

Microlensing searches of dark matter

Esteban Roulet

*Depto. de Física, Universidad Nacional de La Plata
CC67, 1900, Argentina.
E-mail: roulet@venus.fisica.unlp.edu.ar*

ABSTRACT: The evolution of the observational results of microlensing towards the LMC and some of the suggested interpretations to account for them are discussed. It is emphasized that the results at present are indicative of a lensing population of white dwarfs, possibly in the spheroid (not dark halo) of the Galaxy, together with the more standard backgrounds of stellar populations in the Magellanic Clouds and in the Galaxy. This is also hinted by dynamical estimates of the spheroid mass and by recent direct searches of old white dwarfs.

1. Introduction:

To understand the nature of the dark matter is one of the pressing unsolved mysteries in cosmology and particle physics nowadays. The dark matter problem is the fact that the matter in luminous forms (stars and gas) is inferred to account only for $\Omega_{lum} \simeq 0.007$, i.e. for less than one percent of the critical density. On the other hand, dynamical estimates based on the gravitational influence of the mass on test bodies (gas orbiting galaxies, galaxies moving inside clusters) imply that there is at least ten times more ‘dark’ mass than luminous one on galactic scales, and even more ($\Omega \sim 0.3$) on cluster scales. The issue on even larger scales is still unsettled, existing at present indications in favor of some dark energy (cosmological constant) accounting for $\Omega_\Lambda \simeq 0.7$, i.e. filling the gap up to the inflation preferred value $\Omega = 1$ corresponding to a flat universe.

The possible constituents of the dark matter naturally split into baryonic and non-baryonic candidates. The last ones would be some kind of weakly interacting particle permeating the universe, such as supersymmetric neutralinos, axions or massive neutrinos, while the first ones would be made of just ordinary protons and neutrons hidden in some non-luminous forms. The simplest examples to achieve this would be to have them in MACHOs (the acronym for massive astrophysical compact halo objects), such

as stellar remnants (white dwarfs, neutron stars, black holes), brown dwarfs (stars with mass $m < 0.1M_\odot$, which never become hot enough to start sustained nuclear fusion reactions) or even planets. Also cold gas clouds have been suggested as dark baryonic constituents of the galactic halos.

The main constraints on the amount of baryons in the universe come from the theory of primordial nucleosynthesis, which requires $\Omega_b \simeq 0.01-0.05/(H_0/70 \text{ km/s/Mpc})^2$, with the lower (higher) values corresponding to the high (low) primordial deuterium abundance determinations from QSO absorption lines [1]. Hence, we see that for a Hubble constant $H_0 \simeq 50-70 \text{ km/s/Mpc}$ nucleosynthesis indicates that dark baryons should exist and that their total amount is probably insufficient to account for dark galactic halos ($\Omega \simeq 0.1$). Clearly to account for the observations on cluster scales non-baryonic dark matter is also required, and it would then be natural to expect to have some amount of it also at galactic scales.

Although dark compact objects are, by definition, very hard to be seen directly, they may reveal themselves through the gravitational lensing effect they produce on background stars. Indeed in 1986 Paczynski [2] showed that by monitoring a few million stars in the Large Magellanic Cloud (LMC) during a few years would allow to determine whether the dark halo of the Galaxy consists of MACHOs with masses in the range

10^{-7} – $10^2 M_{\odot}$, covering essentially all the range of suggested candidates. Soon after, with the advent of CCDs this program became feasible and several groups started the searches at the beginning of the nineties.

