Spectral Energy Distributions of Companion Galaxies to $z \sim 6$ Quasars

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Abstract

Massive, quiescent galaxies are already observed at redshift $z \sim 4$, i.e., $\sim 1.5$ Gyr after the big bang. Current models predict them to be formed via massive, gas-rich mergers at $z > 6$. Recent ALMA observations of the cool gas and dust in $z \gtrsim 6$ quasars have discovered [C II]- and far-infrared-bright galaxies adjacent to several quasars. In this work, we present sensitive imaging and spectroscopic follow-up observations, with HST/WFC3, Spitzer/IRAC, VLT/MUSE, Magellan/FIRE, and LBT/LUCI-MODS, of ALMA-detected, dust-rich companion galaxies of four quasars at $z \gtrsim 6$, specifically acquired to probe their stellar content and unobscured star formation rate. Three companion galaxies do not show significant emission in the observed optical/IR wavelength range. The photometric limits suggest that these galaxies are highly dust-shrouded, with unobscured star formation rates $\mathrm{SFR}_\mathrm{UV} < 10^{-4} \ M_\odot \ yr^{-1}$, and a stellar content of $\ M_\star < 10^{10} \ M_\odot$. However, the companion to PJ167–13 shows bright rest-frame UV emission (F140W AB = 25.48). Its spectral energy distribution resembles that of a star-forming galaxy with a total SFR $\sim 50 \ M_\odot \ yr^{-1}$ and $\ M_\star \sim 9 \times 10^9 \ M_\odot$. All the companion sources are consistent with residing on the galaxy main sequence at $z \sim 6$. Additional, deeper data from future facilities, such as the James Webb Space Telescope, are needed in order to characterize these gas-rich sources in the first gigayear of cosmic history.

Key words: cosmology: observations – early universe – galaxies: high-redshift – quasars: general

1. Introduction

A large population of massive ($\sim 10^{11} \ M_\odot$), quiescent, and compact galaxies has been observed at very early cosmic times ($2 < z < 4$) when the universe was between $\sim 1.6$ and $\sim 3.6$ Gyr old (e.g., van Dokkum et al. 2008; Straatman et al. 2014). Several studies suggest that these galaxies formed from gas-rich, major mergers at $3 \lesssim z \lesssim 7$ (e.g., Hopkins et al. 2008; Wuyts et al. 2010). High-redshift ($z \gtrsim 3$) submillimeter galaxies (SMGs) have been invoked as possible progenitors of these massive $z \gtrsim 2$ “red-and-dead” sources (e.g., Toft et al. 2014).

SMGs are galaxies with large infrared luminosities ($L_\mathrm{IR} \gtrsim 10^{12} \ L_\odot$), which are thought to experience short and intense episodes of star formation (e.g., Blain et al. 2002; Spilker et al. 2014). Recent studies show that SMGs at $z \sim 3.5$ often have subcomponents or companions when observed at kiloparsec-scale resolution (e.g., Hodge et al. 2013b; Gomez-Guijarro et al. 2018), or located in dense environments (e.g., Hodge et al. 2013a; Riechers et al. 2014), suggesting that these sources have experienced recent mergers. At even higher redshifts ($z \gtrsim 6$), only a few SMGs not hosting a central active galactic nucleus have been observed. Riechers et al. (2013) found a dust-obscured, extremely star-forming SMG at $z = 6.3$ with a star formation rate SFR $\sim 3000 \ M_\odot \ yr^{-1}$; Fudamoto et al. (2017) and Zavala et al. (2018) discovered a $z = 6.03$ galaxy whose SFR was somewhat smaller ($\sim 950 \ M_\odot \ yr^{-1}$); Marrone et al. (2018) discovered a pair of massive SMGs with similar SFR at $z \sim 6.9$. The only other highly star-forming ($\gtrsim 10^{10} \ L_\odot$) objects known thus far at such redshifts, with luminosities extending to slightly fainter values ($L_\mathrm{IR} \sim 10^{11} \ L_\odot$) than classical SMGs, are the host galaxies of $z \gtrsim 6$ quasars (e.g., Walter et al. 2009; Venemans et al. 2012, 2018; Wang et al. 2013; Decarli et al. 2018).

Quasars are among the most luminous sources in the universe; in recent years, the number of such objects known at $z \gtrsim 6$ greatly increased, thanks to the advent of deep, large-area sky surveys (e.g., Fan et al. 2006; Bañados et al. 2016, 2018, Mazzucchelli et al. 2017b; Reed et al. 2017, 2019; Matsuoka et al. 2018; Wang et al. 2018). Observations of the stellar light from their host galaxies have been very challenging, due to the much brighter, nonthermal radiation from the central engine (e.g., Decarli et al. 2012; Mechtley et al. 2012). On the other hand, emission from cool gas and dust in the observed (sub)millimeter wavelength regime has been studied in several sources, providing a wealth of information on the composition, dynamics and conditions in the interstellar medium (ISM) of their hosts (e.g., Maiolino et al. 2009; Willott et al. 2015; Venemans et al. 2016, 2017). In particular, the singly ionized $158 \mu m$ carbon emission line, [C II], is one of the main coolants of the ISM and is very bright (it can emit up to 1% of the total far-infrared emission in star-forming galaxies). It has been used extensively as a key diagnostic of galactic physics (see Carilli & Walter 2013 and Diaz-Santos et al. 2017 for reviews, and Herrera-Camus et al. 2018a, 2018b for recent works).
Recently, Decarli et al. (2018) and Venemans et al. (2018) undertook a survey of [C II] and underlying dust continuum emission in 27 quasar host galaxies at $z \gtrsim 6$, with the Atacama Large Millimeter Array (ALMA), at a resolution of $1 ''$, i.e., $\sim$5.5 pkpc at those redshifts. Surprisingly, they serendipitously discovered [C II]- and far-infrared-bright companion galaxies in the fields of four quasars, with projected separations of $\lesssim 60$ kpc and line-of-sight velocity shifts of $\lesssim 450$ km s$^{-1}$ (Decarli et al. 2017). In addition, Willott et al. (2017) used ALMA observations at $0''7$ resolution (i.e., $\sim$4 pkpc at $z \sim 6.5$) to find a very close companion galaxy to the quasar PSO J167.6415−13.4960 at $z \sim 6.5$, at a projected distance of only 5 kpc and velocity separation of $\sim 300$ km s$^{-1}$. Similar sources have also been observed in lower-redshift systems (e.g., at $z \sim 5$; Trakhtenbrot et al. 2017). These findings, together with the discovery of a couple of galaxies adjacent to two quasars at $z \sim 4$ and 6 (McGreer et al. 2014), a Ly$\alpha$-emitting galaxy $\sim$12 kpc away from a $z \sim 6.6$ quasar (Farina et al. 2017), and a close quasar-galaxy pair at $z \sim 6$ (Neelamn et al. 2019), provide observational support to the theoretical paradigm that $z \gtrsim 6$ quasars reside in rich galactic environments (e.g., Vanlenter & Rees 2006; Overzier et al. 2009; Angulo et al. 2012). However, we note that other studies did not find overdensities of [C II]/dust-continuum-emitting galaxies (e.g., Venemans et al. 2016; Champagne et al. 2018), or of LAEs (e.g., Bahados et al. 2013; Mazzucchelli et al. 2017a; Ota et al. 2018) around a sample of $z \gtrsim 6$ quasars. The observed [C II]-bright companion galaxies have been considered as potential progenitors of $z \sim 4$ red-and-dead galaxies (Decarli et al. 2017). Previous optical/NIR observations have failed to detect rest-frame UV/optical emission from any of these companion galaxies, suggesting that they are heavily obscured and limiting the study of their overall physical properties (Decarli et al. 2017).

