Analysis of the Principle and State-of-art Applications of Astronomical Telescope

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Abstract. Astronomical telescopes have been instrumental in enhancing our comprehension of the cosmos since ancient eras. This study explores these remarkable instruments' principles and state-of-art applications, tracing their development from early refracting telescopes to modern space and ground-based telescopes. The primary focus is to analyze the imaging principles of optical and radio telescopes and showcase their significance in capturing high-resolution observations of celestial objects. It also highlights recent achievements made by advanced telescopes, including the James Webb Space Telescope and the Event Horizon Telescope, which have provided unprecedented clarity and insights into distant galaxies, exoplanets, and supermassive black holes. This research presents breakthrough achievements made by advanced telescopes such as the James Webb Space Telescope and the Event Horizon Telescope in revealing distant galaxies, exoplanets, and supermassive black holes. Despite the limitations in astronomical telescope research, such as errors, atmospheric interference, and high costs, the paper emphasizes a promising future. Through technological advancements, international collaboration, and cost-effective space telescopes, astronomical research is expected to make significant progress. In summary, these results provide a comprehensive analysis of astronomical telescopes, enriches the frontiers of astronomy, underscores the importance of international cooperation, and offer essential guidance for the future development of astronomy.

Keywords: Astronomical telescopes, Webb space telescope, Event horizon telescope.

1. Introduction

Since ancient times, humans have been fascinated by the beauty and mystery of the universe. From our ancestors' basic stargazing to current cutting-edge technology, the development of astronomical telescopes has played a key role in expanding our understanding of the universe. Over the centuries, astronomers and innovators have improved and innovated these extraordinary instruments, allowing us to peer deeper into the universe and uncover its mysterious secrets. The origins of astronomical telescopes can be traced back to the 17th century when Galileo Galilei made significant discoveries through his observations using a refractor telescope [1]. This type of instrument utilizes convex lenses for both the objective and eyepiece, which refract light to form an enlarged image at the focal point. Galileo's findings garnered widespread attention during this time period. This type of refracting telescope is widely used in astronomical observation and scientific research. In 1668, the renowned British scientist Isaac Newton devised a groundbreaking reflecting telescope called the Newtonian telescope [2]. This innovative instrument employed a concave mirror as its primary reflector and a flat mirror positioned at a 45-degree angle as its secondary reflector. By reflecting light rays from the primary mirror onto the secondary mirror and subsequently projecting them outward, an enlarged image was formed. The birth of the reflecting telescope was based on Newton's investigation of the chromatic aberration issue in refracting lenses. Newton discovered that using a reflecting mirror instead of a refracting lens could eliminate the inherent chromatic aberration problem, thus achieving more accurate imaging. The design of the reflecting telescope also offered other advantages, such as alleviating the difficulties and costs associated with lens manufacturing and enabling the construction of larger aperture telescopes. Until today, technologies such as space telescopes and large ground-based telescopes have become more mature and gradually become mainstream, Space telescopes are located above Earth's atmosphere and offer clearer observations by avoiding atmospheric distortion, though they face limitations in size and maintenance complexity. The launch of the Hubble Space

Telescope in 1990 ushered in a new era in astronomical exploration, the Hubble telescope evaded the distortions caused by atmospheric turbulence, granting astronomers unprecedented clarity and resolution in their observations [3]. Large ground-based telescopes can be built with bigger apertures, allowing continuous upgrades and adaptive optics despite atmospheric turbulence. Both complement each other, and ongoing technological advancements hold promising prospects for future astronomical discoveries [4].

These highly sophisticated space telescopes have also produced very rich research results. The Hubble Space Telescope has unveiled the history of cosmic evolution and the process of galaxy formation by capturing images of distant galaxies. The observational findings indicate the existence of a vast number of galaxies, which congregate in various forms to create the large-scale structures of the universe [3] and space telescopes also give us clear images of the depths of the universe. The Large Synoptic Survey Telescope (LSST) is an extremely powerful astronomical telescope designed for conducting large-scale survey observations and achieving continuous monitoring of the entire sky [5]. It has helped us unravel the mystery of black holes, providing a clear and complete picture of the supermassive black hole at the center of galaxies [6].

This study will provide an in-depth analysis of the principles and modern applications of astronomical telescopes, one can gain better insights into the fundamental principles and techniques of astronomical observations. Simultaneously, understanding the modern applications of telescopes can help us recognize their significance and impact in various fields. The research framework of this paper will include types of Astronomical Telescopes, different principles of different telescopes, advanced applications, technological challenges, and future development.

