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WHAT ARE THE GIGAHERTZ PEAKED-SPECTRUM RADIO SOURCES?

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ABSTRACT

We discuss the astrophysical implications of recent radio and optical observations of the powerful, compact gigahertz peaked-spectrum (GPS) radio sources. The defining characteristics of these objects are (1) their peaked radio spectra with narrow spectral shape and steep high-frequency spectrum, (2) low radio (and optical?) polarization, (3) large radio luminosities, and (4) mostly compact radio structure. The nature of these enigmatic objects is still not understood. However, we present some tentative conclusions and suggest a scenario based on the existing data.

The turnover in the spectrum is probably due to synchrotron self-absorption, and we assume this as the basis for our inferences from the radio spectral shape. However, as we discuss below, these sources may have higher than normal electron densities in their nuclei, and it is possible that free-free absorption plays a role in at least some sources. The result that some GPS sources have a very narrow spectral shape is consistent with the hypothesis that there is a narrow range of size scales which dominate the radio luminosity; i.e., very extended ($\gtrsim 100$ pc) and very compact ($\lesssim 0.1$ pc) emission is apparently very weak if it exists at all.

Based on the steep high-frequency radio spectrum and the low variability, there does not appear to be a strong beamed "jetlike" component in these objects. Instead the radio luminosity is dominated by compact (i.e., parsec scale), steep-spectrum emission ("microlobes"?).

The highly inverted low-frequency radio spectrum is consistent with the hypothesis that the radio source is tightly confined.

We put on a firm foundation the result that the radio polarization of these sources is systematically low. This is consistent either with a very tangled magnetic field or very large Faraday rotation measures (implying high magnetic fields and/or very large electron densities). The existence of high rotation measures is tentatively found in two objects (both high-redshift quasars) but it is premature to conclude that this is a general trend in GPS sources.

The optical identifications are a mixture of galaxies and quasars. As previously noted (e.g., Phillips & Mutel; Pearson & Readhead) we find that the galaxies tend to have more symmetric milliarcsecond radio structure than the quasars. CCD imaging of small samples of GPS galaxies suggest that they tend to be interacting/merging. Spectroscopy of two GPS galaxies is consistent with the hypothesis that they have unusually dense, highly reddened narrow-line regions.

We suggest that GPS radio sources are formed when the radio plasma is confined on the scale of the narrow-line region by an unusually dense and clumpy ISM. In this scenario, the high electron densities are responsible for depolarizing the radio source and in some cases producing very high Faraday rotation measures. The existing (sparse) optical spectroscopic results are also consistent with the existence of a dense and dusty nuclear ISM.

The GPS *quasars* tend to have very high redshifts (half with $z \gtrsim 3$). The hosts of these radio sources may be protogalaxies with very dense and clumpy interstellar media. The lower redshift GPS *galaxies* may have recently cannibalized a gas-rich companion, resulting in a very dense and clumpy nuclear ISM.

Subject headings: polarization — quasars — radiation mechanisms — radio sources: galaxies — radio sources: spectra

1. INTRODUCTION

Gigahertz peaked-spectrum (GPS) radio sources are an enigmatic class of active galactic nucleus whose importance has only recently been recognized. These sources have simple convex radio spectra with steep spectral indices at high frequencies and spectral turnovers near 1 GHz (Blake 1970; Peacock & Wall 1981, 1982; Kapahi 1981; Rudnick & Jones 1982; Gopal-Krishna, Patnaik, & Steppe 1983; Spoelstra, Patnaik, & Gopal-Krishna 1985). These sources tend to be very compact ($\sim$10–100 mas $\sim$10–1000 pc; e.g., Mutel & Phillips 1988). The radio luminosities tend to be very high ($L_{\rm radio} \sim 10^{45}$ ergs s^{-1}) comparable to the most powerful quasars. However, as we discuss below, the radio properties are not consistent with the existence of a Doppler-boosted "jetlike" component. Thus, as pointed out by Phillips & Mutel (1982), these sources are intrinsically extremely powerful if they emit isotropically without significant Doppler boosting. VLBI imaging of GPS sources show that some (almost exclusively quasars) exhibit a complex or asymmetric morphology. Others, termed compact doubles (almost exclusively galaxies), show two components of similar flux density and spectral shape (Phillips & Mutel 1980, 1981, 1982; Hodges, Mutel, &

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Phillips 1984; Mutel, Hodges, & Phillips 1985; Mutel & Hodges 1986; Pearson & Readhead 1984, 1988).

Limits have been placed on proper motion of a few compact double galaxies. So far no superluminal and two subluminal sources have been found (Phillips & Shaffer 1983; Readhead, Pearson, & Unwin 1984; Pearson, Readhead, & Barthel 1990; Conway et al. 1990a). Comparable limits have not yet been placed on the GPS *quasars*.

Rudnick & Jones (1982) studied seven GPS sources (six with polarization measurements) and suggested that these sources are less variable and less polarized than sources with flat or "complex" radio spectra. This has been confirmed for the six compact doubles in the Pearson-Readhead sample (Pearson & Readhead 1984, 1988; Seielstad, Pearson, & Readhead 1983; Rusk 1988). Very low polarization has also been found in an additional sample of 10 GPS sources observed by Rusk (1988).

Phillips & Mutel (1982) suggested that the compact double GPS sources represent the early stages of the evolution of classicial double radio sources. Carvalho (1985) presented a simple analytical model of the evolution of classical double sources and showed that the known properties of compact doubles are consistent with such a scenario. Mutel & Phillips (1988) suggested that the compact doubles evolve into compact steep spectrum sources and then later into classical doubles. However, the situation became more complicated when Baum et al. (1990) reported the detection of extended emission associated with the compact double source 0108+388. Diffuse extended emission around compact double and other GPS sources has now been found with a frequency of $\sim$20%–25% (Stanghellini et al. 1990a, b; Rusk 1988). The existence of extended emission is in conflict with the hypothesis that all compact doubles are very young. Baum et al. suggested two alternate hypotheses for those GPS sources with extended emission. The first is that the activity in the core is repetitive, and the current compact double is propagating out amidst the relic of the previous epoch of activity.

The second hypothesis is that a host galaxy with an existing large-scale radio source has recently acquired a large amount of gas and dust (possibly from a companion) which has smothered the nuclear radio jets. A prediction of this scenario is an unusually high gas density in the nucleus of the GPS source. In this second scenario, the compact source is confined to the nucleus by the dense gas and the energy supply to the extended structure is cut off. The core luminosity increases substantially because of continued injection into a compact confined region with minimal adiabatic losses; the extended structure continues to expand and fade, thus making the source more core-dominated. Recently a core-dominated, giant double-lobed radio galaxy with a GPS core has been discovered (1245+67; A. G. De Bruyn et al., in preparation). VLBI observations have shown that the core consists of a compact double with 7 mas separation, making this source a candidate for a smothered radio galaxy.

