth's atmosphere and therefore cannot be observed by telescopes on Earth. It has also studied the atmospheres of Uranus and Neptune, as well as the moons orbiting them and took the first detailed pictures of Pluto and its moon Charon. (ESA, n.d.-f)

While the observations of our Solar System certainly provide many beneficial results, the HST was primarily designed to look further, beyond our own galaxy and answer the most pressing questions about our universe. Since a space telescope is not hindered by the Earth's atmosphere, it can see deeper into the cosmos than any other telescope on Earth. The prospects of finding life somewhere else in the universe have never been brighter. Hubble's role in this search is to look for exoplanets in distant Solar Systems and analyze their atmospheric compositions. It was generally believed that stars other than our Sun also have their own planets, but it took the observational strength of

[3] The planet's angular distance from the Sun needs to be at least 50 degrees, which happens rarely during its orbit (Fischer & Duerbeck, 1996)

the HST to officially confirm their existence. (Wall, 2018)

In addition to this, the telescope was used to determine the age of the universe by estimating the distances to other galaxies and measuring the speed of how fast they are moving away from us. With this information the scientists have ‘run the clock backwards’ and concluded the universe to be 13.8 billion years old (with an accuracy of 3%). Along with this discovery, it was also important to determine how the expansion of the universe behaves with time. Originally, it was believed that the expansion of the cosmos was slowing down due to the effects of gravity, but the data gathered with the HST showed that it was, in fact, speeding up. This acceleration was explained by the presence of some kind of repulsive force across the universe, called ‘dark energy’. During the early stages of the universe, the gravitational force was the prevalent force, slowing down the expansion of the universe. But at some point (around 6 billion years ago), as the space became more spread out and the gravitational force weakened, the dark energy took over and became the dominant force, speeding up the expansion. The discovery of dark energy is one of the greatest achievements of modern-day astronomy. (English, 2017)

There is a certain phenomenon telescopes make use of when they want to see deeper into space than their optics allow: gravitational lensing. Einstein in his theory of relativity stated that matter bends space around it. Cosmic objects which contain a lot of mass, such as galaxies or even clusters of galaxies, distort the space to such an extent that any objects behind them appear magnified. This effect acts as a sort of magnifying glass telescopes can peek through to see celestial bodies which are too far to be discerned otherwise. Hubble has been used to detect a vast number of gravitational lenses and create maps of the dark matter often forming them. (STScI, 2022b) Gravitational lenses have not only broadened our understanding of the previously hidden parts of the cosmos, but also helped us learn more about dark matter and its role in the distribution of mass in space.

An additional way telescopes can see further into space is slightly less exciting. By maintaining longer exposure times during image-taking, telescopes are able to pick up celestial objects in more detail and even to see some very far-away and faint objects that would not be visible on regular images. The HST was first utilized in this way in 1995; it was pointed at one of the darkest and emptiest parts of the night sky and took long-exposure images of it for 10 days. The resulting image, called the Hubble Deep Field, revealed thousands of galaxies at different distances from us and various stages of development. With this data the astronomers could make timelines of how galaxies and the universe as a whole evolve with time. There have been multiple deep field images taken since then, such as Hubble Ultra Deep Field in 2004 or Frontier Fields, which was as a result of the cooperation of three of NASA's Great Observatories in 2013. (NASA, 2023)

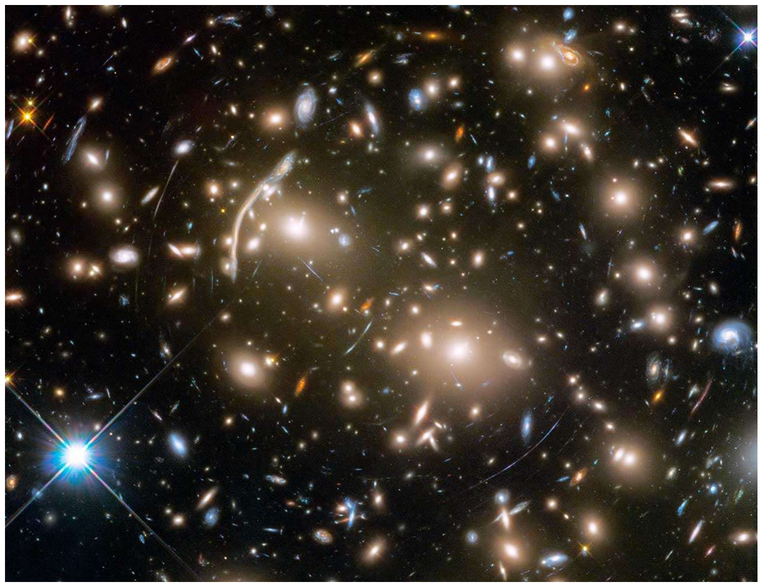

Fig. 21. Frontier Fields image of galaxy cluster Abell 370 showing an effect of a gravitational lens (STScI, 2022b)

