Low Microlensing Optical Depth Toward the Galactic Bar

Piotr Popowski
MPA, Karl-Schwarzschild-Str. 1, Postfach 1317, 85741 Garching bei München, Germany
E-mail: popowski@mpa-garching.mpg.de

ABSTRACT

I make a new evaluation of the microlensing optical depth toward the Galactic bar from Difference Image Analysis (DIA) of the MACHO Collaboration. First, I present supplementary evidence that MACHO field 104 located at $(l, b) = (3.^\circ 11, -3.^\circ 01)$ is anomalous in terms of the event duration distribution. I argue that both the event durations and the very high optical depth of field 104 are not representative and, therefore, exclude this field as an outlier. In addition, I eliminate field 159 at $(l, b) = (6.^\circ 35, -4.^\circ 40)$ based mainly on its separate location, but also on unexplained statistical properties of the event durations. The remaining six DIA fields form a very homogeneous and spatially compact set that is very suitable for averaging. The weighting of the optical depth values for these six DIA fields results in a total optical depth $\tau_{tot} = 2.01^{+0.34}_{-0.32} \times 10^{-6}$ at $(l, b) = (2.^\circ 22, -3.^\circ 18)$. If a fraction of all sources, $f_{\rm disk}$, assumed to be in the disk, does not contribute to microlensing, then the optical depth toward the sources in the bar is $\tau_{\rm bar} = 2.23^{+0.38}_{-0.35} \times 10^{-6} \, \frac{0.9}{1 - f_{\rm disk}}$. Both $\tau_{\rm tot}$ and $\tau_{\rm bar}$ are substantially lower than the original estimates of Alcock et al. Most of the change in the DIA-based optical depths comes from a more appropriate statistical treatment of the results in individual fields and not from the removal of fields 104 and 159. When taken together with $\tau_{\rm bar} = 1.4 \pm 0.3 \times 10^{-6}$ at $(l, b) = (3.^\circ 9, -3.^\circ 8)$ as derived from clump giants, this new result suggests that the conclusions from microlensing experiments are in reasonable agreement with expectations from infrared-based Galactic models.

Subject Headings: Galaxy: center — Galaxy: structure — gravitational lensing

1. Introduction

The structure and composition of our Galaxy is one of the outstanding problems in contemporary astrophysics. Microlensing is a powerful tool to learn about massive objects in the Galaxy. The amount of matter between the source and observer is customarily described in terms of the microlensing optical depth, which is defined as the probability that a source flux will be gravitationally magnified by more than a factor of 1.34. The optical depth, τ, is typically estimated using the following formula:

$$\tau = \frac{\pi}{2NT} \sum_{\text{all events}} \frac{t_E}{\epsilon(t_E)}, \tag{1}$$

where N is the number of observed stars (potential sources), T is the total exposure (roughly equal to the temporal span of observations), and $\epsilon(t_E)$ is the efficiency for detecting an event with a given Einstein radius crossing time t_E.

Early microlensing analyses (Udalski et al. 1994; Alcock et al. 1997) of the lines of sight toward the Galactic center produced two unexpected results: (1) a very high optical depth of $3 - 4 \times 10^{-6}$, exceeding expectations from Galactic models by a factor of a few and (2) an overabundance of long-lasting events. These two issues indicated that either we still lacked a basic understanding of the Galactic structure and/or that the microlensing results needed revision. The second conclusion was certainly true, since these old analyses suffered either from small number statistics or from oversimplified analyses of the detection efficiency of microlensing events.

To describe the current situation, I will use the recent results from the MACHO Collaboration. The main goal of the MACHO Project was to discover and characterize dark matter and other faint objects through detection and analysis of microlensing events seen toward the Magellanic Clouds and the central region of the Milky Way. The MACHO observations were performed with the 1.27-meter telescope at Mount Stromlo Observatory, Australia. A detailed description of the MACHO telescope and photometry is given in Alcock et al. (2001). In total, MACHO collected seven seasons (1993-1999) of two-filter data in 94 Galactic bulge fields, which are of interest here.

Blending is a major concern in any analysis of the microlensing data. The bulge fields are crowded, so that the objects observed at a certain atmospheric seeing are blends of several stars, of which only one is typically lensed. This situation complicates the determination of an event's parameters and the estimate of the detection efficiency of microlensing events. There are two major approaches to minimize these problems: (1) One may work with bright stars like clump giants that are subject to little blending and can be utilized without the knowledge of the stellar luminosity function down to faint magnitudes. Such an analysis was performed by Popowski et al. (2000, 2001), who calculated the optical depth based on data from five seasons (1993-1997) in 77 fields. (2) One may improve the photometry and minimize blending by analyzing only the varying part of flux. This is accomplished by subtracting images of the same fields taken on different nights. This strategy was realized by Alcock et al. (2000, hereafter AD2000), who analyzed three seasons

(1995-1997) of data in 8 MACHO fields.

AD2000 determined a new value of the optical depth based on the Difference Image Analysis (DIA) technique that included a detailed computation of the detection efficiencies. They estimated the optical depth toward the Galactic bar, $\tau_{\rm bar} = 3.23^{+0.52}_{-0.50} \times 10^{-6}$ at $(l, b) = (2^\circ\!.68, -3^\circ\!.35)$. This value was declared to be too high to be reconciled with the constraints coming from the Galactic rotation curve and the local density of stars (Binney, Bissants, & Gerhard 2000; Bissantz & Gerhard 2002). To shed more light on this problem, I will reconsider DIA data using the characteristics of 99 DIA events from AD2000 reported in their Tables 4, 5, and 6.

