Catching butterflies in the sky: Extended catalog of winged or X-shaped radio sources from the latest FIRST data release

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**ABSTRACT**

We present a catalog of 290 ‘winged’ or X-shaped radio galaxies (XRGs) extracted from the latest (17 Dec. 2014) data release of the ‘Very Large Array Faint Images of the Radio Sky at Twenty centimeter’ (VLA FIRST survey). We have combined these radio images with their counterparts in the TIFR GMRT sky survey (TGSS) at 150 MHz (TGSS alternative data release, TGSS ADR1), in an attempt to identify any low surface-brightness radio emission present in these sources. This has enabled us to assemble a sample of 106 ‘strong’ XRG candidates and 184 ‘probable’ XRG candidates whose XRG designation must be verified by further observations. The present sample of 290 XRG candidates is almost twice as large as the number of XRGs presently known. Twenty-five of our 290 XRG candidates (9 ‘strong’ and 16 ‘probable’) are identified as quasars. Double-peaked narrow emission lines are seen in the optical spectra of three of the XRG candidates (2 ‘strong’ and 1 ‘probable’). Nearly 90% of the sample is located in the FR II domain of the Owen-Ledlow diagram. A few of the strong XRG candidates have a rather flat radio spectrum (spectral index $\alpha$ flatter than $-0.3$) between 150 MHz and 1.4 GHz, or between 1.4 GHz and 5 GHz. Since this is not expected for lobe-dominated extragalactic radio sources (like nearly all known XRGs), these sources are particularly suited for follow-up radio imaging and near-simultaneous measurement of the radio spectrum.

**Keywords:** galaxies: active — galaxies: jets — quasars: general — radio continuum: galaxies: miscellaneous — catalogs — surveys

1. **INTRODUCTION: A BRIEF OVERVIEW OF XRGs**

Active galactic nuclei (AGNs) are long believed to be located at the centers of massive galaxies (e.g., Kormendy & Ho 2013). A plausible scenario to account for the enormous energy release from the AGN involves accretion of matter on to a super-massive black holes (SMBH) which, under suitable conditions, can also result in the launch of a pair of relativistic jets of non-thermal radio emission, which can extend up to mega-parsec dimensions (e.g., Heckman & Best 2014; Dabhade et al. 2017). Such galaxies, referred to as ‘radio galaxies’ (RGs), often show a compact radio core flanked by a pair of ‘radio lobes’. Nearly always, powerful RGs are associated with elliptical galaxies (Véron-Cetty & Véron 2001). Remarkably, a small minority of RGs is known to exhibit two pairs of fairly well collimated radio lobes, broadly forming an X-shaped morphology. These ‘winged’ or ‘X-shaped’ radio galaxies (XRGs, Leahy & Parma 1992) form the topic of this work.

XRGs constitute about 5 to 10% of radio galaxies in the 3CRR catalog (Leahy & Williams 1984; Leahy & Parma 1992). Based on an edge-darkened, or edge-brightened radio morphology of the brighter (i.e., primary) radio lobe pair, they are classified as Fanaroff-Riley type I (FR I) or type II (FR II) XRGs, respectively (Fanaroff & Riley 1974). Recall that whereas a pair of radio lobes, each having a ‘hot spot’ near its outer edge, is seen in FR II sources, FR Is often exhibit a jet pair emanating from a prominent radio core, each jet forming an edge-darkened radio lobe. The primary lobe pair in a majority of XRGs in the Leahy & Parma (1992) sam-

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ple belong to the FR II type, whereas all the known secondary radio lobes (‘wings’) are of the FR I type. Also, interestingly, radio luminosities of the known XRGs are mostly near the FR I and FR II division ($P_{178MHz} \approx 2 \times 10^{25}$ W Hz$^{-1}$ sr$^{-1}$, e.g., Cheung et al. 2009; Landt et al. 2010). Their intermediate radio luminosities may hint that XRGs represent a transitional morphology between the FR I and FR II types (Landt et al. 2010).

The origin of XRGs is contentious and several models have been proposed to explain this phenomenon, as reviewed in Gopal-Krishna et al. (2012). The three most discussed scenarios for their formation are: (1) diversion of the backflowing synchrotron plasma of the radio lobes, upon impacting an asymmetric circum-galactic gaseous halo of the parent early-type galaxy; (2) spin-flip of the central SMBH; and (3) precession of the (large-scale) twin-jets. In the backflow model, the radio wings form due to diversion of the backflowing lobe plasma whose subsequent outward expansion is aided by the buoyancy forces exerted by a steep pressure gradient in the circum-galactic medium (CGM) of the parent galaxy (Leahy & Williams 1984; Worrall et al. 1995; Kraft et al. 2005; Miller & Brandt 2009), the diversion occurring preferentially into pre-existing cavities/channels in the CGM (Leahy & Williams 1984; Machalski et al. 2016). However, Leahy & Parma (1992) have cautioned that buoyancy driven backflow cannot propagate faster than the external sound speed and hence, the wings propelled by the buoyancy forces are not expected to be longer than the main radio lobes (which are known to advance supersonically). Since this is not always the case, a possible resolution may lie in the possibility that over-pressured cocoons can drive supersonic outflows of the backflowing lobe plasma, forming gigantic radio wings (Capetti et al. 2002; Hodges-Kluck & Reynolds 2011; Rossi et al. 2017). In order to realize the needed large over-pressure relative to the ambient medium, the jet’s head would be required to first propagate out to sufficiently large distance from the nucleus.

Observational support to the backflow deflection model comes from optical studies of the host galaxies of XRGs (Capetti et al. 2002; Saripalli & Subrahmanyan 2009; Gillone et al. 2016). These studies have demonstrated that the radio axis defined by the two primary lobes displays a preference to align with the optical major axis of the host elliptical galaxy. The two wings (secondary lobes) show a strong tendency to align with the minor axis of the optical host, which is consistent with the expectation that the putative buoyancy driven expansion of the wings should occur along the maximum pressure gradient. In tune with this basic picture, XRGs are found to be associated predominantly with early-type galaxies whose ellipticity is abnormally high (Gillone et al. 2016, and references therein). The strong statistical correlation observed between the host galaxy properties and the X-shaped radio morphology provides support to the over-pressured lobe scenario and this is corroborated by the available X-ray images of a few XRGs, which trace the (asymmetric) shape of their CGM (Hodges-Kluck et al. 2010a).

