Swift observations of unidentified radio sources in the revised Third Cambridge Catalogue

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ABSTRACT
We have investigated a group of unassociated radio sources included in the 3CR catalogue to increase the multi-frequency information on them and possibly obtain an identification. We have carried out an observational campaign with the Swift satellite to observe with the UVOT and the XRT telescopes the field of view of 21 bright NVSS sources within the positional uncertainty region of the 3CR sources. Furthermore, we have searched in the recent AllWISE Source Catalogue for infrared sources matching the position of these NVSS sources. We have detected significant emission in the soft X-ray band for nine of the investigated NVSS sources. To all of them, and in four cases with no soft X-ray association, we have associated a WISE infrared counterpart. Eight of these infrared candidates have not been proposed earlier in the literature. In the five remaining cases our candidate matches one among a few optical candidates suggested for the same 3CR source in previous studies. No source has been detected in the UVOT filters at the position of the NVSS objects, confirming the scenario that all of them are heavily obscured. With this in mind, a spectroscopic campaign, preferably in the infrared band, will be necessary to establish the nature of the sources that we have finally identified.

Key words: galaxies: active – radio continuum: galaxies – radiation mechanisms: non-thermal – X-rays: general

1 INTRODUCTION

The extragalactic subset of the revised Third Cambridge Catalogue (3CR) of radio sources (see, e.g., ??) has a long history as one of the fundamental samples used to understand the nature and evolution of powerful radio galaxies and quasars, as well as their relationship to their host galaxies and environments on parsec through megaparsec scales. Extensive imaging and spectroscopic observations have long been available from the radio through the infrared (IR) and optical bands, with data from Spitzer (?), the Hubble Space Telescope (e.g., ??) and ground-based telescopes (see, e.g., the description of observations performed with the Telescopio Nazionale Galileo reported in ??).

Since a large fraction of 3CR sources were already present in both the Chandra (see, e.g., ?, for a recent review) and XMM-Newton archives of pointed observations (e.g., ?, and references therein), in 2008 a Chandra snapshot survey started to complete the X-ray coverage of the entire 3CR extragalactic catalogue (??). This Chandra survey has enabled investigations of peculiar sources (see, e.g., ? for 3C 17 and ? for 3C 105), samples of radio-loud objects (??), and was the genesis of, e.g., follow-up X-ray observations for

† Dan Harris passed away on December 6th, 2015. His career spanned much of the history of radio and X-ray astronomy. His passion, insight, and contributions will always be remembered.

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3C 89 (Dasadia et al. 2015), 3C 171 (?), and 3C 305 (?). The total number of 3CR extragalactic sources now present in the Chandra archive is 248 out of the 298 included in the update of the 3CR catalogue performed by ?. An additional 16 sources (out of 50) that remain unobserved by Chandra have recently been approved for observation in Cycle 17 (see Massaro et al. 2016). Those observations began as of December 2015.

Amid our investigation of recent Chandra observations, we realised that 25 out of the 298 3CR radio sources are not only unobserved in X-rays, but are in fact completely unidentified, lacking an assigned optical or infrared counterpart. In the latest revised release of 3CR extragalactic catalogue (?), each of these 25 unidentified sources (excluding 3C 86 and 3C 415.2) are marked as obscured active galaxies. This classification has remained unchanged for the past three decades, save for a few tentative associations requiring follow-up observations for confirmation (see, e.g., ?). It therefore became necessary, in nearing completion of the 3CR Chandra snapshot survey, to enact an ancillary optical-to-X-ray campaign with the Swift observatory in order to better characterise the properties of these unidentified sources. Our Swift campaign was augmented by a search for infrared counterparts in the latest ALLWISE Source Catalogue from the Wide-field Infrared Survey Explorer (WISE, ?) mission.

