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MAGNETIC MONOPOLES AND STRANGE MATTER*

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ABSTRACT

We show that if the density of grand unified monopoles at $T \simeq 200$ MeV is of the order of or greater than $4.4 \cdot 10^{21}\,cm^{-3}$ they annihilate all of the strange matter produced in the quagma-hadron phase transition which the Universe undergoes at this temperature. We also study gravitational capture of monopoles by lumps of strange matter. This yields upper limits on the density of monopoles for different sizes of strange ball.

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Witten has recently suggested [1] a scenario for the cosmological phase transition at $T \simeq 200$ MeV in which the quark-gluon plasma is converted into hadrons. In this picture more than 80% of the baryon number finishes in the form of strange quark matter with virtually any value of A between a few tens and the value for neutron stars. This form of matter is a candidate for the dark matter that seems to pervade the Universe.

A detailed study of strange matter shows [2] that it is more stable than ordinary matter if its baryon number is approximately equal to its strangeness. This translates into the fact that the quark lumps are stable only if there is roughly an equal number of quarks of each of the three flavours present (up, down and strange quarks).

However this form of matter is vulnerable because of the ability of grand unified monopoles to change the baryon number [3]. Monopoles are produced in grand unified theories when a semisimple group breaks to $U(1)$; in the $SU(5)$ model monopoles have a mass $M_m \simeq 10^{16}$ GeV and when interacting with quarks they have a strong baryon number violating cross-section ($\sigma \simeq 10^{-27}\,cm^2$) [4].

When monopoles interact with strange matter, the baryon-violating channel will change the composition of the flavour content of the strange balls. By this change in the quark content the energy per baryon of strange quark matter can be higher than the energy per baryon of ordinary nuclei. Therefore the quark balls or nuggets will decay into ordinary matter if the conditions are appropriate to make them unbound. Such conditions are studied in this paper by considering the interaction between monopoles and the strange matter since its formation at $T \simeq 200$ MeV.

The reaction responsible for the change of the flavour content of a strange lump can be written explicitly as

$$u_1 u_2 + M \longrightarrow e^+ \bar{d}_3 + M \quad , \qquad (1)$$

where 1, 2, 3 are colour indices.

We study in two ways the variation of the quark content inside strange lumps caused by the processes (1). First we consider the flux of monopoles over the strange balls, this gives rise to an upper limit on the density of monopoles at $T \simeq 200$ MeV, in order that the strange matter can survive. Secondly, we take account of the gravitational capture of monopoles by strange lumps, so that the existence of strange balls of different sizes will be correlated with upper bounds of the monopole density.

The variation in time of the density of quarks inside the strange quark lumps, due to reaction (1) ocurring as a result of the flux of monopoles will be

$$\frac{d n_q(T)}{dt} = - n(T)\, n_q(T)\, \sigma \langle v \rangle \quad , \tag{2}$$

where $n_q(T)$ is the number of quarks per cm^3 (*) inside a ball of strange matter [originally $n_q(T{=}T_i \simeq 200\text{ MeV}) \simeq 7 \times 10^{38}\ cm^{-3}$] [2] ; $n(T)$ is the number of monopoles per cm^3, which will be diluted by the expansion of the Universe according to $n(T_f) = n(T_i)(T_f/T_i)^3$; $\sigma \simeq 10^{-27} cm^2$ is the baryon -violating cross section; finally $\langle v \rangle \simeq 0.3\ c$ is the Fermi velocity of quarks inside the strange balls (the velocity of monopoles $\sim (T/M_m)^{1/2}$ is negligible).

