A. Proposal for VLA Observing Time: Program AG686

Proposal AG686 has been nominally accepted for D configuration in 2005, pending technical and management review of plans to outfit the VLA/EVLA with VHF receivers.

A.1. Abstract

We propose to search for HI emission from material surrounding the HII regions of quasars during the cosmological epoch of reionization (EOR). For the three known "EOR quasars" detected by Sloan, the HI line is redshifted to 192-196 MHz. If time is awarded, SAO will build 28 VHF receiving systems, which we will help install in time for commissioning and use in the 2005 and later D-configurations. This VHF system will be open for later community use and operationally similar to the 400 cm system. Little data exist to constrain models of the EOR. With direct imaging, we will constrain the state of the IGM (e.g., warm or cold) and neutral fraction, as well as quasar age, formation time, and ionization anisotropy. The proposed system leverages previous investments in the VLA to accomplish pathfinding EOR science several years before facilities to be built from the ground up for > 10 times the cost.

A.2. Science Justification

The structure and evolution of the universe during the Epoch of Reionization (EOR) are essentially unknown. Analyses of Cosmic Microwave Background (CMB) temperature and polarization fluctuations detected with WMAP have been used to infer reionization began between redshifts 11 and 30 (Kogut et al. 2003, ApJS, 148, 161). Study of Lyα absorption in the optical spectra of quasars indicates a rapid change in the HI neutral fraction of the intergalactic medium (IGM) toward the end of the EOR (Fan et al. 2002, ApJ, 123, 1247), with a substantial neutral fraction as late as $z \sim 6.3$ (Mesinger & Haiman 2004, ApJ, 611, L69). On the other hand, surveys of Lyα selected galaxies at $z \sim 6.6$ have been used to argue for earlier completion of reionization (Hu et al. 2002, ApJ, 568, L75; Malhotra & Rhoads, astro-ph/0407408; Stern et al. astro-ph/0407409), although the interpretation of these results is difficult (e.g., Santos 2004, MNRAS, 349, 1137; Haiman 2002, ApJ, 576, L1). Together these results indicate that the history of reionization probably extended over a large redshift interval and was complex, with multiple peaks (Wyithe & Loeb 2004a, Nature, 427, 815, and references therein).

Characterization of how reionization proceeded may be achieved directly through detection and interferometric mapping of the HI heated in advance of the ionization fronts that expand relativistically into the IGM during the EOR. Estimation for any redshift of (1) the shape and size of the bubbles on the sky, (2) velocity structure, and (3) amplitude of the signal would provide critical constraints for theory (Wyithe & Loeb 2004b, ApJ, 610, 117). The amplitude is proportional to the neutral fraction (x_{HI}) of the IGM, and the magnitude may be used to estimate whether the IGM is warm ($T_{spin} \gg T_{CMB}$) or cold ($T_{spin} < T_{CMB}$) - Figures 6, 7. In addition, the sizes and shapes of the regions are governed by the ages of the quasars and the anisotropy of ionizing flux emitted by them. From measurement of size it might be possible to constrain how soon after cosmological recombination the first stars and massive dense objects formed.

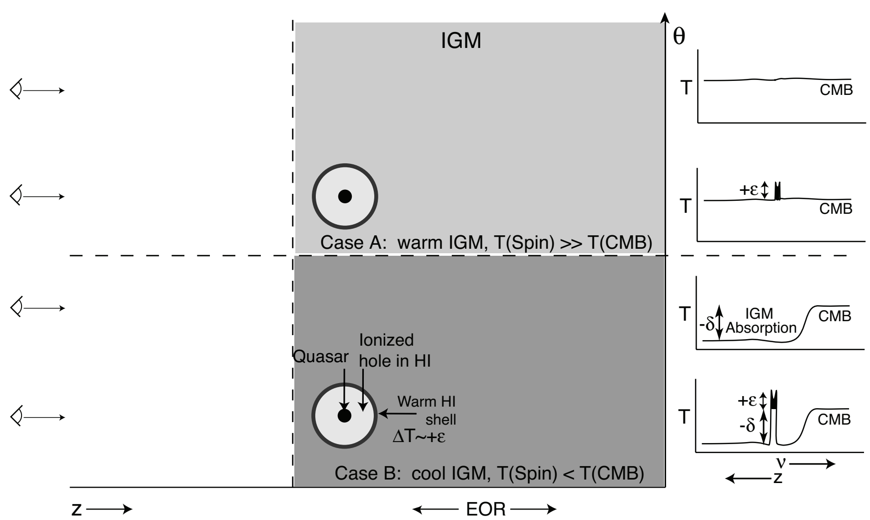

Fig. 6.— HI emission signature of the ionized region around a quasar prior to cosmological reionization. *(bottom)*– Lyα background in the IGM elevates the spin temperature of Hydrogen. If the IGM is largely opaque, then the background is low, and the IGM is cold. In this case $T_{spin} < T_{CMB}$, and HI absorption depresses the CMB (by δ) for frequencies that correspond to $z > 6.2$. However, along lines of sight where a quasar has ionized the HI, the CMB will be unabsorbed. On top of this, there will be emission (ϵ) from a shell of hydrogen surrounding the ionized region and heated by X-rays. The total signal is visible to an interferometer ($\delta + \epsilon$). *(top)*– If $T_{spin} \gg T_{CMB}$, then there is no absorption and only emission from the warm hydrogen is detectable (ϵ).

