MULTIBAND STUDY OF RADIO SOURCES OF THE RCR CATALOGUE WITH VIRTUAL OBSERVATORY TOOLS

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Abstract. We present early results of our multiband study of the RATAN Cold Revised (RCR) catalogue obtained from seven cycles of the “Cold” survey carried with the RATAN-600 radio telescope at 7.6 cm in 1980–1999, at the declination of the SS 433 source. We used the 2MASS and LAS UKIDSS infrared surveys, the DSS-II and SDSS DR7 optical surveys, as well as the USNO-B1 and GSC-II catalogues, the VLSS, TXS, NVSS, FIRST and GB6 radio surveys to accumulate information about the sources. For radio sources that have no detectable optical candidate in optical or infrared catalogues, we additionally looked through images in several bands from the SDSS, LAS UKIDSS, DPOSS, 2MASS surveys and also used co-added frames in different bands. We reliably identified 76% of radio sources of the RCR catalogue. We used the ALADIN and SAOImage DS9 scripting capabilities, interoperability services of ALADIN and TOPCAT, and also other Virtual Observatory (VO) tools and resources, such as CASJobs, NED, Vizier, and WSA, for effective data access, visualization and analysis. Without VO tools it would have been problematic to perform our study.

Key words: astronomical databases: miscellaneous – methods: virtual observatory, statistical – galaxies: radio sources, AGN, variability

1. INTRODUCTION

Optical identification is one of the necessary stages of radio-source investigation. With modern surveys, such as the SDSS (York et al. 2000; Abazajian et al. 2009) and the Large Area Survey of the UKIRT Infrared Deep Survey (LAS UKIDSS) (Dye et al. 2006; Lawrence et al. 2007), we can find optical candidates for radio sources down to an equivalent limiting magnitude of rLim ≈ 22–23 mag. High angular resolution and coordinate accuracy of the FIRST radio survey (White et al. 1997) help to confidently determine confidence the source structure, which is important in selecting an optical candidate.

The RATAN Cold (RC) radio catalogue (Parijskij et al. 1991, 1992) was obtained from observational data of the experiment “Cold” using the RATAN-600
radio telescope in 1980–1981. For a number of years, radio sources of the catalogue, and also the ultra-steep-spectra sample of the catalogue, were being studied using images of the Palomar Sky Survey (Goss et al. 1992; Fletcher et al. 1996) as well as optical observations with the 6-m BTA telescope (Vitkovskij et al. 1987; Kopylov et al. 1995; Parijskij et al. 1996, 1998; Verkhodanov et al. 2001) and the Nordic Optical Telescope (Pursimo et al. 1999). Because of insufficient coordinate accuracy of the RC catalogue for optical identifications, we refined (Zhelenkova & Kopylov 2008) coordinates of RC sources by identifying them with the NVSS (Condon et al. 1998) and FIRST surveys. Then, we performed bulk optical identification of the RC catalogue sample in the region overlapping with the SDSS and FIRST surveys and reliably identified ~70% of the radio sources (Zhelenkova & Kopylov 2009).

Then, the “Cold” survey data were re-processed and observations obtained in 1987–1999 for the same sky strip were also processed in the $7^\text{h} < \text{RA} (J2000) < 17^\text{h}$ right-ascension range. As a result, we obtained the RATAN COLD Revised (RCR) catalogue including 551 sources (Soboleva et al. 2010). We continue optical identification of radio sources of the RATAN-600 surveys of 1980–1999. We used the 2MASS and LAS UKIDSS infrared surveys, the DSS-II and SDSS DR7 optical surveys, the USNO-B1 (Monet et al. 2003 and GSC-II (Lasker et al. 2008) catalogues, the VLSS (Cohen et al. 2007), TXS (Douglas et al. 1996), NVSS, FIRST and GB6 (Gregory et al. 1996) radio surveys for the study of the RCR catalogue, including catalogued data (10 catalogues), as well as digital images (8 surveys). The information collected for RCR sources from the catalogues and a table with the results of identifications were put into a database with the PostgreSQL database management system. We implemented the web interface\(^1\) for the information system, which includes visualization of NVSS and FIRST maps for a region around the chosen RCR source, radio-optics overlaid images, and the spectral energy distribution in radio, optical and infrared ranges, with flux densities and magnitudes converted into the AB photometric system (Oke & Gunn 1983).

