NEUTRINO EMISSION DUE TO COOPER PAIRING OF NUCLEONS IN NEUTRON STARS

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Cooling of middle-age ($t = 10^4$–10^6 yr) isolated neutrons stars (NSs) can serve as an important tool to explore the properties of superdense matter in NS interiors (e.g., Page, 1998a, b). We analyse one specific mechanism of neutrino cooling which operates inevitably in superfluid matter: the cooling due to Cooper pairing (CP) of nucleons N (neutrons n or protons p). It was proposed by Flowers et al. (1976, FRS) and independently by Voskresensky and Senatorov (1987) for singlet CP of neutrons in the NS cores but it has been employed in cooling theories of NSs only recently (see Page, 1998a, and references therein). We study triplet and singlet CP of non-relativistic n and p in the NS cores and crusts and its effect onto NS cooling.

1. Cooper pairing

The CP neutrino emissivity Q [$\mathrm{erg\,cm^{-3}\,s^{-1}}$] in uniform matter can be calculated as prescribed in FRS. Triplet CP is considered using a generalized Bogoliubov transformation (Tamagaki, 1970). CP operates when $\tau \equiv T/T_c < 1$, where T_c is the critical temperature of the nucleon superfluid. The result is

$$Q = \frac{4G_\mathrm{F}^2 m_N^* p_\mathrm{F}}{15\pi^5 \hbar^{10} c^6} \, (k_\mathrm{B}T)^7 \, \mathcal{N}_\nu \, (f_V^2 + 2f_A^2) \, F(\tau), \qquad (1)$$

where G_F is the Fermi weak coupling constant, $\mathcal{N}_\nu$ is the number of neutrino flavors (we adopt $N_\nu = 3$), T is the temperature, p_F is the nucleon Fermi-momentum, m_N^* is the nucleon effective mass, f_V and f_A describe contributions of vector and axial vector nucleon currents, respectively. We have $f_V = 1$ for neutrons, $f_V = 1 - 4\sin^2\Theta_\mathrm{W} = 0.08$ for protons ($\sin^2\Theta_\mathrm{W} = 0.23$, Θ_W being the Weinberg angle), $f_A = 0$ for singlet CP and $f_A = g_A = 1.26$ (axial-vector coupling constant) for triplet CP. Thus $(f_V^2 + 2f_A^2) = 4.17$ and 0.064 for triplet CP of n and singlet CP of p, respectively, that will be adopted for NS cores.

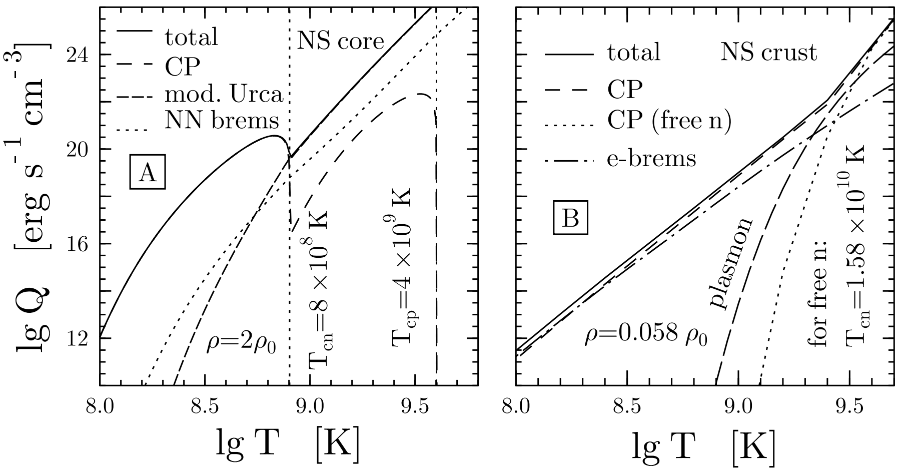

Fig. 1. Temperature profiles of the neutrino emissivities in NS core and crust

The function $F(\tau)$ is given by an integral expression which reduces to Eq. (13b) in FRS for singlet CP. We calculated $F(\tau)$ for case s of singlet CP and for case t of triplet CP with zero projection m_j of Cooper-pair momentum onto z axis. In these cases the superfluid gaps are given by $\Delta_s = \Delta_0^{(s)}(T)$ and $\Delta_t = \Delta_0^{(t)}(T)\sqrt{1+3\cos^2\theta}$ (θ is an angle between a nucleon momentum and z-axis). The results are fitted within 3% by

$$F = \frac{a_2 v^2 + a_4 v^4 + a_6 v^6}{1 + c_2\, v^2} \left(1 - b + \sqrt{b^2 + b_2 v^2}\right)^{1/2} \exp\left(-\sqrt{4\,v^2 + a^2} + a\right), \quad (2)$$

where a=2.245, a_2=0.602, a_4=0.5942, a_6=0.2880, b=0.4453, b_2=0.01130, c_2=0 for case s, and a=0.4616, a_2=1.204, a_4=3.733, a_6=0.3191, b=0.2409, b_2=0.3145, $c_2 = 0.3511$ for case t. The parameter $v = \Delta_0(T)/(k_{\rm B}T)$ is related to τ by the fit expression $v = \sqrt{1-\tau}\,(d_0 - d_1\,\tau^{-1/2} + d_2\,\tau^{-1})$, where d_0=1.456, d_1=0.157, d_2=1.764 for case s, and d_0=0.7893, d_1=0, d_2=1.188 for case t. In case s our results reproduce those by FRS for CP of neutrons at $\mathcal{N}_\nu = 2$. We also considered triplet CP at $m_j = 2$. The asymptote for $\tau \ll 1$ is $F(\tau) = 12.1\,\tau^2$, and $Q \propto T^5$ (no exponential) since the appropriate gap has nodes as a function of θ.

