Appendix I
Multi-Frequency GMRT observations of the H II regions S 201, S 206, and S 209: Galactic temperature gradient
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Multi-frequency GMRT observations of the HII regions S 201, S 206, and S 209

GALACTIC TEMPERATURE GRADIENT

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Abstract. We present radio continuum images of three Galactic HII regions, S 201, S 206, and S 209 near 232, 327, and 610 MHz using the Giant Meterwave Radio Telescope (GMRT). The GMRT has a mix of short and long baselines, therefore, even though the data have high spatial resolution, the maps are still sensitive to diffuse extended emission. We find that all three HII regions have bright cores surrounded by diffuse envelopes. We use the high resolution afforded by the data to estimate the electron temperatures and emission measures of the compact cores of these HII regions. Our estimates of electron temperatures are consistent with a linear increase of electron temperature with Galacto-centric distance for distances up to ~18 kpc (the distance to the most distant HII region in our sample).

Key words. ISM: HII regions – ISM: individual objects: S 201, S 206, S 209 – radio continuum: ISM

1. Introduction

A number of studies have indicated that the electron temperature $T_e$ of HII regions increases with increasing Galacto-centric distance (e.g. Deharveng et al. 2000 and references therein). This effect is attributed to a decrease in heavy elements abundances with Galacto-centric distance. A low metal abundance leads to less effective cooling and consequently higher electron temperature. These studies are based either on estimates of $T_e$ from radio recombination lines (RRLs) (which in turn depend on corrections for departures from local thermodynamic equilibrium (LTE) and for collisional broadening effects), or estimates based on line strengths of the forbidden line transitions of oxygen $[O\text{iii}]\lambda4363, 5007$ (which are strongly dependent on temperature variations, if any, over the observed volume). Further, most of these studies are based on observations of HII regions with Galacto-centric distances $R_0 < 15$ kpc with very few measurements of $T_e$ beyond 15 kpc. Consequently most determinations of metallicities of the outer galaxy HII regions are based on values of $T_e$ taken from an extrapolation of the observed gradient in temperature up to about 15 kpc (e.g., Deharveng et al. 2000). Since the O/H ratio (a commonly used indicator of metal abundance) depends sensitively on $T_e$, metallicities of the outer galaxy HII regions are poorly constrained. In view of this, it is important to get independent estimates of the electron temperatures of HII regions in the outer galaxy.

An independent measurement of $T_e$ can be obtained from radio continuum observations. The ionized material in HII regions emits radio continuum through free-free emission. At sufficiently low radio frequencies where the nebula is optically thick ($\tau >> 1$), the emergent radiation is a black body spectrum, and therefore, the observed brightness temperature is equal to the electron temperature $T_e$. On the other hand, at sufficiently high radio frequencies, where the optical depth $\tau$ of thermal electrons is low ($\tau << 1$), the observed brightness is proportional to the emission measure of the nebula. Most of the available radio maps for HII regions are at high radio frequencies (i.e. above 1.4 GHz, e.g., Fich 1993; Balser et al. 1995). These maps show that HII regions often have a bright core with several knots surrounded by an extended envelope of diffuse emission. These core-envelope structures of HII regions imply that accurate measurement of $T_e$ from low radio frequency observations requires high angular resolution, since, often only bright compact cores will be optically thick at frequencies of a few hundred MHz. This study presents an analysis of the low-frequency GMRT observations of three Galactic diffuse HII regions spanning Galacto-centric distances up to 18 kpc.

The GMRT is an ideal telescope for these observations since it operates at several low radio frequency bands, viz.,
150, 232, 327, 610, and 1420 MHz and also it has a hybrid configuration which makes it sensitive to both diffuse emission (on scales up to ~45' at 232, 30' at 327, and 17' at 610 MHz) while also having the resolution (~15' at 232, 10'' at 327, and 6'' at 610 MHz) to resolve the compact cores.

2. Observations

The observations were carried out during the period of August to December, 1999 at three frequency bands, viz., 232, 327, and 610 MHz. The GMRT has a "Y" shaped hybrid configuration of antennas with six antennas along each of the three arms and twelve antennas randomly placed in a compact arrangement near the centre of "Y" (for details, see Swarup et al. 1991). The compact array at the centre is about a kilometer across and is generally referred to the "central square". Baselines in the central square (shortest baseline ~100 m) provide sensitivity to diffuse large scale emission, while baselines involving arm antennas (longest baseline ~25 km) provide high angular resolution. The GMRT was in its commissioning phase during our observations, and due to various debugging and maintenance activities not all 30 antennas were available for observations. The observations were carried out with typically 20 to 25 antennas in different observing sessions.

The data were recorded in the default correlator mode which produces visibilities in 128 channels over a user selectable bandwidth in multiples of 2 starting from 62.5 kHz and up to 16 MHz. The observational parameters are summarized in Table 1. The observations near 610 and 327 MHz were made using the full 16 MHz bandwidth while observations near 232 MHz were made with a bandwidth of 2 MHz centered at a frequency around which least local interference has been detected in the past observations. The images at all frequencies are however made using data from only one channel which corresponds to a bandwidth of 125 kHz at 327 and 610 MHz, and 15.6 kHz at 232 MHz. This restriction was partly because of a crunch in disk storage at the time when these data were taken, and partly because dynamic range limitations at the GMRT at the time we took the data meant that the increase in bandwidth did not result in a proportionate increase in sensitivity. At each frequency band, we observed the source for about 8–10 hours, primarily in order to have a good (u, v) coverage.

For all the observations, the source 3C 48 was used as the primary flux calibrator. The flux density of 3C 48 at each frequency was estimated using the Baars et al. (1977) flux densities of standard VLA calibrators. The phase and amplitude gains of antennas were derived from observations of a secondary calibrator at intervals of 45 min. For observations on S 206 and S 209, 3C 119 was used as a secondary calibrator while 0107+562 was used as a secondary calibrator for observations on S 201. Both 3C 119 and 0107+562 are standard VLA calibrators. The fluxes of secondary calibrators were determined via boot-strapping the fluxes of the primary calibrator 3C 48.

The data were carefully checked for interference or other problems. At 232 and 327 MHz, a few short baselines were found to be corrupted, possibly by interference, and were removed. The data at 610 MHz were found to be free from any interference. Data reduction was done in classic AIPS. The calibrated data were Fourier transformed using appropriate (u, v) ranges, tapers and weights to make different images, some of which are sensitive to large scale structures, and others which have the maximum possible angular resolution. These images were deconvolved using the "CLEAN" algorithm as implemented in AIPS task "IMAGR". The final gains of the antennas were fixed using several iterations of self-calibration.

The variations in system temperatures of GMRT antennas are currently not routinely monitored during observations. The system temperature at 610 MHz was measured both toward the absolute flux calibrator 3C 48 and the target source by firing the noise calibration diodes. For 327 and 232 MHz images, the system temperature toward 3C 48 and target source were obtained using interpolated values of sky temperature from 408 MHz all-sky map of Haslam et al. (1982). A correction factor equal to the ratio of the system temperature toward the target source and 3C 48 was applied in the deconvolved image. The deconvolved images were finally corrected for the primary beam attenuation, assuming a Gaussian shape for the primary beam. The half power points (HPBW) of the primary beam of GMRT antenna are estimated as 1.85, 1.35, and 0.72 degree for 232, 327 and 610 MHz respectively.

3. Results

Images of S 201 are shown in Figs. 1a–c. S 201, (l = 138.48, b = 1.64; also known as IC 1848), at a Galacto-centric distance of 10.5 ± 1 kpc, is believed to be excited due to a single star of spectral type O9.5 (Mampaso et al. 1989). High resolution (~5") 15 GHz radio continuum image reveals a bright arc core with multiple peaks of emission (Felli et al. 1987). The 616 MHz GMRT low resolution image (Fig. 1c) traces diffuse emission extending up to ~5" which is consistent with the 1.4 GHz VLA image of Fich (1993). The high resolution 231 MHz GMRT image (Fig. 1b) shows the core to be a complex structure consisting of several unresolved compact sources. The diffuse nebula extending toward the west of the core in the 231 MHz image (Fig. 1b) is consistent with the 15 GHz radio image of Felli et al. (1987).

Images of S 206 are shown in Figs. 1d–f. S 206, (l = 150.74, b = -0.75; also known as NGC 1491), is an evolved H II region at a Galacto-centric distance of 11.1 kpc (Deharveng et al. 2000). The excitation is believed to be provided by a single O5 star (Crampton & Fisher 1974). The 5 GHz radio continuum image shows a classic blister type morphology (Fig. 4 in Deharveng et al. 1976) as described in Icke et al. (1980). Our high resolution images at 613 MHz (Fig. 1d), 236 MHz (Fig. 1e) as well as 328 MHz (not shown) show good correspondence to the 5 GHz image of Deharveng et al. (1976). The low resolution 328 MHz image (Fig. 1f) shows a large low intensity envelope surrounding the core emission.

