

The follow-up European VLBI Network observations of twelve GPS radio sources at 5 GHz

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ABSTRACT

Aims. Gigahertz peaked spectrum (GPS) radio sources are compact extragalactic radio sources, assumed to be young radio-loud active galactic nuclei and ideal objects for studying the early evolution of extragalactic radio sources. The Very Long Baseline Interferometry (VLBI) observation with high resolution is vital for studying the structure of these compact sources.

Methods. We defined a sub-sample of twelve GPS sources which have not been observed with the VLBI before, from the Parkes half-Jansky sample, and carried out VLBI observations at 1.6 GHz and 5 GHz with the European VLBI Network (EVN) in 2006 and 2008, respectively, to classify the source structure and to find compact symmetric objects (CSOs). Additionally, we carried out the 4.85 GHz flux density observations for these sources with the Urumqi 25-m telescope between the years 2007 and 2009 to study whether there is any variability in the total flux density of the GPS sources.

Results. The results of the 5 GHz VLBI observations and total flux densities of these sources are presented in this paper. From the VLBI morphologies, the spectral indices of components and the total flux variability of the twelve targets, we firmly classify three sources J0210+0419, J1135–0021, and J2058+0540 as CSOs, and classify J1057+0012, J1203+0414, and J1600–0037 as core-jet sources. The others J0323+0534, J0433–0229, J0913+1454, J1109+1043, and J1352+0232 are labelled CSO candidates, and J1352+1107 is a complex feature. Apart from core-jet sources, the total flux densities of the CSOs and candidates are quite stable at 5 GHz both during a long-term of ~20 years relative to the PKS90 data and in a period between 2007 and 2009. The total flux densities are resolved-out by more than 20% in the 5 GHz VLBI images for 6 sources, probably because of diffuse emission. In addition, we estimated the jet viewing angles (Θ) for the confirmed CSOs by using the double-lobe flux ratio of the sources, the result being indicative of relatively large Θ for the CSOs.

Key words. galaxies: nuclei – quasars: general – radio continuum: galaxies – galaxies: active – galaxies: jets

1. Introduction

Gigahertz peaked spectrum (GPS) radio sources are powerful ($P_{1.4\text{ GHz}} \geq 10^{25} \text{ W Hz}^{-1}$) and compact extragalactic radio sources characterized by a convex radio spectrum peaking at between 0.3 and a few GHz (see O’Dea 1998, for a review). Sources that peak at >5 GHz are called high frequency peakers (HFP, Dallacasa et al. 2000), which are understood to be even more compact and younger. The spectrum turnover of the GPS sources is caused by synchrotron self-absorption (de Vries et al. 2009), in general, and it is also possible that free-free absorption plays a role in producing the spectral turnover in some cases (e.g., Luo et al. 2007; Orienti & Dallacasa 2008).

Extended emission in GPS source is uncommon especially for GPS galaxies, most of which are truly compact ($<1 \text{ kpc } h^{-1}$) (Stanghellini et al. 2005). The compactness of GPS sources is most likely due to their youth ($<10^4$ years) according to a spectral ageing analysis (Murgia et al. 2003). The youth scenario is supported by the hotspot kinematics in a couple of GPS sources that are also identified as compact symmetric objects (CSOs) (Giroletti & Polatidis 2009). A unification model assumes that GPSs/CSOs will evolve into compact steep spectrum (CSS) sources or medium-sized symmetric objects (MSOs, $1\text{--}20 \text{ kpc } h^{-1}$), which in turn, evolve into large radio galaxies ($>20 \text{ kpc } h^{-1}$), i.e., FRI/II radio sources (Fanti et al. 1995, 2009; Snellen et al. 2000).

Furthermore, the GPS sources are associated with either galaxies or quasars. The GPS quasars usually exhibit some form of core-jet structure, while the GPS galaxies often show CSO-like or compact doubles (CD) (e.g., Orienti et al. 2006; Liu et al. 2007), suggesting that the GPS galaxies have relatively large jet-viewing angles. The GPS galaxies have very low polarization (less than 0.5% at 5 GHz, Xiang et al. 2006), which is probably because of the large Faraday depth in the line of sight, implying that their host AGN are largely edge-on to us.

Complete samples of GPS sources are statistically vital for studying the early evolution of radio-loud AGN and the triggering of their nuclear activity, such as the 1 Jy complete GPS sample in the northern sky (Stanghellini et al. 1998), the Parkes half-Jansky (PHJ) sample in the southern/equatorial sky (Snellen et al. 2002), and the CORALZ sample at low redshift (Snellen et al. 2004). The Very Long Baseline Interferometry (VLBI) technique is a key tool for studying the morphologies of GPS sources from the GPS samples. We defined a subsample of twelve GPS sources with declination $>-5^\circ$ that had not been observed with the VLBI before, from the PHJ sample, and carried out the VLBI observations at 1.6 GHz and 5 GHz of them in 2006 and 2008, respectively. It is found that most of the sources exhibit compact double structure by analysing the 1.6 GHz European VLBI Network (EVN) observation (Liu et al. 2007, hereafter Paper I). In the follow-up 5 GHz EVN observation, we demonstrate that we can resolve their VLBI structure more

Table 1. The GPS sample.

