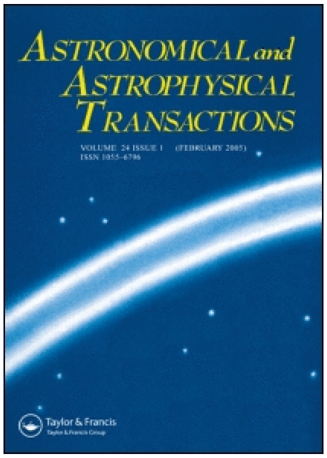

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THE PROGRAM OF DISTANT RADIO GALAXIES AT THE SPECIAL ASTROPHYSICAL OBSERVATORY OF RUSSIA

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The results of optical identification of a sample of ultra steep spectra (USS) RC-catalogue objects with the help of the 6-m Russian telescope are given. The objects were found in the RATAN-600 "Experiment Cold" and investigated with the VLA for morphology and accurate radio positions ("The Big Trio Project"). The USS sources make up about 10% of all of the 1145 RC-catalogue sources in an area of about 100 square degrees. More than 70% of these USS sources have FR II morphology and can be used for investigations of the early universe. With the help of accumulated information on 232 USS sources with $Z > 1$ the relations $R(Z)$ (R-visual magnitude), LAS(Z) (LAS-the largest angular size) and spectral index $\alpha(Z)$ were constructed and the mean red shift of our sample sources turns out to be 2. All sources of our sample were separated into groups: compact steep spectra (CSS) with radio dimensions smaller than the size of the optical galaxy, sources with largest angular sizes, sources with bright nucleus, and so on. The list of 32 most evident candidates in distant galaxies is completed. These sources are the first priority sample for very deep spectroscopy.

KEY WORDS Galaxies, active-radio continuum, galaxies

1 INTRODUCTION

It is now clear to all groups working with early universe objects, that blind searching for high red shift objects is not very efficient and we have a preliminary selection rule to pick up the most probable candidates and only then to apply for very expensive time at big optical telescopes. After pioneering work of the Holland group, Kapahi and Kulkarni (1990) suggested using FR II radio galaxies (RG) combined with the steep spectrum selection rule and demonstrated the efficiency of this approach. It was pointed out that up to now only in radio galaxies has it been possible to observe the rather good spectral content of light from the stellar population; and it is possible to trace back the history of the stellar population and recover the epoch of the beginning of star formation, the most important parameter for cosmology. FR II RG are the most powerful radio emitters, so they should have the most advanced giant black hole evolution history, which includes the process of normal star formation in the protogalaxy, formation of a very dense central star cluster, and growth of the black hole from stellar mass to half a billion solar masses. The "Big Trio Project" was proposed to get maximum information about distant radio galaxies. Here the present status of this project is given. The RATAN-600 is used as one of the best wide field searching survey instruments, the VLA as the best imaging system, and the 6-m Russian optical telescope as one of the world's best instruments for deep optical identification and spectroscopy.

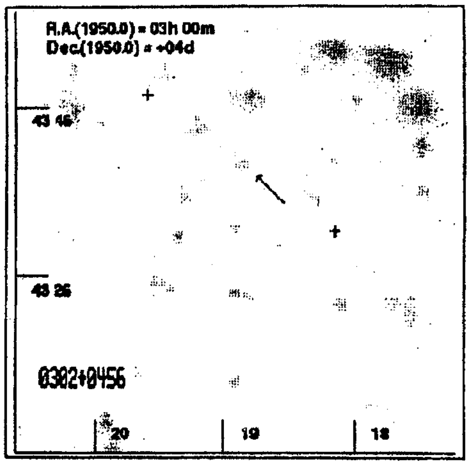
2 RADIO SOURCES WITH ULTRA STEEP SPECTRA (USS) FROM THE RC CATALOGUE (RATAN-600)

The RC catalogue is the result of a multi-frequency survey of the strip of sky at $0^h < \text{RA} < 24^h$, Dec = Dec SS433 ($\sim 5°$) (Parijskij *et al.*, 1991; Parijskij *et al.*, 1992). The median width in declination is about $8'$. Thus, this strip of sky investigated in 1980, has an effective area of about 100 square degrees. 1145 radio sources were discovered in this area, 91 of them with USS characteristics ($\alpha > 0.9$; $S \propto \nu^{-\alpha}$). The flux density median value of RC USS sources is about 60 mJy at 3.9 GHz. Before 1993 several hundred USS sources in the whole sky were discovered (Rottgering, 1993). The peculiarity of our sample (which was selected in 1988 by comparing the RC and UTRAO (Douglas, 1980) catalogues) is the lower mean flux density. The efficiency of selection of USS objects is connected with the profundity of the RC catalogue. All USS UTRAO objects with $\alpha > 1.6$ have a flux density at 3.9 GHz above the threshold sensitivity of the RC catalogue. Therefore, we have a high surface density of USS objects.

