Complex particle acceleration processes in the hotspots of 3C 105 and 3C 445

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ABSTRACT

We investigate the nature of the broad-band emission associated with the low-power radio hotspots 3C 105 South and 3C 445 South. Both hotspot regions are resolved in multiple radio/optical components. High-sensitivity radio Very Large Array, near-infrared/optical Very Large Telescope and Hubble Space Telescope (HST) and X-ray Chandra data have been used to construct the multiband spectra of individual hotspot components. The radio-to-optical spectra of both hotspot regions are well fitted by a synchrotron model with steep spectral indices $\sim 0.8$ and break frequencies between $10^{12}$ and $10^{14}$ Hz. 3C 105 South is resolved in two optical components: a primary one, aligned with the jet direction and possibly marking the first jet impact with the surrounding medium, and a secondary, further out from the jet and extended in a direction perpendicular to it. This secondary region is interpreted as a splatter-spot formed by the deflection of relativistic plasma from the primary hotspot. Radio and optical images of 3C 445 South show a spectacular 10-kpc arc-shape structure characterized by two main components, and perpendicular to the jet direction. HST images in $I$ and $B$ bands further resolve the brightest components into thin elongated features. In both 3C 105 South and 3C 445 South, the main hotspot components are enshrouded by diffuse optical emission on scale of several kpc, indicating that very high energy particles, possibly injected at strong shocks, are continuously re-accelerated in situ by additional acceleration mechanisms. We suggest that stochastic processes, linked to turbulence and instabilities, could provide the required additional re-acceleration.

Key words: acceleration of particles – radiation mechanisms: non-thermal – radio continuum: galaxies.

1 INTRODUCTION

Radio hotspots are bright and compact regions located at the end of powerful radio galaxies [Fanaroff–Riley type II (FR II) galaxies; Fanaroff & Riley (1974)] and considered to be the working surfaces of supersonic jets. In these regions, the jet emitted by the active galactic nucleus (AGN) impacts on the surrounding ambient medium producing a shock that may re-accelerate relativistic particles transported by the jet and enhance the radio emission. Electrons responsible for synchrotron emission in the optical band must be very energetic (Lorentz factor $\gamma > 10^5$), and therefore with short radiative lifetime. Consequently, the detection of optical emission from hotspots supports the scenario where the emitting electrons are accelerated at the hotspots, possibly by strong shocks generated by the impact of the jet with the ambient medium (Meisenheimer et al. 1989; Meisenheimer, Yates & Röser 1997; Brunetti et al. 2003). The detection of X-ray synchrotron counterparts of radio hotspots would imply the presence of electrons with even higher energies. However, the main radiation process responsible for the X-ray emission seems to differ between high- and low-luminosity hotspots (Hardcastle et al. 2004). In bright hotspots, like Cygnus A and 3C 295, the X-ray emission is produced by synchrotron self-Compton (SSC) in the presence of a magnetic field that is roughly in equipartition, while in low-luminosity hotspots, like 3C 390.3, the emission at such high energies is likely due to synchrotron radiation (Hardcastle, Croston & Kraft 2007).
The discovery of optical emission extended to kpc scale questions the standard shock acceleration model, suggesting that other efficient mechanisms must take place across the hotspot region. Although it may seem an uncommon phenomenon due to the difficulty to produce high-energy electrons on large scales, deep optical images showed that diffuse optical emission is present in a handful of hotspots: 3C 33, 3C 111, 3C 303, 3C 351 (Lähteenmäki & Valtaoja 1999), 3C 390.3 (Prieto & Kotilainen 1997), 3C 275.1 (Cheung, Wardle & Chen 2005), Pictor A (Thomson, Crane & MacKay 1995) and 3C 445 (Prieto, Brunetti & Mack 2002). A possible mechanism able to keep up the optical emission in the post-shock region on kpc scale is a continuous, relatively efficient, stochastic mechanism.\footnote{More recently, these stochastic mechanisms have been also proposed for the acceleration of ultrahigh energy cosmic rays in the lobes of radio galaxies (Hardcastle et al. 2009).}

The sample of low-power hotspots presented by Mack et al. (2009) is characterized by low magnetic field strengths between 40 and 130 \(\mu\)G, a factor 2–5 lower than that estimated in hotspots with optical counterparts previously studied in the literature. A surprisingly high optical detection rate (>45 per cent) of the hotspots in this sample was found, and in most cases, the optical counterpart extends on kpc scales. This is the case of 3C 445 South, 3C 445 North, 3C 105 South and 3C 227 West (Mack et al. 2009).

This paper focuses on a multiband, from radio to X-rays, high spatial resolution study of the two most interesting cases among the low-luminosity hotspots from Mack et al. (2009), 3C 105 South and 3C 445 South, in which the hotspot regions are resolved into multiple components. 3C 105 is hosted by a narrow-line radio galaxy (NLRG) at redshift \(z = 0.089\) (Tadhunter et al. 1993). At this redshift, 1 arcsec corresponds to 1.642 kpc. The radio source 3C 105 is about 330 arcsec (542 kpc) in size, and the hotspot complex 3C 105 South is located about 168 arcsec (276 kpc) from the core in the south-east (SE) direction. 3C 445 is hosted by a broad-line radio galaxy (BLRG) at redshift \(z = 0.0562\) (Eracleous & Halpern 1994). At this redshift, 1 arcsec corresponds to 1.077 kpc. The radio source 3C 445 is about 562 arcsec (608 kpc) in size, and the hotspot complex 3C 445 South is located 270 arcsec (291 kpc) south of the core.

Throughout this paper, we assume the following cosmology: \(H_0 = 71\) km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_M = 0.27\) and \(\Omega_L = 0.73\), in a flat Universe. The spectral index is defined as \(S(\nu) \propto \nu^{-\alpha}\).

2 OBSERVATIONS

2.1 Radio observations

Very Large Array (VLA) observations at 1.4, 4.8 and 8.4 GHz of the radio hotspots 3C 445 South and 3C 105 South were carried out in 2003 July (project code AM772) with the array in A configuration. Each source was observed for about half an hour at each frequency, spread into a number of scans interspersed with other source/calibrator scans in order to improve the uv-coverage. About 4 min were spent on the primary calibrator 3C 286, while secondary phase calibrators were observed for 1.5 min about every 5 min. Data at 1.4 and 4.8 GHz were previously published by Mack et al. (2009). The data reduction was carried out following the standard procedures for the VLA implemented in the National Radio Astronomy Observatory (NRAO) AIPS package. Final images were produced after a few phase-only self-calibration iterations. The rms noise level on the image plane is negligible if compared to the uncertainty of the flux density due to amplitude calibration errors that, in this case, are estimated to be \(\sim 3\) per cent.

