Displacement of the Sun from the Galactic Plane

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ABSTRACT

We have carried out a comparative statistical study for the displacement of the Sun from the Galactic plane \(z_\odot\) following three different methods. The study has been done using a sample of 537 young open clusters (YOCs) with \(\log(\text{Age}) < 8.5\) lying within a heliocentric distance of 4 kpc and 2030 OB stars observed up to a distance of 1200 pc, all of them have distance information. We decompose the Gould Belt’s member in a statistical sense before investigating the variation in the \(z_\odot\) estimation with different upper cut-off limits in the heliocentric distance and distance perpendicular to the Galactic plane. We found \(z_\odot\) varies in a range of \(\sim 13 - 20\) pc from the analysis of YOCs and \(\sim 6 - 18\) pc from the OB stars. A significant scatter in the \(z_\odot\) obtained due to different cut-off values is noticed for the OB stars although no such deviation is seen for the YOCs. We also determined scale heights of \(56.9^{+3.8}_{-3.4}\) and \(61.4^{+2.7}_{-2.1}\) pc for the distribution of YOCs and OB stars respectively.

Key words: Galaxy: structure, open clusters, OB stars, Gould Belt – method: statistical – astronomical data bases

1 INTRODUCTION

It has long been recognized that the Sun is not located precisely in the mid-plane of the Galactic disk defined by \(b = 0^\circ\) but is displaced a few parsecs to the North of Galactic plane (GP) (see Blitz & Teuben 1996 for a review) and understanding the exact value of \(z_\odot\) is vital not only for the Galactic structure models but also in describing the asymmetry in the density distribution of different kind of stars in the north and south Galactic regions (Cohen 1995, Méndez & van Altena 1998, Chen et al. 1999). Several independent studies in the past have been carried out to estimate

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using different kind of astronomical objects, for example, Gum, Kerr & Westerhout (1960) concluded that \( z_\odot = 4 \pm 12 \) pc from the neutral hydrogen layer, Kraft & Schmidt (1963) and Fernie (1968) used Cepheid variables to estimate \( z_\odot \sim 40 \) pc while Stothers & Frogel (1974) determined \( z_\odot = 24 \pm 3 \) pc from the B0-B5 stars within 200 pc from the Sun, all pointing to a broad range of \( z_\odot \). More recently various different methods have been employed to estimate \( z_\odot \) e.g. Cepheid variables (Caldwell & Coulson 1987), Optical star count technique (Yamagata & Yoshii 1992, Humphreys & Larsan 1995, Chen et al. 2001), Wolf-Rayet stars (Conti & Vecca 1990), IR survey (Cohen 1995, Binney, Gerhard & Spergel 1997, Hammersley et al. 1995) along with different simulations (Reed 1997, Méndez & van Altena 1998) and models (Chen et al. 1999, Elias, Cabrera-Caño & Alfaro 2006, hereafter ECA06). Most of these studies constrained \( z_\odot \) in the range of 15 to 30 pc in the north direction of the GP.

In recent years, the spatial distribution of open clusters (OCs) have been extensively used to evaluate \( z_\odot \) since continued compilation of new clusters has brought together more extensive and accurate data than ever. Using the OCs as a diagnostic tool to determine \( z_\odot \), Janes & Adler (1982) found \( z_\odot = 75 \) pc for 114 clusters of age smaller than \( 10^8 \) yr while Lyngå (1982) determined \( z_\odot \sim 20 \) pc with 78 young clusters up to 1000 pc. Pandey & Mahra (1987) reported \( z_\odot \) as 10 pc from the photometric data of OCs within \(|b| \leq 10^\circ\) and Pandey, Bhatt & Mahra (1988) using a subsample of YOCs within 1500 pc obtained \( z_\odot = 28 \pm 5 \) pc. Most recently, \( z_\odot \) have been determined in three independent studies based on the analysis of OCs. Considering about 600 OCs within \( 5^\circ \) of GP, we derived \( z_\odot = 22.8 \pm 3.3 \) pc through the analysis of interstellar extinction in the direction of the OCs (Joshi 2005, hereafter JOS05). Bonatto et al. (2006) reported \( z_\odot \) as 14.8 \( \pm \) 2.4 pc using 645 OCs with age less than 200 Myrs while Piskunov et al. (2006, hereafter PKSS06) estimated a value of 22 \( \pm \) 4 pc using a sample of 650 OCs which is complete up to about 850 pc from the Sun. On the other hand using a few thousand OB stars within \( 10^\circ \) of the GP and 4 kpc from the Sun, Reed (1997) approximately estimated the value as 10-12 pc while Maíz-Apellániz (2001) determined this values as 24.2 \( \pm \) 2.1 pc using a sample of about 3400 O-B5 stars obtained from the Hipparcos catalogue.

