Challenges in Panchromatic Modelling with Next Generation Facilities
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Extreme variations in star formation activity in the first galaxies

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Abstract. Recently, spectroscopic detections of O[III] 88 μm and Ly-α emission lines from the $z \approx 9.1$ galaxy MACS1149-JD1 have been presented, and with these, some interesting properties of this galaxy were uncovered. One such property is that MACS1149-JD1 exhibits a significant Balmer break at around rest-frame 4000 Å, which may indicate that the galaxy has experienced large variations in star formation rate prior to $z \sim 9$, with a rather long period of low star formation activity. While some simulations predict large variations in star formation activity in high-redshift galaxies, it is unclear whether the simulations can reproduce the kind of variations seen in MACS1149-JD1. Here, we utilize synthetic spectra of simulated galaxies from two simulation suites in order to study to what extent these can accurately reproduce the spectral features (specifically the Balmer break) observed in MACS1149-JD1. We show that while the simulations used in this study produce galaxies with varying star formation histories, galaxies such as MACS1149-JD1 would be very rare in the simulations. In principle, future observations with the *James Webb Space Telescope* may tell us if MACS1149-JD1 represents something rare, or if such galaxies are more common than predicted by current simulations.

Keywords. galaxies: high-redshift, early universe

1. Introduction

While understanding galaxy evolution at high redshifts and the formation of the first stars is important to create a complete picture of the evolution of the universe, these processes are still largely shrouded in mystery. Much of our understanding regarding how stars are formed in the earliest galaxies comes from theory and numerical simulations. At the same time, the lack of observations at the highest redshifts make it difficult to verify predictions by simulations. Recent (and future) observations of galaxies at high redshifts could, however, provide us with a simple test to determine how well simulations are able to reproduce properties of the first galaxies. Until recently, the only spectroscopically confirmed galaxy at $z \gtrsim 9$ was GN-z11 at a redshift of $z \sim 11$ (Oesch *et al.* 2016). Using observations of the [OIII] 88μm and Ly-α emission lines from the galaxy MACS1149-JD1 made it possible to constrain the redshift of this object to $z \approx 9.1$, adding a second object to the list of spectroscopically confirmed galaxies at $z \gtrsim 9$ (Hashimoto *et al.* 2018).

One interesting feature of JD1 is that *Spitzer*/IRAC observations of the object indicate that it exhibits a strong Balmer break. A possible explanation for this feature is that the galaxy has experienced large variations in the star formation rate (SFR), with a significant period of low star formation activity prior to $z \sim 9$. While certain simulations predict large variations in the SFRs of high-redshift galaxies (e.g. Kimm *et al.* 2015; Trebitsch *et al.* 2017; Hopkins *et al.* 2018; Ma *et al.* 2018) it is unclear whether galaxies such as JD1 are commonly seen in simulations, or if JD1 represents an outlier. Here, we use simulated galaxies from two independent cosmological simulations and generate synthetic spectra for these in order to study the distributions in Balmer break strengths exhibited by galaxies in the simulations. Through this, we are able to discuss how likely we are to find objects like JD1 among the simulated galaxies. We also show simulated distributions of Balmer break strengths that could be compared to future observations with the *James Webb Space Telescope* (JWST) to test if simulations are able to reproduce what is seen in observations, or if simulations may be missing some key ingredient.

2. Model

In this study, we use simulated galaxies from the FIRE-2 simulations (Ma *et al.* 2018; Hopkins *et al.* 2018) and the simulations by Shimizu *et al.* (2016, hereafter S16). Star formation histories and metallicity distributions of stars in simulated galaxies with $M_\star > 10^8 M_\odot$ are extracted in order to obtain galaxies with masses comparable to JD1, which has a stellar mass of $M_\star = 1.08^{+0.53}_{-0.18} \times 10^9 M_\odot$ assuming the fiducial magnification of $\mu = 10$ (Hashimoto *et al.* 2018). We select galaxies in the redshift interval $z \sim 9.5 - 8.5$ for the FIRE-2 galaxies and $z = 9$ for the S16 galaxies, which, in total, provides us with 150 galaxies from the FIRE-2 simulations and 182 galaxies from the S16 simulations. In order to generate synthetic spectra for these, we use synthetic single stellar population spectra from Yggdrasil (Zackrisson *et al.* 2011) consisting of Starburst99 Padova-AGB models (Leitherer *et al.* 1999; Vázquez & Leitherer 2005) for metallicities $Z = 0.0004 - 0.050$ and Raiter *et al.* (2010) models for $Z = 10^{-7} - 10^{-5}$. In order to account for nebular emission, the CLOUDY photo-ionization code (Ferland *et al.* 2013) is used. In order to model the distributions of Balmer breaks, we consider effects of dust reddening on the spectra of simulated galaxies. The S16 simulations provide us with predictions of the galaxy-wide dust extinction at 1500 Å. To account for dust-reddening effects in these galaxies, we utilize the Pei (1992) extinction curve for the Small Magellanic Cloud (SMC). For the FIRE-2 simulations we apply the SMC extinction curve while assuming a fixed extinction in the V-band of $A_V = 0.5$ for all galaxies. This crude recipe provides us with a test of the effects of dust extinction on the overall distribution of Balmer breaks.

