Star formation in the cluster CLG0218.3-0510 at \( z = 1.62 \) and its large-scale environment: the infrared perspective

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ABSTRACT

The galaxy cluster CLG0218.3-0510 at \( z = 1.62 \) is one of the most distant galaxy clusters known, with a rich multiwavelength data set that confirms a mature galaxy population already in place. Using very deep, wide-area (20 Mpc \( \times \) 20 Mpc) imaging by Spitzer MIPS at 24 \( \mu m \), in conjunction with Herschel five-band imaging from 100 to 500 \( \mu m \), we investigate the dust-obscured, star formation properties in the cluster and its associated large-scale environment. Our galaxy sample of 693 galaxies at \( z \sim 1.62 \) detected at 24 \( \mu m \) (10 spectroscopic and 683 photo-\( z \)) includes both cluster galaxies (i.e. within \( r < 1 \) Mpc projected cluster-centric radius) and field galaxies, defined as the region beyond a radius of 3 Mpc. The star formation rates (SFRs) derived from the measured infrared luminosity range from 18 to 2500 M\( \odot \) yr\(^{-1} \), with a median of 55 M\( \odot \) yr\(^{-1} \), over the entire radial range (10 Mpc). The cluster’s brightest far-infrared galaxy, taken as the centre of the galaxy system, is vigorously forming stars at a rate of 256 \( \pm \) 70 M\( \odot \) yr\(^{-1} \), and the total cluster SFR enclosed in a circle of 1 Mpc is 1161 \( \pm \) 96 M\( \odot \) yr\(^{-1} \). We estimate a dust extinction of \( \sim 3 \) mag by comparing the SFRs derived from [O\( \text{II} \)] luminosity with the ones computed from the 24 \( \mu m \) fluxes. We find that the in-falling region (1–3 Mpc) is special: there is a significant decrement (3.5\( \times \)) of passive relative to star-forming galaxies in this region, and the total SFR of the galaxies located in this region is lower (\( \sim 130 \) M\( \odot \) yr\(^{-1} \) Mpc\(^{-2} \)) than anywhere in the cluster or field, regardless of their stellar mass. In a complementary approach, we compute the local galaxy density, \( \Sigma_5 \), and find no trend between SFR and \( \Sigma_5 \). However, we measure an excess of star-forming galaxies in the cluster relative to the field by a factor of 1.7, that lends support to a reversal of SF–density relation in CLG0218.

Key words: galaxies: clusters: individual: CLG0218.3-0510 – galaxies: high-redshift – galaxies: star formation – infrared: galaxies.

1 INTRODUCTION

One of the main concerns of modern astrophysics is the lack of a detailed understanding of galaxy formation in a cosmological context. The star formation rate (SFR) of galaxies in different environments and across cosmic time is one of the key physical parameters to understand their evolution.

In the local Universe, luminous infrared galaxies (LIRGs, \( 10^{11} < L_{IR} < 10^{12} L_\odot \)) avoid the high-density environments of galaxy clusters in which star formation has already been quenched, and ultraluminous infrared galaxies (ULIRGs, \( L_{IR} > 10^{12} L_\odot \)) are virtually absent up to \( z \sim 0.5 \) (e.g. Magnelli et al. 2011; Haines et al. 2013). Since the peak of the cosmological SFR occurred at \( 1 < z < 3 \) (Madau et al. 1996), it is expected that star formation in the denser environments must at some time increase towards higher redshifts. However, the amount, spatial distribution and timing of this increase remain unclear.

The evolution of the SFR with redshift has been studied up to \( z \sim 1 \) and is typically parametrized by a power-law function, \( SFR(z) \propto (1+z)^\alpha \), with a slope \( \alpha \) ranging from 2 to 7 (e.g. Kodama et al. 2004; Geach et al. 2006; Saintonge, Tran & Holden 2008; Bai et al. 2009; Haines et al. 2009). The recent investigation of Webb et al. (2013) using 42 clusters from the Red Sequence Cluster Survey lends...
support to a slope of 5–6 and ascribes this evolutionary trend to the in-falling galaxies in clusters at $z > 0.75$. This conclusion underlines the importance of environment as we probe higher redshifts. Beyond redshift unity, the evolution of the SFR in clusters is unconstrained mostly because of the scarcity of well-studied systems (i.e. few confirmed clusters with good multiwavelength data); however, the recent works of Brodwin et al. (2013) and Zeimann et al. (2013) made a first step in that regime.

A reversal of the star formation–density relationship at $z > 1$ was reported by Elbaz et al. (2007, 2011) in low-galaxy-density environments (i.e. the field) where, unlike in the local Universe, the average SFR of galaxies increases with local galaxy density. On the other hand, mid-infrared observations of a couple of galaxy clusters at the highest known redshifts ($z \sim 1.5$) have revealed a population of IR luminous, actively star-forming galaxies in the cluster cores (Hilton et al. 2010; Tran et al. 2010), indicating a reversal of the SF–density relation in higher galaxy density systems.

At intermediate and high redshifts, most of the energy from star formation and AGN activity is absorbed by dust and re-radiated at IR wavelengths. The Infrared Space Observatory revealed that in intermediate-redshift clusters most of the star formation is hidden at optical wavelengths (e.g. Duc et al. 2002; Metcalfe, Fadda & Biviano 2005). Subsequent observations with Spitzer/MIPS confirmed this scenario (e.g. Geach et al. 2006; Marcillac et al. 2008). Specifically, Saintonge et al. (2008) observed an increasing fraction of dusty star-forming cluster galaxies from 3 per cent locally to 13 per cent at $z = 0.83$ (see also Haines et al. 2009). In addition, it has been shown that most of the dust-obscured star formation in $z < 0.85$ clusters happens in intermediate-density regions (Koyama et al. 2008) or in groups (Tran et al. 2009).

The Herschel space observatory (Pilbratt et al. 2010) is the largest space telescope to date and provides unrivalled sensitivity in the wavelength range 55–672 $\mu$m. Therefore, Herschel brackets the critical peak of far-infrared (FIR) emission of $z \sim 1$–2 galaxies, providing a direct, unbiased measurement of star formation. Up to now only a handful of studies of high-$z$ clusters and protoclusters using Herschel data have been published (Popesso et al. 2012; Seymour et al. 2012; Pintos-Castro et al. 2013; Santos et al. 2013; Alberts et al. 2014), mostly because the angular resolution at the longest wavelengths (up to 18 arcsec) does not allow one to resolve small distant galaxies, and furthermore, most of the observations have a high-SFR detection threshold, enabling the study of the highly star-forming galaxies only. To investigate the relation between star formation activity and environment at the epoch when clusters are assembling galaxies and galaxies are still undergoing their own formation process, several Herschel programmes, namely the key project PEP (PACS Evolutionary Probe; Lutz et al. 2011) and several guaranteed time (GT; PI Altieri) and open time (OT) programmes (PI Pope, Popesso) have targeted several tens of high-redshift clusters in a broad range of halo masses.

In this paper, we present a detailed characterization of the infrared star formation properties in the galaxy population of CLG0218-0510 (hereafter, CLG0218, RA = 34.5995 55 Dec. = −5.173 85) at $z = 1.62$ and its large-scale environment. This distant galaxy system was independently discovered as a strong overdensity of red galaxies using Spitzer-IRAC imaging (Papovich et al. 2010) and as a weak X-ray detection in XMM–Newton data (Tanaka, Finoguenov & Ueda 2010). Subsequently, CLG0218 was observed with deep, multiwavelength follow-up observations using the major astronomical observatories; in particular, the Spitzer public legacy survey (SpUDS, PI Dunlop) and the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS, PI Faber, Ferguson).

