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NEUTRAL HYDROGEN ABSORPTION MEASUREMENTS OF FOUR DISTANT PULSARS AND THE ELECTRON DENSITY IN THE INNER GALAXY

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ABSTRACT

We have used the VLA to measure neutral hydrogen absorption and emission spectra toward four distant low-latitude pulsars in the inner Galaxy whose spectra have not been previously recorded. In two cases, there is also a second reasonably bright source in the main beam of the telescope. We use the companion spectra plus all published H I absorption spectra in the direction of each pulsar to assist in the kinematic determination of pulsar distances. We also derive limits on the main electron density along each line of sight, and we find that even along paths toward the inner Galaxy, the average electron density does not exceed ~ 0.1 cm^{-3}. We test the Taylor & Cordes (1993) Galactic electron density model against our measured electron densities plus additional inner Galaxy values recently determined by Koribalski et al. (1995), and conclude that no major corrections to the model are indicated.

Subject headings: ISM: abundances — ISM: general — pulsars: general — radio lines: ISM — stars: distances

1. INTRODUCTION

Pulsar distance measurements, when combined with pulse dispersion measurements, provide a powerful tool for determining the free electron density of our Galaxy. The dispersion measure DM, easily derivable from pulse timing measurements at two frequencies, is related to the path integral of the electron density along the pulsar-Earth line of sight:

$$\mathrm{DM} = \int_0^d n_e(s) ds . \qquad (1)$$

The average electron density along the line of sight, $\langle n_e \rangle$, is thus related to the dispersion measure and distance d as follows:

$$\langle n_e \rangle = \frac{1}{d} \left[\int_0^d n_e(s) ds \right] = \frac{\mathrm{DM}}{d} . \qquad (2)$$

Measurements of the electron density along numerous lines of sight can then be used to construct a model of the Galactic distribution of electron density (e.g., Frail et al. 1991; Cordes et al. 1991; Taylor & Cordes 1993). These Galactic electron density models are very useful for two purposes. First, they provide constraints for studies of Galactic sources of ionization. Second, through inversion of equation (2), they can be used to estimate the distance of any other pulsar whose dispersion measure is known (e.g., Taylor, Manchester, & Lyne 1993). Since the dispersion measure has been determined for the vast majority of known pulsars, this procedure provides a powerful technique for studies of the Galactic distribution and population statistics of pulsars (e.g., Johnston 1994 and Lorimer et al. 1993, respectively).

The Taylor & Cordes (1993) Galactic electron density model represents a thorough synthesis of data available at the time of its creation, and it has rapidly become the model of choice. It is important to test this model against additional measurements in order to refine it further, especially by improving its treatment of particular regions of the Galaxy. The inner Galaxy was singled out by Taylor & Cordes (1993) as a region particularly requiring additional pulsar distance measurements in order to improve the model. A better determined electron density in the inner Galaxy would in turn permit more detailed estimates of an apparent deficit of pulsars in that region (Johnston 1994). Two high-frequency searches for pulsars in the inner Galaxy (Clifton et al. 1992; Johnston et al. 1992) have yielded new pulsars appropriate for these studies, providing us with additional motivation for the current investigation. Three of the four pulsars observed in the present study were discovered in one of these surveys.

2. OBSERVATIONS AND ANALYSIS

We used the VLA to measure the neutral hydrogen absorption and emission spectra of four low-latitude pulsars plus two nearby sources. All sources lie in the direction of the inner Galaxy. In order to decrease noise in the absorption spectra, we gated the VLA correlators *off* in the interval between pulsar pulses using equipment developed by T. H. Hankins, exactly as described by Frail et al. (1991). We eliminated the spatially smooth H I *emission* from the absorption spectra by making use of the spatial filtering properties of the VLA interferometer, and we separately determined the H I emission spectra by forming and summing single-dish spectra from each of the

