Massive Compact Halo Objects from the relics of the cosmic quark–hadron transition

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ABSTRACT

The existence of compact gravitational lenses, with masses around 0.5 M⊙, has been reported in the halo of the Milky Way. The nature of these dark lenses is as yet obscure, particularly because these objects have masses well above the threshold for nuclear fusion. In this work, we show that they find a natural explanation as being the evolutionary product of the metastable false vacuum domains (the so-called strange quark nuggets) formed in a first order cosmic quark–hadron transition.

Key words: gravitational lensing – cosmology: miscellaneous – dark matter – early Universe.

1 INTRODUCTION

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 its very weak interaction, if at all, with the other forms of matter, excepting of course the gravitational attraction. The present consensus (for a review, see Turner 1999, 2000) based on recent experimental data is that the Universe is flat and that a sizable amount of the dark matter is ‘cold’, i.e. non-relativistic, at the time of decoupling (we are not addressing the issue of dark energy in this work). Speculations as to the nature of dark matter are numerous, often bordering on the exotic, and searches for such exotic matter is a very active field of astroparticle physics. In recent years, there has been experimental evidence (Alcock et al. 1993; Aubourg et al. 1993) for at least one form of dark matter – the Massive Astrophysical Compact Halo Objects (MACHO) – detected through gravitational microlensing effects proposed by Paczynski (1986) some years ago. To date, there is no clear picture as to what these objects are made of. In this work, we show that they find a natural explanation as left over relics from the putative first order cosmic quark–hadron phase transition.

2 MACHOS: WHAT AND WHERE ARE THEY?

Since the first discovery of MACHOs only a few years ago, a lot of effort has been spent in studying them. Based on about 13–17 Milky Way halo MACHOs detected in the direction of LMC – the Large Magellanic Cloud (we are not considering the events found toward the galactic bulge), the MACHOs are expected to be in the mass range (0.15–0.95) M⊙, with the most probable mass being in the vicinity of 0.5 M⊙ (Sutherland 1999; Alcock et al. 2000), substantially higher than the fusion threshold of 0.08 M⊙. The MACHO collaboration suggests that the lenses are in the galactic halo. Assuming that they are subject to the limit on the total baryon number imposed by the big bang nucleosynthesis (BBN), there have been suggestions that they could be white dwarfs (Fields, Freese & Graff 1998; Freese, Fields & Graff 2000). It is difficult to reconcile this with the absence of sufficient active progenitors of appropriate masses in the galactic halo. Moreover, recent studies have shown that these objects are unlikely to be white dwarfs, even if they were as faint as blue dwarfs, since this will violate some of the very well known results of BBN (Freese et al. 2000). There have also been suggestions (Schramm 1998; Jedamzik 1998; Jedamzik & Niemeyer 1999) that they could be primordial black holes (PBHs) (~ 1 M⊙), arising from horizon scale fluctuations triggered by pre-existing density fluctuations during the cosmic quark–hadron phase transition. The problem with this suggestion is that the density contrast necessary for the formation of PBH is much larger than the pre-existing density contrast obtained from the common inflationary scenarios. The enhancement contributed by the QCD phase transition is not large enough for this purpose. As a result a fine tuning of
the initial density contrast becomes essential which may still not be
good enough to produce cosmologically relevant amount of PBH
(Schmid, Schwarz & Widerin 1999). Alternately, Evans, Gyuk &
Turner (1998) suggested that some of the lenses are stars in the
Milky Way disc which lie along the line of sight to the LMC. Gyuk
& Gates (1999) examined a thick disc model, which would lower
the lens mass estimate. Aubourg et al. (1999) suggested that the
events could arise from self-lensing of the LMC. Zatarisky & Lin
(1997) have argued that the lenses are probably the evidence of a
tidal tail arising from the interaction of LMC and the Milky Way
or even a LMC–SMC (Small Magellanic Cloud) interaction. These
explanations are primarily motivated by the difficulty of reconciling
the existence of MACHOs with the known populations of low mass
stars in the galactic discs.

