Reexamination of a Bound on the Dirac Neutrino Magnetic Moment from the Supernova Neutrino Luminosity

A. V. Kuznetsov[a]*, N. V. Mikheev[a]†, A. A. Okrugin[a]‡

[a] *Yaroslavl State University*

Sovietskaya 14, 150000 Yaroslavl, Russian Federation

Abstract

We investigate the neutrino helicity-flip process under supernova core conditions, where the left-handed neutrinos being produced can be converted into right-handed neutrinos sterile with respect to the weak interaction due to the interaction of magnetic moments with plasma electrons and protons. Instead of the uniform ball model for the SN core used in previous analyses, realistic models for radial distributions and time evolution of physical parameters in the supernova core are considered. We have obtained new upper limits on the Dirac neutrino magnetic moment averaged over flavours and time from the condition that the influence of the right-handed neutrino emission on the total cooling time scale should be limited.

1 Introduction

Nonvanishing neutrino magnetic moment leads to the helicity-flip process in which the left-handed neutrinos produced in the stellar interior could convert into the right-handed ones, i. e., sterile with respect to the weak interaction. This can be important, for example, when the stellar energy losses are taken into account.

A considerable interest to the neutrino magnetic moment arised after the great event of the SN1987A in connection with the modelling of a supernova explosion, where a gigantic neutrino outflow determines in fact the process energetics. It means that such a microscopic neutrino characteristic as the neutrino magnetic moment would have a crucial influence on macroscopic properties of these astrophysical events. Too huge outflow of right-handed neutrinos, produced due to the magnetic moment interaction, from the core would leave no enough energy to explain the observed neutrino luminosity of the supernova. Hence an upper bound can be established on the neutrino magnetic moment.

The neutrino helicity flip $\nu_L \to \nu_R$ under physical conditions corresponding to the central region of a supernova has been studied in a number of works (see, e. g., Refs. [1–3]; a more extended reference list is given in Ref. [4]). The process is possible due to the interaction of the Dirac-neutrino magnetic moment with a virtual plasmon, which can be both generated and absorbed:

$$\nu_L \to \nu_R + \gamma^*, \quad \nu_L + \gamma^* \to \nu_R \,. \tag{1}$$

A detailed analysis of the processes (1), with neutrino-helicity conversion due to the interaction with both plasma electrons and protons via a virtual plasmon and with taking account

*e-mail: avkuzn@uniyar.ac.ru

†e-mail: mikheev@uniyar.ac.ru

‡e-mail: okrugin@uniyar.ac.ru

of polarization effects of the plasma on the photon propagator was performed in Ref. [4]. In particular, according to the numerical analysis the plasma proton contribution turned out to be not only significant but even dominant.

However, all of the previous studies [1–4] were based on a very simplified model of the supernova core as the uniform ball with some averaged values of physical parameters. Moreover, according to modern views, the parameter values look rather too high than typical.

The aim of this paper is to make the estimation of the Dirac neutrino magnetic moment from the limit on the supernova core luminosity for ν_R emission by a more consistent way, taking some radial distributions and time evolution of physical parameters from some realistic models of the supernova core. The upper bounds are obtained on the combination of the effective magnetic moments of the electron, muon and tau neutrinos from the condition of not-spoiling the subsequent Kelvin – Helmholtz stage of the supernova explosion by emission of right-handed neutrinos during a few seconds after the collapse.

For completeness, we consider here a general case of the magnetic moment matrix $\mu_{\nu_i \nu_j} \equiv \mu_{ij}$, where ν_i, ν_j are the neutrino mass eigenstates. For the processes with the initial electron neutrino one should replace

$$\mu_\nu^2 \to \mu_{\nu_e}^2 \equiv \sum_i \left| \sum_j \mu_{ij} \, U_{ej} \right|^2 , \tag{2}$$

where $U_{\ell i}$ ($\ell = e, \mu, \tau$) is the unitary leptonic mixing matrix by Pontecorvo – Maki – Nakagawa – Sakata, and similarly for the muon and tau initial neutrinos.

2 The recent model of the O-Ne-Mg core collapse SN

The recent model was developed by H.-Th. Janka with collaborators who presented us the results of their simulations [5] of the O-Ne-Mg core collapse supernovae which were a continuation of model simulations of Refs. [6, 7]. The successful explosion results for this case have recently been independently confirmed by the Arizona/Princeton SN modelling group [8, 9] which found very similar results. So we were provided with a model whose explosion behavior was comparatively well understood and generally accepted.

We should stress that this O-Ne-Mg core collapse model (for the initial stellar mass of $8.8 \, M_\odot$) is not applicable directly to SN1987A which was $15 - 20 \, M_\odot$ prior to collapse and according to the evolution theory it had a collapsing core which consisted of iron-peak elements.