With our colleagues, we have begun acquiring observations of GPS sources with the goal of clarifying and expanding the preliminary observational results and addressing the questions concerning the nature of these sources. The results of simultaneous, multifrequency VLA observations of the compact cores of 15 GPS sources are presented by O'Dea et al. (1990b, hereafter Paper I). The properties of the extended radio emission associated with these 15 GPS cores are presented and discussed by Baum et al. (1990) and Stanghellini et al. (1990, hereafter Paper II). The results of CCD imaging of a separate sample of 14 GPS sources are presented by O'Dea, Baum, & Morris (1990a). The redshift distribution and properties of the GPS quasars are discussed by O'Dea (1990). In this paper we discuss the astrophysical implications of the radio and optical results for our understanding of GPS sources.

2. THE RADIO SAMPLE AND SELECTION EFFECTS

The source list was composed of candidate GPS sources with published radio spectra. Objects were taken mainly from Gopal-Krishna, Patnaik, & Steppe (1983) with a few additional sources from Kühr et al. (1981b) and Owen, Spangler, & Cotton (1980). There was no selection based on optical identification or milliarcsecond structure. The positions, optical identifications, redshifts, and milliarcsecond morphology of these sources are given in Table 1 of Paper I.

There are important selection effects which should be noted.

1. The current sample consists of some of the brightest (in flux density) of the compact sources with spectra which peak near 1 GHz. The fainter sources will be absent from samples like this one until radio spectra are obtained of fainter sources found in the flux density surveys. The faint GPS sources may either be intrinsically less powerful or at higher redshifts than those studied here.

2. Sources with peaks much higher than about 5 GHz are discriminated against. These sources may be even more compact than those currently known.

3. So far, redshifts are available for some quasars and a few of the brighter (and thus nearby) GPS galaxies ($0.1 \lesssim z \lesssim 0.6$). Except for a Seyfert 1 galaxy (0Q 208) there are currently no examples of GPS galaxies with $z \lesssim 0.1$. This is in contrast to the 3C sample which has many objects with $z \lesssim 0.1$. In addition, the redshift distribution and physical parameters of the high-redshift galaxies $z \gtrsim 1$ are currently unknown.

4. Because of the effects of redshift, the high-redshift objects have spectral peaks at intrinsically higher frequencies than the nearby objects. The high-redshift objects also have more compact and asymmetric parsec-scale radio sources than the low-redshift galaxies (see § 5.3), possibly related to the different environments at high redshift. Thus the comparison of high- and low-redshift objects should be done with caution.

3. THE RADIO SPECTRA

The broad-band radio spectra of the cores of the 15 GPS sources are presented in Paper I. There we found that nine sources have steep high-frequency spectra ($\alpha \lesssim -0.8$; where $S \propto \nu^{\alpha}$), and 10 (six in common) have very inverted low frequency spectra ($\alpha \gtrsim +0.8$). Four sources have extremely inverted low-frequency spectra with $\alpha \gtrsim +1.5$! For comparison, most compact extragalactic radio sources have values of "below peak" spectra near 0.3 (e.g., Spangler 1980). In this section we discuss the implications of the properties of the observed radio spectra.

3.1. *What Causes the Turnover?*

In the discussion we adopt the assumption that the turnover in these sources is due to synchrotron self-absorption. The arguments in favor of this mechanism have been given persuasively by Jones, O'Dell, & Stein (1974). In addition, Mutel et al. (1985) and Hodges et al. (1984) find that the estimated physical parameters of compact double sources with VLBI observations are consistent with synchrotron self-absorption rather than free-free absorption. However, in the GPS sources, there

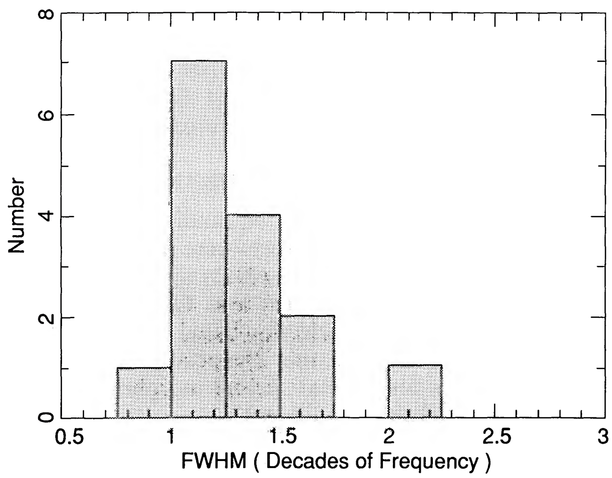

FIG. 1.—A histogram of the FWHM (in decades of frequency) obtained from a least-squares fit to the radio spectrum.

is some evidence that the densities of thermal electrons may be higher than in other AGNs (e.g., from radio depolarization and optical emission-line diagnostics). At this point, we cannot completely rule out the possibility that free-free absorption plays a role in these sources. If free-free absorption is important, then to produce an optical depth of ~ 1 at a rest frequency of 5 GHz would require an electron density of $\sim 10^4$ cm^{-3} assuming a path length of 1 pc, temperature of 10^4 K and a covering factor of unity.

3.2. *The Width of the Spectra*

The six sources with both very inverted low-frequency spectra and steep high-frequency spectra demonstrate that the distribution of spectral shapes extends to sources with very narrow spectral peaks. To quantify this further, we determined the FWHM of the spectra of the 15 GPS sources using the interpolated values obtained from our weighted least-squares fits. The FWHM in decades of frequency is shown in Figure 1. The median value is 1.20 decades of frequency. Sources with much larger FWHM will not be selected as having peaked spectra.

The source with the narrowest spectrum is 0108+388 which has a FWHM value of ~ 0.95. The narrowest FWHM that would be reasonably expected is that of homogeneous self-absorbed synchrotron source with a power law (i.e., nonmonoenergetic) electron energy spectrum. For such an ideal source with spectral index $\alpha = -0.80$ the FWHM is 0.77 decades of frequency and is of course smaller for sources with steeper spectra. Thus, none of the GPS sources have integrated spectra which are too narrow to be explained by self-absorbed synchrotron emission from a homogeneous source with a power law electron energy distribution. Note that the effect of inhomogeneity is to broaden the spectrum (as discussed in § 3.4).

Is the lack of sources with narrower spectra a real effect? Sources with very narrow FWHM may be selected against if they are hard to find in surveys at discrete radio frequencies. However, it seems unlikely that many bright GPS sources with narrow spectra have been missed since surveys are available at 1.4, 2.7, and 5 GHz. The width of the integrated spectrum will be increased if there are multiple components which peak at different frequencies (as is the case for 2050+364; Mutel et al. 1985). Thus, individual components with very narrow spectra could be hidden by the presence of additional components.

3.3. *The Narrow Spectral Shape*

In a homogeneous, self-absorbed, incoherent synchrotron radio source with a power-law electron energy distribution, the turnover frequency is given by (e.g., Kellermann & Pauliny-Toth 1981)

$$\nu_{\max} \sim 8B^{1/5}S_m^{2/5}\,\theta^{-4/5}(1+z)^{1/5}\ \mathrm{GHz}$$

where the magnetic field B is in G, the flux density at the peak S_m is in Jy, z is the redshift, and the angular size θ is in milliarcseconds.

