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EVN + MERLIN OBSERVATIONS OF RADIO-INTERMEDIATE QUASARS: EVIDENCE FOR BOOSTED RADIO-WEAK QUASARS

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ABSTRACT

We present VLBI (EVN + MERLIN) observations of a sample of three low-redshift radio-intermediate PG quasars (RIQ) with flat and variable radio spectrum (III Zw 2, PG 1309+355, PG 2209+184). Their radio-to-optical flux ratio (*R*) is slightly lower than the average *R* for steep-spectrum quasars, but their radio spectral properties are those of core-dominated quasars. It was proposed previously that these sources might be relativistically boosted jets in radio-weak quasars. Our VLBI observations now indeed confirm the presence of a high brightness temperature core in all three of these objects—two of them have lower limits on T_B well in excess of 10^{10} K. Moreover, we find no "missing flux," which means that basically all the flux of these quasars is concentrated in the compact radio core. As the total radio flux is already at the low end for radio-loud quasars, we can place a strong limit on the presence of any extended emission. This limit is consistent with the extended emission in radio-weak quasars but excludes that the flat-spectrum RIQ reside in typical radio-loud quasars. The observations therefore strongly support the idea that relativistic jets are present in radio-weak quasars and, hence, that radio-loud and radio-weak quasars have very similar central engines.

Subject headings: galaxies: active — galaxies: jets — galaxies: nuclei — quasars: general — radio continuum: galaxies

1. INTRODUCTION

The radio properties of quasars with otherwise very similar optical properties can be markedly different. As Strittmatter et al. (1980) and Kellerman et al. (1989) showed, there is a dichotomy between radio-loud and radio-weak quasars that cannot be explained by a single orientation-based scheme. Radio-loudness is usually defined by the *R*-parameter—the radio-to-optical flux ratio, e.g., Kellermann et al. (1989) suggested that $R \sim 10$ separates radio-loud from radio-weak quasars. Investigations of the radio morphology of PG quasars (Miller, Rawlings, & Saunders 1993; Kellermann et al. 1995) show that there are, in fact, three main types of radio structures associated with quasars: flat-spectrum core-dominated sources, steep-spectrum lobe-dominated sources, and those with weak diffuse emission. In the optically selected PG quasar sample (see Schmidt & Green 1983), all of the steep-spectrum radio-loud quasars have a core-lobe structure, which in morphology and flux is similar to those of FR II radio galaxies, while radio-weak quasars have only weak and diffuse extended emission. For the radio-loud quasars this is expected within the basic unified scheme (e.g., Barthel 1989) where it is generally assumed that radio galaxies are just quasars seen edge-on such that the optical nucleus is hidden from our line of sight. Moreover, for the compact core-dominated sources Orr & Browne (1982) already suggested that they might simply be the face-on counterparts to radio-loud quasars where relativistic boosting in a radio jet enhances the core flux and swamps the steep-spectrum and largely orientation-independent lobe emission. One of the critical tests for the unification of core-dominated and lobe-dominated quasars was the investigation of their extended emission. And indeed, Browne & Perley (1986) and Murphy, Browne, & Perley (1993) found that the extended emission of core-dominated quasars and BL Lacertae objects is compatible with those of radio galaxies.

Thus, it seems as if the radio-loudness in quasars—be they core or lobe dominated—can be attributed to the existence of a powerful, relativistic jet, while radio-weak quasars seemingly have a different engine. However, recently Falcke, Sherwood, & Patnaik (1996, hereafter FSP96) investigated the radio spectral indices and average *R*-parameters of PG quasars and found that the fraction of compact flat-spectrum sources (~40%) in the PG sample with $R > 10$ is far larger than expected in the unified scheme for radio-loud quasars. Moreover, the median *R*-parameter of flat-spectrum radio-loud quasars was *lower* than those of steep-spectrum radio-loud quasars. As the extended steep-spectrum lobes should radiate largely isotropically, it appears impossible that the parent population of all radio-loud flat-spectrum sources are steep-spectrum radio-loud quasars. Instead FSP96 suggested that there is a population of flat-spectrum radio-intermediate quasars (RIQ, see also Miller et al. 1993, and Falcke, Malkan, & Biermann 1995, hereafter FMB95) that could be relativistically boosted *radio-weak* quasars. FSP96 showed that moderate Lorentz factors of 2–4 in radio-weak quasars are sufficient to boost the radio fluxes at 5 GHz of a substantial number of radio-weak quasars into the regime $R > 10$ usually occupied by (unboosted) steep-spectrum radio-loud quasars. Wilson & Willis (1980) had already suggested earlier that some core-dominated Seyferts could have relativistically boosted jet. The question whether there is relativistic boosting in radio-weak quasars can therefore be quite important for the proper classification of quasars and for the explanation of the radio-loud/radio-quiet dichotomy.

