Microlensing and Galactic Structure

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**Abstract.** Because we know little about the Galactic force-field away from the plane, the Galactic mass distribution is very ill-determined. I show that a microlensing survey of galaxies closer than 50 Mpc would enable us to map in three dimensions the Galactic density of stellar mass, which should be strictly less than the total mass density. A lower limit can be placed on the stellar mass needed at \( R < R_0 \) to generate the measured optical depth towards sources in the bulge. If the Galaxy is barred, this limit is lower by a factor of up to two than in the axisymmetric case. Even our limited knowledge of the Galactic force field suffices to rule out the presence of the amount of mass an axisymmetric Galaxy needs to generate the measured optical depth. Several lines of argument imply that the Galaxy is strongly barred only at \( R < 4 \) kpc, and if this is the case, even barred Galaxy models cannot generate the measured optical depth without violating some constraint on the Galactic force-field. Galactic mass models that are based on the assumption that light traces mass, for which there is significant support in the inner Galaxy, yield microlensing optical depths that are smaller than the measured value by a factor of more than 2.5.

1. **Introduction**

Notwithstanding the difficulties to which heavy obscuration by dust gives rise, we now have a reasonable idea of how luminosity is distributed in the Galaxy. We know we live in a galaxy that has a bar, \( 3 - 4 \) kpc long, whose nearer end lies at positive longitudes. Within the bar there is a moderately flattened component in which the luminosity density rises roughly as \( r^{-1.8} \) with decreasing galactocentric radius \( r \). Around the bar there is a roughly exponential disk with scale length \( \sim 3 \) kpc, and a moderately flattened metal-poor halo in which the luminosity density varies as \( \sim r^{-3.5} \).

The situation regarding the Galactic distribution of mass is very much less satisfactory. Observations of external galaxies and cosmological theory have convinced us that light is not a good tracer of mass. Hence we cannot straightforwardly translate our models of the luminosity distribution into models of the mass distribution; in principle, we should start afresh and derive the mass distribution by tracing out the Galaxy’s gravitational field \( \mathbf{F}(r) \) and then applying the divergence operator: \( \nabla \cdot \mathbf{F} = -4\pi G\rho \).
From observations of gas that flows in the Galactic plane we have a fair idea of what $\mathbf{F}(r)$ looks like at points $r$ within the plane, but we have very little secure knowledge of $\mathbf{F}$ out of the plane. This deficiency is serious, because until we know $\mathbf{F}$ away from the plane, we cannot apply $\nabla$ anywhere, and can say nothing with security about $\rho$ anywhere!

What we currently know about $\mathbf{F}$ out of the plane relates to points near the Sun. Crézé et al. (1998) and Holmberg & Flynn (2000) have used proper motions of Hipparcos stars to estimate the gradient of $F_z$ near the plane and hence infer that the local mass density is $0.076 \pm 0.015 \, \text{M}_\odot \, \text{pc}^{-3}$ and $0.10 \pm 0.01 \, \text{M}_\odot \, \text{pc}^{-3}$, respectively, while Kuijken & Gilmore (1991) have used the radial velocities of stars at the SGP to estimate $F_z$ at $z = -1.1 \, \text{kpc}$ and thus infer that the surface density of the Galaxy within $1.1 \, \text{kpc}$ of the plane is $71 \pm 6 \, \text{M}_\odot \, \text{pc}^{-3}$. To constrain $\mathbf{F}$ at points that lie far from the Sun, we have to study objects that move to such points. High-velocity stars are the obvious tracers to use, because they are so numerous. They strongly constrain models of $\mathbf{F}$ because stars on essentially the same orbit can be studied both locally and in situ (Binney, 1994; Dehnen & Binney, 1996). Unfortunately, the potential of this approach has yet to be systematically exploited. Recently, there has been considerable interest in using tidal streamers associated with disrupted satellites as tracers of $\mathbf{F}$ (Johnston et al. 1999, Helmi et al. 1999). My own view is that high-velocity stars have greater potential because (a) they are vastly more numerous and (b) they do not require approximations of the level of the (manifestly false) assumption that all elements of a streamer are on the same orbit. Moreover, extracting useful information from streamers requires space-based astrometry, the requisite observations high-velocity stars are available now, and all that’s lacking is machinery for modelling them.

Gravitational microlensing directly probes the Galaxy’s mass distribution, but in a very different way from classical studies of gas and stars. In fact, microlensing does not measure the smooth Galactic force-field $\mathbf{F}$ but graininess in the mass distribution. Hence, it is insensitive to the contribution to the latter from elementary particles and gas, and is therefore complementary to the traditional approach to the determination of $\rho$ from $\mathbf{F}$, rather than competitive with it.

