The Rarity of Star Formation in Brightest Cluster Galaxies as Measured by WISE

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ABSTRACT

We present the mid-infrared (IR) star formation rates of 245 X-ray selected, nearby ($z < 0.1$) brightest cluster galaxies (BCGs). A homogeneous and volume limited sample of BCGs was created by X-ray selecting clusters with $L_x > 1 \times 10^{44}$ erg s$^{-1}$. The Wide-Field Infrared Survey Explorer (WISE) AllWISE Data Release provides the first measurement of the 12 µm star formation indicator for all BCGs in the nearby Universe. Perseus A and Cygnus A are the only galaxies in our sample to have star formation rates of $> 40$ M$_\odot$ yr$^{-1}$, indicating that these two galaxies are highly unusual at current times. Stellar populations of 99 ± 0.6% of local BCGs are (approximately) passively evolving, with star formation rates of $< 10$ M$_\odot$ yr$^{-1}$. We find that in general, star formation produces only modest BCG growth at the current epoch.

Key words: galaxies: clusters: general – galaxies: elliptical and lenticular, cD – galaxies: star formation – infrared: galaxies

1 INTRODUCTION

Brightest cluster galaxies (BCGs) are massive, highly luminous ellipticals located at the bottom of a galaxy cluster’s potential well. They differ from other large elliptical galaxies in size and velocity dispersion (e.g., von der Linden et al. 2007), and are often offset from the cluster red sequence (Bildfell et al. 2008; Bernardi et al. 2009; Dekel & Birnboim 2006; De Lucia & Blaizot 2007, and references therein). In the local Universe, the bulk of BCGs are red, early-type galaxies with spectra lacking emission lines. Any activity is largely quenched, likely due to a combination of dwindling merger activity and successful feedback mechanisms such as virial shock heating and AGN feedback (e.g., Binney & Tabor 1995; Voit & Donahue 2005; Dekel & Birnboim 2006; De Lucia & Blaizot 2007, and references therein).

Despite the predominantly quiescent population at current times, many BCGs possess trickles of star formation (e.g., Bildfell et al. 2008; Pipino et al. 2008; Ford & Bregman 2013). The central cluster environment is known to affect BCG star formation rates (SFRs), for example the presence of a cooling flow is likely to trigger star formation (e.g., O’Dea et al. 2008; Stott et al. 2008; Hicks, Mushotzky & Donahue 2011; Donahue 2009; Rawle et al. 2012, and references therein).

Cooling flow clusters, or clusters with low central gas entropy, were found to produce infrared (IR) and UV excess in the X-ray selected cluster sample of Hoffer et al. (2012). Of the 243 BCGs in the Hoffer et al. (2012) sample, BCGs located in low central gas entropy clusters had an excess above that expected for purely old stellar emission of 43% and 38% in the IR and UV respectively. SFRs determined from the excess emission were moderate, and of all galaxies in the local Universe (defined as $z < 0.1$), only Perseus A and Cygnus A possessed SFRs $> 10$ M$_\odot$ yr$^{-1}$ (34 and 95 M$_\odot$ yr$^{-1}$ respectively). The Hoffer et al. (2012) sample was heterogeneous but uniformly characterised, including only clusters that had been observed by Chandra.

Optically derived BCG SFRs were provided for the X-ray selected sample of Crawford et al. (1999). Emission line spectra comprised 27% of the BCG sample, and a further 6% had only NI in emission and Hα in absorption. After fitting a stellar spectra template to the galaxies in their sample with high Hα luminosities, they found optically-derived SFRs of $< 1-10$s of M$_\odot$ yr$^{-1}$. One cluster at a higher redshift (Abell 1835, $z=0.253$) had a BCG with a SFR of 125 M$_\odot$ yr$^{-1}$.

At $z > 1$, cluster samples with star forming central galaxies are common (e.g., Brodwin et al. 2013). At intermediate redshifts there are some examples of starburst BCGs, such as the Phoenix cluster ($z=0.596$) BCG which...
A homogeneous BCG sample was created based on X-ray selection of host clusters with $L_x > 1 \times 10^{44}$ erg s$^{-1}$ in the ROSAT 0.1–2.4 keV band, corresponding to an approximate cluster mass of $M_{200} \geq 1 \times 10^{14}$ M$_\odot$ (Hoekstra et al. 2011). Selecting only X-ray luminous clusters ensures BCGs are located in comparatively massive clusters. X-ray clusters were taken from the ROSAT Brightest Cluster Survey (BCS; Ebeling et al. 1998), extended BCS (Ebeling et al. 2000), the x-ray Brightest Abell Clusters Survey (Ebeling et al. 1996), the ROSAT North Ecliptic Pole Survey (e.g., Gioia et al. 2001), the ROSAT-ESO flux limited X-ray galaxy cluster survey (e.g., Böhringer et al. 2001), and The Northern ROSAT All-Sky Galaxy Cluster Survey (Böhringer et al. 2004), queried using the Base de Données Amas de Galaxies (BAX; Sadat et al. 2004). The redshift of the sample was limited to $z < 0.1$, creating a sample of 267 nearby, X-ray bright clusters where the completeness limit of each of the input surveys was at least 80%. As we wished to identify BCGs regardless of their SFR, no colour selection criteria were applied.

