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5 radio sources of the Zenith survey at RATAN-600: VLA [1] maps, radio spectra and optical identification

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Abstract. VLA maps obtained at 1.4 GHz with a resolution of $2''.5\times2''$ for three sources and $6''.5\times2''.3$ for two sources detected in the RATAN–600 Zenith survey of 1988 have been analyzed. All five objects have an extended structure. Continuous radio spectra of these objects prepared by using the CATS database and RATAN-600 observations are given. All five objects have linear steep spectra ($\alpha < -0.65$). Using APM database and DSS we have found three candidates for identification. Two radio sources have been observed with the 6 m telescope. The nature of the studied objects, one of which is classified as QSO (BSO) and two others as galaxies, is discussed. One of the radio sources, *RZ*5, being a merging group of one large and several small galaxies, may have appeared in this process.

Key words: radio continuum: galaxies - radio continuum - quasars - survey catalogs

1. Introduction

In 1988 a survey was carried out at the RATAN–600 in the right ascension range between 8^h and 14^h at declination $47°7'$ of $1'$ width with the use of the entire ring surface of the radio telescope (Mingaliev et al., 1991). A catalog of 70 objects (*RZ* sources) has been compiled at the wavelength of 8.0 cm. All the detected sources belong to a population of radio sources with flux densities from 14 to 70 mJy. General statistical investigation, estimation of spectral indices and luminosity calculation (in the assumption of $z \sim 1$) of *RZ* sources have been reported by Verkhodanov (1994). Several sources of this survey were studied using new RATAN–600 observational data obtained by Verkhodanov and Verkhodanova (1997–1999) in 1995 at four wavelengths.

To reveal morphology and select candidates for study with optical telescopes, one has to investigate the radio structure of the objects. By using morphological properties and selecting FRII objects (Fanaroff and Riley, 1974), one could extend the lists of the objects being candidates for distant radio galaxies studied in the programme "Big Trio" (Parijskij et al., 1996). Detection and investigation of this type objects play an important role in the understanding of the origin and evolution of galaxies at early epochs of the Universe. By studying faint radio sources that are close doubles (down to $2''$) we can also select gravitationally lensed candidates which belong to the most interesting objects in the present day astrophysics (Fletcher, 1998). These objects can be found among radio sources extended but unresolved with a beam of $2''.5$.

We studied the structure of 5 sources of the Zenith survey for the purpose of revealing morphology from the images obtained with VLA in intermediate configurations (BnA) in 1994. Besides, we have obtained continuous radio spectra of the objects using the new radio sky surveys NVSS (New VLA Sky Survey), FIRST (Faint Images of the Radio Sky at Twenty-cm) and WENSS (The Westerbork Northern Sky Survey), and the data of other surveys. We have made identification of the studied sources on the optical images of the Digital Sky Survey (DSS) and with the Automized Plate Measuring machine (APM) database via Internet. Two *RZ* objects have been observed at the 6 m telescope. Classification of all five objects has been carried out after the optical and radio investigation.

[1] The National Radio Astronomy Observatory is operated under license by Associated Universities, Inc. under cooperative agreement with the National Science Foundation.

Table 1: *VLA data for RZ sources*

Name	$\alpha+\delta(J2000)$	$\alpha+\delta(B1950)$	σ_α s	σ_δ $''$	S mJy	σ_S mJy	Major $''$	Minor $''$	PA °
RZ5N	082346.18+465200.3	082014.22+470142.0	.02	.1	34	4	5.37	4.28	134.3
RZ5S	082347.37+465148.6	082015.42+470130.4	.01	.1	110	15	8.85	4.46	158.6
RZ5int	082347.13+465150.4	082015.18+470132.2	.04	.6	180	15	23		141
RZ9	084141.23+465234.5	083812.66+470318.2	.01	.1	70	7	3.97	1.64	120.2
RZ14	084818.21+465153.1	084451.01+470258.7	.02	.1	53	4	5.58	0.74	24.6
RZ55	131217.54+465106.0	131005.66+470659.8	.01	.1	150	20	9.24	1.33	164.7
RZ70	135751.31+465130.5	135552.48+470604.7	.01	.1	180	40	5.50	0.66	146.5

