

A NOTE ON THE MILKY WAY AS A BARRED GALAXY

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Abstract. We review recent research on the Milky Way galaxy and try to investigate whether its shape is similar to other barred galaxies. The emphasis is given on microlensing research because this method can be useful in determining the shape of the Galaxy with the minimal set of assumptions. By analyzing plots of the microlensing optical depth, τ as a function of galactic coordinates for different values of the axis ratio, q of the galactic halo, we have shown that observations are best described by a flattened halo with $0.2 \lesssim q \lesssim 0.6$.

1. INTRODUCTION

Over the last decade a growing list of evidence led us to accept the hypothesis proposed back in 1964 by de Vaucouleurs (e.g. Kuijken 1996): our Galaxy is a barred one. The arguments were initially based upon morphological considerations. The development of observational techniques broadens the possibilities of investigation of the central parts of the Milky Way in several research fields. All of them, however, confirm de Vaucouleurs' idea that the Milky Way is a SAB(rs) type galaxy, having a bar, weak rings, and a four-arms spiral structure (Vallée 1995).

We shall only mention here the following observational results (Kuijken 1996) that confirm these facts:

1. **photometric research** that include:
 - a) surface photometry (Blitz and Spergel 1991; Dwek *et al.* 1995); and
 - b) star counts (Gould, Bahcall and Flynn 1997; Nikolaev and Weinberg 1997)
2. **kinematical research** that include:
 - a) gas kinematics (Binney *et al.* 1991); and
 - b) stellar kinematics (Kuijken 1996, and references therein)
3. **gravitational microlensing (ML) researches.**

The existence of the bar successfully explains dynamical peculiarities observed in our Galaxy, and shows that they are normal features in a barred galaxy:

- stellar and gas dynamics in the Galactic center region (Binney *et al.* 1991),
- central activity definitely correlated with a presence of the bar in galaxies (Combes *et al.* 1995),
- a $2.6 \times 10^6 M_\odot$ black hole in the center of the Milky Way (Bower and Backer 1998; Falcke *et al.* 1998),
- the absence of HI and CO gas in the region $1.5 \text{ kpc} \leq r \leq 3.5 \text{ kpc}$, implying that the major axis of the bar is $r_{\text{bar}} \leq r_{\text{cr}}$, where $r_{\text{cr}} = 2.4 \text{ kpc}$ is the Milky Way's corotation radius (Binney and Tremaine 1987; Binney *et al.* 1991).
- a molecular ring at 3.5 kpc, which can be explained by gas accumulation near the outer Lindblad resonance radius ($r_{\text{OLR}} = 4.1 \text{ kpc}$ in Milky Way) (Binney *et al.* 1991; Freundreich 1998),
- asymmetry in the distribution of the red clump stars in the bulge (OGLE) (Stanek 1995),
- asymmetries of the bulge photometric image (COBE-DIRBE) (Dwek 1995, Binney, Gerhard and Spergel 1996), and
- excess of gravitational microlensing events compared to the theoretical estimates (Paczynski *et al.* 1994) in the galactic bulge direction.

All observations agree that the value of the bar inclination angle (to the Sun-Galactic Centre line) is between 10° and 30° .

In this paper we will discuss gravitational ML research and try to establish the connection between the inner parts of our Galaxy (bar) and its outer parts (halo) using this new observational technique. The ultimate goal is to see how the Milky Way as barred galaxy can be compared to other barred spirals and whether some conclusions concerning the shape of the Galaxy can be drawn.

