THE COLOR-MAGNITUDE DIAGRAM IN BAADE’S WINDOW REVISITED

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ABSTRACT

We have reanalyzed the OGLE V and I photometry of ~500,000 stars in Baade’s Window, and we confirm the extinction map published by Stanek. However, we find that the interpretation of the OGLE color-magnitude diagram for the disk stars proposed by Paczyński et al. was incorrect: the dominant disk population in Baade’s Window is old, and we find no evidence for a large hole in the inner Galactic disk. We find evidence for a small systematic error in the OGLE photometry for stars below the “red clump”: the \((V-I)\) color indices of the faint stars with \(V > 18\) are too red by \(~0.1\) mag. We find tentative evidence from the OGLE and HST photometry that the bulge main-sequence turnoff point is brighter by \(~0.5\) mag than it is in either 47 Tuc or NGC 6791, indicating that the dominant population of the Galactic bulge is considerably younger than those clusters.

Subject headings: dust, extinction — Galaxy: structure — Hertzsprung-Russell diagram

1. INTRODUCTION

In this paper we use photometry of about 500,000 stars, measured in the standard Johnson \(V\) and Cousins \(I\) over a 40 arcmin\(^2\) field within Baade’s Window by the Optical Gravitational Lensing Experiment (OGLE) (see Udalski et al. 1992, 1993). All the observations were made with the 1 m Swope telescope at the Las Campanas Observatory, operated by the Carnegie Institution of Washington. A catalog of 33,196 stars in the magnitude range \(14 < I < 18\) in the OGLE field BWC has recently been published by Szymański et al. (1996). The J2000 coordinates of the BWC field are: \(\alpha = 18^h 03^m 24^s, \delta = -30^\circ 02' 00'',\) and the field is \(~15'\) on a side. The catalog gives the \((\alpha, \delta)\) coordinates and the \(I\) and \(V\) magnitudes. It will be extended in the near future to brighter and fainter stars, as well as to a much larger area.

The database of OGLE photometry (Szymański & Udalski 1993) was used to analyze the distribution of disk stars (Paczyński et al. 1994), to demonstrate the presence of the Galactic bar (Staneck et al. 1994, 1997), and to obtain the map of total interstellar extinction (Woźniak & Stanek 1996; Stanek 1996). The purpose of this paper is to verify some of these results.

2. DISK STARS IN BAADE’S WINDOW

The color-magnitude diagram (CMD) of the stars in Baade’s Window shows two distinct groups of stars, as presented in Figure 1. The dominant population is in the bulge (or bar), with a very prominent “red clump” (or red horizontal branch) centered at \((V-I, I) \approx (1.9, 15.2)\). The red giant branch is extended toward higher luminosities and to the red. The red subgiant branch is clearly visible below the “red clump,” and it is traceable all the way to the main-sequence turnoff point (TOP), somewhere near \((V-I, I) \approx (1.6, 18.3)\). In addition there is a well-defined and narrow band of stars extending from \((V-I, I) \approx (1.5, 17.5)\) to \((0.9, 14.5)\) and traceable to higher luminosities. This band has almost the same slope as the Pleiades main sequence moved to a distance of \(~2\) kpc and subject to the interstellar extinction of \(A_V \approx 1.6\). This coincidence led Paczyński et al. (1994) to the incorrect conclusion that there is evidence for a large number of disk stars out to the distance \(~2\) kpc and a hole in the disk at larger distances.

The mistake caused by the slope coincidence of the “main sequence” was pointed out by Bertelli et al. (1995), who used their so-called HRD-GST, the Hertzsprung-Russell Diagram Galactic Software Telescope, to identify the band with the stars located on the disk main sequence and at its TOP at various distances along the line of sight. The slope of the apparent sequence in the CMD was determined by the variation of interstellar extinction with distance. Initially we did not appreciate their result because we were overwhelmed by the complexity of HRD-GST.

