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The nature of powerful compact radio galaxies [★]

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Abstract. Three compact powerful radio galaxies, PKS 1353− 341, PKS 1814−637 and PKS 1934−638, have been imaged. The three galaxies seem to be giant ellipticals, the last two being bluer than normal gEs by 0.2-0.3 mag in B−I, which is expected if they are the result of recent merging.

HI absorption has been detected in all three objects with very different characteristics. The broad absorption in PKS 1353 −341 probably takes place in a torus or a disk with a radius of at least a few tens of pc. For PKS 1814−637 the principal absorption is less broad and the disk radius more likely a few hundreds of pc. The absorption in PKS 1934−638 is very narrow and is probably due to gas not directly connected to the central engine.

Data for a dozen of powerful radio galaxies with H I absorption are reviewed. Such absorption seems to be particularly common at high radio power.

Key words: galaxies: photometry —- galaxies: individual: PKS 1353−341, PKS 1814−637, PKS 1934−638 —- structures of radio lines: 21cm

1. Introduction

Three compact powerful radio galaxies ($P > 10^{26}$ W Hz^{-1} at 1.4GHz) are known south of declination −30° with $z < 0.25$, sufficiently near for rather detailed studies.

PKS 1353−341 is a flat spectrum source at z = 0.223, PKS 1814−637 a compact steep spectrum source at z = 0.064 and PKS 1934−638 a well known compact double GHz-peaked source at z = 0.182. Some optical and radio data on these sources are given in table **??**. Here we present some new optical data obtained at ESO and new H I absorption measurements taken with the Australia Telescope.

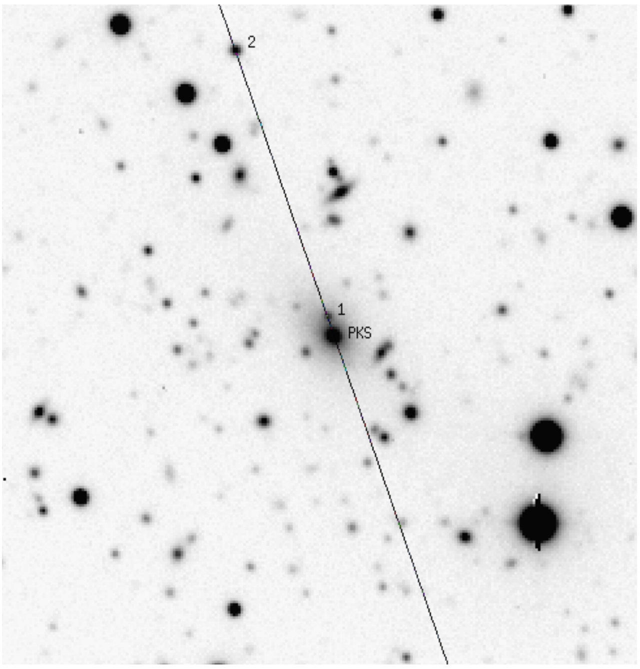

Fig. 1. I image of PKS 1353−341 taken with EFOSC in 1996. North is up, east to the left; the field is ∼155″x 155″. The straight line indicates the position of the spectrograph slit.

2. Optical observations

2.1. PKS 1353−341

A 10 min I image (FWHM = $1''.8$) and a 30 m B image (FWHM = $1''.9$) were obtained with EFOSC at the 3.6m telescope on August 10 and 11, 1996 and three 15 min I images (FWHM = $1''.3$) with the NTT on May 2, 1992. These images show the object to be associated with a large luminous galaxy in a crowded field with many galaxies and stars (fig. **??**). One of these is seemingly situated within the galaxy.

To establish its nature we have obtained on Aug 11, 1996 two 5 min spectra through the EFOSC B300 and R300 grims which yielded a useful spectral range of 3740-9280 Å with a FWHM of 15 Å for the night sky lines. The $1''.5$ slit was oriented in PA = 19°, so as to obtain the spectrum of

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[★] Based on observations obtained with the Australia Telescope and the 3.6m and NTT telescopes of ESO La Silla (Chile) the nucleus, object 1 at $4''.8$ NE and object 2 at $69''$ NE (fig. ??).

Table 1. Data for three radio galaxies. Subsequent lines give the redshift [^{1} this paper, ^{2} see text, ^{3} R. Dickson (Private communication through R. Morganti)], the B−V colour excess due to our Galaxy from the maps of Burstein & Heiles (1982), the measured B−I colour, the measured B−I colour minus that for a standard gE galaxy (B_0-I_0 $=2.10^m$) at the redshift of the galaxy calculated with the k corrections in B from the data of Pence (1976) and in I from the data of Schneider et al. (1983), the B magnitude measured to the largest observed distance, the absolute magnitude computed with H_0=50 km s^{-1} Mpc^{-1} and q_0=0 and with the k corrections appropriate to the measured colours, the radio flux density at 5GHz in Jy from the Parkes catalogue (Wright & Otrupcek, 1990) and the log of the correponding power in W Hz^{-1}, the VLBI separation in mas. The second digit for the photometric results is very uncertain. A crude estimate of the effects of the emission lines on the B−I colours shows that PKS 1353−341 and PKS 1934−638 could be 0.02^m respectively 0.05^m bluer than indicated, while PKS 1814−637 would be unaffected.