2. BARYONIC DARK MATTER CONTENT OF THE GALAXY

The dark matter (DM) content of the Milky Way is still unknown. From shape of its rotation curve (RC) (Merrifield 1992) one can see that a huge amount of mass still has to be identified. The difficulties in the determination of the RC led to uncertainties in the most important parameters such as the galactic constant R_0 , which represents the distance to the Galactic center and the circular speed at the Solar radius, v_0 (Merrifield 1992, Olling and Merrifield 1998, Sackett 1997). Although the IAU 1986 standard values are: $R_0 = 8.5 \text{ kpc}$ and $v_0 = 220 \text{ km s}^{-1}$ some recent estimates allow the smaller values: $R_0 = 7.1 \pm 0.4 \text{ kpc}$ and $v_0 = 184 \pm 8 \text{ km s}^{-1}$ (Olling and Merrifield 1998). In this paper we adopt the value $R_0 = 8.5 \pm 0.5 \text{ kpc}$ (Feast and Whitelock 1997) based upon an analysis of Hipparcos proper motion of 220 Galactic Cepheids and $v_0 = 210 \pm 25 \text{ km s}^{-1}$ that includes the best values from the HI analysis ($v_0 = 185 \text{ km s}^{-1}$) and the estimated values based on the Sgr A* proper motion ($v_0 = 235 \text{ km s}^{-1}$) (Sackett 1997).

Without going into the discussions about the content of the DM in the halo, we only state here that one part (presumably smaller) has to be in the baryonic form. Namely, cosmic nucleosynthesis predicts that (Turner 1996):

$$0.008 \lesssim \Omega_B h^2 \lesssim 0.024 \quad (1)$$

where Ω_B is the universal baryonic mass-density parameter ($\Omega_B = 8\pi G\rho_B/3H_0^2$) and $0.4 \lesssim h \lesssim 1.0$. “Silent” h is used in parametrization of the Hubble constant $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$. Recent estimates (Fukugita, Hogan and Peebles 1998) give:

$$0.007 \lesssim \Omega_B \lesssim 0.041 \quad (2)$$

with the “best guess” $\Omega_B \sim 0.021$ (for $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

Using the simplest dynamical estimate of the mass of the Galaxy (Kepler’s third law):

$$GM(r) = v(r)^2 \quad (3)$$

where $M(r)$ is the mass interior to r , v is the measured rotational velocity and r is the radius within which most of the light in galaxy is emitted. For luminous matter one can obtain:

$$0.003 \lesssim \Omega_{\text{LUM}} \lesssim 0.007 \quad (4)$$

(Roulet and Mollerach 1997, and references therein). This is consistent with severe limits on mass-to-light ratio in the Local Group imposed by deep blank sky surveys (Richstone *et al.* 1992; Hu *et al.* 1994; Flynn, Gould and Bahcall 1996), as well as with huge dynamical mass for the Milky Way inferred by Kulessa and Lynden-Bell (1992).

The mass in the halo is dominated by the matter that is not, at least easily, detectable. So, one can write:

$$\Omega_{\text{HALO}} \gtrsim 0.1 \gtrsim 14 \Omega_{\text{LUM}}. \quad (5)$$

It can be seen the equations (2) and (4) that dark baryonic matter must exist; various types of such material have been suggested: gaseous clouds of plasma or neutral atoms and molecules, snowballs or icy bodies similar to comets, stars, planets, white dwarfs, neutron stars and stellar or primordial black holes (e.g. Peebles 1993).

3. MICROLENSING – METHODS AND RESULTS

In searches for the baryonic DM content the method of microlensing has so far proved successful. Its name derives from the fact that lensing of distant objects is made by bodies with masses characteristic of a star or planet. Although the theoretical development of this idea started in 1964 (e.g. Peebles 1993, and references therein), it was the seminal paper by Paczyński (1986) that showed that one can search for ML events in the Milky Way halo if it is made of stars or brown dwarfs. Rapid development of observational and computer technology led to the detection of a significant number of ML events (e.g. Mellier, Bernardeau and Van Waerbeke 1998). The directions include Large and Small Magellanic Clouds (LMC and SMC) (Alcock *et al.* 1996, 1997b; Palanque-Delabrouille *et al.* 1998), Galactic bulge (Kiraga and Paczyński 1994) and M31 (Crotts 1996).

All these surveys give results concerning two important parameters: masses of the intervening objects and the optical depth. In the Table 1 we give the targets observed,

names of the appropriate survey, mass ranges of the lenses, and corresponding optical depth.

Table 1. Targets in different ML surveys, the mass ranges of the lenses and optical depths.

