MAGNITUDE OFFSET BETWEEN LENSED STARS AND OBSERVED STARS – A NEW PROBE OF THE STRUCTURE OF THE GALACTIC BAR

K. Z. Stanek
Princeton University Observatory, Princeton, NJ 08544–1001
e-mail I: stanek@astro.princeton.edu

ABSTRACT

We propose a new method that can be used to constrain the properties of the Galactic bar (bulge). If the majority of the lensing objects are in the Galactic bar, then we predict a systematic offset in the apparent magnitude between lensed stars and all observed stars. Using OGLE color-magnitude diagram data we model this effect in the region of the diagram dominated by bulge red clump stars and find that for some models of the Galactic bar the expected offset in the apparent magnitude may be as large as 0.2 mag. About 100 lensed stars in the red clump region of the color-magnitude diagram is needed to unambiguously detect this effect, a number within the reach of current microlensing projects. We find a good correlation between the extent of the bar along the line of sight and the expected magnitude offset. We also obtain a constraint for the extent of the bar along the line of sight using the observed luminosity function for the red clump stars.

Subject headings: Galaxy: general – Galaxy: structure – gravitational lensing – stars: Hertzsprung-Russell diagram – stars: statistics

1. INTRODUCTION

The OGLE project (Optical Gravitational Lensing Experiment) recently announced the results from the first two years of the search for gravitational microlensing in the
direction of the Galactic bulge (Udalski et al. 1994). A total of nine lenses were found in the combined data from 1992 and 1993, giving an estimate of the optical depth to gravitational microlensing of the Galactic bulge stars: \( \tau = 3.3 \pm 1.2 \times 10^{-6} \) for Baade’s Window and the nearby Galactic Bar fields. Results of the MACHO experiment (Alcock et al. 1994) give a similar, high value for the optical depth in the bulge. Theoretical models predicted a lower value, somewhere in the range of \( 0.5 - 1.0 \times 10^{-6} \) (Paczynski 1991; Griest et al. 1991; Kiraga and Paczyński 1994; Giudice et al. 1994). Alcock et al. (1994), and also Gould (1994), argue that the extra mass responsible for the observed high event rate may be located in the Galactic disk. However, in considering the results from Udalski et al. (1994), Paczyński et al. (1994b) show that the lenses unlikely occur in the Galactic disk, due to the current constraints on the mass in the Galactic disk (Kuijken & Gilmore 1991; Bahcall, Flynn & Gould 1992) and the observed “hole” in the disk (deficiency of stars as compared to exponential disk, Paczyński et al. 1994a). Instead, they argue for the lenses to be located in the Galactic bar, which is oriented towards us. Calculations by Zhao, Spergel & Rich (1994b) of the microlensing by the bar stars are consistent with the arguments in Paczyński et al. (1994b). Here, we propose and discuss a simple observational method that allows us to distinguish between the two possibilities. The test we propose is a local one, i.e. it does not require observations in fields with different Galactic longitudes (Kiraga & Paczyński 1994; Paczyński et al. 1994b; Evans 1994; Kiraga 1994).

There is now a number of photometric and dynamical indications that the Galaxy is barred (de Vaucouleurs 1964; Blitz & Spergel 1991; Binney et al. 1991; Whitelock & Catchpole 1992; Weinberg 1992; Blitz 1993). The bar shows in the OGLE color-magnitude diagram data as a many sigma difference of \( \sim 0.37 \) mag in the apparent magnitude of the red clump stars in the two opposite \( l = \pm 5^\circ \) OGLE Galactic bar fields (Stanek et al. 1994). It is also clearly seen in COBE data (Weiland et al. 1994), which was used by Dwek et al. (1994) to constrain a number of the bar models existing in the literature. In this paper we will use results of Dwek et al. (1994), combined with ftp-accessible color-magnitude OGLE data (Udalski et al. 1993; for ftp instructions see Paczyński et al. 1994a) to investigate a new effect of the gravitational microlensing. If the majority of the lensing objects are in the Galactic bar, then there should be a systematic offset in the apparent magnitude between observed stars and lensed stars – stars from the far side of the bar are much more likely to be lensed than the stars from the near side of the bar. We discuss various aspects of the magnitude offset between the observed stars and lensed stars and show that it can be used as a new probe of the structure of the Galactic bar (bulge).

