Analysis and Comparison of the State-of-Art Telescopes: James Webb, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE and EVENT HORIZON TELESCOPE

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Abstract: Contemporarily, various telescopes have been constructer for cosmology observation. With this research, this confirms once again the vital contribution of cutting-edge telescope technology in revealing the universe's most profound secrets. This essay have outlined how James Webb Space Telescope(JWST)'s infrared capabilities, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE's record-setting sensitivity at radio wavelengths, and EVENT HORIZON TELESCOPE's Earth-sized interferometric array each make their own distinct contributions to modern astrophysics. The research features spectacular new findings, ranging from earliest galaxy formation signatures, vast pulsar surveys, and direct imaging of black hole event horizons for the very first time. These breakthroughs not only challenging current models but lead the way for future technological and methodological advancements as well. In the future, advances in detection sensitivity along with resolution are predicted to reveal dark matter distribution patterns and the dynamics of cosmic evolution. Implications of this study are profound, providing the robust foundation for future multi-messenger astronomy as well as a richer insight into universe's complicated nature.

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1 INTRODUCTION

The history of telescope research dates back to the 19th century, and early attempts, such as Herschel's use of thermonuclear reactors to detect infrared radiation from stars (Battersby et al., 2018), were limited by the technology and yielded only sporadic results. In the 1940s, the development of radar technology in World War II laid the foundation for radio astronomy, Hay's team discovered solar radio radiation, Cambridge Ryle's team developed interferometer technology, and the Australian Radio Physics Laboratory was the first to identify radio sources such as the Crab Nebula. In the 1950s, the Lovell 76-meter radio Telescope and the 305 Miarecibo radio telescope were built, opening the era of large aperture. Infrared astronomy has experienced a long exploration (Sullivan, 2009). In the 1960s due to the lead sulphide detector, liquid helium cooling technology breakthrough and rise, Johnson established a near-infrared metering system, and Luo developed a germanium bolometer to achieve mid-infrared observation. In the 1970s, with the rise of space infrared astronomy, Spitzer, Herschel and other space telescopes broke through the atmospheric limits, and in 2010 James Webb Telescope achieved 6.5 meters of gold-plated beryllium mirror deep space observation (Tyson, 2002). The current Origin Space telescope design uses a 5.9-meter 4.5-K cooled primary mirror covering 2.8-588 microns, equipped with a high-resolution spectrometer and polarimeter. Radio telescopes reveal invisible phenomena such as pulsars, interstellar molecules, and quasars; infrared telescopes penetrate dust to observe star-forming regions and galactic cores; and space telescopes break through atmospheric interference to obtain full-wavelength data. The Origin telescope will trace the evolution of heavy elements in the universe, and the feedback mechanism of galaxies, analyse the formation of planetary systems through water vapour and organic molecular spectroscopy and detect biomarkers of exoplanet atmospheres (Leisawitz et al., 2021). At the technical level, it promotes breakthroughs in superconducting detectors, space

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refrigeration, interference arrays, etc., at the methodological level, it encourages the development of multi-messenger astronomy and continues to expand the boundaries of human exploration of ultimate questions such as dark matter, dark energy, and the origin of life.

Recent years have seen significant advances in space exploration. Using the Event Horizon Telescope (EHT) (Galison, et al., 2023), the shadow and asymmetric accretion structure of the supermassive black hole at the centre of the nearby galaxy M87 has been directly observed for the first time, confirming both the prominent light bending and event horizon predicted by general relativity in a strong gravitational field, and measuring the black hole's mass to be approximately 6.5 billion solar masses (The Event Horizon Telescope Collaboration et al., 2019). By high redshift observations, the early galaxies, which were the first groups of galaxies formed hundreds of millions of years after the birth of the universe, have been discovered, which revealed the early star formation and assembly process, and traced the evolution history of the neutral hydrogen ionized by ultraviolet radiation during the cosmic reionization period. Studies of exoplanets have thus far uncovered a plethora of different types of planetary systems, resulting in studies of the composition of atmospheric rocky planets and more indirect signatures, such as KBO dust aggregation in protoplanetary disks. As well as the distribution of dark matter correlating with galaxies through gravitational lensing, there has been new information from the observation of supernovae and the large-scale structure of the universe on dark energy and the accelerated expansion of the universe. These and other discoveries have enhanced understanding of black holes, how galaxies form, the beginning of the universe and the likely circumstances for life beyond Earth.

