Extended X-ray emission from non-thermal sources in the COSMOS field: A detailed study of a large radio galaxy at $z = 1.168$

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ABSTRACT

X-ray selected galaxy group samples are usually generated by searching for extended X-ray sources that reflect the thermal radiation of the intragroup medium. On the other hand, large radio galaxies that regularly occupy galaxy groups also emit in the X-ray window, and their contribution to X-ray selected group samples is still not well understood. In order to investigate their relative importance, we have carried out a systematic search for non-thermal extended X-ray sources in the COSMOS field. Based on the morphological coincidence of X-ray and radio extensions, out of 60 radio galaxies, and $\sim 300$ extended X-ray sources, we find only one candidate where the observed extended X-ray emission arises from non-thermal processes related to radio galaxies. We present a detailed analysis of this source, and its environment. Our results yield that external Inverse Compton emission of the lobes is the dominant process that generates the observed X-ray emission of our extended X-ray candidate, with a minor contribution from the gas of the galaxy group hosting the radio galaxy. Finally, we show that finding only one potential candidate in the COSMOS field (in a redshift range $0 < z < 6$ and with radio luminosity between $10^{25}$ and $10^{30}$ W/Hz) is consistent with expected X-ray–counts arising from synchrotron lobes. This implies that these sources are not a prominent source of contamination in samples of X-ray selected clusters/groups, but they could potentially dominate the $z > 1$ cluster counts at the bright end ($S_X > 7 \cdot 10^{-15}$ erg s$^{-1}$ cm$^{-2}$).

Key words: surveys; galaxies: clusters: general, active; radiation mechanisms: general; radio continuum: galaxies; X-rays: galaxies: clusters

1 INTRODUCTION

Radio galaxies constitute the most powerful and the largest-scale active galactic nuclei phenomena. Their jets span distances of up to 1 Mpc. The optical hosts of powerful radio loud AGN usually have colors consistent with that of galaxies in the so called “green valley”, i.e., a region in a color vs. stellar mass plane thought to reflect the evolutionary transition of blue-star forming galaxies to red-and-dead ones (Smolčić 2009). They have a higher molecular gas content relative to less powerful radio galaxies inhabiting the red sequence (Smolčić & Riechers 2011). They often show signs of merger activity (Simpson & Rawlings 2002), and they usually reside in group environments (Baum, Heckman & van Breugel 1992).

As their high brightness in the radio allows detections out to high redshift, powerful radio galaxies are often used as tracers of distant groups/clusters of galaxies. A direct, and powerful way to detect clusters and groups of galaxies is via extended X-ray emission reflecting thermal
bremsstrahlung radiation from the cluster/group gas (i.e. intercluster/intrigroup medium; ICM). With the advent of deep X-ray surveys, and the optimization of cluster/group detection algorithms hundreds of faint X-ray clusters have been detected in such a way out to $z \sim 2$ (Finoguenov et al. 2007, 2009, 2010; Briel et al. 2010; Tanaka, Finoguenov & Ueda 2010; Henry et al. 2010; Gobat et al. 2011). However, large radio galaxies, which are preferentially found in such galaxy groups/clusters, are also luminous in the X-rays, thus possibly biasing the X-ray cluster searches (see below). Furthermore, the X-ray emission of their jets, hot-spots and lobes may outlive the radio emission, as IC-CMB emission can down-grade the electrons required for (high frequency) radio emission (Fabian et al. 2009; Mocz, Fabian & Blundell 2011).

It has been demonstrated that the X-ray emission of radio galaxies arises from three main processes: synchrotron radiation emitted by relativistic electrons, inverse Compton (IC) scattering of the synchrotron photons (so called synchrotron self-Compton, SSC, process) or the cosmic microwave background (CMB) photons (so called external Compton, EC, process) off the relativistic electrons. The first and second processes are predominant in jet-knots and hot-spots of low-redshift radio galaxies, while the last process can regularly be associated with the extended lobes of radio galaxies (see Kataoka & Stawarz 2005 for details). It is important to note that the X-ray flux of EC emission is proportional to $z^{3}$, e.g., Simpson & Rawlings 2002; Fabian et al. 2003; Blundell et al. 2006; Johnson et al. 2007; Erlund, Fabian & Blundell 2008).

Depending on the expected number of extended X-ray–emitting radio lobe sources (via EC), they might be a serious contaminant in deep X-ray surveys searching for clusters/groups at high redshifts. Assuming that radio AGN emit in the X-ray via EC emission, and evolving radio AGN luminosity functions Celotti & Fabian 2004 argued that at redshifts of $z \gtrsim 1$ the EC emission of radio lobes will likely dominate in X-rays ($L_X > 10^{44} \text{erg/s}$) over the thermal gas emission of the clusters/groups. When, however, a radio galaxy lies in a cluster/group, the total X-ray emission from this system is likely a combination of EC emission from the radio lobes of the galaxy, and thermal bremsstrahlung emission from the cluster/group gas. However, so far there has been just a single survey (Finoguenov et al. 2010) that tried to quantify that. Finoguenov et al. (2010) searched for X-ray galaxy clusters in the Subaru-XMM Deep Field (SXDF), covering $1.3 \circ$. They identified 57 cluster candidates, 4 of which they consider likely EC X-ray sources and 2 more which are likely a combination of EC scattering and thermal cluster emission.

