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MICROLENSING IMPLICATIONS FOR HALO DARK MATTER

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Abstract. The French collaboration EROS and the American-Australian collaboration MACHO have reported the observation of altogether ~ 10 microlensing events by monitoring during several years the brightness of millions of stars in the Large Magellanic Cloud. In particular the MACHO team announced the discovery of 8 microlensing candidates by analysing their first 2 years of observations. This would imply that the halo dark matter fraction in form of MACHOs (Massive Astrophysical Compact Halo Objects) is of the order of 45-50%. The most accurate way to get information on the mass of the MACHOs is to use the method of mass moments. For the microlensing events detected so far by the MACHO collaboration in the Large Magellanic Cloud the average mass turns out to be $0.27 M_\odot$.

1 Introduction

It has been pointed out by Paczyński [1] that microlensing allows the detection of MACHOs located in the galactic halo in the mass range [2] $10^{-7} < M/M_\odot < 1$. In September 1993 the French collaboration EROS [3] announced the discovery of 2 microlensing candidates and the American–Australian collaboration MACHO of one candidate [4]. In the meantime the MACHO team reported the observation of altogether 8 events (one of which is a binary lensing event) analyzing 2 years of their data by monitoring about 8.5 million of stars in the Large Magellanic Cloud (LMC) [5]. Their analysis leads to an optical depth of $\tau = 2.9^{+1.4}_{-0.9} \times 10^{-7}$ and correspondingly to a halo MACHO fraction of the order of 45-50% and an average mass $0.5^{+0.3}_{-0.2} M_\odot$, under the assumption of 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 thich disk of our galaxy, the corresponding optical depth is estimated to be $\tau = 5.4 \times 10^{-8}$ [5]. Moreover, the Polish-American team OGLE [6], the MACHO [7] and the French DUO [8] collaborations found altogether more than $\sim$ 100 microlensing events by monitoring stars located in the galactic bulge. The inferred optical depth for the bulge turns out to be higher than previously thought.

An important issue is the determination of the mass of the MACHOs that acted as gravitational lenses as well as the fraction of halo dark matter in form of MACHOs. 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. [9], which will be briefly presented in section 3.

2 Most probable mass for a single event

First, we compute the probability P that a microlensing event of duration T and maximum amplification A_{max} be produced by a MACHO of mass μ (in units of $M_\odot$). Let d be the distance of the MACHO from the line of sight between the observer and a star in the LMC, t=0 the instant of closest approach and v_T the MACHO velocity in the transverse plane. The magnification A as a function of time is calculated using simple geometry and is given by

$$A(t) = \frac{u^2+2}{u(u^2+4)^{1/2}} , \quad \text{where} \quad u^2 = \frac{d^2 + v_T^2 t^2}{R_E^2} . \tag{2.1}$$

R_E is the Einstein radius which is $R_E^2 = \frac{4GMD}{c^2} x(1-x) = r_E^2 \mu x(1-x)$ with $M = \mu M_\odot$ the MACHO mass and D (xD) the distance from the observer to the source (to the MACHO). $D = 55$ kpc is the distance to the LMC and $r_E = 3.17 \times 10^9$ km. We use here the definition: $T = R_E / v_T$.

We adopt the model of an isothermal spherical halo in which the normalized MACHO number distribution as a function of v_T is

$$f(v_T) dv_T = \frac{2}{v_H^2} v_T e^{-v_T^2/v_H^2} dv_T , \tag{2.2}$$

with $v_H \approx 210$ km/s the velocity dispersion implied by the rotation curve of our galaxy. The MACHO number density distribution per unit mass $dn/d\mu$ is given by

$$\frac{dn}{d\mu} = H(x) \frac{dn_0}{d\mu} = \frac{a^2 + R_{GC}^2}{a^2 + R_{GC}^2 + D^2 x^2 - 2DR_{GC} x cos\alpha} \frac{dn_0}{d\mu}, \tag{2.3}$$

with $dn_0/d\mu$ the local MACHO mass distribution. We have assumed that $dn/d\mu$ factorizes in functions of μ and x [9]. We take $a = 5.6$ kpc as the galactic "core" radius (our final results do not depend much on the poorly known value of a), $R_{GC} = 8.5$ kpc our distance from the centre of the galaxy and $\alpha = 82^0$ the angle between the line of sight and the direction of the galactic centre. For an experiment monitoring $N_\star$ stars during a total observation time t_{obs} the number of expected microlensing events is given by [9]

$$N_{ev} = \int dN_{ev} = N_\star t_{obs} 2Dr_E \int v_T f(v_T)(\mu x(1-x))^{1/2} H(x) \frac{dn_0}{d\mu} d\dot{\mu} du_{min} dv_T dx \tag{2.4}$$

where the integration variable u_{min} is related to A_{max}: $A_{max} = A[u = u_{min}]$. For a more complete discussion in particular on the integration range see [9].

