The Cosmic QCD Phase Transition, Quasi-baryonic Dark Matter 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 denote this phase as "quasibaryonic", distinct from the usual baryons. We show that compact gravitational lenses, with masses around 0.5 $M_\odot$, could have evolved out of the quasibaryonic 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. (We shall discuss the possible relevance of the scenario described in this letter to dark energy on a separate occasion.) The estimate of $\Omega_B$ 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\textsuperscript{1,2} for at least one form of dark matter - the Massive Astrophysical Compact Halo Objects (MACHO) - detected through gravitational microlensing effects.\textsuperscript{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 (0.15-0.95) $M_\odot$, with the most probable value being 0.5 $M_\odot$\textsuperscript{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\textsuperscript{4} suggests that the lenses are in the galactic halo. In such a case, the observed number of events is already too large to be reconciled with the BBN limit of $\Omega_B$, even if the lenses are thought to be as faint as blue dwarfs. There are alternate attempts at circumventing this difficulty, which include thick disk halo model, tidal wave debris, self-lensing of the LMC and many others; all of them cannot be adequately mentioned in this letter. We adopt the viewpoint, in line with the claim of the MACHO collaboration, that the lenses are indeed in the galactic halo. In such circumstances, MACHOs cannot be composed of normal baryons for reasons mentioned above. There have, however, been suggestions\textsuperscript{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.\textsuperscript{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 $\sim 100$ MeV. The order of this phase transition is still unsettled;\textsuperscript{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\textsuperscript{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\textsuperscript{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 $10^{40}$, 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. Thus, to distinguish them from the usual baryons and yet account for the baryon number contained in them, we coin the term \textit{quasibaryonic} to describe the SQNs and the CDM component coming from SQNs as \textit{quasibaryonic dark matter}, distinct from nonbaryonic or baryonic dark matter.

We can estimate the size of the SQNs formed in the \textit{first order} cosmic QCD transition in the manner prescribed by Kodama, Sasaki and Sato\textsuperscript{13} in the context of the GUT phase transition. For the sake of brevity, let us recapitulate very briefly
the salient points here; for details, please see Alam et al\textsuperscript{14)} and Bhattacharyya et al\textsuperscript{15)}. Describing the cosmological scale factor $R$ and the co-ordinate radius $X$ in the Robertson-Walker metric through the relation

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

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 spherical 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

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

After some algebra,\textsuperscript{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 macroscopic bodies (radius $R_N \sim 1m$) 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,\textsuperscript{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 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 number at any later temperature $T$ is given by

$$N_N(T) = 10^9 \left( \frac{100 \ \text{MeV}}{T} \right)^3 \quad (3)$$

\textsuperscript{1)} In general, the TFVDs need not be spherical. For the QCD bubbles, however, it is believed that there is a sizable surface tension which would facilitate spherical bubbles.
and the number density of SQNs is consequently

\[ n_N(T) = \frac{N_N}{V_H} = \frac{3N_N}{4\pi(2t)^3} \]  

(4)

since the horizon length in the radiation dominated era is \(2t\). The time \(t\) and temperature \(T\) are related by the relation

\[ t = 0.3g_*^{-1/2}\frac{m_{pl}}{T^2} \]  

(5)

with \(g_* \sim 17.25\) after the QCD transition.\(^4\)

The expression for the gravitational force as a function of temperature \(T\) can be written as

\[ F_{\text{grav}} = \frac{GM_N^2}{\bar{r}_{nn}(T)^2} \]  

(6)

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 \(F_{\text{rad}}\) given by

\[ F_{\text{rad}} = \frac{1}{3}\rho_{\text{rad}}cv_{\text{fall}}(\pi R_N^2)\beta\gamma \]  

(7)

where \(\rho_{\text{rad}}\) is the total radiation energy density, counting all relativistic species at the temperature \(T\), \(v_{\text{fall}}\) (or \(\beta c\)) is the velocity of the SQN and \(\gamma\) 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 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. It should come as no surprise that even for very small values of \(\beta\), 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 quasibaryonic matter within the horizon at \(T_{cl}\) turns out to be \(\sim 0.12M_\odot\); for \(10^{44}\), it is \(0.01M_\odot\). 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

\(^1\) Even though the SQNs are nonrelativistic, a relativistic treatment is necessary to handle the radiation fluid.
threshold of $0.08M_{\odot}$ and once coalesced, the density of the resulting configuration would be so low that they cannot clump any further. (It may also be recalled at this point that quasibaryonic blobs cannot grow to arbitrarily large sizes. We have earlier shown\textsuperscript{16} that there exists an upper limit on the mass of astrophysical compact quark matter objects, about $1.4M_{\odot}$ for the canonical value of $(145 \text{ MeV})^4$ for the MIT Bag parameter.) 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 $2 \cdot 3 \times 10^{13}$ 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 which is the probability that a given star lies within the Einstein ring of a lens, \textit{i.e.} the number density of the lenses times the area of the Einstein ring of each lens. The expression reads\textsuperscript{17}

$$\tau = \frac{4\pi G}{c^2} D_s^2 \int \rho(x)x(1-x)dx$$

(8)
where $D_s$ is the distance between the observer and the source (a star in the LMC in the present case) and $x = D_dD_s^{-1}$, $D_d$ being the distance between the observer and the lens. In particular, $\rho$ is the mass-density of the MACHOs, which is of the form $ho = \rho_0 r^{-2}$ in the spherical halo model. Assuming a halo extending all the way up to the LMC, we obtain $\tau \simeq 2 \times 10^{-7}$, in excellent agreement with observation.

The scenario proposed here could have important consequences. The presence of MACHOs prior to BBN could act as a large sink for baryons (primarily neutron) and influence inhomogeneous BBN significantly. This is now under investigation.\(^{18}\)

Also the gravitational attraction exerted by the MACHOs on the surrounding matter could act as a seed of inhomogeneity for galaxy formation processes. This will have to be explored in depth. Furthermore, the existence of an upper mass limit for astrophysical quark objects implies that if two or more MACHOs collide and merge, the resultant body may exceed this upper limit. In such cases, the additional mass would have to be shed and these could be the source of the ultrahigh energy ($\geq 10^{20}$ eV) cosmic rays, without the necessity of invoking an acceleration mechanism.

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

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