In order to put stronger constraints on extended X-ray sources due to non-thermal processes in deep X-ray surveys, here we present a search for EC dominated X-ray candidates in the Cosmic Evolution Survey (COSMOS, Scoville et al. 2007) field, and discuss their expected abundance in future X-ray surveys. The paper is organized as follows. In Sec. 2 we give a brief overview of the COSMOS survey and the data used for this work. In Sec. 3 we describe our systematic search for EC dominated X-ray sources in the COSMOS field. The radio, X-ray, and optical properties of our single candidate are presented in Sec. 4, while the properties of the associated galaxy group are discussed in Sec. 5. The origin of observed X-ray emission is discussed in Sec. 6. Section 7 presents predictions for EC dominated X-ray sources in future X-ray surveys. We conclude the paper with Sec. 8.

Throughout the paper we assume LCDM cosmology with WMAP7 parameters $(\text{Komatsu et al. } 2011): h = 0.71, \Omega_m = 0.27$ and $\Omega_{\Lambda} = 0.73$, and we use AB magnitude system.

## 2 DATA

The COSMOS survey is designed to probe the formation and evolution of galaxies as a function of cosmic time and large scale structure environment. The survey covers a $2\circ$ area close to the celestial equator (Scoville et al. 2007) with multi-wavelength imaging from X-ray to radio wavelengths, including HST/ACS imaging (see Koekemoer et al. 2007) and optical spectroscopy (zCOSMOS, Lilly et al. 2007, 2009). Due to this broad wavelength coverage the photometric redshifts for galaxies in the COSMOS field are determined to an excellent accuracy of $\sigma_{z} \sim 0.007 \cdot (1 + z)$ for $i^+ < 22.5$ (Ilbert et al. 2009; Salvato et al. 2009). The stellar masses of every source in the photometric redshift catalog are estimated using a Salpeter initial mass function (IMF).

In radio wavelengths, the COSMOS field has been observed at 1.4 GHz (VLA-COSMOS survey, Schinnerer et al. 2007, 2010) and 327 MHz (Smolcic et al., in prep.) with the NRAO Very Large Array (VLA) in A and C configurations. The reached $\text{rms}$ and resolution at 327 MHz (1.4 GHz) are $\sim 0.4 \text{mJy beam}^{-1}$ ($\sim 8 \mu\text{Jy beam}^{-1}$) and $6.0'' \times 5.4'' (1.5'' \times 1.4'')$, respectively. The 1.4 GHz catalog utilized here contains $\sim 2400 (\gtrsim 5\sigma)$ sources, 60 of which are radio galaxies (with clear core/jetlobe features).

X-ray observations of the COSMOS field have been performed both with XMM-Newton (1.5 Ms covering $2\circ$, Hasinger et al. 2007) and Chandra (1.8 Ms covering inner $1\circ$, Elvis et al. 2009). Based on a composite mosaic of both observations, a galaxy group catalogue has been generated (Finoguenov et al. 2007, Finoguenov et al., in prep.). It contains $\sim 300$ extended sources out to redshifts of 1.3 with total masses within a radius of 200 times the critical density in the range of $M_{200} \in [7 \times 10^{12}, 3 \times 10^{14}] \odot$. The extended X-ray source detection is based on a wavelet analysis technique and includes removal of point sources (Finoguenov et al. 2009). Each X-ray cluster candidate has been further independently verified via an optical galaxy cluster search (making use of both the COSMOS photometric and spectroscopic redshifts, following the procedure outlined in Finoguenov et al., 2010).

## 3 SEARCH FOR JOINT RADIO/X-RAY COEXISTANCE IN THE COSMOS FIELD

Using the data mentioned in Sec. 2 we carried out a systematic search for EC dominated X-ray sources. The search is based on the coincidence of radio and X-ray emissions. We compare the centering and positional angle of each of the 60 morphologically complex radio sources drawn from the 20 cm VLA-COSMOS catalog with the associated extended X-ray emission in the 0.5–2 keV band. To avoid a possible identification bias towards availability of an optical counterpart no prior on either source has been applied.

In addition to a positional match, a coincidence in elongation of radio and X-ray emissions (to within $10'$) is required by the method. This creates a robust identification of the extended X-ray source as a counter-part of radio-lobes, as the chance probability of such an alignment is $10^{-4}$, given the density of both X-ray and radio sources, and chance alignment of principal axes. However,
such a search is limited to the early phase of radio-activity and may not select X-ray only lobes. Compared to a similar study done on the 1.3 cm of SXDF survey (Finooguenov et al. 2010), we find just one EC dominated X-ray candidate (Fig.1), which implies a factor of 6 lower frequency of the phenomenon as inferred by Finooguenov et al. (2010). We note that the redshift of the COSMOS source, \( z_{\text{spec}} = 1.168 \), is at a similar redshift as the brightest EC dominated X-ray candidate in SXDF.

Hereafter, we refer to this system as the EC dominated X-ray candidate. Its radio, X-ray, and optical properties are presented in the following section.

## 4 EC DOMINATED X-RAY CANDIDATE

### 4.1 X-ray properties

The extended X-ray emission associated with our candidate has been identified using the full XMM-Newton survey of the COSMOS field (it is outside the area covered by Chandra). However, the best imaging quality is available in the observation 0203362201, which has a 26 ks cleaned exposure and the object is located next to the telescope optical axis (best PSF and sensitivity). We show the X-ray counts, smoothed to 8′′ × 8′′ resolution, in Fig.1.

From the figure it is obvious that the X-ray emission is arising from the region associated with the radio galaxy. The emission shows both unresolved and resolved components with a total flux of \( (3.6 \pm 1.2) \cdot 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) in the observed 0.5-2 keV band (dashed line in left panel of Fig.1).