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VLA antennas. The original 2.6 km s^{-1} resolution of absorption and emission spectra was preserved throughout the analysis and subsequent displays. The overall brightness temperature (T_B) calibration of the emission spectra of the three pulsars with $l > 340°$ was established by defining our peak T_B to be equal to the peak temperature of the nearest point in the Kerr et al. (1986) Parkes 18 m H I emission survey, multiplied by their recommended factor of 0.975 for brightness temperature conversion. The brightness temperature calibration of the one remaining pulsar, at $l \sim 23°$, was similarly determined from the nearest point in the Weaver & Williams (1974) Hat Creek Survey, after multiplying the displayed antenna temperatures by a factor of 1.18 (Williams 1973). These procedures should yield a brightness temperature scale correct to $\sim 10\%$, which is more than adequate for our purposes.

In the case of two of the pulsars, there was another bright source in the main beam of the telescope. This proved advantageous in terms of providing a comparison absorption spectrum along a nearly identical line of sight (see below), but in one case it also required us to eliminate its contaminating presence from the pulsar absorption spectrum. In order to do so, we fitted and subtracted the visibility data for the companion source from the data set, using the NRAO AIPS software task UVSUB.

The basic ideas of kinematic distance determination may be summarized as follows: A radio source (in this case, a pulsar) must be farther along the line of sight than any H I that absorbs its signal, and nearer than an "appropriate" H I feature that does *not* show absorption. The determination of a lower kinematic distance limit based on observed absorption is relatively unambiguous. However, the derivation of an upper limit from the *absence* of absorption generally requires the interpretation of additional information concerning the sensitivity of the observation and the properties of the H I along the line of sight. For example, Weisberg, Boriakoff, & Rankin (1979) found, in an empirical study of the extensive Nançay H I absorption survey (Crovisier, Kazes, & Aubry 1978), that the optical depth of H I absorption in the spectra of sources lying behind H I with $T_B > 35$ K is rarely less than 0.3. They then used this criterion to place a pulsar closer than any such emission if no absorption exceeding this threshold was observed. Frail & Weisberg (1990) pointed out that this criterion represents the conservative limit of the H I T_S-τ scatter diagram.

For their critical evaluation of all pulsar distance measurements, Frail & Weisberg established the following specific criteria for determining lower and upper kinematic distance limits from absorption and emission spectra having adequate spectral resolution, which we shall also use. First, they defined the *velocities* needed for the kinematic distance determinations. The velocity v_L corresponding to the lower *distance* limit is the velocity of the deepest absorption of the farthest (from Earth) observed absorption feature. The velocity v_U corresponding to the upper *distance* limit is the velocity of the closest (to Earth) peak in the emission spectrum with $T_B \geq 35$ K that does *not* also show associated absorption at the $\tau \sim 0.3$ level. Provided that the absorption spectrum noise is sufficiently small, the $T_B \geq 35$ K criterion may be relaxed in accord with the upper envelope of the T_S-τ relation. In addition, the properties of the absorbing gas vary little over 3° or 4° regions in the Galactic plane. Consequently, the absorption spectra of nearby sources may also provide sufficient information to relax this limit, if, for example, they show absorption in H I emission features having $T_B < 35$ K. Next, to determine distance limits D_L and D_U, the velocity limits v_L and v_U are referred to a Galactic rotation model. Following Frail & Weisberg, we use the Fich, Blitz, & Stark (1989) model with standard IAU Galactic parameters (Kerr & Lynden-Bell 1986) of $R_0 = 8.5$ kpc and $V_0 = 220$ km s^{-1} (see Koribalski et al. 1995 for particulars), except in the extreme inner Galaxy, where the strongly non-circular motions of the expanding 3 (or 4) kpc arm must be incorporated (e.g., Caswell & Haynes 1987). When the Fich et al. Galactic rotation model is used to determine kinematic distances, we follow Frail & Weisberg in assigning uncertainties in the resulting distance limits by adding and subtracting a 7 km s^{-1} typical random and systematic contribution to the measured velocity limits. Where distance limits are defined by the expanding 3 kpc arm, whose exact location in poorly known, we estimate distance uncertainties by finding the intersection of the line of sight with an annulus of inner and outer Galactocentric radii of 3 and 4 kpc.