The purpose of this paper is to critically discuss current observational constraints on the microlensing optical depth toward the Galactic bar. I suggest slight modifications of the analyzed samples and appropriate methods of data averaging. First, in §2, I point to some unusual properties of one of the MACHO fields. I show that, despite completely different analysis methods and different event selection criteria, MACHO field 104 is a clear outlier in both clump giants analysis and DIA (Popowski et al. 2001; AD2000). The exclusion of this field does not change DIA results significantly, but has far-reaching consequences for the optical depth based on clump giants. I argue in §3 that excluding field 159 from DIA will result in a more spatially compact group of fields better suited for averaging. In §4, I consider statistical properties of errors in optical depth of individual fields. I show in §5 that the weighted average of all individual DIA fields (with no exclusions!) produces a 20% lower optical depth than the AD2000 value. When fields 104 and 159 are excluded, the optical depth from DIA remains roughly the same but is given at a location closer to the Galactic center. I also discuss the transition from the total observed optical depth, $\tau_{\rm tot}$, to the one toward sources residing in the Galactic bar, $\tau_{\rm bar}$. I conclude in §6 comparing the adjusted optical depths from clump giants and DIA with the recent results from Evans & Belokurov (2002) and Bissantz & Gerhard (2002).

2. Field 104

Popowski et al. (2000, 2001) argued that MACHO field 104 located at $(l, b) = (3^\circ\!.11, -3^\circ\!.00)$ is very unusual from the microlensing perspective when analyzed using events with clump giants as sources. They noticed that one fifth of the ~ 50 MACHO clump events are in field 104, and that there is a high concentration of long-duration events in this field (5 out of the 10 events longer than 50 days are in 104, including the longest 2).

I will now review part of Popowski's et al. (2000, 2001) work to present one of the possible methods for the analysis of duration distributions. One can compare the distribution of event durations in field 104 and all the other fields. Ideally, one would like to account for the change in the efficiency of event detection with different durations in different fields. However, using only uncorrected event durations one can still place a useful, lower limit on the significance of this difference. The efficiency for detecting long events should be similar in most fields, because it does not depend strongly on the sampling pattern. In contrast, the detection efficiency for short events will be lower in sparsely sampled fields. Therefore, the number of short events in some of the fields used for comparison (the ones that are sparsely sampled) may be relatively too small with respect to the frequently-sampled field 104. Proper accounting for this efficiency difference, however, would only increase 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 fields.

The Wilcoxon's number-of-element-inversions statistic is well suited to test whether events in 104 and other fields can originate from the same population. First, one separates the events into two samples: events in field 104 and all the remaining ones. Second, one orders the events in the combined sample from the shortest to the longest. Then, being only allowed to swap the adjacent events, one counts 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 $N_1 N_2/2$ and a dispersion σ of $\sqrt{N_1\, N_2\, (N_1 + N_2 + 1)/12}$. Popowski et al. (2000) found for the clump sample that the events in 104 differ (are longer) by 2.55σ from the other fields.

Here I argue that the analysis of the DIA events taken from AD2000, which are of general type, confirms the clump-based conclusions. I note, however, that a strict mathematical interpretation of this result requires some caution as the clump and DIA samples share 7 events, 4 of which are in field 104. The Wilcoxon's statistic for the DIA sample, split into field 104 and the rest, is equal to 904, whereas the expected number for subsamples drawn from the same parent population is 648 with an error of about 103. Therefore, the events in 104 differ (are longer) by 2.49σ from the other fields.

Figure 1 presents a comparison between event durations in field 104 and the rest of the DIA sample using 97 out of 99 events. The remaining 2 events are not included as they were classified by AD2000 as binaries. The upper panel shows the number of events as a function of event duration based on all 8 DIA fields. Field 104, represented by the black portion of the histogram, clearly dominates the long duration part of this distribution. The middle panel presents a comparison of the number distribution functions (normalized) in field 104 and the remaining seven fields. The distribution in field 104 is much flatter and more extended. The average durations, $< t_E >$, for both distributions are marked with vertical arrows. In field 104, $< t_E >= 48 \pm 10$, in the remaining fields $< t_E >= 24 \pm 2$. The lower panel is a plot of cumulative distributions of durations for field 104 and the remaining fields. Kolmogorov-Smirnov test indicates that the probability that both samples come from the same parent population is $P = 0.0335$.

There is no doubt that the significance of this effect depends on selection criteria of events. However, the fact that the effect is so significant in two weakly overlapping and differently processed samples, makes it more reliable. In addition, the unique character of field 104 is supported by its optical depth. The optical depth is 10 times higher than the average of the other fields as estimated from clump giants (more than 2σ effect) and 2 times higher based on DIA (low significance). Galactic models typically do not account for very localized structures, so they have no way to explain fields like 104. When included, structure like this will bias the results toward a different model.

The above analysis reinforces Popowski's et al. (2001) suggestion to treat field 104 as an outlier and exclude it from the determination of the optical depth. I conclude that in the case of clump giants, $\tau_{\rm bar} = 1.4 \pm 0.3 \times 10^{-6}$ is preferred over the value of $\tau_{\rm bar} = 2.0 \pm 0.4 \times 10^{-6}$ based on the entire sample in 77 fields.

