

## COLOR-MAGNITUDE DIAGRAM DISTRIBUTION OF THE BULGE RED CLUMP STARS: EVIDENCE FOR THE GALACTIC BAR

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### ABSTRACT

The color-magnitude diagrams of  $\sim 5 \times 10^5$  stars obtained for 13 fields toward the Galactic bulge with the OGLE project reveal a well-defined population of bulge red clump stars. We find that the distributions of the extinction-adjusted apparent magnitudes of the red clump stars in fields lying at  $l = \pm 5^\circ$  in Galactic longitude differ by  $0.37 \pm 0.025$  mag. Assuming that the intrinsic luminosity distribution of the red clump stars is the same on both sides of the Galactic center, this implies that the distances to the red clump stars in the two fields differ by a factor  $1.185 \pm 0.015$ . A plausible explanation of the observed difference in the luminosity distribution is that the Galactic bulge is a triaxial structure, or bar, which is inclined to the line of sight by no more than  $45^\circ$ , with the part of the bar at the positive Galactic longitude being closer to us. This agrees rather well with other studies indicating the presence of the bar in the center of the Galaxy. Color-magnitude diagram data are accessible over the computer network with anonymous ftp.

*Subject headings:* Galaxy: general — Galaxy: structure — stars: Hertzsprung-Russell diagram — stars: statistics

### 1. INTRODUCTION

The Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 1992, 1993b, 1994) is an extensive photometric search for the rare cases of gravitational microlensing of Galactic bulge stars by foreground stars, brown dwarfs, and planets. It provides a huge database (Szymański & Udalski 1993), from which color-magnitude diagrams (Udalski et al. 1993a) reveal an expected population of bulge stars, with its turnoff point, red giant branch, and red clump, and also an unexpected concentration of stars in the blue part of the color-magnitude diagrams, which was recently explored in detail by Paczyński et al. (1994). In this *Letter* we use the well-defined population of red clump stars to investigate the presence of a triaxial structure, or bar, in the bulge of the Galaxy.

A number of recent studies show unambiguously the presence of such a structure in the center of the Galaxy. Blitz & Spergel (1991) analyzed  $2.4 \mu\text{m}$  observations of the Galactic center by Matsumoto et al. (1982) and showed convincingly that the observed asymmetry in the Galactic longitude distribution of surface brightness is naturally explained by the bar with the near side in the first Galactic quadrant. They also argue that there is a small tilt of the bar with respect to the Galactic plane, consistent with the tilt proposed by Liszt & Burton (1980) from 21 cm emission kinematics. Binney et al. (1991) have constructed a dynamical model for the H I, CO, and CS emission in the inner Galaxy, and their resulting bar has the same orientation as that suggested by Blitz & Spergel (1991) in the sense that the closer part of the bar is at positive Galactic longitudes. COBE multiwavelength observations of

the Galactic center (Weiland et al. 1994) confirmed the existence of the longitudinal asymmetry discussed by Blitz & Spergel (1991), but Weiland et al. argue that the signature of the tilt disappears when the Galactic center emission is corrected for absorption.

There is also evidence for the triaxial structure in the center of the Galaxy from star counts. Nakada et al. (1991) analyzed the distribution of *IRAS* Galactic bulge stars and found asymmetry in the same sense as Blitz & Spergel (1991) and Binney et al. (1991). Whitelock & Catchpole (1992) analyzed the number distribution of Mira variables in the bulge as a function of distance modulus and found that the half of the bulge which is at positive Galactic longitude is closer to us than the other half. The observed stellar distribution could be modeled with a bar inclined at roughly  $45^\circ$  to the line of sight. Weinberg (1992) used asymptotic giant branch (AGB) stars as star tracers and mapped the Galaxy inside the solar circle. He found evidence for a large stellar bar with semimajor axis of  $\approx 5$  kpc and inclination placing the nearer side of the bar at positive Galactic longitudes. Spergel (1992) gives a detailed account of the evidence for the bulge being barred.

