Abstract. We present the basics of microlensing and give an overview of the results obtained so far. We also describe a scenario in which dark clusters of MACHOs (Massive Astrophysical Compact Halo Objects) and cold molecular clouds (mainly of $H_2$) naturally form in the halo at galactocentric distances larger than 10-20 kpc. Moreover, we discuss various experimental tests of this picture in particular a $\gamma$-ray emission from the clouds due to the scattering of high-energy cosmic-ray protons. Our estimate for the $\gamma$-ray flux turns out to be in remarkably good agreement with the recent discovery by Dixon et al. [1] of a possible $\gamma$-ray emission from the halo using EGRET data.

INTRODUCTION

A central problem in astrophysics concerns the nature of the dark matter in galactic halos, whose presence is implied by the flat rotation curves in spiral galaxies. As first proposed by Paczyński [2], gravitational microlensing can provide a decisive answer to that question, and since 1993 this dream has started to become a reality with the detection of several microlensing events towards the Large Magellanic Cloud. Today, although the evidence for Massive Astrophysical Compact Halo Objects (MACHOs) is firm, the implications of this discovery crucially depend on the assumed galactic model. Moreover, at least two of the events found towards the Large Magellanic Clouds are due to lenses located in the Clouds themselves. Therefore, it might well be that also the other events or at least a fraction of them are due to MACHOs in the Clouds. This issue might be solved when more events will be available.

It has become customary to take the standard spherical halo model as a baseline for comparison. Within this model, the mass moment method yields an average MACHO mass of $0.27 \, M_\odot$. Unfortunately, because of the presently available limited statistics different data-analysis procedures lead to results which are only marginally consistent. For instance, the average MACHO mass reported by the MACHO team based on its first two years of data is $0.5^{+0.3}_{-0.2} \, M_\odot$. Apart from the low-statistics problem – which will automatically disappear from future larger data samples – we feel that the real question is whether the standard spherical halo model correctly describes our galaxy. Although the answer was believed to lie in the affirmative for some years, nowadays various arguments strongly favour a nonstandard galactic halo. Indeed, besides the observational evidence that spiral galaxies generally have flattened halos, recent determinations of both the disk scale length, and the magnitude and slope of the rotation at the solar position indicate that our galaxy is best described by the maximal disk model. This conclusion is further strengthened by the microlensing results towards the galactic centre, which imply that the bulge is more massive than previously thought. Correspondingly, the halo plays a less dominant role than within the standard halo model, thereby reducing the halo microlensing rate as well as the average MACHO mass. A similar result occurs within the King-Michie halo models [5], which take into account the finite escape velocity and the anisotropies in velocity space (typically arising during the phase of halo formation). Moreover, practically the same conclusions also hold for flattened galactic models with a substantial degree of halo rotation. So, the expected average MACHO mass should be smaller than within the standard halo model. Still, the problem remains to explain the formation of MACHOs, as well as the nature of the remaining dark matter in galactic halos.

We have proposed a scenario [6–8] in which dark clusters of MACHOs and cold molecular clouds – mainly of $H_2$ – naturally form in the halo at galactocentric distances larger than 10 – 20 kpc (somewhat similar ideas have also been put forward by Carr and Ashman [9,10], Pfenniger, Combes and Martinet [11], Gerhard and Silk [12] and by Fabian and Nulsen [13]).

Here, we discuss the dark matter problem in the halo of our Galaxy in connection with microlensing searches and we briefly review the main features of our scenario, along with its observational implications in particular with
a γ-ray flux produced in the scattering of high-energy cosmic-ray protons on $H_2$. Our estimate for the halo γ-ray flux turns out to be in remarkably good agreement with the recent discovery by Dixon et al. [1] of a possible γ-ray emission from the halo using EGRET data.

The content is as follows: first, we review the evidence for dark matter in the halo of our Galaxy. As next we present the baryonic candidates for dark matter and we discuss the basics of microlensing (optical depth, microlensing rates, etc.). We then give an overview of the results of microlensing searches achieved so far and we briefly present a scenario in which part of the dark matter is in the form of cold molecular clouds (mainly of $H_2$).

**MASS OF THE MILKY WAY**

The best evidence for dark matter in galaxies comes from the rotation curves of spirals. Measurements of the rotation velocity $v_{\text{rot}}$ of stars up to the visible edge of the spiral galaxies and of HI gas in the disk beyond the optical radius (by measuring the Doppler shift in the 21-cm line) imply that $v_{\text{rot}} \approx$ constant out to very large distances, rather than to show a Keplerian falloff. These observations started around 1970 [14], thanks to the improved sensitivity in both optical and 21-cm bands. By now there are observations for over thousand spiral galaxies with reliable rotation curves out to large radii. In almost all of them the rotation curve is flat or slowly rising out to the last measured point. Very few galaxies show falling rotation curves and those that do either fall less rapidly than Keplerian have nearby companions that may perturb the velocity field or have large spheroids that may increase the rotation velocity near the centre.

There are also measurements of the rotation velocity for our Galaxy. However, these observations turn out to be rather difficult, and the rotation curve has been measured only up to a distance of about 20 kpc. Without any doubt our own galaxy has a typical flat rotation curve. A fact this, which implies that it is possible to search directly for dark matter characteristic of spiral galaxies in our own Milky Way.

In order to infer the total mass one can also study the proper motion of the Magellanic Clouds and of other satellites of our Galaxy. Recent studies [15–17] do not yet allow an accurate determination of $v_{\text{rot}}(LMC)/v_0$ ($v_0 = 210 \pm 10$ km/s being the local rotational velocity). Lin et al. [16] analyzed the proper motion observations and concluded that within 100 kpc the Galactic halo has a mass $\sim 5.5 \pm 1 \times 10^{11} M_\odot$ and a substantial fraction $\sim 50\%$ of this mass is distributed beyond the present distance of the Magellanic Clouds of about 50 kpc. Beyond 100 kpc the mass may continue to increase to $\sim 10^{12} M_\odot$ within its tidal radius of about 300 kpc. This value for the total mass of the Galaxy is in agreement with the results of Zaritsky et al. [15], who found a total mass in the range 9.3 to 12.5 $\times 10^{11} M_\odot$, the former value by assuming radial satellite orbits whereas the latter by assuming isotropic satellite orbits.

