Limit on Neutrino Emission from Neutron Stars

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Abstract

The timing data of the binary pulsar PSR1913+16, are used to establish an upper limit on the rate of neutrino emission from neutron stars. Neutrino emission from each of the neutron stars of the binary system, translates to a decrease in their masses. This in turn implies an increase with time of the binary period. Using the pulsar data we obtain an upper limit on the allowed rate of mass reduction : $|\dot{M}| < 1.2 \times 10^{-12} \text{yr}^{-1} M$, where $M$ is the total mass of the binary. This constrains exotic nuclear equations of state that predict neutrino emissions. It also sets limits on the expected contribution of such processes to the cosmic diffuse background flux of neutrinos.

\textit{keywords:} neutrinos - neutron stars - nuclear matter - pulsars
I. INTRODUCTION

Neutron stars form via the core collapse of massive stars. Most of the gravitational energy
(\approx 0.15M_{\text{core}}c^2 \approx 3 \times 10^{53} \text{ erg} ) is emitted during the first $O(20)$ seconds via $O(10-20) MeV$
neutrinos, from the neutrino-sphere of the proto neutron star, of temperature $T \approx \text{few}$
MeV. This old prediction was experimentally verified in the neutrino pulses from SN 1987A
observed at IMB and Kamiokande underground detectors. Further cooling of the neutron
star via neutrino emission is likely to continue for a long time. A famous cooling mechanism
is the URCA two-step process:

\[ n \rightarrow p + e^- + \bar{\nu}_e; \quad e^- + p \rightarrow n + \nu_e \]

or it’s modified more relevant version:

\[ n + n \rightarrow n + p + e^- + \bar{\nu}_e; \quad n + p + e^- \rightarrow n + n + \nu_e \]

which amounts to $\nu_e + \bar{\nu} - e$ emission from a pair of neutrons.

An estimate of the rate for the latter is quoted in Shapiro and Teukolsky (1983)\cite{1}:

\[ L_{\nu}^{\text{URCA}} \sim 2 \times 10^{40} \text{erg/s M}_\odot \left( \frac{\rho_{\text{nuc}}}{\rho} \right)^3 \left( \frac{T}{100 \text{KeV}} \right)^8 \]

The neutrino luminosity has a weak dependence of factors $O(1)$ on the mass and density
of the star but varies as the eight power of the temperature. Furthermore, the rate of late
$\nu$ emission may strongly vary manifesting novel physics effects.

Is there any physically measured quantity which can indicate such late neutrino emission?

The surface temperature of neutron stars can be estimated using electromagnetic radia-
tions therefrom. It is not clear if the rather low temperatures thus inferred are relevant also
for the $\text{volume}$ emission of neutrinos. Further one may envision genuine $\text{T} = 0$, instabilities
of neutron stars.

It has been noted that the diffuse integrated neutrino luminosity due to all cosmological
supernovae may become observable in future large detectors \cite{2}. The total energies emitted
via the late neutrinos are lower than in the corresponding supernovae. Also the energies
are likely to be lower diminishing the cross section $\sigma(\nu - \text{Nucleon}) \propto E_\nu^2$. Jointly this then
makes the cumulative effect of late emission unobservable.
Recent observations of high energy nuclear phenomena [3], [4] have found strong neutron-proton correlations. This in turn can motivate non-standard nuclear-matter models [5] which imply that neutron stars should continuously emit neutrinos.

In the present work we wish to set observational limits on such and similar processes. The continuous emission of neutrinos will lead to the reduction of the mass of the neutron star. If the neutron star is a member of a stellar binary system, such a reduction will cause, as detailed below, an increase with time of the stellar binary period. In this short paper we employ the timing data of the binary pulsar PSR1913 +16 to set an upper limit on the rate of mass reduction in this system. This limit translates to a limit on the neutrino number luminosity for a given energy distribution.