### 2. THE DATA

Udalski et al. (1993a) present color-magnitude diagrams (CMDs) of 14 fields in the direction of the Galactic bulge, which cover nearly  $1 \text{ deg}^2$  and contain about  $5 \times 10^5$  stars. All observations were made using the 1 m Swope Telescope at the Las Campanas Observatory, operated by the Carnegie Institution of Washington, and a  $2048 \times 2048$  pixel Ford/Loral CCD detector with pixel size  $0''.44$  covering a  $15' \times 15'$  field of view. In this *Letter* we discuss nine fields in Baade's window (BW) and four fields on both sides of the Galactic center (MM5,

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TABLE 1  
PARAMETERS FOR THE FOUR MM FIELDS

Field	$l$	$b$	Number of CMD Stars
MM5-A.....	-4.77	-3.36	28,077
MM5-B.....	-4.94	-3.46	28,906
MM7-A.....	5.43	-3.34	30,298
MM7-B.....	5.53	-3.52	45,480

MM7). Table 1 gives the coordinates of four MM fields analyzed in this *Letter*. CMDs for all the fields analyzed in this *Letter* can be seen in Udalski et al. (1993a). Most of each diagram is dominated by bulge stars, with distinct red clump, red giant, and turnoff-point stars. The part of the diagram dominated by the disk stars was recently analyzed by Paczyński et al. (1994). In this *Letter* we use a well-defined population of bulge red clump stars to investigate the presence of the bar in the center of the Galaxy. Red clump stars are the equivalent of the horizontal-branch stars for metal-rich populations, i.e., relatively low-mass stars burning helium in their cores. From observations and also from stellar evolution theory (Castellani, Chieffi, & Straniero 1992) we expect the bulge red clump stars to be relatively bright and have a narrow luminosity distribution with weak dependence on the metallicity. Therefore, red clump stars form a suitable population with which to investigate the structure of high-metallicity systems, like the Galactic bulge. As we observe several thousand red clump stars in each field, we expect they can be used as a powerful tool in investigating the structure of the bulge. The part of the CMD dominated by bulge red clump stars is shown for the MM5 and MM7 fields in Figure 1, together with two straight lines corresponding to the value of the extinction-

insensitive parameter  $V_{V-I}$  equal to 11.5 and 13.0 (cf. eq. [1] of this *Letter*). It is clearly evident that the red clump stars from the MM7 fields group close to the  $V_{V-I} = 11.5$  line, while red clump stars from the MM5 fields have, on average, larger values of this parameter.

To analyze the distribution of bulge red clump stars in a more quantitative manner, we define the extinction-insensitive  $V_{V-I}$  parameter:

$$V_{V-I} \equiv V - 2.6(V - I), \quad (1)$$

where we use the reddening law  $E_{V-I} = A_V/2.6$ , following Dean, Warren, & Cousins (1978) and Walker (1985). The parameter  $V_{V-I}$  has been defined so that if  $A_V/E_{V-I}$  is independent of location, then for any particular star its value is not affected by the unknown extinction. It was found by Paczyński et al. (1994) that the distribution of the peaks of the  $V_{V-I}$  parameter has a deviation from the mean as small as 0.03 in all nine BW fields, indicating that it is insensitive to the interstellar extinction, as designed. Then for all 13 fields we consider only the region of the CMD clearly dominated by the bulge red clump stars:

$$15 < V < 19.0, \quad 1.5 < V - I < 2.4. \quad (2)$$

All stars observed in nine fields in Baade's window, two fields in the MM5 window, and two fields in the MM7 window that satisfied inequalities (2) were put into three separate data sets and counted in bins of  $\Delta V_{V-I} = 0.05$ . The result appears in Figure 2, where we see the number of stars as a function of  $V_{V-I}$  for MM7, BW, and MM5. The histogram for the red clump stars in nine BW fields was scaled by dividing the total number of stars by 6 to obtain a peak number approximately

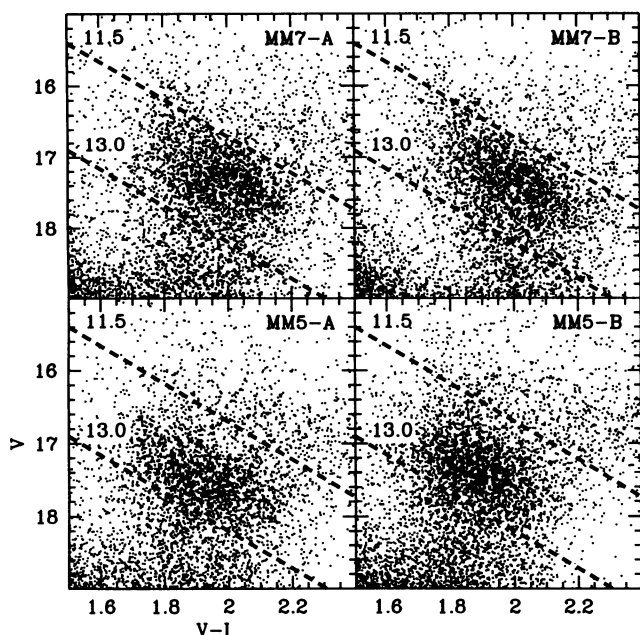


FIG. 1.—Region of the  $V-I$  color-magnitude diagrams dominated by bulge red clump stars for four MM fields of the OGLE experiment (Udalski et al. 1993a). Stars were selected to satisfy the inequalities given by eq. (2). The two straight lines correspond to values of the extinction-insensitive parameter  $V_{V-I}$  equal to 11.5 and 13.0.

