Comparison Of Different Telescopes: James Webb Space, Giant Magellan and Event Horizon

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Abstract. Mankind's obsession with space and the persistence of searching for extraterrestrial life has led to the invention of telescopes as a way to explore the mysterious vastness of the universe. In this paper, the development history of the telescope is studied, as well as the famous events observed by the telescope (black hole, solar structure, etc.), and the structure, environment and interference of the ground-based telescope, space telescope and joint telescope are compared and analyzed. By comparison, it is found that most large telescopes have a variety of research directions and are more restricted, and even if the relevant research part is strengthened, it will still be affected by the inevitable, depending on their geographical location and observation method. After analyzing and comparing different telescopes, the purpose, structure and how to avoid shortcomings of each telescope can be more clearly defined, so as to play a reference role in the future development of telescopes.

Keywords: Telescope; EHT; GMT; JWST; adaptive optics technology.

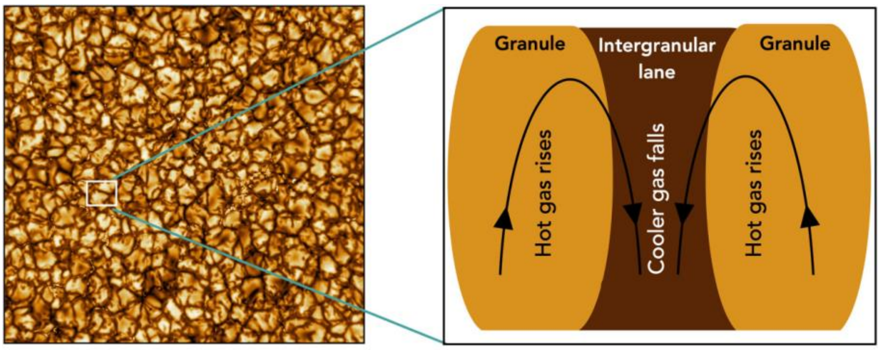
1. Introduction

Throughout history, humanity has held a deep fascination with the vast expanse of space. Ancient civilizations, in their pursuit of understanding life and nature, observed the movements of celestial bodies to grasp the patterns of day and night, the changing seasons, and the passage of time. This knowledge became essential for survival and progress in their interactions with the natural world.Since the Italian scientist Galileo invented the telescope in 1609 the clairvoyance of the ancients became a reality [1].

The advent of the telescope, attributed to Dutch eyeglass maker Lippershey, marked a significant leap forward. Inspired by observing children using lenses to magnify distant objects, Lippershey created the first telescope, featuring a convex lens and a concave eye piece. This breakthrough laid the foundation for the development of astronomical telescopes [2]. In 1609, Italian scientist Galileo Galilei took the telescope to new heights through meticulous experimentation and lens crafting. Galileo's observations of celestial bodies, such as Jupiter's moons and craters on the moon, revolutionized the understanding of the universe [3]. His work paved the way for future discoveries in astronomy.Building upon Galileo's innovations, Johannes Kepler refined the telescope design in 1611, improving image quality and magnification. Over time, telescopes evolved with the introduction of refracting and reflecting types, utilizing lenses and mirrors, respectively, to gather and focus light. Advanced technologies like adaptive optics and interferometry further enhanced image clarity by compensating for atmospheric disturbances. Today, cutting-edge telescopes like the Giant Magellan Telescope (GMT) promise to push the boundaries of astronomical research. With unparalleled light-gathering capabilities and resolution, GMT aims to unlock mysteries such as the formation of galaxies, dark matter, and the evolution of stars. These next-generation instruments hold the key to unraveling the secrets of the universe and shaping the future of scientific exploration [4].