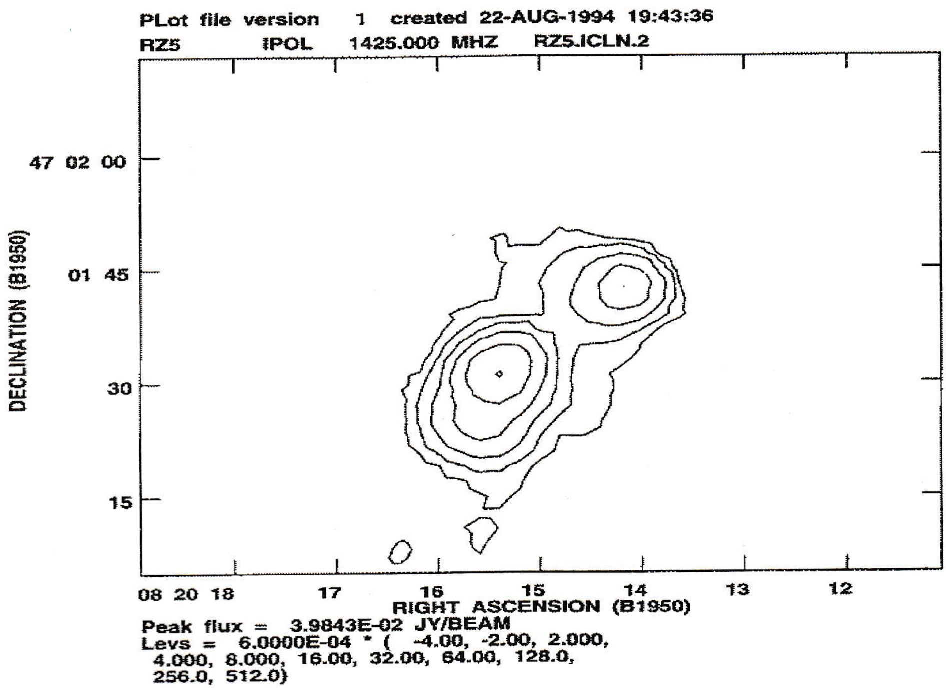

Figure 1: *Radio source RZ5 (J 082347+465150).*

2. VLA maps

Maps of three Zenith survey radio sources, *RZ5* (Fig.1), *RZ9* (Fig.2) and *RZ14* (Fig.3), with a resolution of $2''\!.5\times2''$ at 1425 MHz and of two sources, *RZ55* (Fig.4) and *RZ70* (Fig.5), with a resolution of $6''\!.5\times2''\!.3$ at 1455 MHz were obtained with VLA in 1994. These objects were selected from the general *RZ* list as the brightest ones with steep spectra ($\alpha<-0.6$, $S\sim\nu^\alpha$) and proposed to the VLA observations in the unified list of the "Big Trio" objects. Isophotes shown on the maps of these sources (Figs. 1-5) are drawn by levels proportional to a factor of 2 starting with 1.2, 1.0, 0.6, 1.0, 1.2 mJy, respectively. Positive isophotes are shown by the solid lines, and negative by the dotted lines. Table 1 contains the data for these objects. In the columns are given the object name, coordinates at the epoch of 2000.0 and coordinate errors, flux densities and their errors in mJy, deconvolved major and minor axes of the radio sources in arcsec, positional angle in degrees. Coordinates of the integrated source (*RZ5int*) have been taken from the NVSS data. The major and minor axes and the positional angle for all sources have been borrowed from the FIRST catalog.

3. Radio source spectra

To prepare the radio spectra of the sources, we have used the catalogs of the database CATS (astrophysical CATalogs Support system) (Verkhodanov et al., 1997) and the data of the survey carried out at the North sector of RATAN–600 in 1995 (Verkhodanov and Verkhodanova, 1998, 1999).