2. Microlensing expectations:

The gravitational deflection of light by massive bodies is one of the predictions of general relativity which is now tested to better than the percent level. This phenomenon leads to several beautiful effects such as the multiple imaging of QSOs by intervening galaxies, giant arcs around clusters or weak lensing distortions of faint background galaxies, which have the potential of giving crucial information for cosmology (measurement of H_0 from the time delays between different QSO images, estimates of cluster masses, etc.). When the deflector is a compact star like object, a MACHO, two images of the background sources are produced, one on each side of the deflector. In the particular case of perfect lens-source alignment, the image is a ring with angular size (Einstein's angle)

$$\theta_E \simeq \text{mas} \sqrt{\frac{m}{M_{\odot}} \frac{(1-x) 10 \text{kpc}}{D_{ol}}},$$

where taking D_{os} as the distance from the observer to the source, $D_{ol} \equiv x D_{os}$ is the distance to the lens. Hence, for lenses at a few kpc distance with masses in the range of interest for the MACHO searches this angle is much smaller than the typical telescope resolution (~ 40 mas for HST!) and hence cannot be resolved. However, the important effect is that the brightness of the source is magnified due to a lensing effect (for reviews see refs. [3, 4]) by a total amount

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

where $u^2 = \xi^2/R_E^2$, with $R_E = \theta_E D_{ol}$ being the radius of the Einstein ring in the lens plane and ξ is the distance between the lens and the line of sight to the source. Due to the lens relative motion orthogonally to the l.o.s. with velocity v^{\perp} , one has $\xi^2 = b^2 + v^{\perp 2}(t - t_0)^2$, with b the impact parameter of the lens trajectory and t_0 the time

of closest approach. Hence, the amplification will vary with time in a very specific form and it is sizeable ($A > 1.34$) as long as the lens distance to the line of sight is not larger than R_E . Hence, one can estimate the optical depth, i.e. the probability that a given star is magnified significantly for a given lens distribution with density n_{ℓ} , as the number of lenses within a distance R_E from the l.o.s.. If the lenses are assumed to have a common mass m , one has $n_{\ell} = \rho_{\ell}/m$, and hence

$$\tau = \frac{4\pi}{m} \int_0^{D_{os}} dD_{ol} R_E^2 \rho_{\ell}.$$

In the case of a halo consisting fully of MACHOs, the lens density will be just the halo density, which from the observed rotation curve of the Galaxy should be

$$\rho_H \simeq \rho_0^H \frac{r_0^2 + a^2}{r^2 + a^2},$$

with $r_0 = 8.5$ kpc the distance to the galactic center, the core radius a is of a few kpc and the local halo density is $\rho_0^H \simeq 10^{-2} M_{\odot}/\text{pc}^3$. This would lead to a predicted optical depth for LMC stars of $\tau^H \simeq 4 \times 10^{-7}$.

The timescale of the events, defined as $T \equiv R_E/v^{\perp}$ (and determined from a fit to the light curve with the theoretical expression for $A(u)$) has an average value $\langle T \rangle \simeq 65 \text{d} \sqrt{m/M_{\odot}}$ given the typical velocity dispersion expected for halo objects ($\sigma \simeq 155$ km/s). One can show that for 100% efficient searches the number of expected events is $N = (2/\pi)(\tau/\langle T \rangle) \times \text{Exposure} \simeq 20 \text{ events} \sqrt{M_{\odot}/m} (\text{Exposure})$. Actually, the efficiencies are $\leq 30\%$ and are time dependent, so that a detailed prediction requires to convolute the differential rates with the efficiencies (and also with the mass distribution of the lenses).

3. First microlensing results and their interpretation

By 1992 the observational searches towards the LMC by the french EROS and australo-american MACHO collaborations had started and already after one year the first candidate events had showed up. It soon became apparent however that the number of events observed were a factor ~ 5 below the expectations from a halo made of objects

lighter than a few solar masses. The estimate of the optical depth to the LMC from the first 3 MACHO events [5] was indeed $\tau = 8.8_{-5}^{+7} \times 10^{-8}$ and the one from the first two EROS events [6] was similar, $\tau = 8.2_{-5}^{+11} \times 10^{-8}$. The typical event durations of a few weeks were also indicative of lens masses in the ballpark of $0.1 M_{\odot}$, i.e. in the limit between brown dwarfs and very light main sequence stars. Furthermore, the non observation of short duration events (T less than a few days) by the EROS CCD program and by MACHO set stringent bounds on light lenses ($10^{-7} < m/M_{\odot} < 10^{-3}$) which could contribute no more than $\sim 25\%$ to the overall halo mass [7].

