Influence of magnetic field on beta-processes in neutrino-driven supernova explosion

Alexandra Dobrynina[1,2] & Igor Ognev[1]

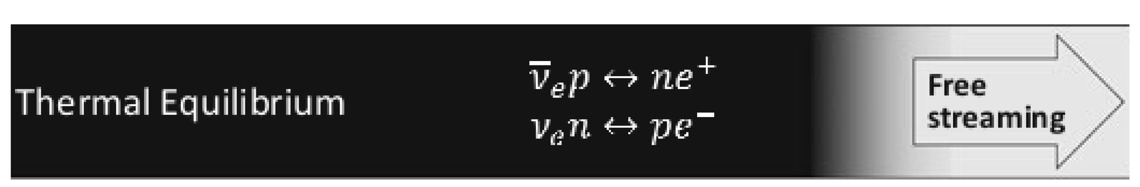
[1]P. G. Demidov Yaroslavl State University, Russia & [2]University of Hamburg, Germany

Beta-processes in supernova

- Core-collapse supernova is the final stage of an evolution for stars with a mass $M_{\text{star}} \gtrsim 10\, M_\odot$
- β-**processes** are the dominant neutrino processes in the **supernova (SN)** matter:

$$\begin{aligned} &1:\ p + e^- \to n + \nu_e \\ &2:\ n + \nu_e \to p + e^- \\ &3:\ n + e^+ \to p + \bar\nu_e \\ &4:\ p + \bar\nu_e \to n + e^+ \end{aligned}$$

- A SN **magnetic field** can enhance and support the neutrino-driven mechanism which is responsible for a revival of the initially stalled shock wave in the core-collapse SN
- The region of the neutrino interaction with the SN matter due to β-processes



Conditions and assumptions

- Arbitrary strength of magnetic field $b = B/B_e$, where $B_e = m_e^2/e \simeq 4.41 \times 10^{13}$ G is the critical Schwinger value
- Nucleons are non-degenerate
- e^-e^+-plasma is moderately degenerate $\Rightarrow$ $\tau = \mu_e/T \lesssim 10$
  μ_e is the electron chemical potential
  T is the temperature of the matter
- e^-e^+-plasma is ultra-relativistic
- SN explosion is spherically symmetric $\Rightarrow$ neutrinos propagate along a radial direction in the SN
- In such a matter, distribution functions of $e^-, e^+, \nu_e, \bar\nu_e$ can be approximated by "α-fit" [1] $\Longrightarrow s, \bar s, \alpha, \bar\alpha$ are pinching parameters for electrons (positrons) and (anti)neutrino

Analytical results

Energies $Q^{(i)}$ transferred from neutrino and antineutrino to the matter through the β-processes (1) – (4) are calculated in the presence of a magnetic field [2]:

$$\begin{aligned} Q^{(1)} =\ & G^2 N_p N_0\, \varepsilon_1^3\, s^s\, \Gamma^{-1}(s) \\ & \times \left[n_\nu\, I_{s+\alpha-3, s+\gamma\alpha}(\varepsilon_1, b) - I_{s,s}(\varepsilon_1, b) \right. \\ & \left. - g_{va} \cos\beta\, \chi_1\, n_\nu\, J_{s+\alpha-3, s+\gamma\alpha}(\varepsilon_1, b) \right], \\ Q^{(2)} =\ & G^2 N_n N_0\, \varepsilon_1^3\, e^{-\tau}\, s^s\, \Gamma^{-1}(s) \\ & \times \left[n_\nu\, I_{s+\alpha-3, s+\gamma\alpha-\gamma_t}(\varepsilon_1, b) \right. \\ & \left. - g_{va} \cos\beta\, \chi_1\, n_\nu\, J_{s+\alpha-3, s+\gamma\alpha-\gamma_t}(\varepsilon_1, b) \right. \\ Q^{(3)} =\ & G^2 N_n \bar N_0\, \bar\varepsilon_1^3\, \bar s^{\bar s}\, \Gamma^{-1}(\bar s) \\ & \times \left[\bar n_\nu\, I_{\bar s+\bar\alpha-3, \bar s+\bar\gamma\bar\alpha}(\bar\varepsilon_1, b) - I_{\bar s, \bar s}(\bar\varepsilon_1, b) \right. \\ & \left. - g_{va} \cos\beta\, \bar\chi_1\, \bar n_\nu\, J_{\bar s+\bar\alpha-3, \bar s+\bar\gamma\bar\alpha}(\bar\varepsilon_1, b) \right], \\ Q^{(4)} =\ & G^2 N_p \bar N_0\, \bar\varepsilon_1^3\, e^{\tau}\, \bar s^{\bar s}\, \Gamma^{-1}(\bar s) \\ & \times \left[\bar n_\nu\, I_{\bar s+\bar\alpha-3, \bar s+\bar\gamma\bar\alpha-\bar\gamma_t}(\bar\varepsilon_1, b) \right. \\ & \left. - g_{va} \cos\beta\, \bar\chi_1\, \bar n_\nu\, J_{\bar s+\bar\alpha-3, \bar s+\bar\gamma\bar\alpha-\bar\gamma_t}(\bar\varepsilon_1, b) \right]. \end{aligned}$$

Here, $G^2 = (g_v^2 + 3g_a^2)/(2\pi) \cos^2\theta_c\, G_F^2$, $g_{va} = (g_a^2 - g_v^2)/(3g_a^2 + g_v^2)$, $\chi_{1,2}$ are the first two neutrino angular momentums, n_ν is the reduced neutrino number density, N_0 is the unmagnetized number densities of electrons, N_n and N_p are the neutron and proton number densities, $\gamma = \varepsilon_1/\omega_1$ is the ratio of the average electron energy to the neutrino one, $\gamma_t = \varepsilon_1/T$, $\cos\beta$ is the cosine of the angle between magnetic field strength and radial direction. All quantities with the bar-symbol correspond to positrons or antineutrinos.

