Flattened Galactic Haloes and Baryonic Dark Matter

Srdjan Samurović,1 Milan M. Ćirković2,3 and Vesna Milošević-Zdjelar4

1 Dipartimento di Astronomia, Università degli Studi di Trieste, Via Tiepolo 11, I-34131 Trieste, ITALY
srdjan@ts.astro.it

2 Astronomical Observatory, Volgina 7, 11000 Belgrade, SERBIA

3 Dept. of Physics & Astronomy, SUNY at Stony Brook, Stony Brook, NY 11794-3800, USA
cirkovic@sbast3.ess.sunysb.edu

4 Dept. of Physics, University of Manitoba, Winnipeg MB, R3T 2N2, CANADA

ABSTRACT
We discuss the tight interconnection between microlensing optical depths, flattening of dark haloes and low-to-intermediate redshift baryonic census. By analysing plots of the microlensing optical depth as a function of galactic coordinates for different values of axis ratio q of the galactic MACHO halo, we have shown that observations are best described by a flattened halo with q ≃ 0.6. There is no dynamical obstacle for such a choice of global halo shape. Both extremely flattened q ≃ 0.2 and spherical q ≃ 1 haloes have several difficulties, although not of equal severity. Consequences of such flattening for the cosmological density fraction contained in MACHOs are considered and comparison with mass in low and intermediate-redshift Lyα forest and other plausiblere reservoirs of gas is discussed in context of a unified description of the evolution of baryonic content of the universe.

Key words: Galaxy: halo – Galaxy: gravitational lensing – dark matter – galaxies: evolution

1 INTRODUCTION
The question of the nature and properties of the baryonic dark matter (BDM) is one of the most active fields of recent astrophysical research (Hegyi & Olive 1986; Persic & Salucci 1992, 1998; Ashman 1992; Gnedin & Ostriker 1992; Richstone et al. 1992; Carr 1994 and references therein; Wasserman & Salpeter 1994; Flynn, Gould & Bahcall 1996; Graff & Freese 1996), because of its impact on the various branches of the modern astrophysics and cosmology. Microlensing searches have proved to be one of the most important tools for investigation of properties of the halo of the Milky Way (Paczynski 1986; Griest et al. 1991; De Rújula, Jetzer & Massó 1992; Paczynski et al. 1994; Aubourg et al. 1993; Sackett & Gould 1993; Gould 1994, 1996; Alcock et al. 1996, 1997a, b, c; Ansari et al. 1996). Comparison of theoretical models and microlensing (ML) data has already yielded intriguing results and insights (Gates, Gyuk & Turner 1995; Steigman & Tkachev 1998). Under the Copernican assumption that the Milky Way is a typical zero-redshift L*, galaxy, it is natural to ask what consequences recently discovered Massive Compact Halo Objects (MACHOs) have for the global picture of evolution of the baryonic structure in the universe.

By MACHOs we denote present-day collapsed objects residing in the halo of the Milky Way (and, by a Copernican assumption, haloes of other normal spirals) that are baryonic in nature and/or origin. Thus, we exclude hypothetical primordial mini black holes (e.g. Canuto 1978) and exotic non-baryonic aggregates (e.g. Kolb & Tkachev 1995; Eichler 1996). The motivation behind this is the crucial importance of the Big Bang nucleosynthesis (BBNS) constraints for cosmological density fraction Ω_B ≡ ρ_B/ρ_crit in baryons (Yang et al. 1984; Walker et al. 1991; but see also Gnedin & Ostriker 1992; Hata et al. 1996). Objects detectable only through microlensing searches may present an important, and indeed a dominant, item in the total baryonic census.

We hereby intend to extend the discussion of an important recent paper by Fields, Freese & Graff (1998; hereafter FFG). While they approach the problem of cosmological density fraction Ω_{MACHO} contained in collapsed halo objects from the point of view of mass-to-light ratio and MACHOs as products of stellar evolution, we take a slightly different approach to achieve similar ends. In our view, microlensing observations give the most significant key to the spatial distribution of baryonic matter in haloes of large spiral galaxies like the Milky Way. Under the assumption that our galaxy is typical for the normal galactic population at zero redshift, we apply integration of spherical and various flattened model MACHO distributions over the luminosity function in order to determine cosmological contribution of these dark haloes. We also extend the discussion of FFG on the comparison between MACHO and Lyα forest mass density, especially in light of recent observational indications that most of the low-redshift Lyα forest is associated with galaxies (Spinrad et al. 1993; Lanzetta et al. 1995; Chen et al. 1998; Yahata et al. 1998). This conjecture is crucial to the understanding of transition between different types of
baryonic dark matter, which does not seem to occur later than the differentiation of galactic structure itself. This is in accordance with the cooling flow-type models of galaxy formation (Nulsen & Fabian 1995, 1997), and offer simple interpretation of the best available cosmic baryon census (Fukugita, Hogan & Peebles 1998, hereafter FHP) strengthening the assumption of FFG that MACHOs were formed before the Lyman systems. Thus, our paper is complementary to FFG in several ways.

Global flattening of the galactic dark halo has been recently considered in detail by a number of authors (Binney, May & Ostriker 1987; Griest et al. 1991; Sackett & Gould 1993; Frieman & Scoccimarro 1994; Nakamura, Ku-ya & Nishi 1996). We use and update their results, especially excellent discussions of Sackett & Gould (1993) and Frieman & Scoccimarro (1994) which, unfortunately, were written before the bulk of the existing microlensing data came, in order to emphasize the tight relation between the global shape of the baryonic halo and its total mass, with all its cosmological implications. The goal of this paper, accordingly, is (1) to update the discussion of discrimination of various halo models according to microlensing optical depths produced, and (2) to investigate the influence of realistic global flattening, constrained in such a way, on estimates of baryonic cosmological density and consequences for the evolution of the baryonic content of the universe. Thus, inclusion of more phenomena, like the global flattening, present another step towards a unified picture of the physical processes of relevance to the baryonic matter.

2 BARYONIC DARK MATTER IN THE GALAXY: A SHORT OVERVIEW

From shape of the Milky Way 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 centre, and the circular speed at the Solar radius, \( v_0 \) (Merrifield 1992; Olling & Merrifield 1998; Sackett 1997). Although the IAU 1986 standard values are \( R_0 = 8.5 \) kpc and \( v_0 = 220 \) kms\(^{-1} \) some recent estimates allow the smaller values: \( R_0 = 7.1 \pm 0.4 \) kpc and \( v_0 = 184 \pm 8 \) kms\(^{-1} \) (Olling & Merrifield 1998). In this paper we adopt the value \( R_0 = 8.5 \pm 0.5 \) kpc (Feast & Whitelock 1997) based upon an analysis of HIPPARCOS proper motion of 220 Galactic Cepheids and \( v_0 = 210 \pm 25 \) kms\(^{-1} \) that includes the best values from the \( H_\alpha \) analysis (\( v_0 = 185 \) kms\(^{-1} \)) and the estimated value based on the Sgr A* proper motion \( v_0 = 235 \) kms\(^{-1} \) (Sackett 1997).