2. THE DATA
We use the color-magnitude diagram (CMD) of Udalski et al. (1993a) for one of the nine fields in Baade's Window (BW3, coordinates of the center of the field: \(l = 0.92^\circ, b = -4.19^\circ\)). This is so far the only field observed by OGLE in which stars from the red clump region were lensed. The observations were made using the 1 meter Swope telescope at the Las Campanas Observatory, operated by the Carnegie Institution of Washington, and 2048 \(\times\) 2048 Ford/Loral CCD detector with the pixel size 0.44 arcsec covering 15' \(\times\) 15' field of view. The CMD for BW3 field can be seen in Udalski et al. (1993).

Most of the diagram is dominated by bulge stars, with a distinct red clump, red giant, and turn-off point stars. The part of the diagram dominated by disk stars for this and other BW fields was analyzed by Paczyński et al. (1994a). Stanek et al. (1994) used well-defined population of bulge red clump stars in nine BW fields and four Galactic Bar fields to find an evidence for the Galactic bar. Red clump stars are the equivalent of the horizontal branch stars for a metal rich population, 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 properties of high-metallicity systems, like the Galactic bulge.

To analyze the distribution of bulge red clump stars in a quantitative manner, we use the extinction-insensitive \(V_{V-I}\) parameter (Paczyński et al. 1994a; Stanek et al. 1994)

\[
V_{V-I} \equiv V - 2.6 (V - I),
\]

where we use 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 (see Stanek et al. 1994). Then we consider only the region of the CMD for BW3 field clearly dominated by the bulge red clump stars:

\[
1.4 < V - I ; \quad 10.5 < V_{V-I} < 14.0
\]

Stars observed in the BW3 field that satisfy the inequalities were counted in bins of \(\Delta V_{V-I} = 0.05\). The result appears in Fig.1, where we see the number of stars as a function of \(V_{V-I}\). Also shown are the values of the \(V_{V-I}\) parameter for the two lenses observed in this field near the red clump \((V_{V-I} = 12.51, 13.11)\).

The region selected above corresponds roughly to stars with \(I < 18\). For such stars it was found by Udalski et al. (1993, their Table 4), from artificial star test, that the completeness of the sample is rather uniform, on the level of 0.8, which makes our further analysis much simpler. Also, red clump stars provide us with very convenient "landmark", a point which will be used in the next section.
3. THE MODEL

We want to reproduce the observed luminosity function (Fig. 1) assuming one of Dwek et al. (1994) best-fit models of the Galactic bar density distribution and fitting some simple form of the intrinsic luminosity function for the stars in the red clump region.

For the Galactic bar density distribution we take Dwek’s et al. G2 model with the exponential cutoff at 2.4 kpc. This model is described by analytical formula

$$\rho_{G2}(x, y, z) = \rho_0 \exp\left(-\frac{r_s^2}{2}\right) \left[ M_\odot pc^{-3}\right],$$

where $r_s$ is defined as

$$r_s \equiv \left\{ \left( \frac{x}{x_0} \right)^2 + \left( \frac{y}{y_0} \right)^2 + \left( \frac{z}{z_0} \right)^4 \right\}^{1/4}. \quad (4)$$