II. BINARY ORBITAL PERIOD CHANGE DUE TO NEUTRINO EMISSION

Jeans (1924) [6], pointed out that the mass of the star that emits electromagnetic radiation decreases with time and therefore the orbital elements of a binary system should evolve with time. Assuming that in the local frame of each star the radiation emission is spherically symmetric, he obtained

\[ Ma = \text{constant} \] (1)

where \( a \) is the semi-major axis and \( M = m_1 + m_2 \) is the total mass of the system. This and the expression for the binary period

\[ P_b = 2\pi \sqrt{\frac{a^3}{GM}} \] (2)

imply

\[ \frac{\dot{P}_b}{P_b} = -2\frac{\dot{M}}{M} \] (3)

Since \( \dot{M} < 0 \) the time derivative of the orbital period is positive: \( \dot{P}_b > 0 \).

Except for the identity of emission process this is the same as the question addressed here.

We wish to use the limits on the residual rate of change of the orbital period of the binary pulsar PSR1913+16, after accounting for the rate due to emission of gravitational radiation,
to set a limit on the rate of mass decrease due to neutrino emission.

The timing data of PSR1913+16\textsuperscript{[7], [8]} are listed below. The first two are the observed binary period, and the observed time-derivative of the binary period, corrected for effects of the acceleration due to the Galaxy. The third is the predicted time-derivative of the binary period due to emission of gravitational radiation.

\begin{align*}
P_b &= 0.322997\, \text{Day} = 27907\, \text{s} \quad (4) \\
\dot{P}_{b,\text{Corrected}} &= \dot{P}_{b,\text{Obs}} - \dot{P}_{b,\text{Galaxy}} = -(2.4056 \pm 0.0051) \times 10^{-12} \quad (5) \\
\dot{P}_{b,\text{GR}} &= -(2.40242 \pm 0.00002) \times 10^{-12} \quad (6)
\end{align*}

so that the unaccounted for time-derivative of the binary period is

\[ \dot{P}_{b,\text{residual}} = \dot{P}_{b,\text{Corrected}} - \dot{P}_{b,\text{GR}} = (-3.2 \pm 5.3) \times 10^{-15} \quad (7) \]

yielding

\[ \frac{1}{P_b} \dot{P}_{b,\text{residual}} = (-3.6 \pm 6) \times 10^{-12} \, \text{yr}^{-1} \quad (8) \]

Therefore the timing data of PSR 1913+16 impose an upper limit on the mass equivalent emitted by the neutrinos

\[ \frac{\dot{M}}{M} \leq 1.2 \times 10^{-12} \, \text{yr}^{-1} \quad (9) \]

Continued timing measurements of additional binary pulsars, notably the double pulsar PSR J0737-3039, could hopefully yield a stronger limit.

In general, the expected mass loss rates of the pulsars due to standard processes, is much smaller than the above value. Indeed in discussing their historic measurements which tested general relativity and the expected gravitational radiation with high precision, Hulse and Taylor noted that the standard mass loss expected is only: \( \frac{|\dot{M}|}{M} \leq 10^{-17} \, \text{yr}^{-1} \) far smaller than the above. (This is excepted for the URCA rates above if a reasonable bound of 5 Kev is imposed on the temperature.) However the relatively stringent bound (9) may still be useful in ruling out some non-conventional neutron star models.

\section*{III. SUMMARY AND CONCLUSIONS}

This note has been motivated by the observation of Leonid Frankfurt that the strong n-p pairing correlations at short distances discovered at Jefferson Lab\textsuperscript{[3]} can significantly
modify the nuclear equation of state and consequently, the physics of neutron stars. In particular it is conceivable that these eventually lead to an instability of neutron stars. En route to the new more stable form one expects significant mass loss. The demand that it will not exceed the above bound does imposes an extra constraint on such models -in addition to those due to the longevity of neutron stars\(^1\).

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\(^1\) Deduced ages of some millisecond pulsars are few times \(10^9\) years.