Table 1. Source Parameters

	3C 147	**2352+495**	**3C119**	**0831+557**
Observed	October 22, 1998	October 12, 1998	September 21, 1998	September 11, 19
RA (J2000)	05:42:36.137881	23:55:09.45816	04:32:36.5030	08:34:54.9040
Dec (J2000)	$49°51'07.233596''$	$49°50'08.340230''$	$41°38'28.430''$	$55°34'21.072''$
Galactic longitude	161.69°	113.71°	160.96°	162.23°
Galactic latitude	+10.30°	−12.03°	−4.34°	+36.56
Angular resolution [mas]	10	10	10	20
Redshift	0.545	0.237	1.020	0.2412
$S_{21\mathrm{cm}}$ [Jy]	22.5	2.36	8.60	8.80

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http://arxiv.org/ps/astro-ph/0011460v1

Table 1. 3C 147 HI Optical Depth Spectrum Fit Gaussian Parameters

Component A Spectral Component	Amplitude [Optical Depth]	Column Density* $\times 10^{20}$ [cm^{-2}]	Center Velocity [km s^{-1}]	Velocity Dispersion [km s^{-1}]
1	0.50	2.44	0.42	5.0
	± 0.009	± 0.06	± 0.03	± 0.07
2	0.67	1.02	-8.0	1.6
	± 0.03	± 0.05	± 0.02	± 0.04
3	0.29	1.72	-10.3	6.0
	± 0.01	± 0.09	± 0.09	± 0.1
Component B Spectral Component				
1	0.58	2.71	0.37	4.7
	± 0.02	± 0.14	± 0.05	± 0.13
2	0.68	1.15	-7.9	1.7
	± 0.07	± 0.14	± 0.03	± 0.1
3	0.33	1.93	-10.2	6.0
	± 0.03	± 0.2	± 0.2	± 0.3
Component C Spectral Component				
1	0.54	2.66	0.49	5.1
	± 0.01	± 0.085	± 0.04	± 0.09
2	0.69	1.12	-8.0	1.7

Table 1—Continued

Component A Spectral Component	Amplitude [Optical Depth]	Column Density* $\times 10^{20}$ [cm^{-2}]	Center Velocity [km s^{-1}]	Velocity Dispersion [km s^{-1}]
	± 0.04	± 0.08	± 0.02	± 0.05
3	0.32	1.95	-10.4	6.2
	± 0.02	± 0.2	± 0.2	± 0.2

*Assuming $T_{spin} = 50$K

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Table 1. 3C 119 HI Optical Depth Spectrum Fit Gaussian Parameters

Component B Spectral Component	Amplitude [Optical Depth]	Column Density* $\times 10^{20}$ [cm^{-2}]	Center Velocity [km s^{-1}]	Velocity Dispersion [km s^{-1}]
1	0.54	3.08	2.5	5.9
	± 0.01	± 0.07	± 0.03	± 0.07
2	0.48	1.18	-5.0	2.5
	± 0.04	± 0.1	± 0.04	± 0.1
3	0.35	1.71	-8.8	5.1
	± 0.03	± 0.2	± 0.1	± 0.3
4	0.35	1.04	-14.9	3.1
	± 0.02	± 0.09	± 0.05	± 0.1
5	0.30	0.80	-19.0	2.6
	± 0.02	± 0.06	± 0.05	± 0.1
6	0.042	0.15	-45.9	3.7
	± 0.01	± 0.06	± 0.3	± 0.8
7	0.093	0.64	-54.1	7.1
	± 0.01	± 0.10	± 0.2	± 0.6
8	0.23	0.66	-62.3	2.9
	± 0.01	± 0.05	± 0.05	± 0.1
Component C Spectral Component				
1	0.51	3.0	2.4	6.0

Table 1—Continued

Component B Spectral Component	Amplitude [Optical Depth]	Column Density* $\times 10^{20}$ [cm^{-2}]	Center Velocity [km s^{-1}]	Velocity Dispersion [km s^{-1}]
	± 0.01	± 0.08	± 0.04	± 0.1
2	0.45	1.14	-5.1	2.6
	± 0.04	± 0.1	± 0.05	± 0.1
3	0.34	1.52	-8.9	4.6
	± 0.03	± 0.2	± 0.1	± 0.3
4	0.35	1.09	-14.9	3.4
	± 0.03	± 0.1	± 0.06	± 0.2
5	0.28	0.73	-18.9	2.7
	± 0.02	± 0.07	± 0.06	± 0.2
6	0.046	0.14	-46.0	3.1
	± 0.02	± 0.06	± 0.3	± 0.7
7	0.093	0.6	-53.9	6.8
	± 0.01	± 0.1	± 0.2	± 0.6
8	0.23	0.64	-62.3	2.9
	± 0.02	± 0.06	± 0.06	± 0.1

*Assuming $T_{spin} = 50$K

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Table 1. 2352+495 HI Optical Depth Spectrum Fit Gaussian Parameters