The Hubble Space Telescope has also played a crucial role in the study of black holes and has proven the existence of supermassive black holes with the mass of more than 3 billion Suns. (English, 2017) Detailed observations of a number of galaxies have determined that black holes are at the center of every galaxy and that the size of the black hole is proportional to the size of the galaxy it is in, proving a direct relationship between them. (Macchetto, 2003)

There are many more contributions this telescope has made to astronomy over the many years of its operation. Many astronomers consider its impact to be so consequential that they informally divide astronomy into pre-Hubble and post-Hubble eras. (NASA, 2023) It has truly shaped the course astronomy would take next; with all the data the HST has uncovered, more and more questions keep arising. And new space telescopes have been developed to look for the answers.

3.2 Kepler Space Telescope

The possibility of finding new, potentially life-bearing planets has always been deemed as one of the most important discoveries in the field of astronomy. This endeavor had to overcome many hurdles over the years, the biggest one being that the brightness of stars would outshine any light coming from their orbiting planets, rendering direct observations impractical. It was only in the last few decades that new progress could be made and different, indirect ways of observing were realizable. It also became apparent that for observing planets with a similar size as Earth, a space telescope had to be utilized. (eoPortal, 2016)

The aim of the Kepler Space Telescope's primary mission was to gather data on the frequency of Earth-like[4] planets in the habitable zones of the stars they were orbiting. This information would then lead to the understanding of how likely the presence of life in the universe is. The original Kepler mission spanned from 2009 to 2013, during which it observed more than 150,000 stars. After the malfunction of two of the four reaction wheels, the telescope's pointing abilities were greatly reduced, resulting in the cancelation of the original mission. From 2014 till 2018, a new mission for the telescope was in action, called K2, and the telescope still continued to discover new exoplanets even despite the pointing difficulties. As of now, more than 2,600 exoplanets have been found thanks to Kepler and more planets are being identified from its data to this day. (NASA, 2022c)

3.2.1 Development and operation

The Kepler Space Telescope detects exoplanets with the help of transit photometry. Transit photometry studies the amount of light gathered from observed stars and looks for small decreases in light intensity, which are attributed to planets transiting in front of the stars. From these minuscule dips of brightness observers can then determine the size of the exoplanet.

In 1971, a paper containing the first quantitative analysis of the potential use of

[4] The term 'Earth-like' corresponds only to the similarity in size, as the Kepler Space Telescope could not detect other properties of the analyzed planets (Borucki, 2016)

transit photometry for identifying exoplanets was submitted by Frank Rosenblatt. After more research, three workshops were held by NASA to further explore and advance this concept, starting with the Workshop on Improvements to Photometry in 1984, followed by the Second Workshop on Photometry in 1988 and ending with the Third Workshop on Photometry in 2000.

The Kepler mission was first proposed to NASA's Discovery Program in 1992. At that time, it was known under the acronym FRESIP (FRequency of Earth-Size Inner Planets). It took multiple proposals (with the name eventually changing to Kepler Space Telescope) in order for the final one in the year 2000 to win. Over those years, the mission goals kept getting improved until they reached a final, stable version.

It was determined that in order for the mission results to be statistically significant, at least 100,000 stars need to be observed at the same time. This requirement had resulted in the large field of view of the telescope's photometer. Another prerequisite for the mission success was that at least three planetary transits needed to be captured so as to accurately determine the exoplanets' existence. A mission length of four years was established to fulfill this condition. Analyses regarding the placement of Kepler's field of view concluded that the most suitable part of sky would be between the constellations Cygnus and Lyra. This area was near the galactic plane and contained a large number of stars. To minimize the necessity of the spacecraft's alignment, a heliocentric orbit was chosen, since less external forces would act upon it. (Borucki, 2016)

Fig. 22. The Kepler Space Telescope (Allen, 2015)

The following years after the mission approval were spent developing the spacecraft, including the most precise photometer ever produced. Then, in 2009, the revolutionary telescope was finally launched. After 3.5 years of operation, the first of the four reaction wheels responsible for the pointing of the telescope failed in 2012. Engineers were working on ways to stabilize the spacecraft, including the temporary use of thrusters, when the second reaction wheel gave out in 2013. Attempts to restore the reaction wheels' mobility were unsuccessful and new mission proposals for the two-wheeled Kepler telescope were being accepted. Despite Kepler being considered lost by most people, a small team of engineers started working on a pointing concept unlike anything done before.