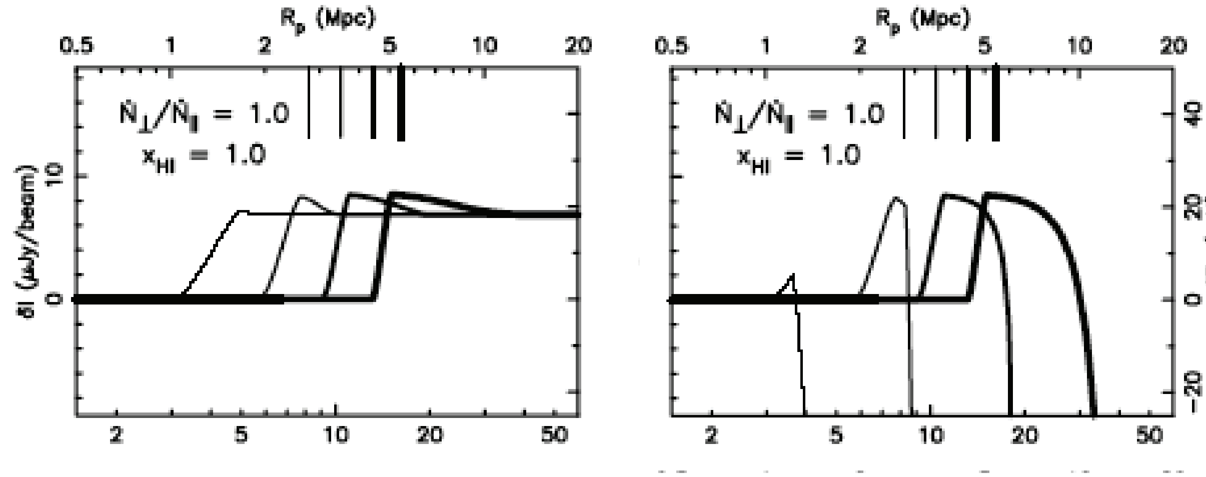

Fig. 7.— Radius of an ionized region in the sky plane and HI line strength, for isotropic quasar emission ($z = 6.5$, $N = 10^{57}$ Ly$\alpha\, s^{-1}$) and a uniform neutral IGM. *(left)*– Warm IGM. *(right)*– Cold IGM, where absorption of the CMB creates a local $\sim$ 320 mK contrast that is detectable by an interferometer. The traces are for quasar ages of (0.5 - 4)$\times 10^7$ yr. The bottom axis is angle on the sky ($'$). From Wyithe & Loeb 2004b.

We propose to directly characterize the IGM and many-Mpc-scale ionized bubbles driven by the three known quasars that "lie in" the EOR (Fan et al. 2001, 2003; AJ, 122, 2833; AJ, 125, 1649): SDSS114816.64 +525150.3 (z = 6.43), SDSS104845.05 +463718.3 (z = 6.23), and SDSS103027.10 +052455.0 (z=6.28).

For these three "EOR quasars," the HI line is redshifted to frequencies of 192-196 MHz and cannot be mapped sensitively with existing low frequency facilities (i.e., GMRT, Westerbork, Molonglo). Innovative new facilities are proposed or under construction, but observing is at least several years away. *We propose to build and contribute to the VLA 28 VHF receiver systems (170-200 MHz) that will enable study of these EOR quasars starting in late 2005 - and higher redshift objects ($z < 7.4$) when they are discovered.* The VHF system will be a pathfinder for EOR science and the new facilities. It will also be a long term addition to the VLA and EVLA, available to the community, and opening a spectral window that is relatively free of RFI (Figure 8). We note the fast pace for construction and deployment is necessary because we may require two D-configurations to complete the project (the first is proposed here), and the targets are up at night in 2005 and 2007, but not 2008. Overall, the accelerated timeline is realistic because the VHF system will be technically and operationally similar to the existing 400 cm system contributed by NRL, i.e., NRL blazed the trail.)

Funding ($\sim$ \$110k) for the design, assembly, and testing of the VHF system has been

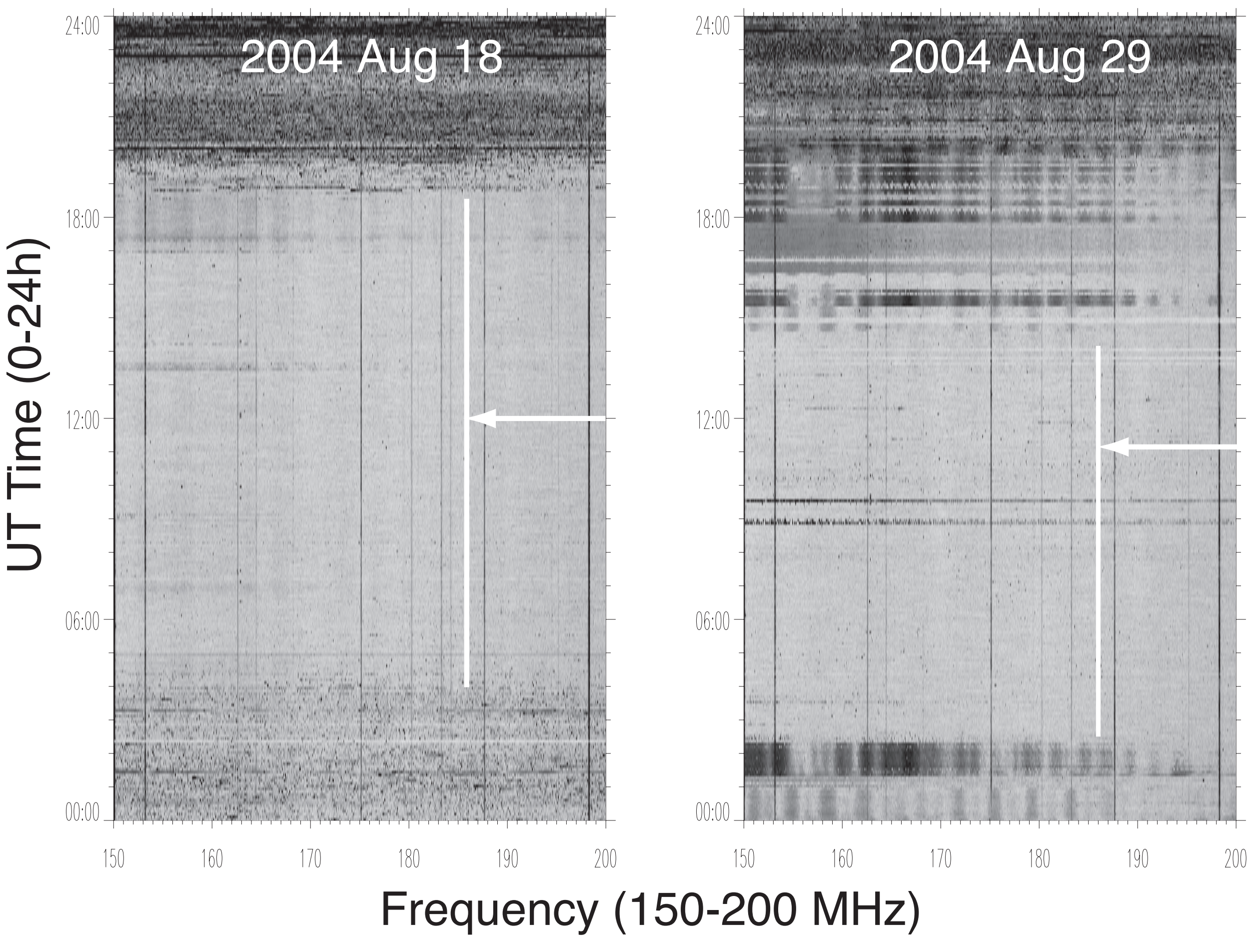

Fig. 8.— Sample RFI plots for the VLA site, with 10 kHz resoluton bandwidth and 5 min time resolution. Vertical white line delimit the proposed observing band. Clear windows are light gray. During mid/late summer 2004, $\sim$ 11 PM to $\sim$ 8 AM is most often clear. Some days are substantially better. Summer lightning causes the black chaff at the top of each plot, and this won't be a factor for the proposed (fall/winter) observing. Narrow vertical black lines are television carriers. Some channels appear to broadcast only carriers most of the time (e.g., 198 MHz). Broad horizotal waves represent modulated transmission, which occurs chiefly during working hours. *Over 48 monitoring days from late 2004 July to late 2004 September, 29 days showed good conditions for* $>$ 6 *hours and 22 days showed good conditions for* $\sim$ 12 *hours.*

secured inside Smithsonian, contingent on the success of this request for observing time. NRAO has indicated that it will consider deploying the VHF system contingent on peer review and delivery of an acceptable technical and management plan. This request for observing time is the next step after approval of funding.

