IL NUOVO CIMENTO VOL. 20 C, N. 5 Settembre-Ottobre 1997

# MHOs and molecular clouds in dark galactic halos(*)

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(ricevuto il 5 Dicembre 1996; approvato il 27 Febbraio 1997)

**Summary.** — We outline a scenario in which dark clusters of Massive Halo Objects (MHOs) and 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 the presence of molecular clouds in our galaxy are discussed. We also discuss how molecular clouds as well as MHOs can be observed directly in the nearby M31 galaxy.

PACS 98.52 – Normal galaxies; extragalactic objects and systems (by type).
PACS 98.58 – Interstellar medium (ISM) and nebulae in external galaxies.
PACS 98.62.Sb – Gravitational lenses and luminous arcs.
PACS 01.30.Cc – Conference proceedings.

## 1. – Dark-cluster formation

One of the most important problems in astrophysics concerns the nature of the dark matter in galactic halos. Although various 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 (MHOs) with masses in the range $10^{-7} < M/M_{\odot} < 10^{-1}$ [1]. Recently, the EROS [2] and MACHO [3] collaborations reported the detection of seven microlensing events, discovered by monitoring over several years millions of stars in the Large Magellanic Cloud.

Our aim is to present a scenario in which the halo of elliptical and spiral galaxies substantially consists of dark clusters of MHOs and molecular clouds, provided baryons are a major constituent of the halo [4].

The proposed picture relies on the theory for the origin of proto globular clusters (PGCs) advocated by Fall and Rees [5] and on the suggestion of Palla, Salpeter and Stahler [6] that the lower bound on the fragment masses in a collapsing, metal-poor cloud can be as low as $10^{-2} M_{\odot}$.

After the initial collapse, proto galaxies (PGs) are expected to be shock-heated to their virial temperature $T_{\rm e} \sim 10^6$ K. This temperature lies near a very unstable region of the cooling curve, so that density enhancements should rapidly grow as the gas cools to lower temperatures. Fall and Rees [5] argued that overdense regions in the PG cool more rapidly than average and then a two-phase medium forms with cool proto globular cluster

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(*) Paper presented at the VII Cosmic Physics National Conference, Rimini, October 26-28, 1994.

(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 $M_J = 1.18\ (k_B T_c/\mu_c)^2\ G^{-3/2} P_e^{-1/2}$. Here $\mu_c \sim 1.22\ m_p$ is the mean molecular weight of the primordial gas, $k_B$ and $G$ are the Boltzmann and the gravitational constant, respectively. Typical density of the PG is $\rho_e \sim 1.7 \times 10^{-24}\ (R/\text{kpc})^{-1}\ \text{g cm}^{-3}$, so that the resulting PGC cloud mass and radius are $M_c \sim 10^6\ (R/\text{kpc})^{1/2}\ M_\odot$ and $r_c \sim (19\ \text{pc})\ (R/\text{kpc})^{1/2}$, where $R$ is the galactocentric distance.

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 [7]. With the knowledge of the molecular hydrogen abundance $f_{H_2} = n_{H_2}/n_H$, one can compute the cooling rate $\Lambda_c$ and the cooling time

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

where $\Gamma$ is the heating rate due to external radiation sources. The subsequent evolution of the PGC clouds depends on the ratio between $\tau_{\text{cool}}$ and the gravitational infall time $\tau_{\text{ff}} = (3\pi/32G\rho_c)^{1/2}$ which results to be $\tau_{\text{ff}} \sim 1.7 \times 10^6\ (R/\text{kpc})^{1/2}$ years [5]. If $\tau_{\text{cool}} \ll \tau_{\text{ff}}$ the PGC clouds rapidly cool to a temperature $T_c \sim 100$ K before the gravitational instability sets in, while for $\tau_{\text{cool}} \leq \tau_{\text{ff}}$ the PGC clouds cool and contract at the same time.

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, molecular formation and cooling are heavily suppressed or delayed. For this case, in which $\tau_{\text{cool}} \geq \tau_{\text{ff}}$, 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 quasi-hydrostatic 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 $\tau_{\text{cool}} \ll \tau_{\text{ff}}$. 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 [8]. This scenario would explain the formation of stellar globular clusters which are observed today especially in the inner part of the galactic halo.

