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The way to explore the Milky Way by using 21cm radio

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Abstract. In recent years, more and more scientists have used ratios to explore Milky Way. This paper delves into the importance of 21cm radio astronomy for investigating the structure and evolution of the Milky Way. Through an exhaustive review of the literature, the paper emphasizes the benefits of radio astronomy relative to optical and infrared astronomy and elaborates on the distinct attributes of the 21cm radio wavelength. Fundamental concepts of 21cm radio astronomy, encompassing the Doppler effect, neutral hydrogen examination, and the era of reionization, are explored in detail. The paper underscores the significance of comprehending the Milky Way's structure, dynamics, and matter distribution. Forthcoming developments in the domain, such as cutting-edge radio telescopes, data handling techniques, and interdisciplinary collaborations, are examined, presenting the potential for additional advancements in understanding our home galaxy and the cosmos at large.

Keywords: 21cm Radio, Milky Way, Radio Telescopes, Neutral Hydrogen, Galaxy Evolution.

1. Introduction

Astronomers and researchers have been captivated by the exploration of the Milky Way for many centuries and have made numerous efforts. Over time, a variety of methods have emerged and been employed to obtain valuable knowledge about our home galaxy, including techniques involving optical, infrared, and radio wavelengths [1]. Despite considerable advances in grasping the Milky Way, a multitude of unresolved challenges remain, such as matter distribution, the spiral structure's dynamics, the galaxy's evolutionary processes, and the obscuring effect of interstellar dust [2]. For example, interstellar gas and dust will absorb those visible lights, making it difficult for scientists to observe. This essay endeavors to probe into these questions by examining 21cm radio astronomy and its utility in studying the Milky Way.

The research methodology encompasses an extensive literature review on 21cm radio astronomy, delving into its principles, techniques, and potential for future advancements [3], by examining the fundamental concepts of radio astronomy, particularly the detection and analysis of 21cm radio emissions from neutral hydrogen [4].

2. Prevalent Astronomical Observation Approaches

To explore the universe, astronomers employ various observation methods, each providing unique insights into different aspects of celestial objects and phenomena. These methods include optical, infrared, and radio observations [1].

Optical astronomy, which has underpinned astronomical research for centuries, revolves around observing visible light emitted by celestial entities like stars, galaxies, and nebulae [5]. As it relies merely on the human eye's sensitivity to visible light, this technique has underpinned astronomical research for centuries [6]. Optical astronomy has facilitated the investigation of star properties, the mapping of galaxy distribution, and the study of celestial object interactions. However, the technique's limitations become evident when attempting to observe objects shrouded in dust or gas or when exploring phenomena emitting light at non-visible wavelengths.

Infrared astronomy mitigates some of these constraints by scrutinizing radiation with wavelengths longer than visible light but shorter than radio waves [5]. It proves particularly adept at observing objects obscured by dust or gas, such as star-forming regions and galactic centers [7]. Infrared observations have yielded vital insights into star formation processes, interstellar dust properties, and galactic nuclei dynamics. Infrared astronomy has also enabled the discovery of previously undetected celestial entities, including brown dwarfs and remote, dust-concealed galaxies.

Radio astronomy focuses on the detection of radio waves emitted by celestial entities such as neutral hydrogen, molecular clouds, pulsars, and other phenomena, which are often difficult to observe at different wavelengths. This approach has significantly expanded human understanding of the universe. [3,8] Insights into a myriad of astronomical phenomena, including neutral hydrogen distribution within galaxies, molecular cloud properties, and pulsar behavior, have been provided by radio observations. Additionally, radio astronomy has been crucial in detecting cosmic microwave background radiation, revolutionizing the understanding of the early universe and the Big Bang [9]. In the 1960s, astronomers discovered the Cosmic Microwave Background Radiation, which is the afterglow of the Big Bang [10].

