Microlensing of disk sources

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Abstract

We analyse the effects on the predictions for the microlensing searches toward the Galactic bulge coming from the fact that not all the stars monitored belong to the bulge itself, but that a non–negligible fraction of them actually are in the Galactic disk. The different distribution and motions of these disk stars make their associated microlensing rates and event duration distributions to be quite different from those of the bulge stars. We discuss the uncertainties in these predictions associated to the modeling of the Galactic components and the main implications resulting from the inclusion of this second source population.

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Three experiments, MACHO (Alcock et al. 1995), OGLE (Udalski et al. 1994) and DUO (Alard et al. 1995), are actively searching for microlensing events in the direction of the Galactic bulge, and their observations are already providing important information on the morphology of the inner Galaxy. Essentially two lensing populations are believed to be responsible for the events: the objects in the disk and those in the bulge itself (Griest et al. 1991, Paczyński 1991, Giudice et al. 1994, Kiraga & Paczyński 1994). The large rates observed are most probably the result of the barred shape of the bulge (Kiraga & Paczyński 1994, Paczyński et al. 1994, Zhao et al. 1995, Han & Gould 1995), with the major bar axis making a small angle with respect to the line of sight to the Galactic centre. A disk close to maximal would also be helpful in explaining the large rates observed.

Up to now, an assumption made in all theoretical analyses is that the source population consists of the bulge stars alone. However, it is known that, in the fields observed, a non–negligible fraction of the source stars actually belong to the disk. For instance, Terndrup (1988) estimated that 15% of the red giant stars in Baade’s Window, at $b = -3.9^\circ$ and $l = 1^\circ$, belong to the disk. Probably this fraction is even larger for main sequence stars in the same field, due to the younger age of the disk. The fraction of disk stars should increase in fields at larger longitudes and similar latitudes, where microlensing observations are also carried out. It is our purpose in this letter to discuss the possible implications of this second source population for the analyses of microlensing results.

Let us assume that, in a given field, a fraction $f$ of the monitored stars belong to the disk, while $1 - f$ is the fraction of bulge stars. We denote $\tau_{ls}$ the optical depth to microlensing of disk or bulge sources ($s = D, B$) arising from disk or bulge lenses ($l = D, B$). Hence, the total optical depth is just

$$\tau = f[\tau_{DD} + \tau_{BD}] + (1 - f)[\tau_{DB} + \tau_{BB}].$$

We recall that the optical depth is averaged over the source distribution (Kiraga & Paczyński 1994)

$$\tau_{ls} = \frac{1}{N_s} \int_0^{D_{max}} dD_{os} \frac{dn_s}{dD_{os}} \int_0^{D_{os}} dD_{ol} \frac{4\pi G}{c^2 D_{os}} \rho_l D_{ol} (D_{os} - D_{ol}),$$

where $D_{os}$ and $D_{ol}$ are the observer distances to the source and the lens respectively, $\rho_l$ is the lens mass density, $dn_s/dD_{os} \propto \rho_s D_{os}^{2-2\beta}$ describes the number density profile of detectable sources along the line of sight (Kiraga & Paczyński 1994), and the normalization factor is $N_s = \int_0^{D_{max}} dD_{os} dn_s/dD_{os}$. The parameter $\beta$ arises because the fraction of sources with luminosities larger than $L$ is assumed to scale as $L^{-\beta}$. A reasonable range has been estimated to be $\beta = 1 \pm 0.5$ in Baade’s Window (Zhao et al. 1995), valid for $4 \text{kpc} < D_{os} < 12 \text{kpc}$. We will adopt in our discussion $\beta = 1$, using this value also for nearby sources in the disk ($D_{os} < 4 \text{kpc}$), for which actually $\beta$ should be somewhat smaller, since we do not expect the main results to change significantly with this last assumption.

We will adopt for the disk distribution a double exponential profile with constant scale height 325 pc (Bahcall 1986), scale length 3.5 kpc and local density, in lensing objects, $\rho_d = 0.1M_\odot/\text{pc}^3$, assuming hereafter that the solar galactocentric distance is $R_0 = 8.5$ kpc. We will show results for $D_{max} = 12$ kpc and 6 kpc, this last value in order to illustrate the possible effects of having a ‘hollow’ disk, as could be suggested by a certain deficit of disk stars beyond $D_{os} \simeq 3$ kpc inferred from the color–magnitude diagram (CMD) in
Table 1: Contributions to the optical depth $\tau_{ls} \times 10^{-6}$, rates $\Gamma_{ls}$ (in events/10$^6$ stars yr) and average event durations $\langle T \rangle$ (in days), for lens and source populations in the disk (D) or bar (B). For $\Gamma$ and $\langle T \rangle$ we assume lenses of mass $m = 0.2 M_\odot$ and use the OGLE efficiency. The first three columns are for Baade’s Window, the last three for $l = +10^\circ$ and $|b| = 3^\circ$.

