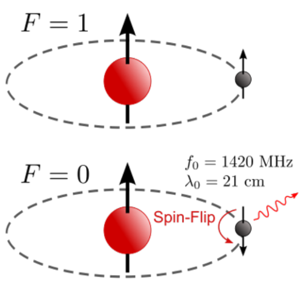
21-centimeter radiation

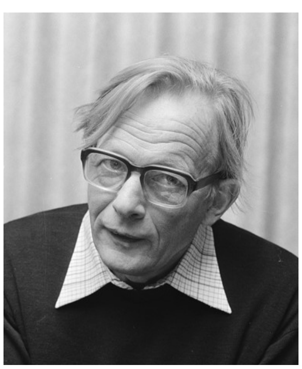
Hanie Hatami[1]
[1]*Department of Physics, Sharif University of Technology, Tehran, Iran*

INTRODUCTION

21 cm radiation refers to a specific wavelength of radio waves emitted by neutral hydrogen atoms which constitute 75% of the gaseous mass of the cosmos. It is named after the 21-centimeter (or 21 cm) wavelength corresponding to the transition between the atom's two lowest energy states. This transition occurs when the electron's spin flips from being parallel to the proton's spin to being anti-parallel.



The discovery of 21 cm radiation can be attributed to the Dutch astronomer Hendrik C. van de Hulst in 1944. During World War II, while studying the properties of interstellar matter, van de Hulst predicted that neutral hydrogen atoms in space would emit radiation at a wavelength of 21 cm due to the hyperfine transition. His prediction was confirmed in 1951 when the American astronomers Edward Purcell and Harold Ewen successfully detected the 21 cm line using a radio telescope. The 21 cm line in spectroscopy provides

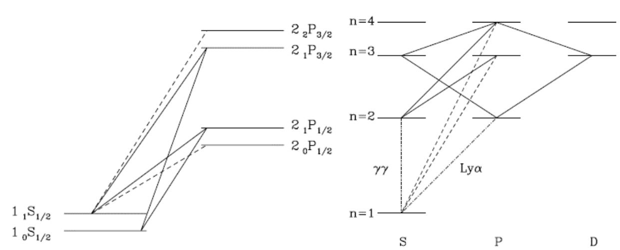


a powerful tool for studying the distribution, dynamics, and physical properties of neutral hydrogen gas in various astrophysical contexts. Its significance lies in its ability to probe the interstellar medium, trace the kinematics of galaxies, and contribute to our understanding of the formation and evolution of cosmic structures.

- Tracing Neutral Hydrogen
- Velocity Measurements
- Probing the Interstellar Medium
- Galactic and Extragalactic Studies

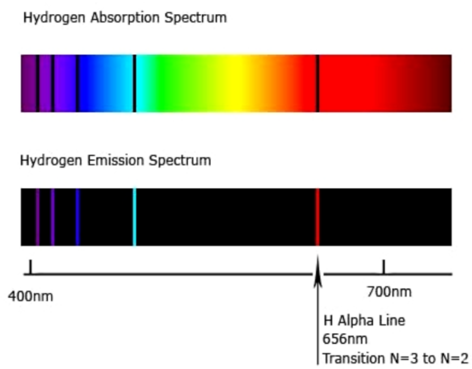
THE PHYSICS OF 21 CM RADIATION

The hyperfine transition is a specific energy transition that occurs within the structure of neutral hydrogen atoms. It involves the interaction between the electron's spin and the proton's spin within the atom. In the ground state of a hydrogen atom, the electron and proton spins can be either parallel or anti-parallel. The hyperfine transition corresponds to the flip of the electron's spin from parallel to anti-parallel (or vice versa) with respect to the proton's spin. This transition releases energy in the form of a photon with a wavelength of 21 cm.



