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EXPLORING THE PHYSICAL CONDITIONS OF DISTANT STAR-FORMING GALAXIES THROUGH THE BALMER JUMP FEATURE: A THEORETICAL AND OBSERVATIONAL PERSPECTIVE

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Abstract

In this report, I will present the progress on my project under the UCTS program. In this project, we study the spectroscopic impact on the galaxy by varing the physical conditions in the nebulae. The nebulae continuum is thought to have impact on the galaxies spectra with more evidence from the observation by JWST. The nebular continuum shape allow us to study important properties of interstellar median in galaxies of the early Universe, such as gas density and temperature. Therefore, first, we conducted systematic experiment through simulation in order to establish a theoretical background for the nebulae continuum, especially on a discontinuity phenomenon: Balmer Jump. Second, we present a catalogue for galaxy candidates with Balmer jump feature, which may serve as objects for future application with our understanding from the simulation works.

Subject headings: Balmer Jump, CLOUDY, JWST, ISM

1. INTRODUCTION

In this section, I would organize important concepts about this project, including current understanding and open questions remained in high-redshifted galaxies researches, features of galaxies spectra, physical interaction between stellar radiation and interstellar median (ISM).

1.1. *Why do we study nebular continuum?*

With the launch of JWST (Gardner *et al.* (2006)), we are able to study the rest optical and UV spectrum of high-redshifted galaxies with its infrared bands. Furthermore, this spectrum allow us to gain more information on the stellar population and ISM conditions of these high-redshifted galaxies in the early universe. These new observation also brought questions to the table. For example, UV luminosity density is higher than most model predictions in these high-redshifted galaxies. Many explanation focus on higher star-formation rate. Another perspective, which considers the nebular continuum's impact, is observed to become important (e.g. Izotov *et al.* (2011)). Therefore, it may indicates that in order to understand the properties of high-redshifted galaxies, we might have to get a sense of how nebulae continuum impacts the stellar spectrum first. Therefore in this project we would like to establish a theoretical background on one of the main features in the nebulae continuum: Balmer jump, which would be further discussed in subsection 1.2.1.

1.2. *Galaxy spectrum*

The spectrum of galaxy is contributed from the stars, gaseous median and dust inside the galaxy. Therefore the spectra of galaxies are informative. We can study the spectrum to investigate the galaxy and median. The spectrum can usually be decomposed to several components: continuum radiation, emission lines and absorption lines, which will be elaborated in section 1.2.1, 1.2.2 and 1.2.3, respectively. A schematic diagram with two major components are shown along with the observed spectrum in figure 1.

1.2.1. *Continuum radiation*

The continuum component in the galaxy spectrum is contributed by the Black body emissions from the stellar population, which spans a range in surface temperature. Such superposition of Black body emissions produce a fairly flat spectrum shape. A primary feature worth noting is the break in 4000 $\AA$. The break is caused by the metal absorption line and the deficiency of hot, blue stars. Thus, it would be more clear in old galaxies. This project studys mostly young galaxies, which shows another kind of discontinuity.

The other kind of continuum discontinuity that could appear in spectra is the main research objective for this project: Balmer jump, caused by the free-bound emission or absorption of electron in atom, which appear in the spectrum as jump or break, respectively. Since the initial energy level of the electron is not fixed, the emitted photons from recombination would have a range of energy and it has to be larger than the ionization energy. In terms of spectroscopy, there could be a continuous emission in wavelength shorter than the Balmer limit. Although there are discontinuity in other Hydrogen se-

