Magnetic fields and extraordinarily bright radio emission in the X-ray faint galaxy group MRC 0116+111

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ABSTRACT

MRC 0116+111 is a nearby (z = 0.132) poor galaxy group, which was previously known for exhibiting a bright diffuse radio emission with no central point-like source, presumably related to a past activity of the active galactic nucleus (AGN) in its central cD galaxy. Here, we present an X-ray observation (~30 ks of cleaned XMM-Newton/EPIC exposure) of this system, allowing us for the first time a detailed comparison between the thermal and non-thermal components of its intragroup medium (IGrM). Remarkably, we find that the radio-to-X-ray luminosity ratio is among the highest ever observed for a diffuse extragalactic source so far, while the extent of the observed radio emission is about three times larger than its associated soft X-ray emission. Although powerful AGN activity may have disturbed the dynamics of the thermal IGrM in the form of turbulence, possibly re-energising part of the relativistic electron population, the gas properties lie within the $L_X-T$ scaling relation established previously for other groups. The upper limit we find for the non-thermal inverse-Compton X-ray emission translates into a surprisingly high lower limit for the volume-averaged magnetic field of the group ($\geq 4.3 \, \mu G$). Finally, we discuss some interesting properties of a distant ($z \approx 0.525$) galaxy cluster serendipitously discovered in our EPIC field of view.

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

1 INTRODUCTION

Well beyond their radii of gravitational influence, supermassive black holes (SMBH) are expected to play a fundamental role in the formation and evolution of the largest structures of the Universe. While the tight correlation between black hole mass and stellar velocity dispersion of the bulge of their galaxy hosts strongly suggests that the formation and growth of these two components happened together (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Ho 2013), active galactic nuclei (AGN) in the centre of massive elliptical galaxies often produce powerful jets – or lobes – that are visible at radio wavelengths (e.g. Kataoka & Stawarz 2005). This form of AGN feedback (often named as "kinetic" or "radio" mode, by contrast to the "radiative" or "quasar" mode which operates when the SMBH is close to the Eddington limit) is thought to play a crucial role in regulating the thermal balance of the hot, X-ray emitting atmospheres of massive ellipticals, groups and clusters of galaxies, as these radio jets provide enough mechanical energy to offset the rapid cooling of the gas and to prevent the formation of new stars, thus keeping giant ellipticals "red

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and dead” (for recent reviews, see Peterson & Fabian 2006; Fabian 2012; McNamara & Nulsen 2012; Werner et al. 2019). In cool-core systems1, specifically, AGN are thought to inject lobes of relativistic plasma and magnetic fields in the intrachuster medium (ICM), in the intra-group medium (IGrM), and in hot atmospheres of elliptical galaxies, thereby creating cavities which are easily observed with the current generation of X-ray observatories (e.g. McNamara et al. 2000; Fabian et al. 2000; Wise et al. 2007; Randall et al. 2011; Hlavacek-Larrondo et al. 2012).

How exactly these bubbles – filled by relativistic, non-thermal particles and magnetic fields – detach, rise buoyantly and re-heat isotropically the surrounding ICM (IGrM) to prevent massive “cooling flows” is still unclear. Among the difficulties encountered in both observations and simulations, our knowledge of magnetic fields in clusters and groups – in particular their origin(s), topologies, coupling with AGN feedback, and even their average intensities – is rather limited. In fact, the existence of magnetic fields in the ICM (IGrM) is revealed thanks to the synchrotron radio emission radiated by accelerating non-thermal electrons along magnetic field lines (for a review, see e.g. Brüggen et al. 2012). In addition to the jets/lobes tracing the most recent AGN activity, synchrotron emission is also observed in the form of (Ferrari et al. 2008; Feretti et al. 2012; van Weeren et al. 2019):

(i) giant radio haloes in merging clusters (≥1 Mpc), presumably tracing an old population of non-thermal electrons that has been recently re-accelerated during the merger;

(ii) radio mini-haloes, found only in the inner ≤500 kpc of cool-core clusters, where an old population of non-thermal electrons has been possibly re-accelerated by AGN feedback,

(iii) radio relics, which exhibit an elongated morphology sometimes extending to Mpc scale, presumably tracing shocks in the outskirts of merging clusters (e.g. Bagchi et al. 2006).

However, radio emission alone cannot constrain directly magnetic field intensities, because the synchrotron emission also depends on the (a priori unknown) relativistic electron density. One approximation commonly found in the literature to break this degeneracy is to assume that the total (i.e. magnetic and particle) energy density in the relativistic plasma is minimal, which implies that the contributions from magnetic and particle energy densities are roughly equal. This so-called “equipartition” approximation provides magnetic field estimates of the order of 0.1–1 G in radio haloes (Petrosian et al. 2008; Feretti et al. 2012) and a few tens of G in central radio lobes/mini-haloes (e.g. Birzan et al. 2008). Because particles and magnetic fields do not necessarily have the same origin and history, however, the validity of the equipartition approximation is not obvious. Magnetic field intensities can also be estimated via Faraday rotation measurements (e.g. Carilli & Taylor 2002; Govoni & Feretti 2004; Böhringer et al. 2016). Although the derived magnetic fields are globally of the same order of magnitude as when using the equipartition assumption (e.g. Govoni et al. 2010, and references therein), there may be appreciable differences due to the fact that Faraday rotation measurements are integrated along the line of sight, and depend thus on the local magnetic field topology (and the possible foreground contamination).

In principle, non-thermal electrons responsible for the radio emission should also boost the energy of the cosmic microwave background (CMB) photons up to keV units via inverse-Compton (IC) scattering, hence producing an additional non-thermal emission in the X-ray band (Feenberg & Primakoff 1948; Felten & Morrison 1966; Rephaeli 1979; Harris & Grindlay 1979; Schlickeiser 1979; Rephaeli & Gruber 1988; Bagchi et al. 1998). Interestingly, since the IC emissivity depends on the relativistic electron population but not on the magnetic field, simultaneous radio synchrotron and IC measurements allow to determine the volume-averaged magnetic field in clusters and groups without the need of the equipartition assumption (Bagchi et al. 1998). So far, this method has provided essentially lower limits on magnetic field intensities of clusters hosting giant haloes or relics (Bartels et al. 2015, and references therein), simply because only upper limits on the IC emission could be constrained. The situation is more problematic for mini-haloes and central radio lobes in cool-core systems, since the emission of the 0.3–10 keV band is almost entirely dominated by the (centrally peaked) thermal X-ray photons, making the non-thermal IC emission virtually impossible to detect. With the current X-ray telescopes, robust constraints on the volume-averaged ICM/IGrM magnetic field within the zone of influence of the central AGN feedback could be inferred only for systems that would be exceptionally bright in radio and with very limited soft (i.e. thermal) X-ray luminosities.