The results of Lin et al. [16] suggest that the mass of the halo dark matter up to the Large Magellanic Cloud (LMC) is roughly half of the value one gets for the standard halo model (with flat rotation curve up to the LMC and spherical shape), implying thus the same reduction for the number of expected microlensing events. Kochanek [17] analysed the global mass distribution of the Galaxy adopting a Jaffe model, whose parameters are determined using the observations on the proper motion of the satellites of the Galaxy, the Local Group timing constraint and the ellipticity of the M31 orbit. With these observations Kochanek [17] concludes that the mass inside 50 kpc is $5.4 \pm 1.3 \times 10^{11} M_\odot$. This value becomes, however, slightly smaller when using only the satellite observations and the disk rotation constraint, in this case the median mass interior to 50 kpc is in the interval 3.3 to 6.1 (4.2 to 6.8) without (with) Leo I satellite in units of $10^{11} M_\odot$. The lower bound without Leo I is 65% of the mass expected assuming a flat rotation curve up to the LMC.

**BARYONIC DARK MATTER CANDIDATES**

Before discussing the baryonic dark matter we would like to mention that another class of candidates which is seriously taken into consideration is the so-called cold dark matter, which consists for instance of axions or supersymmetric particles like neutralinos [18]. Here, we will not discuss cold dark matter in detail. However, recent studies seem to point out that there is a discrepancy between the calculated (through N-body simulations) rotation curve for dwarf galaxies assuming an halo of cold dark matter and the measured curves [19–21]. If this fact is confirmed, this would exclude cold dark matter as a major constituent of the halo of dwarf galaxies and possibly also of spiral galaxies.

From the Big Bang nucleosynthesis model [22,23] and from the observed abundances of primordial elements one infers: $0.010 \leq h^2_0 \Omega_B \leq 0.016$ or with $h_0 \simeq 0.4 - 1$ one gets $0.01 \leq \Omega_B \leq 0.10$ (where $\Omega_B = \rho_B/\rho_{\text{crit}}$, and $\rho_{\text{crit}} = 3H_0^2/8\pi G$). Since for the amount of luminous baryons one finds $\Omega_{\text{lum}} \ll \Omega_B$, it follows that an important fraction of the baryons are dark. Indeed, the dark baryons may well make up the entire dark halo matter.
The halo dark matter cannot be in the form of hot ionized hydrogen gas otherwise there would be a large X-ray flux, for which there are stringent upper limits [24]. The abundance of neutral hydrogen gas is inferred from the 21-cm measurements, which show that its contribution is small. Another possibility is that the hydrogen gas is in molecular form clumped into cold clouds, as we will discuss later on. Baryons could otherwise have been processed in stellar remnants (for a detailed discussion see [25]). If their mass is below around \( 0.08 M_\odot \) they are too light to ignite hydrogen burning reactions. The possible origin of such brown dwarfs or Jupiter like bodies (called also MACHOs), by fragmentation or by some other mechanism, is at present not well understood. It has also been pointed out that the mass distribution of the MACHOs, normalized to the dark halo mass density, could be a smooth continuation of the known initial mass function of ordinary stars [26]. The ambient radiation, or their own body heat, would make sufficiently small objects of H and He evaporate rapidly. The condition that the rate of evaporation of such a hydrogenoid sphere be insufficient to halve its mass in a billion years leads to the following lower limit on their mass [26]: \( M > 10^{-7} M_\odot (T_S/30 K)^{3/2} (1 \text{ g cm}^{-3}/\rho)^{1/2} \) (\( T_S \) being their surface temperature and \( \rho \) their average density, which we expect to be of the order \( 1 \text{ g cm}^{-3} \)).

Otherwise, MACHOs might be M-dwarfs or white dwarfs. As a matter of fact, a deeper analysis shows that the M-dwarf option looks problematic. The null result of several searches for low-mass stars both in the disk and in the halo of our Galaxy suggests that the halo cannot be mostly in the form of hydrogen burning main sequence M-dwarfs. Optical imaging of high-latitude fields taken with the Wide Field Camera of the Hubble Space Telescope indicates that less than \( \sim 6\% \) of the halo can be in this form [27]. However, these results are derived under the assumption of a smooth spatial distribution of M-dwarfs, and become considerably less severe in the case of a clumpy distribution [28].

A scenario with white dwarfs as a major constituent of the galactic halo dark matter has been explored [29]. However, it requires a rather ad hoc initial mass function sharply peaked around 2 - 6 \( M_\odot \). Future Hubble deep field exposures could either find the white dwarfs or put constraints on their fraction in the halo [30]. Also a substantial component of neutron stars and black holes with mass higher than \( \sim 1 M_\odot \) is excluded, for otherwise they would lead to an overproduction of heavy elements relative to the observed abundances.

**BASICS OF MICROLENSING**

In the following we present the main features of microlensing, in particular its probability and rate of events (for reviews see also [31–33], whereas for double lenses see for instance ref. [34]). An important issue is the determination from the observations of the mass of the MACHOs that acted as gravitational lenses as well as the fraction of halo dark matter they make up. The most appropriate way to compute the average mass and other important information is to use the method of mass moments developed by De Rújula et al. [35].

**Microlensing probability**

When a MACHO of mass \( M \) is sufficiently close to the line of sight between us and a more distant star, the light from the source suffers a gravitational deflection. The deflection angle is usually so small that we do not see two images but rather a magnification of the original star brightness. This magnification, at its maximum, is given by

\[
A_{\text{max}} = \frac{u^2 + 2}{u(u^2 + 4)^{1/2}}.
\]

Here \( u = d/R_E \) (\( d \) is the distance of the MACHO from the line of sight) and the Einstein radius \( R_E \) is defined as

\[
R_E^2 = \frac{4GM D}{c^2} x(1 - x)
\]

with \( x = s/D \), and where \( D \) and \( s \) are the distance between the source, respectively the MACHO and the observer.