We integrate over the volume of the neutrino-emitting region V to obtain the spectral density of the energy luminosity of a supernova core via right-handed neutrinos:

$$\frac{\mathrm{d}L_{\nu_R}}{\mathrm{d}E} = \int \mathrm{d}V \, \frac{E^3}{2 \pi^2} \, \Gamma_{\nu_R}(E) \, . \tag{3}$$

Here, taking the values defined in Eqs. (20) and (21) and the corresponding formulas from Appendix A of Ref. [4], we take in account their dependence on the radius R and time t. A comprehensive set of parameter distributions used in our estimation includes the profiles [5] of the density ρ, the temperature T, the electron fraction Y_e, the fractions of electron neutrinos Y_{ν_e}, electron anti-neutrinos $Y_{\bar{\nu}_e}$, and the fractions Y_{ν_x} for one kind of heavy-lepton neutrino or antineutrino ($\nu_x = \nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau}$), which are treated identically. The time evolution of the parameter distributions is calculated [5] within the interval until ~ 2 sec after the collapse. For the sake of illustration, we present in Figs. 1 – 3 the radial distributions within the SN core, from 0 to 20 km, at the moment $t = 1.0$ sec after the collapse for the temperature [5], for the chemical potentials of electrons η_e and electron neutrinos η_{ν_e} (calculated on the base of the data of Ref. [5]), and for the proton nonrelativistic chemical potential $\eta_p^* = \eta_p - m_N^*$ defining the degeneracy of protons (calculated on the base of the data of Ref. [5] and of the effective nucleon mass m_N^* in plasma, see Ref. [10], p. 152).

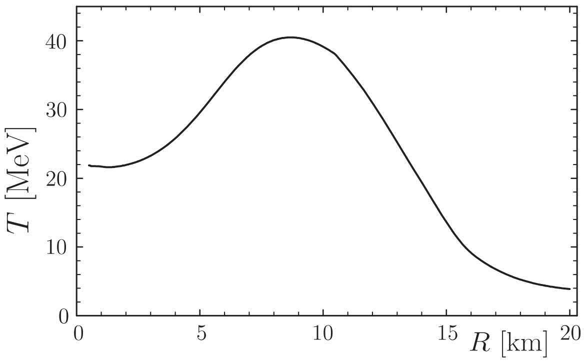

Figure 1: The radial distribution for the temperature within the SN core at the moment $t = 1.0$ sec after the collapse [5].

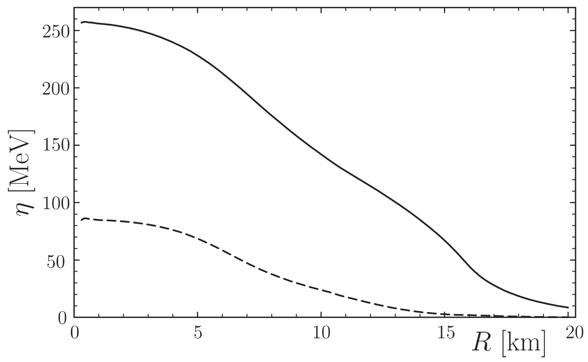

Figure 2: Radial distributions for the chemical potentials of electrons (solid line) and electron neutrinos (dashed line) within the SN core at the moment $t = 1.0$ sec after the collapse [5].

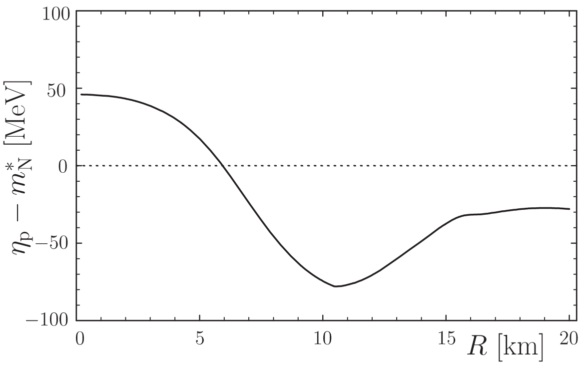

Figure 3: The radial distribution for the proton nonrelativistic chemical potential $\eta_p^* = \eta_p - m_N^*$ within the SN core at the moment $t = 1.0$ sec after the collapse [5].

To analyse the influence of the right-handed neutrino emission on the SN energy loss, we also used the time evolution of the total luminosity of all species of left-handed neutrinos [5], presented in Fig. 4.

