MICROLENSING OPTICAL DEPTH REVISITED WITH RECENT STAR COUNTS

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1. INTRODUCTION

Microlensing surveys were originally proposed as a tool for detecting massive astrophysical compact halo objects (MACHOs) in the Galactic halo (Paczynski 1986). Searches for microlensing events toward the Magellanic Clouds by the MACHO (Alcock et al. 1993) and EROS (Aubourg et al. 1993) groups have placed constraints on the relative size of the Galactic MACHO populations. Searches for dark objects in the halo of M31 have also been performed (AGAPE, Ansari et al. 1999; WeCAPP, Riffler et al. 2003; MEGA, de Jong et al. 2004; VATT-Columbia, Uglesich et al. 2004; POINT-AGAPE, Calchi Novati et al. 2005; Angstrom, Kerins et al. 2006). In addition, microlensing has proved to be a powerful tool in constraining the distribution of faint stellar objects in the Milky Way (Kiraga & Paczynski 1994; Han & Gould 1995, 2003; Wood & Mao 1996; Binney et al. 2000; Zhao & Mao 1996; Han & Gould 2007; Calchi Novati et al. 2008). For instance, Han & Gould (1995) examined theoretical Galactic models by constructing a microlensing map. They explored a triaxial bar-shaped bulge model, which was based on multiwavelength COBE DIRBE observations of the Galactic bulge (Weiland et al. 1994), and demonstrated that observationally determining the microlensing optical depth may provide supplementary information on the Galactic mass distribution.

Unfortunately, however, reality was not so simple. Early measurements of the microlensing optical depth toward the Galactic bulge were significantly higher than predictions, suggesting that efforts on both the observational and theoretical sides were needed to reconcile the difference. Measurements aimed at Baade’s window by OGLE (nine microlensing events; Udalski et al. 1994) and at \((l, b) = (2.55, -3.64)\) by MACHO (13 events from “clump giant” sources; Alcock et al. 1997a) yielded \(\tau = (3.3 \pm 1.2) \times 10^{-6}\) and \(\tau = 3.9^{+1.5}_{-1.3} \times 10^{-6}\), respectively. Alcock et al. (1997a) pointed out the possibility of a systematic bias such as blending effects in microlensing optical depth measurements to explain these values, given that bulge fields are very dense regions. Popowski et al. (2001) suggested that bias due to blending could be avoided by using events only with bright source stars, such as red clump giants (RCGs). Such stars are identified by their well-defined position in a color-magnitude diagram, which ensures that they are most likely in the Galactic bulge. Their large flux also makes blending problems relatively unimportant. Measurements of \(\tau\) using RCGs have tended to reduce discrepancies with models. Based on 16 events, the EROS-2 collaboration (Afonso et al. 2003) reported a microlensing optical depth of \((0.94 \pm 0.29) \times 10^{-6}\) at \((l, b) = (2.5, -4.0)\). The MACHO group calculated the microlensing optical depth toward the Galactic bulge using their 7 yr survey data (Popowski et al. 2005); a measurement of \(\tau = 2.17^{+0.47}_{-0.38} \times 10^{-6}\) at \((l, b) = (1.50, -2.68)\) was obtained from 42 microlensing events detected during the monitoring of about \(7.4 \times 10^5\) clump giant sources covering \(4.5 \deg^2\). More recently, OGLE-II presented a measurement of the microlensing optical depth toward the Galactic bulge based on recent 4 yr survey data (Sumi et al. 2006). Using a sample of 32 microlensing events in 20 bulge fields covering \(\sim 5 \deg^2\), they found \(\tau = 2.55^{+0.57}_{-0.46} \times 10^{-6}\) at \((l, b) = (1.16, -2.75)\). Efforts on the theoretical side also refined the microlensing optical depth estimate by using more sophisticated models based on observational results from wide-field surveys. Theoretical estimates involving a bar in the bulge oriented along the line of sight have converged to a value in the range \((0.8-2.0) \times 10^{-6}\) (e.g., Paczyński et al. 1994; Zhao et al. 1995; Zhao & Mao 1996; Binney et al. 2000; Han & Gould 2003).