This essay will analyse the most advanced telescopes from their principle of device, composition, and detection and include the results of the detections in recent years. In the article, this paper will do a description of the telescope and, an analysis of three different telescopes (Hubble-James Webb, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE, and EVENT HORIZON TELESCOPE-event horizon telescope), a comparison between these telescopes including their difference, common limitations and the prospects.

2 DESCRIPTIONS OF TELESCOPE

A telescope is a scientific instrument that breaks through the sensitivity, resolution and observation band limits of human eyes or traditional detectors by collecting electromagnetic radiation (including radio waves, infrared, visible light, X-rays, etc.). Its core principle is to focus electromagnetic waves and enhance the detection ability of distant celestial bodies. The radio telescope receives radio waves (wavelength from 1 mm to 10 meters) with parabolic antennas, and improves its resolution through interference technology. The Event Horizon Telescope (EHT) network comprising eight radio baselines around the globe forming a millimetre wave VLBI network achieved a resolution of 20 microarcseconds at a 1.3 mm wavelength and the Earth-equivalent aperture capturing the black hole shadow for the first time. Infrared telescopes concentrate on astronomical objects releasing thermal radiation in the range of 0.7 microns to 1 mm. To do so, they need to overcome the thermal noise generated by the instrument, which can be achieved through deployment in outer space or ensuring deep refrigeration; the James Webb Space Telescope (JWST) comprises 18 pieces of gold-coated beryllium mirrors arrayed to make a 6.5-meter mirror (Kalirai, 2018), matched with to withstand the heat using five-layers of sunshade makeup to reach an operating temperature of 40K that can undertake for the composition of the atmosphere in the first galaxies as well as exoplanets utilizing near-infrared camera (NIRCam) and mid-infrared instrument (MIRI) (Li, et al., 2019). The planned Origin space telescope will further expand the aperture to 5.9 meters, 4.5K low-temperature design and interferometer technology, the target tracking galaxy evolution and water molecule distribution. Optical telescopes rely on mirrors to collect visible light and correct atmospheric disturbances through adaptive optics, such as the Hubble Space Telescope with a 2.4-meter primary mirror and a vacuum environment to achieve 0.1 arcsecond resolution, covering ultraviolet to near-infrared bands; large ground-based equipment such as the Keck Telescope uses a 10-meter spliced mirror to improve light collection. X-ray telescopes require nested grazing incidence mirrors to focus high-energy photons, typically in the 0.1-10 KeV band detected by Chandra Observatory through a hyperbolic mirror structure. Space and ground-based cooperative observation constitute an important mode of modern astronomical research: space instruments avoid atmospheric absorption and specialize in ultraviolet, X-ray and far-infrared wavelengths; ground-based facilities rely on high-altitude sites to reduce atmospheric interference and push resolution limits with interferometric array technology. Technology trends focus on multi-sector innovation: Interferometry, multi-band data integration (virtual observatory cross-library analysis), detector innovations (superconducting transition edge sensors, quantum capacitance detectors to improve far-infrared sensitivity), and automated sky surveys are advancing cutting-edge exploration of everything from exoplanet atmospheres to the distribution of dark energy in the universe.

3 JAMES WEBB SPACE TELESCOPE

James Webb Space Telescope (JWST) is currently the biggest and most advanced space telescope, it has been launched on December 25 2021, orbiting at the second lagrange point (L2), which is about 1.5 million km from Earth, focusing on the observations in the infrared band. James Webb Space Telescope has a primary mirror that has a diameter of 6.5 meter and consists of 18 hexagonal element, which made out of beryllium and has a layer of gold-plated material for the surface to improve infrared reflectivity. Apart from its primary mirror, JAMES WEBB SPACE TELESCOPE also have equipped a visor block to block heat and light from the Sun, Earth and moon, this ensures JAMES WEBB SPACE TELESCOPE can work in an extremely low temperature, thus increasing the sensitivity of infrared observation. JAMES WEBB SPACE TELESCOPE also have scientific instruments including the Near-Infrared Camera (NIRCam), the Near-Infrared Spectrometer (NIRSpec), the Mid-Infrared Instrument (MIRI), and the Near-Infrared Imager and Slitless Spectrograph (NIRISS), among others, for the analysis of the spectra and imaging of celestial objects (Gardner, et al., 2023).

