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The Distribution of Free Electrons in the Inner Galaxy from Pulsar Dispersion Measures

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ABSTRACT

We have statistically analyzed the dispersion measures of a sample of 149 pulsars in the inner Galaxy ($|\ell| < 50^o$) to deduce the large-scale distribution of free thermal electrons in this region. The dispersion measure distribution of these pulsars shows significant evidence for a decrease in the electron scale height from a local value greater than the pulsar scale height to a value less than the pulsar scale height at galactocentric radii inside of ~ 7 kpc. An increase in the electron density (to a value around .15 cm^{-3} at 4-5 kpc) must accompany such a decrease in scale height. There is also evidence for a large-scale warp in the electron distribution below the $b = 0^o$ plane inside the Solar circle. We propose a model for the electron distribution which incorporates these features and present Monte Carlo generated dispersion measure distributions for parameters which best reproduce the observed pulsar distributions.

1. INTRODUCTION

Pulsar radio signals are dispersed by free electrons in the interstellar medium which lie along the line of sight. Pulsar dispersion measures are therefore good probes of the interstellar electron density and its galactic distribution. Unfortunately, few pulsars have reliable independent distance determinations and, since the dispersion depends both on distance and electron density, the mean electron densities along lines of sight to individual pulsars cannot be determined in most cases. However, statistical distributions of pulsar dispersion measures can be used to study the electron distribution, provided something is known or assumed about the distribution of pulsars in the Galaxy.

Traditionally, the opposite approach has been taken. The pulsar galactic distribution is determined by assuming a simple model for the free electron distribution which is in agreement with other observations (Davies, Lyne and Seiradakis 1977, Taylor and Manchester 1977, Lyne 1981). These other observations are free-free absorption of the non-thermal radio continuum, interstellar scattering of extragalactic sources, HI absorption of pulsar signals, and radio recombination lines. Both free-free absorption of galactic radio spectra at low frequencies and interstellar scattering indicate a Z scale height for the absorbing electrons of 500–1000 pc. (Bridle and Venugopal 1969, Readhead and Duffett-Smith 1975). The best estimates of mean electron densities on kiloparsec scales come from the distance determinations to pulsars using HI absorption (Ables and Manchester 1976; Weisberg, Rankin and Boriakoff 1980). From the distances and dispersion measures for a sample of low latitude pulsars, Weisberg et al. (1980) conclude that the mean electron density in the plane is $\langle n_e \rangle \sim .025-.03\ cm^{-3}$ in directions away from the galactic center. Therefore, the "standard" model has been an exponential or Gaussian Z dependence with scale height ~ 1000 pc and central density, $n_0 \sim .03\ cm^{-3}$. However, the HI absorption measurements also give mean densities that are somewhat higher toward the inner Galaxy, within a longitude range $330^\circ \lesssim \ell \lesssim 30^\circ$, suggesting that n_e is dependent on galactic radius. Radio recombination line observations (Lockman 1976) also indicate, from the radial distribution of ionized gas, that electron densities increase in the inner Galaxy. There is evidence then, that more complex models may be needed to describe the galactic distribution of electrons.

In this paper, we analyze the pulsar dispersion measure distributions in the inner Galaxy to study the variation of the density and scale height of the electrons with galactocentric radius. We use results of previous analyses to make assumptions about the pulsar galactic distribution. Models for the electron distribution can then be tested by generating Monte Carlo dispersion measure distributions and comparing these to the observed distributions. We show that a particular density and scale height variation with R and Z will reproduce the observed pulsar dispersion measure distributions, and discuss the consistency of this type of model with other observations of free interstellar electrons.

II. PULSAR DISPERSION MEASURES

The dispersion measure (DM) is defined as the integral of the electron density along the line of sight to a pulsar:

$$DM = \int_0^d n_e(s)\, ds \qquad (1)$$

It is determined from the intervals between pulse arrival times at different frequencies and is therefore a direct observational parameter. Information on the Z distribution of electrons and pulsars can be obtained by plotting the number of pulsars in intervals of $\Delta = DM \sin b$, the Z component of dispersion measure. The observed distribution can be compared to the expected distribution of $N(\Delta)$ versus Δ derived by assuming that the pulsars and electrons are functions of Z only. If for example both have exponential distributions in Z,

$$n_e(Z) = n_o \exp(-|Z|/h_e) \qquad (2)$$

$$N_p(Z) = N_o \exp(-|Z|/h_p),$$

then the expected form of $N(\Delta)$ is:

$$N(\Delta) = \begin{cases} \frac{N_o}{n_o}\left(1 - \frac{\Delta}{n_o h_e}\right)^{\frac{h_e}{h_p} - 1} & , \Delta < n_o h_e \\ 0 & , \Delta > n_o h_e \end{cases} \qquad (3)$$

(Taylor and Manchester 1977). This $N(\Delta)$ distribution will have three distinct shapes, depending on the relative sizes of the electron and pulsar scale heights, h_e and h_p. If (1) $h_e > h_p$, then $N(|\Delta|)$ is monotonically decreasing out to $|\Delta| = n_o h_e$ (2) if $h_e = h_p$, then $N(|\Delta|)$ is constant out to $|\Delta| = n_o h_e$ (3) if $h_e < h_p$, then $N(|\Delta|)$ is monotonically increasing out to $|\Delta| = n_o h_e$ where it abruptly drops off. The general dependence of the shape of $N(\Delta)$ on the ratio h_e/h_p was noted previously by Gould (1971) and by Terzian and Davidson (1976) and does not change with different functional forms for the electron and pulsar distributions, as long as they are both monotonically decreasing functions of Z.

A histogram of $N(|\Delta|)$ versus $|\Delta|$ for all the known pulsars turns out to be a decreasing function of $|\Delta|$, with $\Delta_{max} \equiv n_o h_e \sim 25$–$30$ pc. cm^{-3}, indicating that $h_e > h_p$ throughout most of the Galaxy (Taylor and Manchester 1977, Harding 1981). Equation (5) can be fit to the observed distribution to determine one of the quantities h_e, h_p or n_o, assuming values for the other two. This approach has been used for the Molonglo survey (Manchester 1979) to give h_p = 350 pc. for assumed values of h_e = 1000 pc. and n_o = .03 cm^{-3}. Gailly et al. (1978), using distributions for electrons and pulsars which were intermediate between Gaussian and exponential, obtained $<|Z_p|>$ = 380 pc. for $750 < <|Z_e|> < 1500$ pc. and n_o = .025 cm^{-3}.

There is evidence, however, that the electron Z distribution is not so simple. Komesaroff et al. (1973) noted an asymmetry in a plot of DM versus b, in which pulsars at southern latitudes had higher dispersion measures. They suggested that a model of $n_e(Z)$ consisting of a high density electron disk with n_o = .12 cm^{-3} with a small thickness of ~ 124 pc. would explain the effect if the Sun is displaced 22 pc north of the center of the disk. Harding (1981) found a similar asymmetry in a plot of $N(\Delta)$ versus Δ and proposed a two component model consisting of a thin disk of electrons with n_e = .10 cm^{-3} of half thickness ΔZ = 40 pc. and a large scale height exponential component with n_o = .03 cm^{-3} and h_e = 1000 pc. If the Sun were displaced 20 pc. to the north of this distribution, then equal pulsar scale heights of 340 pc. were obtained for both +Z and −Z pulsars from fits to the $N(\Delta)$ versus Δ histogram. It was also noted that this asymmetry in the $N(\Delta)$ versus Δ distribution was most pronounced toward the galactic center, e.g., for a sample of pulsars restricted to a longitude range $|\ell| < 50^{\circ}$ ($310^{\circ} < \ell < 50^{\circ}$). This suggested a possible radial dependence of the electron disk density if the disk is responsible for most of the asymmetry.