The high-precision transit photometry required very stable pointing abilities, which could not be maintained by thrusters, as they would cause too much swaying for any usable data to be gathered. Instead, a special position of the spacecraft was proposed, where the solar wind would put pressure onto its roll axis and opposing thrusters would be deployed occasionally to perform small corrections and maintain the right alignment. This method had proved to be successful and with it the K2 mission could be born. The objective of the K2 mission was similar to the original Kepler mission, which means that the space telescope still searched for exoplanets, just in a more restricted way. During the K2 mission, Kepler Space Telescope observed the fields near the ecliptic during 80 day windows, after which it needed to be redirected to a different spot. The K2 mission lasted until 2018, when the telescope's thruster fuel ran out. (Troeltzsch & Howell, 2020)

3.2.2 Instruments

Kepler's photometer was the sole scientific instrument the telescope carried. All other instruments were designed to either point, cool or provide power to it. The photometer contained a Schmidt optical system (a telescope design allowing for wide fields of view) consisting of an array of 42 charge-coupled detectors (CCDs). For optimal performance to be maintained, the CCDs were kept at -85°C. (Borucki, 2016) The scientific data gathered by the photometer were stored on the Solid State Recorder (SSR) and were transmitted to Earth by the High Gain Antenna (HGA) once per month.

The Attitude Determination and Control Subsystem (ADCS) was responsible for keeping the telescope pointed in the right direction; steady and precise attitude was crucial for obtaining high-quality data results. Fine Guidance Sensors (FGS) provided fine attitude information, while star trackers provided coarse attitude information. Other than these two components, ADCS also comprised of reaction wheels and thrusters, which were responsible for changing the position of the telescope. (STScI, 2016)

Kepler's power was controlled by the Electrical Power Subsystem (EPS). A solar array was installed as a source of electric power and the spacecraft had to be rotated by 90 degrees every three months in order for the array to always face the Sun. Opposite to the solar array was the radiator, which always needed to face the deep space for optimal cooling of the instruments. There was a lithium-ion battery on board acting as a backup, though it was not needed during normal operation.

The Thermal Control Subsystem (TCS) kept all of the components at their ideal operating temperatures – those that required higher temperatures were isolated from the rest. It consisted of heat-conducting pipes and adhesives, heating elements and sensors to measure temperatures. The telescope's solar array was thermally insulated, so it also acted like a sun shield, helping keep the temperatures of the instruments low. (eoPortal, 2016)

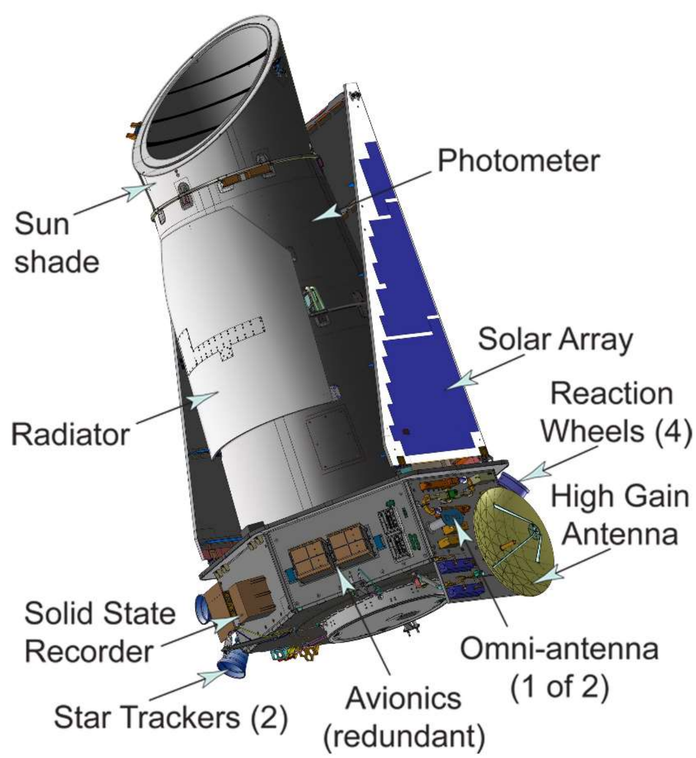

Fig. 23. KST Major Instruments Diagram (NASA, 2017)

3.2.3 Discoveries

Kepler's mission to determine the frequency of Earth-like exoplanets in other solar systems has revealed that every solar system has at least one planet. That means that on average, there are more planets in the universe than stars. This revelation is astounding – before Kepler there was no information about the prevalence of smaller, rocky planets in other star systems.