Without going into the discussions about the content of the dark matter 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; FHP):

\[
0.0062 \leq \Omega_B h^2 \leq 0.026 \tag{1}
\]

where \( \Omega_B \) is the universal baryonic mass-density parameter \( (\Omega_B \equiv \rho_B/\rho_{crit} = 8\pi G \rho_B/3H_0^2) \) and 0.4 \( \leq h \leq 1.0 \). The "silent" \( h \) is used in parametrization of the Hubble constant \( H_0 = 100 h \) km s\(^{-1} \) Mpc\(^{-1} \). Recent measurements of the primordial deuterium abundance (Burles & Tytler 1998) give:

\[
\Omega_B h^2 = 0.0193. \tag{2}
\]

Using the simplest dynamical estimate of the mass of the Galaxy (Kepler’s third law) one can obtain (Roulet & Mollerach 1997, and references therein):

\[
M_{\text{dyn}} \simeq \frac{v_c^2 r_{\max}}{G} \simeq 5.6 \times 10^{11} \left( \frac{v_c}{220 \text{ km/s}} \right)^2 \left( \frac{r_{\max}}{50 \text{ kpc}} \right) M_\odot, \tag{3}
\]

where \( M(r) \) is the mass interior to \( r_{\max} \), \( v_c \) is the measured rotational velocity and \( r \) is the radius within which most of the dynamical mass of the Galaxy is located. For the entire visible matter (stars, interstellar and intracluster gas) one can obtain cosmological density fraction (Persic & Salucci 1992; see also Bristow & Phillips 1994):

\[
\Omega_{\text{vis}} \approx 2.2 \times 10^{-3} + 6.1 \times 10^{-4} \ h^{-1.3}. \tag{4}
\]

The discrepancy between the Eqs. (1) and (4) represents the so-called problem of missing baryons. Various types of such dark baryonic 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. Hegyi & Olive 1986; Peebles 1993).

On the other hand, the dynamical mass in the Eq. (3) corresponds to the cosmological density parameter (if the Milky Way is a typical \( L_\star \) galaxy).

\[
\Omega_{\text{dyn}} \simeq 0.063 h \left( \frac{v_c}{220 \text{ km/s}} \right)^2 \left( \frac{r_{\max}}{50 \text{ kpc}} \right), \tag{3.1}
\]

(This result depends on details of the Galaxy luminosity function which will be discussed in the Section 5). The discrepancy between the Eqs. (3.1) and (4) can be regarded as a formulation of the general dark matter problem on the galactic scales. The necessity for the dark matter is emphasized by 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 & Bahcall 1996), as well as with huge dynamical mass for the Milky Way inferred by Kuijens & Lynden-Bell (1992) and Lee et al. (1993).

The mass in the halo is dominated by the matter that is not, at least easily, detectable. According to the recent observations of satellite galaxies (Zaritsky et al. 1997) dark haloes extend to much larger radius than 50 kpc. So, one can formally write:

\[
\Omega_{\text{dyn}} \sim 0.1 \lesssim 15 \Omega_{\text{vis}}. \tag{5}
\]

3 MICROLENSING AND FLATTENING

In searches for the BDM 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, Bernarddeau & Van Waerbeke 1998). Searches have been directed towards Large and Small Magellanic Clouds (LMC and SMC) (Alcock et al. 1996, 1997b; Ansari et al. 1996; Palanuk-Delabrouille et al. 1998), Galactic bulge (Kiraga & Paczyński 1994) and M31 (Crotts 1992, Crotts & Tomany 1996; see also Gould 1994).

All these surveys give results concerning two important parameters: masses of the intervening lenses and the number of lenses within the Einstein radius around the line of sight to a lensed source—the optical depth. In Table 1 we give the targets observed, names of the appropriate survey, mass ranges of the lenses, and corresponding optical depth.

It is known from the work of Sackett & Gould (1993) that instead of the equation for the mass density in a spherical halo:

$$\rho(r) = \frac{v_c^2}{4\pi G} \left(\frac{1}{r_c^2 + r^2}\right) \theta(R_T - r)$$

(6)

(where r is the Galactocentric radius, v_c is the asymptotic circular speed of the halo, r_c is the core radius of the halo and R_T is the truncation radius), one should use the general formula for flattened halo:

$$\rho(r) = \frac{\tan \psi \cdot v_c^2}{4\pi G} \left(\frac{1}{r^2 + \zeta^2}\right) \theta(R_T - \zeta)$$

(7)

where $\zeta^2 = r^2 + z^2 \tan^2 \psi$ (z denotes height above the Galactic plane). Here the flattening parameter $\psi$ is introduced:

$$\cos \psi = q = c/a, \text{ i.e. its cosine determines the shape of the halo En.}$$

The En notation is related to $q$ as $q = 1 - n/10$.

Following Sackett & 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):

$$\tau(l, b) = \frac{\tan \psi \cdot v_c^2}{4\pi G} \frac{1}{\zeta^2} D \times$$

$$\times \int_0^D \frac{(D - L)L dL}{(r^2 + R_0^2) - (2R_0 \cos l \cos b)L + (1 + \sin^2 b \tan^2 \psi)L^2}$$

(8)

where we use $R_0 = 8.5$ kpc and $r_c = 5$ kpc (e.g. Alcock et al. 1996). Now we integrate this equation and take $D = 50$ kpc (for LMC), $D = 63$ kpc (for SMC) and $D = 770$ kpc for M31 (Binney & Tremaine 1987). While Sackett & Gould (1993) use values for $q$ starting with $q = 0.4$ (shape E6), we will start with admittedly extreme value $q = 0.2$ (shape E8) suggested by some theories, like the halo molecular clouds or the decaying dark matter (see the discussion below).

