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An upgrade of the microlensing rate (*)

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Summary. — We study different models of dark-matter distribution for the halo of our galaxy. Assuming that the dark matter is in form of MACHOs, we compute the expected number of microlensing events and their average time duration for an experiment monitoring stars in the LMC. The main effect of considering models with anisotropy in the velocity space is to reduce the microlensing rate by about 30% and to increase, but only slightly, the mean event duration, as compared to the standard spherical halo model. Consideration of different luminous models for the visible part of the galaxy also induce variations in the microlensing results by roughly the same amount as mentioned above.

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1. – Introduction

An important problem in astrophysics lies in the knowledge of the nature of the non-luminous matter present in galactic halos. Recently, we have proposed a scenario in which the halo dark matter is in form of baryonic dark clusters constituted by MACHOs (Massive Astrophysical Compact Halo Objects) and molecular clouds [1-4]. While halo molecular clouds could be detected in a near future by observations in more spectral bands, MACHOs have been detected by the EROS [5] and the MACHO [6] collaborations by monitoring stars in the Large Magellanic Cloud (LMC). Assuming a standard spherical halo model, Alcock *et al.* [7] found that MACHOs contribute a fraction $0.19^{+0.16}_{-0.10}$ to the halo dark matter, whereas their average mass turns out to be $\sim 0.08\ M_\odot$ [8].

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Several authors have studied the problem of determining the number of the expected microlensing events by considering different models for the mass distribution, both luminous and dark in the galaxy [7]-[11]. Alcock *et al.* [7] considered "power law models" for the halo and found that the microlensing rate can vary by as much as a factor 10 with respect to the value one gets for the standard halo. Kan-ya *et al.* [11] analysed axisymmetric "power law models" and studied the variation of the optical depth to microlensing and found that it can vary within a factor 2.5 compared to the standard halo model. In this paper we investigate another class of models for the halo of our galaxy (for more details see [12]). In particular, we consider the Eddington and King-Michie models which include anisotropy effects in the velocity space.

2. – Microlensing rate

We assume that the galaxy contains two main components, namely, the visible component (stars) and the dark component (MACHOs). We consider stars to be distributed according to a central bulge and an exponential disk [13]. The central concentration of stars obey the density law

$$\varrho_{\mathrm{C}}(x, y, z) = \frac{M_{\mathrm{b}}}{8\pi\tilde{a}bc} e^{-s^2/2}, \qquad \text{with } s^4 = (x^2/\tilde{a}^2 + y^2/b^2)^2 + z^4/c^4, \tag{1}$$

where the bulge mass is $M_{\mathrm{b}} \sim 2\cdot 10^{10} M_{\odot}$ and the scale lengths are $\tilde{a} = 1.49$ kpc, $b = 0.58$ kpc, $c = 0.40$ kpc. The remaining luminous matter is described with a double exponential disk, so that the galactic disk has both a "thin" (D_1) and a "thick" (D_2) component. For the "thin" disk we adopt the law

$$\varrho_{\mathrm{D}}(X, z) = \frac{\Sigma_0}{2H} e^{-|z|/H} e^{-(X-R_0)/h}, \tag{2}$$

where the local projected mass density is $\Sigma_0 \sim 25\ M_{\odot}$ pc^{-2}, the scale parameters are $H \sim 0.30$ kpc and $h \sim 3.5$ kpc and $R_0 = 8.5$ kpc is the local galactocentric distance. For the "thick" component we consider the same density law as in eq. (2) but with variable thicknesses in the range $H = 1 \pm 0.5$ kpc and local projected density $\Sigma_0 \sim 50 \pm 25 M_{\odot}$ pc^{-2}.