The scale lengths of the bar are $x_0 = 1.47$, $y_0 = 0.56$, $z_0 = 0.42$ kpc (assuming the distance to the center of the Galaxy 8.0 kpc) and the angle of inclination to the line of sight is 20° (in Dwek’s et al. nomenclature this corresponds to $\alpha = 70^\circ$). The parameter $\rho_0$ is given by a total mass of the bar by $\rho_0 = M_B/(8\pi x_0 y_0 z_0)$. For the $M_B \approx 2 \times 10^{10} M_\odot$, $\rho_0$ is equal to $\sim 2.3 M_\odot pc^{-3}$. We parametrize the fitted luminosity function in the form

$$\Phi(L) = \left( \frac{N_0}{L_\odot} \right) \left( \frac{L}{L_\odot} \right)^{-\alpha} + \frac{N_{RC}}{\sigma_{RC}\sqrt{2\pi}} \exp \left[ -\frac{(L - L_{RC})^2}{2\sigma_{RC}^2} \right] \left[ L^{-1}\right]. \quad (5)$$

The power-law with index $\alpha$ is intended to represent the underlying broad population of stars, and the Gaussian is intended to represent red clump stars. For a given $V_{V-I}$ bin, the number of stars in that bin is then given by

$$N(V_{V-I}) = C_1 \int_{D_{MIN}}^{D_{MAX}} \rho(D_s) D_s^2 \Phi(L) L dD_s, \quad (6)$$

where we took $\rho(D_s) = \rho_{G2}(x, y, z)$, $D_{MIN} = 3 kpc$, $D_{MAX} = 13 kpc$, $C_1$ is a constant, $D_s$ is a distance from the observer to the source, and $L = C_2 D_s^2 10^{-0.4V_{V-I}}$, where $C_2$ is another constant. The choice of $D_{MIN}$ and $D_{MAX}$ is not important as long as they contain the distance cutoff applied to the density distribution. In equation (6) we assume that the number of observable stars is everywhere proportional to the density of matter and that the intrinsic luminosity function is independent of location, which gives a constant $(M/L)$ throughout the bar.

We then fit the observed luminosity function using the above assumptions. The fit is shown in Fig. 1. The fit is satisfactory, considering the fact that we use an assumed model of
the density distribution, which is not the subject to the fit. The peak of the fitted intrinsic luminosity function for the red clump stars is very narrow, with fitted $\sigma_{RC}$ corresponding to $\sim 0.07$ mag (although luminosity function $\Phi(V_{V-I})$ is no longer Gaussian), a point which we will address in the discussion.

Having the intrinsic luminosity function, we can now obtain the predicted luminosity function for lensed stars, in the case where the lenses are located in the bar with the described density distribution. In this case the equivalent to equation (6) will have the form

$$N_L(V_{V-I}) = C_1 \int_{D_{MIN}}^{D_{MAX}} \tau(D_s) \rho(D_s) D_s^2 \Phi(L) L \, dD_s,$$

where $\tau(D_s)$ is the local optical depth for gravitational microlensing given by the formula

$$\tau(D_s) = \frac{4\pi G}{c^2} \int_0^{D_s} \rho(D_d) D_d (D_s - D_d) D_s \, dD_d,$$

$D_d$ being the distance from the observer to the deflector. The resulting luminosity function for the lensed stars, multiplied by the average optical depth for microlensing for all stars, is shown in Fig.1. Clearly, the expected luminosity function for lensed stars is different from the luminosity function for all observed stars. This is because the stars on the far side of the bar are more likely to be lensed than the stars on the near side of the bar, a purely geometrical effect.

