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Objects with ultra-steep spectra in the central section of the RATAN Zenith Field (RZF) survey

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ABSTRACT

A deep RATAN Zenith Field (RZF) survey at wavelength $\lambda = 7.6$ cm in the region $0^{\rm h} \leq$ R.A. $\leq 24^{\rm h}$, $40.5^\circ \leq$ DEC $\leq 42.5^\circ$ was carried out with the RATAN-600 radio telescope. Within $\pm 2'$ of the center of the survey region, 448 objects were detected, with 73 of them being with ultra-steep spectra (USS), which are the main indicator for finding possible candidates for distant galaxies. Optical identifications for 31 of USS objects using the SDSS (DR7, DR12) surveys have been used. It turned out that 23 objects are galaxies, and 8 are star-forming objects. Photometric redshifts and radio luminosities at 3.9 and 1.4 GHz are determined for 31 objects with spectral indices $\alpha < -1.1$, $S_\nu \propto \nu^\alpha$ for which magnitudes in various filters are presented in the SDSS survey. In the sample of USS objects (23 galaxies and 8 star-forming sources), 15 galaxies have redshifts $z_{\rm ph} < 0.5$, and 8 of them have relatively high radio luminosities $L_{1.4} > 10^{26}$ W/Hz of type FR II. Seven galaxies at $z_{\rm ph} > 0.5$ are also of type FR II. Six sources are of intermediate type FR I–FR II. Only two radio galaxies at $z_{\rm ph} < 0.5$ proved to be a rare nearby galaxy with relatively low radio luminosity $L_{1.4} < 10^{25}$ W/Hz (type FR I). These radio sources are either located in the dense intergalactic media of rich clusters of galaxies or confined within their host galaxies. Nearly all these sources can be observed with the SAO 6-m telescope. Galaxies with $L_{1.4} \geq 10^{26}$ W/Hz (FR II) have m_r magnitudes in the range $18 \leq m_r \leq 23$.

Key words: surveys – radio continuum: general – radio continuum: galaxies – redshifts

1 Introduction

Objects with ultra-steep spectra (USS) are of particular interest because they have become an important selection factor in searching for high-redshift radio galaxies (HzRGs). Such galaxies are commonly powerful galaxies of type FR II (Fanareff, Riley, 1974) and are often found in protocluster environments (Pentericci et al., 2000). They are thought to evolve into present-day dominant cluster galaxies (Best et al., 1997; Miley, De Breuck, 2008). Less than 200 HzRGs are presently known (Miley, De Breuck, 2008), and the highest redshift radio galaxy to date is at $z = 5.19$ (van Breugel et al., 1999). The amount of energy contained in the lobes of these large objects in the form of relativistic gas and magnetic fields is much greater than the amount of energy in any other object in the Universe. These objects may be associated with the first generation of supermassive black holes. Powerful radio galaxies formed in the first 10% of the lifetime of the Universe have been found in very deep surveys at centimeter wavelengths with the RATAN-600 radio telescope. These have been studied using the best available interferometric arrays such as MERLIN and VLBI, as well as with large optical and infrared telescopes.

The spectral index–redshift relation is a key tool in searches and studies of distant radio galaxies. However, the relationship between spectral curvature and redshift remains incompletely understood. The spectral characteristics of radio sources are among the simplest and most easily determined parameters of these objects. One of the first studies describing the relationship between the spectral indices and distances of radio sources was published in Whitfield (1957) and later in Dagkesamanskii (1969, 1970). Detailed studies were then published in Blumenthal, Miley (1979); Tielens et al. (1979). These became the basis for important selection factors in distinguishing distant radio galaxies in a number of groups (Kapahi, Kulkarni, 1986; Rawlings et al., 1990; McCarthy et al., 1990; Roettgering et al., 1994; Parijskij et al., 1994, 1996; Chambers et al., 1996; van Breugel et al., 1999; Klamer et al., 2005, 2006; Miley, De Breuck, 2008; Bryant et al., 2009; Verkhodanov, Parijskij, 2009; Parijski et al., 2010a; Bornancini et al., 2010; Ker et al., 2012; Singh et al., 2014; Coppejans et al., 2015; Morabito et al., 2015).

