

# Extended X-ray emission from the $z = 4.26$ radio galaxy 4C 63.20

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## ABSTRACT

We report on deep *Chandra X-ray Telescope* imaging observations of 4C 63.20, one of the few known radio galaxies at  $z > 3.5$ . The X-ray counterpart is resolved into a core plus two off-nuclear sources that (combined) account for close to 30 per cent of the total X-ray flux. Their morphology and orientation are consistent with a diffuse, lobe-like nature, albeit compact hotspots cannot be ruled out. The broad-band spectral energy distribution of 4C 63.20 can be reproduced with a jet model where the majority of the radio flux can be ascribed to synchrotron emission from the hotspots, whereas the (non-nuclear) X-ray emission is produced via inverse Compton (IC) off of cosmic microwave background (CMB) photons within the extended lobes. This scenario is broadly consistent with the expectation from highly magnetized lobes in a hotter CMB, and supports the view that IC/CMB may quench less extreme radio lobes at high redshifts.

**Key words:** radiation mechanisms: non-thermal – galaxies: active – galaxies: high-redshift – galaxies: jets – X-rays: galaxies.

## 1 INTRODUCTION

Radio emission from jetted active galactic nuclei (AGNs) arises from the sum of the collimated, relativistic jets, plus the extended components, i.e. the hotspots and lobes. If the observer's line of sight lies within an angle  $\sim 1/\Gamma$  of the jet axis, where  $\Gamma$  is the jet bulk Lorentz factor, then the beamed emission from the jet dominates the spectrum, and the system is classified as a blazar. For larger viewing angles, isotropic extended emission from the lobes takes over, and we observe a powerful radio galaxy. Since for each observed blazar, there must exist  $\simeq 2\Gamma^2$  misaligned sources, the very existence of a dozen high-redshift ( $z \gtrsim 4$ ) blazars (Yuan et al. 2006; Sbarrato et al. 2015) indicates that a much larger population of misaligned, powerful, jetted AGNs was already in place when the Universe was  $\lesssim 1.5$  Gyr old.

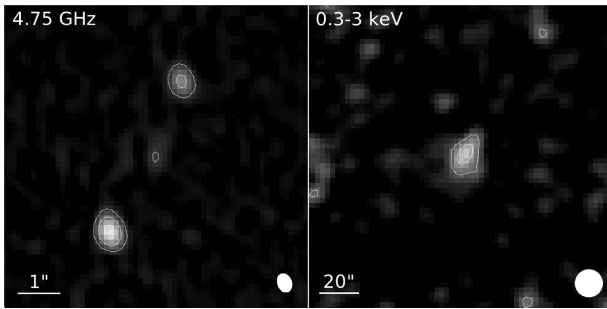
In spite of being well within the FIRST sensitivity threshold, this 'parent population' remains elusive. More specifically, the expected number density of radio-loud quasars (as inferred from the *Swift*-Burst Alert Telescope sample of luminous, massive blazars Ajello et al. 2009), overestimates the number of observed luminous, radio-loud quasars (as identified by cross-matching the FIRST and Sloan Digital Sky Survey (SDSS) catalogues), by a factor  $\sim 3$  in the redshift bin  $z = 3-4$  and by a factor  $> 10$  between  $z = 4$  and 5 (Volonteri et al. 2011). Qualitatively similar conclusions are reached by Kratzer & Richards (2015, see also Haiman, Quataert & Bower 2004; McGreer, Helfand & White 2009). Possible reasons for this discrepancy include

(i) heavy optical obscuration of high- $z$  radio galaxies, which would be missed by SDSS; (ii) a substantial drop in the average  $\Gamma$  for high- $z$  sources; or (iii) substantial, intrinsic dimming of the extended radio lobes at  $z \gtrsim 3$ . The first scenario implies the existence of a large population of infrared-luminous, radio-loud quasars with no optical counterparts, while the second appears at odds with the notion of the most powerful jets being associated with high accretion rates, likely common in the early Universe. With respect to the third hypothesis, the idea has long been entertained of cosmic microwave background (CMB) photons affecting the behaviour of jetted AGNs (e.g. Celotti & Fabian 2004).

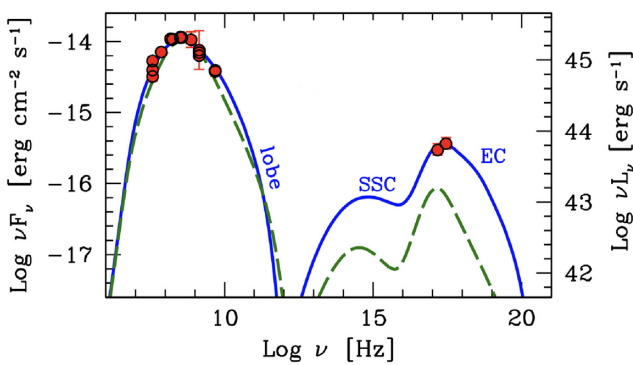
Ghisellini et al. (2014a) explore specifically how the interaction between the CMB radiation and electrons within jet-powered hotspots and lobes affects the appearance of jetted AGNs at different redshifts. The major result can be summarized as follows: Owing to its  $(1+z)^4$  dependence, the CMB energy density starts to dominate over magnetic energy density within the lobes above  $z \simeq 3$ , thereby suppressing the synchrotron radio flux at higher  $z$ . At the same time, high-energy electrons will cool effectively by inverse Compton (IC) scattering off of CMB photons. Combined, these two effects result in a significant suppression of the radio lobes, accompanied by enhancement of the X-ray lobes, in high- $z$  quasars, which would then be *misclassified* as radio-quiet.

From an observational standpoint, it is known that the radio lobes of low- $z$  radio galaxies can be associated with extremely low surface brightness X-ray emission, likely due to CMB scattering (e.g. Hardcastle et al. 2004; Croston et al. 2005). If CMB-quenching of high- $z$  radio lobes is indeed effective, we would expect the X-ray-to-radio flux ratio in lobes to increase with  $z$ , eventually leading to

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**Figure 1.** Left: 5 GHz VLA image of 4C 63.20. The filled white ellipse denotes the 0.4 arcsec beamsize and the contours are at 2, 10, and 30 mJy beam<sup>-1</sup>. The rms noise is 0.11 mJy beam<sup>-1</sup>. Right: 0.3–3 keV *XMM-Newton* image (combined MOS and pn). The filled white circle represents the pn point spread function: at this resolution, the X-ray image is consistent with a point source. The contours represent 3 $\sigma$  and 6 $\sigma$  above the background.