Images of S 209 are shown in Figs. 1g–i. S 209 (l = 151.6, b = -0.24; also known as RAFGL 550) is one of the most distant (dG = 17.7 kpc, Deharveng et al. 2000) Galactic H II region. Although the mean size of H II regions decreases with increasing Galacto-centric distance (Fich & Blitz 1984), S 209 is unusual in that it has a very large size (~50 pc)
for its Galacto-centric distance. The excitation is provided by a cluster of OB stars (Chini & Wink 1984). Our high resolution 613 MHz map (Fig. 1g) shows the core region to consist of an asymmetric, incomplete ring like structure. The high resolution image at 328 MHz and 328 MHz maps, does show some difference in the core region. We are unsure why this should be so. The low resolution 613 MHz image (Fig. 1f) shows that this region too has an extremely large, low surface brightness envelope, which has also been seen at 2.7 GHz image of Walmastey et al. (1975).

4. Discussion

We use these low frequency images to estimate electron temperatures and emission measures of the compact cores of the H II regions. If we approximate these cores to be homogeneous and spherically symmetric, then the flux $S$ is given by

$$S = 3.07 \times 10^{-2} T_e^2 \Omega (1 - e^{-\delta \Omega})$$

(1)

$$\tau(\nu) = 1.643 \times 10^3 \nu^{-2.35} EM T_e^{-1.35}$$

(2)

(Mezger & Henderson 1967) where $S$ is the integrated flux density in Jy, $T_e$ is the electron temperature in Kelvin, $\nu$ is the frequency of observation in MHz, $\tau$ is the optical depth, $\Omega$ is the solid angle subtended by the source in steradian, (which in this case, since the cores are unresolved, is taken to be the synthesized beam size), and $EM$ is the emission measure in cm$^{-6}$ pc. The emission measure $EM$ is defined as $\int n_e^2 dl$; the integral being taken along the line of sight and averaged over the beam. $a$ is a correction factor which depends both upon the temperature and frequency. We have used an average value of $a$ as 0.98 (using Table 6 of Mezger & Henderson 1967) for the frequency range 200–600 MHz and $T_e \sim 10000$ K. The H II region cores can be modeled by solving Eqs. (1) and (2) iteratively for different $EM$ and $T_e$. The fitting procedure converges rapidly when observations at least two frequencies are available and the frequencies are such that the H II region is optically thick at one frequency and optically thin at the other.

We measured the peak flux densities of cores after convolving the images of a H II region at different frequencies to a common angular resolution (i.e. the source size $\Omega$ was taken to be $1.132 \times 2 \delta_x \delta_y$, where $\delta_x$ and $\delta_y$ are the half power points of the common convolved beam). The best fit values for $T_e$ and $EM$ as obtained from the fitting procedure described above are listed in Table 2, and the observed and model fluxes are plotted in Fig. 2. The columns in Table 2 are as follows. Column 1: Name of the H II region, Col. 2: Coordinates (right ascension, declination) of the core for which the electron temperature has been measured, Col. 3: The frequency of observation, Col. 4: Integrated flux of the entire H II region, Col. 5: Area over which radio emission is detected, and over which the flux has been integrated to get the value listed in Col. 4, Col. 6: Estimated electron temperature of the core, Col. 7: Estimated emission measure of the core.

The electron temperature of S 201 is estimated to be $7070 \pm 1100$ K toward the peak radio emission. The earlier estimate for $T_e$ toward S 201 was $\sim 5000$ K based on non-detection of [O II] 44959, 5007 (Mampaso et al. 1989). The electron...
Appendix I

A. Omar et al.: GMRT observations of H II regions

Fig. 1. a) S 201 at 616 MHz. The angular resolution is 26" × 17". b) S 201 at 231 MHz. The angular resolution is 15" × 13". c) S 201 at 616 MHz made using u-v range 0-1 kλ only. The angular resolution is 133" × 129". d) S 206 at 613 MHz. The angular resolution is 13" × 11". The regions marked as A, B, C, & D are from the 5 GHz image of Deharveng et al. (1976). e) S 206 at 236 MHz. The angular resolution is 20" × 20". f) 328 MHz image of S 206 made using u-v range 0-1 kλ only. The synthesized beam is 180" × 149". g) S 206 at 236 MHz. The angular resolution is 10" × 10". h) S 209 at 236 MHz. The angular resolution is 25" × 25". i) 613 MHz image of S 209 made using u-v range only up to 1 kλ. The angular resolution is 160" × 136".

The temperature of 8350 ± 1600 K, derived for the core of S 206 (knot-A in Fig. 1c) is in reasonable agreement with previous measurements, viz. 8400 ± 800 K obtained using the H94α recombination line by Carral et al. (1981), and 9118 K obtained from the [O\textsc{iii}]λλ4363, 5007 lines ratio (Deharveng et al. 2000). The emission measure is 3.93(±0.40) × 10^4 cm^-6 pc, consistent with the value obtained by Deharveng et al. (1976). For S 209, the electron temperature corresponding to the peak radio emission at 613 MHz is estimated to be 10 855 ± 3670 K, somewhat higher than the value of 8280 K obtained using the H137β recombination line by Churchwell et al. (1978) but in reasonable agreement with the estimate of 11 000 K which was derived from H91α & H114β recombination lines (Balser et al. 1994).

Figure 3 is a plot of the electron temperature vs. Galactocentric distance for the three H II regions studied in this paper. The solid line is the relationship obtained by Deharveng et al. (2000) from a sample of six H II regions spanning Galactocentric distances from 6.6 to 14.8 kpc. The data for S 209 shows that this relationship appears to be valid even out to Galactocentric distance of ~18 kpc.

If there are systematic radial temperature gradients within the cores of H II regions, the Te estimated by various methods, viz., radio continuum, RRLs, and [O\textsc{iii}]λλ4363,
A. Omar et al.: GMRT observations of H II regions

5007 lines ratio (all of which probe different physical regions) would be discordant. The radio continuum observations at low frequencies are more sensitive to outermost regions of the core of the nebula (due to the high optical depths at these frequencies). The temperature estimates from high frequency RRLs (which is where most of the observations exist) are weighted toward regions of low temperature. Finally, estimates of $T_e$ from the [$O$ III] lines ratio are expected to be weighted toward high temperature regions due to the high cooling rate provided by [$O$ III] lines. Since, our estimates of $T_e$ are in general consistent with those obtained from RRLs as well as from [$O$ III] lines, any temperature gradients within the cores of these H II regions must be smaller than the combined uncertainties in these different $T_e$ measurements. Similar concordance between $T_e$ measured using these different methods have been obtained for W 51 (Subrahmanyan & Goss 1995) and M 17 (Subrahmanyan & Goss 1996; Wilson et al. 1997). Several authors have discussed the possibility of small scale temperature fluctuations in the cores of H II regions (Peimbert 1967; Rubin et al. 1998 and references therein), these cannot be ruled out based on our observations alone.

5. Conclusions

Three outer galaxy H II regions, S 201, S 206 and S 209 have been imaged at meter wavelengths using the GMRT. The images of these H II regions have been obtained at a resolution of less than a pc. This is the highest resolution achieved for any H II region at such low radio frequencies. All three H II regions show structures down to our resolution limit. The high resolution images near 610 MHz of these H II regions show a good correspondence with the radio continuum images at cm wavelengths. The low resolution radio images show that these H II regions are surrounded by large diffuse envelopes. The high resolution radio images have allowed us to get estimates of $T_e$ of these H II regions. From these measurements we find that:

1) the estimates of $T_e$ are in general consistent with that obtained from RRLs and [$O$ III] lines, 5007 line measurements, and
2) the measured temperatures are consistent with a linear increase of $T_e$ with Galacto-centric distance until $R_0 \sim 18$ kpc.

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References

Appendix I

A. Omar et al.: GMRT observations of H II regions


Appendix II

VLA detection of OH absorption from the elliptical galaxy NGC 1052

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Appendix II

VLA detection of OH absorption from the elliptical galaxy NGC 1052

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Abstract. VLA observations of OH absorption towards the elliptical galaxy NGC 1052 are presented. Both OH lines, at 1665 and 1667 MHz, were detected in absorption towards the center of NGC 1052. The hyperfine ratio of the two OH lines (r1667/r1665) is 2.6 ± 0.8 as compared to 1.8 expected for the excitation under LTE conditions for an optically thin cloud. The column density of OH is estimated to be 2.73 (±0.20) x 10^{14} cm^{-2} assuming VHI = 10 K. The centers of both the OH lines are redshifted from the systemic velocity of the galaxy by ~173 km s^{-1}. The velocity of OH line coincides with the velocity corresponding to the strongest HI absorption. We suggest that OH absorption is arising from a molecular cloud falling towards the nucleus. The OH line, though narrower, is found to be within the much broader and smoother H2O megamaser emission. The possible link between OH/HI and H2O emission is discussed.