The author delved herself into the literature and found some of the latest breakthroughs achieved through astronomical telescopes. One notable discovery involved the observation of a solar flare from its inception to its conclusion, shedding light on how intense heat from the corona descends through the chromosphere. This feat was made possible through the utilization of the Daniel K. Inouye Solar Telescope (DKIST), specifically designed to probe the Sun's magnetic field as show in Fig. 1 [5]. Equipped with state-of-the-art image stabilization, light filtration, and cooling technologies, the

DKIST boasts unparalleled capabilities to scrutinize the Sun's surface, meticulously examine magnetic fields and other dynamic phenomena, all while safeguarding its delicate components from the Sun's formidable energy and radiation. Notably, its 789-nanometer image stands as the highest-resolution depiction of the Sun to date. Leveraging these advancements, scientists aim to deepen their understanding of the underlying physical mechanisms behind solar flares. Moreover, the DKIST is poised to play a pivotal role in observing Mercury during its transits in 2049 and 2052, offering invaluable insights into the behavior of this enigmatic planet. Furthermore, researchers aspire to utilize this cutting-edge telescope to investigate sun-grazing comets. Previous research has shown that sun-grazing comets passing through the corona can act as a kind of probe to help us determine the density, temperature, and solar demeanor of the corona [6] and that helps to unveil a deeper understanding of the home star.



Granulation at the Sun's surface **Convection cell in the star's photosphere.**

Fig. 1 The hot plasma rises at the bright center of the convector, cools, and sinks in the darker dark path. The tiny, bright spots in the dark diameter come from converging magnetic fields that may direct energy to heat the corona [5].

2. Basic Descriptions

The James Webb Space Telescope (JWST) has conducted observations of the atmospheric composition of various planets, including WASP-39, revealing the presence of atoms and molecules such as hydrogen, helium, water, and methane. This groundbreaking achievement marks a significant stride in the quest to ascertain the potential habitability of exoplanets [7]. Situated approximately 700 light-years away from Earth, WASP-39b is a colossal gas giant, boasting a mass equivalent to 28 percent of Jupiter's, yet measuring 1.27 times larger in size. The detection of a substantial quantity of water molecules within its atmosphere suggests the existence of liquid water and hints at the possibility of supporting life forms. Moving forward, Scientists will next study how the molecules in these atmospheres interact with each other and further affect the planet's environment [7].

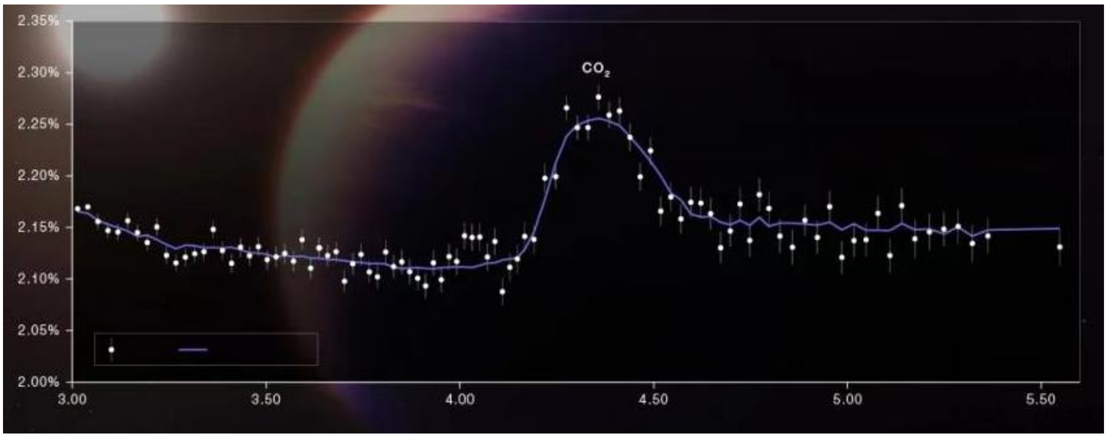


Fig. 2 Observation results [7].