Taking a clue from the observed S-shaped radio morphologies of the nearby radio galaxies Centaurus A and 3C 272.1, Ekers et al. (1978) proposed that geodetic precession of the jet pair, conceivably due to a torque exerted by an external massive body, can explain the huge Z-symmetric radio trails extending from the extremities of the two lobes of the giant radio galaxy NGC 326. The jet precession may also be caused due to a tilted and warped accretion disk (see Caproni et al. 2006, and reference therein), or by a close passage of a neighboring galaxy (Blandford & Icke 1978; Dennett-Thorpe et al. 2002). Indeed, Battistini et al. (1980) reported that NGC 326 is associated with a dumbbell galaxy, i.e., two nearly equally bright ellipticals within a common envelope, of which one is currently hosting jet activity and interacting gravitationally with its elliptical neighbor (Murgia et al. 2001). A study of ~100 radio sources associated with dumbbell galaxies has in fact revealed markedly distorted radio structures in roughly a dozen of them (Wirth et al. 1982). In this picture, the interacting neighbor may either be in a highly eccentric (or, unbound) orbit, or in a circular orbit. In the first case, impulsive gravitational interaction can lead to an inversion-symmetric distortion of the jet pair, resulting in an X-shaped or Z-shaped morphology. In the second case, the continued tidal interaction can cause periodic inversion-symmetric wiggles in the radio jet pair, giving rise to a helical radio morphology. A warped and tilted accretion disk can also be expected to form in SMBH binaries, leading to an X-shaped radio morphology (Begelman et al. 1980). One motivating factor behind this scenario is the discovery of double-peaked emission lines in the optical spectra of a XRGs (Zhang et al. 2007). By modeling the radio morphological distortions observed in 3 XRGs (3C 52, 3C 223.1 and 4C 12.03), Gong et al. (2011) have estimated precession periods of the order of a million years; such a timescale would be consistent with the estimated dynamic ages of active radio lobes and the wings in XRGs (Mezcua et al. 2012).

In the ‘spin-flip’ scenario, the wings of an XRG are regarded as the fossil synchrotron plasma of the earlier (pre spin-flip) lobe pair, while the observed misalignment of the currently ‘active’ lobes from the axis defined by the wing pair is attributed to the jet’s re-orientation, following a sudden tilt of the spin axis of the AGN’s supermassive black hole (SMBH) resulting from coalescence of the two SMBHs belonging to the pair of merging galaxies (Rottmann 2001; Zier & Biermann 2001; Merritt & Ekers 2002). However, it has also been argued that the wings could even form prior to the SMBH merger (Biermann et al. 2002; Gopal-Krishna et al. 2003; Zier 2005). In a systematic study, Mezcua et al. (2011) have found that the host ellipticals of nearly half of the XRGs exhibit signatures of a starburst occurring around $10^9$ to $10^{10.5}$ years (1 to 3 Gyr) ago. Hydrodynamical simulations of galaxy mergers suggest a time interval of about 2 Gyr between a merger-induced starburst and the onset of AGN activity (Lotz et al. 2008), in accord with the idea of a physical link between galaxy merger and XRG formation. There exist other observational evidences implicating galaxy mergers in the XRG formation. These include: (1) ellipti-
galaxies hosting XRG have SMBH of larger than average mass found using a control sample of elliptical galaxies (Mezcua et al. 2011); (2) Detection of X-ray cavities and a likely stellar shell in the XRG system 4C+00.58 (Hodges-Kluck et al. 2010b), as well as the detection of shells around the host galaxy of the XRG 3C-403 (Ramos Almeida et al. 2011). Also, a recent dynamical analysis of the hybrid radio structural distortion observed in the radio galaxy 3C 293 lends support to the rapid jet re-alignment scenario for XRGs (Machalski et al. 2016). On the other hand, the merger-induced rapid reorientation model encounters difficulty in explaining the strong tendency for the wings of XRGs to align with the optical minor axis of host galaxy (Gillone et al. 2016, and references therein).

It is important to bear in mind that none of the above models is capable of consistently explaining the entire gamut of observed properties of XRGs, as emphasized in a review of XRG models, which also dwells upon a few alternative explanations (Gopal-Krishna et al. 2012). One of these alternatives invokes a collision between the radio jet pair with the (partial) shells around the host elliptical, that are believed to form in the process of galaxy merger (see Gopal-Krishna & Chitre 1983; Gopal-Krishna & Saripalli 1984; Zier 2005). A possible substitute for the shells is the interstellar medium (ISM) of the massive host elliptical, which is set in rotation by a captured galaxy as it spirals inward in course of its merger with the massive elliptical (Gopal-Krishna et al. 2003). A distinct merit of this model lies in its ability to provide a natural explanation for the Z-shaped morphology traced by the radio wings, a pattern highlighted in that study where it was noted to be a fairly common feature of the XRGs with well-resolved radio maps. Yet another explanation proposed for the XRGs simply posits that the nucleus possesses not one, but two, SMBHs each of which ejects a jet pair grossly misaligned from the other (Lal et al. 2008, see also Lal et al. 2019). This would have been the most direct explanation for XRGs, but for the difficulty it faces in explaining the observed Z-symmetry of the wings (see above), the observed preferential alignment of the wing pair with the optical minor axis of the host galaxy, as well as the fact that hot spots are never found in both pairs of radio lobes in XRGs (see, e.g., Gopal-Krishna et al. 2003). Furthermore, VLBI observations of XRGs have so far provided no compelling evidence for a dual active nuclei inside the radio core (Burke-Spolaor 2011).

The striking diversity of the different models proposed for the origin of XRGs makes them an extraordinarily interesting subpopulation of radio galaxies. In addition, they carry special astrophysical interest by being potential sources of gravitational waves, if indeed the ‘spin-flip’ model is the correct description for at least a substantial fraction of XRGs (Heckman et al. 1986; Rottmann 2001; Merritt & Ekers 2002; Biermann et al. 2002; Milosavljević & Merritt 2003; Roberts et al. 2015a). Thus, an improved estimation of the fraction of RGs that turn into XRGs via the spin-flip route would enable realistic predictions for the low-frequency gravitational wave background which is thought to pervade the universe (e.g., Roberts et al. 2015b, and references therein).

The studies mentioned above are constrained due to the rather small sizes of the available XRG samples. The first major step towards rectifying this problem was taken by Leahy & Parma (1992). Later, Cheung (2007, hereinafter C07) identified 100 XRG candidates from a systematic search in the FIRST survey catalog (Becker et al. 1995). Their search was limited to sources with radio major axis larger than 15 arcsec, expectedly resulting in a significant under-representation of the XRG population in their list. Furthermore, the available optical and radio details are highly incomplete even for that sample. For instance, out of the 100 XRGs in the C07 sample, only ~50% have been observed spectroscopically (Cheung et al. 2009, hereinafter C09, Mezcua et al. 2012) and only 53 out of the 100 XRGs have been taken up for investigating the host galaxy properties (Gillone et al. 2016). Similarly, analysis of the SMBH mass and starburst history (Mezcua et al. 2011) have been reported for just 29 out of the 100 XRGs, and merely 12 of them are covered in the follow-up study by Mezcua et al. (2012). Therefore, in order to facilitate the scope of the studies of XRGs, it is desirable to extend the XRG search campaign initiated by Cheung (2007). We have undertaken such a search program by lowering the radio component size threshold for XRG candidates from 15" employed in that study, to 10". Based on this revised search threshold, we present here a new catalog of candidate X-shaped radio sources, drawn from the latest data release of the FIRST survey at 1.4 GHz (Becker et al. 1995). In Section 2, we briefly comment on the existing XRG catalogs. Details of our selection procedure and the main results of our campaign are presented in Section 3. The host galaxy identification and radio properties are described in Sections 4 & 5, followed by a brief discussion (Section 6) and a summary of the present results (Section 7). Throughout this paper, we assume a Λ-CDM cosmology with parameters $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