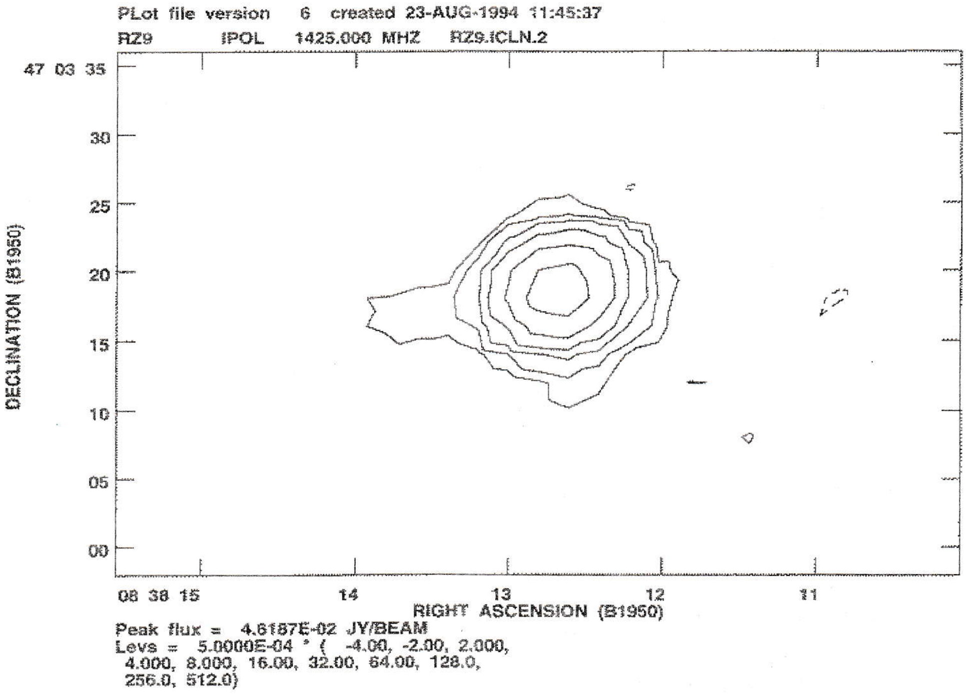

Figure 2: *Radio source RZ9 (J 084141+465234).*

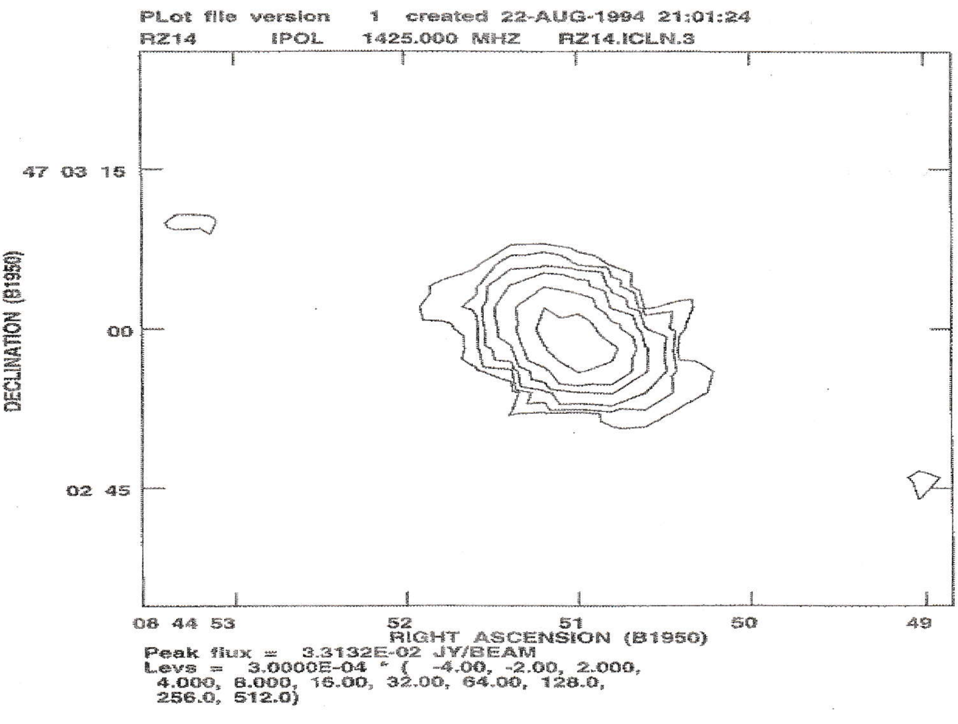

Figure 3: *Radio source RZ14 (J 084818+465153).*

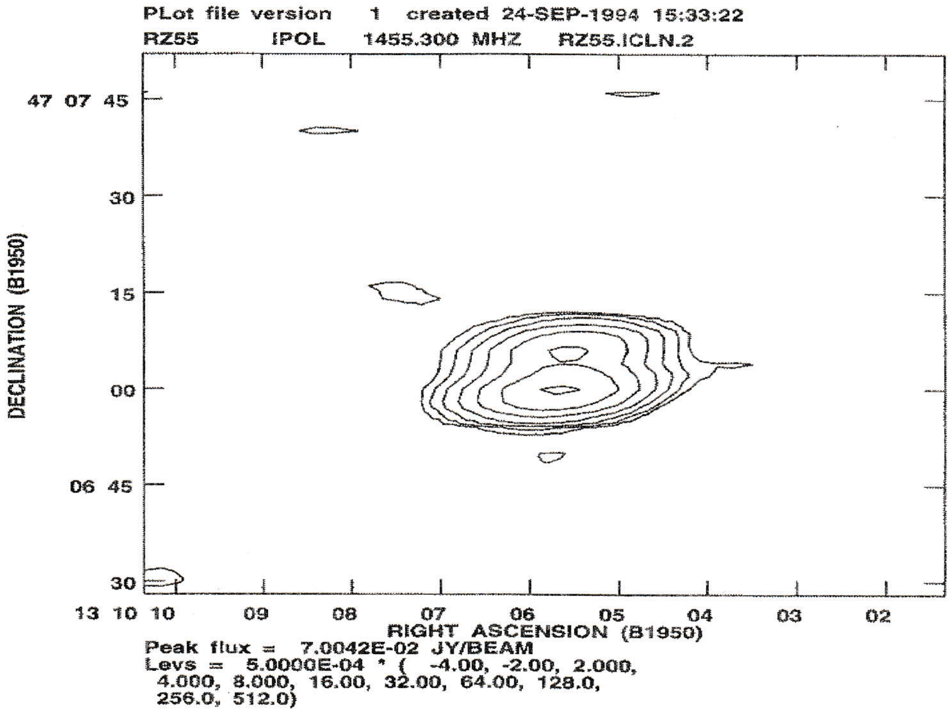

Figure 4: *Radio source RZ55 (J 131217+465106).*

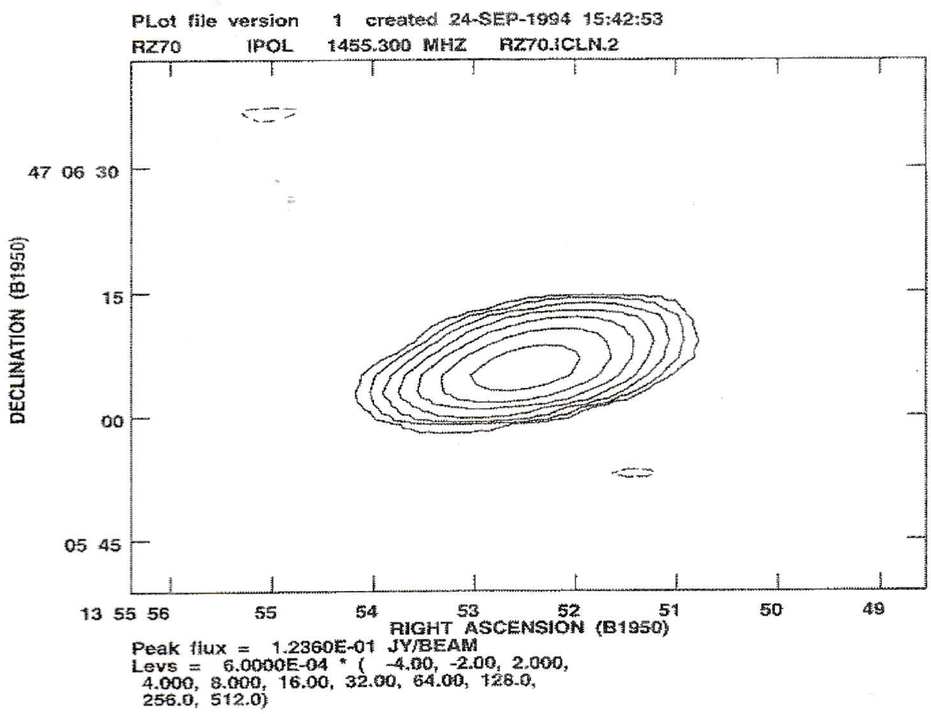

Figure 5: *Radio source RZ70 (J 135751+465130).*

Table 2: *Multifrequency data for 5 RZ radio sources. Fitting curves are derived with $y = logS$ and $x = log\nu$, where S is the flux density in Jy, ν is the frequency in MHz*

α	σ_α	δ	σ_δ	ν	S	σ_S	Catalog
h m s	s	° ′ ″	″	MHz	Jy	Jy	
1	2	3	4	5	6	7	8
RZ 5	$y = 1.478 - 0.736x$						
08 23 46.2	0.5	+46 51 40	5	151	0.72	0.04	6CVI
08 23 45	1.8	+46 51 56.5	24.7	232	0.28	0.05	MIYUN
08 23 47.0 3		+46 51 52.7		325	0.465	0.0055	WENSS
08 23 46.779	0.121	+46 51 50.48	0.62	365	0.445	0.042	TXS
08 23 46.8		+46 51 54		408	0.38	0.05	B3
08 23 47.13	0.04	+46 51 50.4	0.6	1400	0.1522	0.0054	NVSS
08 23 46.84		+46 51 53.05		1400	0.128		WB92
08 23 46.18	0.02	+46 52 00.3	0.2	1400	0.03357	0.00014	FIRST
08 23 47.37	0.01	+46 51 48.6	0.1	1400	0.11003	0.00014	FIRST
08 23 50		+46 51 18		1400	0.17		GB
08 23 47.9	0.2	+46 52 09	15	2308	0.123	0.033	RATAN
08 23 47.1	0.1	+46 51 55	2	3750	0.055	0.006	RZ
08 23 47.9	0.1	+46 52 09	15	3950	0.052	0.008	RATAN
08 23 46.0	0.8	+46 51 51	9	4850	0.075	0.007	GB6
08 23 46.7	1.1	+46 51 56	12	4850	0.069	0.009	87GB
08 23 47.9	0.2	+46 52 09	15	7700	0.05	0.010	RATAN
08 23 47.9	0.2	+46 52 09	15	11111	0.035	0.010	RATAN
RZ 9	$y = -1.663 + 0.001x + 11.190exp(-x)$						
08 41 43.0	0.5	+46 52 08	5	151	0.37	0.02	6CVI
08 41 44.9	0.5	+46 52 19	5	151	0.41	0.02	6CII
08 41 41.15		+46 52 33.9		325	0.182	0.0036	WENSS
08 41 41	0.2	+46 52 52	1.7	327	0.19531	0.00834	WSRTW
08 41 40.3		+46 52 52		408	0.12	0.05	B3
08 41 41.24	0.01	+46 52 34.7	0.1	1400	0.07445	0.00014	FIRST
08 41 41.28	0.05	+46 52 34.9	0.6	1400	0.0737	0.0016	NVSS
08 41 41.8	0.1	+46 52 50	2	3750	0.044	0.006	RZ
08 41 42.1	0.2	+46 53 04	15	3950	0.043	0.008	RATAN
08 41 41.9	1.1	+46 52 56	12	4850	0.035	0.005	GB6
08 41 42.4	1.5	+46 53 43	17	4850	0.057	0.006	87GB
08 41 42.1	0.2	+46 53 04	15	7700	0.039	0.010	RATAN
RZ 14	$y = 1.512 - 0.914x$						
08 48 19.6	0.5	+46 52 34	5	151	0.3	0.02	6CVI
08 48 22.5	0.5	+46 51 54	5	151	0.37	0.02	6CII
08 48 18.18		+46 51 53.9		325	0.17	0.0036	WENSS
08 48 18.6		+46 51 42		408	0.12	0.05	B3
08 48 18.21	0.01	+46 51 53.1	0.1	1400	0.05126	0.00014	FIRST
08 48 18.24	0.05	+46 51 53.2	0.6	1400	0.0503	0.0008	NVSS
08 48 22.5	0.3	+46 52 21	4	3750	0.016	0.006	RZ
08 48 17.6	0.2	+46 52 01	15	3950	0.03	0.008	RATAN
RZ 55	$y = 1.470 - 0.775x$						
13 12 18.8	0.5	+46 51 22	5	151	0.6	0.03	6CII