	1353−341	1814−637	1934−638
z	0.2230^1	0.064^2	0.1818^3
E_{B-V}	0.05^m	0.08^m	0.06^m
B−I	3.01^m	2.1^m	2.64^m
Δ(B−I)	-0.07^m	-0.31^m	-0.32^m
B	16.53	17.1	19.51
k_B	1.06^m	0.23^m	0.73^m
M_{B_0}	−25.6	−21.4	−22.1
S_5	0.67	4.21	6.13
log P_5	26.2	25.9	27.0
VLBI			
sep. (mas)		300	42

The nucleus shows a continuum typical for a gE galaxy with probably Mg I b and Na I D in absorption and with a set of emission lines typical for a Seyfert 2 galaxy with [N II]λ6583/ Hα=2.1, [O I]λ6300/Hα= 0.4 and [OIII]λ5007/Hβ=5.5, measured on the spectrum after subtraction of a template gE galaxy spectrum (fig. ??). For Hα/Hβ we measured an uncertain value of 5.5 and for [OII]λ3727/Hβ ∼3. The FWHM of the lines near Hβ is 23 Å or, upon correction for instrumental broadening of 15Å, about 700 km s^{-1} in the rest frame. We obtained z = 0.2230 ± 0.0001, very close to z = 0.2227 found by White et al. (1988).

Object 1 also has a continuum compatible with a gE, with Hβ, Mg I b and Na I D in absorption and Hα weakly in emission. The rather noisy spectrum yielded a redshift z = 0.2252 ± 0.0004. This corresponds to a relative velocity of 540±100 km s^{-1} in the rest frame. It may well be, therefore, that object 1 is a galaxy being captured by PKS 1353−341, though it could also be an independent galaxy in the surrounding cluster. As we shall discuss later the velocity derived for PKS 1353−341 from emission lines may not necessarily represent the systemic velocity and the velocity difference might well be smaller.

Object 2 turns out to have a blue continuum with Mg I b in absorption and emission lines corresponding to a low excitation H II region (λ6583/Hα =0.6; λ6300/Hα< 0.04 and λ5007/Hβ= 0.6); the emission lines are unresolved at our resolution. The redshift z = 0.2157±0.0001 which corresponds to a velocity of 1800 km s^{-1}, in the rest frame of PKS 1353−341, probably indicating the presence of a substantial cluster of gala- xies.

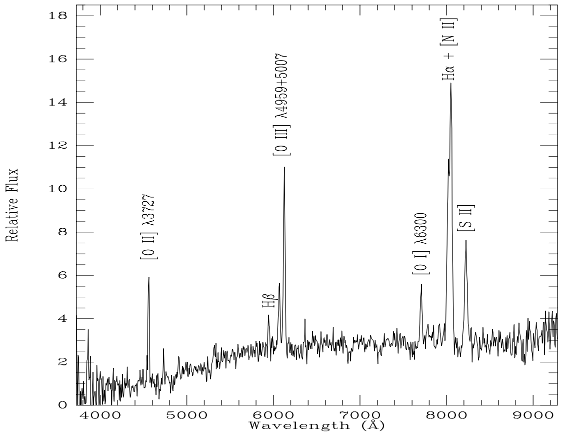

Fig. 2. Low dispersion spectrum of PKS 1353−341 taken with EFOSC on the ESO 3.6m telescope.

Elliptical isophotes with b/a=0.7 and major axis in PA=40° were fitted to the I and B images of PKS 1353−341, excluding the part influenced by object 1. To obtain the surface brightness in V we have corrected for the $(1 + z)^4$ factor, the k-term and for galactic absorption (table ??) and we have assumed q_0=0 and $V_0-I_0=1.15^m$ and $B_0-V_0= 0.95^m$, the standard values for gE. The resulting surface brightness distribution is shown in fig. ??, where also some of Schombert's (1987) standard curves for gE are indicated. PKS 1353−341 appears to have a slightly flatter profile than a typical gE for r less than ∼40 kpc ($r^{1/4}$=2.5). Further from the center the distribution flattens, indicative of a cD galaxy. Between $3''$ and $10''$ from the center where the photometry is most reliable we obtain $B-I=3.01^m$ about the value expected for a standard gE at this redshift.

Upon subtracting an $r^{1/4}$ model and a PSF centered on the nucleus from the observed NTT image one clearly sees the extended nature of the object 1 which may be traced to approximately $5''$ (30 kpc) from its center. The integrated magnitude of object 1 within a 22 kpc radius is I_{KC} $\sim 18.6^m$ with B−I roughly 3.0^m corresponding, with the normal colour of a gE, to $M_V = -21.4^m$, probably a minimum estimate for its total luminosity. Such a galaxy certainly could perturb an object like PKS 1353−341. The more distant object 2 has $B=20.40^m$ and $I=18.42^m$ corresponding to a late type galaxy.

Beyond $10''$ from the center the light distribution flattens and a cD envelope begins to dominate. The integrated magnitudes of the whole system to $120''$ (780 kpc) from the center are $I=13.62^m$, and $B=16.57^m$ from the 10 min and $B=16.49^m$ from the 30 min exposures. As a result of the great extent of the envelope it is possible that our sky level is still contaminated by light from the galaxy. A larger CCD would be needed

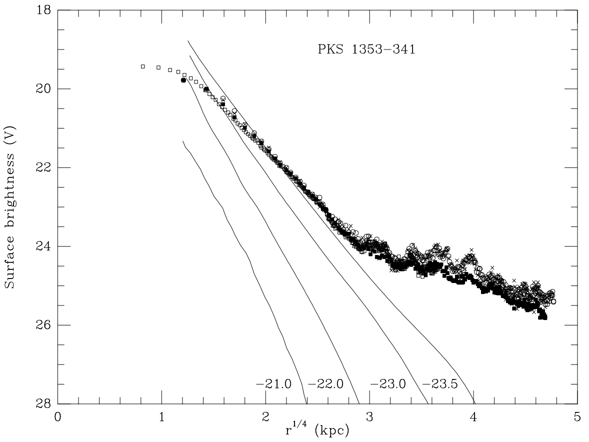

Fig. 3. Surface brightness profile in V magnitude arcsec^{-2} as a function of $r^{1/4}$ [$r=(ab)^{0.5}$] deduced from the profiles in I (NTT image, open square, EFOSC image, filled square) and in B (EFOSC image, crosses). The lines are average profiles of elliptical from Schombert (1986) for M_V (<16 kpc)=−21.0, −22.0, −23.0, −23.5.

to determine the integrated magnitudes and their uncertainty with confidence. Our measured magnitudes give $M_{I_{KC}}=-27.5$ and $M_B=-25.6$ which would correspond to $M_V=-26.4$ or to $\log(L_V/L_{V,\odot})=12.5$. Hence PKS 1353−341 is a very luminous galaxy indeed. In the list of 26 cD galaxies by Schombert (1988) there are only two that are still more luminous.

