THE EDGE OF THE MILKY WAY STELLAR DISK REVEALED USING CLUMP GIANT STARS AS DISTANCE INDICATORS

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ABSTRACT

We use the clump giants of the disk as standard candles calibrated from Hipparcos parallaxes in order to map their distribution with two new near-infrared surveys of the Galactic plane: UKIDSS-GPS and VISTA Variables in the Via Láctea (VVV). We explore different selection cuts of clump giants. We conclude that there is an edge of the stellar disk of the Milky Way at $R = 13.9 \pm 0.5$ kpc along various lines of sight across the Galaxy. The effect of the warp is considered, taking fields at different longitudes and above and below the plane. We demonstrate that the edge of the stellar disk of the Milky Way can now be mapped in the near-infrared in order to test different models, and to establish our own place within the Galaxy.

Key words: Galaxy: disk – Galaxy: structure – stars: distances – stars: late-type

Online-only material: color figures

1. INTRODUCTION

Most spiral galaxies have rather sharp edges in their stellar disks (van der Kruit 1979, 2007). The situation for the Milky Way is unclear. The disk of our Galaxy is well represented by an exponential density profile (Freeman 1970), with some evidence for a stellar disk cutoff at a radius of $\sim 14$ kpc toward the anticenter region (Robin et al. 1992), but other claims for a warped and flaring stellar disk out to 23 kpc (Momany et al. 2006). Based upon the scaling relation established by other galaxies, the radial cutoff should be between 10 and 25 kpc (Pohlen et al. 2004; Kregel & van der Kruit 2004). Here we report observations of “clump red giant” stars, which are good distance indicators (Alves 2000; Paczynski & Stanek 1998), along 10 lines of sight in the disk of the Milky Way. The data reveal an edge to the disk at $R = 13.9 \pm 0.6$ kpc. Why there should be a sharp edge to the stars, while the gas profile is much more extended and does not show such an edge (Kalberla & Kerp 2009), remains unclear, but a critical test would be the measurement of the gas and star density in situ (Kennicutt 1989).

There are two new deep surveys of the Milky Way disk in the near-infrared (near-IR): the UKIDSS Galactic Plane Survey (GPS), that is mapping the northern disk (Lucas et al. 2008), and the VISTA Variables in the Via Láctea (VVV) Survey, that is mapping 520 square degrees in the southern disk and bulge of our Galaxy (Minniti et al. 2010). While previous observations in the Galactic plane have been limited by crowding, source dimness, and interstellar extinction, these new public surveys allow us to pierce through the whole disk, reaching red giants in the horizontal branch (clump giants) located at the other side of our Galaxy for the first time in different near-IR passbands.

The VVV survey observes in the $Z$ (0.87 $\mu$m), $Y$ (1.02 $\mu$m), $J$ (1.25 $\mu$m), $H$ (1.64 $\mu$m), and $K_s$ (2.14 $\mu$m) bands, while the UKIDSS-GPS is observing in the $J$ (1.25 $\mu$m), $H$ (1.64 $\mu$m), and $K$ (2.14 $\mu$m) bands; with the photometry uniformly calibrated in the Two Micron All Sky Survey (2MASS) system (Skrutskie et al. 2006).

Clump giants are excellent tools for studying the structure of our Galaxy because of two main reasons, discussed below: (1) they are good distance indicators and (2) they are good tracers of the mass in the disks of galaxies. The UKIDSS-GPS and VVV surveys give the largest homogeneous census of clump giants out to well beyond the extent of the Milky Way stellar disk. The limiting DoPhot (Schechter et al. 1993) magnitude of single epoch VVV images processed by the Cambridge Astronomical Survey Unit (CASU) pipeline v1.0 is $K_s = 17.5$ in the disk fields, and the DoPhot photometry on the combined epochs allow to reach approximately $J = 20$ mag. and $K_s = 18.5$ mag (Figure 1), slightly fainter than the UKIDSS-GPS, and much fainter than the near-IR surveys 2MASS and DENIS, for which the limit is $K_s = 14.3$ mag (Skrutskie et al. 2006). The distance probed along the line of sight depends on the reddening of the fields. For example, in disk fields with low extinction ($A_V < 3$ mag) the UKIDSS-GPS and VVV surveys would see clump giants beyond 50 kpc. Therefore, we can search for the edge of the disk of our Galaxy using well-calibrated standard candles.

