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How large can the crust of a strange star be?

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Abstract. The effect of the magnetic field on the electrostatic potential of electrons inside and in close vicinity outside the quark surface of the star is studied. Depending on the value of the crust potential and the electron chemical potential at the base of the nuclear crust, we find that the strong surface magnetic field, $1.0 \times 10^{14} \leq H \leq 3.0 \times 10^{16}$ Gauss leads to a considerable reduction of the electrostatic potential which is responsible for holding the nuclear crust. For those values of the magnetic fields, strange stars are unlikely to possess a thick nuclear crust. The magnetic field intensity lying outside this range does not have any effect on the crust mass.

Key words: dense matter – elementary particles – stars: neutron

1. Introduction

The true ground state of the hadrons may be *strange matter* not ^{56}Fe (Bodmer 1971;Witten 1984; Farhi and Jaffe 1984). If it is true, then there would be a possibility of the existence of the strange star (Alcock et al. 1986; Alcock and Olinto 1988). If strange star exists, it opens up a new family of distinguishable compact astrophysical objects like neutron stars and white dwarfs. There is also a possibility that all neutron stars might have been converted into strange stars because the universe is very likely to be contaminated by strangelets and some of the strangelets might be in contact with the neutron stars (Witten 1984; Glendenning 1990; Madsen and Olesen 1991). It is very likely that the pressure at the center of a neutron star is so large that in that region quark matter will be formed via phase transition from hadronic form of matter (Baym and Chin 1976; Freedman and McLerran 1978). Once a strangelet or quark matter component is present in a neutron star, it will quickly develop the equilibrium strangeness content via weak interactions, such as $u\,d \rightarrow u\,s$. The energy will be lowered as strange quarks are created one by one until equilibrium is reached. The conversion of nuclear matter to quark matter may alter the moment of inertia and the epoch over which this conversion takes place may be visible as the spin-down of the pulsar (Glendenning et al. 1997). A new class of strange white dwarfs may also exist in nature which has a central density about $\sim 8 \times 10^3$ times denser than in average normal white dwarf (Glendenning et al. 1995)

Inspite of these theoretical understandings of possible existence of strange matter class stellar objects, the observational searches of these objects have not yielded much positive results. It is due to the fact that it is very difficult to make a distinction between a strange star and a neutron star. The maximum mass and radius of both classes of stars are similar to each other. But the mass-radius relation of a strange star is different from that of a neutron star. It is calculated that the stable neutron star mass generally decreases with radius to a minimum value, while the strange star mass increases in the same range and there is no minimum mass. Such distinguishability feature is taken into account in the calculations made by Li et al. (1995), who determined mass-radius relation semi-empirically from the observations of spin variation and cyclotron spectral line of X -ray source, *Her X-1*. Comparing the results with theoretical models of neutron star and of a strange star respectively, they came to the conclusions that *Her X-1* might be a candidate of strange stars. The another distinguishability feature between a neutron star and strange star is the rotation period. Recently, Madsen (1998) have shown that a young strange star can be distinguished from that of a neutron star by studying the *r-mode* instability which slows rapidly rotating, hot neutron star via gravitational radiation. Strange stars which are not subjected to this instability might have rotation period below 5 - 10 ms (Madsen 1998). To date no pulsars with the range of periods have been detected, therefore future observations will determine whether such young strange pulsars are existing or not.

Previous studies (Alcock et al. 1986; Huang and Lu 1997; Martemyanov 1994) have shown that a strange star may contain nuclear crust. It is still not clear that a strange star with nuclear crust can explain all phenomenon associated with pulsar glitching such as healing times and recurrence rates. A strange star with a very thin nuclear crust possibly rules out the existence of strange pulsar in nature. The evolution of the strange star soon after the formation depends on the crustal thickness. A strange star with thick nuclear crust may have different cooling time and surface temperature from that of a strange star with thin crust. Thus the study of the nuclear crust in the strange star is important for future observations of strange pulsar.

