

Ultra-Violet Luminosity Functions and The Mass-Metallicity Relation

Maolin Wang *

Nanjing University of Aeronautics and Astronautics, Nanjing, China

* Corresponding Author Email: 152130226@nuaa.edu.cn

Abstract. In recent years, high-resolution and highly sensitive telescopes and detectors have emerged, allowing researchers to more accurately measure the ultraviolet luminosity function of dust attenuation, thereby constraining cosmological parameters such as galaxy density, evolution speed, and cosmic geometry. Therefore, the research topic of this article is the relationship between ultraviolet luminosity function (UV-LF) and the mass metal relationship. The research method of this article is as follows: Firstly, consider Stellar population synthesis, Lyman- α Absorption, Dust attenuation, and Lyman Break selection analyzed one of the models of UV-LF, and based on this, study the relationship between UV-LF and the mass metal relationship. Research has found that generally speaking, galaxies or celestial bodies with higher metallicity may experience more significant attenuation of ultraviolet light due to the presence of more dust particles. On the contrary, galaxies or celestial bodies with lower metal abundance may have relatively small ultraviolet luminosity attenuation due to their lower dust content. It should be noted that this correlation is not a simple linear relationship, but is influenced by multiple complex factors.

Keywords: Galaxies; high redshift – galaxies; luminosity function; mass function; ultraviolet.

1. Introduction

The ultraviolet luminosity function of dust attenuation not only enhances our comprehension of the physical processes within galaxies and the universe, but also serves as a crucial tool for researchers to uncover the evolutionary history of the universe. It can reveal the true situation of star formation in galaxies, help researchers understand the exchange and circulation of matter between galaxies, constrain cosmological parameters, and promote the development of observation technology and data processing methods.

In recent years, with the continuous development of astronomical observation technology and the improvement of data processing methods, the observation ability for galaxies and dust has been significantly improved. High-resolution and sensitivity telescopes and detectors enable us to delve deeper into the ultraviolet luminosity function of dust attenuation. By accurately measuring the ultraviolet luminosity function of dust attenuation, researchers can constrain cosmological parameters such as galaxy density, evolution speed, and the geometry of the universe.

As a representative of astronomical telescopes in recent years, the James Webb Space Telescope (JWST) was launched in late 2021 and began functioning in early 2022. The observation data of JWST will provide a large amount of new information and discoveries for the astronomical community, promoting the continuous deepening of human understanding of the universe. The first data sets of JWST were released on 2022 July 12, which will play a significant role in the research of UV-LF [1].

Nonetheless, numerous questions persist regarding the shape and evolution of the ultra-violet luminosity function (UV-LF) at high redshifts ($z > 3$). Scientists have conducted many studies and achieved many results in this area, but there are still some shortcomings. The redshift z mentioned earlier is of great significance in astronomy, especially in the study of luminosity functions. The definition of redshift z is the degree to which spectral lines in the electromagnetic spectrum move towards the longer wavelength direction, or in other words, the degree to which visible light moves towards the red end of the spectrum. In mathematical expression, the redshift z can be expressed by the formula $z = \Delta\lambda/\lambda$ to calculate, where λ the wavelength of the source emission spectral line, $\Delta\lambda$

the amount of wavelength change observed. When $\Delta\lambda > 0$, it indicates an increase in wavelength, illustrating a redshift; When $\Delta\lambda < 0$, it indicates a decrease in wavelength, illustrating a blue shift occurs. Claims suggest that the double-power-law function can effectively explain the bright end of the UV luminosity function at redshifts approximately 4 and higher. However, the Schechter function is deemed inappropriate due to the significant excess of bright galaxies [2]. The population of bright galaxies includes those with spectroscopic redshifts between 10 and 13, as well as candidates at $z \sim 13$, although it has not been concluded with sufficient statistical accuracy and spectroscopic confirmation [2].