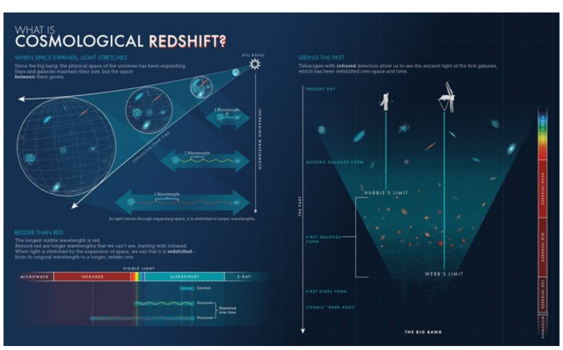
Emission and absorption of 21 cm radiation occur when neutral hydrogen atoms interact with photons at the corresponding wavelength. In the emission process, an electron in an excited state of a hydrogen atom undergoes the hyperfine transition, releasing a photon with a wavelength of 21 cm. This emitted photon carries away the energy difference between the two states.

In the absorption process, a photon with a wavelength of 21 cm interacts with a neutral hydrogen atom in its ground state. The atom absorbs the photon's energy, causing the electron to undergo the hyperfine transition and move to an excited state.



$$\delta T_b = \frac{T_S - T_R}{1+z}\left(1 - \mathrm{e}^{-\tau v}\right)$$
$$\approx \frac{T_S - T_R}{1+z}\tau$$

The redshift of 21 cm radiation is particularly significant in cosmology. As the universe expands, the wavelengths of photons traveling through space also stretch, causing a cosmological redshift. By measuring the redshift of 21 cm radiation from distant galaxies, astronomers can determine the expansion rate of the universe and study its evolution over time. This information provides insights into the age, size, and composition of the universe.



EXPERIMENTAL TECHNIQUES AND OBSERVATIONS

Radio telescopes are specialized instruments designed to detect and study radio waves emitted by celestial objects, including 21 cm radiation. They consist of large parabolic dishes or arrays of smaller antennas that collect and focus radio waves onto receivers. These receivers convert the radio waves into electrical signals that can be analyzed and processed.

Interferometry is a technique used in radio astronomy to enhance the resolution and sensitivity of observations. It involves combining signals from multiple radio telescopes to create a virtual telescope with a larger effective size. By synchronizing the signals and precisely measuring the time delay between them, interferometry allows astronomers to achieve higher resolution and capture finer details in the observed objects.

Detecting and measuring 21 cm radiation poses several challenges due to various factors:

Foreground Contamination: The radio sky is filled with other sources of radio emission, such as synchrotron radiation from our Milky Way galaxy and extragalactic sources. These emissions can overshadow the faint 21 cm signal, making it challenging to isolate and extract the desired signal.

Radio Frequency Interference (RFI): Man-made radio signals, such as those from communication devices and satellites, can introduce unwanted noise and interference in the observed radio spectrum. RFI mitigation techniques and careful site selection for radio telescopes are crucial to minimize these effects.

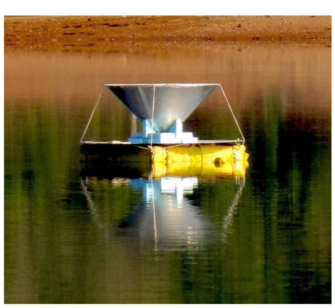
Instrumental Effects: Radio telescopes and receivers have their own limitations, including sensitivity, calibration accuracy, and instrumental noise. Advancements in technology and instrumentation are continuously improving the sensitivity and capabilities of radio telescopes, enabling more precise measurements of 21 cm radiation

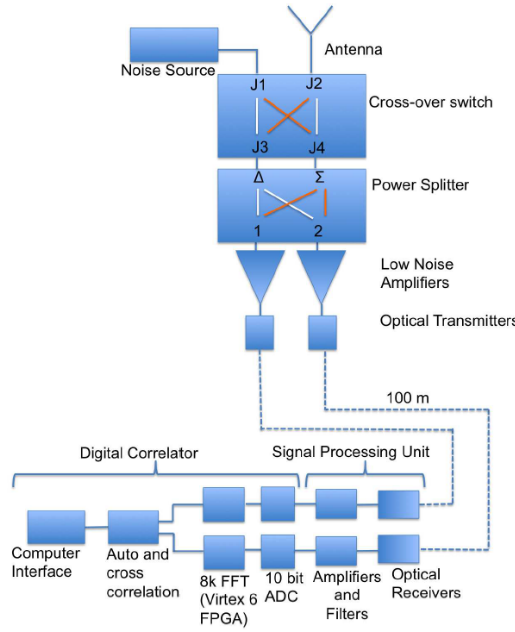
Several experiments and observatories have been dedicated to studying 21 cm radiation and its implications. One notable project is the Square Kilometre Array (SKA), an international effort to build the world's largest and most sensitive radio telescope. The SKA aims to revolutionize our understanding of the universe by observing a wide range of frequencies, including the 21 cm line, with unprecedented sensitivity and resolution.