The large range of \( z_\odot \) derived from these different methods could be possibly caused by the selection of data of varying age, heliocentric distance \( d \), spectral type, etc. along with the method of the determination. The aim of the present paper is therefore to study the variation in \( z_\odot \) following different methods by constraining different upper limits in \( z \) and \( d \) using a large sample of OCs and OB stars. The paper is organized as follows. First we detail the data used in this study in Sect. 2. In Sect. 3, we examine the distribution of \( z \) with the age of clusters while Sect. 4 deals their
distribution with the different \( z \) cut-off and \( d \) cut-off in order to determine \( z_\odot \). The exponential decay of \( z \) distribution of the OCs and OB stars and their variation over the Galactic longitude are discussed in Sects. 5 and 6 respectively. Our results are summarized in Sect. 7.

2 THE DATA

We use two catalogues in this study. The OC catalogue is compiled by Dias et al. (2002)\(^1\) which includes information available in the catalogues of the Lyngå (1987) as well as WEBDA\(^2\) with the recent information on proper motion, age, distance from the Sun, etc. The latest catalogue (Version 2.7) that was updated in October 2006 gives physical parameters of 1759 OCs. Of these, 1013 OCs have distance information for which it is possible to determine \( z \) which is equivalent to \( d \sin b \) where \( b \) is the Galactic latitude. Out of the 1013 OCs, age information is available for 874 OCs with ages ranging from 1 Myr to about 10 Gyr, although the majority of them are young clusters. Though the clusters are observed up to a distance of about 15 kpc, it should be born in mind that the cluster sample is not complete owing to large distance and/or low contrast of many potential cluster candidates (Bonatto et al. 2006) and may be smaller by an order of magnitude since a good fraction of clusters are difficult to observe at shorter wavelengths due to large extinction near the GP (Lada & Lada 2003, Chen, Chen & Shu 2004, PKSS06). When we plot cumulative distribution of the clusters in our sample as a function of \( d \) in Fig. 1, we notice that the present cluster sample may not be complete beyond a distance of about 1.7 kpc. A comprehensive discussion on the completeness of OCs has recently been given by Bonatto et al. (2006) which along with PKSS06 puts the total number of Galactic OCs in the order of \( 10^5 \).

The other sample used in the present study is that of the OB stars taken from the catalogue of Reed (2006) which contains a total of 3457 spectroscopic observations for the 2397 nearby OB stars\(^3\). The distance of OB stars are derived through their spectroscopic parallaxes. It is worth to note that the individual distance of OB stars may not be accurate (Reed 1997), nevertheless, a statistical study with significant number of OB stars can still be useful for the determination of \( z_\odot \). Although, several studies on the determination of \( z_\odot \) using OB stars have already been carried out on the basis of Hipparcos catalogue (Maíz-Apellániz 2001, ECA06 and references therein), however, it is noticed by some authors that the Hipparcos catalogue gives a reliable distance estimation within a distance of only 200-400 pc from the Sun (cf. Torra, Fernández & Figueras 2000).

\(^1\) Updated information about the OCs is available in the on-line data catalogue at the web site [http://www.astro.iag.usp.br/~wilton/](http://www.astro.iag.usp.br/~wilton/)

\(^2\) [http://obswww.unige.ch/webda](http://obswww.unige.ch/webda)

\(^3\) For the detailed information about the data, the reader is referred to [http://othello.alma.edu/~reed/OBfiles.doc](http://othello.alma.edu/~reed/OBfiles.doc)
Figure 1. A cumulative distribution diagram for the number of the open clusters with distance from the Sun. The vertical dashed line indicates the completeness limit while continuous line represents the least square fit in that region.

This is exactly the region where OB stars in the Gould Belt (hereafter GB) lie and this can cause an anomaly in the determination of $z_\odot$ if the stars belonging to the GB are not be separated from the data sample. Further Abt (2004) also noticed that classification of the stars in the Hipparcos catalogue is uncertain by about +/-1.2 subclass in the spectral classifications and about 10% in the luminosity classifications. In the present study we therefore preferred Reed’s catalogue of OB stars over the Hipparcos catalogue despite lesser in numbers but are reported up to a distance of about 1200 pc from the Sun and $V \sim 10$ mag. The OB stars which have two different distances in the catalogue are assigned the mean distance provided they do not differ by more than 100 pc, otherwise we remove them from our analysis. If there are more than two distances available for any OB star, we use the median distance. In this way, we considered a sample of 2367 OB stars in this study.
Figure 2. The distribution of mean $z$ with $\log(\text{Age})$. A vertical dotted line shows upper boundary for the age limit considered as YOCs in the present study. The horizontal dashed lines are drawn to represent the weighted mean $z$ value of the YOCs in the $z > 0$ and $z < 0$ regions. Note that there is one cluster of $\log(\text{Age}) = 10.0$ ($z \sim -172$ pc) which is not shown in the plot.