Fig. 1A shows the temperature dependence of various neutrino emissivities in a NS core (at density $\rho = 2\rho_0$, $\rho_0 = 2.8 \times 10^{14}$ g cm^{-3}) for indicated T_{cn} and T_{cp}, and $m_N^* = 0.8\,m_N$. Here and below the core is assumed to consist of npe matter with a moderately stiff equation of state by Prakash et al. (1988). We show the contribution from the modified Urca reaction, NN bremsstrahlung (sum of nn, np and pp terms), and CP of nucleons (sum of n and p reactions). The direct Urca process is forbidden at given ρ. The rates of the standard neutrino reactions suppressed by nucleon superfluid are taken from Levenfish and Yakovlev (1996). A bump of the total emissivity at $T \approx 10^{8.8}$ K is due to CP of neutrons.

Fig. 1B presents the neutrino emissivities in the inner NS crust at $\rho = 0.058\,\rho_0$, where matter is composed of free neutrons, electrons and spherical atomic nuclei. We show contributions from the well known reactions of plasmon decay (Itoh et al., 1996) and electron-nucleus bremsstrahlung (Pethick et al., 1998) to be compared with singlet CP of neutrons calculated by the Thomas-Fermi method. The profiles of local number density, T_{cn}, and m_n^* of neutrons over a Wigner-Seitz cell are taken from Elgaroy et al. (1996). Superfluid temperature of free neutrons is high. Thus, their CP alone (dots) decays exponentially with decreasing T, but the total CP emissivity decays much slower, as about T^7, due to CP of n within atomic nuclei. We also considered CP for nonspherical atomic nuclei at the bottom of the NS crust, and fitted the emissivity analytically. We obtain that CP is the important neutrino production mechanism in the inner NS crust.

PKS 1209-52	Zavlin et al. (1998)	*atm.*
	Zavlin et al. (1998)	*bb*
PSR 0002+62	Hailey & Craig (1995)	*bb*
Vela	Page et al. (1996)	*atm.*
	Ogelman (1995)	*bb*
PSR 0656+14	Anderson et al. (1993)	*atm.*
	Possenti et al. (1996)	*bb*
Geminga	Meyer et al. (1994)	*atm.*
	Halpern & Wang (1997)	*bb*
PSR 1055-52	Ogelman (1995)	*bb*

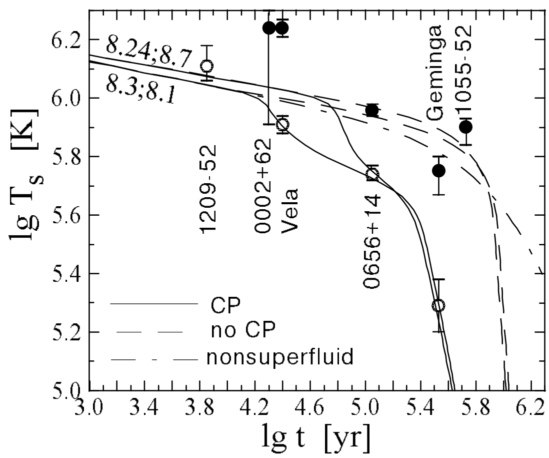

Fig. 2. Redshifted surface temperature vs NS age for two pairs of values of $\lg T_{cn}$[K] and $\lg T_{cp}$[K] (indicated near the curves) compared with observations

2. Cooling calculations and discussion

We simulated standard cooling of a NS of $1.3\,M_\odot$ mass and 11.7 km radius. The NS model is described in Levenfish and Yakovlev (1996). The standard neutrino energy losses are taken from the same source, but we add also the CP contribution in the NS core. The crust mass is too low ($0.0153\ M_\odot$) to affect the cooling. The critical temperatures T_{cn} and T_{cp} were assumed constant throughout the core and treated as free parameters. Fig. 2 shows several cooling curves compared with observations of radiation from six NSs. Error bars are 2σ estimates of the redshifted surface temperatures T_s obtained by fitting the observed NS spectra with black-body models (*bb*, filled dots) and hydrogen atmosphere models (*atm*, open dots). If redshifted T_s is not given in the cited sources we set it to 0.8 of its non-redshifted value. Vela's age is taken according to Lyne et al. (1996). Dash-and-dot line is non-superfluid cooling curve which yields higher T_s than given by atmospheric fits for three NSs. However these low T_s can be explained by the *standard* cooling of NSs with superfluid cores. Solid lines show two possible cooling curves; each hits three H-atmosphere error bars at once. Dashed lines are the same curves but obtained without CP. CP of neutrons is more efficient than CP of protons. When CP is switched on in a middle-age NS, it can strongly enhance the cooling resembling the enhancement by the direct Urca reaction. CP makes the standard cooling very sensitive to superfluid temperatures T_c that is important for constraining T_c from observations.

We are grateful to D. Baiko, D. Page, D. Varshalovich and D. Voskresensky for discussions. This work was supported by RFBR grant 96-02-16870a, RFBR-DFG grant 96-02-00177G and INTAS grant 96-0542.

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