NEUTRAL HYDROGEN ABSORPTION TOWARD XTE J1810–197: THE DISTANCE TO A RADIO-EMITTING MAGNETAR

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ABSTRACT

We have used the Green Bank Telescope (GBT) to measure H I absorption against the anomalous X-ray pulsar XTE J1810–197. Using a flat rotation curve, we find that XTE J1810–197 is located at a distance of 3.4 ± 0.6 kpc. The Galactic bar, however, does have an influence on Galactic rotation velocities that impacts the distance estimate of XTE J1810–197. When rotation curve models that include the Galactic bar are used, we find that XTE J1810–197 is located in the distance range of 3.1–4.3 kpc. From information gleaned from the literature, we find an upper limit on the distance to XTE J1810–197 of 4 kpc based on its infrared detection, its location just in front of an Infrared Dark Cloud (G10.74-0.13), and a measurement of the infrared absorption versus distance for this line of sight. Our best determination for the distance to XTE J1810–197 is thus 3.1–4 kpc. This distance, 3.1–4 kpc, is consistent with the distance to XTE J1810–197 of about 3.3 kpc derived from its dispersion measure, and estimates of 2–5 kpc obtained from fits to its X-ray spectra. We also used the GBT in an attempt to measure absorption in the four OH 18 cm lines against XTE J1810–197. We were unsuccessful in this, mainly because of its declining radio flux density. Analysis of H I 21 cm, OH 18 cm, and 12CO(2 → 1) emission toward XTE J1810–197 allows us to place a lower limit of NHI ≥ 4.6 × 1021 cm−2 on the non-ionized hydrogen column density to XTE J1810–197, consistent with estimates obtained from fits to its X-ray spectra.

Subject headings: H I regions — ISM: bubbles — ISM: clouds — ISM: individual (G10.0-0.3, G10.2-0.3, G10.3-0.1, G10.6-0.4, G10.74-0.13, G11.2-0.3) — pulsars: individual (XTE J1810–197) — radio lines: ISM — supernova remnants

1. INTRODUCTION

Prior to the detection of pulsed radio emission from the anomalous X-ray pulsar (AXP) XTE J1810–197 by Camilo et al. (2006), pulsed emission from the dozen known magnetars had been detected in X-rays in all instances, and in one case at optical wavelengths. Estimating the distance to a magnetar has relied on associating it with a supernova remnant (SNR) of known distance, or by fitting its X-ray spectrum and parameterizing the energy-dependent absorption by interstellar gas along the line of sight with a nonionized hydrogen column density NH (Morrison & McCammon 1983). Using standard relations, NH is related to visual extinction AV, which is turned into a distance estimate using mean values in the Galactic plane (see, e.g., § 6 of Gotthelf et al. 2004), or is directly calibrated as a function of distance using stars of known luminosity in the field (Djuric & van Kerkwijk 2006). Sometimes, the probable location of the X-ray source in a well-studied star cluster can be used to infer its distance (Muno et al. 2006).

The detection of pulsed radio emission from XTE J1810–197 allows one to determine its distance using methods that are not applicable to other magnetars. The dispersion measure (DM: the total column density of free electrons along the line of sight) was obtained on discovery of the radio pulsations (Camilo et al. 2006). A model for the Galactic free electron distribution then yields a distance estimate, in this case d ≈ 3.3 kpc using the most recent model (Cordes & Lazio 2002). Also, bright, pulsed radio emission allows kinematic distance limits to be obtained by observing spectral lines that are seen in absorption against the magnetar, as we report here using H I.

Obtaining a reliable distance to XTE J1810–197 allows for a precise determination of the luminosity of the star based on its measured flux in a variety of wave bands. The distance also allows a proper motion (see Helfand et al. 2007) to be converted into a tangential velocity. Magnetars are thought to be very young neutron stars, and are expected to be found near star-forming regions and/or spiral arms. Knowing the distance to XTE J1810–197 allows this prediction to be tested in this case. Besides providing a kinematic distance, the H I absorption spectrum can also give an independent estimate of NH, which may be compared to results from X-ray spectral fitting.

In § 3 we present the H I and OH observations and data analysis. This is followed by a determination of the hydrogen absorption spectra toward XTE J1810–197 in § 4, and of its kinematic distance in § 5. An upper limit on the distance to XTE J1810–197 is presented in § 6. In § 7 we comment briefly on some features of the neutral hydrogen toward XTE J1810–197, and in § 8 on the OH absorption limits. We obtain a limit on the hydrogen column density in § 9, and comment on models of the line of sight toward XTE J1810–197 in § 11. In § 10 we comment on the distances to other objects with lines of sight near XTE J1810–197. We conclude in § 12 with a discussion of our main results.

2. GALACTIC CONSTANTS

Throughout this paper we will assume that the Sun is located 8.5 kpc from the Galactic center. We will also use a velocity of V_0 = 220 km s⁻¹ as the azimuthal velocity of the local standard of rest (LSR) about the Galactic center. These are the current IAU standards (Kerr & Lynden-Bell 1986). However, there is evidence that these values may not be correct (see the discussions in Reid 1993; Engmaier & Gerhard 2006), which would require a scaling of the kinematic distance estimates presented here.

3. OBSERVATIONS AND DATA ANALYSIS

3.1. H I 21 cm Absorption Observations

XTE J1810–197 was observed with the National Radio Astronomy Observatory (NRAO)4 Robert C. Byrd Green Bank

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Telescope (GBT) for approximately 3 hr on 2006 June 6 in order to measure the H i 21 cm line absorption. The GBT has an unblocked aperture, a spatial resolution of 9.2′ at 21 cm, and a system temperature on cold sky of 18 K. The NRAO spectral processor (SP), a fast Fourier transform spectrometer, was used as the detector. The SP provides good dynamic range for the observations via its 32-bit sampling, and was used in its pulsar mode, whereby it accumulates spectra that are folded synchronously with the pulsar period. The SP was configured to have 1024 channels for each linear polarization across a bandwidth of 2.5 MHz, producing a spectral resolution of 0.52 km s\(^{-1}\). We recorded 128 spectra (phase bins) evenly spaced in time across each individual period of XTE J1810−197. The duty cycle of this 5.54 s pulsar was such that 4−5 of these bins contained pulsed flux.

### 3.2. OH 18 cm Absorption Observations

XTE J1810−197 was observed with the GBT for approximately 38 hr in order to measure absorption in the 18 cm (1612, 1665, 1667, and 1720 MHz) transitions of OH. Observing details are given in Table 1. The GBT’s angular resolution is approximately 8′ for each of the OH transitions. The spectral processor was also used for these measurements, and was configured to provide 256 spectral channels for each linear polarization across each of the four OH transitions. A bandwidth of 0.625 MHz was used, giving a spectral resolution of 0.44 km s\(^{-1}\) channel\(^{-1}\). We chose this narrower bandwidth (with higher frequency resolution), since we already knew which velocities displayed H i absorption. As with the H i measurements, the pulsed flux of XTE J1810−197 was detected in 4−5 phase bins.