Here we present the results of this new observational effort. Our Swift observing strategy is described in §2, the reduction and analysis of Swift X-ray data is discussed in §3, and the search for infrared and optical counterparts is described in §4. Our results, including detections of both infrared and soft X-ray counterparts, are given in §5 and summarised in §6. Throughout this paper we use CGS units, unless stated otherwise. The spectral index α is defined in terms of the flux density $S_\nu$, where $S_\nu \propto \nu^{-\alpha}$ and $\nu$ is the frequency.

### 2 OBSERVING STRATEGY

The coordinates of the 3CR sources were first provided by ? and later modified up to the most recent update carried out by ?. In several cases, including a few sources of interest, the positional uncertainty reaches values up to 60 arcmin in Declination. Given the high flux density threshold used in selecting sources for the 3CR catalogue, we have assumed that a bright source in the more recent NRAO VLA Sky Survey (NVSS, ?) at 1.4 GHz would be associated with all unidentified 3CR sources. The positional uncertainty of NVSS objects with flux density values higher than 100 mJy is always lower than one arcsecond. The 3CR catalogue included sources with flux density values $S_{178}$ higher than 9 Jy: considering the radio spectral index distribution of unidentified 3CR sources reported by ?, we have established a lower limit of $S_{1.4} = 1$ Jy for the expected flux density at 1.4 GHz. Therefore, to establish the most suited coordinates to be used in our Swift campaign, we have searched for NVSS sources with $S_{1.4} > S_{178}$.

In most cases the result of our search was a single NVSS source with a compact radio morphology. In two cases (for 3C 134 and 3C 139.2) we found a group of three catalogued objects that in actuality correspond to the same radio source
- both of these are radio galaxies with Fanaroff-Riley class II (FR II, ?) morphology (?), that NVSS has spatially resolved into a radio core and two jet hotspots. For both of these FR II sources (see, e.g., Fig.11) only one of the NVSS sources is internal to the 3CR positional uncertainty region. We note that for 3C 139.2 the flux density of the NVSS object (presumably the radio core) within the 3CR positional uncertainty region is lower than $S^i_{1.4}$, but we have nevertheless included it in our observational campaign considering the contribution of the two hotspots (0.7 Jy and 0.9 Jy, respectively) to the total flux. We have also decided to include three NVSS objects with an angular separation of a few arcseconds from the closest side of the corresponding 3CR positional uncertainty region: 1.8 and 3.4 arcsec for 3C 390 and 3C 428, respectively, and ~39 arcsec for 3C 86. In these cases, as a consequence of this small angular separation, the NVSS radio contours (up to 10 mJy beam$^{-1}$) largely overlap the corresponding 3CR positional uncertainty region. On the other hand, we have excluded 3C 14.1, 3C 21.1, 3C 33.2, and 3C 389 from our initial dataset as we have found no bright NVSS source in or near (within several arcminutes) the corresponding 3CR positional uncertainty region.

The list of these 21 previously unassociated 3CR sources is given in Table 1. For each, we report the Equatorial coordinates with their statistical uncertainty, the Galactic coordinates, their flux density at 178 MHz, the corresponding NVSS source with its flux density at 1.4 GHz, and the radio spectral index $\alpha$ computed between 178 MHz and 1.4 GHz. The flux density values at 178 MHz include a 9 per cent correction factor (?) to those originally provided by ? and also reported by ?. For both 3C 134 and 3C 139.2 only the NVSS object internal to the 3CR positional uncertainty region has been reported in Table 1; however, in the computation of the radio spectral index $\alpha$ we have included the contribution of the additional NVSS objects that correspond to the same radio galaxy, under the assumption that the older survey at 178 MHz was unable to spatially resolve them.