Rucinski (1996) demonstrated that contact binaries found in the OGLE variable star catalogs (Udalski et al. 1994, 1995a, 1995b, 1996) have a uniform distribution for distances up to \(~8\) kpc, i.e., all the way to the Galactic bulge, with no evidence of a major hole in the inner Galactic disk. The distribution of contact binaries in the CMD was consistent with the Bertelli et al. (1995) interpretation of the diagram. Recently, Ng & Bertelli (1996) used the shape of the sequence made by the disk stars to study the distribution of interstellar extinction with distance.

A simple demonstration of the correctness of the Bertelli et al. (1995) interpretation is provided by Figures 2 and 3, in which the CMDs are shown for two subsets of stars in Baade’s Window. The two subsets correspond to the regions in which the total interstellar extinction toward the Galactic bulge is in the range \(1.29 < A_V < 1.46\) and \(1.95 < A_V < 2.78\), respectively. These two regions have a very complicated geometric structure as given by the extinction map provided by Stanek (1996). It is clear that the slope of the “main sequence” is shallower in the areas of larger interstellar reddening (Fig. 3). There is also more scatter of stars.
Figure 1.—CMD \([V-I]\) for OGLE stars in Baade’s Window is shown for 10% of the stars with \(I < 16.5\) mag, with the fraction declining to 0.7% for the stars with \(I > 18.5\), to avoid excessive crowding. The recent OGLE catalog (Szymański et al. 1996) lists 33,196 stars with \(14 < I < 18\) in the field BWC, with the area 15 arcmin\(^2\), centered at \((l, b) = (1.0, -3.9)\).

In Figure 3 than in Figure 2 because of a larger range of interstellar extinction: 0.83 mag versus 0.17 mag. Note that the stellar populations must be almost identical in these two small regions.

In the following we present a simple demonstration of why the CMD in Baade’s Window features the disk stars forming an apparently narrow sequence, while in many directions farther away from the Galactic plane similar stars form only a distinct blue edge to their distribution, with \((B-V) \approx 0.4\) and \((V-I) \approx 0.7\), but no narrow sequence is apparent in those fields (e.g., Kluźniak & Udalski 1992; Reid & Majewski 1993; Caldwell 1996).

A simple visualization of the effect is presented in Figures 4 and 5. Following Reid & Majewski (1993) we took the stars in the globular cluster 47 Tuc (Kluźniak, Wysocka, &...
Krzymiński (1997) as an approximate representation for the disk color-luminosity function. We considered two forms of number density variation with distance. First, the number density was assumed to vary as

\[ n = n_0 \left(1 + \frac{d}{500 \text{ pc}} \right)^{-3}, \]

where \( n_0 \) is the local number density near us. We also assumed there was no interstellar extinction. As a result we obtained the CMD presented in Figure 4. The sharp blue edge is clearly apparent, but there is no striking red edge. This simulation provides a similar visual impression to the observed CMDs of Krzemiński (1997), Reid (1992), and Caldwell (1993), and Caldwell & Schechter (1996).

In order to simulate the conditions in Baade's Window we adopted the same 47 Tuc color-luminosity function, but we assumed that the number density of disk stars is constant between us and 5.6 kpc and that it follows the number density of stars given by the E2 model for the Galactic bar, proposed by Dwek et al. (1995) and modified by Stanek et al. (1997), at distances larger than 5.6 kpc. The interstellar extinction as a function of distance \( d \) was adopted to be:

\[ A_V = 2 \text{ mag } \left[1 - e^{-d/(1.7 \text{ kpc})^2}\right], \]

i.e., somewhat different than recommended by Arp (1965) or by Ng et al. (1996), but this makes only a small quantitative difference. The corresponding CMD is shown in Figure 5. The sequence of stars from \((V-I, I) = (0.9, 14.0)\) to \((1.5, 18.0)\) has a resemblance to the observed sequence (cf. Fig. 1) and to the model results presented by Bertelli et al. (1995) (see also Ng et al. 1995). This sequence is made of the disk TOP and bright main-sequence stars. Note that the sequence becomes vertical for \( I > 18.2 \), as there is almost no additional extinction (and reddening) beyond \( \sim 3 \text{ kpc} \) in the model. The sequence remains narrow along its full length in Figure 5, for \( 14 < I < 20 \), with the lowest part dominated by the Galactic bulge/bar stars.

