2003MNRAS.346..327T

Mon. Not. R. Astron. Soc. **346,** 327–331 (2003)

Identification of a new low-redshift GHz-peaked spectrum radio source and implications for the GHz-peaked spectrum class

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Accepted 2003 August 7. Received 2003 June 30; in original form 2003 May 21

ABSTRACT

The extragalactic radio source PKS B2254−367, associated with the galaxy IC 1459, is identified as a GHz-peaked spectrum (GPS) radio source. At a distance of 19 Mpc, PKS B2254−367 is one of the closest known GPS radio sources. IC 1459, NGC 1052 (18 Mpc) and NGC 6328 (56 Mpc) are the only GPS radio source host galaxies for which the detailed kinematics of the host galaxies can be studied. All three galaxies present strong evidence for merger activity, an actively fuelled black hole and high-density environments with which the radio sources interact. Although radio luminosity evolution is generally invoked to explain the apparent overabundance of GPS sources relative to radio galaxies, such strong evidence for merger-induced activity in the nuclei of nearby GPS host galaxies argues that at least some GPS radio sources are limited in their development by the effects of merger activity and the resulting likely sporadic fuelling of the central black holes and accretion discs that power the radio sources. The radio structure associated with NGC 1052 may directly suggest such a scenario.

Key words: galaxies: individual: IC 1459 – galaxies: interactions – radio continuum: galaxies.

1 INTRODUCTION

GHz-peaked spectrum (GPS) radio sources have been found to represent approximately 24 per cent of the radio loud quasar population (Bicknell, Dopita & O'Dea 1997) and are therefore a significant subclass of the active galactic nuclei. The physical significance of the GPS sources lies in the assertion that they represent the early evolutionary stages of the FR-II – and perhaps FR-I – radio galaxies (e.g. Snellen et al. 2003). However, it has been known for some time that GPS radio sources are overrepresented relative to FR-II radio galaxies, posing a problem for proposed evolutionary schemes. This problem was originally tackled by suggesting that the GPS sources are frustrated in their evolution, confined, or intermittently active, as a consequence of dense nuclear environments (see O'Dea, Baum & Stanghellini 1991 or Stanghellini et al. 1993 for a review of these ideas). More recently, however, luminosity evolution has come to be favoured as an explanation of this problem (de Vries 2003). In reality, all of these effects may be significant, and, indeed, should be related. Here, we show that the three closest GPS radio galaxies present evidence for substantial merger activity, actively fuelled black holes and high nuclear gas densities with which the radio sources may interact, with likely implications for the class of GPS radio sources.

GPS sources are characterized by having a turnover in the radio spectrum at GHz frequencies, compact radio structures typically on the parsec scale, low radio polarization and low variability at radio wavelengths (O'Dea 1998). Also, GPS sources have been found largely at high redshift; the median redshift of the GPS sample of O'Dea (1998) is $z \sim 0.65$, with the median redshifts of the galaxy and quasar subclasses being 0.36 and 1.3, respectively. The rarity of GPS radio sources in the local Universe means that the relationships between the individual radio sources and their host galaxies are very difficult to study in detail, because the substructures in the host galaxies are, at best, only marginally detected and resolved owing of their distance. Identifying and studying GPS radio sources in the local Universe is critical for formulating and testing models that explain the unique characteristics of these sources (Snellen et al. 2003).

We identify PKS B2254−367 (J2257−3627) as a very nearby GPS source and summarize its host galaxy properties briefly, pointing out common features between its host galaxy, IC 1459, and NGC 1052 (host galaxy of the GPS source PKS B0238−084) and NGC 6328 (host galaxy of the GPS source PKS B1718−649). PKS B2254−367 lies at a distance of 19 Mpc (Prugniel & Simien 1996), making it the second closest GPS radio source after NGC 1052 (18 Mpc, Prugniel & Simien 1996), assuming $H_0 = 75$ km s^{-1} Mpc^{-1}. The only other GPS radio source known within 100 Mpc is PKS B1718−649 at 56 Mpc (Tingay et al. 1997).

