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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 $M_\odot$, 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 leftover relics from the *putative* first order cosmic quark–hadron phase transition.

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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) $M_\odot$, with the most probable mass being in the vicinity of 0.5 $M_\odot$ (Sutherland 1999; Alcock et al. 2000), substantially higher than the fusion threshold of 0.08 $M_\odot$. 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) ($\sim 1\,M_\odot$), 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. Zaritsky & 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 cosmic 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 unambiguous 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 transition. Our interest here is in the deconfinement transition. If it is indeed 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 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. (For a brief review of the formation of SQNs, see Alam, Raha & Sinha 1999). QCD – motivated studies of baryon evaporation from SQNs have established (Bhattacharjee et al. 1993; Sumiyoshi & Kajino 1991) that primordial SQNs with baryon numbers above $\sim 10^{40-42}$ would be cosmologically stable. We have recently shown that without much fine tuning, these stable SQNs could provide even the entire closure density ($\Omega \sim 1$) (Alam et al. 1999). Thus, the entire cold dark matter (CDM) ($\Omega_{\rm CDM} \sim 0.3$–0.35) could easily be explained by stable SQNs.

We can estimate the size of the SQNs formed in the *first order* cosmic QCD transition in the manner prescribed by (Kodama, Sasaki & Sato 1982) 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. (1999) and Bhattacharyya et al. (2000). Describing the cosmological scalefactor R and the coordinate radius X in the Robertson–Walker metric through the relation

$$\begin{aligned} \mathrm{d}s^2 &= -\mathrm{d}t^2 + R^2\,\mathrm{d}x^2 \\ &= -\mathrm{d}t^2 + R^2\{\mathrm{d}X^2 + X^2(\sin^2\theta\,\mathrm{d}\phi^2 + \mathrm{d}\theta^2)\}, \end{aligned} \tag{1}$$

one can solve for the evolution of the scalefactor $R(t)$ 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, eventually evolving to SQNs. The time at which the trapping of the false vacuum (quark phase) 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[1] region of co-coordinate 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

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

After some algebra (Bhattacharyya et al. 2000), it can be shown that if all the cold dark matter (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. It was also seen that there were almost no SQNs with baryon number exceeding 10^{46-47}, comfortably lower than the horizon limit of $\sim 10^{50}$ baryons at that time. Since $\Omega_{\rm B}$ is only about 0.04 from BBN, $\Omega_{\rm CDM}$ in the form of SQNs would correspond to $\sim 10^{51}$ baryons so that there should be 10^{7-9} such nuggets within the horizon limit at the microsecond epoch, just after the QCD phase transition (Alam, Raha & Sinha 1998; Alam et al. 1999). We shall return to this issue later on.

It is therefore most relevant to investigate the fate of these SQNs. Since the number distribution of the SQNs is sharply peaked (Bhattacharyya et al. 2000), we shall assume, for our present purpose, that all the SQNs have the same baryon number.

The SQNs formed during the cosmic QCD phase transition at $T \sim 100$ MeV have high masses ($\sim 10^{44}$ GeV) and sizes ($R_N \sim 1$ 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; till then, they remain in thermodynamic equilibrium with the radiation 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 expansion 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 pressure (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 ∼100 MeV, the mutual separation between the SQNs (of size $\sim 10^{44}$ baryons) is estimated to be around ∼300 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 $T = 100$ MeV can be estimated as,

$$K = \frac{3}{2} N k_{\mathrm{b}} T$$
$$V = \sum_{i,j} G \frac{M_i M_j}{R_{i,j}} = \frac{G M^2 N^2}{2 R_{\mathrm{av}}} \tag{3}$$

where k_{b} is the Boltzmann constant, M_i, M_j are the masses of the ith and jth nugget, $R_{i,j}$ 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 $R_{\mathrm{av}} =$ 300 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 $\sim 10^{-39}$. 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 (∼100 MeV) would be $\sim 10^{51}$ (see above). For SQNs of baryon number b_N each, the number of SQNs within the horizon at that time would be just $(10^{51}/b_N)$. 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. $V_{\mathrm{H}} \sim T^{-6}$ 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:

$$N_N(T) \cong \frac{10^{51}}{b_N} \left(\frac{100\,\mathrm{MeV}}{\mathrm{T}} \right)^3 \tag{4}$$

$$n_N(T) = \frac{N_N}{V_{\mathrm{H}}} = \frac{3 N_N}{4\pi (2t)^3} \tag{5}$$

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

$$t = 0.3 g_*^{-1/2} \frac{m_{\mathrm{pl}}}{T^2} \tag{6}$$

with g_* being ∼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^{-2}. 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

$$F_{\mathrm{grav}} = \frac{G {b_N}^2 {m_n}^2}{\bar{r}_{nn}(T)^2}, \tag{7}$$

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

$$\kappa = \frac{1.114 \times 10^{-12} c^3}{T^3}. \tag{8}$$

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 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 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),