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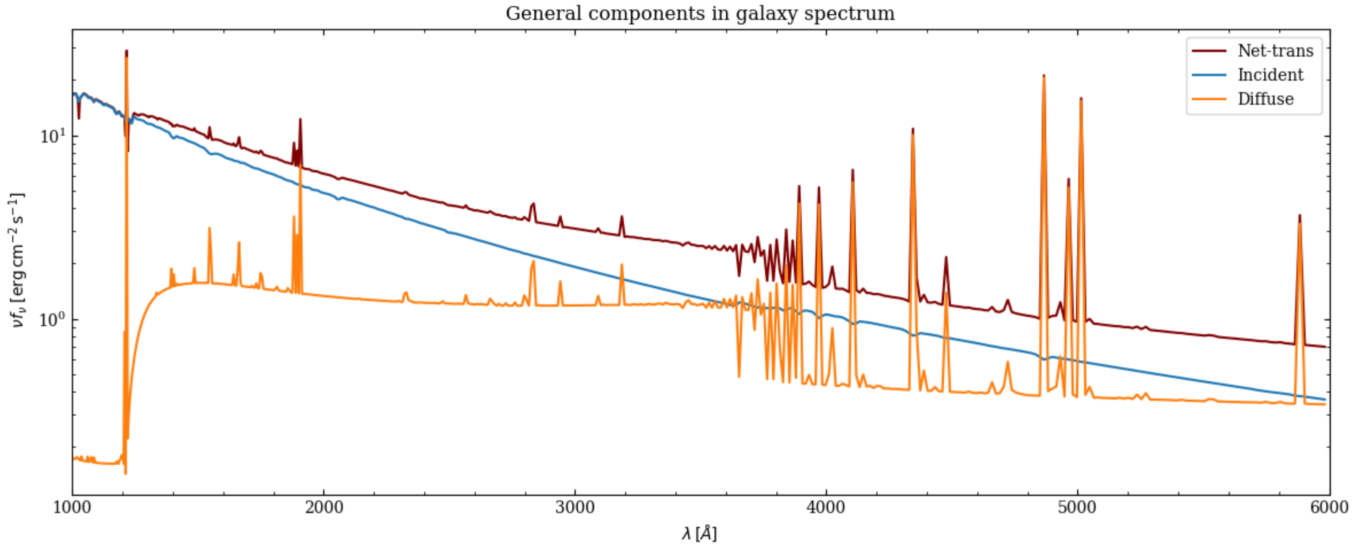

FIG. 1.—

ries like Lyman, Paschen, etc., this project focus on the Balmer jump only.

1.2.2. *Absorption lines*

The spectra of galaxies often come with absorption features superimposed on the continuum component. These absorption lines are caused by the absorption of atom or molecules in the atmosphere of the stars and the cold ISM. The metal lines often points to the existence of old stellar population, while the hydrogen and helium lines trace the cold interstellar median.

1.2.3. *Emission lines*

Emission features superimposed on the continuum radiation could also be observed in galaxy spectra. These excess photons are produced by the recombination of photon-electrons in the gas clouds. The ionizing source are mostly young, massive stars, such as O star, that can efficiently produce photons with energy higher than the ionization energy of species. Therefore, the existence of these features point to hot gas and OB stars in the stellar population. Key features include line series of Hydrogen, Helium and some recombination lines from Oxygen, sulfer, etc.

1.3. *Interaction between the radiation and gas cloud*

The observed spectra can be very different from the incident ones from the galaxy after passing through the ISM. The interaction between the incident radiation and the ISM are complicated but can be studied statistically. The main physical processes involved are the photoionization and recombination, which, qualitatively speaking, contribute to the heating and cooling of the cloud, respectively. When equilibrium of these two effects is reached, we can study the physical conditions of the ISM, especially througth the Balmer jump amplitude in this project. The equilibrium equation can be written as (Osterbrock and Ferland (2006)):

$$n\left(\mathrm{H}^0\right)\int_{v_0}^{\infty}\frac{4\pi J_v}{hv}a_v\left(\mathrm{H}^0\right)dv = n\left(\mathrm{H}^0\right)\int_{\nu_0}^{\infty}\phi_v a_v\left(\mathrm{H}^0\right)dv = n_e n_p \alpha\left(\mathrm{H}^0, T\right) \quad (1)$$

where a_v is the ionization cross section. Thus ϕ_v is the number of incident photons per unit area, per unit time, per unit frequency interval. The integrand basically shows the number of photoionization events. The right hand side shows the total recombination events, where α is the recombination coefficient.

