

## Associated HI Absorption in the $z = 3.4$ Radio Galaxy B2 0902 + 343 Observed with the GMRT

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Received 2004 January 28; accepted 2004 June 14

**Abstract.** We have made observations of the associated HI absorption of a high redshift radio galaxy 0902+34 at  $z = 3.395$  with the Giant Meterwave Radio Telescope in the  $323 \pm 1$  MHz band. We find a narrow absorption line with a flux density of 11.5 mJy at a redshift of 3.397 consistent with that observed by Uson *et al.* (1991), Briggs *et al.* (1993) and de Bruyn (1996). A weak broad absorption feature reported by de Bruyn (1996) has not been detected in our observations. We also place an upper limit of 4 mJy ( $2\sigma$ ) on emission line strength at the position where Uson *et al.* (1991) claimed to have found a narrow emission line.

**Key words.** Galaxies: active; absorption lines—radio lines; galaxies—radio galaxies; individual (0902 + 343).

### 1. Introduction

It is believed that the epoch of galaxy formation lies beyond  $z \geq 5$  but there is considerable uncertainty in their subsequent evolution. Radio galaxies and quasars at high redshifts are useful in studying the early stage of formation of galaxies. Many high redshifted radio galaxies and quasars have been looked at for associated absorption of continuum radiation by neutral hydrogen (HI). Associated absorption provides invaluable information about the environment surrounding astronomical objects. This can be studied either by redshifted 21-cm absorption of HI against the radio continuum or by narrow absorption in the spectra of Ly- $\alpha$  emission or absorption. Till date there is only one object beyond redshift  $z \geq 3$  in which associated 21-cm absorption has been found. This is the radio galaxy B2 0902 + 343 at a redshift of  $z = 3.395$  in which associated absorption was found by Uson *et al.* (1991) and later confirmed by Briggs *et al.* (1993) and de Bruyn (1996).

The radio galaxy B2 0902 + 343 was first identified with an optical object by Lilly (1988) under “1 Jansky empty field survey”. Its very flat optical broad spectral energy distribution indicates that it may be a ‘protogalaxy’, undergoing its first major burst

of star formation (Eisenhardt & Dickinson 1992). The spatial extension of this radio source is  $7'' \times 4''$ . The galaxy shows a bizarre radio structure in high resolution radio images (Carilli 1995). The radio source has two outer lobes and a prominent nuclear core source with a flat spectral index. The flux density of the core at 1.665 GHz is  $\sim 10$  mJy, being about 2.4 % of the strength of the entire source at that frequency. At the northern end of a sharp knotty jet emerging from the core, with a sharp  $90^\circ$  bend towards its outer end, is located a prominent hot spot and also a long ‘plume’ of emission with an ultra steep spectral index of  $-3.3$ . The southern lobe consists of two components having perpendicular orientation with respect to the direction of the core. The source seems to be oriented at an angle of about  $45^\circ$  to  $60^\circ$  with respect to the sky plane (Carilli 1995). Moreover this is one of the unique high redshifted sources which does not follow radio-optical alignment effect. HST observations by Pentericci *et al.* (1999) show that the optical galaxy consists of two regions of approximately the same flux density with a void or valley in between. Astrometry measurements show that the radio core is situated in the valley (Pentericci *et al.* 1999) but do not rule out the possibility that the radio core could be coincident with any of the two components. The presence of narrow Ly- $\alpha$  emission distinguishes it from a high redshifted quasar. Also, recent Chandra observations by Fabian *et al.* (2002) has found X-ray emission from the source. The centroid of the X-ray emission (J2000 09 05 30.17, +34 07 56) is coincident with the flat spectrum nuclear core source (J2000 09 05 30.13, +34 07 56.1), which suggests it to be an AGN.