The RC catalogue contains 91 USS objects with flux density above 10 mJy on the area of 100 sq are degrees. That means that there are approximately 30 000 such objects in the whole sky. The incompleteness of the RC catalogue at this level of flux density can only increase this value. Under Oijk's estimates (van Ojik, 1995), about 50% of such sources have red shift $Z > 2$, and among USS sources with $\alpha > 1.3$ about 30% have $Z > 3$. Thus, we can suppose that the population of distant radio galaxies is sufficiently numerous and can be used for testing cosmological models.

3 OPTICAL IDENTIFICATIONS

The last (third) USS RC source subsample contains 53 radio galaxies. Radio maps of those objects were obtained with the help of the VLA (NRAO, USA) at a frequency of 1425 MHz; 14 sources were mapped at 4860 MHz and three sources at 8440 MHz for the purposes of refinement of the structure (see Parijskij *et al.*, 1996).



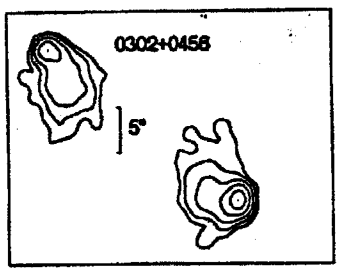


Figure 1 CCD image of RC 0302+0456 in the R band ($R = 24.3^m$) obtained with the 6-m Russian telescope. The arrow shows the optical candidate; the crosses indicate the positions of radio components. The VLA map of this source is given below.

Optical observations were made with the help of the 6-m Russian telescope in 1994–1996. Conditions and image quality were very different. The optical fields of the whole sample are also given by Parijskij *et al.* (1996); a deep CCD image of the source RC 0302+0456, for example, is shown in Figure 1. About 25 sources of our sample were observed with the 6-m telescope in the BVRI bands (see, for example, Figure 2).

4 THE ESTIMATION OF THE RED SHIFT FOR THE WHOLE USS SAMPLE FROM THE RC CATALOGUE

Using the data for the USS population with measured red shifts accumulated to 1997, we tried to estimate red shifts for all sources of our sample (Parijskij *et al.*, 1997). The Z(LAS), $Z(R)$ and $Z(\alpha)$ relations were used. At high red shifts the accuracy of such methods is very poor (about 30%), but the coincidence of all approaches increases the reliability of these calculations. All estimated values are

