SEARCHING FOR HINTS OF NON-THERMAL EMISSION FROM MERGING GALAXY CLUSTERS IN THE LOCAL VOLUME COMPLETE CLUSTER SURVEY

PI: D. J. Turner

1. Abstract

We propose to observe a set of 4 galaxy clusters with *INTEGRAL*, in an effort to detect high-energy X-ray emission. The targeted systems are part of the Local Volume Complete Cluster Survey (LoVoCCS); a complete set of 144 massive ($L_{\rm X,500}^{0.1-2.4\rm keV} > 10^{44}\ \rm erg\,s^{-1}$) local ($0.03 < z < 0.12$) galaxy clusters (selected from MCXC). DECam observations have been taken to a depth similar to the Legacy Survey of Space and Time (LSST) year 1-2 observations, and individual weak-lensing mass maps have been measured for our targets. We wish to try to make high-energy X-ray detections of our targets, and assess whether there is any evidence of non-thermal emission. We would then use the high-quality LoVoCCS observations to attempt to link non-thermal properties to the masses and kinematics of the merging systems, providing insight into a rarely observed phenomena.

2. Description of the Proposed Programme

A) Scientific Rationale:

The study of galaxy clusters can provide powerful probes of some of the greatest astrophysical and cosmological questions of modern physics. By observing and modelling clusters we seek to not only understand the key astrophysical phenomena that underpin the behaviours and evolution of these systems, but also to investigate the processes and fundamental physics of the wider Universe. The dynamics and behaviours of the outskirts of the intra-cluster medium (ICM), the source of ICM enrichment, the nature and strength of cluster magnetic fields, and the mass distribution within clusters will all be the subject of intense study over the coming decade. The use of cluster observations to evaluate potential dark matter candidates, probe whether alternative formulations of gravity might reduce (or entirely remove) the need for dark matter, provide further constraints on H_0 to break the early-late Universe tension, and to derive cosmological parameters through the use of the halo mass function. Galaxy cluster studies provide significant scientific value, and are a priority for many current and upcoming large scale surveys. Studies such as these are possible through a combination of cluster observations in different wavelengths, with each wavelength tracing different components of the cluster.

Galaxy clusters have been studied extensively in the lower-energy X-ray band (i.e. 0.5-12 keV), but there have been only limited investigations in the hard X-ray (HXR) regime. This is partially due to the limited number of telescopes with HXR observing capabilities, but is also because X-ray emission from clusters is primarily through thermal processes, and is focused in the soft X-ray regime probed by telescopes such as *XMM* and *Chandra*. A great deal of information about the ICM can be derived from these lower-energy X-ray observations, including plasma temperatures and densities, metallicities, and even velocity structure functions. Quantities such as temperature, density, and metallicity can also be spatially resolved, both as radial profiles, and as 2D property maps.

Though clusters are not well studied in the high energy band, that is not to say that there has been no effort put into the investigation of HXR emission from galaxy clusters. The last two decades has seen several studies that demonstrate detections of clusters, and the analysis of their emission (e.g. Goldoni et al., 2001; Eckert & Paltani, 2009; Ajello et al., 2010; Wik et al., 2014; Rojas Bolivar et al., 2021). These analyses have been performed using data from *INTEGRAL*, and from *NuSTAR*, and have largely focused on placing constraints on the amount of non-thermal emission from the target galaxy clusters due to inverse-Compton (IC) scattering of cosmic microwave background (CMB) photons by populations of relativistic electrons in the intra-cluster medium. The presence of these electrons is not in doubt, as it is evidenced by radio emission in the form of ‘radio halos’, and is generally attributed to galaxy cluster merger events (or shocks) re-accelerating the population and causing synchrotron radiation emission. Those electrons must also help produce non-thermal X-ray emission through IC scattering, but claimed detections of this emission are still doubted by some, making this subject a very interesting area of study.