We now consider the dispersion measure distribution of this sample of pulsars with $|\ell| < 50^{\circ}$ in more detail. Figure 1 shows a scatter plot of DM sinb (= Δ) (vertical DM) versus DM cosb (horizontal DM) for this sample of 149 pulsars. This plot reveals that essentially all of the asymmetry in the $N(\Delta)$ versus Δ distribution is due to pulsars with DM cosb $\gtrsim$ 100 pc. cm^{-3}, i.e., more distant pulsars. The DM sinb distribution of nearby pulsars is actually quite symmetric. The mean value of DM sinb appears to decrease with DM cosb and reach a minimum at DM cosb ~ 200 pc. cm^{-3}. The distribution also narrows with increasing DM cosb.

In Figure 2, the sample is divided into groups having DM cosb > 100 (distant pulsars) and DM cosb < 100 (nearby pulsars) and plotted in the histogram form $N(\Delta)$ versus Δ, for the entire inner Galaxy, $|\ell| < 50^{\circ}$, and for the central inner Galaxy, $|\ell| < 30^{\circ}$. To make a uniform sample, only pulsars detected by the second Molonglo survey (Manchester et al. 1978) have been plotted in Figure 2. The more sensitive Arecibo survey (Hulse and Taylor 1974) covered a small longitude range, $42^{\circ} < \ell < 60^{\circ}$, and the pulsars detected only by this survey have been removed from the sample.

In spite of the statistics, a significant difference in shape, width and mean is apparent for distributions of nearby and distant pulsars. The $|\ell| < 50^{\circ}$ histogram for nearby pulsars is similar in shape, width and mean to the distribution of pulsars in the outer Galaxy ($|\ell| > 50^{\circ}$). Within statistical errors, it is symmetric and centrally peaked with $\Delta_{max} \equiv n_o h_e \sim 25$ pc. cm^{-3}. According to the model of equation (2), $\langle h_e \rangle > \langle h_p \rangle$ for this sample of pulsars. If $\langle h_e \rangle = 800$ pc., then $\langle n_o \rangle \sim \Delta_{max}/\langle h_e \rangle \sim .03\ cm^{-3}$, which is consistent with models which have been derived from the entire sample of known pulsars. The $|\ell| < 50^{\circ}$ histogram for distant pulsars is decidedly asymmetric with a mean $\Delta_o \sim -4$ pc. cm^{-3}, and a shape more suggestive of the case $\langle h_e \rangle \sim \langle h_p \rangle$, where $N(\Delta)$ is constant or increasing out to Δ_{max}. The histograms for $|\ell| < 30^{\circ}$ are less centrally peaked than the $|\ell| < 50^{\circ}$ histograms. Especially striking is the doubly peaked distribution for the sample having DM cosb > 100 with a mean also around -4 pc. cm^{-3}. The distribution is fairly symmetric about this mean and the shape suggests that $\langle h_e \rangle < \langle h_p \rangle$ for this sample of pulsars, with $|\Delta_{max} - \Delta_o| \sim 15$ pc. cm^{-3}. If $\langle h_e \rangle \sim 200$ pc., significantly less than a pulsar scale height of 340 pc., then $\langle n_o \rangle \sim .08$ cm^{-3}. Therefore, to account for the shapes and widths of the observed distributions, the electron scale height must decrease significantly and the density must increase toward the galactic center.

The displacement of ~ -4 pc. cm^{-3} in the distant pulsar distributions may be caused by a displacement in the electron or pulsar distributions with respect to the plane of the Sun or, most likely, both. Since the asymmetry does not appear strongly for the nearby pulsars, the displacement must be much greater in the inner Galaxy than it is locally. This explanation is consistent with a warping of the galactic plane toward negative Z, an effect which has been seen in CO (Cohen and Thaddeus 1977, Solomon, Sanders and Scoville 1979), HII (Lockman 1977, 1979) and HI (Quiroga 1974) data. From these observations, the maximum displacement south of the plane seems to occur between galactic radii of 6 and 7 kpc and is about 40 pc. in magnitude. This seems roughly consistent with the displacement needed to account for a DMsinb difference of 4 pc cm^{-3}, since if $\langle n_e \rangle \sim .08$ cm^{-3} then $\Delta Z \sim \Delta_o / \langle n_e \rangle \sim 50$ pc.

From the simple arguments outlined above, a free electron distribution that is consistent with the observed distributions of pulsar dispersion measures in the inner Galaxy should have the following properties:

1) An effective scale height which is a function of R, increasing from a value less than the pulsar scale height to a local value greater than the pulsar scale height

2) A density which is a decreasing function of R, at least between 6 and 10 kpc.

3) A Z distribution whose mean is negative for $R \lesssim 8$ kpc.

III. MODEL FOR THE ELECTRON DISTRIBUTION

We have tested specific models for the electron distribution in the inner Galaxy by means of a Monte Carlo program which calculates dispersion measures to randomly chosen points and generates $N(\Delta)$ versus Δ histograms to compare with the data. The points are chosen from an assumed pulsar distribution in the Galaxy and observational selection effects are taken into account. A particular functional form was chosen for the electron Z distribution and the parameters were varied to obtain dispersion measure distributions which were consistent with the observed distributions.

a) The Pulsar Distribution

The program populates the Galaxy with pulsars using a Monte Carlo method. In galactocentric, cylindrical coordinates the radius R, Z distance, and angle, θ, for each pulsar are chosen according to specific probability functions. These functions are chosen to be consistent with determinations of the pulsar galactic distribution (Lyne 1981, Harding 1981). The probability of choosing a pulsar as a function of θ is taken to be constant, i.e., $\frac{dP_\theta}{d\theta}$ = constant. Because we assume azimuthal symmetry about the galactic center for both the pulsar and electron distributions and because almost all pulsars on the opposite side of the Galaxy from the solar system are unobservable, we need to populate only one quadrant of the Galaxy with pulsars. Hence, θ is allowed to vary only between 0 and $\pi/2$.

The probability of choosing a pulsar as a function of R is taken to be

$$\frac{dP_R}{dR} = R \exp\left(-|R_o - R|/W\right) \quad . \tag{4}$$

W and R_o are chosen to be 3 kpc and 5.5 kpc, respectively, such that the peak pulsar surface density projected onto the plane occurr at a radius equal to 5.5 kpc and is 4 times the surface density at the location of the solar system, which is assumed to be at R = 10 kpc. This probability function is integrated from R = 0 to R = 10 kpc and a correspondence table is set up correlating values of the integrated probability with values of radius.

