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Using Lyman Alpha Emitters to Trace the Reionization History of the Universe

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Abstract. The Epoch of Reionization was a major change in cosmic history because it altered the ionization state of the gas between galaxies. Before this transition, much of the universe contained neutral hydrogen. That hydrogen did not block every light frequency equally, but for radiation connected to hydrogen transitions, it was a significant obstacle. As the first stars and galaxies formed, their ultraviolet radiation gradually ionized surrounding hydrogen. Over time, the universe moved from a mostly neutral state toward a more ionized and transparent one. The broad sequence is known, but the detailed history is still uncertain: when reionization began, how quickly it advanced, how uneven it was, and which galaxies supplied most of the ionizing radiation remained unanswered. This paper examines Lyman alpha emitters as one way to study that history. Lyman alpha emission is useful because neutral hydrogen in the intergalactic medium affects whether Lyman alpha photons reach observers; changes in Lyman alpha visibility, rest-frame equivalent width, escape fraction, velocity offset, and emitter fraction can help infer how the neutral hydrogen fraction changed over time. Recent James Webb Space Telescope (JWST) Near-Infrared Spectrograph observations from the JWST Advanced Deep Extragalactic Survey (JADES) provide a stronger observational base, while simulations such as THESAN help interpret the final signal after photons pass through galaxies, circumgalactic gas, intergalactic gas, dust, scattering, and cosmic expansion. Lyman alpha emitters are powerful probes of reionization, but not direct measuring sticks. They are most useful when spectroscopy, completeness corrections, model comparisons, and simulations are used together.

Keywords: reionization, Lyman alpha emitters, neutral hydrogen, James Webb Space Telescope (JWST), intergalactic medium

1. Introduction

1.1. Research background: current status and gaps

Looking at the modern universe, it is easy to start with galaxies already in place. That picture is misleading for the earliest stages. The young universe did not begin with stars, galaxies, clusters, or the large structures seen in deep astronomical images. It began hot and dense, then expanded and cooled. In the first stages, matter was too energetic for stable atoms to remain together, so electrons and atomic nuclei existed separately rather than as neutral atoms.

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As the temperature dropped, electrons and protons were finally able to combine into neutral hydrogen. This stage is called recombination. Recombination is important because it made the universe less opaque to some forms of radiation, but it did not immediately create a bright universe. Neutral atoms existed, yet stars and galaxies had not formed. The interval after recombination therefore remained dark in the ordinary sense: there were no luminous galaxies filling space with starlight. This is why that period is often called the cosmic dark ages.

The Epoch of Reionization matters because it ended that dark interval. When the first stars and galaxies formed from the early gas, they released ultraviolet radiation. That radiation carried enough energy to ionize hydrogen again, separating electrons from protons. The National Aeronautics and Space Administration (NASA) describes the period from the end of the dark ages until the universe was roughly one billion years old as the era when radiation from the first massive stars reionized most neutral hydrogen. NASA also points out why this is scientifically valuable: reionization gives astronomers one of the few indirect ways to study the earliest stars [1].

The basic story can be stated in a few sentences, but proving the detailed history is much harder. The universe is usually described as mostly ionized by around redshift 6. That statement gives an end point, not the full path. Reionization was probably not a single switch that turned on everywhere at once. A more realistic picture is uneven. Early galaxies ionized the gas closest to them first, making local ionized regions around individual sources or groups of sources. As more sources formed, these regions expanded and overlapped.

This patchy behavior is not a small detail. An average neutral hydrogen fraction by itself does not fully describe the state of the universe. Two regions could have similar average neutral fractions but very different structures. In one case, neutral gas might be spread relatively evenly. In another, large ionized bubbles might surround galaxies while neutral material remains concentrated elsewhere. Lyman alpha photons would not move through those two situations in the same way. A useful reconstruction of reionization therefore has to ask about timing, speed, source populations, and spatial structure together.

This is where the main research gaps appear. Researchers still need stronger constraints on when reionization began, how rapidly it developed, how patchy it was, and which galaxies produced most of the ionizing radiation. Earlier work was often limited by small samples, narrow redshift ranges, inconsistent selection methods, or measurements along only a few lines of sight. Because of those limits, it could be difficult to tell whether an observed pattern showed cosmic evolution or just sample bias. Recent James Webb Space Telescope (JWST) observations are important because they can provide larger, deeper, and more systematic samples of distant galaxies.