Target	Survey	Mass range	Optical depth
LMC/SMC	MACHO	$\approx 0.3 - 0.5 M_{\odot}$	$\tau_{\text{LMC}} = 2.9_{-0.9}^{+1.4} \times 10^{-7}$ $\tau_{\text{SMC}} = 1.5 - 3 \times 10^{-7}$
Gal. bulge	MACHO:DUO:OGLE	0.08 - 0.6 M_{\odot}	$\tau_{\text{bul}} = 3.9_{-1.2}^{+1.8} \times 10^{-6}$
M31	KPNO	$\approx 10 M_{\odot}$	$\tau_{\text{M31}} = 5 - 10 \times 10^{-6}$
LMC/SMC	EROS2	0.85 - 8.7 M_{\odot}	$\tau_{\text{SMC}} = 3.3 \times 10^{-7}$

Another important quantity, the optical depth, τ is used in discussion of ML and as we shall show, in determining the shape of the halo. It can be defined as the probability that at a given time a source star is being microlensed with an amplification larger than 1.34 (e.g. Roulet and Mollerach 1997).

Here we wish to investigate in more details one property of the halo of the Milky Way that has often been neglected: its shape. It is known from the work of Sackett and Gould (1993) that instead of the equation for the mass density in a spherical halo:

$$\rho(\mathbf{r}) = \frac{v_{\infty}^2}{4\pi G} \left(\frac{1}{a^2 + r^2} \right) \theta(R_T - r) \quad (6)$$

(where r is the Galactocentric radius, v_{∞} is the asymptotic circular speed of the halo, a is the core radius of the halo and R_T is the truncation radius) one should use the generalized formula:

$$\rho(\mathbf{r}) = \frac{\tan \psi}{\psi} \frac{v_{\infty}^2}{4\pi G} \left(\frac{1}{a^2 + \zeta^2} \right) \theta(R_T - \zeta) \quad (7)$$

where $\zeta^2 = r^2 + z^2 \tan^2 \psi$ (z denotes height above the Galactic plane). Here the flattening parameter ψ is introduced: $\cos \psi = q = c/a$, i.e. its cosine is equal to the axis ratio and determines the shape of the halo En . En is related to q as $q = 1 - n/10$. Following Sackett and Gould (1993) we write the following expression for the estimate of the optical depth as a function of Galactic coordinates l (longitude) and b (latitude):

$$\tau(l, b) = \frac{\tan \psi}{\psi} \frac{v_{\infty}^2}{c^2} \frac{1}{D} \int_0^D \frac{dL(D-L)L}{(a^2 + R_0^2) - (2R_0 \cos l \cos b)L + (1 + \sin^2 b \tan^2 \psi)L^2} \quad (8)$$

where we put $R_0 = 8.5$ kpc and $a = 5$ (e.g. Alcock 1996). Now we integrate this equation and take $D = 50$ kpc (for LMC), $D = 63$ kpc (for SMC) and $D = 770$ kpc for M31. Although Sackett and Gould (1993) take values for q starting with $q = 0.4$ (shape E6) we will start with admittedly extreme value $q = 0.2$ (shape E8) required by some theories such as DDM (decaying dark matter) theory (Sciama 1997), based upon the recent Dehnen-Binney models of the Galaxy (Dehnen and Binney 1998). Attempts

were made to show that this small value of q is not possible since $q = 0.75 \pm 0.25$ (Olling and Merrifield 1997), but at the cost that $R_0 = 7.1 \pm 0.4$ kpc (Olling and Merrifield 1998). We will nevertheless take into account such small value for q since we find DDM theory acceptable in solving different serious astrophysical and cosmological problems (e.g. Sciama 1993).