This peculiar galaxy and its surroundings have been searched for absorption and emission features by several workers using various radio telescopes. Uson *et al.* (1991) detected a narrow absorption line of 11 mJy associated with B2 0902+343. In addition, they claimed to have found an emission line of 11 mJy located about 33' away from the galaxy, which was ascribed to emission by a massive HI condensate as expected for a Zeldov'ich ‘pancake’. Subsequent observations by Briggs *et al.* (1993) using the Arecibo Radio Telescope and by de Bruyn (1996) using Westerbork Radio Telescope (WSRT) confirmed the presence of the narrow associated line but did not detect the emission line. The possible presence of a broad absorption feature extending to several hundred  $\text{km s}^{-1}$  on the blue-ward side of the narrow absorption feature has been reported by de Bruyn (1996). Cody *et al.* (2003) looked for the presence of OH gas in the galaxy to get an insight in the molecular content of the galaxy but did not detect redshifted 1665/1667 MHz OH lines. They put a  $1.5\sigma$  upper limit of 3.6 mJy, which gives an upper limit on the OH column density of  $N(\text{OH}) \leq 10^{15} \text{ cm}^{-2}$ .

We have observed the radio galaxy B2 0902+343 with the Giant Meterwave Radio Telescope (GMRT) in the band  $323 \pm 1$  MHz for studying the associated absorption features. We have detected the narrow absorption line component. However, the broad absorption feature claimed by de Bruyn (1996) is absent in our results. We also place a  $2\sigma$  upper limit of 4 mJy at the position of the emission line claimed by Uson *et al.* (1991). We present observations and data analysis in section 2. Results are given in section 3 and discussions and conclusions in section 4.

## 2. Observations and data analysis

Observations of the radio galaxy B2 0902 + 343 were made with the GMRT in March 1999 and on May 15th, 2000 near 323 MHz. GMRT is an aperture synthesis radio telescope situated about 80 km north of Pune in India. It consists of 30 fully steerable

parabolic dishes of 45 meter diameter each, spread over an extent of about 25 km (Swarup *et al.* 1991). Fourteen out of the 30 antennas are located within a compact array of about 1 square km in size and the remaining 16 antennas are located along a Y-shaped array, with each arm of about 14 km length.

In March 1999, observations of the radio galaxy B2 0902 + 343 were made for  $\sim 8$  hours with 12 to 15 antennas. Although observations were made with 128 channels over a bandwidth of 2 MHz centered at 323 MHz, the data were good for only the central part of 1 MHz. 3C286 was used as flux calibrator and 3C216 and 0834 + 555 were used as phase calibrators. RMS noise of the continuum map after collapsing 40 channels was 4 mJy. RMS noise on the line images, after subtracting the continuum was 1.4 mJy.

On May 15th 2000, observations were made for 6 hours on the source, when only 15 good antennas were available. The observations were made with 128 channels over a bandwidth of 2 MHz. Therefore, the width of each channel was 15.6 kHz. 3C48 and 3C286 were used as flux calibrators. 3C216 was used as a phase calibrator. 3C48, 3C286 and 3C216 were also used as bandpass calibrators. The phase calibrator was observed for 8 minutes after every 40 minutes.