In this work, we present new sensitive optical/NIR follow-up observations obtained from several ground- and space-based facilities, specifically designed to probe companion galaxies to four $6 < z < 6.6$ quasars. In particular, we aim to observe the bulk of their stellar emission in the rest-frame optical wavelength range ($\sim$5000–7000 Å), in order to assess their total stellar mass ($M_*$). We also aim to measure their rest-frame UV radiation ($\sim$1200–1500 Å), to probe the contribution from the young stellar population, and to determine how much of the star formation is unobserved. We observed the fields around three quasars presented in Decarli et al. (2017): SDSS J0842+1218, PSO J231.6576−20.8335, and CFHQS J2100−1715 (hereafter J0842, PJ231, and J2100, respectively), and around PSO J167.6415−13.4960 (hereafter PJ167; Venemans et al. 2015b; Willott et al. 2017). In the following sections, we will refer to each of the respective companions as “quasar_short_name”c. We also obtained data for a millimeter-bright source, detected only in the dust continuum emission, close to the quasar VIK J2211−3206 (hereafter J2211; B. Venemans et al. 2019, in preparation). This galaxy is part of the sample of dust-continuum-emitting sources discovered around several $z \sim 6$ quasars by Champagne et al. (2018), for which no redshift confirmation is available. We present our follow-up data and discuss our constraints on the properties of this source in Appendix A.

This paper is structured as follows. In Section 2 we present our observations and data reduction. In Section 3.1 we compare the companion galaxies’ photometry with the spectral energy distributions (SEDs) of local galaxies, and in Section 3.2 we estimate the (un)obscured star formation rates from the rest-frame (UV) optical emission. In Section 3.3 we place the $M_*$ and SFR of the companions in the context of observations of SMGs and normal star-forming galaxies at comparable redshifts. Finally, in Section 4 we present our conclusions and outlook.

The magnitudes reported in this work are in the AB system. We use a $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Observations and Data Reduction

We collect available observations of the fields in our sample, either from the literature or obtained with dedicated follow-up campaigns. The coordinates, redshifts, spatial and velocity separations of the quasars, and their companion galaxies are reported in Table 1. Details on the optical/NIR observations used here, i.e., dates, instruments/telescopes, exposure times and filters, are shown in Table 2.

2.1. Optical/NIR Spectroscopy

We collected optical and NIR spectroscopic data for the quasars and their respective companions.

We observed the quasars PJ231 and J2100 with the Multi Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) at the Very Large Telescope (VLT), imaging a total field of view of $1 \times 1$ arcmin$^2$, with a spatial resolution of $0''.2$ pixel$^{-1}$ and a

13 This quasar was also recently independently discovered by Chehade et al. (2018), with the name of VST-ATLAS J332.8017−32.1036.

14 The magnitudes reported in this work are in the AB system.
spectral coverage between 4650 Å and 9300 Å. We observed the field of the quasar J2100 using Director’s discretionary time (Program ID: 297.A-5054(A), PI: Decarli) during the nights of 2016 August 25 and 26. Sky conditions were good, with seeing varying from 0''8 to 1''3. PJ231 was observed on 2017 July 2 as a part of our program 099.A-0682A (PI: Farina) in almost photometric sky conditions and median seeing of 0''8. We reduced the data using the MUSE Data Reduction Software (Weilbacher et al. 2012, 2014). The final cubes were then post-processed as in Farina et al. (2017). In particular, the pipeline-produced variance cube was rescaled to match the observed variance of the background at each wavelength channel. This allowed us to compute more realistic errors that reflect possible correlations between neighboring voxels. The spectrum of J2100c was extracted with a fixed aperture of 1'' radius centered at the position derived from our ALMA data. In PJ231, the quasar and companion are separated by only 1''5, requiring careful removal of the quasar contribution. We created a point-spread function (PSF) model directly from the quasar by collapsing the spectral region >2000 km s⁻¹ redward of the Lyα line, at a wavelength not contaminated by strong sky emission. At each wavelength channel, the PSF model was rescaled to match the flux of the quasar within 2 spaxels (0''54) of the central emission and then subtracted. The spectrum of the companion was then extracted from this PSF-subtracted data cube with an aperture of 1'' radius. A more detailed analysis of this full data set will be presented in E. P. Farina et al. (in preparation).

We also acquired spectra of the quasar J0842 with the Multi-Object Double Spectrograph (MODS; Pogge et al. 2010) at the Large Binocular Telescope (LBT), in binocular mode on 2016 May 8 and 10. The orientation of the slit covered both the quasar and the [CII] companion galaxy. We used the 1''/2 slit and the GG495 filter. We collected two exposures of 1320 s, for a total of 2 h 28 m on target. Data reduction was performed with standard Python and IRAF procedures. In particular, we corrected for bias and flat with the modscCDRed package14 and we wavelength- and flux-calibrated the data using IRAF. The wavelength scale was calibrated using bright sky emission lines, delivering an accuracy of ∼0.2 Å at λ > 7000 Å. The standard star GD153 was observed to flux-calibrate the data. We further scale the spectrum of the quasar J0842 to match the observed 2µ limits on the companion’s spectra is detected. In all cases, we estimated the 3σ limits on the Lyα emission line as:

\[ F_{\text{Ly}α,3\sigma} = 3 \times \left( \sum_{i=1}^{N} \text{err}_i^2 \times \sum_{i=1}^{\Delta \lambda_i} \right) \]  

\[ \text{err}_i^2 \times \sum_{i=1}^{\Delta \lambda_i} \]  

14 http://www.astronomy.ohio-state.edu/MODS/Software/modscCDRed/
where \( \text{err} \) is the error vector, and \( N \) is the number of pixels in within a velocity window of (rest frame) 200 km s\(^{-1}\) (i.e., the typical line width measured in LAEs, e.g., Ouchi et al. 2008) around the supposed location of the Ly\( \alpha \) emission line.