In this paper, we focus on the X-ray emission of the galaxy group MRC0116+111 (hereafter, MRC0116). Initially discovered by the Ooty Lunar Occultation Survey at 327 MHz (Joshi & Singal 1980), this radio source – also member of the Molonglo Reference Catalogue (Large et al. 1981) – had been reported a first time using the Giant Metrewave Radio Telescope (GMRT) and the Very Large Array (VLA) data (Gopal-Krishna et al. 2002), then discussed in detail with more recent GMRT and optical observations (Bagchi et al. 2009, where the authors find the dominant galaxy to be at z = 0.1316). Whereas, based on optical observations, the source had also been firmly classified as a galaxy cluster (Lopes et al. 2004), the limited number of galaxies seen in the optical band (Bagchi et al. 2009) suggests instead a rather poor galaxy group. Although, interestingly, the radio source was reported with a surprisingly high luminosity \(L_{\text{621 MHz}} \sim 1.21 \times 10^{25} \text{ W Hz}^{-1}\) and \(L_{1.4 \text{ GHz}} \sim 4.57 \times 10^{24} \text{ W Hz}^{-1}\) and with a mini-halo-like morphology (without emission from the central SMBH), no X-ray observation of MRC0116 has been reported so far in the literature. In fact, results from the ROSAT All Sky Survey are consistent with no detection at the position of the source (Boller et al. 2016), which strongly suggests an anomalously low X-ray-over-radio luminosity ratio. In addition to be a target of potentially high interest to constrain X-ray non-thermal IC emission, this system might have witnessed an extremely powerful (past) AGN activity (Bagchi et al. 2008; Feretti et al. 2012) and a few tens of Mpc scale, presumably tracing an old population of non-thermal electrons that has been recently re-accelerated during the merger;
et al. 2009), whose unique impact on the surrounding IGrM is worth studying.

Here, we present for the first time an XMM-Newton/EPIC observation of MRC0116. The data reduction and analysis are described in Sect. 2. Subsequent results and their interpretation are detailed and discussed in Sect. 3 and Sect. 4, respectively. In these two sections, we also report and discuss the properties of a distant galaxy cluster serendipitously discovered in the same pointing. Finally, Sect. 5 summarises our findings. Throughout this paper, we assume a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km s Mpc$^{-1}$. At $z = 0.132$, 1 arcmin corresponds to $\sim$180 kpc. All the errors given in the following correspond to their 68% confidence level, unless stated otherwise.

2 DATA PREPARATION

2.1 XMM-Newton data

MRC 0116 was observed by XMM-Newton on January 10–11 2010 (ObsID:0722900101), with ~56 ks of raw exposure. We use the latest version (v17.0.0) of the XMM SAS software, as well as the associated calibration files of February 2018, to reduce the data. We first process the EPIC data by using the pipeline commands emproc and epproc for the MOS (i.e. MOS1 and MOS2) and pn instruments, respectively. We then filter the data from significant soft-protons flares. We do so by using the espfilt command on the MOS and pn light curves in the 10–12 keV band. This command builds count histograms within 100 s time bins and selects the count threshold above which the histograms deviate from a Poisson distribution by $>2\sigma$. We then apply the appropriate good time intervals (GTIs) on the raw data to obtain soft-proton cleaned event lists. We repeat the same procedure in the 0.3–2 keV band, as some independent flares might as well be detected at softer energies (Lumb et al. 2002). Unfortunately, about half of the observation was significantly affected by flaring events. The total net exposure of the MOS 1, MOS 2, and pn data is 28 ks, 37 ks, and 28 ks, respectively.

For each instrument, we generate a raw image, a background image, and an exposure map within the 0.3–2 keV band using the SAS task evselect. The background images are obtained from filter wheel closed data (~50 ks for each instrument). Before subtracting it from the raw image, we rescale the background image accordingly to the 10–12 keV energy band, where no source emission is expected. The exposure maps are generated for each of the three instruments using the SAS task eexpmap. The three background-subtracted images and the three exposure maps are first merged separately before we divide the total EPIC image by the total EPIC exposure map with appropriate weights. The final background- and vignetting-corrected EPIC image of MRC0116 (in the 0.2–3 keV band) is shown in Fig. 1. For comparison, we overplot the radio contours (GMRT, 610 MHz) presented in Bagchi et al. (2009). In Fig. 2 (left and right panels, respectively), we also show the X-ray and radio contours separately, overplotted on an optical/infrared mosaic using the g, r, and i bands from the SDSS-III data (Eisenstein et al. 2011).

Regrettably, the limited total number of net counts (~400) detected from MRC0116 and the moderate spatial resolution of XMM-Newton do not allow us to investigate its spatial structure in detail via spectroscopy. However, we can reasonably perform a spectral analysis within the full extent of the system. We extract the MOS 1, MOS 2, and pn spectra within an ellipse region encompassing the bulk of the radio emission (Fig. 2, yellow dashed contour). After visual inspection and using the SAS task edetect_chain, no point-like sources were detected in this region (see also Sect. 3.3). The redistribution matrix file (RMF) and the ancillary response file (ARF) are computed by using the commands rmfgen and arfgen, respectively. Throughout this paper, the spectral analysis is done using the SPEX (v3.04) fitting package (Kaastra et al. 1996; Kaastra et al. 2017). We consequently convert the raw spectra, the RMFs, and the ARFs to SPEX readable files using the appropriate subroutine trafco.

In addition, a careful estimate of the background is important when analysing X-ray spectra of extended objects. In the case of nearby, extended clusters, the entire field of view may be contaminated by the emission of the source, and the safest approach requires to properly model all the background components (see e.g. Mernier et al. 2015, and references therein). Here, however, the very limited angular extent of MRC0116 (i.e. less than 1 arcmin) allows us to estimate the background directly from an external region on the same field of view. Therefore, we extract the EPIC spectra of a box region, in which point-like sources are removed, and about three times larger than the source extraction region (though situated in its vicinity). We then subtract the background from the corresponding raw spectra to obtain spectra with net counts only. This method is robust in the present case, because the extracted background region contains virtually no emission from MRC0116, while all the (astrophysical and instrumental) background components are expected to behave in a very similar way in the source and background regions. For safety, we also select an alternative, less extended background region and we verify that the results presented in the following sections are not significantly affected by this change.
2.2 Chandra data

In addition to XMM-Newton, MRC0116 was observed with Chandra/ACIS on June 24 2010 (ObsID:11865). These data are reduced using the dedicated software CIAO (v4.9). After reprocessing the data following the recommended procedure (i.e. via the chandra_repro command), we create an exposure-corrected ACIS image in the full band of the instrument (0.5–7 keV) using the task fluximage. The very limited exposure of this pointing (18 ks) prevents us from deriving any spatial (and thus spectral) information of the extended emission; therefore the rest of the paper will be essentially devoted to the analysis of the XMM-Newton observation. Nevertheless, the ACIS data can be used to put useful constraints on the emission from individual point-like sources within this group (Sect. 3.3).