3 DISTRIBUTION OF $Z$ WITH THE AGE

It is a well known fact that OCs are born and distributed throughout the Galactic disk. Young clusters are normally seen in the thin disk while old clusters are found mainly in the thick disk of the Galaxy which van den Bergh (2006) termed as a ‘cluster thick disk’. In order to study the $z$ distribution of clusters with their age, we assemble the clusters according to their $\log(\text{Age})$ in 0.2 bins dex in width and estimate a mean value of $z$ for each bin. A distribution of mean $z$ vs $\log(\text{Age})$ is plotted in Fig. 2 which clearly demonstrates that the distribution of clusters perpendicular to the GP has a strong correlation with their ages. While clusters with $\log(\text{Age}) < 8.5$ ($\sim 300$ Myrs) have almost a constant width of $z$ distribution in both the directions of the GP, clusters older than this have mean $z > 100$ pc which is continuously increases with the age. This indicates that the thickness of the Galactic disk has not changed substantially on the time scale of about 300 Myrs and most of the OCs, in general, formed somewhere inside $\pm 100$ pc of the GP. A similar study carried out by Lyngå (1982) using a smaller sample of 338 OCs found that clusters younger than
one Gyr formed within $\sim 150$ pc of the Galactic disk. It is quite apparent from the figure that the clusters with $\log(\text{Age}) > 8.5$ are found not only far away from the GP but are also highly scattered in their distribution. However, this is not unexpected since it is a well known fact that clusters close to GP gets destroyed with the time in a timescale of a few hundred million years due to tidal interactions with the Galactic disk and the bulge, encounters with the passing giant molecular clouds or mass loss due to stellar evolution. The few remaining survivors reach to outer parts of the Galactic disk (cf. Friel (1995), Bergond, Leon & Guibert (2001)). If we just consider the clusters with $\log(\text{Age}) < 8.5$, which we describe as YOCs in our following analysis, we find that the 226 clusters ($\sim 38\%$) lie above GP while 363 clusters ($\sim 62\%$) lie below GP. The asymmetry in cluster density above and below the GP is a clear indication of inhomogeneous distribution of clusters around GP. This asymmetry can be interpreted as due to the location of the Sun above the GP, displacement of the local dust layer from the GP or asymmetry in the distribution of young star formation near the Sun with respect to the GP or a combination of all these effects as pointed out by the van den Bergh (2006). However, it is generally believed that it is the solar offset which plays a major role in this asymmetry.

When we estimate weighted mean displacement along the GP for the clusters lying within $\log(\text{Age}) < 8.5$, we find a value of $z = 37.0 \pm 3.0$ pc above the GP and $z = -64.3 \pm 2.9$ pc below the GP. If we consider a plane defined by the YOCs at $z_{\text{yoc}}$, then $z_{\text{yoc}}$ can be expressed as,

$$z_{\text{yoc}} = \frac{n_1 z_1 + n_2 z_2}{n_1 + n_2},$$

where $z_1$ and $z_2$ are the mean $z$ for the YOCs above and below the GP respectively; $n_1$ and $n_2$ are number of YOCs in their respective regions. This gives us a value of $z_{\text{yoc}} = -25.4 \pm 3.0$ pc. If the observed asymmetry in the $z$ distribution of YOCs is indeed caused by the solar offset from the GP then the negative mean displacement of $z$ perpendicular to GP can be taken as $z_{\odot}$ (towards north direction) which is about 25.4 pc.

However, it is a well known fact that a large fraction of the young populations with ages under 60 Myrs in the immediate solar neighbourhood belong to the GB (Gould 1874, Stothers & Frogel 1974, Lindblad 1974). It is widely believed that this belt is associated with a large structure of the interstellar matter including reflection nebulae, dark clouds, HI gas, etc. and is tilted by about 18 deg with respect to the GP and is stretches out to a distance of about 600 pc distance from the Sun (Taylor, Dickman & Scoville 1987, Franco et al. 1988, Pöppel 1997). In our sample of 589 clusters, we found 38 such clusters which confined in the region of 600 pc from the Sun and have age below 60 Myrs. Out of the 38 clusters, 26 ($\sim 68\%$) follow a specific pattern in the $d - z$
Figure 3. The distribution of YOCs in the $d - z$ plane (a). Clusters towards Galactic center direction are assigned positive distances while clusters towards Galactic anti-center direction are assigned negative distances. Only clusters with $|d| < 1$ kpc are plotted here for the clarity. Dark points in the shaded region indicate the YOC’s which could be associated with the GB and XY-distribution of these 26 GB members on the GP is shown in (b) where clusters are positioned by their distance from the Sun which is marked by a star at the center.