The focus of this paper is therefore not just the definition of the Epoch of Reionization. The focus is how Lyman alpha emitters can be used to study it. The paper first lays out the physical background, then explains what Lyman alpha emitters are, why Lyman alpha emission reacts so strongly to neutral hydrogen, and how recent observations and simulations are used to reconstruct reionization history.

1.2. Methodology

The central question is direct: how can Lyman alpha emitters be used to probe the reionization history of the universe? The answer is not direct in the same way. Lyman alpha is useful precisely because it is sensitive to neutral hydrogen, but that sensitivity also makes the signal difficult to interpret. A photon does not travel from a galaxy to a telescope through an empty pipe. It can be changed by the galaxy that produced it, by dust and gas inside that galaxy, by the circumgalactic medium, by the wider intergalactic medium, and by cosmic expansion.

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For the observational side, this paper focuses on spectroscopy, especially spectroscopy from JWST Near-Infrared Spectrograph (NIRSpec). Spectroscopy separates incoming light by wavelength. That lets researchers identify emission lines, confirm redshifts, and measure line properties. This point matters because Lyman alpha is not mainly an image feature. A telescope image may show that a galaxy exists, but spectra are needed to measure Lyman alpha flux, rest-frame equivalent width, escape fraction, velocity offset, and the presence or absence of the line itself.

The main observational example is the JWST Advanced Deep Extragalactic Survey (JADES) study. Using JWST NIRSpec data, JADES classifies and characterizes Lyman alpha emitting galaxies over a broad redshift interval. The study includes 795 galaxies from redshift 4.0 to 14.3 and identifies evidence for Lyman alpha emission in 150 sources [2]. That sample is important because it allows researchers to move beyond isolated detections. Individual galaxies can be interesting, but a large sample is needed to examine population-level behavior over cosmic time.

Several measured quantities are used throughout this paper. Lyman alpha flux gives the observed strength of the emission line. Rest-frame equivalent width compares that line to the galaxy's continuum light. Lyman alpha escape fraction estimates the share of Lyman alpha radiation that escapes instead of being absorbed or scattered. Velocity offset measures how far the Lyman alpha line is shifted from the galaxy's systemic velocity. Lyman alpha emitter fraction measures what fraction of galaxies show detectable Lyman alpha emission. These quantities are then compared with reionization models to estimate intergalactic medium transmission and the neutral hydrogen fraction.

The method also requires a limit on what can be claimed. A weak Lyman alpha line might indicate a more neutral intergalactic medium, but it might also be caused by dust, gas geometry, weak intrinsic Lyman alpha production, or observational limits. A strong line might mean the galaxy sits in an ionized region, but it does not prove that the whole universe was ionized. For this reason, observations and simulations have to be used together. Observations show the final signal that reached the telescope; simulations help explain the physical route that signal may have taken.

1.3. Research objectives and significance

The first objective of this research is to explain how Lyman alpha emitters can function as probes of reionization history. The goal is not simply to describe distant galaxies. The goal is to show how the Lyman alpha emission from those galaxies can reveal the changing state of the intergalactic medium. Reionization cannot be understood by studying only the galaxies themselves, because the gas between galaxies is also part of the evidence.

The significance of the topic comes from the connection between small-scale galaxy physics and large-scale cosmic history. A single galaxy's Lyman alpha emission depends on star formation, dust, gas motion, and internal structure. When many galaxies are studied across redshift, however, their Lyman alpha properties can also show how the universe around them changed. In that sense, galaxy spectroscopy becomes a tool for studying the history of the universe.

A second objective is to show why observations alone are not enough. James Webb Space Telescope gives astronomers much stronger spectra of distant galaxies than were available before, but interpretation still depends on models. Simulations such as THESAN help connect observed Lyman alpha statistics with the physical condition of the intergalactic medium. THESAN is especially useful because it combines galaxy formation models, dust models, and radiation magnetohydrodynamics, giving researchers a framework for studying Lyman alpha emission and transmission during the Epoch of Reionization [3].