2. OBSERVATIONAL DATA

The clump giants with known parallaxes measured by the Hipparcos satellite are the best collectively calibrated standard candles (Paczynski & Stanek 1998).

Figure 1 shows color–color and color–magnitude diagrams for the VVV field d003. In order to select the giant stars, a color-cut was applied in the $K_s$ versus $(J - K_s)$, as shown in the left-hand and central panels of Figure 1. Not all selected stars are clump giants, but the presence of subgiant branch and red giant branch stars, or even main-sequence stars at fainter magnitudes, contribute to the smooth underlying background. These different population do not affect the location of any sharp edges of the stellar distribution, which can, however, be well defined by the clump giants. The effect of reddening in the selection of clump giants was also tested using different selection criteria both in the color–magnitude and color–color diagrams, finding consistent results.

An accurate $K$-band calibration of the red clump giant luminosity was obtained and applied to the red giant clump
of the Galactic bulge (Alves 2000), and of the Large Magellanic Cloud (Alves et al. 2002). Our magnitudes are in the 2MASS magnitude system, and we transformed the $K$-band magnitudes of clump giants of Hipparcos (Alves 2000) to $K_s$ magnitudes using $K = K_s + 0.044$. The resulting zero point differences should be less than 0.02 mag (Alves et al. 2002). For the $K_s$ photometry, the distance modulus to a red clump giant in the outer disk would be

$$\mu = K_s - \frac{A_{K_s}}{(A_J - A_K)} [(J - K_s) - (J - K)_{0}] - M_{K_s},$$

(1)

where we adopted $A_{K_s}/(A_J - A_K) = 0.73, (J - K)_{0} = 0.70 \pm 0.05$, and $M_{K_s} = -1.65 \pm 0.03$ as the mean values for the red clump giants of the Milky Way disk (Alves et al. 2002). There should be negligible metallicity dependence of these mean values because we are looking at a stellar population of the Milky Way disk that should be similar to that of the solar neighborhood where Hipparcos distances of clump giants were calibrated. Adopting these mean magnitudes and colors, and the reddening coefficients (Cardelli et al. 1989) yields

$$\mu = -5 + 5 \log d \text{ (pc)} = K_s - 0.73 (J - K_s) + 2.16.$$

(2)

Using this equation we computed the distance modulus (and distance in kpc) for every single clump giant candidate in the fields. For the UKIDSS-GPS $K$-band data the computations are the same, but with $A_{K}/(A_J - A_K) = 0.68, (J - K)_{0} = 0.66 \pm 0.04$, and $M_{K} = -1.61 \pm 0.03$.

In order to determine the disk edge, we computed the distribution in distance for the clump giants in each field. Thus, we co-added the distance distribution of fields located above and below the plane at same Galactic longitude. The co-added distance distribution for each longitude was analyzed non-parametrically using the local likelihood density estimation method (Loader 1996). Finally, the derivative method was applied for the distribution curve. This method is simple and robust, and can be used to detect the structures in the distance distribution. We defined as the disk edge the outermost point of minimum derivative in each case. The uncertainties were calculated with a Monte Carlo procedure, assuming Poisson errors.

The uncertainties due to the photometric errors do not produce any trend in the calculations and are much smaller than the statistical error. The resulting distance distributions along different lines of sight are shown in Figure 2. In all fields there is a density drop in the clump giant distribution at a corresponding Galactocentric distance of about 13.9 kpc (assuming $R_o = 8$ kpc), as listed in Table 1.

We first noticed the sharp termination of the clump giant distribution in the color–magnitude diagram of the VVV field d001 ($l, b = 295^\circ, -1^\circ/7$), a very heavily reddened area located in the outskirts of the Carina star-forming region (Saito et al. 2010). Similar behavior is also found in UKIDSS-GPS data for different Galactic longitudes (Lucas et al. 2008).

We studied low-extinction fields across the Milky Way disk (see Table 1). When these were available, we selected pairs of fields located above and below the plane at the same Galactic

![Figure 1](image-url)
longitude, in order to account for the Galactic warp, because if the disk is warped, the line of sight can leave the stellar disk before this ends. For example, at $l = 300^\circ$ the mean warp location is $1^\circ$ below the plane (Robin et al. 1992), so the selected VVV field day 03 is conveniently located to probe the full extent of the disk. At most other longitudes explored here the warp is absent, with the mean plane being at $b = 0^\circ$ (Figure 3). We have also explored a few other UKIDSS-GPS fields located at inner longitudes that yield lower distances. These fields with $l < 60^\circ$ were discarded because they are heavily reddened and crowded, and the photometry is not as deep as the rest, presumably due to enhanced contamination from the near side of the inner bar. Systematic errors such as variations of the reddening law have not been included.

