Starbursting Brightest Cluster Galaxy: a Herschel view of the massive cluster MACS J1931.8–2634

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ABSTRACT

We investigate the dust-obscured star formation properties of the massive, X-ray selected galaxy cluster MACS J1931.8–2634 at z=0.352. Using far-infrared (FIR) imaging in the range 100-500 µm obtained with the Herschel telescope, we extract 31 sources (2σ) within r ∼1 Mpc from the brightest cluster galaxy (BCG). Among these sources we identify six cluster members for which we perform an analysis of their spectral energy distributions (SEDs). We measure total infrared luminosity (LIR), star formation rate (SFR) and dust temperature. The BCG, with LIR=1.4×10^12 L⊙ is an Ultra Luminous Infrared Galaxy and hosts a type II AGN. We decompose its FIR SED into AGN and starburst components and find equal contributions from AGN and starburst. We also recompute the SFR of the BCG finding SFR=150±15 M⊙ yr^-1. We search for an isobaric cooling flow in the cool core using Chandra X-ray data, and find no evidence for gas colder than 1.8 keV in the inner 30 kpc, for an upper limit to the instantaneous mass-deposition rate of 58 M⊙ yr^-1 at 95% c.l. This value is 3x lower than the SFR in the BCG, suggesting that the on-going SF episode lasts longer than the ICM cooling events.

Key words: galaxies: clusters: individual: MACS J1931.8–2634; galaxies: star formation; infrared: galaxies; X-rays: galaxies: clusters

1 INTRODUCTION

The cores of galaxy clusters are ubiquitously populated by old, passively evolving spheroids, with little evidence for ongoing or recent episodes of star formation (e.g., Dressler 1980, Dressler et al. 1997, Von der Linden et al. 2010, Girardi et al. 2015). This suppression of star formation (SF) is mainly caused by interactions among the densely packed galaxies (e.g., Moore et al. 1996, Gnedin 2003), and to a lesser extent by interactions between the hot, X-ray emitting intracluster medium (ICM) and the galaxies. The brightest cluster galaxy (BCG) that usually sits at the bottom of the potential well and is coincident with the peak of the cluster X-ray emission, is typically a very massive, bright, early type galaxy, that only rarely is associated with significant star formation activity (e.g., Samuele et al. 2011, Rawle et al. 2012, Fogarty et al. 2015).

Cool core (CC) clusters are systems whose ICM shows a minimum core temperature that is about one third of the global ICM temperature and a low core entropy (<30 keV cm^2), that reflects significant radiative cooling taking place in the cluster innermost regions (e.g., Peterson & Fabian 2006, Hudson et al. 2010). Observations have shown that BCGs with ongoing star formation activity are usually hosted by CC clusters (Hoffer et al. 2012). However, there is still a large variance in current results on the fraction
of star forming BCGs and the amount of their star formation rate (SFR). This is partly because different diagnostics are used (e.g., optical emission lines, UV continuum, far-infrared) that may be affected by dust emission and AGN contamination, but also because samples are often not representative. In particular, {Samuele et al.} (2011) investigated the star formation activity in a sample of 77 BCGs drawn from a flux limited, X-ray selected cluster sample and reported a lack of star formation in that sample, based on optical emission lines. In contrast, {Rawle et al.} (2012) detected star formation in 15 out of 68 BCGs using a more robust diagnostic based on the FIR emission. The caveat in this fraction is that the sample of BCGs originate from a mix of cluster samples, mostly selected to include massive and relaxed clusters that are thus biased toward CCs, therefore are more likely associated with star forming BCGs.

It is well known that AGN play a crucial role in the regulation of the star formation in BCGs (e.g., Hlavacek-Larrondo et al. 2013 [Russell et al. 2013]). Ample evidence for AGN feedback has been collected in the last decade, where radio jets have been shown to inflate bubbles in the ICM and hence offset cooling, nonetheless the link between AGN and star formation is not yet properly established (e.g., McNamara & Nulsen 2007). For a review). The recent study of the Phoenix cluster at $z=0.596$ (McDonald et al. 2012), the strongest CC cluster known to date, showed a BCG with a very high SFR and an equally significant AGN activity.