2.2. *PKS 1814−637*

PKS 1814−637 is a compact steep spectrum radiosource ($\alpha=-0.86$) identified with a galaxy with a Seyfert 2 nucleus (Thom- pson et al., 1990). Unfortunately there is a galactic star (Tadhunter et al., 1993) which we locate at 1″.7 SE from the nucleus accounting for about half of the total light of the combined image which makes accurate photometry and spectroscopy rather difficult. Danziger & Goss (1979) obtained a redshift of z= 0.0627, Thompson et al. (1990) z=0.065 and Tadhunter et al. (1993) 0.063. We have remeasured the spectrum of Thompson et al., kindly provided by Dr. S.G. Djorgovski and obtained from the [O III] lines z=0.0646 and from the Hα, [N II] and [S II] lines z=0.0642. We adopt z=0.064, but an error of ±0.001 cannot be excluded.

A 15 min I image was obtained with the NTT on May 3, 1992, while with EFOSC three 10 min images were obtained in I and in B on July 27, 1995 and a one min image in I on the same day. Seeing conditions were far from ideal (1″.6 at the NTT and 1″.8-2″.2 at EFOSC). Moreover in the 10 min EFOSC I images, the star near the centre is overexposed.

The subtraction of a stellar image does not give really satisfactory results, especially with the EFOSC images which have a pixel size of 0″.607/pix (the pixel size of the NTT image, 0″.129/pix, is more favorable).

We obtain a (B−I) colour of ∼1.4 for the star 1″.7 SE from the nucleus.

The colour of the galaxy itself could only be determined with some confidence in a 4″.9x8″.5 box centered 14″ W and 2″ N from the nucleus. In that box, the influence of the star is negligible. Combining all the B and I images, we obtain B−I=2.15^{m}. For a gE, we would have expected 2.46^{m}. The radio galaxy is therefore too blue by 0.3^{m} in B−I.

We have measured on the NTT I image the total intensity in a box 23″ x 14″ (42x26 kpc) centered on the nucleus after subtraction of the star 1″.7 SE of the nucleus and found I=14.96. With B−I=2.15^{m} this gives $M_V=-22.3$ if the B_0-V_0 colour is 0.2^{m} less than for a gE.

2.3. *PKS 1934−638*

PKS 1934−638, a galaxy with a Seyfert 2 nucleus (Fosbury et al. 1987), was most recently observed by Heckman et al. (1986) who obtained B and V images and by Fosbury et al. (1987) who present uncalibrated isophotes in R as well as spectra. The images show two galaxies in a common envelope with the brighter component coincident with the radio source. The spectra indicate a velocity difference of 900±300 km s^{-1} between the two galaxies.

We have obtained on July 28, 1995 three 10 min images with EFOSC at the 3.6m telescope through a B and two through an I filter, under poor seeing conditions (2″ - 2″.5). The images may be fitted with two PSF's at the centers of the two galaxies and a $r^{1/4}$ law for the principal galaxy. A residue remains centered on the companion. Taking this to be part of the latter we obtain in a area of 18″.6x12″.6 (or 98x67 kpc) for the principal galaxy B=19.51^{m}, I_{KC}=16.87^{m} or B−I=2.64^{m} and for the companion B=20.84^{m}, I_{KC}=17.76^{m} and B−I=3.08^{m}. For a gE we would expect B−I=2.96^{m}. Within the uncertainties the companion therefore appears to have about a normal colour for a gE, while the B−I colour of the principal galaxy appears to be 0.32^{m} too blue. The integrated B−I for the two galaxies is 2.72^{m} or $\sim 0.2^{m}$ too blue. In fact Heckman et al. (1986) found that the B−V colour of the two galaxies together is $\sim 0.2^{m}$ bluer than a normal elliptical would be, but did not notice a colour difference between them. Taking $V_0-I_0=1.05^{m}$ for the principal galaxy and $V_0-I_0=1.15^{m}$ for the companion we obtain for the two galaxies $M_V = -22.8^{m}$ and -21.7^{m} respectively.

The former value is rather typical for a strong radio galaxy, while the companion certainly should have a powerful influence on the radio galaxy if it is as close to it as it seems to be in projection (15 kpc). At the rather poor resolution of the available images the system looks only moderately perturbed, though the rather high density of stellar images in the field makes it difficult to decide which faint luminous patches belong to the galaxy.

2.4. *Discussion*

It has previously been found that radio galaxies are sometimes rather blue (Smith & Heckman 1989) and that the same appears to be still more the case for quasar galaxies (Véron-

Cetty & Woltjer 1990, 1997). This trend is confirmed by PKS 1814−637 and PKS 1934−638, the latter of which is known to be a very compact double. Long ago Shklovsky (1965) predicted, soon after its discovery, that PKS 1934−638 should diminish in flux quite rapidly, if an expanding source. It was found however to be quite constant (being used now as an Australia Telescope standard: perhaps imprudently?) and therefore it should be located in a high pressure medium that confines it. Nevertheless such a compact object should be relatively young.

Blandford (1990) has proposed that strong radio sources are associated with rapidly rotating black holes and that accretion at close to the Eddington rate is required to reach the necessary angular momentum. Therefore as we discussed before (Véron-Cetty & Woltjer 1997) we should expect that if, as in the Seyferts, gas is supplied rather slowly not much radio emission will result. However in major mergers gas is supplied to the nucleus of the galaxy in adequate quantities to produce a strong radio source and also a high rate of star formation. The black hole would be spun up on an Eddington time scale of a few 10^8 years and at the same time star formation would produce a generation of luminous blue stars. The shake up from the merger would lead to a global r$^{1/4}$ luminosity profile resembling that found in typical ellipticals (Barnes 1988), but during a time of the order of 10^8 years the elliptical would be rather bluish. In such a picture, strong radio emission would not so much be a property of ellipticals, but rather would be a consequence of the mechanism that forms (some of ?) them.