Alcock et al. (1986) first examined the stability of nuclear crust of a cold strange star and calculated the crust mass. Their studies have shown that a strange star of mass $\sim 1.4 M_{\odot}$ contains crust mass $\sim 10^{-5} M_{\odot}$. Kettner et al. (1995) extended the model to include the effect of finite temperature on the crust thickness and found that the temperature lead to a considerable reduction of the electrostatic potential at the surface of the star which holds the crust. Glendenning and Weber (1992) included rotation of the star in the framework of general theory of relativity and calculated the mass, thickness and moment of inertia of the nuclear crust. They found that the general relativistic rotation of the strange star can increase the moment of inertia sufficiently to explain the observed magnitude of pulsar glitches. The electrostatic potential of electrons inside and in the close vicinity of the quark surface is of decisive importance for the existence of the nuclear crust on the quark surface of strange star. This is due to the fact that the strong positive Coulomb barrier prevents atomic nuclei bound in the nuclear crust from comimg into direct contact with strange matter core, where atomic matter would be converted into strange matter. On the other hand neutrons can easily penetrate the Coulomb barrier and are readily absorbed. Therefore, any material which contains free neutrons will not be stable in contact with strange matter. The outer layer of a neutron star is a solid lattice of neutron-rich nuclei neutralized by electrons. This layer can be stable in contact with strange star if *gap* of sufficient width exists between the crust and the quark matter. The electric field which opens the gap must be capable of supporting some *normal* material (i.e. ions and electrons) crust.

Neutron stars are strongly magnetized. Observational data indicate that most isolated pulsars have magnetic fields $\sim 10^{12}$ Gauss while most pulsars in binaries have lower magnetic field strength, going down to $\sim 10^{10}$ Gauss. From the observed cyclotron lines in the massive X-ray binary, the strength of the surface magnetic field of neutron star is found to be $\sim 10^{12}$ Gauss. The structure of the interior field is different from that of the surface. This is due to the fact the interior field is expected to be carried by fluxoids in the superconducting core of the neutron star (Bhattacharya and Srinivasan 1995). These fluxoids have cores of size $\sim 10^{-12}$ cm consisting of normal proton fluid, and the magnetic field strength at the core of these fluxoids can reach $\sim 10^{18}$ Gauss. It has been argued that (Duncan and Thompson 1992) dynamo action may lead to an amplification of the magnetic field in a collapsing star like type II supernovae. The neutron star which is formed as a remnant of the explosion might have magnetic field of strength upto 10^{18} Gauss.

In a strong magnetic field, the electron motion perpendicular to the field lines is quantized to give discrete *Landau Orbitals* (Landau and Lifshitz 1965) and the electron behaves as a one-dimensional gas rather than a three-dimensional gas. The energy of a charged particle change significantly in the quantum limit if the magnetic field $H \geq H_c = m_i^2 c^3/(q_i \hbar)$ Gauss, where m_i and q_i are the mass and charge respectively. For electrons, $H_c \sim 4 \times 10^{13}$ Gauss, while for u and d quarks $H_c \sim 4 \times 10^{15}$ Gauss and for s quark it is $\sim 10^{18}$ Gauss. Therefore, the quantum-mechanical effect of the magnetic field on a neutron star cannot be neglected.

In this paper we attempt a model to study the effect of the magnetic field on electrostatic potential of electrons which hold the nuclear crust of a non-rotating strange star. Our studies are based on a perturbation expansion of pressure, baryon density and energy density from zero magnetic field values at zero temperature by a Taylor series.

In the next section, we describe the effect of the surface magnetic field on electron pressure and electrostatic potential. In the last section, we present our conclusions.