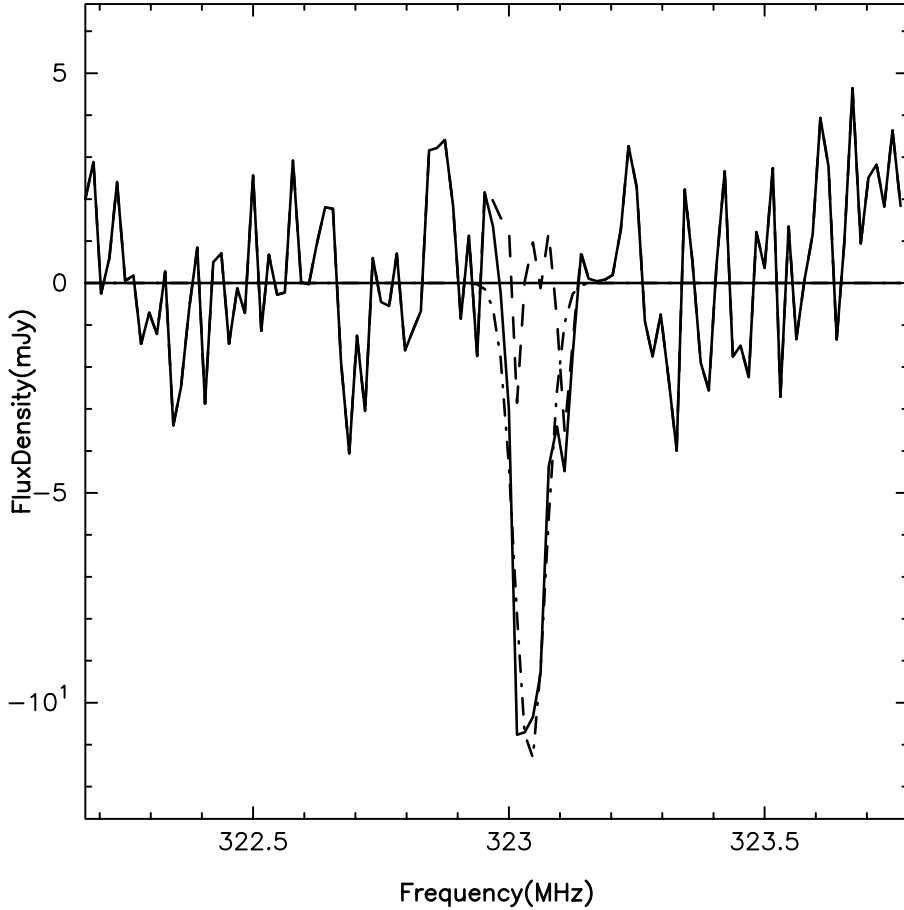
The data were analyzed using Astronomical Image Processing System (AIPS) of NRAO. The gains of the antennas were determined using the flux and phase calibrators after flagging any bad data. The flux densities of 3C48 and 3C286 were calculated to be 43.64 Jy and 26.03 Jy respectively, on the scales of Baars *et al.* (1977) using the AIPS task SETJY. The flux density of 3C216 was found to be  $16.65 \pm 0.21$  Jy. After bandpass calibration using the flux and phase calibrators, AIPS task SPFLG was run on the source 0902 + 34 to flag any data showing RFI. In total, the amount of good data that could be used finally was 76%. We then averaged several line free channels and made a continuum map of the source using AIPS task IMAGR. We also did self calibration in order to get rid of residual phase errors and to improve the quality of the map. The resolution of the map was  $39'' \times 30''$ . The continuum flux density of the source was found to be  $1.357 \pm 0.008$  Jy. The dynamic range obtained in continuum map was  $\sim 450$ . The source is not resolved in our map. The continuum map was then subtracted from the line data using UVSUB. AIPS task UVLIN was then run and the line free channels were used for the baseline fitting. The UVLIN output was used for making a spectral cube of the data. The narrow absorption feature towards B2 0902 + 343 was clearly detected but no other absorption or emission feature was seen in the spectral cube covering the field of view of the 45-m antennas of the GMRT.

### 3. Results

#### 3.1 HI absorption narrow line

Figure 1 shows the HI absorption profile obtained from the observations made on 15th May 2000. The dashed dot line shows a one-component Gaussian fit to the observed absorption line. We find that there is a continuum offset of about 1 mJy. We have made one-component Gaussian fit after removing this “continuum” of 1 mJy offset and the results are summarized in Table 1. A possible weak absorption feature reported by Briggs *et al.* (1993) near 322.5 MHz is not seen in our observations.

