Galactic Bulge Microlensing Events with Clump Giants as Sources

P. Popowski\textsuperscript{1}, C. Alcock, R.A. Allsman, D.R. Alves, T.S. Axelrod, A.C. Becker, D.P. Bennett, K.H. Cook, A.J. Drake, K.C. Freeman, M. Geha, K. Griest, M.J. Lehner, S.L. Marshall, D. Minniti, C.A. Nelson, B.A. Peterson, M.R. Pratt, P.J. Quinn, C.W. Stubbs, W. Sutherland, A.B. Tomaney, T. Vandehei, D. Welch
(The MACHO Collaboration)

\textsuperscript{1} Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory; e-mail: popowski@igpp.ucllnl.org.

Abstract. We present preliminary results of the analysis of 5 years of MACHO data on the Galactic bulge microlensing events with clump giants as sources. In particular, we discuss: 1) the selection of ‘giant’ events, 2) distribution of impact parameters, 3) distribution of event durations, 4) the concentration of long duration events in MACHO field 104 centered on \((l, b) = (3^\circ.1, -3^\circ.0)\). We report the preliminary average optical depth of \(\tau = (2.0 \pm 0.4) \times 10^{-6}\) (internal) at \((l, b) = (3^\circ.9, -3^\circ.8)\). We discuss future work and prospects for building a coherent model of the Galaxy.

1. Introduction

The following short description of the most important observational studies of the Galactic microlensing indicates that there is still an urgent need for a comprehensive analysis of the microlensing events toward the Galactic bulge. Udalski et al. (1994) found 9 events in the first two year of the Optical Gravitational Lensing Experiment (OGLE) data. They set the lower limit on the optical depth to the Galactic bulge at \(\tau = (3.3 \pm 1.2) \times 10^{-6}\). The uncertainties of this study are related to the detection efficiency analysis as well as small number statistics. Alcock et al. (1997) described a set of 45 events. The potential of this sample was not fully explored due to the use of sampling efficiencies only. The unbiased analysis was done only for 13 clump giants, which resulted in large uncertainties of the optical depth \((\tau = 3.9^{+1.8}_{-1.2} \times 10^{-6})\). Udalski et al. (2000) presented just a catalog of over 200 microlensing events from the last 3 seasons of the OGLE-II bulge observation. Unfortunately, no efficiency analysis has been done for those events so the information that can be extracted from this sample is very limited. Alcock et al. (2000a) performed Difference Image Analysis (DIA) of three seasons of bulge data in 8 frequently sampled MACHO fields and found 99 events. They determined \(\tau_{\text{bulge}} = (3.2 \pm 0.5) \times 10^{-6}\). This was a major development in bulge microlensing. The DIA technique resulted in a substantial improvement in photometry, so this analysis was less vulnerable to uncertainties in the parameter determination. However, the results were obtained only for 8 out of
94 MACHO bulge fields. Additionally, the detection efficiency estimate suffered from the fact that HST luminosity function was available for only 1 field. In summary, it is important to check the conclusions of Alcock et al. (2000a) with an independent set of events.

Blending is a major problem in any analysis of the microlensing data involving point spread function photometry. The bulge fields are crowded, so that the objects observed at a certain atmospheric seeing are blends of several stars. At the same time, typically only one star is lensed. In this general case, a determination of the events’ parameters and the analysis of the detection efficiency of microlensing events is very involved and vulnerable to a number of possible systematic errors. If the sources are bright one can avoid these problems. First, a determination of parameters of the actual microlensing events becomes straightforward. Second, it is sufficient to estimate detection efficiency based on the sampling of the light curve alone. This eliminates the need of obtaining deep luminosity functions across the bulge fields. Red clump giants are among the brightest and most numerous stars in the bulge. Therefore, this analysis of the MACHO collaboration concentrates on the events where the lensed stars are clump giants.

2. Data

The MACHO Project observations were performed with 1.27-meter telescope at Mount Stromlo Observatory, Australia, since July 1992. Details of the telescope system are given by Hart et al. (1996) and of the camera system by Stubbs et al. (1993) and Marshall et al. (1994). Details of the MACHO imaging, data reduction and photometric calibration are described in Alcock et al. (1999). In total, we collected seven season (1993-1999) of data in the 94 Galactic bulge fields. The bulge data that are currently available for the analysis consist of five seasons (1993-1997) in 77 fields (Figure 1).

