Spitzer Observations of Star Formation in Brightest Cluster Galaxies

Christopher P. O'Dea*, Alice Quillen†, Jaehong Park†, Nicholas Zufelt†, Stefi A. Baum**, George Privon*, Jacob Noel-Storr**, Alastair Edge‡, Helen Russell§, Andy Fabian§, Megan Donahue¶, Craig L. Sarazin‖, Brian McNamara††, Joel Bregman‡‡ and Eiichi Egami§§

*Department of Physics, Rochester Institute of Technology, Rochester, NY 14623
†Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627
**Center for Imaging Science, Rochester Institute of Technology, Rochester, NY 14623
‡Department of Physics, Durham University, Durham DH1 3LE, UK
§Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
¶Physics and Astronomy Department, Michigan State University, East Lansing, MI 48824
‖Department of Astronomy, University of Virginia, Charlottesville, VA 22904
††Department of Physics and Astronomy, University of Waterloo, Waterloo, ON N2L 3G1, Canada
‡‡Physics Department, University of Michigan, Ann Arbor, MI 48109
§§Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ

Abstract. We summarize the results of Spitzer IRAC and MIPS observations of 62 brightest cluster galaxies (BCGs) with optical line emission located in the cores of X-ray luminous clusters. We find that at least half of these sources have signs of excess infrared emission. The strength of the mid-IR excess emission correlates with the luminosity of the optical emission lines. Excluding several systems dominated by an AGN, the excess mid-infrared emission in the remaining brightest cluster galaxies is likely powered by star formation. The IR luminosity (and thus star formation) is higher in BCGs with shorter cooling times in the central hot ICM suggesting that the gas which cools from the ICM ultimately forms stars. We find a correlation between mass deposition rates estimated from the X-ray emission and the star formation rate estimated from the infrared luminosity. The star formation rates are 1/10 to 1/100 of the mass deposition rates suggesting that the re-heating of the ICM is generally very effective in reducing the amount of mass cooling from the hot phase but does not eliminate it completely.

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INTRODUCTION

X-ray imaging of 'cooling flow' galaxy clusters show a density increase and a temperature decrease toward the centers of these systems, implying that gas should be cooling at rates of a few to $1000 M_\odot\ \mathrm{yr}^{-1}$ (e.g., [9, 2]). A number of studies have found evidence for cooled gas and star formation in galaxy clusters, but at amounts/rates below that corresponding to the cooling rate predicted from the X-ray observations (e.g., [13, 5, 6, 4]). This has led to suggestions that a source of heat is required to resupply energy to the cooling gas (see [14, 17] for reviews). To probe the efficiency of cooling and star formation in cluster galaxies we aim to provide more direct measurements of the star formation rate in central cluster galaxies using broad band images obtained with the *Spitzer Space*

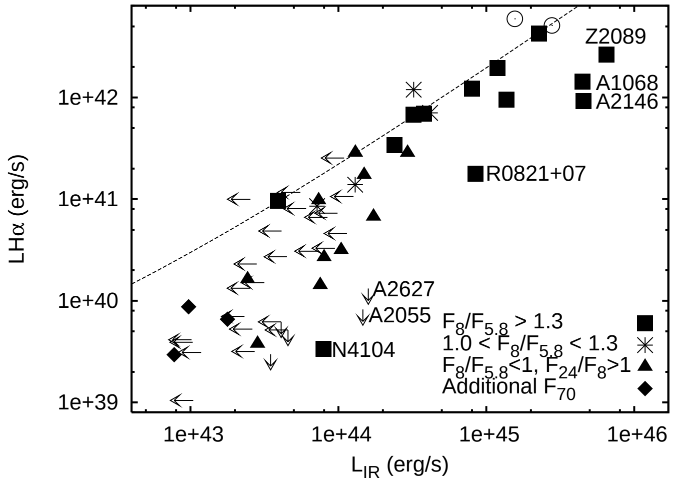

FIGURE 1. Observed Hα Luminosity (listed in Table 1 of [18]) vs Infrared Luminosity estimated from the 8μm and 24.4μm fluxes. The Kennicutt relation [12] inferred from observations of star forming galaxies relating Hα luminosity to star formation rate is plotted as a line.

Telescope (SSC). Detailed discussions of the observations and implications are given by [18, 16]. Here we present some highlights of the results.

SPITZER OBSERVATIONS

The sample was chosen on two criteria - cluster X-ray flux and BCG Hα flux - which tend to favor cooling flow clusters. Targets are drawn from the Brightest Cluster Sample [7] and the ROSAT-ESO Flux Limited X-ray (REFLEX) Galaxy cluster survey [3]. A detection of Hα from the BCG [6] was also required.

