Discovery of inverse-Compton X-ray emission and robust estimation of magnetic field in a galaxy group

F. Mernier1,2, N. Werner3, J. Bagchi4, M.-L. Gendron-Marsolais5,6, Gopal-Krishna7, M. Guainazzi1, A. Richard-Laferrière8, T. W. Shimwell9 and A. Simionescu10,11

1 European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
2SRON Netherlands Institute for Space Research, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands
3Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 2, Brno, CZ-611 37, Czech Republic
4Department of Physics & Electronics, CHRIST (Deemed to be University), Hosur Road, Bengaluru, 560029, India
5European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla, 19001, Santiago de Chile, Chile
6Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía, 18008 Granada, Spain
7UM-DAE Centre of Excellence in Basic Sciences (CEBS), Vidyanagar, Mumbai - 400098, India
8Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
9ASTRON, Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, Dwingeloo, 7991 PD, The Netherlands
10Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, The Netherlands
11Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan

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ABSTRACT

Observed in a significant fraction of clusters and groups of galaxies, diffuse radio synchrotron emission reveals the presence of relativistic electrons and magnetic fields permeating large-scale systems. Although these non-thermal electrons are expected to upscatter cosmic microwave background photons up to hard X-ray energies, such inverse-Compton (IC) X-ray emission has so far not been unambiguously detected on cluster/group scales. Here we report the first robust (4.6 σ) detection of extended IC X-ray emission from MRC 0116+111, a group of galaxies. This unambiguous detection provides the most direct and least model-dependent estimate of the volume-averaged magnetic field within a galaxy group. Such estimates can serve as a fulcrum to theories of magnetic field generation within the largest gravitationally bound systems in the Universe.

Key words: magnetic fields – galaxies: clusters: individual: MRC 0116+111 – galaxies: clusters: intracluster medium – X-rays: galaxies: clusters

1 INTRODUCTION

At the dawn of the high-energy astrophysics era, the origin of the bright, extended X-ray emission seen towards clusters and groups of galaxies was debated (Brecher & Burbidge 1972; Lea et al. 1973). The advent of dedicated space observatories established that these systems shine in X-rays via thermal bremsstrahlung and line emission from a hot (10^7–10^8 K), collisionally ionised medium permeating them (Sarazin 1986). However, radio wavelength detections of diffuse synchrotron radiation from relativistic electrons in some clusters (e.g. van Weeren et al. 2019) implies the existence of a wide-spread relativistic plasma which should also upscatter cosmic microwave background (CMB) photons up to X-ray energies via inverse-Compton (IC) scattering.

The importance of detecting this diffuse IC X-ray emission in clusters/groups of galaxies has been long highlighted (Petrosian et al. 2008; Feretti et al. 2012) because in combination with radio observations, it can yield the most direct estimate of the intracluster magnetic field. The latter is, in fact, a critical input for understanding the origin and evolution of cluster magnetic fields, which is fragmentary at the moment (Vazza et al. 2021). Other methods for estimating magnetic fields in clusters and groups of galaxies are, however, afflicted by observational biases. The estimates based on the well known technique of Faraday rotation (e.g. Böhringer et al. 2016) depend critically on the local topography of magnetic fields along the line of sight and, furthermore, remain highly sensitive to the foreground Galactic interstellar dust. The alternative method utilises the radio synchrotron emission solely, which depends not only on the intensity of magnetic field, but also on the uncertain energy density of their relativistic electron population. Usually, these two parameters are commonly estimated by assuming equipartition between magnetic and particle energy densities – whereby the total energy density is nearly minimised (Feretti et al. 2012). The validity of this assumption on various physical scales, however, remains beset with formidable uncertainty (e.g. Petrosian et al. 2008). The degeneracy inherent to the equipartition assumption can be effectively broken using the detection of IC X-ray emission, enabling a reliable estimate of the energy density of the relativistic electron population.

Measuring diffuse IC emission at large scales constitutes thus a promising way to boost our understanding of cosmic magnetic fields.

