Recent observations of microlensing events in the Large Magellanic Cloud suggest that a sizeable fraction of the galactic halo is in the form of Massive Astrophysical Compact Halo Objects (MACHOs) with mass less than about 0.1$M_\odot$. Here we argue that molecular clouds (mainly of $H_2$) located in the galactic halo can contribute substantially to its total mass. We outline a scenario in which dark clusters of MACHOs and molecular clouds naturally form in the halo at large galactocentric distances. Possible ways of detecting MACHOs via infrared emission and molecular clouds via the induced $\gamma$-ray flux are discussed. Molecular clouds located in the M31 dark halo could be discovered through cosmic background radiation (CBR) anisotropies or emission lines in the microwave band.

**Key words:** dark matter, ISM: clouds, ISM: molecules, gamma rays: theory, Cosmic background radiation, Infrared radiation
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One of the most important problems in astrophysics concerns the nature of the dark matter in galactic halos [1], whose presence is suggested by the observed flat rotation curves in spiral galaxies. Although various exotic dark matter candidates have been proposed, present limits coming from primordial nucleosynthesis [2] still allow a halo made of ordinary baryonic matter. A viable candidate are MACHOs in the mass range $10^{-7} < M/M_\odot < 10^{-1}$ [3], which can be detected, as proposed by Paczyński, via the gravitational lens effect [4]. The few microlensing events found so far [5] by monitoring stars in the Large Magellanic Cloud (LMC) do not yet allow to make a precise estimate of the fraction of halo dark matter in the form of MACHOs nor to infer whether they are located in the halo or rather either in the LMC itself [6] or in a thick disk of our galaxy. Assuming a standard spherical halo model, Alcock et al. [7] found that MACHOs contribute with a fraction $0.20^{+0.33}_{-0.14}$ to the halo dark matter, whereas their average mass turns out to be $\sim 0.08M_\odot$ [8]. Accordingly, the problem arises how to explain the nature of the remaining fraction of the halo dark matter. Here we argue that this fraction can still be baryonic and in the form of molecular clouds (mainly of $H_2$) [9]. Actually, this point of view is corroborated by the result [10] that dissipationless particles, as advocated for cold dark matter, can hardly make up the galactic halo. Moreover, it has recently been claimed [11] that $H_2$ molecular clouds can constitute the dark matter in the disk of our galaxy. Below, we present a scenario in which dark clusters$^{1}$ of MACHOs and molecular clouds naturally form at galactocentric distances $R$ larger than 10-20 kpc, basically because in a quite environment the Jeans mass can drop to

$^{1}$The possibility of clusters of MACHOs has been investigated by several authors (see e.g. [12] - [15]).
values as low as $10^{-2}M_\odot$.

Our picture encompasses the one originally proposed by Fall and Rees [16] for the origin of stellar 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. Since overdense regions cool more rapidly than average (by hydrogen recombination), proto globular cluster (PGC) clouds form in pressure equilibrium with diffuse gas. At this stage, the PGC cloud temperature is $\sim 10^4$ K while mass and size are $\sim 10^6(R/kpc)^{1/2}M_\odot$ and $\sim 10(R/kpc)^{1/2}$ pc, respectively. 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 different in the inner and outer part of the galaxy, depending on the decreasing collision rate and ultraviolet (UV) fluxes as the galactocentric distance increases.

As discussed in [16, 17], in the central region of the galaxy an Active Galactic Nucleus (AGN) and/or a first population of massive stars are expected to exist, which act as strong sources of UV radiation that dissociates the $H_2$ molecules present in the inner part of the halo. As a consequence, cooling is heavily suppressed and so the PGC clouds remain for a long time at temperature $\sim 10^4$ K, resulting in the imprinting of a characteristic mass $\sim 10^6M_\odot$. Later on, when the UV flux decreases and after enough $H_2$ forms, the cloud temperature suddenly drops below $10^4$ K and the subsequent evolution leads to the formation of stars and finally to stellar globular clusters.

Our main point is that in the outer regions of the halo the UV-flux is suppressed due to the larger galactocentric distance, so that no substantial $H_2$ depletion actually happens. On top of this, further $H_2$ is produced via
three-body reactions ($H + H + H \rightarrow H_2 + H$ and $H + H + H_2 \rightarrow 2H_2$), thus the cooling efficiency increases dramatically. This fact has three distinct implications: (i) no imprinting of a characteristic PGC cloud mass shows up, (ii) the Jeans mass can now be lower than $10^{-1} M_\odot$, (iii) the cooling time is much shorter than the collision time. As pointed out in [18], a subsequent fragmentation occurs into smaller clouds that remain optically thin until the minimum value of the Jeans mass is attained, thus leading to MACHO formation. Moreover, since the conversion efficiency of the constituent gas could scarcely have been 100%, we expect the remaining fraction $f$ of the gas to form self-gravitating molecular clouds since, in the absence of strong stellar winds, the surviving gas remains bound in the dark cluster. The possibility that the gas is in diffuse form either in the dark cluster or in the galactic halo is in fact excluded, as the high virial temperature would make it observable in radio or X-ray band.

A few comments are in order. Because the formation of dark clusters of MACHOs and molecular clouds requires sufficiently low UV fluxes, they can mainly form beyond a critical galactocentric distance, which we estimate to be $R_{\text{crit}} \sim 10 - 20$ kpc [9]. Obviously, the above discussion implicitly assumes that dark clusters are stable within the lifetime of the galaxy. This is a nontrivial question, for dark clusters can be disrupted by evaporation and collisions among themselves, whereas molecules can be destroyed by strong UV fluxes. All these effects are avoided, provided the galactocentric distance of dark clusters exceeds $R_{\text{dis}} \sim 10$ kpc and both MACHO and molecular cloud masses are less than about $0.1 M_\odot$ [12].

