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The Typical Massive Quiescent Galaxy at $z \sim 3$ is a Post-starburst

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Abstract

We have obtained spectroscopic confirmation with Hubble Space Telescope WFC3/G141 of a first sizeable sample of nine quiescent galaxies at 2.4 < $z$ < 3.3. Their average near-UV/optical rest-frame spectrum is characterized by low attenuation ($A_V \sim 0.6$ mag) and a strong Balmer break, larger than the 4000 Å break, corresponding to a fairly young age of $\sim 300$ Myr. This formally classifies a substantial fraction of classically selected quiescent galaxies at $z \sim 3$ as post-starbursts, marking their quenching to the quenching epoch. The rapid spectral evolution with respect to $z \sim 1.5$ quiescent galaxies is not matched by an increase of residual star formation, as judged from the weak detection of [O II]3727 emission, pointing to a flattening of the steep increase in gas fractions previously seen from $z \sim 0$ to 1.8. However, radio 3 GHz stacked emission implies either much stronger dust-obscured star formation or substantial further evolution in radio-mode AGN activity with respect to $z \sim 1.5$.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Galaxy quenching (2040); Quenched galaxies (2016)

1. Introduction

Timing the formation and quenching of the most massive ($M_*>10^{11}$ $M_{\odot}$) passively evolving galaxies (PEGs) is the subject of intense debate. Several studies kept unveiling their existence at progressively increasing lookback times, placing their formation at $z > 3$–4 (Gobat et al. 2012; Glazebrook et al. 2017; Forrest et al. 2020; Valentino et al. 2020). Reproducing the observed number density of such galaxies at all epochs is a compelling concern of current galaxy evolution models in cosmological simulations, as the relative importance of the quenching mechanisms is not yet clear (Man & Belli 2018). To this end, several photometric samples of high-$z$ PEGs exist (Straatman et al. 2014; Merlin et al. 2018), yet spectroscopic confirmation is still needed to precisely assess their redshifts and the degree of contamination by star-forming interlopers, especially at epochs when PEGs might be just starting to emerge. At $z \sim 3$ the chances of collecting statistically meaningful samples of PEG spectra are hampered by their rarity and lack of prominent emission lines. Therefore, the assembly of sizeable samples of quiescent spectra is essential to improve upon the photometric age/dust-attenuation estimation for the bulk of their stellar populations, to draw relative comparisons of their spectral properties with respect to lower-redshift massive PEGs and to reveal any residual emission line that might be linked to star formation. The latter point provides useful information on the availability of unstable, cold molecular gas that is, itself, a poorly constrained quantity at this epoch. In this Letter we report on the average stellar population properties in a sizeable sample of nine spectroscopically confirmed 2.4 < $z$ < 3.3 quiescent galaxies. We constrain their global residual star formation from the average [O II] emission, showing implications on their average gas fraction. We assume a $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_0 = 0.27$, $\Omega_\Lambda = 0.73$, and a Salpeter initial mass function (IMF). Magnitudes are given in the AB photometric system.

