VLBI observations of nineteen GHz-Peaked-Spectrum radio sources at 1.6 GHz

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Abstract. Aims and Methods: We present the results of VLBI observations of nineteen GHz-Peaked-Spectrum (GPS) radio sources at 1.6 GHz. Of them, 15 sources are selected from the Parkes Half Jansky (PHJ) sample (Snellen 2002), 4 others are from our previous observation list. We aimed at imaging the structure of GPS sources, searching for Compact Symmetric Objects (CSOs) and studying the absorption for the convex radio spectra of GPS sources. Results: We obtained total intensity 1.6 GHz VLBI images of 17 sources for the first time. Of them, 80% show mini-double-lobe radio structure, indicating that they are CSOs or candidates, and their host AGNs could be edge-on to us. This result suggests that there is a high incidence of mini double-lobe sources (or CSOs) in the PHJ sample. The sources J0332+0534, J1135–0021, J1352+0232, J2058+0540, J2123–0112 and J2325–0344 with measured redshift, showing double-lobe structure with sizes of < 1 kpc, are classified as CSOs. Three sources J1057+0012, J1600–0037 and J1753+2750 are considered as core-jet sources according to their morphologies and flux variability.

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

1. Introduction

GHz-Peaked-Spectrum (GPS) radio sources are powerful (P₁₄ GHz ≥ 10²⁵ W Hz⁻¹), compact (≤ 1 kpc), and have convex radio spectra, and they make up a significant fraction (∼ 10%) of the bright radio source sample, see O’Dea (1998) for a review. In general, the presence of large scale emission associated with GPS galaxies is rare, about a few percent in a GPS sample (Stanghellini et al. 2005). Most GPS sources appear to be truly compact and isolated.

Their small size is most likely due to their youth (< 10⁴ years) according to a spectral aging analysis (Murgia 2003). A couple of GPS sources are certainly young radio sources whose kinematic age from lobe proper motions has been measured and these sources are also identified as Compact Symmetric Objects (CSOs). There is compelling evidence in favour of the youth scenario of GPS sources and CSOs, see e.g. Owsianik & Conway (1998), Tschager et al. (2000), Polatidis & Conway (2003), and Orienti et al. (2007). The GPS sources and CSOs are the key objects to study the early evolution of powerful radio-loud AGN. A unification scenario assumes that GPS sources evolve into Compact Steep Spectrum sources (1-15 kpc), which in turn, evolve into classical extended radio sources (> 15 kpc), i.e. FR I/II radio sources (Fanti et al. 1995, Snellen et al. 2000, de Vries et al. 2007).

GPS galaxies are dominated by lobe/jet emission on both sides of the central engine, and are thought to be relatively free of beaming effects. The GPS galaxies show very low polarization (about less than 0.5% at 5 GHz, Dallacasa 2004, Xiang et al. 2006). The low integrated polarization could be due to large Faraday depths around the radio source, which would depolarize the radio emission, implying that their host-AGNs are probably edge-on to us.

Since GPS sources live in the narrow line region of AGN, it is likely that their low frequency radio emission will be absorbed due to either synchrotron self-absorption or free-free absorption, giving rise to a peaked radio spectrum. Therefore, GPS sources are also suitable for studying radio absorption and scattering in AGNs.

We have carried out EVN (European VLBI Network) observations of 19 GPS sources, 15 of them are from the Parkes Half Jansky (PHJ) sample (Snellen et al. 2002) with declination > -5° and not observed with VLBI before. Four sources are from our previous observation list which we have observed with the EVN at 2.3/8.4 GHz and/or 5 GHz (see Xiang et al. 2005, 2006). We aimed at imaging the GPS sources at 1.6 GHz, in order to confirm whether the GPS sources are double-lobe sources, and to find CSO candidates. For the sources with observations at 2.3, 5.0 and 8.4 GHz, the 1.6 GHz images will further provide information on their source structure and inten-
sity at lower frequency, for further spectral study of the GPS sources in the future.