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From the earliest hunts (Rephaeli et al. 1987) to recent attempts three decades later (Wik et al. 2012; Ota et al. 2014; Cova et al. 2019; Rojas Bolivar et al. 2021), observations have yielded, however, only upper limits for any diffuse IC X-rays from clusters. The rare detections pertain to the Coma cluster (Rephaeli et al. 1999; Rephaeli & Gruber 2002; Fusco-Femiano et al. 1999, 2004), Abell 85 (Bagchi et al. 1998), the Ophiuchus cluster (Eckert et al. 2008), and the Bullet cluster (Petrosian et al. 2006; Ajello et al. 2010); however all these claims have been found spurious (or, rendered controversial) in subsequent more sensitive observations (Rossetti & Molendi 2004; Fusco-Femiano et al. 2007; Eckert et al. 2007; Lutovinov et al. 2008; Durret et al. 2005; Wik et al. 2009, 2014). A key drawback with these observations is that the intracluster gas at such high temperatures radiates thermal X-rays that dominate the IC component at a few keV energies, rendering the latter practically undetectable. This circumstance often mandates complementary observations at higher energies (i.e. even beyond 10 keV), for example using the NuSTAR or INTEGRAL space observatories, in order to confirm the putative IC X-rays. However, this often gets mired in imperfect cross-calibration between the instruments covering different energy bands, which adds substantial uncertainty. Moreover, the hot gas pervading these dynamically disturbed clusters often has a multi-temperature structure, particularly due to recently shocked regions (Donnert et al. 2017), which complicates spectral modelling.

In this Letter, we report results from a deep XMM-Newton observation of the galaxy group MRC0116+111 (or OTL0116+111 at its discovery; Joshi & Singal 1980; Gopal-Krishna et al. 2002). In addition to its relatively cool gaseous medium ($kT \approx 0.7-0.8$ keV) (Mernier et al. 2019), this group is known to be a source of spectrally bright diffuse radio emission possibly related to an ancient pair of relativistic plasma bubbles, and potentially originating from previously intense activity in the supermassive black hole of its central brightest galaxy (Bagchi et al. 2009). The combination of these two extreme properties makes this group a prime target for detecting X-ray diffuse IC emission. Specifically, the emission spectrum of its thermal plasma should peak at soft X-ray energies, with negligible emission above a few keV, where the non-thermal IC emission, shaped spectrally as a power law, is hence expected to dominate.

Throughout this study, we assume that $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$ and $\Omega_L = 0.73$. At the distance of MRC0116+111 ($z = 0.131$), 1 arcmin corresponds to 179.0 kpc. Chemical abundances are given in the (proto-) solar units of Lodders et al. (2009). Unless mentioned otherwise, the quoted uncertainties are 1$\sigma$.

2 DATA AND RESULTS

2.1 XMM-Newton data reduction

This work is based on the three XMM-Newton EPIC observations of MRC0116+111 available so far – taken respectively in January 2014 (ObsID: 0722900101) and December 2020 (ObsID: 0864110101, 0864110101) – for a total raw exposure of $\sim 290$ ks. The data reduction process follows the pilot study of Mernier et al. (2019) and uses the XMM-Newton SAS (Science Analysis System) software (v18.0.0) with the up-to-date calibration files (December 2021). Following the standard pipeline recommendations, the EPIC MOS (1 and 2) and EPIC pn data are processed using, respectively, the commands emproc and epproc. For each of the 9 datasets, we carefully identify flaring events and discard them following the $2\sigma$-clipping method described in Mernier et al. (2015), leaving us with 219.9 ks and 170.5 ks of clean MOS and pn exposures, respectively.

2.2 Spectral analysis

Aiming to analyse spectrally the entire extent of the diffuse radio emission (to maximise the statistics), we extract data from an elliptical region similar to that of Mernier et al. (2019, see their fig. 2). The redistribution matrix file (RMF) and ancillary response file (ARF) are obtained from the same elliptical region. Due to the fairly small X-ray extent of MRC0116+111 ($< 1$ arcmin), the background can be directly subtracted from our spectra. We choose a background region (i) located on the same chip as the source region for all instruments of all observations, (ii) devoid of X-ray sources, and (iii) of the same size and shape as the source region. The small relative separation between this background region and the source ($\sim 1.6$ arcmin) ensures vignetting effects to be negligible. The impact of this method has been already discussed in Mernier et al. (2019), however it is further addressed below.