The optical depth in microlensing is defined as the probability that a source star is located within the Einstein radius of a
foreground lens star. If bulge stars are distributed over a distance $d$ from Earth, the microlensing optical depth is given by

$$\tau = \frac{4\pi G}{c^2} \int_0^d \left[ \int_0^{D_l} dD_l \rho(D_l)D_l dD_s D_s^2 n(D_s) \right] ,$$  \hspace{1cm} (1)

where $n(D_s)$ is the number density of source stars, $\rho(D_l)$ is the mass density of lenses along the line of sight, $D_b, D_s,$ and $D_l$ are the distances from the observer to the lens and source and the distance from the lens to the source, respectively, and $D = D_l D_b / D_s$.

Given that the microlensing optical depth is subject to the underlying mass distribution, it is crucial to employ a mass model that can be constructed from independent observations, for example, star counts. In fact, the stellar contents of the disk and the bulge have been measured by survey projects and modeled to estimate the optical depth. For instance, star counts from the Hubble Space Telescope (HST) have provided constraints on faint stars down to the hydrogen burning limit in the disk and to 0.15 $M_\odot$ in the bulge (Holtzman et al. 1998; Zoccali et al. 2000; Zheng et al. 2001). Using those observational results, one may place relatively stronger constraints on the mass distribution in terms of the microlensing optical depth (e.g., Han & Gould 2003). Results from large-scale surveys such as the Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) and the Sloan Digital Sky Survey (SDSS; York et al. 2000) are also available in the near-infrared and optical wavelength bands. On the basis of those results, new models of the Galactic bulge and disk have been suggested (López-Corredoira et al. 2005; Juric et al. 2008). In the present paper, we calculate the microlensing optical depth with Galactic bulge and disk models based on recent survey observations, as well as with those studied earlier. We then compare the model optical depths with the results from the MACHO, OGLE-II, and EROS-2 surveys.

The paper is organized as follows: We begin with a brief description of the bulge and disk models in § 2. We present the
expected microlensing optical depths from the various models and compare them with observed values in § 3. Finally, we conclude with a summary of our results and a discussion.

2. GALACTIC BULGE AND DISK MODELS

2.1. Bulge Model

We calculate theoretical optical depths based on five different mass distribution models. To begin with, we follow López-Corredoira et al. (2004, 2005), who have suggested two bulge models, triaxial and boxy, on the basis of the number density from 2MASS star counts (Skrutskie et al. 1997). Thus, our first and second models are

\[ \rho_{\text{triaxial}}(x, y, z) = \rho_T \exp\left( -\frac{t_1}{740 \text{ pc}} \right), \]  
\[ \rho_{\text{boxy}}(x, y, z) = \rho_B \exp\left( -\frac{0.866t_2}{740 \text{ pc}} \right), \]

respectively, where

\[ t_1 = \left[ x^2 + \left( \frac{y}{0.49} \right)^2 + \left( \frac{z}{0.37} \right)^2 \right]^{1/2}, \]  
\[ t_2 = \left[ x^4 + \left( \frac{y}{0.49} \right)^4 + \left( \frac{z}{0.37} \right)^4 \right]^{1/4}. \]

The normalizations in the triaxial and boxy bulge models are \( \rho_T = 9.9 M_\odot \text{ pc}^{-1} \) and \( \rho_B = 4.67 M_\odot \text{ pc}^{-3} \), respectively. Following Calchi Novati et al. (2008), we assume a total bulge mass of \( 1.5 \times 10^{10} M_\odot \) within 2.5 kpc of the Galactic center. Note that this value is in the range of generally accepted values of \((1-2) \times 10^{10} M_\odot\) (e.g., Blum 1995; Zhao et al. 1996; Dehnen & Binney 1998). For both bulge models, the longest axis is inclined by 29° with respect to the line of sight.