The case of PKS 1353−341 is perhaps not very different. Here there is evidence for a possible merger taking place at the moment. However the cD galaxy is so luminous that the addition of some blue stars would not very much affect the colour of the main body of the galaxy.

3. Neutral Hydrogen Observations

3.1. *ATCA Observations*

Observations of PKS 1353−341 and PKS 1814−637 were made on 1998 January 16, 17 and 19 using the 6A array at central frequencies of 1161 and 1336 MHz, respectively. The observation of 1934−638 was made on 1995 September 15 with the 6D array at a central frequency of 1201 MHz. The bandwidth of 8 MHz was subdivided into 512 channels, each of width 15.6 kHz, and later Hanning-smoothed to a resolution of 31.2 kHz, corresponding to a rest-frame velocity resolution between 7.0 and 8.1 km s^{-1}, depending on the observing frequency. PKS 1353−341 is weak (0.64 Jy at 1161 MHz) and was observed for a total of 5 h. PKS 1814−637 (13.2 Jy at 1336 MHz) was observed for a total of 1 h. PKS 1934−638 was observed for a total of 6 h. The average system temperature for PKS 1814−637 was 37 K, but for PKS 1353−341, which was observed below the nominal frequency limits of the ATCA, the average system temperature was 85 K and for PKS 1934−638, 55 K. Except for PKS 1353−341, the bandpass calibrators listed in table **??** were observed for approximately the same length of time as the corresponding sources.

3.2. *LBA Observations*

Simultaneous with the ATCA observations, the source PKS 1934−638 was also observed with the Parkes and Mopra telescopes thus forming a Long Baseline Array (LBA) with three telescopes, and three different baselines. The baseline lengths are: ATCA-Mopra 113 km, Mopra-Parkes 207 km, and ATCA-Parkes 321 km. PKS 1934−638 was observed for a total of about 6 h. After each hour, approximately, the bandpass calibrator PKS 1921−293 was observed. This source has a similar flux density to PKS 1934−638 (12.6 Jy, compared with 15.1 Jy), and was also observed for a total of 5 h. Integration times on the Parkes baselines were slightly less owing to the longer slew time of this antenna. The data for each telescope was recorded onto an S2 tape recorder at a bandwidth of 8 MHz. Both hands of circular polarisation were recorded. The ATCA data for the five telescopes on the 3 km track was converted from linear to circular and coherently summed before recording. The observations are summarized in table **??**.

The LBA data were subsequently correlated at ATNF headquarters in Epping. Astronomical delay terms were applied at this stage, and a channel spacing of 15.6 kHz and an integration time of 5 sec was used for the cross-correlated spectra. As for the ATCA-only data, this was later Hanning-smoothed, resulting in a FWHP resolution of 31.2 kHz. The data were edited and scalar-averaged. Spectra were subsequently corrected for the bandpass response on a baseline-by-baseline basis.

Table 2. A summary of the ATCA and LBA observing parameters and results for 1353−341, 1814−637 and 1934−638. Subsequent lines give the observing frequency, the secondary calibrator, the bandpass calibrator, the observing date (YY/MM/DD), the array, the integration time (in hours), the rms noise, the flux density, the peak optical depth τ, the redshift at peak, the uncertainty on the redshift, the equivalent width, the velocity dispersion of the main component σ, the velocity width FWZI, the column density (for T=100 K) calculated from EW.

	1353−341	1814−637	1934−638
ν	1161 MHz	1336 MHz	1201 MHz
Secondary calibrators	1215−457	1934−638	1921−293
Bandpass calibrators	1934−638	1934−638	1921−293
Observing Date	98/01/16	98/01/17	95/09/15
Array	6A	6A	6D, LBA
Integration time	5 h	1 h	6 h
rms noise	5 mJy	6 mJy	7 mJy, 5 mJy
Flux Density	0.64 Jy	13.2 Jy	15.1 Jy
τ	0.125	0.217	0.0022
z	0.222495	0.063979	0.182819
	±0.000008	±0.000003	±0.000003
EW (km s^{-1})	21.2	9.5	0.062
σ (km s^{-1})	66	19	8
FWZI(km s^{-1})	496	372	101
$N_{\rm HI}(100)$	21×10^{20}	9×10^{20}	0.06×10^{20}

3.3. Results

H I absorption was detected in all three galaxies close to the frequency expected from the optical redshifts. Morganti et al. (2000) have independently detected H I absorption in PKS 1814 −637. No emission was detected (or was expected because of the redshifts). For PKS 1353−341 and PKS 1814−637, the absorption was both deep and of large velocity width. The peak optical depths were 0.12 and 0.21, respectively; the rest-frame velocity dispersions of the main absorption line were 66 and 19 km s^{-1}, respectively; and the FWZI velocity extents were 496 and 372 km s^{-1}, respectively. For PKS 1934−638, the optical depth was about two orders of magnitude lower, τ=0.0022, and the velocity dispersion of the absorption line was low, σ=8 km s^{-1}. Although very weak, the H I absorption for PKS 1934−638 was confirmed in both the ATCA and LBA observations. The results are summarized in table **??**.

Fig. **??** shows the H I absorption spectra of the three sources.

