INFORMATION ON THE MILKY WAY FROM THE 2MASS ALL SKY STAR COUNT:
BIMODAL COLOR DISTRIBUTIONS

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Abstract

The $J−K_s$ color distributions (CDs) with a bin size of 0.05 mag has been carried out for the entire Milky Way using the Two Micron All Sky Survey Point Source Catalog (2MASS PSC). The CDs are bimodal, with a red peak at $0.8 < J−K_s < 0.85$ and a blue peak at $0.3 < J−K_s < 0.4$. The colors of the red peak are more or less the same for the whole sky, but those of the blue peak depend on Galactic latitude ($J−K_s ∼ 0.35$ at low Galactic latitudes and $0.35 < J−K_s < 0.4$ for other sky areas). The blue peak dominates the bimodal CDs at low Galactic latitudes and becomes comparable with the red peak in other sky regions. In order to explain the bimodal distribution and the global trend shown by the all-sky 2MASS CDs, we assemble an empirical Hertzsprung–Russell (H-R) diagram, which is composed of observational-based near-infrared H-R diagrams and color–magnitude diagrams, and incorporate a Milky Way model. In the empirical H-R diagram, the main-sequence turn-off for stars in the thin disk is relatively bluer, ($J−K_s)_0 = 0.31$, compared with that of the thick disk which is ($J−K_s)_0 = 0.39$. The age of the thin/thick disk is roughly estimated to be around 4–5/8–9 Gyr according to the color–age relation of the main-sequence turn-off. In general, the 2MASS CDs can be treated as a tool to measure the age of the stellar population of the Milky Way in a statistical manner and to our knowledge it is the first attempt to do so.

Key words: Galaxy: general – Galaxy: stellar content – Galaxy: structure – Hertzsprung-Russell and C-M diagrams – infrared: stars – stars: luminosity function, mass function

Online-only material: color figures

1. INTRODUCTION

One of the obvious properties of the Milky Way that we want to learn more about is its morphology. The fact that we reside inside the Milky Way prohibits us from having the global view of our own Galaxy that we enjoy with other galaxies. William Herschel made use of star count (SC) to get a rough idea of our own Galaxy that we enjoy with other galaxies. William Herschel made use of star count (SC) to get a rough idea of how the Milky Way looked in the eighteenth century (Herschel 1785). The advance in data collecting and analysis methods in the late twentieth century enabled research groups (such as Bahcall & Soneira 1980; Gilmore & Wyse 1985) to quantify the major components (i.e., disks and halo) of our Galaxy using SC. They concluded that the properties of the stellar populations in the different components are distinguishable (see Table 1 in Chang et al. 2011 and references therein). Although many studies have been carried out, a consensus on the structural parameters of the Milky Way has not yet been reached. One of the reasons for this can be attributed to the different sky regions and limiting magnitudes (i.e., limiting volumes) that were used (Siegel et al. 2002; Karaali et al. 2004, 2007; Bilir et al. 2006a, 2006b; Jurić et al. 2008). This problem can be overcome by wide sky coverage SC studies which become possible in the last decade as modern all-sky surveys, such as the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), the Sloan Digital Sky Survey (York et al. 2000), the Panoramic Survey Telescope & Rapid Response System (Pan-Starrs; Kaiser et al. 2002) and the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) become available. However, subsequent research has not settled the issue and the variation in different studies is thought to come from the degeneracy between structural parameters. Moreover, the Galactic structural parameters have been reported to show a dependence on Galactic longitude and latitude (Bilir et al. 2006a, 2008; Ak et al. 2007; Cabrera-Lavers et al. 2007; Yaz et al. 2010). This makes their measurement and interpretation far more complex and challenging.