1	2	3	4	5	6	7	8	9	10	11	12	13
IAU name	Other	Id	z	Scale (pc/mas)	$\theta_{5\text{ GHz}}$ (mas)	LS (pc)	$S_{4.85\text{ GHz}}$ (mJy)	Resolved (%)	Comp.	$S_{\text{int}}^{1.65}$ (mJy)	S_{int}^5 (mJy)	$\alpha_{1.65}^5$
J0210+0419	B0208+040	G	1.5*	$6.11 h^{-1}$	84	$513 h^{-1}$	282 ± 2	~14	A	375	144	0.86
									B	205	99	0.66
J0323+0534	4C+05.14	G	0.1785	$2.13 h^{-1}$	48	$102 h^{-1}$	796 ± 21	~83	A	1270	102	2.27
									B	548	–	–
J0433–0229	4C–02.17	G	0.53	$4.47 h^{-1}$	72	$322 h^{-1}$	612 ± 5	~27	A	1045	396	0.88
									B	111	16	1.75
J0913+1454	B0910+151	G	0.47*	$4.19 h^{-1}$	76	$318 h^{-1}$	275 ± 18	~8	A	501	208	0.79
									B	157	45	1.13
J1057+0012	B1054+004	G	0.65*	$4.97 h^{-1}$	13	$65 h^{-1}$	355 ± 21	~11	A	550	299	0.55
									B	58	–	–
J1109+1043	B1107+109	G	0.55*	$4.62 h^{-1}$	63	$290 h^{-1}$	420 ± 7	~8	A	984	281	1.13
									B	311	91	1.11
J1135–0021	4C–00.45	G	0.975	$5.75 h^{-1}$	110	$633 h^{-1}$	422 ± 13	~15	A	454	196	0.76
									B	271	123	0.71
J1203+0414	B1200+045	QSO	1.221	$5.96 h^{-1}$	72	$429 h^{-1}$	590 ± 21	~22	A	850	423	0.63
									B	81	24	1.10
									C	35	14	0.83
J1352+0232	B1349+027	G	0.607	$4.83 h^{-1}$	188	$908 h^{-1}$	458 ± 10	~56	A	480	189	0.84
									B	120	13	2.00
J1352+1107	4C+11.46	G	0.891	$5.61 h^{-1}$	21	$118 h^{-1}$	403 ± 6	~75	all	598	102	1.59
J1600–0037	B1557–004	G			65		190 ± 5	~11	A	607	85	1.77
									B	255	75	1.10
									C	–	4	–
J2058+0540	4C+05.78	G	1.381	$6.04 h^{-1}$	153	$923 h^{-1}$	351 ± 18	~37	A	513	134	1.21
									B	403	86	1.39

sharply and obtain the spectral indices of components between 1.6 GHz and 5 GHz, and finally identify CSOs from the candidates.

Quite a few GPS sources having been found to have flux variability (Torniainen et al. 2007). Since 2007, we have performed flux monitoring at 4.85 GHz with the Urumqi 25-m radio telescope for GPS sources from the master list for which declination $> -30^\circ$ (Labiano et al. 2007).

Throughout the paper, the cosmological parameters $H_0 = 70.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.721$ and $\Omega_m = 0.279$ (Komatsu et al. 2009) are adopted, and the spectral index α is defined by $S \propto \nu^{-\alpha}$.

2. The EVN observations and data reduction

The 5 GHz VLBI observations were carried out on 12 June 2008 for the first nine targets in Table 1 (proposal code EL036A) and on 25 October 2008 for the remaining three (EL036B), using the MK5 recording system with a bandwidth of 32 MHz and a sample rate of 256 Mbps in dual circular polarization. The EVN antennae involved were Effelsberg, Westerbork, Jodrell (Jb1), Medicina, Noto, Onsala, Torun, Hartebeesthoek, Urumqi, and Shanghai. Hartebeesthoek was not involved in EL036B because of an antenna problem. The snapshot observations of the target sources (see Table 1) were carried out in a total of about 24 h, DA193 and OQ208 were inset as calibrators. The data correlation was performed at the Joint Institute of VLBI in Europe (JIVE).

The Astronomical Image Processing System (AIPS) software has been used for editing, a priori calibration, fringe-fitting, self-calibration, imaging, and model-fitting of the data. The uncertainty in the flux density in the VLBI image is estimated to

be about 10%, and the total time per source and noise level in source image are listed in Table 2.

3. Results and comments on individual sources

We list basic information about 12 GPS sources and some parameters derived from the VLBI images in Table 1. Columns 1 through to 13 provide source names, optical identification (G: galaxy, QSO: quasar), redshift (de Vries et al. 2007; and the literature, those with * are a photometric estimated by Tinti et al. 2005), linear scale factor pc/mas where $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$, maximum angular size from the 5 GHz VLBI observation, maximum linear size, 4.85 GHz total flux density measured with Urumqi single dish in December 2008 (July 2007 value for J0210+0419), the resolved-out fraction in the 5 GHz VLBI image, the VLBI component, the integrated flux density of the component at 1.6 GHz (from Paper I), the integrated flux density of the component at 5 GHz (using the same restoring beam as that used in the 1.6 GHz image), and the spectral index of component calculated from Cols. (11) and (12). More image parameters are listed in Table 2.

In the following, we summarize the VLBI results and comment on the individual sources.

3.1. J0210+0419

The 5 GHz VLBI image (Fig. 1) of this source shows a double lobe structure, which is similar to the 1.6 GHz image in Paper I. The north-east lobe is more compact at 5 GHz, and the south-west one is resolved into “head-tail” components “B1” and “B2”. The spectral indices of component “A” and “B” between 1.6 GHz and 5 GHz are both steeper (0.86 and 0.66, respectively, see Table 1), indicating that they are lobes/hotspots.

Table 2. The component parameters of the VLBI images at 5 GHz.