The GBT Autocorrelation Spectrometer (ACS) was used to obtain pulsar “off” spectra for the four OH lines. The data were obtained in six position-switching observations, each consisting of 2 minutes on-source followed by 2 minutes off-source, resulting in an effective integration time of 12 minutes. An off position 2 minutes of time in right ascension offset from the position of XTE J1810−197 was used so that approximately the same hour angle coverage was obtained for the on and off positions. The ACS was configured to observe all four of the OH 18 cm lines simultaneously with 8192 channels within a bandwidth of 12.5 MHz, resulting in a spectral resolution of 0.27 km s\(^{-1}\). These observations allow for a better calibration of the pulsar-off OH spectra.

### 3.3. Data Reduction

The data were analyzed using a method similar to that described in Weisberg (1978) and Minter et al. (2005). A pulsar “on” spectrum was created using a weighted average for the times when the pulsar was emitting. The weights used were the square of the ratio of the pulsar flux to the system temperature, i.e., the signal-to-noise ratio. A pulsar-off spectrum was also created for the times when the pulsar was not emitting. The difference of these two spectra, divided by the pulsar flux (found via a fitted polynomial to the continuum in the pulsar-on spectrum) then gives the absorption spectrum against the pulsar.

For the H i data, the spectra were converted from detector counts to a Kelvin scale using a calibrated noise diode that was injected during 2 minute calibration scans. Observations of the IAU H i standard source S6 were made to put the spectra on the IAU standard brightness temperature scale (Williams 1973).

### 4. THE ABSORPTION SPECTRA TOWARD XTE J1810−197

The H i absorption spectrum toward XTE J1810−197 is shown in Figure 1. The H i absorption toward XTE J1810−197 is highly linearly polarized (Camilo et al. 2007b), so that the YY polarization signal had a much better signal-to-noise ratio (by a factor of ≈4) than the XX polarization. The two polarizations were averaged together with weights given by their signal-to-noise ratios to produce the spectrum shown. The spectrum has not been smoothed in any way and shows the native resolution of the observations.

Five Gaussians were fitted to the opacities determined from the H i absorption toward XTE J1810−197. The results of the fit are shown in Table 2 and in Figure 2. The columns in Table 2 give for each line, respectively, the opacity, LSR velocity (V\(_{\text{LSR}}\)), and full width at half-maximum (FWHM). The errors listed in Table 2 are 1 \& σ errors from the Gaussian fits.

The OH absorption spectra toward XTE J1810−197 are shown in Figures 3–6. With the strength of the pulsar emission during the OH measurement epochs being much weaker than was the case for the H i measurement epoch (Camilo et al. 2007a), the strong linear polarization of XTE J1810−197 means that only one polarization effectively contributed to the measurement of the OH absorption against XTE J1810−197. Thus, the OH absorption data shown in Figures 3–6 and discussed in this paper are only from a single linear polarization (YY). The 1 \& σ opacity
5. DETERMINING THE KINEMATIC DISTANCE TO XTE J1810–197

5.1. Association of H I Absorption Line with Known Galactic Features

XTE J1810–197 is located at Galactic coordinates (l, b) = 10.726°, −0.158°. We associate the $V_{\text{LSR}} = 7.7$ km s$^{-1}$ H I absorption line with the Heeschen Cloud (Riegel & Crutcher 1972), which has also been called the Riegel-Crutcher Cloud by McClure-Griffiths et al. (2006). The Heeschen Cloud is a nearby, $d = 125 \pm 25$ pc, cold cloud ($T_{\text{spin}} \approx 40$ K) that covers Galactic longitudes $345^\circ - 25^\circ$ and latitudes $\pm 6^\circ$. This cloud is also seen as a self-absorption feature in the H I emission spectrum (top panel of Fig. 1). The weak absorption line at $V_{\text{LSR}} = 14.1$ km s$^{-1}$ can be kinematically associated with gas in the Carina-Sagittarius spiral arm (the first spiral arm inward of the Sun’s Galactic position), assuming that the line arises on the near side of the tangent point and using the Galactic rotation model of Englmaier & Gerhard (2006). Likewise, the $V_{\text{LSR}} = 22.8$ and 25.7 km s$^{-1}$ lines can be kinematically associated with the Crux-Scutum spiral arm (the second spiral arm inward of the Sun). The $V_{\text{LSR}} = 19.1$ km s$^{-1}$ is possibly associated with either the Carina-Sagittarius spiral arm or the Crux-Scutum spiral arm (a random velocity of 5–6 km s$^{-1}$ would place this cloud at a velocity consistent with either spiral arm).

5.2. Near or Far Side of the Velocity-Distance Relationship?

At the Galactic longitude of XTE J1810–197 the kinematic velocity-distance relationship is double-valued (see Fig. 7). Our first concern is whether it is possible to determine on which side of the tangent point XTE J1810–197 lies. At this Galactic longitude, the tangent point is about 8.3 kpc from the Sun and has a $V_{\text{LSR}} \approx 168$ km s$^{-1}$ using the flat rotation curve of Fich et al. (1989). Distance estimates for XTE J1810–197 based on its X-ray-fitted $N_H$ are 2.5–5 kpc (Gotthelf et al. 2004; Gotthelf & Halpern 2005; Durant & van Kerkwijk 2006), and the DM-based distance is 3.3 kpc (Camilo et al. 2006). These strongly suggest that XTE J1810–197 lies on the near side of the tangent point.

| $\tau$ | $V_{\text{LSR}}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|--------|-------------------------------|-------------------|
| 2.15 ± 0.09 | 7.73 ± 0.06 | 3.3 ± 0.2 |
| 0.5 ± 0.1 | 14.1 ± 0.2 | 1.2 ± 0.4 |
| 1.53 ± 0.08 | 19.1 ± 0.1 | 3.8 ± 0.4 |
| 1.2 ± 0.1 | 22.8 ± 0.2 | 2.1 ± 0.4 |
| 0.94 ± 0.1 | 25.7 ± 0.2 | 2.4 ± 0.5 |

Note.—See Figs. 1 and 2 for data on which these fits are based.
Another magnetar, SGR 1806–20, which lies 41′ from XTE J1810–197, has \(\text{H} \, \text{i} \) absorption at velocities greater than \( V_{\text{LSR}} \approx 50 \, \text{km s}^{-1} \) and is thought to lie on the far side of the tangent point (McClure-Griffiths & Gaensler 2005). Both SGR 1806–20 and the Galactic SNR G11.2-0.3 (Becker et al. 1985) also have \(\text{H} \, \text{i} \) absorption features at negative velocities that must arise from the far side of the Galactic disk if the rotation curve is flat. However, as the Galactic rotation model of Weiner & Sellwood (1999) shows, these negative velocities can also arise in the Galactic bar at a distance of 7 kpc toward these sources. The Galactic bar induces large radial motions that deviate from the normally assumed circular Galactic rotation. Along the line of sight to XTE J1810–197, the Galactic bar is responsible for motions >90 km s\(^{-1}\) more negative than the prediction of a flat rotation curve (see Fig. 8). Negative-velocity \(\text{H} \, \text{i} \) absorption is not found toward XTE J1810–197, which according to this model establishes an upper limit to its distance of 7 kpc (i.e., it is closer than the Galactic bar). This strengthens the conclusion that XTE J1810–197 lies on the near side of the tangent point.