<table>
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<th>$ls$</th>
<th>$D_{max}$ [kpc]</th>
<th>$\tau_{ls}$</th>
<th>$\Gamma_{ls}$</th>
<th>$\langle T \rangle$</th>
<th>$\tau_{ls}$</th>
<th>$\Gamma_{ls}$</th>
<th>$\langle T \rangle$</th>
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<td>22</td>
<td>0.46</td>
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observations toward the bulge (Paczyński et al. 1994b). We note that these observations may also suggest that the scale height is smaller toward the centre (see also Kent et al. 1991). Finally, measurements of the scale length provide values in the wide range from 1.8 to 6 kpc (Kent et al. 1991), further increasing the uncertainties associated to disk models. However, the hollow and non–hollow disk models considered already span a representative range of possible expected results.

For the bulge stars, we will use the bar model of Dwek et al. (1995), obtained from COBE–DIRBE maps of the Bulge. The existence of a bar was initially suggested by several bulge observations, including an asymmetry in the infrared surface brightness distribution and in the star luminosities at positive and negative longitudes, and also to explain the non–circular gas motions observed (Spergel 1992). We adopt a total bar mass $M_{bar} = 2 \times 10^{10} M_\odot$, in the upper range of different dynamical estimates (see however Blum 1995), as suggested by microlensing observations. The optical depths and rates due to bar lenses are of course proportional to $M_{bar}$, while the event durations are insensitive to it. The angle between the bar major axis and the direction to the Galactic centre is taken to be $\alpha = 20^\circ$, in the middle of the range $\alpha = 20^\circ \pm 10^\circ$ obtained by Dwek et al.. We take the same velocity dispersion of bar objects as in Han & Gould (1995).

In the third column of Table 1 we give the predictions for the different components of the optical depth toward Baade’s Window. Since the optical depth of disk sources, $\tau_D \equiv \tau_{DD} + \tau_{BD}$, is always smaller than the one for bulge sources, $\tau_B \equiv \tau_{DB} + \tau_{BB}$, taking into account the disk sources will lead to a smaller theoretical prediction for the total depth than in the case $f = 0$. This in turn will imply an underestimate, as noted by Bennet et al. (1994), of the required $\tau_B$, and hence of the inferred bar and/or disk total mass normalizations required. For instance, if we assume $f = 20\%$ in Baade’s Window, $\tau$ is a factor $0.92$ smaller than $\tau_B$ if $D_{max} = 12$ kpc is considered, while it is a factor $\simeq 1 - f = 0.8$ smaller if $D_{max} = 6$ kpc, since $\tau_D$ turns out to be very small in this case. We also see that $\tau_D$ is very sensitive to $D_{max}$, but $\tau_B$ has a milder dependence on it which arises only through $\tau_{DB}$. 

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We turn now to discuss the rates and event duration distributions. Of course, the rates have a similar decomposition as the optical depth in eq. (1). In Fig. 1 we show the differential rate for the different components as a function of the event duration, for Baade’s Window observations. We assume $D_{\text{max}} = 12$ kpc and take for definiteness all lenses to have a common mass $m = 0.2 M_\odot$.

A crucial difference between the disk and bulge sources, besides their spatial distribution, is their motion. Since disk objects have small velocity dispersion, here taken to be $\sigma = 30 \text{ km/s}$, and a similar global motion due to rotation as the observer’s one, $DD$ type events are expected to have particularly long durations when $D_{\text{os}} < R_0$. These long duration events in $\Gamma_{DD}$, centered around $40 \div 80$ d, can clearly be identified in Fig. 1. There is a second contribution to $\Gamma_{DD}$ at smaller times ($\sim 5 \div 30$ d), due to events where the source star lies at $D_{\text{os}} > R_0$, so that it is moving in the opposite direction than most of the disk lenses, which are at $D_{\text{ol}} < R_0$. We assumed the circular speed of the disk to be everywhere 220 km/s, and we expect small modifications of the results obtained due to the slower actual rotation in the very inner bulge. It is apparent from Fig. 1 that the rates associated to disk stars are relatively more important at longer event durations, since short duration events are overwhelmingly due to $\Gamma_{BB}$ (recall that the contributions to $\Gamma$ from disk and bulge sources are weighted by $f$ and $1 - f$ respectively, and that the observational efficiencies are generally very small for $T < 10 \text{ d}$).