3. RESULTS

Figure 1 shows the emission and absorption spectra for each pulsar and a plot, based on the Fich et al. model, of velocity versus distance along each line of sight. The kinematic distance analysis for each pulsar follows here. Results are summarized in Table 1.

3.1. *PSR B1648−42 = J1651−4246*; $(l, b) = (342\overset{\circ}{.}5, 0\overset{\circ}{.}9)$

This pulsar's H I spectrum shows strong absorption out to a feature which is deepest at $v_L = -63$ km s^{-1}, for $D_L = 4.8 \pm 0.3$ kpc. The absence of absorption in the emission feature centered at -125 km s^{-1}, the 3 kpc expanding arm, does not yield a firm upper distance limit, because at $T_B \sim 30$ K, it has not exceeded the $T_B \sim 35$ K threshold which must be met by an emission feature to guarantee that a source lying beyond the emission feature would show absorption in its spectrum, as discussed above. In contrast, Frail et al. (1991) were able to

TABLE 1

KINEMATIC DISTANCES AND ELECTRON DENSITIES

PSR B1950	PSR J2000	t (hr)	l	b	DM (pc cm^{-3})	D_{TC} (kpc)	Distance Limits: Lower (kpc)	Distance Limits: Upper (kpc)	Electron Density Limits: Upper (cm^{-3})	Electron Density Limits: Lower (cm^{-3})
1648−42	1651−4246	2.8	342°.5	0°.9	525	7.21	4.8 ± 0.3	...	0.11 ± 0.01	...
1703−40	1707−4053	3.2	345.7	−0.2	360	5.12	3.8 ± 0.5	...	0.095 ± 0.012	...
1718−35	1721−3532	5.3	351.7	0.7	496	6.36	4.4 ± 0.5	5.2 ± 0.6	0.11 ± 0.01	0.095 ± 0.011
1830−08	1833−0827	5.7	23.4	0.1	411	5.67	4.0 ± 0.4	5.3 ± 0.3	0.10 ± 0.01	0.078 ± 0.004

NOTES.—t is integration time, and D_{TC} is the distance estimated from the dispersion measure and the Taylor & Cordes 1993 Galactic electron density model.