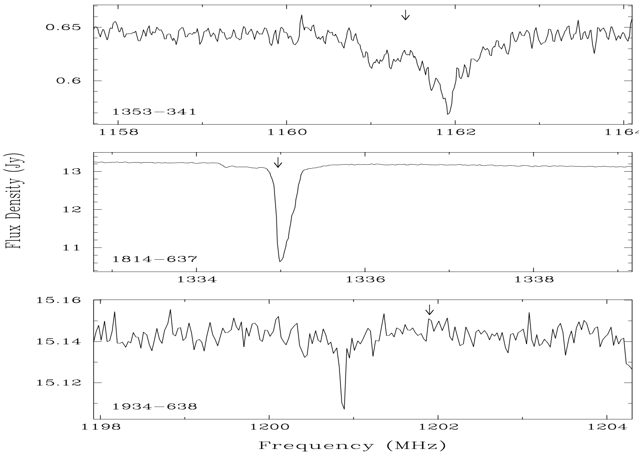

Fig. 4. HI absorption spectra of the radio sources 1353−341, 1814−637 and 1934−638. The data for 1353−341 and 1814−63 are from the ATCA. The data for 1934−638 are a weighted combination from the ATCA and LBA. The frequency axis is heliocentric. The arrows indicate the position of the HI line corresponding to the optical redshift.

The observations suggest that large quantities of H I must be present in 2 of the 3 galaxies: PKS 1353−341 and PKS 1814−637. Assuming a spin temperature $T_S \approx 10^2$ K, the average column densities in front of the continuum sources are 21×10^{20} and 9×10^{20} atoms cm^{-2}, respectively. For 1934−638, the column density is $N_{HI}(100)=0.06 \times 10^{20}$ atoms cm^{-2}. This could indicate little neutral gas belonging to PKS 1934−638 in our line-of-sight. However, much higher column densities may be present if either: (a) the gas is warm (T_S could be $\sim$ 5000 K before the thermal linewidth approaches σ or more if radiative excitation of the spin levels is important); or (b) if there is a very extensive neutral gaseous halo. For example, Véron-Cetty et al. (1995) found a massive (3.1 10^{10} $M_\odot$) H I disk around the nearby compact flat-spectrum radio galaxy PKS 1718−649, whilst the optical depths of the two absorption components in this galaxy were only 0.003 and 0.005, similar to PKS 1934−638.

The Compact Array observations confirmed that all sources were unresolved to a maximum baseline length of 6 km, implying angular extents less than 5 arcsec. Further, the LBA observations showed that PKS 1934−638 has a similar flux density on all baselines up to 322 km, implying that it is unresolved ($<0''.1$) to the accuracy of our calibration. This is in agreement with previous observations showing it to be a 42 milliarcsec double radio source (Tzioumis et al. 1989).

4. Discussion

4.1. General discussion

In all three powerful radio galaxies we have studied, H I absorption was found. In a larger sample of more northerly, on average weaker sources, van Gorkom et al. (1989) detected four radio galaxies with absorption in a sample of 29. It should be noted, however, that they did not have the sensitivity to detect very low optical depth absorption as in PKS 1934−638. Moreover seven of the sources in their list are now known to be BL Lac like and so should not be included in the comparison.

To further investigate whether powerful radio galaxies are perhaps more prone to H I absorption, we have assembled in table 3a the available data for radio galaxies with $\log(P_{1.4GHz}) > 26$ (with P in W Hz^{-1}). We have found data for ten such objects and in all but one, H I absorption has been detected. In five objects with $\log(P_{1.4GHz})$=25.5-26.0 presented in table 3b there are three positive detections. In table 3 we have excluded BL Lac like objects, defined as sources listed in table 2 of the Véron-Cetty & Véron (1998) catalogue. Before concluding from the results in table 3 that powerful radio galaxies are particularly prone to H I absorption we have to take into account that optical depth limits and angular resolution have been different in different studies and that it is not obvious that negative results have always been reported in the literature.

To construct a more unbiased sample we have searched the catalogue of Burbidge & Crowne (1979) and the 1 Jy catalogue of Stickel & Kühr (1993) for radio galaxies with z<0.1 and $\log(P_{1.4GHz}) > 26$. In this sample of 17 objects, the six sources with z<0.1 in table 3a are included, of which four have H I absorption with $\tau > 0.017$, while two have $\tau < 0.017$. For the other 11 sources (0106+130, 0349−278, 0404+035, 0518−458, 0945+076, 1549+202, 1717−009, 1733− 565, 18 42+455, 2243+394 and 2356−611) no data have been reported. The two most southerly of these could only have been observed with the AT and have not been. We conclude that four powerful radio galaxies have H I absorption with $\tau > 0.017$ in a sample of at least six and at the very most 15, the latter corresponding to the unlikely case that for all others, upper limits would have been observed but not reported.

The measured optical depth may depend on the angular resolution. The values of the six low redshift sources in

Table 3. Radio galaxies with log[$P_{1.4\mathrm{GHz}}$(W Hz^{-1})] > 26.0 (table 3a), or with log[$P_{1.4\mathrm{GHz}}$(W Hz^{-1})]=25.5-26.0 (table 3b) and H I observations. Col. 1: name, col. 2: short position, col. 3: redshift, an asterisk indicates that it is based on stellar absorption lines col. 4: spectral classification from Véron & Véron-Cetty (1998), col. 5: Dominant type of radio structure, col. 6: log($P_{1.4\mathrm{GHz}}$), col. 7: peak optical depth τ in H I at VLA type resolution (A, if observed at lower resolution with Arecibo), col.8: estimated FWZI (in km s^{-1} in the rest frame), col. 9: references

Name	Position	z			log$P_{1.4}$	τ	FWZI	ref
Table 3a:								
3C 111	0415+379	0.0485	S1	FR II	26.2	<0.01		1
Hya A	0915−118	0.05414*	S3	FR I	26.7	0.0015	110	2
3C 236	1003+351	0.0988	S3	FR II	26.1	0.03	370	1
4C 12.50	1345+125	0.1217	S2	CSO:	26.5	0.014A	950	3
PKS 1353−341	1353−341	0.2230	S2	Flat sp	26.1	0.122	500	4
3C 321	1529+242	0.0959	S2	FR II	26.2	0.018A	380	5
PKS 1814−637	1814−637	0.064:	S2	CSO	26.3	0.214	300	4
PKS 1934−638	1934−638	0.1818	S2	CSO	27.4	0.0022	100	4
Cyg A	1957+405	0.05562*	S2	FR II	28.4	0.06	420	6
3C 433	2121+248	0.1015	S2	FR I/II	26.7	0.0051A	800	3
Table 3b:								
4C 31.04	0116+319	0.0598	S2	CSO	25.6	0.035	380	1,7
PKS 0625−354	0625−354	0.0553		FR I	25.6	<0.015		1
S5 1946+70	1946+708	0.1007*	(S)	CSO	25.6	0.05	350	8
PKS 2206−237	2206−237	0.0865	S2		25.7	<0.007		1
PKS 2322−123	2322−123	0.0822*	S3		25.7		780	9