From eq.(2.4) with some variable transformation (see [10]) we can define, up to a normalization constant, the probability P that a microlensing event of duration T and maximum amplification A_{max} be produced by a MACHO of mass μ, that we see first of all is independent of A_{max} [10]

$$P(\mu, T) \propto \frac{\mu^2}{T^4} \int_0^1 dx (x(1-x))^2 H(x) exp\left(-\frac{r_E^2 \mu x(1-x)}{v_H^2 T^2}\right) . \tag{2.5}$$

We also see that $P(\mu, T) = P(\mu/T^2)$. The measured values for T are listed in Table 1, where μ_{MP} is the most probable value. We find that the maximum corresponds to $\mu r_E^2/v_H^2 T^2 = 13.0$ [10, 11]. The 50% confidence interval embraces for the mass μ approximately the range $1/3\mu_{MP}$ up to $3\mu_{MP}$. Similarly one can compute $P(\mu, T)$ also for the bulge events (see [11]).

Table 1: Values of μ_{MP} (in $M_\odot$) for eight microlensing events detected in the LMC (A_i = American-Australian collaboration events (i = 1,..,6); F_1 and F_2 French collaboration events). For the LMC: $v_H = 210$ km s^{-1} and $r_E = 3.17 \times 10^9$ km.

	A_1	A_2	A_3	A_4	A_5	A_6	F_1	F_2
T (days)	17.3	23	31	41	43.5	57.5	27	30
$\tau(\equiv \frac{v_H}{r_E}T)$	0.099	0.132	0.177	0.235	0.249	0.329	0.155	0.172
μ_{MP}	0.13	0.23	0.41	0.72	0.81	1.41	0.31	0.38

3 Mass moment method

A more systematic way to extract information on the masses is to use the method of mass moments as presented in De Rújula et al. [9]. The mass moments $< \mu^m >$ are defined as

$$< \mu^m > = \int d\mu \ \epsilon_n(\mu) \ \frac{dn_0}{d\mu} \mu^m . \tag{3.1}$$

$< \mu^m >$ 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

$$< \tau^n > = \int dN_{ev} \ \epsilon_n(\mu) \ \tau^n = V u_{TH} \Gamma(2-m) \widehat{H}(m) < \mu^m > , \tag{3.2}$$

with $m \equiv (n+1)/2$ and

$$V \equiv 2N_\star t_{obs}\ D\ r_E\ v_H = 2.4 \times 10^3\ pc^3\ \frac{N_\star\ t_{obs}}{10^6\ \mathrm{star-years}}\ , \tag{3.3}$$

$$\Gamma(2-m) \equiv \int_0^\infty \left(\frac{v_T}{v_H}\right)^{1-n} f(v_T) dv_T\ , \tag{3.4}$$

$$\widehat{H}(m) \equiv \int_0^1 (x(1-x))^m H(x) dx\ . \tag{3.5}$$

The efficiency $\epsilon_n(\mu)$ is determined as follows (see [9])

$$\epsilon_n(\mu) \equiv \frac{\int dN^\star_{ev}(\bar{\mu})\ \epsilon(T)\ \tau^n}{\int dN^\star_{ev}(\bar{\mu})\ \tau^n}\ , \tag{3.6}$$

where $dN^\star_{ev}(\bar{\mu})$ is defined as dN_{ev} in eq.(2.4) with the MACHO mass distribution concentrated at a fixed mass $\bar{\mu}$: $dn_0/d\mu = n_0\ \delta(\mu - \bar{\mu})/\mu$. For a more detailed discussion on the efficiency see ref.[12].

