A Case for a Baryonic Dark Halo

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Recent observations of microlensing events in the Large Magellanic Cloud by the MACHO and EROS Collaborations suggest that an important fraction of the galactic halo is in the form of massive halo objects (MHO) with mass $\sim 0.1 M_\odot$. We outline a scenario in which dark clusters of MHO with mass $\sim 0.1 M_\odot$ and H_2 molecular clouds form in the halo at galactocentric distances larger than $\sim 10-20$ kpc, provided baryons are a major constituent of the halo. Possible signatures of our picture are discussed.

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One of the most important problems in astrophysics concerns the nature of the dark matter in galactic halos, as suggested by the observed flat rotation curves. Although various exotic dark matter candidates have been proposed, present limits coming from primordial nucleosynthesis allow a halo made of ordinary baryonic matter that should be in the form of massive halo objects (MHO) with masses in the range $10^{-7} < M/M_\odot < 10^{-1}$ [1]. Paczyński suggested to detect MHO using the gravitational lens effect [2].

Recently, the French collaboration EROS [3] and the American-Australian collaboration MACHO [4] reported the possible detection of altogether six microlensing events, discovered by monitoring over several years millions of stars in the Large Magellanic Cloud (LMC), whereas the Polish-American collaboration OGLE [5] and also the MACHO collaboration have found altogether at least forty microlensing events by monitoring stars located in the galactic bulge. Taking these results at face value an average mass $\sim 0.1 M_\odot$ [6] for the MHO in the halo has been derived.

At present the few events which have been found so far by monitoring the LMC do not allow one to make a precise estimate of the fraction of dark halo matter in form of MHO, nor to infer whether the MHOs are located in the halo or rather in the LMC itself [7] or in a thick disk in our Galaxy [8]. It has also been proposed [9] that microlensing by stars within the LMC itself can account for the observed events.

Our aim is to present a scenario in which the halo of the Galaxy substantially consists of dark clusters of MHO and/or H_2 molecular clouds, provided baryons are a major constituent of the halo. We suggest that the dark clusters form at galactocentric distances larger than $\sim 10-20$ kpc.

The proposed picture relies on the theory for the origin of stellar globular clusters advocated by Fall and Rees [10] and on the suggestion of Palla, Salpeter, and Stahler [11] that the lower bound on the fragment masses in a collapsing, metal poor cloud can be as low as $10^{-2} M_\odot$. Here we outline the main facts; for more details see Ref. [12].

As a preliminary step, let us briefly recall the key points of the present wisdom about the formation of stellar globular clusters. After its initial collapse, the proto galaxy (PG) is expected to be shock-heated to its virial temperature $T_e \sim 10^6$ K. This temperature lies near a very unstable region of the cooling curve [13], so that density enhancements should rapidly grow as the gas cools to lower temperatures. Fall and Rees [10] argued that overdense regions in the PG cool more rapidly than average (because the cooling rate by hydrogen recombination is proportional to $n_{\rm H}^2$, where $n_{\rm H}$ is the number density of hydrogen) and then a two phase medium forms with cool proto globular cluster (PGC) clouds in pressure equilibrium with the external hot diffuse gas. The PGC clouds, which have temperature $T_c \sim 10^4$ K, are gravitationally unstable when their mass exceeds the Jeans mass $M_J = 1.18 (k_B T_c/\mu_c)^2 G^{-3/2} P_e^{-1/2}$, where $\mu_c \sim 1.22 m_p$ is the mean molecular weight of the primordial neutral gas and P_e is the pressure of the fully ionized plasma that fills the PG. Typical density of the PG is $\rho_e \sim 1.7 \times 10^{-24}$ $[R/(1 \text{ kpc})]^{-1}$ g cm^{-3}, so that the resulting PGC cloud mass and radius are $M_c \sim 10^6$ $[R/(1 \text{ kpc})]^{1/2} M_\odot$ and $r_c \sim (19 \text{ pc})$ $[R/(1 \text{ kpc})]^{1/2} \Delta^{-1}$, where R is the galactocentric distance and $\Delta \sim 10$ is a factor which takes into account the shrinking of the PGC cloud due to dissipation and collapse during its subsequent evolution (for more details see [14]). The main coolants below 10^4 K are molecular hydrogen and any heavy element produced by a first generation of stars. Molecular hydrogen, however, would be dissociated by various sources of UV radiation such as an active galactic nucleus (AGN) and/or a population of massive young stars in the center of the PG. In the early more chaotic phase of the evolution of the PG, in fact, an AGN is possibly formed at its center and/or a first generation of massive stars due to the disruption of central