We used the built-in capability of the ALADIN interactive sky atlas (Bonnarel et al. 2000), including script commanding, macro-controller and application program interfaces for Perl and Python programming languages for preparation, visualization and analysis of data. We applied the TOPCAT (Taylor 2005) graphics and analysis capabilities and also built-in PostgreSQL interface for requesting the tables of the information system.

Because we worked with a score of digital sky surveys and catalogues, the optical identifications and further analysis would be impossible without VO tools and resources, namely: ALADIN, TOPCAT, Vizier (Ochsenbein et al. 2000), CasJobs (Thakar et al. 2005), SAOImage DS9 (Joye & Mandel 2003), NED, and web capabilities of the WFCAM Science Archive (WSA)\(^2\).

2. OPTICAL IDENTIFICATIONS

There is a relationship between the radio source morphology and location of the parent galaxy. In most cases, angular resolution of the FIRST survey being high enough allows us to correctly classify the morphology of a radio source and determine the expected location of a host galaxy. For classification, we used five

\(^1\)http://www.sao.ru/fetch/cgi-bin/SkyObj/rcrn.cgi

\(^2\)http://surveys.roe.ac.uk/wsa/index.html
morphological types from the classification scheme by Lawrence et al. (1986) classification, namely: point or core (C), core-jet (CJ), core-lobe (CL), double and double-core (D), and triple (T). With the help of contour radio maps of the FIRST or NVSS surveys, we determined the structure of the radio source and the expected position of the host galaxy. Then, we used overlaid radio-optics or radio and infrared images to choose the nearest optical candidate.

To maximally use all freely available data in radio, optical, and infrared ranges, we did not limit the cross-identification of the sample to just the NED, SDSS, WSA, and Vizier databases. If a host candidate was not detected using the optical or infrared image in one band, we analyzed images in all bands of a survey, as well as analyzed co-added frames in several bands, prepared with the ALADIN arithmetic operations for images, to get a deeper image. It turned out that the use of co-added images across two or three bands increases the number of identifications by 10–14%. A final decision on the optical candidate was accepted after the analysis of all available information, taking into account the coordinate coincidence, morphology, photometric and spectroscopic data.

The range of right ascensions of the RCR catalogue overlaps with the DPOSS (Reid et al. 1991; Djorgovski et al. 1998), SDSS, 2MASS (Cutri et al. 2003; Skrutskie et al. 2006), LAS UKIDSS, NVSS, and FIRST surveys. For optical identifications in the J2000 right ascensions range of $7^h00^m \leq RA \leq 7^h57^m$ and $16^h31^m \leq RA \leq 17^h00^m$, we used the DPOSS and NVSS surveys; in the $7^h57^m \leq RA \leq 8^h11^m$ range, we used SDSS and NVSS; for $8^h11^m \leq RA \leq 16^h31^m$, we used SDSS and FIRST; and, in addition to them, we used the LAS UKIDSS survey for $8^h18^m \leq RA \leq 10^h22^m$ and $11^h58^m \leq RA \leq 13^h00^m$. Note that, for 292 objects of the RC catalogue, such work has already been carried out. With the LAS UKIDSS surve and with images co-added in several bands, we wanted to clarify possible identifications and try to find faint optical objects in empty fields.

For the region overlapping with the DPOSS survey, we reliably identified 47% of the sample (“+”); 17% of sources have possible candidates (“?”) and 36% are empty fields (“EF”) down to the $R$-band magnitude limit of $\sim 21.2$ mag, estimated for co-added images in two bands. For the SDSS region, we identified 82%, 9% and 9% respectively, down to the magnitude limit of 22.6 mag, and for the UKIDSS region we identified 86%, 10% and 4% respectively, down to the equivalent limiting magnitude of 22.8 mag in the $R$ band. According to our estimate, we need images with a magnitude limit of $\sim 23.3$ mag in the $R$ band to identify the remaining empty fields.

For the RCR catalogue region in the SDSS database, there are 182 identifications of the FIRST survey sources with SDSS objects. We found that three sources out of 182 were mistakenly identified with bright objects. Correct identifications are faint objects located in immediate proximity to the bright object and better coinciding with the radio coordinates, but absent in the SDSS database. Thus, 212 sources of the RCR catalogue were optically identified for the first time.

