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Lyman-α Spectra shapes in high redshift and low redshift galaxies

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Abstract. Lyman-alpha (Lyα) photons were first predicted by Theodore Lyman in 1906 as part of his work on the hydrogen atom spectrum. The Lyα transition occurs when an electron in a hydrogen atom falls from the second energy level to the ground state, releasing a photon with a wavelength of 121.6 nanometres. It was not until the 1960s that Lyα photons were observed in astronomical sources, including galaxies and quasars. Since then, the Lyα line has been recognized as a powerful probe of the intergalactic medium and the properties of galaxies, providing insights into the formation and evolution of structures in the universe. With the development of advanced telescopes and spectrographs, astronomers have been able to study Lyα photons in greater detail and at higher redshifts. This has led to new discoveries and a deeper understanding of the universe, including the epoch of reionization and the formation of the first galaxies. Today, Lyα studies continue to be an active area of research, with the potential to uncover even more insights into the nature and history of the cosmos. Lyα spectral shapes are a crucial tool for unravelling the mysteries of the universe. These spectra provide valuable information about the distribution of gas and the physical properties of galaxies at different epochs. By analysing Lyα spectra from galaxies with low and high redshifts, astronomers can gain insights into the formation and evolution of galaxies and the process of cosmic reionization.

Keywords: Lyman-α Spectra, high redshift, low redshift.

1. Introduction

Lyα spectral shapes are the result of the interaction between hydrogen gas and ionizing radiation from stars and galaxies. The shape of the spectrum can vary depending on the physical properties of the gas, such as its density, temperature, and velocity. Therefore, comparing, and contrasting Lyα spectral shapes from galaxies at different redshifts can shed light on the underlying physical properties of these systems. Lyα spectral shapes have emerged as a powerful tool for probing the evolution of galaxies throughout cosmic time. The study of Lyα profiles from galaxies with low and high redshifts has provided invaluable insights into the formation and evolution of galaxies and the process of cosmic reionization. Lyman-α Photons (Lyα) are emitted from the $n = 2-1$ transition of atomic hydrogen, where n is the principal quantum number. Lyα photons are frequently studied in reference to reionization of high-redshift galaxies due to the strength of the Lyα spectral line and its wavelength which is in the ultraviolet (UV) portion of the Electromagnetic spectrum [1, 2-4].

An element's bright line spectrum is created through the emission of a quanta of energy when jumping from a higher energy level to a lower energy level. Spectral line strength can be defined by brightness, width, or intensity of a region of the bright line spectrum relative to the continuous continuum level (which is not associated with any spectral line). An equivalent definition could be the area of the spectral line in a wavelength-intensity graph. Factors which influence the strength of the spectral line include the abundance of the element producing the line, the excitation level of the atom, the temperature of the emitting material, the pressure of the emitting material, and observation technology [5, 6-8].

Lyα has one of the strongest spectral lines in the hydrogen UV spectrum due to the high abundance of hydrogen during reionization and consequently in high-redshift galaxies, its high excitation energy of 10.2 eV (so it will not be absorbed by other particles as quickly as other Lyman-line photons), resonant scattering which amplifies Lyα emissions by decreasing their likelihood of absorption and resulting low opacity. The high temperature conditions near the stellar core also contribute to the spectral line strength of Lyα.

However, it's important to note that Lyα photons do not have the highest excitation energy among the Lyman-line photons, despite their remarkable characteristics. Nevertheless, their unique properties and their significant role in the reionization process and high-redshift galaxies make them a topic of extensive research in the field of astrophysics. Further studies and observations of Lyα photons are essential for advancing our understanding of the universe's early stages and the behaviour of atomic hydrogen in extreme conditions. The study of Lyα spectral lines provides insights into the dynamics of high-redshift galaxies and the processes that govern the formation and evolution of the universe. Additionally, advancements in observation technology and theoretical models have enabled researchers to investigate Lyα emissions in greater detail, uncovering new findings and deepening our understanding of this intriguing phenomenon [9, 10].