JAMES WEBB SPACE TELESCOPE mainly uses infrared wavelengths for detection, this allows it to penetrate dust and gas to observe celestial bodies from the early universe. It's working principle involves collecting weak infrared light through a large primary mirror then using the scientific instruments to analyse the result. For instance, the NIRcam can capture images of distant galaxies and star formation regions, while the NIRSpec can analyse the spectra of celestial bodies and reveal their chemical composition and physical properties (Gardner, et al., 2023). A typical observation is shown in Fig. 1 (NIRCam, 2024). In recent years of exploration, JAMES WEBB SPACE TELESCOPE has achieved many significant results, it discovered a galaxy which has a redshift over 13 and only 330million years after big bang, given a name as JADES-GS-z13-1. This discover provides important clues for studying the epoch of reionization. Additionally, JAMES WEBB SPACE TELESCOPE has conducted detailed analyses of exoplanet atmospheres, revealing molecular components such as water vapor and carbon dioxide, which this analyse also provides important useful information of researches on other topic (finding potentially habitable planets). The observations from JAMES WEBB SPACE TELESCOPE have demonstrated the characteristics of galaxies at different evolutionary stages, assisting scientists in better understanding how galaxies gradually evolve from their early stages into the spiral and elliptical galaxies we see today (Sutter, 2024).

Figure 1: Image of the first scientific observation by JAMES WEBB SPACE TELESCOPE (NIRCam, 2024).

The discovery of JADES-GS-z13-1 has really pushed the boundaries of what has been know today and has thrown a curveball to the existing theories about how galaxies are formed. Before this finding, scientists thought that galaxies with such mass and brightness couldn't have come into existence so soon after the Big Bang. This discovery hints that the processes behind early galaxy formation might have been a lot more efficient than ever imagined, leading to some necessary updates in cosmological models. Plus, thanks to the James Webb Space Telescope's ability to see through interstellar dust, and can now observe star-forming regions that optical telescopes just can't pick up. By looking at the spectral signatures from these areas, astronomers can figure out the ages and compositions of different star populations, giving the valuable insights into how stars and planetary systems develop over time (Sutter, 2024). JAMES WEBB SPACE TELESCOPE, with its advanced capabilities, is now being repurposed to support future deep space exploration missions. In addition to its scientific objectives, the JAMES WEBB SPACE TELESCOPE is being used to monitor potential threats such as asteroid trajectories and to assess the feasibility of extracting resources from NEOs. In addition, it assists in the development of technologies for long-term manned space flight, including radiation shielding and life support system optimization. These efforts are in line with broader initiatives to establish a sustainable human presence beyond Earth, such as the Moon Base and Mars colonization projects.

4 FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE

Five-hundred-meter Aperture Spherical radio Telescope (FAST) is the biggest single-aperture radio telescope in the world, located at Guizhou province, China, it is known for its massive 500 meters aperture and one of the most sensitive radio telescopes in the world. FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE consist a complex structure made up using few key components such as the reflective surface, the feed cabin and the feed support system. The reflective surface is made up of thousands of triangular shaped panels stitched together forming a huge sphere which is used for collecting and reflecting the radio wave received from the universe. The feed cabin is located at the focal point of the reflective surface, it is responsible for receiving the reflected signal and locating the significant and accurate location via the feed support system, this is for assuring the signal has been received accurately. The design of reflective surface and the technology used in the structure allows FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE to cover a larger viewing area with a higher sensitivity and resolution.

As mentioned, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE detects celestial bodies by receiving the radio waves from the universe. Radio wave is one of the waves included in the EM waves, radio wave has a longer wavelength compared to other EM waves, while it reaches the reflective surface of FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE, they will be reflected to the focal point of the reflective surface where feed cabin is located at. There will be a receiver in the feed cabin which its main job is converting these radio waves signal into electrical signals, and then these converted signals will be then analysed and processed by a sophisticated signal processing system. This detection method allow FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE can observe objects and phenomena such as, pulsars, Five-hundred-meter Aperture Spherical Radio Telescope radio bursts and neutral hydrogen, that optical telescopes cannot detect, while the design of the feed cabin allows FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE to be fine-tuned during the observation process to suit different observation needs, this well increased the accuracy and efficiency of the observation process.

In the last few years, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE has achieved some exciting breakthroughs in astronomy. In terms of pulsar discovery, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE already has successfully discovered more than 800 new pulsars (Event Horizon Telescope Collaboration, 2019; Event Horizon Telescope Collaboration, 2022a). This huge number of pulsars been found out also refreshed the historical record of pulsar discovery and injected new resources into the study of pulsar astronomy. Else, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE has also conducted in-depth research on Five-hundred-meter Aperture Spherical Radio Telescope radio bursts (FRBs) and detected hundreds of FRB bursts, provided valuable data for revealing the origin and nature of Five-hundred-meter Aperture Spherical Radio Telescope radio bursts. In another section of neutral hydrogen observation, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE provides important clues for study of large-scale structures and galaxy evolution of the universe through the observation of neutral hydrogen in the Milky Way. This research demonstrates the strong capability of FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE and shows that it provides important data and platforms for the next step of research.