Thus, the turnover frequency depends weakly on the magnetic field strength and peak flux density, and most strongly on the angular size. The result that some GPS sources have very narrowly peaked spectra suggests that only a narrow range of size scales contributes significantly to the observed radio luminosity. *This implies that there is both an upper limit and a lower limit to the size of the emitting region.*

3.4. *The Inverted Optically Thick Spectrum*

The role of inhomogeneity in compact sources has been studied by Condon & Dressel (1973), de Bruyn (1976), and Marscher (1977). They demonstrated that inhomogeniety broadens the spectral peak and flattens the optically thick part of the spectrum. The inhomogeneity can be "random" (e.g., in the form of lumpiness in the source structure) or "organized" (e.g., in the form of a jet whose properties change with size scale). In some GPS sources the optically thick spectrum is very inverted and approaches the theoretical maximum value of 2.5 for a homogeneous source. This suggests that these GPS sources are fairly uniform and that they have "sharp edges." At the very least, it implies that the sources are expanding at velocities substantially less than their internal sound speeds. Thus, the highly inverted optically thick spectra are consistent with the hypothesis that the *GPS sources are tightly confined.*

3.5. *The Steep Optically Thin Spectrum*

GPS sources tend to have very steep optically thin spectral indices. This was noted previously for the case of compact double GPS sources (Phillips & Mutel 1982; Pearson & Readhead 1988). The steep spectra are similar to those of the ultra–steep spectrum extended radio galaxies which are often found at high redshift (e.g., Chambers, Miley, & van Breugel 1987); however, they are unusual in compact sources. It is possible that the spectra are intrinsically very steep, i.e., the electrons are injected with very steep dependence on energy. Alternately, the steep spectra may be evidence for synchrotron and inverse Compton losses. Here we discuss the implications of the second possibility.

The interpretation of the spectra in terms of radiative losses is complicated by the effects of adiabatic losses which may also be important in these sources. The steepness of the spectra suggest that the luminosity is dominated by electrons which have experienced significant radiative losses. Recently injected electrons with a flatter energy distribution can only make a minor contribution to the luminosity.

We note that the spectra are very straight in the optically thin regime observed so far. A clean break of 0.5 in the spectral index can be ruled out for many sources (see Paper I for details). Synchrotron losses should produce a break in the spectrum (e.g., Kardashev 1962). The lack of a break in the spectrum suggests that if radiative losses have resulted in a break, this break has moved to frequencies lower than that of the spectral peak so that the break frequency is currently hidden. The break could have moved to frequencies below the spectral turnover either through aging of the electron population or through adiabatic losses. This would be consistent with a scenario in which radiative losses were significant when the sources were substantially more compact, and that as the sources expanded, adiabatic losses moved the break to lower frequency.[5] The position of the break gives an estimate of the electron lifetime (e.g., van der Laan & Perola 1969; Meyers & Spangler 1985). We adopt an upper limit to the break frequency in the rest frame of 5 GHz. Taking a magnetic field strength of 100 μG (e.g., Mutel et al. 1985) gives an electron age of $\gtrsim 2 \times 10^5$ yr. The sources could be much older if the break (due to radiative losses) is at lower frequency. Adiabatic losses and/or a higher magnetic field than assumed will lower the upper limit to the electron age. Particle reacceleration will raise the upper limit.

4. THE RADIO POLARIZATION

4.1. *Fractional Polarization*

In Paper I, we found that most of the GPS sources have fractional polarizations less than 0.5%, confirming the result of Rudnick & Jones (1982) that GPS sources have very low polarization. Additional confirmation is provided by the results of Rusk (1988) and Pearson & Readhead (1988). Combining Paper I with the other published data brings the sample to 38 GPS sources with measured polarization.[6] The median fractional polarization at 21 cm is $\sim 0.2\%$. Thus, the association of GPS spectra with very low radio polarization is on very firm ground.

The low polarization could be caused by (1) an extremely tangled magnetic field in the source and (2) large Faraday depths in or around the radio source. Additional multifrequency observations are needed to examine the wavelength dependence of the polarization, especially at high frequencies in order to distinguish between these two possibilities. In the sample as a whole, there is no significant systematic trend in the percent polarization as a function of wavelength between 6 and 22 cm.

4.2. *Faraday Rotation Measure*

In Paper I we determined rotation measures (RMs) for four GPS sources. "High" polarizations (above 1%) and "low" RMs (below ~ 20 rad m^2) were found in 0237−233 and 0902+490. However, our polarization measurements of 0902+490 might be contaminated by the extended emission (see Papers I and II).

An important result is the tentative discovery of high observed rotation measures ($|\mathrm{RM}| \sim 650$ rad m^{-2}) in two GPS sources with low ($<1\%$) polarization, 0201+113 and 0552+398 (DA 193). Both of these sources are high redshift quasars with values of 3.56 (McMahon and Wolfe 1990, private communication) and 2.365 (Wills & Wills 1976), respectively. Thus, correcting by $(1 + z)^2$ to put the RM in the rest frame of the source, we obtain $|\mathrm{RM}| \sim 1.3 \times 10^4$ and $\sim 7.4 \times 10^3$ rad m^{-2}, respectively.

[5] Thanks to Peter Scheuer for this suggestion.

[6] We have reclassified a few objects from the earlier papers based on new radio spectral data.

Thus at least some, though evidently not all, GPS sources have large Faraday depths in or around the radio source.

5. THE OPTICAL PROPERTIES

5.1. *The Optical Sample and Selection Effects*

We have compiled a heterogeneous "working sample" which currently consists of 95 GPS (or candidate GPS) radio sources (Table 1). We have made use of the lists compiled by Gopal-Krishna et al. (1983) and Spoelstra et al. (1985), though a few sources in the first list have turned out not to be true GPS sources (Paper I) and were dropped from our list. The lists by Gopal-Krishna et al. and Spoelstra et al. were biased toward sources which were either empty fields or stellar identifications without known redshifts since they were interested in quasar candidates and wanted to exclude low-redshift galaxies. We have supplemented this with a search of the literature, in particular relying on the extended 5 GHz sample (Kuhr et al. 1981a, b). Thus, this sample is not "complete" but is large enough to be useful and should be representative of the population of GPS sources with high flux densities at centimeter wavelengths. A complementary list which includes compact steep spectrum sources is given by Dallacasa & Stanghellini (1990).

5.2. *The Identifications*

A summary of the optical identifications and the milliarcsecond structures determined by VLBI are given in Table 2. Sources which are empty fields (EF) on the POSS make up 44% of the objects. CCD imaging has so far reduced the fraction which are empty fields to 19%. At this point the quasars make up 27%, the stellar objects 25%, and the galaxies 28%.

Redshifts are available for only small fraction of the objects so far. The existing redshift distribution for the galaxies and quasars are shown in Figure 2. This is discussed further below (§ 8).