While the number of confirmed cluster members has been steadily increasing with a current sample of ~50 galaxies (Papovich et al. 2010; Tanaka et al. 2010; Tadaki et al. 2012), the analysis of 85 ks X-ray Chandra (Pierre et al. 2012) data rendered inconclusive whether there is extended emission associated with the galaxy overdensity, mostly because a bright point source associated with the central cluster galaxy dominates the X-ray flux. On removing this point source, an upper limit on the cluster mass of $7.7 \times 10^{13}$ $M_{\odot}$ was set, placing CLG0218 in the low-mass/group category, or even protocluster. This value is consistent with the one derived from the deeper XMM–Newton data published in Tanaka et al. (2010), $5.7 \pm 1.4 \times 10^{13}$ $M_{\odot}$, which we adopt in this paper. Throughout this paper, we will simply refer to CLG0218 as a cluster of galaxies. The star formation properties of this cluster have been studied using MIPS 24 $\mu$m in a central region of 1 Mpc by Tran et al. (2010). They found an enhancement of the fraction of star-forming galaxies in the cluster relative to lower redshift clusters. One caveat in this study is that the 24-um-derived SFRs were computed with the Chary & Elbaz (2001) templates which are known to overestimate the SFR for galaxies above $z = 1.5$. Tadaki et al. (2012) followed a different approach using near-infrared (NIR) narrow-band imaging targeted to detect [O ii] emitters in the cluster and the surrounding environment. They found a large filamentary structure around CLG0218 traced by [O ii] emitters with a measured overdensity a factor 10 larger in the high-density regions (cluster core and clumps) than in the field. Here, we use the largest sample of $z_{\text{phot}}$ and spectroscopically confirmed galaxies and infrared maps that cover an area of 20 Mpc $\times$ 20 Mpc, thus enabling the study of the dust-obscured star formation in the cluster and its large-scale environment. For a subset of the galaxy sample, we have robust Herschel measurements which firmly constrains the amount of dust extinction and validates the SFRs from 24 $\mu$m.

The paper is organized as follows: in Section 2, we describe the MIPS, PACS and SPIRE observations and reduction procedures while in Section 4 we describe the multi-$\lambda$ ancillary used in this work. In Section 5, we obtain total infrared luminosities ($L_{\text{IR}}$) and derive SFRs from the 24 $\mu$m data. A detailed analysis of the infrared properties of the central, IR brightest cluster galaxy (BCG) is presented in Section 6. In Sections 7 and 8, we investigate the relations between the environment, stellar mass and star formation. Our conclusions are summarized in Section 9.

The cosmological parameters used throughout the paper are: $H_0 = 70$ $h$ km s$^{-1}$ Mpc$^{-1}$ ($h = 1$), $\Omega_{\Lambda}$ = 0.7 and $\Omega_m$ = 0.3. In this cosmology, 1 Mpc at $z = 1.6$ corresponds to ~2 arcmin in the sky. Quoted errors are at the 1$\sigma$ level, unless otherwise stated.

## 2 INFRARED OBSERVATIONS AND DATA REDUCTION

### 2.1 MIPS data and source catalogue

CLG0218 was observed with Spitzer IRAC and MIPS 24 $\mu$m as part of SpUDS. The MIPS source catalogue was obtained with the PSF-fitting code STARENDER (Diodati et al. 2000) on the publicly available SpUDS images. Details on the MIPS source extraction and catalogue production can be found in Tran et al. (2010) that presented a subset limited to an area of 1 Mpc centred on the cluster. For this work, we select all sources detected with S/N $>$ 5 (which corresponds to a flux of 40 $\mu$Jy) centred on the galaxy ID 16 (see

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1. http://ssc.spitzer.caltech.edu/spitzermission/observingprograms/legacy/spuds/
Section 6) that is associated with an X-ray point source, out to a projected radius $r = 20\ \text{arcmin}$ that corresponds to $10\ \text{Mpc}$ at the cluster redshift.

### 2.2 Herschel data reduction and photometry

The *Herschel* 100/160/250/350/500 $\mu$m observations of CLG0218 were carried out as part of several programmes: (i) a 50 h GT programme (GT1, PI Altieri) aimed at studying the star formation history in high-redshift ($0.8 < z < 2.2$) galaxy clusters, (ii) 80 h observations of the CANDELS fields (PI M. Dickinson) and (iii) 25 h observations of the HerMES key programme (PI S. Oliver). We note that the PACS observations performed by these different programmes cover different areas at different depths. While the GT1 is centred on a $10\ \text{arcmin} \times 10\ \text{arcmin}$ region around the cluster centre, the deeper CANDELS data set imaged a larger rectangular area ($9\ \text{arcmin} \times 20\ \text{arcmin}$) and HerMES imaged a much larger area ($30\ \text{arcmin} \times 30\ \text{arcmin}$) but with shallow exposures. See in Fig. 1 the co-added image of the three programmes. As a consequence, the sensitivity of the PACS images varies significantly across the field of view (FOV); however, it is optimal in the cluster region (magenta square in Fig. 1 with $10\ \text{arcmin} \times 10\ \text{arcmin}$). The $3\sigma$ sensitivity ranges from $1.3\ (3.9)\ \text{mJy}$ (GT1+CANDELS+HerMES area) to $4.0\ (9.6)\ \text{mJy}$ (HerMES only) in the $100\ (160)\ \mu$m image.

The PACS (Poglitsch et al. 2011) GT1 observations at $100/160\mu$m were acquired on 2011 January 19 (obsids = 1342213032-5) with four crossed scan maps of 2.4 h each covering a field of $10\ \text{arcmin} \times 10\ \text{arcmin}$ and the CANDELS observations on the Ultra Deep Survey (UDS) field were spread throughout 2012 July for a total of 80 h. The data were reduced using *HIFI* 9 (Ott et al. 2006). The data cubes were processed with a standard pipeline where detector timelines are high-pass filtered with a sliding median over 21 readouts at $100\ \mu$m and 41 readouts at $160\ \mu$m to remove detector drifts and 1/f noise, with an iterative masking of the sources.

Given the large PSF/beam sizes of PACS and SPIRE, we opt to extract sources using priors, instead of matching blind catalogues using nearest neighbour approaches. Using our MIPS catalogue as prior, we run HIPE/DAOPHOT to extract the sources and perform aperture photometry in the PACS bands. The aperture photometry is corrected with the encircled energy factors given by Balog et al. (2013) in radii of 6 arcsec at $100\ \mu$m and 9 arcsec at $160\ \mu$m. Given the difficulty to obtain reliable errors with standard source detection algorithms because of the correlated noise present in PACS data, we compute the photometric errors as the 1σ detection limits in each band, in addition to 7 per cent of the source’s flux. The astrometry relative to MIPS $24\ \mu$m is excellent and no shift was required to be applied to the PACS maps.