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2. Main content

2.1. Background

2.1.1. Introduction to the epoch of reionization

The Epoch of Reionization was one of the major transitions in the history of the universe. Before this transition was complete, the intergalactic medium contained large amounts of neutral hydrogen. For many purposes that gas was not simply empty space; for Lyman alpha photons and other radiation connected to hydrogen, it could behave like a fog. Once the first stars and galaxies formed, ultraviolet radiation from those sources began changing the state of the surrounding gas.

Ionization means that electrons are separated from protons. As ultraviolet radiation from early luminous sources spread outward, more hydrogen in the intergalactic medium became ionized. The important complication is that this process was probably uneven. The first galaxies did not ionize the entire universe at the same moment. Each source could ionize its own neighborhood first, creating a bubble of ionized gas. Later, as more galaxies formed, those bubbles grew, overlapped, and connected.

For that reason, reionization studies have to consider topology as well as the average neutral hydrogen fraction. In this context, topology means the spatial arrangement of ionized and neutral regions. A universe with the same average neutral fraction could look observationally different depending on how the neutral gas was distributed. Large clustered ionized bubbles would allow Lyman alpha photons to travel differently from a universe in which neutral hydrogen was spread more evenly. The average fraction matters, but the arrangement matters too.

The neutral hydrogen fraction is therefore one of the key quantities in reionization research. When the neutral fraction is high, Lyman alpha photons have more difficulty traveling through the intergalactic medium. When the neutral fraction is low, the universe is more ionized and more transparent to Lyman alpha emission. The difficulty is that neutral hydrogen at these redshifts cannot always be measured directly. Researchers need indirect probes, and Lyman alpha emitters are one of the most useful options.

2.1.2. Lyman alpha emitters: what kind of galaxies

Lyman alpha emitters are galaxies with detectable Lyman alpha emission. The emission comes from hydrogen, the most common element in the universe. In atomic terms, Lyman alpha corresponds to an electron in hydrogen dropping from the first excited state to the ground state. In simpler language, when the electron falls to a lower energy level, a Lyman alpha photon can be released.

Young star-forming galaxies are especially relevant because massive young stars produce strong ultraviolet radiation. That radiation helps create the conditions in which Lyman alpha photons are produced. Many Lyman alpha emitters are therefore young, star-forming galaxies at high redshift, which makes them useful for studying the early universe.

Their importance, however, is not only that they emit Lyman alpha. The key point is that Lyman alpha is difficult to escape. After the photons are produced, they can scatter many times through neutral hydrogen. The signal that finally reaches an observer therefore contains information about the galaxy and also about the material between the galaxy and the observer.

The THESAN intensity-mapping paper explains this point in a simulation setting. It treats Lyman alpha as a line that contains information about both galaxies and the intergalactic medium during the Epoch of Reionization because of resonant scattering. It also explains that Lyman alpha photons can

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be produced through recombination and collisional excitation before undergoing multiple scatterings with neutral hydrogen atoms [4].

A Lyman alpha emitter is therefore more than a galaxy with a bright spectral line. It is a galaxy whose photons survived a complicated route through gas, dust, scattering, and cosmic expansion. Seeing the line tells researchers something about the galaxy and its environment, but it does not point to only one physical cause. Several processes can affect whether the line is visible.

2.1.3. Why lyman alpha can probe the epoch of reionization

Lyman alpha can probe reionization because neutral hydrogen strongly affects Lyman alpha transmission. In a more neutral universe, Lyman alpha photons are more likely to scatter out of the line of sight before they reach observers. In a more ionized universe, more of those photons can escape and be detected. The visibility of Lyman alpha emission is therefore tied to the changing state of the intergalactic medium.

The JADES paper states the basic logic directly: resonant scattering by neutral hydrogen makes the fraction of galaxies emitting Lyman alpha a tracer of the neutral fraction of the intergalactic medium and therefore of the history of reionization [2]. This is the central reason Lyman alpha emitters matter for this topic. They do not measure reionization in a one-step way, but their changing visibility gives indirect evidence for the changing amount of neutral hydrogen.