A comparison between Figures 1 and 5 makes it clear that our single-population model cannot provide a quantitative explanation for the many details of the observed CMD. However, our goal was to provide a simple explanation of the origin of the sharp sequence of disk stars in Baade's Window and the reason for its absence in the other directions. We have shown that the sharp sequence appears because the number density of disk stars remains roughly constant with distance in Baade's Window and that the interstellar extinction is significant.

The many details of the observed CMD as presented in Figure 1 depend on the mix of many stellar populations, each with its own range of chemical compositions, range of ages, geometrical distribution, mass function, and, therefore, its specific luminosity function. In addition, there is a complicated variation of the interstellar extinction with distance. According to Bertelli et al. (1995) and Ng et al. (1996), their multicomponent HRD-GST can explain most of the observed details, but this is at present beyond our ability to assess.

The OGLE data cover only two photometric bands and should not be overinterpreted. It is necessary to take into account the incompleteness as described by Szymański et al. (1996) before making quantitative inferences. Also, there seems to be a systematic error in the colors of stars fainter than \( V \sim 18 \), as discussed in §3. That error will be corrected with a new data set to be obtained shortly with a new instrument.

### 3. Galactic Bulge/Bar

The line of sight through Baade's Window reaches the distance of 8 kpc at \( \sim 500 \text{ pc} \) below the Galactic plane. It is most likely that there is no significant extinction so far out. According to Arp (1965) the extinction ends at a distance \( \sim 2 \text{ kpc} \) away from us, while according to Ng & Bertelli (1996) it may extend out to \( \sim 4 \text{ kpc} \). In any case it is safe to assume that the inner disk, as seen through Baade's Window, and the stars in the Galactic bulge/bar farther out are subject to the same total extinction map (Stanek 1996). Therefore, in order to study the inner parts of the Galaxy we can make a correction following Stanek's prescription. We applied the extinction corrections to all stars, which means we have overcorrected the disk stars that are closer to us than \( \sim 4 \text{ kpc} \). The corresponding CMD is shown in Figure 6, where only 10% of bright stars and 0.7% of the faint stars were plotted, to avoid excessive crowding.

The outlines of stellar sequences observed in the globular cluster 47 Tuc, and in the very old and metal-rich open cluster NGC 6791, are shown with solid lines in Figure 6. The cluster sequences were corrected for reddening. We adopted \( E_{B-V} = 0.06 \) for 47 Tuc following Krzemiński et al. (1997) and \( E_{B-V} = 0.22 \) for NGC 6791 following Krzemiński & Udalski (1992). Both sequences were shifted in magnitude as if moved to the distance of 8 kpc, adopting \( (m-M)_V = 13.4 \) and \( (m-M)_V = 13.52 \) for 47 Tuc and NGC 6791, respectively. The area surrounded with a dashed line at
they are all much bluer than the average colors of OGLE stars at the same magnitude, \(I_0 \approx 18\). This indicates that there is some systematic error in the OGLE photometry, as the faint OGLE stars appear too red.

In fact there was some evidence of a nonlinearity of the CCD camera system used by the OGLE (Udalski et al. 1993). The case seems to be strengthened with a comparison between the OGLE photometry of the TP8 field (at \(l = -0.1, b = -8.0\)) and the recent photometry done on the 2.5 m Du Pont telescope by J. Kaluzny & I. Thompson (1997, private communication). It indicates a systematic color shift of \(\approx 0.1\) mag, indicating that faint OGLE stars are too red.

Note that for the faintest OGLE stars the systematic effects of stellar image blending are significant. Most stars below the bulge TOP are the bulge MS stars, which are redder. Therefore, the measured colors of the unresolved blended images may be systematically too red, adding to the systematic effect caused by a nonlinear response of the CCD detector and the camera electronics.

A much better photometry with the new OGLE-2 telescope is expected to be available soon. Therefore, we think it is not useful to investigate the systematic error in the old OGLE photometry. It had no effect on the microlensing searches or the search for stellar variability. However, the presence of a systematic error limits the use of the old OGLE CMDs for a quantitative analysis of stars with \(V > 18\), or \(I > 16\).