5.3. Is the Last Absorption Feature at the Actual Distance, or a Lower Limit?

The number of \(\text{H} \, \text{i} \) absorption features per kiloparsec in the inner Galaxy is about 1–3 (Garwood & Dickey 1989; see their Table 3). Assuming a flat rotation curve and a distance of 5 kpc, corresponding to a maximum \( V_{\text{LSR}} \approx 40 \, \text{km s}^{-1} \), along with a line width of 3 km s\(^{-1}\) for the average \(\text{H} \, \text{i} \) absorption feature, we expect that 38%–100% of the velocities within \( V_{\text{LSR}} = 0–40 \, \text{km s}^{-1} \) should contain \(\text{H} \, \text{i} \) absorption along the line of sight toward XTE J1810–197. If ~38% of the velocity space were occupied by absorption features, then the highest velocity feature in the absorption spectrum toward XTE J1810–197 should be taken as indicating a lower limit for the distance, since there is likely a significant distance between XTE J1810–197 and the \(\text{H} \, \text{i} \)-absorbing cloud nearest it. If, on the other hand, the whole velocity range

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**Table 3**

| \( \nu \) (MHz) | \( \sigma^a \) |
|-----------------|----------------|
| 1612            | 0.09           |
| 1665            | 0.10           |
| 1667            | 0.10           |
| 1720            | 0.10           |

\(^a\) 1 \(\sigma\) limits.

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![Fig. 5.](image1.png)  
**Fig. 5.** Top: The OH 1667 MHz pulsar-off spectrum toward XTE J1810–197. Bottom: The OH 1667 MHz absorption spectrum against XTE J1810–197.

![Fig. 6.](image2.png)  
**Fig. 6.** Top: The OH 1720 MHz pulsar-off spectrum toward XTE J1810–197. Bottom: The OH 1720 MHz absorption spectrum against XTE J1810–197.

![Fig. 7.](image3.png)  
**Fig. 7.** Top: The \(\text{H} \, \text{i} \) absorption spectrum toward XTE J1810–197 (see bottom panel of Fig. 1). Bottom: The flat Galactic rotation model (solid curve) of Fich et al. (1989). The x-axis is the radial velocity of the gas. The y-axis is the distance from the Sun along the line of sight of XTE J1810–197. The dotted lines indicate the deviation from Galactic rotation of \( \pm 7 \, \text{km s}^{-1} \). The arrow at \( V_{\text{LSR}} = 25.7 \, \text{km s}^{-1} \) indicates the highest velocity \(\text{H} \, \text{i} \) absorption seen toward XTE J1810–197 (see Table 2). The shaded regions indicate the allowed kinematic distances from the flat rotation curve (see discussion in § 5.4 for interpretation of these figures).
should contain H\textsc{i} absorption, it is likely that the last absorbing feature gives the actual distance to XTE J1810–197.

It is useful to look at absorption measurements toward objects near XTE J1810–197 in order to help us determine the H\textsc{i} absorption velocity coverage. The line of sight to XTE J1810–197 lies near to the giant Galactic H\textsc{ii} complex W31 (see Fig. 1 of Corbel & Eikenberry 2004). W31 is comprised of several individual H\textsc{ii} regions, including G10.2-0.3, G10.3-0.1, and G10.6-0.4. Roughly on the opposite side of W31 from XTE J1810–197 lies G10.0-0.3, the wind-blown bubble of LBV 1806–20, and SGR 1806–20. At higher Galactic longitude than XTE J1810–197 lies the SNR G11.2-0.3. All of these objects have H\textsc{i} absorption measurements (except for G10.0-0.3 and LBV 1806–20, which have NH\textsc{iii} absorption measurements) from the literature (see Corbel & Eikenberry 2004).

Corbel & Eikenberry (2004) determined that G10.3-0.1, G10.0-0.3, LBV 1806–20, and SGR 1806–20 all lie on the far side of the tangent point, while G10.2-0.3 and G10.6-0.4 lie on the near side. The H\textsc{i} absorption of G10.3-0.1 (Fig. 2 of Kalberla et al. 1982) and SGR 1806–20 (Fig. 2 of Cameron et al. 2005) fill the range $V_{\text{LSR}} = 0 - 40$ km s$^{-1}$. H\textsc{i} toward G10.6-0.4 shows absorption at all velocities within $V_{\text{LSR}} = 0 - 45$ km s$^{-1}$ (Fig. 32 of Caswell et al. 1975). Likewise, the H\textsc{i} absorption toward G10.2-0.3 (Fig. 4 of Greisen & Lockman 1979) and SNR G11.2-0.3 (Fig. 3 of Becker et al. 1985) completely cover the velocity range $V_{\text{LSR}} = 0 - 45$ km s$^{-1}$. Since G10.6-0.4, G10.2-0.3, and G11.2-0.3 all lie on the near side of the tangent point and are only 16’, 33’ and 30’, respectively, in projection from XTE J1810–197, we argue that all velocities between the Sun and XTE J1810–197 should show H\textsc{i} absorption. Therefore, the highest velocity absorption feature seen along the line of sight toward XTE J1810–197 gives us its true distance, rather than a lower limit.

5.4. The Kinematic Distance to XTE J1810–197

The standard way to determine a kinematic distance has been to take the center velocity of the observed spectral line and add an “error” due to random velocities of clouds. A Galactic rotation (velocity vs. distance) model is then used to convert this velocity with “errors” into a distance estimate with errors. Although this method gives distance errors that are reasonable, they are not determined entirely correctly. This is due to the fact that the random velocities of clouds are an error for the Galactic rotation model and not an error in determining the velocity of the cloud from the spectral data. (The value for the random velocities of the cold clouds was determined from the residuals of fitting a Galactic rotation model to observed data; see Belfort & Crovisier 1984.) In reality we should take the velocity of the spectral line and then use a Galactic rotation model and shift the velocity of the rotation model by the amount of the random motions to determine the distance errors (see Fig. 7). It should be noted that unless there are large gradients in the Galactic rotation model’s velocity at the estimated distance, there should be very little difference between the errors determined using these two methods.