Finally, \( \Delta \lambda = \lambda_{i+1} - \lambda_i \) in the considered wavelength interval. Moreover, we calculated the limits on the underlying continuum emission as:

\[
F_{\text{cont,3\sigma}} = 3 \times \sqrt{\sum_{i=1}^{N} \text{err}_i^2},
\]

where we consider here the spectral coverage at hands, excluding noisy regions at the edges. All the estimated values are reported in Table 3.

We note that the emission from the Ly\( \alpha \) line in \( z \sim 6-7 \) LAEs can be redshifted by \( \sim 100-200 \) km s\(^{-1}\) with respect to the [C\( \text{II} \)] line, and/or it can originate from slightly different spatial locations (e.g., Pentericci et al. 2016). Here, the limits we measure by shifting the center of the Ly\( \alpha \) emission by \( \pm 150 \) km s\(^{-1}\) are consistent with the fiducial values reported in Table 3, i.e., we do not significantly detect a blue/redshifted line.

2.2. IR Photometry

We list here the observations and data reduction of the imaging follow-up data, obtained with ground- and space-based instruments.

2.2.1. LUCI/LBT

We imaged the field of J2100 in the J band (\( \lambda_c = 1.247 \mu \text{m} \) and \( \Delta \lambda = 0.305 \mu \text{m} \)) with the Utility Camera in the Infrared (LUCI1 and LUCI2; Seifert et al. 2003) at the LBT, in binocular mode. We reduced the data following standard techniques, i.e., we subtracted the master dark, divided by the master flat field, and median-combined the frames after aligning them using field stars. The final astrometric solution

![Figure 1. Spectra at the locations of the companions to PJ231, J2100, and J0842, acquired with the FIRE and MODS spectrographs, and extracted from the MUSE data cubes. We highlight the spectral regions where the flux calibration is less reliable with gray shaded areas. Dashed blue lines highlight the expected positions of the respective Ly\( \alpha \) emission lines, established from the observations of the narrow [C\( \text{II} \)] emission with ALMA. The surrounding regions of \( \pm 100 \) km s\(^{-1}\) (rest frame), used to estimate limits on the Ly\( \alpha \) emission line in the companion galaxies, are also shown with light blue shaded areas.](image-url)
used the Gaia Data Release 1 catalog\textsuperscript{15} (DR1; Gaia Collaboration et al. 2016a, 2016b) as reference. We flux-calibrated the image with respect to the 2MASS Point Source Catalog. The seeing of the reduced image is 0\textquoteleft\textquoteleft 98. We calculated the depth of the image by distributing circular regions with radius equal to half of the seeing over the frame, in areas with no sources. The 1σ error of our image is the standard deviation of the Gaussian distribution of the fluxes calculated in these apertures. We do not detect, at signal-to-noise ratio (S/N) > 3, any emission at the location of the companion, after performing forced photometry in a circular aperture whose diameter is corresponding to the seeing (see Figure 2). The 3σ limit magnitude that we will use in the following analysis is $J = 26.24$ ($F_J = 0.116$ μJy; see Table 4).

2.2.2. WFC3/HST

We obtained new observations of all the targets studied here with the Wide Field Camera 3 (WFC3), on board the Hubble Space Telescope (HST), using the F140W filter ($\lambda_c = 1.3923$ μm and $\Delta \lambda = 0.384$ μm; Program ID:14876, PI:E. Bañados). For the quasar J0842, previous WFC3 observations in the F105W filter ($\lambda_c = 1.0552$ nm and $\Delta \lambda = 0.265$ nm) were also retrieved from the Hubble Legacy Archive\textsuperscript{16} (Program ID:12184, PI: X. Fan). We refer to Table 2 for further details on this data set. We analyzed both the archival and new observations in a consistent way. We considered the reduced data produced by the HST pipeline, and we took the zero-point photometry from the WFC3 Handbook.\textsuperscript{17} We recalibrated the astrometry using the Gaia DR1 catalog (see also Section 2.2.1). We calculated the depth of the images in an analogous way as in Section 2.2.1, considering here circular areas of 0\textquoteleft\textquoteleft 4 radius (containing the 84% of the flux from a point source\textsuperscript{18}). We performed aperture photometry using this aperture radius at the positions of the companions. The companion sources of J0842, J2100, and PJ231 were not detected in the F140W filter, and J0842c was also not detected in the F105W image. We report all the 3σ limit fluxes in Table 4. We show the observations of all the fields studied in this work in the F140W filter in Figure 3, and the F105W image of J0842 in Figure 4. In the case of PJ167, the companion is located at a projected distance of only 0\textquoteleft 79, and it is blended with the quasar emission. In order to recover meaningful constraints on the brightness of PJ167c, it is necessary to subtract the quasar contribution by modeling the image PSF. We used the bright star 2MASS J11103221–1330007, in the proximity of PJ167, in order to create an empirical PSF model from the same image. This source is located at a distance of only 30\textquoteleft from the quasar, limiting the errors due to the changes in the PSF over the field. Its $J$ and $H$ magnitudes from the 2MASS Point Source Catalog are 15.249 and 15.105, respectively. The corresponding $J – H$ color of 0.144 is therefore close to that of the quasar ($J – H = 0.216$). We shifted, scaled, and subtracted the PSF model from the quasar emission using the software GALFIT (version 3.0.5; Peng et al. 2002, 2010). In Figure 5 we show the native HST image, the PSF star model, and the residual frame, in which the bright quasar emission has been subtracted. The companion galaxy is well isolated, and its F140W PSF magnitude, measured with GALFIT, is equal to 25.48 ± 0.17 ($F_{140W} = 0.23^{+0.04}_{-0.03}$ μJy). Diffuse emission extending from the companion to the quasar is also tentatively recovered. Additional, high-resolution imaging and spectroscopy are needed to securely confirm and characterize such emission.

2.2.3. IRAC/Spitzer

The fields of all the objects in our sample were observed in the [3.6] ($\lambda_c = 3.550$ μm and $\Delta \lambda = 0.750$ μm) and [4.5] ($\lambda_c = 4.493$ μm and $\Delta \lambda = 1.015$ μm) filters with the InfraRed Array Camera (IRAC; Fazio et al. 2004; Program ID:13066, PI: C. Mazzucchelli; see Table 2). We also use archival data of J0842 (Program ID:40356, PI: X. Fan), covering the IRAC filters [5.8] ($\lambda_c = 5.731$ μm and $\Delta \lambda = 1.425$ μm) and [8.0] ($\lambda_c = 7.872$ μm and $\Delta \lambda = 2.905$ μm; see Table 2).

