NEUTRINO-ANTINEUTRINO ANNIHILATION AROUND COLLAPSING STAR

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60th Anniversary of the October Revolution Prospect 7a, II73I2 Moscow, USSR

ABSTRACT

Stellar collapse is accompanied by emission of $E_\nu \sim$ IO MeV neutrinos and antineutrinos with the energy output $W_\nu \sim$ 10^{53} - 10^{54} erg. Annihilation of these particles($\nu+\bar\nu \to e^+ + e^-$) in the vicinity of collapsar is considered. The physical consequencies are discussed.

I. Introduction. Our interest to the problem of $\nu\bar\nu$-annihilation in the vicinity of collapsing object(collapsar) is stimulated by expected possibility of "quiet collapses" and by prospects of their detection using neutrino radiation/I-6/. Can collapse occur in such a way that neutrino emission will be the only observational consequence? We think that in many cases, if not in all, neutrino burst will be accompanied by X-ray burst. Here we suggest a mechanism of energy deposition in outer layer of collapsing star and beyond it, which can result in ejection of small mass and in generation of X-ray burst. This mechanism is $\nu\bar\nu$-annihilation. At latest stages of evolution of a massive star an isolated stellar core is produced. For a star with $M=2M_\odot$ collapse results in the formation of a hot neutron star which is cooling during I0-20 s mostly by neutrino radiation. For a star with $M=10\,M_\odot$ a hot compact core exists during several seconds followed by the formation of a black hole. The similar compact hot core can be produced as a result of gas accretion to white dwarf in a binary system. In all these cases neutrinos are emitted from "neutrinosphere"(analogous to photosphere). Its radius R_ν is defined by coherent $\nu A \to \nu A$ scattering. The efficiency of $\nu + \bar\nu \to e^+ + e^-$ scattering depends on c.m.-energy of two neutrinos and thus it increases at large angles between neutrinos. Therefore the annihilation beyond the outer boundary of a star heavily depends on the radius of neutrinosphere.

2. Probability of annihilation. Neutrinos emitted from neutrinosphere of radius R_ν have Planck spectrum characterized by temperature T. Neutrinos (and antineutrinos) of all three flavours (e, μ and τ) are equally presented in the flux. Consider antineutrino ($\bar\nu$) moving in radial direction. Colliding with the other neutrinos emitted from neutrinosphere it undergoes at the distance dr $d\nu$ annihilation collisions:

$$d\nu = dr\, n_\nu(\varepsilon,\theta)\, d\Omega\, \sigma(E_c)\,(1-\cos\theta)\, d\varepsilon, \qquad (I)$$

where $n_\nu(\varepsilon,\theta)$ is a space density of neutrinos with energy ε moving at an angle θ to radial direction. At $\theta \le \theta_{max}$ the density $n_\nu(\varepsilon,\theta)$ is given by

$$n_\nu(\varepsilon,\theta)=\frac{1}{c}\frac{dB}{d\varepsilon}=\frac{g_\nu\varepsilon^2}{(hc)^3}\left(\exp\varepsilon/\kappa T+1\right)^{-1} \tag{2}$$

where θ_{max} = arcsin R_ν/r, B is neutrino brightness of the neutrinosphere, g_ν =I is a statistical factor for massless neutrinos, $d\Omega$ is a solid angle $\sigma(E_c)$ is the cross-section of $\nu+\bar\nu\to e^+ +e^-$ -scattering at energy E_c in c.m.-system. Reactions $\nu_\mu+\bar\nu_\mu\to e^+ +e^-$ and $\nu_\tau+\bar\nu_\tau\to e^+ +e^-$ proceed through neutral currents (Z^0-exchange). The cross-section is given by

$$\sigma(E_c)=\frac{2}{\pi}\left(2\xi^2-\xi+\frac{1}{4}\right)\left(1+\frac{P_c^2c^2}{3\varepsilon_c^2}\right)G_F^2\varepsilon_c P_c c, \tag{3}$$

where $\xi=\sin^2\theta_W\approx 0.23$, G_F is Fermi constant, $\varepsilon_c=E_c/2$ and $P_c=(\varepsilon_c^2-m_e^2c^4)^{1/2}$. For $\nu_e+\bar\nu_e\to e^+ +e^-$ the contribution comes from both CC($W^\pm$-exchange) and NC(Z^0-exchange) and cross-section is

$$\sigma(E_c)=\frac{2}{\pi}\left(2\xi^2+\xi+\frac{1}{4}\right)\left(1+\frac{P_c^2c^2}{3\varepsilon_c^2}\right)G_F^2\varepsilon_c P_c c. \tag{4}$$

Integrating (I) over r from R to ∞ one finds the number of collisions ν suffered by neutrino with energy $E=\kappa T$:

$$\nu=\frac{16\pi}{3}g_\nu R_\nu\sigma_0\left(\frac{2m_ec^2}{hc}\right)^3\left(\frac{\kappa T}{2m_ec^2}\right)^2 f(R_\nu/R,T), \tag{5}$$

where $f(R_\nu/R,T)=$

$$=\int_0^{R_\nu/R}\frac{dx}{x^2}\int_0^{1-\sqrt{1-x^2}}y^2dy\int_{z_{th}}^{\infty}dz\,\frac{z^3}{e^z+1}\left(1-\frac{z_{th}}{z}\right)^{1/2}\frac{3}{4}\left[1+\frac{1}{3}\left(1-\frac{z_{th}}{z}\right)\right] \tag{6}$$