2. Sample Selection and Analysis

We selected galaxies from a parent sample of more than 50 reliable PEG candidates with $K_{\text{phot}} < 22.5$ in the McCracken et al. (2010) catalog with photometric redshifts between $2.5 \leq z_{\text{phot}} \leq 3.5$ in the COSMOS field. A first selection was done using the BzK criterion (Daddi et al. 2004) selecting passive BzK galaxies plus objects formally classified as star-forming BzK but having a signal-to-noise ratio (S/N) < 5 in the B and z bands, to retain passive galaxies as they become fainter in such bands with increasing redshift and decreasing mass. We then selected from this sample UVJ quiescent galaxies (Williams et al. 2009), exploiting photometric redshifts calibrated for high-$z$ PEGs (Onodera et al. 2012; Strazzullo et al. 2015). To minimize contamination from dusty star-forming galaxies, objects in McCracken et al. (2010) with Spitzer/MIPS 24 $\mu$m S/N > 4 were discarded, except for galaxies with high-confidence passive spectral energy distributions (SEDs). Objects having SED fits to optical–NIR
broadband photometry consistent with dusty star-forming solutions and contaminated photometry in all images were also discarded. Among the most massive bona fide passive candidates, 10 galaxies were targeted for Hubble Space Telescope (HST) WFC3/IR G141 near-IR\footnote{Rest-frame near-UV/optical.} observations: 9 with $H_{AB} < 22$ ($M_\ast > 1.1 \times 10^{11} M_\odot$) plus 1 robust candidate with $H_{AB} = 22.9$ ($M_\ast = 8 \times 10^{10} M_\odot$) among the highest-$z$ objects. Scheduling from 1 to 3 orbits (17 in total) according to each source’s flux provided low-resolution spectra ($R = 130$) with a mean $S/N \sim 4.5$ per resolution element for each target and ancillary F160W imaging (HST GO 15229 program). The data were reduced and decontaminated from neighboring sources’ overlapping spectra by means of the grizli software package (Brammer 2018).\footnote{https://github.com/gbrammer/grizli} For each target a 2D spectrum was produced and drizzled to a scale of 0.8 times the native pixel size. The 1D spectra were then optimally extracted (Horne 1986) and fitted from 11000 to 16900 Å with Bruzual & Charlot (2003, hereafter BC03) composite stellar populations derived using different star formation histories (SFHs): allowing for a constant, exponentially declining, delayed exponentially declining, and a truncated SFH, where the star formation rate (SFR) drops to 0 after a timescale between $\tau = 0.001$ – 1.0 Gyr. Ages were allowed to vary between $t = 100$ Myr and 10 Gyr, from redshift 5 to 0. The Calzetti et al. (2000) extinction law was adopted with $A_V$ varying between 0 and 8 mag. BC03 templates were broadened to the grism resolution using a Gaussian kernel whose FWHM was derived via a Gaussian fit of the 2D light profile of each source.

The broadband photometry (Laigle et al. 2016) for each galaxy was also fitted imposing the grism-derived redshifts. The addition of the photometric information mostly leads to narrowing down the range of dust extinction values at any confidence level. The detailed analysis of individual galaxies will be presented in a forthcoming paper.

### 2.1. Quiescence of Individual Targets

We tested the quiescent/dusty star-forming nature of each galaxy adding the $\chi^2$ matrices of fits to spectra and photometry and comparing the goodness-of-fit of the best-fitting constant star-forming (CSF) template with that of a solution defined as passive by constraining the best-fitting SFH as follows: $t_{50} \geq 0.3$ Gyr, $A_V < 0.8$ mag, and $t_{50}/\tau \geq 10$, where $t_{50}$ is the lookback time at which the galaxy formed 50% of its stellar mass. To reject a solution (i.e., to classify it as inconsistent with respect to the other one and with the data) its probability had to be $< 0.01$, as inferred from their $\chi^2$ difference. Star-forming solutions were rejected for all sources except for one, whose redshift was not properly constrained by our data. If this galaxy were in our selected range in redshift, its quiescence would be rejected with 80% confidence, hence we excluded it. We were thus left with nine galaxies classified as passive with a median redshift of $z_m = 2.808$ and a median stellar mass of $M_\ast = 1.8 \times 10^{11}$.

### 3. Stacked Spectrum

To fully exploit the sample size we created an average spectrum. We scaled the wavelength vector of each galaxy to $z_m$ and interpolated their fluxes and error spectra on a 5 Å rest-frame grid, increasing the error in each new pixel by the square root of the width ratio between the old and the new spectral bin, to account for the introduced noise correlation. Each spectrum was interpolated in quadrature. Each spectrum was normalized to its average flux between $\lambda_{\text{rest}} = 3800$ and 3900 Å in order to select a wavelength range covered for all galaxies. We then created a stacked spectrum as the inverse variance weighted mean of the individual fluxes in each wavelength bin. The final error spectrum was computed as the error on the flux-weighted mean in each pixel. A jackknife resampling provides consistent results. The median $z_{\text{spec}}$ uncertainty from our individual galaxies is $dz \sim 0.006$ at 68% confidence. This does not affect the final spectral resolution, being three times smaller than the broadening from galaxy sizes. The average spectrum was rescaled to match the average broadband photometry of the sample at $\lambda_{\text{rest}} = 3800$–3900 Å, in turn obtained by stacking the individual galaxy best-fit SEDs (as done for the spectra). Figure 1 shows the average spectrum with clear Balmer absorption lines from H$_\alpha$ to H$_\gamma$, the [O II] (unresolved) doublet at 3727 Å, and the Fe1 absorption line. With a mean $S/N \sim 13$ per pixel at 4000 Å this is, to date, one of the highest $S/N$ spectra available for high-$z$ PEGs and the first spanning a large spectral range around key spectral breaks.