The X-ray selected cluster MACS J1931.8–2634 (MACS1931 hereafter, Ebeling et al. 2001) at $z=0.352$ is part of the CLASH (Cluster Lensing And Supernova survey with Hubble). Postman et al. (2012) sampled 25 massive clusters used to study the distribution of dark matter in clusters. As all of the CLASH clusters, MACS1931 is massive with $M_{200}=9.9±0.7×10^{14}$ M$_\odot$. Merten et al. (2015) with a relaxed X-ray morphology, and harbors a cool core (Ehler et al. 2011). The cluster is dominated by a very large, luminous central galaxy that, contrary to what is common in most massive clusters, is undergoing a phase of copious star formation. Measured star formation rates range from 80 M$_\odot$ yr$^{-1}$ (rest-frame UV imaging, Donahue et al. 2015) to 170 M$_\odot$ yr$^{-1}$ (broad band optical imaging, Ehler et al. 2011). However, these SFRs may be contaminated by AGN activity and underestimated due to dust obscuration.

The work presented in this Letter aims to overcome these two biases. We present the analysis of Herschel (Pilbratt et al. 2010) 100–500 μm observations of MACS1931 that cover the peak of the SED of starbursts. The far-infrared (FIR) is the best diagnostic for star formation as it provides a direct measure of the reprocessed UV light from the on-going star formation, allowing us to measure the total FIR luminosity, star formation rates and dust temperatures of the cluster members. We also focus on the BCG and its environment using Chandra X-ray data. The work presented here is part of a larger Herschel study including all CLASH clusters. The cosmological parameters used throughout the paper are: $H_0=70$ km/s/Mpc, $\Omega_{\Lambda}=0.7$ and $\Omega_m=0.3$.

2 DATA

Although the present work is focused on data from the Herschel space telescope, we use ample ancillary data both proprietary and archival: mid-infrared data from WISE; X-ray data from Chandra; optical data from Subaru (BVR,I,z), the Hubble Space Telescope (HST), and extensive VLT/VIMOS spectroscopy.

2.1 Herschel observations and data reduction

The Herschel observations of MACS1931 were carried out in 2011, 2012 and 2013 as Open Time 1 and 2 programmes (PI Egami, obsid = 1342215993, 1342241619, 1342241681, 1342254639) aimed at studying the star formation properties of lensing clusters. The PACS (Poglitsch et al. 2010) observations at 100 and 160μm were performed in scan map mode. The maps were produced using Unimap (Piazza et al. 2015): a Generalized Least Square map-maker, that allows us to reach ultimate sensitivity with no flux loss, and without iterative masking of the sources. The 1σ noise of the maps is 1.6 mJy in the 100 μm band and 3.5 mJy in the 160 μm image. SPIRE (Griffin et al. 2010) maps with a $\sim5'$ radius were obtained in small map mode. The SPIRE maps at 250, 350 and 500 μm with nominal pixel sizes of 6", 10" and 14", respectively, are dominated by confusion noise with an rms in the center of 6.2, 6.5 and 7.3 mJy.

2.2 Far-infrared sources in MACS1931

Our far-infrared observations of MACS1931 covers a region with 3.6' radius centered on the X-ray cluster center, where the sensitivity of the PACS maps is robust (see Fig. 1). This radius corresponds to 1.1 Mpc in physical units which is about 1/2 of the cluster virial radius measured from lensing ($r_{200}=1.82±0.04$ Mpc. Merten et al. 2015).

Here we outline our procedure to obtain the catalog of FIR sources in the field of MACS1931. Our catalog is based on blind source detections in the 100 and 160μm maps separately, using SExtractor (Bertin & Arnouts 1996). As standard for PACS data, the photometry is made with fixed...
apertures with radii of 6′ and 9′ at 100 µm and 160 µm, respectively, corrected with the encircled energy factors given by Balog et al. (2014). This procedure was validated with manual aperture photometry. 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 1σ detection limits in each band, in addition to 7% (calibration accuracy of the flux scale) of the source flux. The SPIRE source detection was performed using a simultaneous fit to all sources in the prior list based on the PACS detections. We run the XID method (Roseboom et al. 2012) using the same prior catalog on the three SPIRE bands, using the corresponding SPIRE point response function for each band. If the fitted SPIRE flux density at the position of an input PACS source is below the 3σ sensitivity in each band we assigned the 3σ in at least one of the SPIRE bands, within ~29′ distance.