Besides the full-resolution images, we also produced low-resolution images at both 4.8 and 8.4 GHz, using the same uv-range, image sampling and restoring beam of the 1.4-GHz data. These new images were obtained with natural grid weighting in order to mitigate the differences in the sampling density at short spacing and to perform a robust spectral analysis.

2.2 Optical observations

For both 3C 105 South and 3C 445 South, Very Large Telescope (VLT) high spatial resolution images in standard filters taken with both Infrared Spectrometer and Array Camera (ISAAC) in \(J\), \(H\), \(K\) bands and Focal Reducer and Low Dispersion Spectrograph (FORS) in \(I\), \(R\) and \(B\) bands are used in this work. All the images have excellent spatial resolutions in the range of 0.5 arcsec < FWHM < 0.7 arcsec. Details on the observations and data reduction are given in Mack et al. (2009). The pixel scale of the ISAAC images is 0.14 arcsec pixel\(^{-1}\). In the case of the FORS images, the pixel scale is 0.2 arcsec pixel\(^{-1}\), with the exception of the \(I\) band where it is 0.1 arcsec pixel\(^{-1}\).

Further Hubble Space Telescope (HST) observations on 3C 445 South only were obtained with the ACS/HRC camera on 2005 July 7 in the filters F814W (\(I\) band, exposure time \(\sim 1.5\) h) and F475W (\(B\) band, exposure time \(\sim 2.3\) h).

For science analysis, we used the ‘*drz*’ images delivered by the HST ACS pipeline. These final images are calibrated, cosmic ray cleaned, geometrically corrected and drizzle-combined, provided in electrons per second. The final pixel scale of the drizzled images is 0.025 \(\times\) 0.025 arcsec\(^2\) pixel\(^{-1}\). The flux calibration was done using the standard HST/ACS procedure that relies on the PHOTFLAM key word in the respective image headers. The quality of the pipeline-delivered images was adequate for the purposes of analysing the hotspot region.

2.3 X-ray observations

The radio source 3C 105 was observed by Chandra on 2007 December 17 (Obs ID 9299) during the Chandra 3C Snapshot Survey for Sources with \(z < 0.3\) arcsec (Massaro et al. 2010). An \(\sim 8\) ks exposure was obtained with the ACIS-S camera, operating in very faint mode. The data analysis was performed following the standard procedures described in the Chandra Interactive Analysis of Observations (CIAO) threads and using the CIAO software package V4.2 (see Massaro et al. 2009, for more details). The Chandra Calibration Database (CALDB) version 4.2.2 was used to process all files. Level 2 event files were generated using the acis_process_events task after removing the hot pixels with acis_run_hotpix. Events were filtered for grades 0, 2, 3, 4, 6, and we removed pixel randomization.

3C 445 South was observed by Chandra on 2007 October 18 (Perlman et al. 2010), ACIS chip S3, with an exposure time of 45.6 ks. The data were retrieved from the archive and analysed following the same procedure as for 3C 105 South. This re-analysis was necessary in order to achieve a proper alignment with the radio data.

We created three different flux maps in the soft, medium and hard X-ray bands (0.5–1, 1–2 and 2–7 keV, respectively) by dividing the data with monochromatic exposure maps with nominal energies = 0.8 keV (soft), 1.4 keV (medium) and 4 keV (hard). Both the exposure maps and the flux maps were regridded to a pixel size of 0.25 the size of a native ACIS pixel (native = 0.492 \(\times\) 0.492 arcsec\(^2\)).
To obtain maps with brightness units of erg cm\(^{-2}\) s\(^{-1}\) pixel\(^{-1}\), we multiplied each event by the nominal energy of its respective band.

For 3C 445 South, we measured a flux density consistent with what was reported by Perlman et al. (2010). The flux density was extracted from Chandra ACIS-S images in which the hotspot was placed on axis. Both hotspots have been detected also by Swift in the energy range 0.3–10 keV (see Appendix A). This is remarkable given Swift’s survey operation mode and its poor spatial resolution. The detection level is about 7σ and 12σ for 3C 105 South and 3C 445 South, respectively. However, given the large Swift errors in the counts-to-flux conversion and its low angular resolution, we do not provide any further flux estimate.

### 2.4 Image registration

The alignment between radio and optical images was done by the superposition of the host galaxies with the nuclear component of the radio source using the AIPS task LGEOM. This results in a shift of 3.5 arcsec. To this purpose, the optical images were previously brought on the same grid, orientation and coordinate system as the radio images by means of the AIPS tasks CONV and REGR (see also Mack et al. 2009). The final overlay of radio and optical images is accurate to 0.1 arcsec.

For 3C 105 South, the X-ray image has been aligned with the radio one by comparing the core position. Then, the final overlay of X-ray contours on the VLT image is accurate to 0.1 arcsec. In the case of 3C 445, the shape of the nucleus of the galaxy is badly distorted in the Chandra image because of its location far off-axis of Chandra. The alignment was then performed using three background sources visible both in X-ray and B band, and located around the hotspot. The achieved accuracy with this registration is better than 0.15 arcsec, allowing us to confirm a shift of about 2 arcsec in declination between the X-rays and B-band emission centroids, the X-ray one being the closest to the core (Fig. 2).

### 3 PHOTOMETRY

To construct the spectral energy distribution (SED) of individual hotspot components, the flux density at the various wavelengths must be accurately measured in the same region, avoiding contamination from unrelated features. To this purpose, we produced a cube where each plane consists of radio and optical images regridded to the same size and smoothed to the same resolution. Then the flux density was derived by means of AIPS task BLSUM which performs an aperture integration on a selected polygonal region common to all the images. The values derived in this way were then used to construct the radio-to-optical SED, and they are reported in Tables 1 and 2.

In addition to the low-resolution approach, we derive the hotspot flux densities and angular sizes on the full-resolution images in order to better describe the source morphology.

On the radio images, we estimate the flux density of each component by means of TVSTAT, which is similar to BLSUM, but instead of working on an image cube it works on a single image. The angular size was derived from the lowest contour on the image plane.