As a major scientific and technological infrastructure independently developed by China, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE has not only achieved world-leading scientific achievements in the fields of pulsar astronomy and Five-hundred-meter Aperture Spherical Radio Telescope radio burst research, but also provided an important observation platform for astronomers around the world. In the future, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE will keep being a key player in exciting scientific areas like detecting dark matter and finding sources of gravitational waves. It will help to learn more about the universe and discover its mysteries. Its continuous observation and research will help scientists better understand the origin, evolution and structure of the universe, and provide new impetus and direction for the development of astronomy.

5 EVENT HORIZON TELESCOPE

The Event Horizon Telescope (EHT) is a global network of radio telescopes that connect multiple radio telescopes distributed around the world through a very long baseline interferometry (VLBI) technology to form a virtual telescope with an aperture the size of the Earth. This unique design of structure allows EVENT HORIZON TELESCOPE has an unprecedented high resolution and the ability to observe structures at the event horizon scale of black holes. The main components of EVENT HORIZON TELESCOPE include the Atacama Large Millimeter Array (ALMA) in Chile, Hertz Telescope in USA, Submillimeter Array Telescope in Hawaii, and the Antarctic Telescope. The result of these telescopes works together, taking down the record of radio waves emitted by celestial bodies and use the atomic clocks to precisely to accurately updating the data and finally using the supercomputer to synthesize the high-resolution images. This global collaborative approach allows EVENT HORIZON TELESCOPE to transcend the limitation due to the geographic and enable observations of the most mysterious objects in the universe (Event Horizon Telescope Collaboration, 2019).

The detection principle of the EVENT HORIZON TELESCOPE is based on the observations of millimeter wave band, where the Milky way is almost transparent, this reduced the influence of interstellar gas and material around the black hole on observations. The core technology of EVENT HORIZON TELESCOPE is the VLBI technology, it records radio waves emitted by celestial bodies by setting up telescopes at different locations and accurately up dating using the atomic clocks. The data is then will be transferred to a supercomputer for processing, synthesizing the high-resolution images through complex algorithms. This technique can achieve an extremely high angular resolution, sufficient to observe the structure of the event horizon of a black hole. The high-resolution imaging of EVENT HORIZON TELESCOPE allowed scientists to directly observe the shadow of the black hole for the first validated prediction of Einstein's general theory of relativity (Event Horizon Telescope Collaboration, 2022b).

In the past few years, EVENT HORIZON TELESCOPE has made significant achievements in black hole imaging, black hole jet research, and general relativity verification. In 2019, EVENT HORIZON TELESCOPE released humanity's first image of a black hole, showing a supermassive black hole at the centre of the M87 galaxy. This breakthrough provides direct evidence for the existence of black holes and has attracted widespread attention around the world. In 2022, EVENT HORIZON TELESCOPE published the first image of Sgr A*, the black hole at the centre of the Milky Way, further verifying the predictions of general relativity. In addition, EVENT HORIZON TELESCOPE also studied the origin and nature of the jet stream of the black hole, and found that the jet of the black hole in the M87 galaxy is closely related to the strong magnetic field. These discoveries provide important clues for understanding the physical properties and behaviour of black holes, and open up new directions for the study of black hole physics and cosmology (Event Horizon Telescope Collaboration, 2022c). The first image is shown in Fig. 2.

The success of EVENT HORIZON TELESCOPE not only provided direct evidence for the existence of black holes, but also advanced several areas of astronomy and physics. In the future, EVENT HORIZON TELESCOPE plans to further expand its network of telescopes, improve the resolution of observations, and explore more details of black holes, such as the rotation of black holes and the formation mechanism of jets. These studies will provide new perspectives and data support for black hole physics and cosmology, further deepening current understanding of the universe.

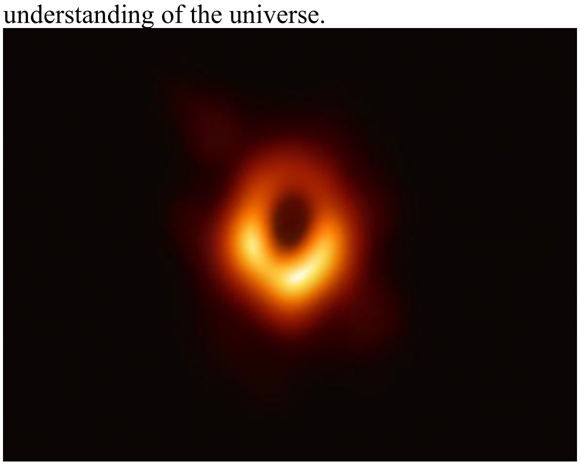

Figure 2: First Image of a Black hole (Event Horizon Telescope Collaboration, 2022c).