5.3. *The Relationship with the Milliarcsecond VLBI Structure*

Tables 1 and 2 show that there are still large numbers of sources without optical identifications or redshifts or VLBI observations. The existing data suggest the trend that sources identified with galaxies tend to be compact doubles or triples, while the other identifications (quasars, stellar objects, EFs) tend not to be compact doubles or triples. This trend was previously noted (e.g., Phillips & Mutel 1982; Hodges & Mutel 1987; Kulkarni & Romney 1990) though the EFs were often lumped in with the galaxies. As seen in § 5.5, EFs can also be faint stellar objects.

5.4. *Unification?*

At this point it is not clear whether the GPS galaxies and quasars can be unified by beaming and projection effects or whether the relationship between host galaxy and VLBI structure reflects intrinsic differences in the central engine and/or gaseous environment. There are several pieces of evidence in favor of the latter hypothesis. GPS sources tend to have (1) low polarization (e.g., Rudnick & Jones 1982; Rusk 1988; Paper I), (2) low variability (e.g., Rudnick & Jones 1982; Seielstad et al. 1983), and (3) a steep high-frequency spectrum (e.g., Phillips & Mutel 1982; Pearson & Readhead 1988; Paper I), which all suggest that a "flat spectrum jetlike" component is not dominant. (4) So far GPS galaxies do not show superluminal motion (e.g., Pearson et al. 1990; Conway et al. 1990a) though compa-

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TABLE 1

WORKING LIST OF CANDIDATE GPS RADIO SOURCES

Source (1)	ID (2)	mag (3)	z (4)	ref (5)	radio spect. ref (6)	VLBI morph (7)	ref (8)
0008−421	EF	...	...	13	10,11	...	...
0018+729	G?	...	...	14	1	...	...
0019−000	G	19 V	...	15	1	cd	4
0022−423	?	21 R	...	10	3	...	...
0026+346	G	20.2 r	...	4	10	cd	6
0039+230	EF	...	...	16	3	...	...
0108+388	G	22 r	0.669	1	1,37	cd	2,29
0144+209	EF	...	...	16	3	...	...
0153+744	Q	16 V	2.338	17,35	13	cx	13
0159+839	S	17 V	...	16	3	...	...
0201+113	Q	19.5 R	3.56	18	1	pt	4
0218+357	S?	21 r	...	11,12	10	cd	6
0237−233	Q	16.6 V	2.223	17	1	cx	14
0248+430	Q	15.5 V	1.316	17	10	...	...
0316+161	G	22 r	...	2	10	cx	7
0319+121	Q	19.0 V	2.67	22,38	10	...	...
0404+768	G	22 r	0.5985	1,4	10	cd	12
0407−658	S	18.0 V	...	19	10,11	...	...
0420−388	Q	16.9 V	3.12	17	31	...	...
0428+205	G	20 R	0.219	20,33	10,11,29	ln	15,16
0457+024	Q	19.4 V	2.384	17	10,17	...	...
0500+019	S	21.2 r	...	2	1	pt	4,16
0528−250	Q	19 V	2.765	29	30	...	...
0528+134	S	19.5 r	...	9	10	pt	39
0552+398	Q	18.0 V	2.365	17	1	cx	18,19
0554−026	S	18.5 V	...	16	3	...	...
0602+780	EF	...	...	16	3	...	...
0615+820	Q	17.5 V	0.71	30	10	pt	33,40
0636+680	Q	19 V	3.184	17	20	...	...
0646+600	S	18.9 R	...	3	1	...	...
0703+468	S	21 R	...	37	20	cd	35
0710+439	G	19.7 r	0.518	4,35	10	ct	2,29
0711+356	Q	17.0 V	1.620	17	10	cd	2
0738+313	Q	16.1 V	0.631	17	10	...	...
0742+103	S	23.5 r	...	2,11	3	pt?	16
0743−006	Q	17.5 V	...	22	10	...	...
0802+212	EF	...	...	21	1	...	...
0858−279	S	17 V	...	13,16	3,10	...	...
0902+490	S	18.5 V	...	21	1	...	...
0904+039	EF	...	...	21	8	...	...
0914+114	EF	...	...	21	8	...	...
0941−080	G	19 V	...	22	10	...	...
1031+567	G	19.5 R	0.459	24	10	...	...
1100+223	?	24 R	...	8	1	...	...
1117+146	S	20 V	...	22	10	...	...
1143−245	Q	18.5 V	1.95	17	10	...	...
1225+368	S	21.6 r	...	3,4,5	1	cd	4,12
1245−197	Q	20.5 V	1.275	39,40	10	...	...
1312+699	EF	...	...	16	3	...	...
1323+321	G	19 R	0.369	19,24	10,21	cd	21,22
1333+459	Q	18.5 V	2.450	17	1	...	...
1345+125	G	17 V	0.122	23	10,11	ct?	12,38
1351−018	Q	19.3 R	3.709	24	3	...	...
1354−174	Q	...	3.147	31	32	...	...
1358+624	G	19.8 V	0.431	22,35	10,	pt?	12,16
1404+286	SyI	14 V	0.0768	20,33	10	pt	23
1413+349	EF	>22 r	...	3,4	1	ln	4,12
1433−040	EF	...	...	16	3	...	
1442+101	Q	17.8 V	3.544	17	10	ln?	24
1518+047	S	22.6 r	...	6	5	cd	5
1519−273	S	18.5 V	...	22	10	pt	25
1543+005	G	20.0 R	...	7	8	...	...
1600+335	EF	...	...	22	10	pt	12

TABLE 1 (CONTINUED).

Source (1)	ID (2)	mag (3)	z (4)	ref (5)	radio spect. ref (6)	VLBI morph (7)	ref (8)
1601−222	EF	...	...	21	8	...	...
1604+315	EF	...	...	16	3	...	...
1607+268	G	20.1 r	0.473	6,36	5,8	cd	5,36
1614+051	Q	19.5 V	3.210	25	26	...	...
1732+094	G	20.7 R	...	7,8	3	cd?	9
1751+278	G	21.7 R	...	7	3	...	...
1824+271	?	22.9 R	...	7	3	...	...
1843+356	S	17 V	...	16	3	...	
1848+283	S	17 V	...	26	20	pt	19,23
1851+488	S	19 V	...	22	10	...	...
1934−638	G	18.4 V	0.183	34	10,11	cd	27
2000−330	Q	19 V	3.780	25	10,26	pt	14
2008−068	G	21.3 R	...	2,7	3	...	...
2015+657	S	19.7 R	...	7	3	...	...
2021+614	G	17.9 R	0.2266	7,32	10	cx	2,16,28
2050+364	G	20.5 R	...	6,7	5	cd	5
2053−201	G	18 V	...	22	10	...	...
2121−014	?	23.4 R	...	7	3	...	...
2126−158	Q	17.3 V	3.270	25	26	...	...
2128+048	G	23.3 r	...	6	4,8	cd?	4
2137+209	S	19 R	...	37	4	pt	4
2149+056	G	20.4 R	...	7,8,9	8	...	...
2153−119	S	21.9 R	...	7	8	...	...
2210+016	S	21.7 r	...	2	10,11	...	...
2223+210	Q	18.2 V	1.959	17	10	...	...
2230+114	Q	17.3 V	1.037	17	10,11	cx	34
2236+124	S	19.5 V	...	22	20	...	...
2322−040	EF	>23.5 R	...	7	3	...	...
2323+790	G	20 V	...	14	3	...	...
2337+264	S	20 V	...	27	8	pt	4
2342+821	Q	20.5 V	0.735	28	3	...	...
2352+495	G	18.4 R	0.237	7	37	ct	2,29

Col. (1).—Name.