The review of Miley, De Breuck (2008) discusses the properties and nature of luminous high-redshift radio galaxies ($z > 2$), as well as the environments in which they are located. One explanation may be that higher ambient density could cause steeper electron energy spectra in the particle acceleration processes at the jet working surfaces. Higher ambient density is expected at higher redshifts, and the radio spectra of HzRGs could therefore be steeper than local radio galaxies (Athreya, Kapahi, 1998; Klamer et al., 2006). The attraction of this explanation is that it could result in both the α–z relation and the α–luminosity relation. The other one is that the high-frequency spectra will also be impacted by losses due to the Inverse Compton (IC) scattering of cosmic microwave background (CMB) photons (Krolik, Chen, 1991). It has been shown (Morabito, Harwood, 2018) that the observed α–z relation can be entirely reproduced by a combination of redshift-dependent inverse Compton losses, coupled with selection effects that are biased toward selecting USS sources from incomplete surveys using spectral modeling. Ker et al. (2012) present a simple method for selecting HzRGs based purely on combining their observed radio properties of α and angular size, luminosity with an addition of the K-band magnitude if available.

A new method for searching for distant active galactic nuclei (AGNs) whose spectra peak at megahertz frequencies was proposed by Falcke at al. (2004); Coppejans et al. (2015, 2017). Searches for distant galaxies have been carried out using high-resolution Low-Frequency Arrays (LOFAR) (van Haarlem et al., 2013). A LOFAR survey of spatially resolved ultra-steep sources (Morabito et al., 2015, 2016) is advantageous for searches for USS sources. However, the presence of an ultra-steep spectrum is not a guarantee that the object is a high-z radio galaxy and vice versa (Waddington et al., 1999; Jarvis et al., 2009).

Very deep surveys with the RATAN-600 telescope have enabled clarification of the nature of very distant FR II radio galaxies at $z >> 1$. The sensitivity of RATAN-600 is sufficient to detect this population at any distance, and the high optical luminosities of these objects admit a measurement of their redshifts using the 6-m telescope of the Special Astrophysical Observatory. Joint radio and optical studies (the Big Trio project) using three large telescopes such as RATAN-600, the Very Large Array (VLA), and the SAO 6-m telescopes with the SCORPIO spectrograph (Afanasiev, Moiseev, 2005) have already enabled the identification of three steep-spectrum sources with $z > 3$ (Parijski et al., 2010a). The radio galaxy RCJ0311+0507 with very high radio luminosity was discovered at $z = 4.514$, which formed in the first billion years of the lifetime of the Universe (Kopylov et al., 2006; Parijski et al., 2010a, b; Parijskij et al.., 2012, 2013; Parijskij et al., 2014, 2017). The second source in the range, RC J1740 + 0502 ($z = 3.57$), is referred to weak quasars. The third source RC J0105 + 0501, a galaxy of type FR II with $z = 3.138$, is identified with a weak galaxy $m_r = 22.8^m$ (Soboleva et al., 2000).

Objects with ultra-steep spectra ($-1.3 < \alpha \leq -1.1, S_\nu \propto \nu^\alpha$) are of special interest. A deep near-zenith survey with RATAN-600 at $\lambda = 7.6$ cm, the RATAN Zenith Field (RZF), in the region $0^h \leq$ R.A. $\leq 24^h$, $40.5° \leq$ DEC $\leq 42.5°$ revealed a number of radio galaxies with ultra-steep and steep spectra that may be candidates for very distant objects (Bursov et al., 2007; Semenova et al., 2007; Parijskij et al., 2019). In the current study, we analyze updated radio sources with USS in the central strip of the RZF survey $40°30'42'' \pm 2'$.

2 Selection of data from the RZF survey

Of 448 sources in the sample considered in the central strip of the RZF catalog, we will consider here 73 objects with ultra-steep spectra $\alpha \leq -1.1$. Different researchers have defined the spectral indices for ultra-steep spectra from $\alpha < -0.981$ to $\alpha < -1.3$ (Blumenthal, Miley, 1979; Wieringa, Katgert, 1992; van Breugel et al., 1999; Bryant et al., 2009; Singh et al., 2014). The low-frequency catalogs used most often for the construction of spectra of USS sources are VLSSr (74 MHz), WENSS (325 MHz), TXS (365 MHz), TGSS ADR1 (150 MHz) with an angular resolution of 25″, nearly a factor of two better than the resolution of NVSS. The detection threshold was taken to be 7σ (Intema et al., 2017). In the sample of 73 sources, 18 of the spectra are power-law shaped, with only six of these constructed using only two points at 1.4 GHz and 3.94 GHz. As a rule, high-z radio galaxies have power-law spectra that do not steepen at high frequencies (Klamer et al., 2006, 2013; Ekers, Feain, 2014), although they may turn over at low frequencies due to synchrotron self-absorption and free-free absorption (Bornancini et al., 2010; Ker et al., 2012). Some sources of this sample have MHz-peaked spectra (MGP), suggesting that they may be high-z radio galaxies (Coppejans et al., 2017), GHz-peaked-spectrum (GPS) sources, which might be young radio galaxies, will evolve into compact steep-spectrum (CSS) sources on their way to becoming large radio galaxies (O'Dea, 1998; O'Dea, Saikia, 2009). Some such spectra are given in Fig. 1.

