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Our approach to the thermodynamic evolution of galaxy clusters

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Abstract. A solid approach to the study of the evolution of the thermodynamic properties of galaxy clusters requires three ingredients: representative samples, challenging observations and advanced tools to perform accurate analyses on them. In this short contribution, we summarize our recent progresses on the development and public distribution of a code for the joint analysis of X-ray and Sunyaev-Zeldovich data, and summarize our results for the thermodynamic profiles of the most distant and the lowest surface brightness cluster with resolved thermodynamic profiles.

Key words. Galaxies: clusters: general — Galaxies: clusters: intracluster medium — dark matter — X-rays: galaxies: clusters

1. Introduction

Galaxy clusters play a fundamental role both in astrophysics and cosmology. The various components of a cluster, i.e., dark matter, intracluster medium and galaxies, are deeply interconnected: galaxy formation and evolution depend on the large scale environment in which galaxies live, and on the physical and chemical properties of the intergalactic gas from which they form; this gas in turn is affected by galaxy feedback. The wide range of physical processes involved, and the different evolutionary histories, necessitate a multi-wavelength approach and large unbiased statistical samples to be probed. In turn, the multi-wavelength approach requires advanced tools able to exploit them.

Our project aims at probing the matter in clusters since their formation epoch through an innovative and multi-faceted approach that will yield a refinement of the main cluster scaling relations and a first characterization of the thermodynamic properties of local clusters, in particular the elusive objects, and of their $z \sim 2$ ancestors, and passes through developing codes allowing to optimally exploit the available data.

2. Tools: JoXSZ

Castagna & Andreon (2020, 2021) built JoXSZ[1], a code that combines Sunyaev-Zeldovich (SZ) and X-ray data into a single analysis following a fully Bayesian forward-modelling approach. JoXSZ accounts for beam smearing and data analysis transfer function, for the SZ calibration uncertainty and X-ray and SZ background level systematics. It adopts

[1] https://github.com/fcastagna/joxsz

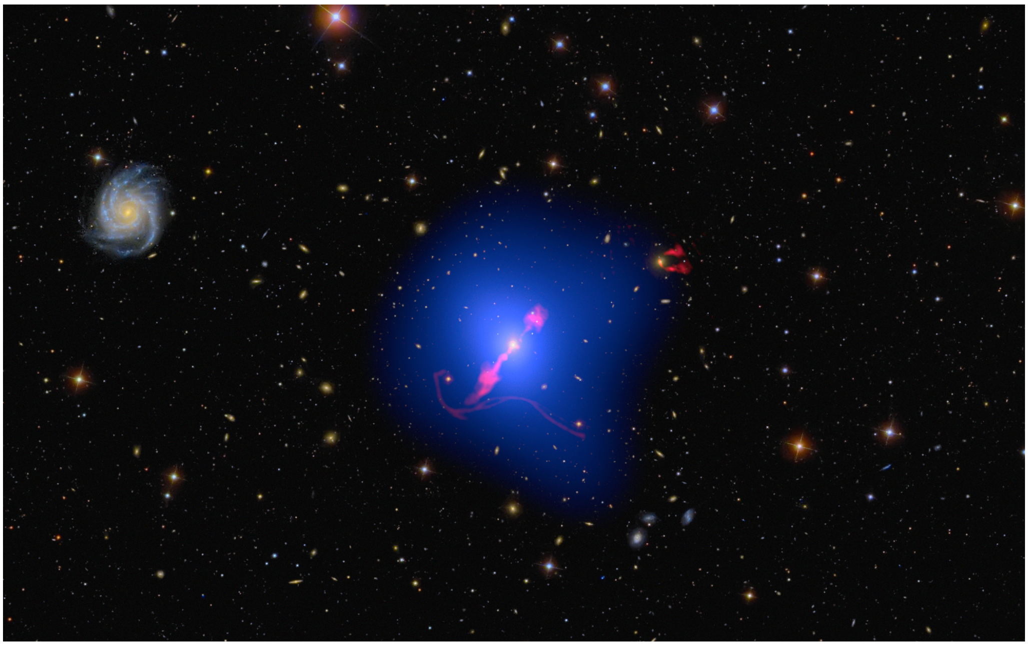

Fig. 1. Multi-wavelength view of CL2015: X-ray/Radio emission is in blue/magenta and these channels are superposed to a three-color optical image. [Image credits: NASA/Swift, NCRA/GMRT, SDSS, B. Franke, S. Andreon]

extremely flexible parametrization for the thermodynamic profiles, either employs a consistent temperature across the various parts of the code or allows for differences between X-ray and SZ gas mass weighted temperatures, and calculates the correct Poisson-Gauss expression for the joint likelihood. The proper combination of the data preserves the angular resolution of the data and, for example, uses Chandra exquisite resolution to measure the temperature profile at the cluster center, and the SZ sensitivity at large radii to measure temperature at radii precluded by X-ray analyses only. Finally, since the fitting model is a fully forward one, all uncertainties are propagated to all quantities. A SZ-only version of the code, PreProFit[2] (Castagna & Andreon 2019) was also made available.

