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INTERNATIONAL CENTRE FOR
THEORETICAL PHYSICS

ON THE FATE OF SUPERHEAVY MAGNETIC MONOPOLES IN A NEUTRON STAR

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ABSTRACT

We propose two possible scenarios of the behaviour of superheavy magnetic monopoles in a neutron star, in which the monopole-antimonopole annihilation rate is sufficiently large to prevent the enormous heating of a neutron star due to the monopole induced neutron decays. We find that the galactic monopole flux of order 10^{-16} cm^{-2} s^{-1} $ster^{-1}$ can be compatible with the observational limit on the X-ray luminosity of neutron stars.

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$$N_M \left(\frac{\sigma_0}{0.1\ \mathrm{fm}^2}\right) < 10^{14} \quad . \qquad (1)$$

If all monopoles whenever captured by the star were present inside the star up to now, Eq.(1) would lead to very strong constraints on the flux of relic monopoles [7-10] which would make their experimental observation almost impossible.

We believe, however, that the question of the survival of magnetic monopoles in a neutron star is by no means clear. In fact, the monopole-antimonopole annihilation rate crucially depends on the particular properties of matter inside the star core, which are still unknown. The main purpose of the present paper is to propose two possible scenarios of the behaviour of superheavy ($m_M \gtrsim 10^{16}$ GeV) monopoles in the neutron star; in both of them the monopole-antimonopole annihilation is sufficiently effective to make N_M consistent with Eq.(1) even for the galactic monopole flux $j_\infty \sim 10^{-16}$ cm^2 s^{-1} $ster^{-1}$, which is close to experimentally observable values [12,4] as well as to other astrophysical and cosmological limits [13-15]. The general feature of both scenarios is that at the first stage monopoles exhaust magnetic fields deep inside the star (but <u>not</u> near the star surface) and then concentrate either near the centre (for neutron stars with non-superconducting interiors), or on the boundary of the central superconductive region, if it exists. In the first case the considerable annihilation rate is simply due to the small size of the region occupied by monopoles, while in the second case the annihilation is enhanced by the presence of the superconductor.

2. Our first scenario applies to the neutron stars with normal (non-superconducting) interiors. As has been argued in Ref.8, a neutron star is likely to contain no monopoles at the moment of its formation. Just after this moment, it begins to capture the relic monopoles with the rate [7-10]

$$\frac{dN_M(t)}{dt} \equiv F = 4\pi^2 j_\infty R_S^2 \left(\frac{v_{esc}}{v_\infty}\right)^2 , \qquad (2)$$

where $v_\infty \sim 10^{-2} \div 10^{-3}$ is the monopole velocity in the Galaxy, $R_S \sim 10$ Km is the star radius and $v_{esc} \sim 0.4$ is the escape velocity at the star surface. Near the star surface, the magnetic force $g_M H_S$ (g_M is the monopole magnetic charge and $H_S \sim 10^{12}$ G is the magnetic field on the surface) is much weaker than the gravitational one, so the monopoles proceed to the star core. If there were no magnetic fields inside the core, the monopoles would fall down to the star centre. However, a neutron star initially has rather large magnetic fields inside the core, $H_0 \sim 10^{12}$ G [16], which are expected to be random [16]. Therefore, the monopoles are initially distributed over the region of radius R_0, at which the magnetic force roughly equals the gravitational one

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where n_M is the monopole density. From (5) we find that the characteristic time of the exhaustion of the magnetic field is independent of H (cf. [17]) and is equal to $t_{exh} = a/8\pi g_M^2 n_M$. The restoration of the magnetic field due to the magnetic flux diffusion occurs with the characteristic time $t_D \sim 4\pi\alpha_S R_0^2$, where $\alpha_S \sim 10^{33}\,(10^6\,{}^oK/T_S)^2\ s^{-1}$ [18] is the electric conductivity of the core matter and T_S is the neutron star temperature. Note that the observational limits [11] imply $T_S \lesssim 10^6\,{}^oK$.