Table 2: *Multifrequency data for 5 RZ radio sources. Fitting curves are derived with $y = logS$ and $x = log\nu$, where S is the flux density in Jy, ν is the frequency in MHz (continued)*

h m s 1	s 2	° ′ ″ 3	″ 4	MHz 5	Jy 6	Jy 7	8
13 12 18	1.4	+46 51 04.7	18.8	232	0.51	0.05	MIYUN
13 12 17.22		+46 51 09.5		325	0.36	0.0036	WENSS
13 12 17.297	0.153	+46 51 07.77	0.67	365	0.28	0.018	TXS
13 12 16.9		+46 51 08		408	0.29	0.05	B3
13 12 17.40	0.01	+46 51 07.4	0.1	1400	0.11988	0.00013	FIRST
13 12 17.43	0.05	+46 51 07.9	0.6	1400	0.1146	0.0005	NVSS
13 12 22		+46 51 42		1400	0.09		GB
13 12 20.1	0.1	+46 51 06	2	3750	0.035	0.006	RZ
13 12 18.9	0.2	+46 52 20	15	3950	0.04	0.008	RATAN
13 12 17.0	1	+46 51 18	11	4850	0.05	0.005	GB6
13 12 17.3	1.6	+46 51 19	22	4850	0.053	0.007	87GB
13 12 18.9	0.2	+46 52 20	15	11111	0.046	0.010	RATAN
RZ 70	$y = 2.113 - 0.936x$						
13 57 51.1	0.5	+46 51 24	5	151	1.23	0.06	6CII
13 57 50.6	0.8	+46 52 02	10.8	232	0.67	0.05	MIYUN
13 57 53.1	0.9	+46 51 39.6	12	232	0.6	0.05	MIYUN
13 57 51.04		+46 51 32.8		325	0.607	0.0031	WENSS
13 57 51.164	0.089	+46 51 31.86	0.36	365	0.471	0.016	TXS
13 57 51.4		+46 51 36		408	0.46	0.05	B3
13 57 51.13	0.1	+46 51 31.45	0.01	1400	0.16628	0.00014	FIRST
13 57 51.2		+46 51 30.3		1400	0.14		UCC R
13 57 51		+46 52 20		1400	0.15		GB
13 57 49.34		+46 51 51.45		1400	0.161		WB92
13 57 51.11	0.04	+46 51 31.87	0.6	1400	0.1674	0.0004	NVSS
13 57 54.0	0.2	+46 52 34	15	2308	0.075	0.033	RATAN
13 57 54.6	0.1	+46 51 29	2	3750	0.024	0.006	RZ
13 57 54.0	0.2	+46 52 34	15	3950	0.068	0.008	RATAN
13 57 51.3	1.1	+46 51 37	13	4850	0.039	0.005	GB6
13 57 49.9	1.9	+46 51 47	25	4850	0.035	0.006	87GB
13 57 54.0	0.2	+46 52 34	15	7700	0.054	0.010	RATAN
13 57 54.0	0.2	+46 52 34	15	11111	0.037	0.010	RATAN

Among the basic catalogs stored in the CATS database several largest ones (NVSS, FIRST, WENSS, Texas) cover entirely the area of the Zenith survey.

Using these catalogs we have detected the five objects to have counterparts in the NVSS (Condon et al., 1998), which has a sensitivity as high as 2.5 mJy, and a resolution of 45″ at 1400 MHz.

In the FIRST survey (White et al., 1997) which is carried out at VLA in the B–configuration at 1400 MHz with a resolution of 5.″4 and a sensitivity limit of 1 mJy at 5σ level, we have detected all five *RZ* sources. The coordinates of the objects coincide with those of 1994 VLA observations within 0.″05. All the basic components of the complex sources (except the tail of the object *RZ9* (Fig.2)) are confirmed by the FIRST data. Images of the FIRST sources are shown in Figs. 6–10.

The WENSS survey (Rengelink et al., 1997) carried out at 325 MHz with a sensitivity of about 18 mJy at 5σ level and a resolution of $54'' \times 54'' \cdot \mathrm{cosec}\delta$ has counterparts for all five sources. The Texas survey carried out at 365 MHz on the Texas radio interferometer (Douglas et al., 1996) with a sensitivity as high as 150 mJy, but complete to 250 mJy, contains counterparts of only three sources: *RZ5*, *RZ55* and *RZ70*.

Table 2 contains a list of identifications with the catalogs of the CATS database (Verkhodanov et al., 1997). The data of the *RZ* catalog have been taken from Mingaliev et al. (1991) and the ones marked as RATAN are from the paper by Verkhodanov and Verkhodanova (1999).

