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Observations of the high-redshift galaxy B2 0902+343 at 92 cm

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Abstract. We present 92 cm observations of the high-redshift galaxy B2 0902+343 ($z = 3.40$) with the Westerbork Synthesis Radio Telescope (WSRT). Twenty-one cm H I is detected in absorption, at a depth of 15.9 mJy ($=6\sigma$) and rest frame velocity width 120 km s^{-1}. We also report a null detection of OH emission or absorption at the 1665/1667 MHz rest-frame transitions. Based on our spectral sensitivity, we derive an upper limit on OH maser luminosity of $\log(L/L_\odot) < 5.2$. In addition, we consider the possibility of absorption, and estimate a maximum column depth N(OH) of 1×10^{15} cm^{-2}, corresponding to at most $2 \times 10^5 - 9 \times 10^6$ $M_\odot$ of OH in the galaxy. The implications of these results are discussed in the context of current efforts to extend the OH megamaser luminosity function and galactic merger rate to high redshift.

Key words. galaxies: individual: B2 0902+343 – radio lines: galaxies – galaxies: high-redshift – cosmology: observations

1. Introduction

Astronomical interest in the early universe, and in particular the epoch of galaxy formation, has spurred numerous attempts to detect and analyze high-redshift objects. Much attention has recently been devoted to the study of galaxies at $z > 1$, as these sources are thought to serve as probes into gas and dust environments at early times. At $z = 3.40$ (Lilly 1988; Uson et al. 1991), the radio source B2 0902+343 (second Bologna survey, Colla et al. 1972) possesses one of the highest known redshifts among radio galaxies. With the exception of quasars, relatively few such distant objects are known.

Both optical and high-resolution radio observations of B2 0902+343 have turned up rather peculiar structures. Lilly (1988) first reported B2 0902+343 to be a galaxy, noting that highly redshifted optical Lyman-α emission is nearly coincident with the radio source. Pentericci et al. (1999) detected two optical components with the Hubble Space Telescope, and observed that they are not aligned with distinct lobes in the radio continuum at 1.65 GHz. Other complex radio features were seen by Carilli et al. (1994) and Carilli (1995). CO lines, on the other hand, have not been detected (Downes et al. 1996) Nevertheless, the existence of gas *is* implied by the significant H I absorption feature at 323 MHz first observed by Uson et al. (1991) and later confirmed by Briggs et al. (1993) and de Bruyn (1996), who noted a potentially significant absorption wing to the blueward side of this line. B2 0902+343 happens to be one of only two galaxies at $z > 3$ that exhibit an H I absorption feature. It is still unclear which of the components seen in high-resolution radio images is (partially) obscured by foreground gas.

In the quest for further insight into the molecular contents of B2 0902+343, we have tested the possibility that it may host an OH megamaser. The companion OH lines at 1665 and 1667 MHz are difficult to observe at moderate redshift because of interference from terrestrial television transmission and a shortage of suitably equipped telescopes. Beyond $z = 3.3$, however, OH once again becomes accessible. As Townsend et al. (2001), Briggs (1998), and others have suggested, there is a strong chance that most ultraluminous and hyperluminous infrared galaxies (ULIRGs and HLIRGs), as well as their high-redshift submillimeter counterparts at $z = 1$–10, display associated OH maser emission. At lower redshifts, a survey performed with the Arecibo Telescope by Darling & Giovanelli (2000, 2001, 2002a,b) has already turned up 50 new OH megamasers at $z = 0.1$–0.2. Bolstering the possibility of OH maser activity at redshift 3.4 in B2 0902+343 are the presence of neutral hydrogen absorption and strong continuum emission from this galaxy, key ingredients in the pumping of megamaser sources.

With the existing spectral observations and potential OH detection in mind, we have undertaken a series of observations with the recently upgraded Westerbork Synthesis Radio Telescope (WSRT), in the 92 cm (310–390 MHz) band. This spectral region is ideally placed for observation of both H I and OH in B2 0902+34, since they fall at frequencies near 323 MHz and 379 MHz, for a redshift $z = 3.40$. The present work has set out to clarify the structure of B2 0902+343's

neutral hydrogen spectrum and to search for the presence of OH in the galaxy. In the following discussions, we describe our analysis and the resulting spectra.

