Investigation of radio sources from the interplanetary scintillation Pushchino Survey

I. Cross-identification with the 7C and FIRST radio catalogues[★]

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Abstract. Interplanetary scintillating (IPS) radio sources from the Pushchino Survey (PS) in the area of 0.11 sr have been cross-identified with objects from the 7C and FIRST catalogues. We have obtained improved positions of IPS radio sources, which are necessary for their optical identification. The data on sizes and morphology provided by the FIRST catalogue have shown that more than 50% of IPS radio sources are single and compact ($<3''$) at $\nu = 1400$ MHz. Most of them belong to the class of compact steep spectrum radio sources. About 15% of IPS radio sources are single partially resolved FIRST objects (sizes of $3''$ – $9''$) and another 11% are double radio sources with compact components. The remaining 22% have larger sizes and, as a rule, a more complex structure too. Because IPS sources certainly contain an appreciable part of their radiation at low frequencies (100 MHz) in very compact ($\sim 0''.1$) components and have steep spectra, we hope that a significant part of the Pushchino Survey objects are very probable candidates for steep spectrum quasars.

Key words. catalogs – radio continuum: galaxies – quasars: general

1. Introduction

Observations of radio sources from the 4C catalogue were made at 81.5 MHz with the IPS method to look for low frequency compact radio sources (Readhead & Hewish 1974). 1500 compact (with angular diameter $<1''$) scintillating sources with different compactness have been found. The compactness R of a radio source is defined as the fraction of the total flux density of the radio source contained in a compact scintillating component. The analysis of these observations was made in Readhead & Longair (1975). Evidence for strong cosmological evolution of strongly scintillating radio sources with high compactness ($R > 0.4$) has been found. The distribution of these sources with $V/V_{\max}$ is significantly different from that of weakly scintillating radio sources with $R < 0.25$, and similar to the distribution for all quasars and powerful radio sources in general. The rapid evolution of all strongly scintillating sources persists at least to a flux density of 3.5 Jy at 178 MHz. No evidence of cosmological evolution of weakly scintillating sources

has been found to 6 Jy at 178 MHz. A similar but more sensitive survey was carried out by Purvis et al. (1987).

The survey of low-frequency compact radio sources was made with the Large Phased Array (LPA) of the Pushchino Radio Astronomy Observatory (PRAO) at a frequency of 102 MHz by the IPS method. It allows us to detect compact radio sources about ten times fainter than the ones known so far (Artyukh & Tyul'bashev 1996; Artyukh et al. 1998). The survey was carried out in two regions with the centers at $\alpha = 06^{\text{h}}28^{\text{m}}$, $\delta = 45^\circ$ and $\alpha = 10^{\text{h}}28^{\text{m}}$, $\delta = 41^\circ$ (B1950). These regions correspond to the first two regions of the 7C survey conducted at 151 MHz (McGilchrist et al. 1990). In the two regions (the total area is 0.144 sr) 414 IPS radio sources were detected (125 in the first region and 289 in the second one). 380 of them were found as compact objects for the first time. The high sensitivity of the observations (~ 0.1 Jy) was reached as the LPA is the largest radio telescope in the meter radio wave range ($A_{\text{geom}} = 70\,000\text{ m}^2$), and the high ($\sim 0''.1$) resolution was obtained by using the IPS method.

The IPS radio sources that were found have a high degree of compactness (the mean compactness was $\langle R \rangle = 0.36$). It was found that for integral flux densities of IPS sources the mean spectral index was $\langle \alpha \rangle = 0.84$ ($S \propto \nu^{-\alpha}$) in the frequency

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[★] Complete Tables 1 and 2 are only available in electronic form at <http://www.edpsciences.org>

range 151–4885 MHz (Tyul'bashev 1997). For comparison, for radio sources from the 7C survey it was $\langle \alpha \rangle = 0.9$ in the frequency range 151–408 MHz (McGilchrist et al. 1990). Thus, the flattening of low frequency spectra of IPS sources is very small if it is real. As there were no VLBI observations of weak IPS sources, it is impossible to obtain spectra of compact scintillating components, but for some radio sources it is possible to make lower estimations of spectral indexes of these components. For compact components it was found that $\alpha > 0.5$ for 60% of the IPS sources (Tyul'bashev 1997).

The counts of IPS radio sources showed that at the flux density of $S < 0.6$ Jy a sharp cut-off is observed, with a slope much steeper than for the counts of the whole population of sources (Artyukh & Tyul'bashev 1996; Artyukh et al. 1998). The analysis of the known factors that could determine the form of the count curve showed that this effect was most probably connected with the cosmological evolution of IPS radio sources (Artyukh & Tyul'bashev 1998).