2. Effect of magnetic field

2.1. Electron pressure at zero temperature

In the presence of an external magnetic field, the charged particles move in quantized orbits. The alignment of the particle spin with the external field gives rise to *paramagnetism*, whereas the orbital motions of the charge particles gives rise to *diamagnetism*. We ignore paramagnetism for the present, however. For a constant magnetic field along the z-axis, the path of the charged particle will be a helix with its axis lying along the z-axis and the plane of projection is a circle in x-y plane. The energy associated with the circular motion in x-y plane is quantized in units of $2q_i H$. The energy associated with charged particle along z-axis is also quantized but we can assume this energy change as continuous in view of the smallness of the intervals in the energy scale.

We assume a constant magnetic field along the z-axis ($\overline{A} = (H_y, 0, 0)$),the single energy eigenvalue can be written as (Landau and Lifshitz 1965)

$$\epsilon_i = \sqrt{k_i^2 + m_i^2 + q_i H(2n + s + 1)}, \tag{1}$$

where n=0,1,2,... being the principal quantum numbers for allowed *Landau levels*, k is the momentum of the particle along z-direction, H is the magnetic field intensity, $s = \pm 1$ refers to spin up (+) and spin down (-), and k_i is the momentum component of species i along the field direction. Putting $2n + s + 1 = 2\nu$, where $\nu = 0, 1, 2,$ in Eq. (1) we write

$$k_i^2 = \epsilon_i^2 - m_i^2 - 2\nu q_i H. \tag{2}$$

The energy state with $\nu = 0$ is single degenerate state while all other state with $\nu \neq 0$ are doubly degenerate state. With Eq. (2) we write the expressions for pressure, number density and energy density as

$$P_i = \frac{g_i}{6\pi^2} \int_{\sqrt{m_i^2 + 2\nu q_i H}}^{\mu_i} f_i \sum_{\nu} \left(\epsilon_i^2 - m_i^2 - 2\nu q_i H\right)^{3/2} d\epsilon_i, \tag{3}$$

$$n_i = \frac{g_i}{6\pi^2} \int_{\sqrt{m_i^2 + 2\nu q_i H}}^{\mu_i} f_i \sum_{\nu} \left(\epsilon_i^2 - m_i^2 - 2\nu q_i H\right)^{1/2} \epsilon_i d\epsilon_i, \tag{4}$$

$$\rho_i = \frac{g_i}{2\pi^2} \int_{\sqrt{m_i^2 + 2\nu q_i H}}^{\mu_i} f_i \sum_{\nu} \epsilon_i^2 \sqrt{\epsilon_i^2 - m_i^2 - 2\nu q_i H}\, d\epsilon_i, \tag{5}$$

where

$$f_i = (exp(\epsilon_i - \mu_i)/T + 1))^{-1}$$

is a Fermi function and g_i is a phase space factor (6 for quarks and 2 for electrons). We impose condition $k_i > 0$ for the summation over ν and this condition gives the maximum value of

