MICROLENSING MAPS FOR THE MILKY WAY GALAXY

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ABSTRACT

At any instant, there are \( \sim 1000 \) microlensing events to sources brighter than 20 mag in the Milky Way. Large-scale maps of the microlensing optical depth and the mean timescale are constructed for a number of models of the Galactic bar and disk, incorporating the effects of streaming and spiral structure. Freudenreich’s model can reproduce the high optical depths toward the bulge. It is also in good agreement with the data toward the spiral arms (except for the field \( \gamma \) Norma). Spiral structure tends to increase the optical depth by \( \lesssim 20\% \) and the mean timescale by \( \lesssim 100\% \). Different bar morphologies give characteristically different shaped contours, especially at low Galactic latitudes (\( |b| < 2^\circ \)). These could be traced out with a \( K \)-band microlensing survey, consuming \( \sim 100 \) minutes per night on a telescope such as the Visible and Infrared Survey Telescope for Astronomy.

Subject headings: Galaxy: kinematics and dynamics — Galaxy: structure — gravitational lensing

1. INTRODUCTION

Microlensing surveys of the Galaxy are important because they delineate the mass distribution directly. The total number of events identified by the OGLE and MACHO collaborations toward the Galactic bulge now exceeds 1000 (e.g., Woźniak et al. 2001; Alcock et al. 2000). The identification of events toward spiral arms has been reported by the EROS and OGLE collaborations (Mao 1999; Derue et al. 2001). Maps of optical depth as a function of Galactic latitude and longitude were first drawn by Evans (1994). Subsequently, a number of authors emphasized the importance of exploiting information on the spatial variation of the optical depth (e.g., Han & Gould 1995; Zhao, Rich, & Spergel 1996; Gyuk 1999).

Microlensing searches are being done, or will be done in the near future, in almost every longitude direction. The first of the next generation experiments is the OGLE III venture, which uses an 8k \( \times \) 8k CCD mosaic camera with a field of view equal to \( 35^\prime \times 35^\prime \). The future holds still greater promise with the advent of the new class of survey telescopes including the VLT Survey Telescope (VST)\(^2\) and Visible and Infrared Survey Telescope for Astronomy (VISTA)\(^3\). VISTA has a field of view of 2.25 deg\(^2\) in the optical, while VST has a smaller, but still substantial, field of view of 1 deg\(^2\). So there is a need for large-scale maps of both the microlensing optical depth and the mean timescale for the Galaxy. These maps can be used to pick target fields, plan search methodologies for future experiments, and assess what can be learned about the structure of the Milky Way from the distribution of microlensing events.

2. MAPS OF THE GALAXY

We study three models of the inner Galaxy. The starting point of all three models is the same, namely, the infrared surface brightness maps seen by the DIRBE instrument on the COBE satellite. The first is the model of Binney, Gerhard, & Spergel (1997), which is partially revised in Bissantz et al. (1997). Here the observed luminosity at \( \sim 240 \) \( \mu \)m, which is dominated by thermal emission from dust, is used to deduce the three-dimensional spatial distribution of the dust. This gives a short, flattened, cuspy bar with an axis ratio of 1 : 0.3 : 0.3 and a viewing angle of \( \phi_0 = 20^\circ \). The second is the model of Freudenreich (1998). Here a mask of areas believed to be contaminated with dust is constructed from maps of color variations. The mask is used to excise portions of the DIRBE data, and the remainder of the data is fitted. Note that the mask removes almost all of the data within \( |b| = 5^\circ \) for longitudes within 90\(^\circ\) of the Galactic center (see Fig. 1 of Freudenreich 1998). This gives an extended, diffuse swollen bar with an axis ratio of 1 : 0.37 : 0.27 and a viewing angle of \( \phi_0 = 14^\circ \). The disk has a central hole with a radius of \( \sim 3 \) kpc. The third is the E2 model of Dwek et al. (1995), as partially revised by Stanek et al. (1997). The density contours are stratified on concentric ellipses with an axis ratio of 1 : 0.42 : 0.28 and a viewing angle of \( \phi_0 = 24^\circ \). In correcting for dust, Dwek et al. (1995) assumed a uniform-foreground screen. The bar is less massive and less elongated than Freudenreich’s, and the disk does not have a central hole. To ensure a fair comparison, all three models are normalized to have the same total mass of \( 1.5 \times 10^{10} M_\odot \) within 2.5 kpc. Optical depths scale in rough proportion with total mass, and so our results can be easily