2. Category of Telescopes

Telescopes can be categorized based on several criteria: location, wavelength range, and optical design. In terms of purpose and range of detection, telescopes can be roughly divided into three categories: optical, infrared, and radio. Currently, the most common optical astronomical telescopes are refracting, reflecting, and catadioptric telescopes. A refracting telescope uses lenses to gather and focus light to form an image. It is called a refractor because it relies on the principle of refraction, where light changes direction as it passes through different mediums, such as glass lenses. In a refracting telescope, light enters through the objective lens at the front of the telescope, as shown in Fig. 1. The objective lens is usually convex and converges the light to a focal point, forming an image at the focal plane. The eyepiece lens, located at the back end of the telescope, then magnifies the image so that it can be observed by the viewer.

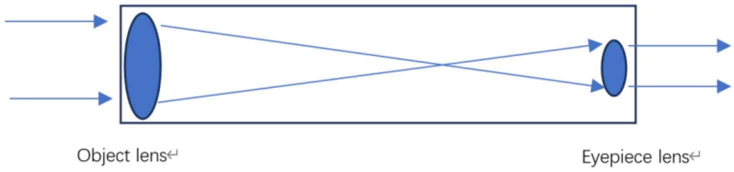

Fig. 1 Basic principle of a refracting telescope.

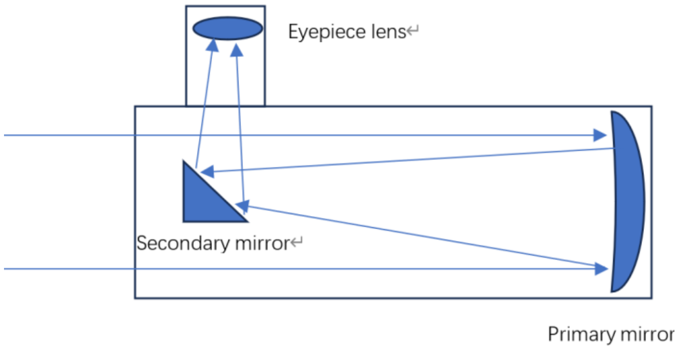

Fig. 2 Basic principle of a reflecting telescope

The refracting telescope was the first type of telescope invented, and early designs were used by astronomers such as Galileo Galilei [1], However, as telescope technology advanced, the limitations of refracting telescopes became apparent, especially in dealing with chromatic aberration. This led to the development of reflecting telescopes, which use mirrors to collect light and focus it, overcoming some of the issues faced by refractors. A telescope that utilizes mirrors to gather and concentrate light for the purpose of producing an image is depicted in Fig. 2. Additionally, it relies on the principle of reflection, where light is redirected by the reflective surfaces of the mirrors used in the telescope's optical system. In a reflective telescope, the incoming light is directed into the telescope through an aperture situated at the bottom of the device. Typically, a concave primary mirror is employed to redirect and concentrate the light towards a focal point, resulting in image formation. The secondary mirror, located closer to the top end of the telescope, then reflects the light to a convenient position, where it can be observed by the viewer or captured by an eyepiece lens or a camera. Reflecting telescopes were invented in the 17th century, independently by Isaac Newton and a few others, and they represented a significant advancement over refracting telescopes due to several advantages. One key advantage is the elimination of chromatic aberration, a major limitation of refractors since reflecting telescopes do not use lenses that refract different colors of light differently [1, 2]. Additionally, reflecting telescopes allow for larger apertures and lighter designs, making them more suitable for modern astronomical research and deep space observations. A catadioptric telescope is also known as a compound telescope or catadioptric reflector. A catadioptric telescope is a special type of telescope design that combines the advantages of both refracting and reflecting telescopes, resulting in a more complex and versatile optical system [7]. The main characteristic of a catadioptric telescope is the simultaneous use of lenses and mirrors in its optical path, as shown in Fig. 3. A catadioptric telescope consists of a primary mirror, typically spherical or parabolic, which reflects and focuses light. Above the central aperture of the primary mirror, a secondary mirror, often in the form of a convex lens, folds the light path back. After this light path is folded, an eyepiece, which is also a convex lens, is positioned to further focus and magnify the image. By blending the simplicity of refracting telescopes with the advantages of reflecting telescopes, such as eliminating chromatic aberration and accommodating larger apertures, catadioptric telescopes deliver a versatile and efficient optical system.