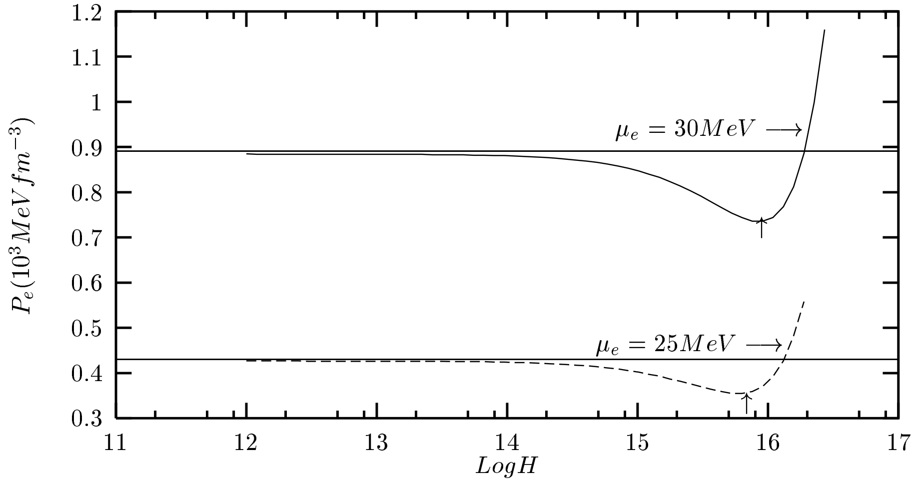

Fig. 1. Degenerate electron pressure (P_e) at the crust base vs. surface magnetic field intensity (H) in logscale. The intensity is measured in Gauss. The pressure at magnetic field intensity, $H = 0$ is shown by horizontal line. Arrow marks show the maximum value of the magnetic field upto which the decrement of pressure is found.

ν, $\nu_{max} = (\mu_i^2 - m_i^2)/2q_iH$ and $\nu \leq \nu_{max}$. In the quantum limit, an electron with chemical potential, $\mu_e \sim 30MeV, m_e \sim 0.5MeV$ is associated with $\nu_{max} \sim 737$, whereas for u and d quarks with current mass 5 MeV, it is $\sim 1560\,(\mu \sim 300MeV)$, for strange quark of mass $\sim 100MeV, \nu_{max} \sim 1$.

We perform a perturbative expansion of pressure, $P_i(\mu, H)$, number density, $n_i(\mu, H)$, and energy density, $\rho_i(\mu, H)$ about their zero magnetic field values $P_i(\mu, 0)$,$n_i(\mu, 0)$ and $\rho_i(\mu, 0)$. Expanding them in a Taylor series and taking only the lowest order terms, we get

$$\xi_i(\mu, H) = \xi_i(\mu, 0) + \frac{\partial \xi_i}{\partial\left(\frac{H^2}{\mu^2}\right)} \frac{H^2}{\mu^2}, \tag{6}$$

where $\xi_i \equiv (P_i, n_i, \rho_i)$.

Neglecting the electron mass, we can obtain the pressure, P_e and number density n_e from Eq. (6) as

$$P_e(\mu_e, H) = P_e(\mu_e, 0) - \frac{1}{4\pi^2} q_e H \left[\mu_e \sqrt{\mu_e^2 - 2q_eH} - 2q_eH \, ln \frac{\mu_e + \sqrt{\mu_e^2 - 2q_eH}}{\sqrt{2q_eH}}\right], \tag{7}$$

$$n_e(H) = \frac{1}{3\pi^2} \mu_e^3(H), \tag{8}$$

where

$$\mu_e(H) = \left[\mu_e^3 - \frac{3}{2} q_e H \sqrt{\mu_e^2 - 2q_eH}\right]^{1/3} \tag{9}$$

is the electron chemical potential at non-zero magnetic field and $P_e(\mu_e, 0) = (1/12\pi^2)\mu_e^4$ is the electron pressure at zero magnetic field. The pressure due to electrons decreases with the increase of the magnetic field when the field intensity exceeds the value of $H \sim 5.0 \times 10^{14} Gauss$ and it is shown in the Fig. 1. When the field strength reaches a critical value, $H_{cr} = \mu_e^2/2$, $P_e(\mu_e, H_{cr}) \rightarrow P_e(\mu_e, 0)$ and it is marked by a sudden increase in pressure in the figure. As is shown in Eq. (9), the critical value of the field, however depends on the chosen value of the electron chemical potential at zero magnetic field. For a representative value of $\mu_e = 25MeV$, where neutron drip occurs at a density $\sim 4.0 \times 10^{11} gcm^{-3}$ (Baym et al. 1971), we find $H_{cr} \sim 3.0 \times 10^{16}$Gauss. To study the effect of the surface magnetic field on the electrostatic potential, we, therefore, choose the value of the magnetic field, $1.0 \times 10^{14} < H < 3.0 \times 10^{16}$ Gauss.