When field 104 is removed the position at which the clump giant optical depth is evaluated does not change significantly. One may see this from the following considerations. Let $\vec{x}_{\rm new}$ indicate the new position, $\vec{x}_{\rm old}$ the old average position for all 77 clump fields, and $\overrightarrow{104}$ the position of field 104. Then we have

$$\vec{x}_{\rm new} = \frac{\vec{x}_{\rm old} - f\,\overrightarrow{104}}{1-f}, \tag{2}$$

where f is the weight of field 104. The exact value of f depends on the weighting scheme, but f is going to be small as one can realize looking at two representative choices for f: (1) $f = 1/N_{\rm fields} = \frac{1}{77} \approx 0.013$, as 77 fields were analyzed by Popowski et al. (2001) (2) $f = N_{*,104}/N_{*,\text{all fields}} \approx 0.028$, where $N_{*,\cdot}$ indicates the number of clump giants in the region described by the second subscript i.e., "104" or "all fields". In both cases, the position at which the new optical depth is determined does not change within the accuracy of the original value, $(l, b) = (3\overset{\circ}{.}9, -3\overset{\circ}{.}8)$.

3. Field 159

Figure 2 displays the spatial distribution of eight fields used by AD2000 (analog of their Figure 5). Field 159 centered at $(l, b) = (6\overset{\circ}{.}35, -4\overset{\circ}{.}40)$ is clearly separated from the others. When averaged together with the other fields it will substantially influence the effective position at which optical depth is determined. The filled circle indicates the average weighted position[1] of 6 fields, excluding fields 104 and 159. The average weighted position of 8 fields is marked with a cross for comparison. The open square indicates the average position for optical depth of $\tau_{\rm bar} = 1.4 \pm 0.3$ based on clump giants (Popowski et al. 2001). Based on its separate location, and somewhat unusual properties of the errors in the optical depth (see next section), I conservatively remove field 159 from the further analysis.

4. Statistical considerations

Table 1 provides additional support of my previous suggestion to remove fields 104 and 159 from the final determination. Columns 1–3 are taken directly from AD2000 and list a field, the number of events in each field, and the corresponding DIA-based optical depth, respectively. Han & Gould (1995) showed that in general the error in an optical depth can be split into two terms: one which is the simple Poisson noise in the number of events and another one that comes from the dispersion in the efficiency corrected duration distribution. Han & Gould (1995) used an example of constant efficiency to argue that this second term can be quite substantial. In reality, the shape of the intrinsic duration distribution and the shape of the detection efficiency curve are quite similar and conspire to produce a rather low dispersion when divided by each other. Therefore, one expects that the ratio between the total error in τ and the error based only on Poisson statistic will be larger than unity but not by much. When I examined errors in the optical depth reported in Table 3 of AD2000, I realized that several of them were of the order or even somewhat smaller than one would expect based on the Poisson distribution alone. Indeed, it turned out that some of the errors needed small adjustments, and the *correct* errors (Andrew Drake; private communication) are reported in columns 4 and 5 of Table 1. Column 6 gives a Gaussian approximation to 1-sigma Poisson errors in the optical depth. Finally, columns 7 and 8 list the ratios of the true error obtained with bootstrapping technique by AD2000 to that expected from the Poisson distribution alone.

I concentrate on the last two columns of Table 1. First, let me notice that now all

[1]The most appropriate way to compute an average position is discussed in §5.

positive and negative errors have larger absolute values than their Poisson counterparts, which is expected based on Han & Gould (1995) argument. Second, the examination of individual values for different fields indicates that both fields 104 and 159 are different from the rest. This different character is particularly well established in the case of fields 104 with 16 events, and somewhat less obvious for field 159 with only 4 events, where the ratios in columns 7 and 8 may be slightly affected by my Gaussian approximation to Poisson confidence intervals. The large values of the error ratios in field 104 suggest that dispersion in $t_E/\epsilon(t_E)$ contributes significantly to the errors in optical depth in this field, implying an unusual duration distribution. In summary, the decision to exclude fields 104 and 159 gains additional justification.

5. Optical depth

The microlensing optical depth can be used to distinguish between different Galactic models. Most models share the same major traits, and so the optical depth must be both accurate and precise to render a definitive answer. Precision depends mostly on the number of detected events and, therefore, is predetermined for a sample of a given size. Accuracy of the result depends mostly on two factors: systematic errors and methods of analysis.

Here I would like to describe one bias that is very hard to eliminate when one obtains a single value of the optical depth based on a "gradient-large" region. "Gradient-large" means that the gradient of the optical depth changes significantly within this region. Suppose that one observes a number of small fields in this region and determines their optical depths $\tau_i \pm \sigma(\tau_i)$. Then, the most natural way to obtain a model-independent, single value of the optical depth representative for the region will be a weighted average of the results in individual fields (see also the discussion below). However, this method implicitly assumes that the optical depth changes in a linear fashion. This is inconsistent with the fact that the gradient in the optical depth changes across the region. The MACHO fields in the Galactic bar that are spread in an area of a few by a few degrees constitute a gradient-large region as can be seen e.g., from microlensing maps by Evans & Belokurov (2002). It is worth noting, however, that in this region some models are much more linear than the others (e.g., Freudenreich's 1998 versus Binney, Gerhard, & Spergel's 1997). Nevertheless, in most cases this type of simple averaging will produce a bias. Therefore, the best solution is to directly compare the models with values in individual fields using the maximum likelihood method. Still, averages may be used for illustrative purposes and as approximate solutions in the case when field-by-field detection efficiencies are not accessible.