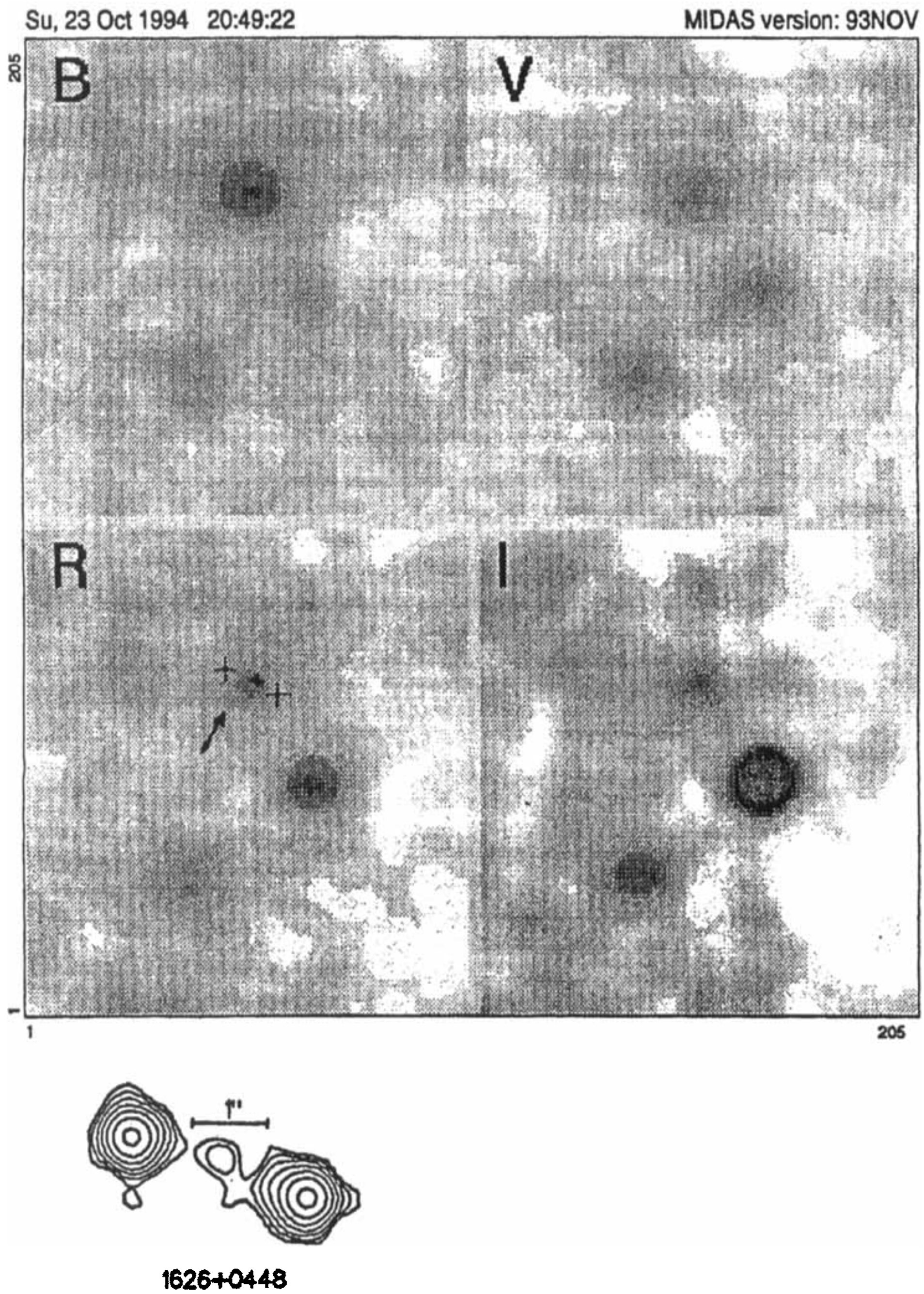


Figure 2 Multicolour observations of RC 1626+0448 ($R = 22.7^m$, $R - I = 0.14$, $V - R = 0.37$, $B - V = 0.7$). Positions of the radio source components are marked with big crosses; the central core components are marked with a small one. The VLA map is shown below.