2.2. *Electrostatic potential: existence of nuclear crust*

The electrons are held to the quark surface electromagnetically. The distribution of electrons extends a few hundreds fermis above the quark surface. The electric field which arises from the distribution of electrons exerts a force on a single ion of a normal matter crust. This electric field is capable of supporting some normal crust that overwhelms the gravity. The amount of normal material that can be supported depends on the value of the electrostatic potential at the surface of the quark core of the star. In the presence of a strong magnetic field along z axis, the electron move in a helical path with its axis lying along the z axis. The energy associated with an electron along z axis is quantized in units of $2q_eH$ but for simplicity, we assume that this energy change is continuous. The circular motion in x-y plane is quantized and the total pressure of an electron decreases with the increase of H in view of the Eq. (7). The amount of normal crust matter which *depends on the value of the electron pressure at the surface of quark core* of the star is also reduced. We will show that the electrostatic potential in the close vicinity of the quark core decreases with the increase of H.

In the presence of a constant magnetic field along z axis, the energy of an electron can be written as

$$E_e(z, H) = \mu_e(z, H) - eV(z, H),$$

where z is a space coordinate measuring height above the quark surface of the star. Far outside the star $z \rightarrow \infty$ and $n_e \rightarrow 0, P_e(\infty) \rightarrow 0$, which establishes that $\mu_e(\infty) \rightarrow 0$, implying $eV(\infty) \rightarrow 0$ and dV/dz=0. Thus one can write

$$\frac{\partial E_e}{\partial z} = \frac{\partial}{\partial z}(\mu_e - eV) = 0.$$

Integrating the above equation with z=z to $z = \infty$ one finds

$$\mu_e(z, H) = eV(z, H). \tag{10}$$

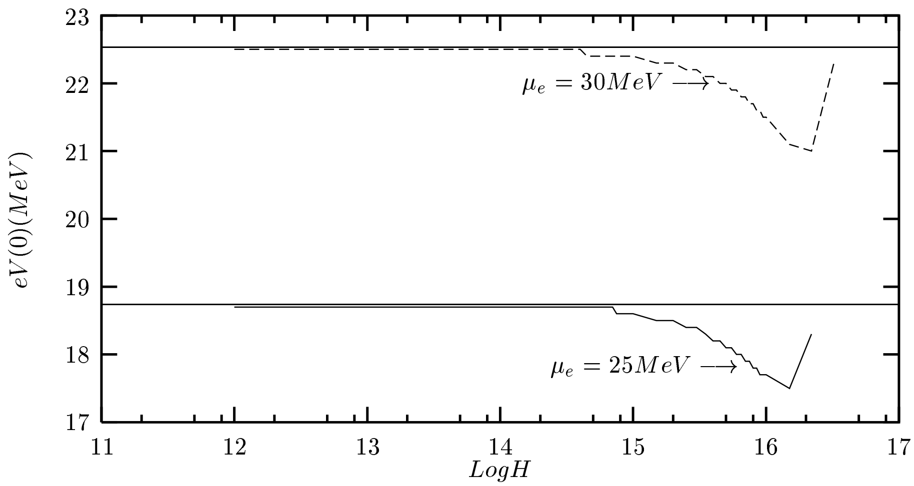

Fig. 2. Electrostatic potential, eV(0) at the surface of the quark core vs. surface magnetic field intensity, H (logscale).The intensity is measured in Gauss. Horizontal lines show the values for magnetic field intensities, $H = 0$.