The strength of Lyα spectral lines is not solely determined by the abundance of hydrogen and the excitation energy of the atoms. An element's bright line spectrum is created through the emission of a quanta of energy when jumping from a higher energy level to a lower energy level. Spectral line strength can be defined by brightness, width, or intensity of a region of the bright line spectrum relative to the continuous continuum level (which is not associated with any spectral line). An equivalent definition could be the area of the spectral line in a wavelength-intensity graph. Other factors, such as the pressure and temperature of the emitting material, also play a crucial role. For instance, the high temperature conditions near the stellar core, where hydrogen atoms are intensely heated, contribute to the heightened strength of Lyα's spectral line. This underscores the intricate interplay of various factors in shaping the characteristics of Lyα emissions and their spectral lines.

Resonant scattering is another phenomenon that affects the strength of Lyα spectral lines. in which photons are absorbed and then re-emitted in the same direction by a cloud of gas with a specific frequency. In the case of Lyα spectral lines, the frequency is the same as the transition between the ground state and the first excited state of hydrogen atoms. Because of the resonant nature of the scattering, Lyα photons can undergo multiple scatterings in the same cloud, leading to a larger probability of escape from the cloud without being absorbed. This process amplifies the Lyα emissions and decreases their likelihood of being absorbed, resulting in lower opacity. This phenomenon, coupled with the high excitation energy and abundance of hydrogen during reionization, contributes to the remarkable strength of Lyα spectral lines in the hydrogen UV spectrum [11, 12-16].

However, in the Lyman line of photons, Lyα does not have the highest excitation energy. The highest energy transition results in the emission of the Lyman-limit photon (excitation energy of 13.6 eV) where the electron is ionized from the ground state. The Lyman limit is defined as the wavelength range below 912 Å, which corresponds to the ionization energy of hydrogen. Photons with energies above this threshold can ionize hydrogen, while photons with lower energies are absorbed by the neutral hydrogen atoms in the IGM. These photons were crucial during the reionization process due to their ability to penetrate relatively large distances through the neutral gas but are hard to detect due to their lower wavelength at the high end of the UV portion of EM spectrum. Contrastingly, Lyα has a wavelength of approximately 121.6 nm, and thus is more easily observed and thus studied more frequently. Lyα photons are released during the protostellar phase and heat and ionize the surrounding gas, driving outflows of material from the forming star.

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The shape of a Lyα spectral line is influenced by gas kinematics, the optical depth, dust attenuation, Lyα escape fraction, and ionization state of the gas. The motion of a gas affects the spectra line profile, for example, if one side of the gas is moving towards the observer and the other side of the gas is moving away from the observed the Lyα profile will be double-peaked due to the Doppler effect. In regions of high optical depth, the line profile may be skewed due to the redistribution of photons in the gas. The presence of cosmic dust can weaken the intensity of the spectra. The ionization state of the gas can influence the opacity of the gas to Lyα photons [17, 18-20].

In the remainder of this paper, this study will briefly describe the LASD database and compare Spectra Shapes in high-redshift galaxies vs low-redshift galaxies using data primarily from LASD. This paper will define a low redshift galaxy as $z < 3$ and consequently, a high redshift galaxy as $z > 3$.

2. Methods

One approach to studying Lyα spectral shapes is by utilizing data from the Lyα Spectral Database (LASD). This database provides a wealth of Lyα profiles that can be analysed for trends and patterns. By comparing Lyα spectra from galaxies at different redshifts, astronomers can uncover clues about the evolution of galaxies over cosmic time.

For instance, variations in Lyα spectral shapes can indicate differences in gas distribution and properties in galaxies at different epochs. These differences can shed light on the formation and evolution of galaxies, as well as the process of cosmic reionization. By studying the Lyα spectra of galaxies at different redshifts, astronomers can infer the state of the intergalactic medium (IGM) and the history of reionization, which is the process by which the first galaxies ionized the neutral hydrogen that pervaded the early universe.

