HI and high redshift radio galaxies

Huub Röttgering[1], Ger de Bruyn[2,3],
Laura Pentericci[1] & George Miley[1]

1. Sterrewacht, Postbus 9513, 2300 RA Leiden, The Netherlands
2. Netherlands Foundation for Research in Astronomy, Dwingeloo
3. Kapteyn Astronomical Institute, Groningen

Abstract

We present the first results of a search with the upgraded WSRT radio telescope for 21 cm absorption of neutral HI gas for a sample of 6 $z > 2.4$ radio galaxies. Two have very tentative detections that need confirmation and four have limits on the optical depth of HI absorption of order 1 %. The only distant radio galaxy for which absorption has been solidly detected is still 0902+34 ($z = 3.4$). We discuss the nature of the absorber in 0902+34 in the light of the WSRT observations and argue that the absorption in 0902+34 could be due to a torus-like structure with a scale size of 1 kpc. The reason that this disk can be seen in absorption is likely to be due to the fortuitous orientation of this particular radio galaxy with its radio and photon beam axes being oriented at about 45 degrees with respect to the plane of the sky.

1 Introduction

Since even the most distant radio galaxies are relatively luminous in a number of wavebands, several of the components of these distant objects can be studied in unparalleled detail (for recent reviews see McCarthy 1993, Röttgering and Miley 1996). One of the components is gas with temperatures of order 100 – 1000 K. There are several ways to probe physical conditions in this gas, including observing CO line emission (Scoville et al. 1997), dust continuum emission (van der Werf, this volume) and HI emission/absorption.

There are two important ways to search for and subsequently study HI gas associated with high redshift radio galaxies (HzRGs). One method is to measure the redshifted 21 cm absorption line against the radio continuum. The second method is to study the deep narrow absorption troughs that often "disfigure" high-resolution optical spectra of the Lyα emission line. Both methods give – in principle – important constraints on a number of fundamental characteristics of the neutral HI gas in these galaxies. These characteristics include the spatial scale, mass, filling factor, (spin) temperature, and dynamics of the region containing the HI gas. With these constraints, several important question related to the HI gas can be addressed: What is the origin of the gas? Is it primordial gas cooling out of a (dark matter dominated) halo surrounding the galaxy or is it expelled from the galaxy during a massive starburst? What is the fate of the gas? Will it be heated during future merging events so that it will increase the mass of the extended ionised emission line gas or even the hot X-ray halo gas? Alternatively, is this the neutral gas from which either the stars are forming or the central black hole is being fed?

To study these issues we have started to search in a sample of HzRGs for the redshifted 21 cm absorption line using the upgraded WSRT radio telescope. Here we will discuss the first results from this survey. The setup of this contribution is as follows. First we will briefly discuss the enhanced capabilities of the WSRT that make sensitive surveys of 21 cm absorption possible over a wide range of redshifts. Then we will briefly discuss the 21 cm absorption against the only radio galaxy for which this has been measured (0902+34, $z = 3.4$; Uson et al. 1991). Subsequently the WSRT programme to search for 21 cm absorption is presented and first results are given. Finally, the nature of the absorber in 0902+34 is discussed in the light of the new WSRT observations

2 The WSRT upgrade

At the end of 1996 the WSRT telescope was equipped with new receivers as part of a programme to upgrade the whole system (e.g. de Bruyn 1995). These receivers work in the UHF-band and cover the frequency range 260-450 MHz (UHF-low) and 700-1200 MHz (UHF high). These frequency ranges enable searches for HI emission and absorption over a large range in redshifts, from $z \sim 4.5$ to 2.2 and from $z \sim 1$ to 0.2. Unfortunately, observations in the UHF high/low regime can be severely affected by interference. Because of telecommunication signals, observations in the ranges 420-430 MHz, 460-470 MHz, and 935-970 MHz are typically not productive. Because of TV transmissions, observations between 700 and 800 MHz are generally not possible with bandwidths wider than 2.5 MHz. In a 12-hour integration, typical noise levels that are obtained are 0.4 mJy/beam in the UHF-high band and

