Determination of the Sun’s Offset from the Galactic Plane Using Pulsars

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ABSTRACT

We derive the Sun’s offset from the local mean Galactic plane ($z_0$) using the observed $z$ distribution of young pulsars. Pulsar distances are obtained from measurements of annual parallax, HI absorption spectra or associations where available and otherwise from the observed pulsar dispersion and a model for the distribution of free electrons in the Galaxy. We fit the cumulative distribution function for a sech$^2$($z$) distribution function, representing an isothermal self-gravitating disk, with uncertainties being estimated using the bootstrap method. We take pulsars having characteristic age $\tau < 10^{5.5}$ yr and located within 4.5 kpc of the Sun, omitting those within the local spiral arm and those significantly affected by the Galactic warp, and solve for $z_0$ and the scale height, $H$, for different cutoffs in $\tau_c$. We compute these quantities using just the independently determined distances, and these together with DM-based distances separately using the YMW16 and NE2001 Galactic electron density models. We find that an age cutoff at $10^{7.5}$ yr with YMW16 DM-distances gives the best results with a minimum uncertainty in $z_0$ and an asymptotically stable value for $H$ showing that, at this age and below, the observed pulsar $z$-distribution is dominated by the dispersion in their birth locations. From this sample of 115 pulsars, we obtain $z_0 = 13.4 \pm 4.4$ pc and $H = 56.9 \pm 6.5$ pc, similar to estimated scale heights for OB stars and open clusters. Consistent results are obtained using the independent-only distances and using the NE2001 model for the DM-based distances.

Key words: Sun – position – pulsar–distance

1 INTRODUCTION

It has long been known that the Sun is offset from the local mean Galactic plane toward the North Galactic Pole. An early estimate of the offset by van Tuller (1942) based on an analysis of mainly local stars gave $z_0 = 13.5 \pm 1.7$ pc. As listed in Table 1, over the last few decades a variety of astronomical objects and methods have been used to estimate $z_0$. In Conti & Vacca (1990), the $z$ distribution of Wolf-Rayet stars within 4.5 kpc of the Sun was fitted with a single, self-gravitating and isothermal disk (Spitzer 1942; Bahcall 1984), giving $z_0 = 15 \pm 3$ pc. The improved photometric accuracy and increased sky coverage of the Palomar Sky Survey (Humphreys & Larsen 1995) and the Sloan Digital Sky Survey (Chen et al. 2001) gave $z_0$ values a little larger than previous results. Maiz-Apellániz (2001) used Hipparcos trigonometric parallaxes to derive the $z$-distribution of local OB stars, fitting it with an isothermal disk to obtain $z_0 = 24.2 \pm 1.8$ pc. More recent studies have analysed the observed distributions of OB stars, open clusters, Cepheid variables, HII regions and giant molecular clouds. For example, Joshi (2007) used three different methods in their analysis, obtaining values in the range 6 – 28 pc for OB stars with $d < 1.2$ kpc and 13 – 20 pc for young open clusters with age $< 10^{8.5}$ yr and $d < 4$ kpc. An asymmetric $z$ distribution of Cepheid variables with respect to the plane through the Sun was discovered by Majaess et al. (2009). They obtained $z_0 = 26 \pm 3$ pc from a Gaussian fit to Cepheids with $d < 2$ kpc.

As Table 1 shows, recent analyses have tended to have smaller uncertainties, although still with a significant spread of values, largely because of the increased number of astronomical objects, improved accuracy of the distances and consideration of perturbing influences. Bobylev & Bajkova (2016) used 639 methanol masers, 878 HII regions and 538 giant molecular clouds located in the inner region of the Galaxy and fitted these data sets to a self-gravitating isothermal disk. After considering the effects of the local spiral arm, the Gould Belt and the Galactic warp, they obtained $z_0 = 5.7 \pm 0.5$ pc for methanol masers, $z_0 = 7.6 \pm 0.4$ pc for HII regions and $z_0 = 10.1 \pm 0.5$ pc for giant molecular clouds. Joshi et al. (2016) used an almost complete sample of 1241 open

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clusters within 1.8 kpc of the Sun and fitted an exponential profile to the data sets, resulting in \( z_0 = 6.2 \pm 1.1 \) pc. An analysis by Buckner & Froebrich (2014) of a different sample of open clusters gave a much larger value of \( z_0 = 18.5 \pm 1.2 \) pc. Finally, Olausen & Kaspi (2014) analysed the \( z \)-distribution of 19 magnetars by fitting to the cumulative distribution function (CDF) and obtained \( z_0 = 13.9 \pm 2.5 \) pc.