A crucial test for the "boosted radio-weak jet" hypothesis are high-resolution VLBI observations of the RIQ. If they are indeed boosted relativistic jets, one expects high brightness temperatures and possibly core-jet structures, and if they are to be preferentially oriented radio-weak quasars, they should—unlike radio-loud quasars—be naked cores on higher resolution images, i.e., having only very weak extended emission. On the other hand, if the RIQ fail this test and are not related to radio-weak quasars, one would have a strong argument that radio-weak quasars are *not* relativistic in their cores at all, because in the PG quasar sample are no sources left, besides the flat-spectrum RIQ, that are unaccounted for and could be the boosted counterparts to radio-weak quasars.

The criteria to select flat-spectrum RIQ are that their spectral index α should be larger than -0.5 ($S_\nu \propto \nu^\alpha$), and their R-parameter should be larger than 10 (the usual threshold for a radio-loud quasar) and smaller than 250 (the median R-parameter for steep-spectrum quasars). To reduce the effects of variability it is helpful to use a time-averaged radio-flux for each source as given for example in FSP96.

In this Letter we now report VLBI (EVN + MERLIN) observations of the three low-redshift ($z < 0.2$) flat-spectrum RIQ in the PG quasar sample that satisfy the above criteria. Those sources are PG 0007+106 (III Zw 2), PG 1309+355, and PG 2209+184.

2. OBSERVATIONS AND DATA REDUCTION

Simultaneous observations were made with six telescopes of the European-VLBI-Network (EVN) and MERLIN on 1995 May 26–27 at 5 GHz using a bandwidth of 28 MHz (Mk3 VLBI recording in mode B). Each source was observed for about 4 hours. 3C 286 was used as the primary flux density calibrator for MERLIN observations, and the EVN data were calibrated using system temperature measurements. Both of the data sets were analyzed separately using the NRAO AIPS software package and the Caltech DIFMAP package.

3. RESULTS

In Figure 1 we show the maps produced from our data. All maps are restored with a circular Gaussian of 5 milliarcsec (mas) FWHM and natural weighting. The size of the maps are 512 × 512 pixels with a pixel size of 1.5 mas × 1.5 mas. The flux densities are expected to have an accuracy of 5%–10% for III Zw 2 and PG 2209+184. The noise levels are 0.3 and 0.6 mJy beam^{-1} for III Zw 2 and PG 2209+184, respectively. If we compare our MERLIN fluxes—which are within the errors similar to the VLBI fluxes—with the VLA observations by Kellermann et al. (1989), we can confirm the strong variability in all sources—while the variability in III Zw 2 is well established (e.g., Teräsranta et al. 1992), PG 2209+184 has now a flux 2 times higher, and PG 1309+355 has a flux 3 times lower than in the earlier VLA measurement.

None of our sources was resolved, and we did not find any significant extended structure in the EVN or the MERLIN data. The sources are also unresolved in the VLA A and D array maps by Kellermann et al. (1995). In order to appear unresolved in our maps the sources have to be even smaller than our nominal beam size of 5 mas. The visibility function for the longest baseline and the shortest baseline for all sources are identical, which translates into an upper limit of $\sim$1 mas for the source sizes. At least for the two brighter sources, a somewhat less conservative estimate for our high

