Optical imaging and spectroscopy of candidate GPS radio sources

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Deep optical imaging and spectroscopy, obtained with the Very Large Telescope (VLT), is presented, targeting the host galaxies of candidate GPS radio sources from the master list of O’Dea et al. (1991). Our goal is to measure new redshifts, identify optical counterparts and address uncertain identifications. We measure redshifts for B0316+161, B0407–658, B0904+039, B1433–040, and identify the optical counterparts of B0008–421, B03161+161, B0407–658, B0554–026, B0742+103, B0904+039. We find that the previous identification for B0914+114 is incorrect. Using literature data we furthermore show that the following sources are not GPS: B0407–658, B0437–454, B1433–040, B1648+015.
3.1 Introduction

GPS radio sources are fairly common – O’Dea (1998) lists a 10% fraction in high frequency selected catalogs. It is fairly well established now that the extended radio galaxies and quasars should be unified with the compact, core-dominated quasars and BL Lac-objects through the combined effects of radio jet orientation and anisotropic obscuration (e.g., Urry & Padovani 1995). These objects are considered to be mature, well developed radio sources. It is likely that GPS objects are young radio sources that will evolve into the 10 – 100 kpc scale objects. Both theoretical work and observational studies of GPS host galaxies support this picture. As for the former, model and data require declining radio luminosity with age. As for the latter, multi-color optical as well as near-IR imaging (e.g., de Vries et al. 2000a) have shown that host galaxy colors of nearby GPS objects are indeed consistent with non- or passively evolving ellipticals, with absolute magnitudes comparable to brightest cluster members, similar to the hosts of intermediate sized and large radio source classes. Determination of the rest-frame broad-band colors (which requires redshifts) in connection with stellar synthesis modeling has proven essential for these investigations1.

O’Dea et al. (1991) presented a list of candidate GPS radio sources. About half of those sources had unknown redshifts and several lacked an optical counterpart. Our goal in this chapter is to increase the number of optical identifications, measure new redshifts and remove non GPS sources present in the list (with the currently available radio data). The sample under consideration is comprised of the unidentified objects from the master list of O’Dea et al. (1991), updated by de Vries et al. (1997a), and consists of all peaked spectrum radio sources having cm flux densities in excess of 0.5 Jy. Here present VLT observations of sources with unknown redshifts or optical counterparts and increase the number of GPS sources (up to ~ 90%) of the complete O’Dea et al. (1991) list. We give new host identifications (down to R ~ 25) and obtain several new redshifts. We use H0=71, ΩM = 0.27, ΩΛ = 0.73 (Spergel et al. 2003) throughout the chapter.

3.2 Observations and data reduction

The sample was observed during two nights (January 30 to 31, 2000, and December 16 to 17, 2001) using VLT’s FORS1/UT1 and FORS2/UT4. We obtained long slit spectroscopy using grism 150I with order separators OG590 and GG375, obtaining a 230 Å/mm dispersion (5.52 Å/pix) and covering wavelengths 6000–11000Å(OG590) and 3850–7500Å(GG375). For the photometry we used a R-Johnson-Cousins filter for the January 2000 run. For the December run, we used B, V- Johnson-Cousins and the R-Special filters2. We covered a 6.8 arcmin field with seeing ranging from 0.5” to 0.7 ” for the January run and 0.5” to 1.1” for the December run.

Standard data reduction was performed using IRAF routines. All the spectra were corrected for bias, flat-field and sky lines. Wavelength calibration was done using internal arc lamps. The flux calibration and removal of atmospheric features were performed using

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1Chapter 7 presents a study on star formation in hosts of GPS and CSS.
2The R-Special filter on FORS2 is a Johnson-Cousins filter with a slightly shortened red end to avoid sky emission lines.
the spectrophotometric standards GD50 and GD108.

The calibration of the imaging data was different for the January and December runs. The January observations were done during a photometric night. We took flat field images and observed the Landolt (1992) standard fields PG1323–086 and SA 95. No useful standard fields or flat fields were observed for the –non photometric– December run. To calibrate these images, we averaged all the observations in each filter separately to create artificial flat-field images, which we used for the calibration. As standard stars, we chose unsaturated field stars with data in the GSC2.2 catalog (~ 40 stars in total). The GSC stars have available magnitudes in the photographic F and J bands. The transformation to the Johnson-Cousins filters was performed following Kent (1985). The January images were taken only in R-band. For the December run, most of the standards lacked color information to perform (first order) color coefficient corrections to our apparent magnitudes. We could only fit the zero point magnitudes in each band.