The radio spectra have been fitted with the package *SPG* under OS Linux (Verkhodanov, 1997). As the main fitting function of the radio spectra the

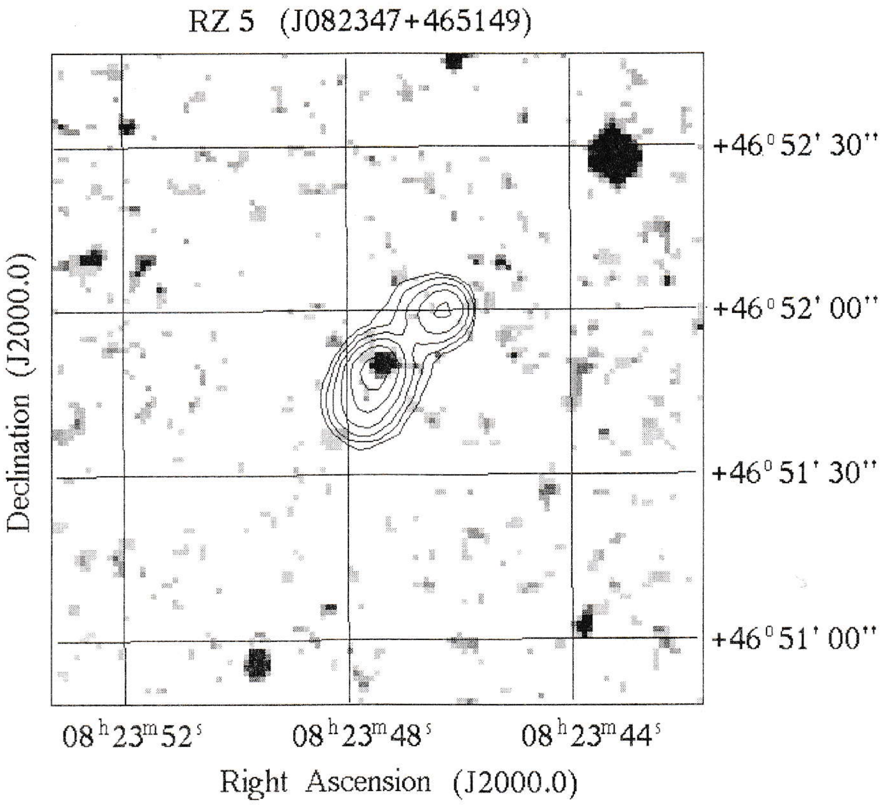

Figure 6: *The FIRST map of the radio source RZ5 (J 082347+465150) overlaid on the* $2' \times 2'$ *DSS image.*

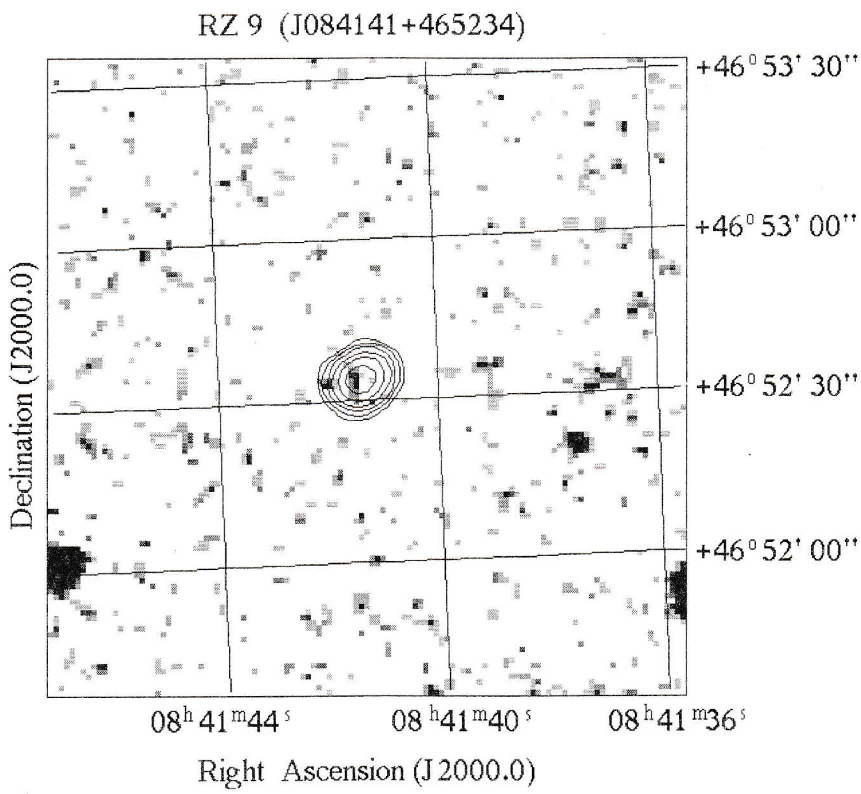

Figure 7: *The FIRST image of the radio source RZ9 (J 084141+465234) overlaid on the* $2' \times 2'$ *DSS image.*