However, we also utilize a set of the FIRE-2 galaxies that have undergone post-processing with the SKIRT dust radiative transfer code (Camps & Baes 2015) in order to account for more realistic dust reddening. The radiative transfer code is run while assuming SMC-type grain distributions (Weingartner & Draine 2001), the dust-to-metal ratio is assumed to be 0.4 and all gas hotter than 10^6 K is assumed to be dust-free. Further details about this version of FIRE-2 simulations and effects of the radiative transfer calculations are presented in Ma *et al.* (2019). For this process, the single stellar populations consist only of Starburst99 Padova-AGB models, and only nebular emission from hydrogen is considered. The difference in the distributions of Balmer break is, however, small, and does not significantly change our results. From the synthetic spectra,

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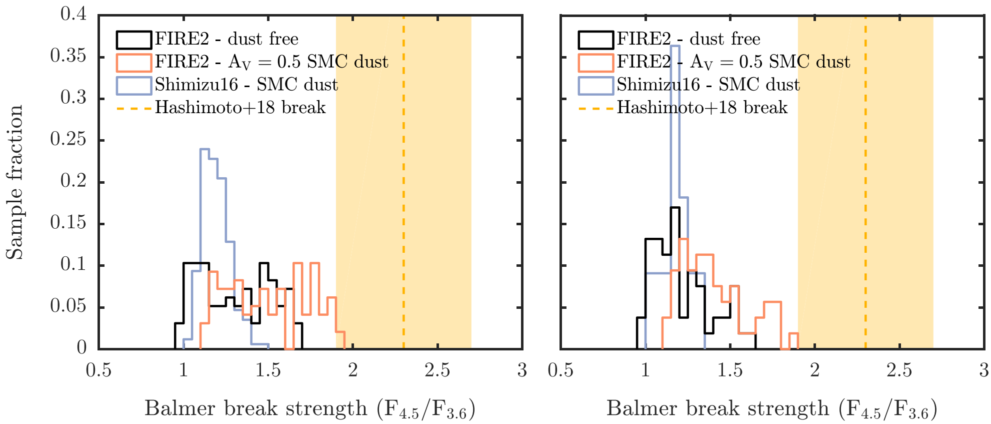

Figure 1. Balmer break strengths as measured by the *Spitzer*/IRAC 4.5/3.6 μm flux ratio for simulated galaxies with $10^8 \leqslant M_\star \leqslant 5 \times 10^8$ (left) and $M_\star \geqslant 5 \times 10^8$ (right) compared to the observed Balmer break in JD1. The yellow area shows the photometric error of the Balmer break observed in JD1.

we also generate fluxes in *Spitzer*/IRAC channel 1 and 2 (3.6 and 4.5 μm), assuming a redshift of $z = 9.1$ in order to compare results to JD1.

3. Results

Figure 1 shows the distributions of Balmer breaks in the simulated galaxies as observed by *Spitzer*/IRAC at $z = 9.1$ for stellar masses $10^8 M_\odot \leqslant M_\star \leqslant 5 \times 10^8 M_\odot$ (left panel) and $M_\star \geqslant 5 \times 10^8 M_\odot$ (right panel). Galaxies from the FIRE-2 simulations exhibit larger Balmer breaks than those seen in the S16 simulation, likely owing to the more stochastic star formation histories seen in the former. While the effect of dust on the synthetic spectra is to shift the distribution toward higher Balmer breaks, $A_V = 0.5$ represents a quite extreme case and leads to average UV slopes that are significantly redder than those observed in the high-redshift universe (e.g. Bouwens *et al.* 2014). However, even in the FIRE-2 galaxies with this extreme dust scenario, JD1 would be a rare type of object.