There are several other lines of reasoning suggesting a high degree of halo flattening in spiral galaxies. One is for long time suspected (e.g. Ninković 1985) flattening of the Population II subsystem, which may be a consequence of the residual rotation, or more probably, global flattening of the gravitational potential created by dark matter. The other is the behavior of the gas distributed in the halo. If the seminal idea of Bahcall and Spitzer (1969) of extended gaseous halos of normal galaxies producing narrow absorption features in the spectra of background objects is correct, as indicated by recent low-redshift measurements (Bergeron and Boissé 1991; Lanzetta *et al.* 1995), then the distribution of gas could tell us something about the shape of the gravitational potential. It is not a simple problem at all (see Barcons and Fabian 1987), but some results are quite suggestive. In an important recent paper, Rauch and Haehnelt (1995) have shown that for the most plausible values of Ly α cloud parameters, the conclusion that their axial ratio (thickness/transverse length) is less than 0.25 is inescapable. This conclusion does not depend on the exact choice of model for Ly α clouds, and, if the observations quoted above are correctly interpreted, would mean that the gaseous halos are also flattened by the same amount. One should keep in mind, though, that such absorption studies probe only “a tip of an iceberg”, since these objects are ionized to extremely high degree, and may as well contain dominant part of the baryonic density in eq. (1).

Bearing this in mind, we solve the integral in the eq. (8) and give estimate for τ in several cases of particular interest:

- Optical depth $\tau(l, b)$ in the parametric space, with the parameter q fixed in steps of 0.2, i.e. $q = 0.2$, $q = 0.4$, $q = 0.6$, $q = 0.8$ and $q \approx 1$.
- Optical depth τ for different targets: LMC, SMC, M31 and Galactic bulge (bar) in order to see what value of q determines the optical depth that is closest to observed value in the appropriate survey.

Due to the space limitations, we hereby present just two three-dimensional plots. In the Figure 1, value of the optical depth τ is plotted against galactic coordinates l and b . This is an estimate for $q = 0.4$, but can easily be done for other values. One can use such plots (on the same or smaller angular scales) in order to choose observing direction where the optical depth reaches maximal values. Such an example is shown in the Figure 2 where we plotted optical depth as function of coordinates $l = 280.^\circ 5$ and $b = -32.^\circ 9$ of the Large Magellanic Cloud. Other plots and results of integration will be presented elsewhere.¹

¹ Some examples of plots and results of integration can be found in the postscript format at the following URL: <http://www.geocities.com/CapeCanaveral/7102/Belgrade-MACHO.html>, or from the authors by e-mail.