## 2. From optical depth to stellar density

The optical depth to microlensing of a stellar object at distance $s_0$ is

$$\tau = \frac{4\pi G}{c^2} \int_0^{s_0} ds \rho_* \hat{s},$$

(1)

where

$$\hat{s} = \left(\frac{1}{s_0 - s} + \frac{1}{s}\right)^{-1}$$

(2)

is the harmonic mean of the source-lens and lens-observer distances. If the source is extragalactic, $\hat{s} \simeq s$, and $\tau$ becomes proportional to $\int ds \rho_* s$ in the direction of the source. Suppose we measure $\tau$ along many lines of sight all over the sky. Can we reconstruct $\rho_*$ from the data?
Figure 1. Contours of equal microlensing optical depth for a distant source for two Galactic models. There are two contours per decade and the heavy contour is for $\tau = 10^{-6}$. The upper panel is for the model one obtains from the luminosity model of Kent, Dame & Fazio (1991) with an assumed mass-to-light ratio $\Upsilon_K = 1$. The lower panel is for Model 1 of Dehnen & Binney (1998), and all components, including the dark halo, have been assumed to contribute fully to $\tau$. Consequently, the optical depth at large $|b|$ is larger in the lower than in the upper panel.
With some simplifying assumptions, we can. Binney & Gerhard (1996) show that if the Galactic luminosity density \( j(r) \) is symmetric about the Galactic plane and two other, orthogonal planes (as it would be if it were triaxially ellipsoidal), then a Richardson–Lucy algorithm can be used to recover \( j(r) \) from its line-of-sight projection, \( I(\Omega) = \int ds \, j(s) \), at each point \( \Omega \) on the celestial sphere. It is straightforward to modify the derivation of Binney & Gerhard to show that, with the same assumptions regarding symmetry, a Richardson–Lucy algorithm for the recovery of \( \rho^* \) from \( \tau(\Omega) \) is

\[
\rho^{(k+1)}(r) = \rho^{(k)}(r) \sum_{i=1}^{8} \frac{\tau(\Omega_i)}{\tau^{(k)}(\Omega_i)} \frac{1}{s(r_i)} / \sum_{i=1}^{8} \frac{1}{s(r_i)}. 
\]  

(3)

Here the sum over \( i \) is over the eight points \( r_i \) that are connected to \( r \) by the assumed symmetry of \( \rho^* \); the lines of sight to these points are in the directions \( \Omega_i \), and their distances from the Sun are \( s(r_i) \).

While it is in principle possible to recover \( \rho^* \) from \( \tau \), it is not clear that this will ever be done. The problem is the small numerical factor in front of the integral in (1). Numerically,

\[
\tau = 6 \times 10^{-6} \left[ \frac{\int_{s_0}^{s_1} ds \, \rho^* s}{10^{10} M_\odot/kpc} \right],
\]  

(4)

where we have again assumed that the source is extragalactic. Figure 1 plots \( \tau \) for two typical Galactic models. The model underlying the upper panel is the \( K \)-band luminosity model of Kent, Dame & Fazio (1991), which has been converted into a model of the stellar mass distribution by assuming a mass-to-light ratio \( \Upsilon_K = 1 \), which appears to be correct for the solar neighbourhood (§10.4.4 of Binney & Merrifield 1998). One sees that \( \tau \) exceeds \( 10^{-6} \) only for lines of sight at fairly low latitudes.

Existing data indicate that the duration of a microlensing event is typically tens of days, so in an observing season one obtains at most a handful of statistically independent observations per line of sight. Hence, in a given area of the sky the number of lines of sight that must be monitored for of order years to distinguish \( \tau \) from zero is \( \sim 1/\tau \gtrsim 10^6 \). Finding this number of extragalactic sources in each of a large number of patches of the sky is hard. Probably our best chance is offered by 'pixel lensing' towards nearby galaxies. Gould (1996) gives the necessary theory and I adopt his notation. A large rôle is played in this by the effective stellar flux \( F_* \), which is defined in terms of the stellar luminosity function \( \phi \) by

\[
F_* = \int dF \, \phi(F) F^2 / \int dF \, \phi(F) F. 
\]  

(5)

Per resolution element on a galaxy image, the rate at which microlensing events can be detected above a signal-to-noise threshold \( Q_{\text{min}} \) is

\[
\Gamma = \frac{2\kappa \xi}{Q_{\text{min}}^2} \tau \alpha F_*,
\]  