3 RESULTS

3.1 Imaging analysis

The optical image of MRC0116 suggests that this group does not contain more than a few galaxy members (see also Sect. 1). As shown in Fig. 2 (left), the location of the brightest group galaxy, USNO-A2.00975-00295178 (Monet 1998), is formally consistent with the location of the X-ray peak (less than ~6 arcsec, which is also the point spread function of the EPIC instruments). However, Figs. 1 and 2 (left) suggest that the IGrM is disturbed. This can be further quantified by computing the centroid shift parameter $w$ (as defined in Mohr et al. 1995; Rasia et al. 2013). Using ten circular regions centred of the X-ray surface brightness peak with their aperture radii spanning from 6 arcsec to 1 arcmin, we find $w \approx 0.035$, which is typical for a disturbed system (Cassano et al. 2010).

Another striking feature seen from Fig. 1 is the apparent surface brightness drop seen at ~40–50 kpc North-East from the X-ray peak, beyond which an elongated re-enhancement seems to follow the radio contours of the Eastern lobe. Although the small number of counts prevents us from confirming this feature with sufficient significance, this might suggest the existence of an X-ray cavity at this location. This possibility will be further discussed in Sect. 4.2. Though even less significant, a similar X-ray decrement, possibly corresponding to another cavity, may be seen ~30–40 kpc South-West from the X-ray peak (roughly surrounding the Western radio lobe).

The net number of counts obtained for the source in the 0.3–2 keV band of the MOS1, MOS2, and pn instruments is 158, 219, and 398, respectively. At first approximation, X-ray fluxes (and luminosities) can be calculated directly from the count rate inferred from our EPIC images. Using the web tool WebPIMMS\(^2\) and assuming a gas temperature of $kT = 0.76$ keV (Sect. 3.2), we find that the fluxes and luminosities estimated within the 0.5–7 keV band from our MOS1, MOS2, and pn individual images are all $<2\sigma$ consistent with the flux and luminosity $f_{X,0.5–7}$ and $L_{X,0.5–7}$, estimated from the spectral analysis and reported in Table 1.

3.2 Spectral analysis

The background-subtracted EPIC spectra are shown in Fig. 3. The MOS1 and MOS2 spectra are stacked for display purpose, however they are fitted simultaneously (with tied parameters) in our analysis. In order to avoid possible biases due to gain calibration of the oxygen edge, the soft energies $E < 0.6$ keV are discarded from the rest of the analysis. After grouping the channels in wider energy bins, nearly all the net counts detected by MOS and pn beyond ~2 keV are consistent with zero. A few specific bins at high energies (particularly at $E > 5$ keV), however, are significantly brighter (with no overlap between MOS and pn) and their reliability may be questioned as instrumental effects cannot be excluded. Therefore, and to be as conservative as possible, we choose to fit our spectra within the 0.6–5 keV band.

\(^2\) https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
We also verify that extending our fitting range to 10 keV does not affect the results presented throughout this paper.

In Fig. 3, we also note the presence of a peak of emission around ~0.6–0.9 keV (~0.7–1 keV rest frame), which is characteristic of the (unresolved) Fe-L complex emitted by a low temperature plasma (typically $kT \lesssim 2$ keV). We start by fitting simultaneously the MOS1, MOS2 and pn spectra with a redshifted ($z = 0.132$, Sect. 1) and absorbed ($N_H = 3.81 \times 10^{20}$ cm$^{-2}$; Kalberla et al. 2005) $\text{c}$ie model. This model assumes a single-temperature thermal plasma (see the SPEX manual for more details)$^3$. The free parameters are the emission measure ($\rho_{\text{cie}} = \int n_e n_H \text{d}V$) and the temperature ($kT$) of the plasma. The chemical abundances, given with respect to the proto-solar units of Lodders et al. (2009), are assumed to be 0.3 (e.g. Urban et al. 2017). The fitting results, as well as the estimated flux and luminosity in the 0.5–7 keV band ($f_{X,0.5-7}$ and $L_{X,0.5-7}$, respectively) and the estimated X-ray bolometric luminosity ($L_{X,\text{bol}}$), are shown in Table 1 (first row). When comparing the observed C-stat with respect to the proto-solar units of Lodders et al. (2009), we find that the emission measure ($\rho_{\text{cie}}$) of the plasma. The chemical abundances, given with respect to the proto-solar units of Lodders et al. (2009), are assumed to be 0.3 (e.g. Urban et al. 2017). The fitting results, as well as the estimated flux and luminosity in the 0.5–7 keV band ($f_{X,0.5-7}$ and $L_{X,0.5-7}$, respectively) and the estimated X-ray bolometric luminosity ($L_{X,\text{bol}}$), are shown in Table 1 (first row). When comparing the observed C-stat with respect to the proto-solar units of Lodders et al. (2009), we find that the emission measure ($\rho_{\text{cie}}$) of the plasma. The chemical abundances, given with respect to the proto-solar units of Lodders et al. (2009), are assumed to be 0.3 (e.g. Urban et al. 2017). The fitting results, as well as the estimated flux and luminosity in the 0.5–7 keV band ($f_{X,0.5-7}$ and $L_{X,0.5-7}$, respectively) and the estimated X-ray bolometric luminosity ($L_{X,\text{bol}}$), are shown in Table 1 (first row). When comparing the observed C-stat with respect to the proto-solar units of Lodders et al. (2009), we find that the emission measure ($\rho_{\text{cie}}$) of the plasma. The chemical abundances, given with respect to the proto-solar units of Lodders et al. (2009), are assumed to be 0.3 (e.g. Urban et al. 2017). The fitting results, as well as the estimated flux and luminosity in the 0.5–7 keV band ($f_{X,0.5-7}$ and $L_{X,0.5-7}$, respectively) and the estimated X-ray bolometric luminosity ($L_{X,\text{bol}}$), are shown in Table 1 (first row).