In order to get a better insight into the X-ray properties associated with the source, we have extracted the counts from three zones within the X-ray map. These zones, illustrated by the dash-dotted green areas in the right panel of Fig.1, encompass the core, both lobes, and a putative group emission. Using both the stowed background and the local background region, selected from the same chip, but 2 arcmin away from the source, we analyzed the spectra in the 0.4 – 7.5 keV range for each zone separately. Significant detections have been obtained in all three zones. Using the XMM PSF model, and for the putative group emission an assumption of azimuthal symmetry, we have solved for intrinsic flux of all these components: in the observed 0.5-2 keV band and in units of \( 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) the lobe emission amounts to 2.7 ± 0.7, core emission to 1.7 ± 0.4, total group emission of 1.4 ± 2 and its contribution to the lobes is 0.5 ± 0.4. The group component has not been significantly detected. In Fig.2 we show the spectrum of the lobes. Given the marginal contribution of the group emission, established above, we ignored it, finding a photon index of 2.6 ± 0.5 (\( \chi^2 = 3.27/7 \) dof). The core shows a hard spectrum with a photon index of 0.6 ± 0.4.

### 4.2 Radio properties

The radio counterpart of the EC dominated X-ray candidate is identified as a large powerful radio galaxy J095822.93+022619.8 with integrated source flux density of \( S_{1.4 \text{ GHz}} = (112.9 \pm 0.5) \) mJy (Schinnerer et al. 2007) and \( S_{327 \text{ MHz}} = (470.6 \pm 0.5) \) mJy (Smolčić et al. in prep.). The spectroscopic redshift of its optical counterpart is 1.1684 ± 0.0007 (see Sec. 5.3), which corresponds to a luminosity distance of \( d_L = 8062 \) Mpc for the adopted cosmology. Thus, the monochromatic radio powers of the source at 1.4 GHz and 327 MHz are \( L_{1.4 \text{ GHz}} = 8.8 \cdot 10^{26} \) W Hz and \( L_{327 \text{ MHz}} = 3.7 \cdot 10^{27} \) W Hz, respectively.

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### Table 1. Integrated flux density and projected angular size of morphological features resolved in the 1.4 GHz radio map.

| Morphological Features | \( S_{1.4 \text{ GHz}} \) [mJy] | Angular Size |
|------------------------|-------------------------------|--------------|
| NE Hotspot             | 19.5 ± 0.5                   | 1.5′′ × 1.4′′ |
| SW Hotspot             | 35.3 ± 0.5                   | 1.5′′ × 1.4′′ |
| NE Lobe                | 36.2 ± 0.5                   | 23.5′′ × 16.4′′ |
| SW Lobe                | 21.9 ± 0.5                   | 24.1′′ × 14.3′′ |

Morphologically, the source shows a structure of Fanaroff-Riley (FR) class II (Fanaroff & Riley 1974), i.e., a luminous radio galaxies with predominant emission from the lobes (see Fig.1 and Table 1). The radio emission of the jets themselves is not detected. The radio core, located centrally between the lobes (see the line joining the lobes in Fig.1) is detected at \( \sim 4 \sigma \) in the 1.4 GHz radio map. The central parts of the lobes are \( \sim 26.5 \) arcsec (\( \sim 220 \) kpc) away from the core in two diametrically opposite directions (NE-SW direction on the plane of the sky). The hotspot of the NE lobe is off the joint line between the lobes, suggesting interaction with a medium.

Combining the images at 327 MHz and 1.4 GHz, the spectral index map of the source is obtained (see Fig.2) \( S_\nu \propto \nu^{\alpha_s} \). Prior to the spectral index calculation (i) the 1.4 GHz image was convolved and re-gridded to match the resolution and pixel scale of the 327 MHz image, (ii) positional alignment between the two images was checked using 45 point sources (Smolčić et al. in prep.); and (iii) pixels with values below 3σ in each image were blanked. The spectral index shows the expected behavior for both lobes. It steepens radially towards the core from \(-0.6 \) to \(-1.5 \). The average spectral index is \( \alpha_s = -(1.0 \pm 0.2) \). For clarity, we also calculate the spectral index from the integrated flux density of the source at 327 MHz and 1.4 GHz, obtaining \( \alpha_s = (\log(S_{327}/S_{1.4})/\log(\nu_2/\nu_1)) = -0.98 \), which is in agreement with the result obtained from the spectral index map. Throughout the paper we will use \( \alpha_s = -(1.0 \pm 0.2) \) as the average spectral index of the lobes and \( \alpha_s = -(0.7 \pm 0.2) \) as the average spectral index of the hotspots.

The total radio luminosity of the source, obtained by integrating the synchrotron spectrum from 1 MHz to 100 GHz (e.g., eq. 1 in Smolčić et al. 2007), is \( L_r = 6.7 \cdot 10^{28} \) W.

### 4.2.1 Magnetic field strength in the lobes and hotspots

Based on the obtained radio properties of our source, we estimate the magnetic field strength in its lobes and hotspots. This will be further used to estimate the expected IC emission (Sec. 6.1).

We follow Smolčić et al. (2007) and apply the minimum energy condition. Briefly, the minimum energy condition corresponds almost to equipartition between the relativistic particles (protons and electrons, \( E_{p,e} \)) and the magnetic field, \( E_{B_{eq}} \) (for details see Pacholczyk 1970). The magnetic field strength is then given by (e.g. Miley 1980):

\[
B_{eq} = \left( \frac{5.69 \cdot 10^{-5}}{\eta} \right) \left( \frac{1 + k S_r (1 + z)^{3 - \alpha_r}}{\eta - \nu^\alpha_r} \right)^{-\frac{\alpha_r + 1/2}{\alpha_r + \frac{1}{2}}} \left( \frac{\nu_2^{\alpha_r + 1/2} - \nu_1^{\alpha_r + 1/2}}{\alpha_r + \frac{1}{2}} \right)^{2/7} \text{ G}
\]