Distances to astronomical objects are key for any analysis of the Sun’s offset from the Galactic plane. Pulsar distances can be estimated from measurements of annual parallax, HI absorption spectra, and associations with globular clusters or supernova remnants and optical observations of binary companion stars. At present, only 189 pulsars have such “independent” distances; these pulsars are listed in the Appendix of Yao et al. (2017) (Table 8 to Table 12). Fortunately, for most pulsars we can estimate distances using interstellar dispersion, quantified by the dispersion measure (DM):

\[
DM = \int_0^D n_e dl,
\]

where \( n_e \) is the free electron density and \( D \) is the pulsar distance, and a model for the Galactic \( n_e \) distribution. Until recently, the NE2001 model (Cordes & Lazio 2002)\(^2\) was the default choice for computing DM-based distances. However, we have recently published the YMW16 model (Yao et al. 2017)\(^3\) which takes advantage of advances in our knowledge of Galactic structure and a significant increase in the number of pulsars with independent distance estimates over the past 15 years. In this work, we consider three pulsar samples: a) pulsars with independent distances, b) pulsars with independent distances plus DM-based distances using the NE2001 model, and c) pulsars with independent distances plus DM-based distances using the YMW16 model.

Since pulsars are relatively high-velocity objects (e.g., Hobbs et al. 2005) and pulsar ages, based on the characteristic age \( \tau_c = P/(2 \dot{P}) \) where \( P \) is the period slow-down rate, can be large, especially for millisecond pulsars, we need to limit the age range of the pulsar sample used in the analyses. Only for relatively young pulsars is the \( z \) distribution dominated by their birth location. For preliminary analyses, we adopt a limit of \( \tau_c < 10^{6.5} \) yr, and then we investigate the effect of age by fitting to samples with five different age limits in the range \( 10^{5.25} \) yr and \( 10^{6.5} \) yr.

The arrangement of our paper is as follows. Data sets and analysis methods are discussed in §2. In §3 we consider the effect of the Gould Belt, the Local Arm and the Galactic warp on our analysis. In §4 we consider the effect of the different \( \tau_c \) cutoffs and present our final results and we summarise our conclusions in §5.

### 2 METHODS

For this analysis, we adopt a coordinate system with origin at the Sun, with the \( x \) axis toward \( l = 90^\circ \), \( y \) axis toward \( l = 180^\circ \) and \( z \) axis toward the North Galactic Pole (Figure 1). Note that this coordinate system is not the same as the Galactocentric coordinate system in which \( z_0 \) is defined, where origin is at the Galactic Centre and the \( X-Y \) plane is the Galactic plane. In the heliocentric system, coordinates of pulsars (or other objects) are \((x, y, z) = (d \sin l \cos b, d \cos l \cos b, d \sin b)\), where \( d \) is distance from the Sun and \( l, b \) are the Galactic longitude and latitude, respectively. In the Galactocentric coordinate system, the Sun is located at \( R_\odot = 8300 \) pc (Brunthaler et al. 2011).

A variety of different methods have been employed to estimate \( z_0 \) as discussed in §1. If the distances to astronomical objects are available, fitting a function to the observed \( z \) distribution is the most common method (e.g., Conti & Vacca 1990; Bobylev & Bajkova 2016; Joshi et al. 2016). Many of these previous works adopted a self-gravitating isothermal disk model in which the \( z \) distribution is described by \( \text{sech}^2(z) \). The Galactic electron density models, NE2001 and YMW16, also adopt this function for \( z \) distributions. Consequently, we also use it and model the number density distribution of pulsars in \( z \) by the following equation:

\[
N(z) = N_0 \text{sech}^2\left(\frac{z + z_0}{H}\right)
\]

where \( N_0 \) is number density in the Galactic plane, \( z_0 \) is the distance between the Sun and the Galactic plane, and \( H \) is the scale height of pulsars with respect to the Galactic plane.