**Figure 2.** Combined radio and X-ray SED of the  $z = 4.261$  radio galaxy 4C 63.20, where the radio data points refer to the off-nuclear sources and the X-ray data points are based on the *XMM* detection shown in the right-hand panel of Fig. 1. The coloured curves represent two realizations of a model which attempts to reproduce the SED with emission from jet-powered lobes, following Ghisellini & Tavecchio (2009). Highlighted are the SSC and EC components, where the latter include inverse Compton scattering of the relativistic electrons off of (primarily) CMB photons (IC/CMB). The solid blue line represents a version of the model where 100 per cent of the X-ray flux can be ascribed to the lobes. By comparison, the dashed green line represents a model where only 25 per cent of the measured X-ray flux is ascribed to the lobes. Suppressing SSC and IC/CMB cooling to this extent requires a higher degree of magnetization within the lobes compared to the former case.

the disappearance of most radio-lobes. Direct confirmation of CMB quenching – i.e. through detecting X-ray lobes around high- $z$  blazars and their parent population – faces major, inherent observational challenges. For blazars and radio-loud quasars the core/jet emission is guaranteed to obliterate any diffuse GHz and X-ray emission (at any  $z$ ; see e.g. Yuan et al. 2003; Siemiginowska et al. 2003; Lopez et al. 2006). At the same time, high- $z$  radio-quiet quasars (the natural target of any such test) are highly risky targets, in that one has no a priori knowledge of which exactly are misclassified as – as opposed to intrinsically – radio-quiet.

Based on the lack of spectral softening below 1 GHz (rest-frame), Ghisellini et al. (2015) conclude that none of the 13 known  $z > 4$  blazars show evidence for extended radio emission based on their GHz spectra, lending indirect support to the CMB-induced radio-quenching of high- $z$  AGNs. Perhaps counterintuitively, a direct, powerful test for this model lies with high spatial resolution X-ray observations of those exceedingly rare  $z > 3.5$  radio galaxies (De

Breuck et al. 2010). In the context of CMB quenching, detectable radio lobe emission in spite of the strong IC coolant provided by the CMB at  $z \gtrsim 4$  can be explained if the lobes of these systems are characterized by high compactness and/or high magnetic field, leading to an unusually strong enhancement of the synchrotron radio emission. For these systems, the CMB quenching model makes strong, testable predictions that (i) the radio lobes must also be X-ray sources and (ii) the X-ray lobes must be more luminous than for a comparably young radio galaxy at low redshift. Among the few known high- $z$  radio galaxies, 4C 63.20 ( $z = 4.261$ ; Spinrad, Dey & Graham 1995) is the only one to have an associated, statistically significant ( $5\sigma$ ) X-ray counterpart at  $z > 4$  (see Section 2 and Fig. 1).

In this paper, we report on deep observations of 4C 63.20 with the *Chandra X-ray Observatory*, aimed at testing the CMB-quenching model by resolving its X-ray emission on sub-arcsec scales. Archival radio and X-ray observations of the field of view of 4C 63.20 are presented and discussed in Section 2. Section 3 describes the *Chandra* data reduction and analysis. An interpretation of the results in the context of the CMB quenching model is presented in Section 4. We conclude in Section 5 with a discussion of our results vis-à-vis a broad assessment of the viability of IC/CMB quenching of high- $z$  radio galaxies.

## 2 ARCHIVAL OBSERVATIONS OF 4C 63.20 IN THE CONTEXT OF THE CMB-QUENCHING MODEL

The left-hand panel of Fig. 1 shows a 5 GHz image of 4C 63.20 [from the Very Large Array (VLA) project AC374; Lacy et al. 1994]. The source is composed of a faint core plus two off-nuclear radio sources, which we shall (temporarily) refer to as SE and NW ‘lobes’, each separated by 1.8–2 arcsec from the core (i.e.  $\approx 12$ –14 kpc at  $z = 4.26$ ). The field of view of 4C 63.20 falls within an archival *XMM-Newton* observation (ObsID 0204400301), performed in 2004 February. We extracted, reprocessed, filtered and analysed the data with SAS v14.0. An X-ray source is clearly detected at position consistent with 4C 63.20 in the combined MOS + pn image, shown in the right-hand panel of Fig. 1. The projected separation of the 5 GHz radio lobes is approximately 4 arcsec, implying that any co-spatial X-ray emission could not be resolved by *XMM-pn*, whose point spread function (PSF) full width at half-maximum (FWHM) is  $< 12.5$  arcsec. The two-point *XMM* spectrum of 4C 63.20 (modelled with a redshifted, absorbed power law) is shown in Fig. 2, together with the broad-band radio spectrum of the extended (i.e. non-core) emission (based on publicly available aggregated data from <https://tools.sdsc.asi.it/>). The solid blue line represents a trial model run where the radio+X-ray spectral energy distribution (SED) is modelled in terms of synchrotron, synchrotron self-Compton (SSC) and IC radiation due to interaction of the lobes’ electrons with photons from the disc, the external torus and the CMB (collectively referred to as external Compton, or EC), following Ghisellini & Tavecchio (2009). This plot illustrates how emission from the lobes alone could account for the entire X-ray and radio emission from 4C 63.20, provided that the lobes are mildly magnetically dominated, i.e. have a magnetic-to-radiation energy density ratio  $U_B/U_{\text{rad}} \approx 4$ . Simply put, for radio synchrotron emission not to be quenched by IC scattering of CMB photons at this redshift, the synchrotron cooling process must be locally enhanced by supra-equipartition values of the magnetic field strength (unless otherwise noted, with equipartition we refer to the balance between magnetic and radiation energy density, rather than particle). The corresponding, inferred total energy in magnetic field and particles within the lobes (about  $2 \times 10^{59}$  erg) would be typical of a very young system,

whose lobes may still be expanding and are yet to reach equipartition (notice that knowledge of the size and radio flux of the lobes enables us to constrain the magnetic field value with no a priori assumption of equipartition in this system). While this is an extreme scenario, where virtually 100 per cent of the X-rays detected by *XMM* would arise from Comptonization of CMB photons within the (unresolved) lobes, this kind of exercise enables us to anticipate what the detection of extended X-ray emission from 4C 63.20 could imply in terms of model constraints. For example, if 25 per cent of the total X-ray flux were emitted from the lobes (this case corresponds to the dashed green line in Fig. 2), this would translate into unusually high magnetization levels, with  $U_B/U_{\text{rad}} \simeq 17$  and a  $B$ -field of  $\simeq 1$  mG, which is on the high end even for GHz-peaked sources (which are thought to be extremely young and tend to have projected linear sizes of  $\lesssim 1$  kpc). This would also imply a total energy of  $10^{60}$  erg within the lobes, which is typical of the most powerful radio galaxies, having  $\sim 100$  kpc-scale lobes.

We wish to stress that these models only serve to illustrate the role of IC/CMB versus synchrotron cooling for a highly idealized case where the radio+X-ray SED is produced by the source extended lobes.