Other notable experiments and observatories include the Low-Frequency Array (LOFAR), the Murchison Widefield Array (MWA), and the Hydrogen Epoch of Reionization Array (HERA). These projects focus on detecting and characterizing the 21 cm signal from the cosmic dawn and the epoch of reionization. These observatories, along with advancements in interferometric techniques, data processing, and computational modeling, are paving the way for significant advancements in our understanding of 21 cm radiation and its role in unraveling the mysteries of the early universe.

The first experimental efforts to detect the 21 cm global signal have been carried out by the COsmological Reionization Experiment (CORE) and the Experiment to Detect the Reionization Step (EDGES). These have been analyzed using a tanh model of reionization that depends upon the redshift of reionization zr and its duration z. EDGES is presently able to rule out the most rapid models of reionization that occur over a redshift interval as short as z ¡ 0:06. These first experimental efforts should be seen as the first steps along a road that may lead to considerably better constraints.

Other experiments using different experimental approaches are underway. Some of these use individual dipoles, such as the Shaped Antenna measurement of the RAdio Spectrum (SARAS) (R. Subrahmanyan, private communications) and the Broadband Instrument for the Global HydrOgen ReionizatioN Signal (BIGHORNS) (S. Tingay, private communications), while others are exploring ways of using many dipoles as with the Large-aperture Experiment to Detect the Dark Ages (LEDA) (L. Greenhill, private communications).





1. Data Acquisition Techniques: Discuss different methods and considerations for acquiring 21 cm data, including the choice of radio telescopes or interferometers, observational parameters, and data recording techniques.

2. Calibration Strategies: Explore various calibration techniques used in 21 cm data analysis, such as gain calibration, antenna response calibration, and system noise calibration. Discuss the challenges and best practices for accurate calibration.

3. RFI Detection and Mitigation: Explain methods for detecting and mitigating radio frequency interference (RFI) in 21 cm data. Discuss techniques like spectral flagging, time-domain flagging, and adaptive filtering to remove RFI contamination.

4. Foreground Removal Techniques: Explore advanced techniques for separating the 21 cm signal from foreground emissions, such as Principal Component Analysis (PCA), FastICA, wavelet-based methods, or polynomial fitting. Discuss their strengths, limitations, and potential applications.

5. Statistical Analysis Methods: Discuss statistical techniques used in 21 cm data analysis, such as power spectrum estimation, correlation function analysis, or Bayesian inference. Explain how these methods can be applied to extract meaningful information from the data.

6. Modeling and Simulation: Explore the use of theoretical models and simulations in analyzing 21 cm data. Discuss how models can be used to interpret the observed data, test different cosmological scenarios, or study specific astrophysical phenomena.

7. Cross-Correlations and Multi-Messenger Astronomy: Discuss the potential of cross-correlating 21 cm data with other observational datasets, such as the cosmic microwave background (CMB), galaxy surveys, or gravitational wave data. Explain how these cross-correlations can provide additional insights and enhance our understanding of the universe.

8. Visualization and Data Presentation: Explore visualization techniques for effectively presenting 21 cm data, such as creating maps, power spectrum plots, or correlation function plots. Discuss the importance of clear and concise data presentation for communicating research findings.

$$dN_{ab} = \langle n_a n_b \rangle = \rho_0^2 \, \mathrm{d}V_a \, \mathrm{d}V_b \left(1 + \varepsilon\left(r_{ab}\right)\right)$$

$$P_\delta(k) = A \left|\delta_k\right|^2$$
$$P_\Phi(k) = B \left|\Phi_k\right|^2$$