An important quantity is the optical depth \( \tau_{\text{opt}} \) to gravitational microlensing defined as

\[
\tau_{\text{opt}} = \int_0^1 dx \frac{4\pi G}{c^2} \rho(x) D^2 x (1 - x)
\]

with \( \rho(x) \) the mass density of microlensing matter at distance \( s = xd \) from us along the line of sight. The quantity \( \tau_{\text{opt}} \) is the probability that a source is found within a radius \( R_E \) of some MACHO and thus has a magnification that is larger than \( A = 1.34 \) (\( d \leq R_E \)).
We calculate $\tau_{\text{opt}}$ for a galactic mass distribution of the form

$$\rho(\vec{r}) = \frac{\rho_0(a^2 + R_{GC}^2)}{a^2 + \vec{r}^2},$$

(4)

$|\vec{r}|$ being the distance from the Earth. Here, $a$ is the core radius, $\rho_0$ the local dark mass density in the solar system and $R_{GC}$ the distance between the observer and the Galactic centre. Standard values for the parameters are $\rho_0 = 0.3 \text{ GeV/cm}^3 = 7.9 \times 10^{-3} M_\odot/\text{pc}^3$, $a = 5.6 \text{ kpc}$ and $R_{GC} = 8.5 \text{ kpc}$. With these values we get, for a spherical halo, $\tau_{\text{opt}} \approx 5 \times 10^{-7}$ for the LMC and $\tau_{\text{opt}} \approx 7 \times 10^{-7}$ for the SMC [36].

The magnification of the brightness of a star by a MACHO is a time-dependent effect. For a source that can be considered as pointlike (this is the case if the projected star radius at the MACHO distance is much less than $R_E$) the light curve as a function of time is obtained by inserting

$$u(t) = \frac{(d^2 + v_T^2)^{1/2}}{R_E}$$

(5)

into eq.(1), where $v_T$ is the transverse velocity of the MACHO, which can be inferred from the measured rotation curve ($v_T \approx 200 \text{ km/s}$). The achromaticity, symmetry and uniqueness of the signal are distinctive features that allow to discriminate a microlensing event from background events such as variable stars.

The behaviour of the magnification with time, $A(t)$, determines two observables namely, the magnification at the peak $A(0)$ - denoted by $A_{\text{max}}$ - and the width of the signal $T$ (defined as being $T = R_E/v_T$).

**Microlensing rate towards the LMC**

The microlensing rate depends on the mass and velocity distribution of MACHOs. The mass density at a distance $s = xD$ from the observer is given by eq.(4). The isothermal spherical halo model does not determine the MACHO number density as a function of mass. A simplifying assumption is to let the mass distribution be independent of the position in the galactic halo, i.e., we assume the following factorized form for the number density per unit mass $dn/dM$,

$$\frac{dn}{dM}dM = \frac{dn_0}{d\mu} \frac{a^2 + R_{GC}^2}{a^2 + R_{GC}^2 + D^2 x^2 - 2D R_{GC} x \cos \alpha} d\mu = \frac{dn_0}{d\mu} H(x) d\mu,$$

(6)

with $\mu = M/M_\odot$ ($\alpha$ is the angle of the line of sight with the direction of the galactic centre, which is $82^\circ$ for the LMC), $n_0$ not depending on $x$ and is subject to the normalization $\int d\mu \frac{dn_0}{d\mu} M = \rho_0$. Nothing a priori is known on the distribution $dn_0/dM$.

A different situation arises for the velocity distribution in the isothermal spherical halo model, its projection in the plane perpendicular to the line of sight leads to the following distribution in the transverse velocity $v_T$

$$f(v_T) = \frac{2}{v_H^2} v_T e^{-v_T^2/v_H^2}$$

(7)

($v_H \approx 210 \text{ km/s}$ is the observed velocity dispersion in the halo).

In order to find the rate at which a single star is microlensed with magnification $A \geq A_{\text{min}}$, we consider MACHOs with masses between $\mu$ and $\mu + \delta \mu$, located at a distance from the observer between $x$ and $x + \delta x$ and with transverse velocity between $v_T$ and $v_T + \delta v_T$. The collision time can be calculated using the well-known fact that the inverse of the collision time is the product of the MACHO number density, the microlensing cross-section and the velocity. The rate $d\Gamma$, taken also as a differential with respect to the variable $u$, at which a single star is microlensed in the interval $d\mu du dv_T dx$ is given by [35,37]

$$d\Gamma = 2v_T f(v_T) Dr_E |\mu x (1 - x)|^{1/2} H(x) \frac{dn_0}{d\mu} d\mu dv_T dx,$$

(8)

with

$$v_E^2 = \frac{4 G M_\odot D}{c^2} \sim (3.2 \times 10^9 \text{ km})^2.$$

(9)

One has to integrate the differential number of microlensing events, $dN_{\text{ev}} = N_* t_{\text{obs}} d\Gamma$, over an appropriate range for $\mu$, $x$, $u$ and $v_T$, in order to obtain the total number of microlensing events which can be compared with an
experiment monitoring $N_\star$ stars during an observation time $t_{\text{obs}}$ and which is able to detect a magnification such that $A_{\text{max}} \geq A_{TH}$. The limits of the $u$ integration are determined by the experimental threshold in magnitude shift, $\Delta m_{TH}$: we have $0 \leq u \leq u_{TH}$.

The range of integration for $\mu$ is where the mass distribution $dn_\mu/d\mu$ is not vanishing and that for $x$ is $0 \leq x \leq D_h/D$ where $D_h$ is the extent of the galactic halo along the line of sight (in the case of the LMC, the star is inside the galactic halo and thus $D_h/D = 1$.) The galactic velocity distribution is cut at the escape velocity $v_e \approx 640 \text{ km/s}$ and therefore $v_T$ ranges over $0 \leq v_T \leq v_e$. In order to simplify the integration we integrate $v_T$ over all the positive axis, due to the exponential factor in $f(v_T)$ the so committed error is negligible.