Fig. 1.—Upper panels: Slices through the principal plane of the bars of the models of the Galaxy. The first is the model of Binney, Gerhard, & Spergel (1997), which is partially revised in Bissantz et al. (1997). Here the observed luminosity at \( \sim 240 \) \( \mu \)m, which is dominated by thermal emission from dust, is used to deduce the three-dimensional spatial distribution of the dust. This gives a short, flattened, cuspy bar with an axis ratio of 1 : 0.3 : 0.3

\(^1\) See http://sirius.astrouw.edu.pl/~ogle/index.html.
\(^2\) See http://www.eso.org/projects/vst.
\(^3\) See http://www.vista.ac.uk.
converted to other preferred values. The three models are illustrated in Figure 1. Cuts through the principal plane of the bar and along the line of sight to the Galactic center are shown. Table 1 shows the masses of the components in the three models. Freudenreich’s bar is the most massive, Binney et al.’s the least massive.

EROS and OGLE are looking toward spiral arms. Accordingly, we include the effects of spiral arms in our calculations. We assume that the inner spiral pattern is two-armed and given by multiplying the density by equation (2) of Binney et al. (1997), namely,

$$1 + \epsilon \cos^6 [\phi - 0.95(r - r_{\text{min}}) - \phi_0], \quad \epsilon = \tanh (r - r_{\text{min}}).$$

Here $r_{\text{min}}$ is proportional to the length of the bar and is 1.5 kpc for Binney et al.’s bar, 2.25 kpc for Freudenreich’s, and 1.7 kpc for Dwek et al.’s. This density factor is applied between $r_{\text{min}}$ and $r_{\text{max}} = 3.5$ kpc. The outer spiral pattern is four-armed and given by $1 + 2\epsilon \cos^6 [2\phi - 1.1(r - r_{\text{min}}) - 15^\circ]$ between $r_{\text{min}} = 4.1$ kpc and $r_{\text{max}} = 8.5$ kpc. The phase and wavenumber of the inner and outer spirals are chosen to match the longitudes of the principal spiral arms given by Englmaier (2000). The arm/inner contrast is 2 for the inner and 3 for the outer spiral (see Rix & Rieke 1993). This is reasonable for a young population but is an overestimate for old low-mass stars that may make up the bulk of the lensing population. So, our results on the effects of spirality are upper limits.

Microlensing maps show contours of the source-averaged microlensing optical depth $\langle \tau \rangle$, computed via (Kiraga & Paczyński 1994)

$$\langle \tau \rangle = \frac{\int_0^b \rho(D_s) D_s^{2+2\beta} D_D dD_D}{\int_0^{\infty} \rho(D_s) D_s^{2+2\beta} dD_D},$$

where $D_s$ is the source distance and $\rho$ is the density of deflectors. For red clump stars, $\beta \approx 0$; for main-sequence stars, $\beta \approx -1$. Red clump stars are bright and distinctive residents of the bar (e.g., Paczyński & Stanek 1998). Figure 2 shows contours of optical depth to the red clump in the three models. The dotted contours show the effect of including the spiral structure. The amplification caused by spirality varies according to the line of sight, but it is typically $\sim 20\%$. Of the three, the Binney et al. model gives the least symmetric microlensing map, especially close to the Galactic plane where the gradients are very steep. The Freudenreich model is the most symmetric, as it possesses the smallest viewing angle. The boxes mark the two locations where the optical depth of bar stars has been measured. The first is $l = 3^\circ 9$, $b = -3^\circ 8$, where Popowski et al. (2002) report $(2.0 \pm 0.4) \times 10^{-6}$ for the optical depth to red clump stars. The second is $l = 2^\circ 68$, $b = -3^\circ 35$, where Alcock et al. (2000) report $(3.2 \pm 0.5) \times 10^{-6}$ for the optical depth to bar stars. The value of the optical depth at $l = 3^\circ 9$, $b = -3^\circ 8$ contributed by each component in the three models is recorded in Table 2. Freudenreich’s model is in good agreement with the two measurements of optical depth to the bar sources.