### Table 2. The list of Swift-XRT detected sources matching one of the NVSS sources listed in Table 1.

| 3C | R.A. (J2000) | Dec. (J2000) | Error (arcsec) | Exposure (s) | Count Rate (ct/s) | S/N | NVSS | Angular Separation (arcsec) |
|----|--------------|--------------|---------------|--------------|------------------|-----|------|-----------------------------|
| 86 | 03 27 19.5   | +55 20 26.0  | 4.5           | 5170         | (1.43+/-0.10) x 10^{-2} | 7.6 | J032719+552029 | 3.7 |
| 91 | 03 37 43.6   | +00 45 46.2  | 4.0           | 4809         | (4.39+/-0.39) x 10^{-2} | 11.3| J033743+504552 | 7.4 |
| 131| 04 53 23.2   | +31 29 33.4  | 6.3           | 5255         | (1.96+/-0.74) x 10^{-3} | 2.6 | J045323+312924 | 9.4 |
| 137| 05 19 32.6   | +50 54 31.4  | 4.7           | 5092         | (9.98+/-1.60) x 10^{-3} | 6.1 | J051932+505432 | 1.9 |
| 158| 06 21 41.2   | +14 32 11.5  | 6.4           | 4974         | (2.04+/-0.78) x 10^{-3} | 2.6 | J062141+143211 | 1.6 |
| 390| 18 45 37.6   | +09 53 48.7  | 4.4           | 4348         | (2.60+/-0.30) x 10^{-2} | 8.6 | J184537+095344 | 4.4 |
| 409| 20 14 27.5   | +25 34 54.5  | 4.0           | 5366         | (3.27+/-0.28) x 10^{-2} | 11.6| J201427+253452 | 1.9 |
| 428| 21 08 22.1   | +10 39 42.1  | 4.6           | 7913         | (7.79+/-1.10) x 10^{-3} | 6.9 | J210822+203637 | 5.6 |
| 454| 22 52 05.2   | +64 40 13.1  | 4.6           | 5571         | (7.76+/-1.40) x 10^{-3} | 5.6 | J225205+644010 | 4.6 |

#### 3. X-RAY DATA REDUCTION AND ANALYSIS PROCEDURES

Each of these 21 NVSS sources was covered by our Swift observational campaign, carried out between November 2014 and March 2015, with a total exposure time greater than 4 ks for each source. The X-ray data reduction and procedures adopted in the present analysis were extensively described in ???, and references therein; here we report only the basic details (see also ?? for further details).

The XRT data have been processed with the XRTDAS software package (v.3.0.0) developed at the ASI Science Data Center (ASDC) and distributed within the HEASoft package (v.6.16) by the NASA High Energy Astrophysics Archive Research Center (HEASARC). All the XRT observations were carried out in the most sensitive photon counting (PC) read-out mode. Event files have been calibrated and cleaned applying standard filtering criteria with the XRTPIPELINE task and using 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 have been used in the analysis. Exposure maps have been also created with XRTPIPELINE. The detection of X-ray sources in the XRT images has been carried out using the detection algorithm DETECT within XIMAGE. In agreement with ?, we have set the DETECT signal-to-noise ratio acceptance threshold to 2.5 $\sigma$. Finally, the positional uncertainty (90 per cent confidence level) of each detected source has been computed using the XRTCENTERD task. When needed, we have computed a 3$\sigma$ upper limit of the count rate at the desired coordinates using the UPLIMIT command within XIMAGE. Source count rate photometry was conducted using square boxes with half-size of 7 pixels, while background intensity was set to a constant equal to the average value computed over the whole image.

The list of XRT sources that we have detected following the above described procedure and matching one NVSS source is reported in Table 2, for a total of nine X-ray sources. For each, we report the corresponding 3CR source (column 1), its Right Ascension (column 2) and Declination (column 3), the error radius (column 4), the XRT exposure time (column 5), the count rate with its error (column 6), the significance of its detection (column 7), the corresponding NVSS source (column 8) and the angular separation from its...
Table 3. The list of the NVSS sources with no matching X-ray detection and the corresponding Swift-XRT 3σ upper limit.