However, the integration range of $d\mu dudv$ does not span all the interval we have just described. Indeed, each experiment has time thresholds $T_{\text{min}}$ and $T_{\text{max}}$ and only detects events with: $T_{\text{min}} \leq T \leq T_{\text{max}}$, and thus the integration range has to be such that $T$ lies in this interval. The total number of micro-lensing events is then given by

$$N_{\text{ev}} = \int dN_{\text{ev}} \epsilon(T),$$

(10)

where the integration is over the full range of $d\mu dudv dx$. $\epsilon(T)$ is determined experimentally [4,55]. $T$ is related in a complicated way to the integration variables, because of this, no direct analytical integration in eq.(10) can be performed.

To evaluate eq.(10) we define an efficiency function $\epsilon_0(\mu)$

$$\epsilon_0(\mu) = \frac{\int dN^*_{\text{ev}}(\bar{\mu}) \epsilon(T)}{\int dN^*_{\text{ev}}(\bar{\mu})},$$

(11)

which measures the fraction of the total number of microlensing events that meet the condition on $T$ at a fixed MACHO mass $M = \bar{\mu} M_\odot$. We now can write the total number of events in eq.(10) as

$$N_{\text{ev}} = \int dN_{\text{ev}} \epsilon_0(\mu).$$

(12)

Due to the fact that $\epsilon_0$ is a function of $\mu$ alone, the integration in $d\mu dudv dx$ factorizes into four integrals with independent integration limits.

The average lensing duration can be defined as follows

$$< T > = \frac{1}{\Gamma} \int d\Gamma T(x, \mu, v_T),$$

(13)

where $T(x, \mu, v_T) = R_E(x, \mu)/v_T$. One easily finds that $< T >$ satisfies the following relation

$$< T > = \frac{2\tau_{\text{opt}}}{\pi \Gamma} u_{TH}. $$

(14)

In order to quantify the expected number of events it is convenient to take as an example a delta function distribution for the mass. The rate of microlensing events with $A \geq A_{\text{min}}$ (or $u \leq u_{\text{max}}$), is then

$$\Gamma(A_{\text{min}}) = u_{\text{max}} \Gamma = u_{\text{max}} D_T R_E \sqrt{\pi} v_H \rho_0 \left(\frac{1}{M_\odot \sqrt{\hbar}}\right) \int_0^1 dx [x(1-x)]^{1/2} H(x).$$

(15)

Inserting the numerical values for the LMC (D=50 kpc and $\alpha = 82^0$) we get

$$\tilde{\Gamma} = 4 \times 10^{-13} \left(\frac{v_H}{210 \text{ km/s}}\right) \left(\frac{\rho_0}{0.3 \text{ GeV/cm}^3}\right) \left(\frac{1}{M/M_\odot}\right) \text{s}^{-1}.$$ 

(16)

For an experiment monitoring $N_\star$ stars during an observation time $t_{\text{obs}}$ the total number of events with a magnification $A \geq A_{\text{min}}$ is: $N_{\text{ev}}(A_{\text{min}}) = N_\star t_{\text{obs}} \Gamma(A_{\text{min}})$. In Table 1 we show some values of $N_{\text{ev}}$ for the LMC, taking $t_{\text{obs}} = 1$ year, $N_\star = 10^6$ stars and $A_{\text{min}} = 1.34$ (or $\Delta m_{\text{min}} = 0.32$).
TABLE 1.

| MACHO mass in $M_\odot$ | Mean $R_E$ in km | Mean microlensing time | $N_{ev}$ |
|-------------------------|-------------------|------------------------|---------|
| $10^{-1}$               | $0.3 \times 10^9$ | 1 month                | 4.5     |
| $10^{-2}$               | $10^8$            | 9 days                 | 15      |
| $10^{-4}$               | $10^7$            | 1 day                  | 165     |
| $10^{-6}$               | $10^6$            | 2 hours                | 1662    |

Mass moment method

A more systematic way to extract information on the masses is to use the method of mass moments [35, 38, 39]. The mass moments $< \mu^m >$ are defined as

$$< \mu^m > = \int d\mu \epsilon_n(\mu) \frac{dn_0}{d\mu} \mu^m .$$  \hspace{1cm} (17)

$< \mu^m >$ is related to $< \tau^n > = \sum_{events} \tau^n$, with $\tau \equiv (v_H/r_E)T$, as constructed from the observations and which can also be computed as follows

$$< \tau^n > = \int dN_{ev} \epsilon_n(\mu) \tau^n = Vu_{TH} \gamma(m) < \mu^m > ,$$  \hspace{1cm} (18)

with $m \equiv (n + 1)/2$. For targets in the LMC $\gamma(m) = \Gamma(2 - m) \tilde{H}(m)$ and

$$V \equiv 2N_* t_{obs} D r_E \, v_H = 2.4 \times 10^3 \, pc^3 \frac{N_* \, t_{obs}}{10^6 \, star \, - \, years} ,$$  \hspace{1cm} (19)

$$\Gamma(2 - m) \equiv \int_0^\infty \left( \frac{v_T}{v_H} \right)^{1-n} f(v_T) dv_T ,$$  \hspace{1cm} (20)

$$\tilde{H}(m) \equiv \int_0^1 (x(1-x))^m H(x) dx .$$  \hspace{1cm} (21)

The efficiency $\epsilon_n(\mu)$ is determined as follows [35]

$$\epsilon_n(\mu) \equiv \frac{\int dN_{ev}^*(\bar{\mu}) \epsilon(T) \tau^n}{\int dN_{ev}^*(\bar{\mu}) \tau^n} ,$$  \hspace{1cm} (22)

where $dN_{ev}^*(\bar{\mu})$ is defined as $dN_{ev}$ in eq.(10) with the MACHO mass distribution concentrated at a fixed mass $\bar{\mu}$: $dn_0/d\mu = n_0 \delta(\mu - \bar{\mu})/\mu$. $\epsilon(T)$ is the experimental detection efficiency. For a more detailed discussion on the efficiency see ref. [40].

