Neutrino sparking and the neutron→strange stars conversion

J. E. Horvath
Instituto Astronômico e Geofísico, Universidade de São Paulo, Avenida M. Stéfano 4200, Agua Funda, 04301-904 São Paulo, SP Brazil

H. Vucetich
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, 1900 La Plata, Argentina
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We address the production of strangelets inside neutron stars by means of high-energy neutrino interactions (sparking). Requiring that neutron stars remain as such along their lifetimes, we obtain a bound on the probability of a strangelet in the final state and compare it with existing laboratory limits. It turns out that this mechanism is not likely to drive a neutron→strange stars conversion for realistic values of the minimum center-mass-energy necessary to produce the quark-gluon plasma, a necessary precondition for the formation of the strangelet. [S0556-2821(99)01602-1]

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I. INTRODUCTION

A great deal of attention has been recently devoted to the astrophysical consequences of the strange quark matter (SQM) hypothesis [1]. Work on different aspects of the birth, structure and evolution of compact strange stars is being done with the aim of predicting signatures which may indicate the actual existence of this class of objects (see, for example, the reviews [2,3,4]).

As SQM is a low-entropy configuration, quark gas is not a lower free energy state than a nucleon gas at intermediate temperatures. Compression (i.e. baryochemical potential $\mu \neq 0$) is therefore needed to compensate the $-TS$ term in the free energy if SQM is to be preferred to nuclear matter (NM) at $T > 2$ MeV [2]. These are precisely the physical conditions generally believed to exist in young proto-neutron stars [5] immediately after the passage of the prompt hydrodynamical shock in type II supernovae, i.e. inside the Kelvin-Helmholtz epoch of the compact object life. Therefore SQM may play a key role in the very type II supernova events as subnuclear energy is released from the conversion of neutron to strange matter. This process should result in an explosive transient mediated by a detonation front [6,7], a phenomenon that would be important for the fate of the collapsed star. Additional work [8,9] proved that this conjecture is worth studying in further detail.

A prompt conversion would need the presence of a ''dormant'' strangelet [10–13] or the nucleation of one [10,11,14]. Neither possibility is excluded, but also they are not guaranteed. For instance, it has been suggested that strong magnetic fields preclude SQM nucleation [15]; therefore it is interesting to explore other alternative mechanisms [10,11]. Generally speaking, these conversion mechanisms have been divided into primary (those in which strangelets are produced inside the star) and secondary (in which strangelets come from outside).

We shall discuss in the present work the appearance of SQM inside degenerate NM characteristic of neutron stars triggered by neutrino sparking. To the best of our knowledge this scenario has not been addressed in any detail after the proposal by Alcock *et al.* [10] In Sec. II we present the relevant neutrino fluxes and cross-sections to this problem. A rough calculation of the strangelet production rate is given in Sec. III. Finally, a brief discussion and conclusions are presented in Sec. IV.

II. HIGH-ENERGY NEUTRINOS

The total cross-sections of neutrinos onto nucleons have been recently recomputed by Gandhi *et al.* [16] using updated parton distributions in the Altarelli-Parisi framework. They incorporate the latest data from the DESY ep collider HERA which goes deeply inside the inelastic regime up to $x \leqslant 10^{-4}$. Since we are interested in reactions of the type $\nu N \rightarrow$anything, we shall employ an ''all process'' version of the cross sections σ given in [16] and valid above a minimum energy $E_0 = 1$ GeV:

$$10^{-38}\left(\frac{E_\nu}{1\ \text{GeV}}\right)\ \text{cm}^2, \quad 1\ \text{GeV} < E_\nu < 10^6\ \text{GeV}, \quad (1)$$

$$10^{-36}\left(\frac{E_\nu}{1\ \text{GeV}}\right)^{0.4}\ \text{cm}^2, \quad 10^6\ \text{GeV} < E_\nu < 10^{12}\ \text{GeV}. \quad (2)$$

We shall be concerned with inelastic reactions initiated by all neutrino flavors. Even though there is considerable uncertainty in the actual contribution to the fluxes from various sources, we shall see that our final results are largely insensitive to the precise value. As in Gandhi *et al.* [16] we shall adopt the (conservative) differential neutrino fluxes dN_ν/dE_ν:

$$10^{-6}\left(\frac{E_\nu}{1\ \text{GeV}}\right)^{-2}\ \text{GeV}^{-1}\,\text{cm}^2\,\text{sr s}^{-1}, \quad E_\nu < 10^6\ \text{GeV}. \quad (3)$$

$$10\left(\frac{E_\nu}{1\ \text{GeV}}\right)^{-3.5}\ \text{GeV}^{-1}\,\text{cm}^2\,\text{sr s}^{-1}, \quad E_\nu > 10^6\ \text{GeV}. \quad (4)$$

Actually we shall see in the next section that only the first range is relevant for our problem and that a rougher estimate than Eqs. (1)–(4) would have sufficed.