Key words. galaxies: active – galaxies: individual: NGC 1052 – galaxies: ISM – radio lines: galaxies

1. Introduction

The most extensive and conclusive confirmation for the presence of cold interstellar material in early-type galaxies came from observations of dust with the Infrared Astronomical Satellite (IRAS) (Neugebauer 1984; Knapp et al. 1985; Knapp et al. 1988). Sensitive observations of HI (van Gorkom et al. 1986; Huchtmeier et al. 1995) have also shown that elliptical galaxies contain a significant amount of cold interstellar matter. The molecular contents of elliptical galaxies has been studied mainly through CO observations of infrared bright elliptical galaxies (Wang et al. 1992; Wiklind et al. 1995; Knapp & Rupen 1996). These observations resulted in the detection of molecular gas in several galaxies in emission and four galaxies in absorption, indicating that the overall detection rate of CO in elliptical galaxies is about 10–15%. The OH radical in absorption is also a good tracer of molecular gas in interstellar clouds (Liszt & Lucas 1996). Single dish OH surveys (Schmelz et al. 1986; Baan et al. 1992; Staveley-Smith et al. 1992; Darling & Giovannelli 2000) of several hundred galaxies of various types resulted in the detection of about 3 dozen galaxies, of which none was an elliptical.

NGC 1052, a moderately luminous (Lb = 1.6 x 10^{10} L_\odot) elliptical galaxy of type E4, is a member of a small group in the Cetus-I cloud. There are several estimates of the velocity for this system in the literature, which differ from each other by a few tens of kms^{-1}. We adopt VHI = 1474 ± 10 km s^{-1}, estimated from the optical emission lines (de Vaucouleurs 1991), which implies that NGC 1052 is at a distance of 21 Mpc (assuming H_0 = 70 km s^{-1} Mpc^{-1} and q_0 = 0). It is classified as a LINER (Fosbury et al. 1978; Ho et al. 1997) and is known for its several water megamasers (Braatz et al. 1996; Claussen et al. 1998). HI absorptions, redshifted from the systemic velocity, were detected at 1486, 1523 and 1646 km s^{-1} against the nuclear continuum source (van Gorkom et al. 1986). NGC 1052 was reported to have CO emission as well as absorption by Wang et al. (1992), but later observations by Wiklind et al. (1995) failed to confirm those detections. More recently, Knapp & Rupen (1996) have reported a possible CO absorption from NGC 1052 near 1622 km s^{-1}. Since the reported CO detections are quite noisy, it remains uncertain whether NGC 1052 has a molecular component associated with the HI (21 cm) absorption.

Here we report the first detection of 1665 and 1667 MHz OH absorption in NGC 1052. The next section describes the observational details and results. Subsequent sections compare these results with observations at
Appendix II

Table 1. Observation parameters.

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<td>rms noise per channel (mJy beam⁻¹)</td>
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optical, X-ray, and other wave bands, and discuss some of the implications.

2. Observations and results

NGC1052 was observed in the B configuration of the VLA, which has interferometric baselines ranging from 100 m to 11 km. Data were recorded in the 4IF correlator mode, recording 1.5625 MHz in each of the two circular polarizations for two frequency bands, one centered at 1656.5 and other at 1658.3 MHz. The details of the observations are listed in Table 1. The data were reduced in AIPS using standard calibration and imaging methods. The amplitude, phase and frequency response of the antennas were calibrated separately for each IF. The phase and amplitude gains of the antennas were derived from observations of the standard VLA calibrator 0240-231 at intervals of 30 min. The flux scale was set using Baars et al. (1977) flux density of the standard VLA calibrator 0319+415 (SC48). A combined bandpass spectrum was generated using all the data taken on the amplitude and phase calibrators as well as on the strong radio source 0319+415 (SC48). A continuum data set was formed by averaging the calibrated visibility data of 30 line-free channels. The continuum data set was self-calibrated and the resulting antenna gain corrections were applied to every spectral channel separately. The continuum emission common to all channels was removed using the task "UVLIN" inside AIPS. Continuum-free images for all channels were made and the source region was searched for absorption. Both 1665 and 1667 MHz lines were detected, in each of the two circular polarizations. Although, a part of the band centered at 1656.5 MHz was affected by interference, the detected 1665 MHz line was outside the affected region.

The core/jet morphology in the continuum image of NGC1052 is in accordance with the previous observations by Jones et al. (1984). The peak continuum flux density of the core is ~1.14 Jy. The total flux density including contributions from the two radio lobes is ~1.23 Jy. The continuum image (Fig. 1) shows that the radio axis is at a position angle (E to N) of 103°. The two radio lobes are asymmetrically located about the radio nucleus, being 14° to the east and 8° to the west. The continuum nucleus and the line absorption are unresolved with the synthesised beam (6.4° x 4.3°, PA = 9.7°). Both 1665 and 1667 MHz lines are detected at a redshifted velocity of ~173 km s⁻¹ with respect to the systemic velocity of the galaxy. The column density of OH can be estimated from

\[ N_{OH} = 2.35 \times 10^{14} \frac{T_{ex}}{dV} \int \tau_{1667} dV \text{ cm}^{-2} \]

(Dickey et al. 1981; Liszt & Lucas 1996) where \( T_{ex} \) is the excitation temperature in Kelvins, \( \tau_{1667} \) is the optical depth of the 1667 MHz line and \( V \) is the velocity in km s⁻¹; for NGC1052, above equation gives an OH column density of 2.73 (±0.26) x 10¹⁴ (\( T_{ex} \)/10) cm⁻² towards the center. For the two lobes, we estimate an average \( \tau \) upper limit of OH absorption as ~0.10. This upper limit implies that 0.6% absorption seen towards the nucleus is undetectable even if absorbing gas cover the entire continuum source.

The AIPS gaussian fitting routine "SLFIT" was used to derive the line parameters. The peak optical depth of the 1667 MHz line is 5.8 (±0.2) x 10⁻³ and that of the 1665 MHz line is 2.9 (±0.1) x 10⁻³. The FWHM of 1667 and 1665 MHz lines are 18.6 ± 1.3 and 14.5 ± 2.6 km s⁻¹ respectively. Given the uncertainty in the overall shape of the 1665 MHz line due to low optical depth, profiles of the 1665 and 1667 MHz lines can be considered similar. The ratio of the integrated optical depth is 2.6 ± 0.8 which is marginally higher than that expected (viz. 1.8) for excitation in thermal equilibrium. The mean value of 1667 to 1665 MHz line ratio is about 1.6 for galactic diffuse clouds (Dickey et al. 1981).

3. Discussion

3.1. Link with HI and X-ray absorbing column

HI components in NGC1052 have been seen in absorption at 1486, 1523 and 1646 km s⁻¹, which are redshifted from the systemic velocity (van Gorkom et al. 1986). The \( N(\text{HI})/T_{ex} \) values of three components are 0.6 x 10¹⁸, 1.0 x 10¹⁸ and 1.4 x 10¹⁸ cm⁻² respectively. The strongest absorption (\( \tau \sim 0.02 \)) is at 1646 km s⁻¹ with a FWHM of about 35 km s⁻¹. Due to the similarity in the velocity of OH absorption with the highest redshifted component of HI absorption, it is reasonable to associate this HI component with the OH detected in these observations. It is interesting that the velocity of OH absorption matches very well with the strongest HI absorption component at 1646 km s⁻¹ even after a difference of about 16 years in the observations. The stability of OH/HI line suggests that the absorbing cloud covers a substantial fraction of the millicore VLBI core in which most of the radio emission lies (Jones et al. 1984; Kameno et al. 2001). The integrated optical depth ratio of HI to OH is ~6, which is in accordance with the values obtained for the galactic diffuse clouds (Dickey et al. 1981). The linewidth ratio of HI
A. Omar et al.: OH absorption from NGC 1052 L31

Fig. 1. The radio continuum image of NGC1052 drawn as contours with levels of 1.8 mJy beam$^{-1}$ x (1, 1.5, 2, 3, 4, 6, 8, 12, 16, 24, 32, 45, 64, 96, 128, 192, 256, 384, 512). The peak flux density in the contour image is 1.14 Jy beam$^{-1}$. The peak flux densities of the E and W lobes are 22.3 and 19.4 mJy beam$^{-1}$ respectively. The grey scale represents the densities of the gas probed via X-ray observations. The figure displays the entire velocity coverage of the gas. The systemic velocity is indicated on top left corner of the upper frame. It is very surprising that the gas observed dispersion is considered as an evidence of infall of gas to the nucleus, where a small fraction of the gaseous mass is converted to luminosity, then, the association of a large amount of molecular gas with the neutral gas will imply a lower efficiency of the central engine in converting mass to luminosity. The observed line widths (FWHM) of the two OH absorptions is considerably higher than would be expected ($\sim 1$ km s$^{-1}$) from purely thermal motions, assuming the gas temperature is at most a few tens of K. However, if the gas is very close (within a few pc) to the nucleus, some kinematical effects will tend to broaden the observed absorption line e.g., turbulence may set up to overcome the gravitational collapse against the nucleus. If the gas is in a disk, then, a velocity gradient along the disk, as seen in some megamaser galaxies (e.g. Hagiwara et al. 2000), can explain the observed line width of the OH absorption. On the other hand, if the observed dispersion is considered due to conglomerate of individual clouds in virial equilibrium, a binding mass will be about $10^8 M_\odot$, a value close to that seen in some giant molecular clouds (GMCs) of our galaxy. The typical velocity width of such GMCs has been estimated close to 10 km s$^{-1}$ (Stark & Blitz 1978).