IPS observations of different active galaxies showed that it was possible to find scintillating sources in any class of galaxies but the largest per cent of them was among quasars and BL Lac objects (Artyukh 1990). From indirect considerations, Tyul'bashev (1997) concluded that scintillating sources from the Pushchino survey were steep spectrum quasars in most cases.

A question arose, as to what the low frequency compact radio sources represents? To obtain an answer to this question, radio and optical identifications of faint scintillating radio sources are necessary. If the majority of these sources prove to be quasars, then the abovementioned effect of cosmological evolution could be related to quasars. Moreover, the samples of the IPS radio sources would be suitable for cosmological investigations, since quasars as the brightest objects are seen at very large distances. So, an elucidation of the nature of scintillating radio sources is a real problem.

For reliable optical identification of radio sources it is necessary to know coordinates with the precision of about $1''$. Unfortunately, the coordinates of the Pushchino Survey radio sources were measured with large errors, 5–15 arcmin, because of the large beam size of the LPA radio telescope ($49' \times 26' \sec(z)$). Therefore, first we should find counterparts to the IPS radio sources in other catalogues where the precision of the coordinates is good enough for follow-up optical identifications. We chose the 7C and the FIRST (White et al. 1996) catalogue for this purpose.

This paper describes radio identification of the IPS radio sources from the PS catalogue (Artyukh et al. 1998). In the following Paper II the results of optical identifications and redshift measurements will be presented.

In Sects. 2 and 3 we describe radio identification of the scintillating radio sources with the 7C and the FIRST catalogues. In Sect. 4 objects with complex morphology are discussed, and in Sect. 5 we give our conclusions.

2. Identifications with 7C radio sources

The 7C survey of radio sources was carried out at 151 MHz (close to our frequency of 102 MHz) with of sensitivity of

about 0.1 Jy (of the same order as ours), but with a narrower (comparing with LPA) beam size of the radio telescope of $70''$ (McGilchrist et al. 1990). The 7C survey contains 4723 radio sources in the same two regions of 0.144 sr. The mean density of 7C radio sources is equal to 1 source per 360 sq arcmin. For the PS radio sources the error box is ~ 300 sq arcmin. Owing to this circumstance, it becomes possible in most cases to identify a scintillating radio source with a unique 7C object.

In this paper we identify IPS radio sources from the second region with the center at $\alpha = 10^h 28^m$, $\delta = 41^\circ$ (B1950). Our working region has boundaries of $09^h 44^m 30^s < \text{RA} < 11^h 08^m 30^s$ and $+29^\circ 00' < \text{Dec} < +51^\circ 39'$ and an area of 360 sq deg (0.110 sr). It contains 289 IPS radio sources detected to a limiting flux density for scintillating component of ≈ 0.2 Jy and about 1900 7C radio sources with flux density ≥ 0.2 Jy compiled from the basic 7C survey (McGilchrist et al. 1990) and several other 7C surveys (Waldram et al. 1996; Pooley et al. 1998; Riley et al. 1999) that complement the basic 7C survey near the edges of our region. This region, unlike the first one, is located inside the region of the FIRST survey and intersects in part with other surveys (B2, B3, Texas, WENSS, NVSS, GB and other). In Fig. 1 we present the sky distribution of the radio sources from the PS and 7C catalogues.

To choose a radio source responsible for scintillations we selected all objects from the 7C catalogue within $15'$ of each IPS radio source position and ranked them by radial distance. Then as possible candidates we retained only such objects that were sufficiently bright at 151 MHz to provide the scintillating flux density assuming the mean spectral index $\langle \alpha \rangle = 0.84$. At this step we took into account, apart from the flux density, angular dimensions as measured in the FIRST catalogue (see Sect. 3), assuming that the smaller radio source is the more likely candidate for the scintillating source. The number of components in the FIRST catalogue was also taken into account, since using securely identified bright (> 0.5 Jy) scintillating sources we established that single FIRST objects showed, as a rule, two times higher compactness (R) than double ones with equal angular size of the brightest component.

In most cases we selected as a counterpart for the IPS radio source that 7C object which was both nearer to the IPS position and considerably more compact than all other possible (by the flux density criterion) candidates within a $15'$ radius. Some of the excluded objects might provide a contribution to the scintillation flux density but only a modest one. In 12 cases two candidates with approximately equal parameters were retained. In 5 cases the counterpart was found just outside the $15'$ circle.