1.3.1. *Photoionization*

The photoionization happens when a photon with energy higher than the ionization energy of certain atom interact with the electron of the atom, and then the electron escapes from the atom with the energy gained from the photon. This process transfer energy into the ISM, so it's treated as a heating effect to the ISM.

1.3.2. *Recombination*

When a free electron is captured by an ion, the ion would emit a photon. This is a recombination process. Since it's free-bound transition, unlike the bound-bound transition, a photon with an energy greater than the ionization potential of the ion or atom is emitted, producing a band of continuous emission. In general, the electron can be recombined to any level, followed by further downward bound-bound transition to the ground state. Thus, we could observe free-bound and bound-bound emission in the spectra of galaxy. This process radiate energy out from the ISM, so it's treated as a cooling effect to the ISM.

2. METHOD

This project involves two approaches to study Balmer jump in the nebulae continuum: The observation data of galaxies spectra from JWST and simulation results from photoionization model "CLOUDY". They will be elaborated in the following sections.

2.1. *JWST data*

The spectra of all the galaxies that JWST has observed are organized in the Dawn JWST archive (DJA). For more detail of data process pipeline used in DJA, see Valentino *et al.* (2023) and Heintz *et al.* (2024). Note that the archive would update whenever new public data are present from JWST. There are over 6000 galaxies with their spectroscopic data in DJA. In this section, I'll elaborate the equipment configuration on JWST and the data set we inspected for this project in the following subsections.

2.1.1. *Instrument*

The spectra studied in this project were observed by the NIRSpec (Near Infrared Spectrograph Instrument) equipped on JWST. NIRSpec has 7 filters covering the 0.6–5.3 µm wavelength region, and 7 dispersive elements that include 6 gratings and a prism. For the observable wavelength and transmission curve, see figure 2. Our goal in this project is to study the Balmer jump feature in nabulae continuum. For this feature to appear in the NIRSpec's observable wavelength region, there's a natural lower limit to the galaxy's redshift value. Besides, one of the most important quantities for Balmer jump feature is the amplitude, or the difference between the continuum at wavelength shorter and longer to the Balemr limit (3645 $\mathring{A}$), so we need to keep enough wavelength space on both sides of the Balmer limit to make measurement with statistical significance. As a result, the lower limit of redshift is further increased. Nonetheless, JWST is still able to observe lots of high redshifted galaxies with its IR band imaging or spectroscopic equipment.

2.1.2. *Data set*

In "Dawn JWST Archive" (DJA), a grading from 0 to 3 is given for reference by the team, which represents the quality of the spectrum data: 0 for "DQ problem", 1 for "No features", 2 for "Ambiguous" and 3 for "Robust". In this study, we focused on the grade 3 sources for better SNR and more clear features.

As mentioned in the previous section, the continuum difference at wavelength shorter and longer to the Balmer limit is important for this study. The PRISM grating is favored because the observable wavelength range is the wildest among all the 7 gratings on NIRSpec. As a result, the Balmer discontinuity is most likely to be observed in this grating configuration. However, the spectral resolution is considerably lower than the other gratings, so the Balmer discontinuity feature would be smoothed due to the low spectral resolution. This problem will be discussed in section 2.2.5. Thus, making a systematic way to determine the altitude of the Balmer jump is necessary to analyze these observation spectra.