The gas is expected to be much hotter in the vicinity of an AGN due to enhanced Ly$\alpha$ pumping which will increase the $T_{\text{ex}}$ to a few thousand kelvin. Assuming, $T_{\text{ex}} \sim 1000$ K, the predicted total N(HI) will be $2.0 \times 10^{21}$ cm$^{-2}$ including all three HI components. For the detected OH component, taking the relative abundance ratio of $OH/H_2 = 1 \times 10^{-7}$ (Geballe 1985; Liszt & Lucas 1999), the implied column density of $H_2$ is $2.73 \times 10^{21} (T_{\text{ex}}/10)$ cm$^{-2}$. The implied CO column density is about $5.5 \times 10^{14}$ cm$^{-2}$, which is about 10 times higher than predicted from CO observations. In comparison, X-ray observations indicate a hydrogen column density greater than $1 \times 10^{21}$ cm$^{-2}$ (Weaver et al. 1999), which is significantly higher than the total hydrogen column estimated via radio observations (Hi & OH). This excess column density inferred from X-ray data has been seen in many active galaxies, and, was explained due to excess absorption by a combination of dust and partially ionized gas (Gallimore et al. 1999). It should be noted here that since HI and OH absorptions are spatially unresolved, the estimated values of OH and HI column densities are only a lower limit. Also, X-ray absorption is arising towards the nucleus which is free-free absorbed at wavelengths corresponding to the HI and OH absorptions (Kameno et al. 2001), therefore, radio observations are sampling off nuclear gas which may be of different composition than the gas probed via X-ray observations.

3.2 Link with $H_2 O$ megamasers?

It is very surprising that the OH absorption, though narrower than the water maser emission, is coincident

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**Fig. 2.** A plot of the optical depth of 1667 and 1665 MHz absorptions towards the nucleus of NGC1052. The spectrum has been Hanning smoothed offline using a window of 3 adjacent channels. The velocity range over which HI absorption and $H_2 O$ masers are observed are indicated in the top and bottom frames respectively. The systemic velocity is indicated on top left corner of the upper frame.
with the velocity centroid of the 22 GHz H2O masers. NGC1052 is the only known elliptical galaxy having H2O megamaser emission. The megamasers and their link with AGNs are generally understood in terms of obscuring torus models. The link is thought to be a consequence of irradiation of the inner face of the torus by hard X-rays from the nuclear continuum source, which enhances the water abundance within a molecular layer at a temperature of 400–1000 K (Neufeld et al. 1994). H2O megamasers of NGC1052 are unusual in showing a relatively smooth profile which moves in velocity over time by about 70 km s^{-1} on a time scale of a year (Bratza et al. 1996). Water masers in NGC1052 are distributed along the jet rather than perpendicular to it (Claussen et al. 1998) unlike in NGC 4258 in which water masers are originating in a torus (see Miyoshi et al. 1995). Claussen et al. (1998) suggested that these masers are excited by shocks in to circumnuclear molecular cloud, or alternatively, amplifying radio continuum emission of the jet by foreground molecular clouds. It should be noted that the shocks can also enhance the abundance of OH by dissociation of H2O before the gas is cooled down below 50 K (Wardle 1999); however, the observed column density of OH is one order of magnitude less than that predicted. A drift in the velocity of maser feature was considered as a consequence of the moving jet which will illuminate different parts of the foreground H2O masering cloud. Efficient maser emission will take place at total column density (Nv) below the quenching density which is estimated as 10^{23}–10^{24} cm^{-2} for NGC1052 (see Weaver et al. 1999). This upper limit on column density is well above than that predicted from our observations. However, it is not clear how HI/OH are quite stable over a long period of time while H2O emission changes substantially over a short time scale. Further simultaneous observations of HI, OH and H2O masers are required to make a connection between molecular gas traced by OH absorption and H2O masering gas.

4. Summary

These VLA observations have resulted in the first detection of OH absorption in an elliptical galaxy. Both, 1667 and 1667 MHz OH absorption, were detected from the elliptical galaxy NGC1052. The linewidths of both the OH lines are significantly large as compared to that expected for a cloud in thermal conditions at few tens of K. The gas is predicted to be close to the nucleus. A remarkable coincidence of velocity is found with the strongest and redshifted HI absorption and H2O emission, however link to the megamaser emission is still not understood. Based on the abundance ratio of OH/H2 as 1 × 10^{-7}, it is predicted that the column density of molecular gas in NGC1052 is comparable to HI. Higher angular and spectral resolution observations would be useful for detail kinematics of the OH absorption while simultaneous observations of H2O and HI/OH observations would be necessary to understand the link between masering gas and molecular gas traced by OH absorption.

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References

Appendix III
GMRT and VLA observations of H\textsc{i} and OH from the Seyfert galaxy Mrk 1
(Reprinted from *Astron. Astroph.*)
GMRT and VLA observations of HI and OH from the Seyfert galaxy Mrk 1

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Abstract. We present Giant Meterwave Radio Telescope (GMRT) observations of the HI 21 cm line and Very Large Array (VLA) observations of the OH 18 cm line from the Seyfert 2 galaxy Mrk 1. HI emission is detected from both Mrk 1 and its companion NGC 451. The HI emission morphology and the velocity field of Mrk 1 are disturbed. We speculate that the nuclear activities of Mrk 1 are triggered by tidal interactions. We estimate the HI masses of Mrk 1 and NGC 451 to be 8.0(±0.6) × 10⁹ M₀ and 1.3(±0.1) × 10⁹ M₀ respectively. We have also detected the HI 21 cm line and the OH 18 cm line in absorption toward the nucleus of Mrk 1 at a blueshifted velocity with respect to its systemic velocity indicating an outflow of atomic and molecular gas. Two OH lines, at 1665 and 1667 MHz, are detected. Each of the profiles of the HI and OH absorption consists of two components that are separated by ~125 km s⁻¹. Gaussian fitting gave dispersions of ~44 km s⁻¹ for both the components of the HI absorption. The profile of the OH absorption is qualitatively similar to that of the HI absorption. Both components of the OH absorption are thermally excited. The peak optical depths of the two components of the HI absorption are (7.3 ± 0.4) × 10⁻² and (3.2 ± 0.4) × 10⁻². The corresponding peak optical depths of the 1667 MHz OH absorption are (2.3 ± 0.3) × 10⁻³ and (1.1 ± 0.3) × 10⁻². The higher velocity components of the HI and OH (1667 MHz) absorption lines are blueshifted from the [OIII]λ5007, [OIII]λ6300, and the systemic velocity by ~100 km s⁻¹, but are consistent with the [OIII]λ3727 velocity. We explain these velocity discrepancies as due to shock ionization of a region which is pushed forward due to shocks in front of the radio nucleus thereby giving apparent blueshift to HI, OH, and [OIII] velocities. The optical depth ratios τ₁₁/H₁ for both the components of the HI and OH absorption are ~3, indicating their origin in dense molecular clouds. Using OH/A, values for the Galactic molecular clouds, we obtain 9 < A < 90 toward the line of sight of Mrk 1.

Key words. galaxies: active – galaxies: interactions – galaxies: individual: Mrk 1, NGC 451 – galaxies: ISM

1. Introduction

Both the AGN and the nuclear starburst activities in galaxies that require inflow of material toward the centre either to fuel the central black hole or to cause rapid burst of nuclear star formation can be accomplished by tidal interactions (Hernquist & Mihos 1995). It is not clear, however, in the case of Seyfert galaxies whether nuclear activities in these low luminosity active galactic nuclei (AGN) are due to interactions as found in QSOs, radio galaxies, and BL Lacs (see De Robertis et al. 1998 for a review on the subject). It is generally accepted that interactions leading to mergers (bound interactions) may play a more significant role in triggering nuclear activities than unbound or hyperbolic encounters (De Robertis et al. 1998). Interactions can be effectively traced via HI 21 cm line emission from galaxies as HI disks often extend well beyond the optical radii of galaxies where the disks respond quickly to gravitational perturbations.

H I emission studies may be particularly useful since most often the HI morphology provides evidence of interactions which are undetectable at optical wavelengths (e.g., Simkin et al. 1987).