(6)

where \( 1 > \kappa, \xi \) are dimensionless functions, and \( \alpha F_* \) is the rate at which the telescope detects photons from an object of flux \( F_* \). In terms of the surface
brightnesses of galaxy and sky $S$ and $S_{sky}$, we have $\kappa \equiv (1 + S_{sky}/S)^{-1} \simeq S/S_{sky}$ over most of a galactic image. The value of $\xi$ depends on the degree to which the image is resolved into stars: if a significant part of the integral on the top of equation (5) comes from stars bright enough that lensing of them can be detected even at large impact parameter ($u \gtrsim 0.25$), then $\xi$ is small, with $\xi \sim 1$ otherwise.

Gould shows that if one is interested only in measuring $\tau$ regardless of the masses of the lenses that generate it, the optimal observational strategy is to work in the regime $\xi \sim 1$ in which one detects only high-magnification events. We shall be in this regime provided

$$ \frac{\kappa \alpha F^2}{\omega F_{psf}} < \frac{Q^2_{\min}}{4\pi}, $$

where $\omega$ is the rate constant of a typical microlensing event and $F_{psf}$ is the flux in a resolution element of the galactic image. How big will these quantities be in a typical case? Suppose we are using a diffraction-limited telescope of diameter $D$ to study a galaxy of distance $s$ at radius $R_{25}$, where the $V$-band surface brightness will be $\sim 24$ mag arcsec$^{-2}$. Gould gives the absolute magnitude corresponding to $F_*$ as

$$ M_{\ast I} = -4.84 + 3(V - I) $$

and estimates that from a star with $I = 20$ our telescope will collect photons at a rate $10(D/1\, \text{m})^2\, \text{s}^{-1}$. Hence,

$$ \alpha F_\ast = 10 \left( \frac{D}{1\, \text{m}} \right)^2 10^{-0.4(30-20-4.84+3(V-I))} \left( \frac{s}{10\, \text{Mpc}} \right)^{-2}. $$

The $I$-band flux in the telescope’s resolution element is

$$ F_{psf} = F_0 10^{-0.4(24-(V-I))} \left[ 0.206 \left( \frac{\lambda/1000\, \text{nm}}{D/1\, \text{m}} \right) \right]^2, $$

where $F_0$ is some universal constant. We can express $F_\ast$ in terms of this same constant and $M_{\ast I}$ thus

$$ F_\ast = F_0 10^{-0.4(30-4.84+3(V-I))} \left( \frac{s}{10\, \text{Mpc}} \right)^{-2}. $$

When we substitute equations (9), (10) and (11) into equation (7) and assume (Table 4.4 of Binney & Merrifield, 1998)

$$ \kappa \sim 10^{-0.4(4-(V-I))} $$

and $V - I \sim 1.25$ (de Jong, 1995) the condition to be in the high-magnification regime becomes

$$ 10.4 \left( \frac{D}{1\, \text{m}} \right)^4 \left( \frac{s}{10\, \text{Mpc}} \right)^{-4} \left( \frac{\lambda}{1000\, \text{nm}} \right)^{-2} \left( \omega \right)_{\text{week}}^{-1} < \frac{Q^2_{\min}}{4\pi}. $$
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Gould finds that $Q_{\text{min}} \sim 7$ is required for detection, so this condition is satisfied for $D \lesssim 4$ m and $s \sim 50$ Mpc. By equations (8), (11) and (12) the event rate in this regime is

$$\Gamma = \frac{2\tau}{Q_{\text{min}}^2} 10^{-0.4(0.66+2(V-I))} \left(\frac{D}{1 \text{ m}}\right)^2 \left(\frac{s}{10 \text{ Mpc}}\right)^{-2} \text{s}^{-1}$$

$$\frac{262\tau}{Q_{\text{min}}^2} \left(\frac{D}{1 \text{ m}}\right)^2 \left(\frac{s}{10 \text{ Mpc}}\right)^{-2} \text{week}^{-1}$$

(14)

Hence, by directing a 4 m telescope along a line of sight with $\tau = 10^{-6}$, we should be able to detect three to four events per $10^6$ resolution elements per week. In fact a somewhat higher event rate could be achieved if the telescope were in space, because the event rate is inversely proportional to the sky brightness, which will at least 2 mag fainter in space than the ground-based value I have assumed.

