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THE SUN'S DISTANCE ABOVE THE GALACTIC PLANE

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ABSTRACT

We have determined the Sun's distance ($Z_\odot$) from the galactic plane using optical star counts in 12 Palomar Sky Survey fields, six each at the North and South galactic poles. The star counts were made in 16 square degree regions at the center of each field in the O (blue) magnitude range 15–18. All stars with $O-E$ color greater than 1.8 mag ($B-V\sim1.1$ mag) were selected to isolate a sample of disk population stars in this magnitude range. The total counts show significantly more stars in the six fields at the SGP indicating that the Sun is above the galactic plane as defined by neutral hydrogen. The observed ratio of N(SGP)/N(NGP) is 1.11±0.02 leading to $Z_\odot$=20.5±3.5 pc above the galactic midplane. © *1995 American Astronomical Society.*

1. INTRODUCTION

It has been known for some time that the Sun is not exactly in the midplane of the galactic disk as defined by the distribution of H I (Blaauw 1960; Gum *et al.* 1960). The equatorial plane ($b=0°$) of the galactic coordinate system, as adopted by the IAU General Assembly in 1958, by definition passes through the Sun. If the Sun were exactly in the midplane, the origin of the galactic coordinate system should coincide with the galactic center. However, it has been shown that the coordinates of Sgr A^* imply that the Sun is actually slightly above the plane. Several independent determinations from different indicators and at different wavelengths (summarized in Table 1) yield values of $Z_\odot$ ranging from 10 pc from interstellar dust to 42 pc from classical star counts.

In Table 1 the classical star count results stand out as the highest value for $Z_\odot$ and significantly different from studies based on the youngest populations—dust, young stars, and molecular clouds. If the $Z_\odot$ inferred from star counts, which are potentially sampling a somewhat older disk population, is higher than that from the younger populations there are important implications for galactic structure and galactic models.

TABLE 1. A sample of previous determinations of $Z_\odot$

Study	$Z_\odot$	Source
Pandey and Mahra (1987)	10 ± 4 pc	IS Dust
Brand and Blitz (1993)	13 ± 7 pc	Local Molecular Clouds
Toller (1990)	13 pc	Pioneer 10 Background
Conti and Vacca (1990)	15 pc	WR Stars
Cohen (1995)	15 ± 0.5 pc	IRAS Source Counts
Hammersley et al. (1995)	15.5 ± 3 pc	COBE, IRAS, TMGS Source Counts
Stothers and Frogel (1974)	24 ± 3 pc	OB Stars
Pandey et al. (1988)	28 ± 5 pc	Open Clusters
Magnani et al. (1985)	30 pc	High Latitude CO
Stenholm (1975)	31 ± 10 pc	WR Stars
Caldwell and Coulson (1987)	37 ± 7 pc	Cepheid Variables
Yamagata and Yoshii (1992)	40 ± 3 pc	Optical Star Counts
Stobie and Ishida (1987)	42 ± 13 pc	Optical Star Counts

We have redetermined this important parameter from star counts in several fields at the North and South galactic poles in the APS Catalog of the Palomar Sky Survey, Epoch I (POSS I). This database is especially useful for galactic structure studies based on star counts because large regions of the sky can be sampled, thus reducing the effects of statistical uncertainties and local density variations. See Pennington *et al.* (1993) and Larsen & Humphreys (1994) for more information about the APS and the APS Catalog of the POSS I.

2. THE STAR COUNTS

To determine $Z_\odot$ we have selected twelve POSS I plates from the APS catalog, six each at the North and South galactic poles. These twelve fields are listed in Table 2 with

TABLE 2. The POSS fields used.

Field	b	O(Comp.)[a]	E(Comp.)[b]	O-E at O limit[c]
NGP Fields				
P321	81.8°	20.0	19.0	$O-E\geq1.0$
P322	86.9°	21.0	19.5	$O-E\geq1.5$
P323	86.0°	21.0	19.5	$O-E\geq1.5$
P268	81.7°	19.0	18.5	$O-E\geq0.5$
P378	85.4°	19.5	19.0	$O-E\geq0.5$
P379	84.7°	20.5	19.0	$O-E\geq1.5$
SGP Fields				
P882	-85.2°	18.5	18.0	$O-E\geq0.5$
P883	-87.4°	18.0	18.0	$O-E\geq0.0$
P884	-82.8°	18.0	17.5	$O-E\geq0.5$
P826	-84.2°	19.0	18.0	$O-E\geq1.0$
P827	-85.9°	19.0	18.5	$O-E\geq0.5$
P828	-81.7°	18.0	18.0	$O-E\geq0.0$