The probability of choosing a pulsar as a function of Z is taken to be

$$\frac{dP_Z}{dZ} = -\frac{1}{h_p} \exp\left(-|Z|/h_p\right) \tag{5}$$

where h_p is the pulsar scale height. A constant pulsar scale height of 340 pc. has been chosen for nearly every model tested.

The probability of choosing a pulsar as a function of radio luminosity is

$$\frac{dP_L}{dL} = -\frac{L_o}{L^2} \tag{6}$$

where L_o is the lower luminosity limit. This choice of probability distribution corresponds to recent, calculated pulsar luminosity functions (Manchester 1979, Lyne 1981). The derived lower luminosity limit is around .3

mJy kpc^2, however, a larger value of L_o = 1 mJy kpc^2 was used when testing models. This greatly speeds up program execution, and pulsars with luminosities less than 1 mJy kpc^2 have only been detected at distances less than ~ 300 pc. in the Molonglo survey. The reason for choosing a luminosity for each pulsar is to check within the program for detectability by the Molonglo survey. Pulsars not observable by this survey are discarded by the program.

b) The Electron Distribution

The model we consider for the electron distribution consists primarily of two components: the disk electrons and the extended electrons. It is described by the following functional form:

$$n_e(R,Z) = \begin{cases} n_e^D(R), & |Z-Z_o(R)|<\Delta Z \\ n_o(R)\exp[-|Z-Z_o(R)|/h_e(R)], & |Z-Z_o(R)|>\Delta Z \end{cases} \qquad (7)$$

The disk component consists of a relatively thin layer of density $n_e^D(R)$ lying in the plane defined by $Z_0(R)$. The thickness of the disk component, ΔZ, was taken to be independent of radius. Both the thickness of the disk and the disk electron density, which was taken to be a function of radius, were varied from one trial to the next to search for a viable model. The electron density within the disk was held constant with Z.

The extended component consists of free electrons extending above and below the disk component. The density of the extended component was taken to fall off exponentially with distance from the galactic plane. Thus, the extended component is characterized by a central density, $n_o(R)$, and a scale height, $h_e(R)$, at each galactocentric radius. Different functional forms for both the scale height and the central density were tested by the program.

Both components have an R dependent mean, $Z_o(R)$, which defines a warp in the plane of the electron distribution, and which is chosen to have the functional form:

$$Z_o(R) = -Z_{max}\exp[-(R-R_o)^2/\Delta R^2] \quad (8)$$

We have adopted the values $R_o = 6.5$ kpc. and $\Delta R = 1.7$ kpc., to be consistent with the warp seen in HII regions in the inner Galaxy (Lockman 1979).

c) Testing Procedure

The cylindrical coordinates and luminosity of a sample pulsar are chosen according to the probability distributions described in IIIa. The longitude, latitude and distance d of the sample pulsar to the Sun are then calculated. With an assumed electron distribution, the dispersion measure is determined by integrating along the line of sight from the pulsar to the Sun. The flux density, S, is determined from the luminosity and distance by $S = Ld^2$ and is compared to the minimum detectable flux density at that ℓ, b, and DM for the Molonglo survey. The effects of a variable sky temperature from the radio continuum background and the dispersion measure cutoff of the survey were taken into account in determining the minimum detectable flux density (see Taylor and Manchester 1977). The latitude, longitude and dispersion measure of each detectable pulsar are accumulated in a file in order to build up a statistical sample which reflects the model being tested.

We can then plot various distributions of $N(\Delta)$ from the Monte Carlo generated sample and compare them in shape, width and mean with the observed distributions. Different variations of $n_e^D(R)$, $n_o(R)$, $h_e(R)$ and $Z_o(R)$ in

Equation (7) were tested until a model was found which gave satisfactory agreement with the data.

IV. RESULTS

A model was found which reproduces the data in Figure 2 reasonably well. The N(Δ) distributions produced by this model are shown in Figure 3. The functional forms for the variation of electron density and electron scale height with galactic radius are shown in Table 1 and plotted in Figure 4.

It is evident that the main feature of the model is the dramatically decreasing electron scale height toward the galactic center. In order that the model produce dispersion measure distributions having the characteristics of the observed distributions with DM cosb > 100, it is essential that the electron scale height be less than the pulsar scale height at galactic radii less than about 7 kpc. The radius at which the transition $h_e > h_p$ to $h_e < h_p$ occurs is ≈ 7.5 kpc and is a critical parameter of the model. It may also be important for the central density of the extended component to increase rapidly with decreasing R in the vicinity of this transition region. In the model described in Table 1, this central density then levels off and remains relatively constant with decreasing R inside about R = 7 kpc. It may be that this sudden increase in electron density corresponds to the location of a spiral arm, or to the beginning of a "galactic ridge" of electrons (Seacord and Gottesman 1977, Lockman 1976, Gordan and Gottesman 1971) seen in radio recombination line surveys. Models without this rapid increase in electron density (e.g., a linear increase from R = 10 kpc to 4 kpc) required a linear decrease in electron scale height from 1000 pc. to ~ 200 pc. over radii of 10 kpc to 7.5 kpc. These models produced poorer fits to the N(Δ) histograms for nearby pulsars because the average scale height between 10 and 8 kpc was too small.

The warping of the electron distributions produces the horizontal offsets in the N(A) histograms for DM cosb > 100. In the model which produced the histograms in Figure 3, the maximum displacement, Z_{max}, below the plane at 6.5 kpc [cf. Equation (8)] was 120 pc. A Z_{max} of 60 pc. can produce the same offset of ~ -4 pc cm^{-3} if the Sun is displaced 20 pc. above the Z = 0 plane of the electron distribution. This distortion is more in agreement with the inner Galaxy warp seen in other gaseous tracers. Furthermore, a maximum displacement as large as 120 pc. at 6.5 kpc. may be incompatible with recombination line data in the inner Galaxy (Lockman, private communication).

There is no assurance that the model in Table 1 is unique. Other models with somewhat different combinations of h_e(R) and N_o(R) might also reproduce the data. The fit to the data was very sensitive to certain of the parameters while for other parameters the values chosen made relatively little difference. It is felt that the choice of parameters for galactocentric radii less than 4 kpc. is not particularly important as relatively few pulsars in the data or detectable points in the model sample this region of the Galaxy. As a result, electron densities and scale heights are poorly determined by the model for this region. The model is also relatively insensitive to the electron disk density inside about 6 or 7 kpc. The lines of sight to only a few sample pulsars pass through this portion of the disk, and hence only a small percentage of dispersion measures are affected by the inner disk. The two component form adopted for the electron Z-distribution [cf. Equation (7)] was one of mathematical convenience and computational efficiency. Any other set of functions giving a similar profile in Z, for example a Gaussian disk plus an exponential extended component, would have worked as well.

Models consisting of an extended component which is independent of R were definitely unsuccessful in reproducing the data, even with R dependent disk components. By way of illustration, we show the N(Δ) distributions resulting from the following electron model:

$$n_e(Z,R) = .025\ \exp(-|Z|/h_e) + n_e^D\ (R) \qquad (9)$$

where

$$n_e^D(R) = \begin{cases} .01[1+1.5(10-R)]\ , & Z<\Delta Z \\ 0 & ,\ Z>\Delta Z \end{cases}$$

and ΔZ = 60 pc., h_e = 1000 pc. The disk density in this model has a linear R variation which is very similar to that in Figure 4, but the extended exponential component has a central density and scale height which is constant with R. This model is also similar to one recently adopted by Lyne (1981) to determine the pulsar galactic distribution. Figure 5 shows the resulting N(Δ) distributions, which clearly have different shapes and widths from the observed distributions. We have not included a warping of the electrons in this model, so that the negative offset in the data has, of course, not been reproduced.