In summary, visible light telescopes are specifically designed for observing the visible spectrum, typically within the range of 400 to 700 nanometers, allowing astronomers to study stars, planets, and galaxies. Infrared telescopes are specialized instruments dedicated to detecting infrared light, covering the wavelength range from 700 nanometers to 1 millimeter, which includes near-infrared, mid-infrared, and far-infrared light. Infrared telescopes are particularly well-suited for studying cold objects, dust-obscured star-forming regions, interstellar dust and gas, distant galaxies, and cosmic background radiation, enabling the investigation of various astronomical phenomena that are not visible in the visible spectrum. the geographic location of telescopes plays a vital role in their observation capabilities.[8] infrared telescopes are often positioned at high-altitude locations or placed in space to circumvent atmospheric absorption, like the James Webb telescope for example. Which can provide more precise and accurate infrared observations. Infrared telescopes use reflective optics to gather, focus, and detect infrared radiation from celestial objects. So, the structure of infrared telescopes may be similar to reflecting telescopes.

Radio telescopes are specialized instruments designed for detecting electromagnetic radiation in the radio wave spectrum. These wavelengths are much longer than those of visible light and infrared radiation, typically ranging from millimeters to tens of meters. Radio telescopes use a reflective optical design, employing one or multiple combinations of parabolic or hyperbolic mirrors to reflect and focus radio waves. Due to the longer wavelengths of radio waves, the primary mirror or reflector size is relatively large [4, 5]. Radio telescopes are typically deployed in high-altitude locations on Earth to ensure precise and accurate radio observations.

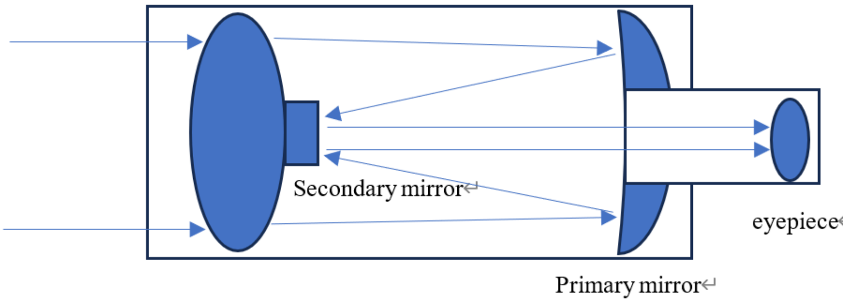

Fig. 3 Basic principle of a catadioptric telescope.

3. Principles

In optical telescopes astronomical telescopes focus light rays to converge the light from distant celestial objects onto a focal plane, creating clear images of the objects. The principle of optical imaging applies to both refracting telescopes and reflecting telescopes, where light rays undergo reflection or refraction on mirrors or lenses before being focused through the optical system to the focal point. As for the way the light is focused the light path diagram in the previous part can be referenced (seen from Fig. 1, Fig. 2 and Fig. 3). The imaging principle of refracting telescopes is based on convex lens imaging in geometric optics, as shown in Fig. 4 [9]. The equation can be given as:

$$\frac{1}{f}=\frac{1}{u}+\frac{1}{v} \tag{1}$$

Here, f is the focal length, v represents the image distance, and u represents the object distance.

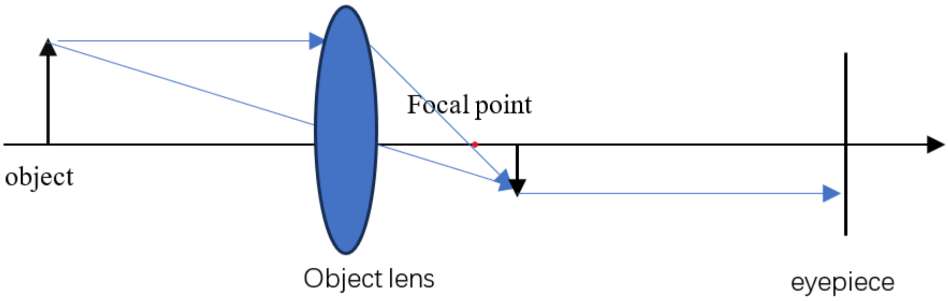

Fig. 4 The geometry of convex lens imaging

Besides, the focal length of a convex lens needs to be derived using Eq (2) [10]:

$$\frac{1}{f}=(n-1)(\frac{1}{R1}-\frac{1}{R2}) \tag{2}$$

The refractive index which represents as n of the lens must be determined, representing the ratio of the light speed in the lens medium to the speed of light in a vacuum. This parameter can be obtained through experimental measurements or provided by the lens manufacturer. The radii of curvature R1 and R2 of both the front and back surfaces of the lens are measured. A positive radius indicates a convex surface, whereas a negative radius signifies a concave surface.