#### Table 1. Radio flux density and angular size of the hotspot components.

| Source | Comp. | \(z\) | Scale \((\text{kpc arcsec}^{-1})\) | \(S_{1.4}\) \((\text{mJy})\) | \(S_{1.4}\) \((\text{mJy})\) | \(\theta_{\text{maj}}\) \((\text{arcsec})\) | \(\theta_{\text{min}}\) \((\text{arcsec})\) |
|--------|-------|------|-------------------------------|-----------------|-----------------|-----------------|-----------------|
| 3C 105 | S1\(^a\) | 0.089 | 1.642 | 130 ± 10 | 67 ± 5 | 45 ± 5 | 1.0 | 0.8 |
|        | S2\(^a\) |       |       | 1250 ± 40 | 620 ± 20 | 460 ± 15 | 1.30 | 1.0 |
|        | S3\(^a\) |       |       | 1180 ± 35 | 510 ± 15 | 320 ± 12 | 1.5 | 0.8 |
|        | Ext |       |       | 174 ± 10 | 75 ± 5 | 50 ± 3 |       |       |
| 3C 445 | SE\(^b\) | 0.0562 | 1.077 | 290 ± 30 | 98 ± 15 | 65 ± 10 | 3.5 | 1.0 |
|        | SW |       |       | 220 ± 25 | 51 ± 10 | 36 ± 6 | 1.5 | 0.5 |
|        | Diff\(^c\) |       |       |       |       | 13.0 ± 1.1 |       |       |

\(^a\)Deconvolved angular sizes from a Gaussian fit.

\(^b\)The angular sizes are derived from the lowest contour on the image plane.

\(^c\)The diffuse emission is estimated by subtracting the flux density of SW and SE from the total flux density (see Section 5.3).

#### Table 2. NIR, optical flux density and X-ray (0.5–7 keV) flux of hotspot components. In the case of 3C 445, the X-ray flux is not associated with any of the two main components. The X-ray flux reported refers to the total emission measured on the whole hotspot region.

| Source | Comp. | \(S_K\) \((\text{µJy})\) | \(S_H\) \((\text{µJy})\) | \(S_I\) \((\text{µJy})\) | \(S_J\) \((\text{µJy})\) | \(S_L\) \((\text{µJy})\) | \(S_B\) \((\text{µJy})\) | \(S_V\) \((\text{µJy})\) | \(S_{\text{J}^{\text{ext}}}\) \((\text{µJy})\) | \(S_{\text{H}^{\text{ext}}}\) \((\text{µJy})\) | \(S_X\) |
|--------|-------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|
| 3C 105 | S1 | 4.6 ± 0.9 | 4.4 ± 1.1 | <2.5 | – | 0.5 ± 0.1 | 0.2 ± 0.1 | – | – | – | 7.5 ± 2.4\(^a\) |
|        | S2 | 18.4 ± 1.4 | 12.3 ± 1.1 | 3.4 ± 1.0 | – | 0.7 ± 0.1 | 0.2 ± 0.1 | – | – | – | <2.0\(^b\) |
|        | S3 | 31.9 ± 2.8 | 25.7 ± 2.9 | 4.4 ± 1.8 | – | 0.9 ± 0.1 | 0.3 ± 0.1 | – | – | – | 3.2 ± 1.6\(^a\) |
|        | Ext | 15.4 ± 2.0 | 5.4 ± 2.0 | – | – | 0.4 ± 0.1 | 0.2 ± 0.1 | – | – | – | – |
| 3C 445 | SE | 8.0 ± 1.0 | 5.6 ± 2.0 | 6.0 ± 1.5 | 2.0 ± 0.2 | 1.3 ± 0.2 | 0.7 ± 0.1 | 0.5 ± 0.3 | 1.7 ± 0.2 | 1.5 ± 0.3 | 9.38 × 10\(^{-4}\)\(^b\) |
|        | SW | 4.6 ± 1.4 | 3.6 ± 1.5 | 3.0 ± 0.4 | 1.7 ± 0.3 | 1.4 ± 0.1 | 0.7 ± 0.1 | 0.5 ± 0.2 | 1.4 ± 0.1 | 0.3 ± 0.1 | – |
|        | SC | – | – | – | – | 0.8 ± 0.1 | 0.6 ± 0.1 | 0.4 ± 0.1 | 0.6 ± 0.1 | – | – |
|        | Diff\(^c\) | – | 2.1 ± 0.6 | 3.2 ± 1.3 | 1.2 ± 0.2 | 1.0 ± 0.2 | 0.8 ± 0.2 | – | – | – | – |

\(^a\)Units in 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) \(\text{µJy}\).

\(^b\)The X-ray value, in µJy, is from Perlman et al. (2010).

\(^c\)The diffuse emission is inclusive of the SC component, and it is estimated by subtracting from the total flux density those arising from SW and SE (see Section 5.3).

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and it corresponds to roughly twice the size of the full width half-
maximum (FWHM) of a conventional Gaussian covering a similar
area. In the case of 3C 105 South, the hotspot components are unres-
solved at 1.4 GHz, and we derive the flux density at this frequency
by means of the task JMFIT, which performs a Gaussian fit in the
image plane. The angular size was measured on the images in which
the components were resolved, i.e. in the case of 3C 105 South, we
use the 4.8- and 8.4-GHz images, which provide the same value,
while for 3C 445 South, the components could be reliably resolved
in the image at 8.4 GHz only (Table 1).

Full-resolution infrared (IR) and optical flux densities of hotspot
subcomponents were measured by means of the mex-based task ATV
using a circular aperture centred on each component. Such values
were compared to those derived from the analysis of the cube, and
they were found to be within the expected uncertainties.

For the X-ray flux, we constructed photometric apertures to ac-
commodate the Chandra point spread function and to include the
total extent of the radio structures. The background regions, with
a total area typically twice that of the source region, have been
selected close to the source, and centred on a position where other
sources or extended structures are not present. The X-ray flux was
measured in any aperture with only a small correction for the ratio
of the mean energy of the counts within the aperture to the nominal
energy for the band. We note that in 3C 105 South, the hotspot com-
ponents are well separated (2 arcsec), allowing us to accurately iso-
late the corresponding X-ray emission. In 3C 445 South, the X-ray
emission is not associated with the two main components clearly
visible in the radio and optical bands, and flux was derived by
using an aperture large enough to include all of the X-ray emission
extending over the entire hotspot region. Our estimated value is in
agreement with the one reported by Perlman et al. (2010). All X-ray
flux densities have been corrected for the Galactic absorption with
the column density $N_H = 1.15 \times 10^{21} \text{cm}^{-2}$ given by Kalberla et al.
(2005). X-ray fluxes are reported in Table 2.