[a]O Completeness Limit (magnitude)
[b]E Completeness Limit (magnitude)
[c]O - E Completeness at the O Magnitude Completeness Limit

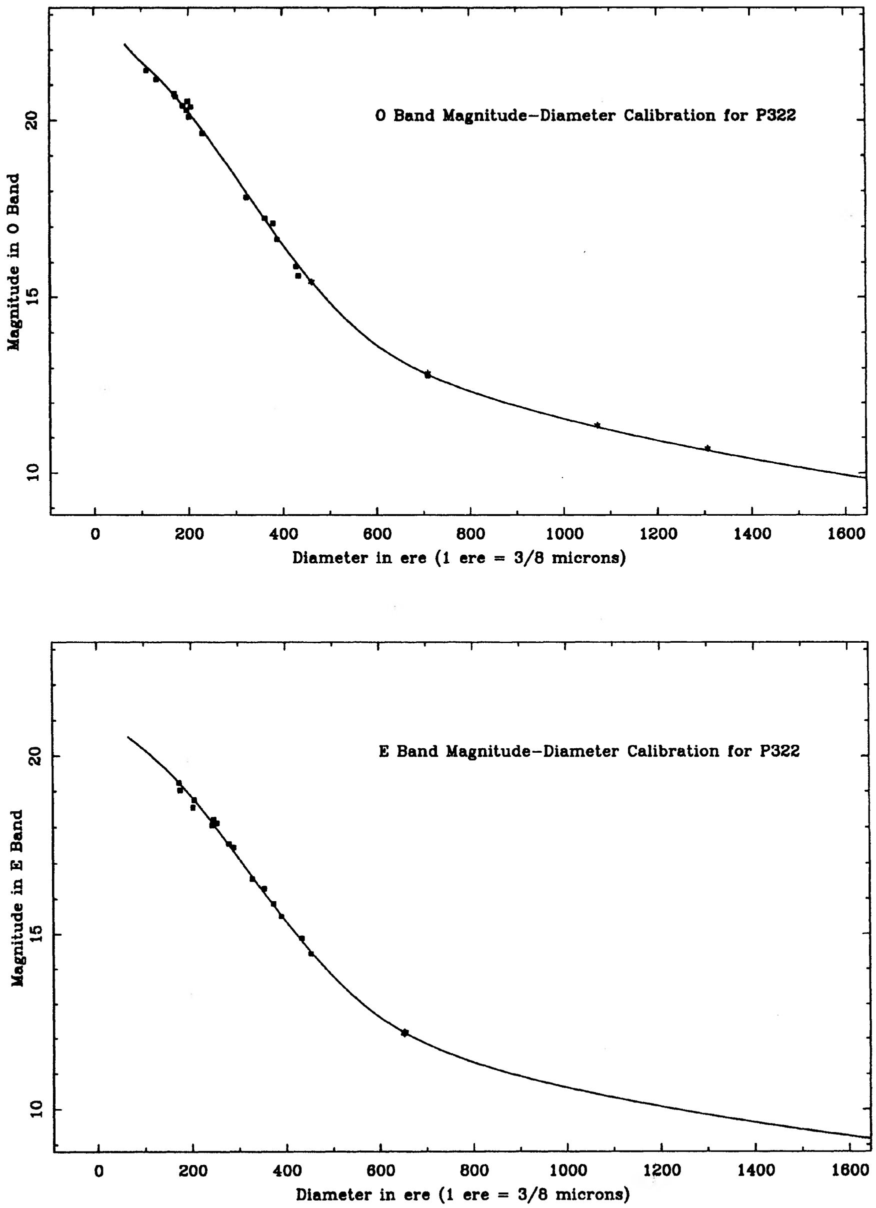

FIG. 1. Sample magnitude-diameter calibration plots for P332, showing the stellar profile fit.

their center positions. These directions are chosen so that the radial dependence of the disk stellar density function will not significantly affect the results.