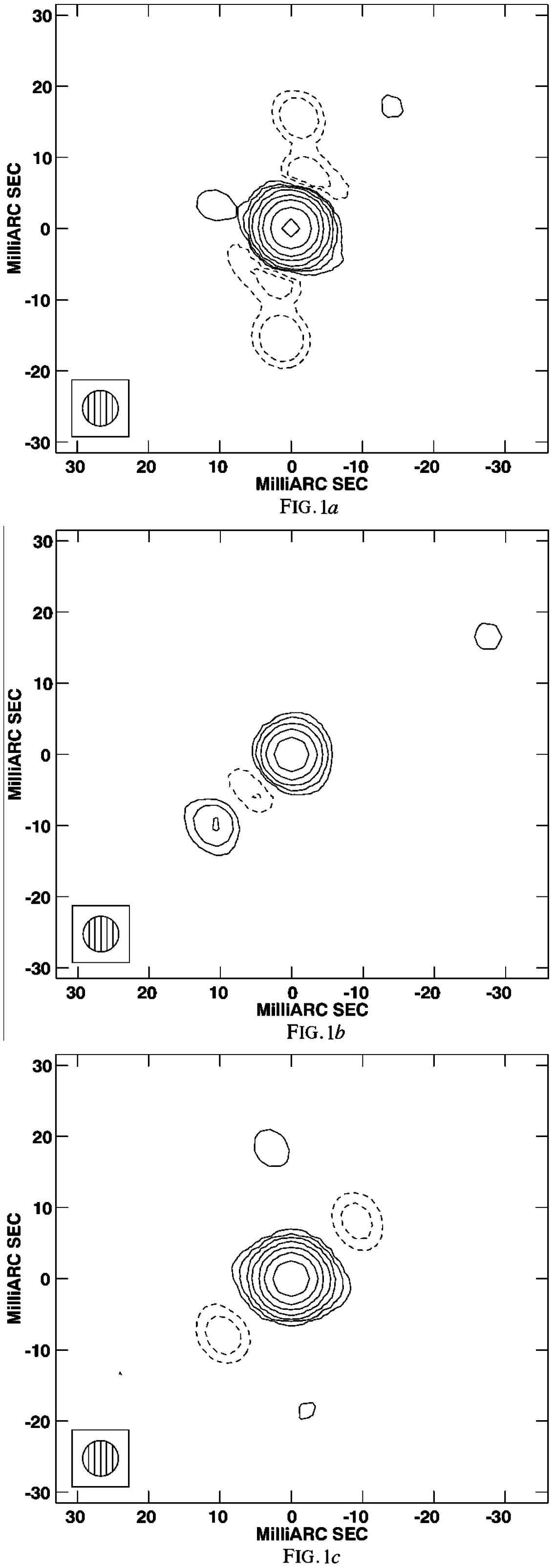

FIG. 1*a*

FIG. 1*b*

FIG. 1*c*

FIG. 1.—VLBI maps at 5 GHz of the three low-redshift RIQ in the PG quasar sample. (*a*) III Zw 2, (*b*) PG 1309+355, and (*c*) PG 2209+184. The maps were restored with a beam size of 5 mas and the noise is less than 0.6 mJy per beam. All sources are unresolved. The secondary component in PG 1309+355 is too weak to be considered significant. Contour levels are (−2, −1, 1, 2, 4, 8, 16, 32, 64, 128, 256) × 1.5 mJy, and peak fluxes are given in Table 1.

TABLE 1

PROPERTIES OF LOW-REDSHIFT FLAT-SPECTRUM RADIO-INTERMEDIATE QUASARS

Name	z	$\langle\alpha_{5\,\mathrm{GHz}}\rangle$	$\langle S_{5\,\mathrm{GHz}}\rangle$ (mJy)	$\langle R\rangle$	S_ν(core) (mJy)	FWHM (mas)	S_ν(ext) (mJy)	R_{ext}	T_{B} (K)
PG 0007+106	0.089	0.66	158	258	234 ± 12	<1	<12	<7	1.7×10^{10}
PG 1309+355	0.184	−0.02	34	11	15 ± 5	<1	<5	<1.7	1.1×10^{9}
PG 2209+184	0.070	0.32	92	188	255 ± 13	<1	<13	<6	1.8×10^{10}