### 3.3 Results

#### 3.3.1 Identifications

The astrometry was performed using the GSC2.2 catalog as reference. It was possible to make accurate (usually with $1\sigma$ error < 0.5 arcsec) positional determinations for the candidate optical counterparts. As in de Vries et al. (1995) and de Vries et al. (2000a), we use the likelihood ratio defined by de Ruiter et al. (1977):

$$R = \sqrt{\frac{\Delta \alpha^2}{\sigma_\alpha^2} + \frac{\Delta \delta^2}{\sigma_\delta^2}}$$

(3.1)

where $\Delta \alpha$ and $\Delta \delta$ are the measured offsets in RA and Dec between the optical and radio positions, $\sigma_\alpha^2$ and $\sigma_\delta^2$ are the sums of the squared $1\sigma$ errors in the optical and radio positions. An $R$-value less than three indicates a probability of less than 1% to miss a true identification (assuming that the optical counterpart is the object closest to the radio position). The probability that a true optical counterpart has an $R$-value larger than some $R_0$ is given by $P(R>R_0) = e^{-0.5R_0^2}$. Most of our identifications have $R$-values smaller than 3 and are likely to be correct. The optical position used in the calculation of $R$ and listed in Table 3.1 corresponds to the pixel of the optical object closest to the radio position. The identification results are listed in Table 3.1 and finding charts for the sources are presented in Figure 3.5.

#### 3.3.2 Magnitudes

The magnitudes were extracted performing aperture photometry. We used apertures large enough to include all light from the object (typically a diameter of ~ 10 pixels) but minimizing the contribution from sky. As judged from internal consistency of field stars with known magnitudes, our photometric accuracy varies between 0.1 and 0.4 magnitudes. The main source of error, except for B0008–421, comes from the uncertainties in the magnitudes of the stars used in the calibration. B0008–421 and B0742+103 were observed in the $R$-Johnson-Cousins filter in the January 2000 night. It was a photometric night and
Table 3.1--. Positions of the optical counterparts. The radio positions are from NED. The "R" factor is the likelihood ratio (see text for details). The optical coordinates of B0914+114 correspond to the galaxy previously - and incorrectly - identified as the counterpart (see notes on individual source). The errors in the magnitudes are divided in photon noise (first error) and calibration (second error). The magnitudes are corrected from galactic extinction, following Schlegel et al. (1998). B0316+161 magnitudes may be affected by close-by (~3") objects.

Comparison with the Hubble diagram (O’Dea et al. 1996a; Snellen et al. 2002) show that the R magnitudes we measure are consistent with previous observations of GPS hosts. We measure V magnitudes consistent with those from di Serego-Alighieri et al. (1994) although ours tend to be slightly fainter. We have not found published B magnitudes for comparison.

3.3.3 Spectra and redshifts

We took spectra of 16 sources to measure their redshifts. Table 3.2 and Figure 3.4 show those sources where emission features were found. We measure redshifts for B0316+161, B0407–658, B0904+039, B1433–040 (with a conservative error of ±0.001) and B0914+114. Some sources show possible emission lines but their redshifts are uncertain (see notes on each individual object below): B0008–421, 1300-059, and B1045+019. The spectra were too noisy to find emission features for B0437–454, B0742+103, B1601-222 and B1648+015.

3.3.4 Stellar synthesis models

We have compared our redshift and magnitude measurements with the Bruzual & Charlot (2003) stellar population synthesis models. Most of our objects are radio galaxies so we expect the contribution from the AGN emission to be minimal: most of the radiation would...
Table 3.2– Line identifications and redshifts. For B1433–040, the redshift is measured with the narrow emission profiles. The * means the redshift estimation is uncertain for that source, see text for details. The FWHM listed is the observed FWHM corrected from the FWHM of the instrumental spectrum. Fluxes in $10^{-16}$ erg/cm$^2$/s. A conservative error for $z$ is ±0.001. The B0914+114 results correspond to the unrelated galaxy. It shows emission and absorption lines mixed so the centers are more uncertain than in the other sources (the 1σ error in $z$ is listed below the mean value) and line properties will depend on the stellar population model. The last column lists the radio power in W/Hz of the source for the redshifts listed. The 5GHz fluxes are from O’Dea (1998) and Wright & Otrupcek (1990).
be associated with stars in the host. Furthermore, previous work (O’Dea et al. 1996a; Snellen et al. 1996) find the R (and K) band magnitudes to be dominated by the host’s stellar population for these sources.