We use the SPEX fitting package to fit most of our data in the 0.55–5 keV energy band (to minimise further contamination from the soft foreground and the hard instrumental background) with the Cash statistics fitting method. Spectral bins are grouped optimally (Kaastra & Bleeker 2016), though with a gradually wider rebinning with higher energy (within factors 5–80) to ensure that the count rate of every bin remains significantly higher than zero. The latter is also necessary to avoid possible biases from C-statistics in low counts, background-subtracted fits (see the SPEX manual).

Our modelling consists of a collisionally ionised plasma emission model with a Gaussian-shaped multi-temperature distribution of width $\sigma_T$ fixed to 0.2 (i.e. $\text{d}m_{\text{tem}}$, thermal model) and a power law model (i.e. $\text{po}$, non-thermal IC emission model), both redshifted ($z = 0.131$; Mernier et al. 2019) and absorbed by atomic interstellar hydrogen ($n_H = 3.81 \times 10^{20}$ atoms cm$^{-2}$; Kalberla et al. 2005). Following its close to universal value, the metallicity ($Z$) of the thermal model is fixed to 0.3 Solar with all relevant abundances tied to the Fe value (Mernier et al. 2018). The slope $\Gamma$ of the po model can be well constrained by the radio spectral index $\alpha_{\text{syn}}$ of the source below its frequency break at $\sim 400$ MHz ($\alpha_{\text{syn}} = 0.55 \pm 0.05$; Bagchi et al. 2009), and is thus fixed to $\Gamma = 1.55$ (see also Mernier et al. 2019). Figure 1 shows our integrated spectrum. Found with an average best-fitting temperature of $kT = 0.62 \pm 0.04$ keV, the pure thermal model (red) systematically leaves an X-ray excess in the 2–5 keV band, which is well reproduced by a non-thermal component (blue) and detected at a high 4.6$\sigma$ significance level. Since the multi-temperature structure of the gas expectedly extends the spectral profile of the thermal component to higher energies, assuming a single-temperature plasma in the group (c1e model) enhances the non-thermal detection to an even higher confidence level ($> 7\sigma$). Further multi-temperature models are discussed in Sect. 3.

2.3 Spatial analysis

Motivated by the presence of a non-thermal component dominating the X-ray emission beyond $\sim 2$ keV, we now analyse its spatial distribution. With the notable exception of two bright sources ($\sim 80$ arcsec NE and SW away from the group (thus outside of our region of interest), the search for point-like sources (performed via the routine edetect_chain) leads to no significant detection in the vicinity of MRC0116+111. The brightest of the two point sources is in fact a background quasar (SDSS J011904.92 +112420.4; $z = 1.0$; Lyke et al. 2020) that is unrelated to the group.

Figure 2 shows that, unlike its soft thermal counterpart (left), the diffuse hard X-ray emission (right) has a peak that coincides strikingly with the eastern peak of radio synchrotron emission imaged at...
indeed preferred here to better isolate systematic effects and under-
forming a series of alternative fitting tests, in which the flux density
limited. These sources of systematics can all be addressed by per-
uncertainties. This is especially true for sources like MRC0116+111
to ensure that any systematic effects are smaller than the statistical
In order to confirm the robustness of our spectral results, it is essential
to ensure that any systematic effects are smaller than the statistical
uncertainties. This is especially true for sources like MRC0116+111
where, despite the deep exposure, the number of net counts remains
limited. These sources of systematics can all be addressed by per-
forming a series of alternative fitting tests, in which the flux density
and significance of the IC emission can be directly compared to a
simple cie+po modelling case. Whilst the modelling ultimately
adopted in this work is that of a multi-temperature modelling, choos-
ing a single-temperature approach as formal baseline modelling is
indeed preferred here to better isolate systematic effects and under-
stand them with minimal interdependence. Table 1 summarises our
tests and their outcome.