Several observables become important because of this connection. Lyman alpha visibility can decrease when the universe is more neutral. Rest-frame equivalent width can decline when the Lyman alpha line is weakened relative to the continuum. Escape fraction can fall when fewer photons escape through surrounding gas and dust. The fraction of galaxies showing Lyman alpha emission can also decrease at higher redshift. Velocity offset matters as well, because photons shifted away from the strongest neutral hydrogen absorption can sometimes travel more easily. Together, these measurements make Lyman alpha emitters useful probes of reionization.

2.2. State of the art research

2.2.1. Observation: data, methods, and results

Earlier observational studies of reionization used several methods. Quasar absorption spectra were one approach. Narrowband surveys for Lyman alpha emitters were another. Researchers also used galaxy luminosity functions and cosmic microwave background constraints. Each method added useful information, but none of them solved the problem by itself. Narrowband surveys could locate Lyman alpha emitters, but they often covered limited redshift ranges. Quasar absorption spectra could probe neutral hydrogen, but only along particular lines of sight. Galaxy surveys could show the early galaxy population, but they did not always show directly how Lyman alpha transmission changed.

James Webb Space Telescope changes the situation because it can observe much fainter and more distant galaxies in the infrared. That capability matters because light from distant galaxies has been stretched by cosmic expansion. JWST NIRSpec is especially important because it provides spectroscopy, not only imaging. Spectroscopy allows researchers to confirm redshifts and measure spectral lines directly. For Lyman alpha work, the line itself is the evidence, so spectroscopy is the core method rather than a minor technical detail.

The JADES study is one of the main observational sources for this paper. It uses JWST NIRSpec data to study Lyman alpha emitters across a large redshift range. The sample includes 795 galaxies

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from redshift 4.0 to 14.3 and identifies Lyman alpha emission in 150 sources [2]. The size and range of this sample matter because they allow researchers to study population-level trends instead of relying only on isolated detections.

The results show several important patterns. The study finds a positive correlation between Lyman alpha escape fraction and rest-frame equivalent width. It also finds a negative correlation between Lyman alpha velocity offset and escape fraction. For reionization, the most important trend is that both escape fraction and rest-frame equivalent width decrease with redshift above about 5.5. The study interprets this decline as evidence for the progression of reionization on a population scale [2].

The JADES data also show increasing intergalactic medium transmission of Lyman alpha from redshift about 14 to 6. That trend follows the expected direction if the universe became more ionized over time. The study measures the completeness-corrected fraction of Lyman alpha emitters from redshift 4 to 9.5 and compares those values with semi-analytical models. One model interpretation gives a high neutral fraction around redshift 7, about 0.8 to 0.9. When the intrinsic equivalent width distribution is updated, the inferred value becomes lower, around 0.64 [2].

The same result is both powerful and limited. It is powerful because a large JWST sample turns Lyman alpha emission into a population-level probe of reionization. It is limited because the inferred neutral fraction depends on assumptions about the intrinsic Lyman alpha distribution. Lyman alpha emitters should therefore not be treated as a direct ruler for reionization. They are a probe whose interpretation depends on models.

Recent JWST discoveries also show why the field is moving quickly. NASA reported that Webb observed a galaxy whose Lyman alpha emission appears to have escaped from a very early universe where neutral hydrogen should have blocked such light [5]. This kind of object suggests that some early galaxies may have created ionized regions around themselves earlier than expected. It also shows why individual discoveries and population studies need each other: one unusual object can reveal a possibility, but a larger sample is needed to decide whether the pattern is common.

2.2.2. Simulation: method and results

Simulations are needed because Lyman alpha properties do not directly give the neutral hydrogen fraction. A weak Lyman alpha signal could be caused by a neutral intergalactic medium, but it could also be caused by dust inside the galaxy, gas geometry, low intrinsic Lyman alpha production, or observational limits. A strong Lyman alpha signal could mean that the intergalactic medium is ionized, but it could also mean that the galaxy is sitting inside a local ionized bubble. Observation alone cannot separate all of these possibilities.

The role of simulations is to connect observed Lyman alpha statistics to physical conditions. THESAN is useful because it models galaxy formation and reionization together. The THESAN Lyman alpha emission and transmission paper states that the visibility of distant Lyman alpha emitting galaxies provides important constraints on galaxy formation and the Epoch of Reionization, but that predicting realistic statistics for comparison with observations is challenging in large-volume cosmological simulations [6].

