Galaxies at High Redshift and Their Evolution Over Cosmic Time
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Are quiescent galaxies truly devoid of star formation? The mid-, far-infrared and radio properties of quiescent galaxies at $z = 0.1 - 3$

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Abstract. Quiescent galaxy candidates are typically identified by their low unobscured star formation rates from deep field photometric surveys. However, their selection technique relies on the assumption of a universal dust attenuation curve. It is important to verify the selection through independent SFR indicators at longer wavelengths. Current mid-, far-infrared and radio surveys are limited to detecting only galaxies with very strong star formation or AGN activity. Here, I present the first comprehensive stacking results across mid-, far-infrared and radio wavelengths using *Spitzer*, *Herschel* and VLA data in the COSMOS field (Man *et al.* 2014). We find that the rest-frame NUV-r and r-J color criteria, combined with low 24 μm emission, provides a robust selection of truly quiescent galaxies out to $z = 3$. Additionally, we find evidence of radio emission in excess of the expected total star formation in quiescent galaxies at $z \sim 0 - 1.5$, indicative of a ubiquitous presence of low-luminosity radio AGN among them.

Keywords. galaxies: evolution; galaxies: fundamental parameters (classification, colors, luminosities, masses, radii, etc.); galaxies: high-redshift; galaxies: photometry; infrared: galaxies; radio continuum: galaxies

1. Introduction

The advent of deep near-infrared (NIR) surveys has extended the statistical studies of massive galaxies to the high redshift Universe. By fitting stellar population synthesis models to multi-wavelength photometry, one can obtain constraints on galaxy properties such as stellar masses ($M_\star$), and star formation rates (SFR). It has been shown that $z \sim 2$ galaxies, like their local counterparts, follow a bimodal distribution on the SFR-$M_\star$ plane (star-forming galaxies SFG vs quiescent galaxies QG; e.g. Wuyts *et al.* 2011). Over time, more galaxies "quench" their SF and become quiescent (e.g. Ilbert *et al.* 2013). These conclusions are based on selecting QGs as: (1) having unobscured SFR (obtained from spectral energy distribution fitting) below a certain threshold; or (2) rest-frame color selections, such as U-V vs V-J (Williams *et al.* 2009), or NUV-r and r-J (Ilbert *et al.* 2013). However, these selection methods rely on the assumption that a universal dust attenuation law (e.g. Calzetti *et al.* 2000) applies. It is well-understood that the age-dust degeneracy is hard to break without IR information when galaxies are barely detected at rest-frame UV, which is the case for QG candidates. An independent check is to measure the reprocessed dust emission at mid- and far-IR wavelengths, to measure the obscured SFR of QG candidates. A recent *Herschel* stacking analysis by Viero *et al.* 2013 found that massive QGs at $z > 2$ have IR luminosities (L_{IR}) comparable to local starbursts, inconsistent with the quiescence inferred from the UV continua as well as their low 24 μm stacked flux densities (Fumagalli *et al.* 2014, Utomo *et al.* 2014). If QGs harbor significant dust-obscured SF, it would challenge the need for powerful quenching mechanisms.

Table 1. *Spitzer* 24 μm and *Herschel* detected fractions for QGs

	$\log(M_\star/M_\odot)$			
	11 – 12.2	**10.6 – 11**	**10.2 – 10.6**	**9.8 – 10.2**
Redshift	$f_{\rm QG,24}$ ($f_{\rm QG,H}$)	$f_{\rm QG,24}$ ($f_{\rm QG,H}$)	$f_{\rm QG,24}$ ($f_{\rm QG,H}$)	$f_{\rm QG,24}$ ($f_{\rm QG,H}$)
0.1 – 0.5	0% (0%)	0.4% (0.2%)	0% (0%)	0.2% (0%)
0.5 – 1.0	4.6% (1.4%)	4.0% (1.0%)	2.2% (0.3%)	0.4% (0.1%)
1.0 – 1.5	9.9% (2.4%)	5.3% (1.0%)	2.4% (0%)	0.6% (0%)
1.5 – 2.0	8.8% (1.5%)	9.0% (1.4%)	7.5% (1.0%)	-
2.0 – 2.5	19.4% (6.0%)	17.4% (2.5%)	-	-
2.5 – 3.0	13.3% (2.7%)	-	-	-