Let us now briefly discuss the possible signatures of the above scenario.
The most promising way to detect dark clusters of MACHOs is via correlation effects in microlensing observations, as they are expected to exhibit a cluster-like distribution. Remarkably enough, a relatively small number of microlensing events would be sufficient to rule out this possibility, while to confirm it more events are needed [19].

A signature of the presence of molecular clouds in the galactic halo should be a $\gamma$-ray flux produced through the interaction with high-energy cosmic ray protons which, scattering on $H_2$ protons, produce $\pi^0$'s which subsequently decay into $\gamma$'s. 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. More precisely, from the mass-loss rate of a typical galaxy, we infer a total cosmic ray flux in the halo $F \simeq 1.1 \times 10^{-4}$ erg cm$^{-2}$ s$^{-1}$. We further assume the same energy distribution of the cosmic rays as measured on Earth and we scale the cosmic ray density with the inverse of $R^2$. Actually, cosmic ray protons in the halo originating from the galactic disk are mainly directed outwards. This circumstance implies that the induced photons will predominantly leave the galaxy. However, the presence of magnetic fields in the halo could 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 stellar globular clusters. Since we are unable to give a quantitative estimate of the above effects, we take them into account by introducing an efficiency factor $\epsilon$, which could be rather small. The best chance to detect the $\gamma$-rays in question is provided by observations at high galactic latitude. Accordingly, we find a
\( \gamma \)-ray flux \( \Phi_{\gamma}(90^0) \simeq 3 \times 10^{-6} \ \epsilon_f \) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) \[4, 20\], while the inferred upper bound for \( \gamma \)-rays in the 0.8 - 6 GeV range at high galactic latitude is \( 3 \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). Thus, the presence of molecular clouds in the galactic halo does not lead at present to any contradiction with the upper bound, provided \( \epsilon_f < 0.1 \).

A perhaps better way to discover the molecular clouds in question relies upon their emission in the microwave band. The temperature of the clouds is close to that of the cosmic background radiation (CBR). Indeed, an upper limit of \( \Delta T/T \sim 10^{-3} \) can be derived \[21\] 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, the only molecule that contributes to the microwave band with optically thick lines is LiH \[22\], 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 the M31 galaxy, for whose halo we assume the same picture as outlined above for our galaxy \[23\]. 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 corre-
sponding to the lowest rotational transitions would show up in the microwave band. In this case, it is more convenient to perform broad-band measurements, because molecular clouds may be discovered using again the Doppler shift effect, thereby producing an anisotropy in the CBR itself. 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 $\sim 4^0$ and with angular resolution of $\sim 1^0$. We suppose that the halo of M31 consists of $\sim 10^6$ dark clusters which lie within 25-35 kpc. Scanning an annulus of $1^0$ width and internal angular diameter $4^0$, centered at M31, in 180 steps of $1^0$, we would find anisotropies of $\sim 10^{-5} f \bar{\tau}$ in $\Delta T/T_{[21]}$. 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 ($\sim 10^{-6}$), only observations can resolve this issue.

For completeness, we mention that another possibility of detecting MACHOs is via their infrared emission [24]. In order to be specific, let us assume that all MACHOs have same mass $0.08 M_\odot$ and age $10^{10}$ yr. Accordingly, their surface temperature is $\sim 1.4 \times 10^3$ K and they emit most of their radiation (as a black body) at $\nu_{\text{max}} \sim 11.5 \times 10^{13}$ Hz. First, we consider MACHOs located in M31. In this case, we find a surface brightness $I_{\nu_{\text{max}}} \sim 1.6 \times 10^3 (1 - f)$ Jy sr$^{-1}$ and $0.4 \times 10^3 (1 - f)$ Jy sr$^{-1}$ for projected separations from the M31 center $b = 20$ kpc and 40 kpc, respectively [21]. 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 future planned satellite SIRFT. For comparison, we recall that the halo of our galaxy would have in the direction of the galactic pole a surface brightness $I_{\nu_{\text{max}}} \sim 2 \times 10^3$ 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 $\sim 20$ kpc is $\sim 1.8'$ and the typical separation among them is $\sim 14'$. As a result, a characteristic pattern of bright (with intensity $\sim 3 \times 10^{-2}$ Jy at $\nu_{\text{max}}$ within angular size $1.8'$\[25\]) and dark spots should be seen by pointing the detector into different directions.

We would like to close this paper by suggesting out that the above scenario might also hold for elliptical galaxies, for which there is evidence for the presence of dark matter (see e.g. \[26\]). Also in this case, the dark matter can be in the form of dark clusters of MACHOs and molecular clouds, which are not destroyed by the X-ray flux (whose intensity is always less than $\sim 10^{43}$ erg s$^{-1}$) present in ellipticals. An advantage of this idea is that the diffuse gas observed in clusters of galaxies can be understood as arising from the tidal stripping from neighboring galaxies. This fact naturally explains the ROSAT observation that $\sim 30\%$ of the dynamical mass in clusters of galaxies is in baryonic form \[27\]. These speculations would lead to a unique picture for galaxy formation. The parameter which mainly discriminates between the formation of either spirals or ellipticals would be the initial total angular momentum.
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