In the outermost part of the halo, where the incoming UV radiation flux is suppressed due to the distance (so that $\tau_{\text{cool}} \leq \tau_{\text{ff}}$), the PGC clouds cool more gradually below $10^4$ K. Then, cooling and collapse occur simultaneously and PGC clouds evolution proceeds according to the scenario proposed by Palla *et al.* [6], leading to a subsequent fragmentation into smaller clouds that remain optically thin until the minimum value of the Jeans mass ($\leq 0.1 M_\odot$) is attained. 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.

As a result of the above picture, dark clusters with MHOs 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 MHOs. Thus, we expect the remaining gas to form self-gravitating molecular clouds, 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 disc is also excluded because then its mass would be of the order of the inferred dark halo mass.

A few comments are in order. 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 $\sim 20$ kpc. Beyond this distance the evolution of the PGC clouds gives rise to the formation of dark clusters of MHOs and molecular clouds.

A further question which naturally arises is whether dark clusters are stable within the lifetime $t_{\rm g}$ of the Galaxy [9]. A mechanism which could destroy dark clusters are collisions among themselves. We find that clusters are disrupted if they are located within a certain galactocentric distance $R_{\rm dis} \sim 10$ kpc. From these considerations we conclude that dark clusters of MHOs and molecular clouds can still be present today at distances larger than $R_{\rm dis}$.

The above scenario allows us to outline a unified picture for the formation of elliptical and spiral galaxies in which the dark matter consists of barionic matter in the form of MHOs and molecular clouds. We consider proto galaxies (PGs) constituted by a set of PGC clouds. Let us first consider the case in which the PG has a total angular momentum different from zero (*i.e.* the PG rotates). Then the gas coming from the PGC clouds (which are broken by collisions) inside $R_{\rm dis}$ collapses into a disc that constitutes a preferred plane of the configuration. In this way we expect the formation of spiral galaxies.

In the case of approximately zero total angular momentum of the PG, the gas coming from the disrupted PGC clouds inside $R_{\rm dis}$ will diffuse in the whole PG reaching a virial temperature $\sim 10^7$ K. In this way we expect the formation of ellipticals, most of which present a diffuse X-ray emission. One can think that the presence in ellipticals of the X-ray emitting gas should prevent the survival of molecular clouds. On the contrary, from considerations on $H_2$ dissociation in the presence of an external radiation field (see [5]), we find that the X-ray emission in ellipticals (always less than $\sim 10^{43}$ erg s$^{-1}$) is not sufficient to destroy molecular clouds.

External PGC clouds at galactocentric distances larger than $R_{\rm dis}$, both in ellipticals and spirals, evolve according to the previous scenario leading to the formation of stellar (in preference up to $\sim R_{\rm crit}$) and dark (for $R > R_{\rm crit}$) clusters. Finally, we expect that in clusters of galaxies, where galactic halos can partially merge, a certain amount of (barionic) dark matter is tidally stripped from the single galaxies and diffuse in the whole cluster. This can naturally explain the recent ROSAT observations that $\sim 30\%$ of the dark matter in clusters of galaxies is in barionic form.

## 2. – Observational tests

Let us briefly discuss the possible signatures of the above picture. The most promising way to detect MHOs in dark clusters is through correlation effects in microlensing observations. A much more difficult task is the detection of molecular clouds. A signature of the presence of molecular clouds in our galactic halo should be a $\gamma$-ray flux produced through interaction with high-energy cosmic-ray protons. Cosmic rays scatter on protons in molecules producing $\pi^0$'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 information comes from theoretical estimates [10]

$$\Phi_{\rm CR}(E,R) \simeq 1.9\times 10^{-3}\, \Phi^{\oplus}_{\rm CR}(E)\, \frac{a^2+R^2_{\rm GC}}{a^2+R^2}\,, \tag{2}$$

where $\Phi^{\oplus}_{\rm CR}(E)$ is the measured primary cosmic-ray flux on the Earth, $a \sim 5$ kpc is the halo core radius and $R_{\rm GC} \sim 8.5$ 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

$$q_\gamma(r) = \sum_n \int {\rm d}E_{\rm p}\, {\rm d}E_\pi\, \frac{4\pi}{c}\Phi_{\rm CR}(E_{\rm p}, R(r))\, \frac{c\rho_{\rm H_2}(R(r))}{m_{\rm p}}\, \frac{{\rm d}\sigma^n_{{\rm p}\to\pi}(E_\pi)}{{\rm d}E_\pi}\, n_\gamma(E_{\rm p})\,, \tag{3}$$