(1)

where \( z \) is the redshift of the source, \( S_r \ [\text{Jy}] \) is the observed radio flux of the emitting region at frequency \( \nu \ [\text{GHz}] \), \( \theta_{e,y} \ [\text{arcsec}] \)}
is the angular size of the emitting region, $s$ [kpc] is the path length through the source along the line of sight, $\nu_{1,2}$ [GHz] are lower and upper frequency cutoffs, and $\alpha_v$ is the spectral index. Equation (4) assumes (i) a cylindrical symmetry of the lobes, (ii) equal energy densities carried by protons and electrons in the lobes ($k = 1$), (iii) no relativistic beaming ($\delta = 1$), (iv) the volume of the lobes to be completely filled with the plasma ($\eta = 1$), and (v) the magnetic field is transverse to the line of sight ($\sin \Phi = 1$). Given the averaged properties of the lobes ($S_{1.4 \text{ GHz}} = (29.0 \pm 0.5) \text{ mJy}$, $\alpha_v = - (1.0 \pm 0.2)$, $\theta_x = 23.8''$, $\theta_y = 15.35''$, and $s = 130 \text{ kpc}$) and taking $1 \text{ MHz}$ and $100 \text{ GHz}$ for $\nu_{1,2}$, the obtained magnetic field strength is $B_{\text{eq}} = (10 \pm 2) \mu \text{G}$. The magnetic energy density is $u_B = B_{\text{eq}}^2/8\pi = (4.0 \pm 1.5) \cdot 10^{-12} \text{ erg cm}^{-3}$. The errors are propagated from uncertainties on $S_{1.4 \text{ GHz}}, \alpha_v$, and $s$.

Given the averaged properties of the hotspots ($S_{1.4 \text{ GHz}} = (27.4 \pm 0.5) \text{ mJy}$, $\alpha_v = - (0.7 \pm 0.2)$, $\theta_x = 1.4''$, $\theta_y = 1.5''$, and $s = 12 \text{ kpc}$) and taking $1 \text{ MHz}$ and $100 \text{ GHz}$ for $\nu_{1,2}$, the obtained magnetic field strength is $B_{\text{eq}} = (53 \pm 2) \mu \text{G}$ and the magnetic energy density is $u_B = B_{\text{eq}}^2/8\pi = (113 \pm 8) \cdot 10^{-12} \text{ erg cm}^{-3}$.

### 4.3 Optical properties

The radio core of the large radio galaxy is associated with an optical source located at $\alpha = 9h58m23.31s, \delta = +02^\circ 26' 28.33''$ (see Fig. 3).

In the HST-ACS image (Koekemoer et al. 2007), with a pixel scale of 0.03'' per pixel, two central cores are clearly visible (see Fig. 4). The separation of the cores is 0.22'', which corresponds to a physical distance of $\sim 1.7 \text{ kpc}$ at the redshift of the source. The presence of two cores could be either interpreted as the two nuclei of merging galaxies or as two star-formation regions in a single galaxy. Alternatively, they are a superposition of two nuclei of two independent galaxies in the same group. Given the average density in the group selected by Voronoi tessellation (see Sec. 5), 2.68 - 10^2 galaxies per deg^2, such a probability is, however, small, i.e., $P = 3.2 \cdot 10^{-3}$.

An optical spectrum (5500-9500 Å) of the source has been taken within the zCOSMOS survey (Lilly et al. 2007, 2009). The zCOSMOS slit was oriented North-South, with the dispersion axis.

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**Figure 1.** Multi-wavelength image of the region around the EC dominated X-ray candidate. Left: HST-ACS i-band image is presented in a red scale. The radio emission of the associated radio galaxy at 1.4 GHz is plotted with solid $3\sigma$ level contours (where $i = 1, 2, \ldots$, and $\sigma = 17.16 \mu\text{Jy/beam}$). The synthesized beam of the radio image is $1.5'' \times 1.4''$ (thick solid ellipse plotted in the bottom left corner). Borders of extended X-ray emission obtained by the wavelet analysis of the XMM-Newton image are shown by the dashed line. Associated optical/IR galaxies identified via the Voronoi method are marked with blue boxes and red diamonds, according to their $i - K_s$ color (see Sec. 5). Right: XMM-Newton, background point-source subtracted and smoothed to $8'' \times 8''$ resolution, image of the region around the EC dominated X-ray candidate (presented in a blue scale; note that darker colors show regions with stronger X-ray emission). The radio emission at 1.4 GHz is smoothed to the resolution of the X-ray image and overplotted as solid white contours. A dashed green line marks the X-ray flux extraction region associated with the extended X-ray emission, while the dash-dotted green circles are regions associated with the core, lobes, and a putative group emission.

**Figure 2.** Fitted power-law spectrum of the X-ray emission in the $0.4 - 10 \text{ keV}$ range using both the stowed background and the local background. Data points are given for the X-ray emission associated with the lobes (see Fig. 1). Note that the spectral shape is hard, which is consistent with the non-thermal emission from EC scattering, rather than thermal emission arising from the galaxy group.
Figure 3. The radio emission of the associated radio galaxy at 327 MHz (left), at 1.4 GHz (middle) convolved to the resolution of the 327 MHz image, and the corresponding spectral index map of the radio emission \((S_\nu \propto \nu^{\alpha_r}}; right). Contours of the radio emission have 3\(\sigma_i\) levels, where \(i = 1, 2, \ldots\), \(\sigma_{327\text{ MHz}} = 0.4 \text{ mJy/beam}\), and \(\sigma_{1.4\text{ GHz}} = 0.14 \text{ mJy/beam}\). The synthesized beams of the radio images are 6.0\('\) \(\times\) 5.4\('\) (thick solid ellipses plotted in the bottom left corner of the images). As expected, the spectral index steepen radially towards the core. The average spectral index of both lobes together is \(\alpha_r = -(1.0 \pm 0.2)\). By comparing the spectral index map with the X-ray emission shown in Fig. 1, we note that the X-ray emission stems from the zones of steeper spectral indexes.

