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Improbability of DUrca Process Constraints EOS *

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Abstract According to recent observational and theoretical progresses, the DUrca process (direct Urca process) may be excluded from the category of neutron star cooling mechanisms. This result, combined with the latest nuclear symmetry energy experiments, will provide us an independent way of testing the EOS (equation of state) for supernuclear density. For example, soft EOSs, such as FPS, will probably be excluded.

Key words: equation of state — neutrinos — stars: neutron

1 INTRODUCTION

Ever since 1965, the MUrca process (Modified Urca process) has become a standard cooling mechanism of neutron stars (Bahcall & Wolf 1965; Yakovlev et al. 2001; Page, Geppert & Weber 2006). This was not changed until the 1980s, when Boguta (1981) argued that the DUrca process (direct Urca process) is possible in a relativistic nuclear theory. Lattimer et al. (1991) made a thorough investigation of the nucleon and hyperon DUrca process (Prakash et al. 1992; Pethick 1992). According to their research, the critical density of the DUrca process is determined by the nuclear symmetry energy. If the central density of a neutron star is above that density, then it will cool via the DUrca process, which is much faster than the MUrca process. Now, for a given neutron star, its central density is determined by the EOS (equation of state). This means that any information about the DUrca process will provide us an independent way of knowing something about the EOS of the neutron star core. Its use was only prospective in the 1990s but there have been dramatic changes recently.

Tsuruta's group has made systematic comparisons between the observations and theories of neutron star cooling. In their view, nucleon DUrca process as well as kaon ones can already be excluded (Tsuruta et al. 2002; Tsuruta 2004, 2006). Thus if one EOS permits DUrca process, then it will probably be excluded. The improbability of DUrca process provides us an independent way of testing the EOS. There has also been tremendous progress on nuclear symmetry energy (Li & Chen 2005; Chen et al. 2005; Li et al. 2006). These two joined together give us deep insight into the EOS of the core of neutron star. For example, soft EOS such as FPS may be excluded. Before looking into the EOS, we will review some details about the DUrca process.

2 THE DURCA PROCESS

Several minutes after a neutron star is born, it enters the neutrino cooling epoch. DUrca process is the simplest neutrino emission process (Gamow & Schoenberg 1941; Pethick 1992). It is simply decay of neutrons and successive electron captures,

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu}\,, \\ p + e^- &\rightarrow n + \nu\,. \end{aligned} \tag{1}$$

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Whereas, if another nucleon is present as a bystander particle, the process will be traditional MUrca (Chiu & Salpeter 1964; Bahcall & Wolf 1965; Yakovlev et al. 2001). Since MUrca involves two additional fermions, it is 5–6 orders slower than DUrca. The MUrca process can proceed without difficulty, conserving both energy and momentum, of course, at the cost of a slower rate. For the DUrca process to occur, there is a minimal proton concentration x in order to meet the momentum conservation condition. We will follow Lattimer's treatment here.

The momentum of the emitted neutrinos and antineutrinos is of order $k\,T/c$, where T is the neutron star's internal temperature taken to be 10^{10} K. While the typical Fermi momentum is of the general order of 100 MeV. Thus, the momentum conservation condition is $p_{F_p} + p_{F_e} > p_{F_n}$. Noting that $n_i \propto p_{F_i}^3$, for a $n\,p\,e$ matter, $n_p = n_e$ as a consequence of charge neutrality, or $p_{F_p} = p_{F_e}$. So, the momentum conservation becomes $2\,p_{F_p} > p_{F_n}$, or $n_p > 1/8 n_n$. We define the proton concentration as $x = \frac{n_p}{n_p + n_n}$. Therefore, we obtain the threshold for the DUrca process to proceed, $x \geq 1/9$. If the proton concentration exceeds that threshold, a neutron star will cool rapidly via the DUrca process.

