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MICROLENSING BY THE GALACTIC BAR

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ABSTRACT

We compute the optical depth and duration distribution of microlensing events toward Baade's window in a model composed of a Galactic disk and a bar. The bar model is a self-consistent dynamical model built out of individual orbits that has been populated to be consistent with the *COBE* maps of the Galaxy and kinematic observations of the Galactic bulge. We find that most of the lenses are in the bulge with a line-of-sight distance 6.25 kpc (adopting $R_0 = 8$ kpc). The microlensing optical depth of a $2 \times 10^{10}\ M_\odot$ bar plus a truncated disk is $(2.2 \pm 0.45) \times 10^{-6}$, consistent with the large optical depth $(3.2 \pm 1.2) \times 10^{-6}$ found by Udalski et al. (1994). This model optical depth is enhanced over the predictions of axisymmetric models by Kiraga & Paczyński (1994) by slightly more than a factor of 2, since the bar is elongated along the line of sight. The large Einstein radius and small transverse velocity dispersion also predict a longer event duration in the self-consistent bar model than in the Kiraga-Paczyński model. The event rate and duration distribution also depend on the lower mass cutoff of the lens mass function. With a $0.1\ M_\odot$ cutoff, five to seven events (depending on the contribution of disk lenses) with a logarithmic mean duration of 20 days are expected for the Optical Gravitational Lensing Experiment (OGLE) according to our model, while Udalski et al. (1994) observed nine events with durations from 8 to 62 days. On the other hand, if most of the lenses are brown dwarfs, our model predicts too many short-duration events. A Kolmogorov-Smirnov test finds only 7% probability for the model with $0.01\ M_\odot$ cutoff to be consistent with current data.

Subject headings: dark matter — Galaxy: structure — gravitational lensing — stars: low-mass, brown dwarfs

Microlensing experiments were proposed to solve one of the outstanding problems of astrophysics: the dark matter problem. They aim to detect the massive compact halo objects (MACHOs) that have been suggested as the dominant mass component of our Galaxy (Paczyński 1986; Griest et al. 1991) through their microlensing of distant stars and the composition of the disk through observations of the bulge (Paczyński 1991). Like many astronomical observations, these experiments appear to raise new questions rather than solve outstanding problems. For, while experiments that look for the halo dark matter by observing stars in the LMC report an event rate which appears too low for MACHOs to be the halo dark matter (Gould 1994), experiments that monitor stars in the Galactic bulge appear to detect too high an event rate (Udalski et al. 1994; Alcock et al. 1994).

Both the Optical Gravitational Lensing Experiment (OGLE) and the MACHO microlensing experiments find an unexpectedly large number of microlensing events toward the Galactic bulge, about 50 at the time of submission. Udalski et al. (1994) have analyzed the OGLE data and derived a very large lensing optical depth $\tau = (3.3 \pm 1.2) \times 10^{-6}$ toward the OGLE fields: Baade's window ($l = 1°$, $b = -4°$) and two adjacent fields ($\pm 5°$, $-4°$). Kiraga & Paczyński (1994, hereafter KP) and Guidice, Mollerach, & Roulet (1994) find that lensing of bulge stars by stars in the disk can account for at most 20% of this observed optical depth. When KP include an axisymmetric bulge in their lensing calculations, they find that it is the dominant source of lens events. However, even their bulge plus disk model can account for only ~30% of the observed events, and it predicts too short an event duration. KP and Paczyński et al. (1994b) sugest that this discrepancy may be due to their modeling the bulge as an axisymmetric rotator (Kent 1992) rather than as a bar. However, they did not make detailed calculations of the prediction of bar models.

There is a growing concensus in the astronomical community that the Milky Way is a barred Galaxy. Binney et al. (1991) argue that a bar could explain the noncircular motions seen in both the CO and the H I observations. Star counts (Nakada et al. 1991; Whitelock & Catchpole 1992; Stanek et al. 1994) find that bulge stars at positive longitudes are systematically brighter than bulge stars at negative longitudes, consistent with the bar hypothesis. Blitz & Spergel (1991) suggest that asymmetries between the first and fourth quadrants in the IR surface brightness distribution from the balloon observation of Matsumoto et al. (1982) imply that the Galaxy is barred. These asymmetries are confirmed by recent Diffuse Infrared Background Experiment (DIRBE) multicolor maps of the Galaxy (Weiland et al. 1994). Dwek et al. (1994) use these DIRBE maps to construct a three-dimensional triaxial model of the bulge, which we use to compute the optical depth for lensing toward Baade's window.