The results of our identifications are given in Table 1, which has the following contents: Cols. 1–2 – coordinates (B1950) of the IPS radio source; Col. 3 – flux density (Jy) at 102 MHz of the IPS radio source; Col. 4 – name of the IPS radio source corresponding to its sequential number in the original catalogue (Artyukh et al. 1998); Col. 5 – rank in angular distance of a 7C counterpart from the IPS radio source (a, b, c, d, e, f – distance rank for objects within $15'$; u – unique object within $15'$ circle; S, E, W – rough direction for objects outside $15'$ circle); Col. 6 – designation of 7C catalogue used: 7C (McGilchrist et al. 1990), 7C4 (Waldram et al. 1996), 7C5 (Pooley et al. 1998), 7Cn (Riley et al. 1999); for the object PS159a the data were

Fig. 1. Distribution of the IPS and 7C radio sources. The IPS radio sources are shown by hexagons of 30' diameter, the 7C radio sources – by filled squares of increasing size for intervals of flux density: <0.5, 0.5–1, 1–2, >2 Jy.

taken from the 6CIII catalogue (Hales et al. 1990); Cols. 7–8 – coordinates (B1950) from the catalogue in Col. 6; Col. 9 – integrated flux density (Jy) at 151 MHz from the catalogue in Col. 6; Col. 10 – angular distance (arcsec) of a 7C radio source from the IPS radio source position.

236 out of 289 IPS radio sources (82%) have a single counterpart and in 12 (4%) cases scintillations are probably caused by the sum of two radio sources from the 7C catalogue. In 41 (14%) cases we failed to identify the IPS radio source with an appropriate (by a flux density in the 7C and compactness in

Table 1. 7C counterparts for IPS radio sources.

RA(1950)	Dec(1950)	S_m	PS	C	Cat.	RA(1950)	Dec(1950)	S_{151}	dR
09 45 00	+49 17	0.25	001	a	7C5	09 44 39.1	+49 15 10	0.338	232.3
09 45 45	+34 48	0.75	002	a	7Cn	09 45 39.7	+34 37 17	0.712	646.3
09 47 30	+41 17	0.46	004	u	7Cn	09 46 58.6	+41 15 22	0.653	367.3
09 48 05	+43 24	0.35	005	a	7C	09 48 28.008	+43 20 54.75	0.453	311.9
09 48 15	+36 00	0.25	006	b	7Cn	09 48 49.7	+35 52 50	0.461	602.2
09 49 23	+50 03	0.88	008	a	7C	09 49 31.531	+49 59 50.81	1.434	206.2
09 50 00	+36 28	0.23	009	u	7Cn	09 49 26.6	+36 20 14	0.586	616.4
09 50 08	+35 17	0.61	010	a	7Cn	09 50 09.5	+35 14 30	0.960	151.1
09 50 40	+33 55	0.22	011	u	7Cn	09 51 29.7	+33 49 35	0.408	699.4
09 50 45	+45 25	0.33	012	u	7C	09 50 39.177	+45 24 23.64	0.663	71.2
09 50 45	+42 14	1.20	013	a	7C	09 51 06.841	+42 15 20.87	2.116	255.6
09 51 00	+40 21	0.28	015	u	7Cn	09 50 58.7	+40 14 02	1.432	418.2
09 51 00	+31 03	0.61	016	u	7Cn	09 51 08.5	+30 57 48	1.371	330.6
09 51 09	+37 50	1.30	017	a	7Cn	09 51 33.0	+37 47 49	1.454	313.1
09 51 30	+45 00	0.60	018	u	7C	09 52 34.479	+45 00 43.45	0.917	685.1
09 51 30	+41 00	0.46	019	a	7Cn	09 51 39.3	+40 50 59	2.173	551.1

Table 2. FIRST counterparts for IPS radio sources.