2. Observations and data reduction

The observations were carried out on 3 March 2006 at 1.65 GHz using the MK5 recording system with a bandwidth of 32 MHz and sample rate of 256 Mbps in dual circular polarization. The EVN antennae in this experiment were Effelsberg, Westerbork, Jodrell, Medicina, Noto, Onsala, Torun, Hartebeesthoek, Urumqi and Shanghai. Snapshot observations of 19 sources (Table 1) in a total of 24 hours were made. OQ208 and DA193 were observed as calibrators. The data correlation was completed at JIVE.

The total flux densities of the sources were also measured at 5 GHz with Urumqi 25 m telescope in order to find any flux variability. The values are listed in Table 2.

The Astronomical Image Processing System (AIPS) has been used for editing, a-priori calibration, fringe-fitting, self-calibration, imaging and model fitting of the data.

3. Results and comments on individual sources

We list the basic information of the sources in Table 1 and the parameters derived from the VLBI images in Table 2. We comment on the results of each source and give a short discussion. We use \( S \propto \nu^{-\alpha} \) to define the spectral index. Optical information and redshifts of the GPS sources in the PHJ sample are given by de Vries et al. (2007), as listed in Table 1.

3.1. J0210+0419 (PKS B0208+040)

The 1.6 GHz VLBI image (Fig. 1) is the first VLBI image of the source. It shows a double-lobe structure, and is most likely a CSO. Optical observations did not result in an identification with a lower limit of \( m_R > 24.1 \), but it is identified with a magnitude of \( K_s=18.3 \) (de Vries et al. 2007).

3.2. J0323+0534 (4C+05.14)

The 1.6 GHz VLBI image (Fig. 2) is the first VLBI image of the source, and it exhibits a strong diffuse component and a weak extended component in the south. Both are likely lobe emission. About 38% total flux density (estimated from Table 1) is resolved out in the VLBI image, due to the diffuse components. For its size of 490 pc, the source can be a CSO.

3.3. J0433−0229 (4C−02.17)

The 1.6 GHz VLBI image (Fig. 3) is the first VLBI image of the source, and the main component is diffuse and extended in the north-south direction, and a possible weak component in the south. About 18% total flux density (estimated from Table 1) is resolved out in the VLBI image. Either a core-jet or a CSO classification is possible for the source.

3.4. J0913+1454 (PKS B0910+151)

The 1.6 GHz VLBI image (Fig. 4) is the first VLBI image of the source. It shows double structure and both components are further resolved. There is probably a hot-spot imbedded in the bright one. We consider it as a CSO candidate.

3.5. J1057+0012 (PKS B1054+004)

The 1.6 GHz VLBI image (Fig. 5) is the first VLBI image of the source. There is a bright compact component followed by a secondary component and a series of possible weak components in the east, indicating this is a core-jet source. A flux variability of \((-11.4 \pm 3.6)\%\) over 15 years at 5 GHz, as reported in Table 2, is consistent with the core-jet classification.

3.6. J1109+1043 (PKS B1107+109)

The 1.6 GHz VLBI image (Fig. 6) is the first VLBI image of the source. It is a double structure, and can be a CSO candidate. The total flux density (1270 mJy estimated from Table 1) is completely restored in the VLBI image (1370 mJy, increased by 8%). There is also an indication of total flux increasing (4.9 \pm 12.4)\% at 5 GHz in Table 2 but with a large error.

3.7. J1135−0021 (4C−00.45)

The 1.6 GHz VLBI image (Fig. 7) is the first VLBI image of the source. It shows a double-lobe structure, and with a size of 720 pc, we classify the source as a CSO.

3.8. J1203+0414 (PKS B1200+045)

The 1.6 GHz VLBI image (Fig. 8) is the first VLBI image of the source. The triple structure may consist of a core and two sided emission, or a one sided core-jet source. The quasar as newly identified by de Vries et al (2007), is possibly a core-jet one, but still we keep the source as a CSO candidate.

3.9. J1352+0232 (PKS B1349+027)

The 1.6 GHz VLBI image (Fig. 9) is the first VLBI image of the source. It shows a double-lobe like structure, for its size of 918 pc we consider it as a CSO.