As part of his doctoral thesis, Zhao (1994) has developed a self-consistent model for the Galactic bar following Schwarzschild's (1979) method. The density profile in this model follows the Dwek et al. (1994) fit to the *COBE* image of the Galaxy. This model is constructed by running 6000 stellar orbits for $\sim$3.5 Gyr and then weighting these stellar orbits to match observations. In this *Letter* we use this bulge model to compute the predicted optical depth and event duration for microlensing toward the bulge.

According to KP, the optical depth averaged over all detectable stars is computed from

$$\tau = \left[\int_0^\infty ds\, w(s)\right]^{-1} \int_0^\infty ds\, w(s) \int_0^s dl\, \rho(l) D\ , \qquad (1)$$

where $w(s)$ is the probablity of the source being at a distance s, $\rho(l)$ is the lens mass density at a distance l, and $D \equiv (s - l)ls^{-1}$ is the characteristic distance between the lens and the source. The averaging over the source distance distribution is necessary, because there are events that both the lens and the source are in the bulge due to the finite depth of the bulge. Following KP we adopt a power-law luminosity function with the fraction of stars more luminous than L being proportional to $L^{-\beta}$. For a magnitude-limited survey, this implies that $w(s) = \rho(s)s^{2-2\beta}$; this is probably valid within the source distance range 4–12 kpc. We derive a raw luminosity function from the color-magnitude data of Paczyński et al. (1994a), and find a good fit when β is between 0.75 and 1. Also in the range of luminosities near the magnitude limit of the OGLE, our fit to the Terndrup, Frogel, & Whitford (1990) star counts implies $\beta \approx 1.5$. We set $\beta = 1 \pm 0.5$; a smaller β would make a slightly larger optical depth.

Dwek et al. (1994) have fitted a series of luminosity density models to the DIRBE surface brightness observations at $|b| > 3°$. They find that the triaxial Gaussian radial profile models (the G1 and G2 models) are the fits with the lowest χ^2. The G2 model is boxy and has a density

$$\rho(x, y, z) = \frac{M}{8\pi abc} \exp\left(-\frac{s^2}{2}\right) , \qquad (2)$$

where

$$s^4 = \left[\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2\right]^2 + \left(\frac{z}{c}\right)^4 .$$

The scale lengths are $a = 1.49 \pm 0.05$, $b = 0.58 \pm 0.01$, and $c = 0.40 \pm 0.01$ kpc for Galactocentric distance $R_0 = 8$ kpc. The long axis of the bar, the x-axis, points toward $l = -13.^\circ4$.

The total luminosity in Dwek et al.'s G2 model, as well as observations of stellar and gas kinematics (Kent 1992), implies a bulge mass of $\sim(1\text{–}2) \times 10^{10}\ M_\odot$. Using this, we estimate the optical depth of the bar at Baade's window to be

$$\tau_{\rm bar} = (0.84 \pm 0.1) \times 10^{-6} M_{10}\ , \qquad (3)$$

where M_{10} is the bulge mass in units of $10^{10}\ M_\odot$. When using their ellipsoidal Gaussian model (G1 model) instead, we find a 5% reduction in optical depth; $\tau_{\rm bar}$ is also 25% smaller for the two adjacent fields ($l = \pm 5°, b = -4°$).

The halo is not expected to make a significant contribution to the optical depth toward Baade's window. Griest (1991) estimate the halo's depth toward the bulge as $\tau_{\rm halo} \leq 0.14 \times 10^{-6}$ for a reasonable halo core radius $a \geq 4$ kpc. Also, the events due to halo objects are likely to be too short to be detectable by OGLE (Paczyński et al. 1994b).