2. EXISTING LISTS AND DEFINITION OF THE ‘WINGED’ OR ‘X-SHAPED RADIO SOURCES

As a class, X-shaped extragalactic radio sources were first discussed by Leahy & Parma (1992), based on their list of 11 XRGs. Of these, the primary lobe pair showing a clear FR II radio morphology with well-defined hot spots is seen in 7 sources. Cheung (2007) collected another 8 XRGs through a literature search, raising the sample to 19 XRGs. The first systematic search for the XRGs was undertaken by Cheung (2007, C07), based on the VLA FIRST survey (Becker et al. 1995). He compiled an initial list of 100 XRG candidates showing a ‘winged’ or X-shaped radio morphology, by visually inspecting 1648 sources in which at least a hint of inversion symmetric radio lobe structure was present. Recently, Roberts et al. (2018) have reported JVLA multi-array (mainly A-array) radio continuum imaging in the L- and/or C-band of XRG candidates from C07. Based on these observations, Saripalli & Roberts (2018) have subsequently identified 12 sources as S- or Z-shaped radio galaxies. Remarkably, more than 75% of the C07 sample has turned out to be
bona-fide XRGs and hence useful for probing the question of origin of XRGs (see Cheung et al. 2009; Mezcua et al. 2011, 2012; Gillone et al. 2016).

A more recent XRG search is reported in Proctor (2011) who applied an automated morphological classification scheme to the FIRST radio sources. Adopting a separation cut of 0.96 arcmin, they classified the radio sources into singles, doubles, triples, and groups of higher membership count. They also visually inspected 7106 higher count group members, thus finding 156 candidates for X-shaped radio morphology. Out of these, 21 sources had already been reported in C07, leaving 134 new XRG candidates (this is ~2% of the sources classified by them as higher-count groups). Two of us (RJ and XLY) have visually inspected the 156 XRG candidates reported in Proctor (2011), in search of an unambiguous X-shaped morphology with well defined wings (see, Section 6.1 for details of our selection procedure) and assessed 43 of them to be strong XRG candidates, and the remaining systems as the probable candidates. Out of these 43 strong candidates, 18 sources are common to C07, and FCG J151340.0+260730 (3C 315) is the archetypal, X-shaped radio galaxy known for over 4 decades (Mackay 1969; Hogbom & Carlsson 1974). Interestingly, 13 of the remaining 24 sources were also picked in the present search for strong XRG candidates in the 2014-12-17 release of the FIRST catalog (see section 3) and these are marked with an asterisk in Column 1 of Table 2.

| Component | Peak Flux (mJy/beam) | Major Axis (arcsec) | Minor Axis (arcsec) |
|-----------|----------------------|---------------------|---------------------|
| Cat.#1    | 7.80                 | 22.88               | 15.44               |
| Cat.#2    | 5.72                 | 14.47               | 7.64                |
| Cat.#3    | 20.29                | 23.41               | 10.98               |
| Cat.#4    | 12.56                | 12.03               | 7.19                |
| Cat.#5    | 12.60                | 14.25               | 7.59                |
| Cat.#6    | 56.57                | 11.28               | 6.79                |

Notes: a The deconvolved synthesized beam major and minor axes.

It is worth emphasizing that even though the visual inspection approach for picking XRG candidates is beset with subjectivity, it does yield promising XRG candidates, as validated by the high (>75%) confirmation rate of the XRG candidates reported in C07 (e.g., Roberts et al. 2018; Saripalli & Roberts 2018). Recalling the standard definition, the XRGs are a subset of radio sources, which exhibit an additional (fainter) pair of radio lobes displaying an inversion-symmetric configuration. These ‘secondary’ radio lobes, often called ‘wings’, are aligned at a fairly large angle from the main radio axis defined by the primary lobe pair. Conventionally, the readily accepted examples of XRGs are those in which the wings extend to at least 80% of the size of the primary lobes. But, since the wings always lack a brightness peak (hot spot) near the extremity, their measured radio extents (and hence the robustness of their XRG classification)
would depend sensitively on the depth and spatial resolution of the radio map. For instance, although only one wing of the well known XRG 3C 63 is apparent in the 1.4 GHz VLA B-array map (Baum et al. 1988), both wings clearly stand out in its subsequent VLA A-array image at 1.4 GHz (Harvanek & Hardcastle 1998). Similarly, the large, prominent wings present in the radio maps of the well known XRGs 3C 192 and 3C 379.1 (Myers & Spangler 1985; Baum et al. 1988; Dennett-Thorpe et al. 1999) only appear as short extensions in their earlier shallower radio maps (Leahy et al. 1997; Myers & Spangler 1985). Furthermore, it now appears quite plausible that XRGs are morphological cousins of Z-shaped radio galaxies, in which the oppositely directed wings launch away from the main radio axis at locations that are relatively close to the host galaxy (e.g. Gopal-Krishna et al. 2003). Thus, in isolation, the two wings can often be described as a Z-shaped double radio source (Gopal-Krishna et al. 2003). Guided by all these considerations and in order to minimize missing out genuine XRGs, we have resorted to a somewhat less conservative approach in assembling the present catalog of XRG candidates, by also including the sources showing short wings (or even a one-sided wing), or just a hint of X-shaped radio structure. This was followed up by classifying them as ‘strong’ and ‘probable’ XRG candidates (section 6.1). Clearly, the latter would inevitably need higher quality radio images for validation as genuine XRGs.

3. SEARCHING FOR X-SHAPED RADIO SOURCES IN THE LATEST RELEASE OF THE FIRST SURVEY

We have assembled the present catalog of 290 XRG candidates by searching in the latest VLA FIRST survey data release version 14Dec17. This version covers 10,575 square degrees of the sky (8,444 square degrees in the northern and 2,131 square degrees in the southern hemisphere) and contains 946,432 radio sources, including those reported in the earlier data releases from 1993 through 2011. The survey achieved a typical rms noise of 0.15 mJy and a resolution of ∼5′′ at 1.4 GHz (Becker et al. 1995). It has been extensively mined for making systematic searches for radio sources of different morphological types, e.g., FR I/FR II radio galaxies (Capetti et al. 2017a,b), double-double radio galaxies (Proctor 2011), and hybrid morphology radio sources (Gawroński et al. 2006; Proctor 2011), also called HYMORS (Gopal-Krishna & Wiita 2000).

The main product of the FIRST survey is a radio intensity map of the sky, using which a catalog of discrete radio sources has been built from the coadded images (White et al. 1997). The catalog also lists for each entry the peak and integrated flux densities and angular size at 1.4 GHz (see, e.g., Figure 1 and Table 1), derived from fitting two-dimensional Gaussians. Note that in the FIRST catalog, an extended radio source can often have multiple entries (Proctor 2003, 2006). As estimated by Proctor (2011), ∼30% of the entries are actually individual multi-component radio sources, which offers a huge data base for morphological studies.