0902+34

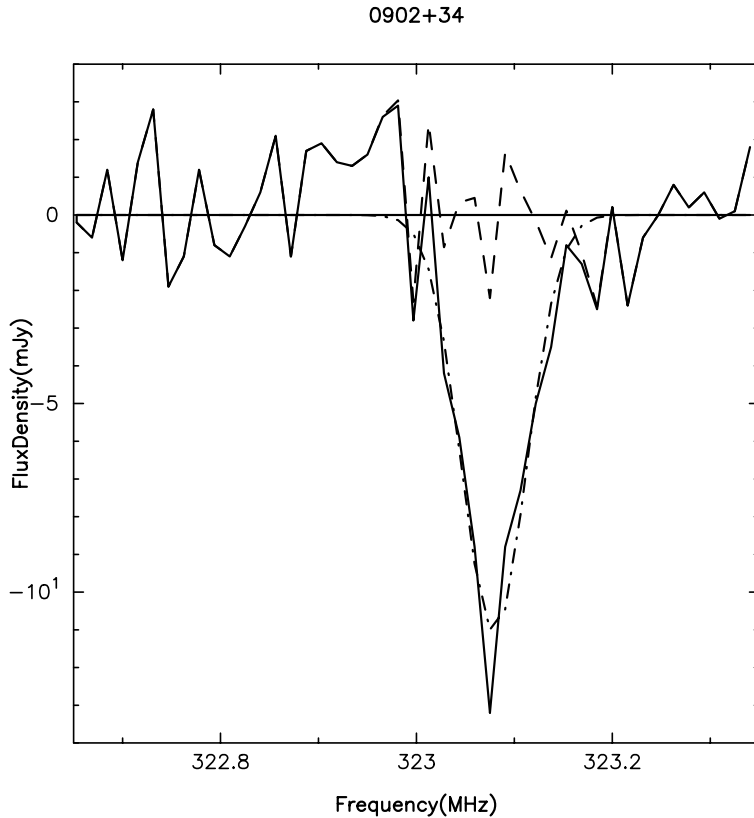


**Figure 1.** One-component Gaussian fit to the absorption line observed on 15th May, 2000. Dot-dashed line shows Gaussian fit to the observed absorption feature. Dashed line shows residual to the Gaussian fit.

**Table 1.** Best fit Gaussian parameters for the March, 1999 and May, 2000 data.

Date of observn	Gaussian fit	Line depth mJy	Position of line MHz	Redshift z	FWHM kms <sup>-1</sup>	rms mJy/beam
2000 May	1-comp.	11.5	323.062 ± 0.005	3.397	76 ± 6	1.8
1999 Mar	1-comp.	11.1	323.058 ± 0.005	3.397	72 ± 6	1.4