### 4. The Bulge/Bar Age

There is an intriguing difference between the OGLE CMD for the Galactic bulge/bar, and the diagrams for 47 Tuc and NGC 6791 at \(I_0 \approx 16.7\)–17.7, \((V-I)_0 \approx 0.8\)–1.0 (cf. Fig. 6). There is a short, almost horizontal segment joining the TOP region with the red subgiant branch. In the two clusters the magnitude difference between this segment and the red clump at \((V-I)_0 \approx 1.05\) is \(\approx 3.2\) mag, while the OGLE data indicate the difference to be only \(\approx 2.6\) mag.\(^3\)

This difference, just like the better known (but more difficult to measure) magnitude difference between the horizontal branch stars and the TOP stars, is a good age indicator (see Bertelli et al. 1994). Taken at the face value it implies that the dominant bulge/bar population is substantially younger than the clusters 47 Tuc and NGC 6791. However, considering the problems with the systematic color errors and blending for faint OGLE stars, and only marginal evidence for the presence of the “horizontal segment” in the OGLE data as presented in Figure 6, the evidence for the age of the bulge is marginal at best.

The blue/bright side of this feature was identified by Ng et al. (1996) as the main-sequence turnoff from the old disk population. However, this leaves a question: where is the “horizontal segment” corresponding to the bulge population responsible for the prominent red clump, and expected to be present at \(3.2\) mag below it? The HST data presented in Figure 2 of Holtzman et al. (1993) have too few stars at \(I < 17.8\) to make any claim about the presence or absence of the segment at \(I \approx 17.8\). However, with the center of the red clump at \(I \approx 15.3\), the “horizontal

\(^3\) The same “horizontal segment” is directly observed in the OGLE \((V-I) I\) diagram; it is marginally apparent in Fig. 1 at \(I \approx 17.8\), \((V-I) \approx 1.7\).
segment” would be expected to be at \( I \approx 15.2 + 3.2 = 18.4 \) if the bulge was like 47 Tuc or NGC 6791, but there is no such thing apparent in the \( HST \) data at \( I \approx 18.4 \). Unfortunately, the number of stars in the \( HST \) CMD is too small to be confident.

Therefore, rather inconclusive \( HST \) data seem to point the same way as the inconclusive OGLE data: the shape of the bulge/bar CMD between the TOP and the red subgiant branch seems to imply a substantially lower age for the dominant bulge population than the age of old globular or open clusters. The unusually rich red clump (red horizontal branch) of the bulge/bar provides yet another indication of a relatively young population (Paczyński et al. 1994).

The issue of the bulge age is vigorously discussed in the literature, and it is not settled yet. It could be resolved with the \( HST \) CMD extending to bright enough stars, and over large enough area, to cover the star sequence joining the TOP with the red subgiant branch. Even more definite resolution of the age problem could be provided by the determination of masses of detached eclipsing binaries in that part of the diagram (Paczyński 1997). Such binaries can be found in the OGLE catalogs (Udalski et al. 1994, 1995a, 1995b, 1996). The main practical problem is the faintness of those stars; the radial velocity curves may have to wait until the 6.5 m and 8 m telescopes become operational.

5. INTERSTELLAR EXTINCTION MAP

Stanek (1996) has used the method developed by Woźniak & Stanek (1996) to construct the extinction map for Baade’s Window. The method took advantage of red clump stars as tracers. In this section we verify the map using two other groups of stars: the red subgiants and the far disk and bulge TOP stars. The regions of the CMD covered by the three groups is shown in Figure 7 with three parallelograms, which have the slope of the upper and lower boundaries fixed by the relation that holds for interstellar extinction: \( E(I) = 1.5 \times E(V-I) \).