At present, there are still many shortcomings in the research on UV-LF. Firstly, the UV luminosity function of dust attenuation typically relies on complex physical models, which may contain many simplified assumptions and approximations. Therefore, the uncertainty of the model may have a significant impact on the results. In addition, different models may draw different conclusions, which makes it difficult to interpret and compare the results. Secondly, although significant progress has been made in multi-band observation technology in recent years, high-quality data on the ultraviolet luminosity function of dust attenuation is still limited. Especially for high redshift galaxies and weak galaxies, the quality and quantity of observational data are insufficient. This limits the in-depth understanding of dust attenuation. Finally, there may be significant differences in the distribution and properties of dust within different galaxies, while the differences between galaxies are more pronounced. This makes it difficult to construct a universally applicable UV luminosity function. In addition, the dust inside a galaxy may be influenced by various factors, such as stellar activity, galactic winds, etc., which may make the process of dust attenuation more complex.

To tackle this issue, the present study aims to investigate and enhance the dust model mentioned in the Dark-ages reionization & galaxy formation simulation IV, specifically focusing on UV luminosity functions of high-redshift galaxies. At the same time, based on the observation results of JWST, the model built by previous researchers, and the data obtained, compare the results with the model in this paper in the chart, discuss and judge the rationality of the model. If the model is reasonable, this article will focus on the relationship between quality, metallicity, and UV-LF, and draw an image to discuss the relationship between the two.

2. Basic information

In this section, the basic information related to this article, including the definition and principles of ultra-violet luminosity function, mass and metallicity, the simple relationship between the two, and their impact on scientific research will be introduced.

2.1. Definition and Principle

2.1.1 UV-LF

The ultra-violet luminosity function of dust attenuation is a function used to describe the impact of interstellar dust on ultraviolet light attenuation. In astronomy, interstellar dust is a small particle widely present in the universe, which scatters and absorbs light, thereby affecting the celestial radiation the scientists observe.

The ultraviolet luminosity function is commonly used to quantify this attenuation effect, taking into account the degree of dust attenuation experienced by ultraviolet light of different wavelengths when passing through interstellar media. This function is usually constructed based on experimental observation data and theoretical models to reflect the scattering and absorption characteristics of dust particles towards different wavelengths of ultraviolet light.

Specifically, the ultraviolet luminosity function of dust attenuation may involve multiple parameters, such as the size, shape, and composition of dust particles, and distribution in interstellar media. These parameters collectively determine the degree of attenuation of ultraviolet light as it passes through interstellar dust.

Through this function, astronomers can more accurately understand the impact of interstellar dust on ultraviolet light, thereby studying the radiation characteristics and evolution process of celestial bodies more accurately. This is of great significance for understanding important issues such as star formation, galaxy evolution, and the circulation of matter in the universe.

2.1.2 The mass-metallicity relation

The mass-metallicity relationship, a prevalent concept in astronomy and chemistry, characterizes the correlation between the mass of a galaxy or celestial body and its metallicity. The metal abundance, in this context, typically pertains to the abundance of heavy elements (in comparison to lighter elements like hydrogen and helium) within stars or galaxies.

The metallicity of a galaxy exhibits a strong link to various characteristics, particularly its stellar mass ($M_{\star}$). Researchers have thoroughly examined the mass-metallicity relation using data sources such as the Sloan Digital Sky Survey, revealing a positive correlation between metallicity and M in star-forming galaxies.

Intriguingly, the metallicity displays an inverse relationship with the star formation rate (SFR). This indicates that galaxies with higher SFRs tend to have lower metal content, even when considering galaxies with fixed $M_{\star}$. This correlation aligns with theoretical models that account for the inflow of metal-poor gas, a process that triggers star formation while diluting the metallicity of the interstellar medium (ISM). Conversely, the release of metal-rich gas suppresses star formation and removes metals from the ISM [3].

Generally speaking, heavier galaxies or celestial bodies often contain a higher proportion of heavy elements because they have sufficient mass to produce these elements through nuclear synthesis during evolution and can more effectively retain them. On the contrary, smaller galaxies or celestial bodies may not be able to effectively retain these heavy elements due to weak gravity or other factors, resulting in lower metallicity.

2.2. The Correlation Between the Two

Firstly, the mass-metallicity relation characterizes the correlation between the mass of a galaxy or celestial body and its metallicity. The abundance of metals not only reflects the degree of chemical evolution within galaxies or celestial bodies but also affects the formation and distribution of dust particles. Dust is mainly composed of metals and other heavy elements, so galaxies or celestial bodies with higher metal abundance often contain more dust particles.