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PGC clouds. The last circumstance is realized because, in the center of the PG, the cloud collision time is shorter than the corresponding cooling time. In a metal poor, dust free protogalactic gas the molecular hydrogen abundance $f_{H_2} = n_{H_2}/n_H$ is determined by considering a set of atomic and molecular processes which involve the creation of intermediate H^- and $H_2{}^+$ [15]. With the knowledge of f_{H_2} one can compute the cooling rate Λ_c and the cooling time

$$\tau_{\rm cool} = \frac{3\rho_c k_B T_c}{2\mu_c(\Lambda_c - \Gamma)}, \qquad (1)$$

where the heating rate Γ due to external radiation sources has also been taken into account. The subsequent evolution of the PGC cloud depends on the ratio between $\tau_{\rm cool}$ and the gravitational infall time $\tau_{ff} = (3\pi/32G\rho_c)^{1/2}$ that, since $\rho_c \sim 400\rho_e$ [10], results to be $\tau_{ff} \sim 1.7 \times 10^6\ [R/(1\ {\rm kpc})]^{1/2}$ yr. If $\tau_{\rm cool} \ll \tau_{ff}$ the PGC clouds rapidly cool to a temperature $T_c \sim 100$ K before the gravitational instability sets in, while for $\tau_{\rm cool} \leq \tau_{ff}$ the PGC clouds cool and contract at the same time. On the other hand, when $\tau_{\rm cool} \geq \tau_{ff}$ the PGC clouds do not cool, remaining at a fixed temperature. The parameters that mainly discriminate between the different situations are Γ and Λ_c.

In the inner halo, because of the presence of an AGN and/or a first population of massive stars at the center of the PG, H_2 formation and cooling are heavily suppressed or delayed for a wide range of both external UV fluxes and/or PGC cloud densities [16]. For this case, in which $\tau_{\rm cool} \geq \tau_{ff}$, the PGC clouds remain at $T_c \sim 10^4$ K for a long time. This results in an *imprinting* of a characteristic mass of $M_c \sim 10^6 M_\odot$. Moreover, during the permanence of the PGC clouds for a long time in quasihydrostatic equilibrium, propagation of sound waves erases all large scale perturbations leaving only those on small scale. After enough H_2 has formed ($f_{H_2} \sim 10^{-3}$), the temperature suddenly drops well below 10^4 K because now $\tau_{\rm cool} \ll \tau_{ff}$. The subsequent evolution of the PGC clouds goes on with a rapid growth of the small scale perturbations that leads directly (in one step) to the formation of stars within a narrow mass range [17]. Thus, this scenario would explain the formation of stellar globular clusters which are observed today especially in the inner part of the galactic halo. The formation of the PGC clouds could have been delayed until after the Galaxy was enriched by metals due to a first generation of stars, in this way explaining the observed absence of globular clusters with only primordial metal abundances and the radial gradient of metallicity in the galactic halo.

In the outermost part of the halo, where the incoming UV radiation flux is suppressed due to the distance (so that $\tau_{\rm cool} \leq \tau_{ff}$), the PGC clouds cool more gradually below 10^4 K. Then, cooling and collapse occur simultaneously and their evolution proceeds according to the scenario proposed by Palla *et al.* [11], leading to a subsequent fragmentation into smaller clouds that remains optically thin until the minimum value of the Jeans mass ($\leq 0.1 M_\odot$) is attained. In this case we expect that, because the PGC clouds do not remain at a fixed temperature, there should be no imprinting of a characteristic mass. In fact, when a PGC cloud is in a quiet ambient as at the edge of the PG, the collapse proceeds with a monotonic decrease of the Jeans mass and a subsequent fragmentation into clouds with lower and lower masses. This process stops when the fragments become optically thick to their own line emission. This happens because in a metal poor cloud virtually all the hydrogen gas is converted into molecular form due to three-body reactions ($H + H + H \rightarrow H_2 + H$ and $H + H + H_2 \rightarrow 2H_2$). As a consequence of the increased cooling efficiency (due to the increase of f_{H_2} up to 1) the fragmentation process goes on until the Jeans mass reaches $\sim 0.1 M_\odot$ or less, which is lower than the minimum mass for nuclear burning.