Notes:
$f_{\rm QG,24}$ is the fraction of QGs (classified by their NUV−r and r−J colors) with 24 μm-inferred SFRs > 20 $M_\odot$yr^{-1}. $f_{\rm QG,H}$ is the fraction of QGs fulfilling the above 24 μm criterion that are also detected in at least two *Herschel* PACS+SPIRE bands (S/N $\geqslant$ 5).

2. Method

In Man *et al.* 2014, we perform a stacking analysis on a sample of ∼14200 QGs with $M_\star = 10^{9.8-12.2}\,M_\odot$ out to $z = 3$, selected from the UltraVISTA survey targeting the COSMOS field. The galaxy parameters are estimated from fitting the UV-to-IRAC photometry (Ilbert *et al.* 2013). QGs are separated from SFGs using their rest-frame NUV-r and r-J colors. By cross-matching the UltraVISTA catalog to the MIPS 24 μm and *Herschel* catalogs (Le Floc'h *et al.* 2009, Lee *et al.* 2013), we find that a small fraction of QGs have strong 24 μm (in some cases, also *Herschel*) detections, equivalent to having SFR exceeding 20 $M_\odot$/yr as inferred from their 24 μm flux densities. The IR detection fractions increases with redshift, as shown in Table 1. They may be misclassified due to their faint optical photometry, or host obscured active galactic nuclei (AGN), therefore we exclude them from our stacking.

We obtain three independent SFR estimates by stacking the *Spitzer* MIPS 24 μm, *Herschel* (PACS and SPIRE), and Very Large Array 1.4 GHz radio maps, respectively. We apply median stacking to the MIPS 24 μm and VLA map. As for the *Herschel* PACS and SPIRE maps, we apply the global stacking and deblending method presented in Kurczynski & Gawiser 2010. This is effectively average stacking that corrects for the contribution of sources clustered within the beam, similar to the method used in Viero *et al.* 2013. The MIPS 24 μm stacked fluxes are converted to L_{IR} using the calibration of Rujopakarn *et al.* 2013, while the *Herschel* stacked fluxes are modeled using a modified blackbody to determine the L_{IR}. The L_{IR} are then converted to SFR using the Kennicutt 1998 relation. Assuming that all the radio emission originates from SF, and a radio spectral index $\alpha = -0.8$, rest-frame 1.4 GHz luminosities ($L_{1.4\,\rm GHz}$) are derived from the radio stacks and subsequently converted to SFR$_{\rm radio}$ using the $L_{1.4\,\rm GHz}$-SFR calibration by Bell 2003.

3. Summary of results

The three independent SFRs measured from MIR, FIR and radio stacking, as a function of $M_\star$ and z, are shown in Fig. 1. We summarize the two major results here:

Rest-frame color selections identify truly quiescent galaxies (in most cases)

The MIPS 24 μm and *Herschel* stacks on the QGs without strong IR detections indicate that they indeed have a suppressed level of obscured SF, compared to the SFGs. This is consistent with the expectation from their low unobscured SFRs, as indicated by their UV-to-NIR photometry and rest-frame colors.