2.2. *CLOUDY*

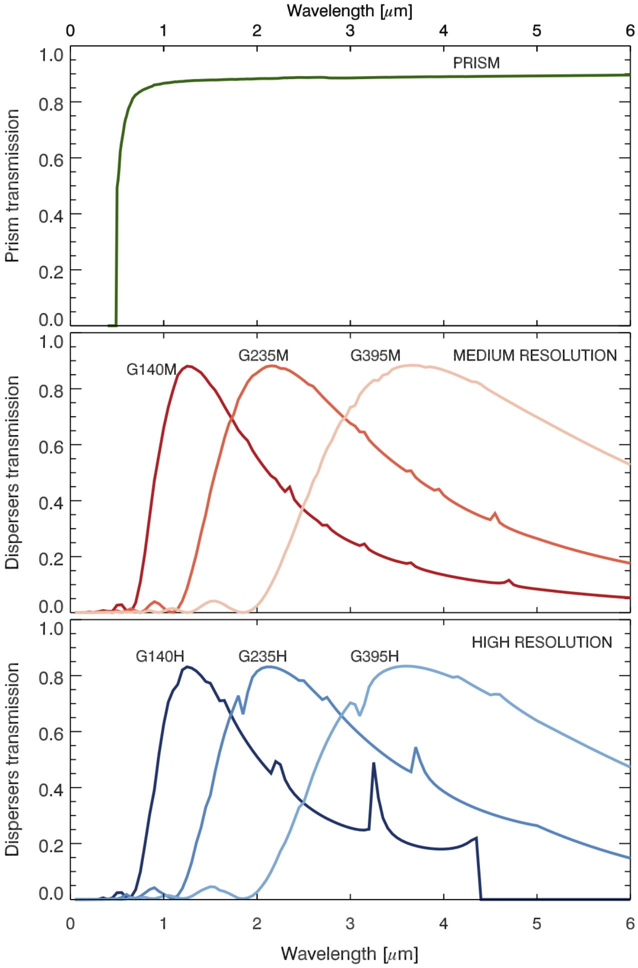

FIG. 2.— Transmission of NIRSpec gratings. Credit: JWST.

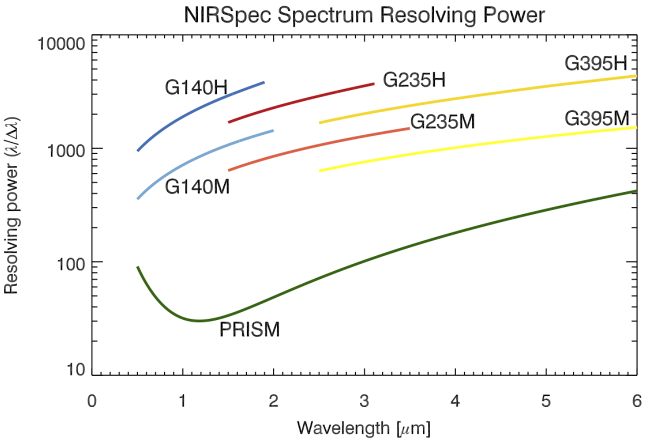

FIG. 3.— Resolving power of JWST's gratings. Credit: JWST.

The photoionization model "CLOUDY" (Chatzikos *et al.* (2023)) is an spectral synthesis code designed to model a wide range of interstellar "clouds", from H II regions and planetary nebulae, to Active Galactic Nuclei, and the hot intracluster medium that permeates galaxy clusters.

We applied this simulation code to build the environment consisting of the the galaxy and the HII region in order to study the spectrum that might show Balmer jump feature. The radiation field of the galaxy and geometry of the gas cloud are described in section 2.2.1 and

2.2.2, respectively. In addition, we need to set reasonable parameters for these objects to simulate the real galactic environment, which are described in section 2.2.3. Finally, CLOUDY offers several mock observation of spectrum with wide range of wavelength, which is described in detail in section 2.2.6

2.2.1. *Geometry*

There are two main geometry describing the system: open and closed. The main difference is the reflection flux from the other side of the cloud in the closed geometry. For galaxy, this situation is relatively rare, thus we just assum open geometry to describe the system.