6 COMPARISONS

Three telescopes—the James Webb Space Telescope (JWST), the Five-hundred-meter Aperture Spherical radio Telescope (FAST), and the Event Horizon Telescope (EHT)—represent different observation methodologies, built-in limitations, and promising research directions, as outlined in the text above. JAMES WEBB SPACE TELESCOPE, using its 6.5-meter segmented primary mirror and advanced infrared instrumentation (NIRCam, NIRSpec, MIRI, NIRISS), operates chiefly in the infrared regime, able to push through dust and gas to unveil the earliest universe's galaxy clusters and star-forming regions; but, because it uses infrared detection, it needs extremely low operational temperatures, submitted to as required by an advanced visor block structure in protecting solar and Earthly heat inputs, both an engineering achievement but at the cost of sensitivity in terms of its spectral range. Alternatively, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE, the largest single-dish radio telescope in the world with its 500-meter reflecting surface made up of thousands of triangular panels, uses radio wavelength detection on observing pulsars, Five-hundred-meter Aperture Spherical Radio Telescope radio bursts, and the emissions of neutral hydrogen inaccessible to optical telescopes; but, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE’s conception and function demand fine calibration of its feed cabin support system in order to accurately convert the signal, one problem serving as an echo of limitations in terms of resolving power of the signal as well as the practical limitations on constructing very large apertures. Alternatively, EVENT HORIZON TELESCOPE utilizes an international array of linked radio telescopes in Very Long Baseline Interferometry (VLBI), gaining an Earth-sized virtual aperture in order to create unparalleled high-resolution imagery of black hole event horizons, as illustrated in its historic snaps of the M87 black hole as well as Sgr A'; but, EVENT HORIZON TELESCOPE’s observation regime is by nature bounded in ability by the problems in coordinating global data sets, the technological requirements of atomic clock sampling, as well as in data synthesizing procedures that limit the frequency as well as breadth of accomplishable observation. Looking ahead, as each telescope has extended the boundaries of current knowledge about astrophysical phenomena—the JAMES WEBB SPACE TELESCOPE with the revelation of galaxies 330 million years after the Big Bang, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE with the detection of more than 800 pulsars, and EVENT HORIZON TELESCOPE with the verification of general relativity with direct black hole imaging—the prospects are strong: JAMES WEBB SPACE TELESCOPE's ongoing deep space explorations can possibly shed light on the reionization era as well as exoplanet atmospheres, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE's developments can lead towards better detection of dark matter as well as gravitational waves, and EVENT HORIZON TELESCOPE's network expansion as well as improvement in resolution is likely to unveil even greater details about black hole dynamics as well as jet formation, together ushering in an era of revolutionary astronomical investigation.

7 CONCLUSIONS

To sum up, the field of telescopes has come on in leaps and bounds since the 19th century, revolutionizing the capacity for observing the universe. This paper discusses the cutting-edge technology of three seminal telescopes—the James Webb Space Telescope (JAMES WEBB SPACE TELESCOPE), the Five-hundred-meter Aperture Spherical Radio Telescope (FAST), and the Event Horizon Telescope (EVENT HORIZON TELESCOPE)—with particular emphasis on their foundational design principles, instrumental structures, and detection methods. In the investigation, it has been found out JAMES WEBB SPACE TELESCOPE’s infrared observing capability has revealed nascent galaxies and exoplanetary atmospheres, FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE’s refined radio measurements have discovered in excess of 800 pulsars and Five-hundred-meter Aperture Spherical Radio Telescope radio bursts, and EVENT HORIZON TELESCOPE’s global interferometer has imaged black hole shadows for the first time in history, confirming predictions central to general relativity. Not only do these findings demonstrate noteworthy technical advances in detector technology and data combination but also enhance current knowledge of galaxy assembly, star formation, as well as the underlying astrophysics processes. Ultimately, the research emphasizes the transformative power of innovative designs in expanding astronomical knowledge and suggests promising areas for future dark matter, dark energy, and the origins of life explorations

AUTHOR CONTRIBUTION

All the authors contributed equally and their names were listed in alphabetical order.

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