Each observation method boasts its unique strengths and weaknesses, making them complementary tools for investigating the universe. For example, optical and infrared astronomy has been essential for examining the properties of stars, galaxies, and the interstellar medium. On the other hand, researchers are able to delve into the universe's hidden depths and study phenomena, with the support of radio technology. Utilizing the capabilities of each technique enables astronomers to develop a more comprehensive understanding of the universe, that would help discover the processes that shape its evolution. The use of telescopes is a common method of astronomy observation.

3. Categorization of Telescopes

Telescopes can be classified into different types with reference to different criteria, such as the type of radiation they detect and their design mechanism [5]. In terms of radiation type, telescopes can be categorized into optical, infrared, and radio telescopes. Optical telescopes are specifically engineered to observe visible light emitted by celestial objects, while infrared telescopes are optimized for detecting infrared radiation, and radio telescopes specialize in capturing radio waves [11].

Infrared telescopes share similarities in design with optical telescopes but are optimized for detecting infrared radiation. These instruments frequently employ specialized detectors and cooling systems to minimize thermal noise, which can disrupt infrared observations [5, 7]. In some instances, infrared telescopes are even placed in space to circumvent the absorption and emission of infrared radiation by Earth's atmosphere.

4. Overview of Radio Telescopes

Radio telescopes are essential instruments for detecting radio waves emitted from celestial objects, thereby allowing astronomers to investigate phenomena that are hidden or challenging to observe at other wavelengths [8]. By getting and analyzing the information from radio telescopes, scientists can get different astronomical phenomena. They have significantly broadened researchers' understanding of the universe by revealing the presence of diverse astronomical phenomena, such as neutral hydrogen in galaxies, molecular clouds, pulsars, and cosmic microwave background radiation [3].

Radio telescope designs generally incorporate sizable parabolic dishes that gather and focus radio waves on a receiver [3, 8]. These telescopes exhibit considerable variation in dimensions and sensitivity, extending from compact, mobile dishes to immense arrays covering several kilometres [12]. A larger dish correlates with heightened resolution and sensitivity, empowering the telescope to identify fainter radio signals emanating from more remote celestial entities.

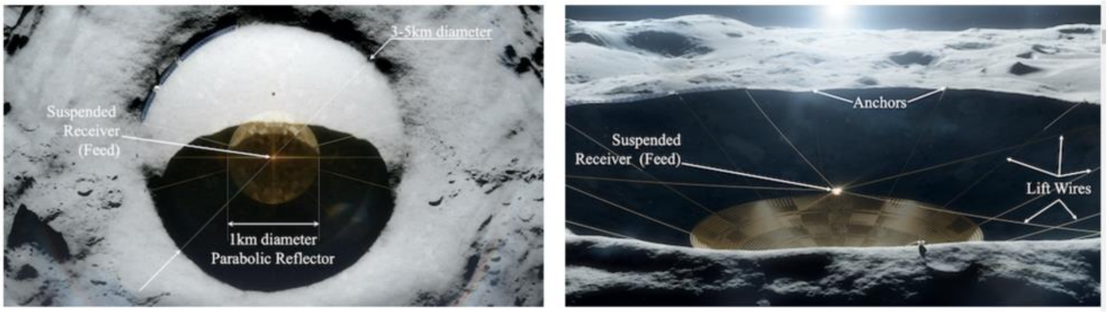

Figure 1. Picture of a radio telescope from Nasa [13]**.**

Certain radio telescopes are structured as interferometers, comprising multiple antennas or dishes operating in unison to emulate a more expansive telescope, which can help combine the signals from those multiple antennas. The aperture synthesis approach would help substantially enhance observation resolution, enabling astronomers to examine the intricate aspects of astronomical occurrences [3]. Radio telescopes have been pivotal in numerous astronomical discoveries and advancements, such as delineating the Milky Way's spiral structure, detecting quasars, and proving essential in gravitational wave detection [8].