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At this time, the number of monopoles inside the star is

$$N_{coll} = F \cdot t_{coll} = \left[\frac{2aR_0^3}{9g_M^2} F \right]^{1/2} \quad . \tag{7}$$

Note that for $R_0 \sim 100$ m and for $F \sim 10\ s^{-1}$, which is consistent with $j_\infty \sim 10^{-16}\ cm^2\ s^{-1}\ ster^{-1}$, Eq.(9) gives $N_{coll} \sim 10^{12}$, which is less than the allowed value (1).

As discussed in Ref.10, monopoles in the neutron star are likely to be described by their own temperature $T_M \sim 100$ MeV arising due to the catalysis of neutron decays. Therefore, the collaped monopoles spread over the region of radius $R_M = (3T_M M_{pl}^2/4\pi m_M n_n m_n)^{1/2}$ at which their gravitational energy is equal to T_M [10]. There they would eventually annihilate; however, the initial annihilation rate turns out to be small (see below).

Now we turn to the monopoles captured by the star after the collapse of the monopole cluster (i.e. later than t_{coll} after the star formation). The magnetic field of the star tends to be restored due to the magnetic flux diffusion. However, as is clear from the above considerations, it is quickly exhausted by incoming monopoles and does not prevent them to fall down to the star centre. In fact, one can show that at any moment the number of monopoles present outside the star centre is much less than that allowed by Eq.(1).

The number of monopoles inside the central region of radius R_M is determined by their annihilation rate and the incoming flux F. According to Refs.[20,10] the annihilation cross-section is

$$\sigma_A \sim 10^{-35} \left(\frac{10^{16}\ \text{GeV}}{m_M}\right)^2 \left(\frac{100\ \text{MeV}}{T_M}\right) \text{cm}^2 \quad . \tag{8}$$

This yields the equilibrium number of monopoles

$$N_M^{eq} = \left(\frac{4\pi R_M^3 \cdot F}{3 v_M \sigma_A}\right)^{1/2} = 10^{14} \left(\frac{F}{10\ s^{-1}}\right)^{1/2} \frac{T}{100\ \text{MeV}} \ , \tag{9}$$

where $v_M = \sqrt{3T_M/2m_M}$ is the average monopole velocity. From Eqs.(2) and (9) we realize that the galactic monopole flux of order $j_\infty \sim 10^{16}\ cm^{-2}\ s^{-1}\ ster^{-1}$ is allowed within our first scenario provided $v_\infty \sim 10^{-2}$ (so that $F \sim 3\ s^{-1}$).

3. Our second scenario can be valid if interiors of neutron stars are superconductive. The monopole behaviour in the superconductive neutron stars has been discussed by Harvey [10] under the assumption that the superconductivity arises due to the proton-proton pairing, and it has been found that the limits on the monopole flux [7-9] remained unaltered. However, the density of protons in a star core is much less than that of neutrons, while proton-neutron interactions are as strong as proton-proton ones, so it seems likely that a Cooper pair would consist of one proton and one neutron, instead of two protons. The question of the actual nature of the superconductivity under the neutron star conditions is interesting by itself; here we simply assume that protons are superconductive due to the formation of (pn) pairs (electrons in the neutron star interior are likely to be non-superconductive ([21]), and that the superconductivity is of the second order (cf. [22]).

The phase transition from normal to superconducting state leads to the squeezing of the initial magnetic field $H_S \sim 10^{12}$ G into flux tubes of the size equal to the penetration length $\lambda \sim 10^{-11}$ cm [22] each carrying the magnetic flux corresponding to that of one Dirac charge monopole (in the case of proton-proton pairing the tubes would carry two such units of flux. Due to the enormous conductivity of (normal) electrons, the characteristic time of the expelling of the magnetic fields out of the superconducting region much exceeds the age of the Universe [22], so we can neglect this process. Except for the magnetic fields squeezed into the flux tubes, there are also initial (more or less random) magnetic fields near the boundary of the superconducting region, which are directed along this boundary [10].