In addition, even in the absence of the above non-linearity bias, the average optical depth based on global efficiencies in all fields taken together is also biased. On average there are more events per source star in fields with higher optical depth. On the other hand, an average position at which the detection efficiency is evaluated depends only on the number of sources in different fields. These two weightings produce a mismatch between the average position of events and the average position for universal efficiency. This type of bias might have affected the clump giants determination, but here I am not able to improve upon the original Popowski et al. (2001) results as the final field-by-field data for clump giants are not available yet.

Let us now turn to the study by AD2000. First, one should notice that the optical depth reported by AD2000, even though based on microlensing efficiencies in eight individual fields, is not equal to the average of values given in their Table 3. The average optical depth from AD2000 was computed based on a "hybrid" type of prescription. The procedure was global in the sense that equation. (1) for the optical depth was used for the entire sample of events and N was taken to be the number of all relevant stars observed in the eight fields. However, the procedure was also local in the sense that efficiencies correcting the durations were taken from individual fields. An average of the optical depths in individual fields determined in a *consistent* fashion yields a less biased solution. I compute a weighted average based on all eight fields and obtain: (1) $\tau_{8\,\mathrm{fields}} = 1.98 \times 10^{-6}$ with $\sigma_{+} = 0.26 \times 10^{-6}$ using positive errors only[2] and (2) $\tau_{8\,\mathrm{fields}} = 1.96 \times 10^{-6}$ with $\sigma_{-} = 0.23 \times 10^{-6}$ using negative errors only. This can be summarized as $\tau_{8\,\mathrm{fields}} = 1.97^{+0.26}_{-0.23} \times 10^{-6}$, where the average position of 8 fields is the same as in AD2000: $(l, b) = (2\overset{\circ}{.}68, -3\overset{\circ}{.}35)$. The "weighted" optical depth $\tau_{8\,\mathrm{fields}}$ is nearly 20% smaller than the value $\tau = 2.43^{+0.39}_{-0.38} \times 10^{-6}$ given in AD2000.

The important problem one faces is how to estimate the appropriate position at which the optical depth is given when computed as an average of values in individual fields. There are three major possibilities:

1. an average of central positions of the fields with no weighting (e.g., AD2000),
2. a weighted average of central positions with the optical depth errors as weights,
3. a weighted average of central positions with the number of stars in different fields as weights.

Let me consider two limiting cases that will show the preferred solution. In both cases, I

[2]In what follows, I will refer to the error that would increase the value of τ as to the positive one, and to the error that would decrease the value of τ as to the negative one.

consider N fields with optical depth measurements, τ_i. First, let the error in k-th field, $\sigma(\tau_k)$ be small, and let $\sigma(\tau_i)/\sigma(\tau_k) \longrightarrow \infty$ for $i \neq k$. It is obvious that one has no information about the optical depth at the unweighted average position of all fields. However, with prescription 1. one will be forced to report τ_k at this average location. Prescription 2. will correctly give τ_k at the position of the k-th field. Second, let errors in all τ_i be identical, and let $\tau_k = C_1$ and $\tau_i = C_2$ for $i \neq k$ with $C_1 \neq C_2$. Moreover let $N_k/N_i \longrightarrow \infty$ for $i \neq k$, where N_i designates the number of stars in i-th field. Prescription 3. will then report a value $C_2 + \frac{C_1 - C_2}{N}$ at the location of the k-th field leading to a disagreement with optical depth $\tau_k = C_1$. I conclude that prescription 2. is the most appropriate. Accordingly, the optical depth for 8 DIA fields computed with the new, corrected errors is given at $(l, b) = (2^\circ\!.68, -3^\circ\!.31)$, which accidentally is almost identical to the original unweighted value.

If one conservatively removes fields 104 and 159, the results from the remaining six fields are as follows: 1. $\tau_{\rm tot} = 2.01 \times 10^{-6}$ with $\sigma_+ = 0.28 \times 10^{-6}$ using positive errors only, 2. $\tau_{\rm tot} = 2.01 \times 10^{-6}$ with $\sigma_- = 0.25 \times 10^{-6}$ using negative errors only. This can be summarized as $\tau_{\rm tot} = 2.01^{+0.28}_{-0.25} \times 10^{-6}$, which at the first glance looks almost identical to the previous result. However, effectively this is a lower optical depth, as the average weighted position of the six fields is closer to the Galactic center at $(l, b) = (2^\circ\!.22, -3^\circ\!.18)$ [average unweighted position is $(l, b) = (2^\circ\!.00, -3^\circ\!.23)$]. If, following AD2000, I add in quadrature the 10% uncertainty in the luminosity function, then

$$\tau_{\rm tot} = 2.01^{+0.34}_{-0.32} \times 10^{-6} \quad \text{at} \quad (l, b) = (2^\circ\!.22, -3^\circ\!.18), \tag{3}$$

Unlike for clump giants, in the case of DIA, the removal of field 104 has little effect on the optical depth! Almost the entire change in the optical depth comes from replacing the "hybrid" procedure of AD2000 with a proper weighting of values in individual fields.