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

$$< \mu^m > = \frac{< \tau^n >}{V u_{TH} \Gamma(2-m) \hat{H}(m)}\ . \tag{3.7}$$

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. In the following we consider only 6 (see Table 1) out of the 8 events observed by the MACHO group, in fact the two events we neglect are a binary lensing event and an event which is rated as marginal. The mean mass, which we get from the six events detected by the MACHO team, is

$$\frac{< \mu^1 >}{< \mu^0 >} = 0.27\ M_\odot\ . \tag{3.8}$$

(To obtain this result we used the values of τ as reported in Table 1, whereas $\Gamma(1)\widehat{H}(1) = 0.0362$ and $\Gamma(2)\widehat{H}(0) = 0.280$ as plotted in figure 6 of ref. [9]). If we include also the two EROS events we get a value of 0.26 $M_\odot$ for the mean mass. The resulting mass depends on the parameters used to describe the standard halo model. In order to check this dependence we varied the parameters within their allowed range and found that the average mass changes at most by $\pm$ 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.

One can also consider other models with more general luminous and dark matter distributions, e.g. ones with a flattened halo or with anisotropy in velocity space [13], in which case the resulting value for the average mass would decrease significantly. If the above value will be confirmed, then MACHOs cannot be brown dwarfs nor ordinary hydrogen burning stars, since for the latter there are observational limits from counts of faint red stars. Then stellar remnants such as white dwarfs are the most likely explanation. A scenario with white dwarfs as a major constituent of the galactic halo dark matter has been explored recently [14]. However, it has some problems, since it requires that the initial mass function must be sharply peaked around $2-6M_\odot$. Given these facts, we feel that the brown dwarf option can still provide a sensible explanation of the above-mentioned microlensing events. Notice also, that brown dwarfs have been discovered quite recently in the solar neighbourhood and in the Pleiades cluster.

Another important quantity to be determined is the fraction f of the local dark mass density (the latter one given by ρ_0) detected in the form of MACHOs, which is given by $f \equiv M_\odot/\rho_0 \sim 126\ \mathrm{pc}^3 < \mu^1 >$. Using the values given by the MACHO collaboration for their two years data [5] (in particular $u_{TH} = 0.661$ corresponding to $A > 1.75$ and an effective exposure $N_\star t_{obs}$ of $\sim 5 \times 10^6$ star-years for the observed range of the event duration T between $\sim$ 20 - 50 days) we find $f \sim 0.54$, which compares quite well with the corresponding value ($f \sim 0.45$ based on the six events we consider) calculated by the MACHO group in a different way. The value for f is obtained again by assuming a standard spherical halo model.

Table 2: Values of μ_{MP} (in $M_\odot$) as obtained by the corresponding $P(\mu, T)$ for eleven microlensing events detected by OGLE in the galactic bulge [12]. ($v_H = 30$ km s^{-1} and $r_E = 1.25 \times 10^9$ km.) (T is in days as above.)

	1	2	3	4	5	6	7	8	9	10	11
T	25.9	45	10.7	14	12.4	8.4	49.5	18.7	61.6	12	20.9
τ	0.054	0.093	0.022	0.029	0.026	0.017	0.103	0.039	0.128	0.025	0.043
μ_{MP}	0.61	1.85	0.105	0.18	0.14	0.065	2.24	0.32	3.48	0.13	0.40

Similarly, one can also get information from the events detected so far towards the galactic bulge. The mean MACHO mass, which one gets when considering the first eleven events detected by OGLE in the galactic bulge (see Table 2), is $\sim 0.29M_\odot$ [11]. From the 40 events discovered during the first year of operation by the MACHO team [7] (we considered only the events used by the MACHO team to infer the optical depth without the double lens event) we get an average value of $0.16M_\odot$. The lower value inferred from the MACHO data is due to the fact that the efficiency for the short duration events ($\sim$ some days) is substantially higher for the MACHO experiment than for the OGLE one. These values for the average mass suggest that the lens are faint disk stars.

Once several moments $< \mu^m >$ are known one can get information on the mass distribution $dn_0/d\mu$. Since at present only few events toward 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 and OGLE II), it will be possible to draw more firm conclusions.

A major problem which arises is to explain the formation of MACHOs, as well as the nature of the remaining amount of dark matter in the galactic halo. We feel it hard to conceive a formation mechanism which transforms with 100% efficiency hydrogen and helium gas into MACHOs. Therefore, we expect that also cold clouds (mainly of H_2) should be present in the galactic halo. Recently, we have proposed a scenario [15, 16] in which dark clusters of MACHOs and cold molecular coulds naturally form in the halo at galactocentric distances larger than 10-20 kpc, where the relative abundance depends on the distance. We have also considered several observational tests for our model. In particular, halo molecular clouds would produce a γ-ray flux through the interaction with cosmic-ray protons. The detection of this γ-ray flux is below current detectability but might be observed with a new generation of gamma-ray satellites.

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