$z_{th}=(I/2y)(2m_ec^2/\kappa T)^2$, σ_0 is $(0.26/\pi)G_F^2 m_e^2c^4$ =I.I.IO^{-45} cm^2 for $\nu_\mu+\bar\nu_\mu\to e^+ +e^-$ and $\nu_\tau+\bar\nu_\tau\to e^+ +e^-$ and $(I.I8/\pi)G_F^2 m_e^2 c^4$ =5.2.IO^{-45} cm^2 for $\nu_e+\bar\nu_e\to e^+ +e^-$. For two cases the approximate analytical formulae can be given:

i) at $R \gtrsim R_\nu$ and $\kappa T >> 2m_ec^2$

$$\nu=1.28\cdot10^{-8}(R_\nu/10^6\,cm)(\sigma_0/10^{-45}\,cm^2)(\kappa T/10\,MeV)^5\left(\frac{5}{R/R_\nu}\right)^5 \tag{7}$$

(ii) at $R >> R_\nu$

$$\nu=\frac{\pi\sqrt{\pi}}{8}g_\nu R_\nu\sigma_0\left(\frac{2m_ec^2}{hc}\right)^3\left(\frac{\kappa T}{2m_ec^2}\right)^4\left(\frac{R_\nu}{R}\right)^4\exp\left[-\left(\frac{2m_ec^2R}{\kappa TR_\nu}\right)\right] \tag{8}$$

For the futher numerical estimates we shall use the calculations of Nadyozhin /7/ for collapse of iron-oxygen core with mass $M=2M_{\odot}$. According to these calculations after neutronization of the core the collapse is slowed down and stops for IO-20s untill the core (hot neutron star) is cooled due to neutrino radiation. At this stage the core is characterized by the following parameters: radius and temperature of neutrinosphere are respectively $R = 11$km and $T=6.5 \cdot 10^{10}$ K, the mass above neutrinosphere is $M=0.011\ M_{\odot}$, the outer radius of the star is $R=12.7$ km, neutrino luminosity is $L_{\nu\bar\nu}=1.65 \cdot 10^{52}$ erg/s and the total energy of neutrino burst is $W_{\nu} = 5.8 \cdot 10^{53}$ erg. Inserting these parameters into (7) one finds for ν_e $\quad \nu \approx 9 \cdot 10^{-6}$. For the case (ii) and ad hoc parameters $R_{\nu} = 13$ km, $R=260$ km and $kT=12$ MeV we find $\nu \approx 2 \cdot 10^{-11}$. Probability for ν_e to annihilate beyond the neutrinosphere radius is $\nu \approx 4 \cdot 10^{-5}$.

3. Applications. The most interesting consequencies are connected with $\nu+\bar\nu \to e^+ + e^-$ annihilation beyond the outer surface of the star. The energy released per Is in the form of e^+-e^--pairs is $\nu L_{\nu\bar\nu} \approx 1.5 \cdot 10^{47}$ erg/s. The production of the new particles (e^+, e^-, γ) in the collisions of e^+ and e^- as well as radiation in magnetic field results in formation of a fireball /8/ and finally in X-ray burst. A duration of the burst is a delicate problem connected with the stellar wind from the surface of the star. Unless neutrino luminosity is higher than $L_{\nu\bar\nu} \approx 10^{55}$ erg/s neutrino pressure cannot produce the stellar wind from the surface. The stellar wind at the considered Kelvin stage of collapsing star results from the heating of the star surface to the temperature $T_S \gtrsim 2.2 \cdot 10^{7}$ K corresponding to Eddington luminosity. The heating is caused by 3 reasons: (i) by thermal flux from neutrinosphere, (ii) by νe-scattering of neutrino flux and (iii) by $\nu\bar\nu$-annihilation beyond the neutrinosphere. If outer shell is composed mainly of carbon, the depth of photosphere is $x \approx 30$g/cm The energy deposition by neutrinos inside this depth results in equlibrium temperature $T_S \approx 2 \cdot 10^{6}$ K. Therefore, the surface temperature depends on the thermal flux from the deeper layers of the shell and hence on the temperature gradient. It is interesting to note that $\nu\bar\nu$-annihilation diminishes the temperature gradient, since the released energy per particle is increasing outward due to diminishing of density. During the time the surface is heated to supereddington temperature and stellar wind makes the surroundings of the star opaque for X-rays, the fireball expands and leaves the star as X-ray burst. If timescale of the surface heating and of the filling of the star surroundings with the gas is $\tau \sim 1$ ms, then energy transferred to the fireball is $W \approx \nu L_{\nu} \tau \approx 10^{44}$ erg. Such a burst undoubtly can be detected if the collapse occurs in our Galaxy. To make the star opaque for X-ray radiation the mass loss $\dot M$ driven by the stellar wind must be rather large. The column density x at the time t due to mass loss $\dot M$ and gas velocity $v=(2\varkappa M/R)^{1/2}$ is $x=\dot M t/4\pi R(R+vt)$ Even for supereddington regime $L \approx 10 L_{Edd}$ /8/ $\dot M = 2 \cdot 10^{18}$ g/s and the column density at $t \to \infty$, $x_{\infty} = 6$g/cm, is less than critical value $x_c \approx 30$g/cm^2.

Acknowledgments. We are grateful to D.K.Nadyozhin for useful discussions.

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