The blue and red plates are calibrated separately using our unpublished *BVR* CCD sequences and data from the *Guide Star Photometric Catalog* (Lasker *et al.* 1988). The *BVR* photometry is transformed to the *O* (blue) and *E* (red) instrumental magnitudes corresponding to the emulsion and filter combinations of the two plates (see Humphreys *et al.* 1991). We then use a magnitude-isophotal diameter relation fit by a smooth function based on the stellar brightness profile of the image (King 1971; Kormendy 1973). An example of this for a typical set of O and E plates is shown in Fig. 1. The calibrations span the range 10 to 21–22 mag *O* and 10 to 20–21 mag in *E* for most fields. The typical rms for the photometry is 0.15–0.20 mag in the 14–20 mag range.

The star counts were then made in 16 square degree regions at the center of each POSS field, for a total of 96 square degrees towards each pole. Figure 2 shows examples of the resulting color–magnitude diagrams for four of these fields; *O* magnitude plotted against the $O-E$ (blue–red) color. The luminosity functions for the matched images in *O* and *E* are shown in Fig. 3 for P321 (at the NGP) and P884 (at the SGP). In Larsen & Humphreys 1994 (Fig. 2) we compared the luminosity function for the *O* band of P323 (which contains the NGP and SA 57) with values from other star count studies in the same region. The agreement between the counts from the APS and the other surveys is excellent.