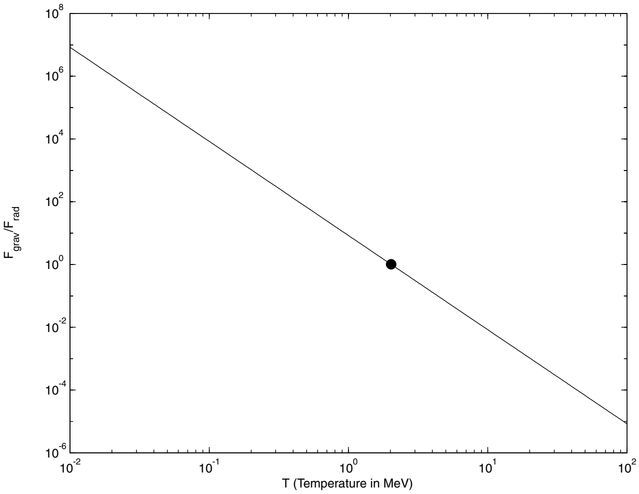

Figure 1. Variation of the ratio $F_{\rm grav}/F_{\rm rad}$ with temperature. The dot represents the point where the ratio assumes the value 1.

whose surface area is given by $2\pi R_N^2[1 + (\sin^{-1}\epsilon)/\gamma\epsilon]$. The eccentricity ϵ is related to the Lorentz factor γ as $\epsilon = \sqrt{\gamma^2 - 1}/\gamma$. For small values of ϵ (small γ), $\sin^{-1}\epsilon \sim \epsilon$, so that the surface area becomes $2\pi R_N^2\,[(\gamma + 1)/\gamma]$. Thus the total radiation force resisting the motion of SQNs is

$$F_{\rm rad} = \frac{1}{3}\rho_{\rm rad} c v_{\rm fall}\left(\pi R_N^2\right)\beta\gamma, \tag{9}$$

where $\rho_{\rm rad}$ is the total energy density at temperature T, $v_{\rm fall}$ or βc is the velocity of SQNs determined by mutual gravitational field and γ is $1/\sqrt{1-\beta^2}$. The quantities $F_{\rm rad}$, β and γ all depend on the temperature of the epoch under consideration. (It is worth mentioning at this point that the t dependence of $F_{\rm rad}$ is actually $t^{-5/2}$, sharper than the t^{-2} estimated above, because of the $v_{\rm fall}$, which goes as $t^{-1/4}$.) The ratio of these two forces is plotted against temperature in Fig. 1 for two SQNs with initial baryon number 10^{42} each. It is obvious from the figure that ratio $F_{\rm grav}/F_{\rm rad}$ is very small initially. As a result, the nuggets will remain separated due to the radiation pressure. For temperatures lower than a critical value $T_{\rm cl}$, 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 $T_{\rm cl}$, 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 $T_{\rm cl}$ 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 the reasonable nucleation rates (Bhattacharyya et al. 1999, 2000); we therefore restrict ourselves to the other cases in Table 1 in what follows.) A more detailed estimate of the masses will require a detailed simulation, but very preliminary estimates indicate that they could be 2–3 times bigger than the values quoted in Table 1.

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

b_N	$T_{\rm cl}$ (MeV)	N_N	$M/{\rm M}_\odot$
10^{42}	1.6	2.44×10^{14}	0.24
10^{44}	4.45	1.13×10^{11}	0.01
10^{46}	20.6	1.1×10^{7}	0.0001

The total number of such clumped SQNs ($N_{\rm macho}$) within the horizon today is evaluated in the following way. With the temperature $\sim$3°K and time $\sim 4 \times 10^{17}$ s, the total amount of visible baryons within the horizon volume can be evaluated using photon to baryon ratio $\eta \sim 10^{-10}$. The amount of baryons in the CDM will be $\frac{\Omega_{\rm CDM}}{\Omega_{\rm B}}$ times the total number of visible baryons. This comes out to be $\sim 1.6 \times 10^{79}$, $\Omega_{\rm CDM}$ and $\Omega_{\rm B}$ being 0.3 and 0.01 respectively. The total number of baryons in a MACHO is $b_N \times N_N$ i.e. 2.44×10^{56} and 1.13×10^{55} 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 $N_{\rm macho}$ comes out to be in the range $\sim 10^{23-24}$.

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 $\boldsymbol{B}$ of (145 MeV)^4, this limit comes out to be 1.4 ${\rm M}_\odot$. The collapsed SQNs are safely below this limit. (It should be remarked here that although the value of $\boldsymbol{B}$ in the original MIT bag model is taken to be $\boldsymbol{B}^{1/4} = 145$ MeV from the low mass hadronic spectrum, there exist other variants of the Bag model (Hasenfratz & Kuti 1978) , where higher values of $\boldsymbol{B}$ are required. Even for $\boldsymbol{B}^{1/4} =$ 245 MeV, this limit comes down to 0.54 ${\rm M}_\odot$ (Banerjee et al. 2000), 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 θ_E 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):

$$\tau = \frac{4\pi G}{c^2} D_s^2 \int \rho(x) x(1-x)\,{\rm d}x, \tag{10}$$

where D_s is the distance between the observer and the source, G is the gravitational constant 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 $\rho = \rho_0(1/r^2)$ in the naive spherical halo model, which we have adopted in our calculations.