Although the number of events were few, they were significantly larger than the backgrounds expected from the known stellar populations. For instance, the faint stars in the galactic disc would contribute little to the optical depth towards the LMC, because although the local disc density is an order of magnitude larger than the halo one ($\rho_0^D \simeq 10^{-1} M_{\odot}/\text{pc}^3$) its scale height is very small ($h \sim 100\text{--}300$ pc). In general, adding an exponential disc like population with local column density Σ leads to an optical depth to the LMC of $\tau^D \sim 10^{-8} (\Sigma/30 M_{\odot}/\text{pc}^2) (h/300 \text{ pc})$ [8]. The column density in the thin disc is $\sim 50 M_{\odot}/\text{pc}^2$, of which 20% is in gas. Furthermore taking into account the measured mass function of disc stars it can be shown that a large fraction of τ^D would be due to stars too bright to go undetected [9], and hence the thin disc predicted depth is actually below 10^{-8} .

The Galaxy is also known to have a thicker disc of stars, with $h \simeq 1$ kpc, probably originating from a past merger of a satellite which somehow heated the disc stars. The column density associated to the observed thick disc stars is typically taken as $\Sigma^{TD} \sim 4 M_{\odot}/\text{pc}^2$, and hence the expected optical depth is tiny ($\sim 0.5 \times 10^{-8}$). However, in ref. [8] it was noticed that the maximum allowed column density consistent with dynamical observations, $\Sigma_{max}^{TD} \simeq 50 M_{\odot}/\text{pc}^2$, would lead to $\tau \simeq 5 \times 10^{-8} (h/\text{kpc})$, and hence for the scale height adopted there (1.4 kpc) it would already be close to the observed value.

Another known stellar galactic population is the spheroid (or ‘stellar halo’), observed through the old metal poor stars at high latitudes and

also as high velocity stars nearby (the observed velocity dispersion is $\sigma \simeq 120$ km/s). It was formed in the first Gyrs of the Galaxy lifetime, has a probably slightly flattened spherical shape ($c/a \simeq 0.7\text{--}1$) with density profile $r^{-\alpha}$, with $\alpha \simeq 2.5\text{--}3.5$ [10]. The predicted optical depth for this population, adopting $c/a = 1$ and $\alpha = 3.5$, is $\tau^S \simeq 0.3 \times 10^{-8} (\rho_0^S/10^{-4} M_{\odot}/\text{pc}^3)$. This value would increase by 50% for $\alpha = 2.5$ and decrease by $\sim 25\%$ for $c/a = 0.7$. The spheroid density inferred from star counts, $\rho_0^S \simeq 5 \times 10^{-5} M_{\odot}/\text{pc}^3$ leads then to a tiny optical depth. However, there have been since many years suggestions that the spheroid density should be larger by an order of magnitude, based on global fits to the galactic rotation curve and other dynamical observations [11]. In these heavy spheroid models the optical depth results $\sim 4 \times 10^{-8}$, and is hence relevant for observations towards the LMC [12].

Another background for LMC searches is that of old neutron stars [13]. These are born in the disc, but they are believed to acquire large velocities in the supernova explosions producing them and hence move to large distances where they become more efficient lenses. For the typical value $N_{ns} \simeq 2 \times 10^9$ for the number of past galactic core collapse supernovae [14], the resulting optical depth is $\tau^{NS} \simeq 0.4 \times 10^{-8}$, comparable to the one from known stars in the spheroid or thick disc.