2.2.2. *SPS model*

The ionizing source in our simulation is galaxies, and in CLOUDY, we are able to apply model grids of galaxies spectra provided by previous researches. The model applied in this project are BPASS (Binary Population and Spectral Synthesis) (Stanway and Eldridge (2018)) and Starburst99 (Leitherer *et al.* (1999)). In general, theses model come with age and metallicity grids but with different range.

2.2.3. *ISM properties*

ISM could be treated as a thermal system. Some important parameters would be the volumn density and metallicity. The former can influences the observed spectrum by varying the radiative transfer process, while the latter affects the cooling rate hence the temperature. In CLOUDY, these parameters could be set as constant. Or we could let the radiation take over and let the model evolve on itself. In our project, we wish to understand the parameters that affect the Balmer jump amplitude, thus we ran the model in multi-dimensional parameter space to check the spectroscopic impact of each parameter.

2.2.4. *Stopping criteria for simulation*

The stopping criteria for a simulation can be set in purpose of simulating different physical conditions. In this project, we have considered three kinds of stopping criteria: electron fraction, neutral hydrogen column density (later for NH0) and Thickness.

In the electron fraction scenario, the simulation stops when electron fraction reaches a given value. In the thickness scenario, the simulation stops when a given thickness of the gas cloud is reached by the photons. In the NH0 scenario, the simulation stops when the column density of neutral hydrogen atom reaches certain given value.

The three scenarios has their own applicable range, beyond which the condition calculated by the model would not be physical. For example: in thickness scenario, simulation wouldn't stop until the certain thickness even if the gas cloud has already become neutral. That's not the condition we intend to simulate since we focus on the recombination lines in the spectrum. Other constraints on the choice of stopping criteria will be discussed in section **??**.

2.2.5. *Resolution*

Our long term goal for this project is to apply the understanding to the real observational data. Thus, we need to make our results applicable to the real observation. One major difference is the spectral resolution. JWST has varing spectral resolution grating by grating (see section 2.1.1). PRISM, which was used mostly in our project, has a resolving power of about 100 $\lambda/\Delta\lambda$ (unitless). In CLOUDY, default value for the spectral resolution is 300 (unitless) in the wavelength range of JWST's PRISM grating. Thus, we scale down the spectral resolution to match that of PRISM. In this way, we could apply or compare our resutls to the real observation by JWST NIRSpec with PRISM grating.

2.2.6. *Model output*

In this project, we care about the amplitude of the Balmer jump. A systematic way to determine the amplitude is necessary. CLOUDY model offers tremendous amounts of information in its output, including emission line flux, continuum spectrum and physical condition of the cloud.

2.2.7. *Balmer jump strength index*

We developed a method to calculate and define the amplitude of the Balmer Jump. Our first idea was to measure the continuum at both sides of the Balmer limit wavelength, and then calculate the difference. However, this is not an representative value in real observation. In real observation, we observe under various resolving power. For example: PRISM, which is used mostly in this project, has a resolving power of about 100. This is poor compared to other grating on JWST. At the vicinity of the Balmer limit wavelength, lots of emission lines may appear on the longer wavelength side, thus the continuum can be elevated due to the poor resolution, which distribute the energy in emission lines into the neighborhood wavelength. The overall effect is a elevation in the continuum level. We demonstrate the effect in figure **??**, which shows that the the elevation of continuum is not negligible.

As a result, we need to find a region to represent the flux on the two sides of the Balmer limit. It should be sufficiently close to represent the jump behavior while not affected severely by the elevation effect. We inspected the spectrum and tried to find a relatively flat region. The chosen region are also shown in figure 4. For these two regions, we take the average of the net-transmission, and define the Balmer index to the difference between them.

$$\text{BJ index} = \frac{f_{below}}{f_{above}} \tag{2}$$

, where the f is the average value on the selected wavelength region; subscripts indicate the relative location of the region to the Balmer limit, which is the red and blue region shown in figure 4.

3. RESULTS

In this section, I will present the jumper candidates list and the analysis work of the Balmer jump from the simulation.