In Figure 7 we show the determination of the distance to XTE J1810–197 using the flat rotation curve of Fich et al. (1989). Cold H\textsc{i} clouds have random motions superposed on the uniform Galactic rotation, as indicated by their measured velocity dispersion of 7 km s$^{-1}$ (Lockman & Dickey 1990). The dotted lines on either side of the rotation model in Figure 7 indicate the deviation from Galactic rotation of $\pm 7$ km s$^{-1}$. The arrow at a constant $V_{\text{LSR}}$ in Figure 7 indicates the highest velocity of H\textsc{i} absorption. The shaded regions in Figure 7 indicate the allowed kinematic distances from the flat rotation curve. Figures 8 and 9 are similar to Figure 7, using instead the Galactic rotation models of Weiner & Sellwood (1999) and Englmaier & Gerhard (2006), respectively.

For the flat rotation curve used in Figure 7, the last H\textsc{i} absorption feature toward XTE J1810–197 at $V_{\text{LSR}} = 25.7$ km s$^{-1}$ (see Table 2) gives a kinematic distance of $3.4 \pm 0.6$ or $13.3^{+0.7}_{-0.5}$ kpc. We can rule out the larger distance, since this is on the far side of the tangent point. Although a flat rotation model may provide a reasonable distance estimate for XTE J1810–197, there are Galactic structures along the line of sight that also need to be taken into account. Spiral arms can have a substantial effect on the expected Galactic rotational velocities (Roberts 1972). The Galactic bar may also have an influence by adding noncircular motions to the general Galactic rotation.

The rotation model of Weiner & Sellwood (1999) used in Figure 8 takes into account the effects of a strong potential associated with the Galactic bar. This model uses a global Galactic gravitational potential to determine the motions of the gas in the interstellar medium (ISM). It uses both the minimum and maximum observed H\textsc{i} velocities along lines of sight in the inner

\footnote{5 We have scaled the Englmaier & Gerhard (2006) model for $R_0 = 8.5$ kpc.}
Galaxy in fitting the properties of the Galactic potential. We can again immediately rule out the distance on the far side of the tangent point. Since no \( \text{H} \, \text{ii} \) absorption is seen at velocities between 30 and 70 km s\(^{-1}\) (see Table 2 and Fig. 8), we can eliminate all distances except \( 4.0^{+0.3}_{-0.8} \) kpc. The Weiner & Sellwood (1999) model, however, does not take into account the effects of spiral arms. Since magnetars are expected to lie in or near spiral arms, this could have a significant impact on the velocity-determined distance to XTE J1810–197.

The rotation model of Englmaier & Gerhard (2006) used in Figure 9 takes into account the effects of a potential associated with the Galactic bar as well as those associated with spiral arms. The Englmaier & Gerhard (2006) model was determined in a similar fashion as the Weiner & Sellwood (1999) model. However, in the Englmaier & Gerhard (2006) model only the maximum (minimum) observed velocities for CO were used for positive (negative) Galactic longitudes. It should be noted that CO observations do not trace column densities as low as \( \text{H} \, \text{ii} \) does, and McClure-Griffiths & Dickey (2007) found that \( \text{H} \, \text{ii} \) provides a more reliable tracer of the tangent point velocities. Combined with fitting to only one side of the velocity-longitude data, this means that the Englmaier & Gerhard (2006) model uses a weaker potential for the Galactic bar compared with the Weiner & Sellwood (1999) model. In fact, the Englmaier & Gerhard (2006) model predicts that there should be no negative velocity gas along the line of sight toward XTE J1810–197, while the Weiner & Sellwood (1999) model does. As can be seen in the Southern Galactic Plane Survey (SGPS) \( \text{H} \, \text{ii} \) data (McClure-Griffiths et al. 2005), there is plenty of gas at negative velocities along this line of sight. We suggest that the Englmaier & Gerhard (2006) Galactic bar potential is too weak, and that the Weiner & Sellwood (1999) model should be used for velocities and distances associated with the Galactic bar.

We can, however, still use the Englmaier & Gerhard (2006) model to determine a distance for XTE J1810–197, since it is likely located in front of the Galactic bar, as is evidenced by the Weiner & Sellwood (1999) model results from above. In fact, comparing the Englmaier & Gerhard (2006) result with the Weiner & Sellwood (1999) result provides an indication of how spiral arms may be affecting the velocity-distance relationship toward XTE J1810–197. We can again rule out distances that lie on the far side of the tangent point and distances that include 30–40 km s\(^{-1}\) gas along the line of sight. As can be seen from Figure 9, we obtain kinematic distances of \( 3.3 \pm 0.2 \) or \( 4.0^{+0.3}_{-0.4} \) kpc. Due to uncertainties in the modeling of the Galactic rotation curve, the 0.1 kpc gap in distance between these two values is in effect negligible. We thus combine these two possible distance ranges into a single value, \( 3.1–4.3 \) kpc.

All of the above Galactic rotation models are derived from empirical models fit to observed data. There is one model that is fully derived from observational data, that of Brand & Blitz (1993). In this model, observations of \( \text{H} \, \text{ii} \) regions are used. The velocities of the \( \text{H} \, \text{ii} \) regions are determined from recombination lines and \( \text{H} \, \text{ii} \) absorption. Independent measurements provide distances to the \( \text{H} \, \text{ii} \) regions. Using the rotation model of Brand & Blitz (1993) shown in Figure 10, we obtain \( 2.4 \pm 0.5 \) kpc. However, this model does not have enough \( \text{H} \, \text{ii} \) regions at \( d \gtrsim 2 \) kpc in the general direction of XTE J1810–197 to be able to provide a good velocity-distance relationship (see Brand & Blitz 1993), so we give it little weight.

We conclude that the best estimate of a kinematically determined distance to XTE J1810–197 is provided by the Weiner & Sellwood (1999) and Englmaier & Gerhard (2006) models, giving \( d = 3.1–4.3 \) kpc.

6. AN UPPER LIMIT ON THE DISTANCE TOWARD XTE J1810–197

In Figure 7 of Durant & van Kerkwijk (2006) we see that toward XTE J1810–197 the extinction versus distance rises steeply between 3.0 and 3.5 kpc, and that for \( d \leq 13 \) the distance can be limited to be less than 4 kpc. The line of sight toward XTE J1810–197 contains the Infrared Dark Cloud (IRDC) G10.74-0.13 (Simon et al. 2006; Carey et al. 2000). IRDCs are thought to be places where giant molecular clouds are either just starting to form massive stars or on the verge of beginning to form stars. The sudden increase in opacity versus distance seen by Durant & van Kerkwijk (2006) is likely associated with this IRDC. We note that the highest opacity regions of the IRDC cover less than half the area on the sky that Durant & van Kerkwijk (2006) used to determine the visual extinction versus distance toward XTE J1810–197. Also, IRDCs can have extremely high opacities such that only the edge of the cloud is seen even in the infrared (Simon et al. 2006; Minter et al. 2001). Since the opacities can be very large, it is plausible that Durant & van Kerkwijk (2006) may have underestimated the actual extinction versus distance toward XTE J1810–197.