Component A Spectral Component	Amplitude [Optical Depth]	Column Density* $\times 10^{20}$ [cm^{-2}]	Center Velocity [km s^{-1}]	Velocity Dispersion [km s^{-1}]
1	0.15	0.36	2.9	2.6
	± 0.02	± 0.07	± 0.08	± 0.2
2	0.076	0.47	-1.7	6.3
	± 0.02	± 0.2	± 0.4	± 1.0
3	0.036	0.16	-10.5	4.6
	± 0.01	± 0.06	± 0.4	± 0.9
Component B Spectral Component				
1	0.14	0.23	3.3	1.7
	± 0.06	± 0.1	± 0.1	± 0.4
2	0.098	0.67	-0.14	7.0
	± 0.02	± 0.2	± 0.6	± 1.0
3	0.089	0.13	-9.6	1.5
	± 0.04	± 0.07	± 0.2	± 0.5
Component C Spectral Component				
1	0.14	0.35	3.2	2.5
	± 0.03	± 0.1	± 0.1	± 0.3
2	0.11	0.66	-2.1	6.1

Table 1—Continued

Component A Spectral Component	Amplitude [Optical Depth]	Column Density* $\times 10^{20}$ [cm^{-2}]	Center Velocity [km s^{-1}]	Velocity Dispersion [km s^{-1}]
	± 0.02	± 0.2	± 0.3	± 1.0
3	0.059	0.27	-10.3	4.8
	± 0.02	± 0.1	± 0.4	± 1.1

*Assuming $T_{spin} = 50$K

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The Structure of the Cold Neutral ISM on 10-100 Astronomical Unit Scales

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ABSTRACT

We have used the Very Long Baseline Array (VLBA) and the Very Large Array (VLA) to image Galactic neutral hydrogen in absorption towards four compact extragalactic radio sources with 10 milliarcsecond resolution. Previous VLBA data by Faison et al (1998) have shown the existence of prominent structures in the direction of the extragalactic source 3C 138 with scale sizes of 10-20 AU with changes in HI optical depth in excess of 0.8 ± 0.1. In this paper we confirm the small scale H I optical depth variations toward 3C 147 suggested earlier at a level up to 20 % $\pm$ 5% . The sources 3C 119, 2352+495 and 0831+557 show no significant change in H I optical depth across the sources with one sigma limits of 30%, 50%, and 100%. Of the seven sources recently investigated with the VLBA and VLA , only 3C 138 and 3C 147 show statistically significant variations in HI opacities.

Deshpande (2000) have attempted to explain the observed small-scale structure as an extension of the observed power spectrum of structure on parsec size scales. The predictions of Deshpande (2000) are consistent with the VLBA H I data observed in the directions of a number of sources, including 3C 147, but are not consistent with our previous observations of the H I opacity structure toward 3C 138.

Subject headings: ISM: structure — ISM:HI — techniques: interferometric

1. Introduction

Structure in the interstellar medium (ISM) is observed on many different size scales, from large kiloparsec scale superbubbles (Dewdney and Lozinskaya 1994) to electron density fluctuations in the ionized neutral medium only a few hundred kilometers in size (Armstrong, Rickett, and Spangler 1995). Previous studies have attempted to characterize the structure of the neutral component of the ISM by observing neutral hydrogen in emission over a range of angular scales (e.g. Green 1993; Crovisier and Dickey 1983). These studies have been limited by the angular resolution of single dish telescopes and connected-element interferometers to size scales from about 0.1 parsec to several hundred parsecs. The results of these studies suggested that the neutral ISM is smooth on scales smaller than about 0.1 pc. Due to the typically low brightness temperature of H I in emission on small scales, H I 21 cm emission can not be detected at milliarcsecond scales using Very Long Baseline Interferometry (VLBI) techniques. However, it is possible to image Galactic H I in absorption towards bright extragalactic continuum sources, and thereby study the structure of the neutral ISM on angular size scales from the resolution of the VLBI array (about 5 mas at 21 cm for the VLBA) up to the angular size of the continuum source ($\propto$ 50 to 200 mas for the sources in this paper). At typical distances to the absorbing gas of 500 to 1000 pc, these angular scales correspond to tens to hundreds of Astronomical Units.

The first VLBI observations of very small scale structure in the neutral ISM were published by Dieter *et al.* (1976). Observing the source 3C147 with a single baseline from Hat Creek to the Owens Valley Radio Observatory (150 km), they observed variations in the ratio of the H I absorption line visibility amplitude to the 21 cm continuum visibility amplitude as a function of projected baseline. This change is caused by non-uniform coverage of the H I absorption across the face of the source (Radhakrishnan *et al.* 1972). Based on the galactic latitude of the source and a model of the continuum emission components, they inferred that there was structure in the absorbing H I with a physical size of 70 AU. These results, based on modeling of sparse visibility data, were qualitative, but suggested that there is structure on very small scales in the diffuse neutral ISM.