4 MORPHOLOGY

4.1 3C 105 South

The southern hotspot complex of 3C 105 shows a curved structure
of about $8 \times 4.5 \text{arcsec}^2$ ($\sim 13 \times 7 \text{kpc}^2$) in size. It is dominated
by three bright components, all resolved at radio frequencies, con-
nected by a low surface brightness emission also visible in optical
and IR (Fig. 1). The central component, labelled S2 in Fig. 1, is
the brightest in radio, and, when imaged with high spatial resolu-
tion, it is resolved in two different structures separated by about
1.2 kpc. Leahy et al. (1997) interpreted this as the true jet termina-
tion hotspot, while S1, with an elongated structure of (1.6 $\times$
1.3) kpc and located 5.7 kpc to the north of S2 is considered as jet
emission. The southernmost component S3, located about 4.1 kpc
from S2, has a resolved structure of (2.4 $\times$ 1.3) kpc in size, and it
is elongated in a direction perpendicular to the line leading to S2.
Its morphology suggests that S3 is a secondary hotspot similar to
3C 20 East (Cox, Gull & Scheuer 1991).

At 1.4 GHz, an extended tail accounting for $S_{1.4} = 608 \text{mJy}$ and
embedding the jet is present to the west of the hotspot complex,
in agreement with the structure previously found by Neff et al. (1995).
At higher frequencies, the lack of the short spacings prevents the
detection of such an extended structure, and only a hint of the jet,
accounting for $S_{1.8} \sim 70 \text{mJy}$, is still visible at 4.8 GHz.

In the optical and near-IR (NIR), the hotspot complex is charac-
terized by the three main components detected in radio. In NIR and
optical, the southernmost component S3 is the brightest one, with
a radio-to-optical spectral index $\alpha_{r-o} = 0.95 \pm 0.10$. It displays an
elongated structure rather similar in shape and size to that found in
radio. It is resolved in all bands with the only exception of $B$ band,
likely due to the lower spatial resolution achieved. Component S1 is
resolved in all NIR/optical bands, showing a tail extending towards
S2. Its radio-to-optical spectral index is $\alpha_{r-o} = 0.95 \pm 0.10$. On the
other hand, S2 appears unresolved in all bands, with the exception
of $K$ and $H$ bands, i.e. those with the highest resolution achieved.
In these NIR bands, S2 is extended in the southern direction, resem-
bling what is observed in radio. Its radio-to-optical spectral index
is $\alpha_{r-o} = 1.05 \pm 0.10$.

Diffuse emission connecting the main hotspot components and
extending to the south-western (SW) part of the hotspot complex is
detected in most of the NIR and optical images.

In the X-ray band, S1 is the brightest component, whereas the
emission from S3 is very weak (formally detected at only 2σ level).
For this reason, in the following, we will use the nominal X-ray
flux of S3 as a conservative upper limit. For component S2, only an
upper limit could be set.

4.2 3C 445 South

The hotspot 3C 445 South displays an extended east–west structure
of about $9.3 \times 2.8 \text{arcsec}^2 (10 \times 3 \text{kpc}^2)$ in size in radio (Fig. 2).
At 8.4 GHz, the hotspot complex is almost completely resolved out
and the two main components, clearly visible in NIR/optical images,
are hardly distinguishable. When imaged with enough resolution,
these components display an arc-shaped structure both in radio
and NIR/optical bands, with sizes of about (3.4 $\times$ 1.5) and (2.1 $\times$
1.1) kpc for SE and SW, respectively. Component SE is elongated
in a direction almost perpendicular to the line leading to the source
core, while SW forms an angle of about $\sim 20^\circ$ with the same line.

In radio and NIR, the SE component is the brightest one, with a
flux density ratio SE/SW $\sim 1.6$, while in the optical, both compo-
nents have similar flux densities. Both components have a radio-to-
optical spectral index $\alpha_{r-o} = 0.9 \pm 0.10$. In the optical $R$, $B$-
and $U$-band images, a third component (labelled SC in Fig. 2) aligned
with the jet direction becomes visible between SE and SW. Despite
the good resolution and sensitivity of the radio and NIR images,
SC is not present at such wavelengths. When imaged with the high
resolution provided by HST, both SE and SW are clearly resolved,
and no compact regions can be identified in the hotspot complex.
Trace of the SC component is seen in the $B$ band, in agreement with
the VLT images.

In the VLA and VLT images, the two main components are enshrouded by a diffuse emission, visible in radio and NIR/optical
bands. The flux densities of the SE and SW components measured
on the HST images are consistent (within the errors) with those
derived on the VLT images.

The optical component W located about 2.8 arcsec (3 kpc) on the
northwestern part of SW does not have a radio counterpart, as it
is clearly shown by the superposition of $I$-band HST and 8.4-GHz
VLA images (Fig. 3), and thus it is considered an unrelated ob-
ject, like a background galaxy. Another possibility is that this is a
synchrotron-emitting region where the impact of the jet produces
very efficient particle acceleration. However, its steep optical spec-
trum ($\alpha \sim 2$ between $I$ and $U$ bands; see Section 5.3, Fig. 10)
coincides with the absence of detected radio emission disfavours this
possibility. Future spectroscopic information would further unveil
the nature of this optical region.

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Figure 1. Multifrequency images of 3C 105 South. From the left to right and top to bottom: radio images at 1.4, 4.8 and 8.4 GHz (VLA A-array), NIR/optical images in K, H, J, R and B bands (VLT) and X-ray 0.5–7 keV (Chandra) contours. Each panel covers 9.5 arcsec (15.6 kpc) in Dec. and 14 arcsec (23 kpc) in RA. In the radio images, the lowest contours are 0.9 mJy beam\(^{-1}\) at 1.4 GHz, 0.20 mJy beam\(^{-1}\) at 4.8 GHz and 0.18 mJy beam\(^{-1}\) at 8.4 GHz, and they correspond to three times the off-source rms noise level measured on the image plane. Contours increase by a factor of 4. The restoring beam is 1.3 \times 1.1 arcsec\(^2\) at 1.4 GHz, 0.38 \times 0.36 arcsec\(^2\) at 4.8 GHz and 0.32 \times 0.22 arcsec\(^2\) at 8.4 GHz. In the optical images, the contour levels are in arbitrary units and increase by a factor of 2. The FWHM is about 0.4, 0.5, 0.7, 0.6 and 0.7 arcsec in K, H, J, R and B band, respectively. The X-ray contours were generated from a 0.5–7 keV image, smoothed with a Gaussian of FWHM \(\approx 0.72\) arcsec. Contour levels increase linearly: 0.02, 0.04, 0.06, ..., 0.14 counts per 0.123 arcsec pixel\(^{-1}\). The X-ray contours are superposed to the R-band image, previously shifted so as to align with X-ray.