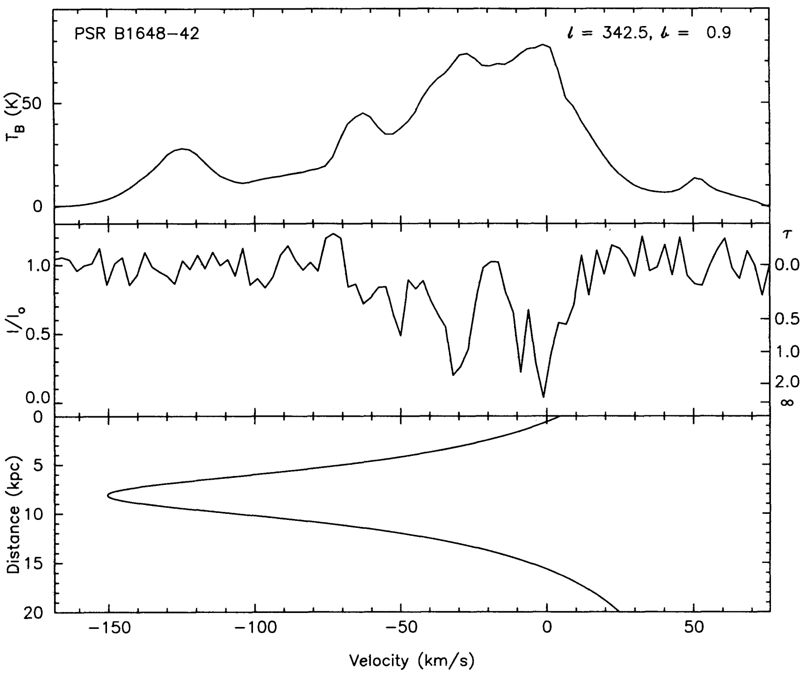

FIG. 1*a*

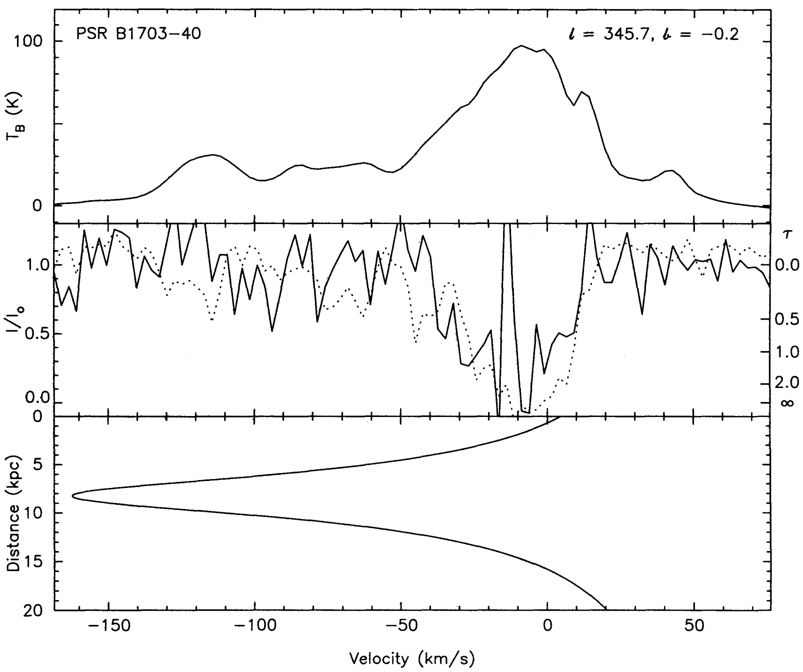

FIG. 1*b*

FIG. 1.—(*a–d*) Neutral hydrogen emission (*top panels*) and absorption (*center panels*) spectra and kinematic distance vs. velocity for the Fich et al. (1989) Galactic rotation model (*bottom panels*) in the direction of four pulsars. In two cases, the absorption spectrum of an additional source in the main beam of the VLA is shown as a dashed line atop the pulsar absorption spectrum.

place an upper limit on the distance to PSR B1641−45, only about 3° away [$(l, b) = (339.^\circ2, -0.^\circ2)$] based on the absence of absorption in a stronger emission feature with $T_B \sim 40$ K at $v = -77$ km s^{-1}. Similarly, Koribalski et al. (1995) placed an upper distance limit on PSR J1709−44, also about 3° away [$(l, b) = (343.^\circ1, -2.^\circ7)$] based on the lack of absorption in a $T_B \sim 40$ K, $v = -30$ km s^{-1} emission feature.

H I absorption and emission spectra have been measured for numerous objects along the plane within 5° of this pulsar by Caswell et al. (1975), Garwood & Dickey (1989), Goss et al. (1972), and Radhakrishnan et al. (1972). Unfortunately, none of these spectra provide additional information on the interpretation of the lack of absorption in the PSR B1648−42 spectrum at −125 km s^{-1}: Either these sources' emission spectra, like