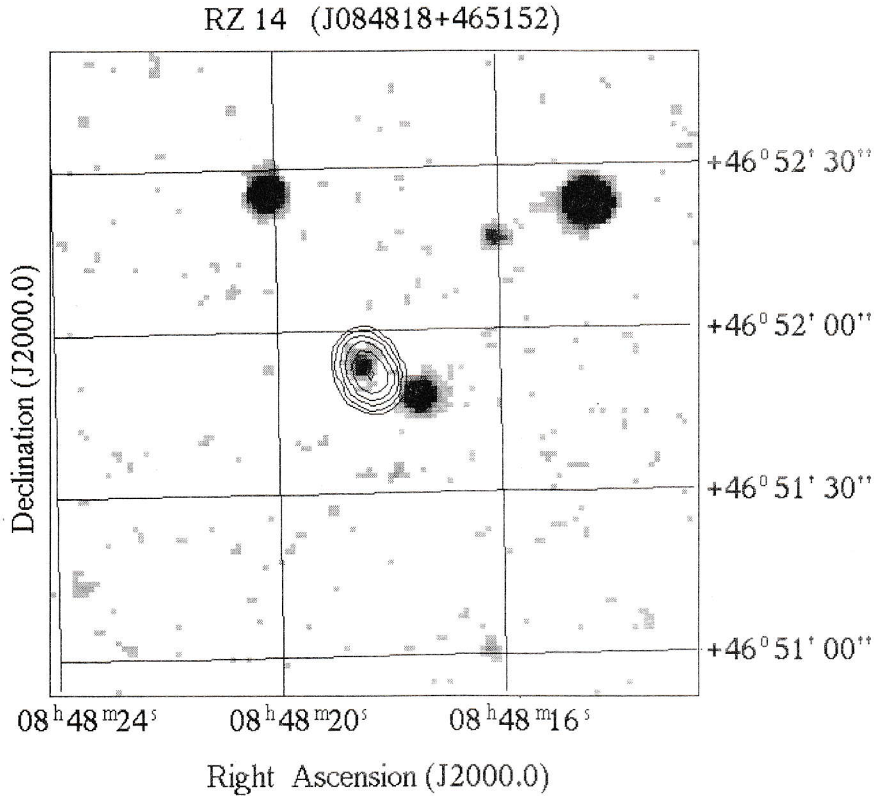

Figure 8: *The FIRST image of the radio source RZ14 (J 084818+465153) overlaid on the 2′×2′ DSS image.*

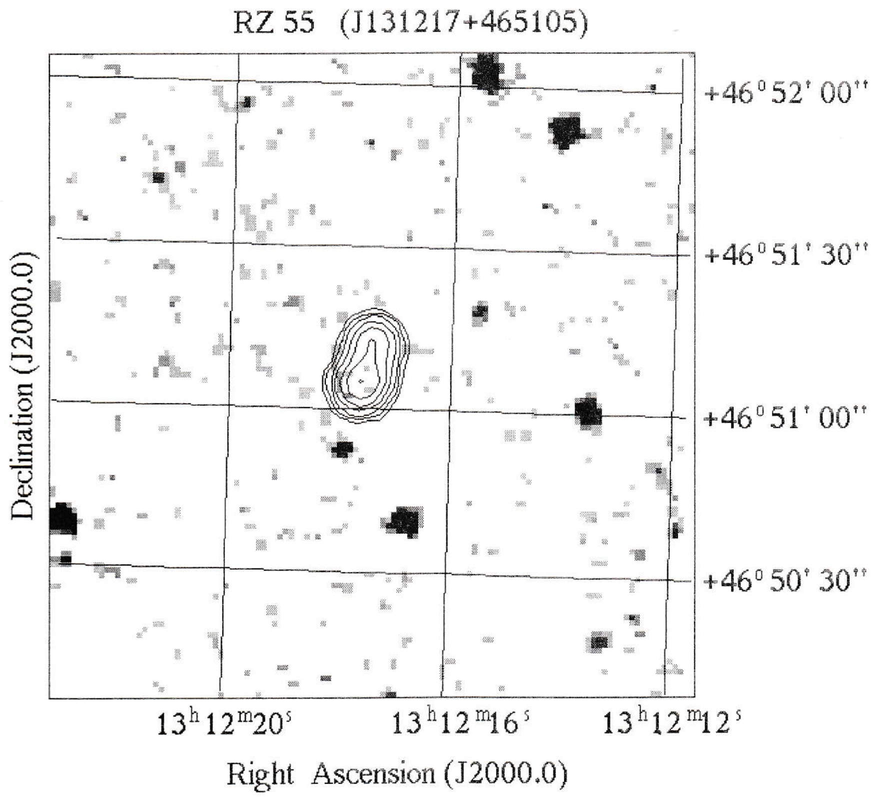

Figure 9: *The FIRST image of the radio source RZ55 (J 131217+465106) overlaid on the 2′×2′ DSS image.*

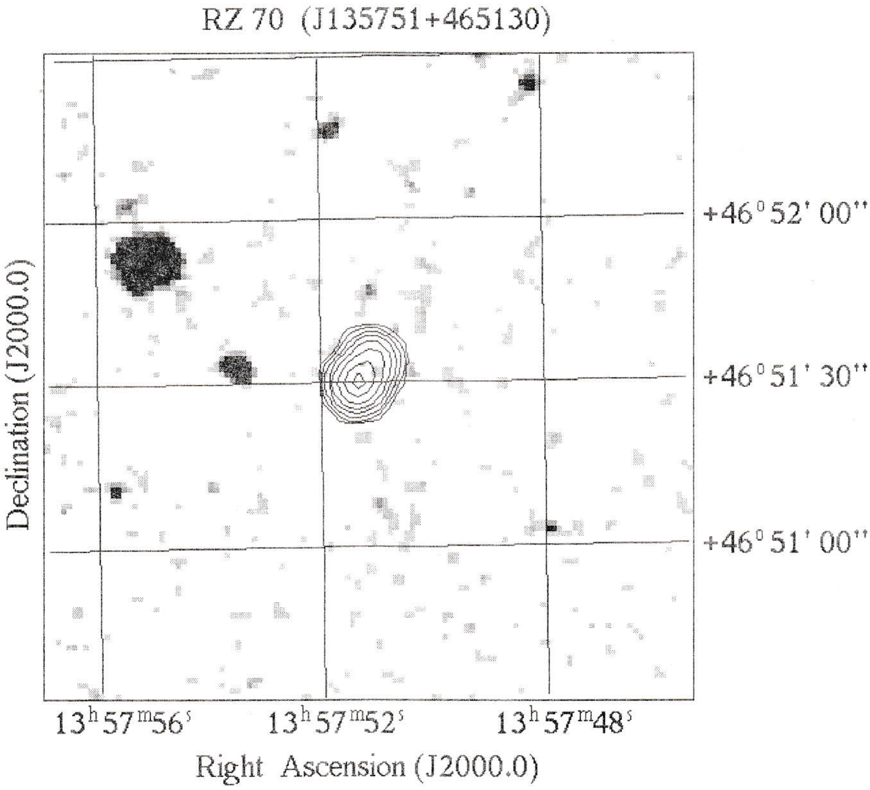

Figure 10: *The FIRST image of the radio source RZ70 (J 135751+465130) overlaid on the 2'×2' DSS image.*

authors have used the curve $y = A + Bx$, where $x = log\ \nu$, $y = log\ S$, ν is the frequency in MHz, S is a flux density in Jy.

The fitting procedure took into account weights of each point in proportion to the value $1/\epsilon^2$, where ϵ is the ratio of the flux density error σ_S and the flux density S. If a point of the spectrum is appreciably away from the spectrum line, its weight is decreased ten times.