2. Observations and data reduction

Observations of B2 0902+343 were made on three separate occasions with the WSRT. The interferometer consists of fourteen 25 m dishes arranged in an east-west configuration; baselines range from 36 m to 2.7 km. The 25 m telescopes offer a primary beam of about 2.6° FWHM in the 92 cm band. All observations were carried out with a total bandwidth 5 MHz, centered near the frequencies of the OH and H I lines. In the 92 cm band, the system temperature is approximately 125 K, giving an expected sensitivity of 0.35 mJy/beam for 12-hour observations. The source confusion limit at 92 cm is just below this level, at 0.3 mJy/beam. A map of continuum sources near B2 0902+343 is displayed in Fig. 1. Not only are observations in the 92 cm band complicated by contaminating emission from numerous unresolved continuum sources, but they are also affected by widespread radio frequency interference (RFI) generated by both local equipment and TV broadcasts. Interference had to be properly removed from the data, and continuum sidelobe structure subtracted before useful images and spectra could be made.

2.1. 1998 observations

Two WSRT observations to search for OH in B2 0902+343 were carried out in the 1998; these took place on October 30 and November 14. The synthesized beam measured $100'' \times 60''$, and data were taken in 256 spectral channels, in 19.5 kHz increments centered about 379 MHz. Integration times for the source were 3 hours and 12 hours, yielding a total expected sensitivity of approximately 8 mJy per channel. On the first date, the quasar 3C 286 was observed for one hour to acquire flux calibration data. During the second run, both 3C 48 and 3C 286 were observed for the same purpose. All data reduction was carried out with the NRAO AIPS package. Based on Baars et al. (1977), flux densities of 24.7 Jy were calculated for 3C 286 and 39.6 Jy for 3C 48. At the wavelengths in question, B2 0902+343 is an unresolved source of about 1 Jy. After amplitude, phase, and bandpass calibrations were carried out separately for each observation, both were merged into a single data set.

Continuum flux models were produced by running the CLEAN iterative source deconvolution algorithm on a "continuum" $u - v$ data set composed of visibilities averaged over the central 75% of the band. Although some of the central channels may contain spectral features, toward B2 0902+343 they will be substantially diluted over a 3.75 MHz bandwidth, as well as over the many other bright continuum sources in the field. The CLEAN continuum images were subsequently employed in a self-calibration routine, and the resulting complex gain solutions were applied to all channels. Broad-band emission was substracted from the data, and channel maps were then constructed to verify that there were no remaining point sources or stray sidelobes near the position of B2 0902+343.

Table 1. Observational parameters.

Parameter	1998 Observations	2002 Observation
Frequency center(s)	379 MHz	323 and 379 MHz
Bandwidth	5 MHz	5 MHz
Number of Channels	256	512
Number of IFs	1	2
Number of receivers	11	13
On-source time	15 hrs.	12 hrs.
Expected sensitivity per channel	6.5 mJy	8.6 mJy

2.2. 2002 observation

The most recent observation WSRT of B2 0902+343 was carried out on March 15, 2002. The backend provided two independent IFs, tuned to 379 MHz and 323 MHz for OH and HI. The number of channels was increased to 512, offering higher spectral resolution in frequency increments of 9.8 kHz, and the synthesized beam measured $97'' \times 56''$. B2 0902+343 was observed for a total of 12 hours, yielding an expected sensitivity per channel of ~6 mJy, consistent with our measured rms values. Additional pointings were devoted to 3C147 and 3C295 for flux scale calibration; flux densities of 49.0 Jy and 55.6 Jy, respectively, were adopted for these sources based on the Baars et al. (1977) formula. Amplitude, phase, and frequency calibrations were carried out with standard AIPS tasks. CLEANing was performed on continuum data sets constructed from only 40 central spectral channels; averages over larger frequency ranges left unwanted residual sidelobes for off-axis sources within the primary beam due to bandwidth smearing. Due to the array's east-west configuration, and hence coplanar u-v points, sidelobe response from bright sources far outside the primary beam also proved to be a problem in the H I IF, even after extensive CLEANing, self-calibration, and continuum subtraction. However, the channels in which the most prominent sidelobe feature crosses the B2 0902+343 position are far enough from the 323 MHz H I frequency to ensure that the absorption line and any broad wing as proposed by de Bruyn (1996) remain uncontaminated. Observational parameters for both the 1998 and 2002 sessions are summarized in Table 1.