3.1. Basic sample selection

Given the enormous size of the FIRST catalog and the abundance of multi-component systems in it, examining the map of each source is not a practical option. Therefore, we first extracted a subset of XRG candidates by demanding (1) a peak flux density sufficiently high to realise an acceptable dynamic range, and (2) a radio extent sufficiently large to reveal the basic morphological features. Below, we describe our sample selection procedure in some detail.

The characteristic feature of XRGs is two (mis-aligned) pairs of radio lobes/jets, such that there is a large angular offset between the axes defined by the brighter (primary) lobe pair and by the two secondary lobes (i.e., ‘wings’) which are usually of much lower surface brightness. Only the primary lobes are known to exhibit an edge-brightened morphology, i.e., a hot spot typically situated near the lobe’s extremity. Considering the typical rms noise of the FIRST maps (0.15 mJy beam$^{-1}$), a 3σ detection threshold would correspond to a minimum peak flux density of 0.45 mJy beam$^{-1}$. Here, we make a reasonable assumption that the peak brightness of the hot spots in the primary lobes is about 10 times the (average) surface brightness of the wings. Accordingly, as the first selection filter, we set a lower limit of 5 mJy beam$^{-1}$ for the peak flux density at 1.4 GHz. This would normally permit a minimum dynamic range of ∼33:1 and one may thus reasonably expect to detect any associated wings (see section 4). Next, in order to minimize missing out any wings we need to ensure that a given source is fairly well resolved with the ∼4.3 arcsec synthesized beam (VLA B-array) of the FIRST survey. Hence our second selection filter is that the radio major ($\theta_{maj}$) and minor ($\theta_{min}$) axes of the fitted Gaussian should be larger than 10′′ and 5′′, respectively. In this way, the present compilation is an extension of the XRG search reported in C07 (see their section 3.1). Application of the above two selection filters left us with a basic list of 5128 sources. Of these, 2350 sources have 10′′ < $\theta_{maj}$ ≤ 13′′, 935 sources have 13′′ < $\theta_{maj}$ ≤ 15′′ and the remaining 1843 sources have $\theta_{maj}$ > 15′′.

3.2. Visual inspection of the radio maps of the short-listed sources

In the next step, we queried the radio field for each of the 5128 short-listed sources, from the online archive of the FIRST survey$^2$ (Becker et al. 1995), with an image size of 6×6 arcmin$^2$. Given the usually complex (multi-component) radio structures of known XRGs, we decided to also make use of their 150 MHz radio continuum images reported in the First alternative data release of TIFR GMRT Sky Survey$^3$ (TGSS ADR1 Interna et al. 2017). Its combination of angular resolution (∼25 arcsec) and a low frequency (150 MHz)

$^1$ Data released on 2014 Dec. 17

$^2$ http://sundog.stsci.edu/index.html

$^3$ https://vo.astron.nl/tgssadr/q_fits/imgs/form
is better suited for picking up diffuse emission (examples in Figure 2). Radio contour maps and pseudo-color images were then generated to facilitate the visual inspection (see Appendix Figure 10 for the ‘strong’ XRG candidates). For each field, we measured the rms noise and used it for setting the base level for the contour plotting. We initially used 3σ level and slightly fine-tuned it in individual cases, so as to minimize the confusion arising from side lobes in the map. For the color images, we carefully set the brightness to emphasize any wing-like features.

The above procedure was then followed up with two of the co-authors independently inspecting the radio structure of each short-listed source and their mutual concurrence was treated as the trigger for admitting a given source as a preliminary XRG candidate. In the final round, radio images of all such sources were individually inspected by three of the co-authors, which led to the final list of 290 XRG candidates. Depending on the level of consensus among the 3 co-authors, these XRG candidates were placed in ‘strong’ (106) or ‘probable’ (184) categories (Table 2 and Table 4). The classification is further discussed in section 6.1. It may be noted that only 25 of these XRG candidates appear in the list of Proctor (2011). Note also that since the present XRG sample is meant to be an extension of the C07 XRG sample, we have decided to retain these 25 XRG candidates, of which 13 systems belong to our list of strong XRG candidates. Those sources are marked with an asterisk in the first column in Table 2 and Table 4.

4. IDENTIFICATION OF THE HOST GALAXY AND ITS PROPERTIES

In this key step, we first defined for each source a likely position of the active core, near the symmetry centre of its radio structure. The radio contours were then overlaid on the Sloan Digital Sky Survey (SDSS) r-band and/or Digital Sky Survey (DSS) red-filter image of the source. For most (∼80%) of our XRG candidates, an optical counterpart could thus be found close to the expected location. For the remaining sources, we have simply used the estimated radio symmetry center as the coordinates of the (undetected) optical counterpart. These coordinates for our 106 ‘strong’ and 184 ‘probable’ XRG candidates are listed in columns 2 and 3 of Table 2 and Table 4, respectively. In Figure 10 (see Appendix) we have displayed the FIRST 1.4 GHz images of our 106 ‘strong’ XRG candidates, the corresponding TGSS_ADR1 150 MHz image is shown in the right panel of each subplot, except for J0710+3546 which is not covered in that survey. The centre of each image coincides with the above estimated most plausible position of the optical host. Interestingly, the radio-active core is detected in only ∼ 10 of our strong XRGs.

Spectroscopic or, alternatively, photometric redshifts were taken from the NED and/or SDSS databases. Spectroscopic redshifts could be found for 40 (∼38%) of our 106 ‘strong’ XRG candidates and 53 (∼30%) of our 184 ‘probable’ XRG candidates. For the remaining ‘strong’ candidates, photometric redshifts were taken from the SDSS archive; these are based on the SDSS photo-tree method. In Table 2 and Table 4 we list the redshift values (Column 4) marked as ‘SPEC’ and ‘PHOT’ for the spectroscopic and photometric redshifts (Column 5), SDSS r-band apparent magnitude (Column 6) and the corresponding absolute magnitude (Column 7) for our 106 ‘strong’ and 184 ‘probable’ XRG candidates, respectively. Figure 3 compares the histograms of spectroscopic redshifts for our strong XRG candidates and for the 50 XRGs from Cheung et al. (2009). It is evident that our strong XRGs are systematically more distant and span a larger range in redshift (from ∼ 0.06 to ∼ 0.7, with a median redshift of z ∼ 0.37), compared to the 50 XRGs in C09, for which the median redshift is z ∼ 0.25. This difference is not unexpected, given that our selection procedure admits sources of smaller radio (angular) extent (section 3).