The disk, however, is expected to make a significant contribution to the optical depth toward Baade's window. KP note that in the Bahcall-Soneira (BS) model the disk density along the line of sight toward $b = -4°$ is nearly constant. On the other hand, infrared observations of the Galaxy (Kent, Dame, & Fazio 1991) suggest a smaller disk scale length than 3.5 kpc in the BS model; this would imply that the stellar density increases along the Baade's window line of sight. We compute the optical depth for a double exponential disk normalized locally by the disk stellar density $\sim 0.1\ M_\odot\ {\rm pc}^{-3}$ (Bahcall, Flynn, & Gould 1992) and the surface density $71 \pm 6\ M_\odot\ {\rm pc}^{-2}$ (Kuijken & Gilmore 1991). We allow the disk to be truncated at some distance (Paczyński et al. 1994a). For disk models with the full range of reasonable scale length from 2.7 to 3.5 kpc (Kent et al. 1991; Bahcall & Soneira 1980), the optical depth $\tau_{\rm disk}$ is from 0.87×10^{-6} to 0.63×10^{-6} for the full disk model, and from 0.47×10^{-6} to 0.37×10^{-6} for a disk truncated at 4 kpc.

If we sum the contributions of a $(2 \pm 0.2) \times 10^{10}\ M_\odot$ bar and a truncated disk with 2.7 kpc scale length ($\tau_{\rm disk} = 0.47 \times 10^{-6}$), then the predicted optical depth $(2.2 \pm 0.45) \times 10^{-6}$ lies within the error range of the optical depth determined by Udalski et al. (1994) from the OGLE data: $(3.3 \pm 1.2) \times 10^{-6}$. The bar mass is from our self-consistent bar model and is also consistent with the value based on virial analysis by Han & Gould (1994a). The fractional error in the observed optical depth will be significantly reduced once the detection efficiency of the MACHO experiment is reported. See Han & Gould (1994b) for a detailed error estimation.

Unlike the optical depth, the event timescale depends on both the lens mass function and the velocity distribution of lens and source. KP note that in their axisymmetric bulge model most of the events are expected to be of such short duration that they would not be detected in the OGLE experiment. Here we compute the predicted event distribution in our bar plus truncated disk model and determine whether the predicted events are consistent with the OGLE observations.

Following KP, we adopt a logarithmic mass function in the mass range $10^{-\gamma}\ M_\odot \leq m \leq M_\odot$ and treat γ as a free parameter. The differential lensing duration distribution $P(t_0)$ is then determined by the density distribution and the phase-space distribution,

$$P(t_0) \equiv \frac{d\Gamma(t_0)}{d \log t_0} = \frac{16G\epsilon(t_0)}{\gamma c^2 t_0} \left\langle \int_0^s g(v, D)\rho(l)D\, dl \right\rangle . \qquad (4)$$

Here the average is over the source distance. G and c are the gravitational constant and the speed of light, and $\epsilon(t_0)$ is the observation detection efficiency of events of timescale $t_0 \equiv R_{\rm E}/v$; for OGLE, we find $\epsilon(t_0) = 0.3 \exp[-(t_0/11\ {\rm days})^{-0.7}]$ is a convenient and good interpolation of values given in Udalski et al. (1994). The dimensionless factor g is the phase-space fraction of sources and lenses whose relative transverse speed satisfies

$$2r_{\rm low} D \leq v^2 t_0^2 \leq 2r_{\rm upp} D\ , \qquad (5)$$

where $r_{\rm low} = 2GM_{\rm low}c^{-2}$ and $r_{\rm upp} = 2GM_{\rm upp}c^{-2}$ are the Schwarzschild radii corresponding to the lower and upper mass cutoffs. In our calculations, we evaluate g by Monte Carlo integration over the six-dimensional phase space.

Before turning to our self-consistent bar model to compute g, we can estimate the event time distribution by approximating the transverse velocity distribution as a twodimensional Gaussian of dispersion σ_t for both the lenses and the sources:

$$g \approx \exp\left(\frac{r_{\rm low} D}{\sigma_t^2 t_0^2}\right) - \exp\left(-\frac{r_{\rm upp} D}{\sigma_t^2 t_0^2}\right) \approx \exp\left(-\frac{r_{\rm low} D}{\sigma_t^2 t_0^2}\right) . \quad (6)$$