| 3C   | NVSS   | Exposure (s) | 3σ upper limit (ct/s) |
|------|--------|--------------|-----------------------|
| 11.1 | J002945+635441 | 5263 | 1.69 × 10⁻³ |
| 125  | J044617+394506 | 4132 | 4.41 × 10⁻³ |
| 134  | J050443+380539 | 6944 | 3.46 × 10⁻³ |
| 139.2| J052427+281255 | 4817 | 3.21 × 10⁻³ |
| 141  | J052642+324958 | 4651 | 2.24 × 10⁻³ |
| 152  | J060428+202122 | 4689 | 1.87 × 10⁻³ |
| 250  | J110851+250052 | 4280 | 4.80 × 10⁻³ |
| 394  | J185923+125912 | 4032 | 5.32 × 10⁻³ |
| 399.1| J191556+301952 | 12339 | 2.20 × 10⁻³ |
| 415.2| J203246+534553 | 5358 | 3.59 × 10⁻³ |
| 431  | J218552+440558 | 7462 | 2.77 × 10⁻³ |
| 468.1| J235054+640418 | 4997 | 3.10 × 10⁻³ |

As a result of our analysis, an infrared counterpart has been found for all sources reported in Table 2, as well as in four additional cases among the X-ray non-detections listed in Table 3. Their list is reported in Table 4, according to the presence/absence of an X-ray counterpart. For each infrared source we have reported the corresponding 3CR (column 1) and NVSS (column 2) sources, the name in the AllWISE Catalogue (column 3), the angular separation from the radio (column 4) and the X-ray source (column 5), and the corresponding magnitudes in the WISE filters (columns 6–9).

We have also carried out a photometric analysis over the images in the available UVOT filters at the position of the NVSS sources. Following ?, the photometry has been performed using the uvotdetect task and taking into account the corresponding exposure maps. An extraction region of 5 arcsec has been adopted for the sources, independently of the image filter, and a larger circle of 20 arcsec radius for the background, in a near source-free region of the sky. Magnitude values, or upper limits, in the Vega System have been finally obtained using the uvotsource task and adopting a 3σ level of significance to compute the background limit; both statistic and systematic errors have been taken into account. Our photometric results show that an optical-UV counterpart has not been detected for any object; only upper limits could be established. This result was not unexpected, considering that almost all of these sources were marked as obscured by ?, and nearly all are at low Galactic latitude (|b| < 10°, see Table 1).

5 SOURCE DETAILS

In this Section we describe details of the 13 radio sources listed in Table 4, distinguishing the presence (Section 5.1) or the absence (Section 5.2) of an X-ray counterpart in addition to the infrared one. For each radio source we show a comparison of the field of view in both the XRT 0.3–10 keV band and in WISE w1 filter (figures 1 to 13). The images have been smoothed with a Gaussian function with different values of FWHM (5 and 1 arcsec for the XRT and WISE images, respectively). In each panel a yellow dashed line marks the positional uncertainty region of the 3CR source. White crosses mark the position of the catalogued NVSS objects, and white continuous lines are used to shape the radio contours that have been obtained from the NVSS maps. The exact values of the contour levels, starting from 10 mJy beam⁻¹, have been reported for each in the corresponding captions. The positions of the X-ray sources and the corresponding error radius (see column 3 of Table 2) have been marked with red circles. The range of the image in the XRT band (left panel) has been generally chosen to cover the whole 3CR positional uncertainty region and the corresponding NVSS source with its contours; in two cases (3C 454.2 and 3C 468.1) this was not convenient due to the large extent in Declination of the positional uncertainty region. The image in the WISE w1 filter shows a smaller field of view in order to aid viewing of the possible infrared counterpart.
Table 4. The WISE counterparts associated to some of the NVSS sources reported in Table 2.