The models have been run using the Chabrier (Chabrier 2003) initial mass function, metallicities $Z=0.008$, $Z=0.02$, $Z=0.05$ and ages (time since the initial starburst) ranging from 5 to 12.5 Gyr. Different star formation histories have been used: instantaneous burst, exponentially declining, and constant star formation. We fitted colors $B-V$ and $V-R$ for those sources where the color information was available, and magnitudes when color information was not available. The hosts of GPS/CSS are usually massive elliptical galaxies (e.g., de Vries et al. 2000a) so we used masses of $10^{11}$ and $10^{12} \, M_\odot$ to fit those sources without color information.

Constant and exponentially declining star formation models seem to be ruled out by our data. The data points and best models disagree by roughly 2 magnitudes for sources without color information and 0.5–1 magnitude for those sources with color information. The data show better agreement with the instantaneous burst models. However our observed colors are predicted by instantaneous burst models with ages of $\sim6$ Gyr and metallicity 0.05, as well as ages of $\sim12$ Gyr and metallicity 0.008; and consequently, all the intermediate models. The probable contribution from emission line gas and this degeneracy between metallicities and ages makes it almost impossible to choose among the instantaneous burst models.

### 3.4 Notes on individual sources

**B0008–421**: Following unsuccessful attempts by di Serego-Alighieri et al. (1994), de Vries et al. (1995) and Costa (2001), we have now identified the bright radio source B0008–421 with an R=24.3, somewhat diffuse galaxy. We detect a faint object, 0.2" from the VLBI position. The spectrum is consequently faint and very noisy making it difficult to distinguish real emission lines from noise. We only find one possibility for redshift: $z=0.457$. Comparison with the GPS Hubble diagram (O’Dea et al. 1996a) shows that for a redshift between 0.4 and 0.5, we would expect an apparent R magnitude around 19 or 20. Our magnitude is consistent with previous non-detections (with limits down to 23 magnitudes) and, according to O’Dea et al. (1996a) the redshift of the object would be around 1.1.

**B0316+161**: Our deep image confirms the earlier identification of this well known GPS radio source, (also known as CTA21), by Stanghellini et al. (1993). We find a rather compact host, and note in passing that the object seen 8" NNW of the CTA21 identification in the Stanghellini et al. image is spurious. The relative faintness of B0316+161, and the proximity (~0.3") of other objects, may be affecting our measured magnitudes. The spectrum shows a weak continuum with bright $[O\,\text{II}]$ and $[O\,\text{III}]$ lines. We measure $z=0.907$ based on five lines.

**B0407–658**: Stickel et al. (1996) identified the optical counterpart of this radio source as a galaxy. The spectrum shows a faint continuum spectrum where we identify nine emission lines at $z = 0.962$. With this redshift, the emission line gas extends extends $3.2" = 25 \, \text{kpc}$
A 2 pixel resolution yields a velocity resolution limit of $\sim 500$ km/s for the central part of the spectrum. Although this source has been classified as GPS previously (e.g., O’Dea et al. 1991), the radio spectrum (Figure 3.1) shows no peak. It is probably a CSS source or a larger radio source. However, ATCA observations have not resolved it (resolution $\sim 5\times 3''$, Morganti et al. 1993).

**B0437–454**: Bright continuum but no emission lines. One possible line at 9539 Å, probably a cosmic ray. If it were [O III] (at z= 0.905), we would not be detecting [O II] 3727 (which should be at 7100 Å for that redshift). A literature search indicated that the radio spectrum of B0437–454 is only marginally peaked. In addition, pronounced variability was reported: 0.6 Jy vs. 1.4 Jy at 5 GHz. Also given the identification with an optical point source, we conclude that the object is a BL Lac object and should be removed from the GPS list.

**B0554–026**: We confirm the identification of de Vries et al. (2000b) (z=0.283) of this galaxy. We find a rather bright (B=18.3, V=17.5) and extended source ($\sim 5''$). We obtain $R = 16.4$ but this band may be affected by calibration problems (see Section 3.3.2).