Col. (2).—Identification: G = extended, S = stellar, Q = quasar (with broad emission lines), SyI = Seyfert I, EF = empty field, ? = too faint to classify with the existing data.

Col. (3).—Magnitude and filter/color.

Col. (4).—Redshift.

Col. (5).—References for Identification, Magnitude, and Redshift.— (1) C. R. Lawrence (1988, 1990 private communication); (2) Fugmann, Meisenheimer, & Röser 1988; (3) Meisenheimer & Röser 1983; (4) Peacock et al. 1981; (5) Allington-Smith et al. 1982; (6) Biretta, Schneider, & Gunn 1985; (7) O'Dea, Baum, & Morris 1990; (8) Chu et al. 1985; (9) Fugmann & Meisenheimer 1988; (10) J. A. Peacock 1989, private communication; (11) K. Meisenheimer 1989, private communication; (12) Johnson 1974; (13) Prestage & Peacock 1983; (14) Kühr et al. 1987; (15) McEwan et al. 1975; (16) Spoelstra et al. (1985); (17) Hewitt & Burbidge 1987, 1989; (18). R. McMahon & A. Wolfe 1990, private communication; A. Kinney & R. White 1990, private communication; (19) Wall & Peacock 1985; (20) Blake 1970; (21) Gopal-Krishna, Patnaik, & Steppe 1983; (22) Kühr et al. 1981b; (23) Gilmore & Shaw 1986; (24) Dunlop et al. (1989); (25) Peterson et al. (1982); (26) Kühr et al. (1981a); (27) Owen & Rudnick 1976; (28) Pearson & Readhead 1988; (29) Morton et al. 1980; (30) Eckart et al. 1987; (31) Savage et al. 1990; (32) Bartel et al. (1984b); (33) Hewitt & Burbidge 1991; (34) Fosbury et al. (1987); (35) Lawrence et al. 1986; (36) Porcas 1990, (37) C. P. O'Dea et al. 1991, in preparation; (38) Spencer et al. 1989); (39). Impey & Tapia 1990; (40) R. Morganti 1991, private communication).

Col. (6).—Reference for radio spectrum (see note to col. [8]).

Col. (7).—Milliarcsecond scale radio morphology. cd = compact double, ct = compact triple, ln = linear, cx = complex, pt = unresolved or slightly resolved (so far).

Col. (8).—Reference for milliarcsecond morphology. References for cols. (6) and (8) are as follows: (1) O'Dea et al. 1990b; (2) Pearson & Readhead 1988; (3) Spoelstra, Patnaik, & Gopal-Krishna 1985; (4) Hodges, Mutel, & Phillips 1984; (5) Mutel, Hodges, & Phillips 1985; (6) Zensus & Porcas 1985; (7) Jones 1984 and Wilkinson et al. 1979; (8) Gopal-Krishna, Patnaik, & Steppe 1983; (9) C. P. O'Dea & D. W. Murphy in preparation; (10) Kühr et al. 1981b; (11) Wills 1975; (12) Kulkarni & Romney 1990; (13) Hummel et al. 1988; (14) Preston et al. 1989; (15) Phillips & Mutel 1981; (16) Waak et al. 1988; (17) Wall 1972; (18) Schilizzi & Shaver 1981 and Fey et al. 1985; (19) Spangler et al. 1983; (20) Kühr et al. 1981a; (21) Mutel, Phillips, & Skuppin 1981; (22) Kulkarni & Romney 1988; (23) Spangler et al. 1981; (24) Marscher & Shaffer 1980; (25) Linfield et al. 1988; (26) Peterson et al. 1982; (27) Tzioumis et al. 1989; (28) Bartel et al. 1984a; (29) Conway et al. 1990a, b; (30) Jauncey et al. 1978; (31) Condon et al. 1981; (32) Savage et al. 1990; (33) Eckart et al. 1987; (34) Wehrle & Cohen 1989; (35) R. L. Mutel 1990, private communication; (36) Phillips & Shaffer 1983; (37) Baum et al. 1990; (38) M. Shaw 1991, private communication; 39. Shaffer 1984; (40) Witzel 1987

TABLE 2

OPTICAL AND VLBI CLASSIFICATIONS

		MILLIARCSECOND MORPHOLOGY			
OPTICAL ID (1)	FRACTIONAL CONTRIBUTION (2)	No Observations (3)	Complex (4)	Point (5)	Double/Triple (6)
Stellar	25.2%	13	0	7	4
Quasar	27.4	17	5	3	1
Galaxy	28.4	6	3	2	13
EF	19.0	16	1	1	0

Col. (1).—Optical identification. Quasars are stellar and have spectra which show broad emission lines, Stellar objects do not yet have spectroscopic observations, Galaxies are extended, and Empty fields (EF) are not seen on the existing images (POSS plates or CCD frames).

Col. (2).—Fractional contribution of that ID class to the entire sample of 95 objects.

Col. (3).—Sources without VLBI observations.

Col. (4).—Sources with complex structure.

Col. (5).—Sources with mostly unresolved structure.

Col. (6).—Sources with compact double or triple structure.

rable limits have not yet been set on GPS quasars. These properties suggest that beaming effects are probably not very important, though they may still be present at low level. More stringent constraints on beaming in the GPS quasars are needed. (5) The redshift distributions of GPS galaxies and quasars are apparently very different (Fig. 2), though selection effects may be important here. Obtaining redshifts for complete samples of GPS quasars and galaxies (especially including the very faint galaxies—see Table 1) is essential in sorting this out.

Note that one of the quasars (0711+356) and some of the stellar objects (0218+357, 0703+468, 1225+368, and 1518+047) are candidate compact double sources (see Table 1). Barthel (1989) has suggested that all quasars are beamed toward us. Yet, as we argue above, at least the compact double galaxies do not appear to be beamed. If spectroscopy and further VLBI imaging shows that these objects are indeed compact double quasars and that they are also not beamed, then they would be a strange type of "unbeamed quasar."

5.5. *What Are the Very Faint Identifications?*

The faint objects which are not observed on the POSS (so $m_R \gtrsim 20$) have recently been the subject of much interest. So far 27 GPS sources which are empty fields on the POSS have been the subject of deep red CCD images (e.g., O'Dea, Baum, & Morris 1990a; C. R. Lawrence 1988, private communication; Fugmann, Meisenheimer, & Röser 1988; Biretta, Schneider, & Gunn 1985; Chu, Zhu, & Butcher 1985; Meisenheimer & Röser 1983; Allington-Smith et al. 1982; Peacock et al. 1981). A summary of the results so far are given in Table 1, and a histogram of the red magnitude (or limits) of the objects is given in Figure 3. Obviously, CCD imaging of GPS sources has proved very successful with ~90% of the observed objects identified so far. About 80% of the 27 objects have red magnitudes brighter than 23.