Table 1. Typical objects with LAS > 3″ and $R > 21^{m}_{.}5$

RC–source IAU 2000	$S_{3.9GHz}$ *mJy*	*LAS* ″	α	*R m*	$R_{lim} - R$ *m*	Z_{LAS}	Z_{ph}	Z_{α}	Z_{mean}	*Morph*
0034+0513	80	12.1	1.05	23.3	–1.2	2.0	2.3	1.8	2.0	D,FRII
0105+0501	33	7.6	1.10	22.2	0.8	2.1	2.0	2.0	2.0	D.FRII
0213+0516	147	35.8	0.96	22.0	–0.6	1.6	2.0	1.6	1.7	T,BC,FRII
0302+0456	50	27.2	0.90	24.3	–1.7	1.7	2.6	1.5	1.9	D,FRII
0318+0456	152	76.2	1.13	23.7	–2.4	1.3	2.4	2.1	1.9	T,BC,FRII
0324+0442	129	11.8	1.02	22.1	–0.5	2.0	2.0	1.8	1.9	FRI
0406+0453	79	21.8	1.02	24.5	–2.4	1.8	2.6	1.8	2.1	T,BC,FRII
0444+0501	69	10.8	1.09	22.6	–0.4	2.0	2.1	2.0	2.0	D,FRII
0458+0506	95	26.1	1.02	21.9	0.	1.7	1.9	1.8	1.8	T,WC,FRII
0743+0445	37	20.5	1.07	23.5	–0.6	1.8	2.5	1.9	2.1	D,FRII
0744+0500	27	10.8	1.20	> 24.3	–1.2	2.0	2.6	2.2	2.3	D,FRII
0836+0511	109	13.5	1.05	24.5	–2.8	2.0	2.6	1.9	2.2	D,FRII
0837+0446	54	3.9	1.0	22.1	0.4	2.2	2.0	1.7	2.0	D,FRII
0934+0505	36	5.0	1.07	24.0	–1.1	2.2	2.5	1.9	2.2	D,FRII
1043+0443	37	48.0	1.14	23.0	–0.1	1.5	2.2	2.1	1.9	D,FRII
1113+0436	52	29.0	0.98	22.3	0.3	1.7	2.0	1.7	1.8	D,FRII?
1152+0449	29	7.0	1.00	22.4	0.8	2.1	2.1	1.7	2.0	D,FRII
1213+0500	74	46.7	1.12	21.8	0.3	1.5	1.9	2.0	1.8	D,FRII
1339+0445	41	34.0	1.07	22.6	0.2	1.6	2.1	1.9	1.9	T,WC
1347+0441	43	4.2	0.98	23.4	–0.6	2.2	2.3	1.7	2.1	T,BC
1429+0501	82	11.1	0.92	> 23.9	–1.8	2.0	2.5	1.5	2.0	CJ
1436+0501	48	15.7	1.25	22.8	–0.3	1.9	2.2	2.4	2.2	D,FRII
1439+0455	40	17.9	1.15	> 24.9	–2.1	1.9	2.8	2.1	2.3	D,FRII
1510+0438	67	3.4	0.90	22.0	0.3	2.2	2.0	1.5	1.9	D,FRII
1551+0458	70	11.6	1.10	23.4	–1.2	2.0	2.3	2.0	2.1	D,FRII
1609+0456	30	6.3	1.15	> 24.4	–1.3	2.1	2.6	2.1	2.3	D,FRII
1735+0454	30	5.3	1.0	22.8	0.4	2.2	2.2	1.7	2.0	D,FRII
1740+0502	32	4.6	1.20	22.2	0.8	2.2	2.0	2.2	2.1	D,FRII
2219+0458	48	4.7	1.04	23.6	–1.0	2.2	2.4	1.8	2.1	D,FRII
2236+0454	42	40.2	1.15	22.0	0.7	1.6	2.0	2.1	1.9	D,FRII
2247+0507	110	5.6	0.98	21.9	–0.1	2.2	1.9	1.7	1.9	D,FRII
2348+0507	140	4.7	0.95	22.8	–1.3	2.2	2.2	1.6	2.0	D.FRII

gathered in Tables 1–4 for four groups of USS RC sources separately. The first group contains typical objects with LAS > 3″, with flux density < 150 mJy at 3.9 GHz, and stellar magnitude > 21.5 in the R band (32 radio sources in total). The second group contains eight "dissident objects" with LAS > 90″, or with flux density > 160 mJy at 3.9 GHz. The sources with bright optical counterparts (< 21.5 stellar magnitude) were included in the third group (27 objects in total). The fourth group consists of 24 radio sources with subgalactic dimensions. The columns of Tables 1–4 represent accordingly the RC source name; the flux density at 3.9 GHz in mJy; LAS in arc sec; spectral index α; stellar magnitude in the R band; the difference between the "limit" and the observed stellar magnitude (the "limit" magnitude was estimated from the equality of the radio and optical luminosities); the red shift obtained from the Z(LAS) dependence; the photometric red shift estimated from the $Z(R)$ relation; the red shift evaluated from the $Z(\alpha)$ relation; the mean estima-

Table 2. "Dissident" objects with LAS > 90″ or $S_{3.9}$ > 16 mJy or S > 160 mJy

RC–source IAU 2000	$S_{3.9GHz}$ *mJy*	*LAS* ″	α	*R* *m*	$R_{lim} - R$ *m*	Z_{LAS}	Z_{ph}	Z_α	Z_{mean}	*Morph*
0015+0503a	19	20.6	0.96	21.9	1.8	1.8	1.9	1.6	1.8	D,FRII
0039+0454	300	16.9	0.99	22.8	−2.2	1.9	2.3	1.7	2.0	D,FRII
0152+0453	53	122.5	1.15	22.5	0.0	1.0	2.1	2.1	1.7	D,FRII
0209+0501b	18	18.1	0.91	22.7	1.0	1.9	2.1	1.5	1.8	D,FRII
1031+0443	191	33.0	1.20	22.1	−1.1	1.6	2.0	2.2	1.9	D,FRII
1219+0446	23	118.0	1.23	21.9	1.4	1.0	1.9	2.3	1.7	D,FRII
1333+0452	16	54.	1.40	23.2	0.2	1.5	2.3	2.7	2.2	D,FRII
1706+0502	257	44.9	1.01	22.6	−1.8	1.5	2.1	1.8	1.8	D,FRII