We also employ three widely used bulge models. Our third model (HG03) is one studied by Han & Gould (2003), which is favored by an analysis of the COBE DIRBE observations (Dwek et al. 1995). Han & Gould normalized this model using HST star
counts. For the fourth model, we adopt Stanek et al.’s (1997) model G2, given by
\[
\rho_{G2}(x, y, z) = \rho_0 \exp\left(-\frac{1}{2} r_z^2\right), \tag{6}
\]
where
\[
r_z = \left(\left(x/x_0\right)^2 + \left(y/y_0\right)^2 + (z/z_0)^2\right)^{1/4}. \tag{7}
\]
Following Stanek et al., we take \(x_0 = 1239 \text{ pc}\) with axis ratios \(x_0/y_0/z_0 = 2.8:1.4:1\) and an inclination angle \(\alpha = 24.9\). The last model is Stanek et al.’s (1997) model E2. The density distribution is given in the form
\[
\rho_{E2}(x, y, z) = \rho_0 \exp\left(-r\right), \tag{8}
\]
where
\[
r = \left(\left(x/x_0\right)^2 + \left(y/y_0\right)^2 + (z/z_0)^2\right)^{1/2}. \tag{9}
\]
Here we take \(x_0 = 897 \text{ pc}\) with axis ratios \(x_0/y_0/z_0 = 3.6:1.5:1\) and an inclination angle of the bulge major axis with respect to the line of sight \(\alpha = 23.8\). For models HG03, G2, and E2, we follow the bulge mass normalizations of Calchi Novati et al. (2008) and Han & Gould (2003). We set the distance to the Galactic center as 8.0 kpc throughout our analysis.

2.2. Disk Model

For the 2MASS bulge models, we employ two disk models (“disk 1” and “disk 2”) derived from 2MASS star counts (López-Corredoira et al. 2004, 2005). For bulge models HG03, G2, and E2, we adopt the disk model of Zheng et al. (2001), in which the density profile is given by a sech\(^2\) function for the thin component and an exponential for the thick component. We normalize it with the disk mass density of the solar neighborhood, \(\rho_{\odot} = 0.05 M_\odot \text{ pc}^{-3}\) (see Han & Gould 2003). In addition, we investigate an SDSS disk model with respect to all the bulge models considered in the present paper. Jurić et al. (2008) estimated the three-dimensional number density distribution of the Galactic disk and halo using the photometric parallax method applied to the SDSS data. We use their disk model consisting of thin and thick exponential disks with a local thick-to-thin disk normalization \(\rho_{\text{thick}}(R_\odot)/\rho_{\text{thin}}(R_\odot) = 12\%\). Again, the local number density is normalized to \(\rho(R_\odot) = 0.05 M_\odot \text{ pc}^{-3}\).

3. RESULTS

In Figures 1 and 2, we show maps of the optical depth difference normalized by the observational error \(\sigma_i\) for each \((l, b)\) field, which is given by
\[
\epsilon \equiv \frac{(\tau_o - \tau_m)}{\sigma_i}, \text{ where } \tau_o \text{ and } \tau_m \text{ are the microlensing optical depths in a given field from observation and model, respectively. We compare the microlensing optical depth observed from MACHO (Fig. 1) and OGLE-II (Fig. 2) with those calculated from the models field by field. In the maps, fields with negative and positive \(\epsilon\) are shown in blue and red, respectively. Those with \(\tau_o = 0.0\) are shown in black. The dotted curves in each panel mark the model’s microlensing optical depth contours in units of 10\(^{-6}\). Each panel in Figures 1 and 2 is from a different mass model, noted at lower left. Table 1 summarizes how to pair a bulge and a disk model. For instance, 2MT1 and 2MB1 represent combinations of the 2MASS triaxial bulge model and 2MASS disk 1 model and the 2MASS boxy bulge model and 2MASS disk 1 model, respectively. In the case of 2MT2 and 2MB2, the 2MASS disk 1 model is replaced by the 2MASS disk 2 for the given bulge model. When the Zheng et al. (2001) disk model is substituted, just the name of the bulge model is used (HG03, G2, and E2). In all cases “SDSS” is appended when that disk model is substituted.