Then, the magnification can then be calculated by Eq. (3) [9, 10]. In this formula, M represents the magnification, h1 is the height of the image formed by the imaging system, and h2 is the actual height of the object being imaged, which can help to realize the function of observing distant celestial bodies.

$$M=\frac{h1}{h2} \tag{3}$$

The imaging method of reflecting telescope is mainly realized by spherical mirror imaging [9], as illustrated in Fig. 5, and the formula and calculation logic are roughly the same as that of convex lens imaging

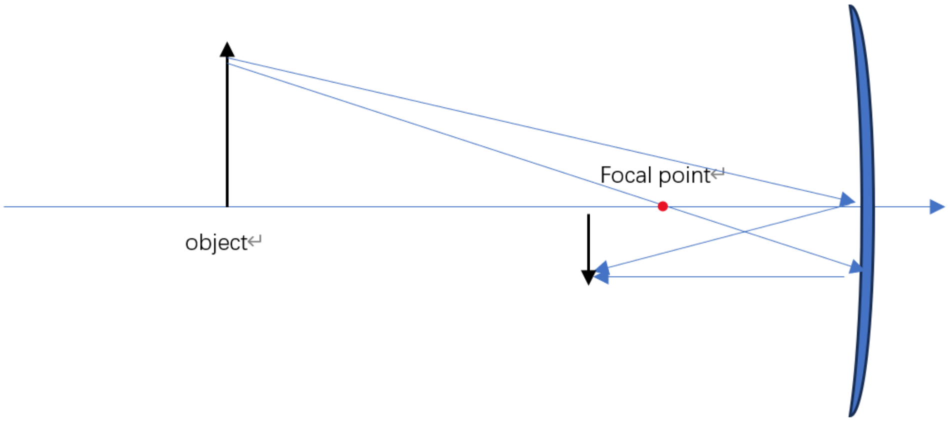

Fig. 5 The geometry of convex lens Spherical mirror imaging

Nevertheless, a radio telescope lies in its ability to receive and analyze electromagnetic radiation in the radio frequency range, enabling the detection, measurement, and study of celestial radio signals. The biggest difference from these telescopes is that they rely more on algorithms to generate images and use data for scientific research than imaging. This process begins with the radio antenna, the primary component of the telescope, which is designed to efficiently capture long-wavelength radio waves emitted or reflected by celestial objects and phenomena [11]. Upon reception, the initially weak radio signals undergo amplification to enhance their strength, allowing for accurate measurements. Prior to amplification, the signals may also undergo preprocessing steps, such as filtering and noise reduction, to improve the signal-to-noise ratio and eliminate unwanted interference. Subsequently, the amplified and preprocessed signals are converted into digital form, enabling advanced data processing and analysis [11, 12].

4. Observation and Applications

Modern telescopes have witnessed remarkable and rapid development, making significant contributions to the field of scientific research. This paragraph will use recent observations from JWST as an example. The James Webb Space Telescope (JWST) is a large optical and infrared space telescope. Equipped with a large-sized mirror, the JWST will utilize an infrared observation window to explore the universe in the wavelength range of 1.0 to 29 micrometers. This capability will enable it to delve deeper into the cosmos, studying targets that are obscured by dust and gas clouds, such as primordial galaxies and planetary systems [13]. The JWST has recently achieved advancements in its investigation of the exoplanet WASP-39b's orientation. Transmission spectroscopy is an effective technique for determining the levels of oxygen and carbon-based substances, but it necessitates a wide range of wavelengths, moderate spectral resolution, and high precision, which were not attainable with previous observatories. Nevertheless, the initiation of scientific operations by JWST to observe exoplanets at previously unexplored wavelengths and spectral resolutions is now accessible. The examination of the transiting exoplanet WASP-39b using a Near InfraRed Camera from JWST reveals distinct molecular absorption characteristics, including identifying gaseous water in the atmosphere and setting an upper limit on methane abundance. The most suitable chemical equilibrium models indicate that the atmospheric metallicity is 1-100 times that of solar levels and a substellar carbon/oxygen ratio exists, suggesting potential substantial accumulation of solid materials during planet formation or imbalances occurring in the upper atmosphere [14, 15].