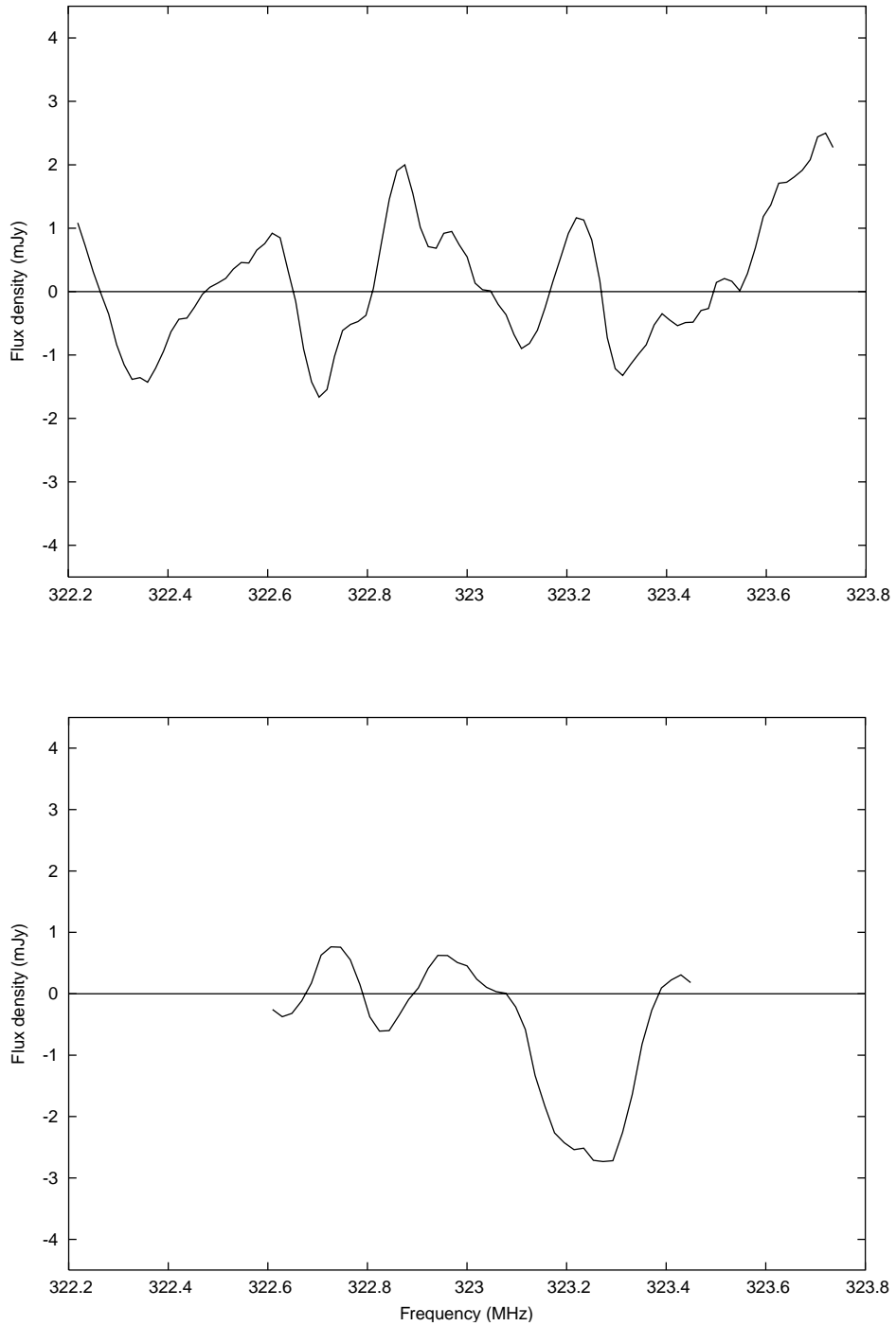
The absorption profile for the March 1999 observations is shown in Fig. 2. This spectrum shows the presence of a small asymmetric profile towards the higher frequency. Hence, we have made both one-component and two-component Gaussian fit to this data. In Table 1, we summarize the results of only 1-component Gaussian fit, since we find from the two-component Gaussian fit that the asymmetry towards higher frequency end of the absorption line is not significant.



**Figure 2.** One-component Gaussian fit to the absorption line observed on March, 1999. Dot-dashed line shows a fit to the observed absorption feature and dashed line shows residual to the Gaussian fit.

