SPECTRAL POLARIZATION OF THE REDSHIFTED 21 cm ABSORPTION LINE TOWARD 3C 286

ARTHUR M. WOLFE1, REGINA A. JORGENSON2, TIMOTHY ROBISHAW3, CARL HEILES4, AND J. XAVIER PROCHASKA5

1 Department of Physics, and Center for Astrophysics and Space Sciences, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0424, USA; awolfe@ucsd.edu
2 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK; raj@ast.cam.ac.uk
3 Sydney Institute for Astronomy, The University of Sydney, NSW 2006, Australia; tim.robishaw@sydney.edu.au
4 Department of Astronomy, University of California, Berkeley, CA 95064, USA; heiles@astro.berkeley.edu
5 Department of Astronomy & Astrophysics, UCO/Lick Observatory, 1156 High Street, University of California, Santa Cruz, CA 95064, USA; xavier@ucolick.org

ABSTRACT

A reanalysis of the Stokes-parameter spectra obtained of the $z = 0.692$ 21 cm absorption line toward 3C 286 shows that our original claimed detection of Zeeman splitting by a line-of-sight magnetic field, $B_{\text{los}} = 87 \mu$G, is incorrect. Because of an insidious software error, what we reported as Stokes V is actually Stokes U; the revised Stokes V spectrum indicates a 3$\sigma$ upper limit of $B_{\text{los}} < 17 \mu$G. The correct analysis reveals an absorption feature in fractional polarization that is offset in velocity from the Stokes I spectrum by $-1.9 \text{ km s}^{-1}$. The polarization position-angle spectrum shows a dip that is also significantly offset from the Stokes I feature, but at a velocity that differs slightly from the absorption feature in fractional polarization. We model the absorption feature with three velocity components against the core–jet structure of 3C 286. Our $\chi^2$ minimization fitting results in components with differing (1) ratios of H$\alpha$ column density to spin temperature, (2) velocity centroids, and (3) velocity dispersions. The change in polarization position angle with frequency implies incomplete coverage of the background jet source by the absorber. It also implies a spatial variation of the polarization position angle across the jet source, which is observed at frequencies higher than the 839.4 MHz absorption frequency. The multi-component structure of the gas is best understood in terms of components with spatial scales of $\sim 100$ pc comprised of hundreds of low-temperature ($T \lesssim 200$ K) clouds with linear dimensions of $\lesssim 100$ pc. We conclude that previous attempts to model the foreground gas with a single uniform cloud are incorrect.

Key words: cosmology: observations – galaxies: high-redshift – galaxies: ISM – ISM: magnetic fields – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

In order to detect magnetic fields in galaxies with significant redshifts, we began a search for Zeeman splitting of 21 cm absorption lines arising in damped Ly$\alpha$ systems (DLAs) toward background quasars (Wolfe et al. 2005) selected to be radio bright. The detection of Zeeman splitting yields the strength, direction, and redshift of the magnetic field, which is an advantage over measurements of Faraday rotation, which yield rotation measures accompanied by huge uncertainties in the strength and redshift of the $B$ fields along the sightlines to background quasars (Kronberg et al. 2008). In Wolfe et al. (2008), we reported the detection of Zeeman splitting in the $z = 0.692$ DLA toward 3C 286. The purpose of this paper is to show that the reported detection was erroneous. In Section 2, we describe the errors that led to the claimed detection and describe our new data reduction procedures. In Section 3, we correct the previous errors and give a correct description of the polarization spectra. The new spectra are shown in Section 4.

In the absence of detectable Zeeman splitting, we can only set an upper limit to the magnetic field in the $z = 0.692$ DLA toward 3C 286. However, in this paper we discuss how the spatial distribution of the strong linear polarization of 3C 286 itself can be used in combination with the observed spectral variation of linear polarization across the absorption profile of the redshifted 21 cm line to infer physical properties of the absorbing H$\alpha$ gas. We demonstrate how comparison between properties of the linearly polarized and unpolarized absorption spectra provides new information about the spatial structure of this gas on scales of $\sim 100$ pc. We use the new data to determine both the kinetic temperature and hyperfine spin temperature of the gas, which in turn tells us about its thermal state. We use these results to evaluate the standard assumption of a large-scale, uniform cloud. We start by constructing models to describe the reanalyzed spectra in terms of multiple clouds distributed across the spatially extended structure of 3C 286. In Section 5.1, we use very long baseline interferometry (VLBI) maps to exhibit the core–jet structure of 3C 286 near the 21 cm absorption frequency. In Section 5.2, we describe a two-cloud configuration to model the absorption feature. We use a chi square minimization technique to fit the model to the Stokes $I$ spectrum and the fractional polarization spectrum and show that the model does not work. In Section 5.3, we show how an adjustment in covering factors and the presence of velocity gradients in the cloud toward the polarized jet source results in a three-component model that provides an adequate fit to the Stokes $I$, fractional polarization, and polarization position-angle spectra. The implications of the results are discussed in Section 6. All the results are then summarized in Section 7.

Throughout this paper, we use a Wilkinson Microwave Anisotropy Probe (Wilkinson Microwave Anisotropy Probe) cosmology in which $(h, \Omega_m, \Omega_{\Lambda}) = (0.7, 0.3, 0.7)$.

2. OBSERVATIONS

We used the Green Bank Telescope (GBT) in 2007 to observe the $z = 0.692$ 21 cm absorption spectrum against 3C 286. We observed all four Stokes parameters simultaneously.
using the digital FX Spectral Processor, which provides all the
necessary self- and cross-products; here “FX” means that first
it Fourier transforms the input signal and then multiplies the
voltage spectra with appropriate phase shifts. This technique is
described in detail by Heiles et al. (2001) and Heiles (2001).

Our original paper reported a very statistically significant
detection of circular polarization (Stokes V) for the 21 cm line
DLA system against 3C 286. As Zeeman splitting, it translates
to a line-of-sight field strength of 84 ±9 μG. Subsequently, after
re-observing 3C 286 in 2009 January and March, we found that
this detection is incorrect, basically because what we reported
as Stokes V—circular polarization—is really Stokes U—linear
polarization. The discussion below explains the origin of this
error, which is a matter of a misplaced 90° of phase.

2.1. Calibrating a Local Noise Source as a Secondary
Calibrator Standard

The sky electric field is sampled by probes in the telescope
feed. In our observations with the GBT, these two native
polarizations are very close to being orthogonal linear.
For convenience, we denote the sampled voltage spectra (i.e., the
Fourier transforms of the sampled voltages) as X and Y. Apart
from small corrections for nonorthogonality and other coupling,
the Stokes parameters are obtained as follows:

\[ I = XX + YY \]  
\[ Q = XX - YY \]  
\[ U = 2R(XY) \]  
\[ V = 2I(XY). \]

We tacitly assume that the voltage spectral products are time
averages. Here, \( R \) and \( I \) mean the Real and Imaginary parts,
respectively. To clarify these equations and their discussion,
we neglect the small corrections for nonorthogonality; these
corrections are embodied in the feed’s Mueller matrix and are
determined as discussed in Section 2.3.