If the PSF of the telescope has FWHM of $x$ arcsec, a galaxy of diameter $y$ arcmin offers $3600(y/x)^2$ pixels to monitor. An $L_*$ galaxy at a distance of 50 Mpc has $y \sim 1$, and will provide $10^8$ pixels if $x \sim 0.06$. Thus, a diffraction-limited telescope of modest aperture monitoring galaxies within 50 Mpc for of order a year could map $\tau$ sufficiently extensively for it to be possible to recover $\rho_*$ from a scheme such as (3).

Of course, the values of $\tau$ recovered from such a survey would include contributions from self-lensing within the target object in addition to the optical depth through the Milky Way. As Crotts (1992) pointed out in relation to pixel lensing of M31, variations in $\tau$ across the image of an highly inclined galaxy would help one to determine how much self lensing occurs in galactic halos rather than in disks or bulges. Consequently, the analysis of the data from the survey would proceed by modelling in some detail the distribution of $\tau$ in each target galaxy, with the Milky Way’s contribution in that direction as a single number to be fitted to a considerable body of data.

### 3. Real data

Before we lobby NASA and ESA for a dedicated microlensing space telescope, we should ask what can be learned from the existing microlensing data. Three areas of the sky have been monitored: (i) towards the Galactic bulge; (ii) towards some spiral arms; and (iii) towards the Magellanic Clouds.

If one believes that the dark halo is comprised of elementary particles, only a very small optical depth is predicted towards the Clouds ($\sim 4 \times 10^{-8}$). At $1.2^{+0.4}_{-0.3} \times 10^{-7}$ the measured optical depth is about three times larger, but still deriving from only 17 events (Alcock et al. 2000a). The nature of these events is controversial. There is a powerful case that many of the lenses lie in the Clouds themselves (Kerins & Evans, 1999) because the only two lenses with reasonably securely determined distances (from finite-source effects) do lie in the Clouds. On the other hand, Ibata et al. (1999) may have detected a substantial population of old white dwarfs from their proper motions in the HDF. It is just possible that these objects provide the lenses for a significant number of the observed
events. The arguments against a large column density in white dwarfs remain powerful, however (Gibson & Mould 1997).

The EROS collaboration (2000) has observed seven probable microlensing events in the directions of spiral arms, and from them derived an optical depth $4.5^{+2.4}_{-1.1} \times 10^{-7}$ that is compatible with conventional Galaxy models. Unfortunately, the error bar on this measurement is rather large.

3.1. The Galactic centre

Several hundred events have been detected by various groups along lines of sight towards the Galactic centre, and these data pose a fascinating puzzle. They are harder to interpret than the data for lines of sight to the Clouds because we do not know a priori where the sources are. However, if we confine ourselves to the data for red-clump stars, we can have quite a precise estimate of their distribution down each line of sight.

The red-clump stars must follow the general distribution of near infra-red light quite closely, because they are part of the population of evolved stars that are responsible for most of the Galaxy’s near-IR luminosity. The DIRBE experiment aboard the COBE satellite mapped the Galaxy’s IR surface brightness in several wavebands, and in the far-IR, where emission by dust is dominant. Spergel, Malhotra & Blitz (1996) used these data to estimate the effects of extinction on the near-IR data, and produce maps of what the Galaxy would look like in the near-IR bands in the absence of extinction.

Binney, Gerhard & Spergel (1997) used their Richardson–Lucy algorithm to deproject these corrected near-IR data under the assumption that the Galaxy has three specified perpendicular planes of mirror symmetry. The upper panel of Figure 2 shows the luminosity density that they recovered when projected perpendicular to the plane from $z = 225$ pc upwards. Excluding the Galactic plane from the projection suppresses local maxima at $\sim 3$ kpc along the $y$ that are a notable feature of the density distribution in the plane (see Fig. 5 of Binney et al.). Binney et al argued that these maxima were artifacts resulting from the presence in the Galactic plane of spiral arms, which violate the assumed eight-fold symmetry.

Bissantz & Gerhard (2000) have recently deprojected the same data with an entirely different technique. Rather than using the Richardson–Lucy algorithm, they formulate the deprojection problem as a regularized likelihood maximization. They do not directly impose any symmetry on the model but have a term in the penalty function that discourages deviations from eight-fold symmetry. Another term in the penalty function encourages luminosity to lie along the spiral arms delineated by Ortiz & Lepine (1993).