As a result of the above picture, dark clusters with MHO of mass $\sim 0.1 M_\odot$ or less would form in the outer part of the galactic halo. However, we do not expect the fragmentation process to be able to convert the whole gas mass contained in a PGC cloud into MHO (see, e.g., [18]). Thus, we expect the remaining gas to form self-gravitating H_2 molecular clouds [19], since in the absence of strong stellar winds (which in stellar globular clusters do eject the gas) the surviving gas remains gravitationally bound in the dark cluster. The possibility that the gas is diffuse in the dark cluster is excluded due to its high virial temperature ($\sim 10^4 - 10^5$ K) that would make the gas observable at 21 cm. In addition, the gas cannot have diffused in the whole galactic halo because it would have been heated by the gravitational field to a virial temperature $\sim 10^7$ K and therefore would be observable in the x-ray band (for which stringent upper limits are available). The further possibility that the gas entirely collapsed into the disk is also excluded because then its mass would be of the order of the inferred dark halo mass. Finally, we expect the ratio between the gas in the form of H_2 molecular clouds and of MHO to be a function of the galactocentric distance which determines the ambient conditions such as incoming UV fluxes and collision rates among PGC clouds.

A few comments are in order. The UV flux incoming in PGC clouds is crucial for determining f_{H_2} from which their subsequent evolution strongly depends. Since the formation of stellar globular clusters requires a sufficiently high UV flux, they can mainly form up to a certain galactocentric distance $R_{\rm crit}$ which we estimate to be $\sim 10-20$ kpc [12]. Beyond this distance the evolution of the PGC clouds gives rise to the formation of dark clusters of MHO and/or H_2 molecular clouds.

A further question which naturally arises is whether dark clusters are stable within the lifetime t_g of the Galaxy. Standard calculations for the evaporation rate due to two-body encounters give $t_{\mathrm{evap}} \sim 100 t_{\mathrm{rel}}$, where t_{rel} is the usual two-body relaxation time. The condition $t_{\mathrm{evap}} > t_g$ requires a constituent mass $m \leq 10 M_\odot$ [14]. Another mechanism which could destroy dark clusters is collision among themselves. We find that clusters are disrupted if they are located within a certain galactocentric distance $R_{\mathrm{dis}} \sim 10$ kpc [12]. From these considerations we conclude that dark clusters of MHO and/or H_2 molecular clouds can still be present today at distances larger than R_{dis}.

Let us briefly discuss the possible signatures of the above picture. Besides detection of microlensing events—which has in fact been our main motivation—we should mention that Maoz [22] has recently considered the possibility to infer from microlensing observations whether MHO are clustered or not. Already a relatively small number of events would be sufficient to exclude this possibility, while to confirm it more events are needed.

A further signature of the presence of H_2 molecular clouds in the galactic halo should be a γ-ray flux produced through interaction with high energy cosmic ray protons. Cosmic rays scatter on protons in H_2 molecules, producing π^0's which subsequently decay into γ'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 information comes from theoretical estimates [23]. More precisely, from the mass-loss rate of a typical galaxy, one can infer the total cosmic ray flux in the halo, which turns out to be $F \simeq 10^{41} A_{\mathrm{gal}}^{-1}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$, where A_{gal} is the surface of the galactic disk. Taking $R_{\mathrm{gal}} \simeq 10$ kpc, we get $F \simeq 1.1 \times 10^{-4}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$. However, this information is not sufficient to carry out our calculations, since we need the energy distribution of the cosmic rays. We assume the same energy dependence as measured on Earth and then scale the overall density in such a way that the integrated energy flux agrees with the above value. Moreover, we assume that the cosmic ray density scales as $1/R^2$ for large R (R is the galactocentric distance). The measured primary cosmic ray flux on the Earth is

$$\Phi_{\mathrm{CR}}^{\oplus}(E) \simeq \frac{2}{1\ \mathrm{GeV}} \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-2.7} \mathrm{particles/cm^2\,s\,sr}\,, \quad (2)$$