5. Core Principles and Significance of 21cm Radio Astronomy

One defining aspect of the 21cm radio wavelength is its susceptibility to the Doppler effect, caused by the distance between the source of the wave and the observer, which is the apparent change in the frequency of waves. This phenomenon results in a shift in the observed wavelength of 21cm radio emissions depending on the relative motion between the source and the observer. When hydrogen clouds approach or recede from an observer, the observed wavelength of the emitted 21cm photons either exhibits blueshift (shorter wavelength) or redshift (longer wavelength), respectively [11]. In detail, a change in the frequency of visible lights will change the colors shown in the Spectrum Chart: high-frequency waves mean deeper blue, otherwise, the color will be redder. The phenomenon of the Doppler effect in 21cm radio astronomy allows scientists to gauge gas cloud velocities and acquire critical data about the dynamics and kinematics of galaxies, such as the Milky Way [2]. A more profound understanding of the Doppler effect in this context can lead to an enhanced grasp of celestial object movements within the cosmos, including the rotation and expansion of galaxies, as well as interactions between galaxies in clusters and superclusters. Additionally, the Doppler effect proves significant in observing remote galaxies and determining their recession velocities due to the universe's expansion.

Utilizing 21cm radio wavelengths, which can permeate through dust and gas that often block optical and infrared observations, researchers can scrutinize distant and hidden regions of the galaxy with heightened clarity and precision. This benefit allows for a more comprehensive comprehension of the Milky Way's structure and properties, as well as the formation, growth, and dynamics of its spiral pattern. By mapping the distribution of neutral hydrogen, astronomers can deduce the physical parameters and features of the galaxy's spiral arms, further probing the processes responsible for their genesis and evolution [2]. This knowledge is crucial for understanding the overall galactic structure, rotation patterns, and dark matter distribution. Additionally, 21cm radio astronomy enables us to comprehend the formation and development of various celestial entities, such as star-forming regions, molecular clouds, and supernova remnants. Through the examination of the 21cm emissions emanating from these objects, scientists can illuminate the physical mechanisms governing their origination and progression.

The investigation of 21cm radio emissions plays a vital part in delving into the universe's large-scale structure, which encompasses matter distribution and the cosmic web's formation. By examining 21cm emissions from hydrogen gas in diverse environments, astronomers can glean insights into the processes steering the formation and evolution of cosmic structures like galaxy clusters, filaments, and voids. Comparing hydrogen properties in varying galaxies allows researchers to explore the fundamental physical processes that dictate their disparate morphologies and star formation rates, as well as the impact of environmental factors on their progression. Furthermore, 21cm radio observations can be employed to scrutinize the distribution of dark matter throughout the universe, as dark matter influences the distribution and dynamics of neutral hydrogen. Studying the large-scale structure via 21cm radio astronomy can substantially enhance researchers' comprehension of cosmology and the formation of cosmic structures over time, offering valuable perspectives into the universe's history and future evolution.

Furthermore, 21cm radio astronomy is of paramount importance in examining the epoch of reionization, a pivotal phase in the early universe when the initial stars and galaxies materialized, ionizing the nearby hydrogen gas [3, 14]. Throughout the epoch of reionization, the first stars and galaxies emitted ultraviolet radiation, ionizing the adjacent hydrogen gas and yielding free electrons and protons. This ionization process left a trace on the 21cm radio emissions from neutral hydrogen, as ionized areas absorbed the 21cm photons. Detecting these traces within the cosmic 21cm radio emission background allows astronomers to investigate the spatial distribution of neutral hydrogen and ionized regions, delivering crucial insights about the formation of early stars, galaxies, and black holes. Furthermore, the epoch of reionization exhibits a strong connection to the development of large-scale structures in the universe. The ionization process was not uniform, and regions with higher concentrations of matter experienced reionization earlier due to the presence of more luminous objects. By studying the variation in 21cm radio emissions from different regions, astronomers can trace the formation and evolution of large-scale structures, such as galaxy clusters and cosmic filaments, during this crucial period.