-The importance of $|\ldots|^2$
-δ_k and Φ_k are small values

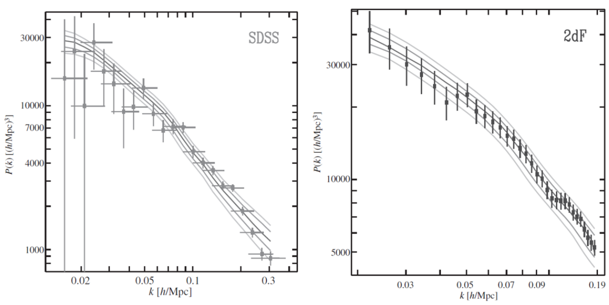


FIG. 1. In the observations, we should pay attention to the effects of redshift and weak lensing

FUTURE PROSPECTS AND APPLICATIONS

21 cm radiation holds immense potential for advancing our understanding of cosmology and astrophysics. Here are some key areas where 21 cm research can make significant contributions:

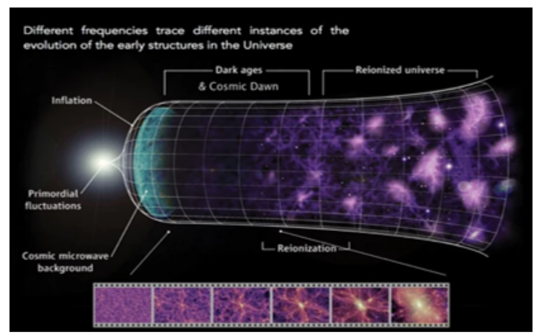
Probing the Early Universe: 21 cm radiation provides a unique window into the cosmic dark ages and the cosmic dawn, allowing us to study the formation of the first stars and galaxies, cosmic reionization, and the evolution of the early universe.

Constraining Cosmological Parameters: By mapping the large-scale distribution of matter using 21 cm observations, scientists can constrain cosmological parameters such as the matter density, the amplitude of density fluctuations, and the expansion rate of the universe. This helps refine our understanding of the universe's composition and evolution.

Dark Matter and Dark Energy Studies: The distribution of matter traced by 21 cm radiation can shed light on the behavior and properties of dark matter. Additionally, studying the large-scale structure can provide insights into the nature of dark energy and its effects on the universe's expansion.

Galaxy Formation and Evolution: 21 cm radiation allows us to study the distribution and properties of neutral hydrogen, a key component in galaxy formation and evolution. By observing the 21 cm signal from different galaxies, we can investigate the processes of gas accretion, star formation, and feedback mechanisms that shape galaxies over cosmic time.

21 cm radiation allows us to study the distribution and properties of neutral hydrogen, a key component in galaxy formation and evolution. By observing the 21 cm signal from different galaxies, we can investigate the processes of gas accretion, star formation, and feedback mechanisms that shape galaxies over cosmic time.



Several upcoming missions and technologies are poised to advance 21 cm research and unlock new discoveries. Here are a few notable examples:

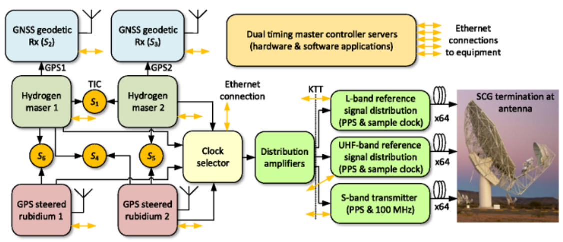
- The Square Kilometre Array (SKA): The SKA, currently under development, will be a game-changer for 21 cm research. With its unprecedented sensitivity and wide frequency coverage, the SKA will enable high-resolution mapping of the 21 cm signal, allowing us to study the cosmic dawn, cosmic reionization, and the large-scale structure of the universe in unprecedented detail.

- Next-Generation Radio Interferometers: Advancements in interferometric techniques and technologies will enhance the sensitivity and resolution of radio telescopes. Instruments like the Hydrogen Epoch of Reionization Array (HERA) and the Low-Frequency Array (LOFAR) are already pushing the boundaries of 21 cm research, and future upgrades and developments will further improve our capabilities.

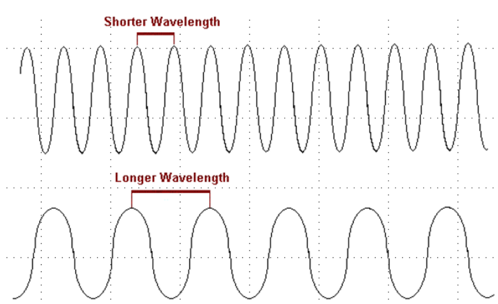
- Data Analysis and Modeling: The increasing complexity and volume of 21 cm data require advanced data analysis techniques and computational modeling. Machine learning algorithms, statistical methods, and simulations will play a crucial role in extracting meaningful information from the data and testing theoretical predictions.

