Most distant large sized FRII radio sources from SDSS, FIRST and NVSS catalogues

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Once again we address the problem of double-lobed radio sources detection. Due to the increasing number of the available radio and optical data and the resolution of the astronomical surveys, the methods of automated detection of the FFII-type radio sources need to be implemented. However, the full automation of this detection process is difficult because of the risk of neglecting the objects with slightly non-typical radio morphology. Here we present the results of the extensive attempt to detect all the potential candidates for the double-lobed FRIIs at $z \geq 2$, corresponding to the optical objects selected from the SDSS survey DR 14. Based on the modified cross-correlation algorithm, we conducted the complete search of the northern hemisphere. We present the preliminary results and the list of the most promising candidates for the remotest large-sized FRIIs.

1 Introduction

The question of detecting radio sources with complex morphology based on their maps and catalogues is raised again due to our attempt to study the problem of the most distant FRII-type radio sources in details. This paper aims to at least approximately determine the largest linear sizes reached by the high-redshifted ($z \geq 2$) FRII (Fanaroff & Riley, 1974) structures. Known samples of such sources are usually constructed based on their optical and radio properties (i.e. the presence of the double radio lobes), however, searching for these extended radio sources (especially the very distant ones) is not an easy task. Their radio lobes are often difficult to observe due to their spatial extent and low surface brightness. Another challenge comes from the fact that typical radio surveys produce large amounts of data that are only possibly correlated to the optical AGN counterparts, including radio artefacts and plenty of point-like radio sources not coinciding with any optical objects. In the case of deriving the *linearly largest* radio sources (the goal of our research), the number of the resulting wrong detection grows along rapidly with the increasing search radius around the central AGN. All this together hinders completing the representative sample of large double-lobed radio galaxies at high redshifts. In particular, there is a necessity to maintain the fragile balance between applying too restrictive search conditions for the hypothetical radio lobes in the automated search routines, and adopting too soft selection criteria that may result in obtaining large amounts of false (although formally correct) detections. This entails the need to involve at least simple machine learning process. We propose such exemplary method of deriving large-sized FRIIs likely related to the high-redshifted AGNs.

2 Methods of detecting double−lobed radio sources

One of the rough but still efficient way of finding any type of radio emission associated with the known AGN is cross-correlation that simply involves searching for the objects in the given celestial area around the known positions of their central (optical) counterparts. Cross-correlation is a very flexible method that can be adopted to any observations on various wavelengths, also in the case of comparing not only two, but three or more data surveys. For example, Best & Heckman (2012) presented a new sample of radio-loud AGNs constructed by combining the SDSS catalogue DR 7 (data release 7) with the NRAO VLA Sky Survey NVSS (Condon et al., 1998), and the Faint Images of the Radio Sky at Twenty centimeters, FIRST (Becker et al., 1995). This sample enabled extensive investigation of the differences between radio galaxies and quasars. More sophisticated methods involved also more complex information extracted from surveys, i.e. the shapes, sizes and general morphologies of the searched objects. Such exemplary approach is described in the paper of Proctor (2016), based on the analysis of close couples and groups of the potential radio lobes derived from the FIRST survey. However, the methods of the two-lobed sources identification typically results in obtaining also the incorrect matches (false detections) and missing the real sources due to the several issues: large amounts of data to look over, not detecting the largest structures caused by neglecting the most distant candidates for radio lobes, too restrictive or unrestrictive conditions for the sizes, shapes and relative positions of the hypothetical radio lobes, or not comparing the detected radio environment with the similar results obtained for the other surveys with different frequency or resolution.