In order to illustrate the dependence of the results in the assumptions done for Fig. 1, we show in Figs. 2 and 3 some variations of the assumed models. Fig. 2 considers the effect

\footnote{the local dispersion of disk stars is $\simeq 20$ km/s, but is larger toward the Galactic centre (see e.g. Lewis & Freeman 1989)}
Figure 2: As in Fig. 1, but for bar models with different lens masses, $m = 0.1M_\odot$ (BB1) and $m = 0.3M_\odot$ (BB3) and for Kent’s axisymmetric model with $m = 0.3M_\odot$ (KK3). We also show the $DD$ distribution for $m = 0.3M_\odot$. Of changing the lens mass as well as the bulge model. There is no reason to expect that the mass function of disk lenses will be similar to that of bulge lenses. As an example to illustrate the implications that this may have, we show the predictions for $BB$ lensing for masses $m = 0.1M_\odot$ (curve BB1) and $0.3M_\odot$ (curve BB3), and compare them to the prediction of $DD$ with $m = 0.3M_\odot$ (curve DD3). If both masses are $0.3M_\odot$, we have the same situation as in Fig. 1 slightly shifted to larger times (and with reduced rates). However, if the bar lenses have a mass smaller than the disk lenses, the relative contribution to the differential rate coming from the disk sources is more important at large times than before. Similar conclusions clearly follow if the total bar mass is actually smaller than the assumed $2 \times 10^{10}M_\odot$. In the same way, if the triaxiality of the bulge is reduced, the contribution coming from the bulge sources would be smaller than before. For instance, we show the predictions (KK3 curve) for bulge–bulge lensing adopting Kent’s axisymmetric model of the bulge (Kent 1992), obtained from Spacelab data, and assuming $m = 0.3M_\odot$. This model has a more centrally concentrated mass distribution and larger transverse velocity motions than the bar model, leading to shorter duration events and smaller rates. Similar results are obtained (Giudice et al. 1994, De Rújula et al 1995) with the spherically symmetric heavy spheroid model of Caldwell and Ostriker, in which the bulge is just the inner spheroid. Although these models fail to account for the observed optical depth to the bulge, Fig. 2 shows that any deviation of the bar model in the direction of the axisymmetric ones would tend to enhance the $DD$ contribution at large event durations.

Fig. 3 instead shows the effect of considering a ‘hollow’ disk. We depict, for $m = 0.2M_\odot$ as in Fig. 1, the $DD$ and $DB$ contributions for $D_{\text{max}} = 6$ and 12 kpc. Clearly the $BD$ contribution, not depicted, becomes negligible for $D_{\text{max}} = 6$ kpc. We see that the long
duration tail ($T > 30$ d) of the $DB$ rates is not greatly affected, since it is mainly due to lenses at $D_{ol} < 6$ kpc, far from the rapidly moving bulge sources. Instead, the $DD$ rates become suppressed, with the short duration events clearly disappearing.

In Fig. 4 we show the differential rate predictions at $|b| = 3^\circ$ and $l = \pm 10^\circ$, for $m = 0.2M_\odot$ and $D_{max} = 12$ kpc as in Fig. 1. The $DD$ contribution is not significantly changed with respect to the situation in Baade’s Window, except that the distinction between short duration events and long duration ones is less clear, due to the different transverse motion of disk objects at larger longitudes. The $BB$ rates turn out to be less important in these fields. The rates involving the bar change significantly in the two fields, due to the inclination of the bar, and make $\Gamma_{DB}$ quite important at negative longitudes, for the assumed $D_{max} = 12$ kpc value, while $\Gamma_{BD}$ (not plotted) becomes quite small. At positive longitudes, on the other hand, $\Gamma_{DB}$ is much smaller, $\Gamma_{BD}$ is sizeable, and the $DD$ contribution to the rate is the largest one for long duration events. Since the fraction of disk stars also increases with longitude, it becomes even more important to take the effects of disk sources into consideration in the microlensing searches in these fields.

The fact that $\Gamma_{BD}$ has the opposite behaviour than $\Gamma_{DB}$ in fields at positive and negative longitudes has the effect of reducing the asymmetric signatures in the microlensing maps of the bulge when disk source stars are taken into account. For instance, we obtain, for $D_{max} = 12$ kpc and $|b| = 3^\circ$, that $\tau(l = 10^\circ)/\tau(l = -10^\circ) \simeq 1.5$ if $f = 0$, while this ratio is $\simeq 0.94$ if we take $f \simeq 0.4$ (0.6) for $l = 10^\circ (-10^\circ)^2$. We note that the asymmetry of

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$2$We note that a rough estimate of the angular dependence of the fraction $f$, in clear windows, may be obtained as $f/(1-f) = \kappa N_D/N_B$, where $\kappa$ is a constant chosen such that $f \simeq 0.2$ at Baade’s Window, and $N_D$ and $N_B$ are the values of $N_s$ in eq. (2) computed for disk and bulge sources respectively. This leads to $f = 0.4$ (0.6) for $|b| = 3^\circ$ and $l = +10^\circ (-10^\circ)$. 