plane as shown by the dark points in the shaded region of Fig. 3(a) which is slightly tilted with respect to the GP and resembles the GB. The association of these clusters with the GB seems to be confirmed by the fact that 23 out of 26 YOCs are clumped in the longitude range of about 180-300 degrees as shown in Fig. 3(b). This contains the most significant structures accounting for the expansion of the GB (Torra, Fernández & Figueras 2000). A mean and median age of these 26 YOCs are 24.4 and 21.2 Myrs respectively. Although no detailed study has been carried out on the fraction of the clusters actually belonging to the GB, however, on the basis of 37 clusters in the $\log(\text{Age}) < 7.9$ which lie within a distance of 500 pc from the Sun, PKSS06 found that
about 55% of the clusters could be members of the GB. On the basis of OB stars in the Hipparcos catalogue, Torra et al. (2000) estimated that roughly 60-65% of the stars younger than 60 Myr in the solar neighbourhood belong to the GB. Although it is difficult to decide unambiguously which clusters belong to the GB, we believe that most of these 26 YOCs could be associated with the GB instead of the Local Galactic disk (hereafter LGD). Hence to reduce any systematic effect on the determination of \( z_\odot \) due to contamination of the clusters belong to the GB, we excluded all these 26 clusters from our subsequent analysis except when otherwise stated. When we re-derived the value of \( z_\odot \) from the remaining 563 clusters, we find it to be \( 22.9 \pm 3.4 \) pc north of the Galactic plane. A further discussion on the \( z_\odot \) and its dependence on various physical parameters shall be carried out below.

4 DISTRIBUTION OF \( Z \) WITH THE MAXIMUM HELIOCENTRIC DISTANCE

4.1 \( z_\odot \) from YOCs

Various studies indicate that the plane of symmetry defined by the OCs is inclined with respect to the GP (Lyngå 1982, Pandey, Bhatt & Mahra 1988, JOS05). If this is the case, then \( z_\odot \) shall be dependent on the distance of OCs from the Sun and inclination angle between the two planes. Therefore, a simple determination of \( z_\odot \) considering all the OCs could be misleading. To examine to what extent \( z_\odot \) depends on the distance, we study the distribution of clusters and their mean displacement from the GP as a function of the heliocentric distance (\( d_{\text{max}} \)) taking advantage of the OCs observed up to a large distance. Since YOCs are primarily confined closer to the GP as discussed in the previous section, it seems worthwhile to investigate \( z_\odot \) using only YOCs despite the fact that the YOCs are generally embedded in dust and gas clouds and many are not observed up to a large distance. Although we found that some young clusters are reported as far as 9 kpc from the Sun but only less than 5% YOCs are observed beyond 4 kpc, most of them in the anticenter direction of the Galaxy which we do not include in our analysis. Following all the above cuts, we retain only 537 YOCs observed up to 4 kpc from the Sun as a working sample for the present study. Their distribution normal to the GP as a function of Galactic longitude is plotted in Fig. 4(a).

Fig. 4(b) shows the logarithmic distribution of the YOCs as a function of \( |z| \). Here we derive the number density in bins of 20 pc and error bars shown in the y-axis is the Poisson error. Following an exponential-decay profile, we estimate a scale height for the YOCs as \( z_h = 59.4^{+3.3}_{-3.0} \) pc which is represented by a continuous straight line in the figure. However, a careful look in the figure
suggests that the \( z_h \) could be better described by the YOCs lying within \( z = \pm 250 \) pc and a least square fit in this region gives a value of \( z_h = 56.9^{+3.8}_{-3.4} \) pc.

It is however interesting to see if the scale height shows any shift in its value when considering a possible displacement of the cluster plane from the GP. In order to analyse any effect of the displacement on \( z_h \), we shift the cluster plane by 10, 15, 20 and 25 pc from the GP and recalculate \( z_h \) using YOCs within \( z < 250 \) pc. Our results are given in Table 1. It is seen that these values of \( z_h \) are quite consistent and we conclude that the solar offset has no bearing in the determination of scale height. Using a sample of 72 OCs younger than 800 Myrs, Janes & Phelps (1994) reported a scale height of \( z_h \sim 55 \) pc. Recently Bonatto et al. (2006) derived a scale height of \( z_h = 48 \pm 3 \) pc.
Table 1. Scale heights determined due to various offsets between cluster plane and GP. All the values are in pc.

| shift | \(z_h\)        |
|-------|----------------|
| 0     | 56.9^{+3.8}_{-3.4} |
| 10    | 55.1^{+3.3}_{-2.9} |
| 15    | 54.7^{+3.2}_{-2.9} |
| 20    | 57.2^{+3.9}_{-3.5} |
| 25    | 56.6^{+3.9}_{-3.3} |

PC using a sample of clusters younger than 200 Myrs, however, they have also found a larger \(z_h\) when considering OCs older than 200 Myrs. PKSS06 obtained a scale height of \(z_h = 56 \pm 3\) pc using the OCs within 850 pc from the Sun. Our value of \(z_h = 56.9^{+3.8}_{-3.4}\) pc obtained with the YOCs within 4 kpc from the Sun and \(z < 250\) pc is thus consistent with these determinations.