We analyzed the stacked spectrum as in Section 2, this time limiting the age grid to the age of the universe at $z_m = 2.808$ (2.3 Gyr) and using the average FWHM derived for the individual targets as spectral broadening.\footnote{This analysis does not include the information from the stacked photometry.} The mean properties of our sample result in $t_{50} = 0.30_{-0.20}^{+0.20}$ Gyr and $A_V = 0.6^{+0.6}_{-0.4}$ mag at fixed solar metallicity given the high ($M_\ast$) of our sample (Mancini et al. 2019; see Table 1). The 1σ uncertainties were estimated marginalizing over these two quantities, taking into account the simple parameterizations used for the SFHs.

We then measured the $H_{\delta A}$, $D_n4000$, and $D_B$ spectral indices (Worthy & Ottaviani 1997; Balogh et al. 1999; Kriek et al. 2006). Since our spectral resolution is worse than in the original Lick system, the $H_{\delta A}$ was measured on the best-fit BC03 model smoothed to the Lick resolution and adding the broadening due to a 200 km s$^{-1}$ stellar velocity dispersion corresponding to our $M_\ast$. The $D_n4000$ and $D_B$ instead are not affected much by resolution. The indices result in $D_{n4000} = 1.28 \pm 0.05$, $D_B = 1.88 \pm 0.07$, and $H_{\delta A} = 10.1^{+0.9}_{-0.6}$ Å. The error on $H_{\delta A}$ was computed measuring the

\begin{table}[h]
\centering
\begin{tabular}{lcccccc}
| $z$ | $M_\ast$ | $t_{50}$ | $A_V$ | $D_n4000$ | $D_B$ | $EW_{[O II]}$ | SFR \\
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<tr>
<td>2.808</td>
<td>1.8 ± 0.8</td>
<td>0.30^{+0.20}_{-0.05}</td>
<td>0.9^{+0.4}_{-0.5}</td>
<td>1.28 ± 0.05</td>
<td>1.88 ± 0.07</td>
<td>2.1 ± 0.6</td>
<td>3.1 ± 0.7 \times 10^{-18}</td>
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\end{tabular}
\caption{Main Properties of our Sample Derived from the Stacked Spectrum (See the Text)}
\end{table}
index maximum variation on the templates within the uncertainties on $t_0$ and $A_V$, accounting for the negative correlation between these two. The weakness of the $D_n4000$ compared the strength of the Balmer break ($D_B$) and of $H_{\alpha}$ classifies the spectrum as post-starburst dominated by A-type stars. We show the indices in Figure 2, where we also show $H_{\alpha}$ measured directly on the stacked spectrum to display the effect of low resolution. We checked whether our spectroscopic sample is representative of the parent photometric sample and of low resolution. We measured directly on the stacked spectrum to display the effect.

Figure 1. Top: number of galaxies contributing to each spectral bin. Middle: stack of nine quiescent galaxies’ spectra. Blue curve: best-fit model from the BC03 library. Red curve: gaussian fit to the residual, added to the blue continuum. Pink curve: best-fit BC03 template smoothed for a $\sigma_c \sim 200$ km s$^{-1}$, shifted in flux for clarity. Vertical dotted lines mark the identified absorption features. Bottom: fit residuals normalized to the error spectrum.

4. Residual Star Formation

Given the tight anticorrelation between the age of a stellar population and the specific SFR ($sSFR = SFR/(M_*)$) of its host galaxy, expected in the case of a smooth intrinsic SFH (as opposed to a simple stellar population (SSP), or a complex SFH), we investigated whether the age decrease at fixed $M_*$ from $z \sim 1.5$ to $z \sim 2.8$ translates into a higher sSFR.