The mission has also shown evidence of just how diverse the planets and solar systems are. The range of planet sizes is very broad, as is the size of their orbits around their stars. The types of planets also vary, some being gas giants, some are assumed to have giant oceans on their surfaces and some are small, rocky worlds similar to Earth. A number of star systems is quite small in size, having up to eight planets orbiting very closely to the star. The nature of solar system formation is as of yet unknown and these findings prompt even more questions than before. (NASA, 2020)

The first terrestrial planet detected by Kepler was discovered only months after its launch. It was given the name Kepler-10b[5]. This planet orbits very closely to its star, 20 times closer than Mercury is to our Sun. As a result, the time it takes for this planet to orbit its star is less than a day. It's orbiting so close, in fact, that the temperatures on the planet's surface exceed 1,300°C, which is hot enough for melting iron alloys. Kepler-10b is likely 'tidally locked' to its star, meaning that the same side is always facing the star, an arrangement which only contributes to the planet's high surface temperatures. (Christiansen et al., 2020; NASA, 2011)

The main points of interest of the space telescope's mission were Earth-like planets in the habitable zones. The first such detected planet was named Kepler-22b, although it was unlikely for this planet to be terrestrial due to its large size, 2.4 times the size of the Earth. Other potential candidates were found in the star system Kepler-62. The two most outer planets, Kepler-62e and f are similar in size to Earth and lie in the habitable zone, making them the first in the long list of such possibly life-harboring exoplanets.

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[5] The number '10' represents the tenth exoplanet-containing solar system observed by Kepler. The letter 'b' stands for the first sub-stellar object discovered in the solar system (the capital letter 'A' being reserved for the star). (Christiansen et al., 2020)

(Christiansen et al., 2020)

The Kepler Space Telescope was also used for research outside of its main mission. Its unique photometric abilities were not only suitable for exoplanet hunting, but also for studying stars directly. One such case was the study of the varying brightness of the seven brightest stars in the star cluster Pleiades. It was challenging to capture data from the stars directly, because they were so bright they oversaturated the pixels capturing them. This is why the researchers must have looked at the unsaturated pixels near the stars and examined the relative brightness variation in these areas. In addition to this, the data needed to be rid of any possible errors, which may have had occurred during their collection. Such errors included varying motion of the telescope or flaws in the detector. As a result, a new observing method was developed and tested, called ‘halo photometry’. This method used algorithms to compensate for imperfect instruments and other unwanted phenomena.

The research has confirmed the star type of six of the Seven Sisters, which is a slowly pulsating type B star with its brightness changing with a period of one day. The seventh star’s brightness changed in a considerably longer period of 10 days. Previous studies have shown that this star has an unusual chemical make-up, in particular, high amounts of Manganese. The researchers have concluded that the brightness variation of this star is caused by a spot of Manganese on its surface, which becomes visible and obscured periodically during the star’s 10 day rotation. Overall, while the research did not reveal any new exoplanets, it did help improve the techniques used in distant star observations, which could also be applicable in the search for exoplanets. (Weitering, 2017)

The Kepler Space Telescope was the first pioneer of the exoplanet search. Its many years of operation brought with them ground-breaking results about the universe we live in. Its legacy lives to this day – its mission has been picked up by the Transiting Exoplanet Survey Satellite (TESS) and the James Webb Space Telescope (JWST), which is the topic of the following subchapter. (eoPortal, 2016)

3.3 James Webb Space Telescope

As the last century was coming to a close and a new era of astronomy supported by the space telescopes was about to begin, a few important figures at NASA were already planning ahead. They were focused on new space missions that would replace the space telescopes already in development. One of these projects was the James Webb Space Telescope, which was planned to replace the Hubble Space Telescope and build upon its findings. Since the first stars and galaxies are too faint and redshifted[6] for Hubble, JWST was designed to be infrared optimal in order to better capture the early stages of the universe.

Webb's development took more than 20 years, during which new telescope technologies were created. It is the most precise and large space telescope built to this day, and while only 1.5 years have passed since its launch in 2021, it is already producing high-quality images and observation data. (Hughes, 2022; McElwain et al., 2023)

3.3.1 Development and operation

JWST first came up as a concept in 1989, at a workshop held by the Space Telescope Science Institute. The telescope concept was named Next Generation Space Telescope (NGST) and was meant to be Hubble's successor. The proposed telescope would have an 8–16 meter wide primary mirror, it would operate in the infrared-visible-ultraviolet spectrum and would be passively cooled by a sunshield.

