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Conversion of neutron stars to strange stars in binary systems

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CONVERSION OF NEUTRON STARS TO STRANGE STARS IN BINARY SYSTEMS: Preprint ITEP 92-75/

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I investigate the conversion of neutron star to strange star via the phase transition of neutron matter to two-flavor quark matter. The rate of conversion is calculated. Some manifestations of conversion and formed strange star are discussed.

Fig. - 4, ref. - 17

1 Introduction.

Astrophysical consequences of strange quark matter (SQM) hypothesis [1] are now widely discussed in particle and astrophysical literature. Particular interest is paid to the possible ways of strange matter formation. One of them is the conversion of neutron star to strange star [2]. There are different mechanisms for starting such a conversion and for its proceeding. Here, I explore the possibility that conversion of neutron star starts at the moment when the pressure in the centre of neutron star is increased up to the point of phase transition to two-flavor quark matter.This can happen in binary system, normal star- neutron star, due to accresion of matter on neutron star. The point of phase transition is considered as a free parameter. The only constraint [3] I have imposed on this point is the assumption that some pulsars (especially the pulsars that exhibited glitches) are neutron stars [4] of approximatly $1.4M_{\odot}$ mass. The process of conversion is assumed here to be a slow combustion [2] although fast combustion (detonation) cannot be, in principle, excluded [5, 6]. During the process of conversion, the nuclear matter (composed mainly from neutrons) is transformed to strange matter (composed of approximatly equal number of $u-, d-, s-$ quarks). Strange quarks are produced at the front of conversion by weak interactions. The thickness of transition region is [2] $d = v \times \tau_{\approx}(10 \div 100)\frac{m}{s} \times 10^{-8}s = (10^{-7} \div 10^{-6})m$,where v is the velocity of front propagation and τ is the characteristic time of weak interactions. Because of d is small compared to the size of compact object considered, the transition region does not contribute to the mass,baryon number etc. of converting star. I assume further that nuclear matter before the front and strange matter behind the front are approximatly at zero temperature. The thin layer of hot ($T \sim 30MeV$) strange matter behind the front is assumed to cool down by neutrino emission in a time small compared to the time of star conversion.

Having this scenario in mind, I shall calculate further the rate of neutron star conversion.

In section 2 I discuss the equations of state (EOS) used for description of neutron matter (NM) and quark matter (QM),the physical processes at the burning front and inside the transition region. In section 3 I present the results of solution of stellar structure equation (known as Tolman-Opeenheimer-Volkoff equations [7]) for all intermediate configurations of converting star. Brief discussion and conclusions are presented in section 4.

2 Equations of state and phase transition.

There is a large number of models for NM. Usually they are divided into two parts: with soft EOS and with stiff EOS. The conditions for the phase transition to two-flavor QM (the start of conversion) are rather different in these groups. For soft EOS this phase transition occurs at higher pressures (larger masses of initial neutron star) than for stiff EOS, if we consider the constant B (bag constant) in some physically interesting range of values [3] (this range is defined by the assumption of stability of SQM on the one hand and by assumption of stability of NM against the conversion to two-flavor QM inside $1.4M_{\odot}$ neutron star on the other hand).

For large mass (and correspondingly for large baryon number) of initial neutron star the conversion is unstable because of the maximum baryon number of strange star is lower

than baryon number of initial neutron star [8]. So, the neutron star converts probably to black hole. I would like to exclude this uninteresting for me situation. This is one reason I prefer here the models of NM with stiff EOS.

Another reason is nonmonotomic dependence of ΔP (the difference of pressures in NM and QM) on μ (baryonic chemical potential) in the case of soft EOS for NM [9]. This can result in physically unexpected phase transition picture when with increasing of density NM transforms to QM, back to NM and once more to QM.