Since this source exhibits a high radio luminosity compared to its X-ray luminosity (see also Sect. 4.2), it is an ideal target to search for IC emission in its X-ray spectrum. This is particularly relevant beyond ~2 keV, where negligible thermal emission is expected from this low-temperature system. We first test the unlikely possibility that the X-ray emission would be predominantly produced by IC scattering via the relativistic electron population. This is done by modelling a (redshifted and absorbed) power law spectrum (hereafter the $\text{po}$ model) instead of a $\text{cie}$ model. The parameters of interest of the $\text{po}$ model are the normalisation ($\rho_{\text{po}}$) and the photon index ($\Gamma$). The spectral index $\alpha_X$ of the (X-ray) IC emission is expected to be the same as the spectral index $\alpha_{\text{syn}}$ of the (radio) synchrotron emission. Bagchi et al. (2009) measured $\alpha_{\text{syn}} = 0.55$ for $\nu \lesssim 400$ MHz and $\alpha_{\text{syn}} = 1.35$ for $\nu \gtrsim 400$ MHz. Since the Lorentz factor of an electron should be on average $\gamma\sim 1500$ to scatter a CMB photon up to energies of $\gtrsim 2$ keV, the radio synchrotron frequencies to be associated with X-ray IC emission should not exceed a few tens of MHz (see also Sarazin 1986). Given that the X-ray spectral and photon indexes are related as $\Gamma = \alpha_X + 1$, we fix $\Gamma$ to 1.55 in our $\text{po}$ model. The best-fit normalisation is $(20.7 \pm 2.1) \times 10^{39}$ ph s$^{-1}$ keV$^{-1}$, and the fit quality (reduced C-stat $\approx 3.8$) is clearly poorer than when using the $\text{cie}$ model (Table 1, second row).

As a more realistic scenario, one may assume that both thermal and IC processes contribute comparably to the total X-ray emission of this group. Therefore, we refit our spectra with a combination of one $\text{cie}$ and one $\text{po}$ component (hereafter the $\text{cie+po}$ model). The best-fit models and their individual components are plotted in Fig. 3, and the best-fit parameters are listed in Table 1 (third row). Compared to the case of a single $\text{cie}$ component, the fit does not improve when adding an additional $\text{po}$ component and only upper limits on the normalisation of the $\text{po}$ component could be obtained ($<3.5 \times 10^{39}$ ph s$^{-1}$ keV$^{-1}$ and $<2.7 \times 10^{39}$ ph s$^{-1}$ keV$^{-1}$ at the 68% and 90% confidence levels, respectively accounting for <11% and <24% of the total 0.6–5 keV luminosity). For consistency, we also checked the fitting results in MOS (MOS 1+MOS 2) and pn separately, as reported in Table 1 (two last rows). We find an excellent agreement between the MOS and pn best-fit parameters, always consistent within 1σ, hence justifying that both instruments can be used and combined to provide more accurate constraints.

### 3.3 Possible point-source contamination?

Since the point spread function of the EPIC instruments is not negligible compared to the spatial extent of the source, one may ask whether the observed X-ray emission is contaminated by one or several point sources. To address this question, we inspect the shallow Chandra/ACIS observation mentioned in Sect. 2.1 and search for possible point-like sources in the region covered by our EPIC analysis. Among the two source candidates we find, the first one coincides with the centre of the brightest group galaxy while the second has no optical counterpart. Using the CIAO task $\text{arfconv}$, and based on their number of counts, we estimate their 0.5–7 keV fluxes to be $(5 \pm 3) \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ and $(9 \pm 6) \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$, respectively. If these sources are real, their fluxes do not contribute more than respectively ~6% and ~11% of the total 0.5–7 keV flux of the diffuse emission measured with EPIC ($\sim 1.4 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$). Therefore, we conclude that the contamination of the X-ray emitting IGrM by EPIC-unresolved point sources is minimal.

### 3.4 Serendipitous discovery of a rich, distant cluster

In the field of view of our EPIC pointings, we find an apparent extended emission, at ~1h19’34.7” RA, +11°21’06.5” DEC (~8 arcmin off-axis). The source was previously known as a radio emitter, as it was detected in the NVSS ($\text{VLA}$, 1.4 GHz; Condon et al. 1998), TXS ($\text{Texas Interferometer}$, 365 MHz; Douglas et al. 1996), TGSS ($\text{GMRT}$, 150 MHz; Intema et al. 2017), and VLSS ($\text{VLA}$, 74 MHz; Cohen et al. 2007) catalogues. While not detected by ROSAT (Boller et al. 2016), the X-ray source was formally detected by the 3XMM catalogue (Rosen et al. 2016, named as 3XMM J011934.7+112106 – hereafter 3XMM J011934), although identified as a point-like source. In optical light, an overdensity of galaxies was previously known in the redMaPPer 6.3.1 catalogue (Rykoff et al. 2016), as ID 5105, and with a spectroscopic redshift of $z \approx 0.525$ for the central galaxy (E. Rykoff, private communication). The source, however, was only labelled as a galaxy cluster candidate because it is situated at the upper redshift limit of the SDSS catalogue. The diffuse X-ray morphology of the source (spanning over at least 1.4 arcmin of diameter and reported for

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$^3$ Admittedly, the ICM/IGrM usually hosts a complex temperature structure (e.g. Frank et al. 2013; Hitomi Collaboration et al. 2018) and may be affected by projection effects; meaning that their emitting plasma is unlikely to be in a pure single-temperature phase. Whereas SPEX offers several multi-temperature plasma models, the quality of our spectra is not sufficient to obtain further accurate information on the temperature structure of MRC0116.
the first time), associated with the optical data described above, provide the decisive evidence for that object being a distant, massive galaxy cluster. An optical RGB mosaic of the source (from the SDSS-III catalogue), overplotted with our EPIC (X-ray) contours and radio contours (1.4 GHz, VLA), is shown in Fig. 4.

The $r_{500}$ limit of 3XMM J011934 can be calculated iteratively by determining $T_X$, i.e. the ICM temperature between $0.1r_{500} < r < 0.4r_{500}$, from spectral fits. This radial range is often considered as well representing the "average" cluster temperature (i.e. excluding the possible cool-core and the temperature decrease towards the outskirts; e.g. Reiprich et al. 2013). After fixing $r_{500}$ arbitrarily and estimating its corresponding $T_X$, the $r_{500}$ limit can be re-estimated as (Vikhlinin et al. 2006, see also Liu et al. 2018):

$$r_{500} = \frac{0.792}{hE(z)} \left( \frac{T_X}{5 \text{ keV}} \right)^{0.53} \text{ Mpc},$$

where $h = H_0/100 \approx 0.7$ and $E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_L} \approx 1.328$. We stop the iteration when $r_{500}$ and $T_X$ provide stable values (i.e. with fluctuations of less than 10%). We find $r_{500} = 0.93 \pm 0.09$ Mpc, corresponding to $1.06 \pm 0.10$ arcmin$^4$.