2.3. Spectra

Given the noisy appearance of the spectra, we chose to smooth them to a resolution approximately 1/3 of the previously observed H I linewidth in B2 0902+343. Therefore, the 1998 OH-frequency spectrum was filtered with a Gaussian FWHM of 3.1 channels, while the same was done for the 2002 OH and H I spectra with 6.2 channels, due to the increased spectral resolution of the more recent observations. To create the highest possible signal-to-noise ratio for an OH detection, we performed a weighted average of the two separate OH spectra. Weights were based on the rms noise levels measured in each (3.2–3.5 mJy), and the rms of the final smoothed spectrum is 2.4 mJy/beam at $\Delta \nu = 60.5$ kHz. For the single H I spectrum,
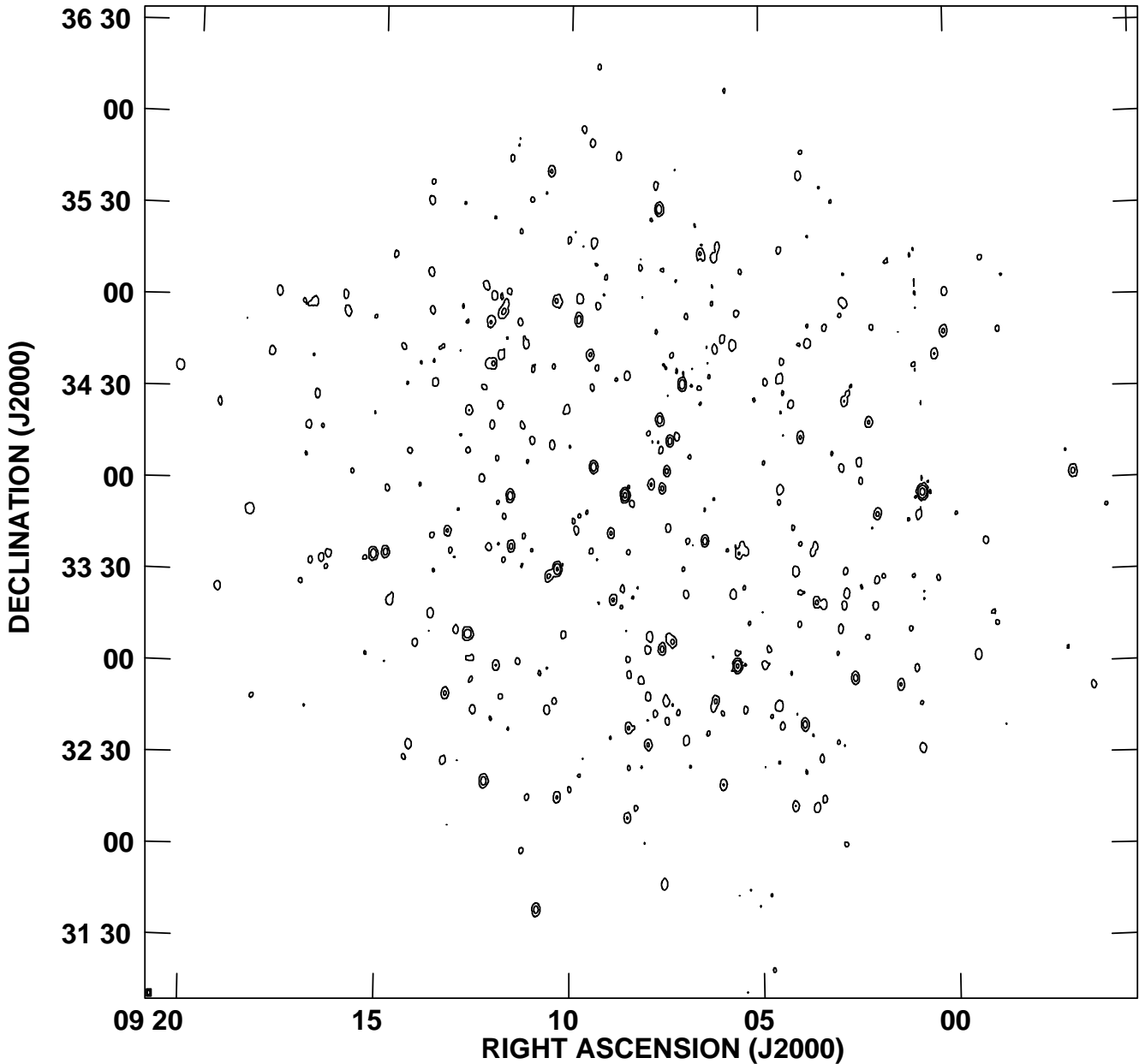
Fig. 1. The field around B2 0902+343 is littered with continuum sources at 92 cm. Contours are drawn at levels of −5, 5, 50 and 500 mJy/beam. The extent of the primary beam can be seen as the central region of this clean map, where the most sources are detected.