Jaffe et al. (1982) associated IRDC G10.74-0.13 with \( ^{12}\text{CO}(1 \rightarrow 2) \) emission centered at 32 km s\(^{-1}\), implying \( d < 3.8^{+0.5}_{-0.5} \) kpc for a flat rotation curve and \( d < 4.4^{+0.6}_{-0.3} \) kpc for the Weiner & Sellwood (1999) and Englmaier & Gerhard (2006) models. Our OH spectra (see § 8 below) show a large spectral feature at the same velocities that we also associate with the IRDC. All observed \( \text{H} \, \text{ii} \) absorption features lie at velocities lower than those associated with the IRDC. This puts XTE J1810–197 no farther than the front edge of the IRDC.

We consider the large increase in opacity at 4 kpc from Figure 7 of Durant & van Kerkwijk (2006) to be a hard upper limit on the distance to XTE J1810–197. This further constrains the distance estimate of XTE J1810–197 to be \( 3.1–4 \) kpc.

7. THE NEUTRAL HYDROGEN TOWARD XTE J1810–197: GBT VERSUS SGPS

The GBT has a resolution of 9.2′ at 21 cm, while the SGPS (McClure-Griffiths et al. 2005) has a resolution of about 3.3′. In Figure 11 we compare the GBT \( \text{H} \, \text{ii} \) spectrum with the SGPS spectrum. For the \( \text{H} \, \text{ii} \) self-absorption associated with the Heeschen Cloud we find the remarkable result that the line width of the
absorption increases with increasing spatial resolution! To our knowledge this effect has never been observed before for HI on arcminute resolutions.

Inspection of the SGPS HI data cube shows that there is structure within the HI emission inside of the GBT beam. We convolved the SGPS data with a beam the size of GBT’s, so that the two data sets would have the same spatial resolution. As can be seen from Figure 11 the GBT spectrum and 9.2’ resolution SGPS spectrum are in very good agreement. If we compare the line width of the HI absorption due to the Heeschen Cloud at ~8 km s\(^{-1}\) with the SGPS data having HI absorption seen against XTE J1810–197, we find that the line widths are identical.

These properties suggest that there is definite spatial structure in the HI emission on size scales of 3.3’–9.2’ (0.12–0.33 pc for a Heeschen Cloud distance of d = 125 pc). That the tiny beam of absorption against the magnetar (limited by the size of the pulsar emission region, which is smaller than the pulsar’s light cylinder radius, or about 1 light-second) has the same line width as the 0.12 pc-wide beam of the SGPS at the Heeschen Cloud, suggests that there are few if any spatial structures left unresolved by the SGPS in the Heeschen Cloud. Since the HI self-absorption line width does change between the GBT and SGPS resolutions, we can infer that either the absorption feature comprises multiple narrow-line features, or that the nonthermal broadening of the absorption feature changes between different structures in the Heeschen Cloud. Attempts to fit the different line width absorption-line structures in the Heeschen Cloud with multiple Gaussian components does not improve the fitting, which suggests that a single Gaussian is sufficient. This implies that the nonthermal contribution to the line width varies within the cloud.

The standard assumption is that nonthermal line broadening arises from turbulence. If the turbulence is intermittent, we can expect that the turbulence has decayed more in some places than in other locations (Frisch 1995). This can then easily explain the observed line widths of the Heeschen Cloud HI absorption. The areas that have undergone more damping of the turbulence will have less turbulent energy and thus have narrower nonthermal line widths.

8. OH ABSORPTION LIMITS TOWARD XTE J1810–197

Although we did not detect any OH absorption against XTE J1810–197, the limits are still interesting. All previous OH absorption detections against pulsars (Stanimirović et al. 2003; Weisberg et al. 2005; Minter 2005, 2008) have found that the absorption is deeper (larger opacity) and has a narrower line width than the pulsar-off spectra: in the three known cases, the OH absorption against the pulsars is 2–3 times deeper than seen in the pulsar-off spectra.

For our OH absorption limits against XTE J1810–197 of \(\tau < 0.1\) (1 \(\sigma\)), we would expect our pulsar-off spectra to have OH opacities \(\lesssim 0.033\). In Table 4 we list the opacities of the OH lines in the pulsar-off spectra. We subtracted the system temperature from the raw OH spectra, and then fitted a third-order polynomial to determine the continuum emission levels. Dividing the spectra by the continuum emission results in \(e^{-\tau}\) spectra for the pulsar-off spectra.

If we assume that the OH pulsar-off spectra should have a factor of 2–3 weaker opacity than the OH absorption against the pulsar, then we were likely within a factor of about 2 of detecting OH absorption against XTE J1810–197 at velocities within the range observed for HI absorption (Table 2), e.g., at 9.9 km s\(^{-1}\) at 1612 MHz, and 9.8 and 16.9 km s\(^{-1}\) at 1720 MHz (see Table 4). Unfortunately, due to the decay of the flux of XTE J1810–197 (Camilo et al. 2007a), we were not able to detect any OH absorption.

Our OH absorption limits toward XTE J1810–197 are also meaningful for the OH seen at \(V_{\text{LSR}} \gtrsim 28 \text{ km s}^{-1}\). The 1665 MHz OH feature at 30.7 km s\(^{-1}\) should have been detected at 2–3 \(\sigma\) if it were between us and XTE J1810–197. However, we would not have expected to detect OH absorption at these velocities based on the HI absorption results (Table 2).

9. THE COLUMN DENSITY TO XTE J1810–197

From the HI and OH observations that we have performed, it is possible to estimate the column density of hydrogen \(N_H\), both atomic and molecular, to XTE J1810–197. This can then be compared with the range of values \(N_H = (6.5–14) \times 10^{21} \text{ cm}^{-2}\) determined from fitting X-ray spectra (Gotthelf & Halpern 2005; Durant & van Kerkwijk 2006).

9.1. Estimate of the Atomic Column Density to XTE J1810–197

We cannot directly measure the HI column density toward XTE J1810–197, since we do not have enough constraints to perform radiative transfer modeling in this direction. We can, however, still make an estimate of the column density to XTE J1810–197. To do this, we just integrate the HI emission spectrum
between 0 and 25.7 km s\(^{-1}\). Since XTE J1810–197 is at the low Galactic latitude of \(-0.2\)°, it is reasonable to assume that half of the emission at any velocity comes from the near side of the tangent point and half comes from the far side of the tangent point. Assuming that half of the emission comes from H\(_i\) on the near side of the tangent point, we obtain an estimate of the column density to XTE J1810–197,

\[
N_{\text{HI}} = \frac{1}{2} \int_0^{25.7} 1.83 \times 10^{18} T_B(v) \, dv \, \text{cm}^{-2}.
\]  

(1)

Since there are clouds on the near side of the tangent point that significantly absorb the H\(_i\) emission from the far side of the tangent point, as is evidenced by the absorption seen against XTE J1810–197, this method provides a lower limit to the column density of H\(_i\) to XTE J1810–197. On performing the integration we find that \(N_{\text{HI}} \approx 1.8 \times 10^{21} \text{ cm}^{-2}\).