In a heterodyne radio receiver, the signal from the sky is
amplified by mixing (multiplying) the sky signal by one or more
locally generated signals of known amplitude and phase. The
resulting signal product, the gain \( G_e \), is a complex number in
which the amplitude is the real part and the phase the imaginary
part. Between the receiver and the Spectral Processor, there are
a variety of electromagnetic components that alter the phase
of the signal. Specifically, there are cables and optical fiber,
each of which adds phase proportional to \( \frac{2\pi L}{\lambda} \), where \( L \) is the
length and \( \lambda \) the wavelength of the signal in the particular cable.
Thus, the gain \( G_e \) is a complex number. Moreover, some of
these electromagnetic components have their own polarization
properties that differ for X and Y, and as a result we have \( G_{e,X} \)
and \( G_{e,Y} \). For the complex portion of these gains, the only part
of concern is the phase angle difference

\[ \phi_e = \phi_{e,Y} - \phi_{e,X} \]  

where

\[ \tan \phi_{e,Y} = \frac{I(G_{e,Y})}{R(G_{e,Y})} \]

and a similar equation for X.

These complex gains must be calibrated and their effects
removed. The standard technique is to inject perfectly correlated
noise at the feed from a noise source, commonly called the
“cal.” Like the sky signal, the correlated noise source injects
voltages into the feed; unlike the sky signal, the cal’s noise
is perfectly correlated and corresponds to 100% polarization.
We compare the cal’s signal with that of a standard polarized
calibration source of known flux to determine the equivalent
antenna temperatures of the cal. We also compare the relative
phase of the cal with that of the source, which relates the
polarization of the cal to that of the sky.

In essence, we determine the gain of the cal in X and Y
relative to the sky signal; these gains are complex and change
with frequency. We assume the cal’s properties to remain
constant with time. In subsequent observations, we use the cal’s
deflection to determine the complex electronic gains \( G_{e,X} \) and
\( G_{e,Y} \).

2.2. Using the Cal to Calibrate the Complex Gains

Consider the frequency dependence of Equation (2a). The
individual phase terms on the right-hand side come from electronic
components and from cables. The phase delays of most electronic components change relatively slowly with
frequency. However, for cables, the phase delay is \( \frac{2\pi L}{\lambda} \) and the
phase difference in Equation (2a) is \( \Delta \phi = \frac{2\pi \Delta L}{\lambda} \), where \( \Delta L \) is the
length difference between Y and X. In our experience, \( \Delta \phi \) varies
fairly rapidly with frequency. In particular, using the techniques
described by Heiles (2001), for the current observations we find

\[ \frac{d\Delta \phi}{dv} \approx 20 \text{ deg MHz}^{-1}. \]  

We have a well-tested software that reliably performs this
determination and its correction (e.g., Heiles & Troland 2004).
Unfortunately, however, this software had a bug, which we
discovered on 2009 June 5 while we were analyzing both the
2007 and 2009 data. If we fed the software an array of spectra
to correct, it performed correctly. But if we fed the software just
a single spectrum, it did not apply any correction at all. Before
the current observations, we had never used the software on
individual spectra.

During our original 2007 observations, this phase delay
tended to average about 91 deg at band center with a slope
of about 20 deg MHz\(^{-1}\); the phase delay fluctuated by about 10 degrees for all of our spectra. For our bandwidth of 625 kHz,
the slope does not matter much. Thus, the phase difference of
~90 deg effectively interchanges the real and imaginary parts of
the cross-correlation product. In turn, this changes the derived
Stokes V into Stokes U, and vice versa. Fortunately, in our 2009
observations the phase delay was about 30 deg, which alerted us
to the error in the 2007 data. Although the precise cause of the
change in phase delay between 2007 and 2009 is unknown, we
note that a change in cable length in either polarization over the
entire signal path between the feed and correlator could result in
such a change.

2.3. The Mueller Matrix

We corrected for polarization impurities in the system by
using the Mueller matrix formulation given by Heiles et al.
(2001). The Mueller matrix relates the measured auto- and
cross-correlation products to the actual Stokes parameters. With
this procedure, one observes a linearly polarized calibrator over
a range of parallactic angle (PA) to derive seven parameters
that describe the complex gains and coupling coefficients of
the receiver system components. One then derives the
Mueller matrix coefficients from algebraic combinations of these coefficients.

In the present paper, we observed 3C 286. This source is, for most purposes at cm wavelengths, the “gold standard” polarization calibrator. Specifically, the fractional polarization and polarization position angle of 3C 286 have been stable over four decades of observations across a wide range of frequencies above $\sim 1400$ MHz (Tabara & Inoue 1980; B. Gaensler 2009, private communication). While these properties have not been established at lower frequencies, the dominance of the large-scale jet at these frequencies argue against any time variations of these quantities at 840 MHz. Hence, we had the fortunate circumstance of observing a source that also happens to be an excellent polarization standard. For about half of our observing days, we had enough PA coverage to derive the Mueller matrix from our observed data for that particular day; thus, we could use our observed astronomical data to also determine the Mueller matrix elements—a form of “self-calibration.” The derived corrections were closely the same from one day to another, although there were small differences. For any particular day’s observations, we used the matrix that was closest in time to that day; for about half the days, this matrix was obtained on that very day. This gives us great confidence in our polarization calibration.

Normally, one determines a single Mueller matrix for the observed band by averaging over the whole band. This leads to small calibration errors that change with frequency across the band, which in turn leads to small “baseline curvature” in the three polarization spectra. The latter are the fractional polarization $p(v)$, polarization position angle $\chi(v)$, and Stokes $V$ parameter $V(v)$; one normally fits a smooth baseline to these spectra and applies them as an ad hoc correction.

Here, we took a different approach. 3C 286 is such a strongly polarized source that, for any one day, we could easily determine the seven receiver system parameters on a channel-by-channel basis. We then fit their frequency dependences by performing a minimum-absolute-residual-sum (MARS) third-degree polynomial fit.$^6$ We used these fit coefficients to derive the Mueller matrix independently for each channel. With this, the polarization calibration is very accurate for each channel independently, so that any features in the polarized spectra are real, characterizing the sky instead of the system. In particular, it is neither appropriate nor necessary to subtract off an ad hoc baseline in any of the polarized spectra. It is these accurately calibrated spectra that we use and plot in this paper. Even with this self-calibration of each channel independently, there remain small residual inaccuracies, which result from applying Mueller matrices obtained on one day to data obtained on another day; this is probably responsible for the small spectral effects in the Stokes $V$ spectrum in Figure 1.

3. REANALYSIS

First, we fixed the above-mentioned software bug. Then, we reanalyzed the data. We used the same software as before and determined the Mueller matrices in the usual way (see Heiles et al. 2001), as we did before. We applied the Mueller matrix corrections and the phase difference correction of Equation (2a) as we did before. We did three things differently.

