A very early onset of massive galaxy formation

Ivo Labbé1, Pieter van Dokkum2, Erica Nelson3, Rachel Bezanson4, Katherine A. Suess5,6, Joel Leja7,8,9, Gabriel Brammer10, Katherine Whitaker10,11, Elijah Mathews7,8,9, Mauro Stefanon12,13

1 Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Melbourne, VIC 3122, Australia
2 Department of Astronomy, Yale University, New Haven, CT 06511, USA
3 Department for Astrophysical and Planetary Science, University of Colorado, Boulder, CO 80309, USA
4 Department of Physics and Astronomy and PITP PACC, University of Pittsburgh, Pittsburgh, PA 15260, USA
5 Department of Astronomy and Astrophysics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064 USA
6 Kavli Institute for Particle Astrophysics and Cosmology and Department of Physics, Stanford University, Stanford, CA 94305, USA
7 Department of Astronomy & Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA
8 Institute for Computational & Data Sciences, The Pennsylvania State University, University Park, PA, USA
9 Department for Astrophysical and Planetary Science, The Pennsylvania State University, University Park, PA 16802, USA
10 Cosmic Dawn Center (DAWN), Niels Bohr Institute, University of Copenhagen, Jagtvej 128, København N, DK-2200, Denmark
11 Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA
12 Departament d’Astronomia i Astrofísica, Universitat de Valencia, C. Dr. Moliner 50, E-46100 Burjassot, Valencia, Spain
13 Unidad Asociada CSIC “Grupo de Astrofísica Extragalactica y Cosmologí” (Instituto de Física de Cantabria - Universitat de Valencia)

Galaxies with stellar masses as high as \( M_\ast \sim 10^{11} M_\odot \) have been identified\(^{[14]}\) out to redshifts \( z \sim 6 \), approximately one billion years after the Big Bang. It has been difficult to find massive galaxies at even earlier times, as the Balmer break region, which is needed for accurate mass estimates, is redshifted to wavelengths > 2.5 \( \mu \)m. Here we make use of the excellent long-wavelength coverage of the JWST early release observations to search for massive galaxies in the first \( \approx 750 \) million years of cosmic history. We find seven galaxies with \( M_\ast > 10^{10} M_\odot \) and \( 7 < z < 11 \) in the survey area, including two galaxies with \( M_\ast \sim 10^{11} M_\odot \). The stellar mass density in massive galaxies is much higher than anticipated from previous studies based on rest-frame UV-selected samples: a factor of \( 10 - 30 \) at \( z \sim 8 \) and more than three orders of magnitude at \( z \sim 10 \). From these first JWST images we infer that the central regions of at least some massive galaxies were already largely in place 500 Myr after the Big Bang, and that massive galaxy formation began extremely early in the history of the Universe. The presence of these galaxies at \( z \sim 10 \) suggests that galaxies with masses \( M_\ast \sim 5 \times 10^9 M_\odot \) may be found out to redshifts as high as \( z \sim 18 \).

The galaxies were identified in the first observations in the context of the James Webb Space Telescope (JWST) Cosmic Evolution Early Release Science (CEERS) program. This program obtained multi-band images at \( 1 - 4 \mu \)m with the Near Infrared Camera (NIRCam) in a “blank” field, chosen to overlap with existing Hubble Space Telescope imaging. The total area covered by these initial data is \( \approx 40 \) arcmin\(^2\). A catalog of sources was created, starting with detection in a deep combined F277W + F356W + F444W image (see Methods for details). A total of 40,244 objects are in this parent catalog.