[2] https://github.com/fcastagna/preprofit

3. Representative samples

It is now well established that our view of the intracluster medium is biased when samples are selected by the intracluster medium itself (Pacaud et al. 2007; Stanek et al. 2006; Andreon, Trinchieri & Pizzolato 2011; Andreon & Moretti 2011; Eckert et al. 2011; Planck Collaboration 2011, 2012; Maughan et al. 2012; Anderson et al. 2015; Andreon et al. 2016), basically because it is hard to infer the properties of the missed part of a sample when no example, or just a few, is/are present. To overcome this problem, previous analyses (e.g. Pratt et al. 2009, see Vikhlinin et al. 2009 as an exception) assumed that the missing population share the same properties (scaling relations, for example) of the observed part. The missing population is, of course, formed by the clusters that are difficult to detect and study because of their low surface brightness. For this reason, Andreon et al. (2016, 2017a,b) followed up in X-ray a sample of clusters selected independently of their

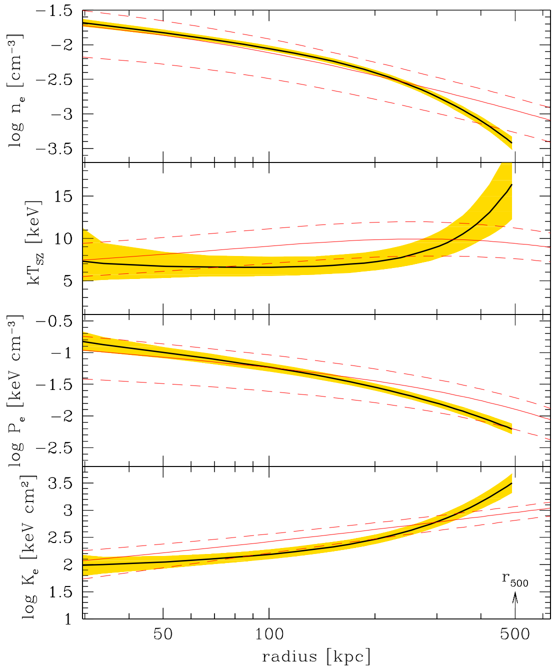

Fig. 2. IDCS J1426.5+3508 (mean value and 68% uncertainties, black line and yellow shading) is compared to its present-day expected descendant (red line with dashed corridor mark the mean value and the $\pm 2\sigma$). Compared to its present-day descendant, at large radii gas is lacking and that present is too hot and with large entropy. To become a present-day cluster, heat and entropy should be dissipated or the gas transported to larger radii plus cold and low entropy gas should be acquired from peripheral regions. [Adapted from Andreon et al. (2021)]

intracluster medium, one third of which turned out to be of low surface brightness. They measured X-ray luminosity, surface brightness, gas density and, from dynamical measurement of galaxies, cluster masses.

Andreon et al. (2019) presented high-quality X-ray data of one of them, CL2015 at $z = 0.05$, which became the lowest surface brightness clusters with resolved thermodynamic profiles. They followed-up it in X-ray with the X-ray telescope with the lowest X-ray background brightness, XRT on Swift (Mushotzky et al. 2019), to maximize S/N. They found that CL2015 has a 3 times lower pressure than X-ray selected clusters of the same mass. The data pointed out the ultimate reason for the low surface brightness and pressure of this specific object: CL2015 has a low mass concentration. See also the press release `https://www.media.inaf.it/2019/09/26/ammasso-depresso/`.

4. Clusters at the epoch when they emerge from the web, $z \sim 2$

At high ($z \sim 2$) redshift, the measurement of thermodynamic profiles profiles is at the very boundary of X-ray observations because of the limited capabilities of present day X-ray satellites: limited sensitivity of Chandra and limited resolution of XMM-Newton, the latter preventing a proper selection against the bright QSOs in the only few known $z \sim 2$ clusters. Andreon et al. (2021) combined intensity and spectral information from Chandra with a SZ map from MUSTANG-2 of IDCS J1426.5+3508 at $z = 1.75$ (Stanford et al. 2012) allowing to probe the thermodynamic profiles of the cluster from well below the SZ resolution, thanks to Chandra, to r_{500}, which is well beyond the radius at which temperature can be estimated from X-ray data. Thanks to this dataset combination, IDCS J1426.5+3508 becomes the most distant cluster with resolved thermodynamic profiles. The analysis used an updated version of JoXSZ (Castagna & Andreon 2020).

As CL2015, IDCS J1426.5+3508 turned out to have a low pressure at most radii compared to clusters in the REXCESS X-ray selected sample (Arnaud et al. 2010). The comparison with a library of plausible descendants (see also Fig. 2) allowed the authors to constraint the evolution of heating, cooling, and entropy over an unprecedented 10 Gyr wide epoch, and also to indirectly detect gas motion and turbulence when the Universe was 2 Gyr old only. See also the press-release `https://greenbankobservatory.org/galaxy-cluster/` and `https://www.media.inaf.it/2021/06/23/cosi-emerge-un-ammasso-dalla-rete-cosmica/`.

5. The bright future in front of us

Deep X-ray follow-up of all clusters of low surface brightness in Andreon et al. (2016) is being acquired. High-quality data for a second $z \sim 2$ cluster have been already collected as well as deeper X-ray data of IDCS J1426.5+3508. For all the clusters of this program, weak-lensing data have been already collected or will be soon available with Euclid. eROSITA will likely augment the known number of clusters of low surface brightness. Other surveys, such as Vera Rubin Observatory, Roman Space Telescope, ACT, and SPT, are providing us a wealth of data useful to study the cluster thermodynamic properties. To exploit this new richness, we are currently extending our analysis from one cluster at a time to jointly fit many clusters, meaning that parameter estimation will be simultaneously conducted at both individual level (e.g. the values of the parameters of the profile of an individual cluster are inferred) and at the level of the population of clusters (e.g., modeling the spread across the population of clusters) through a Bayesian hierarchical model.

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