Subsequent VLBI observations of AU scale H I structure were published by Diamond *et al.* (1989). They observed the three extragalactic radio continuum sources 3C 147, 3C 138 and 3C 380 using three large telescopes of the European VLBI Network. The visibility data from the observations were not sufficient to image the sources and the H I absorption distribution. However, the ratio of the line to continuum visibility amplitudes confirmed the non-uniform H I absorption towards 3C 147 observed by Dieter *et al.* (1976). Large variations towards 3C 138 and moderate variations towards 3C 380 were discovered. Diamond *et al.* inferred structure in the H I gas of 25 AU with densities of $5 - 10 \times 10^4$ cm^{-2}, assuming that the line of sight dimension is equal to the measured transverse dimension. These conclusions were based on modeling the visibility data rather than directly imaging the H I optical depth structure.

Confirmation of AU scale structure in Galactic H I independent of the VLBI data was published by Frail *et al.* (1994). They observed average variations in the total H I column density of 10-15% towards nine pulsars at three observing epochs over a period of 1.7 years. Each pulsar in the Frail *et al.* study probed a range of physical size scales transverse to the line of sight from 5 to 100 AU. The fact that column density variations over time were observed towards all of the pulsars suggests that AU scale structure is common throughout the ISM. Also, the fact that Frail *et al.* observed changes in the total H I column density but not in the overall line shape suggests that the AU scale structure is kinematicly related to the diffuse cold neutral medium as a whole.

The first images of AU scale H I structure in absorption were published by Davis, Diamond, and Goss (1996) (Henceforth DDG). They used the MERLIN array with five EVN telescopes to image 3C 147 and 3C 138 in H I optical depth at an angular resolution of $50 - 150$ mas. They observed significant optical depth variations in one of the two H I absorption lines towards both objects. The largest optical depth variation of $\Delta\tau_{HI} = 0.16 \pm 0.03$ across the source was observed in the 1.3 km s^{-1} absorption line towards 3C 138. A prominent optical depth change of $\Delta\tau_{HI} = 0.09 \pm 0.01$ was also observed in the -8 km s^{-1} absorption line towards 3C 147.

There is also evidence for AU scale structure in the diffuse molecular gas. Moore and Marscher (1995; as well as Marscher *et al.* 1993) have discussed changes observed in the column density of H_2CO towards the compact objects 3C 111, BL Lac, and NRAO 150. They observed the three sources over 3.4 years with the VLA in the 6 cm H_2CO line. The motion of the sources due to parallax as well as the proper motions of the absorbing gas caused the relative line of sight through the molecular gas to the extragalactic sources to change with time. They observed significant variations in the H_2CO opacities towards 3C 111 and NRAO 150, and inferred structure on linear scales $\sim$ 10 AU and H_2 densities $\sim 10^6$ cm^{-3}, sizes and densities similar to those observed for the small scale H I structure.

Heiles (1997) has proposed a geometrical model to explain the large variations in column density. The geometrical model assumes that the structures are due to filaments or sheets observed edge-on, causing larger variations in column densities over smaller scales to be observed and implying much higher volume densities than are actually present. If the observed structure arises from edge-on sheets, the optical depth images should statistically show smaller-scale variations along the axis perpendicular to the sheet compared to variations along the axis parallel with the sheet.

Faison, Goss, Diamond, and Taylor (1998), hereafter FGDT, published high angular resolution (10-20 mas) VLBA images of H I absorption towards 3C 138, 2255+416, and 0404+768. Pronounced H I optical depth variations were confirmed towards 3C 138, consistent with Diamond *et al.* (1989) and DDG. Moderate H I variations were observed towards the small angular size source 2255+417, and no significant variations were observed towards 0404+768, suggesting a minimum size of the H I structure of a few tens of AU.

Deshpande, Dwarakanath, and Goss (2000) have evaluated the structure observed in H I absorption towards Cas A over a linear scale of 4pc to 0.02 pc. Deshpande (2000) has taken the slope of the power spectrum of fluctuations of $\alpha = -2.75$ and extrapolated to scales smaller by factors of three orders of magnitude (sizes scales smaller than 100 AU) and predicts that optical depth variations as large as 0.1 should be expected on scales of tens of AU. The cause of these fluctuations is due to gradients in the distribution caused by the "red" spectrum (larger scales have more power) of the power spectrum of the HI. The fluctuations observed by the VLBA in the direction of 3C 138 are almost an order of magnitude larger than this prediction. In addition, two dimensional HI features are observed.

In this paper we present H I optical depth images towards 3C 147, 3C 119, 2352+495, and 0831+557, and we discuss our current knowledge of AU scale structure in the diffuse neutral ISM.