To compensate for the degeneracy, information other than SC is needed, e.g., dynamics, color. The handiest tool is stellar color as it is available in all-sky surveys. This is the reason why most SC studies include color distribution (CD), which calculates the number of stars in each color bin. In addition to the luminosity function (LF) and density profile (DP) used in a single wavelength SC study, CD requires a Hertzsprung–Russell diagram (H-R diagram) to transform each luminous star into its corresponding color. The H-R diagram could be empirical (i.e., based on observation) or theoretical (i.e., derived from population synthesis). In the empirical case, the H-R diagram and number densities of each spectral-type star are provided from stellar cluster and local field stars (see, e.g., Bahcall & Soneira 1980; Mamon & Soneira 1982; Wainscoat et al. 1992). Difficulties include time-consuming data collection and processing, and possible bias in the sample selection (e.g., incompleteness, improper representation). In general, an observational H-R diagram in optical wavelength is obtained first and then other waveband H-R diagrams are constructed via color transformation (see, for example, Mamon & Soneira 1982; Wainscoat et al. 1992). Thus, the uncertainty in the color transformation needs to be considered carefully. In the theoretical case, a H-R diagram is deduced from the Hess diagram, which is generated by population synthesis based on knowledge of the initial mass function, stellar evolution, and star formation history, etc. The Besançon model (Robin et al. 2003) and the TRILEGAL model (Girardi et al. 2005) are examples of this. Moreover, population synthesis models depend greatly on input parameters, and stellar evolution and atmosphere.

In Chang et al. (2010, 2011), we have shown that the $K_s$ all-sky 2MASS SCs can be well described by a single
power-law LF and a three-component DP (namely, the thin disk, the thick disk, and the halo). In this work, we would like to extend our model to explain the $J - K_s$ CDs of the entire Milky Way. We gather currently available NIR data, i.e., from direct NIR observations, transformations of an optical H-R diagram, and an observational NIR color–magnitude diagram (CMD) of star clusters, to assemble an empirical NIR H-R diagram and incorporate a Milky Way model to explain the 2MASS data. In a way, the H-R diagram we used is a 2MASS-optimized H-R diagram. This article is organized as follows. The features of the all-sky 2MASS CD are described in Section 2. Our Milky Way model, including the LF and DP, is provided in Section 3. The procedure for creating our Hess diagram and H-R diagram is given in Section 4. In Section 5 we present our results on the CDs of the Milky Way, and Section 6 contains a summary and concluding remarks.

2. THE 2MASS DATA AND COLOR DISTRIBUTIONS

We use the 2MASS Point Source Catalog (2MASS PSC; Cutri et al. 2003) to carry out $J - K_s$ CDs with a bin size of 0.05 mag for the entire Milky Way. We select objects with the following criteria: (1) signal-to-noise ratio $\geq 5$, (2) detection in all three ($J$, $H$, and $K_s$) bands, and (3) $K_s$ magnitude between 5 and 14 mag. The last criterion ensures a 99% completeness rate before the $K_s$ limiting magnitude (i.e., 14.3 mag) and avoids the relatively large photometric error for $K_s \leq 5$ mag objects. The whole sky is divided into 8192 nodes according to level 5 Hierarchical Triangular Mesh (Kunszt et al. 2001), which samples the whole sky roughly evenly and has, on average, a 2° angular separation. The radius of each node is 1° (i.e., each node covers $\pi$ square degrees). Because of the shallower limiting magnitudes and the complex extinctions in the Galactic center area, this work does not attempt to explain the 2MASS CDs in this region.

Several common features are identified in the all-sky 2MASS CDs, which are listed below and demonstrated in Figure 1.

1. Most of the 2MASS CDs are bimodal with a blue peak at $0.3 < J - K_s < 0.4$ and a red peak at $0.8 < J - K_s < 0.85$. The 2MASS CDs at low Galactic latitudes has a third peak at $0.55 < J - K_s < 0.6$. Figure 1(a) shows three examples of a typical 2MASS CD at different Galactic latitudes.

2. The blue peak dominates the 2MASS CD at low Galactic latitudes and becomes comparable to the red peak at high Galactic latitudes. The middle peak only shows up at low Galactic latitudes and does not exist in other sky areas. Figure 1(b) shows average CDs over $225^\circ < l < 255^\circ$ at different Galactic longitudes.