For our analysis, we used the SPIRE (Griffin et al. 2010) observations at 250, 350 and $500\ \mu$m from *Herschel-CANDELS UDS*. The *Herschel-CANDELS UDS* observations are one of the deepest SPIRE observations, at a similar depth to GOODS-N from *Herschel-GOODS* (Elbaz et al. 2011), achieving instrumental noise much deeper than the nominal SPIRE extragalactic confusion noise (Nguyen et al. 2010). The *Herschel-CANDELS UDS* observations were performed following an eight-point dithering pattern in order to achieve more homogeneous coverage within the CANDELS UDS area. Adding the shallower smaller area GT1 observations or the HerMES (Oliver et al. 2012) observations in this region do not improve the depth as we are limited by the confusion – it only creates regions of inhomogeneous coverage within the field. The dithering also allows using a smaller than nominal pixel scale. Although this does not improve the resolution (below the Nyquist sampling), it improves the definition of the sources: the maps were made with ($3.6, 4.8, 7.2$) arcsec pixel$^{-1}$ for (250, 350, 500) $\mu$m. The rms noise in the three SPIRE bands$^2$ within the good coverage is ($3.3, 4.0, 5.8$) $\times 1.48\ \text{mJy}$ at (250, 350, 500) $\mu$m and indeed this is similar to the nominal extragalactic confusion noise of ($5.8, 6.3, 6.8$) mJy but still within the field-to-field or flux calibration uncertainties.

The SPIRE source detection was performed using SUSEXTRACTOR (SXT; Smith et al. 2012) with a prior catalogue based on the MIPS+PACS catalogue. SXT finds a maximum likelihood fit of the

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$^2$ We use the median absolute deviation (MAD) $\times 1.48$ as a robust measure of the rms; MAD is not affected by the presence of sources in the region.
SPIRE beam at the position of the input catalogue sources in the three bands independently. In each band, the quality of the fit (e.g. the signal-to-noise) is a measure of the source detection that we also confirmed by visual inspection. When there was no plausible source at the position of the input catalogue, we used the 3σ upper limit in each band, i.e. three times the confusion noise or (17.4, 18.9, 20.4) mJy at (250, 350, 500) μm.

3 ANCILLARY DATA

In addition to the MIPS and Herschel data, we use the optical/NIR imaging and spectroscopy summarized below (see Table 1). Details on the observations and reduction procedures can be found in the appropriate references. When referring to the spectroscopic data, we intend the reduced source catalogues obtained in the literature or private communications. We use the optical spectroscopy catalogue of Papovich et al. (2010) obtained with the IMACS instrument at the Magellan telescope, as well as the NIR spectroscopy obtained with MOIRCS installed in the Subaru telescope and reported in Tanaka et al. (2010) and with FMOS also on Subaru (Tadaki et al. 2012).

Our optical/NIR spectral energy distribution (SED) fitting presented below is based on multiwavelength data collected from a number of surveys. Deep BVRiz imaging has been performed with the Suprime-CAM at Subaru (Furusawa et al. 2008) and we use the publicly available z-band-selected catalogue (z<26.5 mag), which forms the basis of our catalogue. We combine this catalogue with the u-band photometry taken with CFHT MegaCAM (u<26.5 (3σ, 2 arcsec aperture) = 27.0)³ by cross-matching objects in the two catalogues within 1 arcsec. We further include the publicly available JHK photometry from DR8plus taken as part of the UKIRT Infrared Deep Sky Survey (UKIDSS)⁴ (Lawrence et al. 2007). We use 2 arcsec apertures and apply aperture corrections (which are estimated for each data set) to measure total magnitudes. We note that although the K band would be more appropriate than the z band to select red (dusty) galaxies at z = 1.62, the K-band data are 1.5 mag shallower than the z band (K<25 mag, 3σ). We performed several checks to assess the z-band versus K-band selection using our catalogues and we made SED shape predictions based on the limiting magnitudes of the z and K bands, using the templates of Berta et al. (2013) shifted to z = 1.6. We conclude that with the z-band selection we do not significantly miss MIPS sources (7–8 percent of sources at all redshifts) that would otherwise be detected in the K band; therefore, we find that the deep z-band catalogue is suitable for the galaxy selection, in comparison with the shallower K-band catalogue. The Spitzer IRAC observations of CLG0218 obtained by the SpUDS are also included in the optical–NIR SED fitting.

The 85 ks Chandra observation published in Pierre et al. (2012) is also used here. While no diffuse emission was detected in these data, the subarcsecond resolution of Chandra allowed for the detection of three point-sources associated with confirmed cluster members which will be important to evaluate the impact of AGN in the IR SEDs.

4 GALAXY CLUSTER SAMPLE

As detailed below, our galaxy cluster sample is divided in a more robust, spectroscopically confirmed sample and a photometric redshift sample of galaxies with 24 μm emission.

4.1 Spectroscopic galaxies

Our spectroscopic sample of 46 cluster members originates from three observation campaigns: (i) the IMACS (Papovich et al. 2010), (ii) MOIRCS observations (Tanaka et al. 2010) secured 16 cluster members selected by colour and photometric redshifts and (iii) the more recent large-area follow-up with FMOS of [O II] narrow-band emitters (Tadaki et al. 2012) independently confirmed 40 cluster members. Of these, 10 galaxies overlap with the initial IMACS + MOIRCS catalogue. A total of 10 spectroscopic galaxies extending to a radius of 8.5 Mpc at the cluster redshift have 24 μm emission and will be used in our investigation of the star formation of the cluster and its associated large-scale environment.

4.2 Photo-z members

We compute photometric redshifts (z_phot hereafter) using the uBVRIzJHK (3.6, 4.5, 1.6) μm catalogue constructed above. We use the SED-fitting code described in Tanaka et al. (2013). In short, we construct model templates using an updated version of the Bruzual & Charlot (2003) models, which includes an improved treatment of the thermally pulsating AGB stars. We assume exponentially decaying star formation histories with the decay time-scale allowed to vary. Dust attenuation is included using the attenuation curve by Calzetti et al. (2000). Emission lines are added to the spectra using the emission-line intensity ratios given in Inoue (2011), assuming the Calzetti (1997) attenuation to the emission lines. We apply the same template error function as in Tanaka et al. (2013) in order to reduce systematic differences between observations and model templates. We infer the galaxies physical parameters such as stellar mass and SFR from the fitting of the stellar population synthesis models. Each model parameter is marginalized over all the other parameters and we take the median of the probability distribution as a point estimate and quote the 68 percent interval as an uncertainty.

We compare the resultant z_phot with spectroscopic redshifts from the literature (Smail et al. 2008; Papovich et al. 2010; Tanaka et al. 2010; Simpson et al. 2012; Tadaki et al. 2012; Akiyama et al., in preparation). The redshift catalogue is a collection of follow-up campaigns targeting different types of objects and is quite heterogeneous; therefore, we have to exercise some caution when interpreting the numbers. We find σ(Δz/(1+z)) ~ 0.04 with an outlier rate of ~10 percent (see Fig. 2). The σ range of the photo-z uncertainty at z = 1.62 is thus σ(z_phot) = 0.04 × (1 + z) = 0.10. The ±2σ range in photometric redshifts to select candidate galaxy cluster members is then 1.42 < z_phot < 1.82.