As compared to the known population of GPS radio galaxies, these three sources have below average luminosities at 5 GHz,

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ranging between $\log(P_{5\,\mathrm{GHz}}[\mathrm{W/Hz}]) = 23$ and 25, compared to an average of $\langle\log(P_{5\,\mathrm{GHz}}[\mathrm{W/Hz}])\rangle \sim 27$ for the GPS galaxies listed by O'Dea (1998). The effect of flux density limits of $\sim$1 Jy in previous radio source surveys means that current lists of GPS galaxies are highly biased towards GPS sources of high power. Current efforts to survey nearby GPS sources at lower flux density levels, such as that of Snellen et al. (2003), should reveal more of these low-luminosity GPS galaxies. Similarly, the R-band absolute magnitudes of the three galaxies listed above range between $M = -21$ and 22, compared to a range of $-24 < M < -22$ for the general population (O'Dea 1998).

As we will show below, the radio properties of PKS B2254−367 clearly identify it as a GPS galaxy. Likewise, PKS B0238−084 and PKS B1718−649 have been convincingly shown to be members of the GPS galaxy class by Vermeulen et al. (2003) and Tingay et al. (1997), respectively. The fact that these three nearby GPS radio galaxies appear to be very similar in their properties implies that these properties may extend to a significant fraction of the more powerful but more distant and difficult to study GPS radio sources.

2 RADIO DATA

Recent observations with the Australia Telescope Compact Array (ATCA) and historical data have identified the radio source PKS B2254−367 as a GPS source (Table 1). The spectrum of PKS B2254−367 peaks around 2.5 GHz and has a similar form to those given as examples by Snellen et al. (2003). At low frequencies, the spectral index is $\alpha \sim 0.5$ (where $S \propto \nu^{+\alpha}$), and at high frequencies, $\alpha \sim -0.5$. The difference between optically thick and optically thin spectral indices of $\sim$1 easily satisfies the requirement of de Vries, Barthel & O'Dea (1997) that GPS sources have a spectral curvature greater than 0.6. The data in Table 1 are rendered graphically in Fig. 1, with different symbols used for pre- and post-1978 data. The flux density variability is discussed in more detail below.

In addition to the peaked radio spectrum, PKS B2254−367 displays all of the typical characteristics of GPS sources. The radio source was found to be compact on the maximum ATCA baseline of 6 km at the four frequencies (1.4, 2.5, 4.8, and 8.6 GHz) used in the monitoring program of Tingay et al. (2003). Ekers et al. (1989) imaged PKS B2254−367 with the Very Large Array (VLA) at 1.4 GHz and found that it was completely unresolved, with an angular size of <100 mas, corresponding to a projected linear size of less than approximately 10 pc. Slee et al. (1994) used short-baseline Very Long Baseline Interferometry (VLBI) at 2.3 and 8.4 GHz to show that the radio source has significant structure on angular scales less than 30 mas (3 pc). Recent VLBI measurements at 8.4 GHz on baselines between 100 and 10 000 km show that the source becomes fully resolved on baselines greater than 2000 km at this frequency (Ojha, private communication). Thus, a substantial amount of the structure in the source appears to be on angular scales between 3 and 30 mas (between 0.3 and 3 pc). This is typical of GPS sources. Future multibaseline, multi-epoch VLBI observations will enable parsec-scale images of PKS B2254−367 to be made, revealing the detailed structure and evolution of the source. The majority of GPS sources for which parsec-scale component motions have been measured to date have subluminal apparent speeds (Polatidis & Conway 2003). Extrapolation of these motions back to the core yields evidence that GPS sources are relatively young, with ages $\lesssim 3 \times 10^3$ yr.

Low fractional linear polarization is also a characteristic of GPS radio sources (e.g. O'Dea 1998). Gardner, Whiteoak & Morris (1975) measured the linear polarization of PKS B2254−367 to be 0.3±0.2 per cent at 2.7 GHz, and the more recent

Table 1. Compilation of radio data for PKS B2254−367. Data are listed chronologically within each frequency band.