A.3. Technical Justification

The anticipated diameters of the HI emission regions are 10-20′, which is well matched to the tapered beam of the VLA in D-configuration at $\sim$ 194 MHz. (In contrast, the beam of the GBT is too large - and there is no receiver for this band.) Due to cosmological expansion, the line profile is on the order of 2 MHz wide. The best matched VLA correlator mode is 12.5 MHz total bandwidth with 0.8 MHz channel width. In 50 hours, the VLA will achieve $\sim$ 11 mK RMS due to thermal noise, assuming detection of two polarizations, system temperature of 150 K, 26 antennas, 40% aperture efficiency, 78% correlator efficiency, and tapering to achieve a 15′ beam. (In practice, optimal filtering of image data will be used to match the source in frequency and angle, but the listed parameters are reasonable estimates of the results.) To achieve high sensitivity, foreground continuum emission from galactic and extragalactic sources must be eliminated. First, we will subtract strong point sources identified in a *short* integration with an extended configuration (to be proposed later). Second, we will interpolate in frequency and subtract images made off the HI line from images made on the line, incurring a $\sim$ 20% penalty in the RMS. (We have adopted the published VLA efficiency at 320 MHz until we can complete a full electromagnetic analysis at 194 MHz. However, we estimate the 194 MHz system may have similar *or higher* efficiency because it will operate closer to in-focus than the 320 MHz system, $\sim \frac{1}{3}\lambda$ vs $\sim \frac{1}{2}\lambda$ - a difference of $\sim$ 30% in efficiency, which should more than offset at 194 MHz the heightened impact of aperture obstructions. We have also assumed loss of one antenna due to EVLA testing, though loss of three would be acceptable, and we have adopted a preliminary system temperature, based on proximity of the targets to the galactic pole - anticipated $\sim$ 30 K receiver, $\sim$ 20 K spillover as experienced at the GMRT, and $\sim$ 100 K sky temperatures - see Figure 9. The actual system temperature may be on the order of 20% higher due to uncertainties in these quantities.)

Depending on the state of the IGM, the HI signal will be on the order of $23x_{HI}$ mK (warm IGM) or $320x_{HI}$ mK (cold IGM). In an integration of 50 hours, it should be possible to achieve a signal-to-noise ratio (SNR) of 20 to $24fx_{HI}$ for a cold IGM, where f is the beam filling factor of cold material (probably close to unity). It is arguable that toward the end of the EOR a (cold) IGM largely devoid of Lyα background is unlikely. However, we note that there are currently no definitive measurements either way. We propose to use limited integrations on three quasars in 2005 (150 hours) to investigate this "strong signal" case and at the same time conduct extensive hardware and data reduction tests, demonstrating that we can reach predicted noise levels. *In the event the IGM is cold, we will be able to make a statistically significant detection over an almost order of magnitude range in fx_{HI}. Absent a detection, we will establish firmly that the IGM is warmer than the CMB at $z = 6.2$-6.4.*

Investigation of the possilby more likely "weak signal" case will require submission of a large propsoal to NRAO. A 4σ detection could be achieved in ~ 250 hours, for $x_{HI} = 1$ in the vicinity of the quasar. (Since the position of the quasar is known *a priori*, 4σ would be statistically significant.) In addition, we would attempt to detect HI temperature fluctuations due to the evolution of the IGM density and ionization (Zaldarriaga et al. 2004, ApJ, 608, 622) in the 2.5° (very deep) fields around the quasars as a *parallel* experiment. These fluctuations will be too weak to image, but their statistics should be measurable, much as COBE was able to obtain CMB statistics in advance of WMAP imaging. For the D-configuration following 2005, the large proposal deadline is June 1 and precedes commencement of observing. To address this, we will follow submission of a large proposal with monthly updates regarding system performance and initial synthesis results while the proposal is under review, through the end of 2005 or start of 2006.

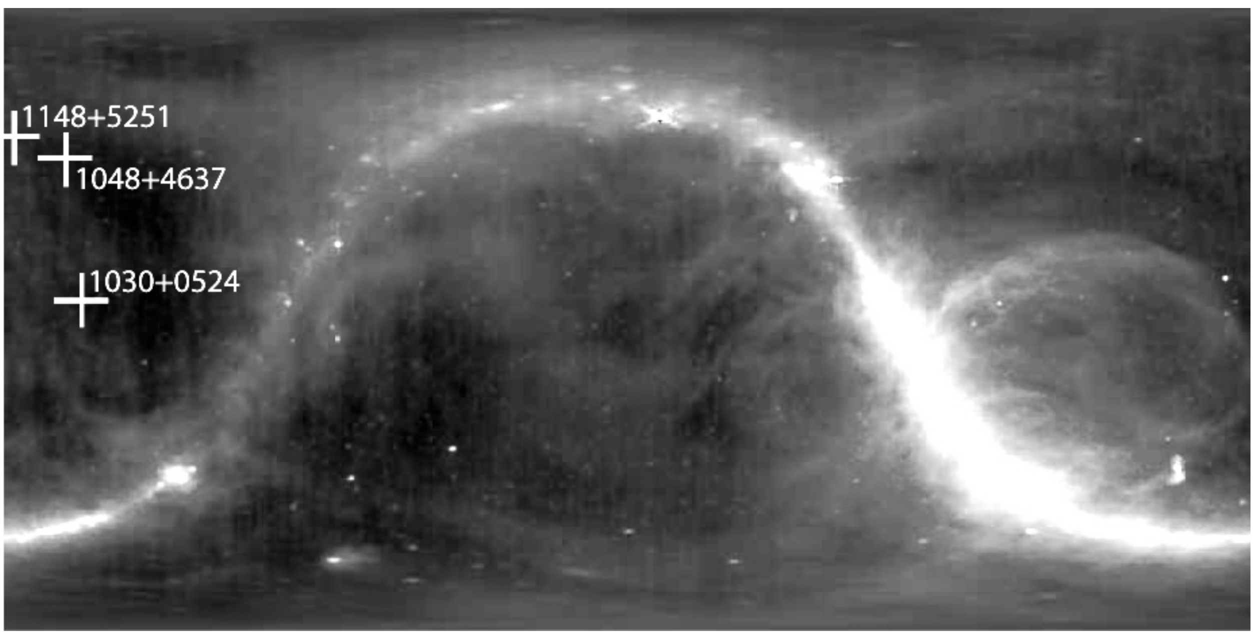

Fig. 9.— All-sky map at 408 MHz (Haslam et al. 1982, A&A, 47, 1; shading by D. Emerson). The proposed targets lie in regions with among the lowest levels of galactic background emission, 14-16K. All lie well away from the galactic plane ($b > 50°$). For 194 MHz, the anticipated sky temperature is $\sim$ 100 K based on global measurements (D. Emerson, www.tuc.nrao.edu/~demerson/radiosky/rsky_p3.htm; Kraus 1986, Fig. 8-6) or scaling of the Haslam results with frequency ($T_{sky} \propto \nu^{-2.7}$).