2. Observations and Data Reduction

FGDT discuss the criteria for selecting sources for imaging in H I absorption with the VLBA. The continuum source must be bright enough at 21 cm to be imaged with acceptable signal-to-noise at sufficient angular and velocity resolution (continuum flux density greater than about 100 mJy beam^{-1} at 5-10 mas resolution). The source must have significant milliarcsecond structure that can be resolved by the VLBA at 21 cm. The source must have significant Galactic H I absorption but not be optically thick ($0.1 < \tau_{HI} < 2.0$). The angular resolution of the VLBA at 21 cm is approximately 5 milliarcseconds (mas). To improve the signal-to-noise ratio in the optical depth cube, we have smoothed the images to 10 mas angular resolution. The source 3C 147 was selected based on previous observations of H I small scale structure. The source 3C 119 was selected as a good candidate for probing small scale H I based on the H I absorption spectrum towards the source published by Mebold *et al.* (1981) and the VLBI continuum images published by Nan *et al.* (1991). The two sources 0831+557 and 2352+495 were selected from the Caltech-Jodrell Bank survey (Polatidis *et al.* 1995) based on the VLBI angular structure and the low Galactic latitude of the sources.

The basic data reduction procedure is described in FGDT. Each source was observed with all of the ten VLBA stations and the phased VLA (as an additional VLBI station) for 12 hours. The data were correlated at the VLBA correlator in Socorro, New Mexico. Four separate IFs were used, with one IF centered on the absorption lines and three IFs separated by at least 100 km s^{-1} in velocity to sample the 21 cm continuum emission. For all of these observations the data were correlated with velocity channels of 0.4 km s^{-1}, and for most of the objects a 500 kHz bandwidth per IF was used with 256 spectral channels per IF. For the observations of 3C 119 a bandwidth of 1 MHz per IF was used with 512 spectral channels per IF to accommodate the larger velocity range (100 km s^{-1}) of H I absorption components.

All data processing for each object was done using the AIPS (Astronomical Image Processing System) package available from NRAO. The data were amplitude calibrated and fringe fitted using standard techniques in AIPS. Once the data were amplitude and bandpass calibrated, the three continuum IFs were averaged together, self-calibrated, and imaged using the AIPS task IMAGR. The self-calibration phase and amplitude solutions from these continuum images were then applied to the line IF, which was then imaged to produce a total intensity cube as a function of RA, Dec, and LSR velocity. The velocity channels in this intensity cube that did not show H I absorption were then averaged together to produce a continuum image. This image was used with the intensity cube to produce an H I optical depth cube as a function of RA, Dec, and LSR velocity. The optical depth cube is calculated as $\tau_{HI}(RA, Dec, V) = -\ln[I_{line}(RA, Dec, V)/I_{continuum}(RA, Dec)]$.

Because the signal-to-noise ratio in the optical depth images is poor where the continuum emission is weak, the optical depth images were blanked where the continuum emission was less than 10% of the peak emission. This optical depth cube with dimensions of RA, Dec, and velocity is the final reduced data for each object.

3. Results

3.1. 3C 147

The continuum image of 3C 147 is shown in Figure 1. This image was convolved to a resolution of 10 mas. The source is a quasar with a redshift of 0.545 and a total 21 cm flux density of 22.5 Jy. The continuum structure consists of a core component with a broad jet extended to the SW. Figure 2 shows an H I optical depth spectrum averaged over the entire source. Kalberla, Schwarz, and Goss (1985) deconvolved the H I optical depth spectrum towards 3C 147 into five Gaussian components. In this paper we will only consider the three components at 0.4, -8.3, and -10.3 km s^{-1}. Figures 3 and 4 show H I optical depth images towards 3C 147 at 0.4 and -8.3 km s^{-1}, respectively. The greyscale indicates H I optical depth from 0 to 1.5 and the contours indicate the low-level continuum emission. Figure 5 shows the 21 cm continuum image with H I optical depth spectra averaged over a beam size of 10 mas towards the three areas of brightest emission (components A, B, and C in Figure 1). The dashed line in these plots indicates the averaged spectrum, and the solid line indicates the Gaussian fit produced using the iterative fitting task PROFIT, using the Groningen Image Processing System (GIPSY) package . The parameters of these Gaussian profile fits are given in Table 2.

In the optical depth image at -8.3 km s^{-1} (Figure 4), there is a increase in optical depth from 0.82 to 1.1(1σ is 0.05) between the bright NE component to the SW component

190 mas away, consistent with that found by DDG. They observed H I optical depth variations in the -8.3 km s^{-1} absorption line towards 3C 147, but not in the 0.4 km s^{-1} absorption feature.

In the 0.4 km s^{-1} optical depth image (Figure 3), there is a slight change in optical depth between the two brightest components. The largest optical depth change at this velocity is from $\tau = 0.5 \pm 0.1$ to 0.7 ± 0.1 between the bright NE component and the component midway along the axis of the source. These are small angular scale optical depth variations that would not have been resolved at the 150 mas angular resolution of the MERLIN images published by DDG.

A problem with determining the physical size of this structure is the uncertain determination of the distance to the absorbing H I gas. Davis, Diamond, and Goss (1996) placed a simple geometrical upper limit on the distance to the H I cloud based on the Galactic latitude of the source with $b = +10.3°$. Assuming that the cold H I is confined to 100 pc of the plane, an intervening H I cloud along this line of sight must be within 600 pc of the sun. At a Galactic longitude of $l = 162°$, a kinematic distance to the -8.3 km s^{-1} component is uncertain; however, an estimate using the rotation curve of Fich, Blitz, and Stark (1989) for the distance to the -8.3 km s^{-1} is 1.1 kpc. The angular separation between components A and C of 190 mas corresponds to a physical scale of 200 AU at a distance of 1 kpc and 100 AU at 600 pc. The angular separation between components A and B of 83 mas corresponds to 90 AU at 1 kpc and 50 AU at 600 pc. These distances are quite uncertain, and so it is reasonable to approximate the distance to the -8.3 km s^{-1} gas at 1kpc and the distance to the low velocity gas at 500 pc.

