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Spitzer Mid-Infrared Spectra of Cool-Core Galaxy Clusters

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Abstract.
We have obtained mid-infrared spectra of nine cool-core galaxy clusters with the Infrared Spectrograph aboard the Spitzer Space Telescope. X-ray, ultraviolet and optical observations have demonstrated that each of these clusters hosts a cooling flow which seems to be fueling vigorous star formation in the brightest cluster galaxy. Our goal is to use the advantages of the mid-infrared band to improve estimates of star formation. Our spectra are characterized by diverse morphologies ranging from classic starbursts to flat spectra with surprisingly weak dust features. Although most of our sample are known from optical/UV data to be active star-formers, they lack the expected strong mid-infrared continuum. Star formation may be proceeding in unusually dust-deficient circumgalactic environments such as the interface between the cooling flow and the relativistic jets from the active galactic nucleus.

1 Introduction

Brightest cluster galaxies (BCGs) have elliptical morphologies and generally do not host significant star formation. However, a subset of BCGs are marked by their cuspy X-ray emission (Crawford et al. 1999; Edwards et al. 2007) and a high incidence of strong nebular line emission, which indicates star formation or nuclear activity. The intracluster gas in these cool-core clusters is thought to be condensing in the form of a "cooling flow" (Fabian 1994). Many such clusters have blue continua and star formation rates (SFRs) as high as $\sim 100\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, suggesting that the star formation is fueled by the cooling flows.

Recent X-ray spectroscopy has demonstrated that cooling flows are subject to regulatory heating, probably associated with nuclear activity (McNamara & Nulsen 2007). The estimated net rates at which gas cools below 1 keV are comparable with the estimated star formation rates (O'Dea et al. 2008; Rafferty et al. 2006). Cool-core clusters present a prime opportunity to test models of the cool-

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ing and energy feedback mechanisms that are thought to dominate early galaxy formation.

Radio observations of CO emission and near-infrared detections of the rovibrational transitions of H_2 have revealed large reservoirs of cool molecular gas in many cooling flows (Edge 2001; Donahue et al. 2000). Furthermore, far-infrared photometry with the *Spitzer* Space Telescope shows that some BCGs in cool-core clusters have spectral energy distributions consistent with emission from cool dust ($T_d \lesssim 100$) (Egami et al. 2006; O'Dea et al. 2008; Quillen et al. 2008). There are similarities between classic starbursts (Brandl et al. 2006) and BCGs in cool-core clusters, but many questions about star formation in the BCGs remain.

We use *Spitzer* to study nine BCGs in cool-core clusters which have been extensively observed in X-ray, optical and ultraviolet light. With one exception, our targets are confirmed star-formers with optical and UV continuum-based SFRs ranging up to $130\,M_\odot\,yr^{-1}$. The mid-infrared (MIR) band contains many diagnostics of star formation, including emission by small warm dust grains and complex emission by polycyclic aromatic hydrocarbons (PAHs). It also contains many narrow emission features, including atomic emission associated with nuclear activity and emission lines from molecular hydrogen in pure rotational states. Our goal is to establish a better understanding of the cooling flow, feedback and star formation processes in BCGs.

2 Observations

The spectra in Figure 1 were taken with the four low-resolution modes of *Spitzer's* Infrared Spectrograph under Program ID's 3384 and 20345. Our targets are Abell 1068, Abell 1835, PKS0745-19, Hydra A, Abell 1795, Abell 2597, Abell 478, ZwCl 1370, and 2A0335+096. We obtained sparse spectral maps of all BCGs, but we restrict our current discussion to a central extraction that yielded the best signal-to-noise. After subtracting background light and correcting to the restframe of each BCG, we renormalized each spectrum to the total light from the target, using the light profile along the SL1 slit and assuming circular symmetry.

3 Discussion and Conclusion

The resulting spectra are compared to a typical starburst template spectrum (Brandl et al. 2006) in Figure 1. Despite the high SFRs derived from optical and UV data, most of our BCGs differ from normal starbursts in one or more of the following characteristics: weaker long-wave continua, weaker PAH features, and strong H_2 features.

The pure rotational lines of H_2 are abnormally strong in our spectra. From the line strengths, we infer a range of gas masses at different temperatures, similar to results discussed by Ferland et al. (2008). The strong H_2 features probably originate in cold gas reservoirs subject to shocks (Guillard & Boulanger 2008) and are probably unrelated to star formation. We will discuss the quantitative interpretation of the H_2 and other features in an ensuing paper.