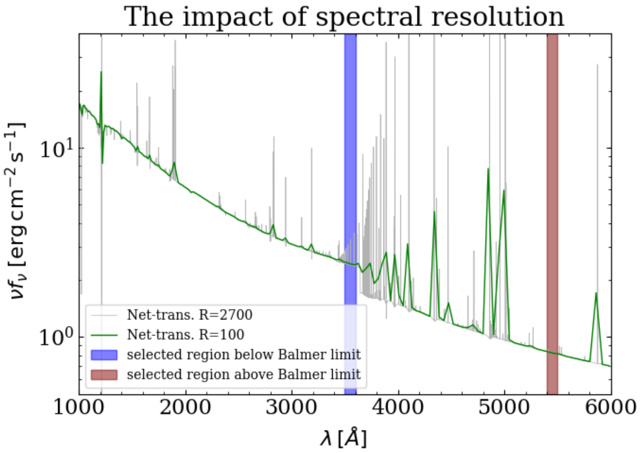

FIG. 4.— Effect of resolving power of gratings to the continuum level in spectrum. The gray line is the SED observed with a resolving power of 2700, while the green one is the same SED but observed with a resolving power of 100. The two color strips show the chosen wavelength region for the calculation of the Balmer jump index.

3.1. *Simulation results*

We investigate the corresponding impact on the amplitude of the Balmer jump by manipulating some parameters in the HII region. The following sections would explain each parameter studied in this project.

3.1.1. *Temperature*

We think one of the most important factor for Balmer jump amplitude is the electron temperature since the electron temperature affects the recombination rate, hence the emission line strength. Therefore, the amplitude of the discontinuity might be sensitive to the electron temperature.

In simulation, as we varied the gas temperature, we found that the amplitude of the Balmer jump changed correspondingly. We think the principle is its relation with the recombination rate. Higher temperature leads to lower recombination rate, thus the jump amplitude is decreased. We did the experiment to all the scenarios of stopping criteria, including electron fraction, neutral hydrogen column density and thickness, and found consistent results among them.

For example: in electron fraction scenario (for explanation, see 2.2.4), the results are in figure 5.

This relation could be applied in real observation, which might serve as a new way to analyze the galaxy and gas cloud properties. But we haven't quantified this relation, it will be the future work.

3.1.2. *Hydrogen density*

After determining the temperature dependent relation on the Balmer jump. We wonder if there are any other parameters other that might affect the jump amplitude. Hydrogen density is one of parameters to describe a gas cloud, too. Thus, we investigate the relation between density and the Balmer jump. We found no strong dependence on the density of the cloud. In this case, since emission strength is dependent on the density as well, the diffuse emission should be normalised before making comparison between different model. We use Balmer lines as standard to do the normalization. The result are present in figure 6.

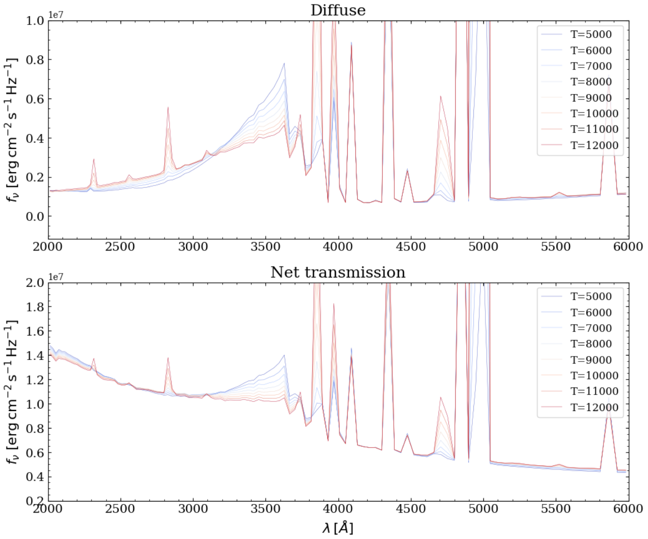

FIG. 5.— The impact of temperature on the amplitude of Balmer jump. Top panel shows the diffuse flux; middle panel shows the incident an attenuated incident flux; the bottom panel shows the observed flux. Note that the lines are shift to match at 4200$\AA$