The 21cm radio wavelength has a unique role in the field of astronomy as it is associated with the hyperfine transition of neutral hydrogen atoms, which indicates a minuscule energy shift occurring within hydrogen atoms [15]. The study of this energy shift is of paramount importance, considering hydrogen's abundance in the universe and its crucial role in forming stars, galaxies, and the interstellar medium. Researchers can map the distribution of hydrogen in the galaxy and examine its properties, such as temperature, density, and velocity, by detecting 21cm radio emissions from neutral hydrogen [3].

Overall, the significance and core principles of 21cm radio astronomy revolve around the investigation of the hyperfine transition of neutral hydrogen atoms, which enables astronomers to map the distribution of hydrogen in the galaxy and explore its properties. By analyzing 21cm radio emissions, researchers can obtain valuable insights into the formation, evolution, and dynamics of galaxies, the large-scale structure of the universe, and the epoch of reionization. Understanding these underlying physical processes is vital for comprehending the universe's development and the formation of cosmic structures. Additionally, 21cm radio astronomy plays a significant role in studying the kinematics of the Milky Way and other galaxies. The Doppler effect, which influences the observed wavelength of 21cm radio emissions, allows astronomers to estimate gas cloud velocities and gather essential information about the dynamics and kinematics of galaxies. Observations at the 21cm wavelength have also been used to study other galaxies, enabling astronomers to estimate their distance, mass, and star formation history [1].

6. Upcoming Advancements

As the comprehension of the universe broadens, novel advancements in 21cm radio astronomy are approaching. These developments are expected to bring significant enhancements to the field, enabling researchers to investigate the universe with more profound depth and detail than ever before. These developments will lead to the construction of the next-generation radio telescopes.

Lying in the center of the developments is improved sensitivity and resolution. For example, the Square Kilometre Array (SKA) is an ambitious international endeavor aiming to construct the world's largest and most sensitive radio telescope. [12] The SKA will comprise thousands of antennas dispersed across vast distances, collaboratively forming a massive collecting area. This unparalleled sensitivity will allow astronomers to study 21cm radio emissions from the epoch of reionization with exceptional precision, enabling them to examine the early universe's history and unravel the mysteries of cosmic evolution [16].

Another notable progression in 21cm radio astronomy involves the advancement of data processing techniques and algorithms. The immense quantities of data generated by contemporary radio telescopes necessitate inventive approaches to data analysis and interpretation. Increasingly, machine learning and artificial intelligence methods are being utilized to analyze intricate data sets and discern patterns and structures within the 21cm radio emissions. These advanced tools will likely become even more indispensable as radio telescopes' capabilities enhance, resulting in more elaborate and detailed observations.

In addition to advancements in radio telescope technology and data analysis techniques, collaborations among researchers from a wide range of fields are vital for the ongoing growth of 21cm radio astronomy. By pooling their expertise, specialists in domains like cosmology, astrophysics, and computer science can develop novel approaches and methodologies that will propel the field forward, ultimately facilitating a more profound comprehension of the cosmos.

As cosmic exploration perseveres, it becomes increasingly important to conceive inventive methods for observing the cosmos and analyzing the gathered data. The forthcoming advancements in 21cm radio astronomy are set to transform the understanding of the universe, affording researchers unparalleled opportunities to investigate the formation and evolution of cosmic structures and delve into the early universe's enigmas.

7. Conclusion

21cm radio astronomy presents an influential approach to examine the structure and evolution of the Milky Way, overcoming constraints encountered by alternative observational methodologies. By scrutinizing the singular characteristics of 21cm radio emissions originating from neutral hydrogen, scientists can acquire an invaluable understanding of the galaxy's spiral configuration, material distribution, and the mechanisms controlling its evolution. Upcoming enhancements in radio telescope technology, data interpretation techniques, and interdisciplinary cooperation are set to transform our comprehension of the universe. As these improvements materialize, the discipline of 21cm radio astronomy will persistently contribute vital information regarding the enigmas of our home galaxy and the expansive universe beyond.

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