We adopt the reduced data from the Spitzer pipeline, and the photometric calibration (i.e., photometric zero-point and aperture correction values) specified in the IRAC Instrument Notebook.\textsuperscript{19} As in the case of the HST/WFC3 observations, we refine the astrometric solution using the recent Gaia DR1 catalog. Given the limited spatial sampling of the IRAC camera (0\textquoteleft 6 pixel\textsuperscript{-1}) and the depth of our [3.6] and [4.5] images, the companion galaxies studied here are blended either with the much brighter quasar, or with foreground sources (see Figure 3). Hence, one needs to properly model and remove these sources. In order to model the PSF, which is undersampled in the IRAC data, we resample the native images over a grid of 0\textquoteright 12 pixel\textsuperscript{-1} resolution, using the IRAF task magnify. In each magnified image, we select a collection of stars identified as such in the HST/WFC3 data within 1\textquoteright × 1\textquoteright of the quasar. We obtain the final PSF model for each image by shifting, aligning, scaling, and combining the images of the selected stars. The number of stars used in each field ranges between 4 and 9. We use GALFIT to sample the PSF image to the original resolution (0\textquoteright 6 pixel\textsuperscript{-1}), and to model and subtract the emission from the quasar and any foreground objects. In Figure 3, we show the postage stamps of the IRAC [3.6] and [4.5] images, and the corresponding images of the residuals. No clear emission from

\textsuperscript{15}http://www.cosmos.esa.int/web/gaia/dr1
\textsuperscript{16}https://hla.stsci.edu/
\textsuperscript{17}http://www.stsci.edu/hst/wfc3/analysis/ir_phot_zpt
\textsuperscript{18}http://www.stsci.edu/hst/wfc3/analysis/ir_ea
\textsuperscript{19}http://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/IRAC_Instrument_Handbook.pdf
the companion galaxies is detected in any of the residual images. We quantify the limits on the photometry of the companions as follows. For each image, we run GALFIT subtracting a source at the exact position of the companion modeled as a PSF and scaled to a fixed magnitude, which we vary between 21 and 25, in steps of 0.1 mag. When adopting magnitudes smaller (i.e., brighter fluxes) than the limit flux to which our image is sensitive, the subtraction will leave a negative residual. We perform aperture photometry in the residual image at the companion position in an aperture of 2″ radius, and we compare the measured flux with the image 3σ flux limit. The adopted flux limit was measured on the same area used for the forced photometry, and by evaluating the background rms in an annulus of radius 14″ and width of 10″ centered on the companion. We assume that the 3σ limit magnitude is the value at which the measured absolute flux in the residual image is equal to the 3σ flux limit. We report these values in Table 4. Finally, we analyze the archival J0842 Spitzer/IRAC observations (see Figure 4), which are much shallower (see Table 2), because they were designed only to detect the bright quasar. No foreground objects overlap the companion location, and we therefore perform aperture photometry on the native images, using the same aperture as in the observations in the [3.6] and [4.5] channels. We do not detect any source at S/N > 3. We report the corresponding flux limits in Table 4.

### 3. Analysis

In this section, we characterize the SEDs of four companions to z ~ 6 quasars, by comparing them with a few examples of local galaxies and by modeling their emission with an SED fitting code. We estimate (or set upper limits to) their unobscured/obscured star formation activity observed in the rest-frame UV/IR range. Finally, we place our measurements in the context of observations of star-forming galaxies and starbursts at similar redshift.

#### 3.1. Spectral Energy Distribution

We first compare the SEDs of our companions with those of prototypical galaxies in the local universe. We consider the SEDs of normal star-forming spiral galaxies (M51 and NGC 6946), starbursts (M82), and ultraluminous infrared galaxies (ULIRGs; Arp 220), from Silva et al. (1998). M51 is a nearby (D = 9.6 Mpc) spiral (Sbc) interacting galaxy, which has been studied in detail over a wide range of wavelength and physical scales (e.g., Leroy et al. 2017). NGC 6946, found at a distance of 6.72 Mpc, is an intermediate (Scd) spiral galaxy (Degioia-Eastwood et al. 1984). Its size is approximately a third of that of our Galaxy and it hosts roughly half of the stellar mass (e.g., Engargiola 1991). M82 is a prototypical edge-on starburst (with a galaxy-wide SFR ~ 10−30 M⊙ yr−1; Forster Schreiber et al. 2003), whose intense activity has been most probably triggered by a past interaction with the neighboring galaxy M81 (e.g., Yun et al. 1994). Arp 220 is one of the closest (77 Mpc) and best studied ULIRGs, with a total infrared luminosity of LIR = 1.91 × 1012 L⊙ (Armus et al. 2009). It is thought to be the result of a merger that happened ~3–5 Myr ago (e.g., Joseph & Wright 1985; Baan & Haschick 1995; Scoville et al. 1998; Downes & Eckart 2007), and has extreme conditions in its nucleus (e.g., with an attenuation of A_V = 2 × 10^27 mag; Scoville et al. 2017). Here, we shift the observed SEDs of these local galaxies to the redshifts of the companions, and we scale them to match the 1.2 mm flux retrieved in the ALMA observations. We plot the SEDs, together with the photometry of the companions presented here, in Figure 6.

The limits on rest-frame UV/optical brightness of PJ231c, J2100c, and J0842c are obtained from the galaxy templates considered here, with the exception of Arp 220. These companions have inferred luminosities in the range of (ultra-)luminous galaxies (e.g., (0.9–5) × 10^{12} L⊙; Decarli et al. 2017). On the other hand, the rest-frame UV emission of PJ167c is detected in our HST/WFC3 observations (see Section 2). Its UV-to-submillimeter ratio is comparable to that of the star-forming galaxy NGC 6946, while the limits from our Spitzer/IRAC data suggest that it has lower stellar content.

We compute the star formation rates for PJ231c, J2100c, and J0842c assuming that their SEDs are equivalent to that of Arp 220, shifted in redshift and scaled as in Figure 6. We derive their star formation rates from the dust emission in the rest-frame infrared region (SFR_{IR}), assuming that the nonobscured SFR is negligible (see Section 3.2). We calculate the total IR luminosity by integrating the emission from 3 to 110 μm, and we measure the SFR as SFR = 1.49 × 10^{−10} LIR (Kennicutt & Evans 2012). The obtained values range between 120 and 700 M⊙ yr−1. We note that, if we had instead assumed a modified blackbody model, f_ν ∝ B_ν(T_d^{1/4}), and adopted typical parameters for high-redshift galaxies (T_d = 47 K and β = 1.6; e.g., Beelen et al. 2006; Venemans et al. 2016), we would have derived comparable star formation rate values (~140–800 M⊙ yr−1; see also Decarli et al. 2017).