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, 1991; Bahcall 1986; Binney et al. 1987) 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. A detailed discussion of these questions was given by Binney et al. (1987), who attributed the flattening to a highly anisotropic velocity dispersion tensor, under the assumption that the velocity ellipsoid of halo objects near the Sun has the same shape as that of the extreme Population II subsystem. Their calculation show that the parameter $q$ for the halo isodensity contours has to be in the range $q = 0.3 - 0.6$. Wyse & Gilmore (1989) review different arguments based on analyses of halo star counts for flattened halo and suggest values $q = 0.6$ as the optimal one. The same is, with additional data, repeated in the extensive review of Gilmore, Wyse & Kuijken (1989) where the authors concluded that star count data definitely favor $0.6 < q < 0.8$ models. One should note that widely used Bahcall-Soneira model of the Galaxy indicates $q = 0.8$, although it is realized that it may be too conservative, even for stellar subsystem (Bahcall 1986). These results supersede older arguments for spherical stellar component (e.g. Oort & Plaut 1975). As far as other galaxies are concerned, observational data are still extremely scarce, but it is indicative that 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 $q > 0.4$ (Koopmans, de Bruyn & Jackson 1998). The flattening of the M31 halo was discussed and appropriate corrections to the mass estimates were considered by Ninković & Petrovskaya (1992).

As pointed out by Sciama (1990), a further theoretical virtue of the halo flattening idea is connected with the Oort limit. Since the amount of the dark matter per unit surface area of the disc is determined by the rotational velocity of the disc, any flattening of the vertical dark matter distribution must be compensated for by an increase in the density of dark matter in and near the galactic plane (i.e. in the disc). Therefore, the amount of the dark matter near the Solar system, traditionally associated with the Oort limit is reduced, and could be even brought down to zero (see also Binney et al. 1987). This is appealing, since many recent results show incompatibility with the large quantities of local unseen matter (e.g. Binney & Merrifield 1998). Two different approaches yielded different values for the local density, $\rho_0$ near the Sun (the Oort limit): Kuijken & Gilmore (1989) found that $\rho_0 = 0.10 \ M_\odot \ pc^{-3}$, while Bahcall (1984) found $\rho_0 = 0.21 \ M_\odot \ pc^{-3}$. However, it seems that recent HIPPARCOS measurements favour lower value ($\rho_0 = 0.11 \pm 0.01 \ M_\odot \ pc^{-3}$) (e.g. Kovalevsky 1998). This value is not in disagreement with the assumption of maximal disc (Sackett 1997).

It is, also, necessary to consider the behaviour of gas distributed in the halo. If the seminal idea of Bahcall & Spitzer (1969) of extended gaseous haloes of normal galaxies producing narrow absorption features in the spectra of background objects is correct, as indicated by recent low-redshift measurements (Bergeron & Boissé 1991; Spinrad et al. 1993; Lanzetta et al. 1995, Chen et al. 1998), then the distribution of gas could tell us something about the shape of the gravitational potential. It is not a simple problem at all (e.g. Barcons & Fabian 1987; Pitts & Tayler 1997), but some results are quite suggestive. In an important recent paper, Rauch & Haehnelt (1995, hereafter RH95) have shown that for the most plausible values of Ly$\alpha$ 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$\alpha$ clouds, and, if the observations quoted above are correctly interpreted, would mean that the gaseous haloes are also flattened by the
same amount. One should keep in mind 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 the Eq. (1). We shall return to discussion of these questions in the Section 6.

4 OPTICAL DEPTHS FOR FLATTENED HALOES

Bearing this in mind, we solve the integral in the Eq. (8) and estimate for \( \tau \) 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. \( q = 0.2, 0.4, 0.6, 0.8 \) and \( q \approx 1 \).
- Optical depth \( \tau \) 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 corresponding survey.

We hereby present several such three-dimensional plots. In Figs. 1, 2 and 3, values of the optical depth \( \tau \) are plotted against galactic coordinates \( l \) and \( b \) for three chosen halo models, with \( q = 0.2, 0.6 \) and 1 (spherical halo), respectively. These axial ratios were chosen as representatives of extremely flattened (like Pfenniger et al. [1994] or the DDM models discussed below), moderately flattened (like those favored by Bahcall-Soneira models or other dynamic discussions) and unflattened models (usual approximation). One can use such plots (on the same or smaller angular scales) in order to choose the observing direction where the optical depth reaches the maximal value. Such an example is shown in Figs. 4 through 6, where we have plotted optical depth as function of coordinates \( l = 280.5^\circ \) and \( b = -32.5^\circ \) of the Large Magellanic Cloud.

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 note that, in general, the best agreement can be attained with \( 0.2 \lesssim q \lesssim 0.6 \). Specifically:

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 \( \tau = 2.9^{+1.4}_{-0.9} \times 10^{-7} \) (Alcock et al. 1997b) while we find that for \( q = 0.5 \) we have \( \tau \approx 3 \times 10^{-7} \) (see Fig. 5).
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 et al. 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 \( 5-10 \times 10^{-6} \) (Crotts & Tomaney 1996), under the assumption that \( q \gtrsim 0.2 \).
4. Determining \( \tau \) towards the Galactic centre 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 centre which is between \( \tau \approx 5 \times 10^{-7} \) (\( q = 0.2 \)) and \( \tau \approx 1.6 \times 10^{-7} \) (\( q \approx 1 \)); the estimated range for the total optical depth towards Galactic centre is

| Target      | Survey          | Mass range    | Optical depth |
|-------------|-----------------|---------------|---------------|
| LMC/SMC\(^4\) | MACHO           | \( \approx 0.3 - 0.5 \) \( M_\odot \) | \( \tau_{\text{MC}} = 2.9^{+1.4}_{-0.9} \times 10^{-7} \) |
| LMC\(^2\)   | EROS            | 0.1 \( M_\odot \) | \( \tau_{\text{MC}} = 1.5 - 3 \times 10^{-7} \) |
| Gal. bulge\(^3\) | MACHO;DUO;OGLE | 0.08 - 0.6 \( M_\odot \) | \( \tau_{\text{MC}} = 0.82^{+0.5}_{-0.2} \times 10^{-7} \) |
| M31\(^4\)   | KPNO            | 1.0 \( M_\odot \) | \( \tau_{\text{MC}} = 3.9^{+1.8}_{-1.2} \times 10^{-6} \) |
| LMC/SMC\(^5\) | EROS2           | 2.6^{+8.2}_{-2.3} \( M_\odot \) | \( \tau_{\text{MC}} = 5 - 10 \times 10^{-6} \) |
|             |                 |               | \( \tau_{\text{SMC}} = 3.3 \times 10^{-7} \) |
Figure 3. The same as in Figs. 1 and 2, but for a spherical (q = 1) case.

$$(\tau = 3.9^{+1.8}_{-1.2} \times 10^{-6})$$ (Alcock et al. 1997a). This discrepancy might be the consequence of the fact that the Galactic disc is maximal: if this is so, then one can expect a higher optical depth towards the bulge due to disc lenses and lower values of optical depth towards targets in the halo, that is measured, cf. Table 1 (Sackett 1997).