Thus, we found reliable identifications for 76% of the objects in the RCR catalogue; 12% of sources have possible candidates; and for 12% of sources, no candidates were found. Using all freely available data and our methods, we identified $\sim 2.2$ times more objects compared to cross-matching of the FIRST and SDSS catalogues.
Table 1. Optical identification of the RCR catalogue by morphological types of radio sources

<table>
<thead>
<tr>
<th>Type</th>
<th>(N_{\text{obj}})</th>
<th>LAS(_{\text{FIRST}}) ((''))</th>
<th>LAS(_{\text{NVSS}}) ((''))</th>
<th>(N_{+})</th>
<th>(N_{?})</th>
<th>(N_{\text{EF}})</th>
<th>(\Delta r) ((''))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>186</td>
<td>1.5</td>
<td>19.1</td>
<td>77</td>
<td>9</td>
<td>14</td>
<td>0.43</td>
</tr>
<tr>
<td>CJ</td>
<td>15</td>
<td>6.1</td>
<td>18.9</td>
<td>87</td>
<td>–</td>
<td>13</td>
<td>1.24</td>
</tr>
<tr>
<td>CL</td>
<td>19</td>
<td>10.3</td>
<td>24.2</td>
<td>89</td>
<td>–</td>
<td>11</td>
<td>1.01</td>
</tr>
<tr>
<td>D</td>
<td>189</td>
<td>15.2</td>
<td>23.0</td>
<td>82</td>
<td>10</td>
<td>8</td>
<td>1.14</td>
</tr>
<tr>
<td>T</td>
<td>45</td>
<td>30.2</td>
<td>34.0</td>
<td>96</td>
<td>4</td>
<td>–</td>
<td>0.91</td>
</tr>
</tbody>
</table>

3. PROPERTIES OF RADIO SOURCES OF THE RCR CATALOGUE

The RCR catalogue is \(\sim 90\%\) complete to flux densities \(S \geq 15\) mJy at 3.9 GHz, which corresponds to \(S \sim 50\) mJy at 1.4 GHz with a mean RCR spectral index \(\alpha_{3.9\,\text{GHz}} = 0.52\) \((S \propto \nu^{-\alpha})\).

After visual inspection of the FIRST images and their contour maps, we classified 55\% of 546 sources in the RCR catalogue as single-component objects; 29\%, as two-component ones; sources with three or more components contribute about 15\%; and \(\sim 1\%\) as extended faint objects, missing in the FIRST survey but present in the NVSS. For one-component sources, the fraction of identifications of the “+” class is 80\%; for the “?” class, 10\%; for “EF” – 10\%. For two-components sources, the fractions are respectively 82\%, 9\%, 9\%; and for sources with a larger number of components, they are respectively 91\%, 7\%, 2\%.

Table 1 presents optical identification of the RCR catalogue by morphological types of radio sources, where ‘Type’ is the morphological type; \(N_{\text{obj}}\), the number of objects; LAS\(_{\text{FIRST}},\) LAS\(_{\text{NVSS}}\), the median largest angular size (LAS) according to the FIRST and NVSS surveys; \(N_{+}\), the fraction of reliable identifications; \(N_{?}\), the fraction of possible identifications; \(N_{\text{EF}}\), the fraction of empty fields; \(\Delta r\), the median distance between the expected position of the host galaxy, defined by the structure of the radio source, and the position of the selected optical candidate.

For identified radio sources, we have magnitudes for several epochs from infrared and optical surveys. The USNO-B1 catalogue (Monet et al. 2003) includes data from the POSS-I and POSS-II plates, with epochs of observations 1949–1958 and 1985–1999, respectively. The GSC 2.3.2 catalogue (Lasker et al. 2008) also used the POSS-II plates. The SDSS data have epochs from 2000 to the present time. The 2MASS survey was conducted from 1997 to 2001 and UKIDSS, from 2005 to the present time. Thus, for some sources, we have up to five epochs of observations.

In the RCR sky region, photometric errors of the GSC 2.3.3 in the \(R_F\) band are \(\sim 0.4\) mag for objects brighter than 19 mag. The 2MASS errors in the same region in the \(H, K\) bands are \(\sim 0.15\) mag for objects brighter than 14 mag and \(\sim 0.26\) mag for fainter objects; the LAS UKIDSS errors in the \(H, K\) bands are \(\sim 0.06\) mag for objects brighter than 17 mag and \(\sim 0.31\) mag for fainter objects. The SDSS errors in \(r\) for objects brighter than 18 mag are \(\sim 0.02\) mag; for fainter objects, down to 22 mag, the errors are 0.20 mag.