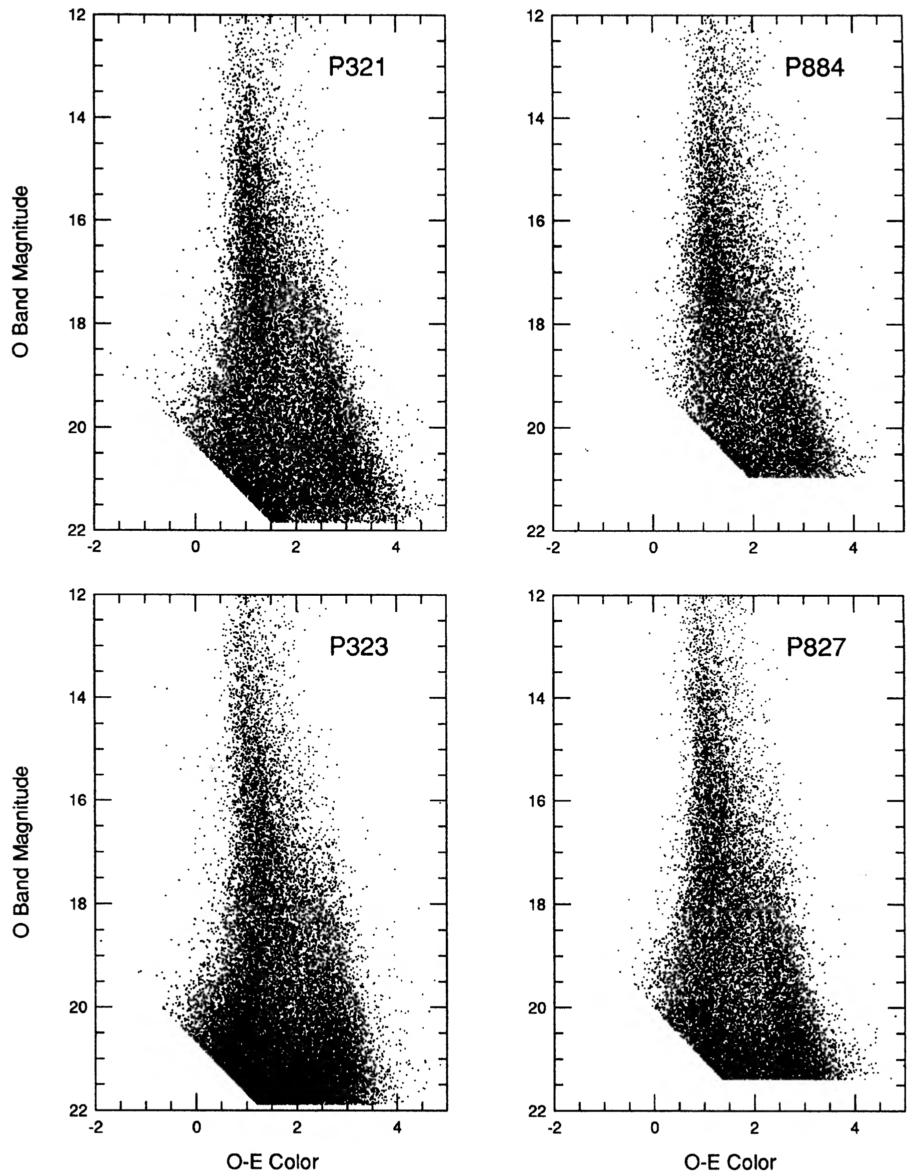

FIG. 2. Sample color–magnitude diagrams for four of the twelve fields used in our determination of $Z_{\odot}$. These show the O (blue) magnitude vs the $O-E$ (blue–red) color and include all stars in the central 16 square degree region.

Completeness—Before we can compare the star counts from these different fields we must first determine the completeness limit for each plate. They are not all the same. For example, from Fig. 2 in Larsen & Humphreys (1994) it is clear that the star counts in P323 are complete to about $O=20.5$ mag. We determined the cumulative star counts as a function of magnitude binned in half-magnitude intervals to estimate the the completeness limits for the matched image data on each plate. The magnitude limits are included in Table 1 along with the color for completeness at the O band magnitude completeness limit.

It is clear from these completeness limits that the fields at the SGP are much shallower than the northern fields. This effect is dramatically illustrated by the luminosity functions in Fig. 3; the line marks the completeness limit for each plate. This significant difference is primarily due to the higher airmass for the SGP plates ($\delta=-24°$ to $-30°$) and also to somewhat shorter exposure times. The southern fields thus set the faint magnitude limit for our star counts at $O=18$ mag.

Selection Criteria—For our measurements of $Z_{\odot}$, we have selected those stars with $O-E$ color greater than 1.8 mag (corresponding to $B-V \geqslant 1.1$ mag) in the range $15 \leqslant O \leqslant 18$ mag. This color cut will isolate a sample of stars identified with the disk population. Down to an O magnitude of 18 there will be very little contribution from the thick disk and virtually no contribution from the halo population.