The R-band absolute magnitudes (M_R) of our XRG candidates were computed from the SDSS r-band apparent magnitudes, by applying the k-correction from Blanton & Roweis (2007). The average M_R of our 40 spectroscopically identified ‘strong’ XRG candidates is found to be −23.2 with an rms scatter of 0.8. It is interesting that these XRG candidates with spectroscopic redshifts contain nine quasars (see Table 3 and Figure 9 for their information and FIRST 1.4 GHz images, respectively). It may be mentioned that X-shaped quasars are known to be quite rare; the first one was reported by Wang et al. (2003) (4C+01.30 at z = 0.132). Subsequently, one more X-shaped quasar, WGA J2347+0852, was reported by (Landt et al. 2006). In C07, 4 quasars were identified among their 36 spectroscopically identified XRG candidates. Recently, Saripalli & Roberts (2018) have confirmed a total of 12 quasars in the C07 sample. It may also be noted that just one X-shaped quasar (4C+01.30) is reported to exhibit a double-peaked (broad) emission line system (Zhang et al. 2007). The present catalog of XRG candidates contains another three such rare objects showing double-peaked narrow emission lines: the quasars J0818+1508 and J1554+3811 belong to the ‘strong’ XRGs (Table 2, see also Figure 9 for their FIRST 1.4 GHz images), while J1247+1948 is a ‘probable’ XRG candidate (see, Table 4). Since the presence of double-peaked emission lines in X-shaped radio sources may be taken as a clue favoring the binary/dual black-hole model (e.g. Lal et al. 2008, 2019), such rare objects are good candidates for confirming a SMBH pair-binary, via high-resolution VLBI. A more detailed analysis of the radio-optical properties of the present XRG candidates is underway and will be presented elsewhere (Joshi et al., in prep.).

5. RADIO PROPERTIES OF THE PRESENT CATALOG OF XRG CANDIDATES

For the present XRG sample, we have gathered the radio flux density information at several frequencies: at 150 MHz from the TGSS_ADR1 catalog (Intema et al. 2017), at 1.4 GHz from the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) and at 8.45 GHz/5 GHz from the Parkes-MIT-NRAO surveys (PMN, Griffith et al. 1995), the MIT-Green Bank 5 GHz Survey (MIT-GB, Bennett et al. 1986) and from the Green Bank 4.85 GHz survey (Becker et al. 1995).
Figure 2. Four examples of ‘strong’ XRG candidates in the present catalog, the radio contours are overlaid on the DSS red filter images. The black contours are for the FIRST 1.4 GHz survey and the cyan contours are for the TGSS_ADR1 150 MHz survey. The contours are plotted at (1, 2, 4, 8, 16, 32, ...)$\times$$3\sigma$. The rms ($1\sigma$) noise values are 0.16 (J1039+4648), 0.14 (J1257+1228), 0.12 (J2028+0035) and 0.16 (J2236+0427) mJy beam$^{-1}$ for the FIRST contour maps, respectively, and 3.5 mJy beam$^{-1}$ for the TGSS_ADR1 maps. These examples underscore the importance of combining the 1.4 GHz maps with their 150 MHz counterparts.

These flux densities are listed in columns 8 - 10 of Table 2 and Table 4 for our ‘strong’ and ‘probable’ XRG candidates, respectively. We also list the 1.4 GHz radio luminosity for all the XRG candidates, based on spectroscopic, or, alternatively, photometric redshifts. In calculating radio luminosity, we assumed a spectral index index $\alpha = -0.8$ (see below). The average luminosity of our strong XRG candidates with available spectroscopic redshifts is found to be $\log(P_{1.4\text{GHz}}) = 25.73$ W Hz$^{-1}$, with an rms uncertainty of 0.65. This is in agreement with the value given in C07 and is close to the division between the FR I and FR II types (Fanaroff & Riley 1974). Figure 4 displays the 1.4 GHz luminosity vs redshift for our strong XRG candidates with known spectroscopic redshifts. It is seen that our XRG candidates have systematically lower radio luminosity compared to the previously reported XRGs (Cheung et al. 2009).
Figure 3. Distributions of spectroscopically measured redshifts for the 40 strong candidates from the present XRG catalog (SPEC, red-lined histogram) and for the 50 XRGs from C09 (black-lined histogram).

Figure 4. Radio luminosity - redshift diagram for the XRG candidates with spectroscopic redshift (SPEC). The 50 XRG candidates with spectroscopic redshifts, from (from Cheung et al. 2009) are shown with black open circles, while our 39 strong XRG candidates are shown with red filled circles. The solid, dashed and dot-dashed curves correspond, respectively, to flux densities of 30 mJy, 100 mJy and 1 Jy, at 1.4 GHz.

Figure 5. Spectral index distributions for our strong XRG candidates. The histogram in red colour refers to the spectral index (150 MHz – 1.4 GHz) values available for 101 strong XRG candidates. The histogram in black colour refers to the spectral index (1.4 GHz – 5 GHz) values available for 64 of our strong XRG candidates. The vertical dashed line marks the division between the steep (left side) and flat spectra (right side).

For our strong XRG candidates, we have determined the spectral index ($S_i \propto \nu^\alpha$) between 150 MHz and 1.4 GHz ($\alpha_{1.4}^{1.5}$), and also between 1.4 GHz and 5 GHz ($\alpha_{5.1}^{1.4}$), based on the flux densities listed in Table 2. Thus, $\alpha_{0.15}^{1.4}$ could be determined for 101 of our strong XRG candidates, out of which 9 (~9%) sources are found to have a flat radio spectrum ($\alpha_{0.15}^{1.4} > -0.5$). In addition, $\alpha_{1.4}^{5.1}$ could be measured for 64 of our strong candidates, with 14 (~22%) of them showing a flat radio spectrum and 3 out of these 14 showing an inverted radio spectrum (i.e. $\alpha_{1.4}^{5.1} > 0$). The XRG candidates showing a flat/inverted radio spectrum would be particularly attractive for probing the dual-AGN scenario for the origin of X-shaped morphology (e.g., Lal & Rao 2007).

Histograms of both spectral indices, for our strong XRG candidates are shown in Figure 5. Both distributions peak near $\alpha = -0.8$.

6. DISCUSSION

6.1. Classification as ‘strong’ or ‘probable’ XRG candidates

Recall that among the 290 XRG candidates reported here, we have classified 106 as ‘strong’ and 184 as ‘probable’ (Tables 2 & 4). The vast majority in the ‘strong’ category is likely to be confirmed as bona-fide XRGs, with a pair of radio wings comparable in extent to their active counterparts, the two primary radio lobes. In this section we briefly com-
ment on the justification for including some sources in the present catalog, despite only a marginal evidence for a secondary lobe pair (wings) in their existing radio maps. This stems from the recognition that visibility of wings can be diminished due to myriad factors related to the source evolution/orientation and their directional offset from the primary lobe pair. These difficulties may be compounded by observational limitations related to angular resolution and/or the sensitivity to diffuse emission at the frequency of radio imaging (see, e.g., Cheung 2007; Cheung et al. 2009; Wang et al. 2003). As an example, the XRG candidates J0941+2147, J1206+3812 and J1444+4147 were included in C07 list despite their showing abnormally short wings. However, the wings stood out clearly in subsequent VLA 1.4 GHz images Roberts et al. (2018). Guided by this, we have included in our XRG catalog several candidates (e.g., J0028-0026 and J0930+2343) whose secondary lobes are visible, albeit no more in size than ~50% of the primary lobes, and yet a hint of inversion symmetry is discernible in their existing radio maps (TGSS ADR1 and/or FIRST). Additional examples are shown in Figure 10. The classification ‘strong’ has been assigned to some XRG candidates in our catalog, in spite of their radio sizes not being comfortably large enough to reveal their structural details in the existing radio maps. In adopting this somewhat less stringent approach we have been guided by the experience of several prominent XRGs which had appeared to be only marginally convincing in their earlier (lower sensitivity/resolution) radio maps. Prominent such examples include NGC 326 (Fanti et al. 1977); 3C 315 (e.g. Mackay 1969; Lal & Rao 2007) and 3C 63 (Harvanek & Hardcastle 1998).