We selected candidate massive galaxies at high redshifts by identifying objects that have two redshifted breaks in their SEDs, the \( \lambda_{\text{rest}} = 1216 \) Å Lyman break and the \( \lambda_{\text{rest}} \sim 3600 \) Å Balmer break. This selection ensures that the redshift probability distributions are narrow and have no secondary solutions at lower redshift and that the galaxies have relatively high mass-to-light ratios. Specifically, we require that objects are not detected at optical wavelengths; that they are blue in the near-infrared with \( F150W - F277W < 0.5 \); and that they are red at longer wavelengths with \( F277W - F444W > 1.0 \) and brighter than \( F444W < 27 \) AB magnitude. After visual inspection to remove obvious artifacts (such as diffraction spikes), this selection produced 14 galaxies with the sought-for “V-shaped”, or double-break, spectral energy distributions. Next, the EAZY code\(^{[3]}\) was used to determine photometric redshifts and stellar masses of the galaxies. A template was included that has extremely strong emission lines, so that their contribution to the rest-frame optical photometry can be included\(^{[4]}\). The masses were verified by fitting the galaxies with the Prospector-\( \alpha \) SED-fitting code which performs more robust nonparametric star formation history modeling\(^{[12]}\).

As shown in Fig. 1 all 14 objects have photometric redshifts \( 7 < z < 11 \). Seven of the 14 have masses \( > 10^{10} M_\odot \), and multi-band images and spectral energy distributions of these galaxies are shown in Figs. 2 and 3. The fits are generally excellent, and in several cases clearly demonstrate that rest-frame optical emission lines contribute to the continuum emission. These lines can be so strong in young galaxies that they can dominate the broad band fluxes redward of the location of the Balmer break,\(^{[7,13]}\) and Spitzer/IRAC de-
Figure 1: Double-break selected galaxies. EAZY-determined redshifts and stellar masses of all objects with S/N > 8 in the F444W band are shown. Galaxies that satisfy our double-break selection (having no optical flux, a blue color below 2.7 μm, and a red color beyond that) are shown by the large symbols. All these galaxies have photometric redshifts 7 < z < 11 and high masses. Seven have $M_* > 10^{10} \, M_\odot$.

Telescopes of optical continuum breaks in galaxies at $z \gtrsim 5$ have been difficult to interpret. With JWST, this ambiguity is largely resolved owing to the dense wavelength coverage of the NIRCam filters and the inclusion of relatively narrow filters (such as F410M, which falls within the F444W band). Several of the seven objects are quite remarkable, even among this group of remarkable galaxies. Galaxy 14924 is the most extreme object in terms of its mass and redshift; it has $z = 9.9$ and a mass of $M_* \approx 9 \times 10^{10} \, M_\odot$, higher than the present-day Milky Way. The brightest galaxy in the sample, 38094, is at $z = 7.6$ and has a mass of $M_* \approx 1.4 \times 10^{11} \, M_\odot$. It has two nearby companions with the same approximate redshift, indicating that it is in a group or proto-cluster.

We place these results in context by comparing them to previous studies of the evolution of the galaxy mass function to $z \sim 10$. These studies are based on samples that were selected in the rest-frame UV using ultra-deep HST images, with Spitzer/IRAC photometry typically acting as a constraint on the rest-frame optical SED. The galaxies previously reported were found to have typical flux ratio of $f_{\nu,4.4 \, \mu m}/f_{\nu,1.5 \, \mu m} = 1 - 3$. In contrast, the median ratio of the new sample reported here is $F444W/F150W \sim 6$, indicating that the new NIRCam color selection is targeting redder galaxies with higher mass-to-light ratios. No galaxies with $\log(M_*/M_\odot) > 10.5$ have been found beyond $z \sim 7$, and no galaxies with $\log(M_*/M_\odot) > 10$ have been found beyond $z \sim 8$. Furthermore, Schechter fits to the data at lower masses predict extremely low number densities of such galaxies at the highest redshifts. This is shown by the solid lines in Fig. 4: the expected mass density in galaxies with $\log(M_*/M_\odot) > 10$ at $z \sim 10$ is less than $10^2 \, M_\odot \, \text{Mpc}^{-3}$, and the total stellar mass density, integrated over the range $8 < \log(M_*/M_\odot) < 12$, is only $\approx 10^4 \, M_\odot \, \text{Mpc}^{-3}$.