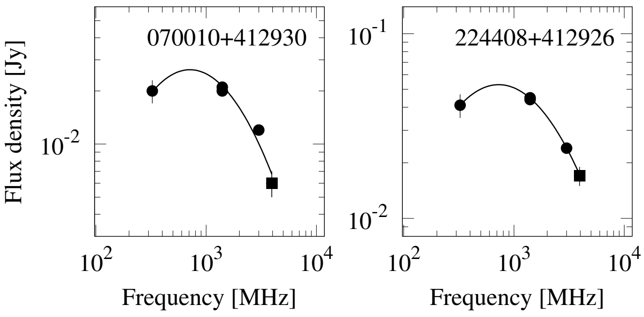

Fig. 1. Some MGP spectra of USS sources (square – data acquired with RATAN-600 at $\lambda = 7.6$ cm).

Figure 2 presents the flux density distribution for 73 sample objects at 3.94 and 1.4 GHz. Most of the objects have flux densities below 10 mJy at 7.6 cm. The median flux density $S_{3.94\text{mean}}$= 6.8 mJy and $S_{1.4\text{mean}}$ = 34.5 mJy.

Most of the objects (Fig. 2) have flux densities of 8–20 mJy at 21 cm (N = 50%); 24 sources have flux densities of $20 \leq S_{1.4} \leq 40$ mJy (36%); 5 ones have $40 \leq S_{1.4} \leq 100$ mJy (7%); and another 5 have $S_{1.4} > 100$ mJy (7%). Thus, this sample of USS sources has relatively weak flux densities ($S_{3.94\text{mean}} \sim 10$ mJy and $S_{1.4\text{mean}}$ = 34.5 mJy) at centimeter wavelengths.

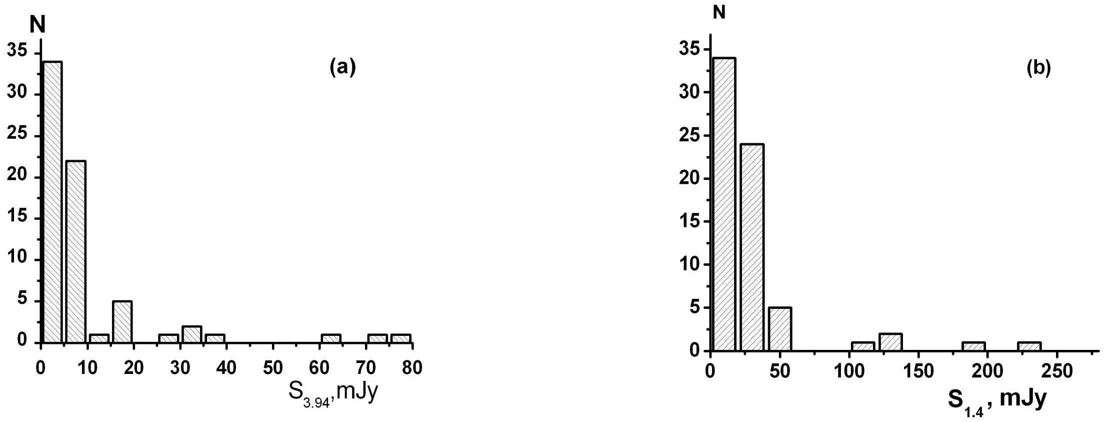

Fig. 2. Flux density distribution at (a) 3.94 GHz and (b) 1.4 GHz for 73 sample objects.