ν (MHz)	S (Jy)	Epoch	Program /Telescope	Reference
80	<2	pre-1977	Culgoora	Ek89
408	0.70	pre-1978	MRC	La81
843	1.00	2000	SUMSS	Ma03
1415	0.80	pre-1968	Nançay	Be68
1420	0.78	pre-1971	OVRO	Le71
1410	0.97	pre-1985	PKS	Wr90
1400	1.28	1996	NVSS	Co98
1384	1.24	~1998	ATCA	Ti03
1384	1.30	2000	ATCA	C007
1384	1.30	2000	ATCA	C007
1384	1.26	2003	ATCA	TET
2700	0.82	1971	PKS	Bo73
2290	1.19	1988	PKS	Du93
2496	1.37	~1998	ATCA	Ti03
2496	1.38	2000	ATCA	C007
2496	1.33	2000	ATCA	C007
2368	1.29	2003	ATCA	TET
5009	0.72	1972	PKS	Bo73
5000	0.89	1973	PKS	Di77
4885	1.00	1979	VLA	Ek89
5000	1.07	1980	PKS	Sa84
4885	1.02	1984	VLA	Sa89
4730	1.18	1990	ATCA	Sl94
4850	1.15	1990	PMN	Wr96
4800	1.18	1994	ATCA	Lo97
4800	1.28	~1998	ATCA	Ti03
4800	1.20	2000	ATCA	C007
4800	1.22	2000	ATCA	C007
4860	1.2	2000	VLA	Ta03
4800	1.15	2003	ATCA	TET
8870	0.58	pre-1975		Ha75
8400	1.00	1989	PKS	Wr91
8600	0.96	1994	ATCA	Lo97
8640	1.03	~1998	ATCA	Ti03
8460	1.0	2000	VLA	Ta03
8640	0.92	2000	ATCA	C007
8640	0.94	2000	ATCA	C007
8640	0.93	2003	ATCA	TET
22200	0.59	2000	ATCA	C007
22460	0.5	2000	VLA	Ta03

Uncertainties in flux measurements, where given, are typically $\lesssim$5 per cent, though are 15–30 per cent for some early observations. Data for which the observation epoch was not able to be determined are constrained (with 'pre') by the year of publication. The data of Tingay et al. (2003) are averages over a 3.5-yr period between 1996 October and 2000 February, and so the year of observation is given as ~1998.

Key to references: Be68 = de La Beaujardière et al. (1968), Bo73 = Bolton & Shimmins (1973), Co98 = Condon et al. (1998), C007 = the ATCA calibrator survey (http://www.narrabri.atnf.csiro.au/calibrators/), Di77 = Disney & Wall (1977), Du93 = Duncan et al. (1993), Ek89 = Ekers et al. (1989), Ha75 = Haynes, Huchtmeier & Siegman (1975), La81 = Large et al. (1981), Le71 = Lequeux (1971), Lo97 = Lovell (1997), Ma03 = Mauch et al. (2003), Sa84 = Sadler (1984), Sa89 = Sadler, Jenkins & Kotanyi (1989), Sl94 = Slee et al. (1994), Ta03 = Taylor (2003), TET = this paper (observations made 2003 March 9), Ti03 = Tingay et al. (2003), Wr90 = Wright & Otrupcek (1990), Wr91 = Wright et al. (1991), Wr96 = Wright et al. (1996).

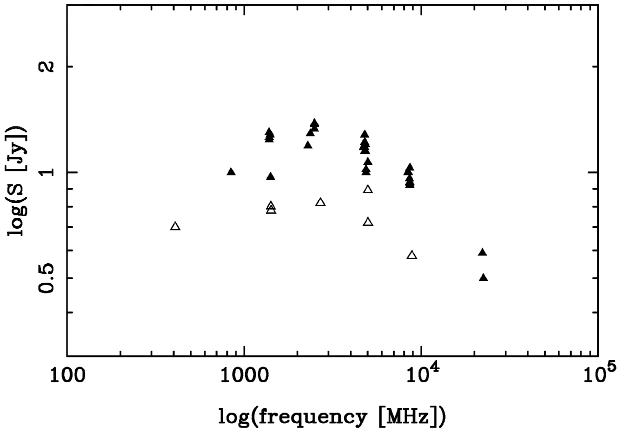

Figure 1. A compilation of recent and historical flux density measurements of PKS B2254−367 between 408 and 22 GHz, showing the persistent peaked spectrum. Pre-1978 data are plotted with open symbols and post-1978 data are plotted with filled symbols. Details of the data points are given in Table 1.