3 Searching for the GRGs sources

Giant Radio Galaxies (GRGs, Ishwara-Chandra & C. H. & Saikia, 1999) are defined as radio sources with projected linear sizes larger than 1 Mpc. Their sizes may be related to the unusually strong jets and/or their location in relatively low density parts of the Universe, however, this question is not yet resolved. Despite their nature, GRGs may serve as the tracers of the large scale galaxy distribution (Malarecki et al., 2015) and the indicators of the properties of the intergalactic medium (IGM). They may also be valuable in the context of the general use of the radio sources as a standard ruler (Daly & Djorgovski, 2003).

Determining the number, frequency of occurrence, and maximum sizes of the large linear sources lying at high redshifts is particularly interesting due to the cosmological implications, i.e. studying the IGM evolution at earlier epochs (Kapahi, 1989). However, this task may be very difficult due to the numerous observational limitations. Referring to the problems described in the previous section we decided to use less strict, but well-proven criteria for retrieving the most likely candidates for the lobes. Although adoption of this strategy seems reasonable from the point of view of the large diversity of morphologies of the observed FRIIs, this method has also one serious drawback: it generates relatively big amounts of data for manual verification. To overcome this problem, we additionally involved supervised machine learning.

3.1 Optical and radio data

We used the newest SDSS catalogue version DR 14 (Abolfathi et al., 2018), providing the homogeneous and good quality data enabling reliable statistical studies. To construct our starting sample of the spectral objects possibly correlated with FRII sources we simply selected all the galaxies and quasars with known redshifts (spectroscopic and/or photometric) equal or higher than 2. This list of more than 200,000 optical objects was correlated with two large radio surveys: NVSS and FIRST, both observing the sky at 21 cm but with different spatial resolutions, presumably allowing for detection of both: the small scale structures with accurate positions (FIRST) and extended emission regions of low surface brightness (NVSS) when analysed together.

3.2 Selection criteria

Simple cross-correlation method may apply to matching the radio-optical data in terms of the central components of radio sources only, but this approach is clearly ineffective in the case of sources with extended radio lobes. Thus we used the improved algorithm which searches for all the optical sources corresponding to the position of the radio counterpart with the assumed accuracy, and then verifies if there are also additional radio counterparts lying within the adopted radius around the host galaxy (possible lobes). In this research we also coded additional verification steps: checking the collinearity of the lobe candidates and the ratio of their distances from the optical centres. Yet another further strategy of extracting real lobes may rely on the elimination of the circular radio detections from the hypothetical lobe-like counterparts.

During the present search based on the supervised machine learning (involving the manual inspection of the resulting maps of the obtained radio structures after numerous runs of the algorithm) we defined the general search criteria that provides the satisfactory ratio of the proper-to-false detection (at this step the search was not restricted to the largest sources only, but we rather tested if the algorithm is efficient in finding the general double-lobed FRIIs of various sizes). Finally adopted search criteria includes: (1) positional coincidences between the optical cores and their FIRST radio counterpart $\delta \leq 5\,\mathrm{arcsec}$, (2) similar FIRST-NVSS coincidence, (3) the presence of at least two extended radio candidates for the lobes from FIRST or NVSS, lying in a given radius from the AGN (2 Mpc), (4) the difference in distances between the members of every pair of the detected lobe candidates and the optical centre not larger than $\leq 1/2$ of the average distances for the given pair, (5) lobes collinearity with the optical core and themselves (angular deviation $\leq 45^\circ$). We did not imposed additional conditions on the limiting flux densities and the previously considered lobes non-circularity. The first was motivated by the risk of the rejection of possible valid radio detections, while the second was due to the results of the machine learning; it turned out that good lobe candidates from FIRST were often roughly circular, possibly due to its limited resolution.