Secondly, the ultraviolet luminosity function of dust attenuation describes the effect of interstellar dust on ultraviolet light attenuation. The scattering and absorption of ultraviolet light by dust particles can cause attenuation of ultraviolet luminosity, which is closely related to the number, size, composition, and distribution of dust particles. Due to the influence of metal abundance on the content and characteristics of dust, the relationship between quality and metallicity indirectly affects the UV luminosity function of dust attenuation. A comprehensive model for the formation and evolution of the faintest Milky Way dwarf satellites.

Specifically, galaxies or celestial bodies with higher metal abundance may experience more significant attenuation in their ultraviolet luminosity due to the presence of more dust particles. These dust particles effectively scatter and absorb ultraviolet light, resulting in a decrease in the observed ultraviolet luminosity. On the contrary, galaxies or celestial bodies with lower metal abundance may have relatively smaller UV luminosity attenuation due to their lower dust content.

It should be noted that this correlation is not a simple linear relationship but is influenced by multiple complex factors. For example, factors such as physical processes, environmental conditions, and observational techniques within galaxies may have an impact on the mass-metallicity relation, as well as the ultraviolet luminosity function of dust attenuation.

2.3. The Impact

The mass-metallicity relation, as well as the ultraviolet luminosity function of dust attenuation, play important roles in astronomical research and have profound impacts on understanding the chemical evolution, material distribution, and overall structure of galaxies.

Firstly, the mass-metallicity relation offers crucial insights to scientists, enabling them to grasp the chemical evolution of galaxies. By studying the correlation between a galaxy's mass and its metallicity, researchers can deduce the nuclear synthesis processes within the galaxy, the historical trajectory of star formation, and the exchange of matter between galaxies. This knowledge is pivotal in comprehending the evolution of galaxies and the intricate material circulation processes occurring both within and among them.

Secondly, the ultraviolet luminosity function of dust attenuation is of great significance for studying the distribution and properties of dust in interstellar media. The degree of attenuation of ultraviolet luminosity can reflect the quantity, size, and distribution of interstellar dust, thereby revealing dust's influence on galaxies' radiation characteristics. This plays an important role in our understanding of the spectral characteristics, energy balance, and interstellar material interactions of galaxies.

In addition, by combining the mass-metallicity relation with the ultraviolet luminosity function of dust attenuation, the researchers can more comprehensively study the overall structure and properties of galaxies. For example, by comparing the metal abundance and ultraviolet luminosity attenuation of galaxies with different masses, can explore the mass-dependent effects in galaxy evolution, as well as the mechanisms of material exchange and energy transfer within and between galaxies.

Overall, the mass-metallicity relation, as well as the ultra-violet luminosity function of dust attenuation, provide valuable tools and perspectives for astronomical research. They not only help us to deeply understand the evolution process of galaxies and the universe but also provide important guidance for future astronomical observations and experiments. By continuously delving into these relationships, researchers can more comprehensively reveal the mysteries of the universe and promote the sustained development of the field of astronomy.

3. Modelling UV Luminosities

3.1. Stellar Population Synthesis

This study traces all progenitor galaxies in the merger tree, where star populations of varying ages are formed. At each snapshot corresponding to a redshift z_i (where $z_i > z_0$), the total star formation rate (SFR) of these progenitors is calculated. The stars that are formed at z_i possess a specific age of

$$\tau = t - t' = t(z_0) - t(z_i) \quad (1)$$

In this study, $t(z)$ represents the age of the Universe at a given redshift z . By employing this approach, the paper establishes a timeline of star formation, denoted as $\Psi(t)$, for the observed galaxy. At higher redshifts, the dynamic time is sufficiently brief for a starburst to trigger a swift alteration in UV flux within a single snapshot. The burst can occur at any moment within the snapshot, not solely at its commencement or conclusion. To capture this, interpolations are made over 10 timesteps between each snapshot, assuming a consistent star formation rate (SFR).