3. The Selection of Giant Events

The events with clump giants as sources have been selected from the sample of all events. The procedure that leads to a selection of microlensing events of general type consists of several steps. First, all the recognized objects in all fields are tested for any form of variability. Next, a microlensing light curve is fitted to all stars showing any variation and the objects that meet very loose selection criteria (cuts) enter the next phase. Here, this selection returns almost 43000 candidates. These candidates undergo more scrutiny and are subject to more stringent cuts, most of which test for a signal-to-noise of the different parts of the light curve. Here, this last procedure narrows a list of candidate events to ∼ 280. The question, which of those sources are clump giants, is investigated through the analysis of the global properties of the color-magnitude diagram (CMD) in the Galactic bulge. The clump giant selection is based on four assumptions:

1) clump in the Baade’s Window is representative,
2) the OGLE-II (e.g., Paczyński 1999) and MACHO photometry are consistent,
3) the intrinsic colors follow the relation: $(V - R)_0 = 0.5(V - I)_0$, 
4) the red clump giants are among the brightest and most numerous stars in the bulge.
4) the extinction toward the bulge follows the relation: $A_V = 5.0 E(V - R)$.

Using the accurately measured extinction towards Baade’s Window (Stanek 1996 with zero point corrected according to Gould et al. 1998 and Alcock et al. 1998) allows one to locate bulge clump giants on the intrinsic color – absolute magnitude diagram. Such diagram can be then used to predict the positions of clump giants on the color – apparent magnitude diagram for fields with different extinction. One obtains the following average values and color ranges: $\langle I_0^{BW} \rangle = 14.35, \langle (V - I)_0^{BW} \rangle = 1.1, (V - I)_0^{BW} \in (0.9, 1.3)$ [which corresponds to $(V - R)_0^{BW} \in (0.45, 0.65)$]. Combination of average $I_0$ and $(V - I)_0$ range allows one to determine a central $V_0$ of the clump for a given color. For example, for $(V - I)_0 = 0.9$ one obtains $V_0 = 15.25$, and for $(V - I)_0$ one gets $V_0 = 15.65$. We assume that the actual clump giants scatter in $V$-mag around this central value, but by not more than 0.6 mag toward both fainter and brighter $V_0$. This defines the parallelogram-shaped box in the upper left corner of Figure 2.

With the assumption that the clump populations in the whole bulge have the same properties as the ones in the Baade’s Window, the parallelogram described above can be shifted by the reddening vector to mark the expected locations of clump giants in different fields. The solid lines are the boundaries of
the region where one could find the clump giants of fields with different extinctions. There are a few more V-mag and \((V-R)\) - color cuts that determine the final shape of the clump region. The clump regions from Figure 2 contains 52 unique clump events. There are 6 identified binary lenses among these events.

Note that several assumptions that went into creating this region should be carefully reviewed. In particular, the assumption that \((V-R)_0 = 0.5(V-I)_0\) is only approximately true, the clump region is rather sensitive to color, the assumed spread in \(V\) magnitudes can be either bigger or smaller or asymmetric around the central value, clump giants in different fields may have different characteristics. Taking into account that all of the above might have gone wrong, the obvious success of the outlined procedure (see Figure 2) is very encouraging.

4. Distribution of Impact Parameters

In Figure 3, we plot the cumulative distribution of the impact parameter \(u_{\text{min}}\) (solid line). The impact parameter was obtained from the maximum amplification, \(A_{\text{max}}\), according to the formula:

\[
 u_{\text{min}} = \sqrt{-2 + \frac{2A_{\text{max}}}{A_{\text{max}}^2 - 1}}. \tag{1}
\]
Figure 3. Cumulative distribution of impact parameters for all the candidates including 6 binaries.

No efficiency correction was applied. Dashed line is the expected theoretical distribution if the minimum recorded $A_{\text{max}}$ equals to 1.5. The agreement is beautiful.