3.10. J1352+1107 (4C+11.46)

The 1.6 GHz VLBI image (Fig. 10) is the first VLBI image of the source. It appears to have a compact double structure or a core-jet alike, and seems diffuse emission around the source. About 30% total flux density (estimated from Table 1) is resolved out in the VLBI image. Either a core-jet or a compact double classification is possible.

3.11. J1600−0037 (PKS B1557−004)

The 1.6 GHz VLBI image (Fig. 11) is the first VLBI image of the source, and it has an overall double structure, the eastern...
component has some extension in the west-east direction. A flux variability of (13 ± 6.9)% at 5 GHz in Table 2 may suggest this is a core-jet source.

3.12. J1648+0242 (4C+02.43)

The GPS source is not detected with VLBI. It is an NVSS double-lobe source, and totally resolved out in the VLBI observation.

3.13. J2058+0540 (4C+05.78)

The 1.6 GHz VLBI image (Fig. 12) is the first VLBI image of the source. It shows a double-lobe source, and for the size of 970 pc, we suggest this is a CSO.

3.14. PKS B2121−014

The 1.6 GHz VLBI image (Fig. 13) shows a double-lobe structure, it is similar to that at 2.3 and 5 GHz (Xiang et al. 2005, 2006), except that a weak jet-like emission ‘B’, which appears at 2.3 and 5 GHz, is missing, probably due to absorption at the lower frequency 1.6 GHz. The source is a CSO for the source size of 488 pc.
Table 2. Source flux and possible variability, columns 2-4 are flux densities at 5.0 GHz (PKS90), 4.85 GHz (Gregory & Condon 1991, and Griffith et al. 1995) and 4.85 GHz flux measured with the Urumqi 25m telescope on 2007/1/24 (J1648+0242, J2058+0540, 1824+271 and 2121–014 were not well measured due to source confusion or weak); column 5 is a flux variability computed from columns 3,4.

| Source            | $S_{5.0}$ | $S_{4.85}$ | $S_{4.85/5}$ | $\delta S_{4.85}$ |
|-------------------|-----------|------------|-------------|------------------|
|                   | mJy       | mJy        | mJy         | %                |
| J0210+0419        | 300       | 298±19     | 302 ± 10    | 1.3 ± 3.1        |
| J0323+0534        | 830       | 819±44     | 868 ± 9     | 6.0±4.6          |
| J0433–0229        | 640       | 640±35     | 637 ± 14    | -0.5±3.3         |
| J0913+1454        | 300       | 315±43     | 297 ± 8     | -5.7±10.3        |
| J1057+0012        | 370       | 396±23     | 351 ± 6     | -11.4±3.6        |
| J1109+1043        | 400       | 408±56     | 428 ± 8     | 4.9±12.4         |
| J1135–0021        | 440       | 446±25     | 427 ± 8     | -4.3±3.6         |
| J1203+0414        | 520       | 640±35     | 611 ± 7     | -4.5±4.1         |
| J1352+0232        | 470       |            | 469 ± 7     |                 |
| J1352+1107        | 410       | 447±62     | 418 ± 5     | -6.5±11.9        |
| J1600–0037        | 180       | 187±14     | 212 ± 3     | 13.4±6.9         |
| J1648+0242        | 260       | 337±20     |            |                 |
| J2058+0540        | 340       | 356±21     |            |                 |
| 2121–014          | 320       | 345±21     |            |                 |
| 2322–040          | 500       | 524±29     | 545 ± 20    | 4.0±1.9          |
| 0914+114          | 140       | 134±19     | 140 ± 1     | 4.5±14.1         |
| 1751+278          | 298±39    | 292 ± 6    | -2.0±10.8   |                 |
| 1824+271          | 122±17    |            |            |                 |
| 2323+790          | 491 ± 7   |            |            |                 |
| OQ208             | 2421±217  | 2514 ± 12  | 3.8±8.8     |                 |

3.17. 1751+278 (MG2 J175301+2750)

The 1.6 GHz structure (Fig. 16) is similar to what we got before at 1.6 GHz (Xiang et al. 2002), and confirms that there is jet-like emission ‘C’ and ‘D’ associated with the southern component ‘B’, indicating this is a core-jet source.