A mass moment $< \mu^m >$ is thus related to $< \tau^n >$ as given from the measured values of $T$ in a microlensing experiment by

$$< \mu^m > = \frac{< \tau^n >}{Vu_{TH} \gamma(m)} .$$  \hspace{1cm} (23)

The mean local density of MACHOs (number per cubic parsec) is $< \mu_0 >$. The average local mass density in MACHOs is $< \mu^1 >$ solar masses per cubic parsec.

The mean mass, which we get from the six events detected by the MACHO team during their first two years, is [3]

$$\frac{< \mu^1 >}{< \mu^0 >} = 0.27 \, M_\odot .$$  \hspace{1cm} (24)

When taking for the duration $T$ the values corrected for “blending”, we get as average mass $0.34 \, M_\odot$. If we include also the two EROS events we get a value of $0.26 \, M_\odot$ for the mean mass (without taking into account blending effects). The resulting mass depends on the parameters used to describe the standard halo model. In order to check
In fact, the two disregarded events are a binary lensing and one which is rated as marginal.  

1) This dependence we varied the parameters of the standard halo model within their allowed range and found that the average mass changes at most by ±30%, which shows that the result is rather robust. Although the value for the average mass we find with the mass moment method is marginally consistent with the result of the MACHO team, it definitely favours a lower average MACHO mass.

Another important quantity to be determined is the fraction \( f \) of the local dark matter density (the latter one given by \( \rho_0 \)) detected in the form of MACHOs, which is given by \( f = M_\odot/\rho_0 \sim 126 \, \text{pc}^3 < \mu^1 > \). Using the values given by the MACHO collaboration for their two years data [4] we find \( f \sim 0.54 \), again by assuming a standard spherical halo model.

Once several moments \( < \mu^m > \) are known one can get information on the mass distribution \( d n_0 / d \mu \). Since at present only few events towards the LMC are at disposal the different moments (especially the higher ones) can be determined only approximately. Nevertheless, the results obtained so far are already of interest and it is clear that in a few years, due also to the new experiments under way (such as EROS II, OGLE II and MOA in addition to MACHO), it will be possible to draw more firm conclusions.

Present Status of Microlensing Research

It has been pointed out by Paczyński [2] that microlensing allows the detection of MACHOs located in the galactic halo in the mass range \( 10^{-7} < M/M_\odot < 1 \), as well as MACHOs in the disk or bulge of our Galaxy [41,42]. Since this first proposal microlensing searches have turned very quickly into reality and in about a decade they have become an important tool for astrophysical investigations. Microlensing is also very promising for the search of planets around other stars in our Galaxy and generates large databases for variable stars, a field which has already benefitted a lot. Because of the increase of observations, since several new experiments are becoming operative, the situation is changing rapidly and, therefore, the present results should be considered as preliminary.

Towards the LMC and the SMC

In September 1993 the French collaboration EROS [43] announced the discovery of 2 microlensing candidates and the American–Australian collaboration MACHO of one candidate [44] by monitoring stars in the LMC.  

In the meantime the MACHO team reported the observation of altogether 8 events (one is a binary lensing event) analysing their first two years of data by monitoring about 8.5 million of stars in the LMC [4]. The inferred optical depth is \( \tau_{\text{opt}} = 2.1^{+1.1}_{-0.7} \times 10^{-7} \) when considering 6 events ¹ (or \( \tau_{\text{opt}} = 2.9^{+3.0}_{-1.9} \times 10^{-7} \) when considering all the 8 detected events). Correspondingly, this implies that about 45% (50% respectively) of the halo dark matter is in form of MACHOs and they find an average mass \( 0.5^{+0.3}_{-0.2} M_\odot \) assuming a standard spherical halo model. It may well be that there is also a contribution of events due to MACHOs located in the LMC itself or in a thick disk of our galaxy, in which case the above results will change quite substantially. In particular for the binary event there is evidence that the lens is located in the LMC. It has been estimated that the optical depth for lensing due to MACHOs in the LMC or in a thick disk is about \( \tau_{\text{opt}} = 5.4 \times 10^{-8} \) [4]. However, this value is model dependent so that at present it is not clear which fraction of the events are due to self-lensing in the LMC (and similarly for the SMC).

Other events have been detected towards the LMC by the MACHO group, which have been put on their list of alert events. The full analysis of the 1996 - 1998 seasons is still not published.

EROS has also searched for very-low mass MACHOs by looking for microlensing events with time scales ranging from 30 minutes to 7 days [45]. The lack of candidates in this range places significant constraints on any model for the halo that relies on objects in the range \( 5 \times 10^{-8} < M/M_\odot < 2 \times 10^{-2} \). Indeed, such objects may make up at most 20% of the halo dark matter (in the range between \( 5 \times 10^{-7} < M/M_\odot < 2 \times 10^{-3} \) at most 10%). Similar conclusions have also been reached by the MACHO group [4].

Recently, the MACHO team reported [46] the first discovery of a microlensing event towards the Small Magellanic Cloud (SMC). The full analysis of the four years data on the SMC is still underway, so that more candidates may be found in the near future. A rough estimate of the optical depth leads to about the same value as found towards the LMC. The same event has also been observed by the EROS [47] and the Polish-American OGLE collaboration [48]. A second event has been discovered in 1998 and found to be due to a binary lens. This event has been followed by the different collaborations, so that the combined data lead to a quite accurate light curve, from which it is possible

¹ In fact, the two disregarded events are a binary lensing and one which is rated as marginal.
to get an upper limit for the value of the proper motion of the lens [49,50]. The result indicates that the lens system is most probably located in the SMC itself, in which case the lens may be an ordinary binary star. It is remarkable that both the binary events detected so far are due to lenses in the Clouds themselves, making it plausible that this is the case for the other lenses as well.

Since the middle of 1996 the EROS group has put into operation a new 1 meter telescope, located in La Silla (Chile), and which is fully dedicated to microlensing searches using CCD cameras. The improved experiment is called EROS II.