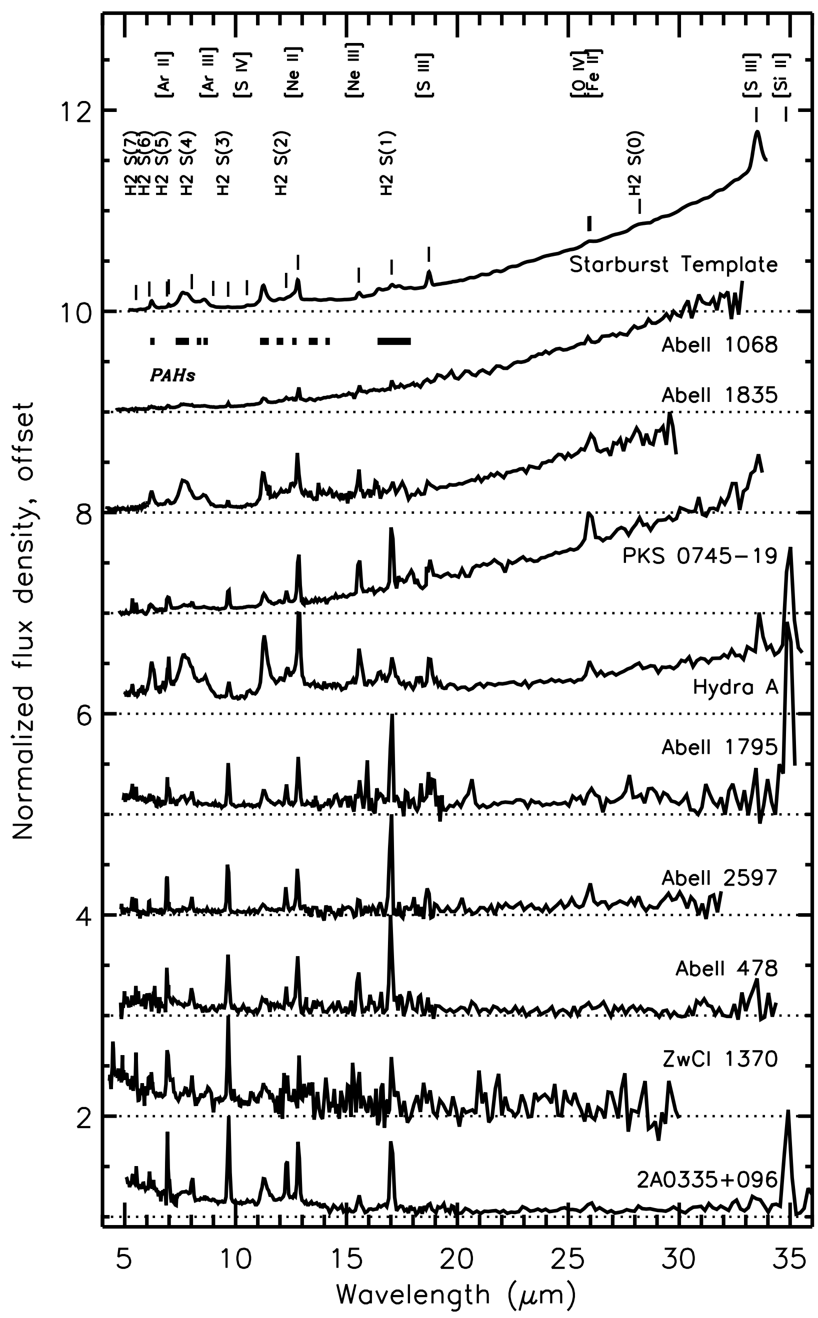

Figure 1. IRS spectra of the nine BCGs, grouped by gross spectral morphology, and a starburst template spectrum (Brandl et al. 2006). Spectra are plotted in units of intensity per unit frequency (mJy/sr), normalized so that the highest point blueward of 30μm is equal to 1, and additively offset. Unresolved emission lines and PAH bands are labeled at the top. Note the strong emission lines, particularly [Ne II] and the pure rotational series of H_2. PAH emission is detected in all cases, but is weaker than normal in most.

Of our nine galaxies, only A1835 has the MIR spectral morphology of a classic starburst. While two others exhibit the expected strong red continuum, they also have anomalous emission feature spectra. The remaining six spectra have weak red continua, despite a firm lower limit on star formation established for five of them by optical and ultraviolet observations. The well-established correlations between IR output and star formation (Rieke et al. 2009) break down. We have established that if the normal MIR continuum signatures of star formation were present in these galaxies, we would have easily detected them; instead, in most of our targets, the MIR continuum is subluminous by factors of 10-70x.

The abnormally weak MIR continua indicate anomalies in the amount of dust, in its grain size or composition, or in its spatial or temperature distribution. Our results may indicate that star formation in BCGs in cool-core clusters is progressing in an unusual environment. Rather than occurring in a dense, disk-like volume, as in normal starbursts, star formation may be concentrated in extended regions outside the main body of the galaxy, such as at the interface between relativistic jets from the AGN and the inner cooling flow. One example is NGC 1275, where star formation occurs in a huge filamentary network (Conselice et al. 2001; Fabian et al. 2008; McNamara et al 1996). In this unusual environment, the dust grain population is expected to differ considerably from the dust in normal starbursts and spiral disks.

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