HI in absorption can trace kinematics and distribution of atomic gas near the centres of active galaxies on the size scales of their background radio sources. The advantage of absorption studies is that they can detect relatively small quantities of gas irrespective of the redshift of the object. Recently, Gallimore et al. (1999) found HI rich absorbing disks on the scales of a few hundred parsecs in several Seyfert galaxies. As a result of intense nuclear activities, gas in the central regions of active galaxies may be perturbed due to interactions of the radio plasma with the surrounding ISM which may result in bulk outflows of material (e.g., Tadhunter et al. 2001; Morganti et al. 1998). The molecular gas near the centres of active galaxies can be traced via the 18 cm OH line in absorption. The 18 cm OH absorption line is sensitive to molecular gas in both the diffuse ISM and in the dark clouds with the OH to H₂ ratio being almost constant over a large range of Galactic clouds (Liszt & Lucas 1996). Studies have shown that chances of detecting OH absorption are higher in infrared luminous galaxies (Schmelz et al. 1986).
In this paper, we present synthesis observations of the H$^\alpha$ 21 cm line obtained with the GMRT and the OH 18 cm line obtained with the VLA of the infrared active galaxy Mrk 1 and its companion NGC 451. The global properties of Mrk 1 are summarized in the next section. The details of observations and data analyses are given in Sect. 3. The results are presented in Sect. 4. Section 5 discusses the radio continuum properties, H$^\alpha$ emission, and H$^\alpha$ and OH absorption. The conclusions are in the last section.

2. Global properties of Mrk 1

The global properties of Mrk 1 are listed in Table 1. Mrk 1 (NGC 449; $D_L = 14.53$) is a member of a poor group (WBL 035) at a redshift of 0.017 (White et al. 1999). The other two members of this group viz., NGC 447 and NGC 451, are at projected separations from Mrk 1 of $\sim 38$ kpc and $\sim 130$ kpc respectively. Mrk 1 is classified as a SB 0/a galaxy with a Seyfert type 2 nucleus (Markarian et al. 1989) with no signatures of interactions in the optical images. Mrk 1 is also a luminous Infrared galaxy ($L_{FIR} = 1.7 \times 10^{10} L_\odot$), indicating a high rate of star formation. Mrk 1 is one among 16 galaxies detected in the 22 GHz water megamaser emission in a sample of 354 active galaxies (Braatz et al. 1994). The nuclear optical spectrum of Mrk 1 studied by Koski (1978) and Weedman et al. (1968) shows strong emission lines typical of an active galaxy photo-ionized by hard continuum. The broad lines indicative of a hidden Seyfert nucleus are not found either in the infrared (Veilleux et al. 1997) or in the polarized light (Kay et al. 1994). High dispersion spectroscopic observation of the [Oiii]~$\lambda$5007 line by Bergeron & Durret (1987) shows a distinct blue asymmetry indicative of an outflow of gas. Keel (1996) suggested that the nuclear activities of Mrk 1 are due to an ongoing interaction with the nearby galaxy NGC 451.

The radio continuum emission from Mrk 1 is known to have a steep spectrum with a spectral index $\alpha$ ($S \propto \nu^{-\alpha}$) of 0.8 (Dickinson et al. 1976). The 1.6 GHz EVN image (resolution $\sim 30$ pc) of Kukula et al. (1999) shows that the nuclear emission to consists of an unresolved core surrounded by a weak diffuse emission with a total flux density of 34 mJy. The NVSS flux density at 1.4 GHz is 75.4 mJy.

The Arecibo observations by Hutchings (1989) detected H$^\alpha$ emission and blueshifted H$^\alpha$ absorption from Mrk 1. This single dish spectrum could not separate H$^\alpha$ emission from Mrk 1 and NGC 451. Observations with the Nobeyama Radio Telescope detected CO ($J = 1-0$) emission with a total flux integral of $11.5 \pm 1.6$ K km s$^{-1}$ from the central 5 kpc region of Mrk 1 (Vila-Vilaro et al. 1998). The search for the 18 cm OH absorption by Schmelz et al. (1986) with the Arecibo reflector resulted in a non-detection with an rms sensitivity to an optical depth of 0.02.

3. Observations and data analyses

3.1. The GMRT observations

The GMRT observations of Mrk 1 were carried out in October, 2000. A summary of the main observational parameters are given in Table 2. At the time of the observations, the GMRT was not fully operational and hence not all 30 antennas were available for observations at any given time. Two runs of observations with 18–20 antennas, each with a field of view (FWHM) 24' centered on Mrk 1, were carried out on two different days. The GMRT has a mix of both short and long baselines (see Swarup et al. 1991 for more details), making it sensitive to diffuse emission of an extent of as much as 7' while having a maximum resolution of $\sim 3''$ at 1.4 GHz. The GMRT uses a 30-station FX correlator which produces complex visibilities over 128 spectral channels in each of the two polarizations. The bandwidth can be selected in multiples of 2 between 62.5 kHz and 16 MHz. These observations were carried out with a bandwidth of 8 MHz centered at 1395.0 MHz, which covered H$^\alpha$ velocities in the range 3730–5460 km s$^{-1}$ with a velocity resolution of $\sim 14$ km s$^{-1}$.

The complex gains of the antennas were determined every 30 min using observations of an unresolved nearby ($\sim 4.5''$) source (3C 48) for 5 min. 3C 48 was also used for the flux and the bandpass calibrations. The data were reduced, following standard calibration and imaging methods, using the Astronomical Image Processing Software (AIPS) developed by the NRAO. The data were calibrated for the amplitude, phase, and frequency response for all antennas separately for each polarization. The flux density of 3C 48 was estimated to be 16.228 Jy at the observing frequency using the 1999.2 VLA flux densities of the standard VLA flux calibrators and the formula given in the AIPS task "SETJY". Due to the close proximity of 3C 48 to Mrk 1 and based on some previous test experiments, we expect that the flux calibration is accurate to within 5%.

A continuum data set was formed by averaging 80 line-free channels. The data were self-calibrated in both phase and amplitude. The resulting antenna gain corrections were applied to all channels. The continuum images were made using the self-calibrated averaged data from the line-free channels. The continuum flux density from each individual channel was subtracted in the ($u, v$) dataset by a linear fit to the visibilities in the line-free channels. Since these observations were also sensitive to H$^\alpha$ emission, the data points were "natural-weighted" to enhance sensitivity to extended features. The resulting spectral cubes were CLEANed for signals greater than 4 times the rms noise in the channel images. The cube was blanked for H$^\alpha$ emission below a level of 1.5σ in the images after applying a Hanning smoothing of three velocity channels and Gaussian smoothing of five pixels (pixel size $= 6''$) in the spatial coordinates. The zeroth and first order moment maps were generated from the blanked channel images containing H$^\alpha$ emission and two additional channels on both the sides.

3.2. The VLA observations

The VLA "B" configuration observations were carried out in March, 2001. The observational parameters are summarized in Table 2. The data were recorded in the 1A correlator mode with a total bandwidth of 6.25 MHz divided into 128 channels. These observations covered a velocity range
Table 1. Global properties of Mrk 1.

<table>
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<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
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<td>1</td>
</tr>
<tr>
<td>Declination (J2000)</td>
<td>33°05'22''</td>
<td>1</td>
</tr>
<tr>
<td>Distance (Mpc)</td>
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<td>2</td>
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<tr>
<td>Hubble type</td>
<td>SB 0/a</td>
<td>1</td>
</tr>
<tr>
<td>Seyfert type</td>
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<td>1</td>
</tr>
<tr>
<td>Inclination</td>
<td>45°</td>
<td>3</td>
</tr>
<tr>
<td>Optical diameter (kpc)</td>
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<tr>
<td>Corrected blue magnitude $B'_e$</td>
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<tr>
<td>Total blue luminosity ($L_b$)</td>
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<tr>
<td>Total H i mass ($M_0$)</td>
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<td>5</td>
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<tr>
<td>H i mass to blue luminosity ratio ($M_0/L_b$)</td>
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<tr>
<td>1.4 GHz radio luminosity (W Hz$^{-1}$)</td>
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<tr>
<td>Spectral index ($S \propto v^{+5}$)</td>
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<tr>
<td>X-ray luminosity (erg s$^{-1}$)</td>
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<tr>
<td>Systemic velocity (km s$^{-1}$)</td>
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<tr>
<td>[O III] $\lambda$ 5007 velocity (km s$^{-1}$)</td>
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<td>10</td>
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<td>[O II] $\lambda$ 3727 velocity (km s$^{-1}$)</td>
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<td>[O I] $\lambda$ 6300 velocity (km s$^{-1}$)</td>
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<td>Mean velocity of H i emission (km s$^{-1}$)</td>
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<td>Mean velocity of CO emission (km s$^{-1}$)</td>
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<td>Mean velocity of CO emission (km s$^{-1}$)</td>
<td>4850</td>
<td>11</td>
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</table>

Notes: $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. The velocity definition is optical and Helio-centric.
1: Markarian et al. (1989); 2: White et al. (1999); 3: Braatz et al. (1997); 4: NED (NASA Extragalactic Database); 5: This paper; 6: IRAS faint source catalog, (1990); 7: Dickinson et al. (1976); 8: Fabbiano et al. (1992); 9: Keel (1996); 10: De Robertis & Shaw (1990) 11: Vila-Vilaro et al. (1998).