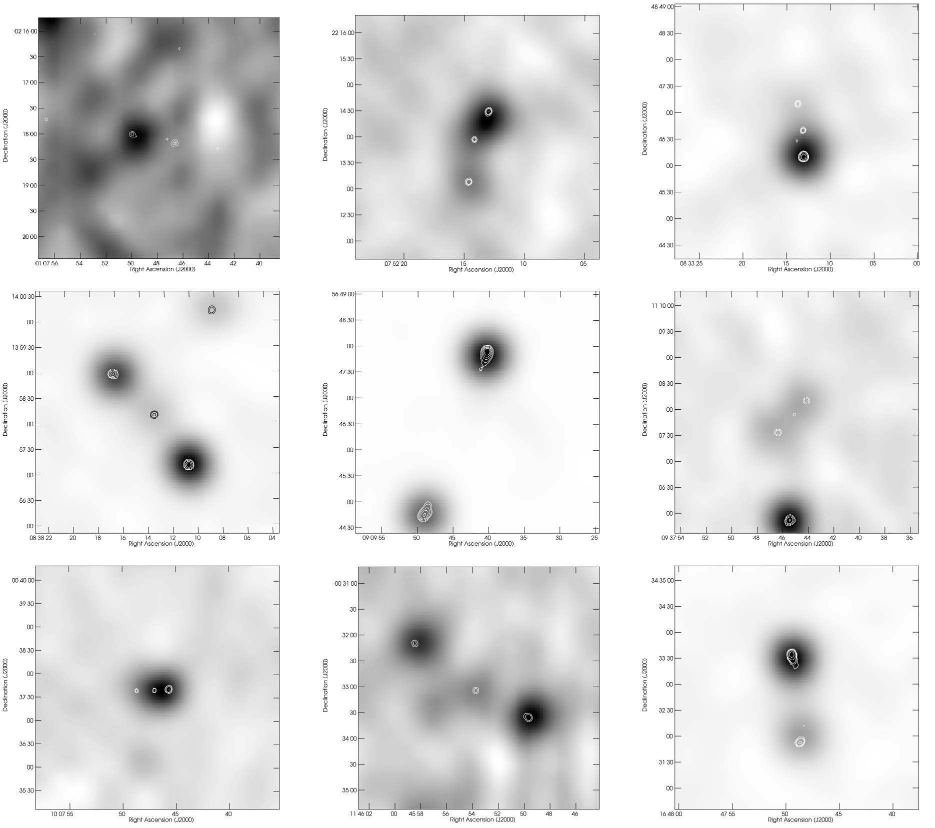

Fig. 1: The radio maps of 9 largest sources. Objects named: J0107-0218, J0752+2213, and J0833+4846 are presented in the upper panels from right to left respectively. Objects: J0838+1358, J0909+5646, J0937+1107 are shown in the middle panels from right to left, and J1007+0037, 1145-0033, are J1647+3442 sources – in the bottom panels, again from right to left.

3.3 Sources with and without detectable radio core

We also investigated the problem of FRII sources that do not have visible compact radio cores corresponding to their optical nuclei. They were initially omitted, since our search algorithm started from looking for the matches between the host galaxies/QSOs and their compact radio counterparts. We decided to split the entire searching process in two separate procedures: (1) finding the optical-radio matches to derive all the radio cores linked to the optical hosts and then finding their lobe candidates in the given radius, and (2) taking all the optical sources (but excluding those for which the central radio counterparts were found in the previous step) and repeating the above procedure with no requirement that the optical hosts must have radio counterparts.

4 The initial results and statistics

After completing the final list of the most likely candidates for the FRII type high-redshifted sources, we automatically retrieved the large amounts of radio (FIRST, NVSS) and optical (DSS) maps centred on the possible optical hosts to perform manual inspection of the results. We rejected approximately half of the several hundred objects selected in previous steps (automated search).