### 3.2 Broad HI absorption line

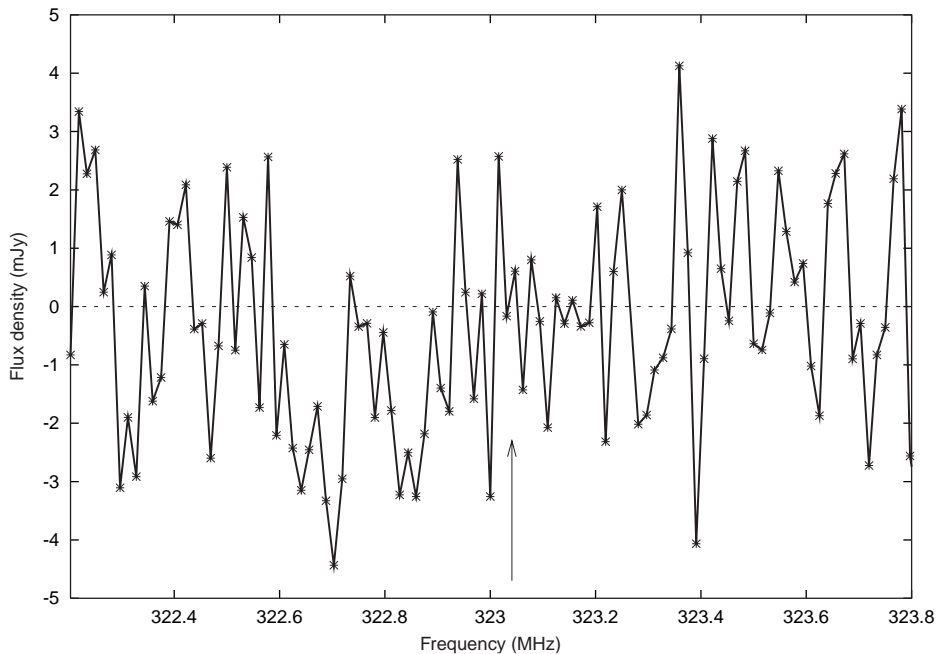
de Bruyn (1996) reported the possible presence of a weak broad absorption feature extending several hundred  $\text{km s}^{-1}$  blue-ward (at a higher frequency) of the prominent narrow absorption line. In order to search for its presence in the GMRT observations, we have removed the Gaussian fit shown in Figs. 1 and 2 and then convolved the residuals with a Gaussian profile of FWHM of  $100 \text{ km s}^{-1}$ . The smoothed residual spectra of GMRT observations on May 15, 2000 are shown in Fig. 3. No broad absorption feature is visible in either spectra. Since a digital file of the spectrum observed with WSRT by de Bruyn was not saved by him (private communication), we have carefully digitized the data from the spectrum published by him as Figure 1 (de Bruyn 1996). We have fitted a Gaussian to the narrow feature of his spectrum and found that the narrow absorption line has a FWHM of  $80 \pm 8 \text{ km s}^{-1}$ . We have also convolved the residuals of his data with  $100 \text{ km s}^{-1}$  FWHM as shown in the last panel of Fig. 3. Figure 3 shows the possible presence of a broad absorption feature at  $3\sigma$  level in the WSRT observations. However, we place an upper limit of  $3 \text{ mJy}$  at  $3\sigma$  level from the GMRT data of 15th May 2000.



**Figure 3.** Upper panel shows the residuals of one-component Gaussian fit to absorption line observed in May, 2000. Lower panel shows the same for de Bruyn's dataset.

### 3.3 Non-detection of HI emission

Uson *et al.* (1991) had claimed the detection of an HI emission feature of 11 mJy at a frequency of 323.041 MHz, towards the direction of  $\alpha = 09^h 03.8^m$ ,  $\delta = 33^\circ 52'$  (B 1950), which is 33' away from the position of the source B2 0923 + 343. We made the spectral cube with 200'' resolution (same resolution as used by Uson *et al.* (1991)) and corrected it for primary beam pattern. We do not see any emission feature at the given position. We place a  $2\sigma$  upper limit of 4 mJy at the position of the above emission feature. The GMRT spectrum towards this direction is shown in Fig. 4.



**Figure 4.** Spectrum at the position of emission claimed by Uson *et al.* (1991) at  $09^h 03.8^m$ ,  $33^\circ 52'$  (B 1950) and frequency of about 323.0 MHz. Arrow points towards the frequency at which Uson *et al.* found the emission.

### 3.4 Search for HI absorption towards background sources

Although the probability of a strong radio source being located in a cluster near B2 0902 + 343 is small, we have searched for any absorption features towards three radio sources in the field of view of the primary beam of the 45 m dishes of the GMRT (see Table 2). No absorption lines were detected.