Towards the galactic centre

Towards the galactic bulge the Polish-American team OGLE [51] announced his first event also in September 1993. Since then OGLE found in their data from the 1992 - 1995 observing seasons altogether 18 microlensing events (one being a binary lens). Based on their first 9 events the OGLE team estimated the optical depth towards the bulge as [52] $\tau_{opt} = (3.3 \pm 1.2) \times 10^{-6}$. This has to be compared with the theoretical calculations which lead to a value [41,42] $\tau_{opt} \simeq (1 - 1.5) \times 10^{-6}$, which does, however, not take into account the contribution of lenses in the bulge itself, which might well explain the discrepancy. In fact, when taking into account also the effect of microlensing by galactic bulge stars the optical depth gets bigger [53] and might easily be compatible with the measured value. This implies the presence of a bar in the galactic centre. In the meantime the OGLE group got a new dedicated 1.3 meter telescope located at the Las Campanas Observatory. The OGLE-II collaboration has started the observations in 1996 and is monitoring the bulge, the LMC and the SMC as well.

The French DUO [54] team found 12 microlensing events (one of which being a binary event) by monitoring the galactic bulge during the 1994 season with the ESO 1 meter Schmidt telescope. The photographic plates were taken in two different colors to test achromaticity. The MACHO [55] collaboration found by now more than ~ 150 microlensing events towards the galactic bulge, most of which are listed among the alert events, which are constantly updated 2. They found also 3 events by monitoring the spiral arms in the region of Gamma Scutum. During their first season they found 45 events towards the bulge. The MACHO team detected also in a long duration event the parallax effect due to the motion of the Earth around the Sun [56]. The MACHO first year data leads to an estimated optical depth of $\tau_{opt} \simeq 2.43^{+0.54}_{-0.45} \times 10^{-6}$, which is roughly in agreement with the OGLE result, and which also implies the presence of a bar in the galactic centre. These results are very important in order to study the structure of our Galaxy. In this respect the measurement towards the spiral arms will give important new information.

Some globular clusters lie in the galactic disk about half-way between us and the galactic bulge. If globular clusters contain MACHOs, the latter can also act as lenses for more distant stars located in the bulge. Recently, we have analysed the microlensing events towards the galactic bulge, which lie close to three globular clusters and found evidence that some microlensing events are indeed due to MACHOs located in the globular clusters [57]. If this finding is confirmed, once more data will be available, it would imply that also globular clusters contain an important amount of dark matter in form of MACHOs, which probably would be brown dwarfs or white dwarfs.

Towards the Andromeda galaxy

Microlensing searches have also been conducted towards M31, which is an interesting target [58-60]. In this case, however, one has to use the so-called “pixel-lensing” method, since the source stars are in general no longer resolvable. Two groups have performed searches: the French AGAPE [61] using the 2 meter telescope at Pic du Midi and the American VATT/COLUMBIA [62], which used the 1.8 meter VATT-telescope located on Mt. Graham and the 4 meter KNPO telescope. Both teams showed that the pixel-lensing method works, however, the small amount of observations done so far does not allow to draw firm conclusions. The VATT/COLUMBIA team found six candidates which are consistent with microlensing, however, additional observations are needed to confirm this. Pixel-lensing could also lead to the discovery of microlensing events towards the M87 galaxy, in which case the best would be to use the Hubble Space Telescope [63]. It might also be interesting to look towards dwarf galaxies of the local group.

2) Current information on the MACHO Collaboration’s Alert events is maintained at the WWW site http://darkstar.astro.washington.edu.
Further developments

A new collaboration between New Zealand and Japan, called MOA, started in June 1996 to perform observations using the 0.6 meter telescope of the Mt. John Observatory [64]. The targets are the LMC and the galactic bulge. They will in particular search for short timescale (\(\sim 1\) hour) events, and will then be particularly sensitive to objects with a mass typical for brown dwarfs.

It has to be mentioned that there are also collaborations between different observatories (for instance PLANET [65] and GMAN [66]) with the aim to perform accurate photometry on alert microlensing events. The GMAN collaboration was able to accurately get photometric data on a 1995 event towards the galactic bulge. The light curve shows clearly a deviation due to the extension of the source star [67]. A major goal of the PLANET and GMAN collaborations is to find planets in binary microlensing events [68–70]. Moreover, microlensing searches are also very powerful ways to get large database for the study and discovery of many variable stars.

At present the only information available from a microlensing event is the time scale, which depends on three parameters: distance, transverse velocity and mass of the MACHO. A possible way to get more information is to observe an event from different locations, with typically an Astronomical Unit in separation. This could be achieved by putting a parallax satellite into solar orbit [71,72].

The above list of presently active collaborations and main results shows clearly that this field is just at the beginning and that many interesting results will come in the near future.

FORMATION OF DARK CLUSTERS

We turn now to the discussion of a scenario for the formation of dark clusters of MACHOs and cold molecular clouds. Our scenario [6–8] encompasses the one originally proposed by Full and Rees [73] to explain the origin of globular clusters and can be summarized as follows. After its initial collapse, the proto galaxy (PG) is expected to be shock heated to its virial temperature \(\sim 10^6\) K. Because of thermal instability, density enhancements rapidly grow as the gas cools. Actually, overdense regions cool more rapidly than average, and so proto globular cluster (PGC) clouds form in pressure equilibrium with hot diffuse gas. When the PGC cloud temperature reaches \(\sim 10^4\) K, hydrogen recombination occurs: at this stage, their mass and size are \(\sim 10^6 (R/kpc)^{1/2} M_\odot\) and \(\sim 10 \,(R/kpc)^{1/2}\) pc, respectively \((R\) is the galactocentric distance). Below \(10^4\) K, the main coolants are \(H_2\) molecules and any heavy element produced in a first chaotic galactic phase. The subsequent evolution of the PGC clouds will be very different in the inner and outer part of the Galaxy, depending on the decreasing ultraviolet (UV) flux as the galactocentric distance \(R\) increases.

