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On the formation epoch of massive galaxies using spatially-resolved HST+JWST imaging data

García-Argumánez, Á.[1,2], Pérez-González, P.G.[3], and Gil de Paz, A.[1,2]

[1] Departamento de Física de la Tierra y Astrofísica, Fac. CC. Físicas, Universidad Complutense de Madrid, Plaza de las Ciencias, 1, Madrid, E-28040, Spain
[2] Instituto de Física de Partículas y del Cosmos, IPARCOS-UCM, Fac. CC. Físicas, Universidad Complutense de Madrid, Plaza de las Ciencias 1, Madrid, E-28040, Spain
[3] Centro de Astrobiología (CAB/CSIC-INTA), Ctra. de Ajalvir km 4, Torrejón de Ardoz, E-28850, Madrid, Spain

Abstract

We study the early assembly of galaxies by applying stellar population synthesis in 2D (2D-SPS) to massive ($M_\star > 10^{10}\,M_\odot$) galaxies at $1 < z < 4$ observed with JWST/NIRCam data in the CEERS survey. These data are combined with previous spatially-resolved HST/ACS optical data from the CANDELS survey in the same field. We use a 2D-SPS method which has been specifically optimized for recovering the first stages of the stellar mass assembly of galaxies using the Illustris cosmological simulation (García-Argumánez+2023). Our method analyzes the spatially resolved SEDs of each galaxy in the sample to derive the galaxy overall SFH by combining the information derived from these spatially resolved SEDs. From the resulting SFH, we calculate the first stages in the stellar-mass formation of each galaxy, i.e., the times at which the galaxy formed a (small) percentage of its total stellar mass, namely, its 5%, 10%, and 25% (t_5, t_{10}, and t_{25}). The application of our method to synthetic images of Illustris galaxies recovers these t_k's with median relative offsets of less than 10% with respect to its true value. In this contribution we present the results of the application of this method to massive, $1 < z < 4$ galaxies in CEERS+CANDELS observations and their resulting spatially-resolved SEDs (García-Argumánez+2024; in prep.). We find that massive galaxies began to form stars at very high redshifts: at $z \sim 30 - 20$ according to the median SFHs derived from our 2D-SPS modelling. Besides, they formed 5% of their stellar mass present at $z = 1$ (the lowest redshift of our sample) by $z_5 \geq 7.3$. Interestingly, the formation times predicted for analogous simulated galaxies in cosmological simulations (Illustris and the more recent TNG100 simulation) show a postponed onset of stellar-mass formation when compared to the formation times derived for our sample of massive galaxies observed in CEERS.

1 Introduction

Before JWST, simulations predicted that the first galaxies in the Universe began to form at $z \sim 10$. Nevertheless, since JWST was launched, many works have reported an unexpected abundance of relatively bright galaxies already in place at that redshift and higher (e.g., [2]).

Although most of these JWST studies focus on observations of high-redshift galaxies, the stellar populations in intermediate-redshift massive galaxies — which are thought to be the descendants of the first galaxies formed — also provide valuable insights into the first stages of stellar mass formation in the early Universe. In this regard, this contribution (based on García-Argumánez et al.; *in prep.*), aims at addressing the question of when massive galaxies began to form their stars by analysing the stellar populations of massive ($\mathrm{M}_\star > 10^{10}\,\mathrm{M}_\odot$) galaxies at $1 < z < 4$ observed with JWST+HST imaging data from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) and the Cosmic Evolution Early Release Science Survey (CEERS).

2 Observations

We use NIRCam observations from CEERS, which cover $\sim 100\,\mathrm{arcmin}^2$. In particular, we use NIRCam/F115W, F150W, F200W, F277W, F356W, and F444W broad-band images available in the public data release version 0.5 (`https://ceers.github.io/dr05.html`). The 5σ depths for point-like sources in these images (in circular apertures of 0.20" of diameter) are between $29.0 - 29.2$ mag, except for F444W which has 28.6 mag of limiting depth ([2]).

The fact that CEERS area overlaps the majority part of the Extended Groth Strip (EGS) observations from CANDELS allows us to combine our NIRCam observations with the HST/ACS F606W and F814W broad-band images from EGS. We use the ACS images provided by the CEERS team in the same public data release, which are pixel-aligned to CEERS/NIRCam images, have the same pixel scale (0.03 arcsec/pixel), and their 5σ depths are 28.6 (28.3) mag for F606W (F814W) for point-like sources in 0.15" apertures ([2]).

3 Methodology

In [3], we proved the efficiency of applying stellar population synthesis in 2D (2D-SPS) to recover the first stages of the stellar mass formation in massive, $1 < z < 4$ galaxies using the Illustris cosmological simulation. Here, we present the results of the application of this 2D-SPS method to broad-band VIS-to-NIR CANDELS+CEERS observations.