This nice illustration of the possible discrimination between various halo shapes, is presented in Figs. 7, 8 and 9 (the same cases as above).

From these estimates and studies summarized in Table 1, it seems that both the spherical (q \sim 1) and extremely flattened (q \approx 0.2) dark halo can be ruled out with high significance. The optimal value for q is the intermediate one q \approx 0.6. Recent research shows that it is not uncommon case with spiral galaxies, not only polar-ring ones (Sackett & Sparke 1990; Sackett et al. 1994; Olling 1995). This has several far-reaching consequences, like implausibility of molecular halo or DDM models, which, in the simplest forms, predict strong flattening of dynamically important halo component.

We also present ratios of optical depth toward LMC and SMC as functions of the flattening parameter q in Table 2. This is significant, since variation in $\tau_{\text{LMC}}/\tau_{\text{SMC}}$ is claimed to sufficiently clearly discriminate between various models of flattening (Sackett & Gould 1993). Our results are in agreement with the more detailed discussion of this problem by Frieman & Scoccimarro (1994).

The necessity of having many more lines of sight for microlensing survey besides LMC, SMC, Galactic bulge and Andromeda galaxy, led several research groups to consider globular clusters as ML targets (Rhoads & Malhotra 1998, Jezter et al. 1998, Gyuk & Holder 1998). The original idea came from Paczynski (1994) who proposed 47 Tuc (monitored by OGLE collaboration) and M22. Gyuk & Holder (1998) and Jezter et al. (1998) composed lists of appropriate clusters for microlensing survey, with corresponding optical depths, stating that by using globular clusters it would be possible to distinguish the flattened models of the galactic halo much easier, and it would allow better determination of halo structure parameters, such as the power-low index, or the core radius. Special advantage of that method is avoiding self-lensing events present in a SMC survey, for example, and fluctuations in halo density due to clumps of stars in tidal tails and intervening dwarf galaxies like recently discovered Sagittarius galaxy.

We briefly note that very recently the EROS collaboration (Derue et al. 1999) found that in the four directions towards the Galactic spiral arms the average value for the optical depth is equal $\bar{\tau} = 0.38^{+0.53}_{-0.15} \times 10^{-6}$. If one compares values obtained for their four targets and the predicted values of $\tau$ from Fig. 2, one could again conclude that the halo is moderately flattened, i.e., q \sim 0.5 – 0.6.

With globular clusters distributed throughout the Milky Way’s halo, this method will further improve on the number of ML events and make it possible to constrain Milky Way’s dark halo shape and content more precisely.

It is of foremost importance to continue theoretical studies of these optical depths, even if we are not in position to find other possible sources of background light for microlensing experiments. Further improvement in number of events will enable precise measuring of abovementioned optical depths, and using their ratios to constrain possible halo shapes.
Table 2. \( \tau_{\text{SMC}}/\tau_{\text{LMC}} \) ratio for different values of the parameter \( q \). Optical depths, \( \tau \), are expressed in units of \( 10^{-7} \).

| \( q \) | \( \langle \tau_{\text{LMC}} \rangle \) | \( \langle \tau_{\text{SMC}} \rangle \) | \( \frac{\tau_{\text{SMC}}}{\tau_{\text{LMC}}} \) |
|---|---|---|---|
| 0.2 | 3.8554 | 5.2082 | 1.3509 |
| 0.6 | 4.0733 | 5.6973 | 1.3987 |
| 1.0 | 4.2184 | 5.6670 | 1.3434 |

Figure 6. The same as in previous two Figures, but for spherical \((q = 1)\) model.

Figure 7. The halo contribution to the microlensing optical depth toward the Galactic Centre for \( q = 0.2 \).

Figure 8. The same as in Fig. 7, for moderately flattened halo \((q = 0.6)\).

Figure 9. The same as in previous two Figures, for the spherical case.

5 TOTAL MASS OF MACHOS AND COSMOLOGICAL DENSITY PARAMETER

The total mass of a MACHO halo of an \( L_* \) galaxy (as typified by the Milky Way) in a model characterized by the Eq. (7) is

\[
M(q, R_T) = 3.648 \times 10^{-12} \frac{\sqrt{1-q^2}}{q \ \text{arccos} \ q} \times
\int_0^{R_T} \int_0^{R_T} r \ dz \ dr \times \frac{r}{r^2 + r^2 + z^2 \frac{\sqrt{1-q^2}}{q}} M_\odot, \tag{9}
\]

where all lengths are in cm, and \( r_c \) has a fixed value. We shall briefly discuss on the variation of core radius below.

The total mass of an \( L_* \) galaxy is shown in Fig. 10 for \( q \) varying between 0.2 and 1, and a truncation radius \( R_T \) between 40 and 60 kpc. Horizontal plane represents the dynamical value of the total mass inferred from satellite studies within much larger radius of \( \sim 230 \) kpc by Kulessa & Lynden-Bell (1992). The choice of interval for the truncation radius is relevant not only because it incorporates the "canonical" value of 50 kpc for the size of MACHO haloes (FFG; Alcock et al. 1996, 1997a), which is reasonable from the point of view of empirical detection of microlensing
events toward Magellanic Clouds; another, entirely theoretical, argument is that the cooling times for protogalactic halo gas in this region ($R \leq 50$ kpc) are an order of magnitude shorter than the dynamical time (Rees & Ostriker 1977; White & Rees 1978), thus making a collapse of baryonic structures a likely outcome. We shall extend somewhat the discussion of the relevant physics in the Sec. 7. As we shall see from the plots in this and subsequent figures, further increase in $R_T$ leads to huge masses of MACHO haloes, which are unacceptable from the point of view of BBNS, unless the fraction of galaxies containing MACHO haloes similar to the one of the Milky Way is, for some quite mysterious reason, very small.

We also note that MACHOs are incapable of explaining galactic dynamics on large scale, and in order to explain dynamical estimates of the Milky Way mass based on satellite systems (Kulessa & Lynden-Bell 1992; Zaritsky et al. 1997) dark matter in form of either invisible gas or non-baryons has to be invoked. As we shall see below, if one chooses to accept the BBNS constraints for the baryonic cosmological density $\Omega_B$, non-baryonic dark matter in the Milky Way halo (and haloes of all normal galaxies) has to be invoked. On the other hand, the presence of non-baryonic dark matter within MACHO halo itself (i.e. at galactocentric distances up to $\sim 50$ kpc) has the effect of relaxing bounds on the MACHO halo and, thus, in principle, subject to empirical verification through detailed comparison of observed optical depths with those predicted by the density profile in the Eq. (7).