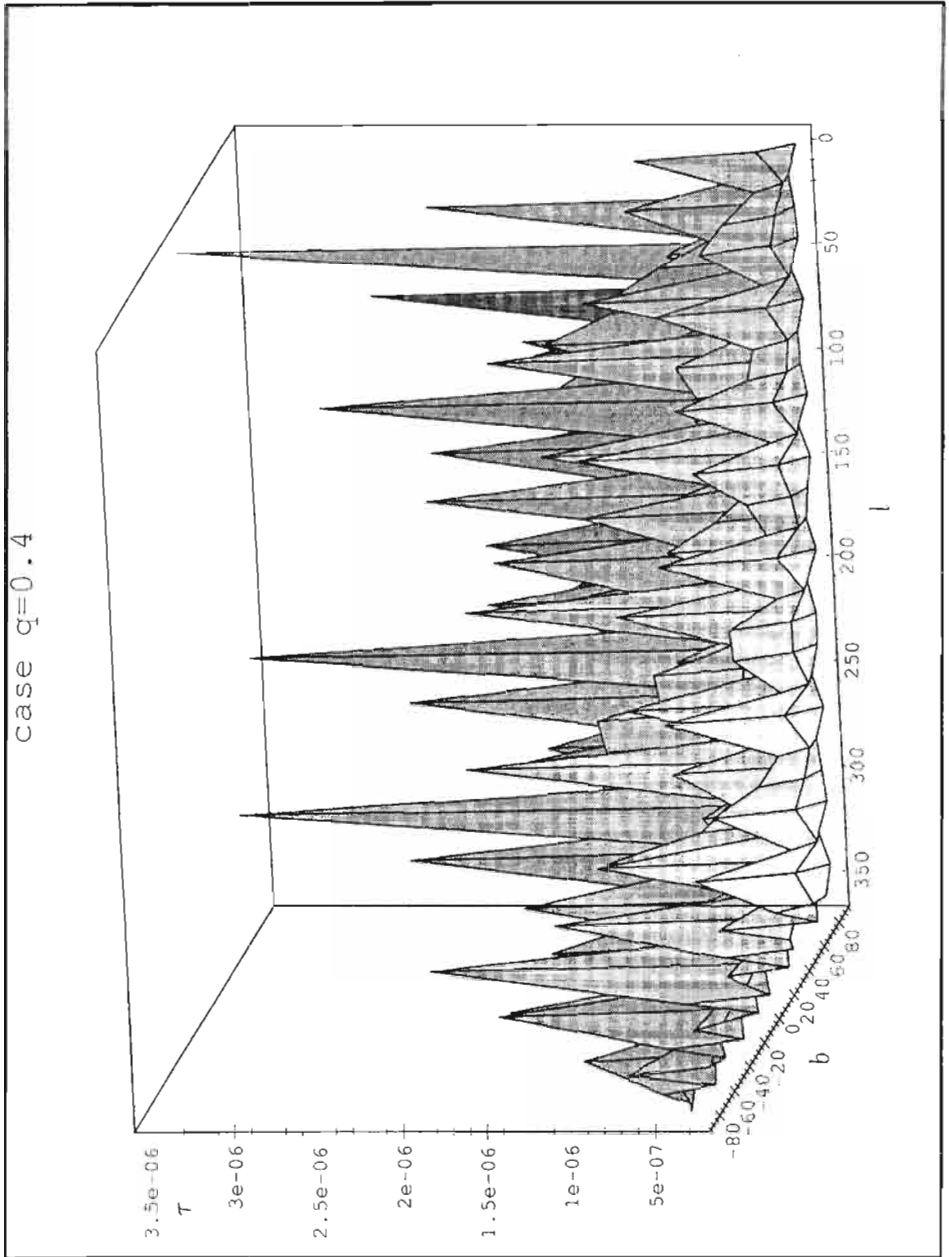


Fig. 1. Optical depth τ as a function of the galactic coordinates l and b . Distance to sources is taken to be 50 kpc and the axes ratio is $q = 0.4$.