3. The $J - K_s$ color of the all-sky red peaks and the middle peaks at low Galactic latitudes are almost fixed. However, the colors of the blue peak depend slightly on Galactic latitudes with $J - K_s \sim 0.35$ at low Galactic latitudes and $0.35 < J - K_s < 0.4$ at medium and high Galactic latitudes. The situation is demonstrated in Figure 1(c), which is the same as Figure 1(b) except that the total count is normalized to $b = 10^\circ$. In contrast, the color of the blue peak does not change along Galactic longitude; see Figures 1(d) and (e).

4. We call the tapering off distribution on the blue side of the blue peak the blue wing. The shapes of the blue wings at different Galactic latitudes are very similar. Due to their bluer blue peaks, the blue wings of the CD at low Galactic latitudes can extend to $J - K_s = 0$. However, the blue wings at medium and high Galactic latitudes seldom extend

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**Figure 1.** Salient features of the 2MASS CDs. (a) Typical examples of the 2MASS CDs $[l, b] = [235^\circ/6, 8^\circ/1]$ (solid line), $[248^\circ/5, 20^\circ/1]$ (dashed line), and $[243^\circ/0, 57^\circ/3]$ (dot-dashed line). (b) The 2MASS CDs averaged over $225^\circ < l < 255^\circ$ at different Galactic latitudes. The Galactic latitudes are indicated by different colors. (c) The same as (b), except that the total count is normalized to that of $b = 10^\circ$. (d) The 2MASS CDs averaged over $15^\circ < b < 20^\circ$ at different Galactic longitudes. The Galactic latitudes are indicated by different colors. (e) The same as (d), except that the total count is normalized to that of $l = 60^\circ$. (A color version of this figure is available in the online journal.)
Figure 2. First column: the 2MASS CDs with an extra peak at medium and high Galactic latitudes. CDs for the entire field, the globular cluster only, and the ambient field are represented by the solid, dashed, and dot-dashed lines, respectively. The identification of the star cluster and its center coordinate are indicated in the upper-right corner of each figure. Second, third, and last columns: the CMDs of the entire field, the globular cluster only, and the ambient field, respectively. The radii of the field of view of CMDs for the entire field and the ambient field are 1° and that of globular-cluster-only CMD is given in the upper-right corner of each figure in the third column.

Figure 3. 2MASS CDs around \(|b| \sim 16^\circ\) with different \(E(J-K_s)\) extinction values. The legend gives the Galactic coordinates and the \(E(J-K_s)\) value.

to less than \(J-K_s = 0.2\). The normalized 2MASS CDs in Figure 1(c) clearly show this property.

5. Occasionally, some 2MASS CDs at medium or high Galactic latitudes have a middle peak, which is different from the middle peak at low Galactic latitudes. We call it “the extra peak” and will explain more in Sections 4.1 and 4.2. The solid lines in the first column of Figure 2 show three examples of the extra peak.

6. The shape of the 2MASS CD can be altered significantly by severe extinction, which is the usual case at low Galactic latitudes. Figure 3 shows the 2MASS CDs at \(|b| \sim 16^\circ\). The figures are arranged according to their \(E(J-K_s)\) extinction.
values. As the $E(J - K_s)$ values increase, the sharpness of the 2MASS CDs decreases gradually, and the $J - K_s$ colors of the blue and middle peaks become increasingly redder. Moreover, the tail in the red end is elongated.

3. THE MILKY WAY MODEL

Our Milky Way model has a three-component DP and a single power-law LF (Chang et al. 2010, 2011). The three-component DP $n(R,Z)$ includes a thin disk $D_1$, a thick disk $D_2$, and an oblate halo $S$,

$$n(R, Z) = n_0 [D_1(R, Z) + D_2(R, Z) + S(R, Z)] ,$$  \hfill (1)

where $R$ is the galactocentric distance on the Galactic plane, $Z$ is the distance from the Galactic mid-plane, and $n_0$ is the local stellar density of the thin disk at the solar neighborhood.