An important issue that needs to be addressed in the determination of \(z_\odot\) is the possible contamination by the outliers which are the objects lying quite far away from the GP that can seriously affect the \(z_\odot\) estimation. Hence it is worthwhile at this point to investigate \(z_\odot\) using a subsample of YOCs in different \(z\) zone excluding the clusters far away from the GP without significantly reducing the number of clusters. If the observed asymmetry in the cluster distribution is really caused by an offset of the Sun from the GP, then a single value of \(z\) should result from the analysis. In order to study \(z_\odot\) distribution using YOCs, we select three different zones normal to the \(z = 0\) plane considering the clusters within \(|z| < 150\) pc, \(|z| < 200\) pc and \(|z| < 300\) pc. Here, we have not made smaller zones than \(|z| = 150\) pc keeping in mind the fact that accounting lesser number of YOCs could have resulted in a larger statistical error while zone larger than \(|z| = 300\) pc can cause significant fluctuations due to few but random clusters observed far away from the GP. To determine \(z_\odot\), we keep on moving the mid-plane towards the southwards direction in bins of 0.1 pc to estimate the mean \(z\) till we get the mean value close to zero i.e. a plane defined by the YOCs around which the mean \(z\) is zero within the given zone that is in fact equivalent to \(z_\odot\). This approach of a running shift of \(z\) in order to determine \(z_\odot\) is preferred over the simple mean to remove any biases owing to the displacement of the cluster plane itself towards the southwards direction. Hence it gives a more realistic value of the \(z_\odot\). We estimate \(z_\odot\) with different cut-off limits in \(d_{max}\) using an increment of 0.3 kpc in each step and for all the three zones. The variation in \(z_\odot\) with \(d_{max}\) for all the zones is illustrated in Fig. 5. The figure gives a broad idea of the variation in \(z_\odot\).
which increases with the increasing distance as well as zone size, however, it has to be noted that the range of variation is very small and varies between $\sim 13$ to $21$ pc throughout the regions.

Here, it is necessary to look into the increasing trend in $z_\odot$ whether it is internal variation or due to our observational limitations. We note that 21 out of 25 YOCs observed beyond 1 kpc in the region $|z| > 150$ pc are observed in the direction of $l = 120^\circ < l < 300^\circ$. Moreover, most of these young clusters are observed below GP and majority of them are located in the direction of $l \sim 200^\circ < l < 300^\circ$. This could be due to low interstellar extinction in the Galactic anti-center direction which is least around the longitude range $220^\circ - 250^\circ$ (Neckel & Kae 1980, Arenou, Grenon & Gómez 1992, Chen et al. 1998). Based on the study of extinction towards open clusters from the same catalogue of Dias et al. (2002), we found the direction of minimum extinction towards $l \sim 230^\circ$ below the GP (JOS05). Hence a lower extinction allows us to have a higher observed cluster density in the surrounding area of the $l \sim 230^\circ$ as well as observable up to farther distance which reflected in our larger value of $z_\odot$ with the increase of the distance. Therefore, we conclude that the larger $z_\odot$ values obtained with the bigger zone or greater distance is not due to

Figure 5. The variation in $z_\odot$ with the maximum distance of YOCs from the Sun (see text for the detail).
Figure 6. The X-Z distribution of the OB stars in (a). The open circles represent the OB stars belong to LGD and filled circles represent possible GB members. The x-axis is drawn for only $\pm 600$ pc to show the GB members clearly which is quite evident in the diagram. Their distribution in the $l-z$ plane is drawn in (b). A number density distribution of the OB stars belong to the LGD as a function of $z$ is shown in (c). The continuous line here indicates a least square fit to the points.

internal variation in $z_\odot$ but due to our observational constraint. In general, we found a value of $17 \pm 3$ pc for the $z_\odot$.