The situation is arguably more complex in the case of 4C 63.20; a careful analysis of all the archival VLA images available for this system suggests that the majority of the off-nuclear radio emission at 5 GHz (observed-frame) emanates from *point-like hotspots, rather than truly diffuse lobes*. Comparing two 5 GHz images with different beam sizes – 1.4 and 0.4 arcsec FWHM – and assuming each detected radio source is point-like in both images, one recovers that 78 per cent (93 per cent) of the flux in the 1.4 arcsec beam is contained in the 0.4 arcsec beam for the SE (NW) source. That is, a strong majority of the emission comes from an  $\sim$ spherical volume of  $\lesssim 1.2$  kpc in radius. Hereafter, we refer to these compact sources, which account for (on average) 85 per cent of the measured off-nuclear flux at 5 GHz, as hotspots.

It should be noted that band C (4–8 GHz) is not ideally suited for detecting extended radio lobes, the more so at high- $z$ . This is because, owing to the spectral steeping of the electron populations (i.e. the particle synchrotron lifetime scales with the inverse of the particle energy), emission at such high rest-frame frequencies (5 GHz corresponds to a rest-frame frequency of 21 GHz for 4C 63.20) will die off very fast in the lobes; additionally, truly extended emission could be resolved out at high rest-frame frequencies. At the same time, however, lower rest-frame frequencies, such as 5 GHz (i.e. 1.4 GHz observed) typically lack the desired resolution. Indeed, the only available image of 4C 63.20 at 1.4 GHz (from the VLA FIRST survey) has  $\gtrsim 5$  arcsec FWHM; this yields a 1.4–5 GHz spectral index of about +1.5, which confirms that the 21 GHz (rest-frame) emitting-plasma should not be expected to contribute substantially to any extended, lobe-like emission.

Mindful of these caveats, we turn to *Chandra*, and the sub-arcsec resolution of its Advanced CCD Imaging Spectrometer (ACIS), to constrain the nature of 4C 63.20's X-ray counterpart on scales that are comparable to those of the observed radio hotspots.

### 3 CHANDRA DATA REDUCTION AND ANALYSIS

We observed 4C 63.20 over three epochs (Observation IDs 20033, 19954, 18106; PI: Gallo) for a total of 100 ks with ACIS-S. The source was placed at the aim point of the back-illuminated S3 chip. The combined exposure was established by running MARX simulations so as to ensure that extended X-ray emission on arcsec scales, if present, could be detected if they each contributed

$\gtrsim 10$  per cent to the total flux measured by *XMM* (see Section 3.2 for a quantitative analysis).

We reduced the data using the *Chandra* Interactive Analysis of Observations (CIAO), v4.10. We first reprocessed the data and created new level 2 event and bad pixel files using the CIAO script `chandra_repro`. The astrometry was corrected by cross-matching the centroid positions of all the point-like X-ray sources (outside of the main target positional error circle) detected by CIAO's `wavdetect` to the SDSS Data Release 8 catalogue. For each of the three observations, we ran `wavdetect` on the reprocessed level 2 event file and required the source match radius to be 2 arcsec or fewer. Each image required an astrometric shift of no more than 0.4 arcsec. Finally, we re-projected the three observations to the same tangent point and merged them.

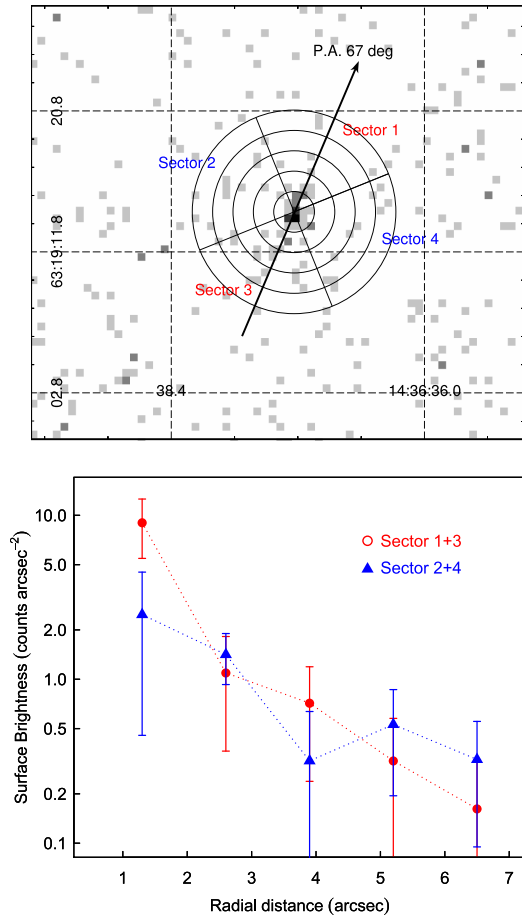
CIAO's `wavdetect` clearly detects an X-ray source within the nominal target error circle. A total of  $52 \pm 8$  net counts were estimated using a 5 arcsec radius circular region for the source, and a (source-free) 20–30 arcsec annulus for the background, both centred at the `wavdetect` source centroid position. Using XSPEC version 12.10.1 (Arnaud 1996), we fit 4C 63.20's 0.5–8.0 keV spectrum using an absorbed redshifted power-law model (`phabs*zphabs*zpov`). We fixed the hydrogen-equivalent Galactic column (i.e. the photoelectric absorption component `phabs`) to  $N_{\text{H}} = 1.4 \times 10^{20} \text{ cm}^{-2}$  (as given by the `COLDEN` tool for the target's coordinates; see also Kalberla et al. 2005) and the redshift to  $z = 4.26$  and implemented the Cash statistic (`cstat`; Cash 1979; Brightman & Ueda 2012) in order to best assess the quality of our model fits. The spectrum is best fit by a power-law index  $\Gamma = 1.51 \pm 0.3$  and a negligible intrinsic hydrogen-equivalent column ( $N_{\text{H}} < 10^{20} \text{ cm}^{-2}$ ). The corresponding, measured 0.5–8.0 keV flux is  $(5.8^{+0.33}_{-3.28}) \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ , consistent, within the errors, with *XMM*'s (i.e.  $3.8 \pm 1.2 \times 10^{-15} \text{ erg sec}^{-1} \text{ cm}^{-2}$ ).