Table 3. Bright objects with $R < 21^{m}_{.}5$

RC–source IAU 2000	$S_{3.9GHz}$ *mJy*	*LAS* ″	α	*R* *m*	$R_{lim} - R$ *m*	Z_{LAS}	Z_{ph}	Z_α	Z_{mean}	*Morph*
0015+0501	36	16.3	1.03	20.5	2.4	1.9	1.6	1.8	1.8	D,FRII
0038+0449	95	3.3	0.90	21.2	0.7	2.2	1.8	1.5	1.8	D,FRII
0042+0504	80	24.8	0.90	19.0	3.1	1.8	1.2	1.5	1.5	D,FRII
0110+0500	84	74.4	0.90	19.4	2.6	1.3	1.3	1.5	1.4	T,WC,FRII
0126+0502	51	18.0	1.06	18.1	4.4	1.9	0.9	1.9	1.6	D,FRII
0135+0450	92	7.8	0.97	18.4	3.5	2.1	1.0	1.7	1.6	T?FRI?
0143+0505	55	7.4	1.03	20.6	1.9	2.1	1.6	1.8	1.8	D,FRII
0159+0448	50	14.7	0.99	20.8	1.8	1.9	1.6	1.7	1.7	D,FRII
0226+0512	82	10.7	0.97	20.1	2.0	2.0	1.5	1.7	1.7	D,FRII
0457+0452	56	34.0	1.12	19.2	3.2	1.6	1.2	2.0	1.6	D,FRII
0459+0456	76	63.8	0.95	22.2	1.5	1.4	2.0	1.6	1.7	D,FRII
0519+0510	120	40.9	0.95	20.3	1.4	1.6	1.5	1.6	1.6	M
0845+0444	135	4.6	1.14	21.3	0.1	2.2	1.8	2.1	2.0	CJ
0908+0451	109	34.5	0.92	19.6	2.2	1.6	1.3	1.5	1.5	D,FRII
1142+0455	108	18.7	1.00	21.0	0.8	1.9	1.7	1.7	1.8	T,FRII
1154+0431	273	6.8	0.97	19.9	0.9	2.1	1.4	1.7	1.7	D,FRII
1155+0444	54	13.0	1.00	18.5	4.0	2.0	1.0	1.7	1.6	D,FRII
1235+0435b	45	9.1	0.98	21.4	1.3	2.1	1.8	1.7	1.9	D,FRII
1322+0449	47	11.7	0.96	20.3	2.4	2.0	1.5	1.6	1.7	CJ
1357+0453	109	12.4	0.95	20.8	1.0	2.0	1.6	1.6	1.7	D,FRII
1646+0501	54	15.7	0.92	20.9	1.6	1.9	1.7	1.5	1.7	D,FRII
1653+0443	92	70.5	0.98	21.1	0.8	1.3	1.7	1.7	1.6	D,FRII
1722+0442	300	21.9	0.99	20.4	0.2	1.8	1.5	1.7	1.7	D,FRII
2013+0508	51	10.0	0.96	20.6	2.0	2.1	1.6	1.6	1.8	D,FRII
2036+0451	75	56.0	1.02	18.7	3.5	1.5	1.1	1.8	1.5	T,C,FRII
2224+0513	145	36.1	0.78	21.1	0.3	1.6	1.7	1.2	1.5	D,FRII
2320+0459	64	15.2	0.94	20.3	2.0	1.9	1.5	1.6	1.7	D,FRII

ted red shift; and the morphology type of the sources: (FR I, II, Fanarov–Rily I, II; P, point source; D, double source; TWC, triple source with weak core; TBC, triple source with bright core; CJ, core with jet). The mean value of the red shifts for the first group turns out to be Z(LAS = 1.9, Z(ph) = 2.2 and $Z(\alpha)$ = 1.9.