B-1. Key and Legacy Science

B-1.1. Baseline Project: The Strömgren Spheres of Quasars During the EOR

Proposal AG686 covers a first installment of observing time for the baseline project discussed in this Appendix. This will enable investigation of the hypothesized strong signal case of Wyithe & Loeb (cold IGM) and first demonstration of high sensitivity, high dynamic range imaging. Additional time will be requested in a subsequent VLA "large" proposal for follow-up and investigation of the hyptothesized weak signal case. AG686 has been nominally accepted for D configuration in 2005, pending technical and management review.

We consider observing the three known quasars believed to lie within the EOR ($z = 6.2 - 6.4$) for 250 hours each, with the VLA in D configuration. We adopt a 12.5 MHz total bandwidth with two polarizations and 16 spectral channels (after hanning smoothing) of 0.8 MHz width (1260 $\mathrm{km\,s^{-1}}$ or a physical line-of-sight scale due to the Hubble expansion of $\sim$ 1.6 Mpc).[1] The expected rms per channel is 14 mK for a naturally weighted image (ie. optimal point source sensitivity), with a resolution of $7\farcm5$ (2.5 Mpc). The diameters of the Strömgren spheres could be somewhat larger, depending on quasar age and assumptions of the cosmological model. (u,v)-tapers will probably be used to match the beam to the source size (see below).

Good spectral coverage is crucial for subtracting the foreground continuum emission (radio galaxies and the Galaxy), and we will explore a number of techniques for dealing with this continuum emission. First, we will obtain a short (12 hour) integration in the A array to find the brighter point sources in the field ($\geq$ 10mJy). These will be subtracted from the UV data. We will then fit baselines (simple power-laws or slowly curving functions) to the spectral data to remove the Galactic emission, and residual radio galaxy emission. Clearly, continuum subtraction will be one of the more challenging aspects of the experiment, since the foregrounds have to be removed to the level of a few$\times 10^4$. We will experiment with real and simulated data using both image-plane and uv-plane subtraction, as well as with the three-dimension fourier analysis techniques proposed in, e.g., Morales & Hewitt (2004).

The magnitude of the signal for a cosmological Strömgren sphere (CSS) depends on whether the spin temperature of the IGM is above or below the CMB temperature. For the "warm IGM" case, we have used the program UVCON in AIPS to simulate a data set for a quasar, using the models in Wyithe & Loeb (2004a) with a neutral fraction of $f(HI) = 1$

[1]The number of channels and bandwidth are limited by the current VLA correlator. While these are adequate for the current experiment, the future EVLA correlator will allow for many more channels over a wider bandwidth. One ramification will be improved RFI excision.

(their Figure 4, upper panel). This model implies a brightness temperature $\sim$ 20 mK and a radius on the order of 5-15$'$, depending on quasar age and isotropy of ionization. (For the "cold IGM" case, the signal is $\sim$ 15 times larger.)

Figure 10 shows simulated images. The left panel shows a full resolution image ($7\overset{'}{.}5$), while the right panel shows a tapered image with a resolution of 15$'$, both for one spectral channel. Because the (u,v)-coverage of the VLA is centrally concentrated, such that the rms increases only slowly as the taper increases, until one reaches the central "hole," which for the VLA D configuration starts at $\sim$ 75 m. Hence, the rms on the full resolution image is 0.09 mJy, while that on the tapered image it is 0.12 mJy. These correspond to brightness temperature sensitivities of $\sim$ 16 mK and 5.3 mK, respectively. The signal is expected in two channels (improving the RMS by $\sqrt{2}$), and its position on the sky is known. The combination of spectral and spatial information will be critical for verification of the line signal, these simulated images show that even for the weak signal case (a warm IGM) we will be able to test models effectively, e.g., constrain angular size and rule-out a universe for which $f(HI) > 0.5$ at $z \sim 6.2$. This will set the first hard limits on the cosmic neutral fraction at the end of cosmic reionization.

We emphasize that, while analyses of the Gunn-Peterson effect and the WMAP large scale polarization results have constrained the EOR to be between $z = 6$ and 17, current data provide only crude lower limits to the neutral fraction at $z \sim 6.3$ of 10^{-3}. Arguments have been made for high neutral fractions, > 0.1 (Wyithe & Loeb 2004a), and for low neutral fractions, < 0.01 (Oh & Furlanetto), based on optical spectra of $z \sim 6$ quasars. It is unlikely that further analyses of line of sight absorption information provided by optical spectra will constrain the neutral fraction and better than has been done so far. In contrast, the direct detection of line emission from HI and imaging of its distribution on the sky is a more simple approach and one that appears more likely to provide hard limits.

B-1.2. General Advantages of a VLA/EVLA VHF System for EOR Studies

For a very modest investment, the VLA will be competitive with and complementary to other near-term experiments intended to detect HI during the EOR, such as PAST. Indeed, one could argue that having two or more complementary experiments is crucial when considering the scientific importantance of these programs, and the potential systematic problems that could dominate the errors.

Critical aspects of the VLA-VHF system relative to the other proposed experiments are the low cost and short timeline. The low cost is due to the highly leveraged aspect of the