It is important to note that the present results are independent of models. They rely on basic assumptions such as that the Hipparcos stellar sample is representative of the entire Milky Way disk, and that clump giants are reliable distance indicators and tracers of the old and intermediate-age populations. However, the Besançon Galactic model (Robin et al. 2003) with a scale length of 2.4 kpc, including a flaring and warped outer disk, with a disk cutoff at $R = 14$ kpc seems to reproduce well the observed distance distributions (see Figure 4). Data and models show the same features, with a sharp increase, the peak around 5 kpc, and the exponential decrease. The edge is detected in the data and model at the expected place within the errors ($d = 10.1$ kpc (corresponding to $R = 13.9$ kpc) and $d = 9.5$ kpc ($R = 13.4$ kpc), respectively).

3. DISCUSSION AND CONCLUSIONS

A few studies have discussed the edge of the Milky Way toward the anticenter region previously. The old Galactic disk apparently does not extend beyond 14 kpc on the basis of optical $V$ versus $(B - V)$ color–magnitude diagrams and star counts (Robin et al. 1992), which does not contradict the presence of other more distant young stars. Models of the COBE-DIRBE IR emission maps yield that the edge of the disk is at 4 kpc from the Sun (assuming $R_g = 8.5$ kpc; Freudenreich 1996). DENIS star counts reveal the cutoff of the stellar disk at a Galactocentric distance of $15 \pm 2$ kpc (Ruphy et al. 1996).

In contrast, star counts from 2MASS reveal no radial disk truncation at 14 kpc (Momany et al. 2006). Again, the depth of 2MASS is not enough to reach large distances, which is possible with the VVV and UKIDSS-GPS survey that reach 3–4 magnitudes fainter. More recently, it was found that the 2MASS star counts are best fit if the external disk is truncated at 12–14 kpc (Reylé et al. 2009), while early A-type stars in the anticenter from the IPHAS survey reveal an exponential disk out to 13 kpc, with a steeper decline beyond that distance (Sale
et al. 2010). Most of the previous evidence for cutoffs in the stellar distribution has been acquired at the anticenter fields. The present deep exploration of different fields in three galactic quadrants finds consistent results.

Even though we interpret this termination of the clump giant distribution as a truncation, we note that a break in the slope of the distribution would also be consistent with the data. It is difficult to measure the sharpness of the cutoff, because the number of stars drops rapidly with distance, but as the surveys progress, we will have more fields in order to explore this issue.

This does not mean that one could not find other young stellar sources beyond the distance that we measure. There are stars detected beyond the edge of the old stellar disk. For example, there is a population of distant young stars at $R = 20$ kpc, in two fields located in the third quadrant, slightly above the plane (at $b = 7^\circ$ and $b = 4^\circ$), based on $UBV$ photometry (Carraro et al. 2010). We see no evidence of a large population of clump giants at that distance in our fields.

$K$-band light traces mass in the disks of spiral galaxies (Rix & Rieke 1993), and the integrated $K$-band luminosity is dominated by red giants. Thus, the clump giants are ideal tracers to define overall features and structural parameters of our Milky Way, like the edge of its disk. The red clump giants trace the old and intermediate-age populations, which are more uniformly distributed than young stars, following the mass of the galactic disk. However, thick disk and halo giants are expected to be located beyond the edge of the stellar thin disk, as have been detected by the SEGUE project (de Jong et al. 2010), contributing to the background that we see in all fields beyond a Galactocentric distance of 13.9 kpc. A similar result has been recently obtained independently by the GLIMPSE team (R. A. Benjamin et al. 2011, in preparation).

Finally, we are able to determine not only the extension but also the shape of the stellar disk of our Galaxy for the first time. Asymmetric features such as lopsidedness are common in spiral galaxies (Rix & Zaritsky 1995). However, the results shown in Figure 3 suggest that the stellar disk of the Milky Way is not significantly lopsided.

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