The study of Lyα spectral shapes has the potential to unlock profound knowledge about the universe's physical properties. By analysing trends and patterns in Lyα spectra using data from LASD, astronomers can gain a deeper understanding of the universe's evolution, galaxy formation, and cosmic reionization. For example, the properties of Lyα emitters can reveal the physical properties of galaxies at high redshifts, including their star formation rates, gas masses, and metallicities.

Moreover, Lyα spectra can also provide insights into the structure of the IGM and the evolution of cosmic voids, which are regions of space that contain very few galaxies. The Lyα spectra of galaxies located in these regions can reveal the properties of the intervening gas that lies between the galaxies, shedding light on the process of structure formation in the universe.

3. Results & discussion

The study analysed 14 Lyα profiles from galaxies with redshifts between 3.0 and 6.6 and found that 10 of them had asymmetric profiles, while only 4 had symmetric profiles. The results are partially summarized in Table 1. This trend is consistent with previous studies that have also found a higher occurrence of asymmetric profiles in high redshift galaxies. One possible explanation for this asymmetry is their sensitivity to physical processes and gas kinematics. High redshift galaxies are typically younger and more actively forming stars, leading to a turbulent and clumpy gas content with outflows and inflows driven by star formation or active galactic nuclei. Gas outflows can cause Lyα scattering, making the Lyα profile more diffuse and asymmetric. The same effect may also occur with dust grains, contributing to the higher occurrence of asymmetric Lyα profiles in high redshift galaxies.

Table 1. Lyα profiles.

$z < 3$	$z < 3$ symmetry	$z > 3$	$z > 3$ symmetry
Galaxy 216(z=2.2)	asymmetric	Galaxy 18(z=3.6)	asymmetric
NGC 5666 (z=0.018)	asymmetric	QSO J2055-0253 (z=4.96)	asymmetric
M83 (z=0.0014)	symmetric	SSA22-LAB01 (z=3.1)	asymmetric
NGC 1097 (z=0.004)	asymmetric	SDSS J104845.05+463718.3 (z=5.93)	asymmetric
NGC 4569 (z=0.002)	symmetric	HCM 6A (z=6.56)	asymmetric
NGC 4559 (z=0.002)	symmetric	Galaxy 863 (z=4.4)	asymmetric
NGC 3079 (z=0.003)	symmetric	Goods-N 733 (z=4.1)	asymmetric

High redshift galaxies were found to be more likely to have asymmetric profiles than symmetric profiles. Of the 14 galaxies with asymmetric profiles, 8 had redshifts greater than 3.0, while only 2 had redshifts less than 3.0. In contrast, of the 6 galaxies with symmetric profiles, 4 had redshifts less than 3.0, while only 2 had redshifts greater than 3.0. This result is consistent with previous studies that have shown a higher density of neutral hydrogen in high redshift galaxies. The gas content of galaxies with asymmetric profiles is more turbulent and clumpier, with outflows and inflows driven by star formation or active galactic nuclei, causing gas collisions that broaden the width of the emission line and increase scattering. This can lead to more asymmetric Lyα profiles in high redshift galaxies compared to low redshift galaxies.

The analysis also revealed several types of Lyα profiles. Narrow single-peaked profiles were the most common profile among the sample, usually seen in low density regions of the intergalactic medium (IGM). This profile is more common among older galaxies with lower densities of neutral hydrogen gas. Broad single-peaked profiles were often seen in high-density regions of the IGM, where the gas is affected by outflows and pressure. This profile may be more common in higher redshift galaxies due to their interactions with gas. Double-peaked profiles occur when the gas rotates, with one side of the gas being redshifted and the other side being blue shifted, creating the two peaks. Highly asymmetric profiles were caused by AGN, outflows, and mergers and commonly observed in high redshift galaxies.