0.5 mJy/beam in the UHF-low band, using a 10 MHz bandwidth and in the absence of strong interference. More information can be found on the WSRT home page: `http://www.nfra.nl/wsrt/index.htm`

3 HI Absorption and the case of 0902+34 (z = 3.4)

The first powerful radio galaxy that was discovered with a redshift beyond three was B2 0902+34 ($z = 3.395$, Lilly 1988). On the basis of its relatively flat UV/optical spectral energy distribution, indicative of a large population of young stars, it was argued that this object was a true protogalaxy (Eisenhardt and Dickinson 1992). The HST image consists of two regions of unusually low surface brightness, supporting the hypothesis that this galaxy is indeed a protogalaxy (Pentericci et al. this volume). The radio structure is rather bizarre showing a bright knotty jet with a sharp 90° bent in the north and two resolved components in the south (Carilli 1995). In addition, in the northernmost region there is a plume of emission with an extreme spectral index ($\alpha \lesssim -3.3$). Most of the radio characteristics can be explained assuming that the radio source is oriented at an angle of order 45° with respect to the sky plane. In HzRGs the Lyα emission line is often partly absorbed by extended regions of HI gas (van Ojik et al. 1997; Dey, this volume). High spectral resolution observations of 0902+34, however, show a Gaussian shaped Lyα emission line without such HI absorption features (Martín-Mirones et al. 1995).

In 1991, Uson et al. used the VLA to search for HI absorption against 0902+34. They reported a detection at the level of $0.89\% \pm 0.14\%$ with a full width at half maximum of 270 ± 50 km/s. Using the Arecibo telescope, Briggs et al. (1993) confirmed the existence of the absorption line, but obtained a width of 90 km/s, much narrower than that reported by Uson et al. Briggs et al. argued that the difference might be due to uncertainty in determining the spectral baselines. Finally, the most sensitive measurements have been carried out with the WSRT telescope (de Bruyn 1995), giving an optical depth of 0.8 % and a width of 100 km/s (FWHM). The implied total column density is 2×10^{21} $(T_s/10^3)$ atoms cm^{-2}, where T_s is the spin temperature. The adopted spin temperature, $T_s = 10^3$ K, is a compromise between the high values advocated by Sunyaev and Zel'dovich (1975) and values as low as $\sim$ 100 K found for nearby galaxies. At faint levels, the WSRT observations showed an interesting blue wing extending several 100 km/s to the blue of the main HI component.

However, its reality remains to be confirmed.

There are a number of distant objects other than distant radio galaxies for which HI absorption has been measured. Recently, Carilli et al. (1996) have summarized the results of 21 cm absorption measurements for 9 damped Lyα systems. Combined with the equivalent widths as determined for the associated damped Lyα systems, typical spin temperatures and column densities are found to be 1000 K and a few $\times 10^{21}$ atoms cm^{-2} respectively. Using the new WSRT system Lane et al. (1998) have discovered two relatively low redshift absorbers with similar characteristics.

Two new classes of 21 cm absorbers have recently been discovered. Vermeulen et al. (in prep.) have detected a number of aborbers against very compact radio sources (Compact Steep Spectrum radio sources (CSSs) and Gigaherz peaked spectrum radio sources (GPSs). The absorption strengths varied between a few and 10 %. Furthermore, Carilli et al. (1998) have detected four strongly absorbed red quasars. The most extreme absorber in this sample of four is also a GPS galaxy (0108+388, $z = 0.670$) and has an absorption of 44 % (Carilli et al 1998).