Integrating Eq. (3) over the neutrino energy, one obtains the time evolution of the right-handed neutrino luminosity:

$$L_{\nu_R}(t) = \frac{1}{2\,\pi^2} \int \mathrm{d}V \int\limits_0^\infty \mathrm{d}E\, E^3\, \Gamma_{\nu_R}(E)\,. \tag{4}$$

This is a novel cooling agent which would have to compete with the energy-loss via active neutrino species in order to affect the total cooling time scale significantly. Therefore, the observed $SN1987A$ signal duration indicates that a novel energy-loss via right-handed neutrinos is bounded by left-handed heutrino luminosity

$$L_{\nu_R} < L_{\nu_L}\,, \tag{5}$$

and we believe this estimation to be applicable also to the considered O-Ne-Mg core collapse model. Within the considered time interval until 2 sec after the collapse, one obtains from

Eqs. (4), (5) the time-dependent upper bound on the combination of the effective magnetic moments of the electron, muon and tau neutrinos. Assuming for simplicity that these effective magnetic moments are equal, one obtains the time evolution of the upper bound on some flavor-averaged neutrino magnetic moment $\bar{\mu}_\nu$ shown in Fig. 5, where $\bar{\mu}_{12} = \bar{\mu}_\nu/(10^{-12}\,\mu_{\rm B})$.

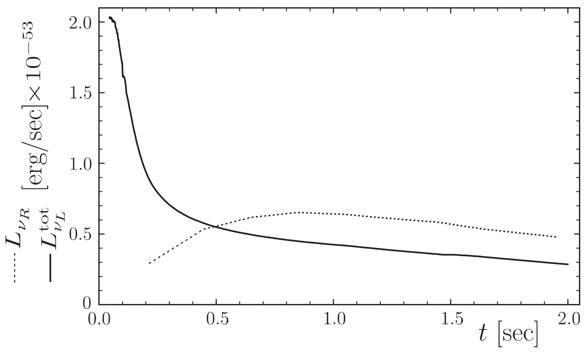

Figure 4: The time evolution of the total luminosity $L^{\rm tot}_{\nu_R}(t)$ of all active neutrino species [5] (solid line) and the right-handed neutrino luminosity $L_{\nu_R}(t)$, Eq. (4), at $\mu_\nu = 3 \cdot 10^{-12}\,\mu_{\rm B}$ (dotted line).

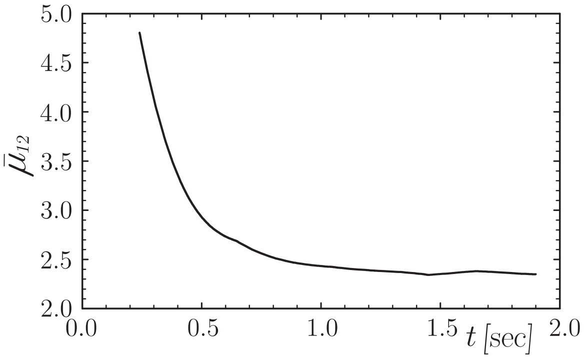

Figure 5: The time evolution of the upper bound on the neutrino magnetic moment within the time interval until 2 sec after the collapse (in assumption that the effective magnetic moments of electron, muon and tau neutrinos are equal).

As is seen from Fig. 5, the averaged upper bound tends to some value, providing the limit

$$\bar{\mu}_\nu < 2.4\,\times 10^{-12}\,\mu_{\rm B}\,. \tag{6}$$

In a general case the combined limit on the effective magnetic moments of the electron, muon and tau neutrinos is

$$\left[\mu^2_{\nu_e} + 0.71\left(\mu^2_{\nu_\mu} + \mu^2_{\nu_\tau}\right)\right]^{1/2} < 3.7\,\times 10^{-12}\,\mu_{\rm B}\,, \tag{7}$$

where the effective magnetic moments are defined according to Eq. (2). This limit is less stringent than the bound [4] obtained in the frame of the uniform ball model for the SN core, but it is surely more reliable. Additionally, the upper bound on the effective magnetic moments of muon and tau neutrinos is established.

3 Earlier models of the SN explosion

The similar procedure of evaluation was performed with using of the data of the model [11] by R. Buras et al. (2006) of the two-dimensional hydrodynamic core-collapse supernova simulation for a 15 $M_\odot$ star. Namely, the radial distributions of parameters at the moments $t = 0.2, 0.4, 0.6, 0.8$ sec after the collapse in the model *s15Gio_32.a* were taken from Fig. 40 of Ref. [11]. Additionally, the fraction of electron neutrinos was evaluated as $Y_{\nu_e} \simeq (1/5)\,Y_e$. Calculating the right-handed neutrino luminosity with those parameters and putting the limit (5), where the total luminosity via active neutrino species L_{ν_L} in that model can be taken from Fig. 42 of Ref. [11], one obtains that the upper bound on the flavor-averaged neutrino magnetic moment $\bar{\mu}_\nu$ also varies in time as in the previous case. The time-averaged upper bound on $\bar{\mu}_\nu$ corresponding to the interval $0.4-0.8$ sec, is:

$$\bar{\mu}_\nu < 2.7\,\times 10^{-12}\,\mu_{\rm B}\,, \tag{8}$$

to be compared with the limit (6).