It needs to be borne in mind that the observed faintness and small sizes of the wings could often be artifacts arising from energy losses suffered by the relativistic plasma radiating in these older/fossil radio components. To overcome this limitation, therefore, low-frequency radio imaging with sufficiently high angular resolution and sensitivity are mandatory with a typical expansion velocity of ~ 0.1c (e.g. Tingay et al. 1998; Arshakian & Longair 2004; Machalski et al. 2010; An & Baan 2012), the active lobes would take ≥ 10^6 yr to grow to their typically observed dimensions (~30 - 60 kpc Mezcua et al. 2011, 2012). This duration is comparable to the expected radiative lifetime of the relativistic plasma in the wings at decimeter or shorter wavelengths, once the energy supply to the wings has been cut-off, following the putative spin-flip (Gopal-Krishna et al. 1989; Komissarov & Gubanov 1994; Kaiser & Alexander 1997; Kaiser et al. 1997; Mocz et al. 2011; Singh et al. 2016). The consequent fading could easily push one or both radio wings below the detection threshold, unless imaged at a sufficiently low radio frequency. This situation may not be uncommon, as exemplified by the sources J0216+0244, J1257+1228 and J2236+0427 (see Figure 10). All these sources could be classified as ‘strong’ XRG candidates only because at the low frequency (150 MHz) of the TGSS ADR1 images, their wings are intrinsically large enough to be resolved and recognized as such. In contrast, the detection of these wings in the 1.4 GHz FIRST survey had remained hampered both due to their shorter radiative lifetimes and the reduced sensitivity of the FIRST survey to extended radio emission.

6.2. The Fanaroff-Riley classification for X-shaped radio galaxies

Radio luminosities of X-shaped radio galaxies have been found to fall near the FR I/FR II division (e.g., Dennett-Thorpe et al. 2002). This trend is further strengthened by the present catalog of XRG candidates (section 5). In the model of Gopal-Krishna et al. (2003, 2012) this property is linked to the formation mechanism of XRGs itself. Going a step further, Cheung et al. (2009) have shown that the XRGs are located near the FR I/FR II dividing line in the ‘radio-optical luminosity diagram’, also known as the Owen-Ledlow plane (Ledlow & Owen 1996). We now briefly examine this issue in relation to the present sample of XRG candidates. It is well known that the active (primary) radio lobes of XRGs are mostly of the FR II type (Leahy & Parma 1992; Saripalli & Roberts 2018), although some XRGs with FR I primary lobes do exist (Leahy & Williams 1984; Jones & McAdam 1992; Murgia et al. 2001). Figure 7 shows the distribution of our XRG candidates (both ‘strong’ and ‘probable’) types on the Owen-Ledlow plane. For this we have only used a subset of 92 sources from our sample having spectroscopic redshifts and NVSS 1.4 GHz flux density, and augmented the sample by including the 50 XRGs with spectroscopic redshifts, taken from the compilation of Cheung et al. (2009). The FR dividing line shown in Figure 7 can be parametrized as log PL4GHz = -0.67MR + 10.13, where PL4GHz is the radio luminosity at 1.4 GHz and MR is the r-band absolute magnitude of the host galaxy (Wold et al. 2007). It is evident that our XRG candidates are clustered near the dividing line defined above, in accord with C09. Furthermore, a vast majority of our XRG candidates (~90%) falls above the dividing line, in the region known to be populated predominantly by FR II sources. This is not unexpected, given that the XRG candidates (both ‘strong’ and ‘probable’) in our catalog are mostly consistent with the FR II morphology. Specifically, we find that only 5 out of the 39 ‘strong’ XRG candidates from our sample with spectroscopic redshifts and NVSS 1.4 GHz flux density, fall below the Owen-Ledlow dividing line (i.e., in the preferred domain of FR I sources). An inspection of their FIRST radio maps shows that J0956+0001 has a clear FR II morphology, whereas J0727+3956, J1145+1529 and J1407+2722 are too small for a reliable morphological classification. Only the source, J0924+4034 has a morphology (Figure 10) clearly reminiscent of the prototypical FR I XRG NGC 326 (marked ‘4’ in Figure 7, see Fanti et al. 1977).

We now turn to the 14 ‘probable’ XRG candidates falling in the FR I region of the Owen-Ledlow diagram, i.e., below the dividing line in Figure 7. Based on the available maps, we found three of them (J1140+1743, J0219+0155 and J0028-0428, see Figure 8) to show an (inner) morphology reminiscent of the FR I type XRG NGC 326 (see Figure 6 in Murgia et al. 2001). J1140+1743, also known as NGC 3801,
Figure 6. The ‘probable’ XRG candidate J1009+0529 in our catalog, the fields are centered on the optical counterparts. The left panel shows the FIRST grey-scale image and the right panel shows the FIRST (black) and TGSS_ADR1 contours (cyan) overlaid on the DSS red filter image. Contours levels are set at \((1, 2, 4, 8, 16, 32, \ldots) \times 3 \sigma\), where \(1 \sigma\) rms noise is 0.18 mJy beam\(^{-1}\) for FIRST map and 3.5 mJy beam\(^{-1}\) for the TGSS_ADR1 map.

Figure 7. The 1.4 GHz radio luminosity versus absolute R-band magnitude. The probable and the strong XRG candidates with spectroscopic redshifts are marked with red open squares (probable) and red filled circles (strong). The XRG candidates recompiled in Cheung et al. (2009) are marked with black open circles (C09). The Owen-Ledlow luminosity division line is from Wold et al. (2007). The representative FRI type XRG, NGC 326 is marked.

has earlier been identified as a Z-shaped source (Hota et al. 2009). We have classified it as a probable XRG (or, an intermediate between the X- and Z-shaped radio galaxies) based on its FIRST image shown in the left panel in Figure 8. As it is known to be a post-merger star-forming galaxy (Hota et al. 2012), its wings could even have formed due to pre-merger gravitational interaction between the two galaxies. Coming to some other XRG candidates in the FR I domain (Figure 7), we find that a few of them (J0924+4034, J0219+0155 and J0028-0428) appear remarkably similar in radio morphology to the XRG NGC 326, which is a classical example of FR I XRG, on account of its prominent twin jets (Murgia et al. 2001). In relation to such sources, Merritt & Ekers (2002) suggested that if the spin of the active SMBH undergoes a reorientation due to an impulsive torque of external origin, the resulting flip of its spin vector could lead to an X-shaped radio morphology (see also Blandford & Icke 1978; Murgia et al. 2001). On the other had, a S- or Z-shaped radio morphology would result if the torque operates on the SMBH only gradually, i.e., its duration is longer than the jet outflow time scale. In the case of the radio galaxy NGC 326, an impulsive torque is, in fact, quite plausible, since its host is a dumb-bell galaxy comprised of a pair of massive ellipticals in gravitational interaction (Battistini et al. 1980). In this scenario, one may expect to find sources with an intermediate morphology (between S/Z-shape and X-shaped), in case the outflow and spin reorientation time scales are comparable.