THESAN addresses this challenge by combining galaxy formation and dust models with radiation magnetohydrodynamics. This matters because Lyman alpha photons are shaped by both galaxy-scale physics and intergalactic gas. A simulation that ignored one side of that problem would be incomplete. THESAN's framework helps researchers study how Lyman alpha is produced, how it travels through ionized and neutral regions, and how it may appear to observers.

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The THESAN intensity-mapping article adds another layer to this discussion. Instead of focusing only on individual Lyman alpha emitters, it models Lyman alpha line intensity mapping, which studies the combined Lyman alpha signal across large regions. The article uses THESAN simulations to produce theoretical predictions for future Lyman alpha line intensity mapping. It includes contributions from recombination, collisional excitation, unresolved H II regions, absorption, damping wing analysis, channel maps, and power spectra [4].

One of the most important findings is that absorption has a major effect. The article finds that the emission-only Lyman alpha power spectrum lies above SPHEREx sensitivity, but the absorption-included signal is about four orders of magnitude lower. It also identifies future needs, including better treatment of resonant Lyman alpha scattering, line interlopers, and larger simulation volumes [4].

This shows why simulations are not just supporting material. They are part of the method. Observations show the final signal, but simulations help explain how that signal was produced, weakened, shifted, or erased. Without simulations, it would be too easy to overinterpret a detection or to assume that every decrease in Lyman alpha visibility must come from the neutral intergalactic medium alone.

2.3. Main observational analysis based on the JADES study

2.3.1. Data sample

The JADES sample gives researchers a larger and more systematic view of distant Lyman alpha emission. Earlier studies often depended on smaller samples, which made it harder to separate real cosmic trends from sample bias. JADES improves this situation by using James Webb Space Telescope NIRSpec spectroscopy across a large sample of distant galaxies.

The study includes galaxies across redshift 4.0 to 14.3. This range is useful because it covers times when the universe was becoming more ionized and also times closer to the earlier stages of reionization. It lets researchers compare Lyman alpha behavior across a long stretch of cosmic history. That matters because reionization was not a single instant; it was a process that developed over time.

The sample is also valuable because it is spectroscopic. Imaging can suggest that a galaxy is distant, but spectroscopy gives stronger confirmation and allows researchers to measure line properties directly. For this paper, the question is not only whether a galaxy exists. The question is whether Lyman alpha emission from that galaxy can escape and be detected. A galaxy can be present even if its Lyman alpha photons are scattered away. Therefore, JADES is valuable because it connects galaxy detection with Lyman alpha visibility.

2.3.2. Spectral fitting and measured quantities

The JADES analysis depends on turning spectra into physical measurements. Lyman alpha flux is the first basic quantity because it measures the observed strength of the emission line. Rest-frame equivalent width is also central because it measures how strong the Lyman alpha line is compared with the galaxy's continuum. A galaxy with a large equivalent width has a Lyman alpha line that stands out strongly from the surrounding light.

Lyman alpha escape fraction is another key measurement because it estimates how much Lyman alpha emission escapes. Many Lyman alpha photons may be produced but never reach the observer.

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They can be scattered by neutral hydrogen, absorbed by dust, or shifted by gas motion. Escape fraction therefore connects the observed line to the physical path the photons took before detection.

Velocity offset matters because Lyman alpha photons do not always emerge at exactly the systemic velocity of the galaxy. If the photons are shifted redward, they may avoid some of the strongest absorption by neutral hydrogen. This means velocity offset can influence how easily Lyman alpha escapes. The JADES finding about velocity offset and escape fraction shows that the relation between gas motion and Lyman alpha visibility is important, even if it is not simple.

The Lyman alpha emitter fraction is especially important for reionization. It asks a population-level question: what fraction of galaxies show detectable Lyman alpha emission? If the universe becomes more neutral at higher redshift, this fraction should generally decline because Lyman alpha photons have more difficulty escaping through the intergalactic medium. The JADES study uses this fraction to help infer intergalactic medium transmission and neutral fraction.

2.3.3. Main results

The main result is that Lyman alpha emission becomes harder to observe at higher redshift in a way that is consistent with reionization. Both escape fraction and rest-frame equivalent width decrease above redshift about 5.5. This does not mean that every galaxy follows the same pattern, but it suggests that the population as a whole is affected by the changing intergalactic medium.