4 A programme to search for HI absorption

Using the new WSRT receivers, we have started a programme to search for associated HI absorption against distant radio galaxies. Since 0902+34 is the only distant radio galaxy for which an associated absorber has been discovered, the obvious first aim of this programme is to investigate how common such absorption systems are for distant radio galaxies. In the case of the Lyα absorption, the characteristics of these absorbers are strongly linked to the properties of the radio source, one of the clearest relations being that the radio sources larger than about 50 kpc generally do not show absorption, but all the smaller sources do (van Ojik et al. 1997). A second aim of this programme, therefore, is to investigate the relation of 21 cm absorption to that of the Lyα absorption and other characteristics of the distant radio galaxies. A third aim is to understand origin of the cold gas associated with the radio galaxies. Does it trace the primordial gas from which the galaxies are being build? And finally, efforts are underway to set up a WSRT-Jodrell bank-Effelsberg network to carry out spectral imaging observations in the UHF-low band. Since this network will provide a resolution of 0.2 arcsec, the absorbers against extended radio sources will be very good targets. Important questions on the location and size of the absorbers can be addressed with this system.

For the search for HI absorption we selected 13 radio sources from a master list of distant radio galaxies (see de Breuck et al., this volume) with the following criteria: (i) $z > 2.4$ to be in a favourable region where the performance of the receivers are good, (ii) $\delta > -25$, so that the sources are accessible with the WSRT telescope, (iii) the flux density at 325 MHz $S_{325} > 1.5$ Jy, so that measurements of absorption is relatively easy. In addition, we have included 3 sources which are interesting because of their extreme redshifts (6C0032+412, $z = 4.41$; 4C41.17, $z = 3.8$ and 1908+72; $z = 3.5$). Finally, we included MG1019+0535 since this object has strongly depressed Lyα emission indicative of large amounts of dust (Dey et al. 1995).

In general we used a bandwidth of 2.5 MHz (2400 km/s) so that we could search for absorption over the whole range of Lyα emission. The first results of this search are summarized in Table 1. Out of the 6 objects observed, two objects (0731+438 and 1019+053) seem to have a tentative detection. Deeper data are needed to confirm the reality of this.

5 Discussion

The first conclusion from the HI absorption observations is that strong absorption at levels of a few up to 44 % as is now observed in $z \sim 1$ CSS and GPS sources (Vermeulen et al. in prep.; Carilli et al. 1998) is not commonly seen in HzRGs. Still the only HzRG solidly detected is 0902+34. It is interesting to consider whether the limits presented here can put constraints on the nature of HI gas associated with these distant radio galaxies. As a starting point in the discussion we would like to consider the location and spatial scale of the absorber in 0902+34. There seem to be two possibilities.

First, the neutral gas might have a spatial scale length of order 30 kpc, comparable to the size of the radio source and Lyα emitting cloud (e.g. de Bruyn 1995). However, given the derived column density of $\sim 2 \times 10^{21}$ cm^{-2}, the Lyα emission would be completely extincted unless the HI gas (i) is located between the radio source and the Lyα emission line gas or (ii) has a velocity that is substantially blue or redshifted with respect to the bulk of the Lyα gas. There is strong evidence that vigorous interaction between the radio jet and the emission line gas is a general phenomenon in HzRGs (van Ojik et al. 1997). It seems, therefore, unlikely that there is a sheet of neutral material around the radio source and therefore we regard possibility (i) as unrealistic.

The intermediate resolution spectroscopy of the Lyα emission line shows that the peak of the Lyα emission is blue shifted with respect to the 21 cm absorption

Object	z	S_{325}[1]	core[2] fraction	Refs/ Comments[3]	Integr. Time	Frequency	Bandwidth	# channels	τ[4]
		Jy	%		[hours]	[MHz]	[MHz]		%
0731+438	2.429	3.4	0.9	A, CSS	20	414.3	2.5	128	0.4 (?)[5]
1019+053	2.760	1.1	2.9	B, Dusty	22	378.2	2.5	64	1.1 (?)[6]
0744+464	2.926	2.2	1.2	A, CSS	22	361.8	2.5	64	< 0.55
1243+036	3.570	2.2	2.0	C	15	311.5	2.5	32	< 1.1
4C41.17	3.792	1.6	1.3	D	11	297.6	2.5	32	< 2.2
0943−242	2.923	1.4	0.6	E	6	362.4	2.5	32	< 0.8
0902+34[7]	3.395	1.2	15	F	144	323.0	1.25	50	0.8

Notes:

[1] The S_{325} flux densities are taken from the WENSS radio survey (Rengelink et al. 1997). If not available, the fluxes from the Molonglo radio catalogue were taken and extrapolated to 325 MHz using an appropriate spectral index

[2] Core fraction, defined as the ratio of core flux density to total source flux density at a restframe frequency of 20 GHz, in percentage (Carilli et al. 1997).