We obtain 31 detections at >2σ in at least one of the PACS bands, within r=3.6′ centered on the BCG. To identify the origin of these sources we match the FIR catalog with our spectroscopic and photometric redshift catalogues. The spectroscopic catalog consists of 2800 redshifts obtained with VIMOS (CLASH-VLT Large Programme 186.A-0798, PI Rosati, Rosati et al. 2014), whereas the photo-z catalogues are based on photometry from the HST and Subaru (Balog et al. 2014). We find that, of the 31 sources in the cluster field, 4 are confirmed members, 2 are candidate members (photo-z) and 18 are interlopers. Since the completeness of our spectroscopic sample of cluster members is close to 90% it is unlikely that the remaining 7 Herschel sources are at the cluster redshift.

| ID | RA      | DEC    | z      | rproj (kpc) | F100µm (mJy) | F160µm (mJy) | LIR (10^11 L⊙) | SFR (M⊙ yr⁻¹) | Tdust (K) |
|----|---------|--------|--------|------------|--------------|--------------|----------------|--------------|-----------|
| 62 | 292.905501 | -26.5669131 | 0.3644 | 923 | 6.5±1.7 | 9.6±3.6 | 0.43±0.04 | 6.4±0.6 | 29±5 |
| 69 | 292.956707 | -26.575807 | 0.352 | 283 | 212.5±15.0 | 231.3±16.5 | 14±2 | 210±23 | 33±2 |
| 75* | 292.956064 | -26.5782649 | 0.3652 | 117 | 3.2±1.6 | 10.7±3.6 | 0.47±0.07 | 7.0±1.5 | 14±1 |
| 89 | 292.941855 | -26.5999476 | 0.3494 | 498 | 4.0±1.6 | 10.1±3.6 | 0.34±0.04 | 5.0±0.5 | 24±4 |
| 68 | 292.936482 | -26.5724383 | 0.36±0.07 | 366 | 8.9±1.7 | 12.4±3.6 | 0.54±0.06 | 8.0±1.0 | 30±4 |
| 80 | 292.913344 | -26.5832069 | 0.34±0.07 | 785 | 21.5±2.2 | 32.2±4.2 | 1.3±0.1 | 19.5±1.7 | 29±2 |

* SPIRE fluxes of ID 75 may be contaminated by the BCG that is located at ~29′ distance.

**Table 1.** Properties of the FIR cluster members, with spectroscopic redshift and photometric redshift concordant with the cluster.

We fit the galaxies FIR SEDs using LePhare (Arnouts et al. 1999) with Chary & Elbaz (2001) templates, to measure the galaxy integrated infrared luminosity \(L_{IR}\) in the range 8–1000 µm. The star formation rates are derived using the updated scaling relation, \(SFR_{IR} = 1.48 \times 10^{-10} L_{IR}/L_{⊙}\), (Kennicutt 2012) Murphy et al. 2011, that uses a Kroupa initial mass function (Kroupa et al. 2001). The SFR of our sample, measured with pure starburst templates, spans the range 5–210 M⊙yr⁻¹. If we exclude the highest star-forming galaxy - the BCG - we find an average SFR of 9.2 M⊙yr⁻¹. The total SFR of the six cluster galaxies amounts to 256 M⊙yr⁻¹. This value is in good agreement with the recent result on the SFR of massive clusters using Herschel data by Popesso et al. (2015). In the next section we perform a more detailed study of the BCG and refine its SFR measure, after accounting for the impact of the AGN. With the exception of the BCG that is an Ultra Luminous Infrared Galaxy (ULIRG, \(\geq 10^{12} L_{⊙}\)), the FIR detected cluster galaxies are LIRGs or normal star forming galaxies.