## 4. Discussions and conclusions

Our observations show that the depth of the HI absorption at a redshift (doppler shift corrected) of  $3.3967 \pm 0.0002$  is 11.5 mJy with a FWHM of  $74 \pm 6 \text{ km s}^{-1}$  (see Tables 1 and 3). In our GMRT observations with only 15 antennas, we could not get sufficient

**Table 2.** The sources in the FoV, looked for any possible absorption feature.

Source	Position J2000	Flux density Jy
1	09 07 17.6, +33 44 10	$0.675 \pm 0.008$
2	09 06 19.4, +34 17 32	$0.289 \pm 0.008$
3	09 04 32.7, +34 32 12	$0.183 \pm 0.008$

**Table 3.** Details of all observations of 0902 + 34 by various workers.

Obs. Date	Telescope	Time hours	Line depth mJy	FWHM . kms <sup>-1</sup>	rms mJy/beam	References
Apr, 91	VLA	14	11.4	$270 \pm 50$	1.8	Uson <i>et al.</i> 1991
1992	Arecibo		14	90	1.9	Briggs <i>et al.</i> 1993
1995	WSRT	144*	12	100**	1	de Bruyn 1996
May, 00	WSRT	12	15.9	$120 \pm 50$	2.4	Cody <i>et al.</i> 2003
Mar, 99	GMRT	8	11.1	$72 \pm 6$	1.4	This paper
May, 00	GMRT	6	11.5	$76 \pm 6$	1.8	This paper

\* As mentioned in Rottgering *et al.* (1999).

\*\* Our estimate to the data of de Bruyn data gives line depth of  $9.93 \pm 1.45$  mJy, FWHM of  $80 \pm 8$  km s<sup>-1</sup>.

resolution to locate the position of the line. The possible scenarios for its position could be either the northern hot spot or a tori/jet surrounding the nuclear source. The observed depth of the narrow absorption line of 11.5 mJy is close to the observed flux density of the radio nucleus (flux density of 9.5 mJy at 1.65 GHz), implying 100% absorption (optical depth of 1) by cold HI gas which could be present in a disk or tori. Associated HI absorption has been found in many compact steep spectrum sources (Vermeulen *et al.* 2003). However, only absorptions up to about 10–40 % have been seen in these sources. Assuming that the surrounding disk has a scale size such that it covers a possible steep spectrum core and part of the base of the jet, Rottgering *et al.* (1999) have suggested that the observed absorption may be associated with a steep spectrum core. In that case the required optical depth could be much less, say 20%.

Although associated HI absorption is generally not seen in extended powerful radio galaxies, there are some radio galaxies in which HI absorption is seen against the hot spots (Morganti 2002 and references therein). de Bruyn (1996) has suggested that the absorption is likely to be against the northern hot spot. The hot spot has an angular size of 0.2'' and contains about 75% of the total flux density. Its extrapolated flux density at 323 MHz is  $\sim 1$  Jy. In this case optical depth of only 1.2% is required, which is pretty reasonable. The implied column density,  $N(\text{HI}) \sim 1.6 \times 10^{21}$  cm<sup>-2</sup>, assuming optical depth of 0.012 and a mean spin temperature of 1000 K. The HI gas could be surrounding the hot spot which is not an unlikely scenario considering that the optical observations of B2 0902 + 343 indicates it to be a protogalaxy. The source may be associated with a merging galaxy located near the hot spot or dwarf galaxy along the line of sight, as a possible scenario suggested by Rottgering *et al.* (1999).



Considering the above discussion, it seems to us that the HI absorption could be associated with the hot spot. However, sub arcsec high-resolution observations at low frequencies are required in order to determine the location of the absorber.

We conclude with the following results:

- We have detected a narrow absorption line with the GMRT in B2 0902+343 with flux density of 11.5 mJy which has a half-power velocity width of  $74 \pm 6 \text{ km s}^{-1}$ . The line depth is consistent with previous observations.
- The broad absorption feature indicated by de Bruyn (1996) is not seen in our observations. We also do not detect the emission line (33' away) as claimed by Uson *et al.* (1991) which is consistent with the results by Briggs *et al.* (1993) using the Arecibo Radio telescope and de Bruyn (1996) using the WSRT.

### Acknowledgements

We thank the staff of the GMRT who made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. We acknowledge valuable comments by Prof. Rajaram Nityananda. N. G. Kantharia is thankful to the late Prof. K. R. Anantharamaiah for suggesting in 1999, the observation of this source. We thank the anonymous referee for useful comments.

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