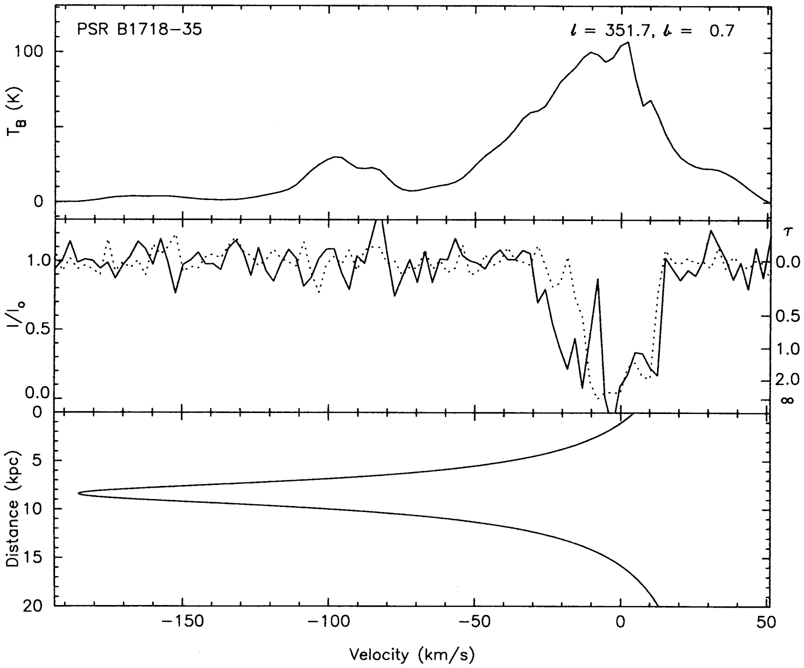

FIG. 1c

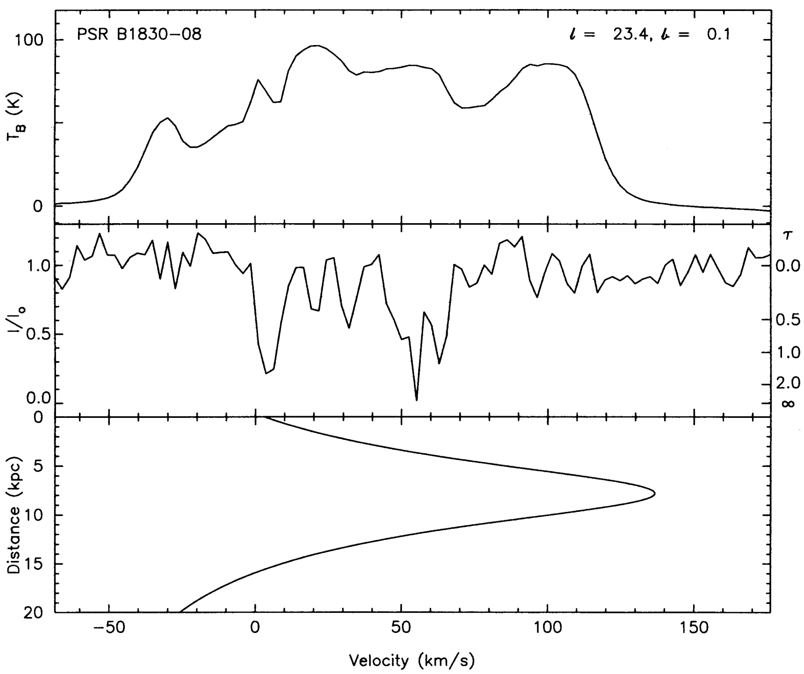

FIG. 1d

those of the two nearby pulsars mentioned above, have stronger H I emission at this velocity than does PSR B1648−42, or else, if they do not, they also do not show absorption near this velocity. Hence it is not possible from this information to choose between two very different alternative locations for this pulsar—either that our observed lack of absorption at these velocities results from the pulsar being closer than this gas, or, alternatively, merely that the gas is not sufficient optically thick to show measurable absorption from the more distant pulsar. As described below for PSR B1703−40 and PSR B1718−35, four sources in the range $l \sim 348°$–$350°$ do show absorption near $v = -110$ km s^{-1} km s^{-1} in rather faint emission features of $T_B \sim 30$ K; nevertheless, the 6° separation between them and PSR B1648−42 is large enough that it is risky to extrapolate these results to the pulsar line of sight. In summary, we have found no additional information from other sources' H I spectra that would enable us to specify an upper distance limit.