1	2	3	4	5	6	7	8	9	10	11	12
Name & Class	T (min)	rms (mJy/b)	S_{vlbi} (mJy)	Comp.	S_p (mJy/b)	S_{int} (mJy)	$\theta_1 \times \theta_2$ (mas \times mas)	PA ($^\circ$)	D (mas)	PA ($^\circ$)	T_b ($\times 10^8$ K)
J0210+0419 CSO	50	0.8	243	A	94	141	3.2×2.0	1.4	0		11.8
				B1	28	65	4.2×3.8	176	71.4 ± 0.1	-152.7 ± 0.1	2.2
				B2	22	63	6.3×2.9	38	67.1 ± 0.1	-152.7 ± 0.1	1.8
J0323+0534 CSOc	149	0.2	135	A1	19	19	5.0×1.0	83	0		0.3
				A2	42	109	16.8×5.1	59	5.2 ± 0.1	42.9 ± 0.1	0.3
				A3	8	16	12.9×3.8	63	22.8 ± 0.1	57.4 ± 0.1	0.1
J0433-0229 CSOc/cj	162	0.8	449	A1	270	388	5.0×3.8	161	0		6.7
				A2	30	35	3.7×1.3	157	13.0 ± 0.1	166.4 ± 0.1	2.4
				B	9	15	7.9×3.2	156	52.6 ± 0.1	154.8 ± 0.1	0.2
J0913+1454 CSOc	108	0.2	253	A1	24	59	2.9×1.5	105	0		4.0
				A2	11	37	3.7×2.6	116	1.4 ± 0.1	-81.8 ± 0.4	1.0
				A3	3	5	3.5×1.6	169	5.5 ± 0.1	-77.0 ± 0.4	0.3
				A4	17	41	2.7×2.3	72	10.6 ± 0.1	-85.5 ± 0.1	2.0
				A5	16	41	3.0×2.0	94	11.5 ± 0.1	-86.9 ± 0.1	2.0
				A6	11	21	2.2×1.6	69	5.6 ± 0.1	91.6 ± 0.1	2.0
				A7	3	9	4.2×3.0	25	6.6 ± 0.1	91.7 ± 0.4	0.2
				A8	2	3	2.8×1.1	37	11.8 ± 0.1	88.8 ± 0.3	0.3
J1057+0012 cj	84	0.3	316	B	19	47	3.0×0.6	117	54.1 ± 0.1	71.7 ± 0.1	8.0
				A	183	289	3.1×1.4	36	0		23.0
J1109+1043 CSOc	90	0.2	386	A	173	278	4.4×1.7	58	0		12.0
				B	55	88	4.3×1.7	65	46.3 ± 0.1	103.3 ± 0.1	4.0
J1135-0021 CSO	60	0.7	358	A1	134	185	3.3×2.2	171	0		11.0
				A2	29	69	7.4×2.4	135	3.3 ± 0.5	165.0 ± 4.2	1.6
				A3	9	27	10.5×2.2	41	14.5 ± 1.9	165.5 ± 3.5	0.5
				B1	44	79	6.0×2.4	176	94.6 ± 0.3	163.3 ± 0.1	2.3
				B2	35	91	8.8×3.0	158	91.4 ± 0.5	162.7 ± 0.1	1.5
				B3	19	69	13.6×2.6	154	86.6 ± 1.2	163.6 ± 0.2	0.8
J1203+0414 cj	48	0.2	461	A1	260	396	2.5×1.1	118	0		68.4
				A2	25	56	4.5×1.3	126	4.3 ± 0.1	119.5 ± 0.1	2.0
				B	11	15	1.9×1.1	94	14.6 ± 0.1	101.4 ± 0.1	3.0
				C	8	12	2.8×0.4	111	63.3 ± 0.1	104.4 ± 0.1	5.0
J1352+0232 CSOc	45	0.2	202	A1	90	106	3.6×1.7	95	0		6.0
				A2	57	68	4.3×1.7	59	7.1 ± 0.1	-133.6 ± 0.1	3.0
				B	10	13	4.9×1.2	168	170.1 ± 0.1	-112.6 ± 0.1	0.8
J1352+1107 cx	54	0.5	102	A	29	77	9.2×3.7	138	0		1.0
				B	13	60	14.3×5.4	39	5.2 ± 0.1	56.4 ± 0.1	0.3
				C	15	46	12.4×2.8	20	4.8 ± 0.1	-39.7 ± 0.1	0.5
J1600-0037 cj	103	0.2	169	A	70	83	2.5×2.2	130	0		
				B1	29	57	10.0×1.0	69	31.8 ± 0.1	84.6 ± 0.1	
				B2	21	46	10.9×1.2	80	25.2 ± 0.1	87.5 ± 0.1	
J2058+0540 CSO	47	0.4	220	C	4	4	1.8×1.1	72	50.8 ± 0.1	77.8 ± 0.1	
				A1	104	124	4.5×1.0	9.3	0		14.0
				A2	8.2	13	7.7×2.1	177	15.5 ± 0.1	-175.0 ± 0.2	0.4
				B	42	68	8.3×2.4	172	132.6 ± 0.1	171.9 ± 0.1	2.0

Notes. The columns provide: (1) source name and classification (CSOc: CSO candidate, cj: core-jet, cx: complex); (2) total observing time per source in minutes; (3) noise level per beam in 5 GHz VLBI image; (4) total VLBI flux density; (5) component identification labelled to Paper I; (6), (7) peak and integral intensity of a fitted Gaussian component at 5 GHz with the AIPS task JMFIT; (8), (9) major/minor axes and position angle of the component at 5 GHz; (10), (11) distance and position angle relative to the first component; and (12) brightness temperature of the component.

The core of the source is not detected. The total flux density is slightly lower than for PKS90 data at 5 GHz in Table 3. According to the double lobes and tail morphologies at both 1.6 GHz and 5 GHz and the steep spectra of the lobes, we classify the source as a CSO.

3.2. J0323+0534

The 83% of the total flux density at 5 GHz (Table 1) is resolved-out in the 5 GHz VLBI image (Fig. 2), confirming that the source

is very diffuse as suggested in Paper I. The southern diffuse component ‘‘B’’ in the 1.6 GHz VLBI image (Paper I) is resolved-out completely in the 5 GHz VLBI image. The north region ‘‘A’’, which is very diffuse at 1.6 GHz, is resolved into three components ‘‘A1’’, ‘‘A2’’, and ‘‘A3’’, which appear to have a ‘‘core-jet’’ shape at 5 GHz; this leads to a very steep spectral index $\alpha_{1.65}^5$ of the component ‘‘A’’, but ‘‘A1’’, ‘‘A2’’, and ‘‘A3’’ are most likely types of hotspots rather than a core-jet. The total flux density is stable compared to PKS90 data at 5 GHz in Table 3, hence we keep this source as a CSO candidate.

Table 3. Flux density and possible variability of the 12 GPS sources.