A magnetic monopole coming from the neighbouring space looses its kinetic energy in the non-superconductive outer region of the neutron star and approaches the boundary of the superconductor with the velocity determined by the gravitational attraction and by the energy losses (4). Entering the superconductor it forms its own flux tube. If the monopole mass is less than 2.10^{17} GeV, the magnetic force turning it back to the boundary, $4\pi g_M^2/\pi\lambda^2$, exceeds the gravitational attraction to the centre, so the monopoles are concentrated on the boundary. In what follows we consider the case $m_M < 10^{17}$ GeV.

Monopoles follow magnetic lines near the boundary and eventually drop down to a flux tube. Since the flux tube carries the magnetic flux equal to that of a monopole, this leads to the disappearance of the tube (see Fig.1). [In this respect the superconductor with (pn)-pairing drastically differs from that with (pp)-pairing.] The magnetic field inside the tube $H_t = 6g_M/\lambda^2 \sim 2.10^{15}$ G, accelerates the monopole up to the velocity

$v_{M(t)} = H_t g_M/a \sim 0.3$, so the monopole destroys the whole tube in $t_d \sim R_S/v_{M(t)} \sim 10^{-4}$ s. It is straightforward to estimate the time of exhaustion of the magnetic fields inside the superconducting region. The initial number of the flux tubes is roughly $N_t \sim 4\pi R_S^2 H_S/2\pi\lambda^2 H_t \sim 10^{31}$ while the rate of the destruction of the flux tubes is $dN_t/dt = -N_M(t)/t_d$, where as before, $N_M(t) = Ft$. Therefore, all flux tubes disappear at $t_0 = (N_t t_d/F)^{1/2}$; at this time the number of monopoles in the neutron star is $N_M(t_0) = (F N_t t_d)^{1/2}$. For $F \approx 10\ s^{-1}$ we have $N_M(t_0) \sim 10^{14}$, which is consistent with Eq.(1). It is worth noting that the destruction of the flux tubes inside the superconducting region has no effect on the magnetic fields near the star surface, since the superconductive interior is surrounded by the thick thrust of the non-superconductive matter [19] (presumably with superfluid neutrons [23,19]), in which the electric conductivity is sufficiently high to prevent the magnetic field diffusion into the inner region (see above).

Once the magnetic fields inside (and thus near the boundary of) the superconductive region are exhausted, monopoles spend all time at the boundary and eventually annihilate. The annihilation is enhanced by the following mechanism. Once the distance between a monopole and an anti-monopole becomes less than λ, the magnetic force preventing them to fall down to the star centre disappears, and the pair penetrates into the super-conductor (Figs.2a-c). There the monopole and antimonopole are confined inside a small bubble (Fig.2d) and then annihilate. The whole process is possible only if the monopole-antimonopole relative velocity $\hat{v}$ is small enough, namely, if the time $\hat{t} = \lambda/\hat{v}$ during which the distance between them is less than λ is sufficient for the gravitational force to cause their penetration into the superconductor at the depth larger than λ, $(4\pi m_n n_n R_S/3M_{P\ell}^2)(\hat{t}^2/2) > \lambda$. This determines the critical velocity, $\hat{v}_0 \sim 10^{-9}$. The velocity distribution of the monopoles on the boundary follows the two-dimensional Boltzmann law with the temperature $T_M \sim 100$ MeV (see above), so the surface density of the monopoles with the velocity below $\hat{v}_0$ is $\tilde{n}(v_M < \hat{v}_0) = \tilde{n}(m_M \hat{v}_0^2/T_M)$, where $\tilde{n}$ is a total surface density (for $m_M \sim 10^{16}$ GeV, $m_M \hat{v}_0^2 << T_M$). Since the "cross section" of the process of Fig.2 is of order λ (remeber that monopoles move along the two-dimensional surface) provided that $\hat{v} < \hat{v}_0$, the rate of the formation of the confined pairs is $dN_p/dt = N_M \tilde{n} \lambda v_0 (m_M \hat{v}_0^2/T_M)^2$, where $N_M \sim 4\pi R_S^2 \tilde{n}$ is the total number of monopoles on the boundary of the superconductor. We conclude that the equilibrium number is

$$N_M^{eq} = (4\pi R_S^2 F/\lambda \hat{v}_0)^{1/2} (T_M/m_M v_0^2) \quad . \qquad (10)$$

For $F = 10\ s^{-1}$, $T_M \approx 100$ MeV and $m_M = 10^{16}$ GeV we find $N_M^{eq} = 10^{14}$, which is still consistent with (1).