| 3C   | NVSS     | WISE         | WISE/NVSS (arcsec) | WISE/XRT (arcsec) | u1 (mag) | u2 (mag) | u3 (mag) | u4 (mag) |
|------|----------|--------------|--------------------|-------------------|---------|---------|---------|---------|
| 86   | J0332719+552029 | J0332719.29+552028.2 | 0.9 | 2.7 | 13.421±0.027 | 12.500±0.026 | 9.757±0.050 | 7.274±0.128 |
| 91   | J033743+504552 | J033743.02+504547.6 | 6.1 | 1.4 | 11.865±0.022 | 10.802±0.021 | 7.936±0.020 | 5.507±0.038 |
| 131  | J045323+312924 | J045323.34+312928.4 | 4.0 | 5.4 | 14.981±0.041 | 14.779±0.082 | 12.306 | 8.300 |
| 137  | J051932+505432 | J051932.53+505431.3 | 1.5 | 0.7 | 13.967±0.027 | 12.896±0.028 | 9.968±0.053 | 7.194±0.116 |
| 158  | J062141+132111 | J062141.01+132128.8 | 1.5 | 3.6 | 15.133±0.046 | 13.953±0.043 | 11.131±0.189 | 8.639±0.417 |
| 390  | J184537+095344 | J184537.60+095345.8 | 0.9 | 3.8 | 12.546±0.043 | 11.575±0.024 | 9.156±0.029 | 6.874±0.088 |
| 409  | J201427+233452 | J201427.59+233452.6 | 0.3 | 2.1 | 13.547±0.050 | 12.377±0.027 | 9.005±0.037 | 6.437±0.065 |
| 428  | J210822+493637 | J210822.08+493641.6 | 5.3 | 0.5 | 14.559±0.064 | 13.097±0.035 | 10.143±0.056 | 7.601±0.136 |
| 454  | J225205+644010 | J225205.50+644011.9 | 2.3 | 4.6 | 14.652±0.030 | 13.341±0.042 | 13.121±0.047 | 9.513 |

5.1 3CR sources with both X-ray and infrared counterparts

5.1.1 3C 86

As shown in the left panel of Fig. 1, the 1.4 GHz source corresponding to 3C 86, NVSS J0332719+552029 (S_1.4=6.9 Jy), is out of the 3CR positional uncertainty region but its radio contours overlap it. We have detected X-ray emission (XRT J0332719.5+552026) copatial with the radio source at S/N=7.6 and with a mean count rate of the order of 10^{-2} ct/s. Furthermore, at an angular separation of 0.9 arcsec from the NVSS coordinates, an infrared counterpart WISE J0332719.29+552028.2 has been found in the AllWISE Source Catalogue with clear detections in all four WISE filters. This is the same counterpart reported by ? in their investigation of three 3CR sources including a spectroscopic analysis: unfortunately, the spectrum they obtained had very low signal-to-noise ratio, showing only faint continuum.

Figure 1. The sky map in the direction of 3C 86 obtained by XRT in the 0.3–10 keV energy band (left panel) and by WISE in the w1 filter (right panel). A yellow dashed line marks the positional uncertainty region of the 3CR source. White continuous lines shape the radio contours obtained from the NVSS map and corresponding to 0.01, 0.2, 0.7, 2, and 4 Jy beam^{-1}; a white cross marks the position of the catalogued NVSS source. A red circle marks the position of the detected XRT source with the corresponding error radius.