The temperature of the dust, \(T_{dust}\), present in the galaxies is computed with a modified black body model with an emissivity index \(\beta\) fixed to 1.5. Apart from galaxy ID 75, that shows some contamination with the BCG fluxes in the SPIRE bands, we find \(T_{dust}\) in the range 24-33 K, which is within the range of dust temperatures for \(z \leq 0.3\) LIRGs and ULIRGs (Magdis et al. 2014). The FIR properties of the cluster members are summarized in Table 1.

### 4. CONNECTION BETWEEN THE BCG, THE AGN AND THE ICM

In this section we analyze in detail the BCG sitting at the core of the cluster. It is uncommon to have a cluster with a massive BCG with a SFR level of 210 M⊙yr⁻¹ (Rawle et al. 2012, Hooper et al, 2012). However, our initial SFR result may be biased by the presence of a strong obscured AGN, which needs to be carefully modeled. We also explore the interconnections between the star formation of the BCG and the mass deposition rate in the cluster core. The UV and optical properties of this galaxy have been studied in Donahue et al. (2015) and Ehler et al. (2011), that computed the galaxy star formation rate using different diagnostics. We convert their values to the ones obtained with the updated calibration used here, as described in Kennicutt (2012). While Donahue et al. (2015) found a SFR = 69 M⊙yr⁻¹ using UV photometry, Ehler et al. (2011), in a crude approximation, derived a value twice larger, 146 M⊙yr⁻¹, based on optical broad band imaging. These calculations do not account for dust extinction nor for contamination from AGN activity.

#### 4.1 SED decomposition: AGN & star formation

The BCG of MACS1931 hosts an X-ray bright AGN, embedded in the ICM emission, which we model and sub-
isobaric cooling. The main difference relative to the previous 30 kpc around the BCG under the same assumption of isobaric cooling. Despite the high cooling rate, this cluster is missing equivalent mass deposition rate of \( \sim \) 700 M\(_{\odot}\) yr\(^{-1}\). We first investigate the contribution of the AGN component to the FIR emission using DecomplR (Mullaney et al. 2011), an SED model fitting software that decomposes the FIR SED in AGN and starburst components. In short, the AGN component is an empirical model based on observations of moderate-luminosity local AGNs, whereas the 5 starburst models represent a typical range of SED types, with an extrapolation beyond 100 \( \mu \)m using a grey body with \( \beta = 1.5 \). The best-fit model obtained with DecomplR considering the Herschel datapoints (Fig. 2) yields \( L_{\text{IR}} = 2.2 \times 10^{12} \) L\(_{\odot}\), with AGN and starburst contributions of 53% and 47%, respectively. This allows us to recompute the SFR removing the AGN contamination. We thus obtain SFR(BCG) = 150\( \pm 15 \) M\(_{\odot}\) yr\(^{-1}\), a value similar to that reported in Ehlert et al. (2011) but much more robust.

4.2 Mass deposition rate and SFR
MACSJ1931 harbors one of the most X-ray luminous cool cores known. The properties of the core of MACSJ1931 have been investigated in detail in Ehlert et al. (2011), where an equivalent mass deposition rate of \( \sim 700 M_{\odot} \) yr\(^{-1}\) in the inner 70 kpc has been estimated in the assumption of isobaric cooling. Despite the high cooling rate, this cluster is missing the central metallicity peak which is otherwise measured in the majority of CC clusters (DeGrandi et al. 2004). This suggests bulk transport of cool gas out to large distances from the centre due to the powerful AGN outburst in Ehlert et al. (2011). In particular, a bright, dense region north of the BCG shows low-temperature and high-density metal-rich gas and is consistent with being a remnant of the cool core after it was disrupted by the AGN (see also Kirkpatrick 2011).