For a neutron star, the actual proton concentration is determined by microscopic interactions such as the isospin dependent part of the three body interaction. Nuclear symmetry energy is well among the list. With a schematic model, the energy per baryon can be expanded quadratically around the symmetry value $x = 1/2$,

$$\epsilon(n, x) = \epsilon\left(n, \frac{1}{2}\right) + S_v(n)(1 - 2\,x)^2 + \cdots\,, \tag{2}$$

where n is the number density of the baryons and $S_v(n)$ is the bulk symmetry energy. The above expansion is a good approximation for all x, at any density (Lattimer et al. 1991, and reference therein).

We are considering a system in β equilibrium, the chemical potentials of the fermions have the relation (Shapiro & Teukolsky 1983)

$$\mu_e = \mu_n - \mu_p = -\frac{\partial \epsilon}{\partial x}\,,$$

where μ_i stands for the chemical potential of the i th Fermi system. Substitute the above expansion of the energy, we obtain the equation which determines the equilibrium proton concentration,

$$\hbar c (3\pi^2 n x)^{1/3} = 4 S_v(n)(1 - 2x)\,. \tag{3}$$

We may adopt a power law nuclear symmetry energy,

$$S_v = S_0 \left(\tfrac{n}{n_s}\right)^q\,, \tag{4}$$

where S_0 is the bulk symmetry energy at nuclear saturation density $n_s = 0.16\,\mathrm{fm}^{-3}$.

A power law symmetry energy has recently been demonstrated by nuclear diffusion experiments at subnuclear density (Li & Chen 2005; Chen et al. 2005). So we are on the edge to see if there is DUrca process in the interior of neutron stars. Corresponding to the minimum proton concentration, the critical density is

$$\frac{n_c}{n_s} = \left[1.71(30\,\mathrm{MeV})/S_0\right]^{1/(q-1/3)}\,, \tag{5}$$

where n_c is the critical number density corresponding to setting $x = x_c = \frac{1}{9}$. For a conservative consideration (Li et al. 2006),

$$32\,\mathrm{MeV}(n/n_s)^{0.7} < S_v < 32\,\mathrm{MeV}(n/n_s)^{1.1}. \tag{6}$$

The selected values of n_c are given in Table 1.

Table 1 DUrca Process Critical Density for Different Values of q

q	0.7	0.8	0.9	1.0	1.1
n_c/n_s	3.62	2.75	2.30	2.03	1.85
n_c (fm^{-3})	0.58	0.44	0.37	0.32	0.30

Combined with the EOS, we can assess whether there is DUrca process in the interior of neutron stars, but whether or not it is present can only be inferred from neutron star cooling observations. That is the subject of the next section.

3 THE IMPROBABILITY OF DURCA

In a series of papers, Tsuruta et al. (2002) have stated clearly their conclusions (e.g. Tsuruta 2004, 2006), which can be summarized into the following three points:

1. Soft EOS, such as BPS, should be excluded from neutron star mass measurements.
2. Nucleon and kaon DUrca process should be excluded especially for the Vela data.
3. Pion cooling is consistent with both observation and theory.

A graphical summary is given in Figure 1.