The disks are in a double exponential decay form in which stellar density decreases exponentially along $R$ and $Z$,

$$D_i(R, Z) = f_i \exp \left[ -\frac{(R - R_{\odot})}{H_{ri}} - \frac{|Z|}{H_{zi}} \right] ,$$  \hfill (2)

where $(R_{\odot}, Z_{\odot})$ is the location of the Sun, $H_{ri}$ is the scale length, $H_{zi}$ is the scale height, and $f_i$ is the density ratio to the thin disk at the solar neighborhood. The subscript $i = 1$ stands for the thin disk and $i = 2$ stands for the thick disk.

The halo is a power-law decay oblate spheroidal flattening in the $Z$ direction,

$$S(R, Z) = f_h \left( \frac{R^2 + (Z/\kappa)^2}{R_{\odot}^2 + (Z_{\odot}/\kappa)^2} \right)^{-p/2} ,$$  \hfill (3)

where $\kappa$ is the axis ratio, $p$ is the power index, and $f_h$ is the local halo-to-thin disk density ratio.

The $M_K$ LF is a single power law (Chang et al. 2010),

$$\psi(M_K) = \frac{2 \log_{10} 10 (\gamma - 1)}{S(10^{2(\gamma - 1)}M_K/5 - 10^{2(\gamma - 1)}M_0/5)} 10^{2(\gamma - 1)M_K/5} ,$$  \hfill (4)

where $\gamma$ is the power-law index, $M_0$ and $M_f$ are the bright and faint cutoffs, respectively. Note that $\psi(M)$ includes all luminosity classes. For convenience, we adopt the peak values of the bright end and faint end distributions of Chang et al. (2010), i.e., $M_0 = -8$ and $M_f = 6.5$ (see Figure 6 in Chang et al. 2010), as the bright and faint ends in this study. We note that the averages in Chang et al. (2010) are $M_0 = -7.86 \pm 0.60$ and $M_f = 6.88 \pm 0.66$. Nevertheless, the model prediction shows no significant difference between using the peak values and the average ones.

The extinction model is adopted from the new COBE/IRAS result (Chen et al. 1999) and the color excess is $E(J - K_s)/E(B - V) = 0.53$ (Schlegel et al. 1998). Table 1 lists the parameters taken from Chang et al. (2010, 2011) and is hereafter referred to as MW-I.

### 4.1. Basic NIR H-R Diagram

We use observational-based NIR H-R diagrams from the literature as our first construction of the loci of the main sequence (MS) and giant branch (GB) in the $M_K = (J - K_s)_0$ H-R diagram. Wainscoat et al. (1992, hereafter W92) and Covey et al. (2007, hereafter C07) provide information for the NIR H-R diagram (i.e., the NIR color, absolute magnitude, and spectral type). W92 also give the number density in the solar neighborhood and the normalization in different components of the Milky Way. Figure 4 shows the data points of the MS, GB, and supergiants taken from W92 and C07. Both data sets agree with each other very well and show several common features: (1) a sharp downturn around the end of the MS (hereafter the MS-downturn), (2) a slight upturn around late A-type stars (i.e., $M_K \sim 3$ mag and hereafter the MS-turnoff), and (3) a sharp curve on the GB around $M_K \sim -1$ mag (hereafter the GB-curve). We fit W92 data to find the loci and integrate it with MW-I to obtain a synthetic CD. When the synthetic CD is compared with the 2MASS CD, some significant discrepancies are observed: (1) overpredictions for the middle peak and for the blue wing (i.e., $J - K_s < 0.3$ mag), (2) underprediction on the blue peak, and (3) the locations of the blue and middle peaks are not correct. The first column in Figure 5 demonstrates several results for different Galactic latitudes. However, we obtain a very useful result that the $J - K_s$ colors of each peak correspond to that of each sharp turn (or “vertical” sections) on the loci. Apparently, the blue, red, and middle peaks are the results of the MS-turnoff around late A-type stars, the MS-downturn, and the GB-curve, respectively.