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Figure 3: Predictions for hollow ($D_{max} = 6$ kpc) and non–hollow ($D_{max} = 12$ kpc) disk models for Baade’s Window.
the individual contributions $\tau_{ls}$ between fields at positive and negative longitudes depends sensitively on the bar inclination assumed (and should disappear for $\alpha = 0$ clearly), but due to the above mentioned cancellations, it should be harder to get information on $\alpha$ from the asymmetries in the microlensing maps. However, the size of $\tau$ do depend on $\alpha$. For instance, the bar–bar optical depth at Baade’s Window takes the values $\tau_{BB}(\alpha = 30^\circ) = 0.97 \times 10^{-6}$, while $\tau_{BB}(\alpha = 10^\circ) = 1.74 \times 10^{-6}$, and hence the large rates observed suggest that the inclination is small.

Going back to Table 1, we show in the last five columns the total rates and average event durations, assuming $m = 0.2M_\odot$ and the observational efficiency of the OGLE experiment, for Baade’s Window and for a field at $|b| = 3^\circ$ and $l = +10^\circ$, as well as the optical depth in this last field. The average durations do not change significantly among the two fields, and reflect the behaviour of the differential rates just discussed in Figs. 1–4. From the total rates (including the efficiency), we may estimate the fraction $F$ of events which result from disk sources, which is just $F = f\Gamma_D/\Gamma$. For Baade’s Window, taking $f = 0.2$ we obtain $F \simeq 0.13$ if $D_{max} = 12$ kpc, while $F = 0.01$ if $D_{max} = 6$ kpc. In the field at $|b| = 3^\circ$ and $l = +10^\circ$ we obtain instead, assuming for illustrative purposes $f = 0.4$, that $F \simeq 0.39$ if $D_{max} = 12$ kpc, while $F = 0.08$ if $D_{max} = 6$ kpc. So, it is quite plausible that some of the events among the almost 100 events observed up to now are due to disk sources. This fact is interesting also because it has been suggested that there is actually a possible excess of long duration events with respect to the predictions made with $\Gamma_B \equiv \Gamma_{DB} + \Gamma_{BB}$ alone (Han & Gould 1995b). The long duration events associated to disk sources may help in this respect, since the total $d\Gamma/dT$ distribution has an enhanced tail at large $T$. Finally, the fact that the time distribution of events is different when the disk sources are taken into account also affects the determination of the mass functions of the disk and bulge lens populations.

Figure 4: Differential rates in fields at $|b| = 3^\circ$ and $l = \pm10^\circ$, assuming $m = 0.2M_\odot$ and $D_{max} = 12$ kpc.
In the longer term, it may become possible to get, with enlarged statistics, more information about the microlensing from the disk source population, considering the lensing effects of stars in certain regions of the CMD. In particular, the bluer end of the main sequence and the brightest red clump stars, should in their majority be foreground disk stars (Paczyński et al. 1994b). In the same way, considering only the region of the CMD where the bulge red clump stars lie, it is possible to minimize the contamination of disk stars (Bennet et al. 1994), though never eliminate it\(^3\). Moreover, the study of line of sight velocity dispersions of the lensed sources, and eventually of their proper motions, should also help to deduce their identity (Terndrup et al. 1995). Stars in a bar should have particularly large line of sight dispersion while the dispersion of disk stars should be much smaller.

As a summary, we have considered the effects resulting from the fact that a fraction of the sources observed in microlensing searches toward the bulge belong to the disk. Since their optical depth is typically smaller than the one of bulge sources, the required \(\tau_B\) needs to be larger than the measured optical depth, affecting then the model parameters inferred. This effect is maximum if the disk is hollow (assuming the same \(f\)), but is probably the only effect resulting from these disk models. If the disk is not hollow, the rates due to disk stars are also relevant. They are relatively more important for long duration events and will then modify the shape of the event duration distribution. The relative contribution from disk and bulge sources also depends on the mass function distributions of the two lensing populations, on the overall normalization of their densities and on the details of the bulge model. The contribution from disk sources increases with increasing longitudes, and can even become comparable to the one from bulge sources in the extreme field considered (\(l = 10^\circ, b = 3^\circ\)). For the barred model of the bulge, the longitude dependence of the rates has the opposite behaviour for disk sources than for bulge ones, reducing the overall asymmetries of the microlensing maps of the bulge.

\(^3\)It is interesting to note that this cut seems already to lead to a larger optical depth than the standard cut including all sources (Bennet et al. 1994).
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