the rms is nearly the same, at 2.5 mJy/beam. Rough estimates of the continuum levels were made by averaging flux densities across the spectra, leaving out the obvious absorption region in the case of HI. No slope was allowed for in the continuum, since both spectra appear fairly flat and far-source sidelobe contamination in the H I spectrum may have produced a disruptive bump over a small frequency region. The spectra are presented in Figs. 2 and 3.

3. Discussion

3.1. H I absorption

A narrow H I absorption line is clearly detected at 323.053 MHz, with a depth of 15.9 mJy (=6σ), relative to the

1.2 Jy total flux, and a Gaussian FWHM of 0.13 ± 0.05 MHz. This value corresponds to a rest frame velocity width of 120 km s^{-1}. Our H I linewidth is in good agreement with the values of 90–100 km s^{-1} exhibited in the Briggs et al. (1993) and de Bruyn (1996) spectra. Thus, the implied values for column density and total mass of H I absorbing material are similar to those inferred by de Bruyn (1996): N(HI) $\sim 3 \times 10^{21}$ cm^{-2} assuming a mean spin temperature of 1000 K, and $M_{\mathrm{H\,I}} = 10^7 – 10^{10}$ $M_\odot$, depending on whether the gas at this column density is assumed to cover a region of only 1.5 kpc^2, corresponding to the radio continuum hotspot, or as much as 750 kpc^2, corresponding to the entire Ly-α emission region. The possible absorption feature detected by Briggs et al. (1993) near 322.5 MHz may be present in our spectrum, but noise levels preclude any confident identification. The same is true of
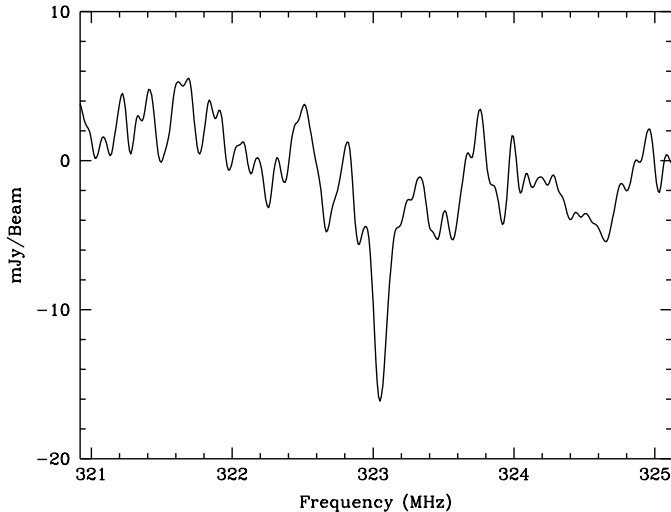
Fig. 2. The B2 0902+343 spectrum in a 5 MHz bandwidth around 323 MHz. The spectrum has been smoothed to a resolution of 60.5 kHz. H I absorption is clearly visible at a frequency just above 323 MHz.