### 4.2. Optimization for the Empirical NIR H-R Diagram

To study the sharp turns in more detail, we utilize several NIR CMDs of star clusters from the literature, such as those from Beletsky et al. (2009), Sarajedini et al. (2009), and Troisi et al. (2010). Some of these (e.g., M67 and NGC 6791 in Beletsky et al. 2009; Sarajedini et al. 2009), which contain
Figure 4. H-R diagram and Hess diagram. The left panel is the NIR H-R diagram. The data points are taken from W92 (color symbols), C07 (black symbols), and M67 (small black open circle; Beletsky et al. 2009). The upper-right legend indicates luminosity classes and the number density is coded by the color bar. C07 do not include number density information, so this is plotted as black. Each small black open circle represents one member star of M67. The lines represent different H-R diagrams used in Sections 4.2 and 4.3. The upper-left legend gives the corresponding models and components. The right panel is the Hess diagram of the thin disk used in MW-II whose number density is color-coded.

(A color version of this figure is available in the online journal.)

Figure 5. Synthetic CDs of different H-R diagrams (see Section 4 for details). The black line is the 2MASS data, and the pink line is the model prediction. The blue, green, and orange dotted lines represent the thin disk, the thick disk, and the halo, respectively.

(A color version of this figure is available in the online journal.)

information down to the faint end of the MS, are used to conclude the important features for our analysis: (1) the MS-downturn \((J - K_s)_0 \sim 0.83\) is a common feature at the faint end of the MS, (2) the MS-turnoff (i.e., the slight upturn around late A stars) reflects stars departing from the MS at the end of their MS stage, (3) the MS-turnoff always accompanies a \(\Delta M_{K_s} \sim 2.5\) \(K_s\) mag vertical height extension and its \((J - K_s)_0\) colors depend on the age of the star cluster, and (4) the MS belt between
the MS-turnoff and the MS-downturn is approximately linear. Since only a few GB stars are shown on these NIR CMDs, we are not able to obtain more details on the GB-curve. However, we believe that the location of the GB-curve should be similar to that of W92 and C07.

Accordingly, a working H-R diagram includes the following features. The MS is divided into three parts: (1) the early MS (i.e., O-A type stars and $M_K \lesssim 3$ mag), (2) the nearly linear late MS (i.e., F-K type stars and $3 \lesssim M_K \lesssim 5$ mag), and (3) the sharp and almost vertical MS-downturn at $(J-K_s)_b \sim 0.83$ (i.e., M type and later stars and $M_K \gtrsim 5$ mag). The GB is separated into upper and lower GBs. Both are linear and connected by the GB-curve at $(J-K_s)_b \sim 0.6$ and $M_K \sim -1$. Consequently, we create an empirical $M_K$ against the $(J-K_s)_b$ locus including a vertical MS-downturn, a linear late MS, an MS-turnoff and the MS-downturn is approximately linear. The Astrophysical Journal

$\Delta$ locus including a vertical MS-downturn, a linear late MS, an MS-turnoff and the MS-downturn is approximately linear. The result shows at different Galactic latitudes.

We believe that the location of the GB-curve should be similar to that of W92 and C07. In Figure 4, we show the empirical NIR locus on top of the H-R diagram (Chang et al. 2010), we construct the Hess diagram of MW-II and 4.3. Incorporating the LF derived from the 2MASS SC (Chang et al. 2010), we construct the Hess diagram of MW-II in the right panel of Figure 4. The joints on the H-R diagram of MW-II are listed in Table 2.