As discussed by Olausen & Kaspi (2014), fitting Equation 2 directly to binned data for the \( z \) distribution fails when the sample is small in number. In such cases, it is better to fit to the CDF which, for the \( \text{sech}^2(z) \) distribution given by Equation 2, is

\[
F(z; z_0, H) = \frac{1}{1 + \exp\left(-\frac{2z}{2H}\right)}
\]

\(^2\) https://www.nrl.navy.mil/rsd/RORF/ne2001/
\(^3\) http://www.xao.ac.cn/ymw16/.
http://www.atnf.csiro.au/research/pulsar/ymw16/

![Figure 1. Coordinate system for analysis of the pulsar \( z \) distribution.](image-url)
where $F$ is in the range $[0,1]$ for $z$ in the range $\pm\infty$. We use the Levenberg-Marquardt algorithm (Press et al. 1992) to fit for $z_0$ and $H$. Because of the small samples, the uncertainties in these parameters are dominated by sample variance rather than the formal fit uncertainties. Consequently, we use the bootstrap method (Efron 1981) to calculate parameter uncertainties. Our bootstrap procedure for a sample of $N$ $z$-values is as follows:

(i) Randomly select a $z$ value from the sample $N$ times to build up a new sample of $N$ values
(ii) Solve for $z_0$ and $H$ using this sample and store the results
(iii) Repeat steps i-ii 500 times, generating 500 $z_0$ and $H$ values
(iv) Take the rms deviation of these values about the mean as the uncertainty in the parameters derived from a fit to the original sample.

We have applied these methods to several different samples of the known pulsar population, selected as follows. We firstly take the sample of 189 pulsars with independent distances given by Yao et al. (2017) and select pulsars with known age ($\tau_c$) and DM, and omit pulsars associated with globular clusters, giving a total of 161 pulsars that we can use for modelling the $z$ distribution. Especially after limiting the age range, this sample is very small, and so we need to supplement it with pulsars with distances obtained from the DM and and a Galactic $n_z$ model. From the ATNF Pulsar Catalogue (V1.54, Manchester et al. 2005), 4, and applying the same selection criteria, we obtain a list of 1923 pulsars. For the 1762 of these without independent distances, we can use either the NE2001 or YMW16 Galactic $n_z$ models to estimate distances and hence $z$ values from the observed DM.

Since we are interested in the offset of the Sun from the local mean Galactic plane, we further restrict our samples to pulsars having estimated distances less than 4.5 kpc. This leaves 134 pulsars in the sample with independent distances, 936 from the sample with NE2001 distances and 911 from the sample with YMW16 distances.

As discussed in §1 we need to limit the age range of pulsars included in the analysis. Figure 2 shows the distribution of pulsars (using the local YMW16 sample described above) and their mean $z$ separately for $z > 0$ and $z < 0$ as a function of characteristic age. The upper panel of Figure 2 shows that pulsars cluster in two groups, one corresponding to normal pulsars with log $\tau_c < 8.5$ and the other at larger $\tau_c$ corresponding to millisecond pulsars. From the bottom panel of Figure 2, the mean $z$ increases with increasing $\log \tau_c$ up to log $\tau_c < 7.0$ showing the effect of pulsar velocities. We select pulsars from the samples described above with log $\tau_c \geq 6.5$ as base samples for further investigations of the effect of pulsar age and other factors on the derived $z_0$ and $H$. These contain 63, 289 and 341 pulsars for the independent, NE2001 and YMW16 distances, respectively.

3 FACTORS INFLUENCING THE $Z$ DISTRIBUTION

3.1 Gould Belt and Local arm

It has long been recognised that the Sun is located interior to a ring of relatively young stars and stellar clusters known as the Gould Belt (e.g., Elias et al. 2006). The Gould Belt has a radius of about 300 pc and is centred about 100 pc from the Sun toward the Galactic anti-centre with an inclination to the plane of about 18° (e.g.,

\[ F \in [0,1] \text{ for } z \in \pm\infty. \]

\[ \text{We use the Levenberg-Marquardt algorithm (Press et al. 1992) to fit for } z_0 \text{ and } H. \]

\[ \text{Because of the small samples, the uncertainties in these parameters are dominated by sample variance rather than the formal fit uncertainties.} \]

\[ \text{Consequently, we use the bootstrap method (Efron 1981) to calculate parameter uncertainties. Our bootstrap procedure for a sample of } N \text{ } z\text{-values is as follows:} \]

(i) Randomly select a $z$ value from the sample $N$ times to build up a new sample of $N$ values
(ii) Solve for $z_0$ and $H$ using this sample and store the results
(iii) Repeat steps i-ii 500 times, generating 500 $z_0$ and $H$ values
(iv) Take the rms deviation of these values about the mean as the uncertainty in the parameters derived from a fit to the original sample.