Fig. 3. The B2 0902+343 spectrum in a 5 MHz bandwidth around 379 MHz. The spectrum is smoothed to 60.5 kHz and reveals no sign of OH emission or absorption near 379 MHz. The rms noise is approximately 2.5 mJy.

the broad wing component detected by de Bruyn (1996) on the blueward side of the H I line.

3.2. Non-detection of OH emission

Although the signature of H I at 323 MHz is clear in a 12-hour observation, we fail to detect any OH lines in the combined 377–381 MHz band spectrum. As seen in Fig. 3, it appears exceedingly flat. With a measured rms of 2.4 mJy at channel intervals of $\Delta \nu = 60.5$ kHz, we can set an upper limit of $\sim 1.5\sigma = 3.6$ mJy for the extent of any undetected spectral line features.

Due to lack of data points, the OH megamaser luminosity function (cf. Briggs 1998; Darling & Giovanelli 2002b) is poorly constrained at high redshift. Therefore, while there is little evidence to point toward the existence of hydroxyl gas in B2 0902+343, it is nevertheless instructive to determine how luminous the system could be in OH emission before exceeding the detection limits. Using a formulation analogous to Darling & Giovanelli (2002a,b), we calculate the maximum OH luminosity based on a 1.5σ detection limit and an average rest frame spectral line width of $\Delta v = 150$ km s^{-1}. The maximum OH luminosity is then $L = 4\pi \times D_L^2 \times f_{obs}$, where $f_{obs} = (1.5\sigma)(\nu_o \Delta v)(1 + z)^{-1} c^{-1}$ is the integrated emission line flux in the observer's frame, and D_L is the luminosity distance. Combining this value with the most recent cosmological paraemters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_o = 75$ km s^{-1} Mpc^{-1} yields $D_L = 27520$ Mpc. Applying the luminosity equation, this translates to a maximum $\log(\frac{L}{L_\odot}) = 5.2$. For other cosmologies, the value is found to be around 5.

Because of the high redshift of B2 0902+343, the maximum possible OH luminosity for this galaxy is quite large. Townsend et al. (2001) and Briggs (1998) have already pointed out the limitations that detector sensitivity places on ability to observe all but perhaps the brightest OH megamasers in high-redshift sources. In the case of B2 0902+343,
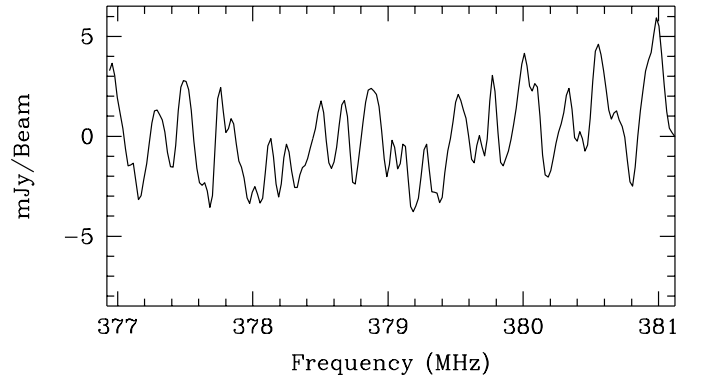
the calculated maximum luminosity serves as a lower limit on detectable OH luminosity imposed by our particular observing parameters. Comparing this limit against luminosities of *known* OH megamasers in the Darling & Giovanelli (2002b) survey at $z = 0.1$–0.25, we find that no OH megamasers more powerful than our detection threshold have been discovered thus far.

However, there is still reason to believe that more luminous masers exist at high redshift. Strong correlation is predicted to exist between galaxy merger rate $((1+z)^m$, Briggs 1998; Darling & Giovanelli 2002a,b; Kandalian 1996), far infrared luminosity (L_{FIR}), and OH megamaser rate (Townsend et al. 2001; Briggs 1998, and references therein), although it has yet to be verified for objects at high redshift. Darling & Giovanelli (2002a) have estimated linear relations between OH and far infrared luminosity based on data from known OH megamasers and find a best fit of $\log(L_{OH}) = (1.2 \pm 0.1) \log(L_{FIR}) - (11.7 \pm 1.2)$. The far infrared luminosity corresponding to our OH luminosity upper limit is then $L_{FIR} \sim 10^{14}$, which is in the "hyperluminous" regime. The B2 0902+343 data point provides a preliminary constraint on the number of such galaxies at $z \gtrsim 3$.

