The Cosmological Quark-Hadron Transition and
Massive Compact Halo Objects

Shibaji Banerjee\textsuperscript{a}, Abhijit Bhattacharyya\textsuperscript{b}, Sanjay K. Ghosh\textsuperscript{c}, Sibaji Raha\textsuperscript{a,d}

and

Bikash Sinha\textsuperscript{b,e}

\textsuperscript{a} Physics Department, Bose Institute, 93/1, A.P.C. Road, Calcutta 700 009, INDIA
\textsuperscript{b} Variable Energy Cyclotron Centre, 1/AF, Bidhannagar, Calcutta 700 064, INDIA
\textsuperscript{c} Theory Group, TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, CANADA
\textsuperscript{d} Nuclear Theory Group, Brookhaven National Laboratory, Bldg. 510A, Upton, Long Island, New York 11973-5000, USA
\textsuperscript{e} Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Calcutta 700 064, INDIA

One of the abiding mysteries in the so-called standard cosmological model is the nature of the dark matter. It is universally accepted that there is an abundance of matter in the universe which is non-luminous, due to their very weak interaction, if at all, with the other forms of matter, excepting of course the gravitational attraction. Speculations as to the nature of dark matter are numerous, often bordering on exotics, and searches for such exotic matter is a very active field of astroparticle physics at the dawn of the new century. Nevertheless, in recent years, there has been experimental evidence\textsuperscript{[1, 2]} for at least one form of dark matter - the massive compact halo objects detected through gravitational microlensing effects proposed by Paczynski some years ago\textsuperscript{[3]}. To date, no clear
consensus as to what these objects, referred to in the literature as well as in the following by the acronym MACHO, are made of; for a brief discussion of some of the suggestions, see below. In this work, we show that they find a natural explanation as leftover relics from the putative first order cosmic quark - hadron phase transition that is predicted by the standard model of particle interactions to have occurred during the microsecond epoch of the early universe.

Since the first discovery of MACHO only a few years ago, a lot of effort has been spent in studying them observationally, as well as theoretically. It is beyond the scope of the present work to cite them adequately; see, for example, Sutherland [4]. Based on about 14 Milky way halo MACHOs detected in the direction of the Large Magellanic Cloud (we are not addressing the events found toward the galactic bulge), the most probable mass estimate [4] for MACHOs is in the vicinity of $0.5M_\odot$, substantially higher than the fusion threshold of $0.08M_\odot$. Assuming that MACHOs are subject to the limit on total baryon number imposed by the Big Bang Nucleosynthesis (BBN), there have been suggestions that they could be white dwarfs [5]. It is difficult to reconcile this with the absence of sufficient active progenitors of appropriate masses in the galactic halo. On the other hand, there have been suggestions [6, 7] that they could be primordial black holes (PBHs) ($\sim 1M_\odot$), arising from horizon scale fluctuations triggered by pre-existing density fluctuations during the cosmic quark - hadron phase transition. While this would not violate the BBN limits on baryon number, the Hawking radiation from such primordial black holes would interfere with the observed $\gamma$ background, which is thought to be reasonably well understood. It is thus safe to conclude that the nature of MACHOs continues to be dark, in the sense of begging elucidation.

We propose that the MACHOs are not subject to the BBN limit on baryon number,
insofar as they do not participate in the BBN process, just like the PBHs. On the other hand, they do not radiate, via the Hawking process or otherwise, having evolved out of the quark nuggets which could have been formed in the cosmic quark-hadron phase transition, at a temperature of $\sim 100 \text{ MeV}$ during the microsecond era in the history of the early universe. In a seminal work in 1984, Witten argued that strange quark matter could be the true ground state of Quantum Chromodynamics (QCD), the underlying field theory of strong interactions and that in a first order phase transition from quark-gluon matter to hadronic matter, 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 SQN-s have established that primordial SQN-s with baryon numbers above $\sim 10^{40-42}$ would indeed be cosmologically stable. More recently, some of the present authors have shown that without much fine tuning, these stable SQNs could provide the entire closure density ($\Omega \sim 1$) and in a subsequent work, some of us have calculated the distribution of SQN-s produced in the (first order) cosmic QCD transition for various nucleation models, with the result that for a reasonable set of parameters, the distribution is rather sharply peaked at values of baryon number ($\sim 10^{42-44}$), evidently in the stable sector. It was also seen that there were almost no SQNs with baryon number exceeding $10^{46-47}$, comfortably lower than the horizon limit of $10^{49}$ baryons at that time.

It is therefore most relevant to investigate the fate of these SQNs and their implications on the later evolution of the universe. While they have enormous appetite for neutrons, becoming more and more strongly bound in the process, the total surface area of these large SQNs is not big enough to absorb so many neutrons as to interfere with BBN.
They remain in equilibrium upto the neutrino decoupling temperature $T_\nu \sim 1$ MeV beyond which they freeze out. From then on, they are subject only to the gravitational interaction. Unlike the usual baryons which are bound by the photon pressure till the recombination era, SQNs become free to collapse at temperatures below $\sim 1$ MeV. Let us thus roughly estimate the number of SQNs contained within the Jeans length at a temperature of 1 MeV. For our present purpose, we take the SQNs to have the same common mass of $10^{44}$ with an abundance of $10^7$ at $T \sim 100$ MeV \cite{11}.

A measure of the Jeans length for the present purpose may be obtained without having recourse to the usual hydrodynamic prescription, just by demanding that the total gravitational energy in the Jeans volume should be greater than or equal to the pressure energy:

$$G\left(\frac{4}{3}\pi R_J^3 \rho_r\right)^2/R_J = v_s^2 \rho_r \frac{4}{3}\pi R_J^3$$

where the subscript $r$ to $\rho$ indicates that the universe is still radiation dominated and $v_s$ stands for the velocity of sound ($=\frac{1}{\sqrt{3}}$). We then have:

$$R_J = \frac{m_{pl}}{\sqrt{4\pi \rho_r}} \sim 1.633t$$

which is just less than the distance to the horizon $d_H(\sim 2t$ in the radiation era \cite{15}). It thus seems that a general relativistic treatment is not strictly required, as was to be somewhat expected at least for the SQNs, given their enormous mass.

The number of SQNs within the horizon as a function of temperature is given by $N_N = 10^7 \left(\frac{100 \text{MeV}}{T}\right)^3$ so that the density of SQNs is $n_N = N_N/V_H = N_N/\left(\frac{4}{3}\pi (2t)^3\right)$. One can readily see that the total number of SQNs in $R_J$ at $T = 1$ MeV turns out to be $\sim 0.58 X 10^{12-13}$. If all these SQNs clump into one, it would then have a mass of $\sim 0.5M_\odot$, making
them ideal MACHO candidates.

It is obvious that there can be no further clumping of these already clumped SQNs; at subsequent times, the density of such objects would be so low that it would be hard to find more than one or two of them within one Jeans radius. A very crude estimate of the collapse time of all the SQNs within $R_J$ can be carried out to ascertain that indeed such a timescale is comparable to the lifetime of the universe at that temperature.

We conclude that gravitational clumping of the primordial SQNs formed in a first order cosmic quark - hadron phase transition appears to be a plausible explanation for the observed halo MACHOs. Needless to say, the estimates presented here should serve only as guidelines and a detailed simulation would of course be needed before any firm conclusions can be drawn. Whether the spatial as well as the size distributions of the SQNs can serve as the necessary initial fluctuations need also to be carefully looked into. Such a study is on our present agenda and we hope to present the results in due course.

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