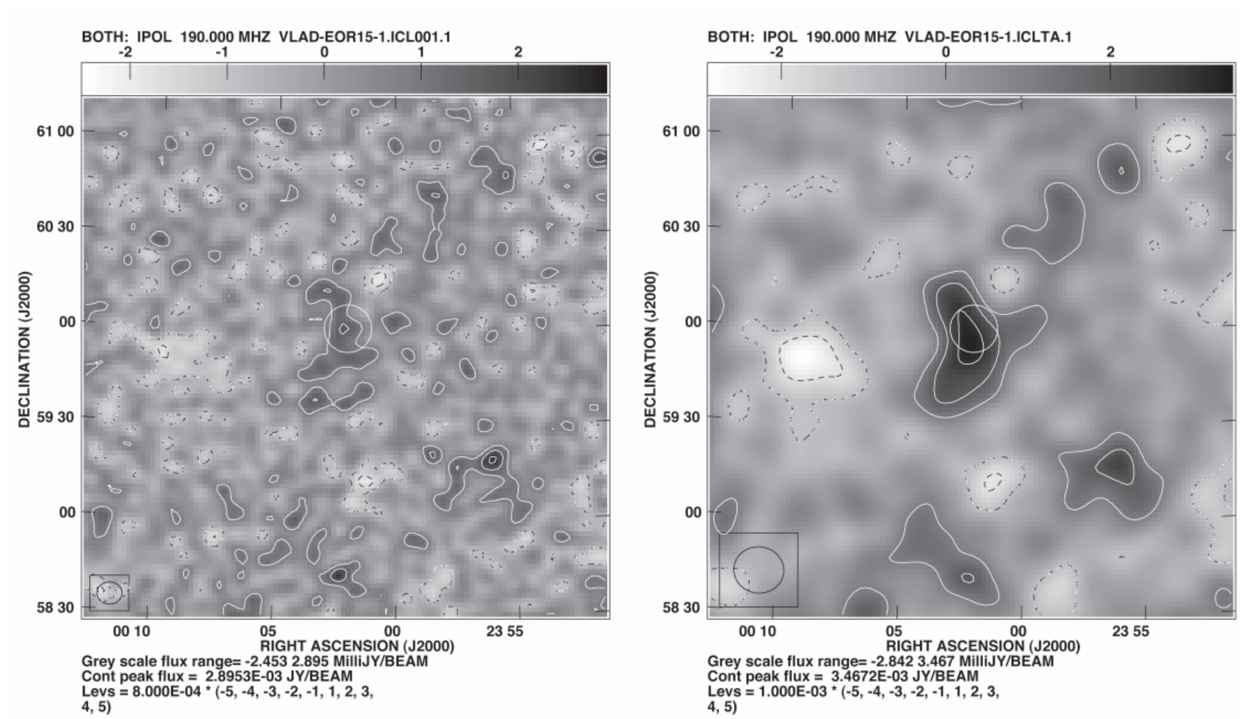

Fig. 10.— Simulation of VLA/EVLA observations of the HI signal from a CSS around a quasar at $z = 6.2$, assuming 250 hrs on source and a 0.8 MHz spectral channel separation. The central figure shows the naturally weighted image ($7'.5$ resolution, 0.09 mJy rms). The right image shows a tapered image ($15'$ resolution, 0.12 mJy rms). The circle shows the size of the sphere. The contour levels are linear, starting at 0.18 mJy beam^{-1} in the left figure, and 0.22 mJy beam^{-1}.

program, i.e., we already have telescopes, and IF and correlator system. All we need are receivers. And fortuitously, the VLA/EVLA u,v-coverage, and primary beam, are reasonably well matched to what is required. The time-line can be agressive for the same reasons, as well as the relative simplicity of the required VHF receivers.

Another advantage enjoyed by the proposed VLA-VHF system is operation at the higher end of the frequency range where potential EOR signals can be detected. Consequently, problems related to the ionosphere and wide field imaging are mitigated. Experience at the GMRT at 230 MHz shows that the ionosphere is often reasonably well behaved, even on baselines out to 10 km, such that normal phase and amplitude calibration procedures can be employed. In particular, the $\sim 4°$ FOV of the VLA/EVLA is comparable to the isoplanatic patch for ionospheric phase fluctuations, such that existing single-solution self-calibration techniques can be employed.

Of course, the disadvantage could be that the neutral fraction toward the end of the EOR ($z \sim 6.2$) may be low ($f(HI) \leq 0.1$), but testing this possibility is exactly what drives the proposed program. Indeed, the EOR programs have been designed such that even non-detections lead to ground-breaking, fundamental conclusions concerning the process of cosmic reionization.

B-1.3. Legacy Science Programs

The VLA-VHF system has been proposed and funded based on the desire to investigate CSSs. However, the system will given to the NRAO for general use by the VLA/EVLA community. In general, the addition of an observing waveband below the existing 320 MHz band will enable broadening of radio source spectral index studies to a regime in which phenomena such as low-energy cutoffs may be important. In this section we consider some of the other high profile science that could be performed with the VHF system. Rather than present a "laundry list" of potential science programs, we consider only a few potential ones, based on general observing capabilities. The science cases developed for LOFAR and the MWA (http://www.lofar.org, http://web.haystack.mit.edu/MWA/) include more complete compilations.

B-1.3.1. Wide-field Surveys

Since imaging noise decreases as the square root of integration time, a figure of merit for wide field surveys is (beam area)/(system noise)^2. To compare surveys at different frequencies, we also need to correct the noise rms to a fiducial frequency assuming a typical source spectral index. We assume a power-law of index -1 ($S_\nu \propto \nu^\alpha$) and use 74 MHz as the fiducial frequency. Column 11 in Table 1 shows a scaled "survey speed" for the VLA bands with the largest fields of view. The combination of large field, relatively low system noise, and low observing frequency, make the proposed VHF system the optimum frequency for surveys of the dominant population of cosmic radio sources.

Wide field low-frequency surveys will reveal high-redshift radio galaxies, giant radio galaxies, radio halo and relic sources (see http://www.lofar.org). For instance, in ~ 100 h a 190 MHz system could cover of order $10^4\,\mathrm{deg}^2$ to 2 mJy rms, or a factor 3 deeper than the WENSS survey at 327 MHz (assuming $\alpha = -1$). For such a survey we expect about 6×10^5 sources. Below a few mJy it is well known that the source populations should change from mostly radio loud AGN to star forming galaxies. About half of the detected sample would be star forming galaxies at $z \leq 1$.

B-1.3.2. Power Spectrum of HI Brightness Fluctuations at the EOR

In addition to the baseline CSS experiment, a second EOR-related experiment would be a study of the power spectrum of HI brightness temperature fluctuations over the full $\sim 4^\circ$ FOV due to the evolution of density and ionization in the IGM (Zaldarriaga, Furlanetto, & Loeb 2004). It is important to realize that the VLA/EVLA will not have the sensitivity to image the fluctuations. But an interferometer is a natural "Fourier filter," and the data can be averaged in the (u,v)-plane to obtain a power spectrum of density fluctuations. One gains a factor $\sqrt{2}$ in SNR due to the fact that the visibility phases are not relevant in such a statistical (i.e., power-spectrum) analysis. Adopting reasonable assumptions about symmetry enables a dramatic improvement in the detectability, in a statistical sense, of the fluctuations on a given scale. The situation is analogous to COBE and WMAP studies of fluctuations in the CMB, with COBE determining the statistics of the signal, and WMAP making a real image of the fluctuations (White et al. 1998).

Figure 11 shows the predicted angular power spectrum for $z = 7$ due to the evolution of the neutral IGM (Zaldarriaga et al. 2004). The error bars represent the VLA 1σ errors after 250 hours on source. For a ionization fraction of 0.75, we obtain a 3 to 5 σ detection of the power spectrum of the fluctuations in at least two (u,v)-annuli per 0.8 MHz spectral channel. There are 15 channels, and an optimal filtering can be performed to best match the size scale of the fluctuations to their frequency structure.

