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The present consensus in cosmology (for a review, see [1]) is that the universe is at and that a sizable amount of the dark matter is "cold", i.e., nonrelativistic at the time of decoupling. Speculations as to the nature of dark matter are numerous, often exotic. In recent years, there has been experimental evidence [2,3] for one form of dark matter - the Massive Astrophysical Compact Halo Objects (MACHO) - detected through gravitational microlensing. To date, there is no clear picture as to what these objects are made of. We show (for details, see [4]) that they find a natural explanation as leftover relics from a first order cosmic quark - hadron phase transition.

Based on about 13 - 17 Milky Way haloMACHOs detected in the direction of LMC - the Large Magellanic Cloud, they are expected to be in the mass range (0.15-0.95) $M_\odot$, with the most probable mass being in the vicinity of 0.5 $M_\odot$ [5], substantially higher than the fusion threshold of 0.08 $M_\odot$. They cannot be composed of normal baryonic matter, as that would violate some established results of Big Bang nucleosynthesis.

Adopting the viewpoint that the lensing MACHOs are indeed in the Milky Way halo, we propose that they have evolved out of the quark nuggets which could have been formed in a first order cosmic quark - hadron phase transition, at a temperature of $\sim$ 100 MeV. In such circumstances, Witten [6] argued, that strange quark matter could be the true ground state of Quantum Chromodynamics (QCD) and that a substantial amount of baryon number could be trapped in the quark phase which could evolve into strange quark nuggets (SQNs) through weak interactions. QCD - motivated studies of baryon evaporation from SQNs have established [7,8] that primordial SQNs with baryon numbers above $\sim 10^{40-42}$ would be cosmologically stable. We have shown [9] that without much fine tuning, these stable SQNs could provide even the entire closure density ($\Omega \sim 1$). We have also calculated the distribution of SQNs [10] for various nucleation models, and shown that for a reasonable set of parameters, the distribution is sharply peaked at values of baryon number ($\sim 10^{42-44}$), evidently in the stable sector. Since Ω_B is only about 0.1 from BBN, there should be 10^{7-9} such SQNs within the horizon just after the QCD phase transition [9].

We shall assume, for our present purpose, that all the SQNs have the same baryon number. Their enormous mass ($\sim 10^{44}$ GeV) and large size ($R_N \sim$ 1m) force them to be non-relativistic. Also their mutual separation would be considerably larger than their radii; for example, at T $\sim$ 100MeV, the mutual separation between the SQN's (of size $\sim 10^{44}$ baryons) is estimated to be around $\sim$ 300m. They therefore behave like discrete bodies in the background of the radiation fluid, and experience sunstantial radiation pressure, because of their large surface area as well as the gravitational potential due to the other SQN's. We therefore have to estimate to what extent the radiation pressure can prevent the SQN's from gravitating towards one another. The mean separation between these nuggets and hence their gravitational interactions are determined by the temperature of the universe. If the universe is assumed to be closed with SQNs, the total baryon number contained in them within the horizon at the QCD transition temperature ($\sim$ 100 MeV) would be 10^{51} . For SQNs of baryon number bN each, the number of SQNs within the horizon at that time would be just ($10^{51}/b_N$). Then at any later time, the number of SQNs within the horizon (N_N) and their density (n_N) as a function of temperature would be given by: $N_N(T) = \frac{10^{51}}{b_N}\left(\frac{100MeV}{T}\right)^3$, $n_N(T) = \frac{N_N}{V_H} = \frac{3N_N}{4\pi(2t)^3}$, where the time t and the temperature T are related in the radiation dominated era by the relation: $t = 0.3 g_*^{-1/2}\frac{m_{pl}}{T^2}$ with g_* being $\sim$ 17.25 after the QCD transition [9].

The expression for the gravitational force as a function of temperature T can written as: $F_{grav} = \frac{G b_N^2 m_n^2}{\bar{r}_{nn}(T)^2}$ where m_n is the neutron mass. $\bar{r}_{nn}(T)$ is the mean separation between the two nuggets, estimated from the density ofnuggets at the temperature T.