To determine the dynamical state of this cluster, we estimate the morphological parameter $w$ following the method described in Sect. 3.1. Specifically, we calculate the dispersion of the best-fit centroids of the source within six concentric apertures spanning from 12 arcsec to 1.1 arcmin ($r \sim r_{500}$) and we find $w \approx 0.019$. When limiting to 500 kpc (i.e. following the prescription of Cassano et al. 2010), we find $w \approx 0.022$, thus not differing much from our first estimate. Similarly, the concentration parameter $c$, defined as the ratio of the measured fluxes within the central 100 kpc and 500 kpc (e.g. Cassano et al. 2010), is found to be $c \approx 0.09$. At first glance, these measurements suggest that 3XMM J011934 is a slightly dynamically disturbed, possibly non-cool-core cluster. However, the limited total number of counts ($\approx 2000$) might result in spurious structures, which in turn may bias our interpretation. To estimate the typical uncertainties of the $w$ parameter, we add Poisson noise on the best-fit surface brightness images obtained in each annulus, following the method proposed by Chon et al. (2012). We repeat the exercise 100 times and we estimate the uncertainty $\Delta w$ as the standard deviation of the $w$ parameters.

$^4$ At $z = 0.525$, 1 arcmin corresponds to $\approx 874$ kpc.

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**Table 1.** Best-fit parameters and inferred fluxes and luminosities for MRC0116+111 (see text). Fixed parameters are indicated with an asterisk (*).

| Model       | $Y_{\text{cie}}$ (10$^{70}$ m$^-3$) | $kT$ (keV) | $Y_{\text{po}}$ (10$^{49}$ ph s$^{-1}$ keV$^{-1}$) | $\Gamma$ | $F_{X,0.5–7}$ (10$^{-14}$ erg s$^{-1}$ cm$^{-2}$) | $L_{X,0.5–7}$ (10$^{41}$ erg s$^{-1}$) | $L_{X,\text{bol}}$ (10$^{45}$ erg s$^{-1}$) | C-stat/d.o.f. |
|-------------|-------------------------------------|-----------|-----------------------------------------------|---------|-----------------------------------------------|---------------------------------|---------------------------------|---------------|
| cie         | 7.6 ± 0.7                           | 0.76 ± 0.07 | 20.7 ± 2.1                                      | 1.55*   | 1.18 ± 0.11                                   | 6.4 ± 0.6                       | 11.4 ± 1.0                      | 47.3/36        |
| po          |                                    |           |                                               |         | 2.7 ± 0.3                                      | 12.3 ± 1.2                      | 165 ± 17                        | 140.8/37       |
| cie+po      | 7.6 ± 0.7                           | 0.76 ± 0.07 | < 1.5                                          | 1.55*   | 1.18 ± 0.11                                   | 6.4 ± 0.6                       | 11.4 ± 1.0                      | 47.3/35        |
| cie+po (MOS only) | 8.8 ± 1.2                           | 0.69 ± 0.09 | < 2.4                                          | 1.55*   | 1.33 ± 0.19                                   | 7.3 ± 1.0                       | 13.2 ± 1.8                      | 27.4/19        |
| cie+po (pn only) | 6.8 ± 1.1                           | 0.87 ± 0.12 | < 2.4                                          | 1.55*   | 1.08 ± 0.18                                   | 5.8 ± 0.9                       | 10.3 ± 1.7                      | 16.1/13        |

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**Figure 3.** Background subtracted XMM-Newton EPIC spectra of MRC0116+111. The MOS (MOS 1+MOS 2) and pn spectra are fitted simultaneously with two components: (i) a cie (thermal) model and (ii) a (non-thermal) power law of fixed photon index $\Gamma = 1.55$, shown here on its 1σ upper-limit. Although for display we show the observed spectra out to 10 keV, we choose to fit it only within 0.6–5 keV (see text).

**Figure 4.** Composite optical image of the serendipitously detected cluster 3XMM J011934 from the SDSS-III data (g, r, and i bands). The X-ray contours (0.3–2 keV, XMM-Newton EPIC) are overplotted in white. The radio contours (1.4 GHz, VLA) are overplotted in dashed yellow. We also show our best estimate of $r_{500}$ (0.93 Mpc; dashed red circle).
estimated from these mock images. We find $\Delta v = 0.009$ and we conclude that the possibility of a relaxed, cool-core cluster cannot be excluded. The effects of the larger point spread function at the off-axis position of the source may also affect the estimate of its morphology (Böhringer et al. 2010).

The spatial extent and the number of counts of 3XMM J011934 allows to perform basic spatial spectroscopy. Working successively within the circular ranges 0–1 $r_{500}$ (entire cluster) and 0.15–1 $r_{500}$ (core-excised region), we extract and fit the EPIC spectra with a redshifted and absorbed model, where the free parameters are the normalisation ($f_{\text{syn}}$), the temperature ($kT$), and the Fe abundance. The best-fit parameters are listed in Table 2 and their interpretation is discussed in Sect. 4.3.

### 4 DISCUSSION

#### 4.1 Inverse-Compton emission and volume-averaged magnetic field

Presumably, both the synchrotron radiation observed in diffuse radio sources and the CMB photons that are boosted to X-ray energies via IC scattering originate from the same population of relativistic electrons. Because the radio synchrotron emission depends on both the relativistic electron distribution and the volume-averaged magnetic field while the IC emission depends on the electron distribution only, constraining radio and X-ray IC fluxes allows us to put further constraints on the average magnetic field of a galaxy cluster/group. Quantitatively, and assuming the relativistic electron population to be distributed as a function of their Lorentz factor $\gamma$ by $N(\gamma) = N_{000} \gamma^{-\alpha}$, the radio and X-ray fluxes $f_r(\nu_{\text{syn}})$ and $f_x(\nu_{\text{IC}})$, emitting respectively at the frequencies $\nu_{\text{syn}}$ and $\nu_{\text{IC}}$, can be written (e.g. eqs. 4.59 and 2.65 of Blumenthal & Gould 1970, see also Ota et al. 2014):

$$f_r(\nu_{\text{syn}}) = \frac{dW_{\text{syn}}}{d\nu_{\text{syn}}dt} = 4\pi N_0 e^3 f_r(\nu_{\text{syn}})$$

$$f_x(\nu_{\text{IC}}) = \frac{dW_{\text{IC}}}{d\nu_{\text{IC}}dt} = 8\pi^2 N_0 e^2 f_x(\nu_{\text{IC}})$$

where $B$ is the volume-averaged magnetic field, $e$ and $m_e$ are respectively the electron charge and mass, $n_0 = e^2 / m_e c^2$ is the classical electron radius, $\hbar$ is the Planck constant, and $T_{\text{CMB}} = 2.73(1+z)$ is the average temperature of the CMB at the considered redshift. The functions $a(p)$ and $F(p)$ depend on the gamma function $\Gamma(x)$ and the Riemann zeta function $\zeta(x)$ as

$$a(p) = 2 \frac{p+2}{p} \sqrt{\frac{3}{\pi}} \left(\frac{3p-1}{12}\right) \Gamma\left(\frac{3p+1}{12}\right) \Gamma\left(\frac{p+5}{4}\right) \left(p+1\right) \Gamma\left(\frac{p+7}{4}\right)$$

$$F(p) = 2^{p+3} \left(\frac{p^2 + 4p + 11}{p + 3}\right)^{p/2} \left(p + 5\right) \Gamma\left(\frac{p + 5}{2}\right) \left(p + 5\right)$$