PS	C	F	dr	dx	dy	RA(1950)	Dec(1950)	S_{peak}	S_{1400}	MAJ	MIN	PA
001	a	1	2.789	-2.65	0.89	09 44 38.82	+49 15 10.5	89.78	92.97	1.11	0.91	180.0
002	a	1	1.075	0.59	-0.67	09 45 39.73	+34 37 16.0	256.31	259.56	0.73	0.46	143.5
004	u	1	5.633	-5.26	1.87	09 46 58.12	+41 15 23.5	39.38	46.36	2.49	2.04	35.3
004	u	2	10.653	10.43	3.22	09 46 59.51	+41 15 24.9	53.28	60.69	2.44	1.50	42.9
005	a	1	2.493	2.25	-0.97	09 48 28.20	+43 20 53.4	98.38	103.84	1.62	0.81	143.1
006	b	1	2.569	-1.05	2.59	09 48 49.60	+35 52 52.2	77.11	81.88	1.79	0.67	153.5
008	a	1	4.469	-2.21	-3.44	09 49 31.56	+49 59 49.2	110.31	116.67	1.47	1.10	168.0
008	a	2	6.281	-0.09	6.67	09 49 31.78	+49 59 59.3	33.40	37.58	2.49	1.14	7.6
009	u	1	1.808	1.70	1.38	09 49 26.72	+36 20 15.0	99.80	146.62	5.14	1.97	5.2
010	a	1	2.125	-1.72	1.20	09 50 09.34	+35 14 30.8	122.30	121.38	0.00	0.00	90.0
011	u	1	2.084	2.12	1.26	09 51 29.85	+33 49 35.9	131.06	143.60	2.12	1.08	41.4
012	u	1	1.211	1.15	1.05	09 50 39.27	+45 24 24.3	105.57	112.97	1.84	0.87	114.1
013	a	1	1.581	1.67	-0.12	09 51 06.98	+42 15 20.4	396.30	431.89	2.12	0.91	56.7
015	u	1	7.662	-6.54	4.05	09 50 58.11	+40 14 05.7	74.21	95.42	3.38	2.35	38.1
015	u	2	1.849	-0.28	2.16	09 50 58.66	+40 14 03.8	5.84	16.09	11.88	2.95	111.4
015	u	3	18.960	18.17	-5.64	09 51 00.27	+40 13 56.0	17.59	30.23	5.37	3.75	127.6

Note.— A portions of Tables 1 and 2 are shown here for guidance regarding their forms and contents. Complete tables are available in electronic form at <http://www.edpsciences.org>

the FIRST) 7C object within 17' of the position of the IPS radio source. We suppose that the anomalously high noise level or confusion with a nearby bright source may cause these false detections.

The precision of coordinates of radio sources in the 7C catalogue is much better than in the PS catalogue but it is not yet always sufficient for a secure optical identification. Therefore, we have cross-identified 7C sources with objects from the FIRST catalogue to obtain more precise coordinates.

3. Identification with the FIRST radio sources

Observations of radio sources from the FIRST catalogue were carried out at 1400 MHz with a sensitivity of 1 mJy and a beam

size of 5''4 (White et al. 1996). The uncertainty of the coordinates in the FIRST catalogue is sufficiently low for reliable optical identification. Moreover, from this catalogue we used the data on sizes and morphology of radio sources to choose more preferable objects when there were several candidates in the 7C catalogue. The results of the identification are presented in Table 2. The table is organized as follows: Col. 1 lists the IPS radio source name as in Table 1 (Col. 4); Col. 2 gives the rank of the 7C counterpart as in Table 1 (Col. 5); Col. 3 lists the number of the FIRST radio source component; Cols. 4–6 list the angular distance (arcsec) of the FIRST radio source from the 7C radio source (radial – dr , and along RA and Dec directions – dx and dy); Cols. 7–8 list the coordinates (B1950) from the FIRST catalogue; Cols. 9–13 give the selected radio parameters

Fig. 2. Distribution of the deconvolved major axis size for single FIRST counterparts (solid line) and most compact component for double FIRST counterparts (dashed line).

from the FIRST catalogue, including the peak (mJy/beam) and integrated flux densities (mJy), deconvolved major and minor axes FWHM (arcsec), and position angle (degrees).

Out of 236 IPS radio sources that have a single 7C counterpart, 125 (53%) have also a single compact FIRST counterpart (as compact we assume here a single radio source or a component of a radio source that has the major axis size $<3''$ in the FIRST catalogue), 24 (11%) are identified with double or triple (in one case) radio sources with compact components, and 87 (37%) objects show at least one well-resolved ($>3''$) component in the FIRST survey.

For comparison we identified 100 randomly chosen 7C radio sources with radio sources from the FIRST catalogue. It turned out that among them 27% are single compact sources, 4% – double sources with compact components, 60% – extended (at least one component with angular size $>3''$), and 9% – unidentified (none of the FIRST objects were found within $4'$ radius). We see that among IPS radio sources single compact objects were found two times more often, and extended ones 1.5 times less often, than among field radio sources.