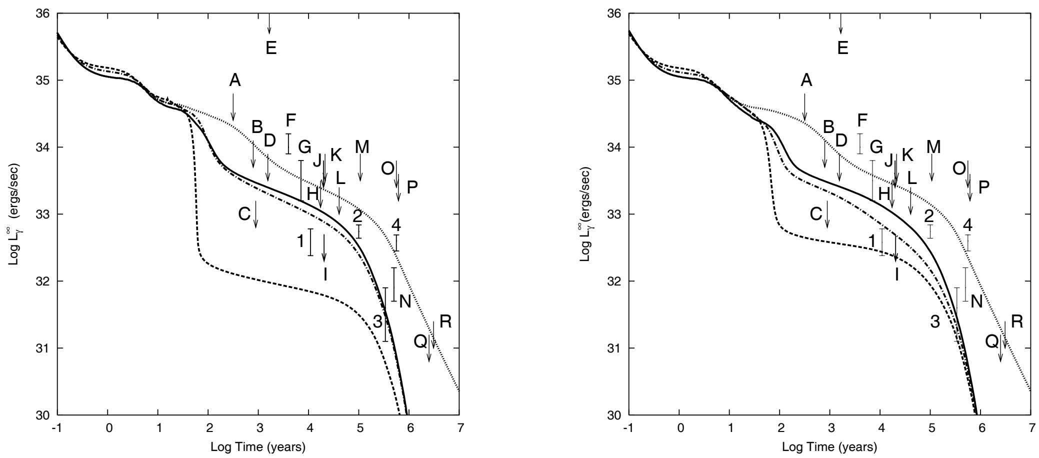

Fig. 1 Thermal evolution curves from Tsuruta (2006). In the left panel, the dotted and solid curves refer to the standard cooling of $M = 1.4\,M_\odot$ neutron stars with and without heating, respectively, and the dot-dashed and dashed curves are for hyperon cooling of 1.6 and 1.8 $M_\odot$ stars, respectively. In the right panel, the solid, dot-dashed and dashed curves refer to pion cooling of 1.4, 1.6 and 1.8 $M_\odot$ stars, respectively. In the same figure the dotted curve refers to thermal evolution of a 1.4 $M_\odot$ pion star with heating. The temperature detection data with error bars are shown with their error bars, while the downward arrows refer to the upper limits. The most accurate detection data are numbered thus: (1) the Vela pulsar, (2) PSR 0656+14, (3) Geminga, and (4) PSR 1055–52. The rest are less accurate estimates. Some of the more interesting among these are shown with letters, (A) Cas A point source, (B) the Crab pulsar, (C) PSR J0205+6449 in 3C58, (F) RX J0822–4300, (G) 1E1207.4–5209, (I) PSR 1046–58, (N) RX J1856–3754, and (R) PSR 1929+10 (©By permission of the author).

Lattimer & Prakash (2006) have also made a survey of the mass-radius relation for neutron stars. Their result for the Tsuruta data is that the surviving EOSs all support large masses. Recently, Özel (2006) has analysed the neutron star EXO 0748–676. From its stringent mass radius relation, only the stiffest EOSs are consistent with the measurement. Conservatively, we consider both the medium and stiff EOSs from now on. Using point 2 of Tsuruta's conclusion, neutron star cooling could provide us an independent way of testing the EOS.

Following the above discussion on the DUrca process, we can calculate the critical mass for a specific EOS, above which the DUrca process will be turned on in the interior of the neutron star. If the critical mass is less than $1.4\,M_\odot$, then the EOS can probably be excluded. Table 2 gives the critical masses calculated for the different EOSs.

The critical mass is given in units of $M_\odot$. FPS (Friedman Pandharipande Skyrme) and SLy (Skyrme Lyon effective interaction) are EOSs taken from Haensel & Potekhin (2004). RMF means relativistic mean field theory. The values 210, 240 and 300 are the compression modulus values. They are taken from Ma (2002) and Glendenning (1997). The EOSs TNI2u, TNI6u, TNI3u (Three Nucleon Interaction, u stands

Table 2 DUrca Critical Mass for Different EOS

q	0.7	0.8	0.9	1.0	1.1
FPS	1.18	0.84	0.64	0.50	0.45
SLy	1.50	1.09	0.84	0.65	0.58
RMF210	1.27	1.16	1.07	0.98	0.93
RMF240	1.40	1.26	1.16	1.05	0.99
RMF300	1.55	1.40	1.28	1.16	1.09
TNI2u	1.01	0.76	0.61	0.50	0.46
TNI6u	1.24	0.94	0.76	0.62	0.56
TNI3u	1.40	1.07	0.86	0.69	0.62