Moreover, The EHT employs an interferometric radio telescope array technique, which combines data from various radio telescopes worldwide to create a virtual radio telescope equivalent in size to Earth. This breakthrough allows for unparalleled high-resolution imaging capabilities. With this level of precision, the EHT can observe the "event horizon" of black holes - the area surrounding a black hole where matter is about to be pulled in beyond recovery. The observed "shadow" appears as a dark region due to the strong gravitational field of the black hole that bends nearby radio emissions and creates a silhouette-like effect [16]. In 2017, the Event Horizon Telescope (EHT) was used to observe a black hole located at the center of the Milky Way galaxy. The observations were conducted using eight telescopes and revealed a compact emission region with rapid variability. Analysis of the images showed that there is a bright ring surrounding the black hole with a diameter of approximately 51.8 μas. Numerical simulations confirmed that this observation is consistent with what one would expect from a Kerr black hole weighing around 4×10^6 solar masses. These findings provide direct evidence for the existence of a supermassive black hole in our galaxy's center and establish connections between dynamical measurements on larger scales and event-horizon-scale images and variability. Furthermore, these results are compared to those obtained for another supermassive black hole known as M87, which shows consistency with general relativity predictions over three orders of magnitude in the central mass range [17, 18]. The imaging of the supermassive black hole M87 resulted in polarization images that revealed a magnetic field and provided insights into the origin of its jets. In addition, EHT recently disclosed their findings on the silhouette created by SgrA, another supermassive black hole situated at the core of our Milky Way galaxy. This shadowy depiction provides valuable insights into the surrounding geometry of the black hole, particularly in close proximity to its event horizon. Consequently, scientists can investigate its mass and rotation with greater precision [18].

5. Limitations and Prospects

Considerable advancements have been achieved in the field of astronomical telescope research, but certain limitations still persist the utilization of human technology introduces inherent inaccuracies during telescope observations. Inaccuracies may arise due to instrument precision and can be influenced by atmospheric interference and other environmental factors. The presence of atmospheric disturbances, particularly when observing visible light and infrared wavelengths, can significantly diminish the resolution and quality of telescope observation. In addition, the costs associated with constructing and maintaining telescopes often prove to be prohibitively high. Establishing a high-performance telescope necessitates substantial investment and long-term financial support. These problems cannot be estimated easily.

While there are certain limitations, the future of astronomical research shows promising advancements. The continuous progress in technology is expected to result in more advanced and precise telescope designs. For example, the utilization of adaptive optics can partially correct atmospheric interference and enhance the quality of observations. Additionally, innovative methods like radio interferometric arrays and virtual telescope technologies have the potential to increase aperture effectiveness and improve resolution. International collaboration will play a crucial role in shaping future astronomical research as researchers can share resources, knowledge, and expertise to drive progress and expand their observational capabilities. Global collaborative initiatives such as the Event Horizon Telescope will continue pushing boundaries in this field. Furthermore, although building space telescopes remains costly at present, advancements in space technologies may lead to more cost-effective solutions in the future. Space telescopes offer extensive observation ranges without atmospheric interference and provide extended time windows for exploration. It is also hoped that the field of astronomical observation will receive more attention.

6. Conclusion

In summary, the illustration above provides an in-depth analysis of the principles and state-of-art applications of astronomical telescopes. The development history of various telescope types including refracting, reflecting, and catadioptric telescopes, each offering unique advantages in observing different celestial phenomena. The principles of optical and radio telescopes, emphasize the significance of light convergence and data analysis in radio telescopes and how to get them by using calculation. Furthermore, Modern telescopes also provide a lot of research, such as the James Webb

Space Telescope and the Event Horizon Telescope, which have revolutionized our understanding of the universe, including the exploration of distant galaxies, exoplanets, and supermassive black holes. There are also limitations of astronomical telescope research, including inherent inaccuracies, atmospheric interference, and the high costs associated with constructing and maintaining telescopes. Despite these challenges, the future outlook remains promising with continuous technological advancements, international collaboration, and the potential for cost-effective space telescopes.

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