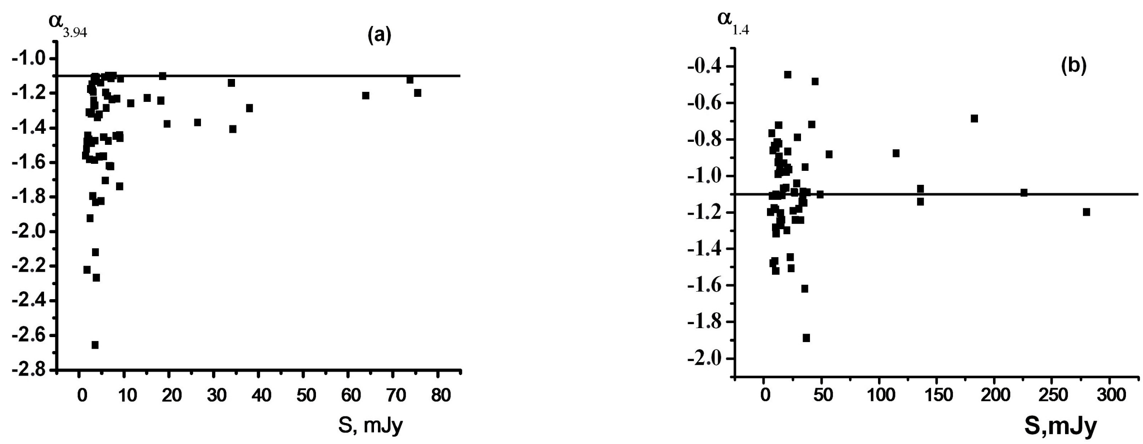

Fig. 3. Dependence of the spectral indices at (a) 3.94 GHz and (b) 1.4 GHz on the flux density for 73 USS sources.

Figure 3 shows the dependence of spectral indices (α) on the flux density at 3.94 and 1.4 GHz for 73 objects. At $\alpha < -1.1$, the selected sources refer to objects with ultra-steep spectra.

We were able to obtain optical identifications for 31 of USS objects using the SDSS (DR7, DR12) surveys (Alam et al., 2015). It turned out that 23 objects are galaxies, and 8 are star-forming objects. Six sources (five galaxies and one star-forming object) have power-law shaped spectra.

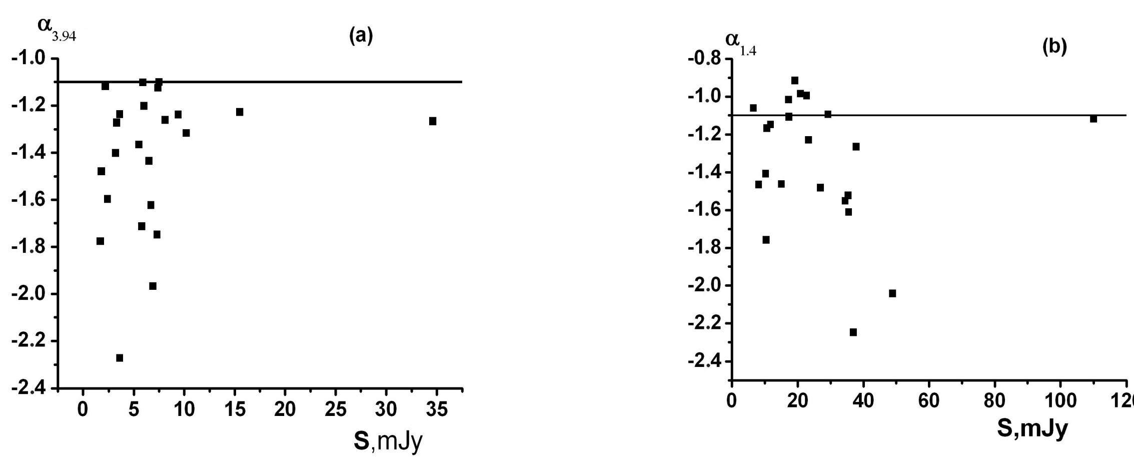

Fig. 4. Dependence of the spectral indices at (a) 3.94 GHz ($S_{3.94\mathrm{mean}}$ = 7 mJy) and (b) 1.4 GHz ($S_{1.4\mathrm{mean}}$ = 24 mJy) on the flux density for 23 galaxies.