Using the results of Ref. [12] by J. A. Pons et al. (1999) where the thermal and chemical evolution during the Kelvin-Helmholtz phase of the birth of a neutron star was studied, taking the data from Figs. 9 and 14, we have obtained the time-averaged upper bound on $\bar{\mu}_\nu$ for the time interval $1-10$ sec of the post-bounce evolution in the form:

$$\bar{\mu}_\nu < 1.2 \times 10^{-12} \mu_{\mathrm{B}} . \tag{9}$$

We also used the results of Ref. [13] by W. Keil and H.-Th. Janka (1995) where the numerical simulations were performed of the neutrino-driven deleptonization and cooling of newly formed, hot, lepton-rich neutron star. Using the data presented in Figs. $3-9$ on the SBH model (of the hot star with a "small" baryonic mass), we have evaluated the time-averaged upper bound on $\bar{\mu}_\nu$ for the time interval $0.5-5$ sec after the collapse in the form:

$$\bar{\mu}_\nu < 1.1 \times 10^{-12} \mu_{\mathrm{B}} . \tag{10}$$

One can summarize that the upper bound on the flavor- and time-averaged neutrino magnetic moment at the Kelvin-Helmholtz phase of the supernova explosion occurs to be

$$\bar{\mu}_\nu < (1.1-2.7) \times 10^{-12} \mu_{\mathrm{B}} , \tag{11}$$

depending on the explosion model.

4 Conclusion

The right-handed neutrino luminosity caused by the neutrino helicity-flip process under the conditions of the supernova core, where the produced left-handed neutrinos could convert due to the neutrino magnetic moment interaction into the right-handed neutrinos, being sterile with respect to the weak interaction, is reinvestigated. Instead of the uniform ball model for the SN core used in previous analyses, realistic models for radial distributions and time evolution of physical parameters in the SN core are considered. The upper bounds on the flavor- and time-averaged magnetic moment of the Dirac type neutrino are obtained in those models, from the condition of not-affecting the total cooling time scale significantly:

$$\bar{\mu}_\nu < (1.1-2.7) \times 10^{-12} \mu_{\mathrm{B}} , \tag{12}$$

depending on the explosion model.

Acknowledgements

We thank Hans-Thomas Janka, Lorentz Hüdepohl, and Bernard Müller, who provided detailed data on the radial distributions and time evolution of physical parameters in a supernova core obtained in their model of supernova explosion and protoneutron star cooling. We are grateful to V. A. Rubakov, G. Raffelt, and O. V. Lychkovskiy for useful remarks.

This work was performed in the framework of realization of the Federal Target Program "Scientific and Pedagogic Personnel of Innovation Russia" for 2009 – 2013 (State contract no. P2323) and was supported in part by the Ministry of Education and Science of the Russian Federation under the Program "Development of Scientific Potential of Higher School" (project no. 2.1.1/510).

References

[1] R. Barbieri and R. N. Mohapatra, *Phys. Rev. Lett.* **61**, 27 (1988).

[2] A. Ayala, J. C. D'Olivo and M. Torres, *Phys. Rev. D* **59**, 111901 (1999).

[3] A. Ayala, J. C. D'Olivo and M. Torres, *Nucl. Phys. B* **564**, 204 (2000).

[4] A. V. Kuznetsov and N. V. Mikheev, *Journ. Cosmol. Astropart. Phys.* **11**, 031 (2007).

[5] B. Müller and H.-Th. Janka, unpublished results (private communication).

[6] F.S. Kitaura, H.-Th. Janka and W. Hillebrandt, *Astron. Astrophys.* **450**, 345 (2006).

[7] H.-Th. Janka, B. Müller, F.S. Kitaura and R. Buras, *Astron. Astrophys.* **485**, 199 (2008).

[8] L. Dessart, A. Burrows, C.D. Ott, E. Livne, S.-C. Yoon and N. Langer, *Astrophys. J.* **644**, 1063 (2006).

[9] A. Burrows, L. Dessart, C.D. Ott, E. Livne, *Phys. Rep.* **442**, 23 (2007).

[10] G. G. Raffelt, *Stars as Laboratories for Fundamental Physics* (Univ. of Chicago Press, Chicago, 1996).

[11] R. Buras, M. Rampp, H.-Th. Janka and K. Kifonidis, *Astron. Astrophys.* **447**, 1049 (2006).

[12] J.A. Pons, S. Reddy, M. Prakash, J.M. Lattimer and J.A. Miralles, *Astrophys. J.* **513**, 780 (1999).

[13] W. Keil and H.-Th. Janka, *Astron. Astrophys.* **296**, 145 (1995).