Thus, the data in Table 1 are consistent with the hypothesis that the optically faint GPS sources are a mixed group of objects (similar to other sources selected at *high* frequencies), although they are preferentially faint radio *galaxies*. The fact that the GPS sources are a heterogeneous group makes it

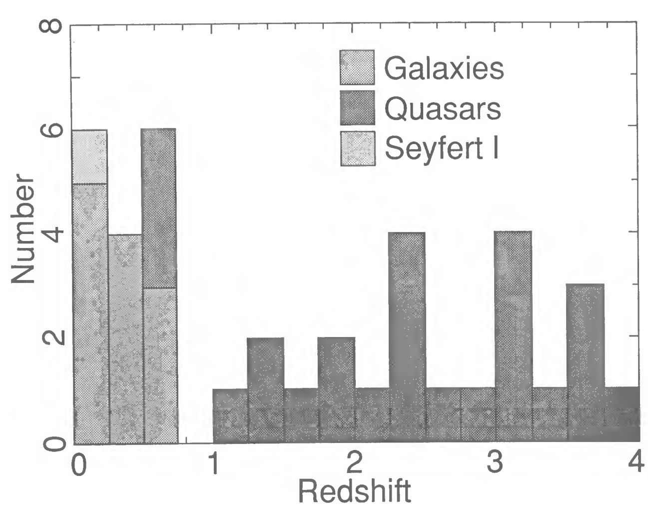

FIG. 2.—A histogram of the distribution of the currently known redshifts of the GPS galaxies and quasars. Note the concentration of the quasars to high redshifts $2 \lesssim z \lesssim 4$.

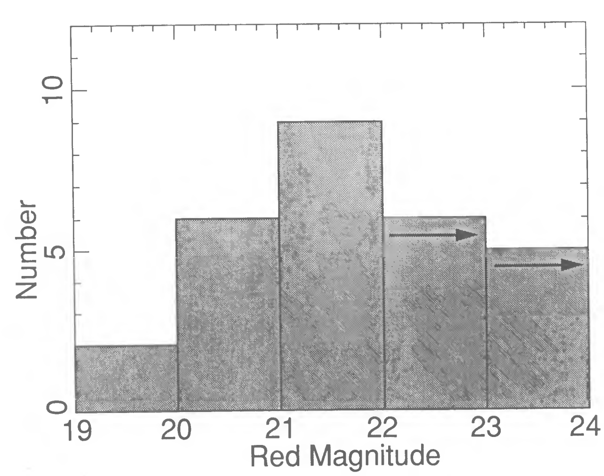

FIG. 3.—A histogram of the red magnitude or upper limit obtained from deep CCD observations of the hosts of the GPS sources which are not visible on the POSS.

difficult to explain them all within a single scenario. A search for correlations between the radio spectrum, radio morphology, and optical classification will hopefully shed some light on these sources. However, additional data (VLBI imaging and optical imaging and spectroscopy of a large sample) is needed before this can be done with confidence.

5.6. *Low Optical Polarization?*

Impey & Tapia (1990) have published a compilation of optical polarization measurements (many of them their own) of 163 radio-selected quasars. Impey & Tapia find that 34% of the quasars have high polarization (defined to be above 3%). They report measurements for only six GPS sources from Table 1, thus the results are not statistically meaningful. We simply point out that only one of the six GPS sources (2230+114, CTA 102) has high polarization. Further optical polarization measurements would be useful to determine whether low optical polarization is another characteristic of GPS quasars.

6. ARE THE HOST GALAXIES OF GPS SOURCES INTERACTING?

Deep CCD images of many GPS sources have now been obtained (e.g., Peacock et al. 1981; Biretta et al. 1985; Jauncey et al. 1987; Fugmann et al. 1988; O'Dea et al. 1990a). The GPS sources tend to show nonelliptical isophotes as well as the presence of companions. Thus, it is clear that at least *some* GPS sources are interacting and possibly also merging. The sample of eight GPS galaxies imaged by O'Dea et al. (1990a) is unbiased since they are so faint that their optical morphologies were not previously known. In this small sample, five ($\sim 60\%$) of the objects have large distortions in their isophotes and are thus apparently interacting (or forming?). More imaging work on larger unbiased samples (and a comparison sample) is necessary before it is clear whether GPS sources have a higher frequency of interaction than extended radio galaxies.

In one scenario (Phillips & Mutel 1982; Carvalho 1985), GPS sources[7] which are not identified with quasars are very young ($t \lesssim 10^4$ yr) powerful radio galaxies. It has been suggested that interactions or mergers are important in triggering activity in powerful AGN (e.g., Toomre & Toomre 1972; see Heckman 1990 for an update). If this is correct, then the evidence for interaction in GPS sources is consistent with the hypothesis that they have recently become active. However, the time scale of a merger or interaction and the existence of the disturbances in the optical morphology may be quite long $\sim 10^9$ yr (e.g., Toomre & Toomre 1972; Schweizer 1986). This suggests that (1) the hypothesis of a *recent* trigger of the activity is not unique and (2) the lifetime of GPS sources may also be comparably long.

The evidence for mergers/interactions in GPS sources is also consistent with the alternate hypothesis for their origin, i.e., that of the "smothered radio galaxy" (see Introduction).

7. RESULTS FROM SPECTROPHOTOMETRY

The diagnostics available from optical spectroscopic observations are likely to provide crucial information about the environment of the sources and their origin. Two of the current scenarios for GPS sources, the "smothered" and "frustrated" radio galaxies, predict much higher densities and/or pressures in the NLR than are found in the nuclei of typical extended radio galaxies. Fosbury (1990) discusses the implications of his spectroscopic observations of 1934−638. He suggests that the data support the hypothesis that the nuclear radio source is confined by gas of atypically high pressure. Here we make a few additional comments concerning the spectra of the compact doubles 1934−638 (Fosbury et al. 1987) and 2021+614 (Bartel et al. 1984b). At this point, these are the only two narrow-line GPS sources with useful spectra, though we are in the process of observing additional objects.

7.1. *High Reddening*

The Balmer decrement is generally thought to be a useful indication of reddening in the narrow-line region (e.g., Ferland & Osterbrock 1985). Typical narrow-line radio galaxies have ratios of ~ 2.9 (e.g., Costero & Osterbrock 1977). The two compact doubles have much higher ratios,[8] ~ 6.4 and $\gtrsim 7.5$, for 1934−638 and 2021+614, respectively. These higher ratios indicate that these sources have larger amounts of gas and dust between us and the emission-line region than found in typical narrow line radio galaxies.

7.2. *Asymmetric Line Profiles*

Bartel et al. (1984b) discovered that the [O III] line profile in 2021+614 is very asymmetric. They characterize the profile with two Gaussians of FWHM $\sim$ 600 km s^{-1} and separation $\sim$780 km s^{-1}. They suggest two possible explanations for the asymmetry. Large-scale mass motions in the nucleus (perhaps caused by interaction with the radio source) are one possibility. The second is (as first suggested by Heckman et al. 1981 for Seyfert galaxies) absorption by dust combined with radial motions of the emission-line clouds. The second possibility is consistent with the large observed Balmer decrement and argues for large amounts of gas and dust in the nucleus.