Even though all three models have the same total mass within 2.5 kpc, Freudenreich’s model has the higher optical depth.
because the bar is more extended. Note that the shape of the contours in Figure 2 becomes very similar for all three models once \(|b| > 4^\circ\). This makes it challenging to characterize the bar morphology on the basis of data from the observed fields. One qulam is that Freudenreich excised most of the DIRBE data within \(|b| \leq 5^\circ\) of the Galactic plane. In this region, his model is entirely extrapolated from the light distribution at higher latitudes and so may be unreliable. Binney et al.’s model reproduces the strong concentration in the light near the Galactic plane. It lies within \(\pm 2\sigma\) of Popowski et al.’s measurement when spiral structure is included. Dwek et al.’s model with spiral structure is just outside \(1\sigma\). Can we modify Binney et al.’s model to reproduce the microlensing optical depth data? To get agreement with the data, the bar needs to be made both longer and fatter. For example, changing the axis ratio to \(1:0.6:0.4\) (as originally envisaged in Binney et al. 1997) and increasing the total mass within 2.5 kpc by 50% gives a model in reasonably good agreement (namely, \(\tau = 1.5 \times 10^{-4}\) at \(l = 3^\circ 9, b = -3^\circ 8\), excluding spiral structure; this rises to \(1.8 \times 10^{-4}\) when spiral structure is included).

Figure 3 shows the contours of optical depth to all sources in the inner Galaxy using Freudenreich’s bar. The Galactic disk has a sech\(^4\) vertical profile with a scale height of 167 pc and an exponential horizontal profile with a scale length of 2.5 kpc. The insets show the details of three areas toward the Scutum, Norma, and Musca spiral arms that are being monitored by the EROS group. We see that there is a factor of \(\sim 0.6\) variation in the optical depth across the EROS fields toward all three spiral arms. Freudenreich’s bar is so distended that it causes a thickening of the optical depth contours even at longitudes well away from the center. We can exploit the maps to estimate the number of ongoing microlensing events of stars brighter than 20 mag in the Milky Way. At any instant, there are \(\sim 1000\) microlensing events, where we have allowed for extinction in the same manner as Belokurov & Evans (2002). Table 3 compares the predictions of the three models with the data provided by EROS. Note that Freudenreich’s model is in excellent agreement with the data, except for the field \(\gamma\) Norma, where the optical depth is about \(\sigma\) away from the data.

3. TIMESCALE MAPS

It is also interesting to build maps of the mean Einstein crossing timescale. We assume that the mass function of the bar (or disk) is a power law between 0.01 and 0.5 \(M_\odot\), with an index of \(-1.33\) (or \(-0.54\)) as suggested by Zoccali et al. (2001). Let \((x, y, z)\) define coordinates along the major, intermediate, and minor axes of the bar. We calculate the average velocity dispersions required to reproduce the shape of Freudenreich’s bar, guided by the tensor virial theorem (e.g., Han & Gould 1995; Blum 1996). We assume that stars on the front side of the bar move along the major axis with a streaming velocity of \(v_s = 50 \text{ km s}^{-1}\), while stars on the back side move with \(v_s = -50 \text{ km s}^{-1}\), and we adjust the dispersion \(\sigma_v\) to preserve the total kinetic energy required by the virial theorem. With these assumptions, the velocity distribution is Gaussian about the streaming velocity with dispersions of \(\sigma_v = 100, \sigma_x = 80,\) and \(\sigma_z = 68 \text{ km s}^{-1}\). For the disk lenses, the random component has \(\sigma_y = 34, \sigma_y = 21,\) and \(\sigma_z = 18 \text{ km s}^{-1}\) about a mean velocity \(\langle v_s \rangle = 214 \text{ km s}^{-1}\) (see, e.g., Edvardsson et al. 1993; Belokurov & Evans 2002). Although small velocity perturbations will be associated with the spiral arms, these are neglected in our calculations.