Table 1. Summary of the data sets used in our analysis. The ‘Type’ column refers to spectroscopy (S) or imaging (I).

| Instrument | Type | Observed band | FOV       |
|------------|------|---------------|-----------|
| IMACS      | S    | MOS           | 15.46 arcmin × 15.46 arcmin |
| FMOS       | S    | MOS, 1.6–1.8 μm | 30 arcmin φ |
| MOIRCS     | S    | MOS, 0.9–1.7 μm | 7 arcmin × 4 arcmin |
| MegaCAM    | I    | u             | 1″ × 1″   |
| SupremeCAM | I    | BVRiz         | 52 arcmin × 52 arcmin |
| WFCAM      | I    | J, H, K       | 41 arcmin × 41 arcmin |
| IRAC       | I    | 3.6/4/5.5/8/8.0 μm | 41 arcmin × 41 arcmin |
| MIPS       | I    | 24 μm         | 41 arcmin × 41 arcmin |
| PACS       | I    | 100/160 μm    | 34 arcmin × 34 arcmin |
| SPIRE      | I    | 250/350/500 μm | 34 arcmin × 34 arcmin |
| ACIS-S     | I    | 0.5–10 keV    | 8.5 arcmin × 8.5 arcmin |

3 Based on publicly available archival CFHT data.
4 http://www.ukidss.org/
Elbaz (2001), Dale & Helou (2002) and Rieke et al. (2009). Herschel observations showed that using these libraries to infer the total infrared luminosity from the 24 μm flux alone significantly overestimates the $L_{IR}$ by a factor of 2–7 for galaxies at $z > 1.5$ with $L_{IR} > 10^{10} L_{⊙}$ (e.g. Nordon et al. 2010; Rujopakarn et al. 2011). To overcome this so-called mid-IR problem, Rujopakarn et al. (2013) recently derived an empirical stretching factor for the Rieke et al. (2009) SED templates, based on the evidence that IR luminous star-forming galaxies at 1 < $z$ < 3 have extended star-forming regions, as opposed to the strongly nuclear concentrated starbursts in local LIRGs and ULIRGs (note that Rieke et al. 2009 consider $L_{IR}$ from 5 to 1000 μm). We use this approach here to obtain the total infrared luminosities. In the next section, we will also check this method by comparing these values with the ones computed with both MIPS (corrected) and Herschel.

To convert the luminosity to an SFR, we apply the Kennicutt relation (Kennicutt 1998) modified for the Chabrier initial mass function (IMF; Chabrier 2003; Erb et al. 2006):

$$\text{SFR} \left( M_⊙ \text{yr}^{-1} \right) = 10^{-10} \frac{L_{IR}}{L_{⊙}}. \tag{1}$$

For simplicity, we assume a redshift of 1.62 for all galaxies in these computations, and we estimate the errors on $L_{IR}$ and SFR by considering photometric redshift errors of 0.1. The SFRs range from 18 to 2500 $M_⊙$ yr$^{-1}$, with a median of 55 $M_⊙$ yr$^{-1}$ (see Table 2 for the results on the spectroscopic and O II sample).

5.2 Results from MIPS+Herschel detections

Even though our infrared analysis is driven by the MIPS data because the sensitivity and spatial resolution of MIPS enables the detection and characterization of a large galaxy sample, we have Herschel detections for a smaller yet sizeable subset of the MIPS catalogue. This is important because it will allow us to evaluate the reliability of the 24 μm-derived SFRs. Of the 693 galaxies at $z \sim 1.62$ individually detected with MIPS, about half are not covered by PACS. Although 97 sources have 3σ detections in both PACS bands, we find it more reliable for the FIR SED fitting to have also a measurement (not upper limit) of the 250 μm band, given that the peak of the FIR SED is around the 250 μm at this redshift. A subset of 40 galaxies have 3σ fluxes in three Herschel bands, either the 100/160/250 μm bands or the 160/250/350 μm bands. After visual inspection for contamination by close neighbours and reliability of the detections – particularly those which lie in the PACS area with poorer sensitivity – there are 29 $z_{\text{phot}}$ members with a robust FIR SED fit (see Table 3). Using the Spitzer and the Herschel flux measurements, we fit the galaxy SEDs with LEPHARE (Arnouts et al. 1999; Ilbert et al. 2006) that adjusts SED templates from the chosen Chary & Elbaz (2001) library based on a $\chi^2$ minimization. In Fig. 3, we compare the SFRs obtained by direct integration of the FIR SED anchored on the Herschel data with the ones extrapolated from the MIPS 24 μm fluxes and corrected according to Section 5.1. For the overlapping sample of 29 galaxies, the range of SFR (24 μm) is 46–397, with a median of 178 $M_⊙$ yr$^{-1}$. Even though there is some scatter around the one-to-one relation, we find a strong correlation between these two measures of SFR, quantified by a Spearman rank $\rho = 0.72$, with a probability for a null-hypothesis of $9.3 \times 10^{-5}$.

It is difficult if not impossible to investigate whether the scatter is due to measurement errors or uncertainties in the calibration of the SFRs. For most galaxies, the Herschel fluxes are close to the 3σ detection limit, with SFR errors ranging from 11 to 30 per cent with...
a median of 21 per cent; hence, we do not have enough information to identify the origin of the scatter. Nevertheless, visual inspection of the K band shows that a third of this sample has close neighbours (i.e. within \( r = 6 \) arcsec); hence, contamination may be an issue causing an artificial boost to the SFRs derived from Herschel fluxes. Indeed, as evidenced in Fig. 3, this may explain why some sources have SFRs (Herschel) significantly greater than the ones measured from 24 \( \mu \)m.

### 5.3 Dust extinction

The mid-to-FIR data allow us to obtain a robust estimate of the amount of extinction due to dust by directly comparing the SFRs obtained from the [O ii] luminosity with the ones measured from the 24 \( \mu \)m fluxes (or full FIR SED if we have Herschel detections).

Using equation 4 of Kewley, Geller & Jansen (2004), we compute dust-uncorrected SFR ([O ii]) for a sample of 33 cluster galaxies detected both in narrow-band imaging and MIPS. We find that in order to reconcile the SFR ([O ii]) with the ones obtained using the 24 \( \mu \)m observations (corrected for the mid-IR excess problem), we require A([O ii]) \sim 3 mag (see Fig. 4). Similar extinction levels have been reported in the literature for galaxies at \( z \sim 1 \) and with similar stellar mass (Koyama et al. 2011; Kashino 2013). This value is a factor 3 higher than the average extinctions we obtain with the optical/NIR SED-fitting analysis. The narrow range of stellar masses (median of 4 \( \times 10^{10} \) \( M_\odot \)) of this sample does not enable the investigation of the role of \( M_\star \) with extinction.
Table 3. Infrared fluxes (24–500 μm) of the spectroscopic and photo-z galaxies at z ∼ 1.62 with Herschel detection. All fluxes are in mJy and the sources are ordered in projected cluster-centric distance. The top, middle, and bottom sections refer to the galaxies at r < 1 Mpc, at 1 < r < 3 Mpc and at r > 3 Mpc, respectively.