3.2. *PSR B1703−40 = J1707−4053*; $(l, b) = (345\overset{\circ}{.}7, -0\overset{\circ}{.}2)$

The most distant absorption feature in the pulsar spectrum is deepest at $v_L = -35$ km s^{-1}, yielding $D_L = 3.8 \pm 0.5$ kpc. The dotted curve atop the pulsar absorption spectrum represents the absorption spectrum of another source in the main beam of the telescope, approximately 13′ west-northwest of the pulsar, at B1950 coordinates $(\alpha, \delta) = (17^h02^m46\overset{s}{.}3, -40°45'45'')$, with a flux density $\sim$2.8 times that of the pulsar. The companion source's spectrum shows absorption similar to the pulsar's out to $v \sim -40$ km s^{-1} (with the exception of a pulsar noise spike at $v \sim -13$ km s^{-1}). In the more distant $v \sim -45, -70$, and -120 km s^{-1} emission feature, the companion spectrum shows $\tau \sim 0.4$ absorption, whereas the pulsar spectrum is too noisy to determine the presence or absence of such absorption. (The pulsar's spectrum is significantly noisier than the companion's because the noise in any absorption spectrum scales inversely with the background source flux density.) Consequently, we are not able to set an upper distance limit. The quality of the companion source spectrum and the presence of its higher negative velocity absorption features indicate that more sensitive observations of the pulsar spectrum might well yield a significant upper distance limit: Although the more distant features do not exceed the $T_B \sim 35$ K threshold, the presence of absorption in those features in the spectrum of a source only 13′ away argues strongly that they will also be present in the pulsar spectrum at similar optical depths if it does lie beyond them. The absorption spectra of probable supernova remnants (SNRs) G348.5+0.1 and G348.7+0.3, both lying in the plane within less than 3° of the pulsar, provide further support for this proposition, since they both show absorption with $\tau \sim 0.4$–0.5 in the expanding 3 kpc arm at $v \sim -110$ km s^{-1}, even though the emission at this velocity is only $T_B \sim 30$ K (Caswell et al. 1975; Garwood & Dickey 1989). The source G347.7−1.1 (Dickey et al. 1983) also appears to show absorption at $v < -100$ km s^{-1} in relatively weak emission features, although the strength of the absorption is uncertain because it appears near the edge of the observing band.

3.3. *PSR B1718−35 = J1721−3532*; $(l, b) = (351\overset{\circ}{.}7, 0\overset{\circ}{.}7)$

The farthest absorption feature is centered at -29 km s^{-1}, giving $D_L = 4.4 \pm 0.5$ kpc. No absorption is detected in the expanding 3 kpc arm, which shows an emission peak at $v \sim -100$ km s^{-1}. Ordinarily it would not be possible to use this observed lack of absorption to place a kinematic upper distance limit, since the corresponding emission peaks at only $T_B \sim 30$ K, which is below the 35 K brightness temperature that is generally required. However, as reported above for PSR B1703−40, two probable SNRs, G348.5+0.1 and G348.7+0.3, which are also 3° away from PSR B1718−35, *do* show absorption in this feature, even at $T_B \sim 30$ K. The sources G349.7+0.2, G350.1+0.1, G351.2+0.7, G351.6+0.2, and G354.2−0.1, which lie between $0\overset{\circ}{.}5$ and 3° from PSR B1718−35, also show absorption in the 3 kpc arm at velocities in the range -70 to -110 km s^{-1} (Caswell et al. 1975; Garwood & Dickey 1989), although in some of these cases the corresponding emission is well above the usual 35 K threshold. For PSR B1718−35, the noise in the absorption spectrum is sufficiently small to confirm that there is no absorption in these 3 kpc arm features, so we are able to place the pulsar in front of them. The arm will first intersect this line of sight 5.7 kpc from the Sun if it is at a Galactocentric distance of 3 kpc, or 4.6 kpc from the Sun if it is at a Galactocentric distance of 4 kpc. Hence we adopt $D_U = 5.2 \pm 0.6$ kpc.