4.2 $z_\odot$ from OB stars

Since YOCs are on an average more luminous than the older clusters and also possess a large number of OB stars hence lends us an opportunity to compare the results with the independent study using massive OB stars which are also a younger class of objects and confined very close to the GP. In the present analysis, we use 2367 OB stars which are strongly concentrated towards the
Displacement of the Sun from the Galactic Plane

GP as those of the YOCs. However, a natural problem in the determination of $z_\odot$ is to separate the OB stars belonging to the GB with the LGD. The issue has already been dealt with a great detail by several authors (Taylor, Dickman & Scoville 1987, Comeron, Torra & Gomez 1994, Cabrera-Caño, Elias & Alfaro 1999, Torra, Fernández & Figueras 2000). A recent model proposed by the ECA06 based on the three dimensional classification scheme allows us to determine the probability of a star belonging to the GB plane or LGD. A detailed discussion of the method can be found in the ECA06 and we do not repeat it here. Though it is not possible to unambiguously classify the membership of the stars among two populations but to statistically isolate the GB members from our sample, we used the results derived for the GB plane by the ECA06 through the exponential probability density function for the O-B6 stars selected from the Hipparcos catalogue while we used an initial guess value of 60 pc and -20 pc for the scale height and $z_\odot$ respectively for the GP. Since typical maximum radius of the GB stars is not greater than about 600 pc (Westin 1985, Comeron, Torra & Gomez 1994, Torra, Fernández & Figueras 2000), we search OB stars belonging to GB up to this distance only.

Following the ECA06 method, we found that 315 stars out of 2367 OB stars of our data sample belong to the GB. Further, 22 stars do not seem to be associated with either of the planes. In this way, we isolate 2030 OB stars belonging to the LGD which are used in our following analysis. A $X-Z$ distribution of the OB stars is shown in Fig. 6(a) (in the Cartesian Galactic coordinate system, positive $X$ represents the axes pointing to the Galactic center and positive $Z$ to the north Galactic pole) and their distribution in the GP as a function of Galactic longitude is displayed in Fig. 6(b). A clear separation of the GB plane from the GP can be seen in the figure which follows a sinusoidal variation along the Galactic longitude and reaches its lower latitude at $l = 200 - 220^\circ$.

A number density in the logarithmic scale of the OB stars belonging to LGD is shown in Fig 6(c) as a function of $|z|$ where stars are counted in the bins of 20 pc. We derive a scale height of $z_h = 61.4^{+2.7}_{-2.4}$ pc from the least square fit that is drawn by a continuous straight line in the same figure. Maíz-Apellániz (2001) using a Gaussian disk model determined a value of $z_h = 62.8 \pm 6.4$ pc which is well in agreement with our result. However, Reed (2000) derived a broad range of $z_h \sim 25 - 65$ pc using O-B2 stars while ECA06 estimates smaller value of $34 \pm 3$ pc using O-B6 stars which are more in agreement with the $34.2 \pm 3.3$ pc derived with the self-gravitating isothermal disk model of Maíz-Apellániz (2001).

It is seen in Fig. 6(b) that the OB stars are sparsely populated around the GP in comparison of the YOCs and a significant fraction of them are below $z = -150$ pc. In order to study the $z_\odot$ distribution with $d_{max}$, we here make four different zones normal to the $z = 0$ plane considering
the OB stars within $|z| < 150$ pc, $|z| < 200$ pc, $|z| < 250$ and $|z| < 350$ pc. The $z_\odot$ is estimated by the same procedure as followed for the YOCs. A variation in the $z_\odot$ with $d_{\text{max}}$ is illustrated in Fig. 7 where we have made a bin size of 50 pc. It is seen that $z_\odot$ derived in this way for the OB stars show a continuous decay with the $d_{\text{max}}$ as well as size of the zone which seems to be due to the preferential distribution of the OB stars below the GP. When we draw the spatial distribution of OB stars in the X-Y coordinate system in Fig. 8, we notice that most of the OB stars are not distributed randomly but concentrated in the loose group of the OB associations. This difference in density distribution of OB stars could be primarily related with the star forming regions. The number of OB stars below the GP are always found to be greater than the OB stars above the GP in all the distance bin of 100 pc. However, in the immediate solar neighbourhood within 500 pc distance, OB stars below the GP are as much as twice than those above the GP. This is clearly a reason behind a large value of $z_\odot$ in the smaller $d_{\text{max}}$ value which systematically decreases as more and more distant OB stars are included. A mean value of $19.5 \pm 2.2$ pc was obtained by Reed (2006) using the same catalogue of 2397 OB stars, albeit without removing the GB members. In

Figure 7. A similar plots as in Fig. 5 but for the OB stars. A big dot here represents the $z_\odot$ using all the OB stars considered in our study.
fact this is also noticeable in the present study (see big dot in Fig. 7). However, we cannot give a fixed value of $z_\odot$ from the present analysis of the OB stars as it depends strongly on the $d_{\text{max}}$ as well as selection of the $z$ cut-off.