Figure 4. HST-ACS \(i\)-band image of the region around the radio core of the EC dominated X-ray candidate. The radio emission at 1.4 GHz is plotted with solid contours \((\sigma = 17.16 \mu\text{Jy/beam})\). The synthesized beam of the radio image is 1.5\('\) \(\times\) 1.4\('\).

in East-West direction. The spectroscopic redshift is 1.1684 \(\pm\) 0.0007, and given the presence of only narrow lines ([NeV] doublet and [OII] at 3727\(\AA\)), the source is classified as a narrow line emission galaxy.

Figure 5. A part of the optical spectrum of the source taken within the zCOSMOS survey. The spectroscopic redshift is 1.1684 \(\pm\) 0.0007, and given the presence of only narrow lines ([NeV] doublet and [OII]), the source is classified as a narrow line emission galaxy.

5 PROPERTIES OF THE ASSOCIATED GALAXY GROUP

To determine whether an optical galaxy overdensity is associated with the X-ray-emitting lobe candidate, we apply a Voronoi tessellation analysis (e.g. [Ebeling & Wiedenmann 1993]) to the field surrounding our radio galaxy to identify potential galaxy group members. The strength of the method is that no a-priori assumptions need to be made about cluster/group properties, making the technique sensitive to non-symmetric (e.g. elongated) structures.
We then evolved the sequence back over time to the red sequence in nearby clusters (Bower, Lucey & Ellis 1992) and updated treatment of thermally pulsating AGB stars. We fitted use the Bruzual & Charlot (2003) population synthesis code with (see e.g. Smolčić et al. 2007; Oklopčić et al. 2010). We first se-

### Table 2. Observed X-ray flux of the EC dominated X-ray candidate compared with expected fluxes of IC emission of the hotspots and lobes (see Sec. 6.1 & 6.2, and thermal emission of the group (see Sec. 6.3).

| OBSERVABLES      | S1.4 GHz [mJy] | α_X | S0.5–2 keV [10^{-15} erg s^{-1} cm^{-2}] | α_X | DERIVED PROPERTIES |
|------------------|----------------|-----|----------------------------------------|-----|-------------------|
| RADIO LOBES      | 58.1 ± 0.5     | -(1.0 ± 0.2) | 2.7 ± 0.7                              | -(1.6 ± 0.5) | 10 ± 2 |
| RADIO HOTSPOTS   | 54.8 ± 0.5     | -(0.7 ± 0.2) | 1.4 ± 1.2                              | 53 ± 2 | (2.5 ± 0.5)_EC   |
| ASSOCIATED GROUP |                |     |                                        |      | (0.4 ± 0.1)_thermal |

### Figure 6. Voronoi tessellation in the area of the EC dominated X-ray candidate. The candidate is marked with the red circle, while the galaxies from the photo-z catalogue are shown as black dots. Green regions correspond to masked-out regions around saturated object in the images used for the photo-z catalogue. We have identified 37 galaxies in the immediate surrounding of the X-ray-emitting lobe candidate.
X-ray fluxes arising from the radio lobes and hotspots, and separately from the gas of the optically identified group. We discuss the implications of the results in Sec. 6.4.

There are two processes involving IC scattering that can result in X-ray emission from a radio source: (i) synchrotron self-Compton (SSC) emission, which results from IC scattering of synchrotron radiation by the same relativistic electrons that produce the synchrotron radiation; and (ii) IC scattering of CMB photons on synchrotron emitting electrons (external Compton, EC). In the high-luminosity hotspots, where the electron density is high, the dominant process is usually SSC (Hardcastle et al. 2004). However, low-luminosity hotspots show X-ray emission that is much brighter than would be expected by SSC process indicating additional component of the X-ray emission (Hardcastle et al. 2004). In the lobes the electron density is much lower than in the hotspots, so IC scattering typically dominates over SSC (Croston et al. 2004). Kataoka & Stawarz (2005) and make the following assumptions: (i) the minimum energy condition; (ii) lobes have a cylindrical shape with radius $R$ and length $l$; (iii) equal energy densities carried by protons and electrons in the lobes ($k = 1$); (iv) no relativistic beaming ($\delta = 1$); and (v) the volume of the lobes to be completely filled with the plasma ($\eta = 1$). Then, we write the ratio between the radio and EC X-ray luminosity, which equals to the ratio between the CMB photon energy density and the magnetic field energy density (both calculated in the rest frame of the emitting region), i.e., $L_{\text{EC}}/L_{\text{R}} \approx u_{\text{CMB}}/u_B$ (e.g. Rybicki & Lightman 1986). The CMB photon energy density in the rest frame is $u_{\text{CMB}} = 4.1 \cdot 10^{-13}(1 + z)^4$ erg cm$^{-3}$ (e.g. Kataoka & Stawarz 2005) and $u_B$ is calculated in Sec. 4.2.1.