We converted available magnitudes into the AB system, using formulas for USNO-B1 (Monet et al. 2003), GSC 2.3.2 (Frei & Gunn 1994), SDSS (Fukugita et al. 1996), 2MASS (Chayer & Nelan 2008), and UKIDSS (Hewett et al. 2006), and compared data for each source. Almost all of the radio sources confidently associated with optical objects brighter than 18 mag can be suspected to have optical variability because of significant variations in stellar magnitudes by more
Fig. 1. The distribution of identified RCR sources with significant magnitude variations (\(\Delta m > 0.7\) mag; black) and sources that have no such variations (grey). The comparison was carried out according to the USNO-B1, GSC 2.3 and SDSS DR7 data as well as to the 2MASS and UKIDSS LAS data.

than \(\Delta m \geq 0.7\) mag in close optical or infrared bands according to USNO-B1, GSC 2.3.2, SDSS DR7, 2MASS and LAS UKIDSS DR5\(^3\). Approximately 40\% of the radio sources, for which there are data in two or more catalogues, have brightness variations in the 0.7–1.0 mag range or larger. Figure 1 shows the distribution of radio sources with (black) and without (grey) significant magnitude variations in optical and infrared ranges.

We tried to classify the optical objects confidently associated with radio sources by their photometric characteristics in optical and infrared bands. Reliable division on resolved and unresolved objects was carried out for SDSS objects with \(r < 21.5\) mag or \(i < 21.3\) mag (Ivezić et al. 2002; Covey et al. 2007). According to these conditions and USNO-B1 classifications (Monet et al. 2003), we have 46\% of resolved objects (galaxies), 20\% unresolved or point objects (stellar); the rest of the sample, 34\%, contains faint objects and empty fields.

For stellar objects, to make sure that they are not stars, we checked USNO-B1 data, and then, for several objects with significant proper motion, we additionally compared them against positions on DPOSS and SDSS images. However, displacements of objects were not found on the images and thus proper motions were not substantiated.

We also compared the colour indices of stellar objects, using colour constrains on SDSS, 2MASS and LAS UKIDSS from Covey et al. (2007), Kinball & Ivezić (2008) and Schneider et al. (2007), to make sure that there are extragalactic objects. Extragalactic objects have the next colour constrains: \(H - K_s > 0.3\) or \(i - K_s > 1.5 + 0.75 \times (g - i)\), and quasars have \(r - z < 0.8\) and \(J - K_s > 1.2\). Quasars with \(Z < 2.5\) in the \((g - r) - (u - g)\) colour–colour diagram inhabit the area limited by \(u - g < 0.8\) and \(-0.2 < g - r < 0.6\), \(i < 19.1\) mag, and objects with \(J - K_s > 1\) and \(g - i > 0.5\) belong to the dust-obscured quasars.

Thus, we consider 93 objects that meet one of these 4 conditions to be quasars;

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\(^3\) A detailed study of the variability of RCR sources in the optical and radio range is an object of a separate future study.
Table 2. Parameters of four sub-samples of the optically identified RCR sources

<table>
<thead>
<tr>
<th></th>
<th>QSO</th>
<th>Late-type galaxies</th>
<th>Early-type galaxies - I</th>
<th>Early-type galaxies - II</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 GHz</td>
<td>10.1</td>
<td>10.4</td>
<td>10.2</td>
<td>10.1</td>
</tr>
<tr>
<td>3.9 GHz</td>
<td>10.2</td>
<td>10.6</td>
<td>10.3</td>
<td>10.4</td>
</tr>
<tr>
<td>u</td>
<td>20.5</td>
<td>22.2</td>
<td>20.9</td>
<td>23.5</td>
</tr>
<tr>
<td>g</td>
<td>20.2</td>
<td>22.0</td>
<td>18.6</td>
<td>21.7</td>
</tr>
<tr>
<td>r</td>
<td>19.8</td>
<td>20.9</td>
<td>17.2</td>
<td>20.1</td>
</tr>
<tr>
<td>i</td>
<td>19.5</td>
<td>19.9</td>
<td>16.8</td>
<td>19.3</td>
</tr>
<tr>
<td>z</td>
<td>19.5</td>
<td>19.4</td>
<td>16.4</td>
<td>18.7</td>
</tr>
<tr>
<td>LAS</td>
<td>18.1</td>
<td>21.7</td>
<td>31.6</td>
<td>23.7</td>
</tr>
<tr>
<td>$R_r$</td>
<td>3.1</td>
<td>3.3</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>$C_r$</td>
<td>2.3</td>
<td>2.3</td>
<td>3.0</td>
<td>2.8</td>
</tr>
<tr>
<td>$Z_{zp}$</td>
<td>1.3(41)</td>
<td>0.5(7)</td>
<td>0.2(31)</td>
<td>0.4(11)</td>
</tr>
<tr>
<td>Flat</td>
<td>60</td>
<td>65</td>
<td>49</td>
<td>30</td>
</tr>
<tr>
<td>Steep</td>
<td>40</td>
<td>65</td>
<td>51</td>
<td>70</td>
</tr>
</tbody>
</table>