The force due to the radiation pressure on the nuggets may be roughly estimated as follows. We consider two objects (of the size of a typical SQN) approaching each other due to gravitational interaction, overcoming the resistence due to the radiation pressure. The usual isotropic radiation pressure is $\frac{1}{3}\rho c^2$, where ρ is the total energy density, including all relativistic species. The nuggets will have to overcome an additional pressure resisting their mutual motion, which is given by $\frac{1}{3}\rho c^2(\gamma - 1)$; the additional pressure whose surface area is given by $2\pi R_N^2(1+\frac{\sin^{-1}\epsilon}{\gamma\epsilon})$. The eccentricity ϵ is related to the Lorentz factor γ as $\epsilon = \frac{\sqrt{\gamma^2-1}}{\gamma}$. For small values of ϵ (small γ), $\sin^{-1}\epsilon \sim \epsilon$, so that the surface area becomes $2\pi R_N^2\frac{\gamma+1}{\gamma}$. Thus the total radiation force resisting the motion of SQNs is $F_{\rm rad} = \frac{1}{3}\rho_{\rm rad} c v_{\rm fall}(\pi R_N^2)\beta\gamma$ where $\rho_{\rm rad}$ is the total energy density at temperature T, v_{fall} or βc is the velocity of SQNs determined by mutual gravitational field and γ is $1/\sqrt{1-\beta^2}$. The quantities $F_{\rm rad}, \beta$ and γ all depend on the temperature of the epoch under consideration.

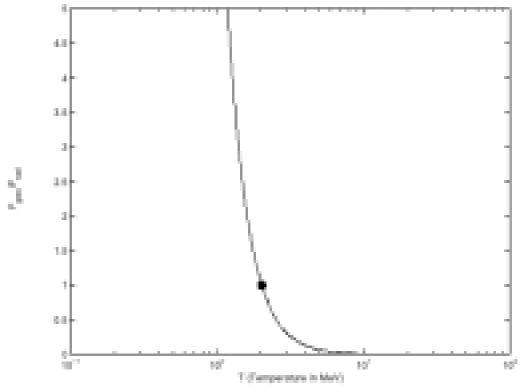

Figure 1: Variation of the ratio $F_{\rm grav} \neq F_{\rm rad}$ with temperature. The dot represents the point where the ratio assumes the value 1.

b_N	T_{cl} (MeV)	N_N	$M/M_\odot$
10^{42}	2.03	1.2×10^{14}	0.12
10^{44}	5.73	1.00×10^{11}	0.11

Table 1: Critical temperatures (T_{cl}) of SQNs of different initial sizes b_N , the total number N_N of SQNs that coalesce together and their total nal mass in solar mass units.

The ratio of these two forces is plotted against temperature in figure 1 for two SQNs with initial baryon number 10^{42} each. It is obvious from the figure that ratio $F_{\rm grav} \neq F_{\rm rad}$ is very small initially. As a result, the nuggets will remain separated due to the radiation pressure. For temperatures lower than a critical value T_{cl}, the gravitational force starts dominating, facilitating the coalescence of the SQNs under mutual gravity. Let us now estimate the mass of the clumped SQNs, assuming that all of them within the horizon at the critical temperature will coalesce together. This is in fact a conservative estimate, since the SQNs, although starting to move towards one another at T_{cl}, will take a finite time to actually coalesce, during which interval more SQNs will arrive within the horizon. In table 1, we show the values of T_{cl} for SQNs of different initial baryon numbers along with the final masses of the clumped SQNs under the conservative assumption mentioned above.

It is obvious that there can be no further clumping of these already clumped SQNs; the density of such objects would be too small within the horizon for further clumping. Thus these objects would survive till today and perhaps manifest themselves as MACHOs. It is to be reiterated that the masses of the clumped SQN's given in table 1 are the lower limits and the final masses of these MACHO candidates will be larger. A more detailed estimate of the masses will require a detailed simulation, but very preliminary estimates indicate that they could be 3-6 times bigger than the values quoted in table 1. A project on detailed simulation of the evolution of SQNs has been embarked upon.

We thus conclude that gravitational clumping of the primordial SQNs formed in a first order cosmic quark - hadron phase transition appears to be a plausible and natural explanation for the observed halo MACHOs. It is quite remarkable that we obtain quantitative agreement with the experimental values without having to introduce any adjustable parameters or any fine-tuning whatsoever.

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