Over the next years, the design underwent numerous changes before eventually settling on a 6.5 meter large mirror. The target waveband shifted to only visible-infrared, since the cool temperatures needed for infrared imaging would hinder ultraviolet observations. In 2002, the name of the telescope was changed to James Webb Space Telescope. (Illingworth, 2016)

Webb was launched on Christmas Day in 2021, after which it undertook a month long journey to its final destination: the Langrange 2 point (L2), located 1.5 million kilometers from Earth. L2 is a point in space, where gravitational forces of the Sun and Earth offset the centrifugal force acting on a smaller object – in this case a space telescope. This position allows the telescope to be gravitationally stable while still being far away from the Earth and Sun, which is optimal for infrared telescopes, since heat from these objects interferes with captured data. It is also far enough for the telescope to be passively

[6] Redshift: due to the expansion of the universe, light from distant cosmic objects gets 'stretched' from higher frequencies into infrared wavelengths

cooled instead of requiring coolant. Another benefit of this spot is broad bandwidth available for communication. (Dobrijevic & Howell, 2023; Howell, 2017)

Approximately half a year later after its launch, JWST's instruments were deemed to be fully functional and the telescope could start observing the most remote parts of the universe. Webb's mission is meant to follow Hubble's and the two telescopes will cooperate for the early stages of Webb's deployment. Another mission JWST will follow up on is Kepler's search for exoplanets. (Dobrijevic & Howell, 2023)

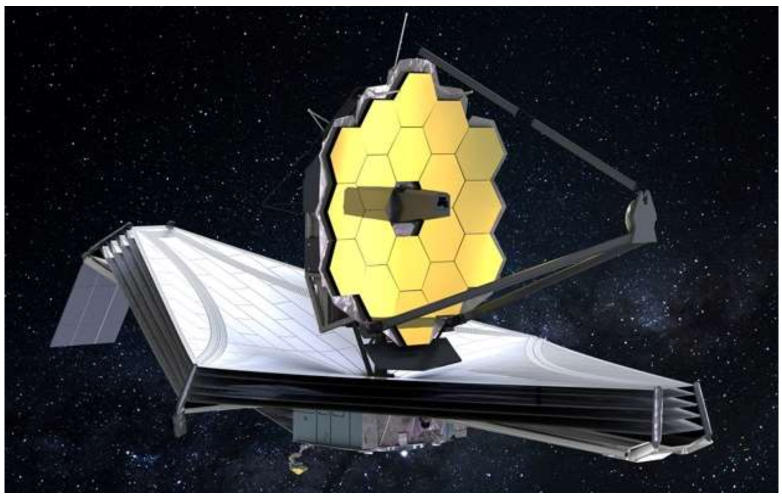

Fig. 24. The James Webb Space Telescope (Hughes, 2022)

3.3.2 Instruments

Webb has a primary mirror with a collecting area of more than 25 m^2. It consists of 18 hexagonal segments, which are all adjustable in six mechanical degrees of freedom. The telescope's primary mirror was too big to fit into the space launcher, so it was launched folded and needed to be unfolded and properly aligned after the telescope's deployment. JWST has four mirrors in total: primary, secondary, tertiary and fine-steering mirror. The first three mirrors are configured as a three-mirror anastigmat, which helps minimize optical aberrations such as coma, astigmatism, spherical aberration and field curvature. The fine-steering mirror ensures that the optical path leading to the scientific instruments remains stable and aligned.

There are four science instruments on board of the telescope, all located within the Integrated Science Instrument Module (ISIM) behind the primary mirror. (McElwain et al., 2023) The Mid-Infrared Instrument (MIRI) operates in the mid-infrared region of the EM spectrum and observes far-away, redshifted galaxies, stars that are just starting to form, cosmic bodies in the Kuiper Belt and less visible comets. MIRI's camera consists of nine broad-band filters, which offer wide-field imaging, while its spectrograph serves for low or medium resolution spectroscopy. (NASA, n.d.-c; STScI, n.d.-b)

Other instruments on board operate in the near-infrared region. The Near-Infrared Camera, or NIRCam, is Webb's primary tool for imaging. It is composed of two very similar and independent modules, which can be used to observe two neighboring sections of the universe at the same time. NIRCam also contains a spectrograph and a coronagraph, which is helpful in observing faint objects in close proximity to stars, such as planets. Other cosmic objects studied with this instrument include distant forming stars or galaxies, newly-formed stars in our galaxy or celestial objects from the Kuiper Belt. (NASA, n.d.-d; STScI, n.d.-b)

JWST's third instrument is the Near InfraRed Spectrograph (NIRSpec). In order to study multiple light sources simultaneously, a microshutter was developed specifically for this mission. It consists of an array of individual microshutter cells that can be controlled independently, allowing the telescope to observe a hundred sources concurrently. (NASA, n.d.-e) The last instrument of the ISIM is the Fine Guidance Sensor/Near Infrared Imager and Slitless Spectrograph, or FGS/NIRISS. The FGS's function is to keep the telescope accurately aimed at the right spots. NIRISS is utilized for observations of the so-called 'first light', the earliest visible stage of the universe after the Big Bang. Other than that, it discovers new exoplanets and provides spectroscopic analysis of their atmospheres. (NASA, n.d.-a)