In order to calculate the net variation of quarks in these lumps we integrate (2) between two times t_i and t_f , or equivalently between two temperatures $T_i \simeq 200$ MeV and T_f. We will restrict ourselves to the radiation-dominated era so that

$$t \simeq \frac{2.3}{(N_{DF})^{1/2}} \left(\frac{1}{T(MeV)} \right)^2 \sec \quad , \tag{3}$$

where N_{DF} is the number of degrees of freedom associated with essentially zero-mass particles which are in equilibrium at temperature T; we can consider $t \simeq (1/T(MeV))^2$ sec, so that $dt \simeq -dT/T^3$. Because of the great dilution of monopoles due to the expansion of the Universe we will take the

(*) CGS units are used throughout this paper. Temperatures are measured in MeV.

final temperature to be $T_f \simeq O(MeV)$, since at low temperatures the flux of monopoles over interesting strange balls becomes negligeable. Integrating (2) we obtain

$$\frac{n_q(T_f)}{n_q(T_i)} \simeq e^{-\sigma \langle v \rangle \frac{n(T_i)}{T_i^2}} \tag{4}$$

As an example, consider $n_q(T_f)/n_q(T_i) = 1/e$ since this suffices to change the proportion of quark flavours sufficiently so that strange matter becomes unstable. We obtain from (4) an upper limit on the density of monopoles at $T_i \simeq 200$ MeV : $n(T \simeq 200\text{ MeV}) \lesssim 4.4 * 10^{21} cm^{-3}$. We emphasize the fact that this limit applies for the early Universe. If there are no other mechanisms for monopole annihilation, the upper limit at the present time will be : $n(T \simeq 2.7°K) \lesssim 8.8 * 10^{-15} cm^{-3}$.

We now consider how the gravitational interaction between strange matter and monopoles modifies this result. We assume for simplicity that monopoles impinging on a strange ball will be trapped if their gravitational potential at the surface of the ball is greater than their kinetic energy.

The gravitational potential energy of a monopole at the surface of a strange ball of radius R is

$$V_R = G \frac{M M_m}{R} \simeq [R(cm)]^2 \text{ erg} \quad , \tag{5}$$

where M is the mass of a lump of radius R and M_m is the monopole mass.

Assuming that the kinetic energy of a monopole takes the thermal value $\langle T_m \rangle \simeq T$, the condition for monopole capture is $V_R \gtrsim T$ which gives a relationship between the radius of strange balls and the temperature at which they can trap a monopole incident on their surface. By (5) we have

$$R \gtrsim 1.4 \times 10^{-3} \left[T(MeV) \right]^{1/2} cm \ . \tag{6}$$

We first calculate the flux of monopoles incident on a strange ball of radius R at a temperature T. We take the cross section to be equal to the effective surface area of the strange ball $4\pi R^2$; then

$$F(T) = n(T) \langle v_m(T) \rangle 4\pi R^2 \quad \sec^{-1} , \qquad (7)$$

where $n(T)$ is the density of monopoles and $\langle v_m(T) \rangle$ is their mean velocity at temperature T ($\langle v_m(T) \rangle \simeq 13.4\,[T(\mathrm{MeV})]^{1/2}\ \mathrm{cm\ sec^{-1}}$). Using the fact that $n(T)=n(T_i)(T/T_i)^3$ we can integrate (7) between two temperatures and obtain the number of monopoles which will arrive at a strange ball of radius R during this interval

$$N_m = \int_{T_i}^{T_f} F(T) \left(- \frac{dT}{T^3} \right)$$

$$\simeq 112.3 \ \frac{n(T_i) R^2}{[T_i(\mathrm{MeV})]^{3/2}} \ . \qquad (8)$$

We have again taken the final temperature $T_f \simeq 0(\mathrm{MeV})$; in fact, due to the expansion of the Universe the flux of monopoles effectively stop at low temperatures for interesting strange ball radii.

There are two distinct regimes of solutions:

i) $R \geqslant R_0 = 2 * 10^{-2}$ cm. In this first case strange balls can start capturing monopoles immediately after their formation at $T_i = T \simeq 200$ MeV. Substituting into (8) we obtain

$$N_m \simeq 0.04\ n(T_i \simeq 200\,\mathrm{MeV})\, R^2 \ . \qquad (9)$$

Equating (9) to one, in order to obtain a rough estimate, we find an upper limit for the density of monopoles at $T \simeq 200$ MeV such that a strange ball of radius R can avoid destruction by flavour composition changing effect of reaction (1). This limit is

$$n(T_i \simeq 200\,\mathrm{MeV}) \lesssim \frac{25}{R^2} \quad , \quad R > R_0 \ . \qquad (10)$$

ii) $R < R_0 = 2 \cdot 10^{-2}$ cm. In this second situation we must integrate (8) starting at the initial temperature given by (6), $T_i \simeq 5 * 10^5 R^2$ MeV.