However, to be able to compare the predicted EC emission with the observed X-ray emission, we need to estimate the flux arising from the EC process in the observed 0.5–2 keV band. In the EC process, electrons upscatter CMB photons to frequencies peaked at $\nu_{\text{EC}}$, which is, in the Thomson regime and the frame of observer, given by (e.g. Kataoka & Stawarz 2005; Kataoka & Stawarz 2005):

$$ \nu_{\text{EC}} = \frac{4}{3} \gamma^2 \nu_{\text{CMB}}(1+z)^{-1}, $$

where $\nu_{\text{CMB}} = 1.6 \cdot 10^{11} (1 + z)$ [Hz] is the frequency of the CMB photons, and

$$ \gamma = \sqrt{\frac{2\pi m_e c \nu_{\nu}}{e B}}, $$

is the Lorenz factor of electrons emitting synchrotron radiation at frequency $\nu_{\nu}$ ($m_e = 9.109 \cdot 10^{-31}$ kg is the electron mass and $e = 1.602 \cdot 10^{-19}$ C is the elementary charge). Then, assuming a power law with a spectral index $\alpha_X \simeq \alpha_{\nu}$ (see Sec. 4.2), we calculate the X-ray flux, $S_X$, at frequency $\nu_X$ by extrapolating the flux $S_{\nu_C}$ at frequency $\nu_C$ (Stawarz, Sikora & Ostrowski 2003):

$$ L_{\text{EC}}/L_{\nu_C} = \frac{\nu_{\nu C} S_{\nu C}}{\nu_X S_X} = \frac{\nu_X S_X}{\nu_{\nu C} S_{\nu C}} \left( \frac{\nu_{\nu C}}{\nu_X} \right)^{1-\alpha_{\nu}} \approx \frac{u_{\text{CMB}}}{u_B}, $$

where $S_{\nu_C}$ is the observed radio flux at frequency $\nu_C$. Finally, we integrate $S_X$ obtained from Eq. 4 over the observed X-ray band (0.5 to 2 keV).

Given the observed/derived properties of the lobes ($\gamma = (1.0 \pm 0.2) \cdot 10^4$, $\nu_{\text{EC}} = (2.3 \pm 0.7) \cdot 10^{19}$ Hz, and see Table 2), the resulting integrated EC flux of the lobes in the 0.5 to 2 keV band is $(2.5 \pm 0.5) \cdot 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. The errors are propagated from uncertainties on $S_{1.4 \, \text{GHz}}, \alpha_{\nu}, z$, and $B_{\text{eq}}$.

6.2 IC scattering in the radio hotspots

To estimate the SSC and EC emission coming from the hotspots, we follow the same procedure as in Sec. 6.1, and make the same implications of the results in Sec. 6.4.
assumptions (i)-(v). Note that for the hotspots we do not assume a cylindrical shape but a spherical shape with radius $R$. For the SSC emission Eq.\[4\] becomes:

$$\frac{L_{SSC}}{L_X} = \frac{\nu X S_{SSC}}{\nu X S_X} = \frac{\nu X S_X}{\nu X S_{SSC}} \left( \frac{\nu X}{\nu S_{SSC}} \right)^{1+\alpha} \approx \frac{u_{\text{syn}}}{u_B},$$

where $\nu_{SSC} = 4/3\gamma^2\nu_R$ and $u_{\text{syn}}$ is the synchrotron photon energy density given in the rest frame of the emitting region by $u_{\text{syn}} = (d^2\nu/v_S)/R^2c$.

Given the observed/derived properties of the hotspots ($\gamma = (4.5\pm0.1)\cdot10^3$, $\nu_{SSC} = (4\pm1)\cdot10^{-16}$ Hz, $\nu_{EC} = (4\pm2)\cdot10^{-18}$ Hz, and see Table\[3\]), the resulting integrated X-ray flux of the hotspots in the 0.5 to 2 keV band is $(8\pm2)\cdot10^{-19}$ erg s$^{-1}$ cm$^{-2}$ for SSC emission and $(4\pm1)\cdot10^{-17}$ erg s$^{-1}$ cm$^{-2}$ for EC emission. The errors are propagated from uncertainties on $S_{14}$ GHz, $\alpha$, $z$, and $B_{eq}$.

### 6.3 Thermal gas emission of the group

In Sec\[5\], we have identified a galaxy overdensity around the large radio galaxy. Here we predict the X-ray flux arising from the hot gas of the group in the following way. We scale the total stellar mass of the group $M_* = 10^{12} M_\odot$, estimated in Sec.\[5\] via the Voronoi tessellation analysis, to the total mass $M_{500}$ (i.e., the total mass within the radius at which the density is 500 times the critical density) using a robust correlation (Giodini et al.\[2009\]):

$$M_* = A \left( \frac{M_{500}}{5 \cdot 10^{13} h_{70}^{-1}} \right)^{-\alpha},$$

where $\log_{10} A = 0.3 \pm 0.02$ and $\alpha = 0.81 \pm 0.11$. The resulting total mass of the group is $M_{500} = (2.1 \pm 0.3) \cdot 10^{13} M_\odot$.

Then, we calculate the X-ray luminosity of the group based on the luminosity-mass $L_X - M$ relation obtained via a weak lensing analysis in the COSMOS field (Leauthaud et al.\[2010\]):

$$M_{200}(z) E(z) = B \left( \frac{L_X E(z)}{10^{44.7} \text{erg s}^{-1}} \right) \beta,$$

where $\log_{10} B = 0.106 \pm 0.0053$, $\beta = 0.56 \pm 0.12$, $E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_L} = 1.866$ for the cosmology assumed here and $z = 1.168$, and $M_{200}$ is the mass within a radius encompassing 500 times the critical density. Note that for the previous calculation $M_{500}$ (the mass within a radius at 200 times the critical density) was used. We can convert $M_{500}$ to $M_{200}$ assuming a NFW profile with a constant concentration parameter ($c = 5$). This yields an X-ray luminosity of $(1.1 \pm 0.3) \cdot 10^{43}$ erg s$^{-1}$. Systematic uncertainty in estimating this number is dominated by the scatter in the stellar mass - total mass relation and is a factor of 2. The resulting X-ray flux in the 0.5–2 keV band, due to hot gas emission of the group, is then $(4\pm1)\cdot10^{-16}$ erg s$^{-1}$ cm$^{-2}$ in the circular area centered on the radio galaxy and encompassing the radio lobes. When calculating the flux we took into account the $L_X - T$ relation to derive the K-correction, following the prescription in Finoguenov et al.\[2007\]. This is consistent with the marginal X-ray detection of the group emission of $14 \pm 12 \cdot 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, reported in Sec.\[4\].