To keep the science instruments at their working temperature under 50 K, or -223°C, a five layer sunshield was developed, acting as a radiator dissipating heat into space. It also keeps the instruments covered from the Sun, shielding them from its heat and maintaining stable temperatures. The essential support functions are supplied by six subsystems. The Electrical Power Subsystem gathers power from two solar arrays located on the sun-facing side of the sunshield. The Attitude Control Subsystem includes star trackers, reaction wheels and thrusters, which work together with the FGS and fine-steering mirror to point the telescope. The Communication Subsystem includes a high-gain, omnidirectional antenna that communicates with Earth. The Command and Data Handling System is made up of Command Telemetry Processor and Solid State Recorder and it handles communication between all systems. The Propulsion Subsystem is composed of thrusters and fuel containers responsible for proper maneuvering. The Thermal Control Subsystem comprises of the sunshield and radiators and manages optimal operating temperatures. (Gardner et al., 2006; NASA, n.d.-f ; STScI, n.d.-a)

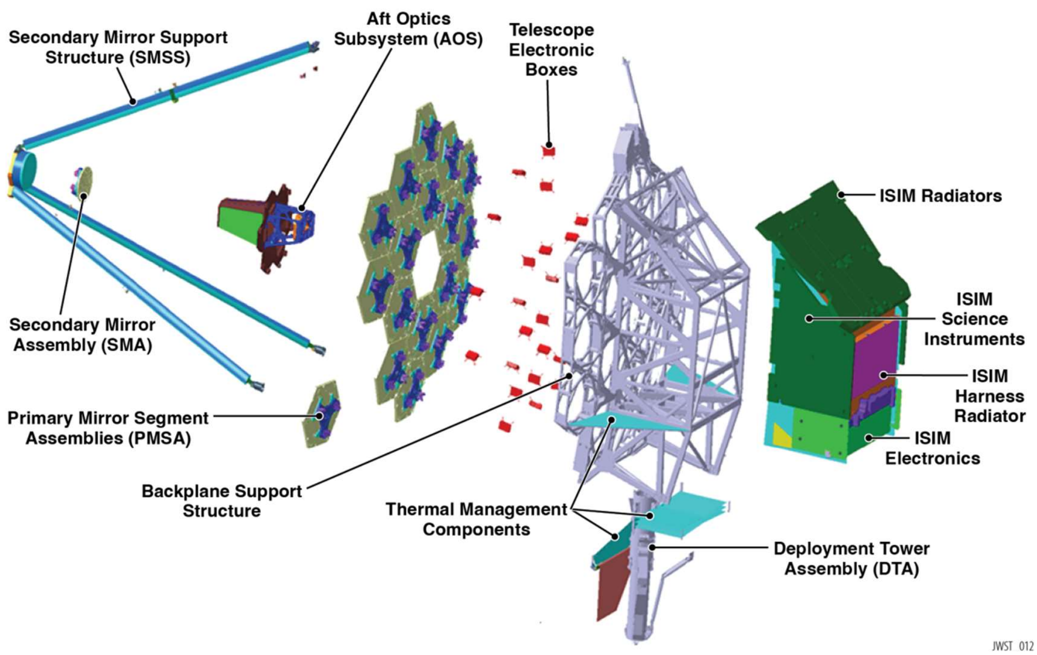

Fig. 25. JWST Major Instruments Diagram (McElwain et al., 2023)

3.3.3 Discoveries

Webb's primary mission was first conceived in the very early stages of its development and it did not change much over the following years. The mission was divided into four main categories: First Light and Reionization, Assembly of Galaxies, Birth of Stars and Protoplanetary Systems and Planetary Systems and Origins of Life. Soon after the original mission proposal, new research possibilities were considered and determined to include dark matter and energy, exoplanet characterization and celestial bodies of the Solar System.

As for the first part of the main mission, the telescope will take a close look at the very first stars and galaxies formed after the birth of the universe. Following the Big Bang, the universe was so dense and hot that it was actually not transparent (scientists call this period the Dark Ages). This initial stage had lasted for hundreds of millions of years, after which the first stars and galaxies obtained the right conditions to form. (Gardner, 2012) The first galaxies, which emitted radiation in the ultraviolet part of the EM spectrum had caused hydrogen atoms to be reionized – a phenomenon also to be studied by the JWST. (Gardner et al., 2006)