Knowing that we should expect differences in the observed luminosity functions of all stars and of lensed stars, we want to ask the question: how many lensed stars in the red clump region of the CMD do we need to tell with a desired accuracy that the two functions are really different? We checked a number of simple tests and various statistics and found that the median of the sample is a good measure of the difference in the case when we restrict the region of comparison to $\pm 1$ mag from the peak of the observed luminosity function. More quantitatively — we take a running region $2$ mag wide. Then for 100 lenses drawn randomly 10,000 times from both the fitted luminosity function and from the predicted luminosity function of lensed stars, we compare the parameter $\kappa = (\langle med_2 \rangle - \langle med_1 \rangle) / (\sigma_{med,2} + \sigma_{med,1})$, i.e. we find a region in $V_{V-I}$, of a given width, where we are maximally sensitive to the difference between the two distributions. Subscript 1 corresponds to all stars, subscript 2 to lensed stars. The value of $\kappa$ as a function of the middle point of the selected region is shown in the panel A of Fig.2. With the thick horizontal line we mark the level of $\kappa = 1.5$. We see that $\kappa$ has relatively flat-topped distribution, so as to include as many predicted lenses into region as possible without losing much sensitivity, we choose the region between $11.2 < V_{V-I} < 13.2$. Then, for this region we draw a random sample of $n$ lenses many times from each distribution and we
compare the corresponding \( \langle \text{med} \rangle \) and \( \sigma_{\text{med}} \). The plot of these values for each distribution as a function of \( \log(n) \) is shown in the panel B of Fig.2. The mean difference between the medians of the two distributions is \( \Delta \text{mag} = 0.185 \text{ mag} \). Also shown is the median value of the \( V_{\nu-I} = 12.81 \) parameter for the two lenses observed by OGLE so far in the red clump region. This value suggests, although with low significance, that the lensing objects may be in the Galactic bar. Visual analysis of the published color-magnitudes diagrams with the positions of lensed stars by MACHO experiment (Alcock et al. 1994) shows that two out of four events for one of the fields have positions close to, but below the red clump.

4. DISCUSSION

In the previous section we have shown that in the case when the majority of microlensing objects are the Galactic bar, there should be an offset in the median magnitude between all observed stars (in the bar) and the lensed stars. We now discuss the implications of this conclusion.

The size of the magnitude offset between the observed and the lensed stars depends on how elongated the bar (bulge) is along the line of sight. We define an elongation parameter for the bar to be

\[
\left( \frac{\Delta l}{2} \right)^2 \equiv \frac{\int_{D_{\text{MIN}}}^{D_{\text{MAX}}} (D_s - \langle D_s \rangle)^2 \rho(D_s) \, dD_s}{\int_{D_{\text{MIN}}}^{D_{\text{MAX}}} \rho(D_s) \, dD_s}.
\]

We take three models of the bar (bulge) from the existing literature, one axially-symmetric model from Kent (1992), and two models from Dwek et al. (1994), noted by G2 (used in this paper) and E3. All these models were subject to the same distance cutoff, discussed earlier in this paper. First we construct the intrinsic luminosity function by fitting the data for the BW3 field. Fitted luminosity functions have \( \sigma_{\text{RC}} \) that correspond to \( \sim 0.07 \text{ mag} \) for G2 model, \( \sim 0.35 \text{ mag} \) for E3 model, and \( \sim 0.25 \text{ mag} \) for Kent’s model. We then calculate, for each of these models, both \( \Delta l \) and the expected magnitude offset \( \Delta \text{mag} \) for the line of sight towards the BW3 field. The results are shown in Fig.3. There is a good correlation between \( \Delta l \) and \( \Delta \text{mag} \), which indicates that the method discussed in this paper may also be used to constrain the elongation of the bar along the line of sight, a constraint that is otherwise difficult to obtain. To some degree such a constraint is already put by inspecting the observed luminosity function of the red clump stars (Fig.1). When using G2 model with 2.4 \( kpc \) density cutoff and angle of inclination of 20°, we were able to fit the observations only with very narrow (\( \sigma_{\text{RC}} \sim 0.07 \text{ mag} \)) intrinsic luminosity function for the red clump stars. When trying to fit the observed luminosity function using Dwek’s et
al. G2 model with 5 \( kpc \) cutoff and angle of inclination to the line of sight of 13\(^\circ\) (one of Dwek’s et al. best-fit models), the overall fit was worse, and even with the red clump stars distribution approaching perfect standard candle (\( \sigma_{RC} = 0 \)), the resulting fitted luminosity function was too broad. This model has the elongation along the line of sight, as defined by Eq.9, \( \Delta l = 2.65 \ kpc \), which we may therefore treat as approximate upper limit for the elongation of the bar along the line of sight towards BW3. As it should be possible to obtain independently the width of the intrinsic luminosity function for the red clump stars, either from the stellar evolution theory or from the observations of high-metallicity clusters, this, already interesting, upper limit of \( \Delta l < 2.65 \ kpc \) can be eventually translated to the purely photometric estimate of the \( \Delta l \) value.