5 EXPONENTIAL DECAY OF THE $Z$ DISTRIBUTION

It is normally assumed that the cluster density distribution perpendicular to the GP could be well described in the form of a decaying exponential away from the GP, as given by,

\[ N = N_0 \exp \left( -\frac{|z + z_\odot|}{z_h} \right), \]

where $z_\odot$ and $z_h$ are the solar offset and scale height respectively. We determine $z_\odot$ by fitting the above function. For example in Fig. 9(a), we have drawn $z$ distribution in 30 pc bin considering
all the 537 YOCs which lie within $|z| < 300$ pc and $d < 4$ kpc. Since we have already derived the scale height for the YOCs as 56.9 pc in our earlier section hence kept it fixed in the present fit. A least square exponential is fitted for all the distance limits. Here we do not divide the data sample in different zones of $z$ as we have done in the previous section since only the central region of $\pm 150$ pc has significant effect on the determination of solar offset in the exponential decay method as can be seen in Fig. 9(a).

Our results are shown in Fig. 9(b) where we have displayed $z_\odot$ derived for the YOCs as a function of $d_{\text{max}}$. We can see a consistent value of about 13 pc for $z_\odot$ except when only YOCs closer to 1 kpc from the Sun are considered. This may be due to undersampling of the data in that region. Our estimate is close to the Bonatto et al. (2006) who reported a value of $14.2 \pm 2.3$ pc following the same approach, however, clearly lower in comparison of $z_\odot$ determined in the previous section. Here, it is worth to point out that following the same approach PKSS06 found a significantly large value of $z_\odot (\sim 28 - 39 \pm 9$ pc) when considering only those clusters within $\log(\text{Age}) < 8.3$. However, the value of $z_\odot$ substantially comes down to $8 \pm 8$ pc for the clusters in
the age range of $8.3 < \log(\text{Age}) < 8.6$ in their study. If we confine our sample to $\log(\text{Age}) < 8.3$ only, we find that $z_\odot$ increases marginally up to 14.6 pc which is not quite different than our earlier estimate but still considerably lower than the PKSS06 and we suspect that their values are overestimated by a significant factor.

A similar study for the $z$ distribution of OB stars is also carried out and our results are shown in Fig. 9(c), as an example, considering all the data sample. The resultant variation of $z_\odot$ for the different $d_{\text{max}}$ are shown in Fig. 9(d). It is clearly visible that $z_\odot$ varies in the range of 6 to 12 pc which is substantially lower in comparison of the values obtained in the previous method for the same data set. Reed (1997, 2000) also reported a similar lower value of $\sim 6$ to 13 pc for the $z_\odot$ using exponential model. A significant feature we notice here is that the $z$ distribution to the left and right of the peak do not seem symmetric particularly in the bottom half of the region where exponential fit in the $z > z(N_{\text{max}})$ region is higher than their observed value while reverse is the case for the $z < z(N_{\text{max}})$ region. Therefore, a single exponential profile fit to the distribution of the OB stars for the whole range results in a large $\chi^2$ since points are well fitted only over a short distance interval around the mid-plane. This may actually shift $z_\odot$ towards the lower value which results in an underestimation for the $z_\odot$ determination. We believe that a single value of $z_\odot$ determined through exponential decay method is underestimated and needs further investigation.

6 DISTRIBUTION OF $Z$ WITH THE GALACTIC LONGITUDE

A distribution of clusters in the Galactic longitude also depends upon the Age (Dias & Lépine, 2005) and it is a well known fact that the vertical displacement of the clusters from the GP is correlated with the age of the clusters. Hence, one alternative way to ascertain the mean displacement of Sun from the GP is to study the distribution of YOCs and OB stars projected on the GP as a function of the Galactic longitude where it is noticeable that the distribution follows an approximately sinusoidal variation. We estimated $z_\odot$ in this way in our earlier study (JOS05) although analysis there was based on the differential distribution of interstellar extinction in the direction of OCs.

To study the variation of $z$ as a function of Galactic longitude, we assemble YOCs in $30^\circ$ intervals of the Galactic longitude and mean $z$ is determined for each interval. Here we again divide the YOCs in three different zones as discussed in Sect. 4 and the results are illustrated in Fig. 10 where points are drawn by the filled circles. Considering the scattering and error bars in mind, we do not see any systematic trend in the $z$ variation and a constant value of $14.5 \pm 2.2, 17.4 \pm$
2.6, 18.5 ± 2.9 pc (in negative direction) are found for |z| < 150, |z| < 200 and |z| < 300 pc respectively. However, when we consider all the YOCs including possible GB members as drawn by open circles in the same figure, we found a weak sinusoidal variation as plotted in Fig. 10 by the continuous lines and has a striking resemblance with z distribution at maximum Galactic absorption versus longitude diagram (Fig. 8 of JOS05). We fit a function,

$$z = -z_\odot + a\sin(l + \phi),$$

to the z(l) distribution with $z_\odot$ estimated from the least square fits in all the three zones and resultant values are given at the top of each panel in Fig. 10. It is clearly visible that the $z_\odot$ estimated in this way varies between 17 to 20 pc and it is not too different for the case when GB members are excluded. The largest shift in the mean z below the GP occurs at about 210° which is the region associated with the GB (see Fig. 6(b)) as can be seen by the maximum shift between filled and open circular points in Fig. 10.