The local charge distribution generates the potential so that the Poisson equation reads:

$$\frac{\partial^2(eV)}{\partial z^2} + \frac{2}{z}\frac{\partial(eV)}{\partial z} = 4\pi^2(n_e - n_q). \quad (11)$$

The boundary conditions for the above equation are: (1) $z \to -\infty, V(-\infty) = \mu_e, dV/dz = 0$, only quarks are present and the charge neutrality is local (2) $z \to \infty, V(\infty) = 0, dV/dz = 0$, only electrons are present and the charge neutrality is global. The charge neutrality between quark and electron gives

$$\int_{-\infty}^{0} n_q(z)dz = \int_{-\infty}^{\infty} n_e(z)dz. \quad (12)$$

Eq. (12) can be transformed to

$$\int_{-\infty}^{0} n_q(z)dV(z) = \frac{1}{e}\int_{-\infty}^{\infty} \frac{\partial P_e}{\partial \mu_e} d\mu_e \quad (13)$$

The upper boundary condition on the right hand side shows that the electrons extend beyond the surface of the star (z=0). The Eq. (13) can be integrated to give

$$eV(0) - eV(-\infty) = -\frac{P_e(-\infty)}{n_e R_m} \quad (14)$$

In fact $z \to -\infty$ and $z = 0$ differs only by a few hundred fermis (Alcock et al. 1986), therefore, to a very good approximation, we can write the charge neutrality condition as $n_q(-\infty) = n_e$ and $eV(-\infty) = \mu_e$. Using $P_e/n_e = \mu_e/4$, Eq. (14) gives

$$eV(0,H) = \frac{3}{4}\mu_e(0,H), \quad (15)$$

where $\mu_e(0,H)$ is given by the Eq. (9). This equation shows that the electrostatic potential at the surface (z=0) is smaller than the electron chemical potential. The electric field associated with this potential requires a gap of sufficient width between strange matter core and nuclear crust. Neglecting the term $\partial(eV)/\partial z$ in Eq. (11), a straightforward integration gives the *nuclear gap*, $\triangle R$ as

$$\triangle R = C\left[\frac{1}{eV_c} - \frac{4}{3\mu_e(0,H)}\right], \quad (16)$$

where eV_c is the potential at the base of the crust, $C = 5.013 \times 10^3$ MeVfm and $\mu_e(0,H)$ is given by the Eq. (9). For a representative solution with $\mu_e = 30MeV, eV_c = 10MeV, H \sim 10^{14}Gauss$ at the quark surface, the gap width, $\triangle R = 160fm$. The gap width calculated here is comparable to the lattice spacing in the crust which is $\sim 200fm$ for $eV_c = 10MeV$, A=118 and Z=36. The change in the electrostatic potential, $eV(0)$ with the magnetic field is shown in Fig. 2. The amount of nuclear crust mass depends on the electron chemical potential, more precisely, the density at the base of the crust ($\mu_e \sim \rho_{crust}^{1/3}$). The surface density of the quark core, $\rho_s \sim 4B$ ($\sim 4.0 \times 10^{14} gcm^{-3}$, for $B = 60MeVfm^{-3}$) and the density at the base is the density at which neutron drip occurs. The nuclear gap between the crust and the core surface is about 160 fm (Eq. (16)). Therefore, the mass of the crust suspended out of contact with the quark core cannot be treated with the usual problem of solving the Oppenheimer-Volkoff Equations with a given equation of state. We calculate the crust mass by considering the fact that the gravitational force exerted by the quark core on the crust mass is balanced by the electrostatic force given in Eq. (15). A simple calculation gives the crust mass, $\triangle M$ as

$$\triangle M = 3.7509\times 10^{23}\,(gm)\left[\frac{(R/10Km)^4}{M/1.4M_\odot}\right][eV(0,H)]^4. \quad (17)$$

We have plotted the variation of the crust mass with the magnetic field in Fig. 3. The electrostatic potential which is responsible for holding the nuclear crustal mass decreases with the increase of the magnetic field. We find that the reduction is rather strong for our range of the fields, $10^{14} < H < 3.0 \times 10^{16}$ Gauss Fig. 2). One can see from Fig. 3 that the amount of *nuclear crust mass* also decreases with the increase of magnetic field for those range of values. For $\mu_e = 25MeV$, we find that the crust mass decreases by an amount of about 25 percent for order of magnitudes for an increase in the field intensity from zero value to $3.0 \times 10^{16} Gauss$. In Fig. 4, we have plotted the variation of the gap width with the magnetic field for a crust potential, $eV_c = 10MeV$. The gap width is also found to decrease with intensity of the field lying within our range of values.