To quantify the differences in the microlensing optical depth, we calculate \(\chi^2_{fb}\), defined as
\[
\chi^2_{fb} \equiv \sum_{i=1}^{N} \frac{(\tau_{o,i} - \tau_{m,i})^2}{\sigma_{o,i}^2}, \tag{10}
\]
where \(\tau_{o,i}, \tau_{m,i}\) and \(\sigma_{o,i}\) are the microlensing optical depths from observation and model and the observational error in each field, respectively. Here the summations are repeated over 14 OGLE-II fields and 19 MACHO fields, excluding fields with \(\tau_o = 0.0\). We summarize the results in Table 2. As can be seen, the 2MASS, HG03, and G2 models agree well with the microlensing optical depth distribution for MACHO and OGLE-II when the 2MASS...
and Zheng et al. (2001) disk models are used. Combinations that include the SDSS disk model produce relatively higher $\chi^2_{LM}$ values. We note that the microlensing optical depths from MACHO have much higher $\chi^2_{LM}$ values than those from OGLE-II, since the $\tau$-values in four of the MACHO fields (176, 113, 109, and 105) are $3\sigma$ below the values expected from all models in those fields. Therefore, comparison between the OGLE-II and MACHO values is meaningless. We repeated the calculation of $\chi^2$ without these four fields and show the results in parentheses for comparison in Table 2. The conclusion remains the same. The reason that four of the MACHO fields deviate by more than $3\sigma$ could be that the models are too smooth to explain the details of Galactic structures while there are components that have more of an optical than a dynamical effect, or that observational contamination such as blending may play a role. For instance, OGLE-II has investigated the effect of blending even in bright events and pointed out that many bright microlensing events include heavily blended events (e.g., Udalski et al. 1994; Alcock et al. 1997b; Smith et al. 2007).

In Figure 3, we show the microlensing optical depths averaged over Galactic longitude as a function of latitude $b$. In the left panel, the averages measured by OGLE-II (circles), MACHO (squares), and EROS-2 (triangles) are shown with their error bars. The best fits are superposed on the observed data, with different line styles representing different experiments: solid, short-dashed, and long-dashed lines are the best-fit curves for OGLE-II, MACHO, and EROS-2, respectively. The analytical expressions for these fits are $\tau_{\text{OGLE-II}} = [(4.48 \pm 2.37) + (0.78 \pm 0.84)b] \times 10^{-6}$ (Sumi et al. 2006), $\tau_{\text{MACHO}} = [5.2 + (1.06 \pm 0.71)b] \times 10^{-6}$ (Popowski et al. 2005), and $\tau_{\text{EROS-2}} = (1.62 \pm 0.23) \exp \{-0.43 \pm 0.16[(b - 3\circ)]\} \times 10^{-6}$ (Hamadache et al. 2006). In the right panel, the microlensing optical depths toward the Galactic bulge expected from the models described in $\S$ 2 are shown as a function of Galactic latitude with thin curves. The dashed curve represents the calculated microlensing optical depth from the 2MASS triaxial bulge model and the 2MASS disk 2 model (2MT2). The dotted curve is the calculated microlensing optical depth from the 2MASS boxy bulge model and the 2MASS disk 2 model (2MB2). Long-dashed, dot–long-dashed, and dot–short-dashed curves represent models HG03, G2, and E2, respectively. For comparison, we also plot the best fits obtained by the different microlensing experiments from the left panel with thick curves. The models in general seem compatible with all the microlensing observations within the observational uncertainties. It is interesting to note that deviations among the model fits become larger with decreasing Galactic latitude. To make a more quantitative evaluation, we calculated $\chi^2_b$ for each $b$ using equation (10) and list the results in Table 3. As seen previously in Table 2, 2MASS, HG03, and G2 result in smaller $\chi^2_b$ for all the microlensing experiments. In Table 3 we show the values of $\chi^2_b$ for all the cases, including those not shown in the right panel of Figure 3. One may again see that when the SDSS disk model is used, the fits become poorer.