We can obtain conservative upper limits on the companion stellar masses by subtracting their gas mass (M_{gas}) from their dynamical mass (M_{dyn}). The latter can be obtained from the widths of the [C II] emission line observed with ALMA (see Decarli et al. 2017). We note, however, that these estimates are based on a number of important assumptions on the companions geometry and dynamics (i.e., they are virialized systems), and that they are obtained from data with a relatively modest resolution of ~1″. We list all dynamical masses in Table 4. Photometric Measurement of the Companion Galaxies to z ~ 6 Quasars Studied in This Work (See Section 2)

| Name | F_1 (μJy) | F_{1050} (μJy) | F_{1400} (μJy) | F_{3.6 μm} (μJy) | F_{4.5 μm} (μJy) | F_{8 μm} (μJy) | F_{10 μm} (μJy) | F_{2 μm} (μJy) |
|------|-----------|---------------|---------------|-----------------|-----------------|----------------|----------------|--------------|
| SDSS J0842+1218c | ... | <0.154 | <0.061 | <1.06 | <9.54 | <12.6 | 0.36 ± 0.12 |
| PSO J167.6415–13.8960c | ... | 0.23 ± 0.03 | 0.78 | <1.28 | ... | ... | 0.16 ± 0.03 |
| PSO J231.6576–20.8335c | ... | <0.053 | 0.64 | <2.79 | ... | ... | 1.73 ± 0.16 |
| CFHQS J2100–1715c | <0.116 | ... | 0.53 | <1.07 | ... | ... | 2.05 ± 0.27 |

Note. The limits provided are at 3σ significance.

*This flux measurement comes from recent 0″35, i.e., ~2 pkpc at z ~ 6.5, ALMA observations (Neeleman et al. 2019).
Table 5. On the other hand, we can estimate $M_{\text{gas}}$ from the dust content ($M_{\text{dust}}$). We take these values from Decarli et al. (2017): $M_{\text{dust}}$ are measured following the prescription by Downes et al. (1992), while $M_{\text{gas}}$ are obtained assuming a typical gas-to-dust ratio of $\sim 100$ (e.g., Berta et al. 2016). We obtain upper limits on the stellar content ranging between $\sim 16$ and $21 \times 10^{10} M_{\odot}$. In the following analysis, we utilize the latter values as upper limits on the stellar masses of the companions (see Table 5 and Figures 7 and 8).

Alternatively, we can compare our photometric measurements with synthetic galaxy templates. We use the SED fitting code MAGPHYS (Da Cunha et al. 2008), which uses an energy balance argument to combine simultaneously the radiation from the stellar component, the dust attenuation, and the re-emission in the rest-frame IR wavelength range. We consider here the MAPGPHYS-high-$z$ extension (Da Cunha et al. 2015), which was specifically designed to characterize a sample of SMGs at $3 < z < 6$ (see also Section 3.3). In particular, this version included younger galaxy templates, with higher dust extinction and a wider choice of star formation histories. Nevertheless, fitting the photometry of the companion galaxies presented here with any code is hard, due to the few (and most of the time only one) broadband detections for each source. This is reflected in strong parameter degeneracies in the fit. Another issue is represented by the potentially inappropriate coverage of the parameter space considered in the fitting machine, which might not be modeling the properties of the peculiar galaxies considered here. Therefore we choose to fit only the companion of PJ167, whose emission is retrieved in more than one broad band. In Figure 6, we show the best-fit template from MAGPHYS-high-$z$ for this galaxy. We take the 50th and 16th/84th percentiles of the marginalized probability distributions as the best-fit values and uncertainties of its SFR and stellar mass. The SED of PJ167c is consistent with that of a star-forming galaxy, with a SFR of $\dot{M}_{\text{SFR}} = 3^{+5}_{-3} \times 10^{10} M_{\odot} \text{yr}^{-1}$, with a stellar mass of $M_{*} = 0.84^{+0.64}_{-0.40} \times 10^{10} M_{\odot}$, a moderate dust extinction ($A_V = 0.66^{+0.35}_{-0.25}$ mag) and a dust content of $M_d = 4.7^{+1.7}_{-1.2} \times 10^7 M_{\odot}$.

Finally, we note that, given the close spatial/velocity separation of the companions and the quasar hosts, they are very likely found in physical connection. In particular, PJ167c is located at only $5 \text{pkpc}/140 \text{km s}^{-1}$ away from PJ167, and emission linking these systems is observed both in the dust continuum and the [C II] line (with a smooth velocity gradient; Decarli et al. 2017; Neeleman et al. 2019) and, tentatively, in the rest-frame UV (see Figure 5). This evidence, together with a measured high velocity dispersion of the cool gas ($\sim 150 \text{km s}^{-1}$; Neeleman et al. 2019) may suggest that these galaxies have already entered an advanced merging stage.

Figure 3. Postage stamps ($20'' \times 20''$) of the four fields (quasar-companion) considered in this study. We also report the residual IRAC images after removing the emission from the quasar and nearby foreground sources (see Section 2.2.3). The positions of the companions and of the quasars are highlighted with magenta circles (of $1''$ radius) and red crosses, respectively.
3.2. SFR$_{UV}$ versus SFR$_{IR}$

The rest-frame UV emission of galaxies directly traces young stars, i.e., 10–200 Myr old. It is thus an excellent probe of recent star formation, but it is also heavily affected by dust attenuation. The energy of the UV photons is absorbed by the dust, and re-emitted in the IR. Therefore, there also exists a natural correlation between star formation rate and IR emission (see Kennicutt & Evans 2012 for a review).

We here first consider the contribution from the obscured star formation activity, as observed in the rest-frame IR range (SFR$_{IR}$). For J2100c, J0842c, and PJ231c, we use the values obtained from the Arp 220 SED (see Section 3.1 and Table 5). In the case of PJ167c, we follow the method described in Section 3.1 to derive its SFR$_{IR}$, but, instead of Arp 220, we use the best SED from the MAGPHYS-high-$z$ fit (see Figure 6 and Table 5).

An alternative way of computing the star formation rate is through the luminosity of the [C II] emission line ($L_{[C\text{ II}]}$; e.g., De Looze et al. 2011, 2014; Sargsyan et al. 2012; Herrera-Camus et al. 2015). Here, we take the values of $L_{[C\text{ II}]}$ reported in Decarli et al. (2017), ranging from $\sim$260 to $\sim$730 $M_\odot$ yr$^{-1}$, i.e., of the same order of magnitude as those measured from the dust continuum. For PJ167c, we consider the measurement of the [C II] line from recent high-resolution ALMA observations, i.e., $F_{[C\text{ II}]} = 1.24 \pm 0.09$ Jy km s$^{-1}$ (Neeleman et al. 2019). We measured the corresponding [C II] luminosity and star formation rate following Carilli & Walter (2013) and De Looze et al. (2014), respectively. In Table 5 we report all the SFR$_{[C\text{ II}]}$ values.