| Part                  | $(J-K_s)_b$ | $M_K$ |
|-----------------------|-------------|-------|
| Common joints         |             |       |
| Faint end of MS       | 0.83        | 6.5   |
| MS-downturn           | 0.83        | 5.0   |
| GB-curve              | 0.6         | -1.0  |
| Bright end of Upper GB| 1.4         | -8.0  |
| Thin disk             |             |       |
| MS-turnoff            | 0.31        | 3.34  |
| Bright end of MS-turnoff | 0.31     | 0.84  |
| Faint end of lower GB | 0.54        | 0.34  |
| Thick disk            |             |       |
| MS-turnoff            | 0.38        | 3.56  |
| Bright end of MS-turnoff | 0.38    | 1.06  |
| Faint end of lower GB | 0.53        | 0.56  |

When experimenting with the parameters of the model in previous subsections, we noted that a thin disk of small height would make the blue peak change more dramatically along Galactic latitudes. This causes the overall blue peak (i.e., that of both the thin and the thick disks) at low Galactic latitudes to be dominated by the thin disk, while the blue peak at medium and high Galactic latitudes is dominated by the thick disk. Therefore, a thin disk of small height with a bluer MS-turnoff can not only eliminate the difference in the blue wing at low Galactic latitudes, but also reduce its contribution to the blue peak at medium and high Galactic latitudes. In this way, the $J-K_s$ colors of the blue peak could be relatively bluer at low Galactic latitudes and relatively redder in the other sky region. With this strategy, we select an acceptable configuration of the Galactic structure with a thin disk of relatively smaller height than that in our previous SC study (see Chang et al. 2011 for details) and come up with the best-fitting model as follows: (1) the scale height of the thin disk is $H_z = 260$ pc and other structural parameters are listed in Table 1 (hereafter MW-II) and (2) the MS-turnoff of the thin disk is $(J-K_s)_b = 0.31$ mag. With this model, the 2MASS CDs at low Galactic latitudes can be fit much better than those in Section 4.2 (see the last column in Figure 5).

In Figure 6 we compare our model prediction (i.e., MW-II in Section 4.3) and the 2MASS CDs at different Galactic latitudes. In order to minimize the uncertainty caused by the extinction correction at low Galactic latitudes, we compare sky areas with relatively small extinction. The model prediction and a significant difference in the blue wing of the blue peak (i.e., $J-K_s < 0.3$), but the rest of the CD is still in good agreement (see the first row of the second column in Figure 5). If a bluer turnoff is assigned to the thin disk, the discrepancy in the blue wing can be compensated somewhat, but it will cause an overprediction in the blue wing and a shift in the $J-K_s$ colors of the blue peak at high Galactic latitudes (see the third column in Figure 5).

4.3. The Final Adjustment

In Figure 6 we compare our model prediction (i.e., MW-II in Section 4.3) and the 2MASS CDs at different Galactic latitudes. In order to minimize the uncertainty caused by the extinction correction at low Galactic latitudes, we compare sky areas with relatively small extinction. The model prediction and
the 2MASS CD agree very well in overall shape and the $J - K_s$ colors of each peak. The number variations along Galactic latitudes of each peak are well reproduced by the model.

In order to present the global trend of the 2MASS CDs, we show the number ratio of the blue part (i.e., $J - K_s \leq 0.6$) to the red part (i.e., $J - K_s > 0.6$) in Figure 7 along with the prediction of MW-II. Both figures have a very similar trend which is relatively blue at low Galactic latitudes and become comparable in other sky regions. The very red Galactic disk is the result of severe extinction.