where $\sigma^n_{\rm p} \to \pi(E_\pi)$ is the cross-section for the reaction ${\rm pp} \to n\pi^0$ ($n$ is the $\pi^0$ multiplicity), $n_\gamma(E_{\rm p})$ is the photon multiplicity, $R(r)$ is the galactocentric distance as a function of $r$, while $\rho_{\rm H_2}(R(r))$ is the fraction of dark matter in form of $\rm H_2$ (that, of course, dominates and for which we assume the usual $R^{-2}$ law). Actually, cosmic-ray protons in the halo which originate from the galactic disc 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 similarly to what happens in the disc. In addition, there could also be sources of cosmic-ray protons located in the halo itself, as for instance isolated or binary pulsars in globular clusters. Unfortunately, we are unable to give a quantitative estimate of the above effects, so that we take them into account by introducing an efficiency factor $\epsilon$, which could be rather small. In this way the $\gamma$-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 $\gamma$-rays in question is provided by observations at high galactic latitude, and so we take $\theta = 90°$. Accordingly, we find for the $\gamma$-ray flux [10]

$$\Phi_\gamma(90°) \simeq \epsilon f\, 3.5\times 10^{-6}\ {\rm photons\ cm^{-2}\ s^{-1}\ sr^{-1}}, \tag{4}$$

where $f$ is the fraction of the initial gas in form of molecular clouds. The inferred upper bound for $\gamma$-rays in the 0.8–6 GeV range for high galactic latitude is $3\times 10^{-7}$ $\rm photons\ cm^{-2}\ s^{-1}\ sr^{-1}$ [11]. Hence, we see from eq. (4) that the presence of molecular clouds does not lead at present to any contradiction with the upper bound provided $\epsilon f < 10^{-1}$.

Let us consider now the possibility to infer information on molecular clouds looking at the microwave band [12]. The first question which arises is: since in the past molecular clouds were hotter than the CBR, how far from the CBR temperature are they now? An upper limit can be set by considering the anisotropy they would introduce in the CBR, assuming that the clouds emit as a black body. Looking at a region of the sky away from the galactic centre and off the galactic disc, we expect to see about a dozen of dark clusters for every degree square. Accordingly, due to the low surface filling factor (1) $S \sim 10^{-2}$,

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(1) Here we suppose, for illustration, that dark clusters are spherically distributed at $\sim 20$ kpc from the galactic centre and consist of $\sim 10^7 f$ molecular clouds each of mass $\sim 10^{-1} M_\odot$ and $\rm H_2$ number density $n_{\rm H_2} \sim 10^5\ {\rm cm^{-3}}$. From the virial theorem, their radius is $r \sim 2\times 10^{-2}$ pc corresponding to an angular size of $\sim 1.8'$. $S$ is the ratio of filled-to-total surface in a field of view.

the ratio of the temperature excess of the clouds to the CBR temperature should not be more than $\sim 10^{-3}$ (from COBE's CBR anisotropies).

Realistically, molecular clouds cannot be viewed as a black body. Indeed, a molecular cloud close to the CBR temperature emits a set of lines due mainly to molecular rotational transitions. If one considers clouds with cosmological primordial composition, the only molecule that contributes to the microwave band with optically thick lines is LiH (see, e.g., [13]). However, the chemical composition of the molecular clouds in the galactic halo is largely unknown. They could well contain heavy molecules made of metals formed during a first chaotic galactic phase. Moreover, the above picture is oversimplified, since molecular clouds are embedded in a radiation field whose maximum lies in the infrared band, giving rise to a much richer spectrum of atomic, ionic and molecular transitions which contribute to the cloud emissivity in the microwave band.

Consider now molecular clouds in M31, for which we assume the same scenario outlined above for our Galaxy. We expect molecular clouds to be at a temperature close to that of the CBR, and so they would be indistinguishable from the background. But—since the clouds are moving—there is a Doppler shift which will show up as an anisotropy in the CBR. This phenomenon is the Sunyaev-Zeldovich Doppler effect for a free-streaming gas with speed $v$ [14]. The corresponding anisotropy is

$$\frac{\Delta T}{T_\mathrm{r}} = \pm \frac{v}{c} \, S \, f \, \tau_\nu \, . \tag{5}$$

The sign depends on the direction of the projected velocity along the line of sight, $T_\mathrm{r}$ is the temperature of the CBR and $\tau_\nu = \int \sigma_\nu \, n_\mathrm{mol} \, \mathrm{d}l$ is the optical depth at frequency $\nu$. $\tau_\nu$ depends on the molecular abundance $n_\mathrm{mol}$ and on the number of molecules in each quantum level, while $\sigma_\nu$ is the resonance cross-section [13]. The integral is performed along the line of sight intercepted by molecular clouds.

