Relics of Cosmic Quark- Hadron Phase Transition and Massive Compact Halo Objects

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We propose that the cold dark matter (CDM) is composed entirely of quark matter, arising from a cosmic quark-hadron transition. We show that compact gravitational objects, with masses around 0.5 $M_\odot$, could have evolved out of the such CDM.

The present consensus in cosmology is that the universe is flat ($\Omega \sim 1$), the baryons contributing only about 10% of the total energy (*i.e.* $\Omega_B \sim 0.1$). There is an abundance of other matter, the *cold dark matter* (CDM), which accounts for clumping on small (galactic/supergalactic scales), amounting to $\Omega_{CDM} \sim 0.35$. The rest of the closure density arises from some kind of vacuum energy, as yet very poorly understood and termed dark energy, which is believed to be responsible for the accelerated expansion of the universe. The estimate of Ω_B comes from Big Bang Nucleosynthesis (BBN), whose success is one of the basic tenets of the standard cosmological model. It is thus believed that the CDM is nonbaryonic; speculations about the nature of CDM, all essentially beyond the standard model of particle interactions (QCD and Electroweak), abound and search for these exotic particles is a most active field of research.

In recent years, there has been experimental evidence [1,2] for at least one form of dark matter - the Massive Astrophysical Compact Halo Objects (MACHO) - detected through gravitational microlensing effects [3]. Based on about 13 - 17 Milky Way halo MACHOs detected in the direction of LMC - the Large Magellanic Cloud, a Bayesian analysis yields their mass estimate in the range (0.15-0.95) $M_\odot$, with the most probable value being 0.5 $M_\odot$ [4,5], substantially higher than the fusion threshold of 0.08 $M_\odot$. (It is thus hard to understand why they do not ignite.) The MACHO collaboration [4] suggests that the lenses are in the galactic halo. In such circumstances, MACHOs cannot be composed of normal baryons for reasons mentioned above. There have, however, been suggestions [6,7] that they could be primordial black holes (PBHs) ($\sim 1\ M_\odot$), arising from horizon scale fluctuations. This suggestion requires a fine tuning of the initial density perturbation and has been criticised in the literature [8].

Within the lore of the standard model, there occurred a phase transition from the quark-gluon phase to the hadronic phase during the microsecond era after the initial Big Bang, at

a temperature of ~ 100 MeV. The order of this phase transition is still unsettled [9]; lattice calculations suggest that in a pure (*i.e.* only gluons) $SU(3)$ gauge theory, it is of first order. In the presence of dynamical quarks on the lattice, the situation is more complicated. However, in the early universe, the large size of the system and the long timescale could facilitate a first order transition. Such a transition could be modeled through a bubble nucleation scenario and Witten [10] argued that the trapped false vacuum domains (TFVD) (*i.e.* the quark phase) could contain a substantial amount of baryon number. QCD-motivated studies [11,12] of baryon evaporation from such TFVD (called strange quark nugget or SQN hereafter) showed that if the SQNs contain baryon number in excess of 10^{40-42}, they would be stable on cosmological time scales and be viable candidates for CDM, as they would be extremely non-relativistic. Note that the number of baryons (which would subsequently take part in BBN) within the event horizon at the microsecond epoch is 10^{49-50}; thus the baryon number contained in SQNs could be 3-4 times as much and SQNs of size $\geq 10^{42}$ could be easily accommodated. However, it has to be reiterated over and over again that the baryon number contained in the SQNs is in the form of quarks and they do not participate in BBN at all.

We can estimate the size of the SQNs formed in the *first order* cosmic QCD transition in the manner prescribed by Kodama, Sasaki and Sato [13]; for details, please see Alam *et al* [14] and Bhattacharyya *et al* [15]. Describing the cosmological scale factor R and the co-ordinate radius X in the Robertson-Walker metric through the relation

$$ds^2 = -dt^2 + R^2 dx^2 = -dt^2 + R^2\{dX^2 + X^2(sin^2\theta d\phi^2 + d\theta^2)\}, \tag{1}$$