We used MPFIT to model the residuals of the fit using a single Gaussian centered and fixed at 3727Å with a width matched to the data spectral resolution, measuring $F_{[O\,\text{II}]} = (3.1 \pm 0.7) \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$. The observed $[O\,\text{II}]$ flux was dereddened adopting the best-fit dust attenuation ($A_V = 0.6$ mag) using a value of $f = 0.83$ for the ratio between stellar and nebular extinction (Kashino et al. 2013) as in Gobat et al. (2017) in order to perform a consistent relative comparison. Following Kennicutt (1998) we then obtained an SFR = $7 \pm 3 M_\odot$ yr$^{-1}$, which is a factor of $\sim$60 below the main-sequence level at $2.5 < z < 3.5$ (Schreiber et al. 2015). This is in agreement with estimates for intermediate redshift quiescent galaxies from.
and yellow diamonds: K+Å local post-starbursts and z ∼ 0.7 A-type post-starbursts, from French et al. (2015) and Sell et al. (2014), respectively. Open star: Hβ computed on the stacked spectrum, as a lower limit due to resolution. Tracks with different amounts of old stars (age > 4Gyr) from Suess et al. (2017) are shown, going from no old stars (dotted line) to 95% of old stars (solid line). Bottom: strength of the Balmer and 4000 Å breaks as a function of the SSP age. Red and green stars represent the indices measured on our stack spectrum and on Gobat et al. (2017) spectrum, respectively. Black stars mark the indices computed on theoretical stellar spectra smoothed to HST resolution (Rodríguez-Merino et al. 2005).

Therefore, the age evolution implied by the continuum appears to occur at constant sSFR. This is also suggested by the equivalent width (EW) of the line that is 2.1 ± 0.6 Å rest-frame. This value is almost half that obtained by Gobat et al. (2017) due to a higher UV continuum produced by ∼1 Gyr younger stars. Assuming that the [O II] flux arises from a 100 Myr old stellar population, forming stars at a constant rate and with AV = 0.6 mag, we subtracted the associated continuum component from the stacked spectrum to explore the effect on the age determination, deriving t50 = 0.30+_0.20 Gyr and AV = 0.9+_0.4 mag. Letting the age and extinction of the star-forming component vary (100–300 Myr and 0.6–1.5 mag, respectively) leaves t50 unchanged while increasing AV up to 1.0 mag. The flux at λ > 4400 Å varies around the 95% of the original flux, suggesting that the CSF component does not account for more than 1%–2% of ⟨M⟩ as also confirmed by the mass produced in a Δt ∼ 300 Myr at a constant SFR of 10 M⊙ yr⁻¹, namely, the upper limit inferred here. We thus conclude that the presence of the youngest stellar population does not impact our results significantly. The sSFR of our sample, (4.35 ± 2.47) × 10⁻¹¹ yr⁻¹, is consistent with the available estimates at z ∼ 1.5–1.8 (Sargent et al. 2015; Bezanson et al. 2019) and with the sSFR for the four quiescent galaxies with a spectral break in Schreiber et al. (2018) for which sSFR[O II] is available. However, the best-fit t50 obtained here implies a formation redshift zform ≥ 3.2, meaning that at z ∼ 4 our galaxies would be actively forming stars. To check that the average spectrum is not dominated by emission from unobscured AGN, we removed from the stack the two X-ray detected sources (LX, unobscured = 10⁴⁴.3 and 10⁴₃.7 erg s⁻¹), getting F[O II]unobscured = (3.53 ± 0.90) × 10⁻¹⁸ erg s⁻¹ cm⁻² consistent within the uncertainties. Stacking the available X-ray data in COSMOS for the undetected sources results in LX, unobscured < 10⁴₃.1 erg s⁻¹. If part of the [O II] luminosity were caused by low AGN activity or shocks, the intrinsic SFR would be even lower, strengthening the conclusion that the young spectral age does not directly map into a higher sSFR. Using the UV-extended Maraston et al. (2009) models the best-fitting template yields a similar t50 ∼ 0.3 Gyr but produces a slightly worse χ² and a less solid [O II] detection, with a flux that is 60% of the one measured with BC03 templates, at 2.9σ confidence.