Chandra observations of 3C 445 South detected X-ray emission from a region that extends over 6 arcsec in the east–west direction (Fig. 2), and it peaks almost in the middle of the hotspot structure, suggesting a spatial displacement between X-ray and radio/NIR/optical emission (Perlman et al. 2010).

5 SPECTRAL ENERGY DISTRIBUTION

5.1 The broad-band energy distribution

We model the broad-band energy distribution, from radio to optical, of the hotspot regions in order to determine the mechanisms at the basis of the emission. The comparison between the model expectation in the X-rays and Chandra data sets additional constraints. In the adopted models, the hotspot components are described by homogeneous spheres with constant magnetic field and constant properties of the relativistic electron populations. The SEDs of the emitting electrons are modelled assuming the formalism described in Brunetti et al. (2002). According to this model, a population of seed electrons (with \(\gamma \leq \gamma_s\)) is accelerated at the shock and is injected in the downstream region with a spectrum \(dN(\gamma)/dt \propto \gamma^{-p}\), for \(\gamma_s < \gamma < \gamma_c\), where \(\gamma_c\) being the maximum energy of the electrons accelerated at the shock. Electrons accelerated at the shock are advected in the downstream region and age due to radiative losses. Based on Brunetti et al. (2002), the volume-integrated spectrum of the electron population in the downstream region of size \(L \propto T_{\text{adv}}\) (\(T\) and \(v_{\text{adv}}\) being the age and the advection velocity of the downstream region) is given by either a steep power law \(N(\gamma) \propto \gamma^{-(p+1)}\) for \(\gamma_b < \gamma < \gamma_c\), where \(\gamma_b\) is the maximum energy of the ‘oldest’ electrons in the downstream region, or by \(N(\gamma) \propto \gamma^{-p}\) for \(\gamma_s < \gamma < \gamma_b\), or by a flatter shape for \(\gamma_b < \gamma < \gamma_{\text{low}}\), where \(\gamma_{\text{low}}\) is the minimum energy of electrons accelerated at the shock.

As the first step, we fit the SED in the radio–NIR–optical regimes with a synchrotron model, and we derive the relevant parameters of the synchrotron spectrum (injection spectrum \(\alpha\), break frequency \(\nu_b\), cut-off frequency \(\nu_c\)) and the slope of the energy distribution of the electron population as injected at the shock \((p = 2\alpha + 1)\). Since hotspots have spectra with injection slope \(\alpha\) ranging between 0.5 and 1 (as a reference, the classical value from the diffuse particle acceleration at strong shocks is \(\alpha = 0.5\); e.g. Meisenheimer et al. 2002).
Particle acceleration in 3C 105 and 3C 445

Figure 2. Multifrequency images of 3C 445 South. From the left to right and top to bottom: radio images at 1.4, 4.8 and 8.4 GHz (VLA A-array), NIR/optical images in $K$, $H$, $J$, $I$, $R$, $B$ and $U$ bands (VLT), optical images in $I$ and $U$ bands ($HST$) and X-ray 0.5–7 keV (Chandra) contours. Each panel covers 7.3 arcsec (7.8 kpc) in Dec. and 11.4 arcsec (12.2 kpc) in RA. In the radio images, the lowest contours are 1.3 mJy beam$^{-1}$ at 1.4 GHz, 0.20 mJy beam$^{-1}$ at 4.8 GHz and 0.10 mJy beam$^{-1}$ at 8.4 GHz, and they correspond to three times the off-source rms noise level measured on the image plane. Contours increase by a factor of 4. The restoring beam is $1.43 \times 0.96$ arcsec$^2$ at 1.4 GHz, $0.45 \times 0.37$ arcsec$^2$ at 4.8 GHz and $0.24 \times 0.21$ arcsec$^2$ at 8.4 GHz. In the optical images, the contour levels are in arbitrary units and increase by a factor of 2. The VLT FWHM are 0.7, 0.6, 0.5, 0.7, 0.6, 0.6 and 0.7 arcsec in $K$, $H$, $J$, $I$, $R$, $B$ and $U$ bands, respectively. In $HST$ images, each pixel is 0.025 arcsec. The X-ray contours in the last panel are superposed on the $B$-band image. They come from an 0.5–7 keV image, smoothed with a Gaussian of FWHM = 0.87 arcsec. Contour levels increase by a factor of 2; the lowest contour is at a brightness of 0.01 counts per 0.0615 arcsec pixel.

We decided to consider the injection spectral index as a free parameter. Such constraints allow us to determine the spectrum of the emitting electrons (normalization, break and cut-off energy), once the magnetic field strength has been assumed, and to calculate the emission from either SSC or inverse-Compton scattering of the cosmic microwave background radiation (IC-CMB) expected from the hotspot (or jet) region (following Brunetti et al. 2002). Models described in Brunetti et al. (2002) take also into account the boosting effects arising from a hotspot/jet that is moving at relativistic speeds and oriented at a given angle with respect to our line of sight.