Figure 4 shows the color histograms for P321 (NGP) and

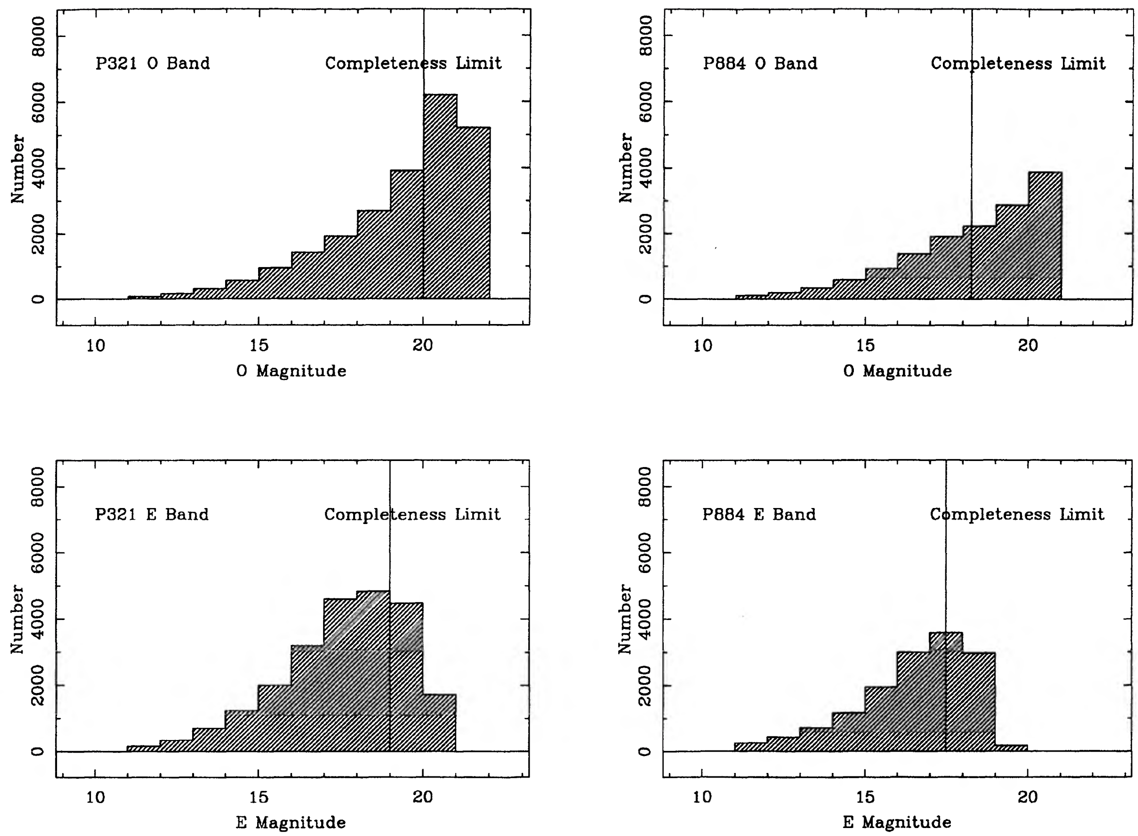

FIG. 3. Luminosity functions for two of the twelve fields (P321 and P884) in the O and E bands. The completeness limit of the field (as determined from the color-magnitude diagrams of Fig. 2) is included as a vertical bar.

P884 (SGP) in the magnitude range $15 \leq O \leq 18$, and Fig. 5 shows the superposed histograms for those stars with $O-E \leq 1.8$ mag. These figures illustrate not only how few stars are available but most importantly the small difference between the two fields. This comparison emphasizes the need to sample a large area of the sky in several independent fields to reduce statistical uncertainties.

The resulting star counts, in one magnitude wide bins, are summarized in Table 3.

3. RESULTS AND DISCUSSION—$Z_\odot$

The total counts in the 15–18 mag range for the thin disk population show significantly more stars at the SGP. There are 4849 stars in the six NGP fields with an uncertainty of 70 from the Poisson statistics and 5398±73 stars for the SGP fields. This gives a ratio of

$$\frac{N(\mathrm{SGP})}{N(\mathrm{NGP})} = 1.11 \pm 0.02, \tag{1}$$

confirming that the Sun is slightly above the midplane of the thin disk.

To determine $Z_\odot$ from the observed ratio, we used the export version of the Bahcall–Soneira model (1989 version), modified to allow the Sun's Z distance to vary. We then calculated the expected ratio of counts as a function of $Z_\odot$ and the vertical scale height of subdwarfs in the galactic disk (H_Z). This method is illustrated in Fig. 6. Adopting 350±25 pc for H_Z (Bahcall & Soneira 1980; Yoshii 1982, Gilmore & Reid 1983) our observed ratio leads to $Z_\odot$=20.5±3.5 pc.

Comparing our value for $Z_\odot$ of 20.5 pc with those in Table 1 we note that our new result is significantly less than

TABLE 3. Summary of O band counts for $O-E \geq 1.8$ T mag.

Field	15-16 mag	16-17 mag	17-18 mag	Total, 15-18 mag
NGP Fields				
P321	86	220	487	793
P322	90	208	435	733
P323	95	223	535	853
P268	109	240	440	789
P378	93	231	488	812
P379	107	260	502	869
SGP Fields				
P882	77	253	576	906
P883	134	284	538	956
P884	127	257	496	880
P826	91	261	537	889
P827	100	206	514	820
P828	130	289	528	947