We note that if we include the small fraction of QGs with IR detections, we reproduce the results of Viero *et al.* 2013, who find that $z \sim 2$ massive QGs have very high L_{IR}

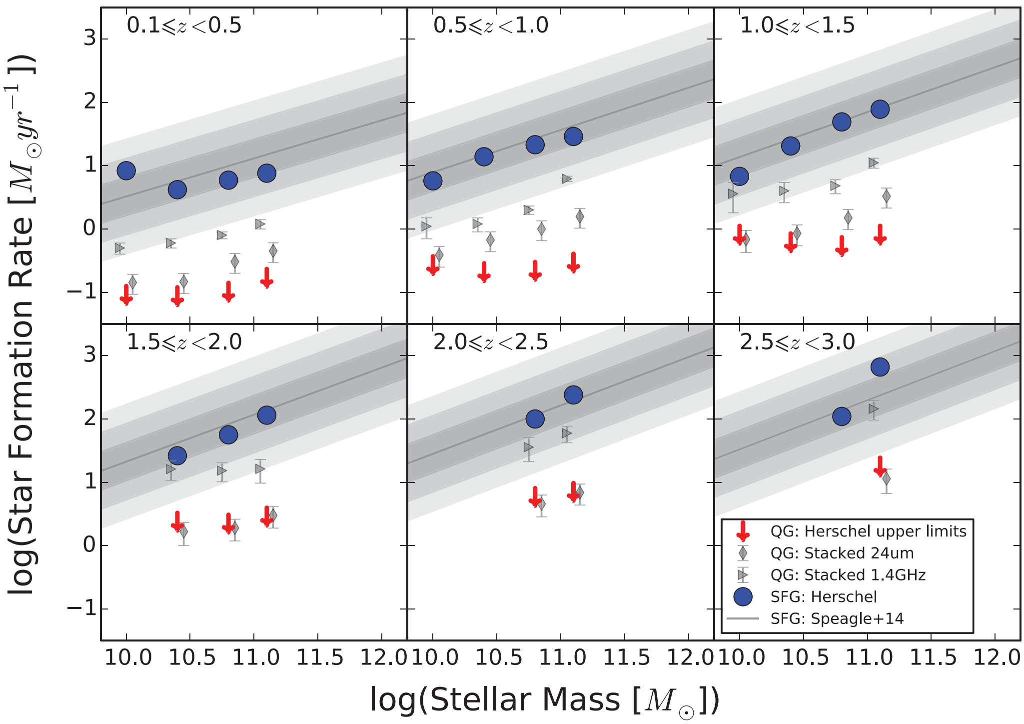

Figure 1. SFRs inferred from stacking as a function of $M_\star$ and z. Blue circles and red downward arrows represent the SFRs from global deblending and stacking in *Herschel* for SFGs and QGs respectively, with the latter ones representing 3σ upper limits for QGs since they are consistent with no detection. Assuming the 24 μm and radio emissions originate from SF only, we plot the inferred SFRs as gray diamonds and triangles. SFR_{radio}, as well as SFR_{24} at $z < 1.5$, show clear offsets from SFR_H for QGs, therefore part of the radio emission in QGs likely arises from low-luminosity AGN. The SFR-$M_\star$ complied by Speagle *et al.* 2014 is plotted as gray lines, and the $1-3\times$ observed dispersion (σ_{SFR}=0.3) are shown as dark-to-light shades.

($> 10^{12} L_\odot$). Although rare, the IR-detected QG candidates boost the average *Herschel* fluxes of QG samples if they are not removed a priori. As these IR-detected QG candidates have obscured SFRs comparable or even higher than SFGs, they are likely misclassifications due to the faint optical photometry. This is reflected in the higher IR detection rates at higher z, as shown in Table 1. We plan to follow them up spectroscopically, in order to draw firm conclusions regarding their nature.

Average radio emission is in excess — indirect evidence for AGN

The SFR inferred from the radio stacks are a few factors higher than the total SFR derived from other indicators (*Herschel* stacks, MIPS 24 μm stacks, UV-to-NIR SED fitting), as shown in Fig. 1. This implies that mechanisms other than SF must contribute to the radio emission of massive QGs. We interpret it as indirect evidence for a widespread presence of low-luminosity radio AGN among massive QGs. This is not a complete surprise as radio AGN preferentially reside in QGs, and provide a mechanism to keep SF quenched through feedback. Interestingly, Olsen *et al.* 2013 reach a similar conclusion via stacking X-ray emissions of massive QGs.

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