The further investigation, including checking the accuracy of the SDSS redshifts of the hosts and the possible projection effects (situation when the detected radio structure corresponds not only to the high-redshifted host, but also to the closer galaxy at lower z) led to the next limitation of our final sample to only 185 probable candidates for extended FRIIs. For statistical reasons (examining the redshift vs. linear size dependence) we decided to set the lower limit of their sizes to as few as 50 kpc. From this 185 sources we derived 9 new (previously undetected) FRIIs with linear sizes larger than 400 kpc, including radio source J1145−0033 formerly found by (Kuźmicz et al., 2011). We re-discovered as well 65 smaller sources previously found by Van Velzen et al. (2015) based on the FIRST catalogue only, but published without identifying them with any optical hosts, as well as 58 val Velzens's sources listed with their likely associated AGNs (half of their redshifts were indeed currently corrected due to the actual SDSS DR 14 release).

Our method resulted also in obtaining 62 brand new FRII candidates (including the ones with sizes above 400 kpc). The radio maps of these 9 large sources (NVSS grey radio images with the overlaid FIRST contours generated with AIPS (Astronomical Image Processing System) for the levels 0.2, 1, 2, 4 and 8) are presented on Fig. 1. Their basic characteristics are given in Tab. 1.

Table 1: Radio and optical characteristics of the 9 new large-sized FRII radio sources.

IAU name	z	D [kpc]	radio core	host type	Number of FIRST components
J0107−0218	2.769	480	no	QSO	2
J0752+2213	2.938	718	yes	QSO	3
J0833+4846	2.274	540	yes	QSO	3
J0838+1358	2.028	1203	yes	QSO	3
J0909+5646	2.494	1745	no	QSO	2
J0937+1107	2.257	438	yes	QSO	3
J1007+0037	2.471	411	yes	QSO	3
J1145−0033	2.052	1349	yes	QSO	3
J1647−3432	2.951	845	no	QSO	2

5 Conclusions and future works

We report here the discovery of the small sample of the new GRGs and large sized FRII type radio sources at $z \geq 2$. These sources have been checked from the point of view of their morphology and redshifts, however we intend to carry out their extensive analysis with the use of all the existing radio catalogues and the Virtual Observatory tools. Consideration should be also given to the spectral and dynamical modelling of their internal parameters.

We conclude that the proposed method of FRII sources detection is effective enough, since it resulted in finding large majority of previously known FRII candidates from the sample of Van Velzen et al. (2015), additionally providing identification of the numerous sources from this sample to their optical counterparts. It also brought the completely new detections, including very large sources. These additional detections may be due to several reasons, including the fact that van Velzen's method adopts radio flux density cutoffs and low value of the search radius, and, last but not least, it is based on the different approach: the authors are trying to derive only the lobe-lobe pairs from FIRST, without referring to the lobes visible only on the NVSS maps and not taking into account very extent radio structures composed of three distinct peaks of the radio emission visible in FIRST. Further studies should also focus on the complete sample of the 185 radio sources obtained in this research – the confirmation of their redshifts and their general properties and spatial distribution in relation to other galaxies, clusters or local voids of the Universe.

Acknowledgements. This research was supported by the Polish National Science Center grant No. 2013/09/B/ST9/00599.

References

Abolfathi, B., et al., *ApJS* **235**, 42 (2018)

Becker, R., White, R., Helfand, D., *AJ* **450**, 559 (1995)

Best, P. N., Heckman, T. M., *MNRAS* **421**, 1569 (2012)

Condon, J. J., et al., *AJ* **115**, 1693 (1998)

Daly, R. A., Djorgovski, S. G., *ApJ* **597**, 9 (2003)

Fanaroff, B. L., Riley, J. M., *MNRAS* **167**, 31 (1974)

Ishwara-Chandra, C. H. & Saikia, D. J., *MNRAS* **309**, 100I (1999)

Kapahi, V. K., *AJ* **97**, 1 (1989)

Kuźmicz, A., Kuligowska, E., Jamrozy, M., *AcA* **61**, 71 (2011)

Malarecki, J. M., et al., *MNRAS* **449**, 1955 (2015)

Proctor, D. D., *ApJS* **224**, 18 (2016)

Van Velzen, S., Falcke, H., Kording, E., *MNRAS* **446**, 2985 (2015)