The most relevant experiment for comparison to the proposed program is the PAST experiment, since both are "path finders" with timescales of just a couple of years. Other experiments (e.g., LOFAR, MWA) have significantly longer timescales and much larger costs (> 4 years, $\gtrsim \$10^7$). The PAST experiment is being designed to have relatively uniform (u,v)-coverage out to baselines of a few to perhaps 10 km, leading to both good sensitivity on small angular scales ($l \geq 1000$, or $\theta \leq 0.2^\circ$) and relatively flat sensitivity as a function of scale. The VLA observations will complement PAST by enabling study of larger scale fluctuations ($\theta = 0.1^\circ$ to 0.3°). The centrally condensed (u,v)-coverage of the VLA, and the limited range of angular scale lead to a narrow peak in sensitivity for the power spectral analysis. Fortunately, this regime corresponds closely to an interesting range in the expected fluctuations.

B-1.3.3. HI Absorption Toward Radio Loud Sources During the EOR

A third EOR HI experminent is a search for absorption by the neutral IGM toward the radio loud AGN that existed during the EOR. This work could be performed with a VHF system and the EVLA correlator. Carilli, Gnedin, & Owen (2002) predict the expected absorption signal due to the neutral IGM during the EOR. Two signals are present: a "21 cm forest" of narrow lines (few $\mathrm{km\,s^{-1}}$) due to filamentary structure in the "cosmic web," (analogous to the Lyα forest seen after reionization) and an overall depression in the continuum due to the mean neutral IGM (analogous to the Gunn-Peterson effect). The proposed VHF system will be able to detect the line forest for a sufficiently bright radio source (probably $\sim$ 1 Jy). There is also the possibility of detecting stronger lines toward fainter radio sources by gas in the host galaxies of the radio sources, including (possible) prompt radio emission from GRBs and GRB afterglows (Furlanetto & Loeb 2003).

Figure 12 shows a simulated spectrum with the VLA for 250 hours toward a bright (1 Jy) radio source within a still largely neutral IGM. We expect about one absorption line per 0.5 MHz bandwidth with optical depth $\geq$ 1% due to the 21 cm forest. These would be detected at the EVLA at $\geq 5\sigma$. If we include possible absorption by "mini-halos," the line density would increase by a factor two. Obviously, the absorption experiment rests on the discovery of the first radio loud AGN inside the observing band of the proposed VHF receivers ($z = 6.2$-6.9). Current models (Rawlings & Jarvis 2004), predict that there should be at least a few (of order 10) radio sources brighter than 1 Jy at $z > 6$ over the sky. Indeed, candidates sources have already been found (de Breuck 2000; Rawlings and Jarvis 2004).

B-1.3.4. The Transient Universe: Prompt (Coherent) Emission from GRBs

Gamma-ray bursts (GRB) represent physics at its most extreme, with large energy releases (10^{51} erg), ultra-relativistic shocks ($\Gamma_\circ \sim$100), and large magnetic fields ($\sim$100 G). If an average GRB were to release only a tiny fraction of its energy (10^{-6}) into the radio band, then it would produce emission bright enough ($\sim$100 Jy) to be detected by existing instruments. Prompt, coherent emission has also been predicted by several recent theoretical studies (e.g. Sagiv & Waxman 2002). However, quantitative flux estimates are difficult to obtain by this approach because we lack any real physical understanding of the detailed plasma properties of GRB outflows (i.e., baryonic versus Poyntying flux).

Ginzburg (1973) was the first to anticipate the rich scientific rewards that the detection of prompt radio emission from a GRB would bring. An electromagnetic signal of frequency ν traveling through an ionized medium will experience a dispersive delay $\Delta t \propto \mathrm{DM}/\nu^2$, where the dispersion measure (DM) is the integrated free electron density along the line of sight DM=$\int n_e dl$. The dispersion measure has at least four components: (*i*) our Galaxy, (*ii*) the intergalactic medium (IGM), (*iii*) the GRB host galaxy, and (*iv*) the circumburst medium. Depending on the expected ionized column density towards GRBs, it is possible, with a sufficiently fast telescope, to slew to the location of a burst and begin observing *prior* to the arrival of the radio signal. A successful detection will not only shed light on GRB central engine properties, but it would provide a powerful new probe of the circumburst environments of GRBs, allow us to search for the missing baryons at moderate z, and probe the epoch of reionization at high z (Palmer 1993, Ioka 2003, Inoue 2004).

In Figure 13 we show the delay times at low frequencies for a range of column densities (or DM). Detailed simulations have been carried out for a population of GRBs as part of VLA project AF 419 to estimate the total DM. The ionized column density is found to range from few$\times 10^{21}$ to 10^{23} cm^{-2}, corresponding to 1000$<$DM$<$30,000 cm^{-3} pc. These estimates are in line with observational constraints from measurements of the GRB gas columns estimated from optical extinction, X-ray photoelectric absorption and damped Lyα absorbers (Stratta et al. 2004; Vreeswijk et al. 2004). The largest uncertainty comes from our rather sketchy understanding of the circumburst environment and the extent to which GRBs might photoinize it (Perna & Lazzati 2002).

A successful experiment must be able to slew the VLA/EVLA to the burst position within a time that depends on the observing frequency and the DM. The VLA/EVLA antennas can slew to any location on the sky within 9 minutes (the distribution of slew times peak at 2.5 minutes). At 74 MHz this requirement is easily met, but beyond 10^{22} cm^{-2} the time delay over which the search is conducted becomes unreasonably large ($>$ 1 hr). This limitation can be offset by simultaneously searching at 327 MHz, a frequency that is sensitive to high DMs. This dual 74/327 MHz approach is what is currently planned for AF 419.

Alternatively, we can use an intermediate frequency. The 190 MHz band clearly is an ideal frequency in which to conduct a sensitive search for prompt, coherent radio emission from a GRB. For the range of DMs above, we expect time delays of approximately 4 to 60 minutes after a burst. This allows the VLA/EVLA to be be on source prior to the arrival of the signal. Our simulations indicate that by using burst alerts provided by the *Swift* satellite, the VLA/EVLA will be on source prior to the arrival of the putative signal 75% to 100% of the time. Furthermore, the superior sensitivity and cleaner interference environment expected at 190 MHz will aid in the detection of a signal in the time domain. Confirmation of any candidates (by imaging the visibilities) will likewise be simplier at 190 MHz than at 74 MHz.