5.2 3C 105 South

In Figs 4–6, we show the SED from the radio band to high-energy emission measured for the hotspot components of 3C 105 South, together with the model fits. Synchrotron models with an injection spectral index $\alpha = 0.8$ provide an adequate representation of the SED of the central and southern components of 3C 105 South, with break frequencies ranging from $5 \times 10^{12}$ to $1.5 \times 10^{13}$ Hz, while the cut-off frequencies are between $3 \times 10^{14}$ and $2 \times 10^{15}$ Hz. In both components, the upper limit to the X-ray emission does not allow us to constrain the validity of the SSC model (Figs 5 and 6). On the other hand, the northern component of 3C 105 shows a prominent X-ray emission. A synchrotron model (dashed line in Fig. 4) may fit quite reasonably the radio, NIR and X-ray emission, but it completely fails in reproducing the optical data. An additional contribution of the SSC is not a viable option since it requires a magnetic field much smaller than that obtained assuming equipartition (see Section 5.4) (solid lines), and implying an unreasonably large energy budget. On the other hand, the high-energy emission is well modelled by IC-CMB (e.g. Tavecchio et al. 2000; Celotti, Ghisellini & Chiaberge 2001) where the CMB photons are scattered by relativistic electrons with Lorentz factor $\Gamma \sim 6$, and $\theta = 5^\circ$ with a magnetic field of 16 $\mu$G. This model implies that boosting effects play an important role in the X-ray emission of this component, suggesting that S1 is more likely a relativistic knot in the jet, rather than a hotspot feature. The weakness of this interpretation is that 3C 105 is a NLRG and its jets are expected to form a large angle with our line of sight. Alternatively, the X-ray emission may be synchrotron from a different population of electrons, as suggested in the case of the jet in 3C 273 (Jester et al. 2007).
of 3C 445 South allow us to study the SED of each component separately in order to investigate in more detail the mechanisms at work across the hotspot region. In Figs 7–9, we show the SED from the radio band to high-energy emission measured for the components of 3C 445 South, together with the model fits. We must note that at 1.4 GHz, the resolution is not sufficient to reliably separate the contribution from the two main components. For this reason, we do not consider the flux density at this frequency in constructing the SED. The X-ray emission (Fig. 2) is misaligned with respect to the radio–NIR–optical position. For this reason, on the SED of both components (Figs 7 and 8), we plot the total X-ray flux which must be considered an upper limit. For the components of 3C 445

3C 445 South

The analysis of the southern hotspot of 3C 445 as a single unresolved component was carried out in previous work by Prieto et al. (2002), Mack et al. (2009) and Perlman et al. (2010). In this new analysis, the high spatial resolution and multiwavelength VLT and HST data

Figure 3. 3C 445 South. 8.4-GHz VLA contours are superimposed on the I-band HST image.

Figure 4. The broad-band SED of the northern component, S1, of 3C 105 South. The solid lines represent the synchrotron model where $\nu_b = 5 \times 10^{12} \text{ Hz}$ and $\nu_c = 2 \times 10^{15} \text{ Hz}$, and the SSC models computed assuming a magnetic field of 50 and 150 $\mu$G. The short-dashed line represents a synchrotron model where $\nu_b = 5 \times 10^{12} \text{ Hz}$ and $\nu_c = \infty$. The long-dashed lines represent the IC-CMB models computed assuming $B = 50$ (and $B = 32$) $\mu$G, $\Gamma = 6$ ($\Gamma = 4$), $\theta = 0.1$ ($\theta = 0.2$) rad, with or without flattening in the observed synchrotron spectrum at $\nu < 60 \text{ MHz}$. The magnetic field is in the rest frame.

5.3 3C 445 South

The analysis of the southern hotspot of 3C 445 as a single unresolved component was carried out in previous work by Prieto et al. (2002), Mack et al. (2009) and Perlman et al. (2010). In this new analysis, the high spatial resolution and multiwavelength VLT and HST data

Figure 5. The broad-band SED of the central component, S2, of 3C 105 South. The solid line represents the synchrotron model where $\nu_b = 7.5 \times 10^{12} \text{ Hz}$ and $\nu_c = 3 \times 10^{14} \text{ Hz}$, and the SSC models computed assuming a magnetic field of 50 and 225 $\mu$G. The arrow indicates the X-ray upper limit.

Figure 6. The broad-band SED of the southern component, S3, of 3C 105 South. The solid line represents the synchrotron model where $\nu_b = 1.5 \times 10^{13} \text{ Hz}$ and $\nu_c = 3 \times 10^{14} \text{ Hz}$, and the SSC models computed assuming a magnetic field of 50 and 150 $\mu$G. The arrow indicates the X-ray upper limit.
Particle acceleration in 3C 105 and 3C 445

Figure 7. The broad-band SED of the western component, SW, of 3C 445 South. The morphology from Chandra image shows that X-rays are not associated with the western component. The synchrotron models assume $\nu_b = 9.4 \times 10^{13} \text{ Hz}$ and $\nu_c = 4.7 \times 10^{15} \text{ Hz}$ (dotted line), $\nu_b = 5.5 \times 10^{13} \text{ Hz}$ and $\nu_c = 2.2 \times 10^{16} \text{ Hz}$ (dashed line), $\nu_b = 4.4 \times 10^{13} \text{ Hz}$ and $\nu_c = 1.8 \times 10^{18} \text{ Hz}$ (solid line) and $\nu_b = 4.4 \times 10^{13} \text{ Hz}$ and $\nu_c = \infty$ (thick solid line).

Figure 8. The broad-band SED of the eastern component, SE, of 3C 445 South. The morphology from Chandra image shows that X-rays are not associated with the eastern component. The synchrotron models assume $\nu_b = 5.2 \times 10^{13} \text{ Hz}$ and $\nu_c = 2.6 \times 10^{15} \text{ Hz}$ (dotted line), $\nu_b = 2.4 \times 10^{13} \text{ Hz}$ and $\nu_c = 9.4 \times 10^{15} \text{ Hz}$ (dashed line), $\nu_b = 1.2 \times 10^{13} \text{ Hz}$ and $\nu_c = 4.7 \times 10^{17} \text{ Hz}$ (solid line) and $\nu_b = 1.2 \times 10^{13} \text{ Hz}$ and $\nu_c = \infty$ (thick solid line).

South, the synchrotron models with $\alpha = 0.75$ reasonably fit the data, providing break frequencies in the range of between $10^{13}$ and $10^{14} \text{ Hz}$, and cut-off frequencies from $10^{15}$ to $10^{18} \text{ Hz}$.

Both the morphology (Fig. 2) and the SED (Figs 7 and 8) indicate that the bulk of Chandra X-ray emission detected in 3C 445 is not due to synchrotron emission from the two components (Section 6).

Figure 9. The broad-band SED of the diffuse emission (see text) of 3C 445 South. The morphology from the Chandra image does not allow us to firmly exclude a connection between the X-rays and the diffuse (including SC component) emission. The synchrotron model assumes $\nu_b = 8 \times 10^{16} \text{ Hz}$, $\nu_c \gg \nu_b$ and $p = 2.7$.