Source	S_{PKS} (mJy)	S_{Jan07} (mJy)	S_{Jul07} (mJy)	S_{Dec08} (mJy)	S_{Jul09} (mJy)	S_{Nov09} (mJy)	\overline{S}_{Ur} (mJy)	$\sigma_{S_{\text{Ur}}}/\overline{S}_{\text{Ur}}$ (%)	$(\overline{S}_{\text{Ur}} - S_{\text{PKS}})/S_{\text{PKS}}$ (%)
J0210+0419	300	302 ± 10	282 ± 2		274 ± 4	298 ± 4	289	4.0	-3.7
J0323+0534	830	868 ± 9	833 ± 5	796 ± 21	814 ± 10	836 ± 4	829	2.9	-0.1
J0433-0229	640	637 ± 14	705 ± 25	612 ± 5			651	6.0	1.8
J0913+1454	300	297 ± 8	289 ± 3	275 ± 18		311 ± 6	293	4.5	-2.3
J1057+0012	370	351 ± 6	369 ± 4	355 ± 21	345 ± 4	373 ± 14	359	3.0	-3.1
J1109+1043	400	428 ± 8	416 ± 5	420 ± 7	434 ± 4	414 ± 7	422	1.8	5.6
J1135-0021	440	427 ± 8	392 ± 4	422 ± 13			414	3.7	-6.0
J1203+0414	520	611 ± 7	561 ± 3	590 ± 21	604 ± 4	632 ± 5	600	3.9	15.3
J1352+0232	470	469 ± 7	453 ± 4	458 ± 10	470 ± 4	465 ± 6	463	1.4	-1.5
J1352+1107	410	418 ± 5	406 ± 3	403 ± 6	411 ± 3	432 ± 3	414	2.5	1.0
J1600-0037	180	212 ± 3	177 ± 5	190 ± 5			193	7.5	7.2
J2058+0540	340		340 ± 3	351 ± 18	343 ± 4	345 ± 5	345	1.2	1.4

Notes. Column 2 is the PKS90 flux density at 5.0 GHz. Columns 3 to 7 indicate the 4.85 GHz flux density measured with the Urumqi telescope in January 2007, July 2007, December 2008, July 2009, and November 2009, respectively; Cols. 8–10 give the mean flux density of the Urumqi data, the standard deviation of the Urumqi data divided by the mean value, and the relative variation between the mean flux density and the PKS90 data.

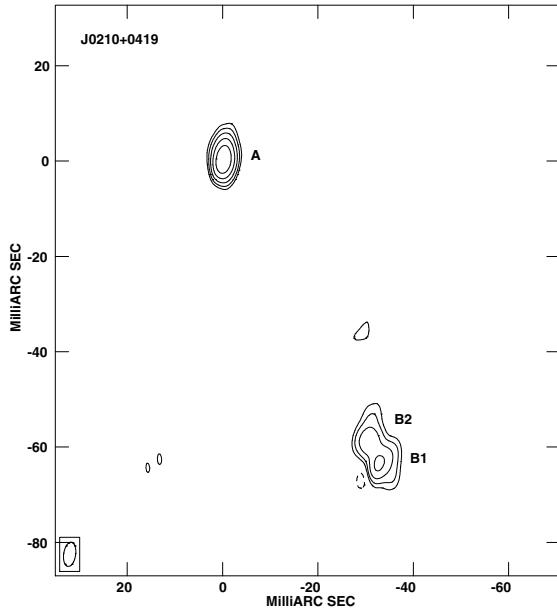


Fig. 1. J0210+0419: the restoring beam is 5.1×2.5 mas in PA -8.2° , the contours are 3 mJy/beam times $-1, 1, 2, 4, 8,$ and 16 , and the peak flux density is 95 mJy/beam.

3.3. J0433-0229

The major component “A” of 1.6 GHz image (Paper I) is resolved into “A1” and “A2” at 5 GHz (Fig. 3), and the weak component “B” is marginally detected. The overall shape of the source at 5 GHz is similar to that at 1.6 GHz, resembling a core-jet. Both of the components “A” and “B” however, have steep spectra (Table 1), and about 27% of the total flux density is resolved-out in the 5 GHz image. The total flux density is stable relative to PKS90 data at 5 GHz in Table 3. This source may be a core-jet one or a CSO candidate, although additional high sensitivity VLBI observation would be needed to clarify this.

3.4. J0913+1454

The 5 GHz VLBI image (Fig. 4) of this source can be resolved into several components “A1” to “A8” in the region “A”, and

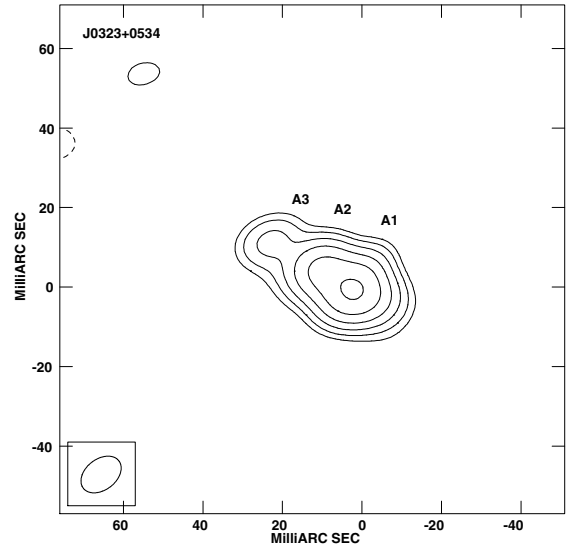


Fig. 2. J0323+0534: the restoring beam is 11.3×7.7 mas in PA -52.3° , the contours are 1.5 mJy/beam times $-1, 1, 2, 4, 8, 16,$ and 32 , and the peak flux density is 54 mJy/beam.

the component “B”, which is more compact at 5 GHz than at 1.6 GHz (Paper I). It is difficult to classify the source, the components “A1” to “A8” most likely representing a core and a set of jets. The core may be at either “A8” or “A5”: in the former case the source may be a CSO, in the latter the source may be a core-jet. The spectral index $\alpha_{1.65}^5$ of component “A” (integrated) and “B” is 0.79 and 1.13, respectively. The total flux density is stable compared to PKS90 data at 5 GHz in Table 3.