As an approximate test of the relative "goodness of fit" of the distributions generated by different electron models with the data, we have determined the χ^2 values and probabilities for each computed histogram. These are listed in Table 2 for the best fit model, the constant scale height model, and the simple exponential model. By the χ^2 test criterion, the best fit model provides a significantly better fit than the simpler models, especially for the $|\ell| < 30°$, DMcosb > 100 sample of pulsars. Because it is difficult to evaluate the number of independent parameters in a model as complex as ours, the number of degrees of freedom are somewhat uncertain so this type of test cannot be considered definitive. We therefore have not attempted to use statistical tests to put uncertainties or any of the model parameters. However, we have shown here that the observed distributions, despite the small numbers of pulsars, differ significantly from those derived from the simpler models (i.e., the probability that the true parent distributions could be those generated by the simpler models is quite small).

Another observational constraint by which electron models can be tested for consistency with the data is the distribution of number of pulsars versus DM cosb. The observed distribution is a decreasing function of DM cosb, reflecting the sensitivity limit on detection of distant pulsars. Provided that one can adequately account for selection effects, a viable electron model should give a ratio of detectable pulsars with DM cosb < 100 to those with DM cosb > 100 that is in agreement with the data. Since the Molonglo Survey was sensitivity limited rather than dispersion measure limited (the maximum detectable DM was 780 pc cm^{-3} in the plane) and there are only a few pulsars in the observed sample with DM > 400 pc cm^{-3}, a viable model should also not produce too many very high dispersion pulsars. Our best fit model gives ratios of N(DM cosb < 100)/N(DM cosb > 100) which are in good agreement with the data for both $|\ell| < 30°$ and $|\ell| < 50°$. The model also produces a sample with ~ 5.5 percent having DM > 400, in comparison to the observed sample with ~ 3 percent having DM > 400. By contrast, the model of Equation (9) giving the distributions shown in Figure 5 produced about twice the ratio N(DM cosb < 100)/N(DM cosb > 100) as is seen in the data. Since the pulsar luminosity cutoff, L_o, is probably less than the value of 1 mJy kpc^2 we have assumed, and a lower L_0 would give an even larger ratio of nearby to distant pulsars, this model seems to be quite inconsistent with the data.

Since the focus of this work was to use the pulsar dispersion measure data to investigate the electron density distribution, we have held the pulsar parameters in the model constant. Our best fit model is relatively insensitive to changes in the ratio of pulsar surface densities at 5 and 10 kpc, at least with the exponential form we have assumed. The low luminosity cutoff in the pulsar luminosity function, L_0, does not affect the distant pulsar distributions at all, since pulsars with low luminosities are only detectable within a kpc or so (depending, of course, on the value of L_0). It does affect the distributions of nearby pulsars, in that low luminosity pulsars tend to fill in the central part of the $N(\Delta)$ distribution since they are not fully sampled in Z. For this reason, we have concentrated primarily on fitting the distributions for DM cosb > 100, and only the general outer shapes and widths of the distributions for DM cosb < 100.

One could probably contrive a model where drastic changes in the pulsar Z distribution in the inner Galaxy would entirely account for the observed changes in the dispersion measure distributions, without invoking any radial dependence in the electron distribution. This model would require that pulsars be somehow excluded from the central galactic plane and peak in density both above and below the plane inside of ~ 8 kpc. We consider this solution to be physically unrealistic, as no Population I objects have been observed to exhibit this structure.

It is possible, though, that the pulsar scale height is a function of galactocentric radius. However, the pulsar scale height cannot decrease very much toward the galactic center. As we have seen, the electron scale height must be less than the pulsar scale height over part of the inner Galaxy. As the electron scale height decreases, the electron density must increase to produce the observed amount of DM sinb. But DM cosb would become too large for a significant fraction of pulsars (those in the inner Galaxy lying close to the plane) if the electron density were increased too much.

V. DISCUSSION

We have shown evidence that the dispersion measure distribution of distant pulsars in the inner Galaxy differs significantly from that of nearby pulsars, indicating that the electron Z distribution undergoes major qualitative changes between the Sun and the galactic center. We have presented a model for the radial dependence of the electron distribution which is consistent with the pulsar data. It should be stressed that the particular model presented here is not meant to be the only consistent model nor is it meant to be correct in every detail. Rather, it is intended to illustrate the general characteristics of a class of models which are consistent with pulsar dispersion measures.

The model we have proposed in this paper incorporates several new features not previously considered in electron density models. One of these is an electron scale height which increases with galactic radius inside the Solar circle, from a value which is smaller than the pulsar scale height. Previous models have assumed a constant electron scale height throughout the Galaxy. This model also includes a radial dependence of the electron density, which is a necessary consequence of the scale height dependence. If the electron scale height decreases toward the inner Galaxy, then the density must increase to compensate for a loss of vertical dispersion measure which would not be consistent with the data. Finally, our model includes a radially dependent displacement of the electron plane towards negative Z, a feature which is necessary to explain the considerable amount of asymmetry in the vertical dispersion measure distribution of pulsars in the inner Galaxy. It is possible that the pulsar distribution has a similar feature, but it could not, by itself, account for the observed vertical dispersion measure asymmetry.

Several of the properties of this electron distribution have, in fact, been suggested by other types of observation or analysis. Cane (1977) found that a two component Z distribution of electrons, a thin disk plus an extended component, was needed to account for the free-free absorption of the low frequency radio background. The longitude distribution of mean electron density along the lines of sight to pulsars with HI absorption distances has indicated higher mean densities in the longitude range $30^{o} < \ell < 330^{o}$. (Ables and Manchester 1976). The radial dependence of the electron density in our model can account for this and gives mean densities in these directions which are consistent with those observed. In analyzing the dispersion measure distribution of the pulsars with independent distances, Hall (1980) derived a mean density, $\langle n_e \rangle \approx .048\ cm^{-3}$, and an electron scale height, $h_e \approx 264$ pc. The disparity of these results with previous electron models can perhaps be understood as indicating that the electron scale height and density, as we have found, vary in different parts of the Galaxy. The Z asymmetry in the pulsar dispersion measure distribution has turned up in several previous analyses (Komesaroff et. al. 1973; Davies, Lyne and Seiradakis 1977). The existence of the asymmetry in the inner Galaxy and its absence in the outer Galaxy (Harding 1981) was a preliminary indication of a radially dependent displacement of the electron disk.

Having used assumptions about the galactic distribution of pulsars to derive properties of the electron distribution, we should ask how the pulsar galactic distribution derived from this electron model would differ from previous results. As discussed earlier, the results of the Monte Carlo calculation are not very sensitive to the form of the pulsar distribution. We have not assumed anything about absolute pulsar densities, since only density ratios entered into the calculation. Therefore, unless the rederived pulsar distributions change drastically with this electron model, the results we have obtained will be valid.