As discussed in Section 4.2, diffuse IR and optical emission surrounds the two components SE and SW of 3C 445 South, and a third component, SC, becomes apparent in the optical. We attempt to evaluate the spectral properties of the diffuse emission (including component SC). When possible, depending on statistics, we subtract from the total flux density of the hotspot, the contribution arising from the two main components, obtaining in this way the SED of the diffuse emission (inclusive of SC component) of 3C 445 South. In the image, we also plot the total X-ray flux. As expected, the emission has a hard spectrum ($\alpha \sim 0.85$) without evidence of a break-up to the optical band, $10^{15} < \nu_b \leq 8 \times 10^{16} \text{ Hz}$. We also note that this hard component may represent a significant contribution of the observed X-ray emission, although the X-ray peak appears shifted ($\sim 1 \text{ arcsec}$) from the SC component. Due to the extended nature of the emission in this hotspot, we created a power-law spectral index map illustrating the change of the spectral index $\alpha$ across the hotspot region (Fig. 10). The SEDs presented in Figs 7–9

Figure 10. Power-law spectral index map for 3C 445 South determined from FORS I band and FORS U band. Contours are 1, 1.3, 1.5, 1.6 and 1.7. First contour is $3\sigma$.® 2011 The Authors, MNRAS 419, 2338–2348

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show the curvature of the integrated spectrum for the main components and the diffuse emission (see Section 5.1). The spectral map in Fig. 10 attempts to provide complementary information on the spectral slope for the diffuse interknot emission. Extracting these maps using the largest possible frequency range is complicated as it implies combining images from different instruments with different scale sampling, noise pattern, etc. These effects sum up to produce very low contrast maps given the weakness of the hotspot signal. To minimize these effects, it was decided to extract the slope maps from the optical and IR images only.

The spectral index map between $I$ and $U$ bands (Fig. 10) shows two sharp edges, at the SW and SE components, with the highest value $\alpha \sim 1.5$. Between these two main regions, there is diffuse emission that is clearly seen in the $I$/$U$-band spectral index map. The slope of this component is flatter than that of the two main regions and rather uniform all over the hotspot, with $\alpha \sim 1$.

### 5.4 Physical parameters

We compute the magnetic field of each hotspot component by assuming minimum energy conditions, corresponding to equipartition of energy between radiating particles and magnetic field, and following the approach by Brunetti, Setti & Comastri (1997). We assume for the hotspot components an ellipsoidal volume $V$ with a filling factor $\phi = 1$ (i.e. the volume is fully and homogeneously filled by relativistic plasma). The volume $V$ is computed by means:

$$V = \frac{\pi d_\text{min}^2 d_\text{max}}{6},$$

where $d_\text{min}$ and $d_\text{max}$ are the linear size of the minor and major axis, respectively. We consider $\gamma_\text{min} = 100$, and we assume that the energy densities of protons and electrons are equal. We find equipartition magnetic fields ranging from $\sim 50$ to $290 \mu$G (Table 3) that is lower than those inferred in high-power radio hotspots which range from $\sim 250$ to $650 \mu$G (Meisenheimer et al. 1997; Cheung et al. 2005). Remarkably, if we compare these results with those from Mack et al. (2009), we see that in 3C 445 South, the value computed considering the entire source volume is similar to those obtained in its individual subcomponents, suggesting that compact and well-separated emitting regions are not present in the hotspot volume. On the other hand, the magnetic field averaged over the whole 3C 105 South hotspot complex is much smaller than those derived in its subcomponents.

In the presence of such low magnetic fields, high-energy electrons may have longer radiative lifetime than in high-power radio hotspots. The radiative age $t_{\text{rad}}$ is related to the magnetic field and the break frequency by

$$t_{\text{rad}} = 1610 B^{-3/2} v_b^{-1/2} (1 + z)^{-1/2},$$

where $B$ is in $\mu$G, $v_b$ in GHz and $t_{\text{rad}}$ in $10^3$ yr. If in equation (2) we assume the equipartition magnetic field, we find that the radiative ages are just a few years (Table 3). As the hotspots extend over kpc distances, it is indicative that a very efficient re-acceleration mechanism is operating in a similar way over the entire hotspot region.

### 6 DISCUSSION

The detection of diffuse optical emission occurring well outside the main shock region and distributed over a large fraction of the whole kpc scale hotspot structure is somewhat surprising. Deep optical observations pointed out that this is a rather common phenomenon detected in about a dozen hotspots (e.g. Thomson et al. 1995; Cheung et al. 2005; Mack et al. 2009). First-order Fermi acceleration alone cannot explain optical emission extending on kpc scale, and additional efficient mechanisms taking place away from the main shock region should be considered, unless projection effects play an important role in smearing compact regions where acceleration is still occurring.

Theoretically, we can consider several scenarios that are able to reproduce the observed extended structures. (1) One possibility is that a very wide jet, with a size comparable to the hotspot region, impacts simultaneously into various locations across the hotspot generating a complex shocked region that defines an arc-shaped structure. This, combined with projection effects, may explain a wide (projected) emitting region. (2) Another possibility is a narrow jet that impacts into the hotspot in a small region where electrons are accelerated at a strong shock. In this case, the accelerated particles are then transported upstream in the hotspot volume where they are continuously re-accelerated by stochastic mechanisms, likely due to turbulence generated by the jet and shock itself. (3) Finally, extended emission may be explained by the ‘dentist’s drill’ scenario, in which the jet impacts into the hotspot region in different locations at different times.

The peculiar morphology and the rather high NIR/optical luminosity of 3C 105 South and 3C 445 South makes these hotspots ideal targets to investigate the nature of extended diffuse emission.

In 3C 105 South, the detection of optical emission in both primary and secondary hotspots implies that in these regions, there is a continuous re-acceleration of particles. The secondary hotspot S3 could be interpreted as a splatter-spot from material accelerated in the primary one, S2 (Williams & Gull 1985). Both the alignment and the distance between these components exclude the jet drilling scenario: the light time between the two components is more than $10^4$ yr, i.e. much longer than their radiative time (Table 3), suggesting that acceleration is taking place in both S2 and S3 simultaneously. The secondary hotspot S3 shows some elongation, always in the same direction, in all the radio and optical images with adequate spatial resolution. This elongation is expected in a splatter-spot, and it follows the structure of the shock generated by the impact of the outflow from the primary upon the cocoon wall.