#### 3.1 X-ray source morphology

To assess the key question whether 4C 63.20 is associated with a point-like or extended X-ray source, we implemented three methods, with increasing levels of refinement. We first used `srcextent`, a CIAO tool that estimates the extent of a source image and, if a PSF image is supplied, returns whether or not the source is extended within a given confidence interval. We simulated the source PSF (at 1.5 keV) using the *Chandra* Ray Tracer (CHART) software to generate the ray files and MARX (Davis et al. 2012) to project the rays on to the detector plane (Fig. 3). We ran `srcextent` several times, each with different choices for the source shape and the region file encompassing the source. Although `srcextent` determined that 4C 63.20's X-ray counterpart is not extended (with 90 per cent confidence) for the majority of our trials, its final assessment depended sensitively on the chosen source extraction region (circle versus ellipse) and shape (Gaussian versus disc), and was thus deemed inconclusive for our purposes.

Secondly, we measured the source surface brightness profiles along and across the position angle (PA) defined by the direction of the known radio hotspots, i.e.  $\simeq 67$  deg (measured counterclockwise relative to the axis in the direction of decreasing RA), as described in Fig. 3. This analysis suggests that 4C 63.20 displays excess X-ray emission along the same direction as the radio hotspots.

To characterize the nature of this excess emission, we analysed the observations with the PYTHON tool BAYMAX (Bayesian Analysis of Multiple AGNs in X-rays; Foord et al. 2019). BAYMAX is capable of ascertaining whether a given *Chandra*-detected source is better

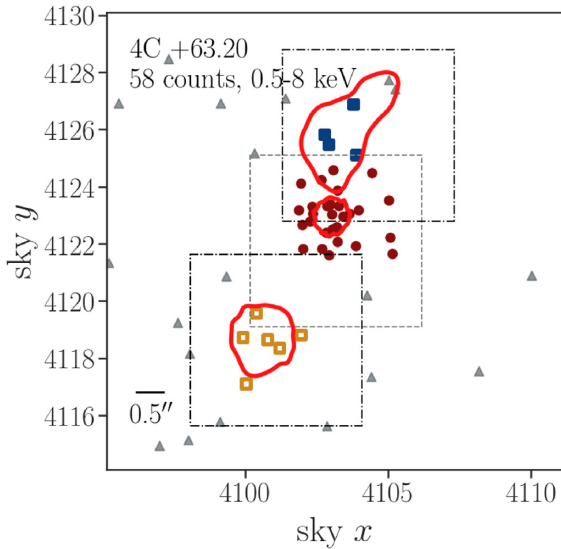


**Figure 3.** Top: *Chandra* image of the field of view of 4C 63.20, in the 0.5–8 keV band, obtained by combining three different visits, for a total of approximately 100 ks of net exposure. The raw image is overlaid with a series of five concentric annuli extending out to about 8 arcsec; these are divided into four, pie-shaped sectors: sectors 1 and 3 are aligned with the PA of the radio hotspots ( $\simeq 67$  deg; see Fig. 1, left-hand panel); sectors 2 and 4 are perpendicular to it. Bottom: Comparison of the source surface brightness profiles as measured along (sector 1 + 3, in red) and across (sector 2 + 4, in blue) the PA of the radio knots. The former reveals an excess of counts within  $\lesssim 2$  arcsec of the centre, suggesting that 4C 63.20 displays extended X-ray emission in the same general direction as its radio counterpart.

described by a model composed of one or multiple point sources by calculating the Bayes factor (BF), which represents the ratio of the likelihood of the observed data, given two different models. In brief, BAYMAX takes calibrated events from reprocessed *Chandra* observations and compares them to simulations based on single and multiple point source models. The properties of the *Chandra* PSF are characterized by simulating the PSF of the optics with MARX. For a source with multiple observations, BAYMAX first models the PSF of each observation and calculates the likelihoods for each observation individually (which is expected to depend on the detector position and start time of the observation), and then fits for astrometric shifts between different observations of the same source. The adopted PSF model is energy-dependent, such that it accounts for the spread at higher energies. Below, we review the details when running BAYMAX on observations of 4C 63.20, however for a more detailed review on the statistical techniques behind BAYMAX’s calculations, we refer the reader to Foord et al. (2019).

For 4C 63.20, we used BAYMAX to compare a single point source model ( $M_S$ ) to a triple point source model ( $M_T$ ). For both models, each photon is assumed to originate from either a point source component or the background. Thus,  $M_S$  and  $M_T$  are parametrized by vectors  $\theta_S = [\mu, \log f_{BG}, \Delta x_k, \Delta y_k]$  and  $\theta_T = [\mu_N, \log f_n, \log f_{BG}, \Delta x_k, \Delta y_k]$ . Here,  $\mu_N$  represents the location for  $N$  point sources ( $N = [1, \dots, N]$ );  $f_{BG}$  represents the ratio of counts between the background and the combined counts from all point source components;  $f_n$  represents the ratio of the total counts between a given point source and the primary point source ( $n = [1, \dots, N - 1]$ ); and  $\Delta x_k$  and  $\Delta y_k$  account for the translational components of the relative astrometric registration for the  $k = [1, \dots, K - 1]$  observation (where  $K = 3$  for 4C 63.20). For a single point source, the probability that a photon observed at sky coordinate  $(x, y)$  with energy  $E$  is described by the PSF centred at  $\mu$  is  $P(x, y|\mu, E)$ , while for a triple point source the total probability is  $P(x, y|\mu_N, E, f_n, f_{BG})$ . Regarding the background, we assume that photons are uniformly distributed across a given region, such that the probability that a photon observed at location  $x, y$  on the sky with energy  $E$  is associated with a background component is  $P(x, y|f_{BG}, E)$ . Here,  $f_{BG}$  represents the ratio of counts between the background and the combined counts from all point source components.