Simply contributing further evidence of galaxy cluster HXR IC emission is a worthy scientific goal, but the level of non-thermal emission from clusters could also help to provide insights into some poorly-explored, complex, astrophysics in these systems. For instance, combined observations of synchrotron and IC emission can help to place constraints on the strength of the magnetic fields of clusters, something which remains extremely difficult, but could be crucial to the next phase of our understanding of the ICM. There is also an expected cosmic-ray contribution to the non-thermal pressure support present in the ICM, which would contribute to the so called 'hydrostatic bias'; a deviation of masses measured through direct investigations of the ICM using X-ray observations from masses measured through techniques that directly probe the total mass, such as weak-lensing. Incidentally, another expected source of non-thermal pressure support is the magnetic fields present in clusters, which IC emission measurements could also help us to constrain. These differences in the astrophysics of each individual galaxy cluster help to contribute to their scatter away from the concept of self-similarity (that every cluster is just a smaller or larger version of every other cluster), and from the scaling relations which underpin cluster cosmology efforts. Studying a representative sample of clusters in extreme detail is the only way to constrain this scatter, and hard X-ray observations could contribute significantly.

The Local Volume Complete Cluster Survey (LoVoCCS; Fu et al., 2022) is studying a complete set of local galaxy clusters to an unprecedented level of detail, and is a precursor survey to the Legacy Survey of Space and Time (LSST) which will be conducted by the Vera Rubin Observatory. This sample of 144 massive galaxy clusters, selected from the Meta Catalogue of X-ray detected Clusters (MCXC; Piffaretti et al., 2011) by applying redshift ($0.03 < z < 0.12$), X-ray luminosity ($L_{\rm X,500}^{0.1-2.4\rm keV} > 10^{44}$ erg s^{-1}), and positional ($\delta > 20°$) cuts, will be studied in optical, near-infrared, and X-ray wavelengths. LoVoCCS-South clusters (107) are being observed with Dark Energy Camera (DECam), and LoVoCCS-North clusters (37) with the Hyper Suprime Cam (HSC) instrument. They are being observed to a depth equivalent to what will be achieved in year 1-2 of LSST. This will enable one of the main goals of LoVoCCS analysis, which is to derive individual weak lensing mass maps for each of the clusters. Stacked weak lensing measurements lose information about the scatter of individual clusters, but are currently necessary to attain the required signal-to-noise. The processing of the optical and near-infrared data is undertaken using software being developed for LSST, and as such is highly sophisticated and open-source. The measurement of weak lensing maps will allow a detailed study of the distribution of matter within the galaxy clusters, enabling the location of cluster substructure, such as filaments and voids. Identifying and understanding the effects that such substructure has on the measurement of cluster properties (such as overall mass), is crucial to quantifying the mass scatter of individual systems. Probing how cluster mass is scattered with respect to other, more easily derived, properties is crucial to cluster cosmology; directly measuring cluster masses is difficult to do at scale, so scaling relations are commonly used. The LoVoCCS sample of galaxy clusters will pave the way to a new era of galaxy cluster science, where missions such as LSST will ensure that many clusters have individual weak lensing measurements; until such missions come online, and incorporate lessons learned from LoVoCCS into their analyses, this will be one of the best optically observed set of clusters in existence. We must make full use of the capable current generation of instruments, to allow us to prepare for the analysis difficulties and insufficient models that will be exposed by the new data.

We are performing a detailed, multi-mission, X-ray study of the LoVoCCS sample of galaxy clusters; X-LoVoCCS. The archival data of *XMM*, *Chandra*, *NuSTAR*, *eROSITA*, and *ROSAT* have been searched for observations of these clusters, and more are being proposed for. We aim to perform the most comprehensive study possible of these clusters, and wish to include *INTEGRAL* to provide a HXR view.

As the LoVoCCS sample are the most luminous (in soft-band X-ray) and lowest redshift clusters available, we consider them the most best candidates for *INTEGRAL* to be able to detect. Indeed, fourteen of the clusters in our sample are included as possible candidates for *INTEGRAL* detection in the catalogue assembled by the *INTEGRAL* Science Data Centre (iSDC).