The evidence so far suggests that the NLRs of the two GPS sources observed so far are unusually dense and dusty. This is consistent with the smothered and frustrated source hypotheses. Sensitive high spectral resolution observations of additional sources are required to establish whether this is a general property of GPS nuclei and if so, to quantify the effect.

8. THE REDSHIFT DISTRIBUTION OF GPS QUASARS

Back in 1982, Peterson et al. pointed out that quasars at high redshift $z > 3$ tended to have a peak in their spectrum near 1 GHz. Menon (1983) noticed the existence of high-redshift quasars with peaked radio spectra and suggested that the quasars became increasingly more compact at higher redshift. Barthel (1986) remarked that steep spectrum extended quasars are rare at high redshift $z \geq 2.5$. O'Dea (1990) has re-examined this question with the larger sample of quasars now available on the Hewitt & Burbidge (1987) catalog. Of the 21 high-redshift $z \gtrsim 3$ quasars, 14 have sufficient data that the shape of the radio spectrum can be determined. Seven (50%) of these appear, based on the current data, to be GPS sources. In

[7] Strictly speaking this model applies to sources with compact double/triple radio structure. The milliarcsec morphology is not known for most of the sources we have imaged. But the excellent correlation between compact double/triple structure and galaxy identifications (e.g., § 5.3, Table 2, and Hodges & Mutel 1987) suggests that it is safe to apply this argument to the galaxy identifications.

[8] In the moderate resolution spectra of both of these sources, the Hα λ6563 emission line is blended with that of [N II] λλ6583 and 6548. We have made a rough estimate assuming the intrinsic line ratios are 1:0.8:0.3, respectively (e.g., Osterbrock 1989).

order to check for selection effects, a complementary (though not completely independent) approach was carried out. The catalog was searched for redshifts of objects currently known to be GPS sources. These objects are clearly concentrated toward high redshifts: 12 of the 14 objects have $z > 2$, and seven (50%) have $z > 3$. There is a deficiency of GPS quasars[9] with redshifts between 0.1 and 2.0. Thus, O'Dea found that using GPS radio spectra to find high-redshift quasars has a remarkable success rate of $\sim 50\%$. Redshifts of stellar GPS sources should be obtained to expand the sample of GPS quasars and test this hypothesis. Assuming this is confirmed, we discuss possible implications below.

8.1. *Confined Sources*

Barthel & Miley (1988) studied a sample of high-redshift $z > 1.5$, steep spectrum $\alpha > 0.6$, quasars. They compared these objects to a sample of low-redshift steep spectrum quasars and concluded that the radio structures on the kpc scale were smaller (and possibly more distorted) in the high-redshift sample. They attributed this to the existence of a denser and clumpier medium at the higher redshifts (see also Allan 1984). O'Dea suggests that the GPS quasars are the extreme cases of sources confined to the nuclear regions of the host galaxy by a dense and clumpy medium (see also Menon 1984; Barthel 1986). In this scenario they are "frustrated" sources which remain compact and therefore have synchrotron self-absorbed radio spectra.

Note that there are some high-redshift radio galaxies with extended structure on scales of tens of kpc (e.g., Miley & Chambers 1989 and references therein). Thus, not all high-redshift radio sources remain confined to the nuclei. At these redshifts, the host galaxies involved are probably still forming. This raises the question of whether radio galaxies and quasars form in different environments. Complete samples of objects are needed to address this question.

8.2. *Young Radio Sources*

An important alternate (though related) hypothesis is that the GPS quasars have compact radio sources because they are young and the sources have not yet propagated out of the nuclear regions (see also Blake 1970; Phillips & Mutel 1982; Carvalho 1985). However, if the sources spend only a very small time in this stage, then it is hard to understand why such a large fraction of the high-z sources ($\sim 50\%$) are found to be compact GPS sources. Thus, if this model is correct, the source propagation must be slowed down by the dense and clumpy environment in the ISM of the young host galaxy. This scenario then becomes more like the "frustrated" source hypothesis discussed above. Perhaps the sources spend a long time in the dense nuclear regions but then finally escape to produce extended radio structures.

A crude dynamical age can be calculated assuming a balance between ram pressure and internal pressure; $\rho v^2 \simeq P$ where ρ is the external density, v is the expansion velocity, and P is the internal pressure. The compact radio structures of GPS sources have minimum pressures in magnetic fields and cosmic rays of $\sim 10^{-4}$ dyn cm^{-2} (e.g., Mutel et al. 1985). The external density is very uncertain since the parameters of the ISM and the amount of clumping are unknown; however, the derived velocity depends on the square root of the assumed density. We adopt a uniform density of 10^4 cm^{-3} which is that required for free-free absorption to be important. The expansion velocity of the radio source is then $v \sim 800$ km s^{-1}. Adopting a lobe separation of 10 pc gives a dynamical age of $\sim 10^4$ yr, which is quite short. The young dynamical ages are one of the main motivations for the hypothesis that GPS sources with compact double structure are very young (e.g., Mutel et al. 1985).

If the typical lifetime of a classical double radio source is $\sim 10^7$ yr and the radio luminosity does not diminish substantially over this lifetime, then the GPS quasars should make up about 0.1% of high-redshift radio-loud quasars. Yet, they seem to be a much larger fraction, of order $\sim 50\%$. This is a problem for the "young radio source hypothesis" for the high-z GPS quasars.[10] We suggest that the dynamical ages inferred from the naive arguments above are seriously underestimated. Recent numerical simulations (Lind 1990; De Young 1990; Balsara & Norman 1990) suggest that dense clouds can be extremely effective in stopping and/or deflecting light radio jets. Thus, the growth of the radio source is dominated by the interactions with dense clouds rather than by the ram pressure from a putative uniform intercloud medium. If the medium around the radio source is indeed very clumpy, then the propagation will be significantly slowed and the ages inferred from ram pressure balance in a uniform medium will be too low. Thus, the compact radio structures in GPS sources could be much older than previously thought. This suggests that the GPS quasars may not be simply younger versions of the objects with extended radio structure.

8.3. *Gravitational Lenses*

M. Rees (1990, private communication) has suggested what he considers an unlikely possibility, namely gravitational lensing. He suggests that if there were a large population of lensing objects of mass $\sim 10^6\ M_\odot$, they would be able to magnify the compact (up to ~ 1 pc) but not the more extended radio components of the sources. In this scenario, if the typical source has a characteristic angular scale which decreases toward higher frequencies, this would give an apparent spectrum with a peak and would be an effect only expected at high redshifts. VLBI observations to determine the parsec-scale radio morphology of the high-redshift GPS quasars could test this hypothesis. (e.g., Gurvitz et al. 1991).

9. RELATIONSHIPS BETWEEN GLOBAL PROPERTIES OF THE GPS SOURCES

9.1. *The Existence of a Uniform Class of GPS Sources*

At the present time, our sample is small, and the amount of data we have collected is still modest and subject to selection effects (see § 2). However, we undertake a preliminary examination of the relationships between different known properties in search of additional clues to the nature of these sources. Examination of the data in Paper I suggests the following.