Speculating on the later evolution of the reoriented (Z/S- and X-shaped) radio sources, Merritt & Ekers (2002) proposed that such sources would eventually evolve into FR II type, on a time scale of \(~ 10^8\) years. For instance, in the FIRST image of J1009+0529 (Figure 6), the large bright-
Figure 8. Radio images of the 3 ‘probable’ XRG candidates located in the FR I domain of the Owen-Ledlow diagram. The radio contours are overlaid on the DSS red filter images, the black contours display the FIRST 1.4 GHz maps and the cyan contours show the TGSS ADR1 images at 150 MHz. The contours are plotted at $1, 2, 4, 8, 16, 32, \ldots \times \sigma$, where $\sigma$ noise values are 0.19, 0.13 and 0.11 mJy beam$^{-1}$ for the three FIRST maps, respectively, and 3.5 mJy beam$^{-1}$ for all the TGSS ADR1 maps.

ness contrast seen between the active radio lobes and the (much older) wings might be indicative of such a transition in making, although this remains to be confirmed through spectral index imaging. On the other hand, Saripalli & Subrahmanyan (2009) have proposed an opposite evolutionary scheme (from FR II to FR I), motivated by the examples of FR I radio galaxies in which a newly formed inner lobe pair has been detected, examples are 3C 315 and B2014-558. In these sources, whereas the extended primary lobes are of FR I type (Leahy & Williams 1984; Jones & McAdam 1992), their inner doubles show an FR II morphology (Saripalli et al. 2008; de Koff et al. 2000), see also MERLIN 1.6 GHz images of 3C 315 (Sanghera & Leahy, unpublished, see http://www.jb.man.ac.uk/atlas/other/3C315.html). However, while the putative evolutionary transition from FR II to FR I morphology may indeed be physically plausible (see also Gopal-Krishna & Wiita 1988), it becomes imperative when the few observed FR I type XRGs are sought to be explained in terms of the backflow deflection model (see Saripalli & Subrahmanyan 2009; Saripalli et al. 2012).

Finally, we highlight the prominent, XRG NGC 326 as a challenge to the simple spin-flip scenario. Unlike its western radio wing, the eastern wing does not show a direct connection to the nucleus. Instead, this wing stretches out almost orthogonally from the vicinity of the observed inner edge of the eastern lobe, which is $\sim$45 kiloparsecs away from the nucleus (Figure 6 of Murgia et al. 2001). Apparently, the two wings do not have a common nucleus, in violation of the essence of the spin-flip paradigm for XRGs. This and a few other such examples of XRGs challenging the standard spin-flip paradigm were highlighted in Gopal-Krishna et al. (2003). A review of the various contending models of XRGs is presented in Gopal-Krishna et al. (2012), where possible roles of the galaxy shells and superdisks, as well as the merger induced rotation of the host galaxy’s ISM, have been explored as potential explanations for the XRG morphology. The invocation of a ‘superdisk’ (or, alternatively, a gaseous filament of the cosmic web within which the host galaxy happens to be located) for diverting the backflowing lobe plasma (Gopal-Krishna et al. 2003; Gopal-Krishna et al. 2012) was motivated by the observed sharp, long and straight inner edge of the radio wings in some XRGs, which also exhibit a strong alignment of magnetic field along the sharp radio edge (Murgia et al. 2001). Another striking examples of this phenomenology is the giant radio galaxy J0116-473 (Saripalli et al. 2002). The non-collinearity of the ridge lines of the two wings and the marked rarity of well-resolved XRGs showing a ‘pure’ X-shaped morphology, has also been noted in some other studies (e.g., Saripalli & Subrahmanyan 2009). At the same time, examples do exist where a persuasive case can be made for a restarted nuclear activity leading to ejection of twin-jets along a significantly altered direction, apparently in accord with the spin-flip scenario (Saripalli et al. 2013, and references therein).

7. SUMMARY AND FUTURE WORK

Based on a careful visual inspection of the radio sources in the latest release of the VLA FIRST Survey at 1.4 GHz, we have presented here a catalog of 290 winged or X-shaped radio galaxies (XRGs), which almost triples the number of XRG candidates cataloged by Cheung (2007). We classify 106 of them as ‘strong’ and 184 as ‘probable’ XRG candidates. The strong candidates are most likely to be confirmed by follow-up radio observations, while the probable candidates would also be particularly useful for designing future search campaigns for XRGs. The present work extends to smaller angular sizes the XRG search conducted by (Cheung 2007), which revealed 100 XRG candidates with a high confirmation rate through follow-up observations. The radio structural information on our XRG candidates has been taken mainly from the FIRST (1.4 GHz), NVSS (1.4 GHz) and TGSS ADR1 (150 MHz) surveys. Combining this information with the SDSS data, we were able to find optical counterparts for 85 of our 106 strong XRG candidates and
145 of our 184 probable XRG candidates. The corresponding numbers of sources with spectroscopic redshifts are 40 (47%) and 60 (41%), respectively, and the median redshifts are 0.37 and 0.41, respectively. Nine quasars are found among the 106 strong XRG candidates. The sample also contains two strong XRGs showing double-peaked optical emission lines ($z = 0.19$ and 0.33), which makes them excellent candidates for AGN harboring binary supermassive black holes.

On the radio side, as expected, a vast majority of the present strong XRG candidates are found to have steep radio spectra between 150 MHz and 1.4 GHz, and also between 1.4 GHz and 5 GHz (median $\alpha \approx -0.81$). However, a rather flat radio spectrum ($\alpha > -0.3$) has been found for 10 of our strong XRG candidates. At present, none of them are known to be a quasars. Recently, Lal et al. (2019) have shown that in terms of radio spectra, active lobes do not seem to differ from the (fainter) wings, which may likely support the twin AGN model where the spectra of the primary lobes and secondary wings are expected to be uncorrelated. It will be interesting to carry out a similar campaign for our bona-fide XRGs, in order to place tighter constraints on the models of X-shaped radio sources.

To the extent permitted by the partially complete redshift and radio structural information, we find that the present enlarged sample of XRG candidates adheres to the previously known trend according to which XRGs cluster around the radio luminosity dividing the FR I and FR II radio sources. More specifically, we find that out of our 39 strong XRG candidates with known spectroscopic redshifts and NVSS 1.4 GHz flux, as many as 34 lie above the FR division in the Owen-Ledlow diagram. Even for the 5 objects falling below the dividing line, an FR II morphology seems plausible in most cases. Together with the previously reported samples of XRGs (Cheung 2007; Proctor 2011), the present large sample would allow a closer look into the relative occurrence of X-shaped and Z-shaped radio morphologies among extragalactic radio sources and, in particular, the occurrence of Z-symmetry among the radio wings in XRGs. In parallel, we are studying possible relationship of the radio structure to the properties of the host galaxy (Joshi et al., in prep.).