In Fig. 11, we plot a similar variation for the OB stars in four different zones as selected in
Sect. 4 and it is noticeable that the sinusoidal variation is more promising for the OB stars. The values of $z_\odot$ ranges from 8.4 to 18.0 and like in all our previous methods, it shows a significant variation among different $d_{\text{max}}$ for the OB stars.

It is interesting to note that mean $z$ shows a lower value in the vicinity of $l \sim 15^\circ - 45^\circ$ region in both the YOCs and OB stars. Pandey, Bhatt & Mahra (1988) argued that since the maximum absorption occurs in the direction of $l \sim 50^\circ$ as well as reddening plane is at the maximum distance from the GP in the same direction of the Galactic longitude, it may cause a lower detection of the objects. We also found a similar result in JOS05. In his diagram of the distribution of OCs as a function of longitude, van den Bergh (2006) also noticed that the most minimum number of OCs among various dips lies in the region of $l \sim 50^\circ$ where there is an active star forming region, Sagitta. However, the lack of visible OCs are compensated by the large number of embedded clusters detected from the 2MASS data (Bica, Dutra & Soares 2003). We therefore attribute an apparent dip in $z_\odot$ around the region $l \sim 50^\circ$ to the observational selection effects associated due
to star forming molecular clouds which may result in the non-detection of many potential YOCs towards far-off directions normal to the GP.

7 CONCLUDING REMARKS

The spatial distribution of the young stars and star clusters have been widely used to probe the Galactic structure due to their enormous luminosity and preferential location near the GP and displacement of the Sun above GP is one issue that has been addressed before by many authors. In the present paper we considered a sample of 1013 OCs and 2397 OB stars which are available in the web archive. Their $z$ distribution around the GP along with the asymmetry in their displacement normal to the GP allowed us to statistically examine the value of $z_{\odot}$. The cut-off limit of 300 Myrs in the age for YOCs has been chosen on the basis of their distribution in the $z - \log(\text{Age})$ plane. We have made an attempt to separate out the OCs and OB stars belonging to the GB from the LGD.

In our study, we have attempted three different approaches to estimate $z_{\odot}$ using 537 YOCs lying within 4 kpc from the Sun. We have studied $z_{\odot}$ variation with the maximum heliocentric distance and found that $z_{\odot}$ shows a systematic increase when plotted as a function of $d_{\text{max}}$, however, we noticed that it is more related to observational limitations due to Galactic absorption rather that a real variation. After analysing these YOCs, we conclude that $17 \pm 3$ pc is the best estimate for the $z_{\odot}$. A similar value has been obtained when we determined $z_{\odot}$ through the $z$ distribution of YOCs as a function of Galactic longitude, however, a smaller value of about 13 pc is resulted through exponential decay method. Considering the YOCs within $z < 250$ pc, we determined that the clusters are distributed on the GP with a scale height of $z_{h} = 56.9^{+3.8}_{-3.3}$ pc and noticed that the $z_{\odot}$ has no bearing in the estimation of $z_{h}$. A scale height of $z_{h} = 61.4^{+2.7}_{-2.4}$ pc has also been obtained for the OB stars belonging to the LGD.

A comparative study for the determination of $z_{\odot}$ has been made using the 2030 OB stars lying within a distance of 1200 pc from the Sun and belonging to the LGD. It is seen that the $z_{\odot}$ obtained through OB stars shows a substantial variation from about 8 to 28 pc and strongly dependent on the $d_{\text{max}}$ as well as $z$ cut-off limit. It is further noted that $z_{\odot}$ estimated through exponential decay method for the OB stars gives a small value in comparison of the YOCs and ranges from 6-12 pc. Therefore, a clear cut value of $z_{\odot}$ based on the OB stars cannot be given from the present study, however, we do expect that a detailed study of OB associations in the solar neighbourhood by the future GAIA mission may provide improved quality and quantity of data to precisely determine $z_{\odot}$.
in order to understand the Galactic structure. This paper presents our attempt to study the variation in $z_\odot$ due to selection of the data and method of determination using a uniform sample of YOCs and OB stars as a tool. It is quite clear from our study that the differences in approach and choice of the data sample account for most of the disagreements among $z_\odot$ values.

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