Table 4. Compact (subgalactic) objects with LAS < 3″

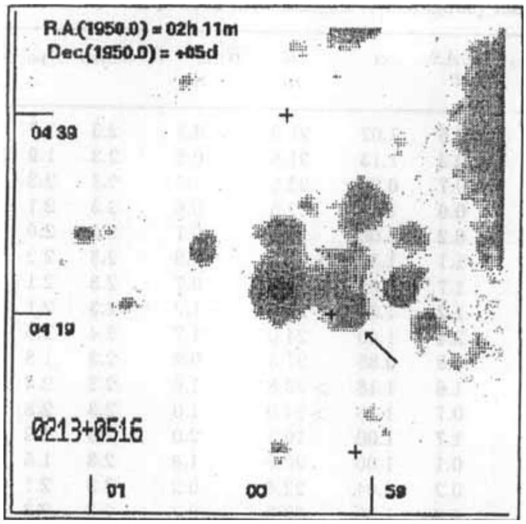
RC–source *IAU 2000*	$S_{3.9GHz}$ *mJy*	*LAS* ″	α	*R* *m*	$R_{lim}-R$ *m*	Z_{LAS}	Z_{ph}	Z_{α}	Z_{mean}	*Morph*
0117+0503	12	< 0.5	1.02	21.0	3.1	2.3	1.7	1.8	1.9	P
0133+0459	62	< 0.2	1.13	21.8	0.5	2.3	1.9	2.1	2.1	P
0137+0539	66	0.7	0.98	23.3	−1.5	2.3	2.3	1.7	2.1	P
0154+0459	31	0.6	1.01	22.5	0.6	2.3	2.1	1.8	2.1	P
0225+0506	69	0.2	1.06	22.1	0.1	2.3	2.0	1.9	2.1	P
0250+0512	70	1.1	1.32	> 22.8	−0.9	2.3	2.2	2.5	2.3	D,FRII
0308+0454	27	1.7	0.95	> 22.6	0.7	2.3	2.1	1.6	2.0	D,FRII
0311+0507	120	1.2	1.36	22.5	−1.2	2.3	2.1	2.6	2.3	CJ
0355+0449	46	2.4	1.40	24.0	−1.7	2.4	2.5	2.7	2.5	D,FRII
0506+0508	70	0.8	0.88	21.3	0.9	2.3	1.8	1.4	1.8	D,FRII
0552+0451	65	1.6	1.18	> 23.8	−1.6	2.3	2.4	2.2	2.3	D,FRII
0756+0450	14	0.7	1.16	> 24.9	−1.0	2.3	2.8	2.1	2.4	P
0820+0454	166	1.7	1.00	19.3	2.0	2.3	1.2	1.7	1.7	D,FRII
0909+0445	64	0.1	1.00	20.5	1.8	2.3	1.6	1.7	1.9	P
1011+0502	70	0.2	1.04	22.4	−0.2	2.3	2.1	1.8	2.1	CJ
1333+0451	11	1.0	1.30	23.3	0.7	2.3	2.3	2.5	2.4	P
1503+0456	61	0.6	1.04	22.8	−0.4	2.3	2.2	1.8	2.1	CJ
1626+0448	46	2.4	1.26	22.7	−0.2	2.2	2.1	2.4	2.2	T,FRII
1658+0454	31	< 0.2	1.25	> 24.2	−1.3	2.3	2.6	2.4	2.4	P
1703+0502	175	1.8	1.18	23.2	−2.1	2.3	2.3	2.2	2.3	D,FRII
1720+0455	19	< 0.5	1.22	20.3	3.2	2.3	1.5	2.3	2.0	P
1725+0457	27	1.0	1.26	> 23.7	−0.6	2.3	2.4	2.4	2.4	P
2144+0513	72	1.8	1.06	18.6	3.6	2.3	1.1	1.9	1.8	CJ
2357+0501	54	0.3	1.17	> 23.8	−1.4	2.3	2.5	2.2	2.3	P

5 DISCUSSION

The mean value of the estimated red shifts turns out to about 2. The photometric red shifts in the K band could give a more precise value, but we have no such possibility now.

More than 50% of the objects happened to be classical FR II RG. Using our red shift estimations we found their radio luminosity to be $P \sim 10^{27}$ w m^{-2} Hz at 1.4 GHz, magnetic field $H \sim 10^{-5}$ G, linear sizes $\sim$ 200 kpc and energy content $\sim 3 \times 10^{59}$ erg.

