MACHOs AS BROWN DWARFS*

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ABSTRACT

Recent observations of microlensing events in the Large Magellanic Cloud suggest that a sizable fraction of the galactic halo is in the form of Massive Astrophysical Compact Halo Objects (MACHOs). Although the average MACHO mass is presently poorly known, the value $\sim 0.1 M_\odot$ looks as a realistic estimate, thereby implying that brown dwarfs are a viable and natural candidate for MACHOs. We describe a scenario in which dark clusters of MACHOs and cold molecular clouds (mainly of $H_2$) naturally form in the halo at galactocentric distances larger than 10-20 kpc. Moreover, we discuss various experimental tests of this picture.

1. Introduction

Since 1993 several microlensing events have been detected towards the Large Magellanic Cloud by the MACHO and EROS collaborations. Everybody agrees that this means that Massive Astrophysical Compact Halo Objects (MACHOs) have been discovered. Yet, the specific nature of MACHOs is unknown, mainly because their average mass turns out to depend strongly on the assumed galactic model. For instance, the spherical isothermal model would give $\sim 0.5 M_\odot$ whereas the maximal disk

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model would yield $\sim 0.1 M_\odot$ for that quantity. What can be reliably concluded today is only that MACHOs should lie in the mass range $0.05 M_\odot - 1 M_\odot$. Remarkably enough, the MACHO team has claimed that the fraction of galactic matter in the form of MACHOs is fairly model independent and – within the present statistics – should be $\sim 50\%$.

What is the most realistic galactic model? Regrettfully, no clear-cut answer is presently available. Nevertheless, the current wishdom – that the Galaxy ought to be best described by the spherical isothermal model – seems less convincing than before and nowadays various arguments strongly favour a nonstandard galactic halo. Indeed, besides the observational evidence that spiral galaxies generally have flattened halos, recent determinations of both the disk scale length, and the magnitude and slope of the rotation at the solar position indicate that our galaxy is best described by the maximal disk model. This conclusion is further strengthened by the microlensing results towards the galactic centre, which imply that the bulge is more massive than previously thought. Correspondingly, the halo plays a less dominant rôles than within the spherical isothermal model, thereby reducing the halo microlensing rate as well as the average MACHO mass. A similar result occurs within the King-Michie halo models, which also take into account the finite escape velocity and the anisotropies in velocity space (typically arising during the phase of halo formation). Moreover, practically the same conclusions also hold for flattened galactic models with a substantial degree of halo rotation. So, the expected average MACHO mass should be smaller than within the spherical isothermal model and the value $\sim 0.1 M_\odot$ looks as a realistic estimate to date. This fact is of paramount importance, since it implies that brown dwarfs are a viable and natural candidate for MACHOs. Still – even if MACHOs are indeed brown dwarfs – the problem remains to explain their formation, as well as the nature of the remaining dark matter in galactic halos.

We have proposed a scenario in which dark clusters of MACHOs and cold molecular clouds – mainly of $H_2$ – naturally form in the halo at galactocentric distances larger than 10 – 20 kpc (somewhat similar ideas have also been put forward by Ashman and by Gerhard and Silk). Below, we shall review the main features of this model, along with its observational implications.

### 2. Formation of dark clusters

Our scenario encompasses the one originally proposed by Fall and Rees to explain the origin of 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. Because of thermal instability, density enhancements rapidly grow as the gas cools. Actually, overdense regions cool more rapidly than average, and so proto globular cluster (PGC) clouds form in pressure equilibrium with hot diffuse gas. When the PGC cloud temperature reaches $\sim 10^4$ K, hydrogen recombination occurs:
at this stage, their mass and size are $\sim 10^5 (R/\text{kpc})^{1/2} M_\odot$ and $\sim 10 (R/\text{kpc})^{1/2} \text{pc}$, respectively ($R$ being the galactocentric distance). Below $10^4$ K, the main coolants are $H_2$ molecules and any heavy element produced in a first chaotic galactic phase. As we shall see in a moment, the subsequent evolution of the PGC clouds will be very different in the inner and outer part of the Galaxy, depending on the decreasing ultraviolet (UV) flux as the galactocentric distance $R$ increases.

As is well known, in the central region of the Galaxy an Active Galactic Nucleus (AGN) and a first population of massive stars are expected to form, which act as strong sources of UV radiation that dissociates the $H_2$ molecules. It is not difficult to estimate that $H_2$ depletion should happen for galactocentric distances smaller than $10^{-20}$ kpc. As a consequence, cooling is heavily suppressed in the inner halo, and so the PGC clouds here remain for a long time at temperature $\sim 10^4$ K, resulting in the imprinting of a characteristic mass $\sim 10^6 M_\odot$. Eventually, the UV flux will decrease, thereby permitting the formation of $H_2$. As a result, the cloud temperature drops below $\sim 10^4$ K and the subsequent evolution leads to star formation and ultimately to globular clusters.