5.1.2 3C 91

The X-ray source that we have detected (XRT J033743.0+504546) with S/N=11.3 and a mean count rate on the order of 4.01 ct/s is 7.4 arcsec from the coordinates of NVSS J033743.02+504552 and 3.3 arcsec from the center of the 3CR positional uncertainty region, as shown in the left panel of Fig. 2. A WISE source, J033743.02+504547.6, has been found within the XRT error circle, at close angular separation (1.4 arcsec) from its center, and is clearly detected in all WISE filters. Considering the good positional agreement between the infrared and the X-ray objects and their low angular separation from the NVSS object (see the right panel of Fig. 2), we have accepted these as counterparts of the same source at different frequencies. Three candidates were noted by ? in their analysis of the optical images obtained by the Wide Field Planetary Camera 2 (WFPC2) on board the Hubble Space Telescope (HST). The angular separation between their candidate #1 (R.A. 03h 37m 42.93s; Dec. +50° 45’ 48.13”), which they considered as the most probable, and WISE J033743.02+504547.6 is 1.0 arcsec. Reported for their candidate #1 an observed magnitude of R_{obs}=19.36 mag; there is no detection in the available UVOT filters (M2, W1, and W2) at the corresponding position. Finally, we report that WISE J033743.02+504547.6

5.1.3 3C 91

The X-ray source that we have detected (XRT J033743.0+504546) with S/N=11.3 and a mean count rate on the order of 4·10^{-2} ct/s is 7.4 arcsec from the coordinates of NVSS J033743.02+504552 and 3.3 arcsec from the center of the 3CR positional uncertainty region, as shown in the left panel of Fig. 2. A WISE source, J033743.02+504547.6, has been found within the XRT error circle, at close angular separation (1.4 arcsec) from its center, and is clearly detected in all WISE filters. Considering the good positional agreement between the infrared and the X-ray objects and their low angular separation from the NVSS object (see the right panel of Fig. 2), we have accepted these as counterparts of the same source at different frequencies. Three candidates were noted by ? in their analysis of the optical images obtained by the Wide Field Planetary Camera 2 (WFPC2) on board the Hubble Space Telescope (HST). The angular separation between their candidate #1 (R.A. 03h 37m 42.93s; Dec. +50° 45’ 48.13”), which they considered as the most probable, and WISE J033743.02+504547.6 is 1.0 arcsec. Reported for their candidate #1 an observed magnitude of R_{obs}=19.36 mag; there is no detection in the available UVOT filters (M2, W1, and W2) at the corresponding position. Finally, we report that WISE J033743.02+504547.6...
has been included by ? in their all-sky catalogue of infrared selected, radio-loud active galaxies due to its peculiar infrared colours.

5.1.3 3C 131

The X-ray source XRT J045323.2+312933 has been detected at 9.4 arcsec from the coordinates of NVSS J045323+312924. There are two WISE objects at close angular separation (~4 arcsec) from the NVSS source: in the image shown in Fig. 3 (right panel) they are not resolved, and reliable magnitude values of both targets are only available for the w1 and w2 filters in the AllWISE Source Catalogue. Only one, WISE J045323.34+312928.4, is within the error circle of the XRT source. No optical candidate counterpart was supported by ? and the only cited source was considered to be unrelated to the radio structure. This region of the sky was also analysed by ?, who reported a list of four objects detected by HST. The angular separation of their candidate #4 (R.A. 04\textsuperscript{h} 04\textsuperscript{m} 53\textsuperscript{s} 23.34; Dec. +31\text deg 29 27.10\textsec) from WISE J045323.34+312928.4 is 1.3 arcsec. Due to their large angular separation from the radio coordinates they took into account, different from the NVSS ones, all the four candidates were considered by ? to be unlikely the optical counterpart of the radio source. However, the angular separation of candidate #4 from NVSS J045323+312924 is 2.9 arcsec, lower than the positional uncertainty for the HST coordinates (3 arcsec) quoted by ?. Therefore, despite a difference of a few arcseconds (exact values are reported in Table 2 and Table 4) between the positions of objects detected at different frequencies, we suggest that the most plausible counterpart to the radio source 3C 131 corresponds to WISE J045323.34+312928.4.

5.1.4 3C 137

The X-ray source XRT J051932.6+505431 matches the coordinates of the NVSS source J051932+505432 with an angular separation of 1.9 arcsec. Also a reliable infrared counterpart, WISE J051932.53+505431.3, is found at 1.5 arcsec from the NVSS coordinates and is well detected in all the WISE filters. The angular separation of this infrared source from the "very faint red object", quoted by ? in their search of an optical identification and hardly distinguished in their finding chart, is 3.4 arcsec.