### 9.2. Estimate of the Molecular Column Density to XTE J1810–197

We can use the pulsar-off OH spectra to make an estimate of the molecular column density to XTE J1810–197. From Figures 3 and 6 we see that the 1612 MHz OH lines are in absorption, while the 1720 MHz OH lines are in emission, with both having approximately the same amplitude. Such conjugate emission arises in regions where the OH column density is in the range \(10^{14} \text{ cm}^{-2} < N_{\text{OH}} \Delta v < 10^{15} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}\), with \(\Delta v\) being the velocity resolution of the observations (Weisberg et al. 2005; Elitzur 1992). The total column density of OH is found by integrating over the whole line.

Integrating over the OH spectrum between 0 and 25.7 km s\(^{-1}\), and assuming that half of the OH emission is from beyond the tangent point, we find

\[
(2.4 \pm 0.3) \times 10^{14} \text{ cm}^{-2} < N_{\text{OH}} < (2.4 \pm 0.3) \times 10^{15} \text{ cm}^{-2}.
\]  

(2)

Using standard abundances, the ratio of the number of OH molecules to the number of hydrogen atoms is \(N_{\text{OH}}/N_{\text{HI}} = 6 \times 10^{-8}\) (Elitzur 1992), which gives

\[
(4 \pm 0.7) \times 10^{21} \text{ cm}^{-2} < N_{\text{HI}} < (40 \pm 7) \times 10^{21} \text{ cm}^{-2}\]  

(3)

between us and the magnetar.

Measurements of the \(^{12}\text{CO}(2 \rightarrow 1)\) spectrum toward XTE J1810–197 are available from Dame et al. (2001). The total column density of hydrogen in molecular form can be determined from the \(^{12}\text{CO}(2 \rightarrow 1)\) spectrum using

\[
N_{\text{HI}} = 2N_{\text{H}_2} = 2X_{\text{CO}} \int_0^{25.7} T_B^{\text{CO}}(v) \, dv,
\]  

(4)

where \(X_{\text{CO}}\) is a conversion factor. The commonly used ”standard” value for this is \(X_{\text{CO}} = 2 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}\). However, \(X_{\text{CO}}\) is known to vary depending on the line of sight (Magnani et al. 1998). The \(^{12}\text{CO}(2 \rightarrow 1)\) spectrum nearest to the line of sight toward XTEJ1810–197 gives \(\int_0^{25.7} T_B^{\text{CO}}(v) \, dv = 28.75 \text{ K m s}^{-1}\), of which we will assume that half arises beyond the tangent point. From Figure 4 of Magnani et al. (1998) we see that \(X_{\text{CO}} = 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}\) is reasonable for the amount of \(^{12}\text{CO}(2 \rightarrow 1)\) toward XTE J1810–197. This then yields \(N_{\text{HI}} \gtrsim 2.8 \times 10^{21} \text{ cm}^{-2}\).

This limit for \(N_{\text{HI}}\) obtained from the CO spectrum is consistent with the range of values determined using the OH spectra (eq. [3]). This also tells us that the OH column densities are near the lower limit of \(N_{\text{OH}} \Delta v = 10^{14} \text{ cm}^{-2} \text{ km}^{-1} \text{ s}\). Since the CO spectra have a higher signal-to-noise ratio, we will use the CO value for the molecular gas contribution to \(N_{\text{HI}}\).

Adding the molecular and atomic components of \(N_{\text{HI}}\), we obtain \(N_{\text{HI}} \gtrsim 4.6 \times 10^{21} \text{ cm}^{-2}\). This limit is in agreement with the values determined from the X-ray spectrum of XTE J1810–197. Unfortunately, we only have a lower limit for the total column density that is below the values determined from the X-ray spectrum.

### 10. Kinematic Distances of Objects Near XTE J1810–197

As can be seen from Figure 8, the Galactic bar can have a significant impact on the distance estimates to objects at low Galactic longitudes. It is worthwhile to reexamine the distance estimates to the objects near the line of sight toward XTE J1810–197. In the discussions below the reader is advised to refer to Figure 8, which provides a relatively good reference velocity versus distance relationship for each of the different lines of sight.

#### 10.1. G11.2-0.3

Becker et al. (1985) claimed that SNR G11.2-0.3 lies well on the far side of the tangent point. However, Green et al. (1988) noted the lack of absorption between \(\nu_{\text{LSR}} = 45 \text{ km s}^{-1}\) and the tangent point velocity, which led them to assign a distance of \(\approx 5 \text{ kpc}\) to G11.2-0.3, while attributing weak absorption at negative velocities to peculiar motions in local gas. A distance of \(\approx 5 \text{ kpc}\) is also in reasonable agreement with the expected expansion of the SNR (Green et al. 1988). If we take the Galactic bar into account using the model of Weiner & Sellwood (1999), we can reconcile the H\(_i\) absorption with the expansion/age-derived distance estimate of Green et al. (1988). The H\(_i\) absorption to G11.2-0.3 at \(\nu_{\text{LSR}} \approx -20 \text{ km s}^{-1}\) arises from the Galactic bar, which is at a distance of \(\approx 5.5\) kpc along this line of sight (see Fig. 8). So we judge that G11.2-0.3 likely lies within the Galactic bar at \(\approx 5.5\) kpc. (Note that very little absorption, if any, is to be expected at 40–75 km in front of the Galactic bar. The velocity-distance relationship has a steep slope in this range, which indicates that there will be low column densities even for smoothly distributed gas.)

#### 10.2. G10.3-0.1

The H\(_\pi\) region G10.3-0.1 is part of the W31 complex. The H\(_\pi\) absorption spectrum of G10.3-0.1 was measured by Kalberla et al. (1982). From Figure 2 of Kalberla et al. (1982) we see that H\(_\pi\) absorption is seen from \(0–45 \text{ km s}^{-1}\) and at \(-20 \text{ km s}^{-1}\). This provides a lower limit distance of \(\approx 7 \text{ kpc}\) using the Weiner & Sellwood (1999) rotation model, allowing G10.3-0.1 to reside in the Galactic bar. The emission-line velocity for G10.3-0.1 is \(13 \text{ km s}^{-1}\). Although it is possible to put the emission line in the Galactic bar behind the H\(_\pi\) absorption line, it is not very likely, since this would require the emission-line velocity to lie within the very large velocity shear where the velocities go from \(-20\) to \(+150 \text{ km s}^{-1}\) within a distance of approximately 0.5 kpc. However, if G10.3-0.1 did lie on the far side of the tangent point, then we would expect H\(_i\) absorption to be seen at high velocities \(>70 \text{ km s}^{-1}\). There is a possible H\(_i\) absorption feature at \(120 \text{ km s}^{-1}\) in Figure 2 of Kalberla et al. (1982), but further observations would be needed to determine if it is real or not.