As is well known, in the central region of the Galaxy an Active Galactic Nucleus (AGN) and a first population of massive stars are expected to form, which act as strong sources of UV radiation that dissociates the \(H_2\) molecules. It is not difficult to estimate that \(H_2\) depletion should happen for galactocentric distances smaller than \(10–20\) kpc. As a consequence, cooling is heavily suppressed in the inner halo, and so the PGC clouds here remain for a long time at temperature \(\sim 10^4\) K, resulting in the imprinting of a characteristic mass \(\sim 10^6 M_\odot\). Eventually, the UV flux will decrease, thereby permitting the formation of \(H_2\). As a result, the cloud temperature drops below \(\sim 10^4\) K and the subsequent evolution leads to star formation and ultimately to globular clusters.

Our main point is that in the outer halo – namely for galactocentric distances larger than \(10–20\) kpc – no substantial \(H_2\) depletion should take place (owing to the distance suppression of the UV flux). Therefore, the PGC clouds cool and contract. When their number density exceeds \(\sim 10^8\) cm\(^{-3}\), further \(H_2\) is produced via three-body reactions \((H + H + H \rightarrow H_2 + H\) and \(H + H + H_2 \rightarrow 2H_2\), which makes in turn the cooling efficiency increase dramatically. This fact has three distinct implications: (i) no imprinting of a characteristic PGC cloud mass shows up, (ii) the Jeans mass can drop to values considerably smaller than \(\sim 1 M_\odot\), and (iii) the cooling time is much shorter than the free-fall time. In such a situation a subsequent fragmentation occurs into smaller and smaller clouds that remain optically thin to their own radiation. The process stops when the clouds become optically thick to their own line emission – this happens when the Jeans mass is as low as \(\sim 10^{-2} M_\odot\). In this manner, dark clusters should form, which contain brown dwarfs in the mass range \(10^{-2}–10^{-1}\) \(M_\odot\).

Before proceeding further, two observations are in order. First, it seems quite natural to suppose that – much in the same way as it occurs for ordinary stars – also in this case the fragmentation process that gives rise to individual brown dwarfs should produce a substantial fraction of binary brown dwarfs. It is important to keep in mind that the mass fraction of primordial binaries can be as large as 50\%. Hence, we see that MACHOs consist of both individual and binary brown dwarfs in the present scenario [74,75]. Second, we do not expect the fragmentation process to be able to convert the whole gas in a PGC cloud into brown dwarfs. For instance, standard stellar formation mechanisms lead to an upper limit of at most 40\% for the conversion efficiency. Thus, a substantial fraction \(\tilde{f}\) of the primordial gas – which is mostly \(H_2\) – should be left over. Because brown dwarfs do not give rise to stellar winds,
this gas should remain confined within a dark cluster. So, also cold $H_2$ self-gravitating clouds should presumably be clumped into dark clouds, along with some residual diffuse gas (the amount of diffuse gas inside a dark cluster has to be low, for otherwise it would have been observed in optical and radio bands).

Unfortunately, the total lack of any observational information about dark clusters would make any effort to understand their structure and dynamics practically impossible, were it not for some remarkable insights that our unified treatment of globular and dark clusters provides us. In the first place, it looks quite natural to assume that also dark clusters have a denser core surrounded by an extended spherical halo. Moreover, in the lack of any further information it seems reasonable to suppose (at least tentatively) that the dark clusters have the same average mass density as globular clusters. Hence, we obtain $r_{DC} = 0.12 (M_{DC}/M_\odot)^{1/3}$ pc, where $M_{DC}$ and $r_{DC}$ denote the mass and the median radius of a dark cluster, respectively. As a further implication of the above scenario, we stress that – at variance with the case of globular clusters – the initial mass function of the dark clusters should be smooth, since the monotonic decrease of the PGC cloud temperature fails to single out any particular mass scale. In addition, the absence of a quasi-hydrostatic equilibrium phase for the dark clusters naturally suggests $M_{DC} \leq 10^6 M_\odot$. Finally, we suppose for definiteness that all brown dwarfs have mass $\simeq 0.1 M_\odot$, while the molecular cloud spectrum will be taken to be $10^{-3} M_\odot \leq M_m \leq 10^{-1} M_\odot$.

**OBSERVATIONAL TESTS**

We list schematically some observational tests for the present scenario.

**Clustering of microlensing events** – The most promising way to detect dark clusters is via correlation effects in microlensing observations, as they are expected to exhibit a cluster-like distribution [76]. Indeed, it has been shown that a relatively small number of microlensing events would be sufficient to rule out this possibility, while to confirm it more events are needed. However, we have seen that core collapse can liberate a considerable fraction of MACHOs from the less massive clusters, and so an unclustered MACHO population is expected to coexist with dark clusters in the outer halo – detection of unclustered MACHOs would therefore not disprove the present model.

**$\gamma$-rays from halo clouds** – A signature for the presence of molecular clouds in the galactic halo should be a $\gamma$-ray flux produced in the scattering of high-energy cosmic-ray protons on $H_2$ [6,7]. As a matter of fact, an essential ingredient is the knowledge of the cosmic ray flux in the halo. Unfortunately, this quantity is unknown and the only available information comes from theoretical estimates. Moreover, we assume the same energy distribution of the cosmic rays as measured on Earth. The presence of magnetic fields in the halo is expected to give rise to a temporary confinement of cosmic ray protons similar to what happens in the disk. In addition, there can also be sources of cosmic ray protons located in the halo itself, as for instance isolated or binary pulsars in globular clusters. The best chance to detect the $\gamma$-rays in question is provided by observations at high galactic latitude. We find that - regardless of the adopted value for the flatness of the halo - at high-galactic latitude $\Phi_{\gamma}^{DM}(\geq 1$ GeV) lies in the range $\simeq 6 - 8 \times 10^{-7} \gamma$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (assuming a fraction $\tilde{f} \simeq 0.5$ for the dark matter in form of cold clouds). However, the shape of the contour lines strongly depends on the flatness parameter [77].