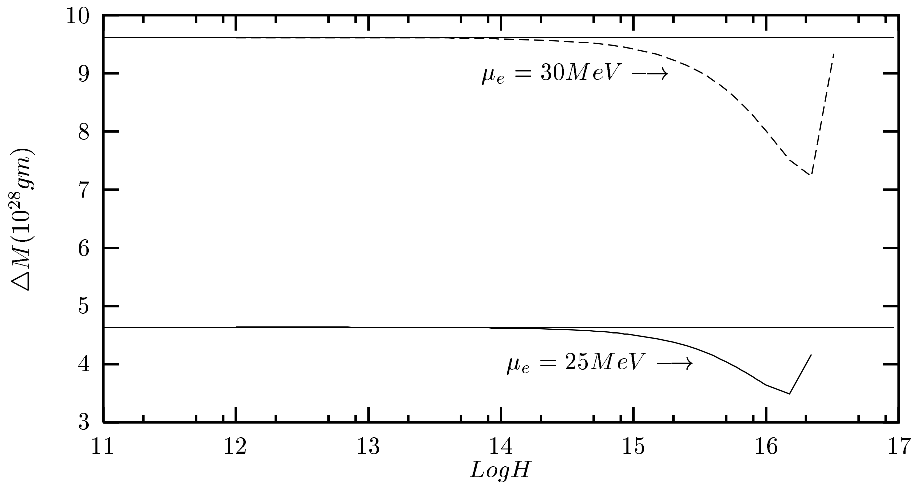

Fig. 3. Nuclear crust mass, $\triangle M$ vs intensity of the magnetic field.

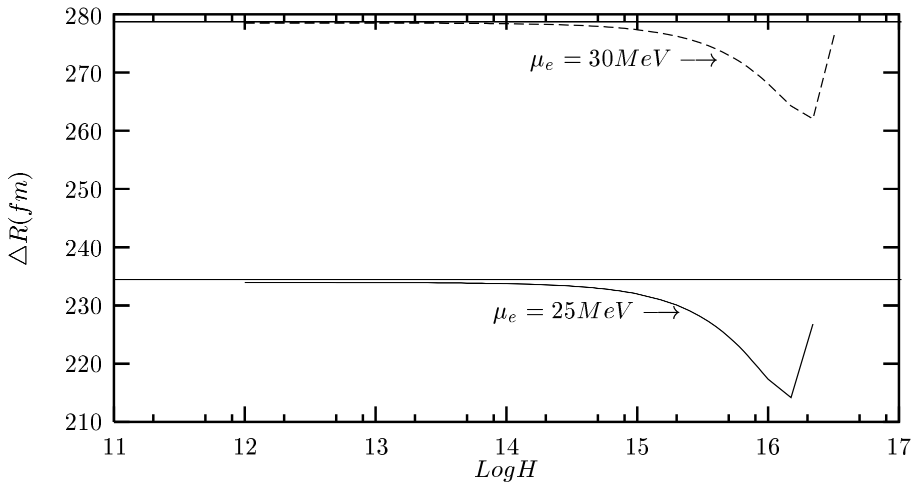

Fig. 4. Crust gap, $\triangle R$ vs. intensity of the magnetic field for $eV_c = 10MeV$.