Using data on sizes of sources from the FIRST catalogue, we analyzed the distribution of IPS radio sources by their sizes as measured at 1400 MHz. In Fig. 2 we show the major axis size distribution for single FIRST counterparts. Most of these objects have a size smaller than $3''$, thus, IPS radio sources are highly compact objects in the overall size too. The distribution of the major axis size of the most compact component for double sources is also shown in Fig. 2. On average, components of double sources are larger than single compact sources. Overall statistics of multiplicity for 7C and FIRST counterparts are given in Table 3.

4. Objects with complex morphology

Several counterparts of the IPS radio sources consist of a dominant compact component that provides more than 50%

of the total flux density at 1400 MHz and one or two much fainter components of compact or diffuse structure. These objects were classified by morphology as CL (core+lobe), CdL (core+diffuse lobe), CH (core+halo), CJL (core+jet+lobe) or CLL (core+lobe+lobe) objects and attributed to the class of single compact radio sources. A more detailed investigation, especially optical identification, should be done to reveal their true nature. It may turn out that some of them are really not core dominated but rather are extremely asymmetric double sources. In Table 2, besides the main compact component, we give for completeness data for faint components too. These objects are: CL (PS020b, PS110W, PS194u, PS236a and PS247b), CdL (PS173a and PS190a), CH (PS268c = the BL Lac object Mrk421), CJL (PS025d and PS281u), CLL (PS126a).

Three radio sources (PS085a, PS171b and PS253b) have a triple structure with a rather bright core component (20–45% of the total flux density) and one object (PS197a) is a double FR II radio source with a very weak core component (0.4% of the total flux density at 1400 MHz). Besides PS197a there are at least ten IPS radio sources that are identified with classical FR II radio sources. They consist of two dominant components, probably containing rather compact “hot spots” that provide scintillations, and a much more diffuse structure between them, which decomposed in the FIRST catalogue into 1–3 (sub)components. It is probable that the majority of the doubles identified with IPS radio sources are objects of similar morphology (but scaled in size and surface brightness).

In our sample there are only two large angular size ($>4'$) radio galaxies (PS064a = 3C236 and PS122a). For these objects in Table 2 we give data for the core component. The four most compact components in the lobes of PS122a are included too. The core of 3C236 is the brightest (4 Jy) IPS radio source in our region. As suggested by O’Dea et al. (2001), it may represent a restored (young) compact radio source in the core of a giant (old) radio source.

5. Conclusions

For the majority of 289 IPS radio sources from the Pushchino Survey in the 360 sq deg region we have performed detailed cross-identification with the 7C and FIRST catalogues and found counterparts with coordinates suitable for follow-up optical identifications. Using the coordinates of the FIRST radio sources we have begun a search for optical counterparts in the Palomar Observatory Sky Survey (POSS1). Our preliminary estimates show that $\sim 20\%$ of IPS radio sources are identified with POSS1 objects. Many of them are bright objects both in the radio and in the optical band. More than 50% of them are quasars according to data published in the literature. We are conducting optical observations in SAO RAS on the 6m (spectroscopy) and 1m (photometry) telescopes. Results of the observations will be presented in Paper II.

Scintillating radio sources of the Pushchino Survey not only contain compact ($\sim 0''.1$) components at 102 MHz but are also more compact in overall size at 1400 MHz in comparison with randomly chosen field radio sources. Since most of them are single and compact in the FIRST catalogue, they are good candidates for steep spectrum quasars.

Table 3. Distribution of 7C counterparts of IPS radio sources by multiplicity in the FIRST catalogue.

Number of counterparts in the 7C	Number of 7C counterparts with			Sum of 7C objects
	1 component in the FIRST	2 components in the FIRST	≥ 3 components in the FIRST	
1	159	60	17	236
2	14	10	–	24
Sum of 7C objects	173	70	17	260

The lack of optical counterparts for most scintillating sources in the POSS1 may mean that they are rather distant ($z > 0.5$). It should be noted that many of the double FIRST counterparts are very compact (have a small angular distance between components) too. It is possible that they are young radio galaxies, so that extended radio lobes have not formed yet.

The complete sample of faint IPS radio sources from the Pushchino Survey offers a new possibility to conduct systematic investigation of compact radio sources with flux densities < 1 Jy at meter radio wavelengths. In order to evaluate which of the scintillating sources are quasars and which are radio galaxies, it is necessary to perform optical identifications for them. Measurements of redshifts for scintillating sources will allow us to make a firm conclusion as to whether these objects are really at large distances, and to what extent samples of scintillating radio sources are suitable for cosmological investigations.

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