#### 10.3. G10.2-0.3

The W31 complex also contains the H\(_\pi\) region G10.2-0.3. Kalberla et al. (1982) and Greisen & Lockman (1979) measured
the H\textsc{i} absorption against G10.2-0.3. From Figure 4 of Greisen & Lockman (1979) we see that the H\textsc{i} absorption covers the velocity range 0–41 km s\textsuperscript{-1}. There are also H\textsc{i} absorption features at –20, 50, 70, and 75 km s\textsuperscript{-1} (Greisen & Lockman 1979). The emission-line velocity for G10.2-0.3 is given as 13 km s\textsuperscript{-1} by Kalberla et al. (1982). The H\textsc{i} absorption gives a minimum distance of 5.5 kpc using the Weiner & Sellwood (1999) rotation model. The emission line then indicates that G10.2-0.3 could reside in the Galactic bar at a distance of 7.0 kpc or on the far side of the tangent point. However, for this to be the case, this H\textsc{i} region would also have to reside in the part of the Galactic bar with the large velocity shear.

10.4. G10.6-0.4

The H\textsc{ii} region G10.6-0.4 is also part of the W31 complex. The H\textsc{i} absorption spectrum of G10.6-0.4 was measured by Caswell et al. (1975). From Figure 32 of Caswell et al. (1975) we see that the H\textsc{i} absorption is seen at velocities from ~–10 to ~–45 km s\textsuperscript{-1}. The emission lines for this H\textsc{ii} region have velocities near zero (Caswell et al. 1975). This suggests that G10.6-0.4 could also be as nearby as 6.9 kpc in the Galactic bar.

10.5. G10.0-0.3 and LBV 1806–20

LBV 1806–20 is the central star that powers the radio nebula, G10.0-0.3, with SGR 1806–20 being a likely member of the same star cluster that contains LBV 1806–20 (Corbel & Eikenberry 2004). Figure 3 of Corbel & Eikenberry (2004) shows the NH\textsubscript{3} absorption spectrum toward G10.0-0.3. Absorption features are seen at 29, 62, and 71 km s\textsuperscript{-1}. Corbel & Eikenberry (2004) set a lower distance limit of 5.7 ± 0.4 kpc using a flat rotation curve for the 71 km s\textsuperscript{-1} absorption line. Using the rotation curve of Weiner & Sellwood (1999) we find a lower limit on the distance to G10.0-0.3 of 5.7 kpc, corresponding to the front edge of the Galactic bar. Radio recombination lines from G10.0-0.3 have a velocity of 7.7 ± 0.5 km s\textsuperscript{-1} (Kim & Koo 2001). Corbel & Eikenberry (2004) measured the Br\gamma spectra of LBV 1806–20 and determined its emission-line velocity is ~–3 ± 20 km s\textsuperscript{-1}. These emission-line velocities must arise at a distance farther away than the NH\textsubscript{3} 71 km s\textsuperscript{-1} absorption line. For a flat rotation curve, this means that G10.0-0.3 must lie on the far side of the Galaxy. However, from the rotation model of Weiner & Sellwood (1999), which includes the Galactic bar, we find that G10.0-0.3 and LBV 1806–20 could be located in the Galactic bar at a distance of ~6.9 kpc, contrary to the result of Corbel & Eikenberry (2004), who determined that LBV 1806–20 and G10.0-0.3 must lie on the far side of the tangent point. We cannot exclude the possibility that LBV 1806–20 and G10.0-0.3 may lie on the far side of the tangent point.

Corbel & Eikenberry (2004) also determined an extinction of AV = 29 ± 2 mag toward LBV 1806–20 in the J, H, and K bands in the infrared. The local extinction of a few AV per kiloparsec would suggest that LBV 1806–20 is located beyond the Galactic bar. However, it should be noted that the extinction can rise rapidly in the inner Galaxy as IRDCs are encountered. The region around LBV 1806–20 contains many IRDCs (see Simon et al. 2006), which can have quite large amounts of extinction. It is difficult to determine if any IRDCs lie along the line of sight toward LBV 1806–20 due to the bright emission from the W31 complex. However, since LBV 1806–20 is a member of a young cluster that could easily have formed within an IRDC, we believe that the extinction value determined by Corbel & Eikenberry (2004) cannot be used to put any limits on the distance to LBV 1806–20.

10.6. SGR 1806–20

H\textsc{i} absorption measurements against the afterglow of SGR 1806–20 were made by Cameron et al. (2005). The absorption lines fall in the velocity range of ~–20 to +80 km s\textsuperscript{-1}. Using a flat rotation curve, McClure-Griffiths & Gaensler (2005) determined that SGR 1806–20 must lie at least ~6 kpc away. Using the rotation curve of Weiner & Sellwood (1999) we find that the +80 km s\textsuperscript{-1} could arise as near as the front side of the Galactic bar. Likewise, the –20 km s\textsuperscript{-1} line could arise within the Galactic bar. This is consistent with the results for LBV 1806–20 and G10.0-0.3, and we suggest that the minimum distance to SGR 1806–20 is 6.7 kpc.

11. MODELS OF THE LINE OF SIGHT TOWARD XTE J1810–197

A detailed molecular model of the ISM toward SGR 1806–20 has been developed by Corbel et al. (1997) and Corbel & Eikenberry (2004), depicted in Figure 8 of the latter. With increasing distance toward SGR 1806–20, their model encounters gas at F_{\text{LSR}} = 4, 24, 30, 38, and 44, and then 13 km s\textsuperscript{-1} in reaching the Scutum-Crux spiral arm (labeled as the 30 km s\textsuperscript{-1} spiral arm in Fig. 8 of Corbel & Eikenberry [2004]). Since the line of sight toward SGR 1806–20 is close to that of XTE J1810–197, we might expect to encounter clouds at roughly the same velocities on the line of sight toward XTE J1810–197. For a flat rotation curve and ignoring random motions of clouds, the velocities observed toward XTE J1810–197 will be shifted by about ~2 km s\textsuperscript{-1} relative to the SGR 1806–20 line of sight.

The gas at 4 km s\textsuperscript{-1} toward SGR 1806–20 is likely one of the two velocity components of the Heeschen Cloud (Riegel & Crutcher 1972) and can be associated with the H\textsc{i} absorption feature at 7.7 km s\textsuperscript{-1} toward XTE J1810–197, which is from the other velocity component of the Heeschen Cloud. The gas at 24 km s\textsuperscript{-1} toward SGR 1806–20 can be associated with the H\textsc{i} absorption features at 22.8 or 25.7 km s\textsuperscript{-1} toward XTE J1810–197. We can associate the 13 km s\textsuperscript{-1} gas toward SGR 1806–20 with the H\textsc{i} absorption seen at 14.1 km s\textsuperscript{-1} toward XTE J1810–197. It thus appears that the same cloud complexes are being seen on both the XTE J1810–197 and SGR 1806–20 lines of sight.