Our main point is that in the outer halo – namely for galactocentric distances larger than $10^{-20}$ kpc – no substantial $H_2$ depletion should take place (owing to the distance suppression of the UV flux). Therefore, the PGC clouds cool and contract. When their number density exceeds $\sim 10^8 \text{ cm}^{-3}$, further $H_2$ is produced via three-body reactions ($H + H + H \rightarrow H_2 + H$ and $H + H + H_2 \rightarrow 2H_2$), which makes in turn the cooling efficiency increase dramatically. This fact has three distinct implications: (i) no imprinting of a characteristic PGC cloud mass shows up, (ii) the Jeans mass can drop to values considerably smaller than $\sim 1 M_\odot$, and (iii) the cooling time is much shorter than the free-fall time. As pointed out by Palla, Salpeter and Stahler, in such a situation a subsequent fragmentation occurs into smaller and smaller clouds that remain optically thin to their own radiation. The process stops when the clouds become optically thick to their own line emission – this happens when the Jeans mass gets as low as $\sim 10^{-2} M_\odot$. In this manner, dark clusters should form, which contain brown dwarfs in the mass range $10^{-2} - 10^{-1} M_\odot$.

Before proceeding further, two observations are in order. First, it seems quite natural to suppose that – much in the same way as it occurs for ordinary stars – also in this case the fragmentation process that gives rise to individual brown dwarfs should produce a substantial fraction of binary brown dwarfs (they will be referred to as primordial binaries). It is important to keep in mind that the mass fraction of primordial binaries can be as large as 50%. Hence, we see that MACHOs consist of both individual and binary brown dwarfs in the present scenario. Second, we do not expect the fragmentation process to be able to convert the whole gas in a PGC cloud into brown dwarfs. For instance, standard stellar formation mechanisms lead to an upper limit of at most 40% for the conversion efficiency. Thus, a substantial fraction $f$ of the primordial gas – which is mostly $H_2$ – should be left over. Because brown
dwarfs do not give rise to stellar winds, this gas should remain confined within a dark cluster. So, also cold $H_2$ self-gravitating clouds should presumably be clumped into dark clusters, along with some residual diffuse gas (the amount of diffuse gas inside a dark cluster has to be low, for otherwise it would have been observed in optical and radio bands).

Unfortunately, the total lack of any observational information about dark clusters would make any effort to understand their structure and dynamics practically impossible, were it not for some remarkable insights that our unified treatment of globular and dark clusters provides us. In the first place, it looks quite natural to assume that also dark clusters have a denser core surrounded by an extended spherical halo. Moreover, in the lack of any further information it seems reasonable (at least tentatively) that the dark clusters have the same average mass density as globular clusters. Hence, we obtain $r_{DC} \simeq 0.12 \left( M_{DC}/M_\odot \right)^{1/3}$ pc, where $M_{DC}$ and $r_{DC}$ denote the mass and the median radius of a dark cluster, respectively. As a further implication of the above scenario, we stress that – at variance with the case of globular clusters – the initial mass function of the dark clusters should be smooth, since the monotonic decrease of the PGC cloud temperature fails to single out any particular mass scale. Finally, we suppose for definiteness (and with an eye to microlensing experiments) that all brown dwarfs have mass $\simeq 0.1 M_\odot$, while the molecular cloud spectrum will be taken to be $10^{-3} M_\odot \lesssim M_m \lesssim 10^{-1} M_\odot$.

3. Dynamics of dark clusters

As we have seen, MACHOs are clumped into dark clusters when they form in the outer galactic halo. Still, the further fate of these clusters is quite unclear. For, they might either evaporate or drift towards the galactic centre. In the latter case, encounters with globular clusters might have dramatic observational consequences and dynamical friction could drive too many MACHOs into the galactic bulge. So, even if dark clusters are unseen, nontrivial constraints on their characteristic parameters arise from the observed properties of our galaxy. Moreover, in order to play any rôle as a candidate for dark matter, MACHOs must have survived until the present in the outer part of the galactic halo. Finally, it is important to know whether MACHOs are still clumped into clusters today, especially because an improvement in the statistics of microlensing observations permits to test this possibility.

Below, we shall schematically address various effects which concern the dynamics of dark clusters.