The lower panel in Figure 2 shows that explicitly modelling the Galaxy’s spiral structure in this way has the effect of making the bar longer and thinner than that recovered by Binney et al. (1997) – the axis ratio in the plane increases from 2:1 to 3:1. This change to the model bar enables the latter to reproduce an important datum that the Binney et al bar did not reproduce: the histograms from Stanek et al. (1994) that give for lines of sight at $l \simeq \pm 5^\circ$ the number of clump stars at each apparent magnitude – see Figure 3. The ability of the model to reproduce these histograms to good accuracy strongly suggests that the model gives a faithful account of the distribution of red-clump stars. Hence,
Figure 2. Top panel: the Galaxy in the $L$ band projected perpendicular to the plane from $z = 225$ pc upwards according to the model of Binney et al. (1997). Lower panel: the same view according to the model of Bissantz & Gerhard (2000). In both plots contours are logarithmically spaced. In the upper plot there are three contours per decade, while below contours are explicitly labelled.
Figure 3. Predicted (curves) and measured (points) apparent-magnitude distribution of clump stars along three lines of sight through the bulge. The predictions are based on the model of Bissantz & Gerhard (2000).

when this model is used to predict the microlensing optical depth to red-clump stars, we may be confident that any discrepancy does not arise from an incorrect distribution of source objects.

Bissantz & Gerhard convert their luminosity model of the inner Galaxy into a mass model by adopting the constant near-IR mass-to-light ratio $\Upsilon$ of Englmaier & Gerhard (1999). This value of $\Upsilon$ was obtained by comparing the pattern of gas flow predicted by the Binney et al. model for some assumed $\Upsilon$ to the observed $(l,v)$ diagrams for HI and CO; if Bissantz & Gerhard were to repeat this exercise with their new photometric model, they would surely obtain a very similar value of $\Upsilon$. Once $\Upsilon$ has been chosen, one can calculate the microlensing optical depth for red-clump stars along any line of sight. In Baade’s window they obtain $\tau = 1.24 \times 10^{-6}$, which is essentially identical to the value obtained by Bissantz et al. (1997) from the shorter, fatter bar of Binney et al. (1997), and significantly short of the values from the MACHO collaboration: $\tau = 3.9^{+1.8}_{-1.2} \times 10^{-6}$ (1$\sigma$) directly measured for bulge clump giants by Alcock et al. (1997) and $(3.9 \pm 0.6) \times 10^{-6}$ estimated by Alcock et al., (2000b) for bulge stars from a difference-imaging analysis of an inhomogeneous collection of sources. Evidently one cannot obtain agreement with the MACHO optical depth under the assumption that mass follows light.

Since the difference between the optical depth implied by constant $\Upsilon$ and the measured value is so large, it is natural to investigate an extreme model in which we ask, what is the minimum mass that is compatible with the red-clump optical depth attaining the MACHO value? Most of the red-clump sources lensed in
Baade’s window \((l, b) = (1°, -4°)\) lie close to the Galaxy’s \(z\) axis, so we simplify the calculation by considering a source that lies distance \(h\) from plane on the axis. Consider the contribution to \(\tau\) from a band of mass \(M\) and radius \(r\) around the Galactic centre. If we assume that the band’s surface density never increases with distance from the plane, then its mass will be minimized for a given optical depth when its surface density is constant and the line-of-sight to the source just cuts its edge. So we take the band’s half-width to be \(h(R_0 - r)/R_0\), which makes the band’s surface density

\[
\Sigma = \frac{M}{4\pi rh} \left(1 - \frac{r}{R_0}\right)^{-1}.
\]  

(15)

Substituting this into equation (1) we find the band’s optical depth to be

\[
\tau = \frac{GM}{c^2h}
\]  

(16)

independent of radius (Kuijken, 1997). This minimum mass estimate holds if the mass is widely distributed in radius rather than concentrated in a single band, because we can imagine a radially continuous mass distribution to be made up of a large number of bands, and we have shown that when the band is optimally configured, its optical depth depends only on its mass.

From equation (16) \((3.8 \pm 0.6) \times 10^{10} \, M_\odot\) is needed to produce the optical depth, to bulge sources that is implied by the latest MACHO results. A more realistic mass estimate is in excess of \(8 \times 10^{10} \, M_\odot\) because realistically we must assume that the surface density of the band falls off smoothly with distance from the plane, and if this decline is exponential with the optimal scale-height \((h[1 - r/R_0])\), the band’s mass must be \(e\) times that given by (16) for a given optical depth, while if the vertical density profile is Gaussian with optimal scale-height \((h[1 - r/R_0])\), equation (16) underestimates the band’s mass by a factor \(\sqrt{\pi e^2/2} \approx 2.07\).