On the other hand, we can obtain measurements of (or limits on) the unobscured contribution to the SFR in the companions, using our HST/WFC3 sensitive observations in the F140W filter. We consider the conversion between far-UV (0.155 $\mu$m) luminosity ($L_{\text{FUV}}$) and SFR$_{\text{UV}}$ provided by Kennicutt & Evans (2012):

$$\log \left[ \frac{\text{SFR}_{\text{UV}}}{M_\odot \text{ yr}^{-1}} \right] = \log \left[ \frac{L_{\text{FUV}}}{\text{erg s}^{-1}} \right] - C_{\text{FUV}}$$

with $C_{\text{FUV}} = 43.35$. We report in Table 5 the estimated SFR$_{\text{UV}}$ values. The limits achieved by our data are very sensitive, down to a few $M_\odot$ yr$^{-1}$. PJ167c, the only companion detected in the rest-frame UV, has an inferred unobscured star formation rate of $\sim$1 $M_\odot$ yr$^{-1}$. We note that the central wavelength of the broadband filter used here (F140W) corresponds to $\lambda_{\text{rest}} \sim 0.18$–0.2 $\mu$m for $z \sim 6$–6.6, i.e., in between the classically defined FUV and near-UV (NUV; 0.230 $\mu$m). In order to check how this impacts our results, we repeat our star formation rate estimates considering the calibration for the NUV ($C_{\text{NUV}} = 43.17$; Kennicutt & Evans 2012). In this case, we measure SFR values only $\sim 1.5 \times$ larger. We also consider the best SED fit from MAGPHYS-high-$z$ for PJ167c, and we calculate the star formation rate in the exact FUV range. We obtain SFR$_{\text{UV}} \sim 8.0$ $M_\odot$ yr$^{-1}$, consistent, within the errors, with the one measured directly from our HST data.

With the exception of PJ167c, the SFRs measured in the IR in the companions studied here are $\sim$two orders of magnitude larger than the limits we set for the companions rest-frame UV emission. The contribution of SFR$_{\text{UV}}$ to the total star formation budget is therefore negligible. In the case of PJ167c, the unobscured star formation rate is instead only $\sim 6 \times$ lower than the obscured one. Another way of performing this comparison is by looking at the fraction of obscured star formation, defined as $f_{\text{obscured}} = \text{SFR}_{\text{IR}}/\text{SFR}_{\text{IR+UV}}$. Whitaker et al. (2017) reported a tight correlation between this quantity and the stellar mass, irrespective of redshift (up to $z < 2.5$), in a large sample of star-forming galaxies from CANDELS and SDSS. We calculate (limits on) $f_{\text{obscured}}$ for the galaxies presented here. We report these values in Table 5, and we show them in the context of previous observations in Figure 7. Again, the star formation rate of the companions is highly dominated by SFR$_{\text{IR}}$, with obscured fractions ranging between 0.74 and 0.99. In particular, taking into account the large uncertainties on $M_*$ and $f_{\text{obscured}}$, PJ167c is consistent with the expectations from lower-redshift studies. The remaining sources seem to also follow the $z < 2.5$ trend (with the caution that we are here only able to set upper limits on their stellar masses).

3.3. SFR versus Stellar Mass

A large number of studies has found a correlation between the SFR and the stellar mass of star-forming galaxies (“main sequence,” MS) over a wide redshift range ($0 \lesssim z \lesssim 6$; e.g., Brinchmann et al. 2004; Noeske et al. 2007; Rodighiero et al. 2011; Whitaker et al. 2011; for an in-depth analysis of the literature, see Speagle et al. 2014). The tightness ($\sim 0.3$–0.2 dex scatter) of this relation has been interpreted as evidence that “regular” star-forming galaxies have smooth star formation histories, in which the majority of the mass is assembled via
steady accretion of cool gas from the intergalactic medium on long timescales (e.g., Daddi et al. 2007; Steinhardt et al. 2014). On the other hand, highly starbursting galaxies, which lie above the MS, are also observed, and are thought to grow mainly via efficient, merger-triggered star formation events (e.g., Santini et al. 2014). The MS normalization is observed to evolve with redshift, and this trend suggests that higher specific star formation rates are common at early cosmic times (e.g., Whitaker et al. 2014). We compare the properties of the companion galaxies considered here with those of typical star-forming galaxies and SMGs at similar redshifts (see Figure 8). We consider the observed MS relation at $z \sim 6$ provided by Salmon et al. (2015) and Speagle et al. (2014), together with predictions from semianalytical models by Somerville et al. (2008, 2012). Salmon et al. (2015) examine $3.5 \leq z \leq 6.5$ galaxies in the GOODS-S field: we take here SFR and $M_\ast$ values of their...
The stellar mass is that derived from our ALMA data around the relationship from De Looze et al. Properties were obtained with the code MAGPHYS.

The companion galaxies to high-unobscured SFR could be derived \((\sim 6.1)\) from Da Cunha et al. (2018). After a careful recalibration of the various data sets, they obtain a robust SFR–\(M_\ast\) relation as a function of the age of the universe (\(t\), here in Gyr):

\[
\log \text{SFR}[M_\ast, t] = (0.84 - 0.026 \times t) \log M_\ast - (6.51 - 0.11 \times t) .
\]

They also find a scatter around the MS of \(\sim 0.2\) dex, irrespective of redshift. We show this relation, calculated at \(z = 6\) with the representative 0.2 dex scatter, in Figure 8. We consider the semianalytical model by Somerville et al. (2012), who use N-body simulations and several feedback/accretion recipes to specifically reproduce the GOODS-S field. In particular, we consider the MS relation for this model at \(z \sim 6\), as provided by Salmon et al. (2015; see their Table 4). In addition, we report observed SMGs at \(4.5 < z < 6.1\) from Da Cunha et al. (2015), whose redshifts and physical parameters were obtained with MAGPHYS-high-\(z\), and at \(z \sim 4.5\) from Gomez-Guijarro et al. (2018), for which recent ALMA millimeter observations and secure spectroscopic redshifts are available. Finally, we show the massive, extremely starbursting galaxies at \(z > 6\) discovered by Riechers et al. (2013) and Mann et al. (2018; see Section 1), and \(z \sim 5.5\) LBGs (Capak et al. 2015).