### Table 2. Best-fit parameters for 3XMM J011934 within $r_{500}$ (see text). The central <0.15$r_{500}$ is successively kept (second column) then excised (last column).

| Parameter | 0–1 $r_{500}$ | 0.15–1 $r_{500}$ |
|-----------|--------------|-----------------|
| $f_{\text{syn}}$ (10$^{22}$ m$^{-3}$) | 9.3 ± 1.4 | 7.8 ± 1.4 |
| $f_{\text{IC}}$ (10$^{13}$ erg s$^{-1}$ cm$^{-2}$) | 1.48 ± 0.22 | 1.32 ± 0.23 |
| $kT$ (keV) | 2.1 ± 0.3 | 1.8 ± 0.3 |
| $f_\text{syn}$ (5) | 4.4$^{+0.7}_{-0.6}$ | 4.5 ± 0.7 |
| $f_\text{IC}$ | 1.7$^{+0.8}_{-0.6}$ | 1.3$^{+1.1}_{-0.7}$ |
| C-stat/d.o.f. | 98.3/58 | 104.0/58 |

The ratio between radio and X-ray fluxes at the two given frequencies provides thus (eq. 5.10 of Sarazin 1986):

$$B_p = \frac{2\pi e h c^3}{m_e c^2} \left(\frac{4\pi m_e c}{3e}\right) \frac{f_r(\nu_{\text{syn}})}{f_x(\nu_{\text{IC}})} \frac{\nu_{\text{syn}}}{\nu_{\text{IC}}} \frac{\Gamma\left(p+1\right)}{\Gamma\left(p+5\right)} \frac{F(p)}{a(p)} (kT_{\text{CMB}})^{p/2}$$

Since the synchrotron spectral index and the slope of the power-law electron distribution are related as $\alpha_{\text{syn}} = \frac{p+1}{2}$, the radio spectral index of $\alpha_{\text{syn}} = 0.55$ (Bagchi et al. 2009) translates into $p = 2.1$. At 2 keV, the combined EPIC instruments provide a flux upper limit of <1.53 $\times 10^{-10}$ Jy (<3.34 $\times 10^{-10}$ Jy at 90% confidence). Adopting the radio flux estimate of 1.15 Jy at 240 MHz (Bagchi et al. 2009), we find that, at 68% confidence, the average magnetic field is higher than $\sim 4.3 \mu G$ (higher than $\sim 2.6 \mu G$ at 90% confidence). We note that, in the unlikely case of the observed X-ray emission being significantly contaminated by point-sources (Sect. 3.3), the upper limit on the IC flux would be lower, and thus the lower limits reported above would be even higher. Repeating the same exercise within the North-Western lobe only (assuming that the X-ray emission – detected as an upper limit only – originates entirely from IC scattering), we find a lower limit for the average magnetic field of $\gtrsim 2.0 \mu G$.

Volume-averaged magnetic fields of the same order have been previously reported by Croston et al. (2005) by comparing the radio and X-ray emission in the radio lobes of isolated radio-galaxies and quasars. The present case is different, as the radio (and X-ray) emission is not clearly concentrated in lobes or jets around one galaxy, but rather widespread over an entire galaxy group. In fact, this is the first time we report a lower limit on the IC flux of the considered redshift. The functions

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assumption of equipartition remains questionable given that relativistic electrons, exhibiting a relatively short lifetime, and magnetic fields, associated with the much longer lifetimes of clusters, might have different origins (e.g. Carilli & Taylor 2002; Petrosian et al. 2008).

4.2 An extremely powerful past AGN activity?

Besides the surprisingly low upper limit of its volume-averaged magnetic field, MRC 0116 is also a unique system in terms of radio vs. X-ray emission. In Fig. 5, we compare the ratio $L_{\text{radio}}/L_X$ (namely the radio luminosity integrated between 10 MHz and 10 GHz over the X-ray luminosity in the 0.5–7 keV band) of our system with that of several other systems (Birzan et al. 2004; Birzan et al. 2008). Quite remarkably, such a radio-to-X-ray luminosity ratio for MRC 0116 is almost 70 times higher than the median ratio of all the other systems. In particular, it is ~13 times and almost ~5 times stronger than respectively M 87 and M 84.

These two elliptical galaxies, however, are both known for hosting powerful, still active synchrotron jets launched from a bright point-like radio source coinciding with the position of the AGN (e.g. Owen et al. 2000; Laing et al. 2011). These bright radio features are not found in MRC 0116 which, instead, shows a much more diffuse and extended emission (see the higher resolution beam size 5′′ – GMRT 1.28 GHz map in figure 1 of Bagchi et al. 2009). From the sample of Birzan et al. (2004), Cygnus A is the only system exhibiting a higher $L_{\text{radio}}/L_X$ ratio than MRC 0116. However, the bulk of the radio emission in Cygnus A originates from its nucleus and hotspots, rather than from the surrounding diffuse lobes (e.g. Carilli et al. 1991; McKean et al. 2016). This makes MRC 0116, to our knowledge, the brightest radio vs. X-ray extragalactic diffuse source reported so far.