As with the observations described by FGDT, the circular polarization ($V = RCP - LCP$) was imaged for each source in addition to the total intensity cube. The circular polarization cube can be fit for the Zeeman splitting due to a line of sight magnetic field. We fit the circular polarization spectrum of these sources using the tasks ZEESTAT and ZEESIM in the MIRIAD data analysis package described by Sault *et al.* (1995). These tasks average the I and V spectra over the entire source and estimate the leakage of the I spectrum in the V spectrum using an iterative fitting procedure. The strength of the field can be calculated from the V and I spectra as $B_{||} = \frac{2\,V}{a\,dI/d\nu}$, where $a = 2.8$ Hz μGauss^{-1}. For 3C 147, the fit gives a 2σ upper limit on the absolute line of sight magnetic field averaged over the entire source of 32 μGauss.

3.2. 3C 119

3C 119 is a compact symmetric object with a redshift of 0.408 (Nan *et al.* 1999)and total flux density of 8.6 Jy. Previous observations of the Galactic H I absorption spectrum towards 3C 119 by Mebold *et al.* (1981) indicated significant H I absorption along the line of sight. The 21 cm continuum image is shown in Figure 6, convolved to 10 mas angular resolution. Only three bright continuum components are observed in the image, labeled “A”, “B”, and “C” in Figure 6.

The source 3C 119 has the lowest galactic latitude ($b = -4.3°$) of of the seven sources in the Galactic H I sample. The source has a complex H I absorption spectrum with Galactic H I absorption over a velocity range from +10 to -63 km s^{-1}. The H I optical depth spectrum towards 3C 119 is shown in Figure 7. Two typical optical depth images for 3C 119 are shown in Figures 8 and 9 for LSR velocities of -4.7 km s^{-1} and -62.6 km s^{-1}, respectively. The inset plots show crosscuts from south to north in optical depth through the centers of the two brightest components “C” and “B”. The optical depth images at most velocities show no H I optical depth variations between the two components B and C ; the 1σ upper limit to any change in the opacity is $\Delta\tau \approx 0.2$.

Figure 10 shows the 21 cm continuum image with optical depth spectra towards continuum components B and C, averaged over a beam size of 10 mas. The angular separation of these components is about 53 mas. These two average spectra were fit with eight Gaussian profiles using PROFIT in the GIPSY data reduction package. The parameters of these two sets of fits are given in Table 3. As with Figure 5 for 3C 147, the dashed lines indicate the data and the solid lines indicate the fits. There is no significant difference in any of the profile fits between the continuum emission components B and C with a 1σ upper limit of about 10% in column density variation.

The source 3C 119 is at a Galactic longitude of $l = 161°$, and a kinematic distance to the H I absorption components can not be reliably determined this close to the Galactic anti-center. A geometric upper limit on the distance to the H I absorption given the galactic latitude of the source ($b = -4.3°$) is 1.3 kpc, again assuming that the H I layer is within 100 pc from the plane. At that distance, the angular resolution in the optical depth images corresponds to a physical size of 13 AU, and the 53 mas separation between components B and C corresponds to 70 AU. The low velocity absorption components are likely due to local gas (closer than 500 pc), and the H I gas at high negative velocity is probably in the Perseus arm at a distance greater than 2 kpc. At that distance, the 10 mas beam in the H I optical images corresponds to 20 AU, and the separation of 53 mas between components B and C corresponds to 100 AU.

As with 3C 147, we fit the circular polarization spectrum towards 3C 119 to determine the line of sight magnetic field. A fit to the overall V and I spectra averaged over the entire source produces a 2σ upper limit on the line of sight magnetic field of 20 μGauss.

3.3. 2352+495

The source 2352+416 is a compact symmetric object selected from the Polatidis *et al.* (1995) VLBI survey. There are no published previous observations of H I absorption towards this source , a radio galaxy with a redshift of 0.237, and a total 21 cm continuum flux density of 2.36 Jy. The morphology of the source is a bright core with two symmetric lobes. The VLBA 21 cm continuum image of 2352+495 is shown in Figure 11, with the three bright continuum components from north to south labeled "A", "B", and "C". The angular resolution is 10 mas.

The H I optical depth spectrum towards 2352+495 is shown in Figure 12. The maximum H I optical depth is 0.25 and occurs at a velocity of 3.3 km s^{-1} with a line width of 2.0 km s^{-1}. The H I absorption line is asymmetrical and consists of several narrow components, with the strongest line at 0 km s^{-1}. Figure 13 shows the optical depth image at the velocity of the maximum H I optical depth at v=0 km s^{-1}.