All prior distributions of  $\mu$  for both  $M_S$  and  $M_T$  are described by continuous uniform distributions. When using non-informative priors, the coordinates of each  $\mu$  are allowed to be anywhere within a given region centred on the X-ray source centroid position; when using informative priors, the coordinates of each  $\mu$  are defined by the locations of the core and off-nuclear radio sources as determined in the archival VLA radio map shown in Fig. 1. We note that our informative prior distributions for  $\mu$  are wide enough to account for the relative astrometric shifts between the *Chandra* and VLA observations ( $> 1$  arcsec). The prior distribution of  $\log f_{BG}$  is described by a Gaussian distribution,  $N(\mu_{BG}, \sigma_{BG}^2)$ , where  $\mu_{BG}$  is estimated by evaluating the count rate in 10 random and source-free regions within a 20 arcsec radius of the X-ray source centroid position. We set  $\sigma_{BG}$  to 0.5, allowing for BAYMAX to easily move in parameter space. For  $M_T$ , the prior distributions of  $\log f_n$  are described by uniform distributions and are constrained between  $-2$  and  $0$ , accounting for a large range of possible count fractions between the off-nuclear sources and core. Lastly, the prior distributions of  $\Delta x_k$  and  $\Delta y_k$  are described by a uniform distribution constrained between  $\delta\mu_{\text{obs}} - 3$  and  $\delta\mu_{\text{obs}} + 3$ , where  $\delta\mu$  represents the difference between the observed central X-ray coordinates of two given *Chandra* observations. Here, we define  $\Delta x_k$  and  $\Delta y_k$  relative to the longest observation (ObsID: 18106). We analysed the photons contained within a  $16 \times 16$  sky-pixel region that is centred on the centroid position (corresponding to  $> 95$  per cent of the encircled energy radius for the 0.5–8 keV photons, and encompassing the majority of the X-ray emission expected to be associated with core and off-nuclear sources; Fig. 4). We masked the known asymmetric *Chandra* PSF feature in each observation (which sits approximately  $0.7$  from the centre of the core; Juda & Karovska 2010), as our PSF model does not take this asymmetry into account. We found BF values strongly in favour of the triple point source when using both non-informative ( $\ln \text{BF} = 2.57 \pm 0.60$ ) and informative priors ( $\ln \text{BF} = 4.85 \pm 0.64$ ). Error bars are defined by the spread of BF values after running BAYMAX 100 times, while BF are classified as ‘strong’ via false-positive tests (see Foord et al. 2019). As shown in Fig. 5, the best-fitting coordinates for the SE component using non-informative priors are consistent with those found using informative priors (albeit, with larger relative uncertainties). Although this remains true for the best-fitting coordinates of the NW component, the coordinates are not as well constrained when using non-informative priors. With informative priors, we find the NW and SE components separated



**Figure 4.** The combined 0.5–8 keV data set for 4C 63.20, as seen by BAYMAX for a triple point source model ( $M_T$ ). Each count is probabilistically assigned to a specific model component. In the case of informative priors, each component is limited by the known location of the radio core and off-nuclear sources, such that each count is allowed to vary within the dashed and dash-dotted boxes, respectively. When using non-informative priors, component counts were allowed to be anywhere within the image field of view. The resulting 68 per cent confidence intervals for the best-fitting sky  $x$  and sky  $y$  positions for the core and the off-nuclear components are illustrated by the solid red contours. Counts most likely associated with the core are denoted by dark red dots, while counts most likely associated with the NW and SE radio sources are denoted by blue (filled) and orange (open-faced) squares. Counts most likely associated with background are shown as faded grey triangles.

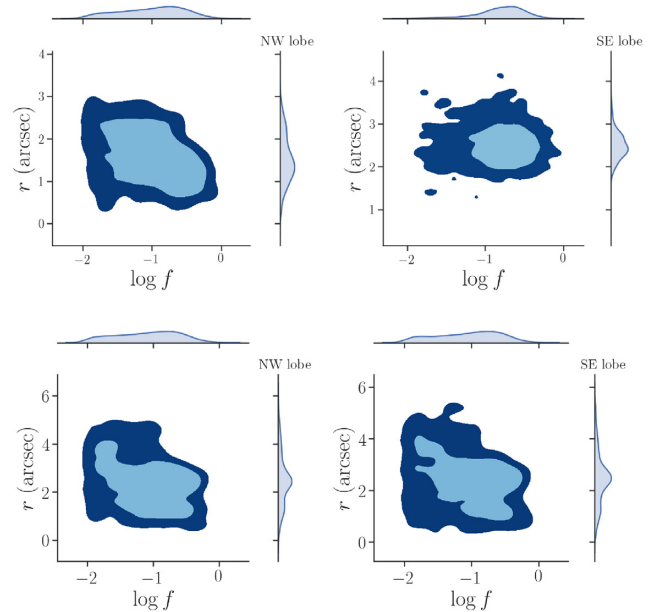
from the core with  $r = 1.59^{+0.69}_{-0.68}$  and  $r = 2.43^{+0.37}_{-0.37}$ , and count ratios of  $\log f = -0.90^{+0.40}_{-0.60}$  and  $\log f = -0.73^{+0.20}_{-0.39}$ , respectively.

Posterior distributions for the PA of the X-ray lobes were generated starting from the posteriors for the best-fitting sky coordinates of each lobe. Both informative and non-informative priors yield PA posterior distributions that are consistent with the PA of the radio lobes ( $\simeq 67$  deg), albeit non-informative priors yields a much broader distribution. Specifically, the median and 68 per cent confidence interval values of the off-nuclear X-ray source PA are  $67.40 \pm 8.75$  ( $61.89 \pm 13.92$ ) and  $8.40$  ( $35.48$ ) deg for the informative (non-informative) priors, respectively.

Based on our three assessments, we conclude that 4C 63.20 is associated with an extended X-ray source, with a SE to NW orientation consistent with the orientation of the known radio hotspots. The best-fitting value for the fractional counts of the NW and SE components (defined as the median of the posterior distributions) are  $\sim 11$  and  $17$  per cent, respectively. As to whether the SE and NW X-ray sources are point-like, and thus consistent with a hotspot versus extended/lobe-like nature, the posterior distribution for the separation allows for both interpretations (as well as a combination of the two).

### 3.2 Nuclear-to-extended flux ratio

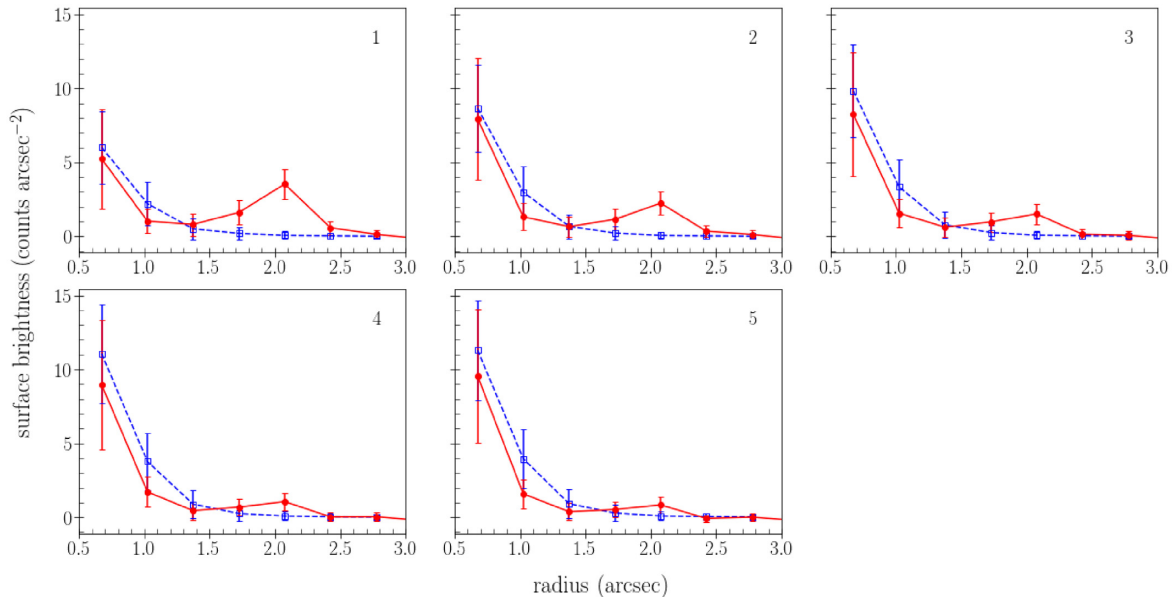
We quantify the fractional contribution of 4C 63.20’s off-nuclear components to the total measured X-ray flux with two methods: first, we compare a suite of simulated radial surface brightness profiles to the profile of a single PSF; second, we turn again to a Bayesian methodology. As a first pass, we use MARX to simulate 4C 63.20