A question of interest is whether such an unusually high ratio is due to one (or several) intense past AGN outburst(s) that had severely disturbed its surrounding IGrM and expelled a significant fraction of the thermal gas outside of its gravitational well. Presumably, such a hypothetical outburst would have reduced the overall X-ray luminosity of the system while it would have provided a substantial source of (re-)heating to the remaining fraction of the radiatively cooling gas, thereby shifting the source away from the well-established $L_X\sim T$ scaling relation (tracing the self-similar evolution of groups and clusters). Such a scaling relation, taken from recent observations of (mostly unrelaxed) clusters (Maughan et al. 2012) and groups (Lovisari et al. 2015; Zou et al. 2016), and its comparison with the corresponding measurements obtained for MRC 0116, is plotted in Fig. 6. Since we adopt $L_X$ as the X-ray bolometric luminosity ($L_X, \text{bol}$; Maughan et al. 2012; Zou et al. 2016, and their corresponding best-fit relations), the luminosities from Lovisari et al. (2015) given in the 0.1–2.4 keV band are extrapolated to their bolometric counterpart by calculating appropriate redshifted, absorbed cte models in SPEX. As shown in Fig. 6, the comparison results in an excellent agreement between our X-ray luminosity and temperature measurements of MRC 0116 and the best-fit relation from recent estimates for other systems, with no excess of $kT$ nor deficiency of $L_X, \text{bol}$. This suggests that the very high $L_{\text{radio}}/L_X$ ratio is explained rather by unusually bright radio emission than by unusual X-ray gas properties. In fact, although MRC 0116 is a poor group, its radio luminosity $L_{\text{radio}}$ (3.64 × 10$^{41}$ erg s$^{-1}$; Bagchi et al. 2009) is comparable to that of M 87 (with a rather different emission distribution, as almost 50% of the flux of the latter originates from its nucleus; Owen et al. 2000) and is several factors more than those found in mini-haloes of much richer clusters (e.g. MKW 3s, A 262, 2A 0335+096, A 478, Centaurus; Birzan et al. 2008).

More generally, one may ask about the true nature of such a radio synchrotron emission exceptionally bright for a group like MRC 0116. Based on the different types of diffuse radio sources typically found at the centre of large-scale, non-merging systems, potential candidates would be (i) a "mini-halo"-like source or (ii) a series of radio bubbles related to past and recent AGN activity. The radio morphology of the source is rather similar to mini-haloes found at the centre of e.g. Perseus (Gendron-Marsolais et al. 2017); however the extent of the radio source – usually limited to cluster cores in the case of mini-haloes – is about three times larger than the extent of the observed X-ray emission. Moreover, mini-haloes are typically found in and associated with relaxed systems (e.g. Gitti et al. 2004), which might not be necessarily the case for MRC 0116 (Sect. 3.1; see also Figs. 1 and 2 left). On the other hand, in addition to the absence of a point-like radio source at the position of the central dominant galaxy (Bagchi et al. 2009), the bulk of the radio source appears too diffuse and too extended to be entirely attributed to a series of well-separated bubbles witnessing of past episodic AGN outbursts. While the two inner lobe-like structures may definitely be related to jets of a relativistic plasma from a recent outburst of the central SMBH (as traced by the possible eastern X-ray cavity reported in Sect. 3.1), the surface brightness of the outer parts of the radio source remains rather uniform (Figs. 1 and 2 right; see also the higher-resolution GMRT 1.28 GHz map in Bagchi et al. 2009).

It is possible, however, that the large-scale radio emis-
Figure 6. Temperature - bolometric luminosity relation comparing several groups and clusters previously measured (Maughan et al. 2012; Zou et al. 2016) with our estimates for MRC 0116+111 (yellow star; Sect. 4.2) and 3XMM J011934 (red diamond; Sect. 4.3). Measurements and the best-fit relation from Maughan et al. (2012) and Zou et al. (2016) are adopted for unrelaxed systems (respectively classified as "(w) ≥ 0.006" and "non-relaxed cool-core") without core excision. For comparison, galaxy groups measurements from the sample of Lovisari et al. (2015) are also plotted (where the bolometric luminosity is extrapolated from the luminosity in the 0.1–2.4 keV band, see text).

sion originates from an older population of relativistic electrons, initially seeded by buoyantly rising bubbles of non-thermal plasma (extending towards North-West and South-East), and later re-energised by turbulent motions, likely triggered by a more recent outburst. This hypothesis would also naturally explain the sudden ageing of electrons in the North-Western lobe – i.e. where the radio-emitting plasma extends beyond the relatively dense central IGrM – as well as the uniformity of the radio spectral index in regions covered by the X-ray emitting gas (see figure 6 right in Bagchi et al. 2009). If this is the case, MRC 0116 would be a unique system, hosting a disturbed hot atmosphere, in which a remarkably powerful past AGN activity would have injected enough turbulence and small-scale motions to re-accelerate relativistic electrons, though without significantly affecting the overall temperature or the gas density of the system. Deeper XMM-Newton and/or Chandra observations, as well as future X-ray missions with micro-calorimeters onboard (which would allow direct measurements of the widths and resonance scattering of Fe-L lines), will be necessary to further confirm or rule out this hypothesis.

4.3 Basic properties of 3XMM J011934

When compared with the $L_X-T$ relation of nearby systems (Fig. 6, see also Table 2), the serendipitously discovered cluster 3XMM J011934 lies within the scatter obtained in previous studies. We note, however, that the cluster appears somewhat under-luminous (and/or hotter) compared to the self-similar relation fitted by Maughan et al. (2012). Assuming that such a trend is real and entirely due to the higher redshift of the source ($z ≃ 0.525$), it would agree qualitatively with the observational results of Reichert et al. (2011), who found hints for distant clusters to be less luminous than their self-similar prediction. On the other hand, these results are still under debate, as a steepening of the $L_X-T$ relation with redshift was recently supported by observations (Giles et al. 2016) and numerical simulations (Truong et al. 2018). Clearly, more high-$z$ systems are needed to confirm and interpret a possible evolution of the $L_X-T$ relation with cosmic time. Future missions like eROSITA and Athena will be essential for this purpose.

Another interesting feature of 3XMM J011934 is its Fe abundance consistent with solar in both our entire and core-excised extracted regions. Whereas a solar value is commonly found in the cool cores of nearby, relaxed systems (for a review, see Mennier et al. 2018) the Fe abundance that we measure outside 0.15 $r_{500}$ is $>1σ$ higher than the mean estimate in similar regions of other clusters at $z = 0.5$ (McDonald et al. 2016; Mantz et al. 2017). Admittedly, our statistical uncertainties are still large and deeper re-observation of 3XMM J011934 would be necessary to get better observational constraints on its chemical enrichment.

5 CONCLUSIONS

Using the EPIC instruments onboard XMM-Newton, we have presented for the first time a detailed X-ray observation of the poor galaxy group MRC 0116+111 ($z = 0.132$). This system hosts a bright, diffuse radio emission (Bagchi et al. 2009). The radio morphology, and the remarkably high radio-to-X-ray luminosity (to our knowledge the highest for a diffuse extragalactic source) strongly suggest that the group has experienced an intense AGN activity from its central cD galaxy over the last ~100 Myr. Although the thermal X-ray emitting IGrM appears morphologically disturbed and is about three times less extended in projection than the non-thermal radio emitting plasma, this source is not found to deviate from the $L_X-T$ scaling relation established for more massive groups and clusters. This suggests that, despite its power, the AGN jets/lobes were not efficient at ejecting baryons nor at heating the thermal IGrM substantially. Instead, a past outburst may have efficiently stirred the hot atmosphere, possibly translating into turbulent re-acceleration of a significant fraction of relativistic electrons traced by the radio emission. This scenario would qualitatively explain the overlap of the region of flat radio spectral index with that of the X-ray emitting gas.