3 COSMIC QUARK HADRON TRANSITION
AND STRANGE QUARK NUGGETS

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 cosmo-
quark–hadron phase transition, at a temperature of ~100 MeV
during the microsecond era of the early Universe. The order of the
deconfinement phase transition is an unsettled issue till date. Lattice
gauge theory suggests that in a pure (i.e. only gluons) SU(3) gauge
theory, the deconfinement phase transition is of first order.
In the presence of dynamic quarks on the lattice, there is no unam-
biguous way to study the deconfinement transition; one investigates
the chiral transition. Although commonly treated to be equivalent,
there is no reason why, or if at all, these two phase transitions
should be simultaneous or of the same order (Alam, Raha & Sinha 1996).
The order of the chiral phase transition depends rather crucially
on the strange quark mass. If the strange quark is heavy, then the
chiral phase transition is probably of first order. Otherwise, it may
be of second order. The strange quark mass being of the order of
the QCD scale, the situation is still controversial (Blaizot 1999).
There are additional ambiguities arising from finite size effects
of the lattice which may tend to mask the true order of the tran-
sition. Our interest here is in the deconfinement transition. If it is in-
deed of first order, the finite size effects which could mask it would
be negligibly small in the early Universe. In such circumstances,
Witten (1984) argued, in a seminal paper, that strange quark mat-
ter 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. (For a brief review of
the QCD scale, the situation is still controversial (Blaizot 1999).
SQNs.

The SQNs formed during the cosmic QCD phase transition at
T ~ 100 MeV have high masses (~10^{35} GeV) and sizes (R_{q} ~ 1 m)
compared to the other particles (like the usual baryons or leptons)
which inhabit this primeval universe. These other particles cannot
form structures until the temperature of the ambient universe falls
below a certain critical temperature characteristic of such particles;
until then, they remain in thermodynamic equilibrium with the radia-
tion and other species of particles. This characteristic temperature
is called the freeze-out temperature for the corresponding particle.
Obviously the freeze-out occurs earlier for massive particles for the
same interaction strength. In the context of cosmological expansion
of the Universe this has important implications; the ‘frozen’ objects
can form structures. These structures do not participate in the ex-
pansion in the sense that the distance between the subparts do not
increase with the scale size and only their number increases due to
the cosmological scalefactor.

For the SQNs, however, the story is especially interesting. Even if
they continue to be in kinetic equilibrium due to the radiation pres-
sure (photons and neutrinos) acting on them, their velocity would
be extremely non-relativistic. Also their mutual separation would be

1 For the QCD bubbles, it is believed that there is a sizable surface tension
which would facilitate spherical bubbles.
considerably larger than their radii; for example, at \( \sim 100 \text{ MeV} \), the mutual separation between the SQNs (of size \( \sim 10^{44} \text{ baryons} \)) is estimated to be around \( \sim 300 \text{ m} \). It is then obvious that the SQNs do not lend themselves to be treated in a hydrodynamical framework; they behave rather like discrete bodies in the background of the radiation fluid. They thus experience the radiation pressure, quite substantial because of their large surface area as well as the gravitational potential due to the other SQNs.

In such a situation, one might be tempted to assume that since the SQNs are distributed sparsely in space and interact only feebly with the other SQNs through gravitational interaction, they might as well remain forever in that state. This, in fact, is quite wrong, as we demonstrate below.