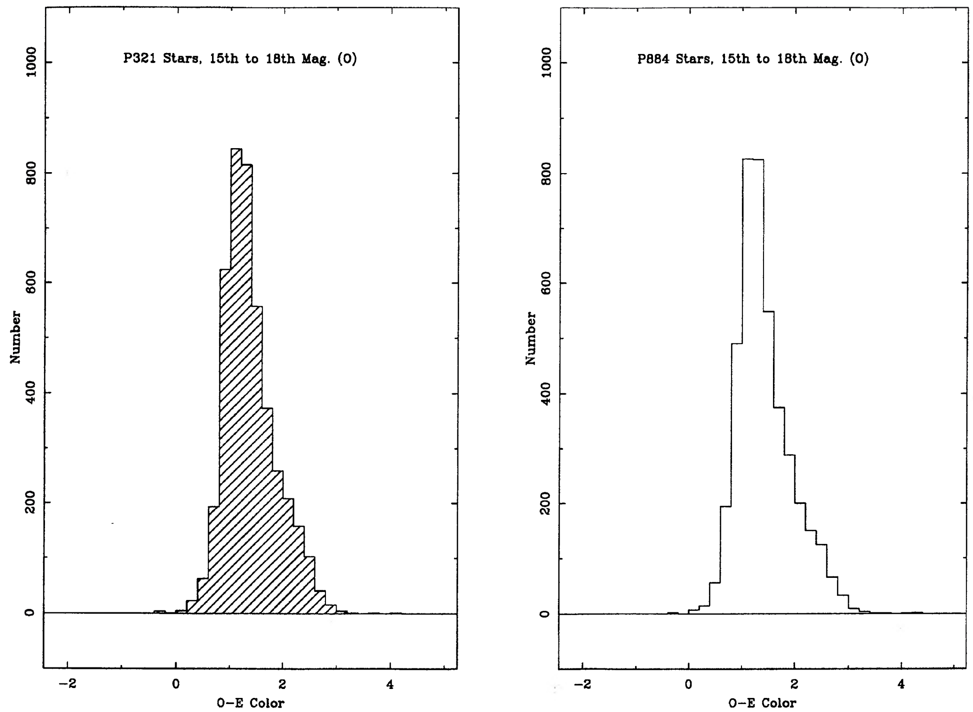

FIG. 4. Color histograms in $O-E$ for stars between 15th and 18th magnitude in O for P321 (NGP) and P884 (SGP).

those from previous optical star counts that relied on only one field each at the NGP and SGP, and only somewhat larger than those measurements sampling the youngest populations. Our value for $Z_\odot$ is consistent with the recent value of 15 pc derived by Cohen (1995) based on *IRAS* source counts at 12 and 25 μm and 15.5 pc from Hammersley *et al.* (1995) from *COBE*, *IRAS*, and *TMGS* data. Like our counts, these results apply to an older and redder population than that represented by the dust, molecular clouds and youngest stars.

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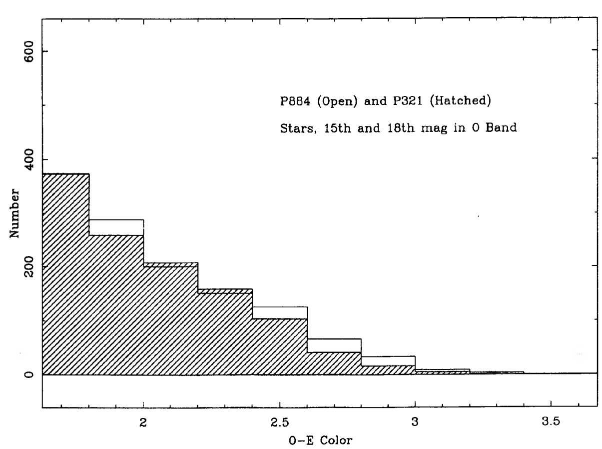

FIG. 5. Superposition of color histograms from Fig. 4 with P884 (SGP) as solid and P321 as open for stars with $O-E \geq 1.8$. Note that there are more stars in the P884 field than there are in the P321 field.

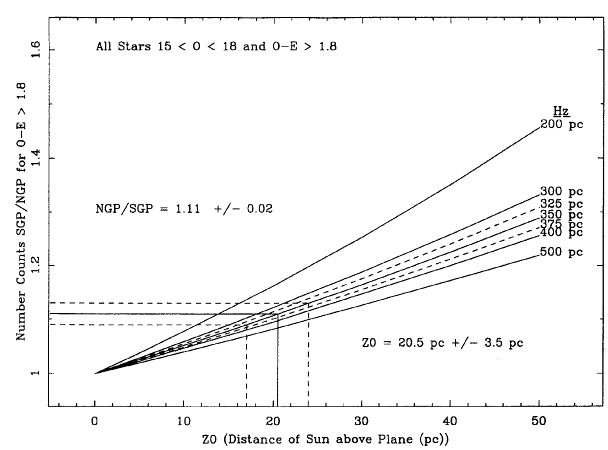

FIG. 6. Plot of the expected ratio of SGP/NGP stars redder than $O-E=1.8$ as a function of vertical scale height and $Z_\odot$. Four our count ratio of 1:11 and a disk scale height of 350 pc, the distance above the plane is 20.5 pc.

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