Somewhat unexpected was the broad class of CSS (compact steep spectra) objects with sizes smaller than the host galaxy sizes (< 3″). Seven of them have the FR II morphology and radio luminosity close to the luminosity of the host galaxy. Twelve sources are unresolved in the VLA A-configuration at 8 GHz (< 0.1–0.2″). Four objects have a core–jet structure. According to our criterion of $L_{\rm rad}/L_{\rm opt}$ (Kopylov, 1995a, b) three objects (0117+0501, 1720+0451 and 2144+0510) are not classical FR II radio galaxies – these are either distant quasars or galaxies with small radio luminosity (Sy I, Sy II, N–gal), and the red shift should be revised. Only one of them could be a quasar, but the presence of a very near galaxy makes this assumption doubtful. The core component is observed only in one object of



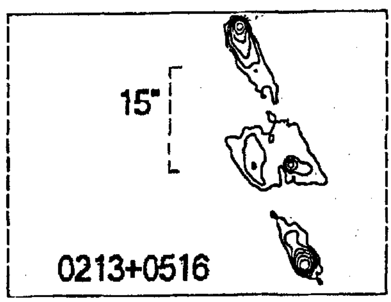


Figure 3 CCD image of RC 0213+0516 in the R band obtained with the 6-m Russian telescope. The arrow shows the position of the host galaxy (22.1^m); the crosses show the positions of radio components. A compact group of galaxies is clearly seen. Below the VLA map of the radio source is given.

this group. All objects of the fourth group need investigation with milliarc second resolution, but the absence of inversion in the short wavelength spectra puts the minimum boundary on the size of the unresolved part of the object. The absence of a decrease in the low frequency part of the spectra gives the lowest boundary of the size of the principal radio emitting region (Slysh, 1963).

Ten objects from the whole sample (six from the first group of HZRG's) have a triple structure, but only part of them have the core component common to the FR II morphology (flux density of the core is about 3–5% of the source flux density). Three cores contain over 15% flux density of the source. But there is no single case with a clear quasar or Sy-galaxy nature. As mentioned earlier (Goss *et al.*, 1992), the distribution of USS RC objects by LAS has two maxima: on 3–5 arc sec and on $\sim$ 30 arc sec. Besides, three groups of sources could be distinguished: giant

USS radio galaxies with LAS > 30 arc sec, powerful double radio sources with subgalactic sizes and high photometric red shift, and, last, unresolved compact steep spectra sources (CSS). The giant galaxies at $Z > 1$ are somewhat unexpected for radio astronomers. As mentioned by Parijskij *et al.* (1996) these sources demand early formation of the "central engine" and give the possibility of diagnosing the early universe geometry with the help of inverse Compton emission (Parijskij *et al.*, 1994) and by their morphology. If very large radio galaxies with high red shifts were discovered, a population of X-ray objects in the early universe appears. We estimate that about 50% of our USS sources could be detected in the X-ray region with AXAF type facilities.

Another aspect of USS HZRG is its relation to the problem of galaxy cluster formation in the early universe. In the sufficiently investigated part of the universe ($Z < 1$) more than 70% of powerful radio galaxies belong to clusters of different types. A perfect correlation was found specifically for USS RG (Andernach *et al.*, 1980; Lary and Perola, 1978). The host galaxy of radio galaxies is as a rule the first ranked bright member of a cluster and is situated near the cluster centre. In our sample we have at least five such events (see, for example, Figure 3). So we conclude that on the whole sky there could be no less than 1000 compact groups. Deep investigations would permit us to increase this number. In spite of difficulties in spectral and X-ray studies of distant cluster of galaxies, the search for clusters by the Sunaev-Zeldovich effect, which is independent of red shift in the radio domain, may be a perfect method. Simple estimation of the density of the clusters at high red shift is important for the selection of evolution models.

Clearly, the search for evolution effects should be postponed until spectroscopic red shifts are done. We only mention that, for our USS sample we have the constancy of the radio to optical luminosity ratio – this property is also noticeable for other USS radio galaxies at $Z > 1$.

6 CONCLUSION

The first three steps of the "Big Trio" program are virtually finished: the selection of USS sources from the RC catalogue (RATAN-600), mapping (with the help of the VLA), and optical identifications of USS RC sources (with the help of the 6-m Russian telescope). Two VLA maps turn out to be not very clear: instead of double source in fact two independent sources may exist. Some sources may need to be reidentified. We have no optical counterparts (the magnitude in R band is > 24–25 m) for 11 sources. They may be very distant. Multicolour photometry with the 6-m telescope continues.

Red shifts were estimated by different methods for all sources in our sample. The mean value of red shifts seems to be about 2. We hope to get deep spectroscopy for 32 typical sources from our first list.

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