**B0742+103**: Neither Stickel et al. (1996) nor de Vries et al. (1995) were able to identify the host of this relatively bright radio source. Our UT1 image, which unambiguously identifies the source with a compact host galaxy, indicates that the Fugmann et al. (1988)
and de Vries et al. (2000b) near-identifications were correct: we establish R=23.1. We took long slit spectra of this source both in the January and the December run. Both observations show a faint spectrum and features which could be lines. However, none of these features are present in both spectra. Best et al. (2003) measure 2.624 ±0.003 based on Lyα, C IV, He II and C III] between 4400 and 6920 Å. We detect a faint (slightly brighter than noise) emission at 6922 Å which could be the Best et al. (2003) C III]. Having only one emission feature, we cannot get an independent redshift measurement. If their redshift is correct, using the 5GHz flux density from O’Dea (1998), the source would have a radio power of $2.1 \times 10^{28}$ W/Hz.

**B0904+039**: The deep UT1 image reinforces the earlier identification of this GPS radio source (de Vries et al. 2000a, I=22.5) with a faint host (V=24.90) in a group of faint galaxies. The spectrum shows a weak continuum. We measure $z=0.830$ based on the [O II] and [O III] lines.

**B0914+114**: Our B and V band images show an empty field at the radio coordinates. Stanghellini et al. (1993) emphasize that the WSRT declination coordinate is affected by the elongated N-S beam for low declination sources and suggest that the disk galaxy ~6" south of the radio position could be the host of the radio source. The FIRST and NVSS surveys agree with the Texas/WSRT position for the radio source. Furthermore, this optical galaxy does not show a radio counterpart in the FIRST image (5σ detection limit of 0.9 mJy). Thus, the disk galaxy is not the optical identification. In fact our VLT observations show an empty field at the radio position. We did obtain a spectrum of the disk galaxy which shows a faint stellar dominated continuum. The low signal to noise makes it impossible to study the stellar population producing it. We observe a narrow Hα in emission on top of a broad absorption which also may be affecting [N II] and [S II] emission. Hβ also shows an emission line on top an absorption line. The fainter emission and absorption of Hβ and the low signal to noise makes it really hard to obtain an accurate center for this line. Lacking a good stellar population model for the object, we cannot measure accurate fluxes or FWHM for the lines. Averaging the redshifts of all the observed features, we obtain $z=0.178$. The Hα emission at 7772 Å had been detected before (de Vries et al. 1998b). However, this galaxy is not the counterpart of the GPS source.

**B1045+019** The weak continuum and noisy spectrum makes it difficult to distinguish real emission lines from noise. We only find one dubious possibility for redshift ($z=0.689$). If this redshift is correct, we are not detecting Hβ and [O III] 5007 (at 8200 and 8550 Å respectively). Radio observations were discussed in de Vries et al. (2000a) suggesting that this radio source may not be a QSO.

**B1300–040**: We find one emission line at 6385 Å. The emission may consist on a narrow (~ 80 Å) and a broad (~ 200 Å) component but the edge of the chip is too close to deblend it accurately. We think this line may be Mg II λ 2799 at $z=1.283$, and in that case the [O II] doublet at 3727 Å is not detected. If it were [C IV]λ1549, we would expect [C III]λ1909 at 7826 Å. The relatively bright continuum suggests a QSO, which would be consistent with broad Mg II.