When we inspect the Galactic disk region (i.e., $|b| < 10^\circ$), there is an obvious discrepancy between the model prediction and the 2MASS CD. This discrepancy can mostly be attributed to improper extinction correction and number inconsistency between the model prediction and the 2MASS data. The number inconsistency, which has been reported in Chang et al. (2011), results in gaps on each peak between the model prediction and the 2MASS CD. Figure 8 demonstrates some cases together with the SC results taken from Chang et al. (2011). In these cases, the sky areas have relatively small extinction. This helps

Figure 6. Comparison between 2MASS CDs (black) and model predictions (pink). The coordinates and the extinction $E(J - K_s)$ are given in the upper-right corner of each figure. The blue, green, and orange dotted lines represent the thin disk, the thick disk, and the halo, respectively. (A color version of this figure is available in the online journal.)
GB of the globular cluster relative to those in the ambient field. In addition, if the limiting magnitude could be reached down to the MS-turnoff of the globular clusters, the observed blue peak would have more stars than the model prediction. Similar number enhancement could happen in the 2MASS CDs if there is an overdensity within the field of view, which has a dominant stellar population over the smooth stellar distribution of the Milky Way (e.g., star cluster, stellar stream, Galactic bulge, Galactic arm). For instance, the extremely dense Galactic bulge, which is not included in our model, creates a prominent middle peak on the 2MASS CDs, which obviously outnumbers the model prediction (see the third column of Figure 9). However, we do not observe any obvious number enhancement in other 2MASS CDs that have known stellar streams in their fields of view, e.g., the Sagittarius dwarf galaxy (Majewski et al. 2003), Monoceros stream (Peñarrubia et al. 2005, Table 1). It is possible that within the 2MASS detection limit the populations of these overdensities are too small.

At low Galactic latitudes there is another possible way to generate the middle peak. This is through the red clump stars (Alves 2000; Cabrera-Lavers et al. 2007), which occupy the space close to the lower GB on our H-R diagram and have a higher number density relative to the other stars in the GB. Such a relatively higher number density would produce more stars in the corresponding color bins. In our model we do not include the red clump stars in our LF and H-R diagram, but our model still has good agreement with the 2MASS CD. The reason for this might be that the net contribution of the red clump stars to generating the middle peak is similar to that of the lower GB.

Our best model for explaining the 2MASS all-sky CDs (see Section 4.3) comprises a thin disk, which has a relatively small scale height (260 pc) and a relatively blue MS-turnoff (i.e., younger) and a thick disk (1040 pc), which has a relatively red MS-turnoff (i.e., older). Our best model, MW-II, that can explain the 2MASS all-sky CDs (see Section 4.3) comprises a thin disk (260 pc) with a relatively blue MS-turnoff (0.31 mag, i.e., younger), and a thick disk (1040 pc) with a relatively red MS-turnoff (0.38 mag, i.e., older). The two populations can be interpreted in the context of the formation of the Milky Way. The thick disk was formed in an epoch earlier than the thin disk. Moreover, both disks have the same single power-law LF which implies that the initial mass function does not change along the Milky Way’s evolution (unless the mass–luminosity relation was time-dependent in the past). In this sense, the 2MASS all-sky CDs can be used as a tool to measure the age of the stellar population in the Milky Way. If we apply the color–age relation of the MS-turnoff of Sarajedini et al. (2009) to our empirical H-R diagrams, we can roughly estimate the ages of the thin and thick disks to be 4–5 Gyr and 8–9 Gyr, respectively. The age estimation should be viewed as the lower limit. The blue boundary of the 2MASS CDs does not allow bluer MS-turnoffs of the disks. Moreover, the 0.05 mag bin size of our 2MASS CD can only provide a low color resolution of the blue peak, hence the color of the MS-turnoff and the derived age cannot be estimated more precisely. Nevertheless, to the best of our knowledge, our result is the first attempt to measure the age of the global stellar components in a general statistical sense. We conclude that the whole population of the thick disk is about 3–4 Gyr older than that of the thin disk.

In this work, we seldom mention the halo component because it has a very limited contribution to the total CDs in the magnitude range in which we are interested (i.e.,
Figure 8. Number inconsistency between the model prediction and the 2MASS CD. The upper panel is the comparison of CDs. The upper-right corner shows the coordinates and the extinction $E(J-K_s)$ value. The solid black, solid pink, dotted blue, dotted green, and dotted orange lines represent the 2MASS CD, the model prediction, the thin disk, the thick disk, and the halo, respectively. The lower panel is the comparison of star counts between 2MASS data (plus) and the model prediction (line).