First, in principle a hard tail seen in cluster/group spectra could be
(at least partly) explained by an over-simplified thermal modelling of
its gas component (Cova et al. 2019). To test this hypothesis, in
addition to the gdem fit discussed above, we replace the cie model
from our baseline fit by, successively (i) a power law-distributed
multi-temperature model (wdem) with its slope $\gamma_T$ fixed to 0.25 (as
found in e.g. the Virgo cluster; Kaastra et al. 2004); and (ii) a two-
temperature model (cie+cie) with free temperatures and emission
measures. Table 1 shows that, in both cases, the additional IC emis-
sion remains significant at more than 4-$\sigma$. We note that, in the
gdem model, reproducing the cooler emission and the hard X-ray excess
would require the temperature distribution width to be exceedingly
broad ($\sigma_T \approx 0.6$). Not only has such an extreme value never been
reported in the literature, it would also imply that half of the group’s
emission originates from a gas with $kT > 5$ keV, extending even
further to $kT = 10$ keV and beyond. This latter consideration seems
hardly physical for a group having so few galaxies and with so faint
X-ray luminosity (Bagchi et al. 2009; Mernier et al. 2019). Similarly,
adding a third cie component to our cie+cie modelling results does not
alter the robustness of our results. Since the gdem model is
physically the most realistic multi-temperature distribution for this
group (the wdem model being suited mostly for cool-core clusters),
we adopt it as our most accurate assumption.

Second, we must ensure that the additional power law component
is not an instrumental artefact. To do so, we re-evaluate our free
parameters for the MOS and pn spectra separately. We find that the
IC component is detected in both instruments with high significance
(4.7-$\sigma$ and 5.4-$\sigma$ for MOS and pn, respectively).

Third, it is essential to ensure that the background is correctly
accounted for in our spectral analysis. In addition to our robust
background-subtracting strategy described above, an alternative ap-
proach consists of modelling spectrally the background instead of
subtracting it (e.g. Mernier et al. 2015). The thermal foreground,
originating from the local hot bubble and from the Galactic thermal
emission, is then modelled with an (unabsorbed) cie model plus
an (absorbed) cie model, with free emission measures as well as
temperatures fixed to $kT_{LHB} = 0.08$ keV and $kT_{GTE} = 0.2$ keV,
respectively. The cosmic X-ray background is modelled with a power
law of index $\Gamma_{\text{CXB}} = 1.41$ and an emission measure of $3.7 \times 10^{69}$
photons s$^{-1}$ keV$^{-1}$, adopted to account for the integrated emission of
point sources unresolved below the (2–8 keV) flux threshold limit of 2.2 \times 10^{-5} \text{ erg cm}^{-2} \text{ s}^{-1} obtained from our observations. In addition, we also model two “instrumental” components and leave them unfolded through the ARF. While the residual soft proton background is modelled with a simple power law, the hard particle background is modelled with a broken power law and a series of Gaussian components to account for the emission of fluorescent lines (Mernier et al. 2015). Despite this very conservative approach resulting into many more degrees of freedom than in our baseline fitting, the IC component remains significantly detected (3.6\sigma) with similar best-fitting results.

Fourth, whilst our adopted fitting range arguably constitutes the best compromise of maximising the true signal from the source while avoiding additional sources of noise, it is important to ensure that our results are not much affected by this choice – in particular by the upper energy limit as main tracer of the IC emission. Encouragingly, the IC emission remains confidently constrained at similar flux densities when varying this upper limit from 4 keV to 10 keV.

Fifth, our results are independent on the atomic code and databases used to model the thermal emission of the gas. In particular, we find no notable difference in our results when using AtomDB (v3.0.9) or an older version of SPEXACT (v2.05) in our fits.

Finally, although thawing more parameters in our fits would inevitably lead to larger statistical uncertainties, it may be instructive to explore how doing so would affect our results. Encouragingly, we find that free \( n_H \) and \( Z \) still result in a comfortable IC detection (3.5\sigma). In this case, we note that the best-fit metallicity is found to drop \( \approx \text{0.07 Solar} \), which seems hardly physical given the \( \geq 30\% \) Solar levels found in virtually all clusters and groups (Mernier et al. 2018). In fact, fixing the metallicity to the most plausible values (i.e. between 0.5 and Solar) results in more line emission – hence a steeper thermal profile and, in turn, further boosting the significance of the IC emission. Similarly, despite the reliability of the radio spectral index (Bagchi et al. 2009), we also verify whether our results remain essentially unchanged if we free the IC X-ray photon index \( \Gamma \). Here we choose to restrict our fitting range to 0.8–5 keV (and fixing the temperature of the thermal model to its best-fitting baseline value 0.64 keV) to ensure the IC slope to reproduce the hard tail preferentially. This fit leads to \( \Gamma = 1.5 \pm 0.6 \), in good agreement with our initially adopted value. Quite remarkably, even in this extreme case the IC emission remains detected with more than 2\sigma confidence.