References: (1) van Gorkom et al. 1989 (2) Taylor 1996 (3) Mirabel 1989 (4) this paper (5) Mirabel 1990 (6) Conway & Blanco 1995 (7) Conway 1996a,b (8) Peck et al. 1999 (9) Taylor et al. 1999.

Notes: -) Hya A: redshift derived from five main absorption lines in Hansen et al. 1995; τ=0.99 for the VLBA core (Taylor 1996) with an infall velocity of 28 km s^{-1} with respect to that systemic velocity (± 100 km s^{-1}).

-) Cyg A: the H I absorption components from Conway & Blanco (1995) combined with the redshift determined from stellar absorption lines give Δ(cz)/(1+z)=+ 300 and +110 km s^{-1} (± 50 km s^{-1}).

-) 4C 31.04: van Gorkom et al. found an infall velocity of the H I of 212 km s^{-1} based on an optical redshift of 0.059. Pravdo & Marshall (1984) obtained z=0.058 from a spectrum of rather modest quality. More recently Marchã et al. (1996) gave 0.060±0.001, while Conway (1996a) quotes an uncited redshift of 0.0598 which would change the infall into an outflow of 14 km s^{-1}. No conclusion can be drawn until a reliable absorption line based systemic redshift becomes available.

-) 1946+708: Stickel & Kühr (1993) give redshifts for three absorption lines from which the value in the table follows. Combined with the H I absorption data from Peck et al. (1999) an outflow of 150 km s^{-1} would follow but the uncertainty is of the order of ±200 km s^{-1}.

-) 2322−123: From Taylor et al. (1999) an infall at 200 km s^{-1} (±100 km s^{-1}) is found, with at VLBA resolution τ=0.4. There is also much more extended absorption probably associated with an Hα nebula (O'Dea et al. 1994).

table 3a generally correspond to what the VLA would have measured, except for 3C 321 which was observed at Arecibo with lower resolution. Since H I absorption appears to occur mainly in the nuclear regions, the Arecibo optical depth should be a lower limit to what would result from an observation at VLA type resolution.

Turning now to lower luminosity sources, we find in the van Gorkom et al. (1989) sample, observed with the VLA, 16 radio galaxies with log($P_{1.4\mathrm{GHz}}$) <25.5 and with observations sufficiently accurate to establish upper limits of τ <0.017. Only two were positively detected.

A sample of dominant cooling flow cluster galaxies was observed at Arecibo by McNamara et al. (1990). All had z<0.1 and log($P_{1.4\mathrm{GHz}}$) <25.5. Eight sources with accurate observations had τ <0.01 (one in common with van Gorkom et al.) and there were no detection above this level. Had the four sources detected in our high luminosity sample been observed with Arecibo type resolution, three would still have had τ >0.01.

Even though carefully selected samples are needed for a clear result, we conclude that there is probably a tendency for powerful radio galaxies to have a higher frequency of H I absorption. Since Compact Symmetric Objects (CSOs) and steep spectrum cores are generally high luminosity sources it may also be that, as suggested by Conway (1996b), these classes are particularly prone to H I absorption. However Cygnus A shows that also other types of luminous sources are involved.

4.2. Discussion of our results

Next we turn to the results of our observations of the three sources. In PKS 1353−341 the deepest absorption is in a broad feature (with possibly a narrow core) centered at -125 km s^{-1} with respect to the optical emission line redshift. A shallower feature is centered at around $+75$ km s^{-1}. The overall absorption extends from -330 km s^{-1} to $+170$ km s^{-1}.

PKS 1353−341 is a radio source with uncertain structural information. According to the VLBI data of Preston et al. (1985) at 2.29 GHz, most of the source is resolved at 3mas (20 pc) resolution (correlated flux $<$0.13 Jy, total flux 1.5±0.4 Jy). However their total flux is substantially above the value of 0.64 Jy at 2.7 GHz in the Parkes catalogue. If this were to indicate variability, the source would have to be rather small; if not, the upper limit on the visibility is increased to 0.2 which would still leave open what structure there may be at 3 mas resolution. In any case the flat spectrum suggests a compact source.

The absorbing column density $N_{\rm HI}(100)$=21 10^{20} cm^{-2} if the source were fully covered but could be higher if not. The large velocity width suggests that the gas is located at modest distances from the nucleus ($<$100 pc?) and could very well form part of the absorbing torus of the unified model of AGN.

In PKS 1814−637 most of the absorption is in a deep component with a FWHM of only 45 km s^{-1} (in the rest frame) and $N_{\rm HI}(100)$=7.4 10^{20} cm^{-2}. Its redshift is the same as our adopted emission line redshift but, as discussed before, the latter is very uncertain. An underlying broad asymmetric feature with an optical depth of about 0.009 extends from about -190 km s^{-1} to $+180$ km s^{-1} with respect to the centroid of the narrow line.

PKS 1814−637 at 2.3 GHz is a moderately compact double with a separation of about 300 mas (550 pc) (Tzioumis et al. 1996a), but with about half of the total flux in more diffuse structures. Without spectral information it is not clear which source in the VLBI map, if any, is the nucleus; if it is the source in between the two extreme components and if at 1.4 GHz the distribution is not too different, the deep absorption cannot be only in front of the nucleus since dilution effects would then give a lower optical depth; the broad component could be. Because of the large separation of the components, it is rather clear that the narrow absorption is likely to occur at a sizeable distance from the nucleus ($>$ a few hundred pc).