3.2. Lyman- α Absorption

As a high-redshift galaxy traverses intergalactic gas clouds, its UV spectrum will display a series of Ly α absorption lines at wavelengths shorter than $\lambda = 1216(1 + z)\text{\AA}$ due to the presence of neutral hydrogen. Towards higher redshifts, the neutral hydrogen fraction in the intergalactic medium (IGM) undergoes a rapid increase, causing a significant enhancement in the Ly α absorption optical depth. Furthermore, the spectral energy distribution (SED) of star-forming galaxies at these redshifts

exhibits a distinct dropout at $1216(1+z)\text{\AA}$, earning them the classification of Lyman-break galaxies. [4].

In this study, we mimic the selection mechanism of Lyman-break galaxies (LBGs) by utilizing a model designed to calculate the Lyman-dropout signature for our semi-analytic galaxies. Specifically, for redshifts below 5.5, this section employs an efficient optical depth to capture the Ly- α absorption phenomenon [5].

$$\tau_{eff} = (0.85 \pm 0.06) \left(\frac{1+z}{5} \right)^{4.3 \pm 0.3} \quad (2)$$

Fan et al. (2006b) discovered that the evolution of τ_{eff} undergoes a notable acceleration at redshifts greater than 0.5, particularly with regards to the effective optical depth.

$$\tau_{eff} \propto (1+z)^{10.9} \quad (3)$$

To simplify our analysis, we adopt the relation derived for redshifts ranging from 5.5 to 6.3 for all redshifts above or equal to 5.5. Although this extrapolation may not be fully physically accurate, the observed Ly- α flux vanishes at redshifts above 6, effectively rendering this assumption unbiased for the purpose of Lyman-break galaxy selection.

3.3. Dust Attenuation

For a galaxy, the UV continuum in its rest frame is presumed to possess the following form:

$$f_{\lambda} \propto \lambda^{\beta} \quad (4)$$

The flux density per wavelength interval is denoted as f_{λ} , and β represents the power-law index. At high redshifts, the value of β can be estimated through photometric SED fitting [6, 7]. Nevertheless, it is crucial to recognize that UV flux can be significantly reduced by dust grains present within galaxies. The attenuation caused by this dust is parameterized as follows:

$$F_0(\lambda) = F_i 10^{-0.4A_{\lambda}} \quad (4)$$

The intrinsic continuum flux density is represented by F_i , whereas F_0 stands for the observed flux density. A_{λ} refers to the change in magnitude at the rest-frame wavelength λ . It is noteworthy that the extent of dust attenuation varies with wavelength, exhibiting greater optical depths at shorter wavelengths. Consequently, dust attenuation results in the reddening of the spectrum, manifesting as a steeper observed spectral slope.

Dust attenuation can be approximated through various indicators, including emission line ratios (like the Balmer series), the slope of the rest-frame continuum, the ratio of infrared to UV radiation, the stellar mass of galaxies, and the star formation rate (SFR) of galaxies [8-11]. In this study, we employ a dust attenuation model that is based on luminosity-dependent parameters. The specifics of this model are outlined in the subsequent sections [6, 7, 12].

Stellar population synthesis suggests that galaxies exhibit comparable intrinsic UV continuum slopes when assuming a consistent star-formation history [13]. Furthermore, galaxies exhibiting dust-attenuated UV continuum slopes, β , will reflect the degree of dust attenuation present. A correlation between UV dust attenuation and the observed UV continuum β has been established by Meurer [8]:

$$A_{1600} = 4.43 + 1.99\beta \quad (5)$$

To calibrate the relation, we compare the dust attenuation at 1600 $\text{\AA}$, denoted as A_{1600} , with starburst galaxies in the local Universe. This comparison assumes that the spectral properties of high-redshift galaxies are equivalent to those of local galaxies [8].

4. Conclusion

This article mainly introduces a model of UV-LF, which mainly considers Stellar population synthesis and Lyman- α absorption, Dust attention, and Lyman Break selection are the four aspects.