CHALLENGES AND OPEN QUESTIONS

One of the primary challenges in 21 cm observations is separating the faint 21 cm signal from various sources of noise and foreground contamination. These include emissions from our own Milky Way galaxy, extragalactic sources, and instrumental effects. Developing sophisticated data analysis techniques and improving foreground removal methods are crucial for extracting the desired 21 cm signal.
Radio telescopes and receivers introduce their own instrumental effects and calibration uncertainties, which can impact the accuracy and reliability of 21 cm measurements. Calibrating the instruments and understanding their systematic effects are ongoing challenges that require careful characterization and calibration techniques.

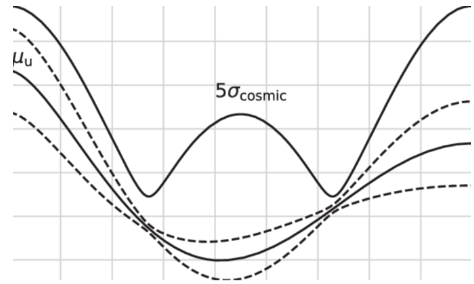


As we observe 21 cm radiation from increasingly distant objects, the signal is redshifted to longer wavelengths. This poses technical challenges as longer wavelengths are more susceptible to contamination and instrumental effects. Developing techniques to mitigate these challenges and accurately measure the redshifted 21 cm signal is an active area of research.

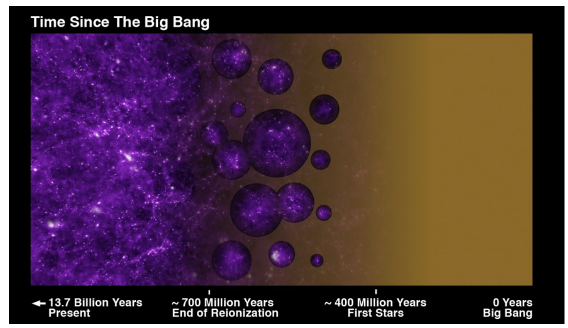


The limited size of observed regions of the sky introduces cosmic variance, which can lead to statistical uncertainties in the measured 21 cm signal. Mitigating these uncertainties and obtaining statistically robust measurements require large-scale surveys and careful statistical analysis.

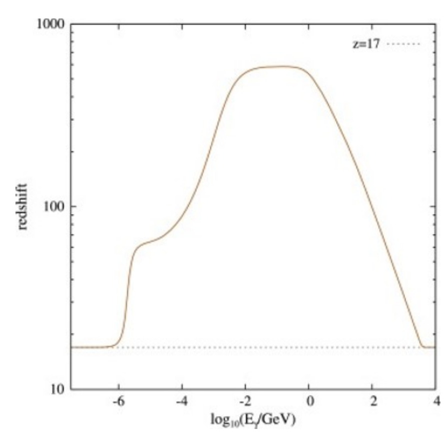
The precise timing and mechanisms of the cosmic dawn and cosmic reionization remain open questions. Further observations and theoretical modeling are needed to understand the formation of the first stars and galaxies, the sources of reionizing photons, and the evolution of the ionization state



of the universe.



While 21 cm observations can indirectly probe the behavior of dark matter and dark energy through their influence on the large-scale structure, the nature of these enigmatic components remains elusive. Further investigations, including cross-correlations with other datasets, are needed to gain deeper insights into the properties and interactions of dark matter and dark energy.
The photosphere of the Universe (i.e., optical depth =1) for a broad range of physical photon energies. The observer is assumed to be located at redshift z=17. In the lowest energy section of the plot, before the first small plateau, the energy losses are dominated by photoionizations. Beyond that, up to the beginning of the large plateau, the Compton losses are dominating. At the large flat plateau region the energy loss is dominated by the pair production on matter. On the final falling part of the curve, the energy losses are determined by photon–photon pair production.