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APPENDIX

Table 2. The ‘strong’ X-shaped radio source candidates

| Short Name     | R.A.        | Dec.        | z   | Qual. | r   | $M_R$ | $S_{0.15}$ | $S_{1.4}$ | $S_{1.5}$ | Ref.5GHz |
|----------------|-------------|-------------|-----|-------|-----|-------|------------|-----------|-----------|----------|
| (J2000)        | (J2000)     |             |     |       |     |       | (Jy)       | (Jy)      | (Jy)      |          |
| J0004+1248     | 00 04 50.27 | +12 48 39.5 | 0.14 | SPEC  | 17.44 | -21.37 | ...        | 0.107     | 0.407     | NRAO     |
| J0028-0026*    | 00 28 28.94 | -00 26 24.6 | 0.287 | PHOT  | 18.96 | -21.52 | ...        | ...       | 0.390     | NRAO     |
| J0030+1121     | 00 30 23.86 | +11 21 12.5 | 0.449 | SPEC  | 20.16 | -22.06 | 0.515      | 0.114     | 0.136     | NRAO     |
| J0121+0051     | 01 21 01.23 | +00 51 00.3 | 0.238 | SPEC  | 17.80 | -22.16 | 1.124      | 0.267     | 0.105     | NRAO     |

Notes:
1. short name; 2. Right Ascension (J2000, hh:mm:ss); 3. Declination (J2000, dd:mm:ss); 4. redshift;
5. redshift quality flag. PHOT: photometric redshift; SPEC: spectroscopic redshift;
6. apparent $r$-band magnitude of the host galaxy;
7. absolute $R$-band magnitude of the host galaxy;
8. integrated 150 MHz flux density (Jy, the uncertainty is 10% of the total flux density);
9. integrated 1.4 GHz flux density (Jy, the uncertainty is 3% of the total flux density);
10. integrated 5 GHz/4.85 GHz flux density (Jy);
11. references for 5 GHz/4.85 GHz flux density, NRAO: NRAO Green Bank 300 Foot 4.85 GHz survey; PMN: The Parkes-MIT-NRAO 4.85GHz Surveys; MIT-GB: The MIT-Green Bank 5 GHz Survey.
* also appeared in Proctor (2011).
$^a$ The full table is available online.

Table 3. The ‘strong’ X-shaped radio source candidates with the quasar nuclei

| Short Name     | R.A.        | Dec.        | z   | Qual. | r   | $M_R$ | $S_{0.15}$ | $S_{1.4}$ | $S_{1.5}$ | Ref.5GHz |
|----------------|-------------|-------------|-----|-------|-----|-------|------------|-----------|-----------|----------|
| (J2000)        | (J2000)     |             |     |       |     |       | (Jy)       | (Jy)      | (Jy)      |          |
| J0814+0602     | 08 14 04.55 | +06 02 38.3 | 0.562 | SPEC  | 19.79 | -22.65 | 1.255      | 0.219     | 0.088     | NRAO     |
| J0818+1508     | 08 18 41.57 | +15 08 33.5 | 0.330 | SPEC  | 18.93 | -21.90 | 0.334      | 0.065     | 0.032     | NRAO     |
| J0822+0519     | 08 22 26.42 | +05 19 51.1 | 0.654 | SPEC  | 19.70 | -22.17 | 3.844      | 0.343     | 0.135     | NRAO     |
| J1004+3506     | 10 04 08.95 | +35 06 23.6 | 0.611 | SPEC  | 20.80 | -22.53 | 0.990      | 0.174     | 0.053     | NRAO     |
| J1138+4950     | 11 38 16.62 | +49 50 25.0 | 0.510 | SPEC  | 20.18 | -22.16 | 0.303      | 0.072     | 0.033     | NRAO     |
| J1324+3334     | 13 24 04.20 | +33 34 07.1 | 0.338 | SPEC  | 18.32 | -22.51 | 0.000      | 0.182     | 0.088     | NRAO     |
| J1437+3519     | 14 37 56.45 | +35 19 37.1 | 0.537 | SPEC  | 18.53 | -22.87 | 0.268      | 0.096     | 0.064     | NRAO     |
| J1554+3811     | 15 54 16.04 | +38 11 32.5 | 0.194 | SPEC  | 20.77 | -18.89 | 0.265      | 0.061     | ...       | ...      |
| J1622+0707     | 16 22 45.42 | +07 07 14.6 | 0.597 | SPEC  | 20.01 | -23.18 | 0.748      | 0.163     | 0.067     | NRAO     |

Notes: The columns are defined to be same with Table 2.
Figure 9. The FIRST 1.4 GHz grey scale images of our ‘strong’ XRG candidates with the quasar nuclei.

Table 4. The ‘probable’ X-shaped radio source candidates $^a$

| Short Name | R.A. (J2000) | Dec. (J2000) | z   | Qual. | $r$  | $M_R$ | $S_{1.0.15}$ (Jy) | $S_{1.4}$ (Jy) | $S_{1.5}$ (Jy) | Ref. \(5\)GHz$^a$
|------------|--------------|--------------|-----|-------|------|-------|-------------------|----------------|----------------|----------------|
| J0009+0457 | 00 09 18.92  | +04 57 53.2  | 0.545 | PHOT  | 21.20 | −21.55 | 1.402             | 0.320          | 0.094          | NRAO           |
| J0028-0428 | 00 28 15.26  | −04 28 55.3  | 0.267 | SPEC  | 17.51 | −22.84 | 0.484             | 0.092          | 0.063          | PMN            |
| J0031-0421 | 00 31 41.91  | −04 21 56.0  | 0.485 | SPEC  | 21.05 | −21.56 | 0.133             | 0.066          | ...            | ...            |
| J0049-0507 | 00 49 55.56  | −05 07 04.3  | ... | ...   | 22.40 | ...    | 0.596             | 0.152          | 0.064          | PMN            |

Notes: The columns are defined to be same with Table 2 $^a$ The full table is available online.
Figure 10. Images of our 106 ‘strong’ X-shaped radio galaxy candidates: VLA FIRST 1.4 GHz images (left figure of each sub-panel) and DSS red filter images (right figure of each sub-panel) overlaid with TGSS ADR1 150 MHz (cyan) and VLA FIRST 1.4GHz contours (black). The fields are centered on the optical counterparts when identified, and otherwise on positions based on the radio morphologies. The radio contours are plotted as $3\sigma \times (1, 2, 4, 8, 16, 32, 64, ...)$, where the $\sigma$ is rms noise. The rms noise for the 1.4 GHz FIRST images is taken from VLA FIRST archive. In addition, a median rms noise of 3.5 mJy beam$^{-1}$ is opted for TGSS ADR1 fields. The full list of figures is available online.