We show in Figure 8 the SFR and \(M_\ast\) values obtained with MAGPHYS-high-\(z\) for PJ167c. This galaxy lies on the MS at \(z \sim 6\). For the remaining galaxies, i.e., J2100c, J0842c, and PJ231c, we only consider the obscured star formation rates and the upper limits on the stellar masses (see Section 3.1). These

| Name                  | SFR\(_{UV}\) (M\(_\odot\) yr\(^{-1}\)) | SFR\(_{IR}\) (M\(_\odot\) yr\(^{-1}\)) | SFR\(_{UV}^{\odot}\) (M\(_\odot\) yr\(^{-1}\)) | f\(_{\text{obscured}}\) = SFR\(_{IR}\)/SFR\(_{UV}\cdot\text{IR}\) | M\(_{dyn}\) (<\(10^{10}\) M\(_\odot\)) | M\(_\ast\) (<\(10^{10}\) M\(_\odot\)) |
|----------------------|--------------------------------------|--------------------------------------|--------------------------------------|------------------------------------------------|--------------------------------------|--------------------------------------|
| SDSS J0842+1218c     | <2                                   | 124 ± 54                             | 260 ± 40                             | >0.98                                         | 12 ± 5                               | <11                                  |
| PSO J167.6415-13.4960c | 11 ± 3                               | 32 ± 4                               | 182 ± 16                             | 0.74 ± 0.20                                   | ...                                   | 0.84±0.64                            |
| PSO J231.6576-20.8335c | <3                                   | 709 ± 157                            | 730 ± 100                            | >0.99                                         | 22 ± 8                               | <16.8                                |
| CFIQs J2100-1715c     | <3                                   | 573 ± 73                             | 360 ± 70                             | >0.99                                         | 27 ± 13                              | <21.5                                |

Note. We report the unobscured (rest-frame UV) SFRs calculated from our \(HST/\text{WFC3}\) observations (Section 3.2), and the obscured (rest-frame IR) contribution from our ALMA data (Sections 3.1 and 3.2). Finally, the dynamical mass estimates and upper limits on the stellar masses are also listed. In the case of PJ167c, the reported stellar mass is that derived from MAGPHYS-high-\(z\) (see Section 3.1). We note that the SFR\(_{UV}^{\odot}\) values have an additional uncertainty of 0.5 dex due to the scatter around the relationship from De Looze et al. (2014).
highly conservative constraints place the companions on or above the MS relation.

Future, deeper observations in the IR regime, together with further development of current fitting machines, will be needed to constrain these galaxies’ SEDs and stellar masses.

4. Conclusions

In this work, we present sensitive follow-up optical and NIR imaging and spectroscopy of companion galaxies adjacent (i.e., <60 kpc and <450 km s\(^{-1}\)) to four \(z \approx 6\) quasars, initially discovered by their bright \([\text{C II}]\) and far-infrared emission with ALMA (Decarli et al. 2017; Willott et al. 2017).

The data reported here have been acquired with several ground- and space-based facilities (i.e., VLT/MUSE, MODS, and LUCI at the LBT, Magellan/FIRE, Spitzer/IRAC, and HST/WFC3), and are aimed at probing the galaxies’ stellar content, recovered in the rest-frame UV/optical regime. We perform aperture photometry at the location of the galaxies (as measured by ALMA), after accounting for both the bright, point-like, nonthermal quasar radiation and any foreground objects. We detect no rest-frame 5000–7000 Å stellar emission (at \(>3\sigma\) significance level) from the companions, observed at 3–5 μm. In addition, no light from young stars, probed at \(\lambda_{\text{obs}} \sim 1.4\) μm by HST/WFC3, is detected in three of the four sources examined, i.e., J2100c, J0842c, and PJ231c. However, the companion galaxy of the quasar PJ167 is detected in our HST observations at 6.4 σ.

From a comparison with SEDs of various local galaxies, we find that the companions PJ231c, J2100c, and J0842c are consistent with an Arp 220-like galaxy at \(z \approx 6\). These objects are heavily dust-obscured and/or they harbor a modest stellar mass. The source PJ167c resembles, instead, a less extreme star-forming galaxy. We compute SFRs and \(M_\ast\) with the SED fitting code MAGPHYS-high-z for this galaxy, whose emission is detected in more than one broad band. We derive the obscured SFR of PJ231c, J0842c, and J2100c by assuming the SED of Arp 220 scaled at the observed fluxes. We place upper limits on their stellar masses by subtracting their gas masses, estimated from the dust content, from their total dynamical masses, derived from the [C II] emission line widths. We also derive tight constraints on their unobscured star formation rate, as obtained from the sensitive HST/WFC3 data. We observe SFR\(_{\text{FUV}} \lesssim 3 M_\odot\) yr\(^{-1}\), i.e., more than two orders of magnitude lower than SFR\(_{\text{IR}}\), with the exception of PJ167c, whose obscured star formation component is only \(\sim 6 \times\) larger than the unobscured value. Finally, we find that the companions examined here are consistent with being on the main sequence of star-forming galaxies at \(z \approx 6\). However, our constraints/limits, in particular on the stellar masses, are still coarse. This is mainly due to the lack of detections in the bluer bands.

In the near future, deep observations with upcoming instruments, e.g., the NIRCAM and NIRSPEC cameras on board the James Webb Space Telescope, will enable us to uncover the emission and dynamics of the stellar content of these galaxies, and, together with updated fitting techniques, to place strong constraints on their SEDs.

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This paper includes data gathered with the 6.5 m Magellan Telescope located at Las Campanas Observatory, Chile.

The LBT is an international collaboration among institutions in the United States, Italy, and Germany. LBT Corporation partners are The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota, and University of Virginia. This paper used data obtained with the MODS spectrographs built with funding from NSF grant AST-9987045 and the NSF Telescope System Instrumentation Program (TSIP), with additional funds from the Ohio Board of Regents and the Ohio State University Office of Research.

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This work is based [in part] on observations made and archival data obtained with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration 2018; http://www.astropy.org).

Facilities: VLT:Yepun (MUSE), Magellan:Baade (FIRE), LBT (MODS, LUCI), ALMA, HST (WFC3), Spitzer (IRAC).

Appendix A

Dust-continuum Emitting Source Adjacent to the Quasar VIK J2211–3206

We detect emission from the dust continuum, but not from the [C II] emission line, from a source in the field of the quasar
J2211 (QSO R.A. 22:11:12.39; decl. −32:06:12.9), at redshift $z_{\text{quasar}} = 6.3394 \pm 0.001$ (Decarli et al. 2018). No secure redshift value is measured for this neighboring source (hereafter J2211c). Note that the detection of an object with flux density comparable to J2211c over the area covered in the ALMA survey (Decarli et al. 2018) is expected from a comparison with the number counts of 1.2 mm bright sources observed in blank fields (e.g., Aravena et al. 2016). Indeed, if one integrates the luminosity function of 1.2 mm detected-sources provided by Fujimoto et al. (2016) down to the flux of J2211c (see Table 6), one expects ~2.4 sources in 1 arcmin$^2$. This amounts to ~9.8 sources in the effective area spanned by our ALMA Survey (i.e., ~4 arcmin$^2$). This number is consistent with that of sources with similar brightness as J2211c (10) found in the sample recently compiled by Champagne et al. (2018).