3.1 Selection of the preliminary sample

Although our work focuses on the early stages of stellar-mass formation of $1 < z < 4$ galaxies with $10^{10}\,\mathrm{M}_\odot$, we will start by building a preliminary sample of $1 < z < 4$ galaxies with a lower stellar-mass cut-off ($M_\star > 10^{9.5}\,\mathrm{M}_\odot$). The results from the SPS analysis on this preliminary sample will allow to discard galaxies with stellar masses inside the integrated photometric apertures below $10^{10}\,\mathrm{M}_\odot$ and to build the final sample of *bona-fide* massive galaxies at $1 < z < 4$, for which we will infer their early stages of mass formation in Section 5.

For the selection of our initial sample, we use the CEERS photometric catalog v0.51 ([2]). We include in our preliminary sample galaxies in the catalog with $M_\star > 10^{9.5}\,\mathrm{M}_\odot$ which have $1 < z_{\mathrm{spec}} < 4$ or, in case no spectroscopic redshift is available, with $1 < z_{\mathrm{phot}} < 4$. This makes an initial sample of 1743 galaxies in CEERS with $M_\star > 10^{9.5}\,\mathrm{M}_\odot$ and $1 < z < 4$.

3.2 Photometry: Measuring Integrated and 2D SEDs

We first PSF-match all the images to the NIRCam/F444W image, with the worst PSF FWHM (~ 0.16"). To measure photometry, we use of the `SExtractor` segmentation maps provided in the [2] photometric catalog and, as our starting integrated apertures, the associated elliptical apertures provided for each source which have a semi-major axes of twice the Kron radius. We reduce these initial integrated apertures, if necessary, to minimize the contamination from other sources, following [3]. If needed, before measuring photometry, we manually edit the segmentation map around each galaxy to make it resemble the RGB galaxy image generated with NIRCam/F115W, F200W, and F356W filters. During this step, we discard galaxies partially outside the images and other sources which have been misidentified as galaxies.

We follow [3] to build SEDs for each source by measuring multi-wavelength photometry in two ways: inside an elliptical integrated aperture (to which we refer as "integrated photometry" and "integrated SED"), and on a grid defined within the integrated aperture ("2D photometry" and "2D SEDs"). The cell size of the grid is $5 \times 5\,\mathrm{pixels}^2$ (i.e., 0.15" $\times$ 0.15").

3.3 Building the galaxy SFH from the SPS modeling

Our 2D-SPS method has been optimized to recover the beginning of the SFH of massive, $1 < z < 4$ galaxies and was validated using simulated imaging data of galaxies from the Illustris simulation (see [3]). Here, we describe how the SFH for each galaxy (or "galaxy SFH") is built from the integrated and 2D-SED fits. We refer the reader to [3] for more information about the SPS modeling input parameters.

All integrated and 2D-SEDs are fit using the `synthesizer` code ([5]) with two stellar population models: STARBURST99 (SB99; [4]) and Bruzual & Charlot (BC03; [1]) models. We assume a Kroupa (2001) IMF for SB99 models and a Chabrier (2003) IMF for BC03. As in [3], we assume each SED is described by a double-burst SFH, which is the sum of one old and one young population, each of them with a SFH given by $SFR(t) \propto t\,e^{-t/\tau}$ for $t > t_{\mathrm{pop}}$, with t_{pop} the age of each population, and τ the star-formation time-scale.

We fit each SED 300 times by performing Monte Carlo simulations (MC) in which we let the photometric points of the SED randomly vary within their error and then refit. This allows us to build 300 SFHs from each SED fit (either integrated or from a grid cell).

The stellar mass for each galaxy is calculated as the median of all the masses provided by its 300 integrated SED fits. To build the SFH for each galaxy, we add all the SFHs derived for each of the 2D-SED fits (i.e., for each of the cells). Then, we normalize this galaxy SFH by the stellar mass provided by the integrated SED fits. For each galaxy, we build 300 realizations of this SFH by considering the different MC solutions obtained for each of the 2D-SEDs, and calculate the final galaxy SFH as the median SFH of these 300 SFHs realizations.

4 Sample of massive, $1 < z < 4$ galaxies in CEERS

We select our final sample of massive galaxies in CEERS by keeping only galaxies in our preliminary sample which have a stellar mass of $M_\star > 10^{10}\,\mathrm{M}_\odot$ in both models at the same time. This makes a sample of 694 galaxies, with a median (with quartiles) stellar mass, in $\log(M_\star/\mathrm{M}_\odot)$, of $10.4^{10.7}_{10.2}$ ($10.5^{10.8}_{10.3}$) for BC03 (SB99) models, and a median redshift of $1.72^{2.48}_{1.38}$.