The transmission spectrum of WASP39b, captured by the JWST's near-infrared spectrometer on July 10, 2022, is the first definitive evidence of carbon dioxide in the atmosphere of an extrasolar planet and the first detailed transmission spectrum of an exoplanet ever observed covering a wavelength range of 3 to 5.5 microns. The white dots represent the specific wavelengths of light blocked by the planet and absorbed by its atmosphere, the short gray lines extending above and below the data points represent errors, and the blue lines are the best fitting models. Peaks with a central wavelength of about 4.3 microns represent CO2 absorption /NASA, ESA, CSA, Leah Hustak (STScI), Joseph Olmsted (STScI) as shown in Fig. 2. In March 2023, researchers from Peking University and the National Astronomical Observatory of the Chinese Academy of Sciences unveiled a groundbreaking discovery using data from the Guo Shoujing Telescope (LAMOST) and the Nanshan Telescope of Xinjiang Observatory. They identified a compact star, approximately 0.98 times the mass of the Sun, alongside a binary star system comprising a late main sequence star. By integrating observations across multiple wavelengths, their findings suggest that the compact star might belong to a class of objects called X-ray faint isolated neutron stars (XDINS), marking the first observation of such an object within a binary system. Based on parallax measurements from the Gaia satellite, this binary system, harboring neutron star candidates, ranks among the nearest known to Earth, located a mere 385 light years away.Simultaneously, in early December 2023, a research collaboration between Xiamen University and the National Astronomical Observances made a striking revelation. Combining radial velocity data from LAMOST, periodic light variation data from the Transiting Exoplanet Survey Satellite (TESS), and high-resolution spectral data from the Canada-France-Hawaii Telescope (CFHT), they unveiled a compact celestial body situated approximately 416 light-years from Earth. TIt forms a single-line spectral binary system with a K7 main sequence star [8]. Detailed ultraviolet and optical analyses dismissed the possibility of it being a cold, massive White Dwarf, leading to the conclusion that the compact object is likely a neutron star.Furthermore, astrometric analysis from the Gaia satellite suggests that this celestial entity approached as close as approximately 160 light-years to the solar system around 2.5 million years ago. Radioactive elements resulting from the supernova explosion of the neutron star could have been deposited on Earth and potentially detected if the event occurred roughly 2.5 million years ago. These findings underscore the capability of LAMOST time-domain survey spectroscopy in identifying neutron stars or stellar black holes in proximity to Earth, thereby enriching the comprehension of the cosmic "ecological environment" surrounding the solar system. In addition to delineating the Lyman-break, the photometry exhibits clear effects from robust rest-frame optical emission lines (resulting from galaxies with metallicities lower than that of the Sun). Notably, the F444W−F410M color proves instrumental in refining redshift estimates and estimating emission-line equivalent widths, thereby facilitating corrections to stellar mass.

While gazing at the moon, the author made a fascinating observation: despite being at the same latitude and longitude on different days, the moon appeared differently each time. This prompted a curious exploration into the functioning of large, stationary national telescopes. Intrigued by groundbreaking discoveries like the first image of a black hole and observations of red and blue shifts across visible and invisible light spectra, the author delved into the mechanisms enabling telescopes to detect objects light years away, beyond human reach. The exploration led to an understanding of three primary telescope types: refractor, reflector, and catadioptric. Among these, the refractor telescope stands as the oldest, initially devised by Galileo Galilei and continuously refined over 400 years. In the upcoming chapters, the author will delve into the intricate world of telescopes, presenting an in-depth exploration of their diverse types, intricate structures, operational principles, typical observational outcomes, and a thorough comparison to elucidate their unique characteristics.

3. Principle and Applications

The James Webb Telescope stands as a testament to human innovation, boasting a meticulously crafted design comprised of several key components: a primary mirror, a secondary mirror, a suite of precision optical systems, and an array of scientific instruments. At its core lies the primary mirror, an unprecedented feat of engineering with a diameter of 6.5 meters, making it the largest space telescope mirror ever constructed. Crafted from lightweight beryllium material, this mirror ensures both precision and efficiency while minimizing overall weight. Operational principles are rooted in the fundamental laws of optical reflection (seen from Fig. 3). Starlight, upon entering the telescope, is initially captured by the primary mirror and then redirected to the secondary mirror before being further reflected to the scientific instruments located at the focal point of the telescope. This ingenious design enhances light collection, thereby improving sensitivity and resolution in observations. The Webb Telescope's sunshield comprises multiple ultra-thin layers, with the thickest layer measuring a mere 0.05 millimeters, positioned closest to the sun. Each layer, coated with a 100-nanometer layer of aluminum, contributes to the shield's reflective properties. To mitigate heat absorption and prevent infrared radiation, the layers are strategically angled to facilitate outward radiation dispersion into space (seen from Fig. 4) [9].