| ID  | F_{24}    | F_{100}  | F_{160}  | F_{250}  | F_{350}  | F_{500}  |
|-----|-----------|----------|----------|----------|----------|----------|
| 16  | 0.288 ± 0.003 | 8.6 ± 1.0 | 17.8 ± 2.5 | 22.8 ± 6.0 | 19.3 ± 6.5 | 14.9 ± 7.0 |
| 17742 | 0.083 ± 0.004 | – | 10.9 ± 2.1 | 22.6 ± 6.0 | 27.6 ± 6.6 | 26.4 ± 7.1 |
| 4862 | 0.214 ± 0.003 | 7.6 ± 1.0 | 22.1 ± 2.8 | 34.4 ± 6.2 | 40.4 ± 6.8 | 27.2 ± 7.0 |
| 3509 | 0.259 ± 0.003 | 12.1 ± 1.3 | 16.5 ± 1.5 | 20.3 ± 6.0 | 13.7 ± 6.4 | – |
| 3622 | 0.255 ± 0.004 | 11.6 ± 1.2 | 26.9 ± 3.2 | 43.0 ± 6.4 | 40.8 ± 6.8 | 23.7 ± 7.0 |
| 9896 | 0.136 ± 0.004 | 8.6 ± 1.0 | 15.2 ± 2.4 | 22.7 ± 6.0 | 21.6 ± 6.5 | 15.6 ± 7.0 |
| 5238 | 0.205 ± 0.004 | 2.5 ± 0.6 | 8.3 ± 1.9 | 21.0 ± 6.0 | 25.5 ± 6.5 | 21.0 ± 7.0 |
| 2154 | 0.339 ± 0.004 | 19.8 ± 1.8 | 34.8 ± 3.7 | 49.1 ± 6.5 | 33.0 ± 6.6 | – |
| 2480 | 0.312 ± 0.002 | – | 8.6 ± 1.9 | 24.6 ± 6.0 | 32.4 ± 6.6 | 24.1 ± 7.2 |
| 2787 | 0.292 ± 0.003 | – | 7.7 ± 1.8 | 18.4 ± 6.0 | 21.2 ± 6.5 | 15.1 ± 7.0 |
| 12996 | 0.110 ± 0.004 | 3.7 ± 0.7 | 4.7 ± 1.6 | 17.7 ± 6.0 | 24.2 ± 6.5 | 24.3 ± 7.0 |
| 3270 | 0.268 ± 0.004 | 5.3 ± 0.8 | 18.4 ± 2.6 | 44.9 ± 6.4 | 42.7 ± 6.8 | 35.4 ± 7.2 |
| 5596 | 0.197 ± 0.004 | 3.7 ± 0.7 | 14.1 ± 2.3 | 20.8 ± 6.0 | 16.9 ± 6.5 | – |
| 1614 | 0.402 ± 0.003 | 13.3 ± 1.4 | 31.9 ± 3.5 | 58.4 ± 6.7 | 50.7 ± 7.0 | 30.5 ± 7.1 |
| 2664 | 0.299 ± 0.003 | 16.1 ± 1.5 | 39.7 ± 4.1 | 54.9 ± 6.6 | 35.8 ± 6.7 | 16.2 ± 7.0 |
| 1608 | 0.403 ± 0.004 | 10.4 ± 1.1 | 18.1 ± 2.6 | 26.7 ± 6.1 | 24.3 ± 6.5 | – |
| 4234 | 0.233 ± 0.004 | 4.8 ± 0.8 | 10.3 ± 2.0 | 19.1 ± 6.0 | 20.8 ± 6.5 | 16.7 ± 7.0 |
| 9772 | 0.137 ± 0.004 | 1.6 ± 0.5 | 12.4 ± 2.2 | 30.5 ± 6.2 | 33.7 ± 6.7 | 35.4 ± 7.2 |
| 9079 | 0.144 ± 0.004 | 1.2 ± 0.5 | 12.3 ± 2.1 | 25.8 ± 6.1 | 28.6 ± 6.6 | 40.3 ± 7.3 |
| 1393 | 0.435 ± 0.004 | 8.3 ± 1.0 | 20.2 ± 2.7 | 35.7 ± 6.2 | 33.6 ± 6.7 | 23.3 ± 7.0 |
| 1829 | 0.372 ± 0.003 | 8.5 ± 1.0 | 20.5 ± 2.7 | 38.6 ± 6.3 | 31.0 ± 6.6 | 17.8 ± 7.0 |
| 5890 | 0.191 ± 0.003 | 1.5 ± 0.5 | 6.0 ± 1.7 | 17.4 ± 6.0 | 23.9 ± 6.6 | 19.1 ± 7.0 |
| 4877 | 0.214 ± 0.003 | 8.0 ± 1.0 | 18.4 ± 2.6 | 32.6 ± 6.2 | 27.5 ± 6.6 | – |
| 1439 | 0.427 ± 0.004 | 7.7 ± 1.0 | 26.6 ± 3.2 | 39.4 ± 6.2 | 36.5 ± 6.7 | 22.2 ± 7.0 |
| 4626 | 0.220 ± 0.003 | 1.4 ± 0.5 | 7.5 ± 1.8 | 21.9 ± 6.0 | 22.8 ± 6.5 | 15.7 ± 7.0 |
| 7053 | 0.171 ± 0.004 | 8.4 ± 1.0 | 20.1 ± 2.7 | 31.8 ± 6.1 | 25.6 ± 6.5 | 15.1 ± 6.9 |
| 14261 | 0.102 ± 0.003 | 3.8 ± 0.7 | 6.6 ± 1.8 | 25.6 ± 6.1 | 29.1 ± 6.6 | 28.6 ± 7.1 |
| 10896 | 0.127 ± 0.004 | 10.9 ± 1.1 | 13.4 ± 2.2 | 22.1 ± 6.0 | 15.2 ± 6.4 | – |
| 2641 | 0.301 ± 0.004 | 1.9 ± 0.6 | 11.2 ± 2.1 | 17.5 ± 6.0 | 16.0 ± 6.4 | – |

Figure 3. SFR (MIPS) versus SFR (Herschel). The red dot indicates the brightest infrared cluster galaxy (ID 16). The blue squares indicate possible contamination from neighbouring galaxies that could boost the SFRs obtained with Herschel.

6 THE BRIGHTEST FIR CLUSTER GALAXY

CLG0218 hosts a relatively massive (7 × 10^{10} M_☉) galaxy at the spectroscopic redshift 1.6238 (ID 16 in our catalogue) that dominates the cluster (i.e. r < 1 Mpc) infrared emission. In previous work (e.g. Tran et al. 2010; Bassett et al. 2013), this galaxy was taken as the cluster centre; hence, we adopt this approach here too. Following the procedure described in Section 5.2, we obtain a total infrared luminosity L_{IR,Herschel} = 3.3 ± 1.0 × 10^{12} L_☉, confirming that ID 16 is a ULIRG, and SFR (Herschel) = 256 ± 70 M_☉ yr⁻¹. We also estimate L_{IR} using the method previously described based on the extrapolation from 24 μm, and correct it for the mid-IR excess problem. We note that Rujopakarn et al. (2013) stress that the proposed methodology may not apply to galaxies hosting an AGN. We also note that for z > 1 the new 24 μm indicator underestimates...
by a factor up to 0.5 dex the total infrared luminosity in comparison with Herschel-derived luminosities (fig. 3 of Rujopakarn et al. 2013). As expected, for ID 16, we find a lower SFR from the 24 μm flux, SFR (24 μm) = 232 ± 20 M⊙ yr⁻¹, although this is fully consistent with the Herschel-derived value. This galaxy is also associated with X-ray emission detected by Chandra; therefore, we investigate the contribution of the AGN component to the FIR emission, using the program DECOMPIR (Mullaney et al. 2011), an SED-model-fitting software that attempts to separate the AGN from the host star-forming (SF) galaxy. Briefly, the AGN component is an empirical model based on observations of moderate-luminosity local AGNs, whereas the five starburst models were developed to represent a typical range of SED types, with an extrapolation beyond 100 μm using a grey body with emissivity β fixed to 1.5. For more details, see Mullaney et al. (2011) and Seymour et al. (2012). The best-fitting model obtained with DECOMPIR, ‘SB5’, indicates that the host galaxy dominates the FIR emission, with a negligible (~4 per cent) contribution from the AGN to the total luminosity as shown in Fig. 5.