Figure 14 shows the continuum image with average H I optical depth spectra towards the three bright emission components. As with Figures 5 and 10, the dashed lines indicate the VLBA data and the solid lines indicate the Gaussian profile fits. The parameters of these Gaussian profile fits are given in Table 4. Three Gaussian profiles were fit to the spectra; however, spectral components 2 and 3 (indicated in Figure 12) are considerably noisier than spectral component 1, and the Gaussian profile fits for those components are not well-determined. These data are consistent with uniform H I absorption across the source with no changes in H I column density exceeding 30% (1σ).

The source 2352+495 is located $l = 113°$ and $b = -12.0°$. The two spectral components near 0 km s^{-1} are assumed to be local gas. Assuming that the thickness of the local H I disk is less than 100 pc, H I gas along a line of sight at this Galactic latitude must lie closer than 500 pc. The resolution of the H I optical depth images of 10 mas corresponds to a linear size of 5 AU, and the separation of 50 mas between continuum components A and C corresponds to 25 AU. Assuming the rotation curve of Fich, Blitz, and Stark (1989), the kinematic distance to the -10 km s^{-1} absorption line is 800 pc. At this distance, the 10 mas beam corresponds to a linear size of 8 AU, and the 50 mas separation between the components A and C corresponds to 40 AU.

Fits to the V and I spectra averaged over the entire source produce a 2σ upper limit on the line of sight magnetic field of 160 μGauss.

3.4. 0831+557

The source 0831+557 was also selected from the VLBI survey of Polatidis *et al.* (1995). There are no published previous observations of H I absorption towards this source. This source has a total 21 cm continuum flux density of 8 Jy. It has the highest Galactic latitude of any of the sources in the sample with $b = 34.6°$. It has very weak H I absorption in two velocity components, at 3 km s^{-1} with a maximum H I optical depth ≈ 0.1, and a possible weak line near -37 km s^{-1} with a maximum H I optical depth of ≈ 0.03. The 3 km s^{-1} line has a velocity width of 2 km s^{-1}. Figure 15 shows a 21 cm continuum image of 0831+557, convolved to an angular resolution of 20 mas. There are two strong continuum components separated by about 180 mas, labeled “A” and “B” in Figure 15. Component A is significantly brighter, with a peak continuum emission of 2.9 Jy beam^{-1}, compared to 0.4 Jy beam^{-1} peak emission for Component B.

Figure 17 shows an optical depth image towards 0831+557 at 3.9 km s^{-1}. The greyscale indicates H I optical depth from 0 to 0.2, and the contours represent weak continuum emission. The image was convolved to 20 mas to improve the signal-to-noise ratio. The inset plot shows a cross cut in optical depth along the dashed line. No significant variations in optical depth are observed between the two continuum components with a 1σ limit in any variation of $\Delta\tau \approx 0.1$.

At a galactic latitude of $b = +36.6°$, a geometric upper limit to the absorbing gas is $\propto$ 200 pc, assuming the thickness of the cold H I gas is 100 pc. At that distance, the angular separation of 160 mas between components A and B corresponds to a physical distance of 30 AU.

4. Structure Functions of the H I optical depth images

Deshpande (2000) has pointed out that the optical depth variations observed between two points on the sky represent contributions in optical depth variations on all scales, including larger scales. The optical depth difference between two points on the sky do not arise entirely from structures with this scale size. Due to the shape of the power spectrum (a "red" spectrum with enhanced fluctuations at larger scales), variations from larger structures contribute to the variations at an observed scale. This effect complicates the interpretation of the optical depth images as representing unique structure on tens of AU scales. A proper interpretation of the actual physical scale of the structure requires knowledge of the power spectrum over larger scales. Deshpande, Dwarakanath, and Goss (2000) have found that the power spectrum of H I optical depth variations towards Cas A (Perseus arm feature) and the Outer Arm towards Cyg A can be fit with a power law index of -2.75 over physical scales from 0.02 pc to 4 pc. The Local Arm in the direction of Cyg A, the slope is shallower at -2.5. The power spectra of both Cyg A features are, however, an order of magnitude less intense than the Cas A Perseus Arm feature. Deshpande (2000) suggests that this power law power spectrum with a steeper index of -2.75 can be extrapolated to size scales of $40--100$ AU, a factor of almost 40 relative to the smallest scale in the measured Cas A power spectrum. Thus optical depth variations would be expected with root-mean-square values of about 0.1. This effect is shown in Figure 2 from Deshpande (2000), based on the -2.75 index for the Cas A Perseus arm data. Most of the objects in this paper and FGDT show H I optical changes which are consistent with this level of variation. However, 3C 138 shows changes in excess of this prediction. For 3C 138 the changes in opacity are in the range 0.6−0.8 over a size scale of 50 mas (25 AU at a distance of 500 pc).