We identified 144 BCGs by cross-matching the cluster sample with the BCG catalogues of Stott et al. (2008), Coziol et al. (2009) and Wen, Han & Liu (2012). The remaining 123 unmatched clusters were inspected visually by AFM and KAP in both optical (Digitized Sky Survey) and infrared (Two Micron All Sky Survey, 2MASS) images, along with a NASA/IPAC Extragalactic Database object search to verify the redshifts of the candidate BCGs. The vast majority of identifications were unambiguous, and in all cases, the brightest galaxy in the 2MASS K-band at the cluster redshift was chosen as the BCG.

In some cases, clusters had to be eliminated from the sample if it was not clear which galaxy was the BCG. Reasons for this included mergers of galaxies of similar magnitude (e.g., Abell 3825), source confusion (e.g., Abell 523), or unavailable redshift information for any candidate BCG (e.g., Abell 72). Clusters were also eliminated from the sample if the WISE image showed source contamination from nearby saturated stars, or in cases, the same cluster was entered twice into BAX under different names.

The final sample comprises 245 BCGs, covering both the northern and southern hemispheres, for which source photometry was extracted from for the AllWISE Data Release Catalog.

3 PHOTOMETRY

WISE (Wright et al. 2010) completed a whole-sky survey in four IR bands: 3.4, 4.6, 12 and 22 $\mu$m (denoted bands W1-W4). Bands W1 and W2 coincide with the Rayleigh-Jeans tail of the stellar emission of a galaxy and provide an accurate estimate of stellar mass. The W3 band is sensitive to warm dust and polycyclic aromatic hydrocarbon (PAH) emission associated with HII regions and molecular clouds.

Photometry for each BCG in the sample was extracted in all bands from the newly released AllWISE Source Catalog, combining improved multi epoch photometry from the WISE and NeoWISE surveys. We use the recommended approach for extended sources from the AllWISE explanatory statement¹, briefly described below.

Sources that are resolved and associated with a 2MASS Extended Source Catalog (XSC) object (232 galaxies in our sample) are measured with elliptical apertures made using apertures scaled from 2MASS XSC apertures to account for the WISE PSF. AllWISE sources that are associated with a 2MASS XSC object but are not resolved in WISE (7 galaxies) are modelled with profile fit photometry to avoid overestimating flux. For the four sources that are extended but not associated with a 2MASS XSC object, a fixed aperture size of 15.6$''$ based on curve of growth was used with the prescribed aperture correction applied to each band. Where the signal to noise ratio is less than 2 in the W3 band, the magnitude of the 95% confidence brightness upper limit is instead used for analysis.

4 STAR FORMATION RATES AND BCG GROWTH

To illustrate the IR excess of BCGs, in Figure 1 we plot the WISE colours of BCGs with W3 band detections. Like local ellipticals (Jarrett et al. 2011), the locus of the BCG sample is slightly offset from the origin at around W2-W3 ~ 0.4 (corresponding to an approximately Rayleigh-Jeans spectrum).

¹ http://wise2.ipac.caltech.edu/docs/release/allwise/faq.html
We subtracted stellar emission using the Cohen et al. (1992) stellar calibration model fitted to the W2 band, which closely resembles the tail of the Rayleigh Jeans spectrum. Subtracting this primarily stellar emission from the W3 band leaves emission solely from warm dust. Hence $L_{W3}$ is the stellar emission-subtracted IR luminosity in the WISE W3 band, and $\nu$ the effective frequency of the W3 passband.

We modelled the WISE apparent and absolute magnitudes of galaxies as a function of both redshift and observed colour using the SED templates of Brown et al. (2014). The k-corrections as a function of colour at a given redshift were estimated and applied. K-corrections are ~0.3 magnitudes or less for the bulk of the galaxies in our sample, corresponding to a $\Delta SFR \sim 0.04 \, M_\odot \, \text{yr}^{-1}$.

The SFRs as calculated by Equation 1 are plotted against cluster redshift in Figure 2. Of the BCG sample with detections in the W3 band, 99 ± 0.6% have SFRs of 10 $M_\odot \, \text{yr}^{-1}$ or less. Two significant outliers, Perseus A and Cygnus A, have SFRs of 41 and 70 $M_\odot \, \text{yr}^{-1}$ respectively. BCG photometry, along with stellar mass and SFR estimates are listed in Table 1. The dominant uncertainty is that from the scatter from the relation of Equation 1 (Cluver 2014, private communication). We matched our BCG sample to the total IR and UV-derived SFRs of Hoffer et al. (2012), and the optically derived SFRs of Crawford et al. (1999), with 18, 49 and 6 matches to our sample respectively. For SFRs > 10 $M_\odot \, \text{yr}^{-1}$, our measured SFRs agree with Hoffer et al. (2012) IR SFR within 26%. IR SED fits are available for Perseus A and Cygnus A (e.g., Mittal et al. 2012, Prixon et al. 2012), providing SFRs of 24 ± 1 and 9 ± 10 $M_\odot \, \text{yr}^{-1}$ respectively. These SFRs are lower than those derived for this study (41 and 70 $M_\odot \, \text{yr}^{-1}$ for Perseus A and Cygnus A respectively), and for Hoffer et al. (2012)’s total IR and UV derived SFRs.