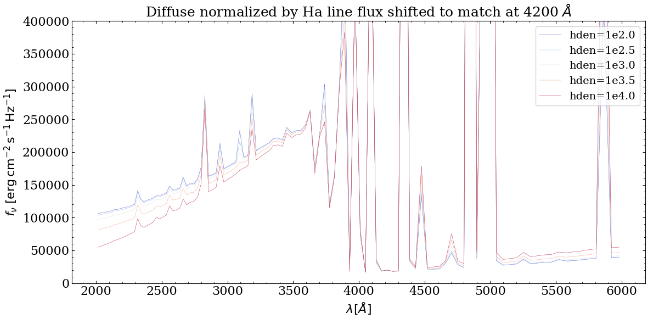

FIG. 6.— The The impact of density on the amplitude of Balmer jump. It shows the diffuse flux. Note that the lines are shift to match at 4200$\AA$.

To compare the impact of the parameters, we applied equation 2 to each model, and present the resutls in figure 7.

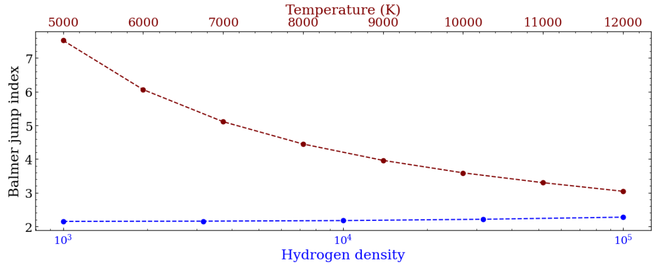

FIG. 7.— This is the comparison between the impact extent of the two parameters.

3.2. *Jumper candidates*

I organized the spectroscopic and imaging data of 20 out of 46 total candidates in Figure 8. The rest 26 are listed in table in the appendix A. Note that some spectroscopic data don't have imaging counterpart.