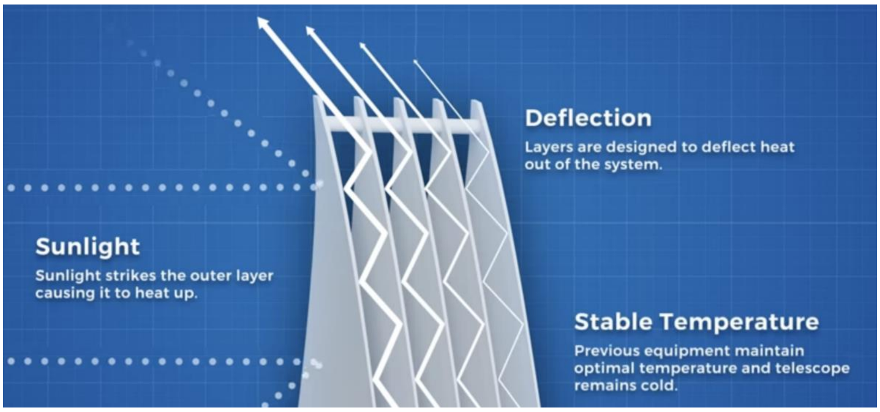


Fig. 3 A sketch of Webb [9].

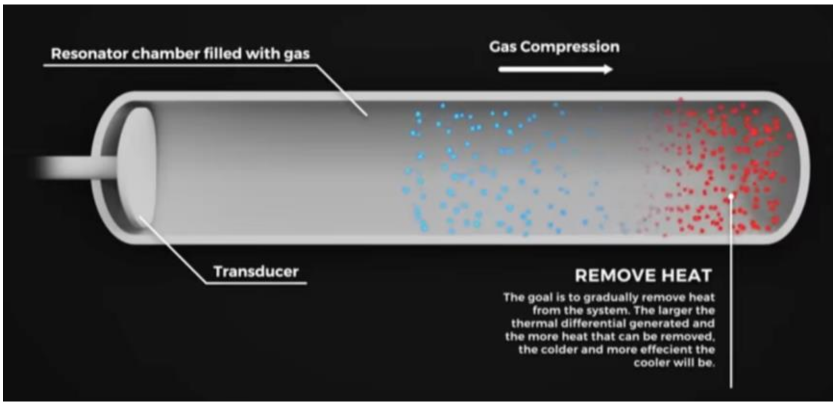


Fig. 4 A sketch of cooler [9].

Comprising an optical telescope module, spacecraft module, and integrated scientific instrument module, the Webb Telescope embodies a seamless fusion of cutting-edge technology and innovative engineering, poised to revolutionize the understanding of the cosmos. Crafted for infrared observation in the cosmos, the James Webb Space Telescope (JWST) boasts a sophisticated structure featuring 18 hexagonal beryllium elements composing its primary mirror, spanning an impressive collection area of 25 square meters. Supported by the spacecraft module, this telescope operates at frigid temperatures, essential for detecting infrared light with precision. The optical telescope module (OTE) houses the primary mirror, secondary mirror, tertiary mirror, and fine steering mirror, forming a cohesive three-mirror anastigmatic telescope system. The James Webb Space Telescope (JWST) is predicted to make great advances in the field of exoplanet atmospheres. Its 25m^2 mirror means that it can reach an unprecedented level of precision in observations of transit spectra and can thus characterize the atmospheres of planets orbiting stars several hundred pc away [9]. The abundances of key molecules have been allowed to coverage of the infrared spectral region between 0.6 and 28 μm to be probed during the transit of a planet in front of the host star, and when the same planet is eclipsed constraints can be placed on its temperature structure [10]. Moreover, its capability to penetrate dense space dust will unveil the ancient universe, unveiling the genesis of galaxies and potential habitable celestial bodies. Unlike its predecessor, the Hubble Telescope, which reached only a few hundred million light-years after the big bang, JWST delves deeper into cosmic history, witnessing the emergence of the first stars and galaxies. By scrutinizing other planetary systems, scientists gain insights into the formation of the solar system. JWST's advanced instrumentation allows for the detection of water vapor, methane, and carbon dioxide in exoplanet atmospheres, providing crucial clues to the presence of life-sustaining elements. With its innovative approach to universe exploration, the JWST promises to unlock countless mysteries, offering a fresh perspective on cosmic evolution.