A few months ago, Dixon et al. [1] have re-analyzed the EGRET data concerning the diffuse $\gamma$-ray flux with a wavelet-based technique. After subtraction of the isotropic extragalactic component and of the expected contribution from the Milky Way, they find a statistically significant diffuse emission from the galactic halo. At high-galactic latitude, the integrated halo flux above 1 GeV turns out to be $\simeq 10^{-7} - 10^{-6} \gamma$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which is slightly less than the diffuse extragalactic flux (Sreekumar et al. [78]). Our estimate for the halo $\gamma$-ray flux turns out to be in remarkably good agreement with the discovery by Dixon et al. [1]. The next generation of $\gamma$-ray satellites like AGILE and GLAST will be able to test our model, thanks to their better angular resolution.

**CBR anisotropy** – An alternative way to discover the molecular clouds under consideration relies upon their emission in the microwave band [79]. The temperature of the clouds has to be close to that of the cosmic background radiation (CBR). Indeed, an upper limit of $\Delta T/T \sim 10^{-3}$ can be derived by considering the anisotropy they would introduce in the CBR due to their higher temperature. Realistically, molecular clouds cannot be regarded as black body emitters because they mainly produce a set of molecular rotational transition lines. If we consider clouds with cosmological primordial composition, then the only molecule that contributes to the microwave band with optically thick lines is $LiH$, whose lowest rotational transition occurs at $\nu_0 = 444$ GHz with broadening $\sim 10^{-5}$ (due to the turbulent velocity of molecular clouds in dark clusters). This line would be detectable using the Doppler shift effect. To this aim, it is convenient to consider M31 galaxy, for whose halo we assume the same picture as outlined above for our galaxy. Then we expect that molecular clouds should have typical rotational speeds of 50-100 km s$^{-1}$. Given the fact that the clouds possess a peculiar velocity (with respect to the CBR) the emitted radiation will be Doppler shifted, with $\Delta \nu/\nu_0 \sim \pm 10^{-3}$. However, the precise chemical composition of molecular clouds in the galactic halo is unknown. Even if the heavy molecule abundance is very low (as compared with the abundance in interstellar clouds), many optically thick lines corresponding to the lowest rotational transitions would show up in
the microwave band. In this case, it is more convenient to perform broad-band measurements and the Doppler shift effect results in an anisotropy in the CBR. Since it is difficult to work with fields of view of a few arcsec, we propose to measure the CBR anisotropy between two fields of view - on opposite sides of M31 - separated by ∼ 4′ and with angular resolution of ∼ 10′. We suppose that the halo of M31 consists of ∼ 10^6 dark clusters which lie within 25-35 kpc. Scanning an annulus of 10^6 width and internal angular diameter 40, centered at M31, in 180 steps of 10^6, we would find anisotropies of ∼ 10^{-5} f_\delta in \Delta T/T. Here, most of the uncertainties arise from the estimate of the average optical depth \bar{\tau}, which mainly depends on the molecular cloud composition. In conclusion, since the theory does not allow to establish whether the expected anisotropy lies above or below current detectability (∼ 10^{-6}), only observations can resolve this issue.

**Absorption-lines** — Cold clouds clumped into dark clusters can also be observed through absorption lines (due to heavy molecules) both in UV and in optical bands in the spectra of LMC stars, which lie very close (within ∼ 1′) to a previously microlensed one.

**Infrared searches** — Another possibility of detecting MACHOs is via their infrared emission [79]. In order to be specific, let us assume that all MACHOs have same mass 0.08 \odot and age 10^{10} yr. Accordingly, their surface temperature is ∼ 1.4 × 10^3 K and they emit most of their radiation (as a black body) at \nu_{max} ∼ 11.5 × 10^{13} Hz. First, we consider MACHOs located in M31. In this case, we find a surface brightness I_{\nu_{max}} ∼ 2.1 × 10^3 (1 - f_\delta) Jy sr^{-1} and 0.5 × 10^3 (1 - f_\delta) Jy sr^{-1} for projected separations from the M31 center b = 20 kpc and 40 kpc, respectively. Although these values are about one order of magnitude below the sensitivity of the detectors on ISO Satellite, they lie above the threshold of the detector abord the future planned SIRFT Satellite. For comparison, we recall that the halo of our galaxy would have in the direction of the galactic pole a surface brightness I_{\nu_{max}} ∼ 2 × 10^3 Jy sr^{-1}, provided MACHOs make up the total halo dark matter. Nevertheless, the infrared radiation originating from MACHOs in the halo of our galaxy can be recognized (and subtracted) by its characteristic angular modulation. Also, the signal from the M31 halo can be identified and separated from the galactic background via its b-modulation. Next, we point out that the angular size of dark clusters in the halo of our galaxy at a distance of ∼ 20 kpc is ∼ 1.8′ and the typical separation among them is ∼ 14′. As a result, a characteristic pattern of bright (with intensity ∼ 3 × 10^{-2} Jy at \nu_{max} within angular size 1.8′) and dark spots should be seen by pointing the detector into different directions.

**CONCLUSIONS**

The mystery of the dark matter is still unsolved, however, thanks to the ongoing microlensing and pixel-lensing experiments there is hope that progress on its nature in the galactic halo can be achieved within the next few year. An important point will be to determine whether the MACHOs are in the halo or rather in the LMC or SMC themselves, as suggested by the binary lens events.

Substantial progress will also be done in the study of the structure of our Galaxy and this especially once data from the observations towards the spiral arms will be available. Microlensing is also very promising for the discovery of planets. Although being a rather young observational technique microlensing has already allowed to make substantial progress and the prospects for further contribution to solve important astrophysical problems look very bright.

It has also to be mentioned that only a fraction of the halo dark matter might be in form of MACHOs, in which case there is the problem of explaining the nature of the remaining dark matter and the formation of the MACHOs. Before invoking the need for new particles as galactic dark matter candidates for the remaining fraction, one should seriously consider the possibility that it is in the form of cold molecular clouds. Several observational methods have been proposed to test this scenario, in particular via the induced γ-ray flux for which the predicted value is in remarkably good agreement with the measurement of EGRET [1].

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