We treat MACHOs with the formalism based on the equation of state assuming that they are spherically symmetric distributed. Then, for MACHOs we adopt the King-Michie distribution function [14]

$$\mathrm{d}n(r) = A(2\pi\sigma^2)^{-3/2} e^{[W(r)-W(0)]}(e^{-v^2/2\sigma^2} - e^{-W(r)})\, e^{-L^2(r)/2L_{\mathrm{c}}^2}\, \mathrm{d}^3 v, \tag{3}$$

for $v \leqslant v_{\mathrm{c}}(r)$ and $\mathrm{d}n = 0$ otherwise. Here $W(r) = v_{\mathrm{c}}^2(r)/2\sigma^2$ is the energy cut-off and L_{c} the angular-momentum cut-off parameter. This function introduces an anisotropy in the velocity space, which increases with the radial coordinate r and leads to highly eccentric orbits for the MACHOs located in the outer regions of the galaxy. This anisotropy can be understood as a consequence of the initial conditions of the galaxy formation as well as of the MACHOs formation processes. Visible and dark components are considered to be in hydrostatic equilibrium in the overall-gravitational-potential V solution of the Poisson equation, which we solve assuming, as stated, spherical symmetry for the dark-mass distribution. Starting from eq. (3) and expressing $L_c = M r_a \sigma$ in terms of the anisotropy radius r_a, we obtain the MACHO mass density,

$$\varrho_H(r) = A(2\pi\sigma^2)^{-3/2} e^{[W(r) - W(0)]} \left(\frac{r_a}{r} \right) \int_0^{W(r)} [e^{-\xi} - e^{-W(r)}] \, F(\lambda) \, d\xi \,, \tag{4}$$

where $\lambda = (r/r_a)\sqrt{\xi}$, $\xi = v^2/2\sigma^2$ and $F(\lambda)$ is the Dawson integral. The distribution function in eq. (3) can be approximated in the limit without energy cut-off ($W \to \infty$) with the Eddington model [14] which implies a density

$$\varrho_H(r) = \varrho_0 \left(\frac{a^2 + R_0^2}{a^2 + r^2} \right) \frac{1}{1 + (r/r_a)^2} \,, \tag{5}$$

where ϱ_0 is the local dark-mass density.

The rate at which a single star is microlensed is given by [15], [16]

$$\Gamma = 2 D r_E \frac{\varrho_0}{M_\odot} \frac{1}{\sqrt{\bar{\mu}}} \int_0^{+v_c} dv_T \int_0^1 d\tilde{x} \, v_T^2 \, f(\tilde{x}, v_T) [\tilde{x}(1 - \tilde{x})]^{1/2} H(\tilde{x}) \,, \tag{6}$$

where all MACHOs have been assumed of the same mass $\bar{\mu}$ (in solar units), D is the LMC distance, $r_E = \sqrt{4 G M_\odot D}/c$, $H(\tilde{x}) = \varrho_H(\tilde{x})/\varrho_0$ and $f(\tilde{x}, v_T)$ is the projection of the MACHO velocity distribution function given in eq. (3) in the plane perpendicular to the line of sight. For an experiment monitoring $N_\star$ stars during an observation time t_{obs} the total number of expected events will be $N_{ev} = N_\star t_{obs} \Gamma$. The expected event duration T is defined as

$$T = \frac{r_E}{v_0} \sqrt{\bar{\mu}} \, \frac{\gamma(1)}{\gamma(1/2)} \,. \tag{7}$$

From the experimental lensing data it is also possible to extract information on the MACHO mass distribution. In particular, the mean MACHO mass M is given by (for details and definitions see [15])

$$\overline{M} = \frac{\langle \tau^1 \rangle}{\langle \tau^{-1} \rangle} \, \frac{\gamma(0)}{\gamma(1)} \,. \tag{8}$$

Here $\langle \tau^1 \rangle$ and $\langle \tau^{-1} \rangle$ are determined through the observed microlensing events, and $\gamma(m)$ are given by

$$\gamma(m) \equiv \int_0^{+v_c} \int_0^1 d\tilde{x} \left(\frac{v_T}{v_0} \right)^{2-2m} v_T \, f(\tilde{x}, v_T) [\tilde{x}(1 - \tilde{x})]^m H(\tilde{x}) \,. \tag{9}$$

3. – Results

We first discuss the results for the Eddington models which we obtain by varying in eq. (5) the parameters a, ϱ_0 and r_a of the MACHO mass density law. For each model we compute the resulting rotation curve considering the circular speed of the exponential disks and the contribution due to the bulge and dark halo. A given model is physically acceptable only if it leads to a flat rotation curve up to the distance of the LMC (with a local rotational velocity $v_0 = 215 \pm 10$ km s^{-1}). In order to check this requirement we perform a $\chi^2_{\rm LMC} < 1$ test, which gives a measure of the flatness of the rotation curve in the region 5 kpc $< r <$ 50 kpc.