Automatic selection using the least square criterion from the fitted curve taken from the set

$y = A + Bx$,
$y = A + Bx + Cx^2$,
$y = A + Bx + C \times \exp(x)$,
$y = A + Bx + C \times \exp(-x)$,

shows the linear fitting for four sources, and for $RZ9$ with the curve $y = -1.663 + 0.001x + 11.190\exp(-x)$. In the case of linear approximation, the best fit for $RZ9$ radio spectrum is done with the line $y = 1.024 - 0.678x$. When we fitted the $RZ9$ spectrum, we took into account that a corresponding point of the 87GB survey is likely to be wrong and the RATAN point at 2.7 cm may be too high because of the noise.

The steep linear spectrum due to synchrotron radiation is typical of radio galaxies and some quasars. If the object $RZ9$ has a concave spectrum, it could be explained in the frames of a model of superposition of two spectra: a flat spectrum of a core, and a steep spectrum of component(s).

The spectra of the radio sources are shown in Fig.11.

4. The search for optical candidates

Electronic versions of the Palomar Observatory Sky Survey have been used to search for candidates for optical identification. We used the APM catalog (see, e.g. Irwin, 1998), to be exact, the modified client program of T. McGlynn *apmcat*, for the stream identification of the sources via Internet and estimation of magnitudes in the R and B filters, and the DSS2 (Digitized Sky Survey), accessible via the Web-page of the Space Telescope Science Institute (http://stdatu.stsci.edu/dss/) for the identification of the Zenith survey sources.

DSS frames of $2' \times 2'$ in size with the overlaid FIRST maps are shown in Figs. 6–10 for all five sources. The candidates for optical identification of the first three sources are situated inside the central isophote. There are no optical candidates brighter than 21^m in E-band for $RZ55$ and $RZ70$ on DSS.

Two radio sources $RZ5$ and $RZ70$ were observed with the 6 m telescope in February, 1994. Three 400^s CCD frames were acquired for $RZ5$ and six 400^s ones

Table 3: *Results of optical identifcation*

Name	$\alpha+\delta$ (radio)	$\alpha+\delta$ (APM)	E	Cl	O	Cl	LR
RZ5C	082347.13+465150.4	082347.14+465152.0	19.53	-1	>21.5	0	93.39
RZ5N	082346.18+465200.3	-"-	-"-	-"-	-"-	-"-	0.00
RZ5S	082347.37+465148.6	-"-	-"-	-"-	-"-	-"-	0.07
RZ9	084141.23+465234.5	084141.46+465236.3	>21[1]	0	21.13	1	4.43
RZ14	084818.21+465153.1	084818.33+465154.8	19.03	−1	19.26	−1	35.37
RZ55	131217.54+465106.0		>21[1]		>21.5		
RZ70	135751.31+465130.5		>24[2]		>21.5		

[1] DSS2 magnitude values
[2] 6 m telescope data

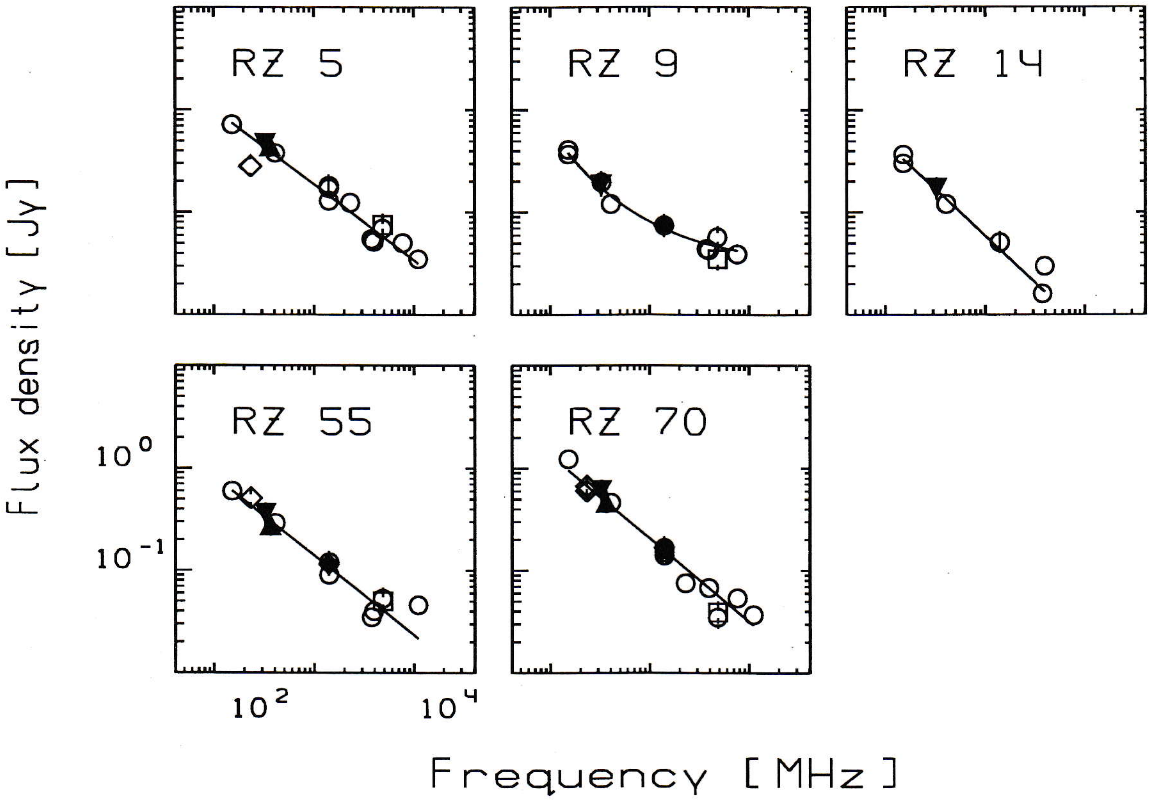

Figure 11: *The spectra of the radio sources.*

for *RZ*70 with a seeing of 3.″1. Isophotes of the *RZ*5 CCD image are shown in Fig. 12. There is an empty field in the zone of *RZ*70 in the R band.

The results of identification with the APM catalog and DSS and the upper limits estimated with the 6 m telescope data are given in Table 3.