5 Results

With the aim to see when this sample of CEERS galaxies began to form, we build the median SFH of the sample for both BC03 and SB99 models (orange and blue, respectively, in Fig. 1 left). Both median SFHs have a very steep rise in the early Universe, before the first gigayear in age of the Universe. This rise occurs over one hundred megayears earlier for BC03 models, which results in earlier formation times (vertical lines) for BC03 than SB99. We see that, in both models, the formation times of massive galaxies in CEERS occur at very young ages of the Universe: if we focus on t_5, according to this median SFHs, these galaxies would have formed 5% of their stellar mass at $z > 7$ (for both BC03 and SB99).

We compare this median SFH for CEERS galaxies to that of Illustris massive galaxies at the same redshifts (in pink), to which the same 2D-SPS method was applied in [3]. The early star formation seen in CEERS is not seen in Illustris galaxies, whose median SFH begins later and has a less steep beginning. As a consequence, the formation times predicted for Illustris massive galaxies occur at significantly lower redshifts (e.g., $z_5 \sim 4.6$).

Instead of focusing on the median SFH of each sample, we now look at the distribution of the individual formation time, t_5, of galaxies in CEERS, computed from the SFH of each galaxy in the sample (Fig. 1 right). For both BC03 and SB99 models, these distributions have median formation redshift higher than $z_5 \sim 7$, with a significant fraction of CEERS galaxies having a formation redshift much higher than that. Nevertheless, Illustris galaxies, to which we have applied the same 2D-SPS method, again do not predict that early stellar-mass formation and have later formation times, with a median for t_5 at redshift $z_5 \sim 6$.

Additionally, we compute the ground-truth distributions for t_5 for massive galaxies at $z = 4$ in Illustris (dotted blak) and TNG100 (dashed dark red) simulations. These ground-truth formation times have been calculated using only the information provided by the stellar particles in those simulated galaxies (and not via our 2D-SPS method). We see that not even when we consider the highest redshifts of our CEERS sample, can simulations reproduce the early formation times of the observed galaxies in CEERS.

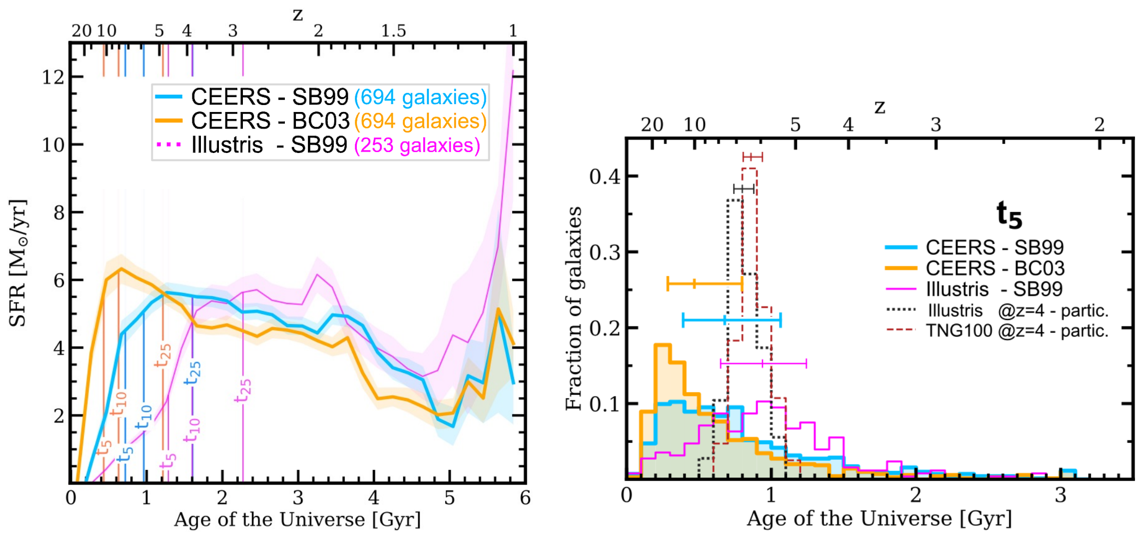

Figure 1: *Left:* Median 2D-SPS-derived SFH for massive galaxies at $1 < z < 4$ in CEERS, for BC03 (in orange) and SB99 (blue) models. The median SFH for massive, $1 < z < 4$ galaxies in Illustris (magenta) is included for comparison, after applying the same 2D-SPS analysis to them. The three SFHs have been normalized to recover the same mass as that of the median SFH for BC03. The formation times t_5, t_{10}, and t_{25} computed from these median SFHs are shown with vertical lines. *Right:* t_5 distribution for galaxies in the sample. CEERS galaxies are shown as filled histograms for BC03 (orange) and SB99 (blue). Illustris massive, $1 < z < 4$ galaxies, analyzed with the same 2D-SPS method, are in solid magenta. We include distributions for all massive galaxies at $z = 4$ in Illustris (dotted black) and TNG100 (dashed dark red), whose SFHs have been built from simulated particles (instead of *via* 2D-SPS). Median and quartiles for distributions are shown as segments at the top.

Acknowledgments

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