In table I we report the mean values of the allowed range for the parameters a, ϱ_0 and $r_{\rm a}$ and we also give the number of microlensing events $N_{\rm ev}$, their average duration T, the ratio $[\gamma(0)/\gamma(1)]$ which is related to the mean MACHO mass $\overline{M}$, as well as the amounts of dark mass $M_{\rm H}^{\rm LMC}$ up to the LMC distance. Results for the standard halo model are given in the first line of table I. The main effect of the anisotropy in velocity space (second line) is to reduce of a factor up to 3 the amount of the total (inside the distance of 250 kpc) dark matter (for more details see [12]). The dark mass $M_{\rm H}^{\rm LMC}$ also decreases with increasing anisotropy, however, by less than 20%. The decrease of $M_{\rm H}^{\rm LMC}$ for anisotropic models compared to isotropic ones implies a smaller number of microlensing events $N_{\rm ev}$, since the MACHOs orbits are now more eccentric. This reduction is also partially due to a shortening of the average transverse MACHO velocity with increasing anisotropy which, on the other hand, leads to an increase of the event duration. Finally, as one can see from the last column of table II, for the anisotropic models there is a decrease of the ratio $[\gamma(0)/\gamma(1)]$ leading, by eq. (8), to a smaller expected average MACHO mass M, which turns out to be definitely smaller than the nuclear burning limit of $0.08\,M_\odot$.

Till now we assumed a flat rotation curve in the range 5–50 kpc. Actually, the galactic rotation curve is well measured only in the range 5–20 kpc [17]. Thus we consider Eddington models for which we relax the condition of a flat rotation curve in the range 20–50 kpc. To select acceptable physical models we now follow the strategy outlined, *e.g.*, in Gates *et al.* [18]. We require that: i) the local rotational velocity is $v_0 = 215 \pm 10$ km/s; ii) the total variation in $v_{\rm rot}(r)$ in the range 5 kpc $< r <$ 20 kpc is less than 14%; iii) the rotational velocity $v_{\rm rot}$(LMC) at the LMC is in the range 150–307 km s^{-1}. The results obtained for these Eddington models are given in table II, where the

TABLE I. – *Mean values of parameters and microlensing results for the Eddington models with flat rotation curves up to the* LMC. *In this and the other tables $N_{\rm ev}$ and T are calculated by assuming an experiment monitoring* 10^6 *stars during 1 year and for a* MACHO *mass of* $10^{-1}\,M_\odot$.

a (kpc)	$\varrho_0/10^{-3}$ ($M_\odot$ pc^{-3})	$r_{\rm a}$ (kpc)	$M_{\rm H}^{\rm LMC}$ ($10^{11}\,M_\odot$)	$N_{\rm ev}$	T (days)	$[\gamma(0)/\gamma(1)]$
6.3 ± 1.4	7.6 ± 1.5	∞	4.9 ± 1.0	5.4 ± 0.9	22.4 ± 0.7	7.3 ± 0.2
6.5 ± 1.4	8.3 ± 1.3	47 ± 12	3.7 ± 0.8	4.1 ± 0.6	27.0 ± 1.1	5.2 ± 0.3

TABLE II. – *Mean values of parameters and microlensing results for the Eddington models with flat rotation curves up to* 20 kpc.