We constrain the ICM mass cooling rate, \( \dot{M} \), in the inner 30 kpc around the BCG under the same assumption of isobaric cooling. The main difference relative to the previous analysis by Ehlert et al. (2011) is that we focus on a limited temperature range, 0.15-3.0 keV, and in particular below 1.8 keV. In fact, the signature of an isobaric cooling flow is given by a specific relation between the emission measure and the gas temperature, as described in the model \( \text{mkcflow} \) (Mushotzky et al. 1988). Therefore we measure the cooling rate of the gas independently in five temperature bins, using a set of \( \text{mkcflow} \) models within XSPEC (Arnaud et al. 1996) in the following temperature intervals: 0.15–0.25, 0.25–0.45, 0.45–0.9, 0.9–1.8,1.8–3.0 keV. We also consider a single temperature \( \text{mekal} \) (Mewe et al. 1985, 1988; Kaast et al. 1992; Liedahl et al. 1995) component to account for the gas hotter than 3 keV. We detect about 13700 net counts (0.5-7.0 keV band) in the inner 30 kpc. Since it is not possible to measure the metal abundance of the cold gas, given its low emission measure, we conservatively assume that its metallicity is equal to that of the \( \text{mekal} \) component which dominates the emission, which is \( Z = 0.35 \pm 0.05 Z_{\odot} \). We find that the mass deposition rate for gas below 3 keV has a 95% single-sided upper limit of \( M < 135 M_{\odot} \) yr\(^{-1}\) (see dashed horizontal line in Fig. 3, left panel), while the temperature of the \( \text{mekal} \) component is \( kT = 6.43_{-0.45}^{+0.50} \) keV. When we try to constrain \( M \) in temperature intervals, we find that we are able to measure a substantial mass deposition rate only in the temperature range 1.8-3.0 keV. Below 1.8 keV, the upper limit on the mass deposition rate is only \( M < 58 M_{\odot} \) yr\(^{-1}\) at a 95% c.l. The upper limits measured in different temperature bins are shown in Fig. 3, left panel. We find that \( M \) is significantly lower - at least by a factor 3 - than the measured SFR.

This result is in broad agreement with the correlation between the SFR observed in the BCG and the properties of the hosting cool core (Rafferty et al. 2006; Rawle et al. 2012), but in disagreement with previous measurements of a mass deposition rate typically higher than the SFR in the BCG (Odea 2006; McDonald 2011 et al. 2011; Mittal et al. 2013). Clearly, the ratio of the mass deposition rate and the SFR is sensitive to the times scales for ICM cooling and star formation and it is not expected to vary much among clusters. To check whether we can reconcile the results for MACSJ1931 with previous results, we also explore the presence of colder clouds (with temperature \( < 10^{7} \) K) in the ICM beyond 30 kpc, where a significant fraction of colder gas can cool and fall into the innermost regions. This is suggested by a recent work by Voit et al. (2015) which showed that colder clouds can precipitate out of the hot gas via thermal instability on a large region centered in the core, feeding black hole accretion and/or star formation in the BCG. Even in this case we find an upper limit (95% c.l.) of 45 and 52 M\(_{\odot}\) yr\(^{-1}\) in annuli of 30-50 and 50-70 kpc, respectively. Therefore, we do not find evidence of a large amount of colder gas within 30 kpc nor falling from beyond 30 kpc onto the centre. The low upper limits on the mass deposition rate found in the case of MACSJ1931, may require a scenario where the time scale for star formation rate in the BCG is longer than the cooling events occurring intermittently in the cluster core. To investigate this possibility, we are currently exploring the relation between \( M \) and SFR in a small sample of nearby clusters whose BCG shows significant star formation (Molendi et al. in preparation).
5 CONCLUSIONS

In this Letter, we present a study of the dust obscured star formation properties in the galaxy cluster MACS1931 at z=0.352, and a detailed investigation on the origin of the BCG SFR. We detect FIR emission in 6 cluster members and we derive SFRs based on broad band FIR SEDs in the BCG SFR. We detect FIR emission in 6 cluster members and we derive SFRs based on broad band FIR SEDs in the BCG SFR. The regions in which we computed $\dot{M}$ are shown in cyan (inner 30 kpc) and in magenta (annulus with 50 – 70 kpc radius). North is up and East to the left.

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