Table 2. Observational parameters.

<table>
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<tr>
<th>Parameter</th>
<th>GMRT</th>
<th>VLA</th>
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<td>Pointing centre (RA J2000.0)</td>
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<td>01°16'07.25</td>
</tr>
<tr>
<td>Pointing centre (Dec J2000.0)</td>
<td>+33°05'22'2</td>
<td>+33°05'22'2</td>
</tr>
<tr>
<td>Observing duration (hrs)</td>
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<td>4.5$^1$</td>
</tr>
<tr>
<td>Range of baselines (km)</td>
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<td>0.1−11</td>
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<tr>
<td>Observing frequency (MHz)</td>
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<td>Bandwidth per IF (MHz)</td>
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<td>6.25</td>
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<tr>
<td>Number of spectral channels</td>
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<td>128</td>
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<tr>
<td>Polarizations</td>
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<td>1</td>
</tr>
<tr>
<td>Frequency resolution (kHz)</td>
<td>62.5</td>
<td>48.8</td>
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<td>Velocity resolution (km s$^{-1}$)</td>
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<tr>
<td>Bandpass calibrator</td>
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</tr>
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</table>

$^1$ Usable time, see Sect. 3.2 for details.
3 channels and every second channel was discarded. The resulting image cube has a resolution of $5\'43 \times 4\'93 \times 27$ km s$^{-1}$. The continuum images were made using the self-calibrated averaged data from the line-free channels.

4. Results

4.1. Radio continuum

The radio continuum images shown in Fig. 1 have a resolution of $30^\prime.75 \times 25^\prime.17$ at 1.4 GHz, and $17^\prime.49 \times 16^\prime.56$ at 1.6 GHz. These images were made using only short $(u, v)$ spacings to enhance the sensitivity to extended features. These images have an rms of 0.35 mJy beam$^{-1}$ at 1.4 GHz, and 0.19 mJy beam$^{-1}$ at 1.6 GHz. Continuum emission is detected from both Mrk 1 and NGC 451. NGC 447 is marginally detected ($\sim 0.35$ mJy beam$^{-1}$) at 1.4 GHz, and 0.19 mJy beam$^{-1}$ at 1.6 GHz. Mrk 1 remains unresolved down to a resolution of $\sim 1$ kpc.

4.2. H$\text{I}$ emission

The H$\text{I}$ cube was made with a resolution of $30^\prime.67 \times 27^\prime.28 \times 13.7$ km s$^{-1}$. The channel images have an rms of 0.92 mJy beam$^{-1}$. The corresponding 3$\sigma$ sensitivity in H$\text{I}$ column density is $5.0 \times 10^{19}$ cm$^{-2}$. The channel images of H$\text{I}$ emission and absorption are shown in Figs. 2 and 3. The results are summarized in Table 3. H$\text{I}$ emission is detected in the velocity range of 4698 to 4984 km s$^{-1}$. H$\text{I}$ emission from Mrk 1 appears from 4698 to 4848 km s$^{-1}$. The flux integral ($\int S \ dV$) of H$\text{I}$ emission in this range is $0.73 \pm 0.05$ Jy km s$^{-1}$ which at the distance of Mrk 1 corresponds to a total H$\text{I}$ mass of $8.0(\pm 0.6) \times 10^8 M_\odot$ for Mrk 1. The estimated H$\text{I}$ mass is a lower limit due to the effects of absorption. H$\text{I}$ emission from NGC 451 is detected from 4807 to 4984 km s$^{-1}$ with a total flux integral of $1.20 \pm 0.10$ Jy km s$^{-1}$ corresponding to a H$\text{I}$ mass of $1.31(\pm 0.11) \times 10^9 M_\odot$ assuming a distance to NGC 451 of 68 Mpc. The summed flux integral of Mrk 1 and NGC 451 is $1.93(\pm 0.11)$ Jy km s$^{-1}$, which is consistent with the value obtained by the single dish observations of Hutchings (1989). See Fig. 4 for a global H$\text{I}$ profile.

The moment zero map shown in Fig. 5 indicates that the H$\text{I}$ emission from Mrk 1 is distributed in three clumps with almost all H$\text{I}$ seen outside the optical extent of Mrk 1. The individual clumps having velocity dispersions of 30 to 60 km s$^{-1}$ are distributed over an extent of $\sim 30$ kpc. The velocity field of Mrk 1...
### 4.3. HI absorption

The channel images shown in Fig. 3 also show HI absorption from Mrk 1 (dotted contours at the location of Mrk 1) in the velocity range 4589 km s\(^{-1}\) to 4752 km s\(^{-1}\). The HI absorption spectrum shown in Fig. 7 is extracted at the radio position of Mrk 1 from a HI cube made with a resolution of 6'23 x 4'39 x 13.7 km s\(^{-1}\). The rms in this cube was 0.6 mJy beam\(^{-1}\). The spectrum shows a broad 

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**Fig. 2.** Channel images from GMRT showing HI column density contours in the velocity range 4807 km s\(^{-1}\)-5011 km s\(^{-1}\). The crosses mark the optical positions of Mrk 1 and NGC 451. Solid contours representing column density of HI emission are drawn at 3.6, 5.4, 7.2, 9.0, 10.8, and 12.7 x 10\(^{19}\) cm\(^{-2}\). The negative contours (dashed curves) are drawn at 2, 3, 4, 5, 6 mJy beam\(^{-1}\). The HPBW of the synthesized beam (30'67 x 27'28, PA = -80.4\(^\circ\)) is indicated at the bottom left hand corner of the first channel image. The velocity resolution in the cube is ~13.7 km s\(^{-1}\). 

Shown in Fig. 6 indicates that there is a smooth rotation of HI from one end to the other.

The HI emission from NGC 451 shown in Fig. 5 looks like that of a disk galaxy with a total projected velocity width of 170 km s\(^{-1}\). The HI diameter of NGC 451 is ~20 kpc which is about twice that of the optical disk. The global parameters of NGC 451 given in Table 3 were derived from a fit to the velocity field made using a higher resolution (17" x 14") HI cube which is not shown here.
Fig. 3. Channel images showing column density contours in the velocity range 4589 km s\(^{-1}\)-4793 km s\(^{-1}\). The contour levels are the same as in Fig. 2. The H\(_1\) absorption is seen toward Mrk 1 as dotted contours.

Multi-component absorption in between the velocities 4500 km s\(^{-1}\) and 4800 km s\(^{-1}\). Two Gaussian components were fitted to the H\(_1\) absorption profile. The resulting parameters of the fit are given in Table 4. The peak optical depths of the two components are 0.073 ± 0.004 and 0.032 ± 0.004 respectively and the velocity dispersions are ∼44 km s\(^{-1}\) for both the components. The column density of H\(_1\) is estimated using the relation \(N_{H_1} = 1.82 \times 10^{18} \times (T_{\text{spin}}/f) \int \tau \, dv \, \text{cm}^{-2}\), where \(T_{\text{spin}}\) is the spin temperature of H\(_1\) in Kelvin, \(f\) is the covering fraction of H\(_1\) gas, \(\int \tau \, dv\) is the velocity integrated optical depth in km s\(^{-1}\). We assume \(f\) to be unity. \(T_{\text{spin}}\) is an unknown quantity and we adopt a value of 100 K, typical of cold clouds in our Galaxy. The H\(_1\) column densities are then 1.5(±0.2) \(\times 10^{21}\) cm\(^{-2}\) and 6.0(±1.5) \(\times 10^{20}\) cm\(^{-2}\) for the two components respectively.

4.4. OH absorption

The OH spectrum shown in Fig. 8 was extracted at the radio position of Mrk 1 from the image cube made using the VLA data with a resolution of 5′43 × 4′93 × 27 km s\(^{-1}\). The cube has an rms of 0.5 mJy beam\(^{-1}\).
Appendix III

A. Omar et al.: Mrk 1 – GMRT and VLA observations

Fig. 4. Global H\textsubscript{I} emission profile of Mrk 1 and NGC 451 from GMRT. The flux integral is 1.93 ± 0.11 Jy km s\textsuperscript{-1} which is consistent with the single dish observations of Hutchings (1989).

Fig. 5. The column density contours of the total H\textsubscript{I} image from GMRT of Mrk 1 (top) and NGC 451 (bottom) overlaid upon the grey scale optical image from the DSS (blue). The contour levels are 0.3, 0.8, 1.3, 1.8, 2.3, 3, 4, 5, 6, 7, 8, and 9 in units of 10\textsuperscript{20} cm\textsuperscript{-2}. The HPBW of the synthesized beam, shown in the bottom right hand corner, is 30\textquoteleft\texttimes\textquoteleft 27:28, PA = -80.4\textdegree. Although the H\textsubscript{I} emission is surrounding Mrk 1, H\textsubscript{I} absorption (marked as white circle) is detected toward Mrk 1 indicating the presence of cold H\textsubscript{I} gas in front of it.