Deshpande (2000) also suggests that structures observed on small scales should only be observed as gradients in optical depth, since the changes on AU scales are only due to larger scale variations. Our H I optical images toward 3C 147 and 3C 138 clearly show discrete H I structures, not simply gradients. Especially convincing is the elongated two dimensional structure in the NE part of the image where the continuum emission of 3C 138 is very strong, and therefore the H I optical depth is well determined. This part of the H I optical depth image at 0.4 km s^{-1} from FGDT is reproduced in Figure 18. These stuctures clearly are ınot simply gradients in optical depth.

5. Discussion and Conclusions

The optical depth variations towards 3C 147 are shown in the position-velocity plot for 3C 147, shown in Figure 19. The vertical axis of this position-velocity corresponds to the axis along the source from the NW to the SE as indicated in Figures 3 and 4. As can be noticed in the individual optical depth images, the optical depth variations along the axis of the source are larger in H I absorption line near −8.3 than in the line near 0.4 km s^{-1}. The fluctuations in the opacity in Figure 19 far away from the absorption lines are a good indication of the noise in the optical depth at a given position along the axis of the source. This position-velocity plot can be compared with the position-velocity plot for 3C 138 from FGDT. Although there are obvious optical depth variations in each absorption line towards

3C 147, the striking optical depth structure changes in velocity observed towards 3C 138 are not observed in the 3C 147 position-velocity image. In the 3C 138 position-velocity plot, the velocity features that slope diagonally across are quite striking and indicate that we are observing real, three dimensional features coherent in velocity.

The constraints on the line of sight magnetic field towards these sources suggest that the magnetic field towards these sources is not enhanced relative to the average interstellar magnetic field of $40 - 100$ μGauss. Diamond *et al.* (1989) determined that field strengths of 200 μGauss would be required to confine the small scale structure observed towards 3C 138 relative to the pressure of the diffuse ISM. The upper limits on the line of sight magnetic field towards 3C 147 and 3C 138 are an order of magnitude below this value.

In conclusion, we have imaged Galactic H I in absorption towards four extragalactic continuum objects at 10 milliarcsecond resolution. The -8.3 km s^{-1} H I absorption line towards the source 3C 147 shows variations of 10 to 20 % in H I column density across the source (1σ error of 5%), and variations in optical depth from about 0.82 to 1.1 (at about a 4σ level). No significant variations H I optical depth are observed across the source 3C 119 to within a 1σ error of 0.2 in optical depth and a 10% change in H I column density. The source 2352+495 shows no significant H I column density variations in column density to within a 1σ limit of 30%. The high Galactic latitude source 0831+557 has weak H I absorption and shows no significant column density variations to within a 1σ limit of 50%.

All of these results are consistent with the prediction of Deshpande (2000) that optical depth variations as large as $\delta\tau \approx 0.1$ on scales of 100's of AU. However, the source 3C 138 is unique among the objects we have observed in showing very large H I optical depth variations of $\Delta\tau \approx 0.1$ on scales of 10's of AU.

It is of considerable interest to probe the cold, neutral medium on intermediate scales between the few tens of AU probed by VLBI observations and the 0.1 pc scales probed by connected-element interferometers such as the WSRT and the VLA. The only observations published to date on these angular scales between the resolution of the VLBA at about $10 - 500$ mas and the VLA at about $1 - 30''$ are observations of ISM optical lines towards binary stars (e.g., Lauroesch *et al.* 1999; Watson and Meyer 1996) separated by 500 to 30,000 AU. However, most of these observations are of variations in Na I column density, which may not reliably trace the H I column density. Observations of H I column density variations should be carried out on these size scales to compare the AU scale structure with the larger scale structure. These observations could be carried out with the MERLIN array and also by observing H I column density variations towards pulsars as done by Frail *et al.* (1994). The Green Bank Telescope will be an especially sensitive instrument for observing H I in absorption towards pulsars. Also, more pulsar and VLBI studies of AU scale structure should be carried out in the southern hemisphere, outside the field view of the VLBA. To date no observations of AU scale structure in H I have been made from $l = 187°$ to $l = 20°$.

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Fig. 1.— Continuum image of 3C 147 at 21 cm obtained with the VLBA and phased VLA. The beam has been convolved to an angular size of 10 milliarcseconds from an original resolution of 5×4 mas. The contours correspond to the continuum emission at 23.1, 46.2, 115, 231, 462, 694, 924, and 1160 mJy beam^{-1}.

Fig. 2.— H I optical depth spectrum towards 3C 147 averaged over the entire source using the VLBA and phased VLA. The velocity resolution is 0.4 km s^{-1}.

Fig. 3.— H I optical depth image towards 3C 147 in a single 0.4 km s^{-1} velocity channel at 0.4 km s^{-1} LSR velocity. The angular resolution is 10 mas. The greyscale represents H I optical depth from 0 to 1.0, and the contours represent 21 cm continuum emission at 23.1, 46.2, 116 mJy beam^{-1}. The optical depth image has been blanked where the continuum emission is weak (where the error in the optical depth is greater than 0.1). The inset plot shows a cross cut in optical depth with 2 σ errorbars along the axis indicated by the dashed line.