4 DISCUSSION AND IMPLICATIONS

There are a number of claimed detections of IC X-ray emission from X-ray “hot spots” seen in radio-galaxies (e.g. Hardcastle et al. 2002) and from collimated jets of relativistic particles in blazars (e.g. Worrall et al. 2020), although validity of such an interpretation for the latter objects has been questioned in some cases (e.g. Breiding et al. 2017). Regardless of this, the present finding differs both in the nature of the system and the physical scale and kinematics of the IC emitting plasma. Whilst our hard X-ray image reveals a non-thermal contribution from the vicinity of the likely remnant radio lobes associated with the central dominant galaxy (see Fig. 2), the flux contributed by these lobes accounts for less than half of the total IC emission detected from the entire volume of the group, the remainder fraction originates from the intragroup gas beyond the remnant radio lobes. To our knowledge, this is the first time that extended IC emission – associated both with relativistic electrons pervading the entire group and with a more concentrated, lobe-like component – has been robustly detected in a system containing multiple galaxies.

Both the diffuse radio emission and the diffuse IC X-ray emission share a common origin from a population of relativistic electrons permeating large-scale structures. Whereas the flux of the former depends on both the relativistic electron density and the volume-averaged magnetic field (hence implying a degeneracy between these two a priori unknown values), the flux of the latter depends solely on the relativistic electron density. Consequently, the ratio between these two fluxes provides unique constraints on the magnetic field strength ( Feretti et al. 2012; Ota et al. 2014; Mernier et al. 2019), devoid of any bias unlike other methodologies (Sect. 1). In fact, upper limits to IC X-ray emission from previous work on clusters only translate into lower limits in intracluster magnetic fields of \( \geq 0.1 - 1 \mu \text{G} \) ( Bartels et al. 2015; Cova et al. 2019; Rojas Bolivar et al. 2021). Our present robust detection of IC emission allows accurate and essentially model-independent estimate of the volume-averaged magnetic field of the group, which is found to be \( (1.9 \pm 0.3) \mu \text{G} \). In addition to being close to the lower limit of \( \geq 2.6 \mu \text{G} \) (90% confidence; Mernier et al. 2019), it lies well within the lower limits estimated for rich clusters. Cosmological magneto-hydrodynamical simulations do predict \( \mu \text{G} \) level magnetic fields in the cores of rich clusters; however they suggest fields that are smaller by an (or, sometimes, even two) order of magnitude in the case of groups having gas densities and...
temperatures similar to MRC0116+111 (e.g. Donnert et al. 2018). Interestingly, were the magnetic field in our object indeed so weak, the corresponding diffuse IC X-ray emission would be a factor $\geq 30$ stronger than even our highly significant detection reported here. Therefore, it may be instructive to devise suitable alternative mechanisms for the seeding and growth of cosmic magnetic fields, allowing them to be stronger in groups of galaxies. Whereas NuSTAR observations could in principle allow to set even stronger constraints on the IC X-ray emission of this source, targeted searches using current and future observing facilities will be vital for ascertaining whether the present object has a magnetic field that is representative of a wider population of groups. This will be attempted by taking advantage of (i) synergies between X-ray surveys (such as eROSITA) and radio surveys (such as LOFAR or SKA), and (ii) the outstanding spectral and/or photon collecting capabilities offered by the next generation of X-ray observatories (e.g. XRISM, Athena).

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DATA AVAILABILITY

The original data presented in this article are publicly available from the XMM-Newton Science Archive (https://nxsa.esac.esa.int/nxsa-web/). The corresponding XMM-Newton data are reduced with the SAS software (https://www.cosmos.esa.int/web/xmm-newton/sas) and further analysed spectrally with the SPEX fitting package (https://www.sron.nl/astrophysics-spx). Additional derived data products can be obtained from the main author upon request.

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