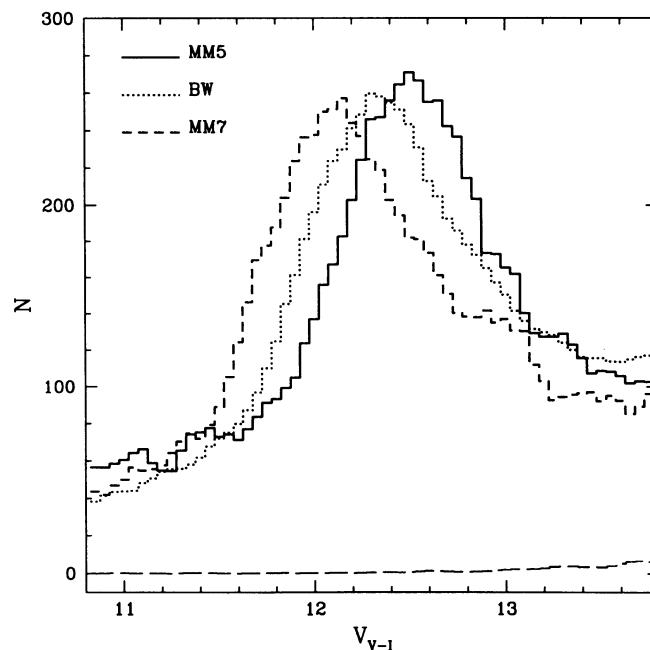


FIG. 2.—Histograms of the  $V_{V-I}$  distribution for red clump stars from MM5 (continuous line), BW (dotted line), and MM7 (short-dashed line). The histogram for the red clump stars in BW was scaled by dividing the total number of stars by 6 so as to obtain approximately the same peak number as in MM5 and MM7. For the purpose of presentation the distributions were boxcar-smoothed with a filter width of three bins. Also shown is the estimated contamination from disk stars at the red clump, based on the Bahcall & Soneira (1980) model of the Galaxy (long-dashed line).

equal to those in two MM5 fields and two MM7 fields. For the purpose of presentation the distributions were boxcar-smoothed with a filter width of three bins. Also shown is the expected contamination of the selected CMD region by disk stars in the BW field (normalized to the same area as contained by the MM fields), calculated using the standard Bahcall & Soneira (1980) model of the Galaxy. Clearly this contamination can be safely neglected.

The distributions shown in Figure 2 are similar in shape, with red clump stars forming a pronounced peak in observed distributions. There is, however, a clear shift between the distributions, with MM7 red clump stars having on average the smallest values of the  $V_{V-I}$  parameter and MM5 red clump stars having the largest ones with BW stars in between. To quantify this shift in more detail, we applied the iterative bootstrap technique (for the discussion of the bootstrap method see Press et al. 1992, p. 691). First, we estimated the shift between the distributions by eye, and we selected for all three fields the same region of distributions, which for the BW7 field corresponded to  $11.0 < V_{V-I} < 13.5$ . The region of comparison was asymmetric with respect to the peak value of the  $V_{V-I}$  distribution so as to avoid those values of  $V_{V-I}$  which are contaminated by bulge red giants and also, to a lesser extent, by disk stars. Then for every field using bootstrap-selected samples we estimated the mode of the distribution (Lupton 1993, p. 6) and obtained the shift between the distributions, which we then applied to correct the comparison region of  $V_{V-I}$  distributions. The resulting plot of  $\Delta V_{V-I}$  for 10,000 Monte Carlo bootstrap-selected data sets is shown in Figure 3. We find that the distribution of the shift  $\Delta V_{V-I}$  is very well fitted by a Gaussian, with parameters  $\Delta V_{V-I}(\text{MM5} - \text{BW}) = 0.15 \pm 0.02$  for BW and  $\Delta V_{V-I}(\text{MM5} - \text{MM7}) = 0.37 \pm 0.025$  for MM7.