For comparison, the mass of the Galaxy interior to the Sun is of order \(M = (220 \, \text{km} \, \text{s}^{-1})^2 \times 8 \, \text{kpc}/G \approx 8.9 \times 10^{10} \, M_\odot\). Thus this naivest estimate of the mass interior to the Sun is just barely equal to the minimum mass required in a circular configuration to produce the reported optical depth, which suggests that an axisymmetric Galaxy is incompatible with the MACHO results. This must be a tentative conclusion, however, until one has taken into account the effect on a body’s circular-speed curve \(v_c(r)\) of the body being strongly flattened. Binney, Bissantz & Gerhard (2000) show that it is possible to choose the Galaxy’s radial density profile in such a way that the required optical depth is obtained without generating a value of \(v_c\) that conflicts with observation. However, such radial density profiles require more matter in the solar neighbourhood than observations of the Oort limit (Crézé et al, 1998; Holmberg & Flynn, 2000) and the mass within 1.1 kpc of the plane (Kuijken & Gilmore, 1991) imply. Consequently, we can safely conclude that an axisymmetric Galaxy cannot have as large an optical depth as that reported.

Can one achieve a higher optical depth within a given mass budget by making the bands elliptical rather than circular? Imagine deforming an initially circular band into an elliptical shape while holding constant the radius \(r\) at which the line of sight to our sources cuts the band. It is straightforward to show that if
the column density through the band to the sources is to be independent of the
band’s eccentricity $e$, its mass $M(e)$ must satisfy

$$M(e) = M(0) \frac{1 - e^2 \cos^2 \phi}{\sqrt{1 - e^2}},$$  \hspace{1cm} (17)

where $\phi$ is the angle between the band’s major axis and the Sun–centre line. For
$\phi < \pi/4$, $M(e)$ is a minimum with respect to $e$ at

$$e_{\text{min}} = \sqrt{2 - \sec^2 \phi}. \hspace{1cm} (18)$$

Substituting equation (18) in equation (17) we find the minimum mass to be

$$M_{\text{min}} = M(0) \sin 2\phi, \hspace{1cm} (19)$$

and to require axis ratio $q_{\text{min}} = \tan \phi$ (Zhao & Mao, 1996).

For $\phi = 20^\circ$, a value favoured by Binney et al. (1997), $q_{\text{min}} = 0.36$ and
$M_{\text{min}}/M(0) = 0.64$; for $\phi = 15^\circ$, we find $q_{\text{min}} = 0.27$ and $M_{\text{min}}/M(0) = 0.50$.
Hence, making the bands elliptical realistically reduces the mass required to
generate a given optical depth by at most 50%. In practice we cannot reduce our
requirement for mass by so large a factor because the structure of the Galaxy’s
stellar bar is strongly constrained by both near-IR photometry (Blitz & Spergel,
1991; Bissantz et al., 1997) and radio-frequency observations of gas that flows in
the Galactic plane (Englmaier & Gerhard, 1999; Fux, 1999). Binney et al. (2000)
estimate the possible reduction in mass by assuming that material at $R < 4 \text{kpc}$
forms a bar of optimal eccentricity whose long axis makes an angle of 20$^\circ$ with
the Sun–centre line, while the Galaxy is axisymmetric at $R > 4 \text{kpc}$. They show
that if the vertical structure of such a Galaxy is chosen to be optimal for lensing,
then a radial density profile can be found that nowhere exceeds the observed
value of $v_c$ and is also compatible with the constraints on the density of matter
at $R_0$. They argue, however, that such Galaxy models can be excluded for two
main reasons. First, they predict values of $v_c$ that are too small at $R \leq 350 \text{pc}$
because at small $R$ they place significant mass high above the plane, where it
contributes to $\tau$ but not $v_c$.
Second, these models do not leave enough room
in $v_c$ for (i) departures from the optimal vertical profile and (ii) the presence of
matter, such as interstellar gas and non-baryonic matter, that contributes to $v_c$
but not $\tau$.

Hence, even though we don’t know much about the Galactic force-field, we
know enough to exclude the measured optical depth in Baade’s window! In fact,
if we were to take seriously the prediction of simulations of the cosmological
clustering of CDM that dark matter contributes substantially to the mass inter-
ior to the Sun (e.g., Navarro & Steinmetz, 2000), our predicted optical depth
for Baade’s window would be significantly less than $10^{-6}$, a factor of 4 or more
below the measured value. Something is seriously wrong here.

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