NOTES.—The columns are (1) source name; (2) redshift; (3) time-averaged spectral index; (4) time-averaged total radio flux at 5 GHz; (5) time-averaged radio-to-optical flux ratio (all three from FSP96); (6) VLBI core flux; (7) upper limit to FWHM of source size in order to appear unresolved in our map; (8) missing VLBI flux; (9) upper limit for radio-to-optical flux ratio of extended flux; (10) lower limit for core brightness temperature.

signal-to-noise data could actually be a factor of 2 lower, i.e., 0.5 mas. Using the formula

$$T_{\mathrm{B}} = 1.8 \times 10^{9}\ \mathrm{K}\,\frac{S_\nu}{\mathrm{mJy}}\left(\frac{\nu}{\mathrm{GHz}}\,\frac{\mathrm{FWHM}}{\mathrm{mas}}\right)^{-2}, \qquad (1)$$

we then calculated a lower limit for the brightness temperatures of these sources, which for III Zw 2 and PG 2209+184 are in excess of 10^{10} K and may almost approach 10^{11} K if the less conservative size limit is used.

Moreover, by comparing the total flux density to that obtained in the EVN and MERLIN maps, we found no evidence for any missing flux at a 5% level in the two brighter sources and at the 30% level in PG 1309+355. This gives us a strong limit for the flux from any extended radio components, e.g., as expected in radio galaxies. If we divide this upper limit to the extended flux by the optical flux at 4400 Å as given in Kellermann et al. (1989), we obtain an upper limit to the R-parameter for the extended flux only (R_{ext})—this value should be much less subject to orientation effects. The limits for R_{ext} obtained this way[1] for our sample of RIQ are listed in Table 1 and are all smaller than $R_{\mathrm{ext}} = 10$. We note that for the steep-spectrum radio-loud quasars always $R_{\mathrm{ext}} \simeq R$ and for radio-weak quasars with detected extended emission R_{ext} also is only slightly less than R (see Kellermann et al. 1989). In Figure 2 we show the distribution of R (reproduced from FSP96) and R_{ext} for the PG quasars, where we have left out all flat-spectrum sources except for the three RIQ investigated here, to highlight how the RIQ's classifications change if one considers the extended rather than the total emission. While in total flux the three flat-spectrum RIQ are in the radio-loud distribution, the upper limits for their extended emission push them already down to the tip of the radio-weak and below the radio-loud distribution.

4. SUMMARY AND DISCUSSION

The hypothesis that the flat-spectrum RIQ in the low-redshift PG quasar sample are actually boosted radio-weak quasars was initially based only on their peculiar position in an radio vs. optical diagram and their flat radio spectrum (FMB95; see also Miller et al. 1993). The notion was then further strengthened by the finding of more flat-spectrum RIQ in the whole PG quasar sample (FSP96), which in number and R distribution were then consistent with the boosting hypothesis. Our VLBI observations of the three low-redshift RIQ in the PG sample now confirm two of the three predictions for these quasars in more detail: a high T_{B} and a low extended flux. The lower limits for brightness temperatures of 10^{10} K for the two brighter quasars are already large enough to exclude any reasonable thermal models (e.g., the starburst model), especially in conjunction with their strong variability. If we take the less conservative estimates for the source sizes, the limits on the brightness temperatures for III Zw 2 and PG 2209+184 already approach the theoretical limit of ~10^{11} K derived from