The absorption spectrum of a companion source in the main beam of the array is again shown as a dotted line atop the pulsar absorption spectrum. The companion is at B1950 coordinates $(\alpha, \delta) = (17^h17^m29\overset{s}{.}3, -35°43'09'')$, 13′ south of the pulsar, with a flux density $\sim$1.5 times that of the pulsar. This source is apparently closer than the pulsar, as its absorption spectrum cuts off significantly closer to zero velocity, with the last significant feature at $v = -9$ km s^{-1}. Hence it is far closer than the $v \sim -100$ km s^{-1} emission feature, and therefore would not be expected to show absorption at that velocity. H I absorption measurements have been made on numerous radio sources near the line of sight to this pulsar in addition to the ones discussed here, but they provide no additional useful kinematic distance information, generally because they are not sufficiently distant to probe the 3 kpc arm.

3.4. *PSR B1830−08 = J1833−0827*; $(l. b) = (23\overset{\circ}{.}4, 0\overset{\circ}{.}1)$

This pulsar's H I spectrum presents a "textbook case" for both upper and lower kinematic distance limit determinations. Absorption is present out to $+63$ km s^{-1}, resulting in $D_L = 4.0 \pm 0.4$ kpc. At the emission peak at $+94$ km s^{-1}, the absorption spectrum shows larger fluctuations that at higher velocities, but no absorption. This $T_B \sim 60$ K emission peak would show strong absorption if the pulsar were beyond it (and indeed strong absorption is seen near this velocity in the spectrum of H II region G24.8+0.1; Caswell et al. 1975), so $D_U = 5.3 \pm 0.3$ kpc. The emission and absorption spectra of this pulsar are similar to those of PSR B1829−08 (Frail et al. 1991), only a few tenths of a degree away at $(l, b) = (23\overset{\circ}{.}3, 0\overset{\circ}{.}3)$.

4. DISCUSSION

We have determined upper and/or lower kinematic distance limits for four distant pulsars in the inner Galaxy. These distance limits can be converted directly to limits on the average free-electron density along each line of sight via equation (2), given the known dispersion measures. The results are listed in Table 1. It is interesting to note that all limits lie near 0.1 cm^{-3}, which is well above the "canonical" value of 0.025 cm^{-3} (Weisberg et al. 1979).

A rise in the line-of sight average electron density $\langle n_e \rangle$ in the inner Galaxy has been noted by several H I absorption studies, beginning with Ables & Manchester (1976). Frail et al. (1991) analyzed all electron density data toward the first and fourth quadrants of the Galaxy. They showed that most pulsars in the inner Galaxy, defined by $|l| \leq 45°$, $|b| \leq 2°$ and DM ≥ 100 pc cm^{-3}, give $\langle n_e \rangle$ values about 3 times the local value of 0.025 cm^{-3}.

The four pulsars in this study plus the two newly measured pulsars J1559−4438 and 1709−4429 (Koribalski et al. 1995) are important as they sample a region of the Galaxy ($|l| \leq 25°$) toward which very few $\langle n_e \rangle$ measurements have been made, whereas the bulk of earlier measurements in the inner Galaxy were made within $|l| = 35° \pm 5°$ (Frail et al. 1991). Thus existing electron density models are not well calibrated in this area (Cordes et al. 1991; Taylor & Cordes 1993).

Our new measurements confirm the rise in $\langle n_e \rangle$ seen in previous observations toward the inner Galaxy. However, the measured density does not continue increasing monotonically in to the lowest $|l|$'s. Rather, there appears to exist an upper threshold on $\langle n_e \rangle$ at $\sim$0.1 cm^{-3}. Values of $\langle n_e \rangle$ in excess of 0.1 cm^{-3} were previously shown to be rare (Frail & Weisberg 1990) and in all known cases can be attributed to a contribution to the DM from a discrete H II region along the line of sight toward the pulsar. Our new measurements show that this