Because of the relatively low temperature of less than 1 keV, only negligible thermal X-ray emission is expected in the 2–10 keV band, this source is an ideal target to search for and constrain the emission originating from IC scattering of the CMB photons by the relativistic electron population. Although the limited cleaned exposure allows only to derive an upper limit for this non-thermal X-ray flux, this also translates into a lower limit for the group’s volume-averaged magnetic field of $≥ 2.4$ µG. Whereas this is not inconsistent with the typical magnetic field estimates derived using the assumption of equipartition and/or Faraday rotation measurements, this is, to our knowledge, the highest lower limit reported to date using constraints from the IC X-ray emission. Deeper XMM-Newton observations and future missions will help setting better constraints on its average magnetic field.
field intensity and on the coupling of the AGN feedback with the thermal and non-thermal components of the plasma.

In the field of view of our EPIC observation, we also serendipitously discovered a distant (z ∼ 0.525) galaxy cluster. The X-ray emission, which had been previously detected as a point-like source in the 3XMM catalogue (ID: 3XMM J011934.7+112106), clearly shows an extended morphlogy, and its location is coincident with an overdensity of galaxies, reported by the redMaPPer 6.3.1 catalogue but labelled as a cluster candidate only. Our analysis suggests a moderately hot (~ 4.5 keV), possibly unrelaxed cluster, which also exhibits radio emission in its core.

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REFERENCES

Bagchi J., Puls V., Lima Neto G. B., 1998, MNRAS, 296, L23
Bagchi J., Durret F., Neto G. B. L., Paul S., 2006, Science, 314, 791
Bagchi J., Jacob J., Gopal-Krishna Werner N., Wanderkar N., Belapure J., Kumbharkhane A. C., 2009, MNRAS, 399, 601
Bartels R., Zandanel F., Ando S., 2015, A&A, 582, A20
Birzan L., Rafferty D. A., McNamara B. R., Wise M. W., Nulsen P. E. J., 2004, ApJ, 607, 800
Birzan L., McNamara B. R., Nulsen P. E. J., Carilli C. L., Wise M. W., 2008, ApJ, 686, 859
Blumenthal G. R., Gould R. J., 1970, Reviews of Modern Physics, 42, 237
Böhringer H., et al., 2010, A&A, 514, A32
Böhringer H., Chon G., Kromberg P. P., 2016, A&A, 596, A22
Boller T., Freyberg M. J., Trümpfer J., Haberl F., Voges W., Nandra K., 2016, A&A, 588, A103
Brüggen M., Bykov A., Ryu D., Röttgering H., 2012, Space Sci. Rev., 166, 187
Carilli C. L., Taylor G. B., 2002, ARA&A, 40, 319
Carilli C. L., Perley R. A., Deeher J. W., Leahy J. P., 1991, ApJ, 383, 554
Cassano R., Ettori S., Giacintucci S., Brunetti G., Markevitch M., Venturi T., Gitti M., 2010, ApJ, 721, L82
Chon G., Böhringer H., Smith G. P., 2012, A&A, 548, A59
Cohen A. S., Lane W. M., Cotton W. D., Kassim N. E., Lazio T. J. W., Perley R. A., Condon J. J., Erickson W. C., 2007, AJ, 134, 1245
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Croston J. H., Hardcastle M. J., Harris D. E., Beseloe E., Birkinshaw M., Worrall D. M., 2005, ApJ, 626, 733
Douglas J. N., Bash F. N., Boyzan F. A., Torrence G. W., Wolfe C., 1996, AJ, 111, 1945
Eisenstein D. J., et al., 2011, AJ, 142, 72
Fabian A. C., 2012, Annual Review of Astronomy and Astrophysics, 50, 455
Fabian A. C., et al., 2000, MNRAS, 318, L65
Feneberg E., Primack H., 1948, Physical Review, 73, 449
Felten J. E., Morrison P., 1966, ApJ, 146, 686
Feretti L., Giovanniini G., Govoni F., Murgia M., 2012, Astronomy and Astrophysics Review, 20, 54
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Ferrarese L., Govoni F., Schindler S., Bykov A. M., Rephaeli Y., 2008, Space Sci. Rev., 134, 93
Frank K. A., Peterson J. B., Andersson K., Fabian A. C., Sanders J. S., 2013, ApJ, 764, 46
Gebrhardt K., et al., 2000, ApJ, 539, L13
Gendron-Quintal M., et al., 2017, MNRAS, 469, 3872
Giles P. A., et al., 2016, A&A, 592, A3
Gitti M., Brunetti G., Ferretti L., Setti G., 2004, A&A, 417, 1
Gopal-Krishna Kulkarni V. K., Bagchi J., Melnick J., 2002, in Pramesh Rao A., Swarup G., Gopal-Krishna eds, IAU Symposium Vol. 199, The Universe at Low Radio Frequencies. p. 159
Govoni F., Ferretti L., 2004, International Journal of Modern Physics D, 13, 1549
Govoni F., et al., 2010, A&A, 522, A105
Harris D. E., Grindlay J. E., 1979, MNRAS, 188, 25
Hitomi Collaboration et al., 2018, Publications of the Astronomical Society of Japan, 70, 11
Hlavacek-Larrondo J., Fabian A. C., Edge A. C., Ebeling H., Sanders J. S., Hogan M. T., Taylor G. B., 2012, MNRAS, 426, 1360
Hudson D. S., Mittal R., Reiprich T. H., Nulsen P. E. J., Anderson H., Sarazin C. L., 2010, A&A, 513, A37
Intema H., Jagannathan P., Mooley K. P., Frail D. A., 2017, A&A, 598, A78
Joshi M. N., Singal A. K., 1980, Memoirs of the Astronomical Society of India, 1, 49
Kaastra J. S., 2017, A&A, 605, A51
Kaastra J. S., Mewe R., Nieuwenhuijzen H., 1996, in Yamashita K., Watanabe T., eds, UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas. pp 411–414
Kaastra J. S., Raassen A. J. J., de Plaa J., Gu L., 2017, SPEX

MNRAS 000, 1–11 (2018)
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Zou S., Maughan B. J., Giles P. A., Vikhlinin A., Paccagnella F., Burenin R., Hornstrup A., 2016, MNRAS, 463, 820
van Weeren R. J., de Gasperin F., Akamatsu H., Brüggen M., Feretti L., Kang H., Stroe A., Zandanel F., 2019, arXiv e-prints, p. arXiv:1901.04986

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