1. We derived the linear polarization by fitting the PA dependence of Stokes $U$. Stokes $U$ is a cross product and produces more reliable results, free of zero offsets, than Stokes $Q$, which is the difference between two large numbers. (As it happens, the results from Stokes $Q$ are indistinguishable from those of Stokes $U$).

2. We reduced the off-line (i.e., the 3C 286 continuum) spectral channels to ensure that we obtain the correct results. That is, we did not “subtract off the continuum baseline.” 3C 286 is the premier polarization calibrator in radio astronomy, and this ensures that our spectral line and continuum results correspond to what is known about 3C 286.

3. The one wrinkle in this is that we have been unable to find a primary measurement of the polarization properties of 3C 286 at frequencies as low as ours, 840 MHz. While 3C 286 exhibits essentially zero change with frequency of polarization position angle above 1.4 GHz, we cannot be sure that the angle at 840 MHz is not somewhat different. We did not wish to address this question and therefore our
reported polarization position angles have an arbitrary zero point.

3. We edited the data much more carefully than before, which produced only minor improvements.

4. THE PROPER DATA: STOKES PARAMETERS

Figure 1 shows a four-panel plot of the data (black curves), now reduced properly. No “baseline corrections” have been subtracted or applied. The data consist of 12.6 hr of on-source integration obtained in 2007. The orange curves are least-squares fits to the data. The top panel shows Stokes \( I(v)/I \) (where \( I \) is the off-line continuum intensity, which is independent of velocity \( v \)), which has an absorption line with a fractional absorption of about 5%. The frequency centroid determined by the fit to the Stokes I spectrum is 839.408348 ± 0.000046 MHz and its location is depicted by the vertical dot-dashed line. The corresponding redshift \( z = 0.69215109 \pm 0.00000009 \). The second panel shows the percent polarization, \( p(v) = \sqrt{(U(v)^2 + Q(v)^2)}/I \), and the third panel shows the position angle \( \chi(v) \) (zero point is arbitrary).

The linearly polarized \( p(v) \) line also appears in absorption (i.e., the percent polarization goes down in the line) and its fractional polarized absorption is close to that for Stokes \( I \). Its line center differs from the Stokes \( I \) line center by 5.0 ± 0.25 kHz. This 20σ difference has high statistical significance. Taken together, these two results are consistent with the absorbing gas covering both nonpolarized and polarized portions of the continuum source image, and the velocity of the part that covers the polarized portion differing from that covering the unpolarized portion by 5.0 kHz (which is about 1.8 km s\(^{-1}\)).\(^7\) The third panel shows that the line changes the position angle by about 1.5 deg at line center, which is consistent with the absorbing gas covering only a fraction of the polarized source image and requires that the position angle of polarization of the continuum changes across the source image.

The fourth panel shows the percentage circular polarization \( V(v)/I \). The absorption line exhibits a dip in fractional Stokes \( V \) of 0.03%. However, we believe this apparent circular polarization is meaningless. The line is 5% linearly polarized, and some of the total intensity and also the linear polarization will leak into Stokes \( V \). The observed Stokes \( V \) intensity of the line is only about 1% of its linearly polarized intensity. Errors in the Stokes parameters at these levels are not unexpected, because of the small day-to-day changes in the Mueller matrix elements.

5. CLOUD STRUCTURE PRODUCING THE ABSORPTION FEATURE

We now show that the GBT polarization spectra provide new and unique information about the kinematic and spatial structure of the gas that gives rise to 21 cm absorption toward 3C 286. In particular, we note the following model-independent facts. (1) The difference between the velocity centroids of the Stokes \( I \) and fractional polarization spectra is inconsistent with a single-cloud origin for the absorption. (2) The Gaussian shape of the absorption profile is plausibly explained through the central limit theorem by the superposition of many small clouds. (3) The position-angle spectrum reinforces the conclusions drawn from the fractional polarization, but requires detailed modeling as described below. Besides studying the spatial and kinematic structure of the absorbing gas, we also investigate its two-phase structure; i.e., whether the gas is a cold neutral medium (CNM) with temperature \( T \sim 100 \) K, a warm neutral medium (WNM) with \( T \sim 8000 \) K (Wolfire et al. 1995), a thermally unstable phase with temperature between these two extremes, or some combination of any of these. Furthermore, we consider clues to the identity of the galaxy hosting the absorbing gas.

5.1. Core–Jet Structure of the Radio Source

The 21 cm absorption likely forms against a source with the core–jet configuration shown in Figure 2 (Wilkinson et al. 1979). This VLBI map, obtained at 609 MHz, indicates that 3C 286 is an asymmetric source consisting of a compact core and an extended jet. The core, which covers a solid angle, \( \Omega_{\text{core}} \approx 10 \times 5 \) mas\(^2\) with major-axis position angle equals 42°, contributes a flux density \( S_{\nu}(609) = 3.5 \) Jy, while in the case of the jet \( \Omega_{\text{jet}} = 40 \times 15 \) mas\(^2\), P.A. = 42°, and \( S_{\nu}(609) = 14 \) Jy. Since a similar core–jet structure is detected at 329 MHz, 1667 MHz (Simon et al. 1980), 5 GHz (Jiang et al. 1996; Cotton et al. 1997), and 15 GHz (K. I. Kellermann et al. 1997, private communication), it is safe to assume that such a structure is present at the absorption frequency of 839.4 MHz. Adopting the spectral indices measured by Simon et al. (1980) of \( \alpha_{\text{core}} = -0.29 \pm 0.15 \) and \( \alpha_{\text{jet}} = -0.55 \), we find that \( S_{\nu}^\text{core} \approx 3.2 \) Jy and \( S_{\nu}^\text{jet} \approx 11.7 \) Jy at \( \nu \approx 840 \) MHz.

While the polarization structure of 3C 286 has not been detected at low frequencies, VLBI measurements of all four Stokes parameters have been obtained at 5 GHz (Jiang et al. 1996; Cotton et al. 1997; W. D. Cotton 2010, private communication). These data show that unlike most quasar VLBI sources, the fractional polarizations, i.e., fraction of total surface brightness in \( \sqrt{U^2 + Q^2} \), where \( U \) and \( Q \) are the Stokes parameters, of the core and jet are comparable. More specifically, the ratio of jet to core polarized surface brightnesses is about 0.4. Nevertheless the ratio of polarized flux densities \( P_{\text{jet}}/P_{\text{core}} \approx 5 \) owing to the much larger solid angle subtended by the jet, where the polarized flux density \( P = \sqrt{U^2 + Q^2} \). Because of the steeper spectral index of the jet, it is reasonable to assume that this ratio increases with decreasing frequency. As a result, we shall ignore the core source when computing absorption in Stokes \( U \).
Figure 3. Foreground clouds (gray) superposed on VLBI map from Figure 2. Cloud 2 at NE completely covers core source, while cloud 1 toward SW partially covers resolved jet source. Cloud 1 is shaded darker to illustrate its larger 21 cm optical depth. Light blue shading indicates that region emitting polarized radiation is the jet. Thick red bars depict direction of E vector polarization. Orthogonal straight lines are 0.02 arcsec in length corresponding to 142 pc at the absorber.