(A color version of this figure is available in the online journal.)

Figure 9. First column: improper extinction correction. Second column: examples from the blue population. Third column: examples in the Galactic center region. The solid black, solid pink, dotted pink, dotted blue, dotted green, and dotted orange represent the 2MASS CD, the model prediction, the model prediction without extinction correction, the thin disk prediction, the thick disk prediction, and the halo prediction, respectively.

(A color version of this figure is available in the online journal.)
4 mag < \(K_s\) < 14 mag). Thus, we are not able to extract solid and useful information about the halo from the 2MASS CD.

6. SUMMARY

We use the 2MASS PSC to carry out the all-sky \(J - K_s\) CDs, which show a bimodal distribution with a blue peak and a red peak. The blue peak is the dominant feature at low Galactic latitudes and becomes comparable to the red peak at high Galactic latitudes. The all-sky \(J - K_s\) colors of the red peak are almost the same (between 0.8 and 0.85 mag). However, the \(J - K_s\) colors of the blue peak at low Galactic latitudes are a bit bluer (0.35 mag) than those at medium and high Galactic latitudes (between 0.35 mag and 0.4 mag). However, the \(J - K_s\) colors of the blue peak at low Galactic latitudes are a bit bluer (0.35 mag) than those at medium and high Galactic latitudes (which is between 0.35 and 0.4). In addition, a middle peak shows up at \(J - K_s\) ∼ 0.55 at low Galactic latitudes and does not exist in other sky areas. Several medium and high Galactic latitudes have an extra peak at \(J - K_s\) ∼ 0.55, which is not the same as the middle peak at low Galactic latitudes.

In order to explain the 2MASS all-sky CDs, we create an empirical \(M_\text{M}\) against the \(J - K_s\) H-R diagram optimized for the 2MASS data by gathering available NIR H-R diagrams and CMDs (Wainscoat et al. 1992; Covey et al. 2007; Beletsky et al. 2009; Sarajedini et al. 2009; Troisi et al. 2010) and incorporate a Milky Way model (Chang et al. 2010, 2011). The H-R diagram of the thin disk has a bluer MS-turnoff (i.e., younger), and that of the thick disk has a redder MS-turnoff (i.e., older). For a better explanation of the 2MASS CDs, the result is in favor of a thin disk with a relatively small height (260 pc, MW-II, compare with 360 pc in MW-I and MW-II are given in Table 1). We note that the configuration of MW-II is within the “acceptable” solutions due to the degeneracy between the structural parameters, which has been pointed out as a problem for using SC to study the Galactic structure (e.g., Chang et al. 2011). Now, however, information from the CD helps to rule out this degeneracy, and we conclude that MW-II should be the preferred model.

We find that the blue peak, the red peak, and the middle peak are due to the MS-turnoff, the MS-downturn, and the GB-curve, respectively (see Figure 4). Moreover, the extra peak at some medium or high Galactic latitudes is due to globular clusters. Our model cannot trace the CDs that suffer severe extinction and need a more elaborate extinction correction.

When we apply the color–age relation of the MS-turnoff (Sarajedini et al. 2009) to our empirical H-R diagram, the thin and thick disks are estimated to be around 4–5 Gyr and 8–9 Gyr, respectively. The idea is consistent with the Milky Way’s formation theory. We realize that the 2MASS all-sky CDs can be used as a tool to measure the age of the stellar populations of the Milky Way in a statistical manner. To the best of our knowledge, this study is the first attempt to measure the ages of the thin and thick disks from the all-sky stellar population.

There is no doubt that the 2MASS PSC provides a unique tool for studying the global properties of the Milky Way, not only for its tremendous sky coverage (which avoids the selection effect of limited sky coverage), but also for the benefits of using NIR wavelengths (which maintains fine angular resolution and is less affected by interstellar extinction).

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