The study also shows that intergalactic medium transmission increases from redshift about 14 to 6. This fits the expected direction of cosmic evolution. At earlier times, the universe should contain more neutral hydrogen, making Lyman alpha transmission more difficult. At later times, the universe should be more ionized, allowing more Lyman alpha photons to reach observers.

The inferred neutral fraction around redshift 7 is one of the most important conclusions. The JADES study reports that applying the Lyman alpha emitter fraction to earlier semi-analytical models suggests a high neutral fraction of about 0.8 to 0.9. With an updated intrinsic equivalent width distribution, however, the inferred value becomes lower, about 0.64 [2].

This result supports the idea that the universe was still significantly neutral around redshift 7, but it also shows that the exact value depends on model assumptions. That is the point that has to be treated carefully. The JADES result does not mean that Lyman alpha emitters give a perfectly direct measurement of reionization. Instead, they provide strong evidence when combined with models. That is a more defensible conclusion, and it explains why one observational statistic should not be treated as the final answer by itself.

2.4. Discussion: strengths and limitations

The strength of Lyman alpha emitter research is that it connects direct galaxy observations to the state of the intergalactic medium. This is difficult to do. Many galaxy properties tell researchers mainly about the galaxy itself. Lyman alpha is different because it is also affected by gas outside the galaxy. That makes it especially valuable for studying reionization.

The JADES study is strong because it uses a large James Webb Space Telescope NIRSpec sample, direct spectroscopy, and multiple measured quantities. It does not depend only on one detection or one galaxy. It studies correlations and population trends. It also applies completeness corrections and compares observations with models, which makes its conclusions stronger than a simple count of detected emission lines.

At the same time, the limitations are serious. Lyman alpha emission is affected by many things besides the neutral fraction of the intergalactic medium. Dust can absorb photons. Gas inside

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galaxies can scatter them. Outflows can shift them. The circumgalactic medium can alter them before they even reach the wider intergalactic medium. Because of this, a change in Lyman alpha visibility cannot automatically be assigned to reionization alone.

Cosmic variance is another limitation. Even a JWST deep field covers only a limited region of the sky. If that region contains more ionized bubbles or more dense structure than average, the results may not fully represent the universe as a whole. Future research therefore needs larger survey areas and multiple fields.

The modeling limitation is also important. The inferred neutral fraction changes depending on the assumed intrinsic equivalent width distribution. This means that the final estimate depends partly on what researchers assume Lyman alpha emission would look like without intergalactic absorption. This does not invalidate the method, but it does mean the results must be presented with uncertainty.

Simulations have their own limits as well. The THESAN intensity-mapping article identifies missing or incomplete effects such as resonant scattering, line interlopers, and simulation volume [4]. These are not minor details. Lyman alpha is deeply shaped by scattering, so improved radiative transfer treatment is necessary for stronger future predictions.

3. Conclusion

3.1. Summary of results and conclusions

Lyman alpha emitters are useful probes of reionization because Lyman alpha photons are highly sensitive to neutral hydrogen. During the Epoch of Reionization, the universe changed from being filled with mostly neutral hydrogen to becoming mostly ionized. Since Lyman alpha photons are resonantly scattered by neutral hydrogen, their visibility changes as the intergalactic medium changes. This makes Lyman alpha emitters an indirect but powerful way to study reionization history.

The JADES James Webb Space Telescope NIRSpec study provides one of the strongest current observational examples. Its results show that Lyman alpha escape fraction and rest-frame equivalent width decrease at higher redshift, while intergalactic medium transmission increases from redshift about 14 to 6. Its model comparison also suggests that the universe was still significantly neutral around redshift 7.

The main conclusion is that Lyman alpha emitters can trace reionization, but they must be interpreted carefully. They do not give the neutral hydrogen fraction by themselves. They become powerful when combined with completeness corrections, model comparisons, and simulations such as THESAN.

3.2. Research significance

The significance of this research is that it links galaxy spectroscopy with large-scale cosmic evolution. By measuring Lyman alpha emission from distant galaxies, researchers can study not only the galaxies, but also the intergalactic medium around them. This makes Lyman alpha emitters valuable because they connect small-scale astrophysical processes with the large-scale history of the universe.