The James Webb Space Telescope has recently produced images of six early galaxies that are going against theories of early cosmos evolution. The observed galaxies were formed 500-700 million years after the beginning of the universe and they contain a lot more mass than what was previously thought possible. In accordance with our current understanding of the universe, the galaxies at that point in time should have been in very early stages of their development. Instead, the six observed galaxies are as mature as our own Milky Way and a hundred times more massive than expected. Spectroscopic analysis of these so-called 'universe breakers' is required in order to conclusively determine their properties. (Penn State University, 2023)

The second part of Webb's mission is the study of galaxy assembly and it is closely related to the first one. It is assumed that matter in space is formed hierarchically – from small cosmic objects, which were then gathered together to create bigger bodies. This theory is still not confirmed and there are many other unknowns, such as what determines the shape of the galaxies, what sort of processes occur inside of them or what is the function of black holes at their centers. (Gardner et al., 2006)

Among Webb's first images was the Stephan's Quintet, a group of five galaxies, which was observed in unprecedented detail. This picture reveals a lot of information about how these galaxies interact with each other. There is gas, dust and even stars, all being dragged away from the galaxies caused by the gravitational forces present. Major blast-waves can be discerned after one of the galaxies collides with the rest of the group. Although, the most fascinating sight is how these galaxies cause star formation in each other. This galaxy group is a perfect research subject when it comes to studying the evolution of galaxies, the formation of stars and the behavior of active black holes. It is possible that galaxy formations such as this one were more common in the younger cosmos and this quintet can serve as a suitable point of reference in future observations. (NASA, 2022d)

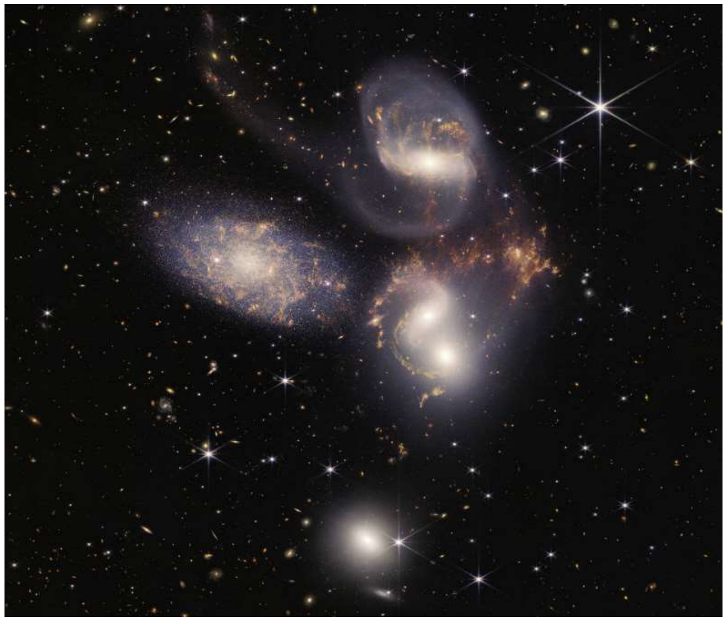

Fig. 26. Stephan's Quintet observed by JWST (NASA, 2022d)

For the third part of its mission, Webb will observe how stars and planetary systems are created. The telescope will uncover more information about how the stars are born from dust and gas clouds, the reason why they most often form in groups and the details about how are protoplanetary systems assembled. For a complete theory of planet formation there is a need for more observational data, which the JWST will provide. (Gardner et al., 2006)

One of the most famous birth places of stars are the Pillars of Creation, located in the Eagle Nebula. It has already been famously photographed by Hubble, but Webb's advanced infrared-imaging capabilities pierced straight through the dust clouds and revealed the forming stars underneath. The dust keeps merging together due to the gravitational forces acting upon it, slowly gathering more mass and after efficiently heating up, the star starts to radiate light. The size of these stars is multiple times bigger than our Solar System and they are estimated to be only a couple of thousands years old.

(Sohn, 2023; STScI, 2022c)

The last part of JWST's mission is the study of planetary systems, which includes finding the determiners for planet formation and orbit properties, as well as their chemical composition and possible conditions for life. (Gardner et al., 2006) Webb's impressive instruments are made for spectroscopic analysis of exoplanets' atmospheres, allowing it to search for environments suitable for life. Unlike Hubble, which can only detect water, Webb can detect other substances, such as carbon dioxide, sodium or methane, which is considered to be a signature of metabolic processes of carbon-based life forms. (O'Callaghan, 2023)

The first exoplanet that Webb observed is WASP-96b. It produced a full transmission spectrum analysis of the planet's atmosphere. In order to determine the atmosphere's composition, transmission spectrum analysis compares data from when a planet passes in front of its star and when it does not. The result after the extrapolation of necessary data is an absorption pattern, showcasing which elements are present, the planet's temperature and whether it is cloudy. This gas giant has a sodium-rich atmosphere and it is so close to its star that it orbits it once per 3.5 days. Even though further observations are needed to gather more information, it is known that the planet has water vapor in its atmosphere in the form of clouds. This was a surprising revelation, as prior research indicated that it had no actual clouds. (Sohn, 2023; STScI, 2022a)