and then the corresponding integrated energy flux is $\simeq 5.7 \times 10^{-2}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$ (integration range $1 \leq E \leq 10^6$ GeV). Hence, $\Phi_{\mathrm{CR}}(E) \simeq 1.9 \times 10^{-3} \Phi_{\mathrm{CR}}^{\oplus}$, and then we get

$$\Phi_{\mathrm{CR}}(E,R) \simeq \Phi_{\mathrm{CR}}(E)\, \frac{a^2 + R_{\mathrm{GC}}^2}{a^2 + R^2}\,, \quad (3)$$

where $a \sim 5$ kpc is the halo core radius and $R_{\mathrm{GC}} \sim 8.5$ kpc is our distance from the galactic center. The source function $q_\gamma(r)$ giving the photon number density at distance r from the Earth is

$$q_\gamma(r) = \sum_n \int dE_p\, dE_\pi\, \frac{4\pi}{c}\, \Phi_{\mathrm{CR}}(E_p, R(r)) \times \frac{c\rho_{\mathrm{H}_2}(R(r))}{m_p}\, \frac{d\sigma_{p\to\pi}^n(E_\pi)}{dE_\pi}\, n_\gamma(E_p)\,, \quad (4)$$

where $\sigma_{p\to\pi}^n(E_\pi)$ is the cross section for the reaction $pp \to n\pi^0$ (n is the π^0 multiplicity), $n_\gamma(E_p)$ is the photon multiplicity, $R(r)$ is the galactocentric distance as a function of r, while $\rho_{\mathrm{H}_2}(R(r))$ is the fraction of dark matter in form of H_2 molecular clouds [for which we assume the same dependence on R as in Eq. (3)]. Actually, the cosmic ray protons in the halo which originate from the galactic disk are mainly directed outwards. This fact implies that also the induced photons will leave the Galaxy. However, the presence of magnetic fields in the halo might give rise to a temporary confinement of the cosmic ray protons similar to what happens in the disk. In addition, there could also be sources of cosmic ray protons located in the halo itself, for instance, isolated or binary pulsars in globular clusters. Unfortunately, we are unable to give a quantitative estimate of the above effects, so we take them into account by introducing an efficiency factor ϵ, which could be rather small. In this way the γ-ray photon flux reaching the Earth is obtained by multiplying $q_\gamma(r)$ by $\epsilon/4\pi r^2$ and integrating the resulting quantity over the cloud volume along the line of sight. The best chance, if any, to detect the γ rays in question is provided by observations at high galactic latitude, and so we take $\theta = 90°$. Accordingly, we find for the γ-ray flux [12]

$$\Phi_\gamma(90°) \simeq \epsilon\, 1.7 \times 10^{-6}\ \mathrm{photons/cm^2\,s\,sr}\,. \quad (5)$$

The inferred upper bound for γ rays in the 0.8–6 GeV range for high galactic latitude is $3 \times 10^{-7}\ \mathrm{photons\,cm^{-2}\,s^{-1}\,sr^{-1}}$ [24]. Hence, we see from Eq. (5) that the presence of H_2 molecular clouds does not lead at present to any contradiction with the upper bound provided $\epsilon < 10^{-1}$.

In conclusion, we have outlined a scenario for a baryonic dark halo in which the formation of MHO and/or H_2 molecular clouds in the outermost part of the halo naturally arises, because in a quiet ambient the Jeans mass can reach values as low as $10^{-2} M_\odot$. Crucial in discriminating the evolution of PGC clouds towards stellar globular clusters or dark clusters are the decreasing collision rate and UV flux with increasing galactocentric distances. The most promising way to detect dark clusters of MHO is through correlation effects in microlensing observations, as we expect the dark clusters not to have been disrupted up to now. A much more difficult task is the detection of H_2 molecular clouds. A possible signature of such clouds would be their γ-ray flux induced by halo cosmic ray protons. Our calculation gives only an upper bound that is not in conflict with present detection limits. At any rate, the fact that our scenario naturally explains the formation of MHO at large galactocentric distances strongly supports—we believe—the idea that galactic dark matter is mostly baryonic after all.

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