5.1.5 3C 158

The X-ray source XRT J062141.2+143212 matches the NVSS source J062141+143211, within the positional uncertainty region of 3C 158, with an angular separation of 1.6 arcsec consistent with the XRT error circle. An infrared counterpart in the AllWISE Source Catalogue, WISE J062141.01+143212.8, is well detected in all the remaining WISE filters and is found at 1.5 arcsec from the NVSS source. This object, with a nice positional agreement with other sources emitting at different frequencies, is here presented for the first time as candidate to be investigated with a spectroscopic analysis; no infrared/optical candidate has been previously reported in the literature for this radio source.
5.1.6 3C 390

The X-ray source XRT J184537.6+095349 \((S/N=8.6)\) matches the radio source NVSS J184537+095344 in the field of view of 3C 390 at an angular separation of 4.4 arcsec equal to the XRT error radius. As shown in the left panel of Fig. 6 the NVSS source is not well centered with respect to the 3CR positional uncertainty region. The cross-match with the AllWISE Catalogue has provided as infrared counterpart the source \textit{WISE J184537.60+095345.0}, at 0.9 arcsec from the NVSS coordinates. We note that there is another \textit{WISE} source close to the one just reported; both are not fully resolved in the image shown in the right panel of Fig. 6. However, the angular separation of the latter from the NVSS source is higher (6.7 arcsec) and also larger than the established matching radius (3.3 arcsec). Moreover, we emphasise that \textit{WISE J184537.60+095345.0} has been recently included in the all-sky catalogue of blazar candidates. Its coordinates, the 3CR positional uncertainty region: nonetheless, a sub-

5.1.7 3C 409

The soft X-ray source XRT J201427.5+233455 has been detected with \(S/N=11.6\) in the field of view of 3C 409 and matches the coordinates of NVSS J201427+233452 with an angular separation of 1.9 arcsec. X-ray emission in this region of the sky was indeed detected by the Imaging Proportional Counter (IPC) on board the \textit{Einstein} satellite and reported by \(\text{?}\). These authors also reported of a 7.3 ks exposure with the High Resolution Imager (HRI) in which the X-ray source was located at RA.(B1950) \(20^h\) \(12^m\) \(18.4^s\), Dec.(B1950) \(+23^\circ\) \(25^\prime\) \(45^\prime\) with an uncertainty of 5 arcsec. Considering the angular separation (5.8 arcsec) of this source from XRT J201427.5+233455 the X-ray emission detected from \textit{Einstein} and \textit{Swift} is probably related to the same object. The match with the AllWISE Source Catalogue has provided the infrared counterpart \textit{WISE J201427.59+233452.6} to the NVSS source, at only 0.3 arcsec from its coordinates; this infrared object is well detected in all of the four \textit{WISE} filters. As in other cases found in our analysis, this \textit{WISE} infrared object has been included in the all-sky catalogue of blazar-like radio-loud sources recently produced by \(\text{?}\). Apart from this, it is the first candidate ever indicated in the literature as a possible counterpart to 3C 409.