This article also focuses on the relationship between UV-LF and the mass-metal relationship, understanding that the mass-metal relationship can affect the quantity, size, composition, and distribution of interstellar dust, these dust particles effectively scatter and absorb ultraviolet radiation, leading to a decrease in observed ultraviolet luminosity and indirectly affecting UV-LF. Generally speaking, due to the presence of more dust particles, the ultraviolet luminosity of galaxies or celestial bodies with higher metal abundance may experience more significant attenuation. On the contrary, galaxies or celestial bodies with lower metallicity may have relatively small ultraviolet luminosity attenuation due to their lower dust content. This article may provide a model for the research direction of UV-LF and an opinion on the relationship between UV-LF and the mass metal relationship. The limitation of this article is that there is only a qualitative conclusion on the relationship between UV-LF and the mass metal relationship. In the future, factors such as physical processes, environmental conditions, and observation techniques within the galaxy may be considered, and a high redshift galaxy may be selected as the observation object. The constructed model will be used for analysis first, and then compared with the observation data to draw detailed images and conduct in-depth analysis.

References

- [1] Mahler G, Jauzac M, Richard J, et al. Precision modeling of JWST's first cluster lens SMACS J0723. 3–7327. *The Astrophysical Journal*, 2023, 945(1): 49.
- [2] Ochsenbein F, Bauer P, Marcout J. The VizieR database of astronomical catalogues. *Astronomy and Astrophysics Supplement Series*, 2000, 143(1): 23-32.
- [3] Maier C, Lilly S J, Ziegler B L. Oxygen abundances of zCOSMOS galaxies at $z \sim 1.4$ based on five lines and implications for the fundamental metallicity relation. *Proceedings of the International Astronomical Union*, 2014, 10(S309): 281-282.
- [4] Steidel C C, Giavalisco M, Pettini M, et al. Spectroscopic confirmation of a population of normal star-forming galaxies at redshifts $z > 3$. *The Astrophysical Journal*, 1996, 462(1): L17.
- [5] Fan X, Strauss M A, Becker R H, et al. Constraining the evolution of the ionizing background and the epoch of reionization with $z \sim 6$ quasars. II. A sample of 19 quasars. *The Astronomical Journal*, 2006, 132(1): 117.
- [6] Bouwens R J, Illingworth G D, Oesch P A, et al. UV-Continuum slopes at $z \sim 4-7$ from the HUDF09+ERS+ canels observations: discovery of a well-defined UV color-magnitude relationship for $z \geq 4$ star-forming galaxies. *The Astrophysical Journal*, 2012, 754(2): 83.
- [7] Bouwens R J, Illingworth G D, Oesch P A, et al. UV-continuum slopes of > 4000 $z \sim 4-8$ galaxies from the HUDF/XDF, HUDF09, ERS, CANDELS-South, and CANDELS-North fields. *The Astrophysical Journal*, 2014, 793(2): 115.
- [8] Meurer G R, Heckman T M, Calzetti D. Dust absorption and the ultraviolet luminosity density at $z \approx 3$ as calibrated by local starburst galaxies. *The Astrophysical Journal*, 1999, 521(1): 64.
- [9] Pannella M, Carilli C L, Daddi E, et al. Star formation and dust obscuration at $z \approx 2$: galaxies at the dawn of downsizing. *The Astrophysical Journal*, 2009, 698(2): L116.
- [10] Heinis S, Buat V, Béthermin M, et al. HerMES: dust attenuation and star formation activity in ultraviolet-selected samples from $z \sim 4$ to ~ 1.5 *Monthly Notices of the Royal Astronomical Society*, 2014, 437(2): 1268-1283.
- [11] Reddy N A, Steidel C C, Fadda D, et al. Star formation and extinction in redshift $z \sim 2$ galaxies: Inferences from Spitzer MIPS observations. *The Astrophysical Journal*, 2006, 644(2): 792.
- [12] Smit R, Bouwens R J, Franx M, et al. The star formation rate function for redshift $z \sim 4-7$ galaxies: evidence for a uniform buildup of star-forming galaxies during the first 3 Gyr of cosmic time. *The Astrophysical Journal*, 2012, 756(1): 14.
- [13] Leitherer C, Heckman T M. Synthetic properties of starburst galaxies. *Astrophysical Journal Supplement Series (ISSN 0067-0049)*, 1995, 96(1): 9-38, 1995.