3.3. Possibility of OH absorption

Although B2 0902+343 may not exhibit detectable maser lines, we note that the absence of emission does not necessarily imply the absence of OH gas. If emission is to be observed in the 1665/1667 MHz transitions, the OH molecules must lie along our line of sight, be pumped by an appropriate far-IR source and lie in front of a bright radio continuum source. These restrictive secondary conditions are only met some fraction of the time. Similar arguments may be made for an OH *absorption* scenario. It is plausible that OH is present in our observation throughout a moderate range of velocities, yet with a small enough opacity or covering factor that absorption can not be detected above the noise floor. Since this is clearly not the case for HI, any OH gas which is present is likely to have a significantly lower absorption optical depth or be spatially offset from the hydrogen absorbers. That may be true if most of the H I gas is located in the continuum "hot spot" observed by Carilli (1995), while OH is instead associated with other regions of the galaxy.

On the whole, OH absorption is probably of less interest than emission, since it is unlikely to shed light on the galaxy merger rate. However, studies of absorption could offer insight into the abundance of molecular gas in the early universe. The signature of OH absorption has already been detected in the spectra of some low to moderate redshift galaxies, including PKS 1830-21 at $z = 0.89$ (Chengalur et al. 1999). In the case of B2 0902+343, we derive an upper limit for OH column density and mass. With an rms limit of 2.4 mJy and a total continuum flux of 1.1 Jy, the optical depth, τ, for any absorption line is less than ~0.3%. We adopt a linewidth of 120 km s^{-1}, based on value measured for H I in B2 0902+343. From Liszt & Lucas's measurements of galactic OH absorption and emission, we select $T_{ex} = T_{CMB} + 1$ of order 10 K. Together, these parameters give a maximum N(OH) of 8×10^{14} cm^{-2}. A rough check of this value may be carried out by considering the ratio N(OH)$/N$(HI) $< 5 \times 10^{-8}$ for galactic sources that follows from Liszt & Lucas (1996) and Lucas & Liszt (1996). With N(HI) approximately 3×10^{21} (assuming a mean HI spin temperature of 1000 K), we expect an OH column density less than 1.5×10^{14} atoms cm^{-2}. The implication is that our upper limit to OH absorption is roughly consistent with the Galactic ratio of N(OH)$/N$(HI).

To convert from column density to molecular mass, it is necessary to specify the amount of cross-sectional area that OH molecules might occupy in B2 0902+343. At $z = 3.40$, these angular sizes are a function of angular diameter distance and linear size. One arcsecond at the distance of B2 0902+343 corresponds to 6.9 kpc ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_o = 75$ km s^{-1} Mpc), or values in the neighborhood of 5–10 kpc for other cosmologies. Adopting the same range of areas considered previously for the HI absorbing region of only 1.5 kpc^2, corresponding to the radio continuum hotspot or as much as 750 kpc^2, corresponding to the entire Ly-α emission region, yields OH mass limits of between 2×10^5 $M_\odot$ and 9×10^6 $M_\odot$.

4. Summary

With the WSRT, we have achieved a redetection of HI 21 cm absorption in B2 0902+343 at $z = 3.3962$, at a significance in excess of 6σ. Our linewidth and depth are consistent with previous observations. Our non-detection of associated redshifted OH 1665/1667 emission or absorption at the 0.2% level yields an (1.5σ) upper limit to the OH mega-maser luminosity of $\log(\frac{L}{L_\odot}) = 5.2$, and an upper limit to the OH column density along this line-of-sight,

N(OH) $< 10^{15}$ cm^{-2}. Although no OH emission or absorption is detected, our upper bounds on these values may help to constrain predictions of gas quantity and merger activity at high redshift, once a larger galaxy sample is available. We encourage work to search for OH megamasers in other high redshift galaxies at $z > 3$. Future observations with more sensitive instruments, such as the proposed Square Kilometer Array (SKA; Blandford 2001), will provide for either new detections or further limits. Higher angular resolution could also pinpoint the location of the HI gas in relation to the optical, infrared, and radio continuum emission features.

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