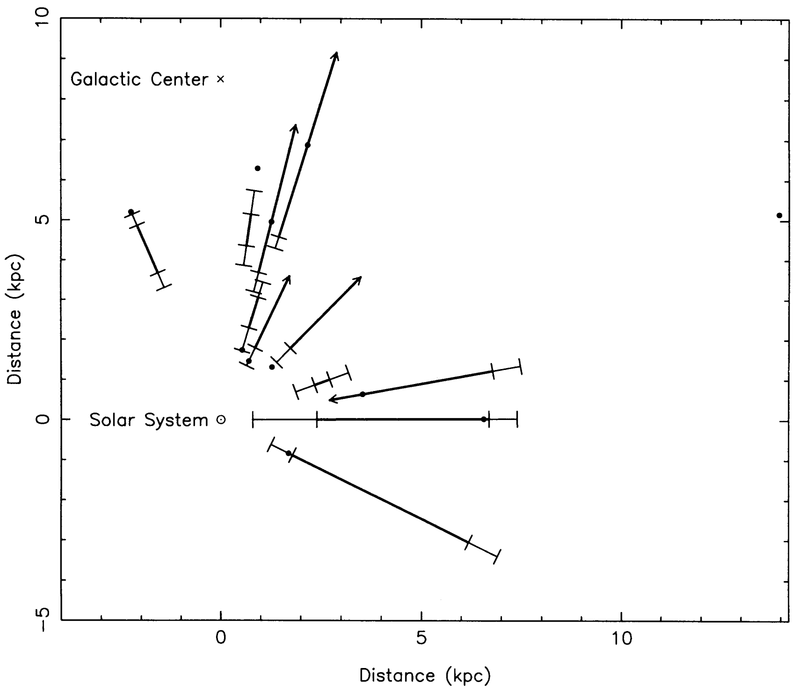

FIG. 2.—Measured distances for pulsars from this study and from Koribalski et al. (1995), and Taylor & Cordes (1993) model distances, all projected onto the Galactic plane. Thick lines represent distance ranges up to the limits D_L and D_U, while thinner lines depict estimated uncertainties on these limits. Circles indicate distances D_{TC} estimated from dispersion measures and the Taylor & Cordes (1993) Galactic electron density model.

trend continues in even closer to the Galactic center than previously found. There are several possible explanations for the existence of a ceiling to $\langle n_e \rangle$ at the innermost Galactic longitudes. The local electron density in the inner Galaxy might reach a maximum in an annular region centered on the Galactic center of radius several kiloparsecs, declining at both larger and smaller Galactocentric radii, in concert with the distribution of star-forming regions and other presumed sources of Galactic ionization. Alternatively, the maximum may represent a selection effect resulting from the continuing paucity of distance measurements on pulsars within a few kiloparsecs of the Galactic center. This uncertainty in the source of the ceiling is also reflected in current Galactic electron density models, in which it has not been possible to choose clearly between Galactocentrically filled or annular density models of the inner Galaxy (Cordes et al. 1991; Taylor & Cordes 1993). Additional pulsar H I absorption measurements in the extreme inner Galaxy are needed to help resolve this issue.

It is useful to test the Taylor & Cordes (1993) Galactic electron density model against our new measurements and those of Koribalski et al. (1995). In Figure 2 we display the results of these comparisons. In this plot, we project onto the Galactic plane the measured limits on pulsar distances from this investigation and from Koribalski et al. (1995), and additionally the model distances D_{TC} which are obtained from integration of the Taylor & Cordes model along each line of sight until the path-integrated electron density is equal to the measured dispersion measure. The model distances correspond approximately to the measured distances in all cases with the glaring exception of PSR J1056−6358 at $l = 290°$, which Koribalski et al. find to be in the direction of an H II region. In the inner Galaxy it is interesting to note that the model distances frequently lie near or just outside the measured limits. This is to be expected in a region where the calibration data were somewhat sparse when the model was created, but is suggests that no major corrections are needed. Figure 2 indicates a few regions where minor corrections could be made. The model distances are at or near the extreme lower end of the measured distance limits for the three pulsars J1453−6413, J1559−4438, and J1709−44, all located beyond about 2 kpc from the solar system in the range $315° < l < 345°$, which suggests that the model electron density may be systematically slightly high along lines of sight to this region. Conversely, the pulsar J1718−35 at $l \sim 352°$ is significantly closer than the model indicates, suggesting that the actual density is higher than modeled along this path toward the Galactic center.

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