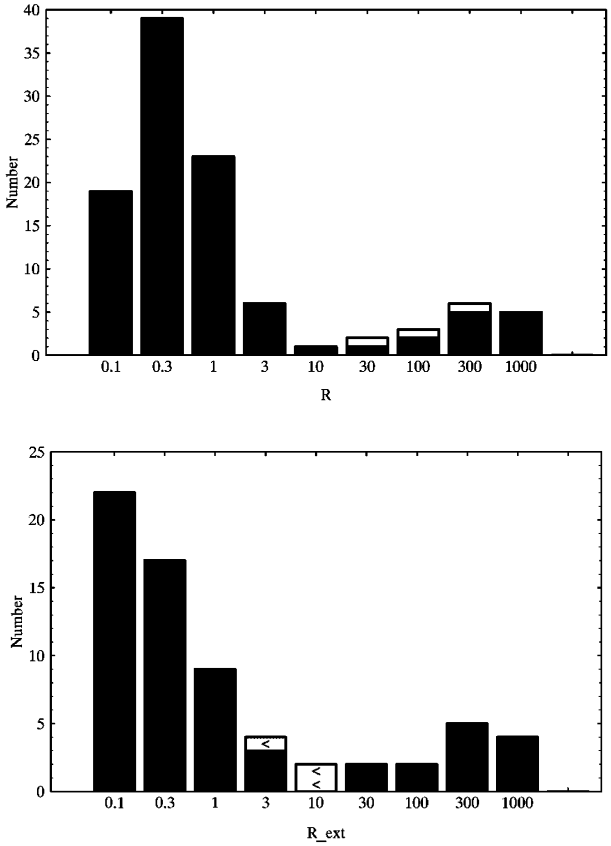

FIG. 2.—*Top*: Distribution of the (total) radio-to-optical flux ratio for "steep-spectrum" PG quasars (i.e., all sources except those with known flat spectrum—the spectral information is only complete down to $R \sim 1$) is shown as filled bars (from FSP96). The position of the three flat-spectrum RIQ investigated in this paper are shown as shaded bars. *Bottom*: Distribution of the extended radio-to-optical flux ratio R_{ext} for all "steep-spectrum" PG quasars with extended emission (*black bars*) and the three flat-spectrum RIQ (*shaded bars*), where we have used the upper limits derived from this paper. While in total flux the flat-spectrum RIQ appear to be part of the radio-loud distribution, their low limits on the extended flux indicate that they might rather be part of the radio-weak distribution.

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[1] For III Zw 2 Unger et al. (1987), detected a week and steep second component with the VLA (8 mJy at 1490 MHz, i.e., ~3.2 mJy at 5 GHz for $\alpha = -0.75$). Likewise, Kellermann et al. (1995) claim a ~2 mJy secondary component for PG 2209. If these week components contain all the extended flux, one would obtain an even lower value of $R_{\mathrm{ext}} \sim 2$ for III Zw 2 and PG 2209.

equipartition arguments (e.g., Falcke & Biermann 1995, eq. [58]), which would imply relativistic boosting. For III Zw 2 Teräsranta & Valtaoja (1994) even estimate a T_B around 10^{12} K from their variability data. Such high values for T_B are typical for compact radio cores in radio galaxies and radio-loud quasars associated with powerful radio jets. However, the upper limit on the extended flux of the flat-spectrum RIQ we have obtained reduces the already low R-parameter to values at $R_{\rm ext} < 10$—values that are typical for radio-weak quasars. This basically excludes that these compact, variable, high-brightness cores reside in the usual type of radio-loud quasar with bright extended emission from the large-scale lobes, otherwise we would have expected a missing flux of at least 30%–50%, based on the typical lobe fluxes of the steep-spectrum radio-loud quasars—this was neither seen in our EVN + MERLIN maps nor in the earlier VLA A and D array maps. The third prediction of the "boosted radio-weak jet" hypothesis, namely core-jet structure and superluminal motion could not be tested in our experiment because of our relatively low resolution. For this we have to await future VLBA or even global VLBI experiments. Nevertheless, our observations show that the RIQ are indeed a homogenous class of sources with unique properties and they have brought strong, direct evidence for the presence of relativistic boosting in radio-weak quasars.

This finding may be quite significant for our interpretation of radio-weak quasars and especially the radio-loud/radio-weak dichotomy. It means that radio-weak and radio-loud quasars have central engines that are in many respects very similar: not only are the optical properties almost undistinguishable but also do *both* types of quasars produce relativistic jets in their nuclei. Unfortunately, this makes the reason for the radio dichotomy of quasars an even deeper mystery.

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Note added in proof.—The high brightness temperature of III Zw 2 was also confirmed in recent VLBA observations by Zensus, Kellermann, Vermeulen, & Cohen (in preparation) in their 2 cm survey. The source is basically a point source with the visibility falling off to 0.7 at 400 Mλ, thus indicating some structure at a scale of less than 0.5 mas.

Moreover, Blundell et al. (in preparation) have found similar/higher brightness temperature limits for all three of our objects in a larger sample of radio intermediate/quiet quasars from recent VLBA observations.

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