5. Distribution of Event Durations

We note that the first accurate description of the bulge event durations was given by Dr. Seuss (1960): “We see them come. We see them go. Some are fast. And some are slow.” Left panel of Figure 4 shows the number of events as a function of event duration uncorrected for detection efficiencies. The right panel presents a contribution of events with particular duration to the optical depth. About 40% of the optical depth is in the events longer than 50 days ($t_E > 50$). This is at odds with standard models of the Galactic structure and kinematics.

6. Concentration of Long Events in Field 104

Ten clump giant events out of 52 are in the MACHO field 104. There is a high concentration of long-duration events in this field (5 out of 10 events longer than 50 days are in 104, including the longest 2). We investigate how statistically significant is this concentration. Ideally, one would like to account for the change in the detection of efficiency of events with different durations in different fields. However, the reliable efficiencies for individual fields are not available at this point. Nevertheless, it should be possible to place a lower limit on significance
of this difference. The efficiency for detecting long events should be similar in most fields, because this does not depend strongly on the sampling pattern. The detection of short events will be lower in a sparsely sampled fields. Therefore, the number of short events in some of the fields used for comparison may be relatively too small with respect to a frequently-sampled field 104, but this is only going to lower the significance of the $t_E$ distribution difference. In conclusion, the analysis of event durations uncorrected for efficiencies should provide a lower limit on the difference between field 104 and all the remaining clump giant fields. We use the Wilcoxon’s number-of-element-inversions statistic to test this hypothesis. First, we separate events into two samples: events in field 104 and all the remaining ones. Second, we order the event in the combined sample from the shortest to the longest. Then we count how many times one would have to exchange the events from field 104 with the others to have all the 104 field events at the beginning of the list. If $N_1$ and $N_2$ designate numbers of elements in the first and second sample, respectively, then for $N_1 \geq 4$, $N_2 \geq 4$, and $(N_1 + N_2) \geq 20$, the Wilcoxon’s statistic is approximately Gaussian distributed with an average of $N_1N_2/2$ and a dispersion $\sigma$ of $\sqrt{N_1N_2(N_1 + N_2 + 1)/12}$. The Wilcoxon’s statistic is equal to 320, whereas the expected number is 210 with an error of about 43. Therefore the events in 104 differ (are longer) by $2.55 \sigma$ from the other fields. That is, the probability that events in 104 and other fields originate from the same parent population is of order of 0.011.

7. The Optical Depth

We use the following estimator of the optical depth

$$\tau = \frac{\pi}{2NT} \sum_{\text{all events}} \frac{t_E}{\epsilon(t_E)},$$

(2)

where $N$ is the number of observed stars (here about 2.1 million clump giants), $T$ is the total exposure (here about 2000 days) and $\epsilon(t_E)$ is an efficiency for detecting an event with a given $t_E$. The sampling efficiencies were obtained with the pipeline that has been previously applied to the LMC data (for a description see Alcock et al. 2000b). In brief, artificial light curves with different parameters have been added to 1% of all clump giants in our 77 fields and the analysis used to select real events was applied to this set. For a given duration of the artificial event, the efficiency was computed as a number of recovered events divided by a number of input events. The efficiencies used in this analysis are global efficiencies averaged over clump giants in all 77 fields. The optical depth is reported at the central position that is an average of positions of 1% of the analyzed clump giants.

We obtain:

$$\tau = (2.0 \pm 0.4) \times 10^{-6} \text{ at } (l, b) = (3^\circ.9, -3^\circ.8).$$

(3)

with the error computed according to the formula given by Han & Gould (1995). We caution that this result is only preliminary. The details of the analysis as well as full discussion of the statistical and possible systematic errors (which may be a fair fraction of the statistical error) will be given in Alcock et al. (2000c).
8. Future work and conclusions

Microlensing gives two major types of constraints: the optical depth spatial distribution and the distribution of event durations. The first type of information measures the mass density along different lines of sight, whereas the second one is related to the mass function of the lenses and the kinematics of involved populations. These suggest two major routes of attack. The structure of the Galaxy (e.g., disk scale length and height, bar shape and inclination) can be constrained by analyzing the average and gradient of the optical depth. This is most easily achieved with maximum likelihood technique (e.g., Gyuk 1999), which allows one to extract information from fields with and without any events. Additionally, it is possible to constrain the location of clump sources comparing reddening-free indices of lensed and unlensed stars (Stanek 1995). The difference can be up to 0.2 mag depending on the bulge/bar model, and our sample allows one to find the difference with the accuracy of 0.07 mag. The microlensing data in the bulge should be combined with all the other types of information e.g., kinematic and density distributions of RR Lyrae stars, rotation curve, star counts, motions of the Milky Way’s satellites etc.