Regarding the LMC populations, in the same way as the Milky Way has a dark halo, the rotation curve of the LMC suggests that this galaxy also has a dark halo around it. The optical depth associated to it amounts to $\sim 8 \times 10^{-8}$ [15, 16]. Hence, if all the dark matter were in MACHOs the total optical depth would be 20% higher than the prediction from the Milky Way halo alone, and this clearly worsens the discrepancies with the observations. It has to be stressed that no stellar population has been observed with the expected LMC halo distribution. The predictions for the observed distributions of LMC stars (disc and bar) are more delicate. It was actually suggested that the optical depth towards the central bar could be $\sim 5 \times 10^{-8}$ [17], and hence of the order of the observed τ . However, outside the bar, where several of the observed events actually are, τ falls significantly, and the most recent

estimates for the expected average depth [18] are $\tau \simeq 2.4 \times 10^{-8}$, although with some spread among different models.

Summarizing, the expectations from known stellar populations amount to $\tau \simeq 3\text{--}4 \times 10^{-8}$, while from the Milky Way and LMC halos one would expect $\tau \simeq 5 \times 10^{-7}$. The observed value $\sim 8 \times 10^{-8}$ was clearly larger than the first one, but only a small fraction of the second. Since the main purpose of the microlensing searches was to establish whether the halo consisted of MACHOs, the results are most commonly presented in terms of the fraction f of the Milky Way halo in the form of compact objects, which for the observed τ would correspond to $f \simeq 20\%$. The remaining fraction could be just in cold gas clouds or in non-baryonic dark matter. An alternative explanation was to have instead a heavy spheroid or thick disc made mainly of MACHOs or a very large LMC self-lensing contribution, and instead a completely non-baryonic halo.

4. The second period (1996-2000)

In 1996, the results of the analysis of the first two years of MACHO data were announced [19]. A total of 8 candidate events were observed and the average event duration turned out to be longer. The conclusion was that now $\tau = 2.9_{-0.9}^{+1.4} \times 10^{-7}$ and also that the typical lens masses increased to $m \simeq 0.5M_{\odot}$. The picture which emerged then was that 50% of the halo should be in objects with the characteristic mass of a white dwarf. This scenario was quite unexpected, and was shown to be also potentially in trouble with the chemical enrichment of the galaxy due to all the metal pollution which would result from the white dwarf progenitors [20, 21]. There were also attempts to explain the observed rates as due to some tidal debris of the LMC or even due to a previously undetected satellite galaxy along the l.o.s. to the LMC [23], but it is not clear whether these ideas are actually supported by observations [24, 25, 26, 27].

In the period after 1996 significant improvements on the observational programs took place: the EROS and OGLE collaborations started to use better cameras in new telescopes and networks of telescopes were organized to follow on-

going alerted microlensing events (GMAN, MOA, PLANET, MPS). This allowed for instance to measure in great detail an event in the Small Magellanic Cloud caused by a binary lens [22]. When the lens is a binary, the signatures are quite different from the single lens case. For large impact parameters there are now three images of the source, one on the exterior side of each of the lenses and the third one in between the lenses. An extra pair of images can appear however for small impact parameters when the source crosses the so called caustic, and then two images disappear again when the source leaves the region delimited by the caustic. At these caustic crossings the magnification formally diverges. This means that one has an extremely powerful magnifying glass to look at the source. Actually, effects associated to the finite size of the source become observable and in particular they limit the maximum amplification to a finite value. If one knows the radius of the source, one can also infer the relative lens-source proper motion μ , and since this quantity is expected to differ significantly for lenses in the Magellanic Clouds ($\mu \sim 1$ km/s/kpc) or in the galactic populations ($\mu \geq 10$ km/s/kpc), it was possible to establish that the binary lens belonged to the SMC and not to the halo. Also one of the MACHO LMC events was a binary and its proper motion again suggested that it belonged to the LMC. This shows that indeed the contribution of the lenses in the Magellanic Clouds is significant, and actually in the SMC it is expected to be relatively larger than in the LMC due to the elongated shape of the SMC along the l.o.s..