3.5. J1057+0012

The 5 GHz image (Fig. 5) contains a point-like source, the possible jet in the 1.6 GHz image (Paper I) being neither detected nor resolved-out. The spectral index $\alpha_{1.65}^5$ of main component is 0.55, which is flatter than that of a typical lobe component in other sources. The total flux density is slightly lower than that of the PKS90 data at 5 GHz in Table 3. We classify it as a core-jet source on the basis of both the 1.6 GHz and 5 GHz images.

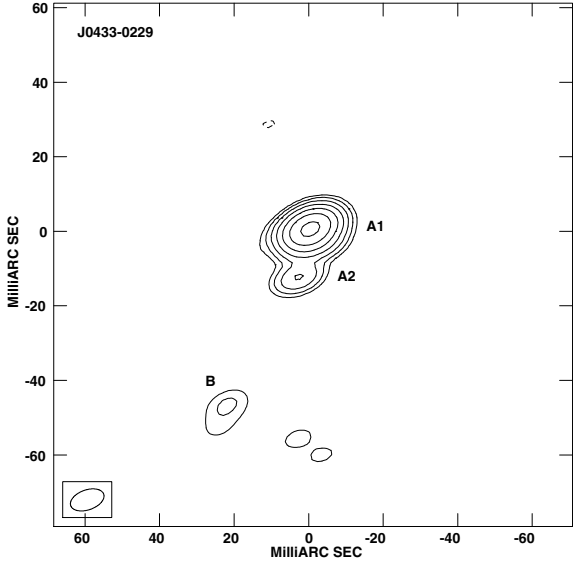


Fig. 3. J0433–0229: the restoring beam is 9.4×5.3 mas in PA -70.5° , the contours are 3.5 mJy/beam times $-2, 1, 2, 4, 8, 16, 32,$ and 64 , and the peak flux density is 270 mJy/beam.

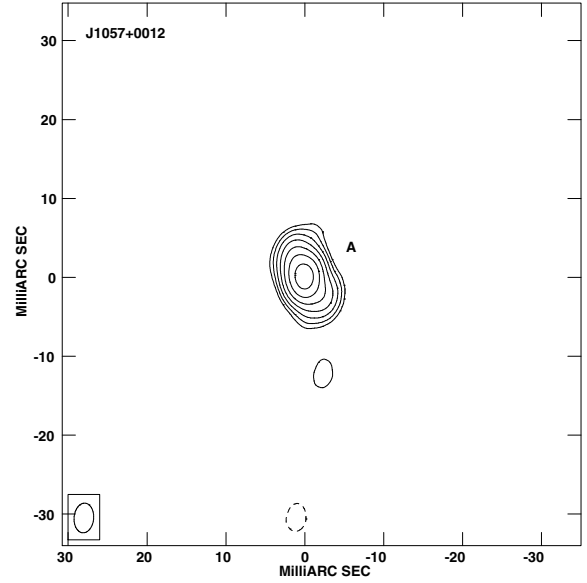


Fig. 5. J1057+0012: the restoring beam is 3.8×2.5 mas in PA -4.7° , the contours are 2 mJy/beam times $-1, 1, 2, 4, 8, 16, 32,$ and 64 , and the peak flux density is 192 mJy/beam.

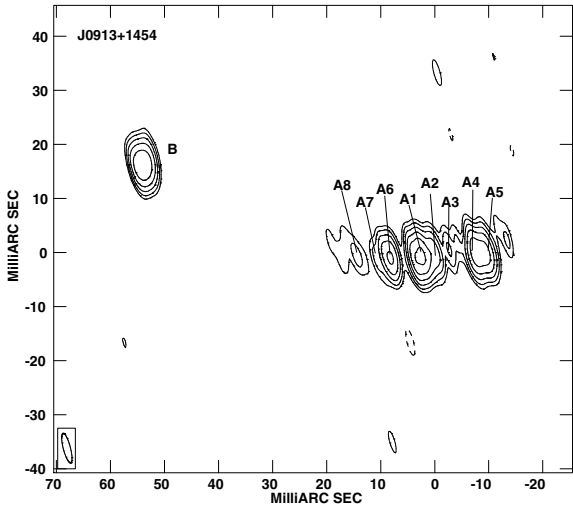


Fig. 4. J0913+1454: the restoring beam is 5.7×1.3 mas in PA 14.5° , the contours are 0.6 mJy/beam times $-2, 1, 2, 4, 8, 16,$ and 32 , and the peak flux density is 24 mJy/beam.

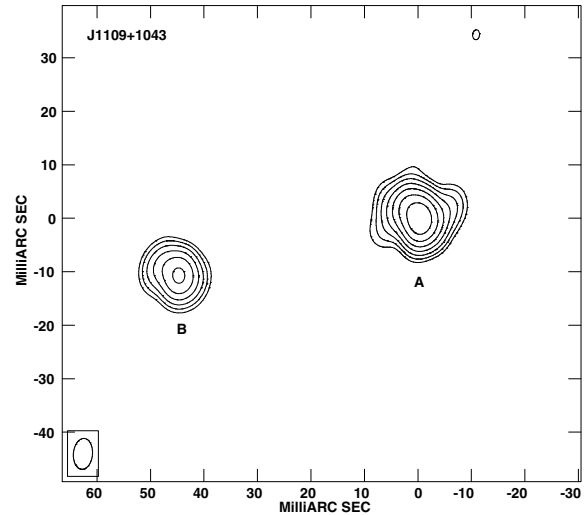


Fig. 6. J1109+1043: the restoring beam is 5.8×3.6 mas in PA -5° , the contours are 1.5 mJy/beam times $-1, 1, 2, 4, 8, 16, 32,$ and 64 , and the peak flux density is 178 mJy/beam.