Figure 4 presents the dependence of the spectral indices on the flux densities at (a) 3.94 GHz ($S_{3.94\mathrm{mean}}$ = 7 mJy) and (b) 1.4 GHz ($S_{1.4\mathrm{mean}}$ = 24 mJy) for 23 galaxies.

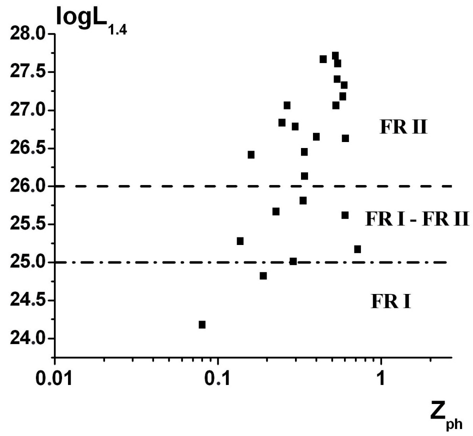

Fig. 5. Dependence of log $L_{1.4}$ (L in W/Hz) on the redshift z_{ph} for 23 galaxies.

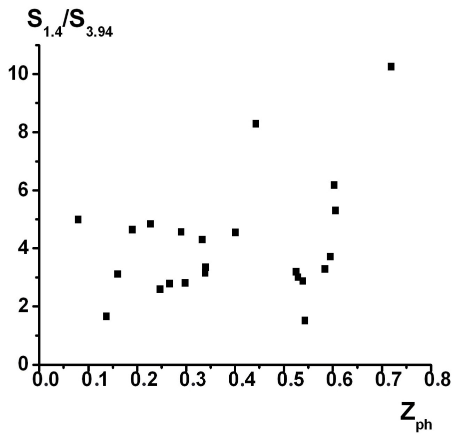

Fig. 6. Dependence of the flux ratio $S_{1.4}/S_{3.94}$ on z_{ph} for 23 galaxies.

We estimated the photometric redshifts z_{ph} for 31 objects whose color characteristics we were able to determine from SDSS using the PEGAS model (Fioc, Rocca-Volmerange, 1997; Verkhodanov et al., 1997, 2005; Verkhodanov, Parijskij, 2009) for their spectral energy distributions. Figure 5 presents the dependence of log $L_{1.4}$, and Fig. 6 shows the flux ratio $S_{1.4}/S_{3.94}$ as a function of the photometric redshifts z_{ph} for 23 USS radio galaxies.

As can be seen in Fig. 5, 14 galaxies have photometric redshifts in the range $0.08 \leq z_{\mathrm{ph}} < 0.5$, and they are nearby galaxies ($z_{\mathrm{mean}} = 0.27$); nine galaxies have redshifts $0.5 \leq z_{\mathrm{ph}} < 1.0$. As noted in Simpson et al. (2012), a comparison of the spectroscopic and photometric redshifts shows that these two essentially coincide at relatively low z, right to $z \leq 1.5$. All the galaxies in our sample have $z_{\mathrm{ph}} < 1.5$. The flux density ratio $S_{1.4}/S_{3.94}$ ranges from 1.5 to 10.5 (Fig. 6).

The radio luminosity of USS sources can be used to infer their possible nature, i.e., radio galaxy, radio-quiet AGN, star-forming galaxy. We also calculated the radio luminosities of these objects at 1.4 and 3.94 GHz using the formula of Miley, De Breuck (2008):

$$L_\nu = 4\pi D_L^2 S_\nu (1+z)^{-(\alpha+1)}, S_\nu \propto \nu^\alpha, \qquad (1)$$

where D_L is the photometric distance, and S_ν is the flux density at frequency ν.[1]

The radio luminosities at 1.4 GHz lie in the range $1.51\times10^{24} \leq L_{1.4} \leq 17\times10^{27}$ W/Hz, with $L_{1.4\mathrm{mean}} \sim 4.25\times10^{26}$ W/Hz. The galaxies with log $L_{1.4} \geq 26.0$ W/Hz are FR II sources, while FR I, FR II, and mixed FR I/FR II sources are encountered among galaxies with intermediate luminosities ($10^{25} \leq L_{1.4} \leq 10^{26}$ W/Hz). FR II sources comprise 65% of these galaxies; seven sources in our USS sample with $z > 0.5$ and $L_{1.4} > 10^{26}$ W/Hz are candidates for radio-loud AGNs (Jang et al., 2007; Lacy, Sajina, 2020). Six sources have intermediate luminosities, with four of these being nearby galaxies. Fifteen galaxies are FR II sources, with eight of these being nearby ones.