The lifetime of a confined pair shown in Fig.2d is very short. Indeed, one can show that the volume of the bubble is typically less than 10^9 fm^3; using Eq.(10) we obtain the lifetime of order 10^4 c. Therefore, only $N_p = F\tau_A \sim 10^5$ pairs are present in the superconductive region at each moment, so they produce no effect on the star.

4. We have discussed two possible scenarios of the neutron star evolution in the presence of a considerable galactic monopole flux, which make the flux $j_\infty \sim 10^{-16}$ cm^2 s^{-1} ster^{-1} and the neutron "decay" parameter $\sigma_0 \sim 0.1$ fm^2 consistent with the observational limit on the X-ray luminosity of the neutron stars. None of these scenarios gets in conflict with the observed or theoretically well established properties of the neutron stars, such as their density, radius or surface magnetic field. We conclude that the reliable derivation of the limits on the monopole flux and/or "decay" parameter requires better knowledge of particular features of the neutron star interiors, and that the observation of the superheavy monopoles catalyzing the baryon decay is much less unlikely than it has been thought previously. On the other hand, in both scenarios the number of monopoles inside a star turns out to be close to the allowed value (1), so that the discovery of the X-ray temperature of the neutron stars (including old ones!) at the level close to the present limit would provide some evidence of the existence of the monopoles inside them. Moreover, the dependence of the temperature of a neutron star on its age and other parameters (radius, mass, etc.) is predictable within both scenarios, so it might be possible (at least in principle) to identify the heat source of the neutron stars with the neutron decays catalyzed by the grand unified monopoles.

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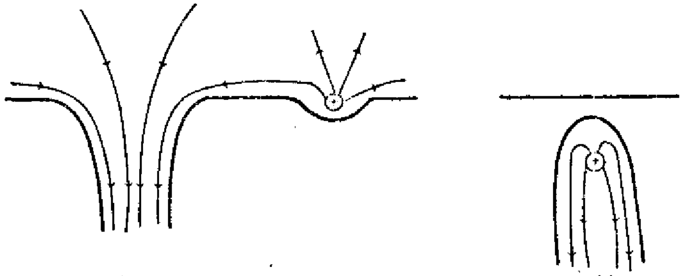
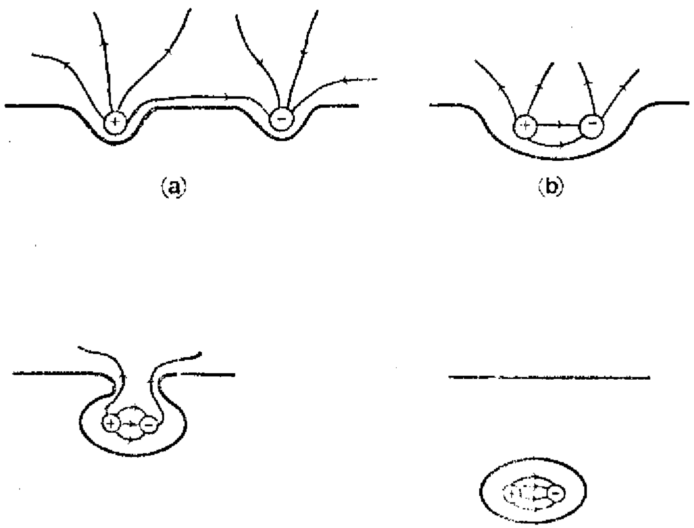


(a) (b)

Fig.1



(c) (d)

Fig.2

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