The major effect of this model would be to shrink the distance scale for pulsars in the inner Galaxy. There would be little or no effect on pulsars within 1 kpc, since the local form of our electron distribution is the same as in previous models, but distant pulsars would be somewhat closer then previously thought. Since pulsar densities are almost entirely determined by the low luminosity pulsars lying within the nearest 500 pc. or so, only the form of the radial distribution would be expected to change, not the absolute densities. Distances to the very nearby pulsars, which determine densities and, ultimately, the pulsar birthrate in the Galaxy, depend critically on the local fluctuations in the electron density and the presence of HII regions. The ionized gas is probably clumped on scales of 1 - 100 pc. (McKee and Ostriker 1977, Dickey et al. 1981), but this "fine structure" has been averaged over in our large-scale model. Local HII regions affect somewhat the dispersion measure distributions of nearby pulsars, but make negligible contributions to the dispersion measures of more distant pulsars.

In summary, pulsar dispersion measures can provide a great deal of information on the large-scale galactic distribution of ionized gas. It is uncomplicated by a lack of knowledge of the temperature, fractional ionization and small-scale structure of the gas, as are other probes of the electron density. The only present observational determinations of $\langle n_e \rangle$ come from pulsar dispersion measures; other observations measure $\langle n_e^2 \rangle$ from emission measures. Combining these two quantities can determine a very important parameter describing the structure of the ionized gas: the filling factor, $f = \langle n_e \rangle^2 / \langle n_e^2 \rangle$. Higher electron densities in the inner Galaxy, as suggested by the pulsar data, imply that either the densities of the ionized regions are higher or the filling factor of ionized gas is larger than locally. Combining this information on $\langle n_e \rangle$ from pulsars with that on $\langle n_e^2 \rangle$ from the other observations which probe the interstellar electron density should give a more complete and detailed picture of the structure and sources of ionized gas in the Galaxy.

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REFERENCES

Ables, J. G. and Manchester, R. N. 1976, Astron. Astrophys., 50, 177.

Ashworth, M. and Lyne, A. G. 1981, M.N.R.A.S., 195, 517.

Bridle, A. H. and Venugopal, V. R. 1969, Nature, 224, 545.

Cane, H. V. 1977, Ph. D. Thesis, Univ. of Tasmainia.

Cohen, R. S. and Thaddeus, P. 1977, Ap. J., 217, L155.

Davies, J. G., Lyne, A. G. and Seiradakis, J. H. 1977, M.N.R.A.S., 179, 635.

Dickey, J. M., Weisberg, J. M., Rankin, J. M. and Boriakoff, V., 1981, Astron. Astrophys. 101, 332.

Gailly, J. L., Lequeux, J. and Masnou, J. L. 1978, Astron. Astrophys., 70, L15.

Gordon, M. A. and Cottesman, S. T. 1971, Ap. J., 168, 361.

Gould, R. J. 1971, Astrophys. Space Sci., 10, 265.

Hall, A. N. 1980, M.N.R.A.S., 191, 751.

Harding, A. K. 1981, Pulsars, ed. W. Sieber and R. Wielebinski (Dordrecht: Reidel), p. 439.

Hulse, R. A. and Taylor, J. H. 1974, Ap. J. (Letters), 191, L59.

Jackson, P. D. and Kellman, S. A. 1974, Ap. J., 190, 53.

Komesaroff, M. M., Ables, J. G., Cooke, D. J., Hamilton, P. A., McCulloch, P. M. 1973, Astrophys. Letters, 15, 169.

Lockman, F. J. 1976, Ap. J., 209, 429.

Lockman, F. J. 1977, A. J., 82, 408.

Lockman, F. J. 1979, Ap. J., 232. 761.

Lyne, A. G. 1981, Pulsars, ed. W. Sieber and R. Wielebinski (Dordrecht:Reidel), p. 423.

Manchester, R. N. 1979, Australian J. Phys., 32, 1.

Manchester, R. N., Lyne, A. G., Taylor, J. H., Durdin, J. M., Large, M. I. and Little, A. G. 1978, M.N.R.A.S., 185, 409.

McKee, C. F. and Ostriker, J. P., 1977, Ap. J., 218, 148.

Newton, L. M., Manchester, R. N. and Cooke, D. J. 1981, M.N.R.A.S., 194, 841.

Quiroga, R. J. 1974, Astrophys. Space Sci., 27, 323.

Readhead, A. C. S. and Duffett-Smith, P. J. 1975, Astron. Astrophys., 42, 151.

Solomon, P. M., Sanders, D. B. and Scoville, N. Z. 1979, The Large-Scale Characteristics of the Galaxy, ed. W. B. Burton (Dordrecht:Reidel), p.35.

Seacord, A. W. and Gottesman, S. T. 1977, M.N.R.A.S., 179, 671.

Taylor, J. H. and Manchester, R. N. 1977, AP. J., 215, 885.

Terzian, Y. and Davidson, K. 1976, Astrophys. Space Sci., 44, 479.

Weisberg, J. M., Rankin, J. and Boriakoff, V. 1980, Astron. Astrophys., 88, 84.

TABLE 1

ELECTRON DENSITY MODEL

GALACTOCENTRIC RADIUS (kpc.)	DISK COMPONENT: DENSITY (CM^{-3}) $n_e^D(R)$	DISK COMPONENT: HALF WIDTH (PC.) ΔZ	EXTENDED COMPONENT: CENTRAL DENSITY (CM^{-3}) $n_o(R)$	EXTENDED COMPONENT: SCALE HEIGHT (PC.) $h_e(R)$
$7.5 < R < 10$	$0.15 - .02\ (R-4)$	60	$.055-.01(R-7.5)$	$1000 \exp[-\frac{(10-R)^2}{6.5}]$
$4 < R < 7.5$	$0.15 - .02(R-4)$	60	$.055(3 - \frac{1}{(8-R)})$	$\frac{370}{(8.5-R)}$
$0 < R < 4$	0	0	0.10	100

$Z_{max} = 120$ pc.

TABLE 2

χ^2 VALUES AND PROBABILITIES OF FITS TO PULSAR DATA

		$\|\ell\| < 50^\circ$		$\|\ell\| < 30^\circ$	
		DMcosb < 100	DMcosb > 100	DMcosb < 100	DMcosb > 100
number of bins	n	13	12	12	10
1. Best fit model	χ^2	13.3	19.5	14.0	5.8
(Table 1, Figure 3)	$P_n(\chi^2)$	.425	.078	.30	.832
2. Constant h_e model	χ^2	42.1	38.7	34.2	60.9
(Eqn. 9, Figure 5)	$P_n(\chi^2)$	$6X10^{-5}$	$1.2X10^{-4}$	$6X10^{-4}$	$2.5X10^{-9}$
3. Constant n_o, h_e model	χ^2	19.6	30.0	22.2	28.8
$n_e(Z)=.03\ \exp(-\|Z\|/1000)$	$P_n(\chi^2)$	.105	$2.7X10^{-3}$	$3.5X10^{-2}$	$1.3X10^{-3}$

$P_n(\chi^2)$ = probability that χ^2 is greater than the calculated value for n "degrees of freedom"