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3.2 Galactic Warp

It is well known that the outer Galactic disk has a substantial warp (e.g., Urquhart et al. 2014). Following Robin et al. (2003) and using a Galactocentric ($X, Y, Z$) coordinate system, Yao et al. (2017) have modeled the $Z$ offset due to the Galactic warp as follows:

\[ Z_w = Z_c \cos(\phi - \phi_c), \]

\[ Z_c = \gamma_c (R - R_w), \]

\[ \text{http://www.atnf.csiro.au/research/pulsar/psrcat} \]

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\[ \text{Figure 2. The upper panel shows the histogram of number of pulsars vs } \log r, \text{ separately for pulsars with } z > 0 \text{ and } z < 0 \text{ with model distances based on YMW16. The lower panel shows the mean } z \text{ for each bin sub-sample. Only pulsars within 4.5 kpc of the Sun are included in the sample.} \]

\[ \text{Perrot & Grenier 2003). Although Joshi et al. (2016) omitted 26 open clusters believed to be associated with the Gould Belt from their analysis, we see no effect of the Gould Belt on the observed pulsar distribution, most probably because only a few pulsars are located within the Gould Belt region.} \]

\[ \text{Studies of the Galactic distribution of young objects (see, e.g., Hou & Han 2014) show evidence of a weak spiral feature close to the Sun, known as the Local Arm. From an analysis of 29 methanol masers believed to be associated with the Local Arm, Bobylev & Bajkova (2016) found that the Local Arm is centred 25 – 35 pc above the Galactic plane. To investigate the effect of the Local Arm on our results, we adopt the age-limited sample with independent and YMW16-based distances containing 341 pulsars described above and fit the CDF (Equation 3) to the observed pulsar cumulative $z$ distribution. The results of the fits are presented in the top left panel of Figure 3.} \]

\[ \text{Using the definitions of Yao et al. (2017), a total of 32 pulsars from this sample have perpendicular distances from the Local Arm } \rho_c < 300 \text{ pc. If we exclude these pulsars and repeat the fit to the cumulative distribution, we obtain the results presented in the bottom left panel of Figure 3. The larger value of } z_0 \text{ for the sample omitting Local Arm pulsars (20.2±6.0 pc versus 17.6±5.9 pc) is consistent with the Local Arm being located above the mean Galactic Plane as found by Bobylev & Bajkova (2016). Although the effect of the Local Arm is marginal, to avoid any bias we choose to omit the Local Arm pulsars from subsequent analyses.} \]
Figure 3. Cumulative $z$-distributions for four pulsar samples as described in the text. The effect of the Local Arm is shown in the left panels and the right panels show the effect of the Galactic warp. In each case, the black dots show the observed distribution and the blue line shows the fit of Equation 3.

where $Z_0$ and $\phi_0$, respectively represent the maximum warp offset at a given Galactocentric radius $R > R_0$ and the direction for which the warp offset is maximum, and $\phi$ is measured counterclockwise from the $+X$ direction, parallel to $l = 90^\circ$. For $\phi_0 = 0$ and $R_0 = 8400$ pc, Yao et al. (2017) obtain $\gamma_w = 0.14 \pm 0.066$ and we adopt these parameters here. The warp affects the disk at $R > R_0$ and is toward $+Z$ in the $+X$ direction and toward $-Z$ in $-X$ direction. In Figure 3, the top right panel is a repeat of the bottom right panel which ignores the warp, whereas for the bottom right panel, we omit the 38 pulsars for which $Z_0 > 10$ pc. Again, although the effects of omitting the warp-affected pulsars are marginal, we choose to exclude them from the samples used for further analysis. For the independent distances, independent plus NE2001 model distances and independent plus YMW16 model distances, the resulting sample sizes are 45, 222 and 271 pulsars, respectively.

4 RESULTS AND DISCUSSION

Taking the final samples discussed in the previous section, we fit the cumulative $z$-distributions for $Z_0$ and $H$ using the CDF given by Equation 3 for cutoffs in $\log \tau_c$ between 5.25 and 6.5. The results are tabulated in Table 2 and plotted in Figure 4. Uncertainties are estimated by using the bootstrap method described in Section 2. These are generally a factor of three or so larger than the uncertainties given by the least-squares fit, but we believe that they better represent the true uncertainty in the derived values, especially for the smaller samples. Because of the much smaller sample sizes, results for the independent-only samples are much more uncertain, but never-the-less consistent with the larger samples which include the DM-based distances.