Figure 2 shows the $F_\nu(4200\text{Å})/F_\nu(3500\text{Å})$ distribution of galaxies in the simulations, where $F_\nu(4200\text{Å})$ and $F_\nu(3500\text{Å})$ are flux densities at rest-frame 4200 and 3500 Å, respectively. Continuum fluxes at these wavelengths should be observable with *JWST*/NIRSpec even at the lowest resolution setting without emission/absorption lines blending into the relevant spectral bins. The right panel in figure 2 show the FIRE-2 galaxies that have been post-processed using SKIRT for five different viewing-angles without dust and the same five viewing-angles when dust is taken into account. The effect of dust on the distributions of Balmer breaks is in this case insignificant. While dust is suggested as a possible explanation for the large Balmer break observed in JD1 by Katz *et al.* (2018), none of the post-processed FIRE-2 galaxies exhibit a large difference on the Balmer break as an effect of dust reddening. This could, of course, be an effect of differences in the exact treatment of dust extinction.

4. Summary

We have presented distributions of Balmer breaks in simulated galaxies from two independent simulations. While there is a span in observed Balmer breaks exhibited by the simulated galaxies, objects such as MACS1149-JD1 represents a type of galaxy that seems to be extremely rare in the simulations. Other studies have suggested that effects of dust reddening could explain the Balmer break observed in JD1 without the need of

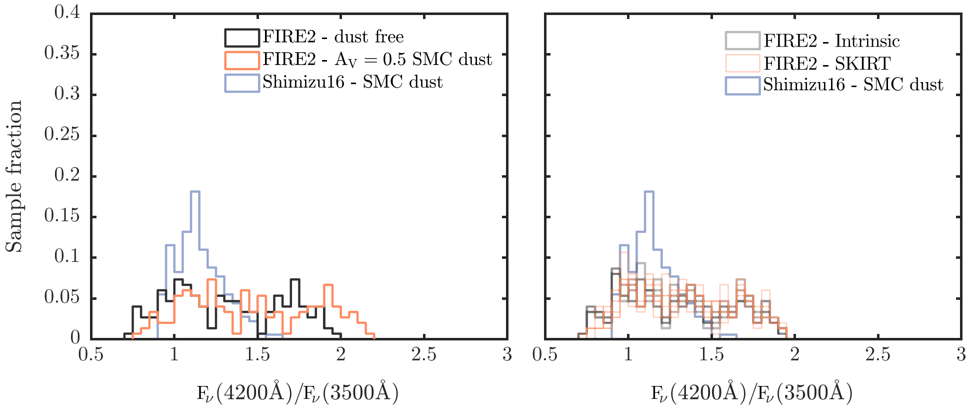

Figure 2. $F_\nu(4200Å)/F_\nu(3500Å)$ distributions in the simulated galaxies, where $F_\nu(4200Å)$ and $F_\nu(3500Å)$ are the flux densities at rest-frame 4200 and 3500 Å, respectively. Left panel: The S16 (blue) simulations, the dust-free FIRE-2 galaxies (black) and the FIRE-2 galaxies with the simplified dust treatment ($A_V = 0.5$, orange). Right panel: S16 galaxies (blue) and the FIRE-2 galaxies that have been post processed in SKIRT for five viewing-angles without dust (gray) and with dust taken into account (pale orange).

extreme variations in star formation activity. We do not see such an effect in the galaxies used here. We argue that future JWST observations of Balmer breaks in high-redshift galaxies may reveal if JD1 is just an extremely rare type of galaxy, or if models may be missing some key physics required to explain such large Balmer breaks.

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Discussion

Shohei Aoyama: Recently, high-z galaxies such as JD1 have been detected. In this sense, do simulation need to be improved in order to explain these objects?

Christian Binggeli: If future observations reveal that Balmer breaks like the one seen in JD1 are common and we find that here are very rare in simulations, this may indicate that simulations are missing some crucial ingredient.

Themiya Nanayakkara: What effect would you think stellar libraries have on reproducing the observed Balmer break? Going from Padova to FPSP, BPASS, etc.

Christian Binggeli: I have calculated Balmer break strength distributions for the simulated galaxies using the BPASSv2 stellar libraries. While there is a difference in the shape of the Balmer break strength distributions, they are still inconsistent with what is seen in JD1.

Daniel Ceverino: You may need to increase your sample of simulated galaxies if you want to find an analogue of the JD1 galaxy (Hashimoto *et al.* 2018). This is because of the large diversity of star formation histories of galaxies at high z.

Christian Binggeli: Yes, if we want to find an analogue or estimate a more exact probability of finding a galaxy like JD1, a larger sample may be required. However, we may still be able to determine if Balmer breaks like the ones seen in JD1 are common in simulations using a more limited sample.