[1] Giodini et al.\[2009\] combined stellar mass estimates in 118 galaxy groups in the COSMOS field with the weak lensing measurements of the group total mass obtained by Leauthaud et al.\[2010\].

### 6.4 Comparison of thermal and non-thermal X-ray emission

The observed X-ray flux of the EC dominated X-ray candidate is compared in Table\[2\] to the fluxes expected from EC emission of the lobes and hotspots (see also Fig.\[8\]), as well as the thermal emission of the group. From Table\[2\] one can see that thermal emission of the group is almost an order of magnitude lower than what is observed. Therefore, it is very likely that the observed X-ray emission of our EC dominated X-ray candidate is mostly produced by the EC process in the lobes with only a small contribution arising from the thermal emission of the group. The sum of the two agrees within the error with the observed emission. Note that the total flux expected from SSC and EC emission of the hotspots is two orders of magnitude smaller than the observed emission and thus can be ignored.

As presented in Sec.\[4.1\] the EC dominated X-ray candidate clearly shows extended X-ray emission associated only with the lobes of the radio galaxy, and exhibiting a hard X-ray spectrum. Both of these results support the idea that the X-ray emission from the lobes of the radio galaxy predominantly arises from non-thermal IC scattering, rather than thermal group emission.

Based on our optical analysis we have unambiguously associated a galaxy overdensity with the large radio galaxy, i.e., the EC dominated X-ray candidate. Our results suggest that the distribution of the group galaxies is irregular, i.e., inconsistent with that in relaxed groups or clusters. Furthermore, the optical host of the radio galaxy is found to be a likely merging (double nucleus) source. This resembles the case of 3C 356 at $z = 1.08$ (Simpson & Rawlings\[2002\]). Identifying two sub-clusters associated with 3C 356, and combining their results with the studies of other powerful radio galaxies, Simpson & Rawlings\[2002\] suggested that triggering of powerful radio galaxies (at least at $z \sim 1$) is related to galaxy-galaxy interaction which can be coordinated by sub-cluster mergers. The unrelaxed state of the X-ray lobe overdensity and the
double-nucleus host of the radio galaxy seem to be consistent with this scenario.

To date 6 extended X-ray sources, where the X-ray emission is not dominated by thermal group/cluster emission, at $z > 1$ have been studied in deep X-ray surveys (Geach et al. 2007; Vardoulaki et al. 2008; Iu et al. 2009; Finoguenov et al. 2010). As the CMB energy density is proportional to $(1+z)^2$, the number of extended X-ray sources emitting via inverse Compton scattering of CMB photons off the relativistic synchrotron electrons is expected to rise with redshift. This may affect samples of X-ray selected galaxy clusters/groups in deep X-ray surveys, which are regularly based on extended X-ray emission. The contribution of extended non-thermal (EC) sources to such samples is still an open issue. This is addressed in Sec. 7.

7 EXPECTED X-RAY–COUNTS FROM SYNCHROTRON LOBES

Celotti & Fabian (2004) have studied the contribution of IC-related X-ray emission in the universe in comparison to that of cluster/group emission. They have shown that IC scattered X-ray emission may dominate that of galaxy clusters/groups above redshifts of 1 and X-ray luminosities of $10^{44}$ erg/s. In the 24” COSMOS field, searching over all (∼300) extended X-ray sources with X-ray flux $S_X \geq 6 \times 10^{-16}$ erg/s/cm² we have found only one X-ray candidate where the X-ray emission may arise from IC scattering, rather than thermal ICM emission. In the following we compute how many of such sources we would expect in the COSMOS field, and generally in deep X-ray surveys.

First we need to determine the radio luminosity function (LF) to use for this analysis. Willott et al. (2001) have generated radio LFs for the two main types of radio AGN – high radio-power (predominantly FR Is; high-excitation sources) and low radio-power (predominantly low-excitation FR I and FR IIs). The shape of the LFs, as well as their evolution is significantly different for the two (see Willott et al. 2001 for details; see also Smolčić et al. 2009). In order to estimate the number of expected extended X-ray sources on the sky, we start with the radio LF that best describes extended radio AGN, i.e. large radio galaxies.

In deep radio surveys such as the 20 cm VLA-COSMOS, that sample well the low-power radio AGN, the fraction of large radio galaxies relative to unresolved sources (at a resolution of 1.5”) is only ∼ 10% (Schinnerer et al. 2007; Smolčić et al. 2008, 2009). Furthermore, the mean radio power of these large radio galaxies is ∼ 9 × $10^{24}$ W/Hz, i.e. much higher than that for unresolved sources (∼ 3 × $10^{23}$ W/Hz; see e.g. Schinnerer et al. 2007; Smolčić et al. 2009). On the other hand, in shallower surveys that sample predominantly high radio-power AGN, such as e.g. the Third Cambridge Survey (with the average radio luminosity of sources from the 3CRR catalog of $10^{27}$ W/Hz sr at 151 MHz) the fraction of large radio galaxies relative to compact sources is substantially higher, i.e. ∼ 95%. Thus, we adopt the luminosity function of powerful radio AGN from Willott et al. (2001) to compute the number of extended X-ray sources on the sky.