This scenario, able to explain the presence of optical emission from two bright and distant components, fails in reproducing the

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2 The magnetic field energy density in these hotspots are at least an order of magnitude higher than the energy density of the CMB radiation. Inverse-Compton losses due to scattering of CMB photons are negligible.
diffuse optical emission enshrouding the main features and the extended tail. In this case, an additional contribution from stochastic mechanisms caused by turbulence in the downstream region is necessary. Although this acceleration mechanism is in general less efficient than Fermi-I processes, the (radiative) energy losses of particles are smaller in the presence of low magnetic fields, such as those in between S2 and S3, (potentially) allowing stochastic mechanisms to maintain electrons at high energies.

In 3C 445 South, the observational picture is complex. The optical images of 3C 445 South show a spectacular 10-kpc arc-shape structure. High-resolution HST images allow a further step since they resolve this structure in two elongated components enshrouded by diffuse emission. These components may mark the regions where a ‘dentist’s drill’ jet impacts on the ambient medium, representing the most recent episode of shock acceleration due to the jet impact. On the other hand, they could simply trace the locations of higher particle-acceleration efficiency from a wide/complex interaction between the jet and the ambient medium. However, the transverse extension, about 1 kpc, of the two elongated components is much larger than what is derived if the relativistic particles, accelerated at the shock, age in the downstream region (provided that the hotspot advances at typical speeds of 0.05–0.1c). Furthermore, the diffuse optical emission on larger scale suggests the presence of additional, complex, acceleration mechanisms, such as stochastic processes, able to keep particle re-acceleration ongoing in the hotspot region. The detection of X-ray emission with Chandra adds a new grade of complexity. This emission and its displacement are interpreted by Perlman et al. (2010) as due to IC-CMB originating in the fast part of the decelerating flow. Their model requires that the angle between the jet velocity and the observer’s line of sight is small. However, 3C 445 is a classical double radio galaxy and the jet should form a large angle with the line of sight (see also Perlman et al. 2010).

On the other hand, we suggest that the X-ray/optical offset might be the outcome of ongoing efficient particle acceleration occurring in the hotspot region. An evidence supporting this interpretation may reside on the faint and diffuse blob seen in U and B bands (labelled SC in Fig. 2) just about 1 arcsec downstream the X-ray peak. The surface brightness of this component decreases rapidly as the frequency decreases, as is shown in Fig. 2: well detected in U and B bands, marginally visible in I band and absent at NIR and radio wavelengths. The SED of the diffuse hotspot emission (including SC component and excluding SW and SE) is consistent with synchrotron emission with a break at high frequencies, $10^{15} < \nu_b < 8 \times 10^{16}$ Hz, and may significantly contribute to the observed X-ray flux. Such a hard spectrum is in agreement with (i) a very recent episode of particle acceleration (the radiative cooling time of the emitting particles being $10^2$–$10^3$ yr); (ii) efficiently spatially distributed acceleration processes, similar to the scenario proposed for the western hotspot of Pictor A (Tingay et al. 2008; see their fig. 5).

7 CONCLUSIONS

We presented a multiband, high spatial resolution study of the hotspot regions in two nearby radio galaxies, namely 3C 105 South and 3C 445 South, on the basis of radio VLA, NIR/optical VLT and HST, and X-ray Chandra observations. At the subarcsecond resolution achieved at radio and optical wavelengths, both hotspots display multiple resolved components connected by diffuse emission detected also in optical. The hotspot region in 3C 105 resolves in three major components: a primary hotspot, unresolved and aligned with the jet direction, and a secondary hotspot, elongated in shape and interpreted as a splatter-spot arising from continuous outflow of particles from the primary. Such a feature, together with the extremely short radiative ages of the electron populations emitting in the optical, indicates that the jet has been impacting almost in the same position for a long period, making the drilling jet scenario unrealistic. The detection of an excess of X-ray emission from the northern component of 3C 105 South suggests that this region is likely a relativistic knot in the jet rather than a genuine hotspot feature. The optical diffuse emission enshrouding the main components and extending towards the tail can be explained possibly assuming additional stochastic mechanisms taking place across the whole hotspot region.

In the case of 3C 445 South, the optical observations probe a scenario where the interaction between jet and the ambient medium is very complex. Two optical components pinpointed by HST observations mark either the locations where particle acceleration is most efficient or the remnants of the most recent episodes of acceleration. Although projection effects may play an important role, the morphology and the spatial extension of the diffuse optical emission suggest that particle accelerations, such as stochastic mechanisms, add to the standard shock acceleration in the hotspot region. The X-rays detected by Chandra cannot be the counterpart at higher energies of the two main components. It might be due to IC-CMB from the fast part of a decelerating flow. Alternatively, the X-rays could pinpoint synchrotron emission from recent episodes of efficient particle acceleration occurring in the whole hotspot region, similarly to what was proposed in other hotspots, that would make the scenario even more complex. A possible evidence supporting this scenario comes from the hard spectrum of the diffuse hotspot emission and from the appearance of a new component (SC) in the optical images.

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APPENDIX A: Swift Images

Both the radio hotspot 3C 105 South and 3C 445 South have been detected by Swift in the energy range 0.3–10 keV.

The reduction procedure for Swift data follows that described in Massaro et al. (2008). In the following, we report only the basic details.

3C 105 has been observed by Swift in four occasions (Obs. ID 00035625001-2-3-4) for a total exposure of ~22 ks, while 3C 445 only for ~12 ks (Obs. ID 00030944001-2). During all these observations, the Swift satellite was operated with all the instruments in data-taking mode. We consider only XRT (Burrows et al. 2005) data, since our sources were not bright enough to be detected by the BAT high-energy experiment. In particular, Swift-XRT observations have been performed in photon-counting (PC) mode.

The XRT data analysis has been performed with the XRTDAS software, developed at the ASI Science Data Center (ASDC) and distributed within the HEASOFT package (v. 6.9). Event files were calibrated and cleaned with standard filtering criteria using the xrtpipeline task, combined with the latest calibration files available in the Swift CALDB distributed by HEASARC. Events in the energy range 0.3–10 keV with grades 0–12 (PC mode) were used in the analysis (see Hill et al. 2004, for more details). No signatures of pile-up were found in our Swift XRT observations. Events are extracted using a 17-arcsec radius circle centred on the radio position of the southern hotspots in both cases of 3C 105 and 3C 445 (see Fig. A1). We measured 15 counts in the southern hotspot of 3C 105 and 12 counts for that of 3C 445, while the background estimated from a nearby source-free circular region of the same radius is 1.8 and 0.9 counts, respectively.

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