In PKS 1934−638 only a narrow absorption line was detected with FWHM of some 18 km s^{-1} and very low optical depth centered at $+260$ km s^{-1} with respect to the optical emission line redshift of Morganti & Dickson (1999), but at -50 km s^{-1} with respect to the earlier result of Fosbury et al. (1987).

PKS 1934−638 is a compact double with a separation of 42 mas (168 pc) and components about 2.5 mas (10 pc) across, but with some 40% of the total flux in a more diffuse uncertain structure between the components (Tzioumis et al. 1989,1996b). Even at 8.4 GHz, there is no evidence for a radio nucleus. In view of its narrow profile it is probable that the H I absorption covers only part of the source, but which part is unknown.

The precise location and distribution of the absorbing gas is difficult to determine. In the unified model it is generally assumed that the gas is in some torus around the nucleus which is geometrically thick. In Barthel's (1989) unification model the vertical thickness of the torus must be about equal to its radius to obtain the observed percentage of radio galaxies and quasars. If the torus is thick because of random motions of gas clouds, these must be comparable in magnitude to the rotational motions and if these are isotropic, the line widths of the absorption lines should give an indication of the latter.

Since the Broad Line Region is undoubtely of sub-pc scale, it has frequently been assumed that the radius of the torus is of the order of a pc. While there are some indications that this may be the case in typical Seyfert galaxies, there is accumulating evidence that the radii in strong radio galaxies are larger. A detailed discussion of the torus in Cyg A led to the conclusion (Conway & Blanco 1995; Maloney 1996) that it should be at least 50 pc from the nuclear X-ray source to avoid a large optical depth in free-free absorption at 1.4 GHz which would make the radio nucleus invisible. Of course, the "torus" may be a misnomer and it is likely that the gas is located in a more extended disk with a surface density and thickness as a function of radial distance to the nucleus still largely unknown, but to be determined by observation. In such a disk the larger velocities are likely to be found closer to the nucleus. This is confirmed by the VLBI data of Taylor et al. (1999) on PKS 2322−123 in which the nucleus is absorbed by H I with a FWHM velocity spread of 735 km s^{-1}, while one of the jet components 34 pc away has absorption with a FWHM of only 133 km s^{-1}. Interestingly Taylor et al. also find such a relatively narrow component in the nuclear absorption but with a five times lower $N_{\rm H}$ than in the jet component. This may be indicative of an absorbing disk in which the thickness increases at larger radii.

In the case of 4C 31.04 a compact double with separation of some 120 pc, Conway (1996a,b) found H I absorption which fully covers one component, but only part of the other. The FWHM was 133 km s^{-1}. Conway interpreted this as due to a disk 100 pc thick and with inner radius about 100 pc.

It seems possible that PKS 1814−637 is similar to 4C 31.04. With a FWHM of only 45 km s^{-1}, the absorption might be inferred to occur rather far out in the disk which would be expected in any case because of the 550 pc separation of the components. With such a low velocity dispersion the disk would be too thin to cover both components, and it seems likely that the one component covered would have twice the average optical depth. The inferred value of $N_{\rm HI}$ is comparable to that in 4C 31.04. It would be interesting to confirm by VLBI measurements that only one of the components is absorbed. Some uncertainty is introduced in this discussion by the fact that not all the flux comes from the two components. As we noted before the shallow broad absorption could be from material in front of the faint nucleus.

Some quantitative estimates may be made about the kind of torus or disk responsible for the absorption in PKS 1353−341. The nature of such a torus depends on the column density of matter, the local pressure and the intensity of the X-ray irradiation. Depending on these, such a torus could be atomic or mainly molecular (Neufeld et al. 1994; Maloney et al. 1996). The simplest case is the atomic torus. Here the temperature is typically 8000K or somewhat less and the degree of ionization of the order of 0.03. Two important effects need be considered: the radiative excitation of the spin levels by the non-thermal continuum of the radio source may change the spin temperature of the H I and the ionized component of the torus may become optically thick at 1.4 GHz.

With regards to the former, according to the results of Field (1958) and Bahcall & Ekers (1969) the spin temperature (in the absence of Ly α excitation which in the torus should be negligible on account of the high dust opacity) may be written as $T_S = \frac{T_R + y_C T_K}{1 + y_C}$ with T_R the radiation temperature, T_K the kinetic temperature and y_C=2100 n_{HI} $T_K^{-0.8}$ where electron de-excitation has been included (accounting for 1/4 of the value of y_C) assuming n_e=0.03 $n(HI)_{HI}$ and T_K of the order of 8000 K, but its slightly different temperature dependence neglected. The factor y_C is proportional to the collisional de-excitation rate and the formula given assumes only collisions with H atoms and electrons. If the H_2 abundance is significant, the expression for y_C may well have to be changed, but to our knowledge the appropriate cross section has never been calculated. If $n_H \gg 1 cm^{-3}$ and $T_K < 10^4$K, we have $y_C \gg 1$. Replacing then 1 + y_C by y_C and inserting the appropriate expression for T_R we may write T_S=F T_K with

$$F = 0.57 \times 10^{-9}(1+z)(D/r)^2 S_{1.4/(1+z)} n_{HI}^{-1} T_K^{-0.2} + 1.$$

(D is the luminosity distance and r the distance of the absorber from the radio emitter). Writing $10^6 n_{HI} = n_6$, taking T_K=8000K and inserting parameters appropriate for PKS 1353−341, we obtain F=126 n_6^{-1} $r_{pc}^{-2} + 1$.