Fig. 4.— H I optical depth image towards 3C 147 in a single 0.4 km s^{-1} velocity channel at -8.3 km s^{-1} (LSR). The angular resolution is 10 mas. The greyscale represents H I optical depth from 0 to 1.3, and the contours represent 21 cm continuum emission at 23.1, 46.2, 116 mJy beam^{-1}. The optical depth image has been blanked where the continuum emission is weak (where the error in the optical depth is greater than 0.1). The inset plot shows a cross cut with 2 σ errorbars in optical depth along the axis indicated by the dashed line.

Fig. 5.— Continuum image of 3C 147 with inset plots showing optical depth spectra averaged over the areas of brightest continuum emission. The dashed line in the inset plots shows the VLBA data, and the solid line indicates the Gaussian component fits. The parameters of the fits are given in Table 2.

Fig. 6.— Continuum image of 3C 119 at 21 cm from the VLBA and phased VLA. The beam has been convolved to an angular size of 10 mas. The contours represent continuum emission at 169, 337, 674, 1010, 1350, and 1690 mJy beam^{-1}.

Fig. 7.— H I optical depth spectrum towards 3C119, averaged over the source. The velocity resolution is 0.4 km s^{-1}. The numbered velocity components are referred to in Table 3.

Fig. 8.— H I optical depth image towards 3C 119 in a single 0.4 km s^{-1} velocity channel centered at -4.7 km s^{-1} (LSR). The greyscale represents H I optical depth from 0.35 to 0.85, and the contours represent continuum emission at 112, 374, and 748 mJy beam^{-1}. The angular resolution is 10 mas. The inset plot shows a cross cut with 2 σ errorbars in optical depth along the axis indicated by the dashed line.

Fig. 9.— H I optical depth image towards 3C 119 in a single 0.4 km s^{-1} wide velocity channel centered at -62.6 km s^{-1} LSR velocity. The greyscale represents H I optical depth from 0.1 to 0.4, and the contours represent continuum emission at 112, 374, and 748 mJy beam^{-1}. The resolution of the beam is 10 mas. The inset plot shows a cross cut with 2 σ errorbars in optical depth along the axis indicated by the dashed line.

Fig. 10.— Continuum image of 3C 119 with inset plots showing optical depth spectra averaged over the areas of brightest continuum emission. The dashed line in the inset plots shows the VLBA data, and the solid line indicates the Gaussian component fits. The parameters of the fits are given in Table 3.

Fig. 11.— Continuum image of 2352+495 at 21 cm from the VLBA and the phased VLA. The beam has been convolved to 10 mas. The contours correspond to continuum emission at 91, 182, 273, 364, 455, 547, 638, 729, and 820 mJy beam^{-1}.

Fig. 12.— H I optical depth spectrum towards 2352+495, averaged over the source. The

velocity resolution is 0.4 km s^{-1} per channel.

Fig. 13.— H I optical depth image towards 2352+495 in a single 0.4 km s^{-1} velocity channel centered at 3.3 km s^{-1} (LSR). The resolution of the beam is 10 mas. The greyscale corresponds to H I optical depth from 0.1 to 0.3, and the contours represent continuum emission at 18, 46, and 91 mJy beam^{-1}. The inset plot shows a cross cut with 2 σ errorbars in optical depth along the axis indicated by the dashed line.

Fig. 14.— Continuum image of 2352+495 with inset plots showing optical depth spectra averaged over the areas of brightest continuum emission. The dashed line in the inset plots shows the VLBA data, and the solid line indicates the Gaussian component fits. The parameters of the fits are given in Table 4.

Fig. 15.— Continuum image of 0831+557 at 21 cm from the VLBA and the phased VLA. The beam has been convolved to 20 mas. The contours correspond to continuum emission at -29.2, 29.2, 58.3, 146, 292, 583, and 1460 mJy beam^{-1}.

Fig. 16.— H I optical depth spectrum towards 0831+557 observed with the VLA. The velocity resolution is 1.3 km s^{-1}.

Fig. 17.— H I optical depth image towards 0831+557 in a single 0.4 km s^{-1} velocity channel centered at 3.9 km s^{-1} (LSR). The greyscale represents H I optical depth from 0.0 to 0.2, and the contours represent continuum emission at 29.2, 58.3, and 292 mJy beam^{-1}. The angular resolution is 20 mas. The inset plot shows a cross cut with 2 σ errorbars in optical depth along the axis indicated by the dashed line.

Fig. 18.— A section of the H I optical depth image at 0.9 km s^{-1} of 3C 138, taken from FGDT. Two cross sections in optical depth are shown with 2σ errors.

Fig. 19.— Position-velocity plot for 3C 147 along the axis of the source indicated by the dashed line in Figures 3 and 4. The horizontal axis indicates LSR velocity, and the vertical axis indicates angular distance from the upper NW corner of the source. The greyscale indicates H I optical depth from 0.0 to 1.0. Variation in optical depth can be observed as a change in the greyscale along a vertical line in this plot. More prominent variations in optical depth are observed along the source axis at the -8.3 km s^{-1} line than at the 0.4 km s^{-1} line .