In the present case ρ_0 is given by

$$\rho_0 = \frac{M_{\mathrm{macho}} \times N_{\mathrm{macho}}}{4\pi R} \quad (11)$$

where $R = \sqrt{D_e^2 + D_s^2 + 2D_e D_s \cos\phi}$, ϕ and D_e being the inclination of the LMC and the distance of observer (earth) from the Galactic centre respectively. M_{macho} and N_{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 ($\sim 1.6 \times 10^{11}\,\mathrm{M}_\odot$) corresponds to $\sim 2 \times 10^{68}$ 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, $N_{\mathrm{macho}} \sim 10^{13-14}$ in the Milky Way halo for the range of baryon number of initial nuggets $b_N = 10^{42-44}$. The value of D_e and D_s 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 η, Ω_{CDM} and Ω_{B}, 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 $\geqslant 10^{20}$ 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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REFERENCES

Alam J., Raha S., Sinha B., 1996, Phys. Rep., 273, 243
Alam J., Raha S., Sinha B., 1998, Nucl. Phys. A, 638, 523c
Alam J., Raha S., Sinha B., 1999, ApJ, 513, 572
Alcock C. et al., 1993, Nat, 365, 621
Alcock C. et al., 2000, ApJ, 542, 281
Aubourg E. et al., 1993, Nat, 365, 623
Aubourg E., Palanque-Delabrouille N., Salati P., Spiro M., Taillet R., 1999, A&A, 347, 850
Banerjee S., Ghosh S. K., Raha S., 2000, J. Phys., G, 26, L1
Bhatia V. B., 2001, A textbook on Astronomy and Astrophysics, with elements of Cosmology. Narosa Publishing, New Delhi
Bhattacharjee P., Sigl G., 2000, Phys. Rep., 327, 109
Bhattacharjee P., Alam J., Sinha B., Raha S., 1993, Phys. Rev., D, 48, 4630
Bhattacharyya A., Alam J., Sarkar S., Roy P., Sinha B., Raha S., Bhattacharjee P., 1999, Nucl. Phys., A, 661, 629c
Bhattacharyya A., Alam J., Sarkar S., Roy P., Sinha B., Raha S., Bhattacharjee P., 2000, Phys. Rev., D, 61, 083509
Blaizot J. P., 1999, Nucl. Phys., A, 661, 3c
Chodos A., Jaffe R. L., Johnson K., Thorn C. B., Weisskopf V. F., 1974, Phys. Rev., D, 9, 3471
Evans N. W., Gyuk G., Turner M. S., 1998, ApJ, 501, L45
Fields B. D., Freese K., Graff D. S., 1998, New Astron., 3, 347
Freese K., Fields B. D., Graff D. S., 2000, in Weiss A., Abel T., eds, Proc. MPA-ESO Workshop on the First Stars. Springer, Berlin, p. 4
Gyuk G., Gates E., 1999, MNRAS, 304, 281
Hasenfratz P., Kuti J., 1978, Phys. Rep., 40, 75
Jedamzik K., 1998, Phys. Rep., 307, 155
Jedamzik K., Niemeyer J. C., 1999, Phys. Rev., D, 59, 124014
Kodama H., Sasaki M., Sato K., 1982, Prog. Theo. Phys., 8, 1979
Narayan R., Bartelmann M., 1999, in Dekel A., Ostriker J. P., eds, Formation of structure in the universe. Cambridge University Press, Cambridge
Paczynski B., 1986, ApJ, 304, 1
Peebles P. J. E., 1980, The large scale structure of the universe. Princeton Univ. Press, Princeton, NJ
Schmid C., Schwarz D. J., Widerin P., 1999, Phys. Rev., D, 59, 043517
Schramm D. N., 1998, in Sinha B., Viyogi Y. P., Srivastava D. K., eds, Proc. ICPA-QGP'97, Physics and Astrophysics of Quark-Gluon Plasma. Narosa Publishing, New Delhi, p. 29
Sumiyoshi K., Kajino T., 1991, Nucl. Phys. (Proc. Suppl.), 24, 80
Sutherland W., 1999, Rev. Mod. Phys., 71, 421
Turner M. S., 1999, Rev. Mod. Phys., 71, S145
Turner M. S., 2000, Phys. Scr., T, 85, 210
Witten E., 1984, Phys. Rev., D, 30, 272
Zaritsky D., Lin D. N. C., 1997, AJ, 114, 2545

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