a (kpc)	$\varrho_0/10^{-3}$ ($M_\odot$ pc^{-3})	$r_{\rm a}$ (kpc)	$M_{\rm H}^{\rm LMC}$ ($10^{11}\,M_\odot$)	$N_{\rm ev}$	T (days)	$[\gamma(0)/\gamma(1)]$
6.2 ± 1.4	7.0 ± 3.8	∞	4.5 ± 1.5	4.7 ± 1.5	22.5 ± 0.9	7.7 ± 0.2
6.4 ± 1.4	7.6 ± 4.0	40 ± 15	2.9 ± 1.5	3.5 ± 1.3	27.7 ± 1.5	5.7 ± 0.3

TABLE III. – *Mean values of parameters and microlensing results for King-Michie models with flat rotation curve up to the* LMC.

a (kpc)	$\varrho_0/10^{-3}$ ($M_\odot$ pc^{-3})	r_a (kpc)	M_H^{LMC} ($10^{11} M_\odot$)	N_{ev}	T (days)	$[\gamma(0)/\gamma(1)]$
4.9 ± 0.9	9.1 ± 0.9	∞	6.0 ± 0.9	6.4 ± 0.9	22.6 ± 1.0	8.2 ± 0.8
6.6 ± 1.9	6.4 ± 0.7	∞	6.3 ± 0.9	5.9 ± 0.9	21.7 ± 1.0	8.5 ± 1.0
13 ± 4	4.0 ± 0.5	∞	6.9 ± 1.0	5.8 ± 0.9	19.2 ± 1.0	10.2 ± 1.1
5.7 ± 1.5	9.7 ± 1.1	40 ± 15	4.9 ± 0.7	5.7 ± 0.8	25.1 ± 0.9	6.9 ± 0.6
8.9 ± 3.5	7.0 ± 1.0	42 ± 16	5.1 ± 0.8	5.2 ± 0.8	24.1 ± 1.3	7.3 ± 1.1
17 ± 3	4.5 ± 0.6	45 ± 13	5.8 ± 0.7	5.0 ± 0.9	21.6 ± 1.0	8.6 ± 0.8

first row corresponds to isotropic models. A comparison between tables I and II shows that relaxing the requirement that the rotation curve has to be flat at distances larger than ~ 20 kpc does not change much the previous results. The main effect seems to be a larger range of variation for our results, although in table II there is a trend towards a decrease of N_{ev}.

Finally, we consider King-Michie model results in table III. Here, again we adopt the same strategy as in table I, considering only models which lead to a flat rotation curve up to the LMC distance (performing again a $\chi^2_{LMC} < 1$ test). As for the Eddington models the numerical results depend on the assumed amount of luminous matter, so we consider, as an illustration, the two extreme models corresponding to the "minimum" (rows 1 and 4) and the "maximum" (rows 3 and 6) disk together with an intermediate model (rows 2 and 5). Results in table III for the King-Michie models confirm that the anisotropy in phase space decreases N_{ev} and $\overline{M}$, while it increases T. However, the variation is not so marked as for the Eddington models in table I.

The larger scatter of the values in table III as compared to the ones in table I can be understood as being due to the variation of the amount of luminous matter as well as to the fact that the King-Michie models have an additional parameter (the central energy cut-off parameter W_0) with respect to the Eddington models (for which $W_0 \rightarrow \infty$). Due to the presence of this additional parameter, for the King-Michie models it is not possible to see a clear correlation between the microlensing results and the degree of anisotropy in velocity space, since the latter effect can be smaller than the one induced by the variation of W_0. The amount of the halo dark matter as well as the rotational velocity at the LMC distance also depend on the values of the parameter W_0. Therefore, it is clear that the knowledge of the LMC rotation velocity is crucial for determining the number of microlensing events, besides the ambiguity due to the uncertainty of the amount of the galactic luminous matter. The difficulty of getting precise microlensing results for the King-Michie models becomes even more evident if we adopt the conditions i)-iii) to select physical models (for more details see [12]).

In conclusion, we find that with the present knowledge of the various parameters for the visible component of the galaxy the variation in the expected number of microlensing events is at least within 30% from the value one gets for the standard halo model (flat rotation curve up to the LMC). This factor can even increase if one allows for less restrictive conditions.

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