We acquired new observations of this field as part of our follow-up campaign of [CII]-bright companions to high-redshift quasars, using HST/WFC3 and Spitzer/IRAC (see Table 2 for details of the observations). We reduced and analyzed the data following the procedures reported in Section 2. In what follows, we assume that J2211c is located at the redshift of the quasar. No emission from the stellar population in the rest-frame optical regime is measured (at 3σ significance) in the Spitzer/IRAC images. However, we tentatively measure (S/N = 2.1) emission in the F140W filter with the HST/WFC3 camera. We report our photometric measurements/3σ limits in Table 6, where we also list the galactic properties (coordinates and millimeter flux) obtained from ALMA data (Decarli et al. 2017; Champagne et al. 2018). In Figure 9 we show the postage stamps of our follow-up observations.

In analogy with the companions discussed in the main body of the paper, we compare the SED of J2211c with those of local galaxies, and we fit our photometric data with MAGPHYS-high-$z$ (see Figure 9). From the latter, we find that the SED of J2211c is better reproduced by a galaxy model in between Arp 220 and M82 (i.e., a powerful local ULIRG and a starburst), with $M_\ast \sim 3 \times 10^{10} M_\odot$ and $SFR \sim 130 M_\odot \, \text{yr}^{-1}$. We further measure the obscured/unobscured SFR ratio of J2211c, following the procedure used for PJ167c (see Section 3.2). The star formation rate is dominated by the obscured contribution ($SFR_{\text{UV}} \sim 2 M_\odot \, \text{yr}^{-1}$ and $f_{\text{obsured}} \sim 0.99$). We report all these estimates in Table 6. The lack of a secure redshift confirmation prevents us from drawing further conclusions on the nature of this source, or from placing it in the context of previous observations.

### Table 6

| VIK J2211–3206c |  |
|------------------|--|
| R.A. (J2000)     | 22:11:12.11 |
| Decl. (J2000)    | −32:06:16.19 |
| $\Delta r_{\text{projected}}$ (kpc) | 26.8 |
| F140W (mag)      | 27.39 ± 0.52 |
| $F_{\text{3.5 \mu m}}$ (mJy) | <3.42 |
| $F_{\text{4.5 \mu m}}$ (mJy) | <1.80 |
| $F_{\text{mm}}$ (mJy) | 0.64 ± 0.06 |
| SFR$_{\text{IR}}$ ($M_\odot \, \text{yr}^{-1}$) | 257 ± 36 |
| SFR$_{\text{UV}}$ ($M_\odot \, \text{yr}^{-1}$) | 2 ± 2 |
| $f_{\text{obsurred}}$ | 0.99 ± 0.14 |
| SFR$_{\text{magphys}}$ ($M_\odot \, \text{yr}^{-1}$) | 132$^{+230}_{-99}$ |
| $M_\ast$$_{\text{magphys}}$ ($M_\odot$) | 2.75$^{+1.13}_{-1.0}$ \times 10^{10} |

**Note.** Given the lack of any redshift measurement, we are not able to securely identify this galaxy as physically interacting with the quasar, and place it in the context of the analysis of the companions. We report here its coordinates and projected spatial separation to the quasar, obtained from ALMA data (Champagne et al. 2018; Decarli et al. 2018), and our HST/WFC3 and Spitzer/IRAC follow-up photometric measurements/limits (see Figure 9). We also list our constraints on its physical properties, given the assumption that J2211c lies at the quasar redshift.
Appendix B
Quasar Photometry

In the framework of our study of companion galaxies, we also perform forced photometry at the position of the quasars in the Spitzer/IRAC and HST/WFC3 images (see Section 2 for methodology). In Table 7 we report the derived quasars' photometry. In Figure 10, we show the quasars SEDs. The fluxes measured in our follow-up data are consistent with those expected from the observed optical/NIR spectra, when available, and/or from a lower-z quasar template (Selsing et al. 2016) rescaled to match the observed J band magnitude.

Figure 9. Source adjacent to the quasar J2211, detected solely in the dust-continuum emission, i.e., with no secure redshift measure. Top: postage stamps (20″ × 20″) of our follow-up observations; labels are as in Figure 3. Bottom: spectral energy distribution of J2211c. We assume that the source is located at the same redshift of the quasar. We report our photometric measurements/limits and, for comparison, various templates of local galaxies and the best SED fit from MAGPHYS-high-z. The labels and templates are as in Figure 6. J2211c SED results to be intermediate between the low-z ULIRG Arp220 and the starbursting galaxy M82 (see Section 3.1). On the basis of our follow-up observations, and considering the predicted density of millimeter-sources, we are not able to exclude that this source is a foreground (see the text for details, and Champagne et al. 2018).
Figure 10. Spectral energy distribution of the quasars in our sample. The observed photometric measurements (filled points) are obtained from our new follow-up data and from the literature (see Table 7; the filter responses are reported in the lower right panel). We also show the available optical/NIR spectra (light gray; see also Mazzucchelli et al. 2017b), and a lower-redshift composite template shifted at the redshift of the quasar (black solid line; Selsing et al. 2016). The location of the Lyα line is highlighted with a light blue dashed line.

Table 7
Photometric Measurements of the Quasars Studied in This Work (see Section 2)

| Name                | $F_{p1}$ (mJy) | $F_I$ (mJy) | $F_{F140W}$ (mJy) | $F_{3.6 \mu m}$ (mJy) | $F_{4.5 \mu m}$ (mJy) | $F_{1.2 \text{mm}}$ (mJy) | References $J$ |
|---------------------|----------------|-------------|-------------------|----------------------|----------------------|--------------------------|----------------|
| SDSS J0842+1218     | 40.55$^{+23}_{-12}$ | 44.46 ± 1.2 | 50.19 ± 0.02       | 76.29 ± 0.22         | 93.33 ± 0.25         | 0.87 ± 0.18               | (1)            |
| PSO J167.6415−13.4960 | 23.12$^{+23}_{-12}$ | 11.91 ± 1.0 | 20.89 ± 0.02       | 30.56 ± 0.23         | 34.32 ± 0.17         | 0.87 ± 0.05               | (2)            |
| PSO J231.6576−20.8335 | 36.31$^{+23}_{-26}$ | 49.66$^{+3}_{0}$ | 49.13 ± 0.02       | 66.95 ± 0.22         | 67.91 ± 0.22         | 4.41 ± 0.16               | (3)            |
| CFHQS J2100−1715    | 10.86$^{+23}_{-12}$ | 9.82 ± 0.9  | 19.95 ± 0.02       | 31.65 ± 0.25         | 34.76 ± 0.26         | 1.20 ± 0.15               | (4)            |
| SDSS J2211−3206     | ...            | 51.52$^{+50}_{-43}$ | 57.93 ± 0.02       | 116.05 ± 0.23        | 131.45 ± 0.19        | 0.57 ± 0.05               | (5)            |

Note. The measurements in the $y_{0}$ band are from the PS1 PV3 catalog, while the $J$ band values are from (1) Jiang et al. (2015), (2) Venemans et al. (2015b), (3) Mazzucchelli et al. (2017b), (4) Willott et al. (2010), and (5) B. Venemans et al. (2019, in preparation).

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