Three of the galaxy clusters in the LoVoCCS sample are present in the recent IBIS source catalogue presented by Krivonos et al. (2022), which provided the initial motivation for this proposal. Expanding the sample of clusters detected in the hard X-ray band by even a few would be a huge percentage increase, and is a worthy feat to attempt for *INTEGRAL*'s last year of service.

We propose to observe 4 members of the LoVoCCS sample with *INTEGRAL*, to complement the three LoVoCCS clusters detected by Krivonos et al. (2022). A uniform analysis of these clusters will should help to constrain the level of non-thermal emission of a selection of LoVoCCS systems. All archival data will be utilised in addition to the new observations, and attempts will be made to place upper limits on hard X-ray luminosity for all LoVoCCS

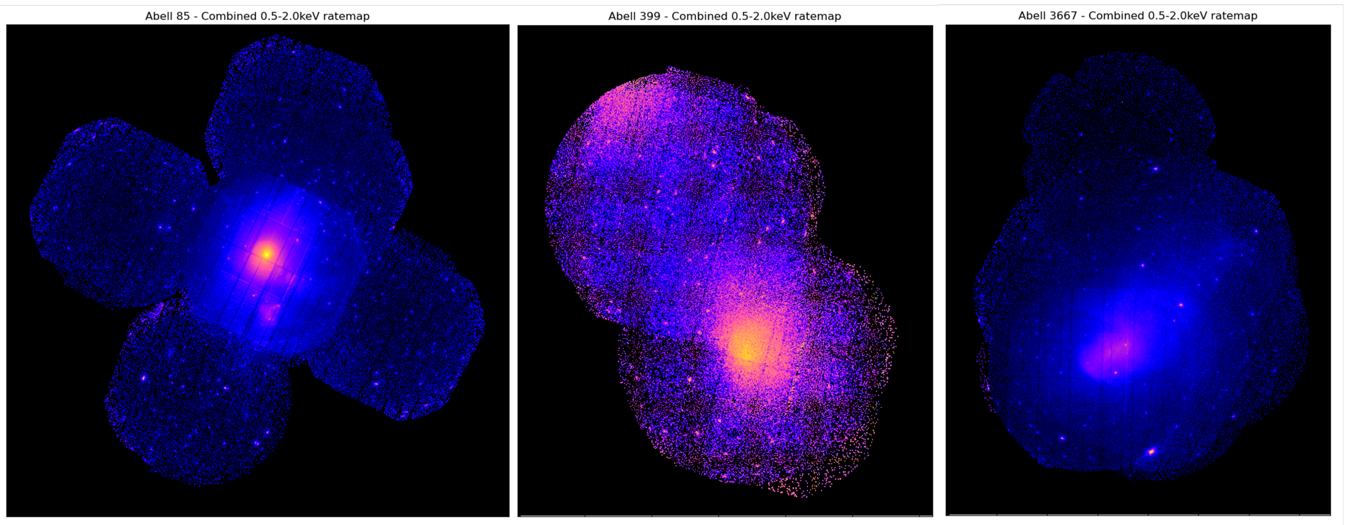

Figure 1: Mosaic *XMM* 0.5-2.0keV count-rate maps of the galaxy clusters we propose to observe with *INTEGRAL*. Note that only part of A401 can be seen, in the middle figure, but that it has been completely covered by *XMM* observations.

clusters. The primary instrument for these observations will be IBIS, as our chief interest is in the ∼20-60 keV band, though JEMX observations will also be requested to probe the lower energy bands (and to help in cross-calibration checks between *INTEGRAL* and other telescopes).