There is considerable scatter between different SFR estimates for BCGs with SFRs < 10 $M_\odot \, \text{yr}^{-1}$, and the Cluver et al. (2014) relation may underestimate SFRs for low IR luminosity galaxies. In the low redshift (z < 0.05) regime, the Cluver et al. (2014) relation works well for galaxies with SFRs > 3 $M_\odot \, \text{yr}^{-1}$, but may underestimate SFRs lower than this. Despite this, for SFRs < 3 $M_\odot \, \text{yr}^{-1}$, our SFRs agree with the multi-wavelength-derived SFRs of Hoffer et al. (2012) and Crawford et al. (1999) within 1 dex. Importantly, the scatter introduced in the low SFR sample either by the SFR relation, or possible excess emission by AGN contamination (e.g., Donley et al. 2008, Donoso et al. 2012) is not enough to push any low SFR galaxies into the highly star forming regime, preserving our primary conclu-
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AllWISE makes use of data from WISE, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, and NEOWISE, which is a project of the Jet Propulsion Laboratory/California Institute of Technology. WISE and NEOWISE are funded by the National Aeronautics and Space Administration.

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**Table 1. WISE photometry and derived star formation rates of BCGs in the BAX X-ray selected cluster sample with \( L_x > 1 \times 10^{44} \text{ ergs}^{-1} \).** When there was no W3 detection for a BCG, the photometry and star formation rates are left blank. Similarly for when the BCG could not be unambiguously identified, we report the cluster coordinates and leave the stellar mass and star formation rates blank. Reasons for each BCG exclusion are listed in the footnotes. Table 1 is published in its entirety in the electronic edition.

| Cluster Name | BCG RA (°, J2000) | BCG Dec (°, J2000) | z | \( L_x (10^{44} \text{ erg/s}) \) | W1 (mag) | W2 (mag) | W3 (mag) | Stellar Mass \( (10^8 \text{ M}_\odot) \) | SFR \( (\text{M}_\odot/\text{yr}) \) |
|--------------|-------------------|-------------------|---|-----------------------------|----------|----------|----------|-----------------|-----------------|
| RXCJ0003.8+0203 | 0.9570            | 2.0665            | 0.092 | 1.50             | 11.51 ± 0.01 | 11.47 ± 0.01 | 11.07 ± 0.21 | 64.5 ± 0.11 | 0.35 ± 0.09 |
| RXCJ0011.3-2851 | 2.8403            | -28.8547          | 0.062 | 2.42             | 11.23 ± 0.01 | 11.21 ± 0.01 | 11.03 ± 0.16 | 34.1 ± 0.02 | 0.07 ± 0.02 |
| RXCJ0013.6-1930 | 3.3917            | -19.4838          | 0.094 | 2.26             | 12.19 ± 0.01 | 12.10 ± 0.01 | 11.84 ± 0.28 | 33.5 ± 0.58 | 0.12 ± 0.14 |
| RXCJ0017.5-3511 | 4.3958            | -35.1833          | 0.095 | 1.22             | 12.54 ± 0.01 | 12.49 ± 0.02 | 11.89 ± 0.20 | 24.0 ± 0.39 | 0.22 ± 0.06 |
| ABEll0021a | 5.1545            | 28.6590           | 0.095 | 2.64             | –         | –         | –         | –              | –              |
| IVZw015       | 5.4033            | 28.0505           | 0.094 | 1.72             | 11.95 ± 0.01 | 11.89 ± 0.01 | 12.06 ± 0.36 | 43.3 ± 0.73 | 0.02 ± 0.03 |
| RXCJ034.2-0204 | 8.5612            | -2.8467           | 0.082 | 2.40             | 11.37 ± 0.01 | 11.34 ± 0.01 | 10.49 ± 0.10 | 56.7 ± 0.99 | 0.86 ± 0.22 |
| RXCJ034.6-0208b | 8.6500           | -2.1400           | –     | –                | –         | –         | –         | –              | –              |
| ABEll0077      | 9.6366            | 45.7247           | –     | –                | –         | –         | –         | –              | –              |
| ABEll0077      | 10.1180           | 29.5557           | 0.071 | 1.74             | 11.28 ± 0.01 | 11.26 ± 0.01 | 10.83 ± 0.13 | 44.5 ± 0.48 | 0.25 ± 0.13 |

**Notes:**
- a: No extended source data in AllWISE catalogue
- b: Source Confusion

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