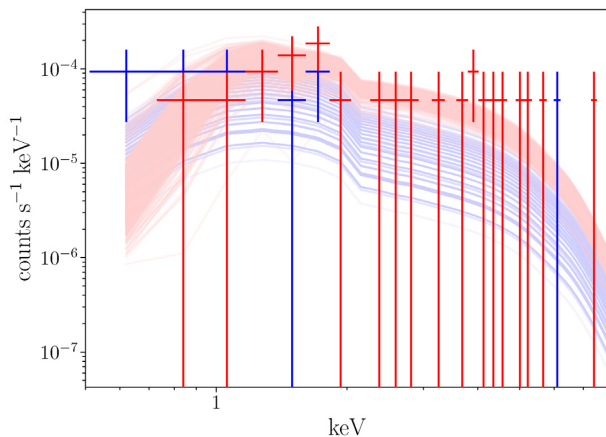
**Figure 5.** Joint posterior distribution for the inferred separation  $r$  (in arcsec) and the count ratio (in units of  $\log f$ ) for the NW (left-hand panel) and SW (right-hand panel) X-ray source, as determined by BAYMAX for the case of informative priors (top panels) and non-informative priors (bottom). The 68 and 95 per cent confidence intervals are shown in light and dark blue contours, respectively, while the marginal distributions are shown along the border. The NW and SE X-ray sources are estimated to contribute  $\sim 11$  and  $\sim 17$  per cent of the total counts, respectively.

as the sum of three PSFs – for the core, NW and SE component – with varying degrees of flux contribution assigned to the off-nuclear components, i.e.: 25, 15, 10, 5, and 3 per cent (we do not explore the case where each source contributes different percentages). The nominal positions of the off-nuclear sources were chosen to match the measured peak of the SE and NW radio sources at 5 GHz (i.e. the hotspots). Given the low number of counts, the spectral shape of each simulated PSF was set to the best-fitting model for the entire X-ray source. For each choice of  $Y$  (with  $Y = 25, 15, 10, 5, 3$  per cent), we simulated three PSFs 100 times each, concatenated them and converted them to event files, using MARX’s `marx2fits`, and performed a pixel-by-pixel averaging of the 100 event files to obtain a single, representative event file for each choice of  $Y$ . The appropriate blank-sky background files were generated, combined and aligned with the simulated source events file using the CIAO script `blanksky` and `blanksky_sample`; MARX’s `marxasp` was used to create an aspect solution file for the internal dither model.

We carried out a comparative radial surface brightness analysis between the simulated data set profiles and the profile of a single PSF (shown in Fig. 6). We fit various functional shapes to the single PSF’s profile and found that the residuals were minimized for an exponentially declining function. Then we ran a  $\chi$ -square test between this exponential fit and the radial profiles of the five simulated data sets, where a  $p$ -value of 0.05 was chosen as the threshold for a statistically significant difference between the profiles. Based on this analysis, we confirm that any extended emission that contributes to less than 10 per cent (i.e. panels 4 and 5 in Fig. 6) of the total flux from 4C 63.20 could not be significantly detected in our merged, 100 ks *Chandra* observation (this, however, assumes that the two extended sources, each located at a position consistent with the radio hotspots, contribute equally to the extended flux).



**Figure 6.** Comparative radial surface brightness profile analysis, where the profile of a single PSF (shown in blue) is compared to five sets of simulated data profiles (shown in red). Each data set is composed of three simulated PSFs with centroid positions fixed to 4C 63.20’s core, SE and NW radio sources, each having a different ratio of the core ( $X$ ) to off-nuclear sources X-ray counts [ $Y = (100 - X)/2$ , with  $Y = 25, 15, 10, 5, 3$  corresponding to panels 1, 2, 3, 4, and 5]. Based on a statistical analysis (see the main text), we conclude that, collectively, the SE and NW X-ray sources must contribute to  $\gtrsim 10$  per cent of the total measured X-ray flux from 4C 63.20 in order to be significantly recovered in a 100 ks *Chandra* exposure.



**Figure 7.** Fits to the 1000 BAYMAX-generated spectra of the core (shown as red solid lines) and the SE and NW X-ray sources (shown as blue solid lines). Fits are performed using a redshifted, absorbed power-law model with fixed slopes ( $\Gamma = 1.5$  and  $1.8$  for the SE/NW sources and core, respectively). Overplotted to the fits is one (out of 1000) simulated spectrum for the core (red points and error bars) and one for the off-nuclear sources (blue points and error bars).

To estimate the actual flux from each X-ray source, we used BAYMAX to create 1000 spectral realizations for each component within  $M_T$  (i.e. the three-component model), plus the background. This is done by probabilistically assigning each count to a specific model component, where the probabilities drawn from  $\theta_T$ . Spectral fits are carried out within XSPEC and evaluated with the Cash statistic. We model both the spectral realizations of the core and the combined off-nuclear emission as an absorbed power law ( $\text{phabs} * \text{zphabs} * \text{pow}$ ), where we fix the Galactic hydrogen-equivalent column density to  $1.4 \times 10^{20} \text{ cm}^{-2}$  and the redshift to

$z = 4.261$ . We also fix the intrinsic absorption parameter ( $\text{zphabs}$ ) to the Galactic value when fitting the SE and NW sources. Unsurprisingly, for both we find that the models where  $\Gamma$  is fixed (to 1.8 and 1.5 for the core and the off-nuclear sources, i.e. consistent with typical AGNs and Comptonization spectra, respectively) are statistically preferable to those where  $\Gamma$  is free to vary (this is quantified by comparing the distributions of the best-fitting  $C_{\text{stat}}$  values; see Fig. 7). For both the core and the off-nuclear sources, we created distributions of spectral parameters based on the best-fitting values from each fit. The X-ray flux and luminosity values are determined by the median of the distributions, where the quoted errors represent the 68 per cent confidence levels. For the core, we infer an intrinsic absorption column of  $N_{\text{H}} = 3.6^{+1.2}_{-0.9} \times 10^{23} \text{ cm}^{-2}$  and a total observed 0.5–8 keV flux of  $3.7^{+0.3}_{-0.3} \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$ . For the SE/NW sources, the observed 0.5–8 keV flux is  $9.8^{+5.3}_{-4.0} \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ . We adopt the above values in the following section, for the purpose of modelling 4C 63.20’s core and off-nuclear X-ray emission.