The topic also shows why modern astrophysics depends on both observation and theory. James Webb Space Telescope can provide high-quality spectra of early galaxies, but simulations help interpret what those spectra mean. THESAN shows that Lyman alpha transmission depends on emission mechanisms, absorption, radiative transfer, and the evolving structure of the intergalactic

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medium. Without simulations, observational results would be much harder to translate into a reionization history.

3.3. Future research prospects

Future research should move in three directions. First, James Webb Space Telescope NIRSpec should continue building larger and deeper spectroscopic samples. More galaxies across more fields will reduce sample bias and cosmic variance. Second, researchers need improved models of intrinsic Lyman alpha emission, because assumptions about the intrinsic equivalent width distribution can change the inferred neutral fraction. Third, Lyman alpha emitter studies should be combined with other probes rather than treated as a complete solution alone.

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer, or SPHEREx, is important for future large-area spectral mapping. The THESAN intensity-mapping article notes that SPHEREx has identified Lyman alpha as a key target line for distant line intensity mapping, especially in the redshift range 5.2 to 8 [4]. NASA reports that SPHEREx is observing the sky in 102 infrared wavelength bands, making it useful for broad mapping rather than only deep targeted spectroscopy [7].

The strongest future approach will probably combine Lyman alpha emitter studies, Lyman alpha intensity mapping, 21 cm observations, cosmic microwave background constraints, and simulations. Lyman alpha gives one view of reionization, but no single method is enough. Reionization was a complex, uneven process, so it needs multiple probes. Lyman alpha emitters are valuable not because they solve the entire problem alone, but because they provide one of the clearest links between early galaxies and the neutral hydrogen that surrounded them.

References

[1] NASA Science Editorial Team. (n.d.). Early universe. NASA Science. https: //science.nasa.gov/mission/webb/early-universe/

[2] Jones, G. C., Bunker, A. J., Saxena, A., Arribas, S., Bhatawdekar, R., Boyett, K., Cameron, A. J., Carniani, S., Charlot, S., Curtis-Lake, E., Hainline, K., Johnson, B. D., Kumari, N., Maseda, M. V., Rix, H.-W., Robertson, B. E., Tacchella, S., Übler, H., Williams, C. C., ... Zhu, Y. (2025). JADES: Measuring reionization properties using Lyman-alpha emission. Monthly Notices of the Royal Astronomical Society, 536(3), 2355-2380. https: //doi.org/10.1093/mnras/stae2670

[3] Kannan, R., Garaldi, E., Smith, A., Pakmor, R., Springel, V., Vogelsberger, M., & Hernquist, L. (2022). Introducing the THESAN project: radiation-magnetohydrodynamic simulations of the epoch of reionization. Monthly Notices of the Royal Astronomical Society, 511(3), 4005-4030. https: //doi.org/10.1093/mnras/stab3710

[4] Almualla, M., Smith, A., Kannan, R., Hernquist, L., Garaldi, E., Lidz, A., Lorinc, K., Chan, J. Y. H., & Vogelsberger, M. (2025). The THESAN project: Lyman-alpha intensity mapping of cosmic reionization. arXiv preprint arXiv: 2512.06085. https: //arxiv.org/abs/2512.06085

[5] NASA Webb Mission Team. (2025, March 26). NASA's Webb sees galaxy mysteriously clearing fog of early universe. NASA Science. https: //science.nasa.gov/missions/webb/nasas-webb-sees-galaxy-mysteriously-clearing-fog-of-early-universe/

[6] Smith, A., Kannan, R., Garaldi, E., Vogelsberger, M., Pakmor, R., Springel, V., & Hernquist, L. (2022). The THESAN project: Lyman-alpha emission and transmission during the epoch of reionization. Monthly Notices of the Royal Astronomical Society, 512(3), 3243-3265. https: //doi.org/10.1093/mnras/stac713

[7] NASA. (2025, May 1). NASA's SPHEREx space telescope begins capturing entire sky. NASA. https: //www.nasa.gov/missions/spherex/nasas-spherex-space-telescope-begins-capturing-entire-sky/