In the case of stiff EOS for NM, we don't encounter such unexpected picture. To be more precise let me consider the Relativistic Mean Field (RMF) [10] EOS for NM at densities above $0.19\frac{1}{fm^3}$ and BBP [11] EOS at lower densities. The plot μ_{NM} (baryonic chemical potential)-P_{NM} (pressure) for RMF+BBP EOS is shown on Fig.1. For SQM, let me consider the simplest case: no interaction of quarks ($\alpha_c = 0$), massless $u-, d-, s-$ quarks ($m_s = 0$),zero temperature ($T = 0$). In this case, QM is described by equation

$$P_{QM} = \frac{1}{4\pi^2} \cdot \frac{\mu^4{}_{QM}}{(1 + (1+a)^{\frac{4}{3}} + (1-a)^{\frac{4}{3}})^3} - B, \quad (1)$$

where $a = (n_d - n_s)/(n_d + n_s)$, n_q is the quark number density.

SQM corresponds to $a = 0$, two-flavor QM corresponds to $a = 1$,in transition region from NM to SQM a varies from some a_0 to 1.

At the burning front neutrons can be absorbed by QM if the following equilibrium conditions are fulfilled [12]

$$P_{NM} = P_{QM}, \quad (2)$$

$$\mu_{NM} = \mu_u + 2\mu_d = \mu_{QM} \cdot \frac{1 + 2(1+a_0)^{\frac{1}{3}}}{1 + (1+a_0)^{\frac{4}{3}} + (1-a_0)^{\frac{4}{3}}}. \quad (3)$$

These two equations give the third one from which a_0 can be determined for each value of pressure at the burning front:

$$P_{NM} = \frac{1}{4\pi^2} \cdot \frac{\mu^4{}_{NM}(P_{NM})}{(1 + 2(1+a_0)^{\frac{1}{3}})^4} \cdot (1 + (1+a_0)^{\frac{4}{3}} + (1-a_0)^{\frac{4}{3}}) - B. \quad (4)$$

According to approximate formula of Olinto [2] (corrected by factor 24), the quantity a_0 is simply related to the velocity of front propagation

$$v \approx 2\sqrt{\frac{24a_0{}^4}{2(1-a_0)} \cdot \frac{\mu_u}{T}}(\frac{m}{s}), \quad (5)$$

where T is the temperature inside the transition region (to be defenite I take $T \approx 30MeV$). I use this formula in the paper although more complicated (and rigorous) approach is possible.

The entropy and temperature are generated in the transition region due to nonequilibrium weak reaction of strange quark production

$$u + d \rightarrow u + s.$$

If this process proceeds at constant baryon number density and pressure, then the resulting temperature of transition $QM(a = a_0, T = 0) \rightarrow SQM(a = 1, T \neq 0)$ can be easily evaluated

$$T = \frac{\mu_u}{\pi}\sqrt{\frac{1+(1+a_0)^{\frac{4}{3}}+(1-a_0)^{\frac{4}{3}}-3}{2}} \approx \frac{\sqrt{2}\mu_u a_0}{3\pi}. \qquad (6)$$

In principle, this expression for T can be used in formula (5), but I don't do this because of the lack of understanding the heat transport picture in the converting star. I take the value $T \approx 30MeV$ that is inside the range of possible values of T given by formula (6).

The last point of this section concerns the discussion of SQM cooling behind the conversion front. I have no rigorous calculations of this process. My assumption (used later in calculations of stellar structure) is following. As far as SQM is heated up to $30MeV$, e^+e^- pairs of the same temperature are easily produced. The reactions

$$e^- + u \rightarrow \nu_e + d,$$

$$e^+ + d \rightarrow \bar{\nu}_e + u$$

become the sources of $\nu_e(\bar{\nu}_e)$ neutrinos. These neutrinos (let them call primary neutrinos) are energetic and have the mean free path about $1m$. They heat the matter near the front ($\approx 1m$ in thickness) up to some temperature ($\approx 3 \div 5MeV$). Then, neutrinos of lower energy (secondary neutrinos) are emitted. Presumably, for them the converting star is transparent and they leave the star freely. May be, the third and others steps are necessary. So, the star is permanently cooled by $\nu_e(\bar{\nu}_e)$ of comparetively low energy. I understand that such a scenario of cooling is possible only if the conversion is slow combustion (not detonation) and takes minutes of time (not seconds or fractions of seconds).