5.1.8 3C 428

The X-ray source XRT J210822.1+493642 matches the NVSS source J210822+493637 in the field of view of 3C 428, at an angular separation of 5.6 arcsec; the radio contours appear to be stretched in one direction (see Fig. 8). As for 3C 86 and 3C 390 (see Fig. 1 and Fig. 6) the coordinates of the NVSS source are not well centered with respect to the 3CR positional uncertainty region: nonetheless, a substantial overlap with its radio contours is evident. From an infrared point of view a reliable infrared counterpart, \textit{WISE J210822.08+493641.6}, has been found within the XRT error circle: the angular separation from its center is only 0.5 arcsec, much lower than the XRT error radius. The image in the \textit{WISE} w1 filter showing this infrared source is given in the right panel of Fig. 8; the source is well detected in all the remaining \textit{WISE} filters. As for 3C 91, 3C 390, and 3C 409, this infrared source has been recently included in the all-sky catalogue of blazar candidates (?). Given the good match between the infrared and the X-ray source and their low angular separation with respect to the NVSS coordinates, we have finally accepted the match among these different sources indicating \textit{WISE J210822.08+493641.6} as the best target to be investigated with a spectroscopic campaign. We note that this position is at \(\sim\) 2 arcsec from one of the four candidates (candidate B) suggested by \(\text{?}\) in their analysis of a CCD image obtained at the Canada-France-Hawaii Telescope (CFHT); these authors claimed for this object a magnitude \(R=21.8\) mag.
and shows the good match between the positional uncertainty region of 3C 139.2, and the NVSS source J235054+644018 with respect to the positional uncertainty region of 3C 152, with no X-ray emission detected by XRT. From the cross-match with the AllWISE Catalogue we have found the source J060428.62+202121.7, with an angular separation of only 0.8 arcsec between the two sources. The infrared object is well detected in three of the WISE filters, excluding w4. The image in the w1 filter is given in the right panel of Fig. 12 and shows the good match between the positions of the radio and the infrared objects. In their analysis of the corresponding field of view with HST they reported a single candidate (R.A.(J2000) 06h 04m 28s.63, Dec.(J2000) +20° 21′ 25″.07). The angular separation of this object from WISE J060428.62+202121.7 is 3.4 arcsec.

5.2.4 3C 468.1

The left panel of Fig. 13 shows the position of the 1.4 GHz source NVSS J235054+644018 with respect to the positional uncertainty region of 3C 468.1. The WISE candidate J235054.78+644018.1, that we have found from the NVSS/AllWISE cross-match at an angular separation of 1.3 arcsec from the NVSS source, is detected in all the four WISE filters, and presented the corresponding field of view as observed by HST and reported a list of three tentative optical identifications. Their source #1 (R.A.(J2000) 23h 50m 9s and Dec.(J2000) 64° 10′ 06″.07) grossly overlaps the infrared counterpart.
54°.38, Dec.(J2000) +64° 40' 18.06") is the closest (2.6 arcsec) to the WISE source addressed by our analysis. This value is consistent with the positional uncertainty (3 arcsec) they reported for all their candidates.

6 SUMMARY AND CONCLUSIONS

After conducting Swift observations of 21 bright NVSS sources corresponding to 3CR sources classified as unassociated in the third update of the 3CR catalogue, we have obtained new X-ray detections for nine of them. Moreover, cross-matching the NVSS with the recent AllWISE Catalogue, we have found a WISE counterpart to all these nine X-ray sources, as well as to four cases with no X-ray detection. We have provided candidate counterparts emitting in the infrared band for 3C 125, 3C 137, 3C 139.2, 3C 152, 3C 158, 3C 390, 3C 409, and 3C 454.2. Furthermore, we have confirmed an unambiguous association for 3C 86, 3C 91, 3C 131, 3C 428, and 3C 468.1 where multiple candidates had been suggested in previous analysis. Four of these infrared sources are listed in the recent all-sky catalogue of γ-ray blazar candidates (?): the infrared colours of these objects are similar to those of quasars (?), and only a spectroscopic campaign will reveal the real nature of these as well as of the remaining identified WISE counterparts.

It is worth mentioning that no optical/UV counterpart has been detected in the UVOT filters at the position of the 21 NVSS sources: this is in agreement with the notes reported in the 3CR catalogue (?) in which the large fraction of these 3CR unidentified radio sources were classified as obscured active galaxies. Therefore, our analysis suggests that a spectroscopic analysis in the infrared range will be more helpful to identify their nature as well as potentially obtain a redshift measurement.

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