one can solve for the evolution of the scale factor $R(t)$ in the mixed phase of the first order transition. In a bubble nucleation description of the QCD transition, hadronic matter starts to appear as individual bubbles in the quark-gluon phase. With progressing time, they expand, more and more bubbles appear, coalesce and finally, when a critical fraction of the total volume is occupied by the hadronic phase, a continuous network of hadronic bubbles form (percolation) in which the quark bubbles get trapped, the TFVDs. The time at which this happens is the percolation time t_p, whereas the time when the phase transition starts is denoted by t_i. Then, the probability that a region of co-ordinate radius X lies entirely within the quark bubbles would obviously depend on the nucleation rate of the bubbles as well as the coordinate radius $X(t_p, t_i)$ of bubbles which nucleated at t_i and grew till t_p. For a nucleation rate $I(t)$, this probability $P(X, t_p)$ is given by

$$P(X, t_p) = exp\left[-\frac{4\pi}{3}\int_{t_i}^{t_p} dt I(t) R^3(t)[X + X(t_p, t_i)]^3\right]. \tag{2}$$

After some algebra [15], it can be shown that if all the CDM is believed to arise from SQNs, then their size distribution peaks, for reasonable nucleation rates, at baryon number $\sim 10^{42-44}$, evidently in the stable sector. Recalling that $\Omega_B \sim 0.1$ corresponds to 10^{49-50} baryons within the horizon at the microsecond epoch, the total baryon number contained in SQNs to account for $\Omega_{CDM} \sim 0.35$ would imply 10^{7-9} SQNs within the horizon just after the QCD phase transition. Because of their enormous mass, they would be nonrelativistic immediately after their formation. It may thus be remarked that they would be discrete macrosopic bodies (radius $R_N \sim 1$m) separated by rather large distances (100 - 300m) in the background of the radiation fluid.

Any deviation from a uniform distribution of SQNs should result in a large attractive force, under which they should gravitate toward one another. Given the property that they become more and more bound with increasing mass [10], they should tend to coalesce and grow to larger sizes. However, the radiation pressure acting on the moving SQNs would serve to inhibit such motion till such time when the gravitational force dominates over it. We can estimate the
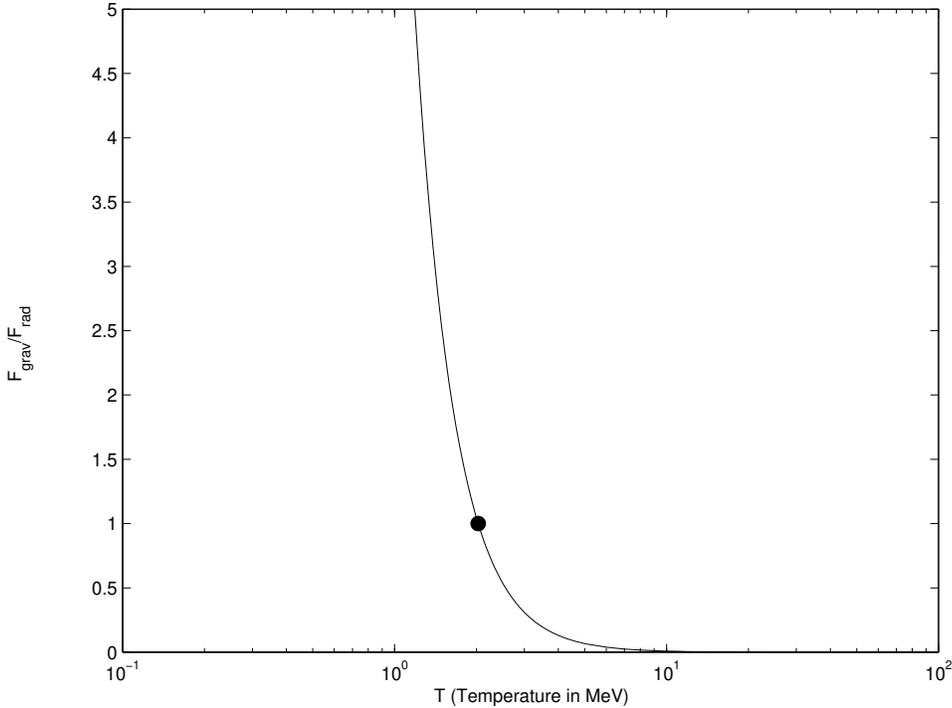
Figure 1. Variation of $F_{\text{grav}}/F_{\text{rad}}$ with temperature. The dot represents the point where the ratio assumes the value 1.

relative magnitude of these two forces in a straightforward manner. If the number of SQNs within the horizon at the time t_p is 10^9 (see above), then the total number and the number density of SQNs at any later temperature T is given by

$$N_N(T) = 10^9 \left(\frac{100 \ MeV}{T} \right)^3; \quad n_N(T) \equiv \frac{N_N}{V_H} = \frac{3N_N}{4\pi(2t)^3} \tag{3}$$

since the horizon length in the radiation dominated era is $2t$. The time t and temperature T are related by the relation $t = 0.3 g_*^{-1/2} \frac{m_{pl}}{T^2}$ with $g_* \sim 17.25$ after the QCD transition [14].