As far as other components of the total cosmological density in baryons $\Omega_B$ are concerned, we adopt the Persic & Salucci (1992) estimate for the mass of visible baryons (i.e. stars, ISM and gas in rich clusters) given by the Eq. (4). Further contribution is expected to come from the intergalactic and/or "invisible" galactic gas. At later epochs, this is what FHP call "warm gas around galaxies and small groups". Since these are presumably the same objects as those recently detected as the dominant fraction of the low-redshift Ly$\alpha$ forest, we shall denote this contribution as $\Omega_{\text{Ly}\alpha}$ in further discussion.

There are basically two ways in which one can discuss relationship between Ly$\alpha$ clouds and baryonic dark matter: (i) direct comparison of their cosmological density in various epochs (as in FFG), and (ii) we can consider transformation of high-$z$ Ly$\alpha$ clouds into present day MACHOs. We proceed with (i), and shall return to the topic (ii) in the next section.

In order to translate individual galactic masses, as in the Eq. (9) into global cosmological density parameter $\Omega_{\text{MACHO}}$, it is necessary to perform integration over the luminosity function (LF), with some assumptions. Beside universality of the luminosity function, we have to assume that there is no diffuse, intergalactic population of MACHO-like objects. This is not just a formal statement – it puts obvious constraints on epoch of formation of such objects and their degree of clustering. It is natural to speculate that, due to dynamical effects, some MACHOs will be ejected from the halo during galactic history, thus creating such an intergalactic population, with its own particular contribution to the value of $\Omega_B$. In this sense, our present picture is not completely self-consistent, since it neglects this intergalactic population of collapsed objects (expression "MACHO" is, obviously, inadequate here). In the course of future work, we hope to quantify this assumption in detail and, especially, demonstrate implications for high-density regions (e.g. rich clusters), where "sharing" of the BDM among galaxies may have crucial influence upon its evolutionary history, and result in observable peculiarities (e.g. White & Fabian 1995).

Cosmological density parameter in such MACHOs residing in haloes of typical luminous galaxies can be written...
as

\[ \Omega_{\text{MACHO}} = \frac{1}{\rho_{\text{crit}}} \int_{L_{\text{min}}}^{L_{\text{max}}} M(L) \varphi(L) \, dL, \]

(10)

where \( \rho_{\text{crit}} \) is the critical density of Friedmann-Robertson-Walker universes, \( L_{\text{min}} \) and \( L_{\text{max}} \) are the minimal and maximal luminosity of galaxies possessing such MACHO haloes, respectively, and \( \varphi(L) \) is the universal galaxy LF (Schechter 1976; Binggeli, Sandage & Tamman 1988; Willmer 1997). We use the LF in Schechter’s form

\[ \varphi(L) = \varphi_* \left( \frac{L}{L_*} \right)^{-\gamma} \exp \left( - \frac{L}{L_*} \right), \]

(11)

and alternative mass form can be found in Nulsen & Fabian (1997). LF parameters are chosen to be (Willmer 1997)

\[ \varphi_* = 2.5 \times 10^{-2} \, h^3 \, \text{Mpc}^{-3}, \]

(12)

and

\[ \gamma = 1.27. \]

(13)

The influence of their variation on our results is discussed in detail below. The standard Schechter luminosity is chosen to be \( L_* = 1.0 \times 10^{10} \, e^{+0.23} \, h^{-2} \, L_\odot \), i.e. corresponding to the absolute B-band magnitude of \( M_* = -19.2 \) (Willmer 1997). The Hubble parameter \( h \) is chosen to be \( h = 0.5 \) in all calculations, except where otherwise mentioned.

We note from the Eqs. (9) and (11) that a unique value of \( \Omega_{\text{MACHO}} \) corresponds to each pair of values \((q, R_T)\). The distribution of possible values of this cosmological density parameter is shown by the 3-D plot in Fig. 12 for \( r_c = 5 \, \text{kpc} \) and \( h = 0.5 \).

We have used fiducial value for the core radius \( r_c = 5 \, \text{kpc} \). Variation of this quantity in the usual range 5–8 kpc (Binney & Tremaine 1987) causes changes in our results of \( \delta M/M = 12 \text{per cent} \) (see Fig. 11). In addition, we have also investigated somewhat unorthodox value \( r_c = 20 \, \text{kpc} \) (but, see Gerhard 1999). This is motivated by some recent indications that the Milky Way rotation curve may be satisfactorily explained by nearly homogeneous dark matter distribution within a few solar circles (Ninković, private communication); see also Frieman & Scoccimarro (1994). Also, such a large core-radius would be completely in accord with suggestion, originating with N-body simulations (Cole & Lacey 1996), that the density profile becomes significantly flatter than the isothermal one in inner halo regions (becoming simultaneously steeper than \( r^{-2} \) in outermost regions). The influence of varying core radius on the mass of a fiducial halo with our model profile is shown in Fig. 11.

Variation of other parameters also does not remedy the high value of the total mass in MACHOs. For example, \( v_\infty \) is only bound from below, by the IAU value of Galactic rotation at the solar circle of 220 \( \text{km s}^{-1} \) which was used in these calculations. If, as indicated, Milky Way rotation curve rises all the way to \( 3 r_\odot \) (Ninković, private communication), \( v_\infty \) can be as high as 280 \( \text{km s}^{-1} \) (Frieman & Scoccimarro 1994), and the mass \( M(q, R_T) \) would be increased for a factor \( \approx 1.62 \) with corresponding increase in \( \Omega_{\text{MACHO}} \), which, taking into account the bounds in the Eq. (1), is not insignificant.

In Figures 12 and 13, we have shown the total MACHO + visible cosmological density vs. the constraints emerging from the BBNS for \( h = 0.5 \). We notice that MACHOs within 50 kpc are certainly capable of solving the problem of missing baryons resulting from comparison of the Eqs. (2) and (4). Again, exceptions are very flattened haloes with \( q \simeq 0.2 \), which make them still less appealing possibilities. On the other hand, if higher nucleosynthesis estimates of \( \Omega_B \), for example \( \Omega_B \approx 0.077 \) (Burles & Tytler 1998), are reconfirmed by impending observations, there seems to be no alternatives to discarding little flattened values \( q \geq 0.8 \) either.