The fact that the nuggets remain almost static is hardly an issue which requires justification. The two kinds of motion that they can have are random thermal motion and the motion in the gravitational well provided by the other SQNs. This other kind of motion is typically estimated using the virial theorem, treating the SQNs as a system of particles moving under mutual gravitational interaction (Bhatia 2001; Peebles 1980). The kinetic energy \( (K) \) and potential energy \( V \) of the nuggets at temperature \( T = 100 \text{ MeV} \) can be estimated as,

\[
K = \frac{3}{2} N k_b T
\]

\[
V = \sum_{i,j} G \frac{M_i M_j}{R_{ij}} = \frac{G M_i^2 N^2}{2 R_{av}}
\]

where \( k_b \) is the Boltzmann constant, \( M_i, M_j \) are the masses of the \( i \)th and \( j \)th nugget, \( R_{ij} \) is the distance between them and \( R_{av} \) is the average inter-nugget distance. Substituting the number of nuggets \( N = 10^7 \), the baryon number of each nugget to be \( 10^{44} \) and \( R_{av} = 300 \text{ m} \), one gets \( K = 2.4 \times 10^{-4} \) and \( V = 3.09 \times 10^{35} \) (in MKS units) so that the ratio of \( K \) and \( V/2 \) becomes \( \sim 10^{-30} \). Thus it is impossible for these objects to form stable systems, orbiting round each other. On the other hand the smallness of the kinetic energy shows that gravitational collapse might be a possible fate.

Such, of course, would not be the case for any other massive particles like baryons; their masses being much smaller than SQN, the kinetic energy would continue to be very large till very low temperatures. More seriously, the Virial theorem can be applied only to systems whose motion is sustained. For SQNs, a notable property is that they become more and more bound if they grow in size. Thus SQNs would absorb baryons impinging on them and grow in size. Also, if two SQNs collide, they would naturally tend to merge. In all such cases, they would lose kinetic energy, making the Virial theorem inapplicable.

One can argue that the mutual interaction between uniformly dispersed particles would prevent these particles from forming a collapsed structure, but that argument holds only in a static and infinite universe, which we know our Universe is not. Also a perfectly uniform distribution of discrete bodies is an unrealistic idealization and there must exist some net gravitational attraction on each SQN. The only agent that can prevent a collapse under this gravitational pull is the radiation pressure, and indeed its effect remains quite substantial until the drop in the temperature of the ambient universe weakens the radiation pressure below a certain critical value. In what follows, we try to obtain an estimate for the point of time at which this can happen.

It should be mentioned at this juncture that for the system of discrete SQNs suspended in the radiation fluid, a detailed numerical simulation would be essential before any definite conclusion about their temporal evolution can be arrived at. This is a quite involved problem, especially since the number of SQNs within the event horizon, as also their mutual separation, keeps increasing with time. Our purpose in the present work is to examine whether such an effort would indeed be justified.

Let us now consider the possibility of two nuggets coalescing together under gravity, overcoming the radiation pressure. The mean separation of these nuggets and hence their gravitational interaction are determined by the temperature of the Universe. If the entire CDM comes from SQNs, the total baryon number contained in them within the horizon at the QCD transition temperature \( \sim 100 \text{ MeV} \) would be \( \sim 10^{43} \) (see above). For SQNs of baryon number \( b_N \) each, the number of SQNs within the horizon at that time would be just \( (10^{43}/b_N) \). Now, in the radiation dominated era the temperature dependence of density \( n_N \sim T^3 \), horizon volume \( V_H \) varies with time as \( t^3 \), i.e. \( V_H \sim T^{-6} \) and hence the variation of the total number inside the horizon volume will be \( N_N \sim T^{-3} \). So 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:

\[
N_N(T) = \frac{10^{51}}{b_N} \left( \frac{100 \text{ MeV}}{T} \right)^3
\]

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

where the time \( t \) and the temperature \( T \) are related in the radiation dominated era by the relation:

\[
t = 0.3 g_\ast^{-1/3} \frac{m_{pl}}{T^2}
\]

with \( g_\ast \) being \( \sim 17.25 \) after the QCD transition (Alam et al. 1999).