B) Immediate Objective:

(1) The primary objective is to make high-energy X-ray detections of these sources, and then to assess whether there is any excess emission that can be attributed to non-thermal processes within the galaxy clusters. This will involve characterising the continuum slope of any excess emission, as well as measuring the HXR luminosity of thermal and non-thermal components. Failing direct detections, we wish to place upper-limits on the non-thermal HXR luminosity of these systems; this may include stacking observations of different clusters to increase signal to noise. We will include the three LoVoCCS clusters that have been previously detected with IBIS in this sample, and perform a uniform analysis. **(2)** Secondly, we will leverage the extremely high quality optical/near-infrared LoVoCCS observations, as well as the 2D weak-lensing mass maps that have been derived from them, to link the properties of the merger events to the HXR emission. This will also include analysis of the velocity dispersion of the galaxy populations, to probe the kinematics of the mergers. **(3)** If high-energy X-ray detections of the systems are made, we wish to localise the region of the galaxy clusters that the emission is coming from. Though the spatial resolution of IBIS is limited, it may be possible to resolve some detail for these sources, as they are local and large. **(4)** Finally, as each of the target clusters has some level of radio coverage, it may be possible to explore the relationship between any non-thermal emission and the properties of radio relics and sources in the galaxy clusters. Radio emission from clusters can help to constrain the properties of the relativistic electron population, and in combination with high-energy X-ray observations may allow us to estimate the mean strength of the cluster magnetic field (Eckert et al., 2008).

All analyses of *INTEGRAL* data will be performed in conjunction with the ongoing multi-mission X-ray analyses being undertaken for these clusters. Each of our proposed targets has coverage by both *XMM* and *Chandra*, which gives us an excellent understanding of the lower energy X-ray emission of these sources. These existing observations are high signal-to-noise, and allow us to put excellent constraints on the thermal emission; this understanding will be necessary for us to have any chance of identifying any non-thermal emission. The large field-of-view and sensitivity of *XMM* is particularly well suited to the detailed analysis of these galaxy clusters, and has been used to generated radial profiles and 2D maps of spectral properties of our clusters. The high-spatial-resolution data provided by *Chandra* will gives us the additional benefit of being able to separate point source emission from the extended emission of the ICM; being able to quantify the spectra of those point sources will allow us to account for the potential of unresolved sources of hard X-ray emission in the *INTEGRAL* data.

Name	z	R_{500} [$'$]	$t_{\rm cur}^{\rm IBIS}$ [ks]	$d_{\rm SCW}$ [$'$]	$T_{\rm X}$	$t_{\rm req}$ [ks]
A3667*	0.0556	18.51	417.1	153.30	7.1	300
A85†*	0.0555	18.71	179.5	268.35	4.8	300
A399/A401†	0.0722	13.54/14.74	565.5/564.3	5.69/39.55	6.3/7.3	300

Table 1: The targets of this proposal, galaxy clusters which are a part of LoVoCCS. We use their names from the Abell catalogue, the quoted redshift is from the MCXC catalogue, $t_{\rm cur}^{\rm IBIS}$ values are current cumulative exposure values taken from the exposure map tool, $d_{\rm SCW}$ is the distance from the cluster to the central coordinate of the nearest *INTEGRAL* pointing, $T_{\rm X}$ is the preliminary LoVoCCS global temperature as measured by *XMM*, and $t_{\rm req}$ is the requested observing time for each source.

† Observed by BEPPOSAX (according to the HEASArc catalogue)

* Detected by SWIFT Burst Alert Telescope (BAT) Ajello et al. (2010)

LoVoCCS X-ray analyses are performed using the X-ray: Generate and Analyse (XGA;[1] Turner et al., 2022, 2023) Python module, and as such support for *INTEGRAL* will be added. XGA is completely open-source and fully documented, aims to make X-ray analyses accessible, particularly those involving complex sets of multi-mission data. XGA was initially designed for *XMM* analyses, and support for various other telescopes (e.g. *eROSITA* and *Chandra*) is under development.

Another Python module has been created by the PI, called Democratising Archival X-ray Astronomy (DAXA;[2] Turner et al., prep). This is designed to assemble sets of multi-mission X-ray data, and process them into a form useful for science.