One should always keep in mind that there is no physical reason for assumption that \( R_T \) is close to the canonical value of 50 kpc; rather, it is just an empirical convenience, at least for the time being. Caution suggests to take these values (i.e. \( R_T \) and the corresponding masses) as lower limits only, with consequences that flattening looks even more appealing as a way to reduce \( \Omega_{\text{MACHO}} \). If MACHO haloes extend to anything similar to the extent of dynamical haloes inferred, for example, by Zaritsky et al. (1997), then rejecting of anything with \( q > 0.6 \) is unavoidable. On the other hand, it is possible that our reliance on the Occam’s razor is misleading, and only some fraction \( f \) of the mass distribution creating potential responsible for the rotational curve is
in form of MACHOs. The rest 1 – f must then be in the form of non-baryonic dark matter, if we wish to remedy the high \( \Omega_b \) problem, which leads to a degeneracy, where flattened full-MACHO halo may contain the same amount of mass as non-flattened realistic halo with \( f < 1 \). On the other hand, optical depth estimates and ratios discussed in the Sec. 4 would still be dependent only on the MACHO fraction, and therefore optical depths are expected to be reduced by the factor \( f \) and their ratios to be unaffected. This offers a further opportunity for improved microlensing statistics, which should be able to easily discriminate between values of \( f \) close to unity and any other significantly smaller value (at present, as visible from the Table 1 and comparison with Figs. 4 through 6, we can only claim \( f > 0.1 \) with reasonable certainty).

6 GASEOUS CONTENT OF GALAXIES AND FLATTENING

The discovery that a large fraction of low-redshift Ly\( \alpha \) forest is associated with normal luminous galaxies (Spinrad et al. 1993; Lanzetta et al. 1995; Chen et al. 1998) presents a further difficulty for the total baryonic census, as recognized by FHP. This means that at least some debris from the galaxy formation epoch remained in the gaseous state till relatively late epochs; the question whether this gas (discovered up to huge galactocentric distances, with maximal absorption radius for \( L_* \) galaxies being \( \sim 300 \) kpc) was partially recycled through some galactic stellar population is unimportant in this respect. Possible contribution to the baryonic budget is enormous; it is the largest (albeit the most uncertain) entry in the list of FHP. In fact, its magnitude is such that the BBNS constraints are seriously jeopardized by a direct extension of column-density statistics to the total mass contained along all lines of sight, an insight which prompted RH95 to suggest a significant flattening of these gaseous structures.

In that work, it is shown that constraints following from the general formula for the cosmological density of Ly\( \alpha \) systems

\[
\Omega_{\text{Ly}\alpha} = \frac{\kappa m_H H_0}{c \rho_{\text{crit}}} \int_{N_{\text{min}}}^{N_{\text{max}}} x^{-1} N f(N) dN, \tag{15}
\]

(both \( N \) is the neutral hydrogen column density spanning the interval between \( N_{\text{min}} \) and \( N_{\text{max}} \), \( x \) neutral gas fraction, and \( f(N) \) the neutral hydrogen column density distribution) coupled with the BBNS bounds leads to inevitable conclusion of global flattening, if sizes (or coherence) lengths obtained from double line-of-sight analyses are taken seriously. Typical values of \( \Omega_{\text{Ly}\alpha} \simeq 0.04 \) are obtained for typical sizes of 100 kpc, in spherical case, from several of their simple models, which is, obviously, quite high. If large coherence sizes inferred from double lines of sight (e.g. Donahue et al. 1995) are characteristic (and they are in general accord with the huge sizes of galactic gaseous haloes obtained by Chen et al. [1998]) the cosmological density is even higher. The way out is to assume that axial ratio of these structures (without entering the question of their physical origin and location) is small, and for the most conservative of their models, RH05 obtain \( q_1 \simeq 0.1 \). It is interesting that

they suggest clumping of the neutral content as an alternative way of decreasing the total mass, a frequent suggestion which has not been fully investigated to date (e.g. Mo & Miralda-Escudé 1996).

Conclusions of RH95 are, it should be reemphasized, essentially independent of the true nature and location of the Ly\( \alpha \) forest clouds. They are valid for both inter- and intragalactic types of absorbers. But the discovery of large population of halo absorbers at \( z \leq 1 \) prompts us to ask whether aspect ratio of absorbers in RH95 can, in fact, be interpreted as the flattening parameter of gaseous haloes. In addition, not only the fact that low- and intermediate-\( z \) absorbing clouds preferentially lie in galactic haloes, without noticeable morphological segregation (Yahata et al. 1998), but also the fact that the covering factor of such haloes was found to be close to unity everywhere in the absorbing radius (Chen et al. 1998), suggests that gaseous haloes should be flattened at late epochs. It should be noted that flattening of Ly\( \alpha \) absorption systems was much earlier proposed, for different reasons, by Barcons & Fabian (1987) and Milgrom (1988).

Unfortunately, exact knowledge of the baryonic content of the Ly\( \alpha \) absorbing clouds requires certain knowledge on their ionization structure, which is still very elusive. The value of metagalactic ionizing background, which is the only always operating ionizing source, is still painfully uncertain even in the local universe and at low redshift, and the more so at high-\( z \) (Bajtlik, Duncan & Ostriker 1988; Kulkarni & Fall 1993; Vogel et al. 1995; Donahue, Aldering & Stocke 1995). The presence of internal ionizing sources, inferred in some local intergalactic clouds (Donahue et al. 1995; Bland-Hawthorn et al. 1995) is also quite uncertain. Finally, geometric properties of ensembles of clouds, i.e. their clumpiness and global flattening, are still only speculative.

The comparison of FFG with the mass estimate of the Ly\( \alpha \) forest of Weinberg et al. (1997) is interesting, especially in view of possible absence of mixing between the two types of unseen baryonic matter. Weinberg et al. (1997) value, quoted by FFG,

\[
\Omega_{\text{Ly}\alpha} = 0.02 \, h^{-\frac{1}{2}}, \tag{16}
\]

is not at all especially high when considered within a "family" of closure fractions obtained for \( \Omega_{\text{Ly}\alpha} \).

Higher values are required for high-\( z \) intergalactic Ly\( \alpha \) forest by many models, e.g. Bi & Davidsen (1997) suggest \( \Omega_{\text{Ly}\alpha} = 0.025 \, h^{-2} \), adopting the values of metagalactic ionizing flux from Haardt & Madau (1996). Alternatively, one may wish to reduce the value of \( \Omega_{\text{Ly}\alpha} \), but at a price of having significantly different ionizing background (since models are able only of constraining choices for \( \Omega^2 / J_{\text{UV}} \)). Furthermore, any increase in the cosmological bias would tip the scales toward larger contribution of gas in comparison to the visible matter assembled in stars and "normal" luminous galaxies.

In our opinion, the association of significant fraction (if not all) low-\( z \) Ly\( \alpha \) forest with galactic haloes does give additional credence to FFG conjecture about MACHOs being distinct baryon reservoir from Ly\( \alpha \) forest. At least this is so after some particular epoch, which we shall denote by \( z_{\text{sd}} \), when bulk of today’s MACHOs was formed out of gas-rich protogalactic fragments, and which may be called the epoch
of baryonic decoupling.