All stars in the OGLE database for Baade’s Window were ordered according to the value of their extinction using Stanek’s (1996) software, and divided into 20 groups with equal number of stars in each group. Next, the stars in the three regions as shown in Figure 7 were selected for each of the 20 groups. Finally, the stellar \( (V-I)_0 \) and \( I_0 \) values were shifted for each group along the extinction lines so as to achieve the best match among all the groups. This way residual corrections were found to the average values of interstellar extinction for each reddening group and for each type of stars: the red clump stars, the red subgiants, and the TOP stars. If these were perfect methods to measuring interstellar extinction then all the corrections should be close to zero, and there should be no systematic trend between them.

The comparison between the extinction values obtained for each of the 20 reddening groups for all three types of stars is shown in Figure 8, together with the dashed line that indicates the perfect relation. The overall agreement is reasonable, but a small but systematic trend is disturbing. It is most disturbing for the red clump stars that are shown with the small filled circles. The range of reddening values as determined in this paper is larger than the range obtained from the Stanek’s map.

It turns out that a significant fraction of the systematic trend apparent in Figure 8 is caused by the interpolation, as described by Stanek (1996). This is demonstrated in Figure 9, where the estimate of the reddening for all stars in the OGLE database in the field BW3 is shown for 20 groups ordered according to the value of their extinction (the field BW3 was selected because it has the largest range of extinction). The value of \( E(V-I)_{WS} \) was obtained with the Stanek (1996) extinction map, and it involved interpolation between the original subframes for which the values of \( E(V-I)_{WS} \) were estimated by Woźniak & Stanek (1996).

![Fig. 7.—CMD \([V-I]_0-I_0\) for OGLE stars in Baade’s Window, together with the three boxes indicating the location of the red clump stars, red subgiant stars, and TOP stars, which were used for the three independent estimates of interstellar reddening.](image1)

![Fig. 8.—Relation between the interstellar reddening as determined in this paper \([E(V-I)]_{WS}\) and as given by Stanek (1996) \([E(V-I)]_0\) is shown for three groups of stars. The location of the three groups in the CMD is shown with three boxes in Fig. 7.](image2)
The data on which the extinction map was based had the resolution limited by these subframes, which were 28" on a side. The difference between the perfect system (Fig. 9, dashed line) and the real world (solid line) is in the same sense and about the same magnitude as the systematic trend present in Figure 8. However, some part of the trend may be caused by the systematic errors in the OGLE photometry, as discussed in § 3.

The fact that the values of interstellar reddening estimated with three different types of Galactic bulge stars are all in a fair agreement, as shown in Figure 8, demonstrates that Stanek’s (1996) reddening map can be used with some confidence. On the other hand the differences apparent in Figure 8 indicate how large the differential errors of the map are. Of course, there is a separate issue of the reddening zero point, as discussed by Stanek (1996).

6. DISCUSSION AND CONCLUSIONS

This paper addresses two errors that we have found in the previous analysis of the OGLE data, and in the data themselves: the incorrect interpretation of the disk star sequence in the CMD by Paczyński et al. (1994), and a systematic photometric error of 0.1 mag for the faint stars. The correct interpretation of the disk sequence as made of stars on the main sequence at various distances, and suffering interstellar reddening increasing with the distance, was first proposed by Bertelli et al. (1995). In this paper we explained the sharpness of the sequence as caused by the fact that the number density of stars seen through Baade’s Window remains roughly constant as a function of distance, and there is just the right amount of the interstellar extinction to enhance the sharpness of the apparent sequence. This is approximately the same population that dominates the CMDs far from the Galactic plane, and creates the characteristic blue edge at \((B-V) \approx 0.4\), and \((V-I) \approx 0.7\) (e.g., Kaluzny & Udalski 1992; Reid & Majewski 1993; Caldwell & Schechter 1996).

Clearly our single-population model based on 47 Tuc is a gross oversimplification, yet it is sufficient to account, at least qualitatively, for the sharpness of the main-sequence feature that misled Paczyński et al. (1994).

The photometric error is most likely caused by a nonlinearity of the detector system, as mentioned by Udalski et al. (1993) and confirmed by Kaluzny & Thompson (1997, private communication), with some additional contribution resulting from crowding and blending of the faint stars with the bulge main-sequence stars that are below the detection threshold and systematically redder than the stars just above the detection threshold. We expect that photometry from the new OGLE-2 system will not be subject to such systematic errors.