The velocity axis of Fig. 8 corresponds to the 1667 MHz OH line. In this velocity system, the 1665 MHz line will appear at +360 km s\textsuperscript{-1} from the 1667 MHz line. Since the spectrum of Fig. 8 does not have enough baseline for the 1667 MHz line and not enough signal to noise ratio for both the 1665 MHz line to get reliable estimates for velocity dispersions of individual components, only peak optical depths and center velocities were fitted while the velocity dispersions were fixed at those values found in fitting the H\textsubscript{I} absorption profile. This is a reasonably good assumption since both the 1665 and 1667 MHz profiles are qualitatively similar to the H\textsubscript{I} absorption profile. This procedure gave a reasonably good, though not unique, fit to the OH spectrum. The fitted parameters are given in Table 4.

Fig. 6. The velocity fields of Mrk 1 and NGC 451 from GMRT are shown as contours and in grey scale.

Fig. 7. The GMRT spectrum showing H\textsubscript{I} absorption in Mrk 1. The dotted curve is the Gaussian fit to the absorption spectrum. The fitted parameters are given in Table 4. The vertical lines along the velocity axis mark the positions of several velocity systems as indicated.

Table 4. H\textsubscript{I} and OH absorption results.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>H\textsubscript{I}</th>
<th>OH(1667)</th>
<th>OH(1665)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_1$</td>
<td>0.073 ± 0.004</td>
<td>0.023 ± 0.003</td>
<td>0.014 ± 0.004</td>
</tr>
<tr>
<td>$\sigma_1$ (km s\textsuperscript{-1})</td>
<td>4705 ± 5</td>
<td>4721 ± 6</td>
<td>4710 ± 19</td>
</tr>
<tr>
<td>$\tau_2$</td>
<td>0.032 ± 0.004</td>
<td>0.011 ± 0.003</td>
<td>0.006 ± 0.004</td>
</tr>
<tr>
<td>$\sigma_2$ (km s\textsuperscript{-1})</td>
<td>4579 ± 10</td>
<td>4585 ± 12</td>
<td>4601 ± 45</td>
</tr>
<tr>
<td>$\sigma_3$ (km s\textsuperscript{-1})</td>
<td>43.4 ± 9.1</td>
<td>43.4</td>
<td>43.4</td>
</tr>
</tbody>
</table>
The peak optical depths of the two components of the 1667 MHz absorption are 0.023 ± 0.003 and 0.011 ± 0.003 respectively. The column density of OH is estimated using the relation \( N_{\text{OH}} = 2.35 \times 10^{14} \times (T_{\text{ex}}/f) \int T_{1667} \, d\theta \) cm\(^{-2}\); where \( T_{\text{ex}} \) is excitation temperature which is assumed to be 10 K and \( \int T_{1667} \, d\theta \) is the velocity integrated optical depth of the 1667 MHz line in units of km s\(^{-1}\). The OH column densities are estimated to be 6.0(±1.0) x 10\(^{15}\) cm\(^{-2}\) and 2.9(±0.9) x 10\(^{15}\) cm\(^{-2}\). The peak optical depth ratio \( T_{1667}/T_{1665} \) of the stronger OH component is 1.6 ± 0.5, indicating that this component is excited under LTE conditions — the ratio is predicted to be in between 1.0 and 1.8 for LTE excitations. This ratio for the weaker component, viz., 1.8 ± 1.3 indicates that this is also most likely thermally excited.

5. Discussion

5.1. Interaction of Mrk 1 with NGC 451

The disturbed H\(_{\text{i}}\) morphology of Mrk 1 (Fig. 5) indicates a gravitational interaction possibly with the nearest companion NGC 451. We explore this possibility using the two body interaction described in Binney & Tremaine (1987). The dynamical masses of galaxies are estimated using rotation curves. Since the H\(_{\text{i}}\) morphology of Mrk 1 is disturbed, it was not possible to obtain a reliable H\(_{\text{i}}\) rotation curve. We used the H\(_{\alpha}\) rotation curve of Mrk 1 (Keel 1996). The dynamical mass of NGC 451 was estimated using the H\(_{\alpha}\) rotation curve. The dynamical masses of Mrk 1 and NGC 451 are \( 3.4 \times 10^{10} \, M_{\odot} \) and \( 4.5 \times 10^{10} \, M_{\odot} \) respectively. The interaction parameters are listed in Table 5.

The projected velocity difference between Mrk 1 and NGC 451 of \( -117 \, \text{km s}^{-1} \) indicates the minimum dynamical mass of this pair to be \( -10^{11} \, M_{\odot} \). This value of dynamical mass is in close agreement with the dynamical masses of Mrk 1 and NGC 451, indicating that Mrk 1 and NGC 451 are most likely in a bound system. Tidal radii (cf. Eq. (7–84), Binney & Tremaine 1987) for the given masses of Mrk 1 and NGC 451 indicate that the outer regions of the H\(_{\text{i}}\) disk of Mrk 1 can be perturbed easily. The dynamical friction time scale (cf. Eq. (7–26) and (7–13b), Binney & Tremaine 1987) of \( \sim 0.2 \, \text{Gyr} \) for this system is much smaller than their orbital time scale of \( \sim 2 \, \text{Gyr} \). This implies that the interaction is bound and will lead to a merger within a small fraction of the orbital time period of the two galaxies.

### Table 5. Interaction properties of the Mrk 1–NGC 451 system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projected velocity difference (km s(^{-1}))</td>
<td>117</td>
</tr>
<tr>
<td>Projected separation (kpc)</td>
<td>38</td>
</tr>
<tr>
<td>Total dynamical mass (( M_{\odot} ))</td>
<td>( -10^{11} )</td>
</tr>
<tr>
<td>Tidal radius (Mrk 1) (kpc)</td>
<td>24</td>
</tr>
<tr>
<td>Tidal radius (NGC 451) (kpc)</td>
<td>29</td>
</tr>
<tr>
<td>Impact parameter</td>
<td>( -0.1 )</td>
</tr>
<tr>
<td>Dynamical friction time (Gyr)</td>
<td>( -0.2 )</td>
</tr>
<tr>
<td>Orbital time (Gyr)</td>
<td>( -2.0 )</td>
</tr>
</tbody>
</table>

5.2. Comparison of H\(_{\text{i}}\) and OH velocities with other velocity systems

Comparison with optical line velocities — from the comparison of the H\(_{\text{i}}\) and OH absorption velocities of Mrk 1 with the optical line velocities listed in Table 1, it appears that the higher velocity components of the H\(_{\text{i}}\) and OH absorption are consistent with the [O\(_{\text{iii}}\)]A3727 line velocity, but are blueshifted by \( \sim 100 \, \text{km s}^{-1} \) from the [O\(_{\text{iii}}\)]A5007, [O\(_{\text{ii}}\)]A6300 and the systemic velocity. We explain this discrepancy in terms of co-existence of photo-ionized and shock ionized gas in active galaxies. The [O\(_{\text{iii}}\)]A5007 line is primarily due to excitation from a hard continuum, and therefore, should be arising close to the nucleus. The [O\(_{\text{iii}}\)]A3727 line intensity is enhanced in shock ionized regions (Dopita & Sutherland 1995). Most often, optical line profiles are asymmetric and only peak line velocities are quoted without fitting a line profile. Mrk 1 is known to be such a case (Bergeron & Duruet 1987; Dickinson et al. 1976). Such an analysis of the optical spectrum may bias the line velocities of different species toward different regions, e.g., the peak of the [O\(_{\text{iii}}\)] line may indicate a region which is shock ionized while the [O\(_{\text{iii}}\)] line velocity may indicate gas which is close to the nucleus. We speculate that the higher velocity H\(_{\text{i}}\) and OH absorption component in Mrk 1 arises in a region which is pushed forward due to shocks, thereby giving an apparent blueshift to H\(_{\alpha}\), OH, and [O\(_{\text{ii}}\)] lines. The fact that the [O\(_{\text{i}}\)] line velocity is close to the [O\(_{\text{iii}}\)] line velocity, and hence associated with photo-ionized regions, is not surprising since the [O\(_{\text{i}}\)] line intensity is suppressed in the shock excited regions (Dopita & Sutherland 1995).
Appendix III