The Giant Magellan Telescope (GMT) is poised for a monumental leap, amalgamating seven colossal mirrors to form a staggering 25-meter mirror, surpassing the size of any existing telescope by twofold. Achieving precise shaping and alignment of these mirrors is imperative to capture and focus photons from faint astronomical objects, where photons are scarce. To craft these mirrors, a special low-expansion borosilicate glass is cast into honeycomb molds and subjected to intense heat of up to 1,200 degrees Celsius in an electric oven. Through this process, the glass melts and conforms to the desired parabolic shape. Following polishing, an ultra-thin layer of aluminum is applied. Equipped with an advanced adaptive optics system, GMT features thin secondary mirrors with actuators capable of dynamically adjusting to counter atmospheric distortions in real-time. Leveraging its expansive aperture and adaptive optics, GMT achieves resolution down to its diffraction limit, enabling the detection of planets fainter than their host stars by over a million times as shown in Fig. 5 [11].

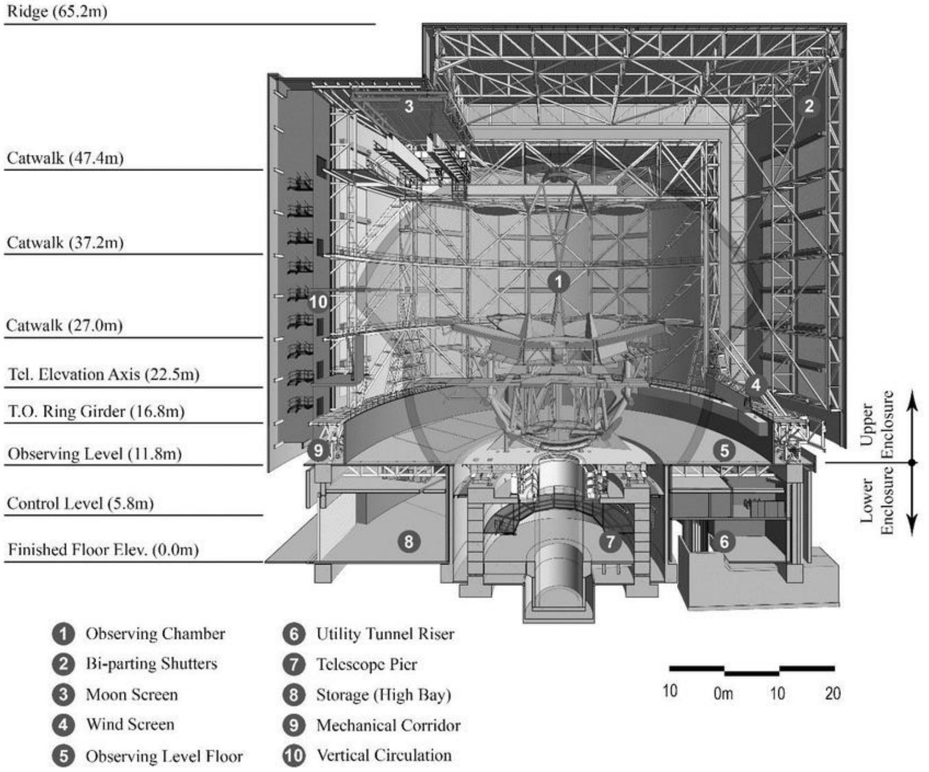


Fig. 5 A sketch of GMT [11].