There is an additional quantity that one can obtain from our data. This is the density of red clump stars for different fields. We find that there were  $\sim 45,740$  red clump stars in nine BW

fields,  $\sim 7280$  in two MM7 fields and  $\sim 7540$  in two MM5 fields, satisfying inequalities (2) and falling, after the shift, within the comparison region mentioned above. This corresponds to a number of red clump stars per field ( $15' \times 15'$ ) of 5080 for BW, 3640 for MM7, and 3770 for MM5. In the following section we will discuss the implications of our observations for the structure of the Galactic bulge.

### 3. DISCUSSION

In the previous section we have shown that the distributions of bulge red clump stars, located on both sides of the Galactic center, as a function of extinction-adjusted apparent magnitude are very similar in shape but differ by a substantial shift, which was found to be  $\Delta V_{V-I}(\text{MM5} - \text{MM7}) = 0.37 \pm 0.025$ . One possible explanation for this shift is a difference in the reddening law (see discussion following eq. [1]) for different fields in the Galactic bulge. If the ratio of  $A_V/E_{V-I}$  for the BW field is 2.6, as shown by Paczyński et al. (1994), then one needs this ratio to be  $\sim 2.9$  for the MM5 field and  $\sim 2.3$  for the MM7 field, with exact values depending on the  $E_{V-I}$  value for the BW field. We find such large differences rather unlikely, especially considering the small distances between the fields, but we expect to address this question in more detail in the future. If we attribute the observed shift as being due to the difference in distance to the bulge red clump stars in MM5 and MM7, then we can obtain the ratio of distances to both fields,  $d_1/d_2 = 1.185 \pm 0.015$ . If we then assume that the observed peaks in the  $V_{V-I}$  distributions correspond to the stars lying along major axis of the bar, we can obtain the angle of inclination of the bar to the line of sight  $\theta \approx 45^\circ$ . To check how this angle corresponds to the real inclination of the bar to the line of sight, we modeled the bar with Blitz & Spergel's (1991) equation (1), taking  $x_s = 1$  kpc,  $z_s = 0.6$  kpc, and changing  $y_s$  from 0.05 to 1.0 kpc. We then calculated how the observed inclination changes with increasing thickness of the bar. Figure 4 shows the result for three values of intrinsic inclination  $15^\circ$ ,  $30^\circ$ , and  $45^\circ$  ( $\theta = 90^\circ$  corresponds to the major axis of the bar being perpendicular to the line of sight). For a bar that is very thin along the line of sight the inclination angle as measured corresponds directly to the true inclination angle. However, if the bar is thick, then the true inclination angle is smaller than the angle measured on the basis of the mean distance to stars in the fields MM5 and MM7. We suspect that the tendency of the observed angle to be always greater than the intrinsic value is the generic feature of all realistic models of the bar. So at present we can safely state only that there is substantial asymmetry in the distance to the red clump stars on both sides of the Galactic center, strongly indicating the presence of the bar in the Galactic center.

Star counts can also provide very useful, direct information about the space distribution of the star density along the line of sight. In Figure 2 notice that the red clump star  $V_{V-I}$  distribution is relatively narrow (FWHM  $\approx 1.0$  mag), which gives us an upper limit for the spatial extent of bar red clump stars along the line of sight of about 4 kpc. To obtain more stringent limitations, one needs some additional knowledge about intrinsic luminosity distribution of red clump stars.

We also see that for BW fields there are about 40% more red clump stars than in the MM fields. At the distance of the Galactic center, which we assume to be 8 kpc,  $5^\circ$  corresponds to about 700 pc in the plane of the sky, or to about 1 kpc if we apply the  $\sim 45^\circ$  inclination discussed above. This tells us that the bar major-axis scale length is comparable to 1 kpc, but to