3.6. J1109+1043

The 5 GHz VLBI image (Fig. 6) of this source exhibits a double structure, which is similar to the 1.6 GHz image (Paper I). Both components have equally steep spectra between 1.6 GHz and 5 GHz, of index 1.13 for component “A” and 1.11 for component “B”, whose values indicate that they are lobes/hotspots. The total flux density is slightly higher than that of the PKS90 data at 5 GHz in Table 3. The source is most likely a CSO or a compact double (CD) since no tail/jet emission has been detected.

3.7. J1135–0021

The 5 GHz VLBI image (Fig. 7) shows a double-lobe structure, which is similar to that in 1.6 GHz image (Paper I). The lobes/tails can be fitted by several subcomponents (“A1”, “A2”, “A3” for “A”, and “B1”, “B2”, “B3” for “B”). The spectral indices of “A” and “B” between 1.6 GHz and 5 GHz are equally

steep, and the linear size is smaller than $1 \text{ kpc } h^{-1}$ (Table 1). The total flux density is slightly lower than for the PKS90 data at 5 GHz in Table 3. We confirm that the source is a CSO.

3.8. J1203+0414

This is a GPS quasar, and the 5 GHz VLBI image (Fig. 8) exhibits a core-jet like structure. The component “A1” probably presents the core of the source, since the spectral index 0.63 of “A” corresponds to a flatter spectrum than those of other components “B” and “C”. The total flux density is higher by 15.3% than the PKS90 data at 5 GHz in Table 3, and it is resolved-out by about 22% in the 5 GHz VLBI image, some weak jets possibly being resolved. We classify the quasar as a core-jet source.

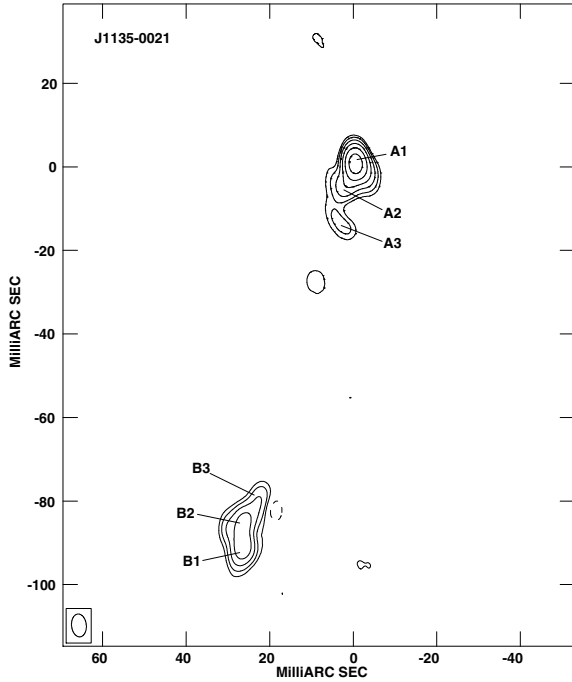


Fig. 7. J1135–0021: the restoring beam is 5.5×3.5 mas in PA 5.7° , the contours are 2.8 mJy/beam times $-1, 1, 2, 4, 8, 16,$ and 32 , and the peak flux density is 137 mJy/beam.

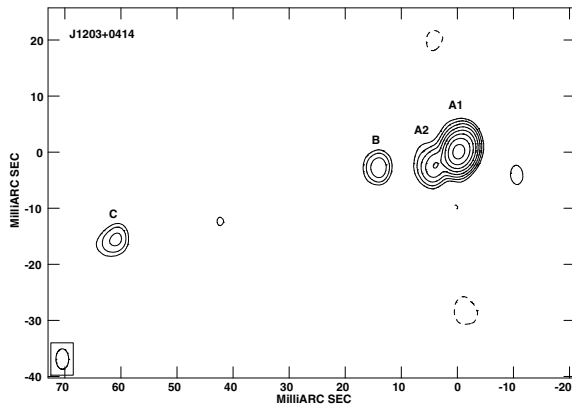


Fig. 8. J1203+0414: the restoring beam is 3.7×2.3 mas in PA 0.9° , the contours are 1.5 mJy/beam times $-1, 1, 2, 4, 8, 16, 32, 64,$ and 128 , and the peak flux density is 262 mJy/beam.

3.9. J1352+0232

As in the 1.6 GHz VLBI image in Paper I, the 5 GHz VLBI image (Fig. 9) exhibits a strong component “A” and a weak component “B”. The bright component “A” can be fitted with two close components “A1” and “A2”. The components “A” and “B” have the integrated spectral indices $\alpha_{1.65}^5$ of 0.84 and 2.0, respectively. The total flux density of the source is resolved-out by about 56% in the 5 GHz VLBI image. The total flux density is stable compared with PKS90 data at 5 GHz in Table 3. The source could be a CSO if it were really a double-lobe source, or a core-jet source if the core resided in the component “A1”.

3.10. J1352+1107

The 5 GHz VLBI image of the source detected a complex feature (Fig. 10), which is fitted with three components “A”, “B”, and “C”. About 75% of the total flux density (Table 1) is resolved-out

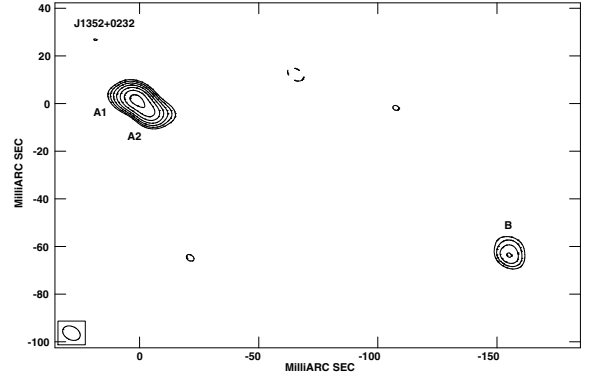


Fig. 9. J1352+0232: the restoring beam is 7.8×5.5 mas in PA 62.3° , the contours are 1.2 mJy/beam times $-1, 1, 2, 4, 8, 16, 32,$ and 64 , and the peak flux density is 102 mJy/beam.