The value $\tau_{\rm tot}$ is the total optical depth toward the bar where all stars that belong to different populations (predominantly bar and disk) can be both sources and lenses. Oftentimes, one is interested in the optical depth toward sources that reside in the bar only, $\tau_{\rm bar}$. This quantity is the easiest to evaluate directly for a well defined group of sources that are much more abundant in the bar than in the disk. Clump giants are believed to be such a population. The events detected by DIA do not share this property. Fortunately, under certain assumptions, we can also evaluate $\tau_{\rm bar}$ indirectly based on $\tau_{\rm tot}$. Let me assume that: (1) microlensing detection efficiency does not depend on the membership in a given stellar population, (2) the contribution of events with a disk star as a source to $S \equiv \sum_{\rm all\ events} \frac{t_E}{\epsilon(t_E)}$ is negligible. Then, assuming that the disk and the bar are the only relevant populations, one has the following relations:

$$\tau_{\rm tot} = \frac{\pi}{2(N_{\rm bar} + N_{\rm disk})T} S, \tag{4}$$

and

$$\tau_{\rm bar} = \frac{\pi}{2N_{\rm bar}T} S, \tag{5}$$

which imply that

$$\tau_{\rm bar} = \frac{N_{\rm bar} + N_{\rm disk}}{N_{\rm bar}} \tau_{\rm tot} = \frac{1}{1 - f_{\rm disk}} \tau_{\rm tot}, \tag{6}$$

where $f_{\rm disk} \equiv \frac{N_{\rm disk}}{N_{\rm bar}+N_{\rm disk}}$. This is a classical correction applied by Alcock et al. (1997) and AD2000. In this case, $f_{\rm disk}$ does not describe a contribution of any population to the optical depth[3], but rather the effect of "dilution" of the optical depth caused by the foreground sources. Alcock et al. (1997) took $f_{\rm disk} = 0.20$ adjusting infrared estimates from the DIRBE maps of Weiland et al. (1994) to the optical. Probably following Alcock et al. (1997), AD2000 took even somewhat higher value of $f_{\rm disk} = 0.25$. However, from the definition of $f_{\rm disk}$, one sees that it should be approximately equivalent to a factor p that was estimated by AD2000 for each field and is given in column 8 of their Table 3. On average $p \approx 0.1$, with very little scatter around this value. Therefore, in what follows, I will take $f_{\rm disk} = 0.1$ as more appropriate. Consequently, equations (3) and (6) imply that:

$$\tau_{\rm bar} = 2.23^{+0.38}_{-0.35} \times 10^{-6} \, \frac{0.9}{1 - f_{\rm disk}} \quad \text{at} \quad (l, b) = (2\overset{\circ}{.}22, -3\overset{\circ}{.}18), \tag{7}$$

where, similarly to AD2000, I computed the final error adding in quadrature 10% error originating from uncertainty in the luminosity function. The values of $\tau_{\rm bar}$ for individual fields are listed in Table 2. The errors in optical depths in columns 6 and 7 do not include additional error in the luminosity function. Boldfaced are the fields that have been used in my final determination of the optical depth.

6. Conclusions

I have critically assessed the current observational situation regarding the microlensing optical depth determinations toward the Galactic bar using the results from the two recent analyses by the MACHO Collaboration (AD2000; Popowski et al. 2000, 2001). First, based on 97 events from DIA, I confirm the unusual character of the MACHO field 104 located at

[3]Note that Alcock et al. (1997) discussion of the relation between $\tau_{\rm bar}$ and $\tau_{\rm tot}$ is clearer than the one in AD2000.

$(l, b) = (3\overset{\circ}{.}11, -3\overset{\circ}{.}00)$ previously documented by Popowski et al. (2001), and reinforce their suggestion to disregard this field as an outlier. As a result, clump giant analysis produces $\tau_{\rm bar} = 1.4 \pm 0.3 \times 10^{-6}$ at $(l, b) = (3\overset{\circ}{.}8, -3\overset{\circ}{.}9)$ from 76 fields with field 104 eliminated. This value seems to be better motivated than $\tau_{\rm bar} = 2.0 \pm 0.4 \times 10^{-6}$ from the entire clump sample.

Second, I make three important adjustments to DIA by AD2000.

- I estimate the average optical depth by weighting the optical depths in individual fields using the optical depth errors as weights. This replacement of AD2000's "hybrid" procedure reduces the optical depth by almost 20%.
- I eliminate 2 out of 8 fields: 104 as an outlier in duration distribution and optical depth and field 159 based on its separation from the other DIA fields. I also discuss the preferred determination of the position at which the optical depth is reported.
- I argue for a smaller "dilution" factor, $f_{\rm disk}$, that allows one to convert between the total measured optical depth, $\tau_{\rm tot}$ and the optical depth toward sources in the bar, $\tau_{\rm bar}$. This correction alone reduces the optical depth by 17%.

The final DIA-based results are $\tau_{\rm tot} = 2.01^{+0.34}_{-0.32} \times 10^{-6}$ and $\tau_{\rm bar} = 2.23^{+0.38}_{-0.35} \times 10^{-6}$ for $f_{\rm disk} = 0.1$, both at $(l, b) = (2\overset{\circ}{.}22, -3\overset{\circ}{.}18)$.