#### 4 SPECTRAL ENERGY DISTRIBUTION MODELLING

The high redshift of the source ( $z = 4.26$ ) implies that the radiation energy density of the CMB is enhanced by a factor  $(1 + z)^4 \simeq 760$  with respect to the local value. As a consequence, it is unavoidable that IC scattering off of CMB photons (IC/CMB) must play an enhanced role in cooling the system’s relativistic electrons compared to an otherwise equal system at  $z = 0$ . Here, we aim to quantify the contribution of this process in 4C 63.20 and, by extension, assess its efficacy as a viable mechanism to quench radio emission from the lobes of jetted AGNs at high redshifts.

The complete SED of 4C 63.20 is shown in Fig. 8. Data points (other than X-ray) were retrieved from <https://tools.ssdc.asi.it/>; to those, we add the core (red butterfly) and extended sources (orange



**Table 1.** Jet model parameters. Col. [1]: disc luminosity, in  $10^{45}$  erg  $s^{-1}$ ; Col. [2]: distance of the dissipation region from the black hole, in units of  $10^{15}$  cm; Col. [3]: logarithm of the power injected in the form of relativistic electrons, in the co-moving frame, in erg  $s^{-1}$ ; Col. [4]: magnetic field, in G; Col. [5]: bulk Lorentz factor; Col. [6]: viewing angle, in degrees; Col. [7] and Col. [8]: break and maximum Lorentz factor of the injected electron distribution; Col. [9] and Col. [10]: slopes of the injected electron distribution; Col. [11]: logarithm of the total kinetic plus magnetic jet power, in erg  $s^{-1}$ . Quoted power and energy values refer to *one* jet.

$L_d$	$R_{diss}$	$P'_e$	$B$	$\Gamma$	$\theta_V$	$\gamma_b$	$\gamma_{max}$	$s_1$	$s_2$	$P_{jet}$
[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]
15.6	288	43.8	2.3	10	10	50	3000	1.5	2.2	47.8

### 4.3 Extended emission: hotspots and lobes

The *Chandra* observations presented here have established that  $\sim 30$  per cent of the X-ray emission from 4C 63.20 can be ascribed to two off-nuclear components; nevertheless, the angular separation and low number of counts of both off-nuclear X-ray sources allow for both a hotspot and/or a lobe interpretation. At the same time, as discussed in Section 2, since the source is not resolved at low radio frequencies (e.g.  $\lesssim 1$  or  $\lesssim 5$  GHz rest-frame) the intrinsic amount of truly diffuse, lobe radio emission cannot be estimated. Our best guess is based on the comparison of the available maps at 5 GHz, where the majority of the emission emanates from a pair of hotspots, with only about 15 per cent likely arising from the diffuse lobes (to be clear, this does not imply the absence of extended radio lobes in 4C 63.20, nor does it imply that any lobe emission only contributes to 15 per cent of the total radio flux, as any extended lobe would hardly be detectable at such high rest-frame frequency, due to the short synchrotron lifetime of the emitting particles).

For the purpose of our modelling, thus, we consider two extreme (mutually exclusive) scenarios: (I.) a ‘pure hotspot’ model, in which all of the (off-nuclear) radio and X-ray emission arises from compact, 2.4 kpc-scale (1.2 kpc radius) hotspots and (II.) a ‘pure lobe’ model, where all of the (off-nuclear) X-ray emission, along with 15 per cent of the radio, arise from extended, 12 kpc-scale (6 kpc radius) lobes. For reference,  $\simeq 2.4$  kpc corresponds to the beam size of the highest resolution VLA image available (i.e. 0.4 arcsec), where the hotspots are only marginally resolved, whereas 12 kpc corresponds to the NW hotspot-radio core distance (since a spherical geometry approximation likely overestimates the lobe volume, we chose to adopt the smallest projected size for the radius; although the inferred model parameters are sensitive to this choice, the relative ratios, which we are mostly interested in, are not).

In both cases, the extended X-ray emission is produced via EC, that is, IC scattering off of disc, torus and (mainly) CMB photons. This mechanism competes with the standard synchrotron cooling that is responsible for generating the radio spectrum, as well as the SSC component at intermediate frequencies. Attempting to simultaneously reproduce the extended X-ray emission with either model yields an estimate of the local magnetic-to-CMB radiation energy density ( $U_B/U_{rad}$ ), as well as the total energy in magnetic field ( $E_B$ ) and particles ( $E_e$ ). In turn, different degrees of magnetization correspond to different relative contributions of the SSC versus EC component. We discuss the adopted parameters for each model in turn next.

We follow closely Ghisellini et al. (2015) in modelling the hotspot and lobe radiation. The particle energy distribution function obeys

equation (1), but with different parameters from the jets’. The size, combined with the injected power, constrain the magnetic field and particle energy density. We approximate each component as a sphere which is homogeneously filled with magnetic field.<sup>2</sup> Unlike for the hotspots, the magnetic field energy within the lobes is assumed to be nearly in equipartition with the electron energy ( $E_e \simeq E_B$ ), which enables us to estimate the lobes’  $B$ -field strength. At the hotspot location, the lobes are injected with energy at rate  $P_e$ ; the electron distribution function is given again by equation (1), but with a different set of parameters than for the jet and the hotspots. A complete list of the adopted parameters for the lobe and hotspot models is given in Table 2. Worth noting are the inferred  $B$ -field strength and the magnetic to CMB radiation energy density ratio: for the pure lobe model,  $B = 0.12$  mG and  $U_B/U_{rad} \simeq 2$ , to be compared against  $B = 0.45$  mG and  $U_B/U_{rad} = 28$  for the pure hotspot model.

### 4.4 Modelling results

Fig. 8 illustrates our best attempt at reproducing the broad-band SED of 4C 63.20 with the models described in Section 4. The black dotted line represents the contribution from the accretion disc and the dusty torus. The solid green line is the emission from the relativistic jet, which is responsible for the measured core X-rays. The diffuse X-ray spectrum is fit by either a pure hotspot model (I., solid blue line), where the hotspots also produce the measured radio spectrum, or a pure lobe model (II., solid red line), where the lobes are responsible for 15 per cent of the measured radio emission.<sup>2</sup> Assuming a pure hotspot model naturally requires a high degree of magnetization within the hotspots, with  $U_B/U_{rad} \simeq 30$ . As expected, the high  $U_B$  in the hotspots enhances the SSC contribution, and diminishes the relative role of IC/CMB in cooling the electrons. In contrast, the pure lobe model, which only accounts for 15 per cent of the measured radio emission, yields  $U_B/U_{rad} \simeq 2$  and  $E_e/E_B \simeq 1$ , implying that IC/CMB dominates dramatically over SSC. In both cases, the striking effect of IC/CMB is illustrated by the dashed blue/red lines (‘no CMB’), where CMB/IC is switched off.