With decreasing age cutoff, the scale height $H$ stabilises at a little less than 60 pc for cutoffs (in $\log \tau_c$) of 5.75 and lower. This shows that, for pulsars younger than about 550 kyr, the observed $z$-distribution is dominated by the dispersion in birth location (in $z$) rather than the dispersion resulting from pulsar space velocities over their lifetime. It is notable that the derived scale height increases much more rapidly with increasing age for the NE2001 sample compared to both the independent and YMW16 samples. This is most probably a consequence of the typically smaller spiral-arm densities in the NE2001 model compared to the YMW16 model, especially for the Carina arm.

An age cutoff of $10^{5.75}$ yr also gives the smallest uncertainties in the derived $Z_0$ for all samples. These minima result from the competing effects of tighter distributions and smaller sample sizes as the age cutoff is reduced.

Figure 5 shows the observed and fitted CDFs for the three samples with age cutoff at $10^{5.75}$ yr. All of the observed CDFs have a similar form although the effects of the different sample sizes are evident. While the bulk of the population is well modelled by the self-gravitating isothermal disk, with most pulsars lying within 100 pc of the Galactic plane, there is a significant number of outliers at larger $z$ for all three samples. The fact that these outliers are present in the sample of independent distances shows that they do not result from deficiencies in the $n_\tau$ models, but represent a distinct high-$z$ population. Whether this results from a population of high-$z$ birth locations or from a high-velocity tail on the pulsar velocity distribution is unclear. In any case, it has little influence on the fitted values of $Z_0$ and $H$.

Of the three samples with age cutoff at $10^{5.75}$ yr, the one using YMW16 model distances gives the smallest uncertainties. We therefore adopt the results from fitting to the sample with YMW16-
Table 2. Values of \( z_0 \) and \( H \) from fits to cumulative \( z \)-distributions with samples based on just independent distances, independent distances plus NE2001 model distances, and independent distances plus YMW16 model distances with different cut-off ages. Uncertainties are estimated using a bootstrap method.

| Samples          | Independent | NE2001 | YMW16 |
|------------------|-------------|--------|-------|
|                  | \( N \) | \( z_0 \) | \( H \) | \( N \) | \( z_0 \) | \( H \) | \( N \) | \( z_0 \) | \( H \) |
| \( \log \tau_c < 6.5 \) | 45 | 30.2±15.5 | 111.5±29.3 | 222 | 20.0±9.7 | 181.9±14.3 | 271 | 20.9±6.1 | 119.4±11.0 |
| \( \log \tau_c < 6.0 \) | 28 | 20.3±13.3 | 72.5±25.4 | 113 | 17.1±8.3 | 99.5±12.3 | 151 | 17.1±5.2 | 74.9±8.1 |
| \( \log \tau_c < 5.75 \) | 21 | 7.1±12.1 | 44.6±26.5 | 78 | 12.0±6.6 | 68.2±12.8 | 115 | 13.4±4.4 | 56.9±6.5 |
| \( \log \tau_c < 5.5 \) | 15 | 16.2±18.2 | 57.0±35.9 | 53 | 13.2±8.0 | 54.8±14.1 | 79 | 15.9±6.0 | 54.5±7.0 |
| \( \log \tau_c < 5.25 \) | 14 | 21.5±30.2 | 67.6±74.7 | 44 | 11.5±9.3 | 58.5±15.9 | 66 | 12.5±6.4 | 53.9±6.4 |

Figure 5. Cumulative \( z \)-distributions for the final samples with only independent distances (top), NE2001 distances (middle) and YMW16 distances (bottom). In each case, the black dots show the observed distribution and the blue line is the best-fit of Equation 3.

Figure 6. Histograms of the \( z \)-distributions for the final samples with NE2001 distances (upper), YMW16 distances (lower). The blue line is the best-fit of Equation 2 for each case.

As a consistency check, we have directly fitted the sech\(^2\) distribution function (Equation 2) to binned histograms of the observed \( z \) distributions for the final YMW16 and NE2001 samples; there are insufficient pulsars in the independent-distance sample for this method to work reliably. The results are shown in Figure 6. The derived values of \( z_0 \) are very similar to those from fitting of the cumulative histograms (Table 2 and Figure 5). Estimates of pulsar scale height \( H \) tend to be smaller with the histogram fits, but still quite consistent within the uncertainties with those from the CDF fits. Evidently, outliers have less effect on the histogram fits.