The steep drop-off of g and $\epsilon(t_0)$ for short events, together with the t_0^{-1} drop-off for long events, implies that $P(t_0)$ peaks near

$$t_p = (t_\epsilon^2 + R_{\rm E}^2 \sigma_t^{-2})^{0.5} , \quad (7)$$

where the timescale $t_\epsilon = 7$ days is due to the steep drop-off of OGLE detection efficiency for very short events, and the characteristic Einstein radius $R_{\rm E}$ is (80 days × 100 km $\rm s^{-1})M_{\rm low}^{0.5} D_{\rm kpc}^{0.5}$. A more massive lens and a larger distance between the lens and the source makes a larger Einstein radius. Together with a lower transverse dispersion, it shifts the distribution toward longer duration. The Spaenhauer, Jones, & Whitford (1992) analysis of proper-motion data in Baade's window finds $\sigma_t \equiv (\sigma_l^2 + \sigma_b^2)^{1/2} = 150$ km s^{-1}. We estimate the value $D \simeq 0.75$ kpc for the average characteristic distance in the Dwek G2 model. A bar model dominated by brown dwarfs with a lower mass cutoff at $10^{-2}\ M_\odot$ predicts a peak in duration distribution at about 8 days, inconsistent with the distribution of OGLE's detected events. The observed event durations are between 8 and 62 days.

We can improve our estimate of event distribution by using Zhao's (1994) self-consistent bar which fits the G2 model of Dwek et al. (1994), the radial velocity and proper-motion dispersions at Baade's window (Sharples, Walker, & Cropper 1990; Spaenhauer et al. 1992; Zhao, Spergel, & Rich 1994), and a mean stellar rotation curve of slope 60 km s^{-1} kpc^{-1} (e.g., Izumiura et al. 1992). Our Galactic potential consists of the G2 model for the bar, a Miyamoto-Nagai potential for the disk, and an isothermal dark halo (Binney & Tremaine 1987). The bar mass is fixed at $2 \times 10^{10}\ M_\odot$ with a pattern speed of 60 km s^{-1} kpc^{-1} similar to the Binney et al. (1991) model. The disk parameters are fitted to the BS model, and the halo parameters are fixed so that the rotation curve is flat out to 20 kpc. The stellar distribution function is composed of the weighted sum of 6000 orbits, each of which has been run for 1024 orbit crossings. Quadratic programming (e.g., Merritt 1993) is used to assign weights to each of these orbits so that their sum reproduces the G2 model and the observed kinematics. We estimate a 10% error for the mass of the bar based on the radial velocity dispersion at Baade's window, 113 ± 6 km s^{-1} (Sharples et al. 1990).

In Figure 1 we plot the distribution of lens properties along the line of sight predicted from the Zhao (1994) model. The probability includes the disk lenses. As both the disk and the bar are truncated at 4 kpc, there is a break in lens density at the truncation point. Note that most of the lenses are at 6.25 kpc in the bulge, well in front of the sources. The large Einstein radius, together with the low transverse velocity dispersion at the most probable location of lenses, shifts the event distribution toward longer duration in the Galactic bar model.

Using this bar model, we can evaluate g directly by a Monte Carlo integration over the stellar distribution function. Combining this result with the reported OGLE efficiencies yields our prediction for the event duration distribution in the OGLE experiment. A truncated small–scale-length disk is also included in the calculation with a disk velocity distribution the same as that of KP. We compute the duration distribution $P_m(t)$ for the hypothetical case that all lenses have the same mass m and the detection efficiency is 100% for all event durations, and find that it can be well fitted by a polynomial,

$$\log P_m(t_0) = -0.5 \log m - 5.3 + 9.7x - 4.2x^2 + 0.42x^3 , \quad (8)$$

where $x = \log t_0 - 0.5 \log m$. Figure 2 compares the event

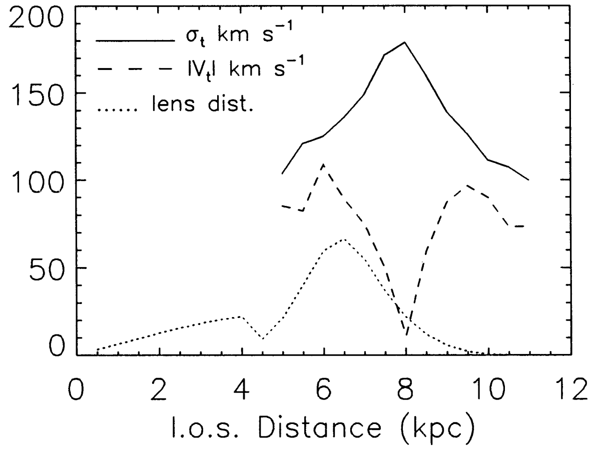

FIG. 1.—Predicted probability of lens location (*dotted line*; arbitrary scale) as a function of line-of-sight distance along Baade's window. We also show the transverse velocity distribution of stars in the bar: the dashed and solid lines show respectively the absolute value of the mean transverse speed $|V_t|$ and the dispersion σ_t in km s^{-1} as functions of distance. Note that the bar model predicts that most of the lenses are at 6.25 kpc in the bulge, where σ_t is also low. The break in lens density near 4 kpc is due to truncation.