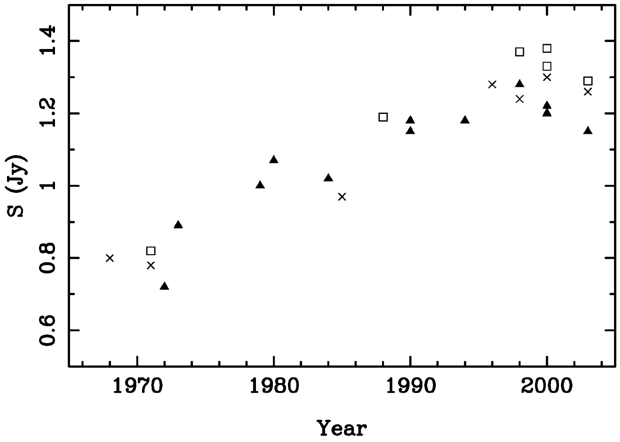

Figure 2. Time variation of the measured flux density of PKS B2254−367 in the 1.4 (crosses), 2.5 (open squares) and 5.0 (filled triangles) GHz bands. Details of the data points are given in Table 1.

multi-epoch, multi-frequency ATCA monitoring of Tingay et al. (2003) confirmed that PKS B2254−367 has a low fractional linear polarization of less than 0.5 per cent between 1.4 and 8.6 GHz.

The ATCA data also show that PKS B2254−367 is at most weakly variable over the 3.5-yr period over which it was monitored, again typical of GPS sources (although see, for example, Tornikoski et al. 2001). The variability index, defined as the rms deviation from the average flux density divided by the average flux density, was $\lesssim 0.05$ at all four frequencies (Tingay et al. 2003). However, Slee et al. (1994) showed that PKS B2254−367 varied monotonically from 0.7 to 1.2 Jy at 5 GHz over the 20-yr period from 1970, which is confirmed in the compilation of data in Table 1. As is shown in Fig. 2, this longer-term variability is visible in the 1.4- and 2.5-GHz bands as well as the 5-GHz band, with the flux densities in all three bands appearing to have peaked in the late 1990s.

NGC 1052 (PKS B0238−084) and NGC 6328 (PKS B1718−649) were also included in the monitoring program of Tingay et al. (2003), and both showed the same evidence for compact structure and low polarization as seen for PKS B2254−367. PKS B1718−649 displayed relatively low variability over the 3.5-yr period; however, PKS B0238−084 was somewhat more variable, particularly at 8.6 GHz. Slee et al. (1994) noted long-term variability for PKS B0238−084 at 5 GHz similar to that seen for PKS B2254−367, but with additional evidence of shorter-term variability on a ~1 yr time-scale.

3 DISCUSSION

3.1 IC 1459 (PKS B2254−367)

The host galaxy of PKS B2254−367, IC 1459, is a giant elliptical galaxy in a loose group of otherwise spiral galaxies. IC 1459 shows strong evidence that it is the product of merger activity, and has one of the strongest counter-rotating core components observed in an elliptical (Forbes, Franx & Illingworth 1994). Hernquist & Barnes (1991) demonstrated the formation of a counter-rotating central gas disc in a merger of two gas-rich disc galaxies of equal mass. However, a study of the environments of galaxies with counter-rotating cores by Bettoni, Galletta & Prada (2001) suggests that counter-rotating cores may be associated with galaxies that are formed through the merger of small objects early in their formation history. Although the nuclear emission line gas appears to be well ordered in IC 1459, the dust distribution is irregular near the nucleus, indicating non-equilibrium motions and the possibility that material infalling into the nucleus may be currently fuelling the active nucleus (Forbes et al. 1994). Huchtmeier & Tammann (1992) made a marginal detection of CO emission from IC 1459, the line blueshifted relative to the systemic velocity of the galaxy, further evidence for irregular gas motions in the galaxy. Recently, the central black hole mass in IC 1459 has been determined by Cappellari et al. (2002), with different techniques yielding values between 4×10^8 and 3×10^9 $M_\odot$. IC 1459 has optical emission line ratios that identify it as a Low Ionization Nuclear Emission-line Region (LINER) galaxy (Verdoes Kleijn et al. 2000).