Two nearby objects are with luminosity $L_{1.4} < 10^{25}$ W/Hz (J072248+412924, log $L_{1.4}$ = 24.17 W/Hz and z_{ph} = 0.08; and J221650+413008, log $L_{1.4}$ = 24.81 W/Hz and z_{ph} = 0.19). Such sources are very rare and reside overwhelmingly in regions of high baryonic densities.

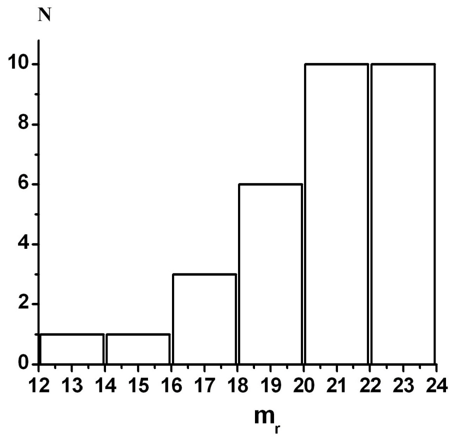

Fig. 7. Distribution of magnitudes m_r.

One possible explanation for this (Klamer et al., 2006) is that nearby radio sources in steep spectrum selected samples reside almost exclusively in rich clusters of galaxies (Baldwin, Scott, 1973; Slingo, 1974a, b). It is also known that cluster radio sources display steeper spectral indices than field radio sources, with the steepest spectrum sources residing closest to the cluster centers (Slee et al., 1983). This has been interpreted as a manifestation of pressure-confined radio lobes, which show adiabatic expansion losses (Baldwin, Scott, 1973; Komissarov, Gubanov, 1994; Jones, Preston, 2001). A radio lobe will expand adiabatically until gas pressure equilibrium is reached between the lobe and the ambient gas pressure. Thus, it follows that in the center of rich clusters and other similar environments where the ambient

[1] The following cosmological parameters were adopted: H_0 = 71 km s^{-1} Mpc^{-1}, $\Omega_m = 0.266$, $\Omega_\Lambda = 0.734$.

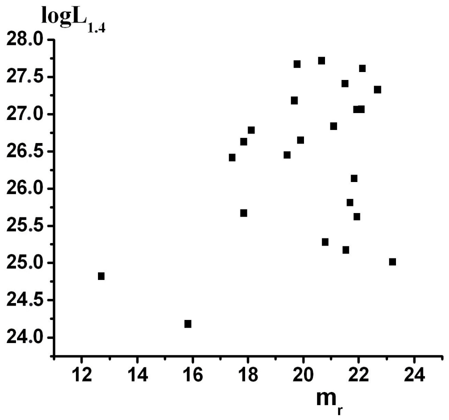

Fig. 8. Dependence of log $L_{1.4}$ on m_r for 23 galaxies.

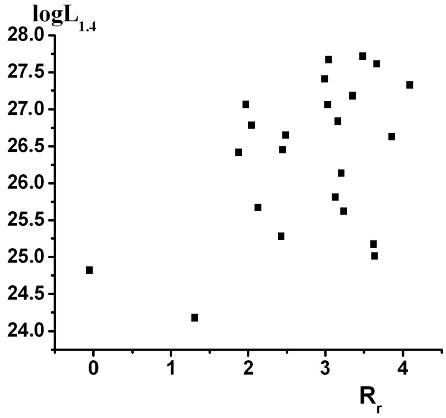

Fig. 10. Relationship between the radio luminosity log $L_{1.4}$ and the radio activity index R_r for 23 galaxies.

baryon densities are large, the radio lobes will be pressure-confined and lose energy primarily via synchrotron and IC losses. In more rarefied environments, like those surrounding isolated galaxies, the luminosity of the radio lobes would fade out much faster due to adiabatic expansion energy losses and surface brightnesses. These nearby galaxies are of FR I classification.