The stability of the crust is limited by neutron drip point or the absence of the gap (Alcock et al. 1986). The crust mass will be determined by the neutron drip density when $eV(0) > 19MeV, \mu_e > 25MeV$, where μ_e is the electron chemical potential at neutron drip point. Thus our results in models with $\mu_e > 25MeV$ (Fig. 3) are likely to be altered by a more careful choice of the neutron drip point. For $\mu_e = 25MeV$, the minimum crust mass which can be supported by a $1.4M_\odot$ core should not be smaller than $\sim 3.5 \times 10^{28} gm$ for $H \sim 3.0 \times 10^{16} Gauss$ (Fig. 3). For $\mu_e < 25MeV$, the crust mass will be limited by the gap width and the amount of crust mass may be smaller than this value. The transmission probability with which an ion at the base of the crust strikes the gap can be determined from

$$T = exp\left[\frac{\left(\frac{4ZAm_p}{\mu_e}\right)^{1/2} eV_c(\triangle R)}{\hbar c}\right],$$

where μ_e and $\triangle R$ are given by the Eqs. (9) and (16). For A=118, Z=36, $\mu_e = 25MeV$ and $eV_c = 10MeV, T \sim 10^{-106}$ for $H \sim 3.0 \times 10^{16}$ Gauss, it shows the stability of the crust against strong interactions. We find no change in the oscillation frequency for a strange star with magnetic field due to the motion of the center of nuclear crust relative to strange matter core, as first proposed by Broderick et al. (1998). For a strange star at zero magnetic field with $M = 1.4M_\odot$, R=10 Km, $\mu_e = 25MeV, \triangle M \sim 10^{28} gm$, we find $\triangle R \sim 233 fm$ and the oscillation frequency, $\nu_o \sim 250GHz$. If the magnetic field rises to $3.0 \times 10^{16} Gauss$, V(0) falls by about 8% and the change in frequency is almost negligible.

3. Conclusion

In this work we have studied the effect of magnetic field on the existence of nuclear crust for a non-rotating strange star. We find that the electrostatic potential, electron degenerate pressure and the amount of nuclear crust decrease with the magnetic field for a certain range of values. This range, however, *depends on the value of the electron chemical potential at the neutron drip point*. For $\mu_e = 25MeV$, we find that the surface magnetic field, $10^{14} \leq H \leq 3.0 \times 10^{16}$ Gauss can reduce the nuclear crust mass. The magnetic field with intensity lying outside this range does not have any effect on the crust mass. However, if rotation is included, it will contribute to the crust by adding a centrifugal force to the electric intensity and the crust may contain larger amount of nuclear mass (Glendenning and Weber 1992). Therefore, under the joint influence of these two effects the crust thickness may not be as thick as obtained by Glendenning and Weber (1992). In such a case, arguments against the strange star pulsar exhibiting glitches may be stronger (Alpar 1987).

The dipolar magnetic field strengths of isolated pulsars are calculated from the magnetic dipole radiation breaking in the standard way. The recent *ROSAT* data collected for a few radio pulsars have shown that the diploar magnetic field strength, $H_p < 10^{13}$ Gauss (Tsuruta 1998). Should evidence of very high surface magnetic field become available, our model may be useful for at least observational grounds.

If a rotating strange star with very strong surface magnetic field contains thin nuclear crust, it will be very difficult to supply charged particles sufficiently to form a rotating, charged magnetosphere, as first described by Goldreich and Julian (1969). This is due to the fact that the pulsar emission mechanism which depends on the stellar surface as a source of plasma will not work for a very thin surface.

Strong magnetic fields may influence strange star's cooling rates: a thinner crust is less insulating and gives faster cooling of strange star surface during the first few years. This fact can be important for future observations of young compact objects. The results for the reaction rates as a function of magnetic fields are available (Cheng et al. 1994), but the application to strange star's cooling with thin or thick nuclear crust is yet to be done. A model for the X-ray burst phenomenon involving unstable helium burning on the surface of an accreting strange star with nuclear crust may be an interesting problem because its consequences are observable in the form of well separated *flashes*. A model for X-ray burster involving unstable helium burning on an accreting neutron star have already worked out (Wallace et al. 1982). Strong magnetic fields may influence the reaction rates and the consequences of this alteration for the helium flashes have not been explored yet.

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