B-1.3.5. Radio Recombination Lines

Hydrogen Radio Recombination Lines (RRL) arise close to ionizing sources, located typically in relatively dense regions. In contrast, Carbon RRLs arise in the surface layers of dense regions and in the diffuse ISM. The ionization potential for neutral Carbon is slightly below that for Hydrogen. As a result, radiation slightly too weak to ionize Hydrogren escapes into the ISM where it can be responsible for RRL emission and absorption features from Carbon in the surrounding material. The passband of the proposed VHF system includes transitions close to $\sim$C(320α). The combination of VHF and 320 MHz maps of RRL emission/absorption may be used to constrain conditions in the ISM better than 320 MHz alone because the transitions are widely separated and the specific intensity of background emission will differ substantially between wavebands. We also note that the detection of the effects of dielectronic recombination may also be possible (Walmsley & Watson 1982), enabling broader studies of relative line intensities.

B-1.3.6. Pulsars

A VHF observing system would achieve high sensitivity at frequencies where pulsar emission is strong because of steep spectral indices. The proposed system would especially benefit millisecond pulars surveys of globular clusters, for which dispersion measure is small and spectra steeper than the median. A comparison of sensitivities for the VLA/EVLA and single dish facilities operating at higher frequency (e.g., the Lovell telescope, Effelsberg) is difficult in advance of VHF field testing, but it is reasonable to expect VLA/EVLA studies to be competitive. In principle, searches for giant pulses in long integrations may be feasible because of the large primary beam of the VLA/EVLA at VHF frequencies and the very steep spectrum of these particular pulses.

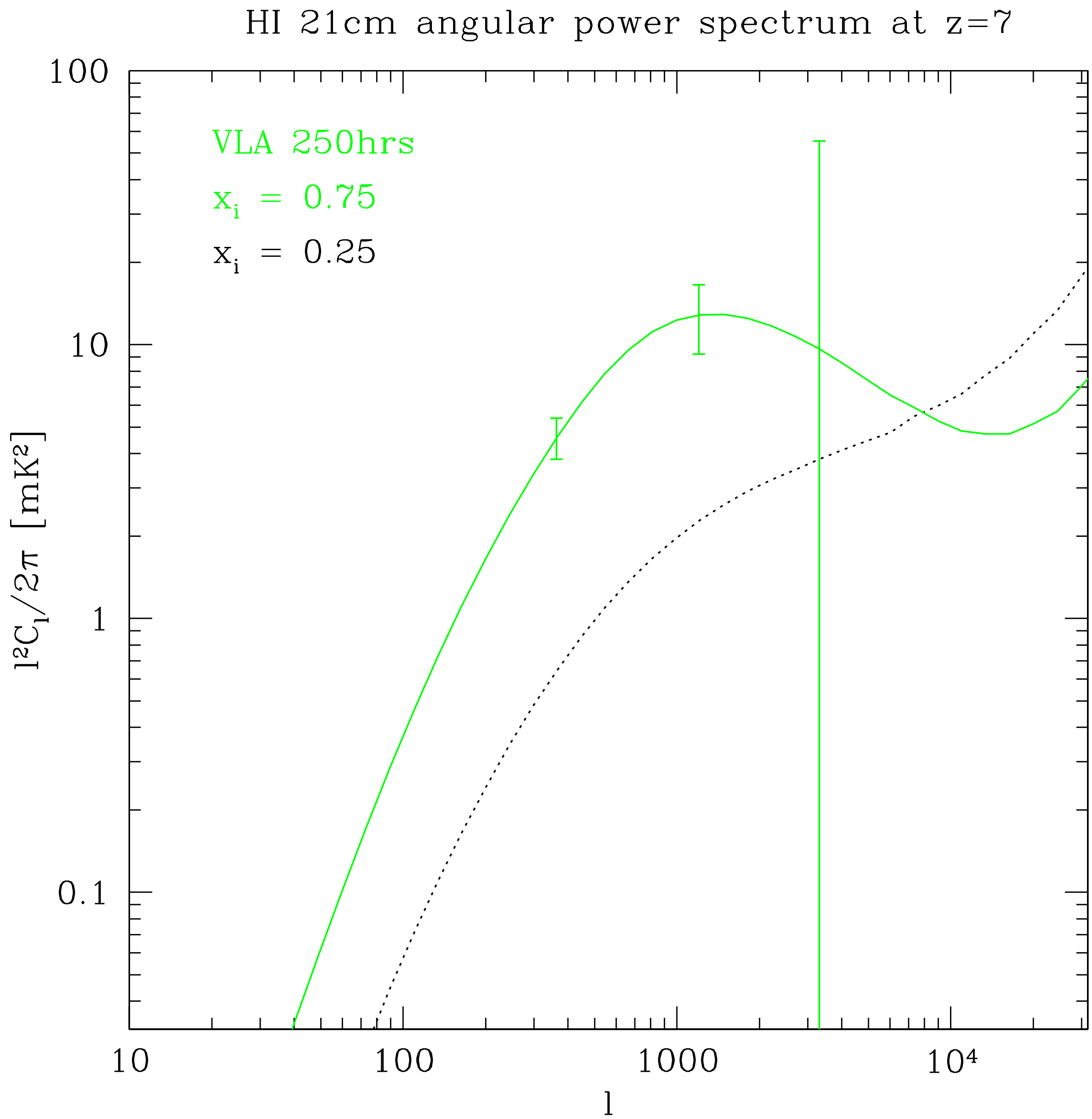

Fig. 11.— The angular power spectrum of HI brightness fluctuations at $z = 7$, plus VLA/EVLA measurement errors in a 0.8 MHz spectral channel averaged over three annuli in (u,v)-space. The solid line shows the expected signal for an ionization fraction of 0.75, while the dotted line shows an ionization fraction of 0.25.