The seven JWST-selected objects are shown by the large symbols in Fig. 4, split in two redshift bins and two mass limits. The JWST points are far higher than the expected values based on the UV-selected samples. The mass in galaxies with $\log(M_*/M_\odot) > 10$ is a factor of $\sim 10 - 30$ higher at $z \sim 8$ and a factor of $\sim 10^3$ higher at $z \sim 10$. The differences are even greater for $\log(M_*/M_\odot) > 10.5$. One way to phrase this is that the expectation from the Schechter fits was that we would have to survey 10 degree$^2$ rather than 40 arcmin$^2$ to find these massive $z \sim 10$ galaxies. At $z \sim 8$ errors in our masses could be partially responsible; the dashed lines, which assume errors of a factor of 3, come close to matching the data points. However, at $z \sim 10$ the difference is very large, irrespective of the precise masses of the objects.

We infer from these first JWST data that the high mass end of the mass function evolves surprisingly little from $z \sim 10$ to $z \sim 6$. This echoes the finding that the UV luminosity function also seems to show little evolution at the bright end, although we note that these UV-bright galaxies have much lower masses. Another comparison is to high redshift QSOs: it has become clear that black holes with masses of $\sim 10^9 \, M_\odot$ already existed at $z \gtrsim 7$, requiring a very early onset of accretion.

Taken together, these results indicate that the central regions of massive galaxies began forming very early in processes that were distinct from the gradual build-up of the rest of the galaxy population. In this context it is interesting that the mass density in the most massive galaxies exceeds the total previously-estimated mass density (integrated down to $M_* = 10^8 \, M_\odot$) by a factor of $\sim 2$ at $z \sim 8$ and by two orders of magnitude at $z \sim 10$. Unless the low mass samples are highly incomplete, the implication is that most of the total stellar mass at $z = 8 - 10$ resides in the most massive galaxies. This is qualitatively consistent with the notion that the central regions of present-day massive elliptical galaxies host the oldest stars in the universe (together with globular clusters), and with the finding that by $z \sim 2$ the stars in the central regions of massive galaxies make up 10% – 20% of the total stellar mass density at that redshift. We note here that the seven galaxies are all extremely compact, with sizes $r_e \lesssim 0.5 \, \text{kpc}$. 

Figure 2: Images of the seven galaxies with \( \log(M_*/M_\odot) > 10.0 \) as a function of wavelength. Each cutout has a size of 2.4\( '' \) \( \times \) 2.4\( '' \). The filters range from the 0.6\( \mu m \) F606W filter of HST/ACS to the 4.4\( \mu m \) F444W JWST/NIRCam filter. The galaxies are undetected in the optical filters; blue in the short-wavelength NIRCam filters; and red in the long-wavelength NIRCam filters. Galaxy 38094 has two neighbors at 1\( '' \) distance and the same photometric redshift, indicating an early group or proto-cluster.
Figure 3: Spectral energy distributions (SEDs) and photometric redshift probability distributions $P(z)$ of the 7 galaxies with $\log(M_*/M_\odot) > 10.0$. The flux density units are in $F_\lambda$ versus wavelength in $\mu$m. All galaxies show characteristic V-shaped SEDs, with a clear upturn at $3-4 \mu$m and a double break. The redshifts are well-constrained owing to the presence of two breaks. The two most massive galaxies are highlighted on the top row. Shown are the contribution of each template in the fit, where the fit produces a prominent contribution of an older stellar population (left) or dusty stellar population (right) shown in red. Emission lines clearly contribute to the F356W and F444W bands, but the emission-line sensitive F410M medium band providing a powerful diagnostic, improving both the redshift and the SED fit. The two brightest, most massive galaxies (top panels) were previously detected with Hubble, but misidentified as low mass galaxies at $z \sim 1$.23
Figure 4: Stellar mass density in JWST-selected massive galaxies. The large symbols show the total mass density of the seven galaxies in two redshift bins, $7 < z < 9$ and $9 < z < 11$, and for two limiting masses, $\log(M_*/M_\odot) > 10$ and $\log(M_*/M_\odot) > 10.5$. The lines are derived from Schechter fits to UV-selected samples. Dashed lines are derived from Monte Carlo simulations that perturb the masses of individual galaxies. The perturbations are drawn from a log-normal distribution with a $1\sigma$ width of 0.48 dex (a factor of 3). The JWST-selected galaxies greatly exceed the expected mass densities of massive galaxies at these redshifts.