CONCLUSION

Studying 21 cm radiation has yielded key findings and insights that have significantly advanced our understanding of the universe. Here is a summary of some of the key findings and the ongoing quest to unlock the secrets of the universe through 21 cm research:

1. Cosmic Dark Ages and Cosmic Dawn: 21 cm radiation has allowed us to probe the cosmic dark ages and the cosmic dawn, shedding light on the formation of the first stars and galaxies, the epoch of reionization, and the transition from a neutral to an ionized universe.

2. Large-Scale Structure: Mapping the distribution of neutral hydrogen using 21 cm observations has provided insights into the large-scale structure of the universe, including the cosmic web of filaments and voids that connect galaxies on the largest scales.

3. Cosmological Parameters: By comparing the observed large-scale structure traced by 21 cm radiation with theoretical models, scientists have been able to constrain cosmological parameters such as the matter density, the amplitude of density fluctuations, and the expansion rate of the universe.

4. Dark Matter and Dark Energy: 21 cm research has indirectly probed the behavior and properties of dark matter and dark energy through their influence on the large-scale structure. This has provided valuable insights into these enigmatic components of the universe.

The ongoing quest to unlock the secrets of the universe through 21 cm research involves addressing challenges such as foreground contamination, instrumental effects, and statistical uncertainties. Researchers are developing advanced data analysis techniques, improving foreground removal methods, and refining calibration techniques to extract the faint 21 cm signal from the noise.

Furthermore, the quest involves pushing the boundaries of technology and instrumentation, such as the development of the Square Kilometre Array (SKA) and next-generation radio interferometers. These advancements will enhance the sensitivity, resolution, and frequency coverage of radio telescopes, enabling more precise measurements and deeper insights into the early universe, galaxy formation, and the fundamental properties of the cosmos.

By combining 21 cm observations with other observational techniques and data analysis methods, researchers aim to achieve a more comprehensive understanding of the universe, including the nature of dark matter and dark energy, the processes driving galaxy evolution, and the connections between different astrophysical phenomena. The ongoing quest to unlock the secrets of the universe through 21 cm research continues to push the boundaries of our knowledge and inspire new discoveries.

[1] L. Amendola and S. Tsujikawa, *Dark energy: theory and observations* (Cambridge University Press, 2010).

[2] J. R. Pritchard and A. Loeb, Reports on Progress in Physics **75**, 086901 (2012).

[3] S. Singh, R. Subrahmanyan, N. U. Shankar, M. S. Rao, B. Girish, A. Raghunathan, R. Somashekar, and K. Srivani, Experimental Astronomy **45**, 269 (2018).

[4] S. Fraser, A. Hektor, G. Hütsi, K. Kannike, C. Marzo, L. Marzola, A. Racioppi, M. Raidal, C. Spethmann, V. Vaskonen, *et al.*, Physics Letters B **785**, 159 (2018).

[5] Milky Way structure detected with the 21 cm Neutral Hydrogen Emission - PhysicsOpenLab — physicsopenlab.org, `https://physicsopenlab.org/2020/09/08/milky-way-structure-detected-with-the-21-cm-neutral` [Accessed 27-09-2024].

[6] Astronomers detect earliest evidence yet of hydrogen in the universe — news.mit.edu, `https://news.mit.edu/2018/astronomers-detect-earliest-evidence-yet-hydrogen-u` [Accessed 27-09-2024].

[7] PH_206 Interstellar medium — khadley.com, `http://khadley.com/Courses/Astronomy/ph_206/topics/interstellarMedium/`, [Accessed 27-09-2024].

[8] Hydrogen line - Wikipedia — en.wikipedia.org, `https://en.wikipedia.org/wiki/Hydrogen_line`, [Accessed 27-09-2024].

[9] Hydrogen cloud — Astronomy & Formation Process — britannica.com, `https://www.britannica.com/science/hydrogen-cloud`, [Accessed 27-09-2024].

[10] Peering into the dark (ages) with low-frequency space interferometers - Experimental Astronomy — link.springer.com, `https://link.springer.com/article/10.1007/s10686-021-09743-7`, [Accessed 27-09-2024].

[11] The EDGES 21 cm anomaly and properties of dark matter — sciencedirect.com, `https://www.sciencedirect.com/science/article/pii/S0370269318306488`, [Accessed 27-09-2024].