(A color version of this figure is available in the online journal.)

and $Q$ parameters, or equivalently in the spectrum of polarized flux density $P$ (note, $P = \rho I$) and polarization position angle $\chi = 0.5 \times \arctan(U/Q)$. We check the self-consistency of this assumption in Section 7.

5.2. Two-cloud Model

We now describe the procedures used to model the Stokes parameter spectra.

5.2.1. Model Description

To account for the absorption spectrum we first adopt a simplified model, illustrated in Figure 3, comprised of one uniform H I “cloud” toward the jet (cloud 1) and another uniform H I “cloud” toward the core (cloud 2). A single-cloud model is ruled out by past VLBI observations of the 839.4 MHz absorption feature that indicated an inhomogeneous structure of the absorbing gas. The velocity difference between the maximum depths of the phase-shift and fringe amplitude spectra detected by a two-element VLBI experiment (Wolfe et al. 1976) indicates a velocity difference between the H I toward the core and jet sources. As a result, the relative change in Stokes $I$ parameter at velocity $v$ is given by

$$\Delta I(v)/I = \sum_{i=1}^{n_c} C_i f_i[\exp(-\tau_i(v)) - 1],$$

where the number of clouds $n_c = 2$, $C_i$ and $C_2$ are the area covering factors of the gas toward the jet and core, $f_1$ and $f_2$ are the fractions of Stokes $I$ flux density in the jet and the core sources, and $\tau_1(v)$ and $\tau_2(v)$ are the 21 cm optical depths averaged across the areas subtended by the jet and core at the absorber. Note, $I$ in the denominator of Equation (4) is the continuum Stokes $I$ parameter extrapolated across the 21 cm absorption line.

In order to fit the model to the data, we made the following assumptions (see Figure 3). First, because most of the polarized flux density arises from the jet,$^8$ we assume the absorption spectrum of polarized flux density, $P(v)$, arises only in “cloud” 1. Since the line center of the $P(v)$ spectrum is shifted by $+5.0 \pm 0.25$ kHz ($-1.8 \pm 0.1$ km s$^{-1}$) relative to the line center of the Stokes $I(v)$ spectrum, we assume that the velocity centroid of cloud 1 is lower than that of cloud 2. Second, the shift in polarization position angle with frequency, $\Delta \chi(v) = \chi(v) - \chi_{\text{cont}}$ (where $\chi_{\text{cont}}$ is the polarization position angle averaged over the continuum source), indicates that “cloud” 1 partially covers source 1, i.e., $C_1 < 1$, and the intrinsic value of $\chi$ varies across the source, as is observed in VLBI experiments at high frequencies (Jiang et al. 1996; Cotton et al. 1997). With a covering factor $C_1 < 1$, the position angle of polarized flux behind the cloud is weighted less in the line than in the continuum, thereby causing a shift of position angle in the line. Third, because of the smaller dimensions of the core source, we assume $C_2 = 1$. Fourth, we assume Gaussian velocity distributions for each cloud, in which case the optical depth of the $i$th cloud at velocity $v$ is given by

$$\tau_i(v) = \tau_{0,i} \times \exp[\left(-(v - v_i)/\sqrt{2}\sigma_{v,i}\right)^2],$$

where $v_i$ and $\sigma_{v,i}$ are the velocity centroid and velocity dispersion of the $i$th cloud. In the case of 21 cm absorption the central optical depth

$$\tau_{0,i} = N_{\text{HI},i}/(4.57 \times 10^{18}\sigma_{v,i} T_{s,i}),$$

where $T_{s,i}$ is the spin temperature and $\sigma_{v,i}$ is in units of km s$^{-1}$. Fifth, because the polarized radiation is assumed to be emitted only by the jet source, the relative change in fractional polarization is given by

$$\Delta P(v)/P = C_1[\exp(-\tau_1(v)) - 1],$$

where we again extrapolate across the line to obtain $P$ in the denominator of the last equation. The geometry of the model is illustrated in Figure 3.

5.2.2. Model Fits to the Data

We adopted an incremental approach by first modeling the $\Delta I/I$ spectrum alone. When a successful fit was found, we then fitted $\Delta I/I$ together with either the $\Delta P/P$ or $\Delta \chi$ spectrum simultaneously. If a successful fit were obtained, we followed up by fitting $\Delta I/I$, $\Delta P/P$, and $\Delta \chi$ spectra simultaneously. The $1\sigma$ errors, which were derived by computing the standard deviations from portions of the spectra displaced from the absorption features, are as follows: $\sigma_{\Delta I/I} = 0.00050$, $\sigma_{\Delta P/P} = 0.0034$, and $\sigma_{\Delta \chi} = 0.042$.

We obtained the relevant parameters by fitting the model to the data with the Levenberg–Marquardt method that makes use of the nonlinear chi square minimization routine, mrqmin (Press et al. 1996, p. 680). For the $\Delta I/I$ spectrum, we fixed the area covering fractions $C_1 = 0.5$ and $C_2 = 1.0$ as discussed above, but allowed the other parameters to float after making initial guesses that were guided by the discussion in Section 5.2.1. Specifically, we solved for $N_{\text{HI},i}/T_{s,i}, v_i, \sigma_{v,i}$, and $f_i$. A successful fit was found and the output parameters were then used as inputs for fitting the $\Delta I/I$ and $\Delta P/P$ spectra simultaneously. The results are shown in Figure 4.

While the fit to the $\Delta I/I$ spectrum appears to be quite accurate, the fit including the $\Delta P/P$ spectrum has a chi square per degree of freedom, $\chi^2/\nu = 12.6$, which is unacceptable. The reasons for the failure of the model are straightforward.

$^8$ Because the source is weakly polarized, the flux from the jet is dominated by Stokes $I$ with smaller contributions from Stokes $U$ and $V$ comprising the polarized contribution.
Both the depth of the model $\Delta P/P$ absorption feature and the location of its frequency centroid are in significant disagreement with the data. Altering the input parameters to get a better fit to the $\Delta P/P$ spectrum does not solve the problem, because such changes also alter the $\Delta I/I$ spectrum, which result in significant disagreement between the model and observed $\Delta I/I$ spectra. The dilemma is that while cloud 1 produces both the $\Delta P/P$ spectrum and most of the $\Delta I/I$ spectrum, the difference between the velocity centroids of these spectra are too large to be modeled with a single velocity component. Because of a similar difference between the frequency centroids of the $\Delta I$ and $\Delta I/I$ spectra, it is clear that the polarized radiation is incident on a third velocity component. As a result, we abandon the two-cloud model in favor of a three-component model to which we now turn.