It makes it simple to search for and download data from many different X-ray telescope archives, all from a Python terminal or Jupyter notebook. It also makes processing, updating, and organising very large sets of data easy. Support for *XMM*, *Chandra*, *NuSTAR*, *eROSITA*, and *ROSAT* is already implemented, and *INTEGRAL* support will be added to aid the proposed project.

The addition of *INTEGRAL* support to these two software packages will have the added benefit of making the *INTEGRAL* archive even more accessible, and simplifying the process of combining *INTEGRAL* data with other telescopes.

3. Justification of Requested Observing Time, Feasibility, and Visibility

We have selected the targets listed in Table 1 because they appear to be good candidates for potential non-thermal emission, because they are large (and thus we may be able to resolve some structure to potential hard X-ray emission), and because they already have significant coverage by the other X-ray telescopes we're making use of. Each of these clusters is either actively merging (demonstrated by multiple peaks in the LoVoCCS weak-lensing mass maps, as well as multiple red-sequence galaxy peaks, and X-ray morphology) or are considered to be post-merger. All three of the systems appear to have radio emission consistent with synchrotron radiation from a radio halo. Both A3667 and A85 have been detected by the hard X-ray telescope on Swift, making an observation with *INTEGRAL* to gather more data a logical choice. The A399 and A401 clusters are on the same line because they are undergoing a merger, and will be observed simultaneously.

As the hard X-ray emission from non-thermal processes in clusters of galaxies is relatively unknown, it is difficult to make predictions for the observing time required to resolve it. As such we intend to request two observations of 150ks per target, nearly the maximum allowed observing time per revolution. We have ensured that the targets are observable during 2024 for that length of time using the visibility predictor tool. We believe that these observation times will substantially increase the signal to noise and allow for the detection of these systems by *INTEGRAL*. Unfortunately we were not able to perform the XSPEC simulations that we wished to make better predictions, but as this is the final AO for *INTEGRAL* we could not delay this proposal.

4. Justification of Duplication

[1] X-ray: Generate and Analyse GitHub

[2] Democratising Archival X-ray Astronomy GitHub

The High Energy Astrophysics Science Archive Research Centre (HEASArc) archive of *INTEGRAL* science windows was searched for entries within $600'$ of the central coordinates of the proposed targets. The separation between the cluster coordinate and the central coordinate of the nearest pointed science window is reported in Table 1. The *INTEGRAL* exposure map tool was also used to determine the cumulative exposure for the IBIS instrument, for each of the targets. All proposed targets have some level of coverage, but we cannot find reported detections of them - though we have not yet reanalysed all available data ourselves to determine upper limits on their emission with *INTEGRAL*. A detection with IBIS is the minimum we wish to achieve with our proposal, as then we may start to quantify what non-thermal emission is present, and as such we feel justified in asking for further, on-axis, observations of our targets.

5. Report on Previous INTEGRAL Programmes

PI Turner does not have any previous INTEGRAL programmes to report, this is their first time proposing for and using INTEGRAL data, though they have significant experience with lower-energy X-ray data. They have begun to make use of archival observations of the Coma cluster in preparation for this project.

References

Ajello, M., et al., 2010. , 725, 1688

Eckert, D., et al., 2008. , 479, 27

—, 2009. , 495, 415

Fu, S., et al., 2022. , 933, 84

Goldoni, P., et al., 2001. In A. Gimenez, V. Reglero, C. Winkler, editors, *Exploring the Gamma-Ray Universe*, vol. 459 of *ESA Special Publication*

Krivonos, R. A., et al., 2022. , 510, 4796

Piffaretti, R., et al., 2011. , 534, A109

Rojas Bolivar, R. A., et al., 2021. , 906, 87

Turner, D. J., et al., 2022. arXiv e-prints, arXiv:2202.01236

—, 2023. XGA: Efficient analysis of XMM observations. Astrophysics Source Code Library, record ascl:2301.012

—, 2023 in prep.

Wik, D. R., et al., 2014. , 792, 48