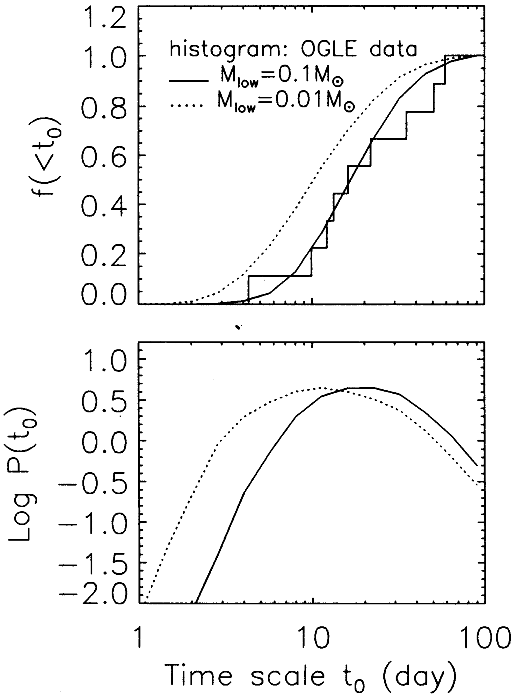

FIG. 2.—Event duration distributions of the OGLE data (*histogram*) and models with the lower mass cutoffs at $10^{-1}\ M_\odot$ (*solid line*) and $10^{-2}\ M_\odot$ (*dotted line*). The upper panel shows the fraction of events $f(<t_0)$ with duration shorter than t_0. The lower panel shows the predicted duration differential distribution per 10^6 bulge stars per year. The observations appear to favor the model with higher cutoff. The distribution by single mass lenses is given in eq. (8).

duration distribution between the OGLE data (Udalski et al. 1994) and models. The model with cutoff at 10^{-2} $M_{\odot}$ predicts too many short-duration events, consistent with the previous simple estimate; a Kolmogorov-Smirnov (KS) test finds only a 7% probability that it is consistent with the data. The observations appear to favor a higher cutoff; the model with a 10^{-1} $M_{\odot}$ cutoff predicts five to seven microlensing events detectable by OGLE with a typical timescale of 20 days. These results hint that there are few brown dwarfs in the bulge. A larger sample will enable a more definitive determination of the bulge mass function.

In summary, stars in the Galactic bar are the major source of optical depth for microlensing in the Baade's window fields monitored by the OGLE program. Using a self-consistent bar model that has been fitted to the DIRBE observations of the bulge surface brightness distribution and to the observed stellar kinematics, we have computed the optical depth toward Baade's window and the predicted event duration distribution. We find that the bar model provides a better fit to the microlensing observations than an axisymmetric model for the Galaxy. The optical depth of the bar model is consistent with the OGLE value. The OGLE observed event duration distribution also favors models with few brown dwarfs in the bulge.

If most of the lenses are ordinary stars, one generally sees the light from the lens as well as the source throughout a lensing event; a typical lens with 0.3 $M_{\odot}$ has $M_I \approx 10$ mag (Allen 1973), or $I \approx 25$ at 6.25 kpc along Baade's window assuming $A_I = 1$. One expects the lensing light curve to have a profile different from that of lensing by a MACHO, and there could even be a small fraction of color-shifted events (Kamionkowski 1994). With the detection of more microlensing events at several fields of the bulge and better understanding of the detection efficiency of the MACHO experiment, future observations can better constrain the mass distribution of the Galaxy and the lower end of the initial mass function (Evans 1994; Han & Gould 1994a, b; Kamionkowski 1994; Stanek 1994) and test the hypothesis that ordinary stars in the bar are the dominant microlenses.

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