5.3. Three-component Model

For this model, we again ignore polarized radiation from the core and assume that it is emitted only by the jet.\(^{10}\) Again we assume that most of the flux from the jet is in Stokes $I$. But we now assume that part of the jet has low or vanishing polarization and that “cloud” 1 covers both this unpolarized portion of the jet and that part of the jet which emits polarized radiation (the faint blue section of the source in Figure 5): the covering factor for the latter is $C_3$. We further assume the presence of a velocity gradient in “cloud” 1 such that the velocity centroid for the Stokes $I$ spectrum is again $v_1$, but for the $\Delta P/P$ spectrum is now $v_3$ (see Figure 5). As a result, we now have

$$\Delta P(v)/P = C_3[\exp(-\tau_3(v)) - 1],$$

(8)

where $\tau_3(v)$ is the 21 cm optical depth of the gas in cloud 1 toward the polarized portion of the jet source: the velocity centroid of this gas is $v_3$. Therefore, this model has velocity components centered on $v_1$, $v_2$, and $v_3$.

Since we shall also consider fits to the $\Delta \chi$ spectrum in this case, we develop a model for the intrinsic change in polarization position angle across the jet source. We assume that $\chi = \chi_0$ for the polarized flux density emitted by the fraction of the jet source that is not incident on the cloud and $\chi = \chi_3$ for the fraction of emitted polarized flux density that is incident on the cloud. Noting that the net flux densities in Stokes $Q$ and $U$ parameters are given by $Q = Q_a + Q_b$ and $U = U_a + U_b$, and $\chi = 0.5 \times \arctan(U/Q)$, we find that

$$\chi(v) = \frac{1}{2} \arctan \left[ \frac{rC_3 \tan(2\chi_b) \exp(-\tau_3(v)) + (1-C_3) \tan(2\chi_a)}{rC_3 \exp(-\tau_3(v)) + 1 - C_3} \right].$$

(9)

Here, $r = (\langle I_Q \rangle_b/\langle I_Q \rangle_a)$, where $\langle I_Q \rangle_a$ and $\langle I_Q \rangle_b$ are the surface brightnesses in Stokes $Q$ averaged over regions $a$ and $b$, respectively, and we make use of the relation $Q_b/Q_a = rC_3/(1 - C_3)$. The observed value of $\chi$ averaged over the unattenuated continuum source, $\chi_{\text{cont}}$, is obtained from the last equation by setting $\tau_3 = 0$. The difference between $\chi$ in the line and $\chi_{\text{cont}}$ is denoted by $\Delta \chi(v) = \chi - \chi_{\text{cont}}$.

We fitted the three-component model parameters to the spectra as follows. First, observing that the parameters characterizing the Stokes $\Delta I/I$ spectrum are independent of those characterizing the $\Delta P/P$ and $\Delta \chi$ spectra, we did not fit the three Stokes spectra simultaneously. Rather, we fitted the $\Delta I/I$ spectrum alone, and then the $\Delta P/P$ and $\Delta \chi$ spectra simultaneously. Given the reasonable fit to the $\Delta I/I$ spectrum discussed in Section 5.2, we adopt the parameters found for clouds 1 and 2 in that fit here. Second, in the case of the polarized spectra we need

\(^{10}\) Although the core is observed to be polarized at higher frequencies (e.g., Jiang et al. 1996), in Section 5.1 we argued that the flux density of polarized radiation mainly comes from the jet.
to find the gas parameters, $N_{\text{HI,3}}/T_{\text{e,3}}$, $v_3$, $\sigma_{e,3}$, and $C_3$ as well as the source parameters $r$, $x_a$, and $x_b$. For the source parameters, we are guided by single-dish polarization measurements above 1.5 GHz that show the continuum polarization position angle for the entire source $\chi_{\text{cont}} = 33^\circ \pm 5^\circ$ (Tabara & Inoue 1980). The VLBI polarization data at 5 GHZ (Jiang et al. 1996; Cotton et al. 1997; W. D. Cotton 2010, private communication) further show that along the jet $\chi$ decreases with increasing distance from the core source (i.e., in the SW direction) by as much as $\approx 40^\circ$ which is consistent with the orientation of the polarization bars in Figure 5. We found that the $\Delta \chi (v)$ line spectral feature is more naturally explained by a large central optical depth $\tau_3$ combined with a low covering factor $C_3$ rather than vice versa. By contrast, $C_3$ and $\tau_3$ are degenerate in the case of the $\Delta P/P$ spectrum (see Equation (8)).

We used mrqmin to determine the cloud 1 and 2 parameters by fits to the $\Delta I/I$ spectrum. As discussed above, the parameters of the third velocity component were found by separately fitting the $\Delta P/P$ and $\Delta \chi$ spectra together. This is possible since the polarized spectra are independent of the cloud 1 and 2 parameters, while the Stokes $\Delta I/I$ spectrum is independent of the component three parameters. After trials with several values of $C_3$ we fixed $C_3 = 0.2$ at the outset. Larger values of $C_3$ must be accompanied by smaller values in $\tau_{0,3}$ in order to maintain the observed value of $\Delta P/P$ (see Equation (8)), but an increase in $C_3$ generates unacceptably large values of $\chi_b = \chi_a$ in order to retain the maximum dip of $\Delta \chi \approx -1:5$ (see Equation (9)). On the other hand smaller values of $C_3$ imply larger values of the ratio $(I_Q)_b/(I_Q)_a$, i.e., larger variations of polarized surface brightness across the source, than observed at 5 GHz (Jiang et al. 1996; Cotton et al. 1997). We considered letting $C_3$ be one of the floating variables, but decided to let it remain fixed, because the spatial variation of $\chi$ across the jet is at best a qualitative rather than a robust constraint. For these reasons we fixed $r = 1$ at the outset (where $r$ is the ratio of average Stokes $Q$ surface brightnesses in region b relative to a), but let the remaining parameters float.

The results are shown in Figure 6, which plots model and observed spectra. The output parameters are listed in Table 1 along with 1σ errors. These were obtained from $\Delta \chi^2$ confidence ellipses containing 68% of the distributed data by projecting the ellipses onto each parameter axis (see Press et al. 1996, p. 680). We did this for all possible pairs of the parameters in Table 1 and chose the largest value of the projection as the 1σ error. While the fit to the $\Delta I/I$ spectrum appears to be quite good, the chi square per degree of freedom $\chi^2/\nu = 1.73$, which corresponds to a probability of $\approx 10^{-8}$ that $\chi^2$ exceeds 294 for 169 degrees of freedom. One reason for the elevated $\chi^2/\nu$ is that our model is undoubtedly inadequate given the $\approx 100:1$ signal-to-noise ratio of the $\Delta I/I$ data. In principle, we could improve the fit by adding more velocity components. But this would be an unconstrained ad hoc procedure, given our limited knowledge of the source-gas configuration, and thus we decided against it. The main reason for the high value of $\chi^2/\nu$ is that the largest contribution to $\chi^2$ comes from the relatively large scatter of the data around the model between 839.385 MHz and 839.397 MHz (i.e., between $\Delta v = -0.023$ and $-0.011$ MHz in Figure 6). As the cause of this effect is currently uncertain, we attribute it to some unknown systematic error.