Gaseous density profile and global shape should, in principle, follow profile and shape of the underlying dark matter distribution, which is supposed to be dynamically dominant (Nulsen 1986). This is the necessary link between arguments concerning flattening of gaseous structures around galaxies and flattening of MACHO halo. Of course, exact amount of flattening (as well as the exact density profile) would be different because dark matter is, in contradistinction to gaseous matter, assumed to be dissipationless (no matter whether it is mainly MACHO or non-baryonic elementary particle), but the difference is not expected to be very large on the scales of \(\sim 50\) kpc. If there is a significant inflow from the halo to the disc, the constraints could be much tighter. In this respect, it is important to mention that an argument of this type was advanced by Sancisi & van Albada (1987), namely, that recent accretion of gas found in the optical plane at outer fringes of spiral galaxies already implies flattening of the dynamical halo in these regions.

Conclusions of FFG actually receive multifold support from considerations of low-redshift \(\text{Ly}_\alpha\) forest:

1. Probable overestimate of the \(\Omega_{\text{Ly}_\alpha}\) in N-body simulations and other models of unclustered population of \(\text{Ly}_\alpha\) clouds makes it easier to accommodate large \(\Omega_{\text{MACHO}}\).

2. The very fact that we perceived much stronger \(\text{Ly}_\alpha\) absorption at recent epochs than expected on the basis of naive extrapolation supports the conclusion that \(\text{Ly}_\alpha\) clouds are rather decoupled from star-formation histories (at least after some fiducial epoch \(z_d\)), so the discussion in the Sec. 3 of FFG is justified.

In addition, recent observational indications that Milky Way still possesses extended gaseous halo with densities \(\sim 10^{-4}\) cm\(^{-3}\) at galactocentric distances \(\sim 50\) kpc (i.e. similar to those discussed with respect to the MACHO halo) underline the necessity of having large fraction of dark baryons in gaseous form at present day (Weiner & Williams 1996). This further narrows available range for \(\Omega_{\text{MACHO}}\), and suggests that all possibilities to reduce it should be explored, flattening being the simplest one of them and most in line with the principle of economy of hypotheses.

Various baryonic components are represented in the \(\Omega - h\) diagrams in Figs. 14 and 15. If the \(\text{Ly}_\alpha\) mass estimated by Weinberg et al. (1997) is correct, and the assumption of FFG about essential decoupling of the baryonic contents of \(\text{Ly}_\alpha\) forest and MACHOs after some initial period, high values of \(h \geq 0.8\) seem to be highly implausible for both flattened and unflattened MACHO haloes. For spherical haloes, we ran into troubles for almost all values of \(h\).

It is marginally acceptable for \(h = 0.5\), but it is inconsistent with any higher values (again, we should keep in mind that there is no physical reason for the truncation of MACHO halo at the LMC distance, and many arguments that dynamical haloes extend much further). Flattened haloes, on the other hand, are quite securely within the BBNS margin for \(h \simeq 0.5\).

7 DISCUSSION

Mass considerations could, in principle, lead us to an important clue in solving the puzzle of the fate of the halo gas. All scenarios of hierarchical structure formation (e.g. White & Rees 1978; Navarro & White 1994) have massive dark haloes in place by \(z \sim 2 - 3\), which form gravitational potential wells accreting diffuse baryonic matter (Mo & Miralda-Escude 1996). It is almost certain that at high and intermediate redshift exactly this gas dominates cosmic baryonic budget (RH95; FHP). Its subsequent history is still shrouded in mystery, but the fact that estimates of the cosmological density fraction in MACHOs in both FFG and present work point out that at some point in the galactic history the transition between the halo gas (or its significant fraction) and collapsed objects, like the present day MACHOs occurred.

As the phase transition of baryonic dark matter we denote the process of transformation of pregalactic/proto-galactic gas into MACHOs. It seems obvious that transition from the diffuse (gas) to the collapsed (MACHO) phase of the BDM must have occurred at some point in the history of the universe. This process, whatever form and in whichever epoch it took place, is of the crucial importance for understanding the evolution of baryonic content of the universe. Parenthetically, this is return to the authentic physical meaning of the concept of phase of matter, since \(\text{Ly}_\alpha\) clouds and MACHOs do possess different symmetry properties.

This transition from gaseous to collapsed phase can proceed in several ways. While exact behavior is still too difficult to investigate in detail, since it depends on the initial dynamical and chemical conditions, we can sketch several possibilities.
An early transition probably occurs through Population III stars, and in this scenario, MACHOs are stellar remnants (Carr 1994; FFG). Only detailed chemical modelling can show whether this is viable. Apart from possible overproduction of metals, a further problem with this picture is the necessity for the Pop III initial mass function (IMF) to be significantly different from that observed today in the ISM. This is not only to avoid conflicts with results of deep searches (Richstone et al. 1992; Flynn, Gould & Bahcall 1996), but also to avoid problems with massive stellar black holes (disruption of stellar discs, excessive X-ray emission due to accretion, etc.).

Otherwise, it can proceed via cold gas, passing through a phase similar to that depicted in models of Pfenniger, Combes & Martinet (1994), Pfenniger & Combes (1994), Gerhard & Silk (1996) or Walker (1998) and Walker & Wadle (1998). It is not clear how the IMF in such cases can be restricted to low-luminosity objects. On the other, it may be significant that Pfenniger et al. (1994) models do predict extreme flattening of baryonic haloes (or thick discs), composed of fractal distribution of small, sub-Jeans mass cloudlets (Pfenniger & Combes 1994).

Finally, gas may form MACHOs in an early cooling flow, similar to those we perceive today in rich clusters and around isolated giant elliptical galaxies (Fabian, Nulsen & Canizares 1982; Sarazin 1988; Fabian et al. 1986; Nulsen, Johnstone & Fabian 1987). This is scenario of Nulsen & Fabian (1995; 1997). It has the advantage that it creates conditions favorable to low-luminosity objects in a natural way (Sarazin & O’Connell 1983; Sarazin 1986; Ferland, Fabian & Johnstone 1994; Fabian & Nulsen 1994). Further virtue of this picture is the necessity for the Pop III initial mass function (IMF) to be significantly different from that observed today.

Fig. 15. The same as in Fig. 14, for the maximized MACHO cosmological density (non-flattened $q = 1$ case).