### Table 3

| Model | OGLE-II | MACHO | EROS-2 |
|-------|---------|-------|--------|
| 2MT1  | 2.27    | 1.66  | 10.71  |
| 2MT2  | 2.26    | 1.76  | 10.57  |
| 2MT+SDSS | 3.48 | 6.94  | 22.03  |
| 2MB1  | 2.76    | 4.41  | 18.41  |
| 2MB2  | 2.73    | 4.35  | 18.00  |
| 2MB+SDSS | 4.81 | 13.41 | 35.59  |
| HG03  | 2.41    | 1.76  | 10.83  |
| HG03+SDSS | 3.13 | 5.20  | 17.46  |
| G2    | 3.30    | 6.25  | 21.11  |
| G2+SDSS | 4.54 | 12.05 | 31.55  |
| E2    | 4.94    | 13.42 | 28.00  |
| E2+SDSS | 6.60 | 21.26 | 39.22  |
4. SUMMARY AND DISCUSSION

By comparing a microlensing optical depth map constructed from a mass model with the observed microlensing optical depth, one may place tight constraints on the Galactic model. We have estimated the microlensing optical depths toward the Galactic bulge using Galactic bulge and disk models constructed from survey observations and compared them with the sample of microlensing events observed toward the bulge with RCG sources reported by the MACHO, OGLE-II, and EROS-2 collaborations. The analysis shows that the model estimates are in general compatible with the microlensing observations. According to the calculated $\chi^2$ values, we find that 2MASS, HG03, and G2 models reproduce the microlensing optical depth distribution from observations well. We also find that for those well-fitting models, the contribution to the microlensing optical depth from the disk components is not crucial. For example, for the 2MASS case the two separate disk models do not make any difference in the $\chi^2$. It is, however, interesting to note that the SDSS disk models yield somewhat different results. That is, models including the SDSS disk model produce relatively higher $\chi^2$ values than do the others.

It should be pointed out that the current observational data on both the microlensing optical depth in two-dimensional fields and the optical depth averaged over $l$ are yet statistically insufficient to conclusively rule out any specific model we have considered, since the number of observed microlensing events from monitoring RCGs in recent microlensing surveys is still small. On the other hand, the difference of the average optical depth among models increases with increasing proximity to the Galactic center. Therefore, we suggest that microlensing observations toward regions closer to the Galactic center, if possible, may be more effective in constraining the Galactic model than extending microlensing searches to detect more microlensing events.

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REFERENCES

Afonso, C., et al. 2003, A&A, 404, 145
Alcock, C., et al. 1993, Nature, 365, 621
———. 1997a, ApJ, 479, 119 (erratum 500, 522 [1998])
———. 1997b, ApJ, 486, 697
Ansari, R., et al. 1999, A&A, 344, L49
Aubourg, E., et al. 1993, Nature, 365, 623
Binney, J., Bissantz, N., & Gerhard, O. 2000, ApJ, 537, L99
Blum, R. D. 1995, ApJ, 444, L89
Calchi Novati, S., De Luca, F., Jetzer, P., Mancini, L., & Scarpetta, G. 2008, A&A, 480, 723
Calchi Novati, S., et al. 2005, A&A, 434, L49
Dehnen, W., & Binney, J. 1998, MNRAS, 294, 429
de Jong, J. T. A., et al. 2004, A&A, 417, 461
Dwek, E., & Blum, R. D. 1995, ApJ, 445, 716
Hamadache, C., et al. 2006, A&A, 454, 185
Han, C., & Gould, A. 1995, ApJ, 449, 521
———. 2003, ApJ, 592, 172
Holtzman, J. A., Watson, A. M., Baum, W. A., Grillmair, C. J., Groth, E. J., Light, R. M., Lynds, R., & O’Neil, E. J., Jr. 1998, AJ, 115, 1946
Jurić, M., et al. 2008, ApJ, 673, 864
Kerins, E., Darnley, M. J., Duke, J. P., Gould, A., Han, C., Jeon, Y.-B., Newsam, A., & Park, B.-G. 2006, MNRAS, 365, 1099
Kiraga, M., & Paczynski, B. 1994, ApJ, 430, L101
López-Corredoira, M., Cabrales-Lavers, A., & Gerhard, O. E. 2005, A&A, 439, 107
López-Corredoira, M., Cabrales-Lavers, A., Gerhard, O. E., & Garzón, F. 2004, A&A, 421, 953
Paczynski, B. 1986, ApJ, 304, 1