41 of them are confirmed by their spectra from the NED and SDSS databases or from Parijskij et al. (2010). There remain only 17 faint stellar objects that do not satisfy the above constraints, because of large photometric errors, making them difficult to classify.

Strateva et al. (2001) found that SDSS galaxies ($g < 21$ mag) can be subdivided into early-type galaxies (E, S and Sa or “red” sequence) with $u - r \geq 2.22$ and late-type galaxies (Sb, Sc and Irr or “blue” sequence) with $u - r \leq 2.22$. There is also a correlation between the colour of the galaxy and its radial profile, measured by a concentration index defined as follows: $C = r_{90}/r_{50}$, where $r$ is the radius, including 90% and 50% of the light of the galaxy expressed in Petrosian magnitudes, respectively. If $C > 2.6$, the galaxy belongs to the early types (Strateva et al. 2001). We subdivided the colour-constrained galaxies, with $r \leq 21.5$ mag, into two groups and then checked their concentration indices for confirmation of membership in the “red” or “blue” sequences. In the end, we identified 35 blue galaxies and 89 red galaxies.

For 440 RCR sources, we constructed an index of radio-loudness following Ivezić et al. (2002), defined as $R_r = 0.4(r - t_{NVSS})$, where $r$ is the magnitude in the $r$ band and $t_{NVSS}$ is the NVSS flux density converted to the AB magnitude. The radio sources with $R_r > 1$ are radio-loud sources. In our sample, only $\sim 2.5\%$ of sources have $R_r < 1$. Our red galaxies are subdivided into two groups by the index of their radio loudness, one with the median value of $R_r \sim 1.8$ and the other with $R_r \sim 3.1$.

Thus, for 52% of the sample (217 sources), we are able to determine first-approximation types of their host objects. They are subdivided into four groups: quasars (93 objects), late-type galaxies (35), early-type galaxies (47) with a relatively low index of radio-loudness (‘I’), and early-type galaxies (42) with the high index (‘II’). In Table 2, we present median values of flux densities at 1.4 GHz (NVSS) and 3.9 GHz (RCR), along with $ugriz$-band magnitudes converted into the AB system, median values of radio-loudness indices $R_r$, concentration indices $C_r$, redshifts$^4$, LAS (″), and fractions (%) of sources with flat ($\alpha \leq 0.5$) and steep spectra.

$^4$The number of objects with known redshifts is indicated in parentheses.
3. CONCLUSIONS

The VO infrastructure is already an effective tool for multiband research of radio sources. However, there are still no convenient software tools to work with the accumulated information of user collections that would also provide a possibility of actualization with new data.

Our work targets on preparing an optically identified sample of radio sources for further study of properties of their host galaxies. Using the data of the SDSS, UKIDSS, and FIRST surveys allowed us to identify the main part (up to 86% in the region overlapping with the LAS UKIDSS survey) of the flux-density-complete \((S_{3.9GHz} > 15 \text{ mJy})\) sample of the RCR catalogue. We could not identify 14% of sources due to faintness of optical objects or when we had two or more suitable candidates and there was no additional photometric or spectroscopic information to make the choice or when the FIRST survey angular resolution was insufficient for classification of some radio sources (we did not define types for only three RCR sources). For 4% of the objects, we could not detect any optical candidates. Some of these sources may be distant objects.

We found that many, if not the vast majority of, radio sources of the sample host galaxies were variable in the optical and/or infrared ranges. However, final conclusions require a more detailed study.

About half of the identified radio sources, which have enough data for classification, are subdivided into 4 groups by their optical and radio properties: radio-loud quasars (\(~40\%)\), radio-loud late-type galaxies, early-type galaxies with higher and lower index of radio loudness (to \(~20\%) of each subsample).

We hope that the resulting catalogue will be used for further detailed studies of radio sources of the RCR catalogue.

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