3.2 NGC 1052 (PKS B0238−084)

NGC 1052, which lies at essentially the same distance as IC 1459, also hosts a GPS radio source (PKS B0238−084) (de Vries et al. 1997; Tornikoski, Lainela & Valtaoja 2000; Kameno et al. 2001; Vermeulen et al. 2003). NGC 1052 also has a counter-rotating core (Bettoni et al. 2001) and a LINER optical spectrum. An analysis of *Hubble Space Telescope* data by Gabel et al. (2000) shows that photoionization of the nuclear gas by a central continuum source can explain the nuclear optical spectrum in NGC 1052. To reproduce the optical spectrum, Gabel et al. (2000) use a multidensity gas with gas density of $\sim 3 \times 10^3$ cm^{-3} within 100 pc of the central source and with gas density of $\sim 2 \times 10^6$ cm^{-3} within 2 pc of the central source. They also find that a significant contribution from dust in the nuclear region is likely, which agrees with their finding of substantial intrinsic reddening toward the nucleus and a relatively large minimum covering factor of 0.53 for the nuclear gas. The broad linewidths in the nucleus of NGC 1052 constitute evidence for a compact central source, although no estimate of the black hole mass has been made to date. Gabel et al. (2000) find no correlation between linewidth and critical density, indicating that the nuclear gas cannot be described as having Keplerian orbits around the nucleus.

Omar et al. (2002) have detected OH absorption against the nucleus of NGC 1052, redshifted in comparison with the systemic velocity of the galaxy, that coincides with H I absorption (van Gorkom et al. 1989), and take these results to indicate that molecular clouds are currently falling into the nucleus of the galaxy.

The turnover frequency of the total flux density spectrum of the GPS radio source in NGC 1052 is 10 GHz (de Vries et al. 1997). The VLBI observations of Kameno et al. (2001) resolved the individual parsec-scale components, revealing that different components turn over at different frequencies.

Extensive VLBI observations by Vermeulen et al. (2003) show that the GPS of the radio source in NGC 1052 is partly caused by free–free absorption due to a geometrically thick, patchy and ionized structure in the inner 2 pc of the galaxy, supporting the findings of Gabel et al. (2000).

VLA imaging reveals that the extended radio source spans 30 arcsec, corresponding to a projected linear size of approximately 2.8 kpc (Wrobel & Heeschen 1984). Thus, the NGC 1052 radio source lies far from the bulk of the GPS sources that define the relationship between turnover frequency and linear size for GPS radio sources (Bicknell et al. 1997). The high turnover frequency in NGC 1052 is consistent with the size of the compact nuclear radio source rather than the extended radio source. Under the hypothesis that GPS sources are young, this result could be taken to imply that NGC 1052 is a ‘restarted’ radio source – one that has been fuelled in the past, creating the extended radio source. The current GPS source at the nucleus may be much younger than the extended radio source and may have been generated through a completely different fuelling event.

The extended radio source in NGC 1052 appears to be in pressure equilibrium with the ambient gaseous medium, Wrobel & Heeschen (1984) concluding that significant interaction between the radio source and the nuclear gas should be expected.