III. STRANGELET PRODUCTION RATE

We wish to address the number of neutrino events that produce a strangelet in the final state inside the neutron star. The interesting stellar region is that above the neutron drip point ($\rho_D \simeq 4\times 10^{11}$ g cm^{-3}), since a strangelet could be even produced in the outer shells (nuclear lattice) *without* necessarily triggering the full conversion of the star. Free neutrons do not feel the strangelet Coulomb barrier ($\sim 10-20$ MeV) and guarantee the growth and eventually the full burning, justifying the focusing on the condition $\rho_{reaction} > \rho_D$. We may say that the outer crust acts as a shield against harmful strangelet-producing neutrino reactions. If we assume an exponential decrease of the outer crust from the drip point up to the surface as a reasonable approximation, the optical depth of the outer crust is

$$\tau(E_\nu) = \sigma(E_\nu)\overline{n}\delta r, \tag{5}$$

where $\overline{n} = n_D/4$ and $\delta r \sim 100$ m is the minimal width of this region taken from model calculations.

Let us define the probability of a strangelet production in the final state (i.e. the ''anything'' of the neutrino interaction) in the $\rho > \rho_D$ region as $P_{prod} = P_{QG}\times P_s$, where P_{QG} is the probability of a quark-gluon plasma formation and P_s is the probability of distilling (that is, fragmenting into a reasonable size, separating strangeness from antistrangeness and cooling to the ground state [17]; see also [18] for a through discussion of the physics of the process) a strangelet out of the pre-existing quark-gluon plasma (QCP). We have assumed the simple parametrized expressions $P_{QG} = \Theta(E_\nu - E^{min})$ and $P_s =$ const in our calculation (see Ref. [18] and below). Here E^{min} is the minimum neutrino energy in the laboratory frame which would yield enough energy density in the center-of-mass to produce the quark-gluon plasma (which is probably not less than a few GeV/fm^{-3} [19]). The strangelet production rate in this approximation is simply

$$\xi = 4\pi R_{NS}^2 \int_{E_0}^{\infty} P_{prod}(E_\nu)\, \frac{dN_\nu}{dE_\nu} \exp[-\tau(E_\nu)] dE_\nu. \tag{6}$$

An approximate integration of Eq. (6) yields the result

$$\xi \simeq 4\pi 10^4 P_s \exp(-10\,\delta_{100} E_{GeV}^{min}) \times (E_{GeV}^{min})^{-2} \delta_{100}^{-1}; \tag{7}$$

where we have defined $\delta_{100} \equiv (\delta r/100\ \mathrm{m})$ and $E_{GeV}^{min} \equiv E^{min}/\mathrm{GeV}$. If we want that neutron stars remain as such along their lives τ, we shall demand the product to be $\xi\overline{\tau} < 1$ or (adopting a neutron star mean age of $\overline{\tau} = 1$ Myr) that P_s satisfies the bound

$$P_s < 6\times 10^{-15} \delta_{100} \times (E_{GeV}^{min})^2 \exp(10\,\delta_{100} E_{GeV}^{min}). \tag{8}$$

For reference, an upper bound on the strangelet production rate $P_{prod} \sim 10^{-10}$ has been derived from data in heavy ion collisions [19] at ultrarelativistic center-of-mass energies. The main uncertainty of our estimate is the actual value E^{min}. However, for the reactions at energies substantially higher than 1 GeV, the strangelet production is exponentially suppressed by the opacity of the crust and the conversions cannot be triggered by sparking. We note in passing that this fact justifies the approximation $P_s =$ const made in Eqs. (6)–(8). In other words, that the exact energy dependence of P_s is irrelevant for our considerations.

IV. DISCUSSION AND CONCLUSIONS

We have estimated the strangelet production rate inside neutron stars using a simple scheme for understanding that process. Given its production, the details of a quark-gluon fireball production and further evolution are quite complicated as discussed in Refs. [17,18]. The additional complication of the fireball evolution being not in vacuum but in dense matter should not really change the situation too much because the thermal pressure of the fireball is expected to exceed the sum of the vacuum pressure and external pressures. However, the main result of this calculation is that neutrino sparking is *not* likely to be an effective mechanism for the conversions unless the minimum neutrino energy for the production of the quark-gluon plasma happens to be very low in the stellar environment. Only if that minimum is ~ 1 GeV is the astrophysical bound on P_s better than the heavy ion one [19] and there is a possibility maintaining neutron stars as such without conflicting with laboratory limits. For E^{min} as low as $\simeq 3$ GeV an effective sparking mechanism would require $P_s \sim 1$, which is clearly ruled out. At even higher energies neutrinos would eventually reach the required threshold, but in this case they will be completely stopped in the outer crust [see Eq. (8)]. Since no QGP signature is seen in deeply inelastic scattering experiments at energies much greater than $E_\nu \gg 1$ GeV, we conclude that the process is never effective in converting neutron stars into strange stars.

It should be kept in mind that the discussed scenario is not the only one which can give rise to strangelets in neutron stars. Conversion via two-flavor quark matter formation [10] and the presence of strangelets in the supernova progenitor becoming active after neutronization [12,13] are likely alternatives (and there may be another one as well; see [11]). We conclude that, as long as neutrino sparking goes, the case for a mixed neutron star–strange star population seems to be weak.

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