The expression for the gravitational force as a function of temperature T can be written as $F_{\text{grav}} = \frac{GM_N^2}{\bar{r}_{nn}(T)^2}$ where M_N is the SQN mass. (For the sake of simplicity, we assume that all SQNs have the same mass.) $\bar{r}_{nn}(T)$ is the mean separation between the two nuggets, estimated from the density of nuggets at the temperature T. The force due to the radiation pressure on the SQNs arises only due to their relative motion; when they are at rest, there is no resultant force on them. But when the SQNs are in motion, the radiation fluid in front of the moving SQN gets compressed and thus exerts an additional pressure opposing the motion. In a relativistic framework,[1] this amounts to a force F_{rad} given by $F_{\text{rad}} = \frac{1}{3}\rho_{\text{rad}} c v_{\text{fall}} (\pi R_N^2) \beta \gamma$ where ρ_{rad} is the total radiation energy density, counting all relativistic species at the temperature T, v_{fall} (or βc) is the velocity of the SQN and γ the corresponding Lorentz factor. The ratio of these two forces, $F_{\text{grav}}/F_{\text{rad}}$ is plotted against temperature in Fig. 1 for SQNs of initial size 10^{42}. Fig. 1 readily reveals that the ratio $F_{\text{grav}}/F_{\text{rad}}$ is very small initially. As a result, the nuggets will

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[1]Even though the SQNs are nonrelativistic, a relativistic treatment is necessary to handle the radiation fluid.

remain separated due to the radiation pressure. For temperatures lower than a critical value $T_{\rm cl}$, the gravitational force starts dominating, facilitating the coalescence of the SQNs under mutual gravity. It should come as no surprise that even for very small values of β, the large surface area of the SQN is responsible for a considerable resisting force due to radiation pressure.

We can estimate the size of the coalesced SQNs from the number of SQNs within the horizon at T_{cl}. This is, of course, a lower limit, as the collapse would only start at T_{cl} and would take some time during which more SQNs will enter the horizon. For SQNs of size 10^{42}, the total mass in corresponding matter within the horizon at T_{cl} turns out to be $\sim 0.12 M_\odot$; for 10^{44}, it is $0.01 M_\odot$. The actual value could be much (3-10 times) higher but that can be ascertained only through a detailed simulation. Such a calculation is rather involved and remains a future project. In any case, it can be safely assumed that the coalesced SQNs will have masses above the fusion threshold of $0.08 M_\odot$ and once coalesced, the density of the resulting configuration would be so low that they cannot clump any further. They could thus persist till the present time and manifest themselves as MACHOs. For $\Omega_{CDM} \sim 0.35$, there would be about 10^{23-24} such objects within the horizon today and about 2 - 3 $\times 10^{13}$ within the Milky Way halo. We should verify whether this abundance is consistent with the observed number of MACHO events.

The abundance of gravitational lenses is estimated through the optical depth τ which is the probability that a given star lies within the Einstein ring of a lens, $i.e.$ the number density of the lenses times the area of the Einstein ring of each lens. The expression reads [16] $\tau = \frac{4\pi G}{c^2} D_s^2 \int \rho(x) x(1-x) dx$ where D_s is the distance between the observer and the source (a star in the LMC in the present case) and $x = D_d D_s^{-1}$, D_d being the distance between the observer and the lens. In particular, ρ is the mass-density of the MACHOs, which is of the form $\rho = \rho_0 \frac{1}{r^2}$ in the spherical halo model. Assuming a halo extending all the way upto the LMC, we obtain $\tau \simeq$ 2 - 5$\times 10^{-7}$, in excellent agreement with observation [5].

To conclude, we have shown that in a first order cosmic quark-hadron phase transition, cold dark matter could arise entirely within the framework of the standard model of particle interactions. The observed halo MACHOs could be the natural manifestation of such CDM.

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