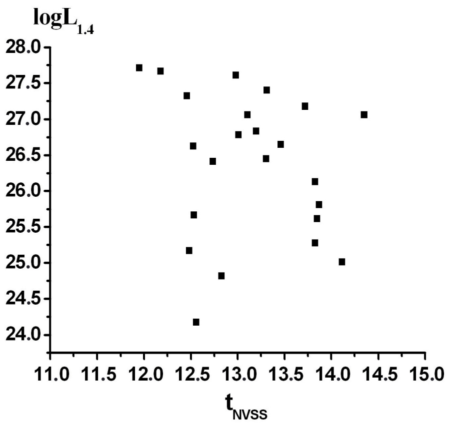

Fig. 9. Dependence of the luminosities log $L_{1.4}$ of 23 galaxies on the flux densities in magnitudes in the AB system.

Figure 7 shows a histogram of magnitudes m_r for 31 objects, and Fig. 8 presents a plot of radio luminosity log $L_{1.4}$ versus m_r for 23 USS radio galaxies. As can be seen in these figures, nearly all these sources can be observed with the SAO 6-m telescope. Galaxies with $L_{1.4} \geq 10^{26}$ W/Hz (FR II) have magnitudes in the range $18 \leq m_r \leq 23$.

Figure 9 presents a plot of log $L_{1.4}$ as a function of the NVSS flux densities $t_{\rm NVSS}$ of flux densities in magnitudes in the AB photometric system.

The flux densities were converted into AB magnitudes using the formula

$$t_{\rm NVSS} = -2.5 \log S_{\rm NVSS}/3631 \text{ Jy}, \qquad (2)$$

where $S_{\rm NVSS}$ is the flux density from the NVSS. The radio luminosity of the galaxies decreases with decreasing flux density (Fig. 9).

We calculated the radio-activity indices R_r of the sources in our sample (Fig. 10) using the following formula (Kimball, Ivezic, 2008):

$$R_r = 0.4(m_r - t_{\rm NVSS}), \qquad (3)$$

where m_r is the r magnitude from the SDSS survey, and $t_{\rm NVSS}$ is the NVSS flux density in magnitudes in the AB photometric system. Objects with $R_r > 1$ are active in the radio, with the bulk of the integrated radio emission contributed by the active nucleus. Only one source in our sample had $R_r < 1$; it can be considered as a radio-quiet object, with its radio emission coming from either a radio-quiet object AGN or a star-forming source.

We considered only 31 USS sources ($\alpha \leq -1.1$) in details in the central section of the RZF wavelength (7.6 cm). Additional studies are needed for 42 other USS sources in the sample of 73.

3 Conclusions

We have detected 448 objects in the central strip of the RZF survey at 3.94 GHz, DEC = 40°30′42″ ± 2′, with 73 of these objects having ultra-steep spectra. We have calculated fluxes and spectral indices for the entire usable dataset. Optical identifications between the RZF and SDSS sources were possible for 31 of 73 USS sources.

The sample of USS sources considered includes relatively weak radio sources in terms of their flux densities: $S_{3.94\rm mean}$ = 10 mJy and $S_{1.4\rm mean}$ = 34 mJy. We have determined photometric redshifts for 31 radio sources in the sample of 73 USS objects (42%) with spectral indices $\alpha \leq -1.1$. These redshifts show that our sample of USS sources (23 galaxies and 8 star-like objects) are mainly nearby galaxies with $z_{\rm mean} = 0.27 \pm 0.01$ (N = 14 galaxies) detected at centimeter wavelengths (λ = 7.6 cm). These radio sources may be either located in the dense intergalactic media of rich clusters of galaxies or confined within their host galaxies.

The radio luminosities of these sources at 1.4 GHz vary in the range $1.51 \times 10^{24} \leq L_{1.4} \leq 17 \times 10^{27}$ W/Hz. Eleven galaxies with radio luminosities $L_{1.4} \geq 10^{26}$ W/Hz are FR II sources; two galaxies with $10^{24} < L_{1.4} < 10^{25}$ W/Hz are rare USS FR I sources. The remaining six ones with intermediate luminosities are objects of mixed type FR I–FR II.

Objects with unresolved radio morphologies could include compact steep spectrum (CSS) and GPS–MPS objects, which may be galaxies located in the early stage of their evolution toward becoming large-scale radio sources. Of 73 USS sources in our sample, 12 are candidates for GPS objects. According to their activity indices, all but one of the objects are active in the radio ($R_r > 1$), with the main contribution to their integrated radio emission coming from an active nucleus. Obtaining more complete material on these sources requires radio observations with higher resolution in order to determine their morphologies, physical sizes, and the brightness temperatures of radio-emitting regions, as well as deep optical observations.

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