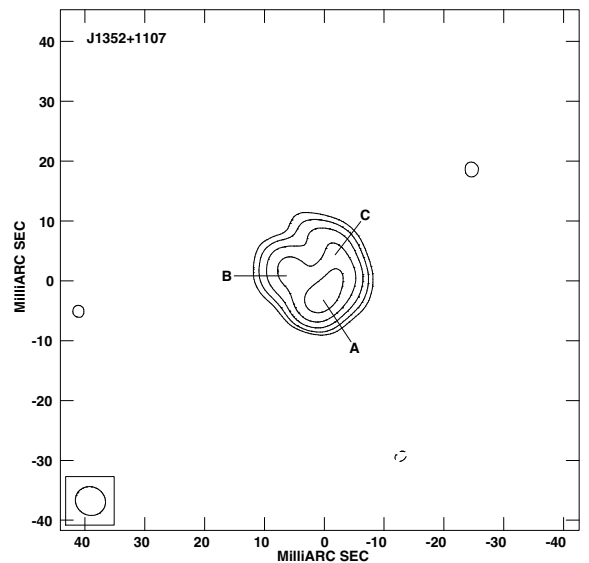


Fig. 10. J1352+1107: the restoring beam is 5.1×4.7 mas in PA 61.1° , the contours are 1.2 mJy/beam times $-1, 1, 2, 4, 8,$ and 16 , and the peak flux density is 29 mJy/beam.

in the 5 GHz VLBI image, confirming that the source is very diffuse as suggested in paper I. The whole source exhibits a steep spectrum of 1.59 between 1.6 GHz and 5 GHz. The total flux density is stable compared to PKS90 data at 5 GHz in Table 3. With the current data in hand, it is difficult to classify this source; both a core and curving jets are probably embedded in the diffuse emission.

3.11. J1600–0037

The 5 GHz VLBI image (Fig. 11) has a core-jet like feature, which consists of a bright component “A”, components “B1”/“B2”, and a weak component “C”. The spectral index of the component “A” between 1.6 GHz and 5 GHz is 1.77. It is difficult to identify the core because the “B” is not clearly resolved in the 1.6 GHz VLBI image (Paper I), the component “B1” in the 5 GHz VLBI image probably being a candidate core. The weak component “C” emerging in the 5 GHz image, which is not detected in 1.6 GHz image (probably because of low-frequency absorption), is possibly a counter-jet. The total flux density has a variability of 7.5% in 2007–2009 and a variation of 7.2% relative to PKS90 data at 5 GHz in Table 3. We therefore classify the

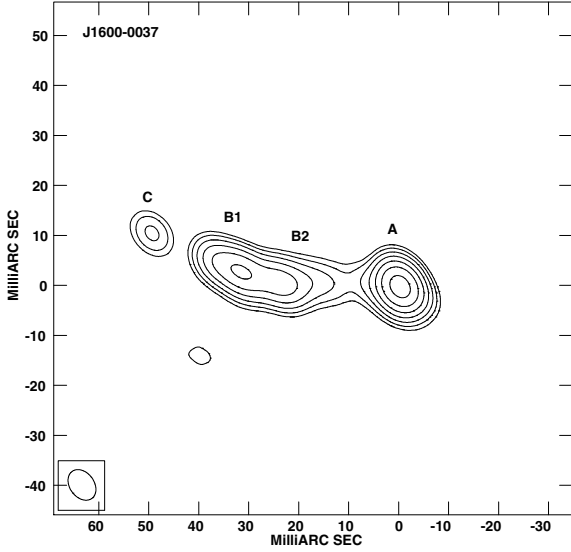


Fig. 11. J1600–0037: the restoring beam is 6.7×4.9 mas in PA 36.3° , the contours are 0.8 mJy/beam times $-1, 1, 2, 4, 8, 16, 32,$ and 64 , and the peak flux density is 71 mJy/beam.

source as a core-jet source on the basis of its VLBI morphology and flux variability.

3.12. J2058+0540

The 5 GHz VLBI image (Fig. 12) shows a double-lobe source, which is similar to the 1.6 GHz image in Paper I. The northern lobe is resolved into “head-tail” components “A1” and “A2” in the 5 GHz image. The spectral indices of components “A” and “B” between 1.6 GHz and 5 GHz are 1.21 and 1.39, respectively. The total flux density is stable relative to the PKS90 data at 5 GHz in Table 3. We classify the source as a CSO. We found that 37% of the total flux density is resolved-out in the 5 GHz image, indicating that in the source some form of jet and/or diffuse emission is missing in the VLBI image.

4. Flux density observations of the sources at 4.85 GHz

At high radio frequencies in particular, it has been reported that, many GPS/HFP sources exhibit significant flux variability (Tornaiainen et al. 2007; Orienti et al. 2007). Jauncey et al. (2003) found that $\sim 10\%$ of GPS sources experienced flux density variability over a period of 30 months. We measured the flux densities of the GPS sources in the Labiano et al. (2007) sample at 4.85 GHz, by observing with the Urumqi 25-m telescope between 2007 and 2009. Compared to 87GB data, Liu et al. (2009) found that 44% GPS quasars exhibit $>10\%$ flux variation over a period of about 20 years, while this fraction is only 11% for GPS galaxies. Detailed analysis of our monitoring data will be presented in another paper, and here we just list the measured flux densities of our VLBI targets in Table 3 for epochs during which most of the VLBI targets are observed.