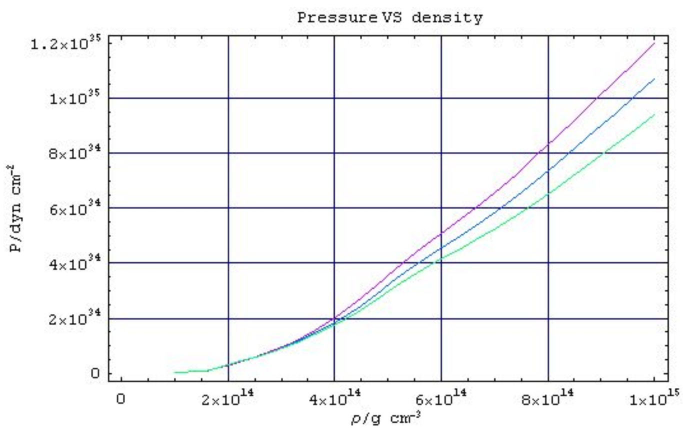

Fig. 2 EOS for RMF210, RMF240 and RMF300, from the bottom up. The behavior of TNI2u, TNI6u and TNI3u is similar.

for universal inclusion) are taken from Takatsuka et al. (2006), from which the Tsuruta group derived their conclusions. For a comparison of the EOSs, see Figure 2.

When the critical mass is less than $1.4\ M_\odot$, a normal neutron star will cool via the rapid DUrca process. Of course, this is in contradiction to Tsuruta's conclusions. So, soft EOS, such as FPS, RMF210, TNI2u, may be excluded. Even medium soft EOS TNI6u is in danger.

On the other hand, some of the stiff EOS, such SLy, RMF300, do meet the improbability of the DUrca process, with a tendency for smaller q values (Li & Chen 2005). A smaller q value, 0.7 or 0.8, say, satisfies better the astronomical requirement. This may be tested by further measurement of nuclear symmetry energy, but it may take many years.

Excluding the soft EOSs is consistent with Tsuruta (2006) and Lattimer & Prakash (2006). Our result can also be compared with Özel (2006). In the case of neutron star cooling, not only the stiffness of the EOS, but also the composition, is a determining factor. The key point is, we present an independent way of testing the EOS, from the improbability of DUrca process. Following this treatment, we can separate the more likely EOSs from the less likely ones.

4 DISCUSSION

Four points are to be noted:

1. The presence of muon. When we include muons in our consideration, we obtain a larger minimal proton concentration and a smaller critical density (Lattimer et al. 1991). So the exclusion of soft EOSs is strengthened.
2. About hyperons. The hyperon DUrca process only adds to the more effective nucleon DUrca process (Prakash et al. 1992). Whether it exists in the neutron star interior is still an open question (Takatsuka et al. 2006).
3. The consistency problem. The symmetry energy here is an extrapolation of subnuclear density experiment. When we choose a particular form of the symmetry energy, we also fix the EOS to some degree.

Maybe by combining with compression modulus data, one can make a more consistent calculation, but it will not concern us here: it would be an independent way of testing the EOS.

4. The presence of quark matter. In this case, things will be more complicated (see general discussion by Pan & Zheng 2007). First, the threshold of the quark DUrca process is not just a simple ingredient fraction: the quark-quark interaction must be taken into account (Pethick 1992). Second, the cooling scenario in the presence of quark matter contains some considerable difference from a neutron star (Page 2006). Moreover, deconfinement heating must be included (Yuan & Zhang 1999; Kang & Zheng 2007). Since Tsuruta's exclusion of DUrca process is done in the frame of necleon processes, plus pion and kaon condensation. If we want to extrapolate our conclusions here, e.g. to hybrid stars, it will be a systematic project that will provide scope of further studies.

Excluding soft EOSs is a general tendency of neutron star researches. The preference of smaller q values needs further study. As Lattimer said 16 years ago, the continuing attempts to observe thermal radiation from neutron stars will have important implications for these properties of nuclear matter. That is what we try to do here.

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