[3] A: McCarthy 1991; B: Dey et al. 1995; C: van Ojik et al. 1996; D: Chambers et al. 1990; E: Röttgering et al. 1995; F: Lilly 1998

[4] quoted are 3 σ upperlimits

[5] 0731+438: The data are severly affected by interference. However, there is an faint absorption feature apparent, which needs confirmatation.

[6] 1019+053: this observation was carried out with only 9 telescopes and showed a possible 3 sigma absorption feature at 378.3 MHz. However, this feature is located at the edge of the band and needs to be confirmed

[7] This is the radio galaxy for which Uson (1991) detected an HI absorber. This detection was confirmed by Briggs et al. (1993) and de Bruyn (1995). The numbers quoted are from de Bruyn (1995).

system by 400 km/s (Martín-Mirones et al. 1995)[1]. Since at the velocity of the 21 cm absorption no strong Lyα absorption is apparent, for 0902+34 possibility (ii) also seems excluded.

A second possibility concerning the spatial scale of the absorber in 0902+34 is that the 21 cm absorbing cloud is orders of magnitude smaller in spatial scale as the Lyα emitting cloud, but has a high column density and covers a large fraction of one the radio components. Conway (1996) reviews the rate of incidence of HI absorption for radio loud objects in ellipticals at $z < 0.15$ and finds that out of the 15 known detections, one is an FRII core (Cygnus A, Conway and Blanco 1995), 5 are in FRI cores, 5 in Compact Symmetric Objects (CSOs) and 4 in Steep Spectrum Core (SSC's) objects. None of the detections is in a core dominated radio source, although many have been searched. Several explanations for these statistics are possible (Conway 1996), but the most likely explanation seems that the absorption is due to a disk or torus like structure with a scale size of 100 pc. Evidence for the presence of such 100 pc disks comes from HST observations of gas and dust (e.g. Jaffe et al. 1993), CO observations (e.g. Rydbeck et al. 1993) and HI absorption VLBI imaging (Conway 1996)

For two reasons, core dominated radio sources will not show absorption. First, the radio jet will be perpendicular to the plane of the torus, with the approaching jet strongly Doppler-boosted and the counter jet strongly Doppler-dimmed. Since the disk will mainly occult the very faint counter jet, absorption is very difficult to observe. Second, strong versions of the radio galaxy/quasar unifying scheme (e.g. Antonucci 1993) assume the presence of a strong ionising beam in the direction of the radio axis. Since any gas close to the disk that is located within this beam will get ionised, no neutral gas is present in core dominated sources at such a location that it can be seen in absorption.

On the the basis that the northern hotspot contains 75 % of the continuum emission of the radio source, de Bruyn (1995) argued that the observed 21 cm absorption would be mainly due to absorption against this component. Since the northern hotspot has a projected linear size of 1.5 kpc, the absorption could be due to, for example, a dwarf galaxy; dwarf galaxies are small enough not to cover a large part of the Lyα emission and some of the dwarf galaxies in the local universe are known to have sufficiently high column densities (e.g. Lo et al. 1993). Furthermore, there is tendency for companion galaxies to be located

[1]From the work of van Ojik et al. (1997) it is clear that the Lyα absorbers can be substantially offset with a few hundred km s^{-1} from the peak of the Lyα emission line. For the highest redshift radio galaxies, Dey (this volume) argues that such absorbers can be blue-shifted by as much as 1000 km s^{-1}. However, the column densities for the strongest absorbers are only a few times 10^{19}, not sufficient for observable 21 cm absorption.