These new estimates can be compared with the most recent modeling results from Evans & Belokurov (2002) and Bissantz & Gerhard (2002). Evans & Belokurov (2002) considered three Galactic models by Binney et al. (1997), Dwek et al. (1995), and Freudenreich (1998), and included the effects of spiral structure and streaming motions in the Galactic bar. Bissantz & Gerhard (2002) constructed a non-parametric model with spiral arms. Based on the previous higher estimates of the optical depth, Evans and Belokurov (2002) suggested that Freudenreich's (1998) model is preferred, although at a rather low significance. Table 3 presents a comparison of various Galactic models with the optical depths derived here. The optical depth values for the clump location are taken directly from Evans & Belokurov (2002) or Bissantz & Gerhard (2002), whereas the unpublished values at the DIA location were kindly provided by Wyn Evans and Ortwin Gerhard. The numbers in parentheses include the effect of the spiral structure. Note that such comparison is only qualitative due to: (1) possible biases in average values of the optical depth, and (2) inconsistency between the disk model indirectly implied by the AD2000 luminosity function and the disk model used by Evans & Belokurov (2002) or derived by Bissantz & Gerhard (2002). Nevertheless, Table 3 suggests that the new, lower values of the microlensing optical depth derived here are consistent with the infrared-based models of the Milky Way but do not clearly favor a specific Galactic model.

I thank Andrew Drake for illuminating discussions about the issues considered in this paper and his comments to the original draft of this manuscript. The detailed comments and suggestions made by Greg Rudnick substantially improved the presentation of the results. I am very grateful to Wyn Evans and Ortwin Gerhard for providing unpublished values of the optical depth for different Galactic models.

REFERENCES

Alcock, C., et al. 1997, ApJ, 479, 119

Alcock, C., et al. 2000, ApJ, 541, 734 (AD2000)

Alcock, C., et al. 2001, ApJS, 136, 439

Binney, J., Gerhard, O., & Spergel, D. 1997, MNRAS, 288, 365

Binney, J., Bissantz, N., & Gerhard, O. 2000, ApJ, 537, L99

Bissantz, N., & Gerhard, O. 2002, MNRAS, 330, 591

Dwek, E., et al. 1995, ApJ, 445, 716

Evans, N. W., & Belokurov, V. 2002, ApJ, 567, L119

Freudenreich, H. T. 1998, ApJ, 492, 495

Han, C., & Gould, A. 1995, 449, 521

Popowski, P. et al. 2000, in ASP Conference Series 239, Microlensing 2000: A New Era of Microlensing Astrophysics, eds. J.W. Menzies & P.D. Sackett (San Francisco: Astronomical Society of the Pacific) (astro-ph/0005466)

Popowski, P. et al. 2001, in ASP Conference Series 245, Astrophysical Ages and Times Scales, eds. T. von Hippel, C. Simpson, & N. Manset (San Francisco: Astronomical Society of the Pacific), 358 (astro-ph/0202502)

Udalski, A., et al. 1994, Acta Astron., 44, 165

Weiland, J. L., et al. 1994, ApJ, 425, L81

Table 1. Errors in the Optical Depth for Individual Fields

Field	N_{DIA}	τ ($\times 10^6$)	σ_+	σ_-	σ_G	$\frac{\sigma_+}{\sigma_G}$	$\frac{\sigma_-}{\sigma_G}$
101	11	1.72	0.61	0.54	0.52	1.18	1.03
104	16	4.18	1.65	1.37	1.04	1.57	1.31
108	16	2.39	0.68	0.61	0.60	1.13	1.03
113	17	1.96	0.54	0.49	0.47	1.14	1.03
118	13	2.64	0.97	0.84	0.73	1.33	1.15
119	12	2.43	0.95	0.81	0.70	1.35	1.15
128	10	1.62	0.62	0.54	0.51	1.21	1.06
159	4	1.06	0.85	0.65	0.53	1.61	1.23

Note. — Columns: (1) MACHO field number, (2) number of events from DIA, (3) total microlensing optical depth from AD2000, (4) & (5) *correct* asymmetric errors in microlensing optical depth, (6) Gaussian approximation to a Poisson confidence interval based on the number of events, (7) & (8) the ratios of errors: columns (4) or (5) divided by column (6). Similarly to the optical depth from column (3), the values given in columns (4)—(6) are expressed in units of 10^{-6}.

Table 2. Optical Depth in Individual Fields

Field	N_{DIA}	l [°]	b [°]	$f_{\rm disk}$	$\tau_{\rm tot}(\times 10^6)$	$\tau_{\rm bar}(\times 10^6)$
101	11	3.728	−3.021	0.118	$1.72^{+0.61}_{-0.54}$	$1.95^{+0.69}_{-0.61}$
104	16	3.109	−3.008	0.106	$4.18^{+1.65}_{-1.37}$	$4.68^{+1.84}_{-1.53}$
108	16	2.304	−2.649	0.114	$2.39^{+0.68}_{-0.61}$	$2.70^{+0.76}_{-0.69}$
113	17	1.629	−2.781	0.089	$1.96^{+0.54}_{-0.49}$	$2.15^{+0.59}_{-0.54}$
118	13	0.833	−3.074	0.100	$2.64^{+0.97}_{-0.84}$	$2.93^{+1.08}_{-0.93}$
119	12	1.065	−3.831	0.093	$2.43^{+0.95}_{-0.81}$	$2.68^{+1.05}_{-0.89}$
128	10	2.433	−4.029	0.084	$1.62^{+0.62}_{-0.54}$	$1.77^{+0.67}_{-0.59}$
159	4	6.353	−4.402	0.093	$1.06^{+0.85}_{-0.65}$	$1.17^{+0.94}_{-0.72}$

Note. — Columns: (1) MACHO field number, (2) number of events from DIA, (3) & (4) location of the field, (5) fraction of disk stars along the line-of-sight to $V = 23$ from AD2000 (their factor p), (6) total microlensing optical depth from AD2000 with corrected errors, (7) microlensing optical depth toward sources in the Galactic bar.