5. Recent developments

The most recent microlensing results appeared a few months ago and again changed the overall picture. The analysis of 5.7 yrs of MACHO data [9] in 30 fields (out of a total of 82) found 13–17 events (depending on the criteria used), leading to a significantly reduced depth $\tau = 1.1_{-0.3}^{+0.4} \times 10^{-7}$ (for the 13 event sample). Another relevant observation was that no particular increase in τ towards the center of the Cloud was observed, contrary to the expectations from a rate dominated by LMC stars. Also the EROS group pre-

sented the reanalysis of their old data together with two new years of EROS II data [28], finding a total of only 4 events, a result inconsistent with the '96 MACHO result. This shifted the situation somehow back to the initial stage in which the observed rates are a factor ~ 5 below the halo predictions but $\sim 3-4$ above the expectations from known populations. The inferred masses $m \simeq 0.5M_{\odot}$ continue to suggest however that the objects could be old white dwarfs.

Another important related result has been the recent activity related to the direct search of old white dwarfs. Hansen [29] realized that the spectra of old white dwarfs having molecular hydrogen atmospheres (i.e. probably half of the total) would look much bluer and brighter than previously believed due to the strong absorption at wavelength larger than $1 \mu\text{m}$ by their atmospheres. This prediction was actually confirmed by the direct measurement of the spectrum of a cool ($T \simeq 3800 \text{ }^{\circ}\text{K}$) nearby white dwarf [30]. With this new scenario the search for old white dwarfs becomes feasible, and indeed analyses of two Hubble Deep Fields taken two years apart were done searching for objects with large proper motions [31]. The candidate objects they found, with colours consistent with being old 'halo' white dwarfs, led them to infer that their density could be comparable to the local halo density ($\sim 10^{-2}M_{\odot}/\text{pc}^3$). However, recently two new searches in larger nearby volumes (not so deep but wider) have found results inconsistent with such large white dwarf densities. Flynn et al. [32] found no candidates while expecting a few tens based on ref. [31], while Ibata et al. found two nearby white dwarfs [33], inferring a density of $\sim 7 \times 10^{-4}M_{\odot}/\text{pc}^3$ for these hydrogen atmosphere white dwarfs. A remarkable thing is that this value is just in the required range to account for the missing mass of the heavy spheroid models, whose proper motions would be only $\sim 20\%$ smaller than those assumed for 'dark halo' objects and hence consistent with those found. To analyse the possibility that these old white dwarfs are genetically related to the old population II spheroid stars, and not to an independent halo population with no observed counterpart, seems then particularly relevant. If this were the case, the initial

mass function of spheroid stars would have to be peaked at a few solar masses to account for the large number of white dwarf progenitors, and the gas released during the ejection of their envelopes would have ended up in the disc and bulge, but producing certainly less metal pollution than the halo white dwarf models due to the much smaller total spheroid mass. The future searches of white dwarfs should also be able to distinguish between thick disc and spheroid/halo populations due to their significantly different proper motions.

Regarding the future of microlensing observations, the MACHO experiment has finished taking data, while EROS II and OGLE II are still running. A significant increase in the number of events is then expected when all the data available gets analysed. Furthermore, a new analysis technique (Difference Image Analysis), devised for the study of lensing in crowded fields such as the Andromeda galaxy, has been successfully applied to several bulge fields by the MACHO group [34], doubling the number of observed events with respect to previous analyses, and also by EROS to their first CCD data [35]. The use of this technique for all the LMC data should then also help to get more decent statistics and hence to discriminate among the population(s) responsible for the microlensing events. Clearly the possibility that the dark halo is completely made of non-baryonic dark matter still remains open, and hence the search for its even more elusive constituents is crucial to finally unravel the dark matter mystery.

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