This remarkable resolution enables GMT to observe planets in close proximity to their stars, scrutinize their rotations, measure their masses, and analyze their atmospheres for signs of habitability. With these capabilities, GMT holds promise for groundbreaking discoveries in the quest to uncover worlds capable of sustaining life. Supermassive black hole (SMBH) images were first captured in 2019 by the Event Horizon Telescope Collaboration (EHTC) using Very Large Baseline

Interferometry (VLBI). The Event Horizon Telescope (EHT) boasts a unique structure, comprising radio telescopes situated across the globe. Its operational concept relies on radio interferometry technology, where in radio emissions from celestial objects are captured by the EHT 's antenna. Due to the spatial distribution of antennas, each one receives a distinct radio signal. By analyzing these variations, details regarding the position, morphology, and radio emission properties of celestial entities can be inferred. Through Very Long Baseline Interferometry (VLBI) technology, these telescopes collectively form a virtual Earth-sized telescope. The EHT collaboration employs various imaging techniques to delineate the fine-scale structure of objects, especially those opaque at longer wavelengths. These methods encompass traditional VLBI approaches like CLEAN, alongside innovative techniques tailored for high-frequency VLBI imaging, such as EHT imaging, SMILI, DMC, and Themis. Key features of the EHT setup include its distributed array configuration, comprising multiple radio telescopes strategically positioned worldwide. To ensure synchronized observations across this array, meticulous time synchronization and data processing techniques are imperative. Each telescope functions as a substantial radio antenna, equipped with a sizable collection area to capture faint radio signals from space. Furthermore, the EHT relies on robust data processing systems comprising high-performance computers and specialized software for signal analysis [12]. Operating primarily through interferometry, the EHT compares signal discrepancies from diverse telescopes to deduce the spatial orientation, morphology, and other physical attributes of observed objects. The estimated parameters are shown in Table 1.

Table 1. Estimated parameters of SMBHs using EHT observables.

Model	SMBH			
	$\boldsymbol{M87}^{*}$		$\boldsymbol{SgrA}^{*}$	
	g/M	a/M	g/M	a/M
Kerr-Newman	$0.37^{+0.09}_{-0.12}$	$0.74^{+0.07}_{-0.08}$	$0.40^{+0.08}_{-0.11}$	$0.73^{+0.08}_{-0.08}$
Rotating Bardeen	$0.37^{+0.08}_{-0.14}$	$0.66^{+0.11}_{-0.09}$	$0.40^{+0.08}_{-0.11}$	$0.65^{+0.10}_{-0.10}$
Rotating Hayward	$0.85^{+0.06}_{-0.16}$	$0.54^{+0.13}_{-0.07}$	$0.89^{+0.03}_{-0.15}$	$0.53^{+0.13}_{-0.05}$
Ghosh-Culetu	$0.37^{+0.09}_{-0.12}$	$0.74^{+0.08}_{-0.08}$	$0.40^{+0.08}_{-0.11}$	$0.73^{+0.07}_{-0.08}$

Extrinsic or intrinsic black hole parameters may be estimated by the approach employing EHT, and it is found to be applicable to SMBHs. The three telescopes also differ in structure and use. GMT is a ground-based telescope, JWST is a space telescope, and EHT is a virtual telescope composed of several Earth-based telescopes. Since GMT is based on the ground, with main mirror consisting of seven sub-mirrors that improve light collection efficiency through a large aperture and provide high-resolution, highly sensitive observation capabilities. Its structure is characterized by collecting light reflected from the primary mirror, and constantly adjusting it through the secondary concave mirror to filter out interference from the atmosphere, so as to obtain clear observations. Although it employs advanced adaptive optics technology to mitigate this effect, its observations may also be impacted by the environment and climate. Its primary uses include light, infrared, and celestial body wavelengths.