The high number density that we find here can be verified with future JWST surveys over larger areas, and it may be possible to confirm the redshifts of the brightest individual galaxies with future NIRSPEC spectroscopy. Our results also have implications for JWST searches for galaxies at even higher redshifts. Assuming that the galaxies formed stars at a constant rate until the epoch of observation (a reasonable assumption given the formation histories determined with Prospector-$\alpha$), the progenitors of the massive $z \sim 10$ galaxies would have masses of $\geq 5 \times 10^9 M_\odot$ at $z \sim 18$, within the reach of deep JWST studies.

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**Methods**

**Observations, reduction, and photometry.** This paper is based on the first imaging taken with the Near Infrared Camera (NIRCam) on JWST as part of the Cosmic Evolution Early Release Science (CEERS) program (PI: Finkelstein; PID: 1345). To date four pointings have been obtained, covering \sim 40 square arcminutes on the Extended Groth Strip HST legacy field and overlapping fully with the existing HST/ACS and WFC3 footprint. NIRCam observations were taken in six broadband filters, F115W, F200W, F150W, F277W, F356W, and F444W, and one medium bandwidth filter F410M. The F410M medium band sits within the F444W filter and is a sensitive tracer of emission lines, enabling improved photometric redshifts and stellar mass estimates of high-redshift galaxies.

Flux calibrated exposures produced by Stage 2 of the JWST calibration pipeline (v1.5.2) were downloaded from the MAST archive. The data reduction pipeline Grism redshift and line analysis software for space-based spectroscopy (Grizli) was used to process, align, and co-add the exposures. The pipeline masks various artifacts, such as “snowballs” and 1/f noise, subtracts a large scale sky background, aligns the images to stars from the Gaia DR3 catalog, and drizzles the images to a common pixel grid using astrodizzle. Existing multi-wavelength ACS and WFC3 archival imaging from the Hubble Space Telescope was also processed with Grizli. A paper by G. Brammer et al. describing
these aspects in detail is in preparation. For the analysis in this paper we project all images to a common 40 mas pixel grid. Significant background structure due to scattered light was visible in the NIRCam mosaics. The background is generally smooth and was effectively removed with a $5''$ median filter after masking bright sources.

We use standard astropy and photutils procedures to detect sources, create segmentation maps, and perform photometry. We detect sources in a inverse variance weighted combined F277W + F356W + F444W image, after convolution with a Gaussian of 2.5 FWHM pixels to enhance sensitivity for point sources. Photometry was performed at the locations of detected sources in all filters using 0.32'' diameter circular apertures. The fluxes were corrected to total using the Kron autoscaling aperture measurement on the detection image and a further small correction was applied for light outside the aperture based on the encircled energy provided by the WebbPSF software. The final catalog contains all available HST/ACS and JWST/NIRCam filters (10 bands, spanning $0.43$ to $4.4$ micron).

Photometry for HST/WFC3 bands was also derived, but only used for testing purposes as the HST/WFC3 images are significantly shallower than NIRCam. No significant offsets were seen comparing to HST/WFC3. JWST calibration is still preliminary and several checks were performed to make sure there are no significant magnitude zero-point offsets. Comparison to NIRCam photometry in larger $0.5''$ diameter apertures showed no significant offsets in colors (less than $2\%$). We used a list of 320 spectroscopically confirmed galaxies at $0 < z < 4$ compiled from 3DHST$^{22}$ and MOSDEF$^{23}$ to iterate determine zeropoint offsets using the iterate_zp_templates functionality of the eazy-py photometric redshift software. No significant zero-point offsets were found (ranging from $-2\%$ to $+6\%$), not significantly affecting the current analysis.