3.18. B2 1824+271

The 1.6 GHz VLBI image (Fig. 17) exposes a symmetric double structure and jet-like emission associated with the two lobes, confirming this is a CSO as we have suggested (Xiang et al. 2006).

3.19. [WB92] 2323+790

The 1.6 GHz image (Fig. 18) shows a central component ‘A’ and a weak one ‘B+C’ in the north-west, and the components ‘A’ and ‘B+C’ show steep spectra between 1.6 GHz and 5 GHz (Xiang et al. 2006). The source can be a CSO candidate.

4. Discussion

In the sample (Table 1), J1648+0242 is an NVSS double source and is not detected in this VLBI observation; all others are point-like in the NVSS images, indicating that GPS sources are compact. Except four sources (J1057+0012, J1352+1107, J1600–0037 and 1751+278), 14 out of 18 sources exhibit double or triple VLBI structure and can be CSOs or CSO candidates though some of them have no measured redshift. The sources with redshift show double or triple structure with sizes < 1 kpc, suggesting these GPS sources are certainly compact and likely CSOs.

The mini double-lobe sources or CSOs could be more stable in flux density than other type of compact sources. We have measured the flux densities for the sources (Table 2) at 4.85 GHz and compared with the values observed 15 years ago, we found that 12 among 14 GPS sources are likely stable in flux (1σ level), two sources (J1057+0012 and J1600–0037) show about 10% variability in 3σ level respectively. The flux variability on J1057+0012 and J1600–0037 is consistent with their core-jet classification. ‘Core-jet’ sources are defined to show a one-sided jet, and the jet is often closely pointing to us (from a pole-on AGN). It is hard to estimate the real source size due to Doppler boosting, hence the ‘core-jet’ sources might not be young radio sources even if they appear to be compact in some cases.

In addition, some sources are resolved out in our VLBI image by more than 10% of total flux estimated from Table 1 probably due to diffuse emission associated with lobes and tail/jet emission. They are J0210+0419 (-14%), J0323+0534 (-38%), J0433–0229 (-18%), J1352+0232 (-15%), J1135+1107 (-31%), J2058+0540 (-12%), 2322–040 (-15%), and J1648+0242 is completely resolved out. The VLBI flux densities of the other nine sources at 1.6 GHz are consistent with the estimated total flux densities within an error of 15%.
Table 3. The component parameters of the VLBI images at 1.6 GHz. The columns give: (1) source name and possible classification (CSOc: CSO candidate, cj: core-jet); (2) total cleaned flux density of image at 1.6 GHz; (3) component identification labeled to Xiang et al. 2002, 2005, 2006; (4),(5) peak and integral intensity of a fitted Gaussian component at 1.6 GHz in the AIPS task JMFIT; (6),(7) major and minor axes and position angle of component at 1.6 GHz; (8),(9) distance and position angle relative to the first component; (10) brightness temperature of component.