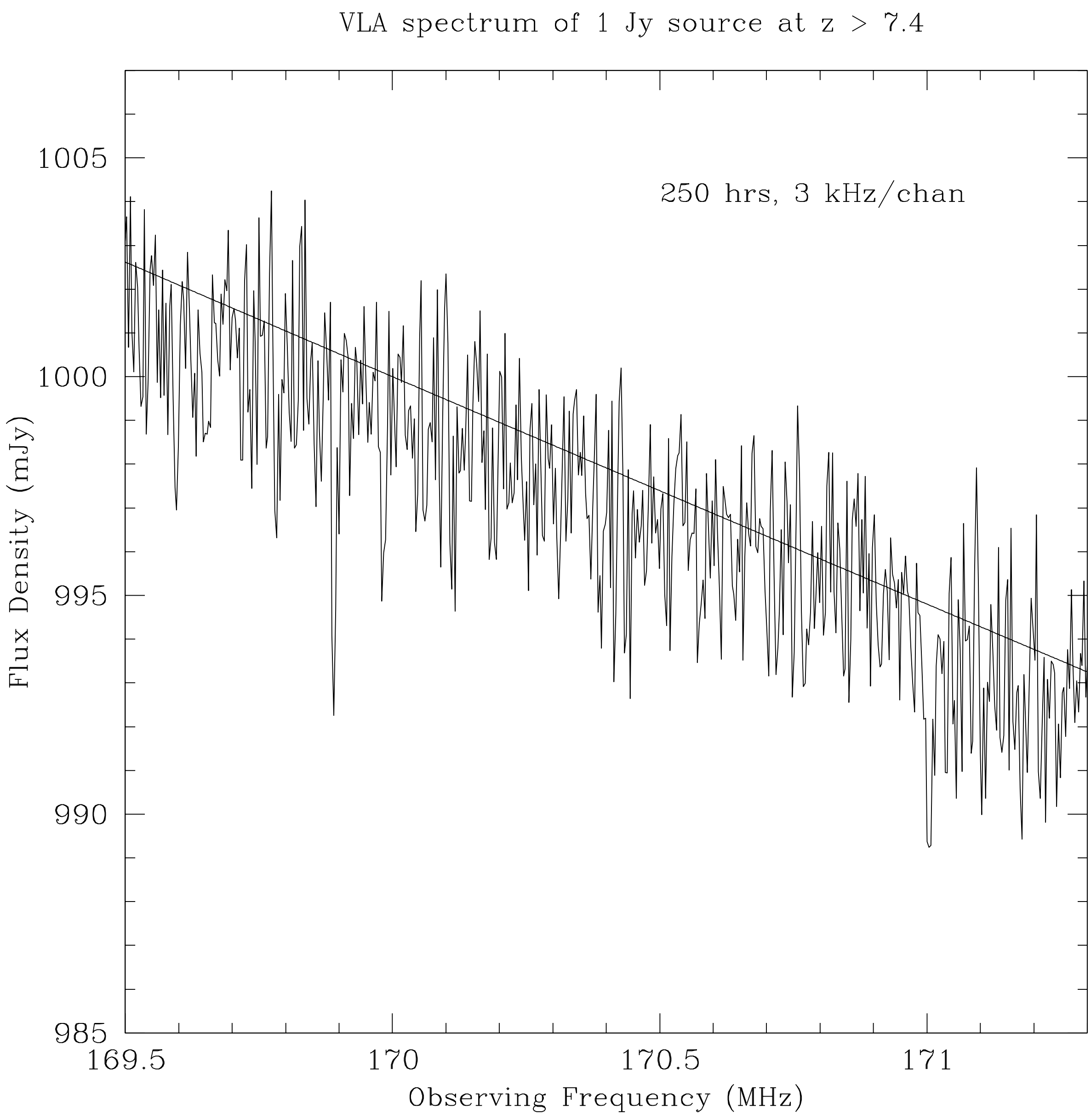

Fig. 12.— A simulated HI absorption spectrum of a $z > 7.4$ radio loud AGN. The solid line is the power-law continuum.

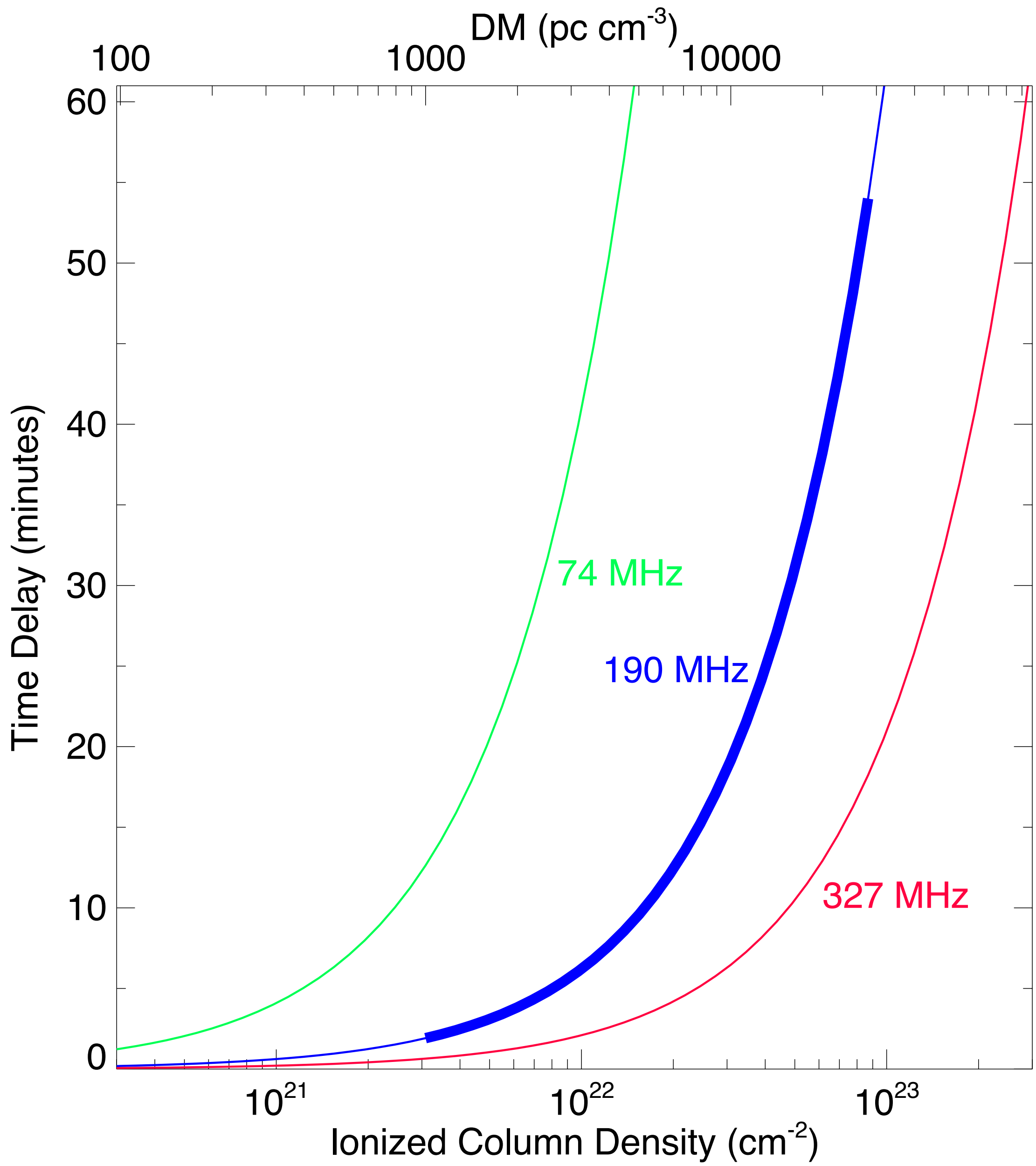

Fig. 13.— The delay in the arrival times of signals which are propagating through ionized gas as a function of the column density (or equivalently the dispersion measure, DM). The delay is a function of frequency so the two existing VLA low frequency bands are plotted, as well as the proposed 190 MHz band. Given the expected range in the ionized column density towards GRBs (thick blue line), the choice of 190 MHz is an ideal frequency for this VLA experiment (see text for more details).