Sample selection. The JWST/NIRCam imaging in this paper reaches $5\sigma$ depths from 28.5 to 29.5 AB, represents an order of magnitude increase in sensitivity and resolution beyond $2.0\mu$m, and allowing us for the first time to select galaxies at rest-frame optical wavelengths to $z \sim 10$. Our goal in this study is to perform an initial study of the high mass end of galaxies at $z = 7 - 11$.

To prevent model dependency of the selection, and to enable straightforward reproduction of the results, we avoid selecting on inferred photometric redshift or stellar mass. Instead, we designed a new, purely empirical selection of high-redshift galaxies based on NIRCam photometry. This selection complements the traditional “drop-out” color selection techniques based on isolating the strong Lyman $1216 \, \AA$ break as it moves through the filters, which is not feasible here for the HST ACS data are not deep enough to select dropout galaxies to the limits of the NIRCam imaging. Instead, we select on a “V-shaped” spectral energy distribution (blue in the NIRCam Short Wavelength filters, red in the NIRCam Long wavelength filters), which is expected for sources at $z \gtrsim 7$ with moderately blue rest-frame UV-slope but with red UV-optical colors. Such a signature can be produced by galaxies some relatively unobscured star formation, in combination with either strong optical emission lines$^{10}$, or a Balmer Break indicating evolved stellar populations$^{11}$. The inclusion of the NIRCam F410M filter is particularly helpful, because it response strongly to bright emission lines, improves redshift determination, and provides an estimate of the equivalent width of the line$^{11}$.

The full NIRCam selected catalog contains 40,244 sources. The following color selection criteria were applied to isolate $7 < z < 10$ galaxies:

$$F150W - F277W < 0.5$$

$$F277W - F444W > 1.0$$

in addition to a non-detection requirement in HST ACS imaging

$$SNR(B_{435}, V_{606}, I_{814}) < 2$$

and at least $10\sigma$ detection in F444W. As this is a first exploration with NIRCam at these redshifts we limit our sample to F444W $< 27$ AB magnitude. We manually inspected selected sources and removed artifacts, such as hot pixels, diffraction spikes, and sources affected by residual background issues or bright neighbors.

This selection produced a total of 14 sources, with a median S/N ratio in the F444W band of $\sim 30$. The resulting sample is completely dark at optical wavelengths ($2\sigma$ upper limit of $I_{814} \sim 30.4$ AB) and faint in F115W and F150W with median $\sim 28$ AB magnitude, beyond the limits reached with HST/WFC3 except in small areas in the Hubble Ultra Deep Field and Frontier Fields. The absence of any flux in the ACS optical, the red $I_{814} - F115W > 2.5$ and blue $F115W - F150W \sim 0.3$ AB colors are indicative of a strong Lyman break moving beyond the ACS $I_{814}$ band and consistent with a mean redshift of the sample of $z > 6$. The NIRCam F444W magnitudes are bright $\sim 26$ AB, and the median F150 – F444 = 1.8 color is redder than any sample reported previously at $z > 7^{11}$.

**Fits to the photometry** The redshifts used in this paper are determined with the EAZY code$^8$. EAZY fits a non-negative linear combination of a set of templates, with the redshift and the weight of each template free parameters in the fit. The allowed redshift range was 1 – 20 and no luminosity prior was applied. The redshift distribution of the sample is $7 < z < 10.5$, with no low-redshift interlopers. EAZY was also used to derive stellar masses. Each template is generated using FSPS (Conroy et al. 2010; Conroy & Gunn...
2010) and has associated stellar population properties such as SFH, age, dust. As each template has a known $M_\ast/L$ ratio the weights can be converted to a stellar mass (assuming a Chabrier initial mass function).