3.3 NGC 6328 (PKS B1718−649)

The only other known GPS radio source within 100 Mpc is PKS B1718−649, in NGC 6328 (Tingay et al. 1997). Véron-Cetty et al. (1995) concluded from the H I kinematics of NGC 6328 that the galaxy was likely to have formed in a merger involving at least one gas-rich spiral. NGC 6328 also has a LINER optical spectrum that contains very broad lines. Filippenko (1985) concluded that photoionization is the likely mechanism behind the LINER spectrum and that the gas density within 500 pc of the nucleus is 10^6–10^7 cm^{-3}, a result similar to that of Gabel et al. (2000) for NGC 1052. Recently, Tingay & de Kool (2003) have studied the detailed variability behaviour of PKS B1718−649 and find that neither synchrotron self-absorption nor free–free absorption by itself can provide a convincing explanation of its spectrum.

3.4 Implications for the GPS sources

IC 1459, NGC 1052 and NGC 6328, the only three known GPS radio source host galaxies within 100 Mpc, all show substantial evidence for past merger activity (gas dynamics of the host galaxies), the existence of compact central masses (black hole mass estimate in IC 1459 and broad optical emission lines in NGC 1052 and NGC 6328), and high-density nuclear environments (LINER optical spectra). In the two closest galaxies, NGC 1052 and IC 1459, evidence exists for non-equilibrium motions in the nucleus and the infall of material into the nuclear region.

Under these conditions, it must be expected that the jet produced by accretion on to the compact object (perhaps triggered by the merger causing the infall of gas) is affected by interactions with the environment. In some cases, the interactions may be significant enough to disrupt the jet completely and cause the dominant radio structure in the source to appear small over a significant portion of the radio source lifetime. The latest numerical simulations of jet interactions with ensembles of clouds by Bicknell (2003) suggest this, showing that jets entering environments with large cloud filling factors can be highly disrupted.

However, the small size of GPS sources may not necessarily be caused by a persistent confinement of the radio source. In such an environment, a black hole may undergo many fuelling events and each event may completely disrupt and/or restart the jet. After each renewal, the jet may need to force its way through the dense nuclear environment.

These ‘restarted’ jets may be a significant contributor to the population of GPS sources, as first suggested by Baum et al. (1990) (and reviewed in O’Dea et al. 1991; Stanghellini et al. 1993), and contribute to the apparent overdensity of GPS sources relative to radio galaxies. Furthermore, in the early restarting phase of the source, the compact structure will appear bright, owing to the interaction of the jet with its environment, with shocks re-accelerating electrons in the jet and increasing the synchrotron emissivity of the jet plasma, perhaps dominating any older, extended radio emission. Therefore, there is a plausible link between the mechanical effects of jet–cloud interactions (causing GPS sources to remain small) and luminosity evolution (with the small interacting GPS sources tending to be more luminous than larger GPS sources).

A specific nearby example of a restarted GPS source may be the radio source in NGC 1052, where the nuclear radio source has a high-frequency peaked radio spectrum, implying that it is younger than the rest of the extended radio source. It is plausible that the jet that produced the extended radio structure in NGC 1052 has been disrupted by an accretion event and that a restarted jet may force its way through the dense nuclear region once again. A parallel can be drawn with the behaviour seen in the galactic microquasar GRO J1655−40, which revealed accretion events through enhanced X-ray emission, but which only produced collimated radio jets once the initial, presumably chaotic, accretion of matter on to the black hole ceased (Tingay et al. 1995). In GRO J1655−40, accretion events appear to have initially suppressed, but ultimately fuelled, the formation of radio jets.

The radio source in NGC 1052 may represent the early stage of a restarted radio galaxy, similar to the proposed young double source evolving within older lobe material in the giant radio galaxy J0116−473 (Saripalli, Subrahmanyan & Udaya Shankar 2000). We suggest that this type of behaviour may not be uncommon in GPS sources and, given the strength of evidence from the three nearby GPS sources, may well be a direct consequence of merger activity.

ACKNOWLEDGMENTS

This research has made use of NASA’s Astrophysics Data System Bibliographic Services and the NASA/IPAC Extragalactic Data base (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Australia Telescope National Facility is funded by the Australian Commonwealth Government for operation as a national facility managed by CSIRO. The referee is thanked for a helpful suggestion.

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