CONCLUSION

The telescope is possibly the most influential invention in the field of astronomy. The first telescopes were made by lens makers and their progress was mostly empirical in nature. But even after the scholars took the lead, they were limited by the quality of manufacturing available at that point in time. In this sense, it took the optical telescope more than two centuries to fully reach its potential. But even if the development of its optical theory and manufacturing technologies had mostly peaked already, there is always more progress to be made. Various advancements to the telescope are being made today. Improvements to signal detection are constantly researched. New mirror materials are being developed and enhanced in order to increase resolution. Every couple of years, a new space telescope is launched, carrying on board the most cutting-edge technology the world has to offer.

In this thesis, various types of space telescopes were listed and compared. They were categorized in accordance to the part of the electromagnetic spectrum they study. The properties of the electromagnetic signal change across the spectrum; with shorter wavelengths comes higher energy of the wave. Different cosmic objects emit their radiation in different parts of the EM spectrum, with the general rule being that the cooler the object, the less energetic is its radiation. This means that the coolest objects in the universe emit radio waves and the hottest objects emit gamma rays. Examples of the hottest celestial objects are black holes, supernovae and hot gas. Cool objects would be clouds of cool gas or dust or cool stars and planets.

The differences in wavelengths mean that different techniques need to be utilized to detect particular waves. Radio waves and microwaves are captured by antennae, infrared, visible light, ultraviolet and X-ray radiation is focused by mirrors and gamma rays are gathered by particle detectors. Each spectral band carries unique information about the universe, and thus it cannot be determined which part of the spectrum is the best for observations. Each band has its own set of challenges needing to be overcome, as well as its uses, which no other wavelength is able to fulfill. Together they act as separate parts of the same puzzle – the puzzle of the true nature of the universe we live in.

The era of space telescopes began with the launch of the Hubble Space Telescope in 1990. The results of the telescope's observations were remarkable, bringing about a much deeper understanding of our universe than ever before. It analyzed every part of the cosmos, be it our own Solar System, our galaxy or the most distant areas of space it could capture. It captured breath-taking images of nebulae, galaxies and stars, analyzed most of the planets in our Solar System and performed high-quality, long-exposure images called Hubble deep fields.

Hubble has also corrected certain notions, which were previously regarded as general truths. For instance, it rectified the supposition that the expansion of the universe is slowing down, when, instead, the rate of the expansion is increasing. Additionally, it has confirmed some working hypotheses, like the existence of planets in star systems other than our own. Ultimately, the Hubble Space Telescope is a revolutionary scientific instrument that has drastically altered the course of modern astronomy.

Another trailblazing telescope was the Kepler Space Telescope, which studied the frequency of exoplanets in the habitable zones of their stars in 2009 to 2018. It had found much more planets than what was originally anticipated and its mission was a resounding success. Even a couple of years after its decommission, new exoplanets are still being discovered in the data gathered by this innovative telescope. Thanks to Kepler, we now have a much broader knowledge about the formation of other star systems and the potential presence of life in the cosmos.

As technology advances, so do the capabilities of newly built telescopes. The James Webb Space Telescope is the most ambitious astronomic endeavor yet – it is the largest, most precise space telescope up to date. First conceived even before the launch of Hubble, scientists were already planning on making sure it surpasses its predecessor and elaborates on its mission. Launched in 2021, it carries on board the most cutting-edge equipment up till now. Webb is already providing new ground-breaking information about the origins of stars and galaxies and one can only imagine what other surprises are just waiting to be uncovered by this influential instrument.

Every space telescope contributes vital data to humanity's search for answers, be it by presenting new evidence, which fills the missing gaps, or by correcting already pre-existing notions. Each such space telescope has a large amount of effort and care put into it by all members of its team. However, for every successfully approved project, there are dozens of those that simply do not make the cut. The reasons for this are mostly budget constraints. Since most space agencies are funded by governments (with the exception of a few private-owned ones), the budgetary restrictions are imposed by politicians elected by the public. Therefore, by maintaining and uplifting the public's interest in science, a higher number of advanced space telescopes can be built. It is apparent that the breath-taking images and scientific articles published with the help of space telescopes have so far never ceased to amaze both scientists and laymen alike. The cooperation of numerous countries and institutes on these instruments brings about a sense of togetherness transcending nationalities and borders. The space telescopes are the culmination of these efforts and the results they provide bond people together and propel humanity forward on its never-ending quest of unveiling the mysteries of the world around us.

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