From the above, it is obvious that the density of SQNs decreases as \( t^{-3/2} \) so that their mutual separation increases as \( t^{-1/2} \). Therefore, the force of their mutual gravitational pull will decrease as \( t^{-1} \). On the other hand, the force due to the radiation pressure (photons and neutrinos) resisting motion under gravity would be proportional to the radiation energy density, which decreases as \( T^4 \) or \( t^{-3} \). It is thus reasonable to expect that at some time, not too distant, the gravitational pull would win over the radiation pressure, causing the SQNs to coalesce under their mutual gravitational pull. The expression for the gravitational force as a function of temperature \( T \) can written as

\[
F_{grav} = \frac{G b_N m_s^2}{\bar{r}_{av}(T)}
\]

where \( b_N \) is the baryon number of each SQN and \( m_s \) is the baryon mass. \( \bar{r}_{av}(T) \) is the mean separation between two nuggets and is given by the cube root of the ratio \( \kappa \) of total volume available and the total number of nuggets

\[
\kappa = \frac{1.114 \times 10^{-12} c^3}{T^3}
\]

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 resistance due to the radiation pressure. The usual isotropic radiation pressure is \( \frac{1}{3} \rho c^2 \), where \( \rho \) 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 arises from a compression of the radiation fluid due to the motion of the SQN. The moving SQN would become a prolate ellipsoid (with its minor axis in the direction of motion due to Lorentz contraction),
where \( \rho \) is the mass-density within the horizon at the critical temperature will coalesce together. This is in fact a conservative estimate, since the SQNs, of them within the horizon at the critical temperature will coalesce together. Let us now estimate the mass of the clumped SQNs, assuming that all the baryons along with the baryon numbers along with the mass of the clumped SQNs; the density of such objects would be too small under the conservative assumption mentioned above.

As a result, the nuggets will remain separated due to the radiation pressure. For temperatures lower than a critical value \( T_{\text{cl}} \), the gravitational force starts dominating, facilitating the coalescence of the SQNs under mutual gravity.

**4 SQN AND MACHO**

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 toward one another at \( T_{\text{cl}} \), 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 \( T_{\text{cl}} \) 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 SQNs given in Table 1 are the lower limits and the final masses of these MACHO candidates will be larger. (The case for \( b_N = 10^{46} \) is not of much interest, especially since such high values of \( b_N \) are unlikely for

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

| \( b_N \) | \( T_{\text{cl}} \) (MeV) | \( N_N \) | \( M/M_\odot \) |
|---|---|---|---|
| \( 10^{42} \) | 1.6 | \( 2.44 \times 10^{14} \) | 0.24 |
| \( 10^{44} \) | 4.45 | \( 1.13 \times 10^{11} \) | 0.01 |
| \( 10^{46} \) | 20.6 | \( 1.1 \times 10^{7} \) | 0.0001 |

The amount of baryons in the CDM will be \( \frac{g_{\text{CDM}}}{g_B} \) times the total number of visible baryons. This comes out to be \( \sim 1.6 \times 10^{79}, \Omega_{\text{CDM}} \) and \( \Omega_B \) being 0.3 and 0.01 respectively. The total number of baryons in a MACHO is \( b_N \times N_N \) i.e. \( 2.44 \times 10^{46} \) and \( 1.13 \times 10^{45} \) for initial nugget sizes \( 10^{42} \) and \( 10^{44} \) respectively. The quantities \( b_N \) and \( N_N \) are taken from the Table 1. So dividing the total number of baryons in CDM by that in a MACHO, the \( N_{\text{macho}} \) comes out to be in the range \( 10^{23} \)–\( 10^{24} \).