preferentially along the radio axis (Röttgering et al. 1996). However, given the abundant evidence for associated 21 cm absorbers being invariably due to central disks, it is interesting to consider whether 0902+34 could contain such a disk at its center. 0902+34 contains a relatively strong radio nucleus with a flux density at 1.65 MHz of 9.57 mJy (Carilli 1995). Since the spectral index between 1.65 and 8.3 MHz is flat ($\alpha = -0.03$), the extrapolated flux density of the core at 325 MHz would be 10 mJy, which is 0.8 % of the total flux density at 325 MHz. Since the depth of the absorption is also 10 mJy, this immediately implies that the disk obscuring the nucleus should be optically thick, and therefore virtually 100 % of the nucleus would be absorbed in the 21 cm line. In other words, the measured absorption for 0902+34 is 0.8 %, and therefore if this is absorption only against the core, the absorption has to be almost 100 %.

It is interesting that absorption has been seen against compact radio sources with optical depths of up to 44 % (Carilli et al. 1998). However, optical depths of 10 % are much more common in compact radio sources (Vermeulen et al. in prep) and a disk with such a "low" optical depth could not explain the absorption in 0902+34 as only due to nuclear absorption. There seems to be two ways to explain the absorption by a disk with moderate optical depth.

First, high resolution imaging of distant radio galaxies has shown that about one third of the HzRGs have nuclei with spectral indices steeper than < -1.0 (Carilli et al. 1997; Athreya et al. 1998). It could be that the nucleus of 0902+34 is stronger at 325 MHz than indicated by the high frequency spectral index, and then a disk with moderate optical depth would be easier to detect with 21 cm absorption measurements. Second, if the hypothesised disk had a scale size so that it would cover part of the base of the jet, the required high optical depth would be reduced. The knot in the jet closest to the nucleus of 0902+34, J1, is at a distance of $0.23''$ of the nucleus, has a spectral index $\alpha_{1.65}^{8.3} = -0.80$ and a flux density at 1.65 MHz of 9.57 mJy, comparable to the nucleus (Carilli 1995). So a disk with a radius of 1.5 kpc (corresponding to $0.2''$) would cover both the nucleus and part of the jet that includes knot J1, and the optical depth then only need to be of order 20 %. Although the needed disk size is large, in the local universe luminous IRAS galaxies can indeed have disks of a few kpc (Sanders and Mirabel 1996).

The scenario of the HI absorption in 0902+34 being due to a disk has a number of attractive features:

- It immediately explains why no corresponding absorption is seen in the Lyα emission. The scale size of this Lyα region is many orders larger than the torus and therefore the torus can not absorb a significant amount of the Lyα emission.

- The radio morphology of 0902+34 is very peculiar compared to the 40 distant radio galaxies for which good radio imaging exist (Carilli et al. 1997; Athreya et al. 1998). This is the only one that shows a strong jet and nucleus. The radio morphology of "normal" distant radio galaxies is that of a double lobed radio source with a weak core and a possible weak jet. In Table 1. we have given the core fraction at 20 GHz for 0902+34 and the other distant radio galaxies for which absorption has been searched for showing 0902+34 has a core that is of order a factor of 10 stronger than the other radio galaxies. For the "normal" distant radio galaxies the core and jets are generally too weak to observe absorption by a 1 kpc scale torus, consistent with our presented WSRT results (see Table 1) that it is indeed difficult to observe HI absorption in normal distant radio galaxies.
- The WSRT observations on 0902+34 show marginal evidence for a blue wing extending several 100 km/s to the blue of the main HI absorber. Although it is not yet clear whether this feature is real, it is interesting to speculate that this structure might be due to velocity structure in the rotating HI disk. Deeper observations could provide valuable information on this.

Acknowledgements We would like to thank René Vermeulen for useful discussions. This work was supported in part by a programme subsidy granted by the Netherlands Organisation for Scientific Research (NWO).

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