5. Discussion

Table 3 contains the results of optical identification of the objects with the APM data. In the columns are listed the object name (for *RZ5* the northern and southern components, and a gravity center by NVSS), APM coordinates at 2000.0, the magnitude and object class on the E plate, the magnitude and object class on the O plate (the class is described in terms of APM, with −1 (stellar like), 0 (noise like) and 1 (extended)), likelihood ratio, calculated by the following formula (de Ruiter et al., 1977):

$$LR(r) = (1/2\lambda)\exp[0.5r^2(2\lambda-1)],$$

where $\lambda = \pi\sigma_{RA}\sigma_{Dec}\rho$, ρ is the density of background objects equal to 5.16×10^{-4} sec^{-2} (Cohen et al., 1977), $r = [(\Delta RA/\sigma_{RA})^2 + (\Delta Dec/\sigma_{Dec})^2]^{0.5}$,

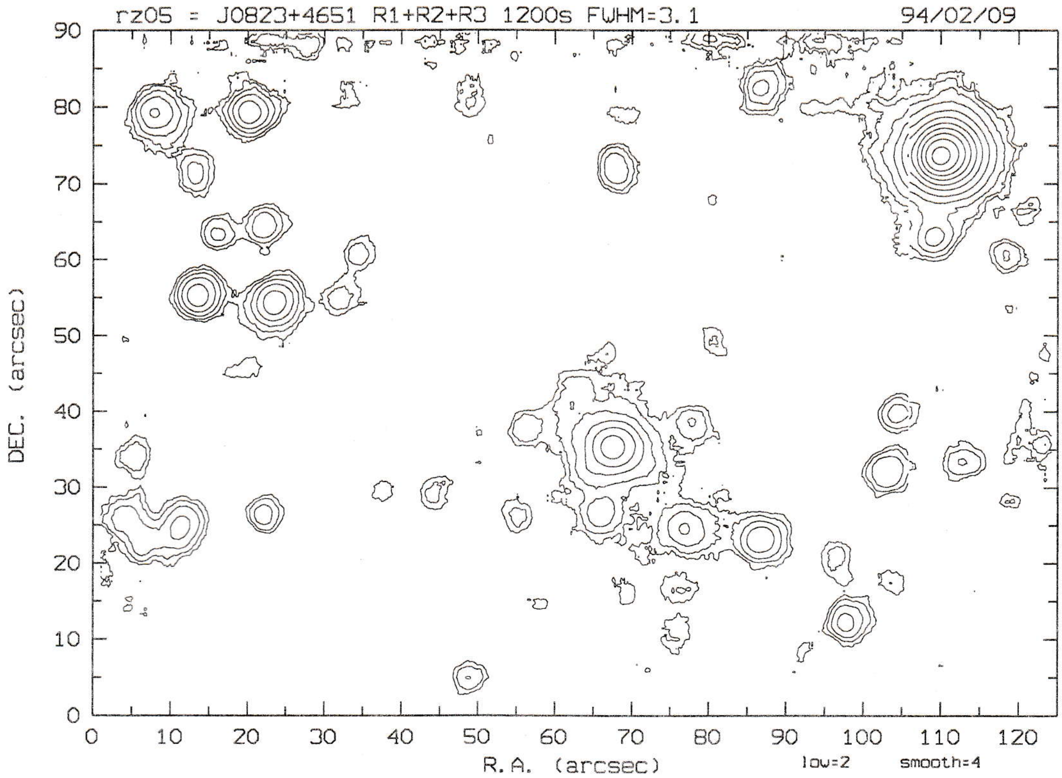

Figure 12: *The map of the 6m telescope CCD image of radio source RZ5 (J 082347+465150).*

ΔRA, ΔDec are differences of radio and optical positions, σRA and σDec are root-mean-square errors of the radio and optical coordinates, respectively. The identification is considered reliable if LR>2.

Analyzing the VLA maps (see Table 1) one can find that all five objects are not point-like. Two objects (*RZ5* and *RZ55*) have distinguished radio components. Identification of the objects with DSS and APM shows only 3 radio sources identified with a high probability with the optical objects visible on DSS. Despite the fact that *RZ5* is identified with a red star–like object of $19^{m}5$, BTA observations of 1994 have shown that it is rather an elliptical galaxy. An averaged 6 m CCD image (Fig. 12) of *RZ5* shows that merging of galaxies is probably observed in this object. Actually, it is not merging of equal galaxies, but we have a case of "cannibalism", i.e. a giant galaxy "eats up" surrounding galaxies of lower mass. Radio emission of this merged group of at least 8 galaxies, with the largest one at the center, may be produced by active processes working during the merging, which may have an explosive character (Kontorovich et al., 1992).

The source *RZ9*, which is slightly extended at 1400 MHz, is identified with an extended one in optics (O-plate) and, may be, with a galaxy or a QSO, i.e. a radio core. If the $2''.5$-wide tail on the left side of *RZ*5 (Fig. 2) is not a false structure, then it may be a jet flying out from the core.

The source *RZ14*, having an extended but unresolved into components structure and a steep radio spectrum, coincides with a star-like object with a very blue O-E color index, which is most likely a QSO (blue star–like object, BSO). Taking into account that it has an extended structure (probably two close radio components) we can suppose it to be a candidate for a gravitationally lensed object (Fletcher, 1998).

The sources *RZ55* and *RZ70*, showing an extended structure (although *RZ70* is not resolved into components) and having steep spectra, are not visible on the Palomar Observatory Sky Survey plates. Therefore, they may be selected as candidates for distant radio galaxies and objects for further investigation.

6. Conclusions

VLA maps with a resolution of $2''.5\times2''$ for three RATAN–600 Zenith radio sources, *RZ5*, *RZ9* and *RZ14*, and with a resolution of $6''.5\times2''.3$ for two sources, *RZ55*, *RZ70*, have been analyzed.

All five objects are extended and two of them (*RZ*5 and *RZ*55) are clearly resolved. All the sources have linear steep spectra ($\alpha < -0.65$), and one of them (*RZ*14) has an ultrasteep spectrum.

Confident optical counterparts have been found in the Palomar Digitized Sky Survey for 3 radio sources.

The radio source $RZ5$, being a merging group of one large and several small galaxies (as 6 m telescope observations show), may have appeared in this process.

The radio source $RZ14$ is probably a BSO and could be a candidate to a gravitationally lensed object.

Two radio sources, *RZ55* and *RZ70*, which have no optical counterparts up to $21^{m}_{\cdot}5$ ($RZ70$ up to 24^{m}), may be distant radio galaxies ($z > 0.5$).

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