The fits to the polarized spectra result in $\chi^2/\nu = 1.54$. This corresponds to a probability of $\approx 3 \times 10^{-10}$ that $\chi^2$ exceeds 536 for 348 degrees of freedom. The reasons for the high value of

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**Table 1**

Properties of Clouds and Source Causing the Absorption Feature

| Cloud | Gas Properties | Source Properties |
|-------|----------------|-------------------|
|       | $\tau_{0,i}$  | $N_{\text{HI,i}}/T_{\text{e,i}}$ | $v_i$ | $\sigma_{e,i}$ | $C_i$ | $f_i$ | $\chi_a$ | $\chi_b$ |
| 1     | 0.128 ± 0.005 | (2.03 ± 0.01) × 10^{18} | -0.82 ± 0.02 | 3.48 ± 0.02 | 0.5  | 0.72 | 3  | 5  |
| 2     | 0.057 ± 0.005 | (7.94 ± 0.10) × 10^{17} | +2.37 ± 0.07 | 3.05 ± 0.07 | 1.0  | 0.28 | 2  | 3  |
| 3     | 0.280 ± 0.004 | (4.40 ± 0.02) × 10^{18} | -1.44 ± 0.04 | 3.42 ± 0.04 | 0.2^a | >0.40^b | 2.70 ± 0.9 | 43.6 ± 0.9 |

Notes.

1 $\approx$ 10
2 Fraction of polarized flux density incident on “cloud 3.”
3 Fractional area of jet source emitting polarized radiation, assuming $r = 1$.

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(A color version of this figure is available in the online journal.)
of $\chi^2/\nu$ in this case stems from the small, $\approx 3$ kHz difference between the velocity centroids of the $\Delta P/P$ and $\Delta \chi$ spectra. In contrast to the velocity difference between the centroids of the polarized and Stokes $I$ spectra, this effect is difficult to understand. In any plausible model the velocity centroids of the $\Delta P/P$ and $\Delta \chi$ spectra coincide with the centroid of the optical-depth velocity distribution (see Equations (4), (8) and (9)). We tested the possibility that the error might be due to a constant frequency offset between the $\Delta P/P$ and $\Delta \chi$ profiles by shifting the frequency scale of the $\Delta P/P$ spectrum. We found that $\chi^2/\nu$ decreased to a minimum of 1.48 when the shift was one frequency pixel (i.e., 1.2 kHz). However, the improvement of the fit was insufficient for the error to be a frequency offset. More likely this is also an unknown systematic error. Adding another velocity component does not help since, though it might improve the fit to the $\Delta P/P$ spectrum at 839.405 MHz, it also worsens the fit to the $\Delta I/I$ spectrum. Despite these problems, the model provides an adequate fit to the data, given that our goal is to determine a general picture of the cloud structure rather than obtain a precise evaluation of cloud sizes, locations, etc. As a result, we shall adopt the three-component model in further discussions.

6. DISCUSSION

In this section, we discuss implications of the models used to describe the 21 cm absorption in 3C 286.

6.1. Cloud and Galaxy Properties

In Section 5.3 we discussed the three-component model used to model the $\Delta I/I$, $\Delta P/P$, and $\Delta \chi$ absorption spectra. As illustrated in Figure 5, the three-component model is actually based on two clouds. One cloud (cloud 2) completely covers the core source. The other cloud (cloud 1) partially covers the jet source and contains a velocity gradient such that the part of the cloud toward the polarized portion of the jet (component 3) causes the velocity centroid of the polarized spectra to be offset in velocity from the unpolarized $\Delta I/I$ spectrum. We simplified the model by letting component 3 be a uniform sub-region of cloud 1 with a velocity centroid, velocity dispersion, and 21 cm optical depth that differ from their values in the parent cloud. Table 1 indicates that the polarization position angle for the part of the source absorbed by the foreground cloud is $\chi_a = 43\,^\circ/6$. Because the ratio of the Stokes parameters, $U/Q = \tan(2\chi_a)$, the predicted ratio $U/Q = 20.4$. By contrast, $U/Q = 0.046$ toward the part of the jet that bypasses the absorbing gas where the model predicts $\chi_a = 2\,^\circ/6$. This is consistent with the independent Stokes $U$ and $Q$ absorption spectra, which show a clear detection of the absorption feature in Stokes $U$ but not in Stokes $Q$. The absorption feature, which is detected at a signal-to-noise ratio of about 20:1 in Stokes $U$, is predicted to be below the $1\sigma$ noise level in Stokes $Q$. The model also predicts $\chi_{\text{cont}} = 38\,^\circ$ for the position angle integrated over the entire source, which is consistent with single-dish measurements of $33^\circ \pm 5^\circ$ at 1.5 GHz (Tabara & Inoue 1980). Our model predicts that the intrinsic polarization position angle of the jet decreases by $\chi_a - \chi_b = -40^\circ 9$ in the SW direction (see Figure 5). Polarization maps at 5 GHz (Jiang et al. 1996; Cotton et al. 1997) do show shifts by about this amount in the sense of decreasing $\chi$ along the jet axis in the SW direction. However, the value of $\chi$ at the extreme edge of the jet appears to be greater than our prediction of $\chi_a = 2\,^\circ/6$. These predictions could be checked with VLB1 polarization measurements at lower standard frequencies such as 609 MHz.

Next we turn to the properties of the absorbing gas. The large projected areas subtended by the sources at the absorber ($A_{\text{core}} \approx 70 \times 35$ pc$^2$ for the core and $A_{\text{jet}} \approx 280 \times 60$ pc$^2$ for the jet) likely indicate that the gas causing 21 cm absorption in 3C 286 is comprised of many interstellar clouds. In the Galaxy, a beam with area $A_{\text{fit}}$ directed perpendicular to the plane of the disk would subtend $N_{\text{CNM}} \approx 1000$ CNM (i.e., cold neutral medium; Wolfe et al. 1995) clouds. This is because $N_{\text{CNM}} = n_{\text{CNM}} \times A_{\text{fit}} \times 2H$ where the space density of CNM clouds $n_{\text{CNM}} \approx 3 \times 10^{-4}$ pc$^{-3}$ (McKee & Ostriker 1977) and the disk half-thickness $H \approx 100$ pc. This value of $N_{\text{CNM}}$ is a lower limit, since $N_{\text{CNM}} = n_{\text{CNM}} \times A \times 2H \cos(i)$ for a disk with inclination angle $i$. For the core source $N_{\text{CNM}} \geq 60$. As a result, the Gaussian shape of the absorption profile is naturally explained as the optical-depth weighted sum of multiple Gaussians (i.e., the central limit theorem).