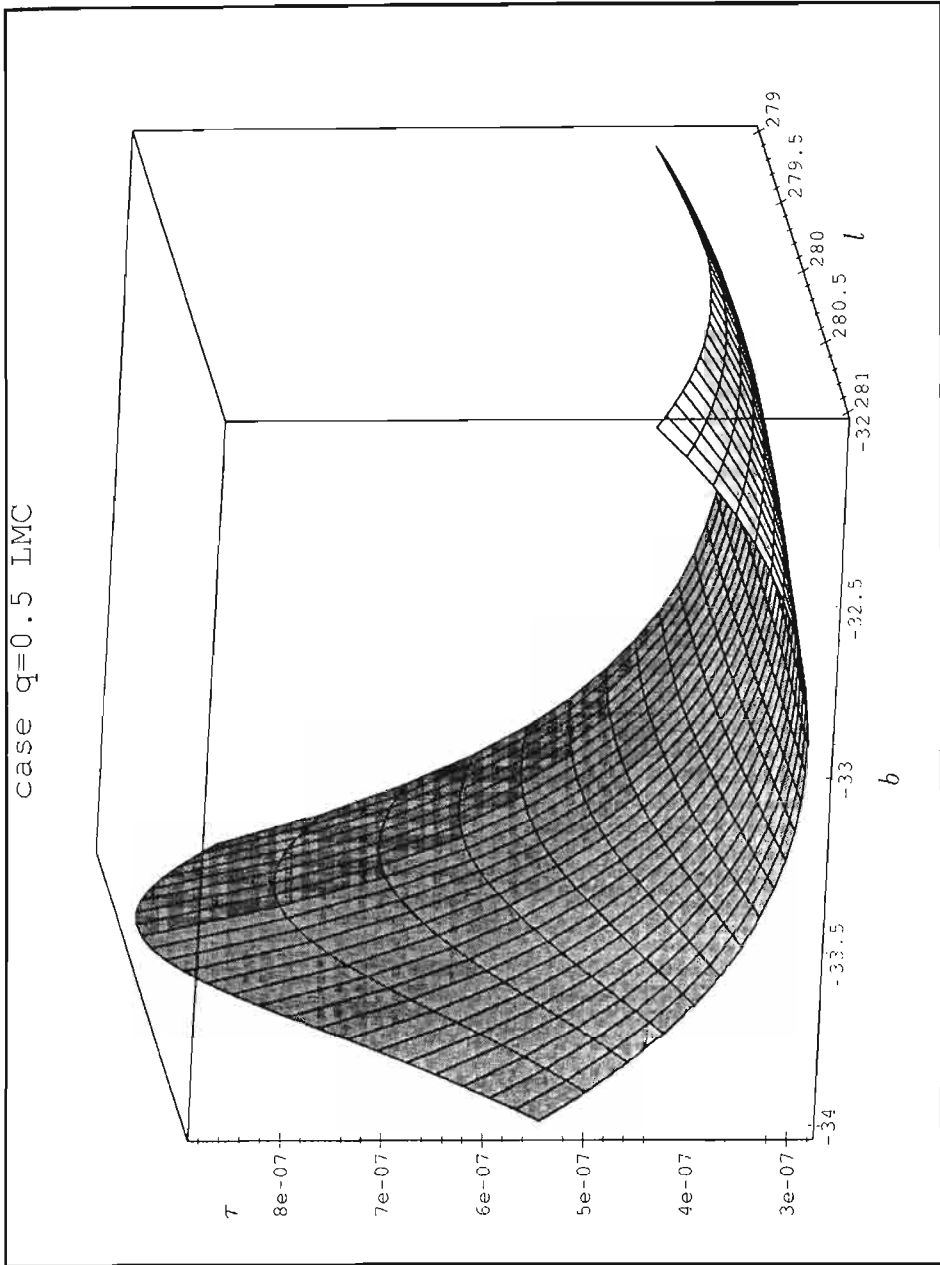


Fig. 2. Optical depth τ as a function of the galactic coordinates l and b for the Large Magellanic Cloud (LMC) for the axis ratio $q = 0.5$.

4. RESULTS AND CONCLUSIONS

After solving the integral in the eq. (8) for given values of the parameter q we looked for the values that match the optical depth obtained in various surveys. We found that the best agreement can be attained if we take $0.2 \lesssim q \lesssim 0.6$. Namely:

1. For the case of the LMC, that has been studied rather well, the measured value of the optical depth based upon the sample of 8 events is $\tau = 2.9_{-0.9}^{+1.4} \times 10^{-7}$ (Alcock 1997b) while we find that for $q = 0.5$ we have $\tau \approx 3 \times 10^{-7}$ (see Figure 2).
2. For the case of the SMC, that is studied less thoroughly, the optical depth is estimated as $\tau = 1.5 - 3 \times 10^{-7}$ (Alcock 1997c). Our results show that the model in the eq. (8) gives the value $\tau \gtrsim 4 \times 10^{-7}$ for $q \approx 0.5$ and above.
3. For the case of the galaxy M31 we found $\tau \approx 5 \times 10^{-6}$ which is an accordance with the estimates $5 - 10 \times 10^{-6}$ (Crofts 1996), under the assumption that $q \gtrsim 0.2$.
4. Determining τ towards the Galactic center is more complicated and we will not discuss it here. We only state that using the model in the eq. (8) we can estimate the halo contribution to the ML rate towards Galactic center which is between $\tau \approx 5 \times 10^{-8}$ ($q = 0.6$) and $\tau \approx 1.6 \times 10^{-7}$ ($q = 0.2$); the estimated range for the total optical depth towards Galactic center is ($\tau = 3.9_{-1.2}^{+1.8} \times 10^{-6}$) (Alcock 1997a).

From our estimates it is obvious that the spherical dark halo can be ruled out: the value for q lies in the interval: $0.2 \lesssim q \lesssim 0.6$. Recent research shows that it is not uncommon case with spiral galaxies (Sackett and Sparke 1990; Sackett *et al.* 1994; Olling 1995). Very recently, the observations of the gravitational lens system B1600+434, consisting of two spiral galaxies (G1 and G2), where G2 is a barred one, suggest that it has $q \gtrsim 0.4$ (Koopmans, de Bruyn and Jackson 1998).

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