| Name            | S_vlbi | Comp | S_p | S_int | θ1 × θ2 | PA  | d   | PA  | Tb   |
|-----------------|--------|------|-----|-------|----------|-----|-----|-----|------|
|                 | mJy    |      | mJy | mas×mas|          | deg | mas | deg | K°   |
| J0210+0419      | 715    | A    | 290 | 375   | 5.7 × 2.9 | 169 | 0   | 0   | 11.9 |
| CSOc            |        |      |     |       |          |     |     |     |      |
| J0323+0534      | 1497   | A    | 536 | 1270  | 32.6 × 11.1 | 70  | 0   | 0   | 0.5  |
| CSO             |        |      |     |       |          |     |     |     |      |
| J0433−0229      | 1095   | A    | 407 | 1045  | 14.5 × 4.7 | 171 | 0   | 0   | 2.4  |
| CSO/cj          |        |      |     |       |          |     |     |     |      |
| J0913+1454      | 796    | A    | 211 | 501   | 8.2 × 4.9  | 65  | 0   | 0   | 2.1  |
| CSO             |        |      |     |       |          |     |     |     |      |
| J1057+0012      | 810    | A    | 381 | 550   | 3.6 × 2.7  | 66  | 0   | 0   | 17.5 |
| cj              |        |      |     |       |          |     |     |     |      |
| J1109+1043      | 1370   | A    | 420 | 984   | 5.7 × 4.7  | 110 | 0   | 0   | 6.6  |
| CSO             |        |      |     |       |          |     |     |     |      |
| J1135−0021      | 1025   | A    | 279 | 454   | 6.6 × 2.7  | 142 | 0   | 0   | 4.9  |
| CSO             |        |      |     |       |          |     |     |     |      |
| J1203+0414      | 1029   | A    | 571 | 850   | 4.7 × 2.9  | 107 | 0   | 0   | 25.1 |
| CSO             |        |      |     |       |          |     |     |     |      |
| J1352+0232      | 885    | A    | 173 | 480   | 7.4 × 4.5  | 53  | 0   | 0   | 2.1  |
| CSO             |        |      |     |       |          |     |     |     |      |
| J1352+1107      | 896    | A    | 198 | 395   | 8.1 × 5.4  | 117 | 0   | 0   | 2.0  |
| CSO/cj          |        |      |     |       |          |     |     |     |      |
| J1600−0037      | 936    | A    | 394 | 607   | 5.4 × 4.1  | 157 | 0   | 0   | 1.1  |
| cj              |        |      |     |       |          |     |     |     |      |
| J2058+0540      | 914    | A    | 356 | 513   | 7.6 × 3.7  | 163 | 0   | 0   | 8.2  |
| CSO             |        |      |     |       |          |     |     |     |      |
| 2121−014        | 976    | A    | 363 | 594   | 5.1 × 3.9  | 123 | 0   | 0   | 10.4 |
| CSO             |        |      |     |       |          |     |     |     |      |
| 2322−040        | 965    | A    | 229 | 509   | 14.6 × 3.3 | 161 | 0   | 0   | 3.6  |
| CSO             |        |      |     |       |          |     |     |     |      |
| 0914+114        | 578    | A    | 37  | 50    | 4.9 × 2.7  | 16  | 0   | 0   | 0.4  |
| CSO             |        |      |     |       |          |     |     |     |      |
| 1751+278        | 596    | A    | 400 | 522   | 4.8 × 2.9  | 71  | 0   | 0   | 14.5 |
| cj              |        |      |     |       |          |     |     |     |      |
| 1824+271        | 296    | A    | 145 | 174   | 3.9 × 2.1  | 164 | 0   | 0   | -0.1 |
| CSO             |        |      |     |       |          |     |     |     |      |
| 2323+790        | 900    | A    | 439 | 621   | 5.8 × 2.1  | 159 | 0   | 0   | -0.1 |
| CSO/cj          |        |      |     |       |          |     |     |     |      |

10% the estimated amplitude uncertainty of the EVN observations.

5. Summary and conclusion

1. We obtained total intensity 1.6 GHz VLBI images of 17 GPS sources for the first time. The majority (80%) show mini-double-lobe radio structure, indicating that they are CSOs or candidates, and their host AGNs could be edge-on to us. This result suggests that there is a high incidence of mini double-lobe sources and CSOs in the GPS source sample.
2. The sources J0323+0534, J1135–0021, J1352+0232, J2058+0540, 2121–014 and 2322–040 with measured redshift, are double-lobed with sizes of < 1 kpc, and are classified as CSOs.

3. Three sources (J1057+0012, J1600–0037 and 1751+278) are classified as core-jet sources according to their morphologies and flux variability.

4. The 1.6 GHz images of the sources 0914+114, 1824+271, 2121–014 and 2322–040, for which we had observations at 2.3, 5.0 and 8.4 GHz, have provided information on their source structure and spectra at the lower frequency, permitting further spectral study in the future.