Since we have a good sampling of the FIR SED for this galaxy, we are able to measure the galaxy dust temperature using a modified blackbody model with an emissivity index β = 1.5. The fit relies only on the PACS and SPIRE data that effectively straddle the peak of the SED. We find that the cold dust component of the galaxy has a temperature T_dust = 34.5 ± 4.2 K, a value typical of high-z ULIRGs (e.g. Hwang et al. 2010).

We note that, if any, the contamination from the close neighbour located at ~1.5 arcsec from ID 16 must be small since it is not centred with the 24 μm emission (see Fig. 6). This galaxy may belong to the cluster, with z_{cluster} = 2.0.

Since ID 16 clearly dominates the cluster SFR (the second highest star-forming galaxy in the cluster has SFR = 160 M⊙ yr⁻¹), we can draw a comparison with the Spiderweb galaxy (PKS1138) embedded in a protocluster system at z = 2.16 (Miley et al. 2006), because less than 1 Gyr separates the two galaxies in the adopted cosmology. Unlike the Spiderweb, ID16 is not associated with significant radio emission as seen by the deep VLA catalogue of Simpson et al. (2006), nor does the AGN (X-ray) emission appear to significantly contribute to the FIR SED. The recent Herschel study of PKS1138 by Seymour et al. (2012) shows that 60 per cent of the total infrared luminosity is due to the AGN component, and the SFR from the starburst corresponds to 772 ± 83 M⊙ yr⁻¹ (we scaled here the published value to the Chabrier IMF). Therefore, the core of CLG0218 appears to have a different history in comparison to PKS1138. Studies on the formation of galaxy clusters indicate that the development of the intracluster medium in the initial process of cluster virialization takes place around the BCG (Voit 2005). Therefore, another interesting aspect to explore is whether galaxy ID 16 could be seen as a precursor of the cluster BCG (Lapi et al. 2011). Again in PKS1138, the Spiderweb galaxy is undoubtedly the dominant galaxy of the system, with a stellar mass of the order of 10¹² M⊙ and will most likely form the BCG. In CLG0218, the scenario is different. In Papovich et al. (2010), the formation of the BCG is discussed using a sample of K-band-selected quiescent galaxies. The authors consider that the two most massive (~2 × 10¹¹ M⊙) spectroscopically confirmed galaxies (ID 39716 and ID 40170 in their nomenclature), separated by a projected distance of 126 kpc, will eventually merge and form the BCG with a stellar mass > 3 × 10¹¹ M⊙. Here, we raise the possibility that ID 16, though at a projected distance of about 300 kpc from these two massive, quiescent galaxies, could also merge with them, contributing to the BCG as well (see Fig. 7). With the current data, this is difficult to assess let alone prove, mainly because it is not possible to accurately establish the cluster centre; however, it would be interesting to follow up on this point with kinematic studies.

7 THE sSFR–M_* RELATION

In this section, we investigate the relation between stellar mass and SFR. The stellar masses were computed with the same optical/NIR SED-fitting technique as described in Section 4.2. We estimate a 5σ mass completeness limit of 1.5 × 10¹¹ M⊙ based on the z-band limiting magnitude (26.5 mag).

We first explore the relation between the stellar mass and SFR. In Fig. 8, we plot the specific star formation rate (sSFR = SFR/M_*) versus the stellar mass for the three galaxy samples used in our study. The deep 24 μm data allow us to reach the main sequence in this distant cluster (horizontal dashed line in the figure), sSFR MS = 1.3 Gyr⁻¹ obtained with the relation proposed by Elbaz et al. (2011), sSFR MS [Gyr⁻¹] = 26 × z^−2.2. The majority of the (U)LIRGs in the CLG0218 system and environment are therefore

Figure 5. SED (black points) of the brightest infrared cluster galaxy (ID 16) and best fit (blue solid line). The negligible contribution from the AGN component is shown by the red dotted line.

Figure 6. The brightest infrared cluster galaxy (ID 16). 40 arcsec × 40 arcsec cutouts centred on the galaxy, from left to right: K band, 24 μm, 100 μm, 160 μm, 250 μm.
starbursts (see Fig. 8). As shown in Table 4 and Fig. 8 right-hand panel, we find that the median SFR increases with increasing stellar mass. This trend as well as the absolute median SFR values are very similar for the three galaxy samples. Given the low number statistics of the spectroscopic and [O II] emitter samples, we will use from now on the overall sample of 693 galaxies detected by MIPS.

The sSFR is essentially a measure of the star formation efficiency of galaxies, and the large scatter in the sSFR–M∗ relation is generally attributed to complex processes related with the amount of gas available or used to convert to stars (e.g. Salmi et al. 2012). A negative trend in the sSFR–M∗ relation has been reported at all redshifts (e.g. Rodighiero et al. 2010). In CLG0218, we confirm this trend, where the most massive galaxies have the lowest sSFR that implies that more massive galaxies formed their stars earlier and more rapidly than their low-mass counterparts.

The locus of the 14 star-forming cluster galaxies (i.e. within 1 Mpc) forms a tight relation, described by a linear fit with slope α = −0.012, a mean of 2.0 Gyr−1 and a standard deviation of 0.89 (see diagonal black solid line in Fig. 8). We compare our results on the sSFR–M∗ relation of CLG0218 with other published work. The redshift evolution of the specific SFR has been studied in a number of recent papers of which we highlight a recent compilation of data by Sargent et al. (2012). The authors find an evolutionary trend described by a power law ∝(1 + z)2.8 ± 0.1. At redshift ∼1.6, fig. 1(c) of Sargent et al. (2012) predicts an sSFR for galaxies with M∗ ∼ 5 × 1010M⊙ of ∼1.34 Gyr−1. In CLG0218, we measure, for the same stellar mass and using the linear fit to the 14 cluster members, an sSFR of 1.89 Gyr−1, a value that is slightly higher than the one expected with the power-law-fitting function, but closer to the observational results at the same redshift from Elbaz et al. (2011). Therefore, the sSFR–M∗ relationship of the cluster CLG0218 agrees well with the relationship for the GOODS field galaxies presented in Elbaz et al. (2011).