FIGURE CAPTIONS

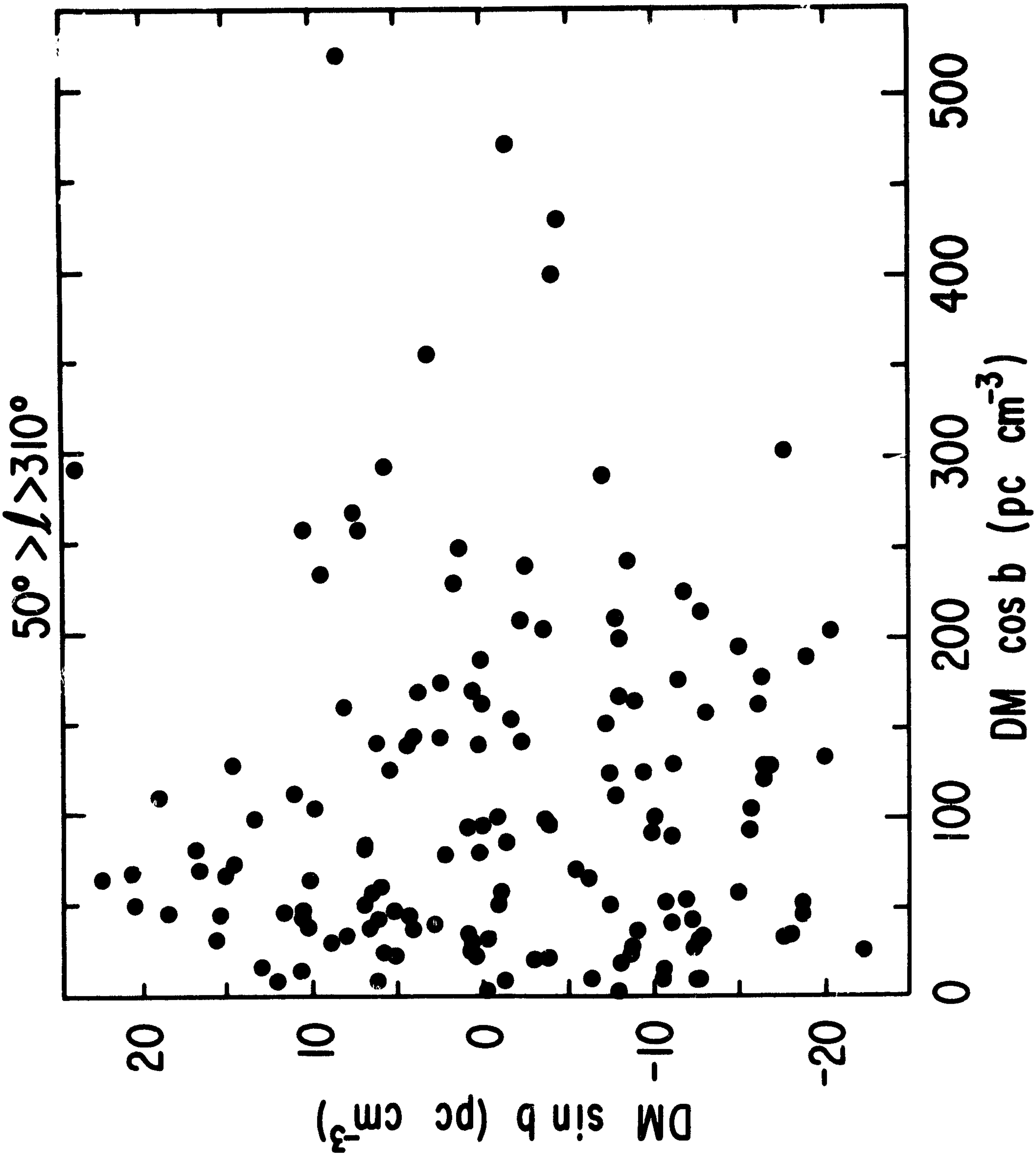
Figure 1: Vertical dispersion measure (DM sinb) plotted against horizontal dispersion measure (DM cosb) for a sample of 149 pulsars in the inner Galaxy ($310^{\circ} < \ell < 50^{\circ}$). The data is from Manchester et. al. 1978, Newton et. al. 1981 and Ashworth and Lyne 1981.

Figure 2: Distributions of DM sinb for Molonglo survey pulsars with DM cosb < 100 pc. cm^{-3} and DM cosb > 100 pc. cm^{-3} for longitude ranges $310^{\circ} < \ell < 50^{\circ}$ and $330^{\circ} < \ell < 30^{\circ}$.

Figure 3: Monte Carlo generated distributions of DM sinb for the best fitting electron model [cf. Eqn. (7) and Table 1].

Figure 4: Radial dependence of the disk electron density, n_e^D (R), and of the central density, $n_o(R)$, and scale height, $h_e(R)$, of the extended electron component for the best fitting model.

Figure 5: Monte Carlo generated distributions of DM sinb for an electron model with no radial dependence of the extended component [cf. Eqn. (9)].



50° > l > 310°
DM cos b (pc cm^{-3})
DM sin b (pc cm^{-3})
0
100
200
300
400
500
20
10
0
-10
-20