The same as in Fig. 14, for the maximized MACHO cosmological density (non-flattened $q = 1$ case).
the haloes are extremely flattened – the halo of the Galaxy is flattened so the axial ratio is \( q = 0.2 \) (Sciama 1990, 1997). This is a consequence of the effort to reconcile the observed electron densities obtained from the pulsar dispersion measure data (Nordgren, Cordes & Terzian 1992) according to which \( n_e \sim 0.03 \text{ cm}^{-3} \). DDM theory would give the value of \( n_e \sim 0.017 \) under the assumption of spherical halo. Agreement is thus obtained with significant flattening of the halo that reduces the scale height by the factor \( 4 \) to \( 2 \) kpc. One can notice that this flattening could be achieved by extending the mass models of the Galaxy by Dehnen & Binney (1998). However, recently, an attempt has been made to show that in the case of the Galaxy the axis ratio \( q \) is \( q = 0.75 \pm 0.25 \) thus ruling out cold molecular gas and decaying massive neutrino as viable dark matter candidates (Olling & Merrifield 1998). It is somewhat beyond the scope of the present paper, and we only notice that the aforementioned result with this, rather high, value of the parameter \( q \) is attained if the galactocentric distance is \( R_0 = 7 \pm 1 \) kpc, which is a rather unorthodox value. On the other hand, microlensing optical depths indicate that "standard" versions of these theories, requiring \( q \approx 0.2 \) are no longer viable. This conclusion can be avoided if MACHOs are dynamically insignificant within 50 kpc. However, it can be shown that one can easily accommodate a much larger value of \( q \), i.e. \( q \sim 0.6 \), into the DDM theory without significant changes of the theory’s fundamental parameters such as mass and lifetime of the decaying neutrino (Samurović & Ćirković 1999).

8 CONCLUSIONS

On the basis of still scarce empirical data, and still undeveloped and unsophisticated theoretical models, one can, however, draw some important inferences regarding the global shape of haloes of spiral galaxies, taking the Milky Way as a prototype \( L \sim L_\odot \) galaxy at zero-redshift. It seems that a whole array of different arguments point to an oblate gravitating dark halo, which, in turn, causes flattening of other types of haloes, like stellar and gaseous (Lyα-absorbing) haloes. Our conclusions are thus summarized as follows:

1. The set of measured optical depths for microlensing, although still statistically incomplete, strongly indicates moderately flattened haloes.
2. We reconfirm the conclusion of FFG that \( \Omega_{\text{MACHO}} \) is very high in all plausible cases, specifically,

\[
\frac{\Omega_{\text{MACHO}}}{\Omega_B} = 0.1 - 1.
\]

For spherical or little-flattened haloes, it is, in fact, unpleasantly close to \( \Omega_B \), as obtained from the primordial nucleosynthesis and flattening seems to be the simplest remedy for this situation.

3. Review of relevant literature reveals a multitude of arguments for flattened haloes of the Milky Way and other spiral galaxies. We find the arguments based on the total mass of Lyα forest clouds especially convincing, in conjunction with strong arguments for association of low and intermediate-redshift Lyα forest with normal galaxies.

4. We find the FFG conclusion that baryons in MACHOs and Lyα forest are essentially decoupled is strengthened on the basis of low-\( z \) absorption studies and indications of extended gas around present-day galaxies.

5. Baryonic census clearly favors low values of the Hubble constant, essentially irrespectively of flattening.

Further investigations, especially of the epoch of MACHO formation, probed by early damped Lyα and similar gas-rich systems will be necessary to completely clear the picture of ramification of the baryonic matter in the universe into diffuse and collapsed components. This, coupled with microlensing advances, should be able to finally solve the problem of baryonic component of dark matter and unify several branches of astrophysical research into a coherent picture of the evolution of matter, as we know it, in the universe.

ACKNOWLEDGEMENTS

The authors are happy to express their gratitude to Dr. Geza Gyuk for stimulating comments and encouragement. Useful discussions with Dr. Slobodan Ninković and helpful remarks by Dr. Giuliano Giuricin are also acknowledged. SS acknowledges the financial support of the University of Trieste where part of this work was carried out.

REFERENCES

Alcock, C. et al., 1996, ApJ, 461, 84
Alcock, C. et al., 1997a, ApJ, 479, 119
Alcock, C. et al., 1997b, ApJ, 486, 697
Alcock, C. et al., 1997c, ApJ, 491, L11
Ansari, R. et al., 1996, A & A, 314, 94
Aubourg, E. et al., 1993, Nat, 365, 623
Bahcall, J.N., 1984, ApJ, 287, 926
Bahcall, J. N. 1986, ARA&A, 24, 577
Bahcall, J.N., Spitler, L., 1969, ApJ, 156, L63
Bajtlik, S. Duncan, R. C., Ostriker, J. P., 1988, ApJ, 327, 570
Barcons, X., Fabian, A. C., 1987, MNRAS, 224, 675
Bergeron, J., Boissé, P. 1991, A & A, 234, 344
Bi, H., Davidsen, A. F., 1997, ApJ, 479, 523
Binggeli, B., Sandage, A., Tammann, G. A., 1988, ARA&A, 26, 509
Binney, J., 1995, Oxford Univ. preprint OUTP/95/09A
Binney, J., Gerhard, O.E., Spergel, D., 1997, MNRAS, 288, 365
Binney, J., Gerhard, O.E., Stark, A.A., Bally, J., Uchida, K.I., 1991, MNRAS, 252, 210
Binney, J., May, A., Ostriker, J.P., 1987, MNRAS, 226, 149
Binney, J., Merrifield, M., 1998, Galactic Astronomy, Princeton Univ. Press, Princeton, NJ
Binney, J., Tremaine, S., 1987, Galactic Dynamics, Princeton Univ. Press, Princeton, NJ
Bland-Hawthorn, J., Ekers, R. D., van Brueggen, W., Koekemoer, A., Taylor, K., 1995, ApJ, 442, L77
Bristow, P. D., Phillips, S., 1994, MNRAS, 267, 13
Burles, S., Tytler, D., 1998, ApJ, 499, 699
Canuto, V., 1978, MNRAS, 184, 721
Carr, B. J., 1994, ARA&A 32, 531
Chen, H-W., Lanzetta, K.M., Webb, J.K., Barcons, X., 1998, ApJ, 498, 77
Cole, S., Lacey, C., 1996, MNRAS, 281, 716
Combes, F., Boissé, P., Mazure, A., Blanchard, A., 1995, Galaxies and Cosmology, Springer-Verlag, Berlin
Croots, A. P. S., 1992, ApJ, 399, L43
Croots, A. P. S., Tomanay, A. B., 1996, ApJ, 473, L87
De Rújula, A., Jetzer, P., Massó, E., 1992, A & A, 254, 99
Dehnen, W., Binney, J., 1998, MNRAS, 294, 429
This paper has been produced using the Royal Astronomical Society/Blackwell Science TeX macros.