For GPS sources, the very low radio polarization and the exact details of the shape or steepness of the radio spectrum do not depend on the optical identification or milliarcsecond radio structure. In particular we find that low polarization and steep optically thin spectra are characteristic of GPS sources as

[9] There is at least one low-redshift GPS source that has been classified as a Seyfert 1 galaxy, OQ 208 with $z = 0.077$, so low-redshift analogs do exist.

[10] A similar problem may exist for the GPS galaxies since there appear to be too many compared with the numbers of classical double radio galaxies.

a class and not just the compact doubles or galaxy identifications.

Thus, the data show that the GPS sources share common properties including radio spectral shape, low radio polarization, and low radio variability. This suggests that the GPS sources are linked by a common process and/or physical conditions in their environment. Based on the current data, we suggest that the GPS galaxies and quasars are both produced when radio sources are confined to the nucleus of the host galaxy by a dense and clumpy ISM.

9.2. *What Are Compact Doubles?*

This leads us to question whether the compact doubles are really a distinct subclass of GPS source. The relationship between identification and mas radio structure is not as simple as the early data suggested. Some sources with simple symmetric structure are identified with quasars (0711+356; Pearson & Readhead 1988) or stellar objects (1225+368; Peacock et al. 1981, Meisenheimer & Röser 1983; 1518+047; Biretta et al. 1985). On the other hand, some GPS sources identified with galaxies have complex milliarcsecond radio structure (0316+161: Wilkinson et al. 1979, Jones 1984; 2021+614; Bartel et al. 1984a).

The trend for GPS quasars to lack simple symmetric double structure may be caused by a number of things.

1. The higher redshifts of the quasars means that the available linear resolution may not be sufficient to resolve the double components.
2. The quasars are at higher redshifts and have their peaks at intrinsically higher frequencies and so may be intrinsically more compact than the galaxies.
3. Projection effects may disguise the double morphology if orientation and beaming effects are important in the quasars (e.g., Orr & Browne 1982; Barthel 1989); though we doubt that these are important (§ 5.4).
4. The radio morphology may be more distorted in the quasars than in the galaxies if the nuclear emission-line regions are more clumpy or turbulent in the quasars and the radio plasma interacts strongly with the ambient medium.

The term "compact double" may itself be a misnomer since when looked at with higher resolution and/or dynamic range, the compact double sources show increasing amounts of substructure and complexity (Mutel et al. 1985; Bartel et al. 1984a). We suggest that the compact doubles are simply the most symmetric sources of a distribution of radio morphology in GPS sources.

9.3. *The Relationship between CSS and GPS Sources*

The radio properties of the compact steep spectrum (CSS) sources have been well studied (van Breugel, Miley, & Heckman 1984; Wilkinson et al. 1984a, b, 1985; Pearson, Perley, & Readhead 1985; Fanti et al. 1985, 1989, 1990; van Breugel et al. 1988; Spencer et al. 1989; Akujor, Spencer, & Wilkinson 1990; Simon et al. 1990). These sources have very similar properties to the GPS sources and appear to be simply larger (though still subgalactic) scaled up versions of GPS sources. However, the redshift distribution of the CSS quasars (Fanti et al. 1990) does not show the same preference for high redshift found in the GPS quasars. The CSS sources may also be confined by a very dense and clumpy ISM (van Breugel et al. 1984, 1988; Wilkinson et al. 1984a, b; Spencer et al. 1989; Fanti et al. 1990). Two possibilities for the relationship between GPS and CSS sources have been discussed. Mutel & Phillips (1988) have suggested that GPS sources evolve into CSS sources. This implies that GPS sources are small simply because they are young. The alternative hypothesis is that the GPS and CSS sources have become trapped at their present sizes and will not become much larger (see Fanti et al. 1990 and Wilkinson et al. 1984a for discussions of this for the CSS sources). This trapping or smothering may have been caused by cannibalism of a gas-rich companion (Baum et al. 1990) which dumped in sufficient gas to interact strongly with the radio source and halt further expansion.

There are several items which support the smothered radio source explanation.

1. The young source hypothesis cannot explain the $\sim 20\%$ of GPS sources with extended structure (Baum et al. 1990; Stanghellini et al. 1990a, b).
2. There are too many GPS sources relative to the number of classical doubles (see § 8.2).
3. The existing radio and optical data are consistent with the existence of an unusually dense medium surrounding the radio source. Thus, we suggest that the smothered radio source hypothesis is currently favored by the data. This does not rule out the possibility that *some* GPS sources are young, which would be very interesting.

10. FINAL REMARKS

At present, the GPS sources remain very enigmatic, and their origin and their relationship to other compact and extended sources are not understood. The defining characteristics of these objects are (1) their peaked radio spectra with narrow spectral shape and steep high-frequency spectrum, (2) low radio (and optical?) polarization, (3) large radio luminosities, and (4) mostly compact radio structure. However, the host objects of GPS radio sources are a heterogeneous mix of radio galaxies and quasars. The radio galaxies and quasars have different properties (milliarcsecond radio morphologies, optical spectra, redshift distributions), and their relationship is not yet clear. Orientation and Doppler-boosting may not be the dominant effects distinguishing the galaxies and quasars. In an effort to shed some light on these sources we have discussed here some recent radio and optical results which we and others have obtained. We draw the following conclusions.

The radio spectra are consistent with tight confinement of the radio source and the lack of a bright beamed "jetlike" component. The radio luminosity is dominated by "old" electrons ($t \gtrsim 2 \times 10^5$ yr) with a steep high-frequency spectrum emitted in regions which are fairly homogeneous and/or are expanding much slower than their internal sound speed.

Interaction with dense clouds of gas is likely to slow the propagation of the radio source significantly below that expected on the basis of naive ram pressure estimates.

The GPS sources share common radio properties with and appear to be smaller versions of the CSS sources and are thus probably related. We suggest that the GPS sources are trapped on smaller size scales by a dense medium and are not necessarily younger than the CSS sources.

GPS galaxies tend to have distorted isophotes which suggests that they are interacting. These interactions may result in cannibalizing gas and dust from a companion. The sudden accretion of large amounts of gas and dust could have significant effects on the properties of the narrow line region and the embedded radio source. It might produce the inferred dense, highly reddened narrow emission-line regions (based on spectrophotometry of two compact double sources). It might also produce the observed depolarization (and possibly high Faraday rotation measures) in the radio source. It might also confine the radio source to the nucleus as discussed by Baum et al. in our "smothered radio source" model.

The GPS quasars tend to be found at high redshift (half with $z > 3$). At these epochs galaxy formation is expected to be an ongoing process. It is possible that the radio sources in the high-redshift GPS quasars are trapped or "frustrated" in the nuclear regions by the dense clumpy ISM of the young protogalaxy, though other explanations are still possible.

In summary, we suggest that GPS sources are formed when the radio source is trapped in the nucleus of the host galaxy by a very dense and clumpy ISM. This has observational consequences which we are in the process of testing.

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