8 MAPPING THE SFR IN THE CLUSTER AND ITS ENVIRONMENT

In this section, we investigate the relation between SF, environment and galaxy stellar mass. We explore two main approaches to define and study the environment: (i) fixed aperture, (ii) local galaxy

Table 4. SFRs measured from the MIPS 24 µm fluxes as function of stellar mass for the three samples: 10 spectroscopic galaxies, [O II] emitters, photometric redshift candidates with 1.52 < zphot < 1.7.

| Sample      | Mass bin          | Median SFR (M⊙/yr) |
|-------------|-------------------|--------------------|
| Spec.       | 1.5–5 × 1010      | 47                 |
| Spec.       | 5–10 × 1010       | 191                |
| Spec.       | ≥1011             | –                  |
| [O II], zphot | 1.5–5 × 1010      | 46                 |
| [O II], zphot | 5–10 × 1010       | 222                |
| [O II], zphot | ≥1011             | 229                |
| zphot       | 1.5–5 × 1010      | 56                 |
| zphot       | 5–10 × 1010       | 92                 |
| zphot       | ≥1011             | 161                |

Figure 8. Left – specific SFR as function of stellar mass for the three samples of galaxies: (1) spectroscopic galaxies at z ∼ 1.62 (red), (2) [O II] zphot members (blue) and (3) MIPS emitters with 1.52 < z < 1.72 (orange). The vertical dotted line indicates our mass completeness limit; the horizontal dashed line marks the main-sequence level and the diagonal dash–dotted line establishes the 5σ sensitivity limit of our MIPS data. The solid black line is a fit to the 14 member galaxies within the cluster region (r < 1 Mpc). Right: SFR as function of stellar mass. The median SFR of the full sample per mass bin is indicated by the horizontal black solid lines.
density. We also study the spatial distributions of the star-forming and passive galaxies at $1.52 < z_{\text{phot}} < 1.72$. Finally, we calculate the normalized total cluster SFR and compare it with works in the literature to gain insight on the redshift evolution of the SFR in groups and clusters.

8.1 SFR versus cluster-centric distance

We divide our full sample of 693 star-forming galaxies in three mass bins, taking into account our mass completeness level of $1.5 \times 10^{10} M_\odot$: (1) the low-mass bin, $1.5 - 5 \times 10^{10} M_\odot$, (2) an intermediate-mass category, $5 - 10 \times 10^{10} M_\odot$, and (3) massive galaxies with $\geq 10^{11} M_\odot$. We then group the galaxies in 1 Mpc slices. As in Tran et al. (2010) and Bassett et al. (2013), we consider the cluster region to be within a radius of 1 Mpc. As suggested by Bassett et al. and Tadaki et al., the field is defined by the galaxies beyond a radius of 3 Mpc cluster-centric distance. Fig. 9 shows the total SFR in each bin, normalized by the bin area for the three stellar mass regimes and the combined sample. The low- and intermediate-mass curves follow similar trends and absolute values, with a sharp transition at a radius 1–2 Mpc where the SFR decreases by a factor of ~2 relative to the inner bin and then increases at $r = 4 – 5$ Mpc, stabilizing to a level of $70 – 90 M_\odot$ yr$^{-1}$ Mpc$^{-2}$. The high stellar mass galaxies present a different behaviour, though we are limited by small number statistics. The inner bin with four galaxies has a lower value of $50 M_\odot$ yr$^{-1}$ Mpc$^{-2}$, immediately followed by a sharp decline with no galaxies in the 1–2 Mpc bin. From then on, we see a marked increase in the total SFR reaching $120 M_\odot$ yr$^{-1}$ Mpc$^{-2}$ at $r = 3 – 4$ Mpc, again a decrease to nearly 0, resuming to a total SFR per area at $r > 6$ Mpc concordant with the lower stellar mass bins.

This figure suggests that galaxy stellar mass may play an important role in the distribution/environment of star-forming galaxies in clusters. In particular, high-$M_*$ star-forming galaxies have a low SFR contribution in the cluster region and are nearly absent in the in-falling region. In addition, we highlight the quenching action of the transition region at 1–3 Mpc, characterized by a lower SFR in star-forming galaxies of any mass bin.

8.2 SFR and galaxy density

One of the most widely used techniques to study the environment in and around galaxy clusters is the use of a local density (e.g. Tanaka et al. 2006) defined as the number of galaxies within a circle of radius equal to the distance of the $n$th neighbour, normalized by the enclosed area. To be consistent with previous work, we consider a local density defined with $n = 5$, $\Sigma_5$. To compute the local density, we use the combined sample of star-forming and passive galaxies that lie above the mass cut $M_* > 1.5 \times 10^{10} M_\odot$.

We find no obvious trend between SFR and local density, in line with the result found by Tadaki et al. (2012) using a smaller and somewhat different sample including the [O II] emitters, and more recently Ziparo et al. (2013). However, the galaxy density maps computed with the distance to the fifth nearest neighbour for the star-forming and passive galaxies independently, show two large filamentary structures several Mpc across (Fig. 10). This confirms the view that groups and clusters are found at the crossings of such matter filaments and what is generally termed the field is not simply a random distribution of galaxies.

8.3 The relative fraction of SF to passive galaxies

Besides studying the star-forming population of this cluster and its surrounding region, we also investigate the relative fraction of SF to passive galaxies in the same area. This is important because in the lower redshift Universe, galaxy clusters are typically dominated by quiescent galaxies, particularly in the core (Dressler 1980; Wilman et al. 2009). Therefore, the study of the fraction of star-forming galaxies covering such a large area (i.e. reaching the low galaxy density of the field) enables us to investigate a potential reversal of the SF–density relation at high redshift.
The selection of passive galaxies was done using our optical/infrared SED catalogue. We selected galaxies with the same $z_{\text{phot}}$ range considered for the star-forming galaxies, 1.52–1.72, and we excluded all sources with $\text{sSFR} > 0.01 \text{Gyr}^{-1}$. Using these criteria, we end up with a sample of 205 quiescent galaxies. By applying the mass cut $M_* > 1.5 \times 10^{10} \text{M}_\odot$, we finally have a sample of 174 quiescent galaxies, in contrast with the 547 star-forming galaxies above the mass-completeness level.

In the left-hand panel of Fig. 11, we plot the relative fractions of passive and star-forming galaxies (normalizing to the total number of galaxies in each sample) as a function of radius, again by binning the galaxies in 1 Mpc slices and normalized by the area covered by each bin. The errors in each bin are simply the Poisson errors. While in the cluster region ($r < 1$ Mpc) and in the field area ($r > 3$ Mpc) there is no statistical difference between the two samples, we find an excess of the SF fraction relative to the corresponding passive fraction in the intermediate bin, $1 < r < 3$ Mpc. This behaviour is quantified in the right-hand panel of Fig. 11, where we plot the ratio between the two samples. The fraction of star-forming galaxies in the transition region is $\sim 4$ times larger than that of the passive galaxies, albeit the large associated errors.

Another way to compare the spatial distribution of the star-forming and passive galaxies that does not rely on binned data is to compute the two-sided Kolmogorov–Smirnov statistic of the galaxies in 1 Mpc slices and normalized by the area covered by each bin. The errors in each bin are simply the Poisson errors. While in the cluster region ($r < 1$ Mpc) and in the field area ($r > 3$ Mpc) there is no statistical difference between the two samples, we find an excess of the SF fraction relative to the corresponding passive fraction in the intermediate bin, $1 < r < 3$ Mpc. This behaviour is quantified in the right-hand panel of Fig. 11, where we plot the ratio between the two samples. The fraction of star-forming galaxies in the transition region is $\sim 4$ times larger than that of the passive galaxies, albeit the large associated errors.