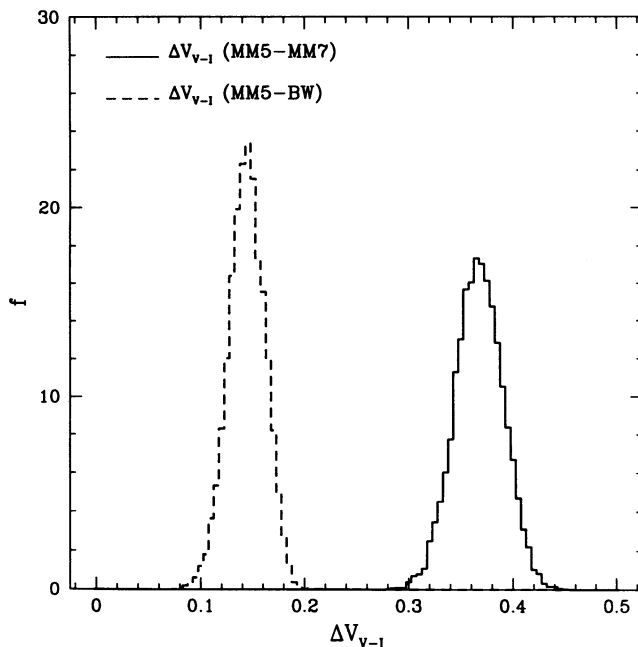


FIG. 3.—Plot of the  $\Delta V_{V-I}$  shift distribution for the MM7 field (continuous line) and the BW field (dashed line) vs. the MM5 field. For details see text.



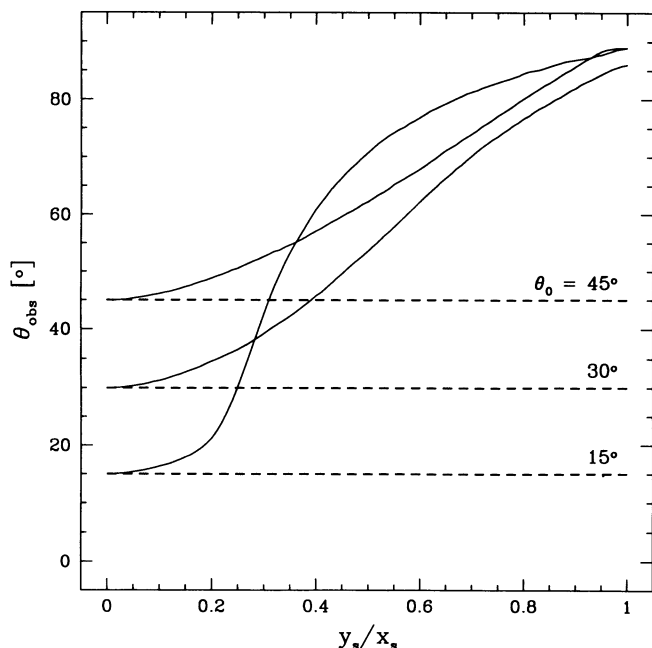


FIG. 4.—Observed angle of inclination  $\theta_{\text{obs}}$  (continuous line) as a function of the bar axis ratio  $y_s/x_s$ . The bar was modeled using Blitz & Spergel's (1991) eq. (1), with fixed  $x_s = 1.0$  kpc,  $z_s = 0.6$  kpc, and a changing value of  $y_s$ . Three values of the intrinsic inclination  $\theta_0 = 15^\circ, 30^\circ, 45^\circ$ , shown with dashed lines, were investigated.

obtain a better estimate for this value we need additional fields with larger values of  $|l|$ . The Galactic bar observed by COBE can still be seen at  $l = \pm 15^\circ$  (Weiland et al. 1994).

The presence of the bar in the Galaxy seems to be firmly established by various authors and methods (Blitz & Spergel 1991; Binney et al. 1991; Nakada et al. 1991; Weinberg 1992;

Whitlock & Catchpole 1992; Weiland et al. 1994), but there are still considerable differences as to details of the bar structure or angle of inclination to the line of sight. We have shown that the red clump stars can be very useful for investigating the Galactic bar, being both numerous and relatively bright. We expect to address this problem in the future with data covering a much wider range of Galactic coordinates.

We also note here the possibility that the Galactic bar may be associated with the deficiency of Galactic disk stars beyond  $\sim 3$  kpc from the Sun toward the Galactic bulge (Paczynski et al. 1994), as compared with standard models of the Galaxy. The disks of barred galaxies often show a decrease in brightness interior to the end of the bar (Kormendy 1994). This effect was recently observed in the near-infrared by Spillar et al. (1992) in the galaxy NGC 5195. A similar decrease may exist in our Galaxy, although such a deficiency also occurs in inner disks of nonbarred galaxies (Freeman 1970; Kormendy 1977).

This Letter and the distribution of stars in the color-magnitude diagram as observed by OGLE in the BW, MM5, and MM7 fields is available over the computer network using anonymous ftp on astro.princeton.edu. Login as ftp; use your name as a password. Change the directory to stanek/bar. The file read.me contains a list of the necessary files and instructions on how to retrieve the data.

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