Dynamical friction – Dark clusters are subject to dynamical friction as they orbit through the Galaxy, which makes them lose energy and therefore spiral in toward the galactic centre. It is straightforward to see that in our model – since $R > 10 – 20 \ kpc$ and $M_{DC} \lesssim 10^6 \ M_\odot$ – a dark cluster originally at galactocentric
distance $R$ will be closer to the galactic centre today by an amount $\Delta R \lesssim 5.8 \times 10^{-2}$ kpc. Therefore, dark clusters are still confined in the outer galactic halo. As a consequence, encounters between dark and globular clusters as well as disk and bulge shocking of dark clusters are dynamically irrelevant.

**Encounters between dark clusters** – Encounters between dark clusters may (under the circumstances to be analyzed below) lead to their disruption. What is important to notice is that the (one-dimensional) velocity dispersion of dark clusters in the halo $\sigma \simeq 155$ km s$^{-1}$ is much larger than the (one-dimensional) velocity dispersion of MACHOs and molecular clouds inside a dark cluster $\sigma_* \simeq 7 \times 10^{-2} (M_{DC}/M_\odot)^{1/3}$ km s$^{-1}$. Hence we shall work within the impulse approximation. Our strategy is as follows. If we denote by $\Delta E$ the change of internal energy of a dark cluster in a single encounter, it is possible to express the rate $\dot{E}(R)$ at which the cluster’s energy changes because of encounters in terms of $\Delta E$. At this point, a natural definition of the time required by encounters to dissolve a cluster is provided by $t_d(R) = E_{\text{bind}} / \dot{E}(R)$, with $E_{\text{bind}} \simeq 0.2 \, G M_{DC}^2 / r_{DC}$. Demanding next that $t_d(R)$ should exceed the age of the Universe, we find under what conditions encounters will be harmless. It turns out that in our picture distant encounters are always harmless, whereas close encounters are harmless provided $M_{DC} \lesssim 10^6 M_\odot$.

**Evaporation** – As is well known, any stellar association evaporates within a finite time. Specifically, relaxation via gravitational two-body encounters leads to the escape of MACHOs approaching the unbound tail of the cluster velocity distribution, and this process gets enhanced by the tidal truncation of dark clusters due to the galactic gravitational field. A key rôle in the present analysis is played by the relaxation time. However, this is a local quantity, which can vary by various orders of magnitude in different regions of a single dark cluster. Therefore it is more convenient to characterize a dark cluster by a single value of the relaxation time. This goal is achieved by the introduction of the median relaxation time $t_{rh}$. Now, it turns out that the cumulative effect of several weak encounters – which gradually increase the velocity of a given MACHO until it exceeds the local escape velocity – dominates over single close encounters. Correspondingly, the evaporation time is $t_{\text{evap}} \simeq 300 \, t_{rh}$. Therefore, by requiring that $t_{\text{evap}}$ should exceed the age of the Universe we find that dark clusters with $M_{DC} \gtrsim 3 \times 10^2 M_\odot$ are not yet evaporated. It goes without saying that dark clusters are tidally disrupted by the galactic gravitational field unless $r_{DC}$ is smaller than their tidal radius. It is easy to see that this is always the case for $R > 10 - 20$ kpc, and so within the present model dark clusters are not tidally disrupted by the galactic gravitational field.

**Core collapse** – Much in the same way as it happens for globular clusters, core collapse is expected to occur also for dark clusters. A thorough analysis shows that the dark clusters with $M_{DC} \lesssim 5 \times 10^4 M_\odot$ should have already began core collapse. Although the further fate of such clusters crucially depends on the (unknown) model
which describes them correctly, two points seem to be firmly establis hed. First, evaporation and subsequent mass ejection make the number of MACHOs in the dark clusters monotonically decrease with time. Second, in spite of the fact that the rise of central density leads to the formation of *tidally-captured* binary brown dwarfs in the cluster cores, their fraction turns out to be too small to play any rôle in the considerations to follow (however they are likely to stop and reverse core collapse).