We have also investigated the effect of uncertainties in the adopted distances for pulsars in our sample. Uncertainties in the independent distances are tabulated in Yao et al. (2017). Uncertainties in DM-based distances are harder to assess, but the analysis in Yao et al. (2017) (Table 5) suggests an rms deviation of about 45% for YMW16 model distances and 60% for NE2001 model distances. We used a Monte Carlo procedure to investigate the effect of these uncertainties on the results, randomly choosing a distance within the uncertainty range for each pulsar in the log \( \tau_c \) < 5.75 samples, fitting for \( z_0 \) and \( H \) from the cumulative distributions, and repeating this 500 times. The rms deviations of the resulting \( z_0 \) distributions were just 1.1 pc and 0.75 pc for the NE2001 distances and YMW16 distances respectively, much less than the quoted rms uncertainties (Table 2) which are dominated by sample variance and measured using the bootstrap method. To a lesser extent, the same is true for the distributions in \( H \).

Our final result for the solar offset, \( z_0 = 13.4±4.4 \) pc, is well within the range of other recent determinations of this parameter (Table 1) and essentially identical to the result of Olausen & Kaspi (2014) from a fit to the \( z \) distribution of magnetars. In a recent pa-
per, Karim & Mamajek (2017) compiled 55 estimates of $z_0$ made over the past century. The median of these, 17±2 pc, is consistent with our result. These agreements show that pulsars, despite their relatively large space velocities, can give a reliable independent measure of the Sun’s offset from the local mean Galactic plane.

Similarly, our final result for the scale height of local pulsars with $\tau_e \leq 10^{7.75}$ yr, 56.9±6.5 pc, is consistent with the derived scale height of 60±2 pc for open clusters (Joshi et al. 2016) and 61.4±2 pc for OB stars (Joshi 2007). This again shows that, for these relatively young pulsars, the space velocity of pulsars does not significantly affect their $z$ distribution. Scale heights for methanol masers, HII regions and giant molecular clouds determined by Bobylev & Bajkova (2016) are much smaller, in the range 34–40 pc. This reflects the younger age of these Galactic components and the fact that pulsars are born at a later stage of evolution.

It is important to note that the YMW16 Galactic $n_e$ model includes an offset of the Sun from the Galactic plane of +4.0 pc, whereas the NE2001 model has no such offset. The agreement of the derived values of $z_0$, using the two models for estimation of pulsar distances where no independent distances are available, illustrated in Figure 4, shows that the inclusion of a non-zero $z_0$ in YMW16 has no effect on the results derived in this analysis. Other factors dominate the variations in pulsar distances derived from the pulsar DM and Galactic $n_e$ models.

5 CONCLUSIONS

Using independent distances for pulsars and, where these are not available, distance estimates based on the pulsar dispersion measures and two models for the Galactic $n_e$ distribution (NE2001 and YMW16) we have fitted the observed $z$ distribution of young pulsars to estimate the offset of the Sun $z_0$ from the local mean Galactic plane. After limiting the distance of the pulsars from the Sun ($d < 4.5$ kpc), omitting pulsars located within the local spiral arm and those which may be affected by the Galactic warp ($Z > 10$ pc), and taking only young pulsars ($\tau_e < 10^{7.75}$ yr), we derive $z_0 = 13.4±4.4$ pc. This result is consistent with recent determinations of $z_0$ using other young tracers of the Galactic disk such as OB stars, open clusters, methanol masers, HII regions and giant molecular clouds. It is also independent of which Galactic $n_e$ model is used to estimate pulsar distances from their dispersion measure. The derived scale height for pulsars with $\tau_e \leq 10^{7.75}$ yr, 56.9±6.5 pc, is dominated by the pulsar birth locations and is comparable to the observed scale height of OB stars and open clusters, but about 50% larger than that of HII regions, methanol masers and giant molecular clouds.

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5 Bobylev & Bajkova (2016) use a scale factor of $\sqrt{2}H$ for an isothermal self-gravitating disk whereas we simply use $H$. We have therefore multiplied their quoted scale heights by $\sqrt{2}$ for comparison with our results.