Note that the central velocities of the Gaussians are likely superposed on large-scale velocity gradients present both in “cloud” 1 toward the jet and “cloud” 2 toward the core. While such a gradient in “cloud” 1 is required to explain the velocity shifts between the Stokes $I$ and polarized spectra, as explained above, the necessity for a gradient in “cloud” 2 stems from the approximate agreement between the optical redshift and redshift of “cloud” 2 illustrated in Figure 6. This implies that the optical continuum source is, as expected, physically associated with the compact radio core. The small, but significant, difference between these redshifts further suggests that since the optical beam size is small compared to the dimensions of “cloud” 2, the optical beam samples only a limited portion of the velocities spanned by the gradient in “cloud” 2. Therefore, although the UV resonance lines form in gas within “cloud” 2, the velocity centroids formed by averaging over the optical and wider radio beams need not be equal.

To determine whether the absorbing gas is CNM, WNM, or something else, we need to determine its kinetic temperature, $T_k$. Assuming the foreground gas covers the entire source with a uniform cloud characterized by $\sigma_\text{r} = 3.75$ km s$^{-1}$ (Wolfe et al. 2008), one finds an upper limit of $T_{\text{max}} = 1690$ K. If we further assume that $N_{\text{HI}}$ equals the UV-determined value of $1.77 \times 10^{21}$ cm$^{-2}$ (e.g., Wolfe & Davis 1978), then Equation (6) implies $T_k = 1035$ K, since the central 21 cm optical depth $\tau_0 = 0.10$ (Wolfe et al. 2008). Because $T_k < T_{\text{r}} < T_{\text{max}}$ for diffuse warm gas (Liszt 2001), these results would indicate that the gas is neither standard CNM where $T_k \approx 80$ K nor standard WNM where $T_k \approx 8000$ K (Wolfe et al. 1995), but rather resembles the thermally unstable phase found by Heiles & Troland (2003) in the Galaxy ISM.

On the other hand the frequency-dependent change in polarization position angle across the absorption feature (panel 3 in Figure 5) provides strong evidence against the assumption of a single uniform cloud (see Section 5.3). From the values of $\sigma_{r,i}$ in Table 1 we find that $T_{\text{max}} = 1450$ K, 1115 K, and 1400 K for gas in velocity components 1, 2, and 3. If we again assume that $N_{\text{HI,i}} = 1.77 \times 10^{21}$ cm$^{-2}$ in each case, the values of $N_{\text{HI,i}}/T_{\text{r,i}}$ in Table 1 indicate that $T_{\text{r,1}} = 892$ K, $T_{\text{r,2}} = 2230$ K, and $T_{\text{r,3}} = 394$ K. However, since the values of $N_{\text{HI,i}}/T_{\text{r,i}}$ in Table 1 are spatial averages over dimension much larger than the $\approx 1$ lt. yr. size of the UV continuum, it is unlikely that the UV determined value of $N_{\text{HI}}$ applies to the gas in each component, nor that each component has the same value of $N_{\text{HI}}$. It is equally plausible to assume that $N_{\text{HI}}$ averaged across cloud 1 is a factor of two lower than the UV determined value, and $C_1$ equals 0.25 rather than 0.5. In that case $T_{\text{r,1}} = 223$ K. Similarly, if $N_{\text{HI,3}} =$
massive galaxy, the metallicity \( M \) temperatures for CNM gas with the low metal abundances in-

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between the absorption epoch and the present, which is given

absolute magnitude

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low metallicity and absence of C

into gas comprised of many clouds. This is consistent with the

explained by a reduced supernovae input of mechanical energy

cloud rather than an ensemble of clouds. But this might be

optical source is located in the compact core source implies

optical spectrum again exhibits the

and vice versa. As a result, what we interpreted as the

where the error is dominated

applied by a reduced supernovae input of mechanical energy

consistent with the low metallicity and absence of C

absorption both of which

indicate a lower than normal star formation rate (SFR; Wolfe

clouds, this is consistent with the

absorption to determine the optical redshift,

Wolfe et al. (2008) is erroneous.

Zeeman splitting by Wolfe et al. (2008) is erroneous.

an insidious software error failed to remove a spurious

phase delay of \( \approx 90^{\circ} \) between orthogonal linearly polarized

signals from the GBT antenna. This phase difference

changed the derived Stokes V parameter into Stokes U

and vice versa. As a result, what we interpreted as the

spectral signature of Zeeman splitting in Stokes V was a

shift between the velocity centroids of the Stokes I and U

absorption spectra.

A proper reanalysis of the GBT spectra is presented

in Figure 1. The Stokes I spectrum again exhibits the

21 cm absorption feature at \( \nu = 839.408348 \text{ MHz} \) ( \( z = 0.692115109 \)).

The spectrum of fractional polarization,

\( \rho \equiv \sqrt{Q^2 + U^2} / I \), where \( Q \) and \( U \) are the Stokes parameters,

shows that the frequency centroid of the absorption feature

is offset by \( 5.0 \pm 0.25 \text{ kHz} \) from the frequency centroid

of the Stokes I spectrum. The polarization position-angle

spectrometer exhibits a frequency centroid that is also offset

from the frequency centroid of the Stokes I spectrum, but

by an amount that differs slightly from the centroid of the

fractional polarization spectrum. The Stokes V spectrum

exhibits an absorption feature at 839.41 MHz, but this is

most likely an artifact due to leakage from the other Stokes

parameters. The latter imply a \( 3 \sigma \) upper limit of 17 \( \mu \text{G} \)

on the line-of-sight component of the magnetic field in the

absorbing gas.

We modeled the absorption feature with a core–jet radio

structure of 3C 286 behind three velocity components: in

the jet will differ. The predictions

gradient in this cloud the velocity centroids in Stokes

spectrum again exhibits the

for the Stokes

radiation, but

for the polarized radiation

spectrum, but

for the Stokes

spectrum.

Thus, we assume the presence of a velocity

gradient in this cloud the velocity centroids in Stokes I and

the polarized radiation in the jet will differ. The predictions

of this model are in reasonable agreement with the data.

Comparison between the model and observed spectra is

shown in Figure 6, and the physical parameters of the model

are given in Table 1.

7. SUMMARY AND CONCLUSIONS

Reanalysis of the polarization spectra of the 21 cm absorption

line detected at \( z = 0.692 \) toward 3C 286 leads to the following conclusions.

1. The detection of an 84 \( \mu \text{G} \) magnetic field inferred from

Zeeman splitting by Wolfe et al. (2008) is erroneous.

2. A proper reanalysis of the GBT spectra

is shifted by 1.8 km s\(^{-1}\) from \( z_{\text{opt}} \) (see Table 1). In that
case \( \Delta \ln (\alpha^2 g_p m/M) < 0.6 \times 10^{-5} \). Both of these limits are
comparable to results from recent measurements by Kanekar
et al. (2010; see also Tzanavaris et al. 2007) who used redshifts
deduced from C I absorption to determine the optical redshift,
since C I is a more accurate tracer of the CNM gas that gives
rise to 21 cm absorption than the Si II, Fe II, Zn II, and Cr II
resonance transitions used to determine the optical redshift of
the 21 cm absorber toward 3C 286 (Wolfe et al. 2008). In principle
the present limit could be improved with a future space-based
detection of C I absorption lines in this absorber, and a reduction
of the systematic errors in wavelength calibration of the HIRES
spectrograph.