We first compute the expected number of extended X-ray sources due to IC scattering of CMB photons (EC) in a 24” field (such as COSMOS) by evolving the LF for powerful radio AGN covering the range of $10^{25}$ to $10^{30}$ W/Hz (Willott et al. 2001) see also Smolčić et al. (2009). For each redshift we convert the radio luminosities to radio flux assuming a typical spectral index of $−0.75$. Assuming that the X-ray emission is caused by the EC process, we then compute the expected X-ray flux arising from EC-scattering as described in Sec. 6.1. Given our COSMOS detection thresholds in radio and X-rays, we then calculate the expected number of sources that could be detected above a radio flux of $S_r \geq 50 \mu$Jy (VLA-COSMOS detection limit) and an X-ray flux of $S_X \geq 6 \times 10^{-16}$ erg/s/cm² (COSMOS X-ray group detection limit) in a 24” field. The differential and integrated number of expected EC X-ray sources is shown in Fig. 9. In a field like COSMOS with deep radio and X-ray observations, only one X-ray source where the emission arises from IC-scattered electrons of the CMB is expected. This is consistent with our systematic search for non-thermal extended X-ray sources which yielded only one EC dominated source (discussed in detail here).

Extending this line of reasoning further we can predict the IC X-ray counts as a function of X-ray flux. Again, evolving the radio luminosity function for powerful radio galaxies (10$^{25}$–10$^{30}$ W/Hz; Willott et al. 2001) in a redshift range 0 < $z$ < 6, we compute the total expected number of EC (extended) X-ray sources per deg$^2$ of sky. However, unlike in the calculation above, no radio X-ray limit is imposed here. The differential and cumulative counts are shown in Fig. 10. The peak in the differential source counts (that corresponds to the flattening in the cumulative counts) at $L_X \sim 5 \times 10^{-14}$ erg/s/cm² is due to the shape of the radio luminosity function for powerful radio galaxies that has a strong peak at $L_{20,\mu m} \sim 10^{27}$ W/Hz (see Smolčić et al. 2009). Thus the major contribution to the X-ray counts arises from such galaxies at redshifts 1–3. On the other hand, the number density of $z > 1$ extended X-ray sources in the COSMOS field is $\sim 20$ per deg$^2$. Thus the expected ∼ 0.5 non-thermal X-ray extended source per deg$^2$ (under the assumption that the underlying radio LF is correct) are not likely to dominate samples of extended (thermal) X-ray sources, i.e. clusters/groups in deep X-ray surveys. To investigate this further, following Finoguenov et al. (2010), we have also computed the source counts for clusters in the redshift range of 1 < $z$ < 3 (dashed line in Fig. 10). As one can see from Fig. 10 the number of high-z clusters becomes comparable to that of high-z radio galaxies at fluxes exceeding $7 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. Thus, EC dominated X-ray sources may produce a serious contamination for the upcoming eROSITA survey (Predehl et al. 2010).

8 SUMMARY AND CONCLUSIONS

In the COSMOS field we have carried out a systematic search for non-thermal extended X-ray sources, i.e. sources in which the X-ray emission is mostly arising due to IC scattering of CMB photons off electrons in the radio lobes (EC process), rather than thermal emission from the hot gas in the galaxy cluster/group. Based on a concurrence of morphological structures in the radio and X-ray images, we have found only one candidate.

The radio counterpart of our candidate is a large powerful radio galaxy ($L_r = 6.7 \times 10^{38}$ W) hosted by a double-nuclei galaxy at $z = 1.1684$. The observed X-ray emission ($S_{0.5-2}$ keV = (3.6 ± 1.2) $\times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$) is extremely elongated in the direction of the radio lobes (see Fig. 1), suggesting a non-group origin. In order to identify the origin of the X-ray emission in our source, we have performed a detailed analysis of the expected X-ray emission arising from inverse Compton emission in the radio lobes, the hotspots, as well as that expected from the group environment of the radio galaxy. We find that External Inverse Compton emission of the lobes is the dominant process that generates the observed X-ray emission of our candidate (see Fig. 8), with a minor
Figure 9. The top (bottom) panel shows the expected differential (cumulative) number of X-ray-emitting lobes in the COSMOS 2° field, drawn from the evolving luminosity function of powerful radio AGN [Willott et al. 2001] covering the range of $10^{25}$ to $10^{30}$ W/Hz; see text for details.

contribution from the intragroup gas of the galaxy group associated with the radio galaxy.

Making use of the radio luminosity function for powerful radio galaxies, we have estimated the expected number of extended non-thermal X-ray sources (due to Inverse Compton scattering of CMB photons off the synchrotron electrons) on the sky as a function of X-ray flux. In a 2° field, such as COSMOS, we expect to find only one such source, consistent with our results. Furthermore, our analysis shows that such sources (in a redshift range $0 < z < 6$ and with radio luminosity between $10^{25}$ and $10^{30}$ W/Hz) are not expected to be a significant contaminant of deep X-ray selected cluster/group catalogs, but they dominate the $z > 1$ cluster counts at the bright end ($S_X > 7 \cdot 10^{-15}$ erg s$^{-1}$ cm$^{-2}$).

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Figure 10. Differential (top panel) and cumulative (bottom panel) number counts (per 2°) as a function of X-ray flux expected for extended inverse Compton X-ray sources (solid lines) and for clusters (dashed line). The radio counts were obtained by evolving the radio luminosity function for powerful (FR II) radio galaxies [Willott et al. 2001] covering the range of $10^{25}$ to $10^{30}$ W/Hz; see text for details, while the cluster counts, in the redshift range of $1 < z < 3$, were obtained following Finoguenov et al. (2010).

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