We also checked how the efficiency of the proposed method depends on the Galactic coordinates of the observed field. For number of fields with different galactic coordinates we investigated the value of \( \kappa \), analogously to what was done for the BW3 field. We found no significant differences in the maximum value of \( \kappa \) one can obtain, the only difference was the expected shift in the peak \( V_{V-I} \) value of the red clumps stars distribution due to the bar geometry.

The lensing events of the stars on the far side of the bar are not only more probable, but should also be longer lasting, for geometrical reasons. However, the timescale of the event is not only a function of how big the Einstein ring of the lensing object is, but it also depends on the velocities of both the lens and the source, which is difficult to quantify without a kinematical model of the stars in the bar (see Zhao 1994, used by Zhao et al. 1994b). One may however expect that the average timescale of the observed events \( \langle t_0 \rangle \) will be a function of \( V_{V-I} \) in the red clump region of the CMD, and in the case when geometry is most important for the timescales, lensed stars that are fainter should have on average longer lasting microlensing events.

The lensed stars in the vicinity of the red clump region provide us with an important opportunity in studying the kinematics of the stars in the Galactic bar. As Zhao, Spergel & Rich (1994a) mention, it would be very useful to obtain a sample of stars with the distances known with accuracy sufficient to place the star on either the near or far side of the bulge. But as we have shown, the lensed stars in the red clump region of the CMD may be very likely on the far side of the bulge, and they are bright enough to be found on old photographic plates to determine their proper motions.

In order to unambiguously detect the effect discussed in this paper, we estimate the number of required lensed stars in the red clump CMD region be about \( \sim 100 \). For the OGLE project it translates to a total of \( \sim 500 \) observed microlensing events. For the MACHO group, which because of poorer seeing has a brighter limiting magnitude, the total
number may be factor of $\sim 2$ smaller. These numbers are certainly within the reach of current or next generation microlensing experiments.

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FIGURE CAPTIONS

Fig. 1.— Observed number of stars as a function of the $V_{V-I}$ parameter for BW3 OGLE field ($l = 0.92^\circ, b = -4.19^\circ$) is shown, with error-bars corresponding to square-root of $N$ in each bin. For the purpose of presentation, the data were box-car smoothed with the bin width equal to 3 and only every third point is shown. Vertical long-dashed lines correspond to the values of the $V_{V-I}$ parameter for the two lenses observed in this field near the red clump. Also shown, with the continuous thick line, is the fit to the observed luminosity function, and with the dotted thick line, the expected luminosity function for lensed stars.

Fig. 2.— Panel A shows the efficiency $\kappa$ of the magnitude offset measurement as a function of mid-range point for 2 mag wide running region (see text). Panel B shows the average magnitude and standard deviation for the randomly drawn lenses from the fitted luminosity function (lower points) and expected luminosity function for lensed stars (upper points) as a function of number of the lenses in the sample $n_{lens}$. The black dot corresponds to the median of $V_{V-I}$ for the two lenses observed so far by OGLE in the red clump region.

Fig. 3.— Correlation between the elongation of the bar (bulge) model along the line of sight $\Delta l$ and the expected magnitude offset $\Delta mag$ between all observed stars and lensed stars. The dashed line is shown only to guide the eye.