The optical depth in column (7) is estimated from the data given in columns (6) and (5). Boldfaced fields are used in the final estimate of the optical depth toward sources residing in the Galactic bar.

	Method	Clump giants	DIA
	Optical depth	1.4 ± 0.3	$2.01^{+0.34}_{-0.32}$
	Location (l, b)	$(3^\circ\!.9,\ -3^\circ\!.8)$	$(2^\circ\!.22,\ -3^\circ\!.18)$
	Sources	bar	bar+disk
Models	Lenses	bar+disk	bar+disk
Binney et al. (1997)		0.9 (1.2)	1.0 (1.1)
Freudenreich (1998)		2.0 (2.4)	1.8 (2.2)
Dwek et al. (1995)		1.2 (1.5)	1.3 (1.6)
Bissantz & Gerhard (2002)		(1.27)	(1.23)

Table 3: The optical depth in units of 10^{-6} for three Galactic models considered by Evans & Belokurov (2002) and the non-parametric model of Bissantz & Gerhard (2002). The optical depth values for clump location are taken directly from Evans & Belokurov (2002) or Bissantz & Gerhard (2002), whereas the unpublished values at DIA location were kindly provided by Wyn Evans and Ortwin Gerhard. The numbers in parentheses include the effect of the spiral structure. Note that clump giants and DIA events probe different populations of microlensing sources. Observational constraints are given in the top part of the table. As explained in the main text, the interpretation of this comparison is difficult.