As a starting point we adopt the default template set `tweak_fspss_QSF_12_v3` with two modifications to make it more suitable for applications at very high redshifts. First, we remove two extremely dusty templates with $A_V \sim 3$. The rest-frame wavelength coverage of NIRCam is limited to $0.4 - 0.5 \mu m$ at $7 < z < 10.5$, which means that optically thick templates are unconstrained and could inflate the derived stellar masses. Also removed were two very old, high $M_\ast/L$ elliptical templates with ages much older than the universe at $z > 6$. Second, the default set does not contain extreme emission lines. An intermediate color star forming template `tweak_fspss_QSF_12_v3_009.dat` was modified by boosting the emission lines to $\text{EW}(\text{H}/\beta + [\text{O} \, \text{III}]) \sim 1100 \AA$ reflecting strengths thought to occur at high redshift. We note that these choices deliberately lower the $M/L$ ratio and flexibility of the template set, and could potentially underestimate the stellar mass if the galaxies are very dusty.

The template modifications did not change the redshift distribution of the sample. For five galaxies the reduced, emission-line enhanced template set yielded better fits, with lower $\chi^2$, a narrower $P(z)$, and on average 0.3 dex lower stellar masses; for seven galaxies the fits were unchanged; and for two the fit was noticeably worse. For galaxy $ID = 38094$ the emission line enhanced set resulted in a poor fit of the UV, so we reverted to an template set which included a $A_V = 1.8$ dusty template (and yielded 0.2 dex higher mass). Galaxy $ID = 2589$ is the only galaxy where including emission lines caused the redshift to go up considerably to 10.5 (from $z = 9$). A faint detection of flux in $F115W$ suggests that the redshift of this source must be $z < 9$ (because the Lyman break should lie in the F115W filter). Indeed, there is a small secondary peak in the redshift probability distribution at $z = 8.9$ and we adopt this as the fiducial redshift (with a 0.2 dex lower derived mass). The higher redshift fit appears to have been driven by the much higher SNR in the rest-frame optical compared to rest-frame UV. Overall, the redshifts change remarkably little with the change of templates (median 2% in $dz/(1+z)$).

We perform a more controlled stellar populations fit using Prospector, using the Prospector-α setting and MIST stellar isochrones from FSPS. This mode includes nonparametric star formation histories, with a continuity prior that weighs against large changes in star formation rate between time bins. It also uses a two-component dust model, free gas-phase and stellar metallicity, nebular emission where the nebulae are self-consistently powered by the stellar ionizing continuum from the model and similarly adopts a Chabrier IMF. For speed, this fit was performed with a neural-net emulator which mimics standard stellar population synthesis models but is a factor of $\sim 300$ faster. The masses from Prospector are consistent within the uncertainties with the EAZY masses, with a median offset of $\log(M_{\text{pros}}/M_{\text{pros}}) = -0.2$ and a mean offset of $\log(M_{\text{pros}}/M_{\text{pros}}) = +0.1$ for the 7 objects. Importantly, all objects remain at $\log M_\ast/M_\odot > 10$ in the Prospector fits. Prospector also provides ages and star formation rates. The star formation rates are not well constrained in the fits, due to the lack of IR coverage. The ages are better determined, as they are sensitive to the strength of the Balmer break. We find that they are $\approx 0.3$ Gyr for the 7 galaxies, with small variations.

**Lensing.** A potential concern is that the fluxes (and therefore the masses) of some or all of the galaxies are boosted by gravitational lensing. None of the galaxies is close to the expected Einstein radius of another object; the bright galaxy that is $1.2''$ to the southwest of 38094 has $z_{\text{grism}} \approx 1.15$ and $M_\ast \approx 10.63$ (object number 28717 in 3D-HST Aegis catalog), and an Einstein radius ($\sim 0.3''$) that is $0.3 \times$ the distance to 38094.

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**Author Information.** The authors declare that they have no competing financial interests. Correspondence and requests for materials should be addressed to I.L. (email: ilabbe@swin.edu.au).