We verified the extinction map based on the red clump stars obtained by Stanek (1996) using the bulge red subgiant stars and the bulge TOP stars. We found reasonable agreement between these groups of stars, but we have also found a small systematic error caused by the interpolation process used by the map software. At this time Figure 8 can be used to estimate the map accuracy.

We found some evidence in the OGLE data, and in the HST data as presented by Holtzman et al. (1993), that the dominant bulge population is considerably younger than either the moderately metal-weak globular cluster 47 Tuc, or the metal-rich open cluster NGC 6791. This relatively young age is indicated by the location of stars between the TOP and the red subgiant branch, barely detectable in Figure 6. A definite confirmation of the effect can be obtained with new HST data that must cover a larger area and extend to brighter stars than those analyzed by Holtzman et al. (1993), so that the location of the star sequence connecting the bulge TOP with its red subgiant branch can be clearly established.

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REFERENCES

Arp, H. 1965, ApJ, 141, 43
Bertelli, G. et al. 1994, A&A, 106, 275
Bertelli, G., Bressan, A., Chiosi, C., Ng, Y. K., & Ortolani, S. 1995, A&A, 301, 381
Caldwell, J. A. R., & Schechter, P. L. 1996, AJ, 112, 772
Dwek, E., et al. 1995, ApJ, 445, 716
Holtzman, J. A., et al. 1993, AJ, 106, 1826
Kaluzny, J., & Udalski, A. 1992, Acta Astron., 42, 29
Kaluzny, J., Wysocka, A. & Krzemiński, W. 1997, in preparation

Ng, Y. K., & Bertelli, G. 1996, A&A, 315, 116
Ng, Y. K., Bertelli, G., Bressan, A., Chiosi, C., & Lub, J. 1995, A&A, 295, 655
Ng, Y. K., Bertelli, G., Chiosi, C., & Bressan, A. 1996, A&A, 310, 771
Paczynski, B. 1997, in Proc. Extragalactic Distance Scale STScI May Symp., ed. M. Livio, M. Donahue, & N. Panagia (Cambridge: Cambridge Univ. Press)
Paczynski, B., Stanek, K. Z., Udalski, A., Szymański, M., Kaluzny, J., Kubiaik, M., & Mateo, M. 1994, AJ, 107, 2060
Reid, N., & Majewski, S. R. 1993, ApJ, 409, 635
Rucinski, S. 1996, preprint
Stanek, K. Z. 1996, ApJ, 460, L37
Stanek, K. Z., Mateo, M., Udalski, A., Szymański, M., Kalužny, J., & Kubiak, M. 1994, ApJ, 429, L73
Stanek, K. Z., Udalski, A., Szymański, M., Kalužny, J., Kubiak, M., Mateo, M., & Krzeminski, W. 1997, ApJ, 447, 163
Szymański, M., Udalski, A. 1993, Acta Astron., 42, 253
Szymański, M., Udalski, A., Kubiak, M., Kalužny, J., Mateo, M., & Krzeminski, W. 1996, Acta Astron., 46, 1
Udalski, A., Kubiak, M., Szymański, M., Kalužny, J., Mateo, M., & Krzeminski, W. 1994, Acta Astron., 44, 317
Udalski, A., Olech, A., Szymański, M., Kalužny, J., Kubiak, M., Mateo, M., & Krzeminski, W. 1995a, Acta Astron., 45, 433
Udalski, A., Olech, A., Szymański, M., Kalužny, J., Kubiak, M., Mateo, M., Krzeminski, W., & Stanek, K. Z. 1996, Acta Astron., 46, 51
Udalski, A., Szymański, M., Kalužny, J., Kubiak, M., & Mateo, M. 1992, Acta Astron., 42, 253
--- 1993, Acta Astron., 43, 69
Udalski, A., Szymański, M., Kalužny, J., Kubiak, M., Mateo, M., & Krzeminski, W. 1995b, Acta Astron., 45, 1
Woźniak, P. R., & Stanek, K. Z. 1996, ApJ, 464, 233