Figure 4 shows contours of the mean timescale for events with sources and lenses in either the disk or Freudenreich’s bar, including (dotted lines) and excluding (solid lines) the spiral structure. The mean timescale is shortest toward the Galactic center and becomes longer at increasing Galactic longitudes. This is easy to understand because the motion of the lens is directed more and more along the line of sight at larger longitudes, and so the transverse velocity is typically smaller. Note that spiral structure has a dramatic effect on the mean
timescale. For example, at Baade’s Window, the mean timescale is increased by a factor of $\sim 100\%$ upon incorporating the effects of spirality. Figure 5 shows the inner $20^\circ \times 20^\circ$ in Freudenreich’s model including (dotted lines) and excluding (solid lines) the effects of bar streaming. This detail is drawn for sources in the bar only, and so the asymmetry in the map is substantial. Streaming is an important effect because it removes kinetic energy from random motions and places it in systematic motions that are directed almost along the line of sight. There is an increasing gradient in the mean timescale from the near side to the far side of the bar. This is a geometric effect in that lines of sight to the near side are more nearly perpendicular to the major axis than lines of sight to the far side. Popowski et al. (2002) report that about 40% of the optical depth is in events with timescales longer than 50 days and that this is at odds with standard Galactic models. By contrast, we find that long timescale events are to be expected when streaming is taken into account in the modeling.

4. CONCLUSIONS

We have drawn large-scale maps of the optical depth and timescale distribution for microlensing in the Galaxy. Freudenreich’s bar does give a reasonable representation of the microlensing data to the bulge. It recovers the optical depth toward the spiral arms (with the exception of $\gamma$ Norma). However, Freudenreich’s model is hollow. Stars otherwise expected to be in the central parts of the disk can instead be used to augment the bar where they are efficient at microlensing.

As pointed out by Gould (1995), microlensing surveys in the $K$ band would be very valuable to distinguish between models. This is all the more true given the capabilities of the new generation of survey telescopes. VISTA has a field of view of 0.5 deg$^2$ in the $K$ band. Assuming that the seeing is 0.8 in Chile and scaling the results of Gould (1995), we estimate that VISTA will monitor $\sim 1.5 \times 10^8$ stars in a single field of view for crowding-limited $K$-band images toward the bulge. This means that we are probing the luminosity function down to $K \sim 16$ assuming 3 mag of extinction. Photometry accurate to 3% for a $K \sim 16$ star will take $\sim 1$ minute on VISTA. Hence, a $K$-band survey of a $5^\circ \times 5^\circ$ field close to the Galactic center will take $\sim 100$ minutes every night, allowing 50 minutes for readout, slew, and guide-star acquisition time. So a $K$-band microlensing survey of the inner Galaxy is an attractive and feasible proposition with VISTA.

REFERENCES

Alcock, C., et al. 2000, ApJ, 541, 734
Belokurov, V., & Evans, N. W. 2002, MNRAS, in press (astro-ph/0112243)
Binney, J., Gerhard, O., & Spergel, D. 1997, MNRAS, 288, 365
Bissantz, N., Englmaier, P., Binney, J., & Gerhard, O. E. 1997, MNRAS, 289, 651
Blum, R. 1995, ApJ, 444, L89
Derue, F., et al. 2001, A&A, 373, 126
Dwek, E., et al. 1995, ApJ, 445, 716
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&AS, 102, 603
Englmaier, P. 2000, Rev. Mod. Astron., 13, 97
Evans, N. W. 1994, ApJ, 437, L31
Freudenreich, H. T. 1998, ApJ, 492, 495
Gould, A. 1995, ApJ, 446, L71
Gyuk, G. 1999, ApJ, 510, 205
Han, C., & Gould, A. 1995, ApJ, 449, 521
Kiraga, M., & Paczynski, B. 1994, ApJ, 430, L101
Mao, S. 1999, A&A, 350, L19
Paczynski, B., & Stanek, K. Z. 1998, ApJ, 494, L219
Popowski, P., et al. 2002, in ASP Conf. Ser., Microlensing 2000: A New Era of Microlensing Astrophysics, ed. J. W. Menzies & P. D. Sackett (San Francisco: ASP) in press (astro-ph/0005466)

Rix, H. W., & Rieke, M. J. 1993, ApJ, 418, 123
Stanek, K. Z., Udalski, A., Szymański, M., Kaluzny, J., Kubiak, M., Mateo, M., & Krzeminski, W. 1997, ApJ, 477, 163
Woźniak, P. R., Udalski, A., Szymański, M., Kubiak, M., Pietrzyński, G., Soszynski, I., & Zebrun, K. 2001, Acta Astron., 51, 175
Zhao, H. S., Rich, R. M., & Spergel, D. N. 1996, MNRAS, 282, 175
Zoccali, M., Cassisi, S., Frogel, J. A., Gould, A., Ortolani, S., Renzini, A., Rich, R. M., & Stephens, A. W. 2000, ApJ, 530, 418