**B1433–040**: de Vries et al. (2000a) already drew attention to the fact that the GPS source
Figure 3.2. Model of how the asymmetry in emission gas can be produced (Whittle 1985). The black circle in the middle represents the center of the AGN. We have the two outgoing jets with emitting gas (small circles) and further away in the jet we have a line absorber (or scattering) source (white blobs) which blocks (or scatters) the emission in the direction of the jet. If the line of sight of the observer is close to the direction of the jet, the absorbing clouds block the emission of the incoming jet, but not from the furthest jet. This distribution (absorber in the jet behind the emitter) would produce the red asymmetry wing we see in 1433–040. If the absorber were in front of the emitter in the jet, we would see a blue wing.
B1433–040 should not be identified with the considerably brighter radio source 4C–04.51. The optical spectrum shows a very strong continuum. Broad ($\sim 200 \, \text{Å}$) and narrow ($\sim 30 \, \text{Å}$) emission lines. The spectral shape and presence of bright broad lines is consistent with a QSO. We observe a strong asymmetry in the broad emission. The asymmetry index (AI20, Heckman et al. 1981) is defined as \( \frac{W_{L20} - W_{R20}}{W_{L20} + W_{R20}} \), where \( W_{I20} \) is the half width of the line to the left (L) and right (R) at the 20% intensity level. We measure \( AI_{20} = 0.35 \), towards the red, for H\(_\beta\) (and H\(_\gamma\)), which is large, but not unusual. This asymmetry can be explained by inflow or outflow of gas, together with a line opacity (or scatter) cloud which blocks the emission at one side of the AGN (e.g Whittle 1985, and references therein; see Figure 3.2). The optical spectrum of this radio source displays hydrogen emission lines of striking velocity width: we measure 28000 km/sec FWZI for H\(_\beta\), and note in addition its double-peaked nature. Although the radio spectrum seems to peak around 1 GHz (Figure 3.3, the high flux observed at 178 MHz suggests that B1433–040 is not a GPS source. It may be a flat spectrum quasar where Doppler boosting is affecting the spectrum, or even a BL Lac: there seems to be some variability in the 408 MHz and $\sim 1.4$GHz (Large et al. 1981; Wright & Otrupcek 1990; White & Becker 1992) observed fluxes. Given the unresolved optical host, we suggest that the optical counterpart of B1433–040 is a quasi-stellar object at $z=0.796$.

**B1601–222:** Featureless, very noisy spectrum with a moderately bright continuum. Snellen et al. (2002) measure $z = 0.141$ based on G 4300, Mgb 5169, Na 5899 and H\(_\beta\) which
correspond to \( \sim 4900–5550 \, \text{Å} \). We covered the range between 5700 and 9200 Å and observe no emission (H\(\alpha\) with their redshift would be at 7488 Å).

\textit{B1648+015}: Featureless with a not very bright continuum. Stickel et al. (1996) identifies this source as a quasar. The radio spectrum shows a very variable source so it is probably a flat spectrum quasar or a BL Lac object.

3.5 Summary

We presented VLT deep optical imaging and spectroscopy targeting the host galaxies of GPS radio sources. The sample was comprised of unidentified objects from the master list of O’Dea et al. (1991), updated by de Vries et al. (1997a).

We have found new optical counterparts (down to magnitudes \( \sim 25 \)) of GPS sources B0008–421 and B0742+103 and confirmed previous identifications of GPS sources: B0316+161, B0407–658, B0554–026, B0904+039. The radio spectra of B0407–658, B0437–454, B1433–040 and 1648+015 suggest that these sources are not GPS. However, high resolution radio observations are needed to confirm it. We cannot find the optical counterpart of B0914+114 and suggest that previous identifications correspond to an unrelated galaxy (at \( z=0.178 \)), 6” south of the radio position.

We measure new redshifts for B0316+161, B0407–658, B0904+039, B0914+114 (unrelated galaxy) and B1433–040, uncertain redshifts for B0008–421, B1045+019, 1300–059. The following sources remain with undetermined redshift: B0437–454, B0914+114 and B1648+015. We cannot confirm previous redshifts of: B0742+103, B1601–222.

Our magnitudes seem to be consistent with previous measurements of GPS counterparts. We find redder V–R colors for some sources but this can be due to problems in the calibration of the \( R \)-band observations. Comparison with stellar population synthesis models seem to rule out constant or exponentially declining star formation in the host. The data generally agree with single instantaneous burst models but do not yield useful information on age or metallicity.
Figure 3.4–. Spectra of the sources with identified emission lines. Flux is in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$.
Figure 3.4-. Continued.
Figure 3.4- Continued. B0914+114: The horizontal lines show an estimation of the possible extent of the absorption Hydrogen lines.
Figure 3.4-. Continued.
Figure 3.5–. Finding charts for the identified sources. The images correspond to the band of our VLT observations were sources were brighter.
Figure 3.5-. Continued.
Figure 3.5.- Continued.
Figure 3.5-. Continued. The radio position of 0914+114 is 6’’ north of the observed galaxy (circled) which was previously - and incorrectly - identified as the optical counterpart (see text). The radio position is marked with a cross.