From Spitzer (1978), the free free optical depth may be written as τ_{ff}=0.106 n_e^2 $T^{-3/2}$ ν^{-2} d, where we have evaluated the Gaunt factor for T=10^4 and ν=1GHz and neglected its logarithmic dependence on T and ν for slightly different values, and where d is the path length. Taking n_e=0.03 n_{HI}, T_K=8000 K, ν=1.41GHz and writing the column density as $N_{24}=10^{-24}$ n d, we obtain τ_{ff}=67 n_6 N_{24}.

For PKS 1353−341 we have found $N_{HI}(100)$=21 10^{20} cm^{-2} or in an atomic torus with T_K=8000 K, N_{24}= 0.17 F cm^{-2}. Inserting the expression for F we may write this as n_6 N_{24}=21 r_{pc}^{-2}+0.17 n_6. The condition that the source have a free free optical depth less than about unity to be observable then becomes 1420 r_{pc}^{-2}+ 11.4 $n_6 < 1$, from which it follows that in any case r>38 pc and n_6 <0.09 cm^{-3}. Hence such a torus must have a radius much larger than that assumed for Seyfert galaxies and a pressure n T < 7 10^8 K cm^{-3}, compatible with the pressures found in the Narrow Line Region. The mass of the atomic gas then becomes at least a few times 10^7 $M_{\odot}$. Similar conclusions were previously reached for the torus around Cyg A (Conway & Blanco 1995; Maloney 1996).

If the torus were molecular, it should still have an atomic layer with at 10 GHz a free free optical depth given by approximately τ=0.5 $F_{X5}^{1.1}$ $p_{11}^{-0.1}$ with F_{X5} the hard X-ray flux in units of 10^5 erg cm^{-2} s^{-1} and P_{11} the pressure (defined as n T) in units of 10^{11} K cm^{-3} (Neufeld et al. 1994). The value of P_{11} is not very critical and we take P_{11}=0.01. For the optical depth at 1.4 GHz we may then write τ_{ff}=200 $L_{44}^{1.1}$ $r_{pc}^{-2.2}$ with L_{44} the 2-100 keV X-ray luminosity in units of 10^{44} erg s^{-1}.

PKS 1353−341 has been identified with a weak ROSAT source (RX J13560−3420, Brinkman et al. 1994) with a 0.1-2 keV flux of 1.5 10^{-12} erg cm^{-2} s^{-1}, corresponding to a soft X-ray luminosity of 3.2 10^{44} erg s^{-1}. It is unclear if this is associated with the radio source or with hot gas in the cD galaxy and associated cluster. If we estimate the hard X-ray flux from the absorption corrected [O III] flux, we would obtain L_{44} ≈3, evidently a very uncertain value. Inserting this into the expression for τ_{ff}, the condition $\tau_{ff} < 1$ would become 670 $r_{pc}^{-2.2} < 1$ or r>19 pc. Thus the conclusion is confirmed: the torus or the disk in which the H I absorption takes place in PKS 1353−341 should have a radius of tens of pc. With similar conclusions for Cyg A (Conway & Blanco 1995) and probably also for S5 1946+708 (Peck et al. 1999), it seems that this may well be a general result for strong radio galaxies.

It would be of particular interest to determine if the H I in strong radio galaxies is falling in towards the nucleus to feed the central engine or if it flows out as a result of energetic processes there. Both processes may occur in the same object as seen, for example, in the Seyfert 2 galaxy IC 5063 (Morganti et al. 1998).

However the question is not easy to answer because the systemic velocities of radio galaxies tend to be uncertain. It was noted by Mirabel & Wilson (1984) that in a sample of 20 nearby Seyfert galaxies the difference between the optical emission line velocities and the systemic velocities (determined from extended H I emission disks) ranged from more than −200 km s^{-1} to +50 km s^{-1} with an average of −74 km s^{-1} (blueshift). In more remote strong radio galaxies such effects may well be still larger, and the only way to obtain reliable systemic redshifts is to measure stellar absorption lines. We have attempted to do this for the three galaxies we have studied, but because of poor weather conditions no sufficiently reliable results were obtained.

From the notes to table 3, it appears that the only strong radio galaxy for which infall has been demonstrated is Cyg A. This is an illustrative case, because Conway & Blanco (1995) had found a blueshifted component at −149 km s^{-1}, which became redshifted at +110 km s^{-1} when a reliable systemic redshift was obtained. The value of the H I absorption data would be much increased if more reliable systemic redshifts were obtained.

5. Conclusions

Three compact powerful radio galaxies were imaged in B and I colours. Two of these galaxies, PKS 1814−637 and PKS 1934− 638 have colours bluer than gE galaxies; PKS 1353−341 has normal colours: it is a very luminous cD galaxy.

In all three sources H I absorption has been detected. The optical depth are 0.12, 0.21, 0.002 respectively for PKS 1353−341, PKS 1814−637 and PKS 1934−638.

We find that in PKS 1353−341 the torus or disk in which the absorption takes place should have a radius of tens of pc.

From our results and a search in the literature, we conclude that powerful radio galaxies tend to have a high probability to show H I absorption.

However, we could not determine if the H I is falling in towards the nucleus or if it flows out, because of the difficulty in determining the systemic velocities of the galaxies.

6. Appendix

The NTT images were calibrated on the basis of $I_{\rm KC}$=11.65$^{\rm m}$ for LTT 3218 (Landolt 1992, Hamuy et al. 1992) and $I_{\rm KC}$=15.72$^{\rm m}$ and 15.02$^{\rm m}$ for stars o respectively m in the E5 region (Graham 1982). The EFOSC images were calibrated based on B=12.29$^{\rm m}$ and $I_{\rm KC}$= 11.12$^{\rm m}$ for LTT 6248 in the case of PKS 1353−341 and on B=10.88$^{\rm m}$ and $I_{\rm KC}$=11.27$^{\rm m}$ for EG 274 for the other two (Landolt 1992, Hamuy et al. 1992). The colour equation determined by Benetti (1996) has been taken into account. The atmospheric extinction coefficients are those measured by the Geneva observatory Photometric Group.

The spectra were calibrated with W485A (Oke 1974).

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