Figure 1

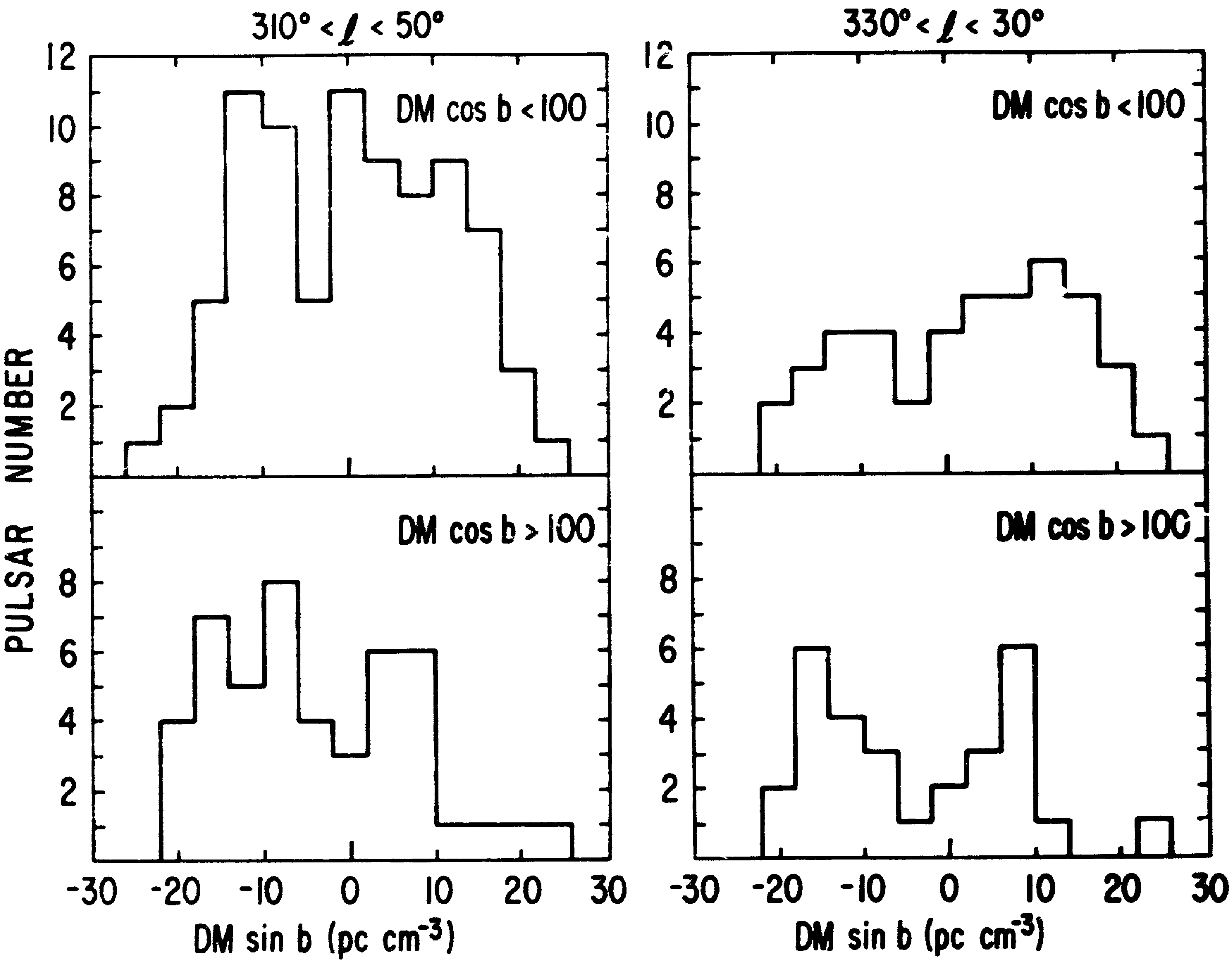

310° < ℓ < 50°
330° < ℓ < 30°
PULSAR NUMBER
DM cos b < 100
DM cos b > 100
DM cos b < 100
DM cos b > 10C
12
10
8
6
4
2
-30 -20 -10 0 10 20 30
DM sin b (pc cm^{-3})

Figure 2

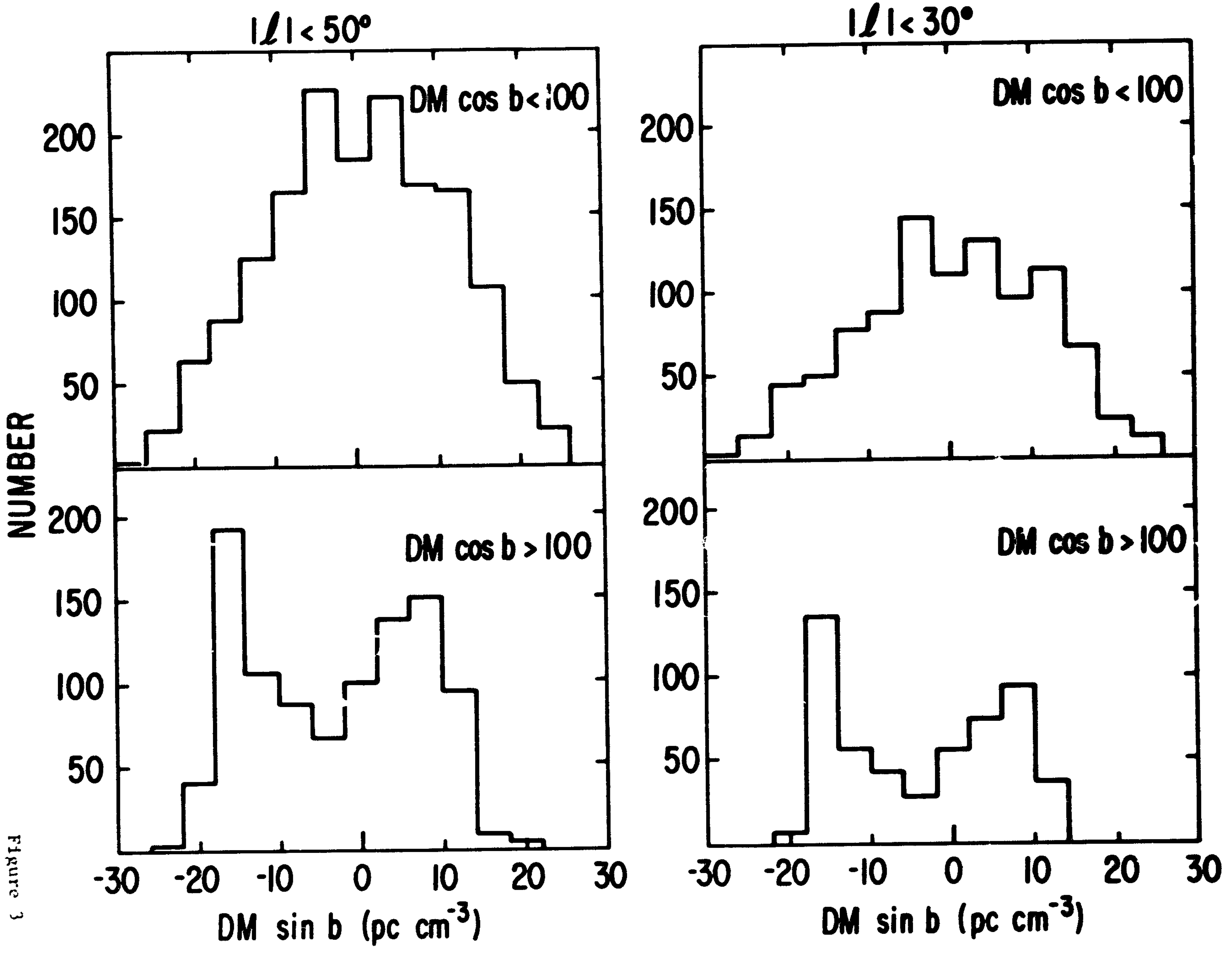
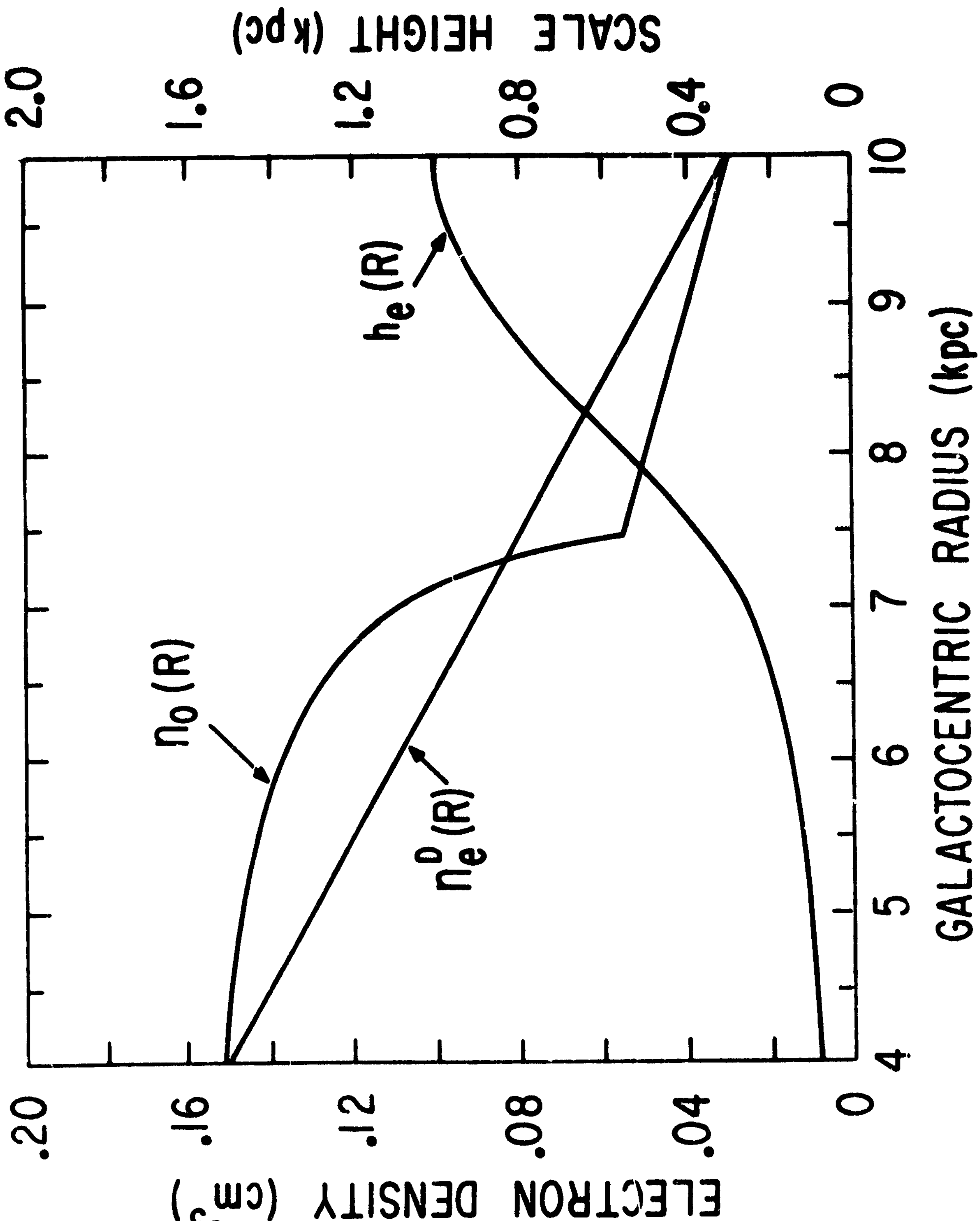