We can also mention here that if the MACHOs are indeed made up of quark matter, then they cannot grow to arbitrarily large sizes. Within the (phenomenological) Bag model picture (Chodos et al. 1974) of QCD confinement, where a constant vacuum energy density (called the Bag constant) in a cavity containing the quarks serves to keep them confined within the cavity, we have earlier investigated (Banerjee, Ghosh & Raha 2000) the upper limit on the mass of astrophysical compact quark matter objects. It was found that for a canonical Bag constant \( B \) of \((145 \text{ MeV})^4\), this limit comes out to be \( 1.4 M_\odot \). The collapsed SQNs are safely below this limit. (It should be remarked here that although the value of \( B \) in the original MIT bag model is taken to be \( B_{\text{MIT}} = 145 \text{ MeV} \) from the low mass hadronic spectrum, there exist other variants of the Bag model (Hasenfratz & Kuti 1978), where higher values of \( B \) are required. Even for \( B_{\text{MIT}} = 245 \text{ MeV} \), this limit comes down to 0.54 \( M_\odot \), which would still admit such SQN.

As a consistency check, we can perform a theoretical estimate of the abundance of such MACHOs in the galactic halo which is conventionally given by the optical depth. The optical depth is the probability that at any instant of time a given star is within an angle \( \theta_s \) of a lens, the lens being the massive body (in our case MACHO) which causes the deflection of light. In other words, optical depth is the integral over the number density of lenses times the area enclosed by the Einstein ring of each lens. The expression for optical depth can be written as (Narayan & Bartelmann 1999):

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

where \( D_s \) is the distance between the observer and the source, \( G \) is the gravitational constant and \( x = D_s/D_{\text{crit}} \), \( D_{\text{crit}} \) being the distance between the observer and the lens. In particular \( \rho \) is the mass-density of the MACHOs, which is of the form \( \rho = \rho_0 (1/r^2) \) in the naive spherical halo model, which we have adopted in our calculations.
In the present case $\rho_0$ is given by

$$\rho_0 = \frac{M_{\text{m},\text{macho}} \times N_{\text{macho}}}{4\pi R}$$

(11)

where $R = \sqrt{D_1^2 + D_2^2 + 2D_1 D_2 \cos \phi}$ and $D_1$, $D_2$ being the inclination of the LMC and the distance of observer (earth) from the Galactic centre respectively. $M_{\text{m},\text{macho}}$ and $N_{\text{macho}}$ are the mass of a MACHO and the total number of MACHOs in the Milky Way halo.

The total visible mass of the Milky Way ($\sim 1.6 \times 10^{11}$ M$_\odot$) corresponds to $\sim 2 \times 10^{8}$ baryons. This corresponds to a factor of $\sim 2 \times 10^{-9}$ of all the visible baryons within the present horizon. Scaling the number of clumped SQNs within the horizon by the same factor yields a total number of MACHOs, $N_{\text{macho}} \sim 10^{13}$, in the Milky Way halo for the range of baryon number of initial nuggets $b_\eta = 10^{42-44}$. The value of $D_1$ and $D_2$ are taken to be 10 and 50 kpc, respectively. The value of the inclination angle used here is 40 degrees. Using these values for a naive inverse square spherical model comprising such objects up to the LMC, we obtain an optical depth of $\sim 10^{-6}$, 10$^{-7}$. The uncertainty in this value is mainly governed by the value of $\eta$, $\Omega_{\text{CMB}}$, and $\Omega_{\Lambda}$, and to a lesser extent by the specific halo model. This value compares reasonably well with the observed value and may be taken as a measure of reliability in the proposed model.

As an interesting corollary, let us mention that the scenario presented here could have other important astrophysical significance. The origin of cosmic rays of ultra-high energy $\geq 10^{20}$ eV continues to be a puzzle. One of the proposed mechanisms (Bhattacharjee & Sigl 2001) envisages a top-down scenario which does not require an acceleration mechanism and could indeed originate within our Galactic halo. For our picture, such situations could easily arise from the merger of two or more such MACHOs, which would shed the extra matter so as to remain within the upper mass limit mentioned above. This is currently under active investigation.

5 CONCLUSION

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. We may finish by quoting a famous teaching of John Archibald Wheeler, ‘One should never do a calculation unless one knows an answer’. Our attempt in this work has been to find an answer so that a calculation (in this case, a detailed simulation of the collapsing SQNs) can be embarked upon.

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