The JWST, which uses infrared wavelengths to help understand the origin and evolution of the universe, is currently the largest space telescope, consisting of 18 lenses coated with metallic gold to improve reflectivity. The structure of the JWST is designed so that it can operate at the second Lagrange point, where the farthest planet is 1.5 million kilometers from Earth, avoiding interference from Earth and the Sun. However, it takes a long time to reach the observation position, cannot observe rapidly changing astronomical phenomena, and its deployment mechanism is more complex and requires higher infrared observation environment. The EHT consists of several radio telescopes, and by combining their observational data, a virtual telescope of equivalent aperture is formed. It mainly uses radio wave interference phenomenon to enhance the intensity of the observed signal to directly observe the black hole and the surrounding accretion disk and jet but may be affected by the Earth's ionosphere and other radio interference, reducing the accuracy of the observation results. In the future GMT may improve its adaptive optics technology for better ground observation. The JWST will be changed to a lighter, simpler structure to speed up the transition, and to observe changes in the universe in the first place. The EHT may improve the accuracy of observations by reducing radio interference through more advanced techniques. With the continuous development of technology, telescopes will reveal more secrets of the universe to us in the future.

4. Conclusion

To sum up, a stark contrast emerges when one examines different types of telescopes, revealing distinct design principles and intended uses. Furthermore, despite the remarkable achievements of current astronomical telescopes, certain limitations persist. These constraints predominantly manifest in terms of sensitivity (the ability to detect faint objects) and resolution (the capability to discern fine details). For instance, although the Webb Telescope exhibits prowess in locating organic molecules, it encounters challenges in detecting minute dust particles. Moreover, ground-based telescopes are susceptible to atmospheric disturbances, stemming from technical and environmental factors, which further impede their observational capabilities.

However, there remains optimism for the future. Continued advancements in technology promise to enhance the observational capabilities through the development of innovative telescopes. For instance, projects like the "China Compound Eye" boast real-time response systems that can swiftly adapt observation directions to meet evolving scientific objectives. Additionally, prospects for improved sensitivity and resolution are on the horizon, with the anticipated completion of state-of-the-art facilities like the Guo Shoujing Telescope.In essence, each type of telescope possesses unique characteristics and applications, while enhancing sensitivity and resolution remains a paramount challenge for astronomical telescope advancement. Overcoming existing limitations and delving into the profound mysteries of the universe will hinge on technological innovation and the construction of novel telescopes in the years to come.

References

[1] Wen X. The first person to point a telescope at the sky one of the 400-year series of Celestial Observation. Space Exploration, 2002, 1: 35-37.

[2] King H C. The history of the telescope. Courier Corporation, 2003.

[3] Julio M. Technological revolution in astronomy. City University of New York, 2015.

[4] Barnes III A A, Knight J S, Lightsey P A, et al. Technology advancements for future astronomical missions. UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VIII. SPIE, 2017, 10398: 204-212.

[5] Rimmele T R, Warner M, Keil S L, et al. The Daniel K. Inouye solar telescope–observatory overview. Solar Physics, 2020, 295(12): 1-49.

[6] Matsumoto T, Kawabata Y, Katsukawa Y, et al. Synthesis of infrared Stokes spectra in an evolving solar chromospheric jet. Monthly Notices of the Royal Astronomical Society, 2023, 523(1): 974-981.

[7] Holmberg M, Madhusudhan N. Exoplanet spectroscopy with JWST NIRISS: diagnostics and case studies. Monthly Notices of the Royal Astronomical Society, 2023, 524(1): 377-402.

[8] Wang J, Fu J, Zong W, et al. Properties and evolutions of starspots on three detached eclipsing binaries in the LAMOST–Kepler survey. Monthly Notices of the Royal Astronomical Society, 2022, 511(2): 2285-2301.

[9] Kemp T W, Dunlop J S, McLure R J, et al. Maximizing the power of deep extragalactic imaging surveys with the James Webb Space Telescope. Monthly Notices of the Royal Astronomical Society, 2019, 486(3): 3087-3104.

[10] Barstow J K, Aigrain S, Irwin P G J, et al. Transit spectroscopy with James Webb Space Telescope: systematics, starspots and stitching. Monthly Notices of the Royal Astronomical Society, 2015, 448(3): 2546-2561.

[11] Johns M, McCarthy P, Raybould K, et al. Giant magellan telescope: overview. Ground-based and Airborne Telescopes IV, 2012, 8444: 526-541.

[12] Afrin M, Ghosh S G. EHT observables as a tool to estimate parameters of supermassive black holes. Monthly Notices of the Royal Astronomical Society, 2023, 524(3): 3683-3691.