|ℓ|< 50°
|ℓ|< 30°
NUMBER
DM cos b< 100
DM cos b > 100
200
150
100
50
-30
-20
-10
0
10
20
30
DM sin b (pc cm^-3)

Figure 3



SCALE HEIGHT (kpc)
2.0
1.6
1.2
0.8
0.4
0
$h_e(R)$
$n_0(R)$
$n_e^D(R)$
4
5
6
7
8
9
10
GALACTOCENTRIC RADIUS (kpc)
.20
.16
.12
.08
.04
0
ELECTRON DENSITY (cm^{-3})

Figure 4

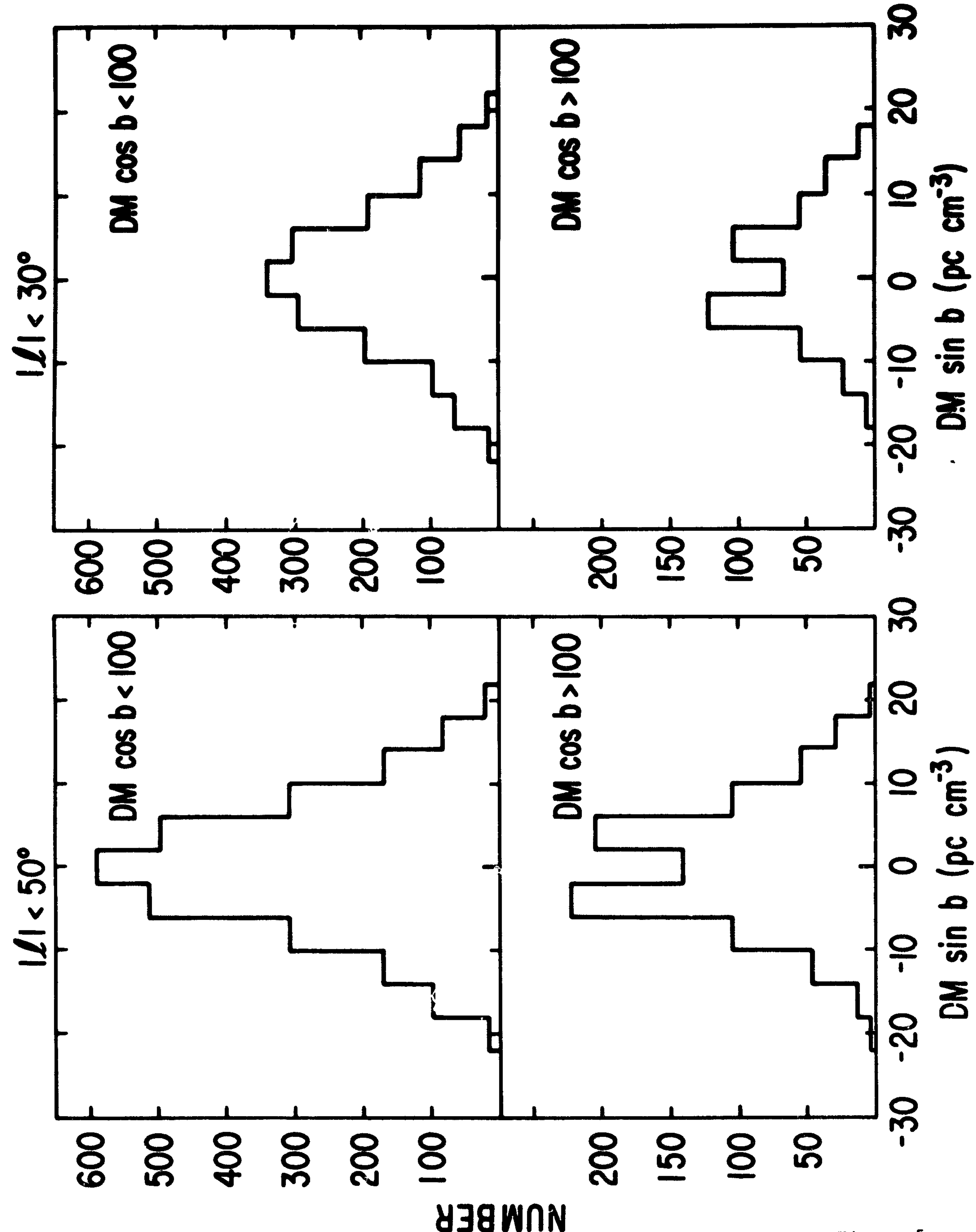

|ℓ| < 30°
|ℓ| < 50°
DM cos b < 100
DM cos b > 100
DM cos b < 100
DM cos b > 100
NUMBER
600
500
400
300
200
100
200
150
100
50
-30
-20
-10
0
10
20
30
DM sin b (pc cm^{-3})
DM sin b (pc cm^{-3})

Figure 5