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Athena X-IFU synthetic observations of galaxy clusters to probe the chemical enrichment of the Universe

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ABSTRACT

Answers to the metal production of the Universe can be found in galaxy clusters, notably within their Intra-Cluster Medium (ICM). The X-ray Integral Field Unit (X-IFU) on board the next-generation European X-ray observatory *Athena* (2030s) will provide the necessary leap forward in spatially-resolved spectroscopy required to disentangle the intricate mechanisms responsible for this chemical enrichment. In this paper, we investigate the future capabilities of the X-IFU in probing the hot gas within galaxy clusters. From a test sample of four clusters extracted from cosmological hydrodynamical simulations, we present comprehensive synthetic observations of these clusters at different redshifts (up to $z \leq 2$) and within the scaled radius R_{500} performed using the instrument simulator SIXTE. Through 100 ks exposures, we demonstrate that the X-IFU will provide spatially-resolved mapping of the ICM physical properties with little to no biases ($\lessapprox 5\%$) and well within statistical uncertainties. The detailed study of abundance profiles and abundance ratios within R_{500} also highlights the power of the X-IFU in providing constraints on the various enrichment models. From synthetic observations out to $z = 2$, we also quantify its ability to track the chemical elements across cosmic time with excellent accuracy, and thereby to investigate the evolution of metal production mechanisms as well as the link to the stellar initial mass-function. Our study demonstrates the unprecedented capabilities of the X-IFU in unveiling the properties of the ICM but also stresses the data analysis challenges faced by future high-resolution X-ray missions such as *Athena*.

Key words. Galaxies: abundances - Galaxies: intra-cluster medium - Galaxies: fundamental parameters - Instrumentation: *Athena*/X-IFU - Methods: numerical - Techniques: imaging spectroscopy - X-rays: galaxies: clusters

1. Introduction

Metals and other heavy elements in the intra-cluster medium (ICM) represent a fossil record of the chemical evolution of the Universe. Trapped in the dark matter (DM) potential of galaxy clusters (White et al. 1993), they remain unaltered within the optically-thin collisionless thermal plasma. Elements originate within stars or through supernovæ (SN), before being spread by stellar winds or by the SN explosions. Hence, the chemical enrichment of a given cluster relates to the integrated star formation history of the cluster, as well as to the overall stellar initial mass function (IMF). The abundances and spatial distribution of metals in the ICM can also be connected to its dynamical history and to the mechanical action of AGN (Active Galactic Nuclei) outflows or jets (e.g. Gaspari et al. 2011).

Most of the low-mass elements (C, O, Mg, Si, S) are produced by end-of-life massive stars ($\geq 10 M_{\odot}$) undergoing core-collapse supernovæ (SN_{cc}) (see Nomoto et al. 2013, for a review). The evolution of SN_{cc}-related enrichment through time is dictated by the initial mass and metallicity of the progenitor star. High-mass elements, from Si-like elements (Al, Si, S, Ca, Ar) to Fe and Ni, are on the other hand the result of thermonuclear reactions occurring during the explosion of white dwarfs (type Ia supernovæ – SN_{Ia}) (Hillebrandt et al. 2013). Although the mechanisms of these explosions – either via accretion of a companion star onto the white dwarf (Whelan & Iben 1973) or via mergers of binary systems (Webbink 1984) – is still poorly understood (see Maoz et al. 2014), the time scale of these events, related to longer-living low-mass stars, suggests a later enrichment across cosmic time. Traces of other elements (C, N, Ne, Na) can also be produced when low- and intermediate-mass stars (typically $\leq 6 M_{\odot}$) enter their Asymptotic Giant Branch (AGB) phase (Iben & Renzini 1983). The individual study of these phe-

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resolution spectra will provide new proxies to estimate quantities such as the temperature by using e.g. line-ratio techniques. Eventually, hyper-spectral methods (e.g. Blind Source Separation algorithms) or machine-learning-based fitting techniques (see, e.g., Ichinohe et al. 2018) could open new perspectives for the post-processing of high-resolution X-ray spectra. We would like to underline that, even though not applicable in our simulation case, the expected level of spectral resolution of the X-IFU will challenge our current knowledge accuracy of the spectral lines (centroid energies and intrinsic widths), which is critical to allow a meaningful interpretation of the results (as demonstrated in Hitomi Collaboration et al. 2017e, for line ratios) and to disentangle fine spectroscopic effects (such as resonant scattering, Hitomi Collaboration et al. 2017b). This emphasises the need for dedicated tools able to process and analyse future X-IFU high-resolution spectroscopy data-cube. On this regard, the *Athena* mission will certainly benefit from the advances expected in processing tools, fitting methods and atomic databases, from the future *XRISM* mission (Ishisaki et al. 2018).

Not only do these E2E simulations allow to explore the capabilities of the future X-IFU instrument, but they also give crucial information on the effect of instrumental parameters in science observations. In this study for instance, the spectral shape of all the foreground/background components were assumed to be perfectly known. For the more local and massive clusters however, the field-of-view of the X-IFU will easily be encompassed within the angular extension of R_{500}. Cluster emission-free regions might thus be unavailable for local background calibration. The spectral resolution of the X-IFU will help mitigate this effect, by allowing to disentangle various components through the characteristics of their spectral energy distribution. The instrument background may also contaminate the observation of faint sources, as the level of precision to which X-IFU is expected to perform requires its accurate and reproducible knowledge in flight. This may be achieved, e.g., through inflight cross-correlation with the WFI or the X-IFU cryogenic anti-coincidence detector (Cucchetti et al. 2018). Future developments could take advantage of this simulation pipeline to test other realistic instrumental effects (e.g. stray-light for galaxy cluster outskirts observations). More detailed studies of the abundance ratios recovered here will also be at the center of a forthcoming study to highlight the capabilities of the X-IFU in constraining the ICM chemical enrichment, and notably to disentangle between the contributions of the various mechanisms of chemical enrichment (e.g. SN, AGB) throughout cosmic time.

Our study underlines the revolutionary capabilities brought by the X-IFU in future X-ray spectroscopy. With typical routine observations, the X-IFU will drastically change our understanding of ICM mechanisms and provide a quantum leap forward in X-ray astronomy.

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