The 3.6, 4.5, 5.8 and 8.0μm broad band images were obtained during Cycle 3 (2007-2008) using the Infrared Array Camera (IRAC) on board the *Spitzer Space Telescope*. The 24.4 and 70 μm images were obtained using the Multiple Imaging Photometer for Spitzer (MIPS). All but 1 source (Z9077) was detected at 24μm, but only about 1/4 of the sample were detected at 70μm. At least half the BCGs showed excess IR emission consistent with star formation.

RESULTS AND DISCUSSION

We compare the Hα luminosities from limited aperture spectroscopy to the infrared luminosities in Figure 1 finding a strong correlation between the two. We also see a correlation in Hα flux vs. 24 micron flux density [16]. These correlations show that the Hα and infrared emission arises from the same or a related power source. We suggest that the dominant power source for the Hα and infrared emission is star formation. This is consistent with previous evidence that the optical emission line nebulae are mostly powered by UV photons from young stars with a possible secondary contribution from

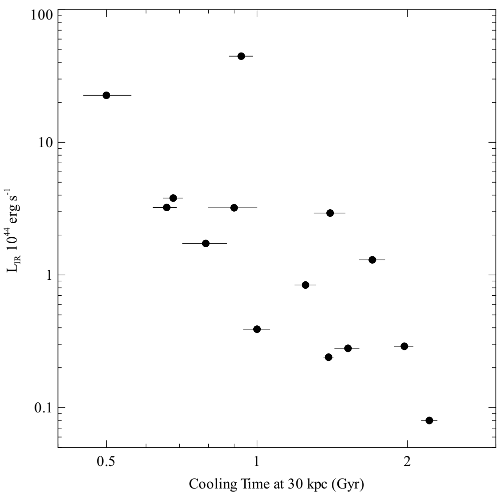

FIGURE 2. IR luminosity vs. X-ray derived cooling times at a radius of 30 kpc. BCGs have higher IR luminosity in clusters with shorter cooling times.

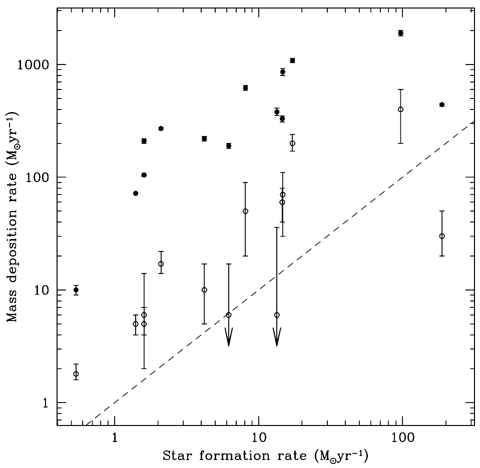

FIGURE 3. X-ray derived mass deposition rate upper limits against estimated star formation rates. The closed circles correspond to maximum mass deposition rates, $\dot{M}_I$ if heating is absent, and the open circles refer to $\dot{M}_S$, the mass deposition rate consistent with the X-ray spectra. The dashed line is for equal star formation and mass deposition rates.

another mechanism (e.g., [11, 1, 19, 6, 15, 20, 10]). The Hα luminosity is a bit lower than predicted by the Kennicutt relation. This might be due to missing the extended Hα emission which falls outside the slits/fibers used for the spectroscopy.

In Figure 2 we plot the Infrared Luminosity vs. the cooling time at a radius of 30 kpc. We see that BCGs with shorter cooling times have higher IR luminosities as also found by [8]. This suggests that the clusters with shorter cooling times in the ICM have higher star formation rates which result in higher IR luminosity. This is consistent with the hypothesis that the gas which cools from the hot ICM ultimately forms stars.

In Figure 3 we plot the star formation rate (SFR) derived from the IR luminosity (as described by [18]) vs. two estimates of the X-ray derived mass accretion rate. $\dot{M}_I$ is a maximum mass deposition rate, calculated from the X-ray luminosity; and $\dot{M}_S$ was calculated by spectral fitting to the annuli within the cooling radius and including a cooling flow model (`mkcflow`) to the absorbed single-temperature model (`phabs(mekal+mkcflow)`). We see that the SFR is proportional to (but significantly less than) the two estimates of mass accretion rate. The results show that the star formation rate is about 30–100 times smaller than $\dot{M}_I$, and 3–10 times smaller than $\dot{M}_S$. The observed trends between cooling time and the IR luminosity and between $\dot{M}_S$ and the infrared star formation rates are consistent with the hypothesis that the cooling ICM is the source of the gas which is forming stars. If star formation is the ultimate sink for the cooling gas, then the fraction of the few keV gas which does cool all the way down should be comparable to the ratio SFR/$\dot{M}_X$ - which we find to be roughly a few percent. This fraction is comparable for all the clusters. This suggests that the re-heating mechanism (whatever it is) is very effective over a range of size scales and operates nearly all the time (i.e., with a short duty cycle).

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