6.2. Limits on Variations of Physical Constants

The difference between the optical redshift, \( z_{\text{opt}} \), and radio
redshift, \( z_{\text{radio}} \), places limits on variations of physical constants
between the absorption epoch and the present, which is given by

\[
\Delta \ln (\alpha^2 g_p m/M) = \left[ (z_{\text{opt}} - z_{\text{radio}}) / (1 + z_{\text{radio}}) \right].
\]

(10)

Here, \( \alpha \) is the fine structure constant, \( g_p \) is the gyromagnetic
ration of the proton, and \( m/M \) is the electron-to-proton mass
ratio (Wolfe et al. 1976). Because the radio redshift \( z_{\text{radio}} = 0.69215109 \pm 0.0000000109 \) and the optical redshift \( z_{\text{opt}} = 0.69217485 \pm 0.00000058 \), \( \Delta \ln (\alpha^2 g_p m/M) = 4.2 \text{ km s}^{-1} \pm 0.10 \text{ km s}^{-1} \) (in velocity units), where the error is dominated
by the uncertainty in \( z_{\text{opt}} \). However, this estimate ignores the
much larger systematic error determined from night-to-night
changes in wavelength calibration on HIRES, which can be as
large as 2 km s\(^{-1}\) (Kanekar et al. 2010). Therefore, adopting
the 4.2 km s\(^{-1}\) difference as a conservative 2\( \sigma \) upper limit,
we find \( \Delta \ln (\alpha^2 g_p m/M) < 1.4 \times 10^{-5} \) in the redshift interval
\( z = [0, 0.692] \). On the other hand, our conclusion that the
optical source is located in the compact core source implies
that the relevant radio redshift is given by cloud 2, which

\( N_{\text{HI,1}} \), then \( T_{K,3} = 197 \text{ K} \). Since these are physically plausible
temperatures for CNM gas with the low metal abundances in-
ferred for this absorber (Wolfe et al. 2008), it is reasonable to
assume that they represent kinetic temperatures. Interestingly,
the assumption \( N_{\text{HI,2}} = 1.77 \times 10^{21} \text{ cm}^{-2} \) results in the unrea-
sonable prediction that \( T_{K,2} \) is higher than \( T_{K,2}^\text{max} \) : we take this as
direct evidence that \( N_{\text{HI,2}} \) is lower than \( 1.77 \times 10^{21} \text{ cm}^{-2} \) and/
or \( C_2 < 1 \), thereby implying that cloud 2 could also be CNM.
Of course, we cannot entirely rule out the possibility that the
gas is in a thermally unstable phase. But the above arguments
in addition to the results from the VLBI line experiment, which
indicates individual components toward the core and jet with
kinetic temperatures \( T_k < 500 \text{ K} \) (Wolfe et al. 1976), make a
compelling case that the gas causing 21 cm absorption in 3C 286
is mainly CNM. Although this conclusion is at odds with the
anti-correlation between \( T_k \) and \( [M/H] \) found by Kanekar et al.
(2009), the evidence provided by our polarization measurements
suggests either that physical conditions in this absorber deviate
from typical conditions in DLAs or that most values of \( T_k \)
deduced from UV-determined values of \( N_{\text{HI}} \) are poor indicators
of \( T_k \).

Identification of the galaxy hosting the absorbing gas is
difficult to ascertain. Le Brun et al. (1997) used Hubble Space
Telescope images to tentatively identify an object (2c in their
nomenclature) as the leading candidate for the host. Although its
absolute magnitude \( M_B = -20.1 \) (in our cosmology) suggests a
massive galaxy, the metallicity \( [M/H] = -1.6 \) of the absorbing
gas (Wolfe et al. 2008) is at the low end for this redshift, which
suggests a low-mass galaxy (Tremonti et al. 2004). Although
the area subtended by 3C 286 at the absorber would encompass
over 1000 CNM clouds, the 3.75 km s\(^{-1}\) velocity dispersion of
the absorption feature more closely resembles that of a single
cloud rather than an ensemble of clouds. But this might be
explained by a reduced supernovae input of mechanical energy
into gas comprised of many clouds. This is consistent with the
low metallicity and absence of C II absorption both of which
indicate a lower than normal star formation rate (SFR; Wolfe
et al. 2008). As a result, the evidence accumulated so far suggests
that the gas causing 21 cm absorption in 3C 286 is embedded in
a massive galaxy with a history of low SFRs.
4. In Section 7, we discuss implications of these models. We show that the change in polarization position angle predicted by the model is consistent with polarization measurements made at higher frequencies, but with some important differences that may be tested with future VLBI observations. We show that the area of the jet projected onto the absorbing gas would encompass more than 1000 standard CNM type clouds found in the Galaxy. This provides a natural explanation for the Gaussian shape of the absorption feature through the central limit theorem. We argue that the high spin temperatures deduced from the single uniform cloud model are unlikely to be correct due to evidence for an inhomogeneous distribution of the foreground gas. While we cannot rule out the possibility that we have detected warm, thermally unstable gas, we have presented independent arguments favoring the CNM hypothesis. The evidence accumulated so far also indicates the absorbing gas is in a massive galaxy with a lower than average history of SFR.

5. A comparison between the radio and optical redshifts of the 21 cm absorber sets a conservative 2σ upper limit on variations on the product of three physical constants given by \( \Delta \ln(\alpha^2 g_{p,m}/M) < 1.4 \times 10^{-5} \) within the redshift interval \( z = [0,0.692] \). Based on our conclusion that the optical absorption occurs in cloud 2, this limit reduces to \( \Delta \ln(\alpha^2 g_{p,m}/M) < 0.6 \times 10^{-5} \).

To conclude, our measurement of 21 cm absorption in all four Stokes parameters has provided new information about the foreground gas at \( z = 0.692 \) toward 3C 286. The difference between the velocity centroids of the absorption feature in unpolarized radiation on one hand and in fractional polarization and polarization position angle on the other hand demonstrates evidence for spatial variations of \( N_{\text{HI}}/T_e \) on scales less than \( \sim 100 \) pc. Our observations demonstrate that simple models of uniform clouds covering the entire radio source structure are incorrect. This is clearly illustrated by our analysis of cloud 2 in front of the compact core source: application of the UV-determined value of \( N_{\text{HI}} \) leads to a value of the spin temperature significantly higher than the upper limit to the kinetic temperature set by the velocity dispersion of the gas, which is physically implausible. Instead, the data are more consistent with a model in which each of the three velocity components is comprised of large numbers of small CNM clouds that produce the smooth Gaussian velocity profile of the absorption feature.

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