3 Evolution of converting star.

The start of neutron star conversion is, by assumption, the point at which the pressure in the centre of neutron star becomes critical for phase transition of NM to two-flavor QM. This critical pressure depends on constant B. I have assumed that critical pressure corresponds to neutron star of $1.58M_\odot$ (for example) and calculated the constant $B(B = 76\frac{MeV}{fm^3})$. At such B the SQM is self-bound with binding energy

$$\epsilon_c = -51MeV$$

After the phase transition in the centre of neutron star, the conversion process starts. In the process of convesion, the only conserved quantity is the baryon number of the star. The conservation of baryon number allows to calculate the structure of all intermediate configurations of converting star [8]. On Fig.2 the process of conversion is presented in the form of some number of curves. Each curve represents the dependence of baryon number of object with fixed baryon number in SQM core on central pressure. The left point on horisontal line $N_B = 2.12 \cdot 10^{57}$ corresponds to initial neutron star, the right point - to final strange star. During the conversion the central pressure is increased, the mass of the star and its radius are decreased. The evolution of mass and radius is shown on Fig.3. All the mass (energy) difference is emitted by neutrinos. Due to the change of radius and the moment of inertia, the star should exhibit a superglitch phenomenon (if

this star is observed as a pulsar). Finally, on Fig.4 the growth of the front radius as a function of time is shown. I have not taken into account the outer crust of neutron star. That is why the conversion is here complete. In principle, if we consider the outer crust, some part of it could survive and form the crust of strange star [13].
All the conversion takes about two minutes.

4 Discussion and conclusion.

I have considered one of the possible scenarios of neutron star conversion to strange star. In this scenario, conversion takes place in binary system with accretion where the mass and central pressure of neutron star grows up to the critical point. If neutron star has born with mass $\sim 1.4M_\odot$ and critical mass is $\sim 1.6M_\odot$ and rate of accretion $\dot{M}$ is $\sim 2 \cdot 10^{-8} M_\odot yr^{-1}$ [14], then at the critical point neutron star is $10^7 yr$ old. Due to accretion neutron star can spin-up its rotation [15]. So, pulsars that lie near the spin-up line on $\dot{P}, P$ plot are the systems where proposed conversion could happen. In fact, some of them could be strange stars.[1] It is known that these pulsars are very quiet ones: the period P has small micropulsations [16]. If micropulsations of pulsars are due to superfluidity [17] of inner crust of neutron star, then quiet pulsars can be assumed to have no superfluid layers. This is the case of strange star.

In my approach the conversion has two visible manifestations: the superglitch and neutrino signal. May be there are others.

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[1] The following argument was proposed by O.Benvenuto is private discussion.

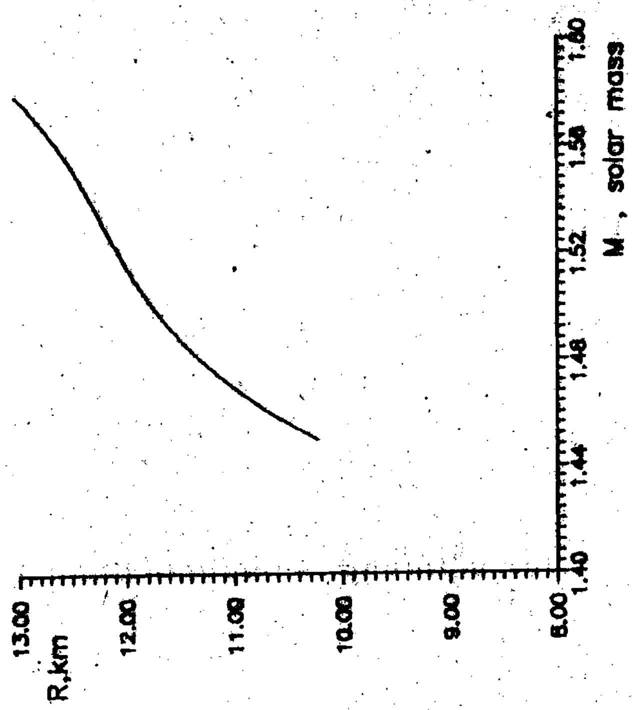

Fig.3. Variation of mass and radius of converting star (from up to down).