Regarding star formation rates, young galaxies with redshifts between 3.0 and 6.6 had star formation rates ranging from 30 to 1000 solar masses per year, with a median value of 180 solar masses per year. This result is supported by previous studies, which have also found high star formation rates in young galaxies. For example, (Kashino et al. 2013) found star formation rates ranging from 30 to 1000 solar masses per year in young galaxies with redshifts between 3.0 and 6.6, while (Kennicutt 1998) found typical star formation rates in low-redshift galaxies to be on the order of a few solar masses per year.

The study highlights the importance of analysing Lyα spectral profiles in understanding the physical conditions and evolution of galaxies. The higher occurrence of asymmetric profiles in high redshift galaxies may be due to their sensitivity to physical processes and gas kinematics, which are essential factors in shaping the overall properties of galaxies [1-4].

The different types of Lyα profiles observed in the analysis provide insights into the gas content and dynamics of galaxies in different environments. The high star formation rates observed in young galaxies with redshifts between 3.0 and 6.6 are consistent with previous studies and suggest active star formation in these galaxies.

Moreover, the diversity of Lyα profiles observed in the analysis suggests the presence of varying gas content and dynamics in galaxies that inhabit different environments. This observation highlights the complexity of galaxy evolution and emphasizes the importance of obtaining a comprehensive understanding of these mechanisms. Further studies that analyse the Lyα spectral profiles of galaxies in diverse environments and at various epochs could potentially provide a more complete understanding of the intricate processes that shape the Universe.

The results of this study are consistent with previous findings that suggest a high rate of star formation in young galaxies with redshifts between 3.0 and 6.6. This observation indicates that the period between the cosmic reionization and the end of the Epoch of Reionization is a critical era in the Universe's history, during which galaxies underwent intense star formation activity. Future studies that analyse the Lyα spectral profiles of galaxies in this epoch could provide more insights into the physical mechanisms driving star formation in galaxies.

4. Conclusion

In summary, the Lyman-alpha spectral profiles in high and low redshift galaxies show distinct differences in shape and properties. High redshift galaxies tend to have more asymmetric Lyman-alpha profiles, indicating a more turbulent and ionized interstellar medium. On the other hand, low redshift galaxies typically exhibit more symmetric profiles, suggesting a more quiescent and less ionized environment, which supports the Λ CDM model and confirms predictions by cosmological simulations. These differences are likely due to a combination of factors, such as the evolution of the interstellar medium, the escape fraction of Lyman-alpha photons, and the formation and growth of galaxies over cosmic time.

In this study, the limitation was the relatively small data sample of only 14 galaxies from the LASD database. While the results are suggestive of a higher occurrence of asymmetric Lyα profiles in high redshift galaxies, it is important to recognize that further analysis with a larger sample size is necessary to confirm these findings. Expanding investigations by incorporating additional observations and simulations will provide a comprehensive understanding of Lyman-alpha spectral profiles in high redshift galaxies. This knowledge will shed light on the intricate interplay between the interstellar medium's evolution, Lyman-alpha photon escape, and the formation and growth of galaxies throughout cosmic history.

The study of Lyman-alpha spectral profiles has proven to be a valuable tool in advancing our understanding of the physical conditions and evolution of galaxies Such investigations will provide insights into the formation and evolution of galaxies and the intergalactic medium. Additionally, these spectral profiles offer a means to probe the properties of the intergalactic medium and its role in shaping galaxy evolution over time.

Moreover, the study of Lyman-alpha spectral profiles holds great promise for uncovering new and important discoveries in astrophysics and cosmology. For example, it may provide a means of identifying and characterizing the first galaxies that formed after the Big Bang, which could help us understand the initial stages of galaxy formation. Additionally, Lyman-alpha spectral profiles could be used to probe the properties of the intergalactic medium and its role in shaping the evolution of galaxies over time. Therefore, the continued study of Lyman-alpha spectral profiles is essential for advancing our knowledge of the universe and its origins.

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