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The environmental effect on galaxy evolution: Cl J1449 + 0856 at z = 1.99

Rosemary T. Coogan, E. Daddi, R. Gobat, M. T. Sargent

Max-Planck-Institut für extraterrestrische Physik (MPE), Giessenbachstr.1,
85748 Garching, Germany
email: rcoogan@mpe.mpg.de

Abstract. This work focuses on understanding the formation of the first massive, passive galaxies in clusters, as a first step to the development of environmental trends seen at low redshift. Cl J1449 + 0856 is an excellent case to study this - a galaxy cluster at redshift z = 1.99 that already shows evidence of a virialised atmosphere. Here we highlight two recent results: the discovery of merger-driven star formation and highly-excited molecular gas in galaxies at the core of Cl J1449, along with the lowest-mass Sunyaev-Zel'dovich detection to date.

Keywords. galaxies: evolution, galaxies: clusters: individual, galaxies: ISM, galaxies: starburst

1. Cl J1449 + 0856: A mature cluster in the early universe

In order to understand the origins of the most massive, early-type galaxies that dominate the cores of local galaxy clusters, we must trace these structures back in time, to the epoch of peak galaxy and cluster assembly at $z \geqslant 1.5$ (e.g. De Breuck *et al.* 2004; Wang *et al.* 2016; Castignani *et al.* 2018; Lee *et al.* 2019). In Coogan *et al.* (2018); Coogan *et al.* (2019), Strazzullo *et al.* (2018) and Gobat *et al.* (2019) we use Atacama Large Millimeter/submillimeter Array (ALMA) and Karl G. Jansky Very Large Array (VLA) observations to study dust-obscured star-formation, interstellar medium (ISM) content and the intra-cluster medium (ICM) in Cl J1449+0856. Cl J1449, an X-ray detected galaxy cluster at z = 1.99, is one of the highest redshift mature clusters discovered to date, with the mass of a typical Coma-like progenitor (Gobat *et al.* 2011). Unlike unrelaxed proto-clusters more commonly found at this redshift, Cl J1449 already contains a large fraction of passive galaxies at its core, in addition to a diverse population of highly star-forming galaxies.

1.1. *Merger-driven star formation in the core of Cl J1449 + 0856*

In Coogan *et al.* (2018) we measure the star-formation activity and ISM content of 11 galaxies in the core of Cl J1449 at z = 1.99 - a crucial epoch for mass assembly, where no consensus on the environmental effect on galaxy evolution has yet been reached. Molecular gas masses are calculated from both dust and CO[1-0] emission, and we discover that the fuel for star-formation in these galaxies will be depleted within ∼100-400 Myrs, as observed for starburst galaxies at $z \sim 2$. A key result of Coogan *et al.* (2018) is the discovery of a large fraction of galaxies in the core of Cl J1449 with highly excited molecular gas (the ratio of denser, star-forming gas at high quantum state $J > 1$, to the total molecular gas reservoir), revealed through CO Spectral Line Energy Distribution modelling. When compared with expectations for co-eval field galaxies, we conclude that this cluster contains a strongly enhanced fraction of excited, starburst-like

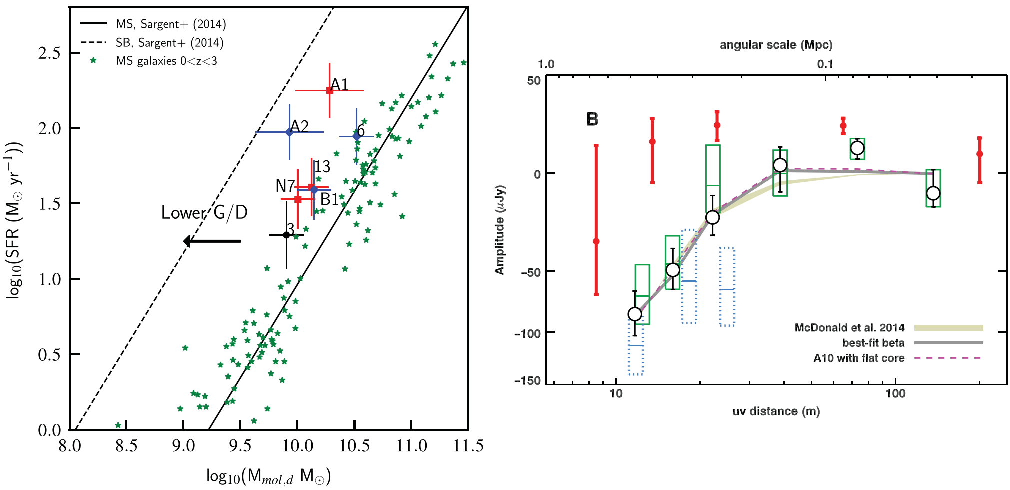

Figure 1. Left: SFR vs. molecular gas mass for Cl J1449 (red/blue/black, Coogan *et al.* 2018). We see a high fraction of cluster galaxies with excited CO (red), and the cluster galaxies lie at enhanced SFE compared to Main Sequence galaxies (green), regardless of their CO excitation. **Right**: The SZ pressure profile in uv-space of Cl J1449 (white circles, Gobat *et al.* 2019). Red points show the pressure profile if positive galaxy emission is not removed before analysis.

galaxies compared to the field, driven by the high fraction of mergers, interactions and Active Galactic Nuclei (AGN) in the core. This also leads to increased star-formation efficiencies (SFEs, Fig. 1 left, Coogan *et al.* 2018), and depletion of molecular gas on short timescales.

1.2. *Sunyaev-Zel'dovich detection of Cl J1449: The pressure profile in uv-space*

The next step was to investigate the large-scale cluster environment, using 92 GHz observations of the Sunyaev-Zel'dovich (SZ) decrement arising from the ICM, presented in Gobat *et al.* (2019). As there is a significant amount of positive 92 GHz continuum present in the core of Cl J1449 (originating from galaxy dust emission), observations were made using both ALMA and the ALMA Compact Array (ACA), in order to first subtract the positive emission from known galaxies using the smaller ALMA beam. Having done this - without disrupting the SZ signature itself - the ALMA and ACA data were combined, uncovering a 5σ extended SZ decrement at $z = 1.99$, shown in the right panel of Fig. 1 (Gobat *et al.* 2019). The pressure profile of the SZ decrement as a function of spatial scale can give constraints on the physics of the ICM and the cluster halo mass, and the total mass recovered for Cl J1449 is found to be consistent with that derived from X-ray observations ($\sim 6\times10^{13}$M$_\odot$, Gobat *et al.* 2011). This is the lowest mass single SZ detection to date. We compare the pressure profile at $z = 1.99$ with models from local galaxy clusters, and do not find strong evidence for an evolution with redshift. However, a slight tension at small-to-intermediate spatial scales suggests a flattened central profile, which could potentially be related to the effects of energy injection by AGN.

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