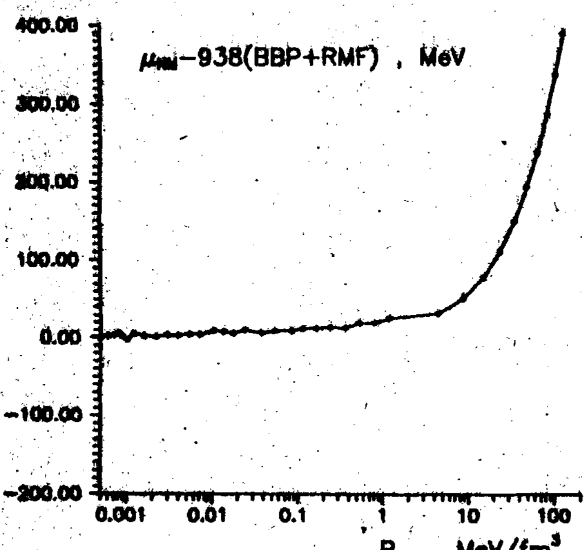

Fig.1. The dependence of baryon chemical potential on pressure for nuclear matter described by BBP+RMF EOS.

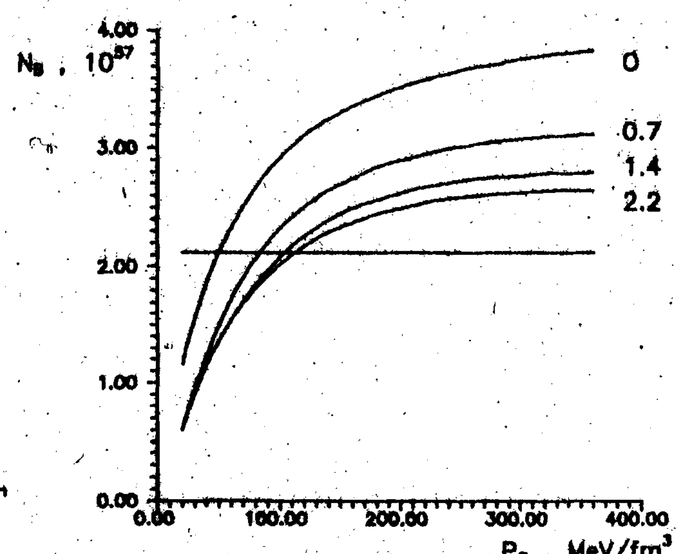

Fig.2. The dependence of baryon number on central pressure for mixed star with different baryon number in strange matter core.

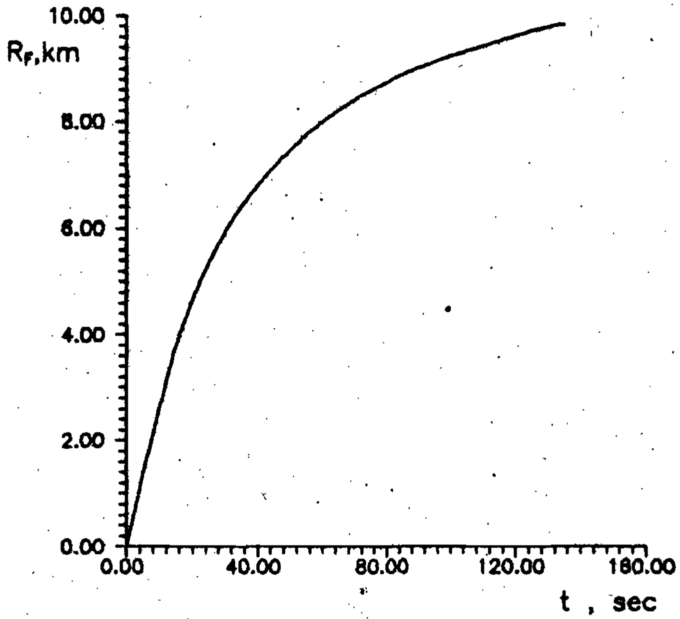

Fig.4. The growth of radius of burning front with time.

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