The region of integration then covers the range of temperatures for which a monopole must be bound gravitationally if it impinges on a strange ball of radius R. We obtain

$$N_m \simeq 3.2 \times 10^{-7} \ \frac{n(T_i)}{R} \ . \qquad (11)$$

Again we take $N_m \gtrsim 1$ to obtain an upper limit for the density of monopoles at $T_i \simeq 5 * 10^5 R^2$ MeV in order that a strange ball of radius R can survive. The limit is

$$n(T_i) \lesssim 3.1 \times 10^6 R \ . \qquad (12)$$

At $T \simeq 200$ MeV ($> T_i$) the bound corresponding to (12) is

$$n(T \simeq 200\,\mathrm{MeV}) \lesssim \frac{2 \times 10^{-4}}{R^5} \quad , \quad R < R_0 \ . \qquad (13)$$

Terrestrial lumps of strange matter are referred as nuclearites and recently, various ways have been proposed for detecting nuclearites of different sizes [5]. If they are detected, their sizes will place limits on the density of monopoles at $T \simeq 200$ MeV (by relations (10) and (13)), if it is assumed that these strange balls were formed in the quark-hadron phase transition*).

In Fig.1 we plot for different strange ball sizes, the upper limits on the density of monopoles according to (10) and (13). These limits are taken at $T \simeq 200$ MeV and at the actual temperature of the Universe (supposing that no annihilation of monopoles has occurred at $T < 200$ MeV). The size-independent upper limit n $(T \simeq 200\,\mathrm{MeV}) \lesssim 4.4 * 10^{21}\ \mathrm{cm^{-3}}$ is also shown.

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*) In ref. [1] the possibility has been suggested that strange matter might be formed in head-on collisions of neutron stars.

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FIGURE CAPTION

Fig.1 - Upper limits on the density of monopoles, at $T \simeq 200$ MeV and at $T \simeq 2.7^{\circ}K$, are plotted for different strange ball sizes. The size-independent upper limit $n\ (T \simeq 200\ \text{MeV}) \lesssim 4.4 * 10^{21}\ \text{cm}^{-3}$ is also shown (dashed line).

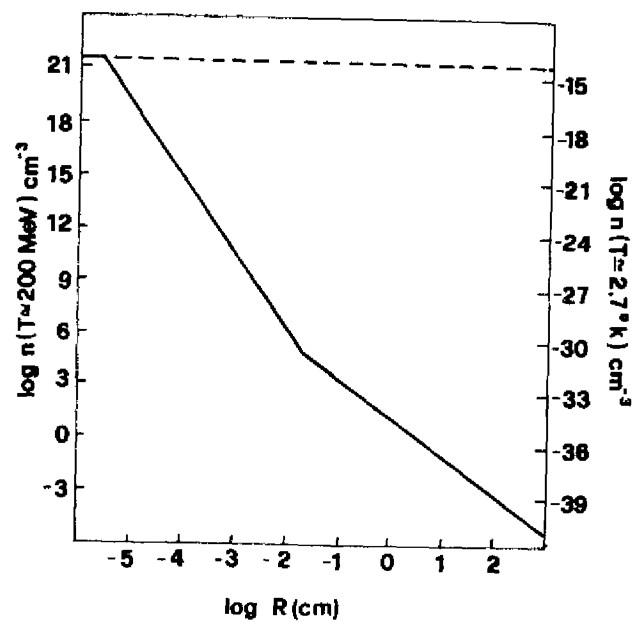

Fig. 1