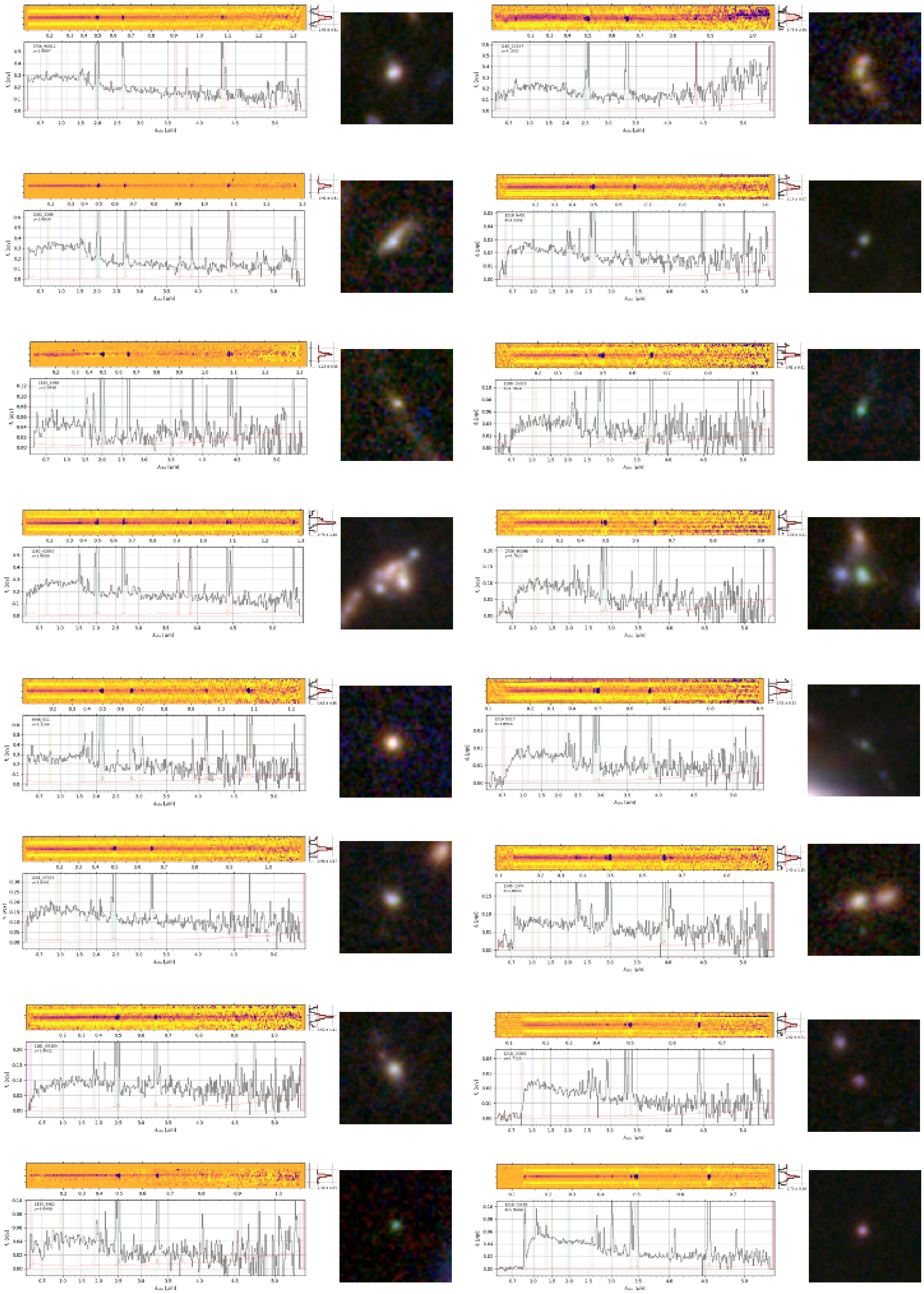

Fig. 8.— 20 out of 46 visually identified galaxies with Balmer jump feature in DJA.

4. DISCUSSION

For the simulation part, we find that the jump amplitude is larger with increasing gas temperature, while hydrogen density has little impact on the Balmer jump amplitude. The impact of nebulae continuum are considered more and more important on the spectrum of galaxies in the early universe (Katz *et al.* (2024)). Discussion and studies on the overall elevation of the UV parts of spectrum is important in solving the excess UV luminosity density problem. This project, however, focus on the information that might be embedded in the finer feature. However, it's not straightforward since the parameters at play is a lot. In simulation, we either fix the age of the galaxy (ionizing source) or the density to determine the corresponding relation. But in reality the ionizing source also plays a role in the determination of the Balmer jump. Thus, in order to apply our results, we need the information about the ionizing source, which might be obtained by other method. In this project, we want to show the possibility of obtaining information about the properties of the gas from the feature in Balmer jump.

For the simulation part, the JWST observation presents unprecedented objects with Balmer features, which is basically not detected in optical and UV survey. Combined with the spectroscopically determined redshift value, we know they are galaxies in the early Universe, thus we might reach a conclusion that galaxies in the early universe has colder gas. However, this is counter-intuitive in the sense of cosmological theory. In addition, it may just be the result of selection bias and as mentioned in the previous paragraph, the ionizing source varies case by case. In summary, the application of our results could be helpful in determining the properties of gas and galaxy but still need other information to be certain.

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APPENDIX

APPENDIX 1: JUMPER CANDIDATES

APPENDIX 2: MORE ANAYSIS OF BALMER JUMP AMPLITUDE