The flux densities were determined using antenna slews with “cross-scans” in azimuth and elevation, fourfold in each coordinate. This enabled us to check the pointing offsets in both coordinates. After applying a correction for small pointing offsets, the amplitudes of both AZ and EL were averaged. We then corrected the measurements for the elevation-dependent antenna gain and the remaining systematic time-dependent effects, using a

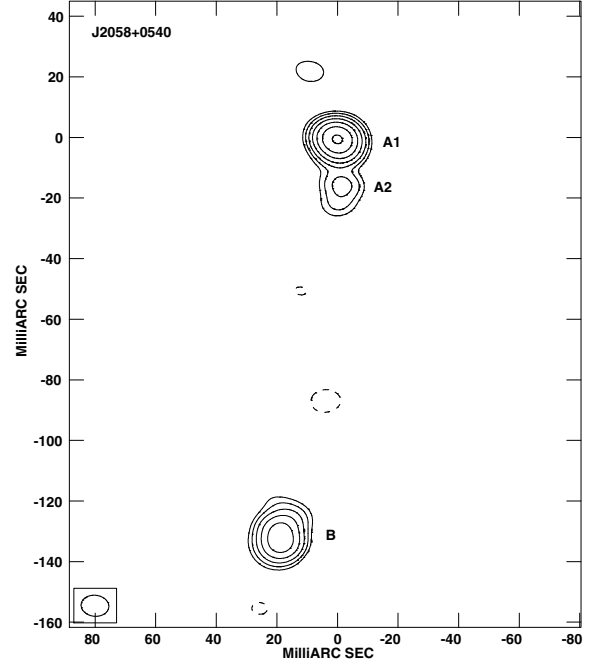


Fig. 12. J2058+0540: the restoring beam is 9.2×6.9 mas in PA 84.2° , the contours are 1.5 mJy/beam times $-1, 1, 2, 4, 8, 16, 32,$ and 64 , and the peak flux density is 105 mJy/beam.

Table 4. The jet viewing angles estimated for the CSOs.

Source	Type	$\Theta_{1.6\text{G}}^{k=2}$	$\Theta_{1.6\text{G}}^{k=3}$	$\Theta_{5\text{G}}^{k=2}$	$\Theta_{5\text{G}}^{k=3}$
J0210+0419	CSO	–	37	48	60
J1135–0021	CSO	22	47	33	52
J2058+0540	CSO	66	72	41	56

number of steep spectrum and non-variable secondary calibrators. Finally, we related our observations to the absolute flux density by using the scale 7.5 Jy at 5 GHz of the primary calibrator 3C 286 (Ott et al. 1994).

Given the flux variation measured in 2007–2009, and by comparing with PKS90 5 GHz data in Table 3, we find that the flux densities are quite stable or slightly different for the majority of the twelve GPS sources, but that two core-jet sources J1203+0414 (quasar) and J1600–0037 exhibit considerable variability in total flux density.

5. Discussion

It is interesting to estimate the jet-viewing angles for the confirmed CSOs, because the CSOs are assumed to lie nearly within the plane of sky. From the VLBI morphologies and the steep spectral indices of the VLBI components between 1.6 GHz and 5 GHz, we can firmly classify J0210+0419, J1135–0021, and J2058+0540 as CSOs that display symmetric double lobes/tails. We estimated the jet viewing angle from the flux ratio between the approaching and receding lobes with the formula (Taylor & Vermeulen 1997)

$$\frac{S_a}{S_r} = \left(\frac{1 + \beta \cos \Theta}{1 - \beta \cos \Theta} \right)^{k+\alpha},$$

where S_a/S_r is the flux ratio between the approaching (stronger) lobe and receding lobe, Θ is the viewing angle (degree) of the jet axis, α is the source spectral index α_h in optical-thin regime

(from Paper I), $k = 2$ or $k = 3$ for a continuous or discrete jet, respectively, and β is the lobe velocity as a fraction of the speed of light. By adopting $\beta = 0.1$, which is a mean lobe velocity in CSOs (Giroletti & Polatidis 2009), we estimated the jet viewing angles for the continuous and discrete cases at 1.6 GHz and 5 GHz, respectively, in Table 4. From a rough estimation, we could say that the three CSOs have relatively large jet-viewing angles. Although this method should be used only for the confirmed double-lobe sources, and the lobes of the CSOs are not resolved too much in the VLBI images.

Nevertheless the majority of sources in our sample have double-lobe like morphologies and total flux densities that are quite stable over 20 years. Only 3 CSOs are firmly classified according to Fanti's suggestion that a CSO should have a core in-between double lobes or have double lobes with twin jets/tails if a core is not detected (Fanti 2009).

Furthermore, 6 sources are resolved-out in the 5 GHz VLBI images by more than 20% of total flux density, probably due to diffuse emission in the sources. This may lead to quite steep spectral indices of VLBI components of the sources as listed in Table 1. The spectra of all 6 sources peak at 0.4 GHz (Snellen et al. 2002), which is close to the spectral peaks of CSS sources (see e.g., Fanti et al. 1995), so some of the sources are probably not GPS but rather CSS sources if they have larger-scale diffuse emission that is resolved-out by the VLBI observations.

6. Summary and conclusion

We have presented the results of 5 GHz EVN observations of 12 GPS sources from the sample of Snellen (2002) for the first time. The source structure and spectral indices between 1.6 GHz and 5 GHz are obtained. We have also carried out total flux density measurements with the Urumqi 25-m telescope at 4.85 GHz in 2007–2009, and compared the mean flux density with the PKS90 data.

1. From the source morphologies, the component spectral indices and the total flux variability, we can firmly classify three sources J0210+0419, J1135–0021, and J2058+0540 as CSOs, and J1057+0012, J1203+0414, and J1600–0037 as core-jet sources. The others J0323+0534, J0433–0229, J0913+1454, J1109+1043, and J1352+0232 remain as CSO candidates, and J1352+1107 is a complex VLBI feature whose nature need to clarify in the future.
2. The total flux densities of the GPS sources at 5 GHz were quite stable in 2007–2009 and over the long term compared with the PKS90 data, except for core-jet sources.

3. We estimated the jet viewing angles Θ for the CSOs by using the double-lobe flux ratio. The three CSOs were found to have systematically larger Θ .
4. We plan to observe the CSOs in the future with the VLBI at 5 GHz to measure the expansion speeds of lobes and estimate the ages of these young radio sources.

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