Because the distribution of event durations depends on both the mass function of the lenses as well as kinematics of the observer, sources and deflectors, an unambiguous solution of the entire system requires hundreds of events. However, Han & Gould (1996) showed that for a sample of ~50 events, the errors in mass function reconstruction are small if the kinematics are assumed to be known. The kinematics are not exactly under control but it is possible to construct a plausible model consistent with observational constraints. Determination of the mass function of the microlenses toward the Galactic bulge would be a very exciting development. As a matter of fact, microlensing is currently the only method that could enable one to find a mass function of objects as distant as several kpc.

The conclusions from the analysis described above are the following. It is possible to select an unbiased (when \( u_{\text{min}} \) is concerned) sample of clump events in a universal way based only on \( V \) and \( (V - R) \) (or more generally, an event’s
position on the CMD). Ten out of 52 clump events have durations > 50 days, which implies that ∼ 40% of the optical depth is in the long duration events. This is surprising, because long events are the most likely a result of the disk-disk lensing (Kiraga & Paczyński 1994). However, it is widely believed that clump giants trace the bar rather than the inner disk (Stanek et al. 1994). Events in the area of field 104 centered at \((l, b) = (3\,^\circ\,1, -3\,^\circ\,0)\) have longer durations than the events in other fields. The explanation can be as exotic as a cluster of remnants along the line of sight or some conspiracy of the bar orbits. The optical depth averaged over the clump giants in 77 fields is \(\tau = (2.0 \pm 0.4) \times 10^{-6}\) at \((3\,^\circ\,9, -3\,^\circ\,8)\). Allowing for the optical depth gradient of ∼ 0.5 \times 10^{-6}/\text{deg}, this optical depth is lower but consistent both with the Alcock et al. (1997) clump result of \(3.9^{+1.8}_{-1.2} \times 10^{-6}\) at \((l, b) = (2\,^\circ\,55, -3\,^\circ\,64)\) as well as the DIA result of \((3.2 \pm 0.5) \times 10^{-6}\) at \((l, b) = (2\,^\circ\,68, -3\,^\circ\,35)\) (Alcock et al. 2000a). The new optical depth is still rather high but in the range accessible to some models of the Galactic structure.

Acknowledgments. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

References

Alcock, C., et al. 1997, ApJ, 479, 119
Alcock, C., et al. 1998, ApJ, 494, 396
Alcock, C., et al. 1999, PASP, 111, 1539
Alcock, C., et al. 2000a, ApJ, 541, 000 (astro-ph/0002510)
Alcock, C., et al. 2000b, submitted to ApJ (astro-ph/0003392)
Alcock, C., et al. 2000c, in preparation
Gould, A., Popowski, P., & Terndrup, D.T. 1998, ApJ, 492, 778
Gyuk, G. 1999, ApJ, 510, 205
Han, C, & Gould, A. 1995, ApJ, 449, 521
Han, C, & Gould, A. 1996, ApJ, 467, 540
Hart, J., et al. 1996, PASP, 108, 220
Kiraga, M., & Paczyński, B. 1994, ApJ, 430, L101
Marshall, S.L., et al. 1994, in IAU Symp. 161, Astronomy From Wide Field Imaging, ed. H.T. MacGillivray, et al., (Dordrecht: Kluwer)
Paczyński, B., et al. 1999, Acta Astron., 49, 319
Seuss, Dr. 1960, in “One fish, two fish, red fish, blue fish”, (New York: Random House)
Stanek, K.Z., et al. 1994, ApJ, 429, L73
Stanek, K.Z. 1995, ApJ, 441, L29
Stanek, K.Z. 1996, ApJ, 460, L37
Stubbs, C.W., et al. 1993, in Proceedings of the SPIE, Charge Coupled Devices and Solid State Optical Sensors III, ed. M. Blouke, 1900.
Udalski, A., et al. 1994, Acta Astron., 44, 165
Udalski, A., et al. 2000, submitted to Acta Astron. (astro-ph/0002418)