Table 6. Properties of the absorbing gas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(H\textsubscript{2}) \textsuperscript{(cm\textsuperscript{-2})}</td>
<td>1.5(\pm 0.2) \times 10\textsuperscript{21}</td>
</tr>
<tr>
<td>N(H\textsubscript{2}) \textsuperscript{(cm\textsuperscript{-2})}</td>
<td>6.0(\pm 1.5) \times 10\textsuperscript{20}</td>
</tr>
<tr>
<td>N(H\textsubscript{2}) \textsuperscript{(cm\textsuperscript{-2})}</td>
<td>6.0(\pm 1.0) \times 10\textsuperscript{19}</td>
</tr>
<tr>
<td>N(H\textsubscript{2}) \textsuperscript{(cm\textsuperscript{-2})}</td>
<td>2.8(\pm 1.0) \times 10\textsuperscript{19}</td>
</tr>
<tr>
<td>N(H\textsubscript{2}) \textsuperscript{(cm\textsuperscript{-2})}</td>
<td>2.1(\pm 0.6) \times 10\textsuperscript{19}</td>
</tr>
<tr>
<td>N(H\textsubscript{2}) \textsuperscript{(cm\textsuperscript{-2})}</td>
<td>8.8(\pm 3.4) \times 10\textsuperscript{19}</td>
</tr>
<tr>
<td>(T_{\text{HI}} / T_{\text{OH} 1667}) (1)</td>
<td>3.2 \pm 0.4</td>
</tr>
<tr>
<td>(T_{\text{HI}} / T_{\text{OH} 1667}) (2)</td>
<td>2.9 \pm 0.9</td>
</tr>
<tr>
<td>(N_{\text{HI}} / N_{\text{OH} 1667})</td>
<td>1.6 \pm 0.5</td>
</tr>
<tr>
<td>(N_{\text{HI}} / N_{\text{OH} 1667})</td>
<td>1.8 \pm 1.3</td>
</tr>
<tr>
<td>(N_{\text{HI}} / N_{\text{OH} 1667}) \textsuperscript{11} (cm\textsuperscript{-2})</td>
<td>(-10\textsuperscript{23})</td>
</tr>
<tr>
<td>(N_{\text{HI}} / N_{\text{OH} 1667}) \textsuperscript{11} (cm\textsuperscript{-2})</td>
<td>(-4.3 \times 10\textsuperscript{-4})</td>
</tr>
<tr>
<td>(A_{\text{v}}) (mag)</td>
<td>9-90</td>
</tr>
<tr>
<td>(N_{\text{HI}}) cm\textsuperscript{-2}</td>
<td>(-1.1 \times 10\textsuperscript{23})</td>
</tr>
<tr>
<td>(\tau^{\text{MW}}) \textsuperscript{11}</td>
<td>30</td>
</tr>
</tbody>
</table>

\textsuperscript{1}: Assuming \(T_{\text{em}} = 10\text{K}\); \textsuperscript{2}: Assuming \(T_{\text{em}} = 10\text{K}\); \textsuperscript{3}: Assuming OH/H\textsubscript{2} = 10\textsuperscript{-7}.

Comparison with H\textsubscript{2}O megamaser and CO emission – the water megamasers are seen from Mrk 1 at a velocity of 4868 km s\textsuperscript{-1} (Braatz et al. 1994). Since these masers are redshifted by \(-90\text{ km s}\textsuperscript{-1}\) from the systemic velocity of the galaxy, they are most likely the high velocity “satellite” features commonly seen in water megamaser galaxies (Braatz et al. 1997) and thought to originate in the accretion disks near the nuclei (Neufeld et al. 1994). Since the observed H\textsubscript{i} and OH absorption velocities in Mrk 1 are blueshifted from both the water megamaser velocity and from the systemic velocity of the galaxy, the absorption in the present case is most likely not related either to the gas in the accretion disk or to the torus close to the nucleus. The mean velocity of the CO emission from Mrk 1 is 4850 km s\textsuperscript{-1} (Vila-Vilaro et al. 1998), which is a redshifted by \(-150\text{ km s}\textsuperscript{-1}\) from H\textsubscript{i} and OH absorption velocities, implying that the gas traced via H\textsubscript{i} and OH absorption in Mrk 1 is also not related to the molecular gas traced by CO emission.

5.3. Kinematics and composition of the absorbing gas

The general properties of the gas seen in absorption are summarized in Table 6. The total column density of OH is comparable to that observed in other active galaxies (e.g., Schmelz et al. 1986; Baan et al. 1985, 1992). Both components of the OH transitions appear to be thermally excited as their optical depth ratios \((r_{1667} / r_{1665})\) are between 1.0 and 1.8; the values predicted for excitations in LTE conditions. The optical depth ratios \(r_{1667} / r_{1665}\) for both the components of the absorbing gas are \(-3\). This ratio has been found to be varying from as low as 5 to more than 400 in Galactic clouds (Dickey et al. 1981). The smaller values correspond to the molecular clouds while larger values correspond to the diffuse clouds. It is therefore suggested that the H\textsubscript{i} and OH absorption, in the present case, are associated with dense molecular clouds.

The observed velocity dispersion \((\sigma)\) of the 1667 MHz OH absorption, viz., 44 km s\textsuperscript{-1} is higher than the typical velocity dispersions \((\sigma = 3-7\text{ km s}\textsuperscript{-1})\) in giant molecular clouds (GMCs) of the Galactic disk. However, several high dispersion clouds \((\sigma \sim 40\text{ km s}\textsuperscript{-1})\) have been detected in 18 cm OH absorption within a kpc of the Galactic centre (Boyce & Cohen 1994). The simplest explanation for such a high velocity dispersion could be a chance alignment of several normal GMCs along the line of sight, but Kumar & Riffert (1997) have shown that the probability of such alignments is small. Alternatively, if the velocity dispersion is due to a single gravitationally bound system in virial equilibrium, the mass of such an object (assuming a size of 50 pc) could be \(\sim 10^7 \text{ M}_\odot\). Cloud–cloud collisions (Klein et al. 1994b) and interaction of shock with ISM (Klein et al. 1994a) are also known to enhance the internal velocity dispersions of molecular clouds.

The OH column density is known to correlate with the visual extinction, \(A_v\), of molecular clouds in our Galaxy (Magnani et al. 1988). Magnani et al. (1988) found that \(N(\text{OH}) / A_v\) ratios are in the range of \(10^{14}-10^{15} \text{ cm}\textsuperscript{-2} \text{mag}\textsuperscript{-1}\). For the OH column density toward Mrk 1, these ratios indicate \(9 < A_v < 90\) toward the line of sight of Mrk 1. In comparison, Veilleux et al. (1997), based on some infrared measurements, obtained a lower limit on \(A_v\) to be 26 consistent with above predictions.

Using \(\text{OH/H}_2 = 10^{-7}\) (Liszt & Lucas 1996), the implied column density of \(\text{H}_2\) is \(\sim 10^{23} \text{ cm}\textsuperscript{-2}\). Using values of the photo-electric absorption cross sections from Morrison & McCammon (1983) for a gas having the solar abundance, a total hydrogen column density of \(\sim 10^{25} \text{ cm}\textsuperscript{-2}\) indicates that the optical depth for X-ray absorption at 1 keV will be \(-30\). Such a high value of the optical depth will absorb almost all soft X-ray radiation from the nucleus of Mrk 1. Consistent with this prediction, Mrk 1 has not been detected as a X-ray source down to a sensitivity of \(\sim 10^{41} \text{ erg s}\textsuperscript{-1}\) (Fabbiano et al. 1992).

6. Conclusions

We have presented the observations of the Seyfert 2 galaxy Mrk 1 in the H\textsubscript{i} 21 cm line using the GMRT and in the OH 18 cm line using the VLA. Unlike the optical morphology, the H\textsubscript{i} emission morphology of Mrk 1 indicates that this galaxy is disturbed which we interpret as due to tidal interactions with the nearby companion NGC 451. We also showed based on the dynamical study of Mrk 1 – NGC 451 system that the interaction is bound leading to a merger within a small fraction of their orbital time period. This is consistent with the hypothesis that the bound interactions should be more efficient in triggering nuclear activities than unbound interactions. The H\textsubscript{i} and OH absorption detected toward the nucleus of Mrk 1 indicates an outflow of both atomic and molecular gas. The column densities of the detected H\textsubscript{i} and OH absorption indicate that the line of sight toward the nucleus of Mrk 1 is rich in both atomic and molecular gas. The gas detected in absorption is kinematically different than that traced via CO emission and water megamaser emission from Mrk 1. We found evidences that shocks (presumably due to nuclear activities) can affect the kinematics of gas near the nucleus. The H\textsubscript{i} and OH absorption being blueshifted from the systemic velocity and the [O\textsubscript{I} 6300]
velocity while consistent with the \([\text{O} \, \text{II}] 3727\) velocity is understood in terms of the shock ionization of gas (which predicts enhancement of the \([\text{O} \, \text{II}]\) line intensity) and an outflow of ISM in front of the shock. Based on the optical depth ratios and the line widths of the \(H\) and \(OH\) absorption, we speculate that the absorption is arising in turbulent molecular clouds of similar type to those found near the Galactic centre. These observations also imply that the line of sight toward the nucleus of Mrk 1 is heavily obscured.

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