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Fig. 1. J0210+0419 at 1.65 GHz, the restoring beam is $10.2 \times 7.5$ mas with PA $-75.5^\circ$, the peak is 293 mJy/beam, the contours are 12 mJy/beam times levels -1, 1, 2, 4, 8, 16, 32, 64, 100, 200, 400, 800, and the same levels are used in the following images, the grey scale unit is mJy.

Fig. 2. J0323+0534 at 1.65 GHz, the restoring beam is $21.3 \times 17.7$ mas with PA $-20.2^\circ$, the peak is 586 mJy/beam, the first contour is 15 mJy/beam.

Fig. 3. J0433–0229 at 1.65 GHz, the restoring beam is $8.0 \times 6.3$ mas with PA $-1.7^\circ$, the peak is 435 mJy/beam, the first contour is 15 mJy/beam.

Fig. 4. J0913+1454 at 1.65 GHz, the restoring beam is $6.9 \times 4.6$ mas with PA $24.4^\circ$, the peak is 217 mJy/beam, the first contour is 6 mJy/beam.
Fig. 5. J1057+0012 at 1.65 GHz, the restoring beam is $7.3 \times 3.3$ mas with PA $13.4^\circ$, the peak is $390$ mJy/beam, the first contour is $6$ mJy/beam.

Fig. 6. J1109+1043 at 1.65 GHz, the restoring beam is $7.9 \times 3.3$ mas with PA $16.5^\circ$, the peak is $434$ mJy/beam, the first contour is $10$ mJy/beam.

Fig. 7. J1135−0021 at 1.65 GHz, the restoring beam is $7.8 \times 5.3$ mas with PA $20.4^\circ$, the peak is $281$ mJy/beam, the first contour is $8$ mJy/beam.

Fig. 8. J1203+0414 at 1.65 GHz, the restoring beam is $7.0 \times 4.9$ mas with PA $15.2^\circ$, the peak is $575$ mJy/beam, the first contour is $10$ mJy/beam.
**Fig. 9.** J1352+0232 at 1.65 GHz, the restoring beam is $6.7 \times 3.2$ mas with PA $9.9^\circ$, the peak is 183 mJy/beam, the first contour is 8 mJy/beam.

**Fig. 10.** J1352+1107 at 1.65 GHz, the restoring beam is $14.0 \times 12.5$ mas with PA $-75.3^\circ$, the peak is 379 mJy/beam, the first contour is 20 mJy/beam.

**Fig. 11.** J1600–0037 at 1.65 GHz, the restoring beam is $7.4 \times 5.5$ mas with PA $-39.8^\circ$, the peak is 400 mJy/beam, the first contour is 8 mJy/beam.

**Fig. 12.** J2058+0540 at 1.65 GHz, the restoring beam is $10.6 \times 6.5$ mas with PA $0.7^\circ$, the peak is 362 mJy/beam, the first contour is 10 mJy/beam.
**Fig. 13.** B2121−014 at 1.65 GHz, the restoring beam is $5.9 \times 5.5$ mas with PA $-1.4^\circ$, the peak is 370 mJy/beam, the first contour is 15 mJy/beam.

**Fig. 14.** 2322−040 at 1.65 GHz, the restoring beam is $8.6 \times 6.8$ mas with PA $-2.1^\circ$, the peak is 233 mJy/beam, the first contour is 10 mJy/beam.

**Fig. 15.** 0914+114 at 1.65 GHz, the restoring beam is $8.3 \times 4.7$ mas with PA $16.8^\circ$, the peak is 246 mJy/beam, the first contour is 1 mJy/beam.

**Fig. 16.** 1751+278 at 1.65 GHz, the restoring beam is $10.7 \times 6.0$ mas with PA $7.0^\circ$, the peak is 406 mJy/beam, the first contour is 3 mJy/beam.
Fig. 17. 1824+271 at 1.65 GHz, the restoring beam is 9.0 × 5.1 mas with PA 8.1°, the peak is 146 mJy/beam, the first contour is 1 mJy/beam.

Fig. 18. 2323+790 at 1.65 GHz, the restoring beam is 11.6 × 5.4 mas with PA −82°, the peak is 438 mJy/beam, the first contour is 10 mJy/beam.