If the model of Corbel et al. (1997) and Corbel & Eikenberry (2004) is correct, then we should also expect to see H\textsc{i} absorption at velocities of roughly 30, 38, and 44 km s\textsuperscript{-1} toward XTE J1810–197, since we observe absorption that can be associated with the 13 km s\textsuperscript{-1} cloud in their model. In fact, we do not observe any H\textsc{i} absorption against XTE J1810–197 at these velocities. This suggests that either (1) the model of Corbel et al. (1997) and Corbel & Eikenberry (2004) does not place the MC 30, MC 38, and MC 44 clouds (following the notation of Corbel et al. 1997) at the correct distances and in the proper order (we do not dispute the distance to SGR 1806–20); or (2) it cannot be applied to the line of sight toward XTE J1810–197, which is 41’ away; or (3) there is molecular material without H\textsc{i} along these lines of sight. The last possibility is not likely, since molecular clouds are expected to have cosmic-ray ionization and photodissociation regions within and at their outer edges, which would produce atomic hydrogen (see Minter et al. 2001; their § 9.2 and references therein).

The results of § 10, in which we take into account the effects of the Galactic bar on kinematic distances, shows that all of the H\textsc{ii} regions in the W31 complex as well as LBV 1806–20 and SGR 1806–20 could lie within the Galactic bar. This contradicts the results of the Corbel et al. (1997) and Corbel & Eikenberry
(2004), which assumed a flat rotation curve for kinematical distance determination.

12. DISCUSSION

Using the DM = 178 ± 5 cm$^{-3}$ pc measured for XTE J1810–197 (Camilo et al. 2006), its distance according to the Cordes & Lazio (2002) electron density model is 3.3 kpc. This model has a claimed average uncertainty of about 20%, which, however, can be much larger for individual objects. For the sake of discussion, we assume an uncertainty of 1 kpc. The electron density model was derived using distances to pulsars that in many cases were determined via H i absorption spectra assuming a flat rotation curve, so that it seems most appropriate to compare the DM-derived distance of 3.3 ± 1 kpc with our flat rotation curve’s kinematic distance of 3.4 ± 0.6 kpc. These two values agree remarkably well and imply that along the line of sight to XTE J1810–197, the Cordes & Lazio (2002) model gives a good representation of the average free electron density out to about 4 kpc.

The distance to XTE J1810–197 has been estimated from X-ray observations to range over 2.5–5 kpc (Gotthelf & Halpern 2005; Gotthelf et al. 2004). These distances are determined by converting $N_{\text{HI}}$ values obtained from fits to the X-ray spectra into visual extinction, $A_V$, and an estimate of the $A_V$ per kiloparsec in the Galaxy. This method is limited by a number of complications: (1) the spectral model used to fit the X-ray data, e.g., two blackbodies versus a blackbody and a power law; (2) the $N_{\text{HI}}$ versus $A_V$ relationship determined locally (within ~1 kpc) but used for large distances ($>$1 kpc); (3) the large deviations from the fitted $N_{\text{HI}}$ versus $A_V$ relationship for any particular line of sight; and (4) the $d-A_V$ relationship also determined locally but used for large distances.

Durant & van Kerkwijk (2006) determined $d = 3.1 ± 0.5$ kpc toward XTE J1810–197 assuming an X-ray $N_{\text{HI}} = 14 \times 10^{21}$ cm$^{-2}$, which is higher than any of the values fitted by Gotthelf et al. (2004) or Gotthelf & Halpern (2005). A consistent value of $N_{\text{HI}} = 6.5 \times 10^{21}$ cm$^{-2}$ was obtained by the latter authors fitting a two-blackbody model, and by Güver et al. (2007) fitting a surface thermal plus magnetospheric scattering model to the X-ray spectra. We consider the $d-A_V$ relationship of Durant & van Kerkwijk (2006) using red clump stars in the line of sight to XTE J1810–197 to be an improvement, although it is still necessary to choose an X-ray-fitted value of $N_{\text{HI}}$ and convert it into a visual extinction $A_V$. Using $N_{\text{HI}} = 6.5 \times 10^{21}$ cm$^{-2}$, the extinction toward XTE J1810–197 becomes $A_V \approx 3$–4.5 mag using Figure 3 of Predel & Schmitt (1995). This then yields a distance estimate of 2.3–3.5 kpc based on Figure 7 of Durant & van Kerkwijk (2006).

The kinematic distances determined from the H i absorption measurements presented in this paper rely only on the model of Galactic rotation used to convert the measured velocity into a distance. The Weiner & Sellwood (1999) and Englmaier & Gerhard (2006) models both give consistent results (see Table 5). The infrared extinction curve versus distance of Durant & van Kerkwijk (2006) provides a hard upper limit on the distance to XTE J1810–197. We prefer the distance of 3.1–4 kpc determined in this paper over the DM- and X-ray-derived distances, because our conversion of measured velocity to distance is more direct and better constrained than through these other methods.

Overall, we can thus summarize that the distance to XTE J1810–197 is 3.1–4 kpc. Together with the measured proper motion of the AXP, this results in a transverse velocity corrected to the LSR of 212 ± 35 km s$^{-1}$ (Helfand et al. 2007), a perfectly ordinary velocity among pulsars.

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Notes.—See §§ 6 and 12. Overall, our best distance determination comes largely from the direct H i measurements on XTE J1810–197, and is 3.1–4 kpc.

Table 5

| Measurement | Method | $d$ (kpc) | References |
|-------------|--------|----------|------------|
| DM          | $n_e$ model (Cordes & Lazio 2002) | 3.3 ± 1 | 1 |
| X-ray: blackbody + power law | $N_{\text{HI}} \rightarrow A_V \rightarrow 1.5 - 2.0$ mag kpc$^{-1} \rightarrow d$ | ~5.0 | 2 |
| X-ray: two blackbodies | $N_{\text{HI}} \rightarrow A_V \rightarrow 1.5 - 2.0$ mag kpc$^{-1} \rightarrow d$ | ~2.5 | 3 |
| X-ray: two blackbodies | $N_{\text{HI}} \rightarrow A_V \rightarrow 1.5 - 2.0$ mag kpc$^{-1} \rightarrow d$ | 3.1 ± 0.5 | 4 |
| X-ray: two blackbodies | $N_{\text{HI}} \rightarrow A_V \rightarrow 1.5 - 2.0$ mag kpc$^{-1} \rightarrow d$ | 2.3-5 | 5 |
| H i absorption | Flat rotation curve (Fich et al. 1989) | 3.4 ± 0.6 | 5 |
| H i absorption | Weiner & Sellwood (1999) model | 4.0 ± 0.3 | 5 |
| H i absorption | Englmaier & Gerhard (2006) model | 3.1–4.3 | 5 |
| H i absorption | Brand & Blitz (1993) model | 2.4 ± 0.5 | 5 |

References.—(1) Camilo et al. 2006; (2) Gotthelf et al. 2004; (3) Gotthelf & Halpern 2005; (4) Durant & van Kerkwijk 2006; (5) this work.