4. MACHOs as binary brown dwarfs

As already pointed out, it seems natural to suppose that a fraction of primordial binary brown dwarfs – possibly as large as 50% in mass – should form along with individual brown dwarfs as a result of the fragmentation process of the PGC clouds. Subsequently, primordial binaries will concentrate inside the core because of the mass stratification instability. We recall that a binary system is hard when its internal energy exceeds the kinetic energy of field stars. In the present case, binary brown dwarfs happen to be hard when their orbital radius \( a \) obeys the constraint
\[
a < 1.4 \times 10^{12} \left( \frac{M_\odot}{M_{DC}} \right)^{2/3} \text{km}.
\]
Now, consistency with the results of microlensing experiments demands that the overwhelming majority of binary brown dwarfs should be detected as unresolved objects. This requirement entails in turn that their orbital radius should be (roughly) less than one-half of the corresponding Einstein radius, thereby implying that the stronger bound \( a < 3 \times 10^8 \text{km} \) has to be satisfied. As is well known, soft binaries always get softer whereas hard binaries always get harder, and so only those which are hard can survive until the present. Still, all values for the orbital radius of primordial binaries consistent with the above constraint are in principle allowed (tidally-captured binaries have \( a \approx 2.5 \times 10^5 \text{km} \), and so they are no problem). Therefore, it is crucial to see whether any mechanism exists which makes primordial binaries shrink in such a way that also the latter constraint is eventually obeyed. One might think that collisional hardening – namely the process whereby hard binaries get harder in encounters with individual brown dwarfs – is able to do the job. However, a detailed analysis shows that this is not the case. Remarkably enough, the goal is achieved by frictional hardening on molecular clouds (inside the dark cluster cores). That is, whenever a primordial binary crosses a cloud, dynamical friction operates. As a consequence, the binary releases binding energy; thereby getting harder. It can be seen that this process is very effective and indeed makes the overwhelming majority of primordial binary brown dwarfs unresolvable in microlensing experiments.

5. Observational tests

We list schematically some observational tests for the present scenario.

**Clustering of microlensing events** – The most promising way to detect dark clusters is via correlation effects in microlensing observations, as they are expected to
exhibit a cluster-like distribution. Indeed, it has been shown that a relatively small number of microlensing events would be sufficient to rule out this possibility, while to confirm it more events are needed. However, we have seen that core collapse can liberate a considerable fraction of MACHOs from the less massive clusters, and so an unclustered MACHO population is expected to coexist with dark clusters in the outer halo – detection of unclustered MACHOs would therefore not disprove the present model.

**γ-rays from halo clouds** – A signature for the presence of molecular clouds in the galactic halo should be a γ-ray flux produced in the scattering of high-energy cosmic-ray protons on $H_2$. 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 $F \simeq 3.5 \times 10^{-5}$ erg cm$^{-2}$ s$^{-1}$. We further assume the same energy distribution of the cosmic rays as measured on Earth and we rescale the overall density in such a way that the integrated energy flux agrees with the above value. Moreover, we suppose that the cosmic-ray density scales with $R$ like the dark matter density (i.e. $\sim R^{-2}$ in the outer halo). The best chance to detect the γ-rays in question is provided by observations at high galactic latitude. Accordingly, we find a γ-ray flux (for $E_\gamma > 100$ MeV) $\Phi_\gamma(90^0) \simeq (0.4 - 1.8) \times 10^{-5}$ f photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ if the cosmic rays are confined within the galactic halo, whereas we get $\Phi_\gamma(90^0) \simeq (0.6 - 3) \times 10^{-7}$ f photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$ if they are confined within the local galaxy group. These values should be compared with the experimental result from EGRET satellite $\Phi_\gamma(90^0) \simeq 1.5 \times 10^{-5}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Actually, D. Dixon has re-analyzed the EGRET data and claims that the γ-ray flux from the halo is $\Phi_\gamma(90^0) \simeq 2 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Thus, our values turn out to be neither too large nor too small to be interesting, and the γ-ray flux predicted by the present scenario may have already been detected!

**CBR anisotropy** – An alternative way to discover the molecular clouds under consideration relies upon their emission in the microwave band. The temperature of the clouds has to be close to that of the cosmic background radiation (CBR). Indeed, an upper limit of $\Delta T / T \sim 10^{-3}$ can be derived 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, then the only molecule that contributes to the microwave band with optically thick lines is $LiH$, 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 M31 galaxy, for whose halo we assume the same picture as outlined above for our galaxy. 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 corresponding to the lowest rotational transitions would show up in the microwave band. In this case, it is more convenient to perform broad-band measurements and the Doppler shift effect results in an anisotropy in the CBR. 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 $\Delta T/T$. 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.

**Infrared searches** – Another possibility of detecting MACHOs is via their infrared emission. 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 $I_{\nu_{\text{max}}} \sim 2.1 \times 10^3 (1-f) \text{ Jy sr}^{-1}$ and $0.5 \times 10^3 (1-f) \text{ Jy sr}^{-1}$ for projected separations from the M31 center $b = 20$ kpc and 40 kpc, respectively. 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 detector aboard the future planned SIRFT Satellite. For comparison, we recall that the halo of our galaxy would have in the direction of the galactic pole a surface brightness $I_{\nu_{\text{max}}} \sim 2 \times 10^3 \text{ Jy sr}^{-1}$, 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 $1.8'$) and dark spots should be seen by pointing the detector into different directions.
6. References

All relevant references can be found in our papers:

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