In addition, we find that the fraction of star-forming galaxies is higher in the cluster than anywhere in the field (see blue line in Fig. 11, left-hand panel). We quantify this behaviour by performing a linear fit to the fraction of star-forming galaxies over the radial range 1–10 Mpc. We obtain a value $f_{\text{SF}} > 1$ Mpc of 0.0041 that represents the area-normalized mean fraction of star-forming galaxies across the transition and field regions. The central value, 0.0070 ± 0.0050, is 1.7 times greater than the mean value, $f_{\text{SF}} > 1$ Mpc; however, this value is hampered by the statistical errors. Hence, our conclusion that the fraction of star-forming galaxies is significantly enhanced in the cluster relative to the field is a tentative one (1σ).

**8.4 The mass-normalized cluster SFR**

The total SFR of the system ($\Sigma\text{SFR}$) is obtained by summing up the SFR of all members above the mass limit, enclosed in a circle with 1 Mpc radius: total SFR ($<1$ Mpc) $= 369 \pm 31 \text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-2}$. We also calculate the total SFR within a radius of 0.5 Mpc to be able to compare our results with Tran et al. (2010), who quote an SFR ($r < 0.5$ Mpc) equal to 1740 $\text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-2}$. We find instead a lower value of the star formation in the same region: $990 \pm 121 \text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-2}$, using Herschel SFRs where possible. This discrepancy can be understood, considering that Tran et al. used the Chary & Elbaz (2001) templates that overestimate $L_{\text{IR}}$ at these redshifts. If we use SFRs from MIPS only, we get a lower value, $786 \text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-2}$. Assuming that the SFRs derived from Herschel are the most accurate, this points to an overcorrection of the 24 $\mu$M SFRs when using the Rujopakarn et al. method.

The mass-normalized cluster SFR is obtained by dividing $\Sigma\text{SFR} (<1$ Mpc) by the system gravitational mass, $5.7 \pm 1.4 \times 10^{13} \text{M}_\odot$ (Tanaka et al. 2010). We thus obtain $\Sigma\text{SFR}/M_\delta = 6.5 \times 10^{-12} \text{yr}^{-1} \text{Mpc}^{-2}$. The parameter $\Sigma\text{SFR}/M_\delta$ has been used by several authors to quantify the evolution of the global SFR in clusters with redshift. Koyama et al. (2011) confirmed previous findings on the rapid increase of the mass-normalized SFR with redshift, following the relation $\propto (1+z)^3$, though his study was based on a small sample of a dozen clusters reaching only $z \sim 1$ and the aperture considered to compute the total SFR was 0.5 Mpc, instead of the virial radius. More recently, Webb et al. (2013) performed a similar study using the Red Sequence Cluster sample with 42 clusters within the range $0.3 < z < 1.0$ and found a similar evolutionary trend with a slope of 5.4 ± 1.9. The authors used $r_{300}$ to compute the total SFR of the cluster and attribute the evolution to variations in the in-falling field galaxy population.

For consistency, since we consider the total cluster gravitational mass, we consider as well a radius that encompasses the total cluster mass, 1 Mpc. Comparing our value, $\Sigma\text{SFR}/M_\delta = 6.7 \times 10^{-12} \text{yr}^{-1} \text{Mpc}^{-2}$, with figs 11 and 12 of Koyama et al. (2011), we find that CLG0218 actually falls in very good agreement with the $(1+z)^3$ relation. Although this comparison is only qualitative, it lends support to the empirically expected significant increase in the global star formation of CLG0218, relative to lower redshift clusters. However, our investigation of the radial distribution of the SFR presented in Fig. 9 as well as the fraction of star-forming galaxies depicted in Fig. 11 seems to be inconsistent.
with the hypothesis raised by Webb et al. (2013) that the in-falling galaxy population is responsible for a high level of SFR in high-$z$ clusters. Instead, the high level of SFR in the CLG0218 at $z = 1.62$ is most likely due to a reversal of the SFR–density relation.

9 CONCLUSIONS

In this paper, we perform a new large-scale characterization of the dusty star-forming properties in and around CLG0218, a low-mass galaxy cluster at $z = 1.6$, using deep 24 $\mu$m MIPS and Herschel 100–500 $\mu$m imaging data covering an area of 20 Mpc $\times$ 20 Mpc (comoving scale at the cluster redshift). Here, we summarize our main findings as follows.

(i) Using the 24 $\mu$m fluxes, we measure luminosity-based SFRs in the range 18–2500 $M_\odot$ yr$^{-1}$ for a sample of 693 spectroscopic and $z_{\text{phot}}$ galaxies across a radius of 10 Mpc from the cluster centre.

(ii) For a subsample of 29 galaxies, we have robust Herschel detections that allow us to assess the MIPS SFRs: although the scatter is large, the overall agreement is good. While contamination from neighbouring galaxies may explain SFRs (Herschel) $>$ SFRs (MIPS), it is also possible that the methodology proposed by Rujopakarn et al. (2013) may overcorrect the SFR for high-luminosity galaxies.

(iii) We characterize the brightest FIR cluster galaxy, ID 16, a spectroscopic member with $M_*=7 \times 10^{10} M_\odot$, SFR (Herschel) $=256 \pm 70 M_\odot$ yr$^{-1}$ and a dust temperature of 34.5 $\pm$ 4.2 K. This galaxy is also taken to be the centre of the cluster. Even though there is X-ray emission associated with this galaxy, we do not detect a significant AGN contribution to the FIR SED.

(iv) We estimate an extinction of 3 mag in [O ii] for the galaxies associated with CLG0218 and its environment.

(v) The SFR contribution from high-$M_*$ galaxies varies significantly with cluster-centric distance and is much lower than that of the lower $M_*$ galaxies. High $M_*$ are absent in the in-falling region at 1–3 Mpc.

(vi) We do not find any obvious trend between the individual galaxy SFRs and local galaxy density parametrized by $\Sigma_5$.

(vii) We measure an enhancement by almost a factor of 2 in the fraction of star-forming galaxies in the cluster (defined by an aperture with $r = 1$ Mpc) relative to the field (i.e. $r > 3$ Mpc).

(viii) We find a significant decrease (by a factor of 3.5) in the fraction of passive relative to star-forming galaxies in the in-falling region.

(ix) We find two large-scale filamentary structures in the galaxy density maps of both the passive and the star-forming samples, showing that the galaxy distribution in the field surrounding CLG0218 is not uniform.

The enhanced fraction of star-forming galaxies at $r < 1$ Mpc seen in Fig. 11 shows that SF is nearly two times larger in the higher density environment of the cluster with respect to the lower galaxy density of the surrounding field and in this sense it can be interpreted as a reversal of the SF–density relation. In addition, the similar relative fraction of SF and passive galaxies within the cluster (also seen at $r > 3$ Mpc) is surprising and indicates that this system has a young, active population of galaxies.

Our study shows that the in-falling region (1–3 Mpc) is where most differences are seen in terms of dependence with stellar mass, lower SFR and deficiency of quiescent galaxies. This result is in stark contrast to the study of XMMUJ2235.3-2557, a massive galaxy cluster at $z = 1.39$, in which most of the SFR seen by Herschel is at $r_{\text{vir}}$ and beyond (Santos et al. 2013). This suggests that as we move from massive distant clusters to even more distant but less massive clusters/groups, star formation migrates from the field, through the outskirts and on to the cluster core. To better understand this effect, future studies of the star formation in high-redshift clusters should include the surrounding cluster environment.

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