Unfortunately, it is very difficult to compute $\tau_\nu$ because we do not know the exact chemical composition and the radiation field in the clouds. For a black-body spectrum $\tau_\nu \equiv 1$. Since the clouds are optically thick only at some frequencies, it is convenient to use in eq. (5), instead of $\tau_\nu$, an averaged optical depth over the frequency range ($\nu_1 \leq \nu \leq \nu_2$) of the detector:

$$\bar{\tau} = (\nu_2 - \nu_1)^{-1} \int_{\nu_1}^{\nu_2} \tau_\nu \, \mathrm{d}\nu \, . \tag{6}$$

At worst, we expect at least the lowest rotational transition line of LiH to be present in the microwave band. If the detector frequency range ($\nu_2 - \nu_1$) is tuned in such a way to contain this line, we can easily estimate (2) $\bar{\tau} \sim 10^{-3}$. In general, this value must be multiplied by the number of the optically thick lines (due to metals) within the detector frequency range. Moreover, it is well possible that future instruments will have a better spectral resolution, thereby increasing $\bar{\tau}$. Hence, $\bar{\tau} \sim 10^{-3}$ should be understood as a lower limit.

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(2) To evaluate $\tau_\nu$, we take the abundance ratio $n_\mathrm{LiH}/n_{\mathrm{H}_2} \sim 10^{-10}$ and the number of clouds intercepted in the dark clusters along the line of sight $\sim 200$, while $\sigma_\nu \sim 5 \times 10^{-10}$ cm$^2$ at $T = 2.76$ K (note that if $T < 20$ K, $\sigma_\nu$ remains above $\sim 10^{-12}$ cm$^2$). With these values the line corresponding to the lowest lying rotational transition of LiH at the frequency $\nu_0 = 4.44 \times 10^{11}$ Hz and broadening (mainly caused by the turbulent velocity of the clouds $\sim 10$ km s$^{-1}$) $\Delta\nu/\nu_0 \sim 5 \times 10^{-5}$, turns out to be optically thick (even if $T$ goes up to 20 K). Then, setting $\tau_\nu = 1$ in eq. (6) and assuming a spectral resolution of $(\nu_2 - \nu_1)/\nu_0 \sim 0.05$, typical of the DMR instrument on COBE, we get $\bar{\tau} \sim 10^{-3}$.

Dark clusters in M31 galaxy (at $\sim$ 650 kpc from us) would have typical rotational speeds 200–250 km $\mathrm{s}^{-1}$. Below we calculate the expected CBR anisotropy between two fields of view (on opposite sides of M31) separated by $\sim 4^\circ$ and with angular resolution of $\sim 1^\circ$.

Supposing that the halo of M31 consists of $\sim 10^6$ dark clusters and that all of them lie between 25 kpc and 35 kpc, we would be able to detect $10^3 - 10^4$ dark clusters per observed degree square. Thus, we could scan the annulus of $1^\circ$ width and internal angular diameter $4^\circ$, centered at M31, in 180 steps of $1^\circ$ and would find anisotropies of $\sim 5 \times 10^{-5}\ f\ \bar{\tau}$ in $\Delta T/T_{\mathrm{r}}$ (since $S = 1/25$). Actually, the value $5 \times 10^{-5}$ should be considered as an upper limit because we have assumed that i) all dark clusters lie between 25 kpc and 35 kpc and ii) clusters in the scanned field of view have the same radial velocity of $\sim$ 250 km $\mathrm{s}^{-1}$. In conclusion, although the estimated value of $\Delta T/T_{\mathrm{r}}$ lies below current detectability ($\sim 10^{-6}$), this needs not to be what happens in reality. As stressed above, $\bar{\tau}$ may well be bigger than $10^{-3}$ even substantially, thereby making $\Delta T/T_{\mathrm{r}}$ observable. Only future observations (see, *e.g.*, [15]) can resolve this issue.

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