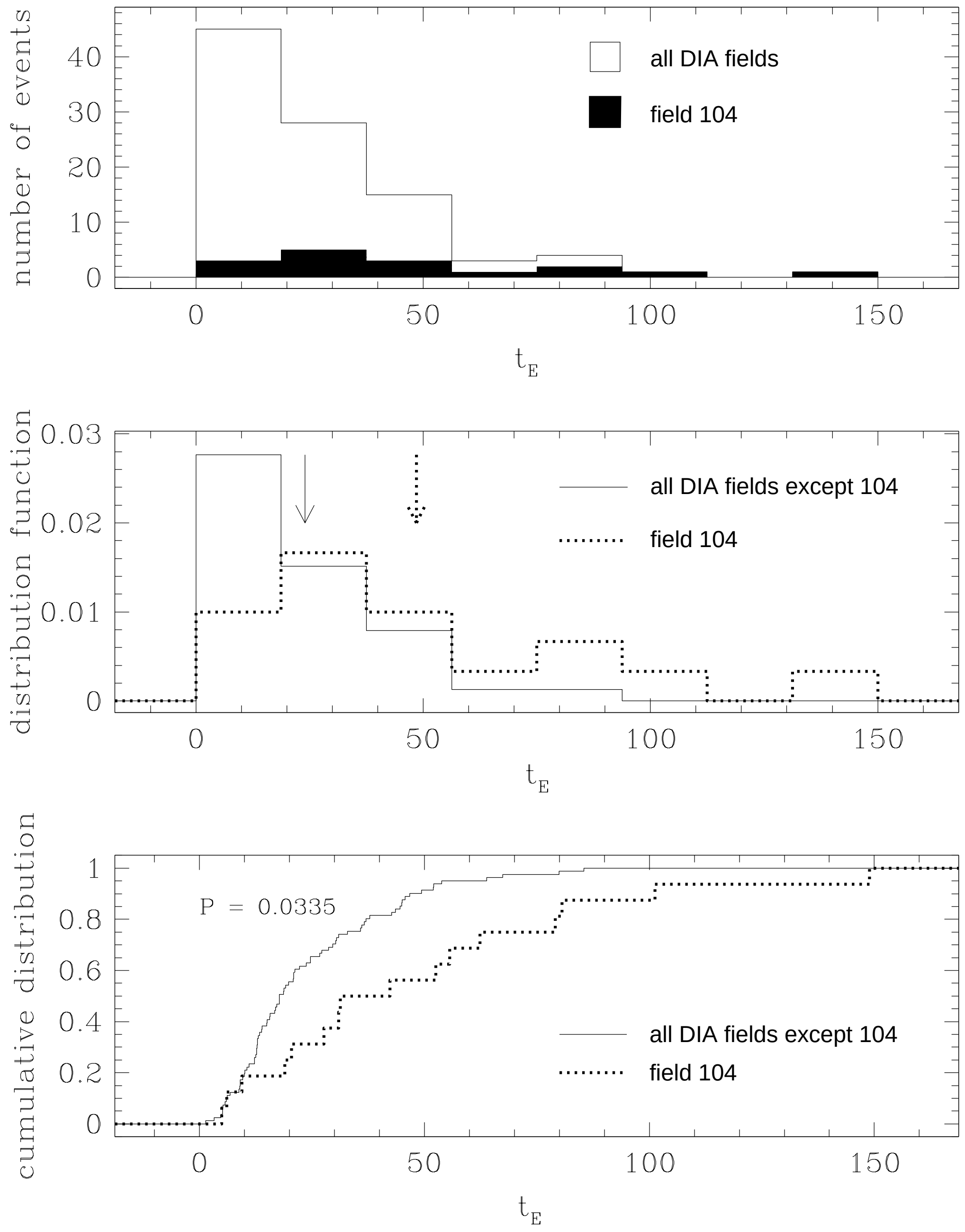

Fig. 1.— The *upper panel* shows number of events as a function of event duration based on all 8 DIA fields (97 events from the sample of 99). Field 104 clearly dominates the long duration part of this distribution. The *middle panel* presents comparison of the number distribution function in field 104 and the remaining 7 fields. The distribution in field 104 is much flatter and more extended. Average durations for both distributions are marked with vertical arrows. The *lower panel* is a plot of the cumulative distributions of event durations for field 104 and the remaining fields. Kolmogorov-Smirnov test indicates that the probability that both samples come from the same parent population is $P = 0.0335$.

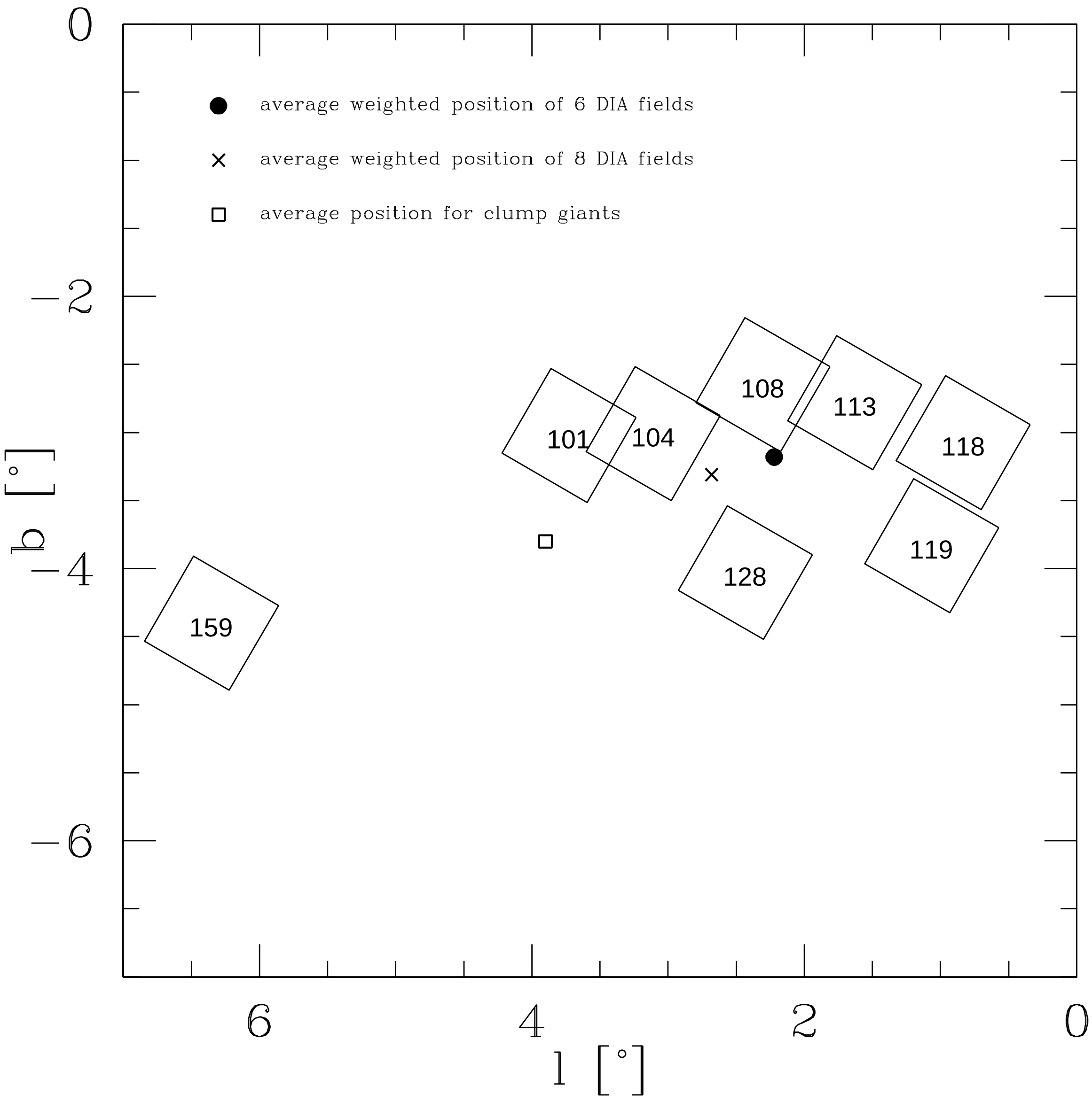

Fig. 2.— Location of 8 MACHO fields used by AD2000. Field 104 is highly anomalous and field 159 is clearly separated from the others. The filled circle indicates an average weighted position of 6 fields, at which I give a new optical depth of $\tau_{\rm bar} = 2.23^{+0.38}_{-0.35} \times 10^{-6}$ for $f_{\rm disk} = 0.1$. The average weighted position of 8 fields is marked with a cross for comparison. The open square indicates the average position for optical depth of $\tau_{\rm bar} = 1.4 \pm 0.3 \times 10^{-6}$ based on clump giants (Popowski et al. 2001).