5. Discussion

It is interesting to place our z ∼ 3 results in the overall evolutionary context of passive galaxies. In order to be able to compare to the available literature we express, for convenience, the SFR constraints in terms of the available gas fraction through the relation fgas = sSFR/SFE, where SFE is the star formation efficiency. We caution that this is just an alternative way to look at the SFR result, as we are using the same single constraint: we use both quantities interchangeably in the following and notably in Figure 4. We assume the same SFE derived in G18 (5 × 10⁻¹⁰ yr⁻¹), which is lower by ∼2–3 than that of typical star-forming galaxies, noticing that such reduced SFE is also typical of post-starburst galaxies (Suess et al. 2017). Our SFR thus converts
\[ M_{\text{mol}} = (1.5 \pm 0.6) \times 10^{10} \, M_\odot \] hence \( f_{\text{mol}} \sim 9 \pm 4\% \). We compare it to CO or dust-continuum-based gas fractions and upper limits (converted to Salpeter) for quiescent and post-starburst galaxies: Davis et al. (2014) and Saintonge et al. (2011) for local massive PEGs; Sargent et al. (2015), Bezanson et al. (2019), Spilker et al. (2018), Zavala et al. (2019), Rudnick et al. (2017), Suess et al. (2017), Spilker et al. (2018), Hayashi et al. (2018), and Gobat et al. (2018) for intermediate-\( z \) quiescent galaxies; Schreiber et al. (2018) and Valentino et al. (2020) for \( z \sim 3-4 \) galaxies. Despite the uncertainties, our data at \( z \sim 3 \) seem to disfavor the
steep \((1+z)^{4.5}\) trend inferred from \(z = 0\) to 1.5–2, suggesting a flattening in the \(M_{\text{mol}}/M_\star\) evolution (or, equivalently, of the sSFR).

The published SFR \(\text{[OII]}\) for \(z > 3\) galaxies with a clear spectral break in Schreiber et al. (2018) and Valentino et al. (2020) also seem to support this trend.

Our data thus suggest that a substantial fraction of the massive quiescent population at \(z \sim 3\) is approaching the quenching epoch, becoming intrinsically young and with spectra of post-starburst galaxies, but with a more or less constant \(f_{\text{mol}}\) (or, equivalently, sSFR) over \(1.5 < z < 3\). Various processes could be simultaneously acting: cosmological cold flows, AGN feedback, dust grain growth in the interstellar medium, satellite accretion or dust destruction by sputtering with a hot X-ray halo. It is beyond the scope of this Letter to investigate this further.

One could wonder if highly obscured star formation could be present and go unrecognized, given that their post-starburst nature might suggest that a highly obscured starburst might have been previously present. Stacking at 3 GHz (excluding two clear radio AGN detections at \(S_{\text{1GHz}} = 0.58 \pm 0.03\) mJy and \(14 \pm 4\) \(\mu\)Jy) results in a 3σ signal with \(S_{\text{1GHz}} = 2.72 \pm 0.93\) \(\mu\)Jy, which translates into a rest-frame \(L(1.4\text{GHz}) \sim 2 \times 10^{23} W\text{ Hz}^{-1}\), 4 times higher than in Gobat et al. (2018). This is probably just suggesting a higher radio AGN activity at fixed stellar mass closer to the quenching epoch, continuing the rapid evolution seen from \(z = 0\) to 1.5–2. On the other hand, such a detection would also be formally consistent with 40–50 \(M_\odot\) yr\(^{-1}\) of obscured star formation (assuming the IR–radio correlation at \(z = 3\); Delhaize et al. 2017). This would still place the typical object 8 times below the MS. While we tend to interpret strong Balmer absorption lines plus weak \([\text{OII}]\) emission as a sign of post-starburst galaxies with residual unobscured star formation, we cannot fully rule out stronger obscured star formation, which could be analogous to what seen locally for \((a)\) galaxies (Poggianti & Wu 2000). Only future Atacama Large Millimeter/submillimeter Array observations of several of these targets could conclusively solve this issue.

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