## 5 DISCUSSION

The *Chandra* observations presented here have revealed that the X-ray counterpart to the  $z = 4.26$  radio galaxy 4C 63.20 is made of a compact core plus extended SE-to-NW emission, which accounts for  $\simeq 30$  per cent of the flux and is aligned with the known hotspots seen at 5 GHz. The (loosely constrained) separation and centroid positions of the SW and NE X-ray sources allow for both a hotspot as well as a truly diffuse, lobe-like interpretation.

When we attempt to reproduce the system SED with a jet model which accounts for the contribution from the either the jet termination hotspots (I.) or the jet-powered lobes (II.), including IC scattering off of CMB photons, we find that both scenarios require a high degree of magnetization, with supra-equipartition magnetic field energy densities. The magnetic to CMB radiation energy density ratio is even more extreme for the pure hotspot model ( $U_B/U_{rad} \simeq 25$ , versus  $\simeq 3$  for the pure lobe case); this implies a lesser (relative) IC/CMB contribution with respect to SSC compared to the pure lobe scenario.

<sup>2</sup>The lobe size is smaller than the field coherence length-scale,  $\lambda = 10$  kpc (Carilli & Taylor 2002; Celotti & Fabian 2004), consistent with the hypothesis that the magnetic field is indeed homogeneous.

**Table 2.** Adopted parameters for the extended emission model; the pure lobe model corresponds to the solid red line in Fig. 8, whereas the pure hotspots is shown as a solid blue line. Col. [1]: region radius, in kpc; Col. [2]: logarithm of the power injected in relativistic electrons in  $\text{erg s}^{-1}$ ; Col. [3]: magnetic field in mG; Col. [4] and Col. [5]: break and maximum Lorentz factor of the injected electron distribution; Col. [6] and Col. [7]: slopes of the injected electron distribution; Col. [8]: logarithm of the total energy in relativistic electrons, in erg; Col. [9]: logarithm of the total energy in magnetic field, in erg; Col. [10]: ratio of magnetic to radiation energy density, where the latter includes the CMB, synchrotron radiation (the disc and torus contributions are negligible); Col. [11]: ratio of magnetic to CMB radiation energy density. Energetics value refers to one hotspot/lobe, while the lobe flux shown in the figures corresponds to two hotspots/lobes.

Model	$R$ [1]	$P_e$ [2]	$B$ [3]	$\gamma_b$ [4]	$\gamma_{\max}$ [5]	$s_1$ [6]	$s_2$ [7]	$E_e$ [8]	$E_B$ [9]	$U_B/U_{\text{rad}}$ [10]	$U_B/U_{\text{CMB}}$ [11]
Lobe	5.8	46.2	0.12	$10^3$	$10^4$	-1	4.0	58.1	58.1	2.4	1.8
Hotspot	1.2	46.9	0.45	800	$10^4$	-1	4.5	58.1	57.2	4.4	26

Although we considered admittedly extreme either-or scenarios, the results from this modelling exercise are not incompatible with the conclusions drawn by Wu et al. (2017), who followed the same approach in modelling the SED of 4C 41.17 and 4C 03.24, i.e. the two other (known)  $z > 3.5$  radio galaxies with (reliably) extended X-ray emission. For both systems, the energy density in magnetic field was found to vastly exceed that of the CMB radiation in the hotspots (whereas the opposite is true for the extended lobes). This implies that, in both systems, most of the X-ray signal is likely produced within the lobes, via IC/CMB, whereas most of the radio signal is produced within the hotspots, via synchrotron, thus washing out the steep  $(1+z)^4$  enhancement of the X-ray versus radio luminosity expected of IC/CMB. It is likely, albeit not proven, that a similar process takes place in 4C 63.20: modulo the lack of a firm detection of truly extended lobes in this system, the (observed-frame) 5 GHz emission is clearly dominated by hotspots, where the magnetic energy density largely dominates over radiation.

Admittedly, for 4C 63.20 to exhibit a similar behaviour as 4C 41.17 and 4C 03.24 we would require the (majority of the) off-nuclear X-ray emission detected by *Chandra* to be lobe-like, i.e. truly diffuse in nature. In 4C 41.17 and 4C 03.24, it was possible to decompose the X-rays into core, lobes, and hotspots. This is not the case in 4C 63.20, which motivates our two bracketing cases. Nevertheless, just as in the case of 4C 41.17 and 4C 03.24, the magnetic energy density is found to be substantially higher than the radiation energy density for either models.

The next question we wish to address is whether these new results have any meaningful implication for the larger population of high- $z$ , jetted AGNs, and in particular for the viability of the so-called CMB-quenching mechanism, which posits that the inferred dearth of high- $z$  radio galaxies (Volonteri et al. 2011; Sbarrato et al. 2015) stems from a cooling offset which makes this population emit primarily in the X-rays rather than radio band.

Under the assumptions discussed above, our modelling results paint a picture where, as expected, these objects are highly magnetized. A useful comparison can be drawn with the lower redshift ( $z \lesssim 2$ ) radio-loud sample examined by Hardcastle et al. (2004): there, the quoted equipartition magnetic energy density values for the hotspots range between  $10^{-12}$  and  $10^{-9} \text{ J m}^{-3}$ . Adopting  $10^{-10.5} \text{ J m}^{-3}$  as an indicative value, and for a hotspot radius of 0.7 kpc, yields a total magnetic energy of about  $10^{55}$  erg, which is indeed two to four orders of magnitude lower than the inferred values for the hotspots of the above three  $z > 3.5$  radio galaxies. Summarizing, radio galaxies at high- $z$  are already exceptional because they are clearly not radio-quenched; nevertheless the X-ray luminosities in 4C 63.20, 4C 41.17, and 4C 03.24 are consistent with the expectation

from highly magnetized lobes in a hotter CMB. In turn, this is consistent with the view that the CMB may quench less exceptional lobes. A broader theoretical investigation of the range of  $B$ -field, lobe sizes and intrinsic radio luminosity required for making high- $z$  radio galaxies undetected by FIRST will be the subject of a forthcoming work.

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## DATA AVAILABILITY

The main data underlying this article can be downloaded from the Chandra Data Archive, at <https://cda.harvard.edu/chaser/>, under Sequence Number 703172.

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