The **magnetic-field dependence** enters $Q^{(i)}$ only through the functions:

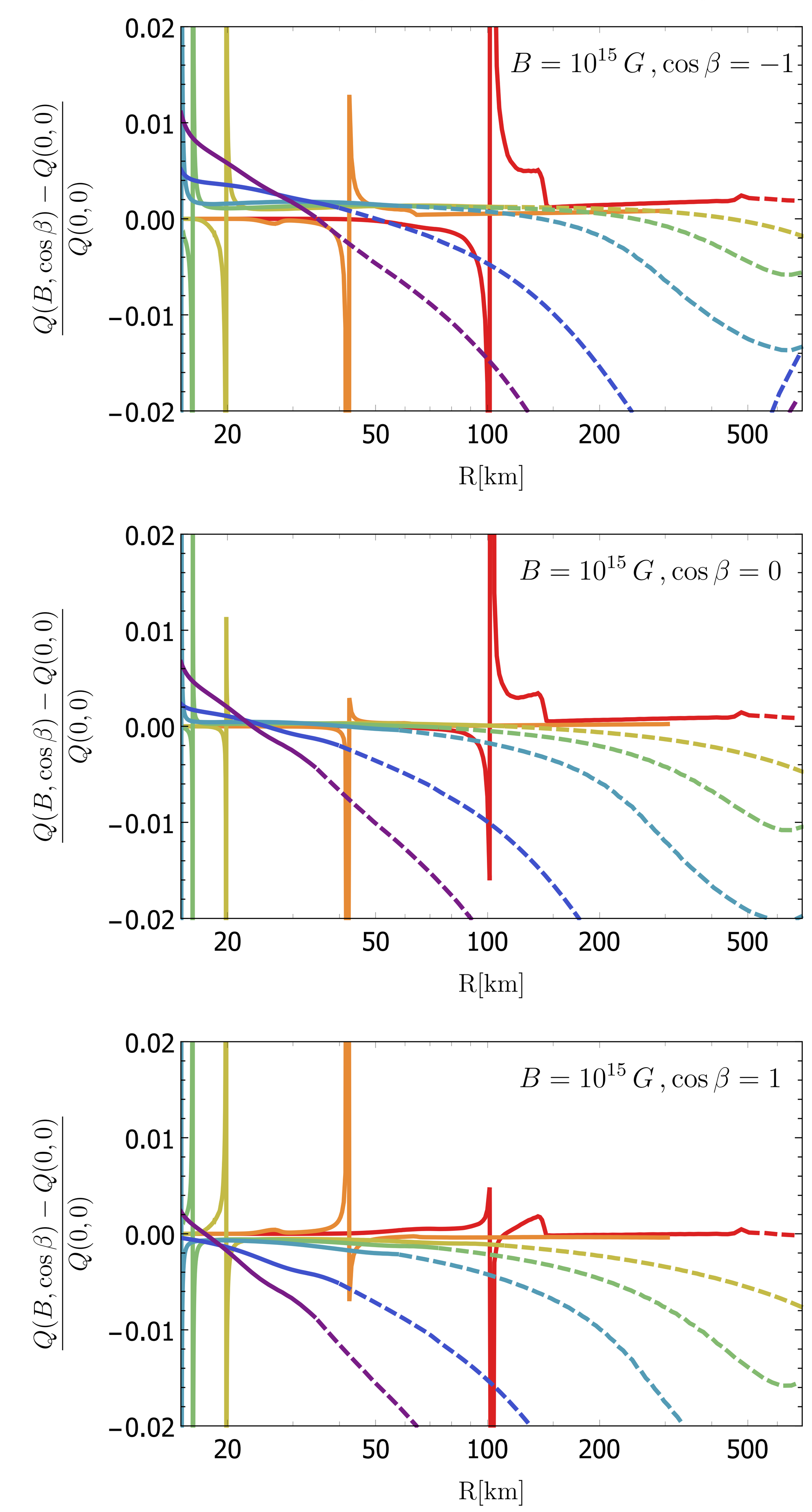
$$\begin{aligned} I_{k,\varkappa}(\varepsilon_1, b) =\ & \varkappa^{-k-3}\, \Gamma(k+3, \varkappa\, \boldsymbol{z_b}) \\ & + \varkappa^{-k-1} \frac{b\, m_e^2}{2\varepsilon_1^2} \Big[\Gamma(k+1) - \Gamma(k+1, \varkappa\, \boldsymbol{z_b}) \Big], \\ J_{k,\varkappa}(\varepsilon_1, b) =\ & \varkappa^{-k-1} \frac{b\, m_e^2}{2\varepsilon_1^2} \Gamma(k+1), \end{aligned}$$

where $\boldsymbol{z_b} = (m_e/\varepsilon_1)\sqrt{1 + 2b}$. For the β-**processes** (1)–(4), the heating rate has the form:

$$Q(B, \cos\beta) = Q^{(1)} + Q^{(2)} + Q^{(3)} + Q^{(4)}$$

Numerical results

We used the results of **1D PROMETHEUS-VERTEX simulations** [3]. In this analysis, the SN progenitor mass is equal to 27 $M_\odot$ and the final neutron star has a baryonic mass 1.76 $M_\odot$.



R (in km) is the distance from the PNS center
t (in sec) is the time after a bounce
Red lines: $t = 0.1$ sec; *orange:* $t = 0.5$ sec; *yellow:* $t = 1.5$ sec; *green:* $t = 4$ sec; *cyan:* $t = 5.5$ sec; *blue:* $t = 10$ sec; *violet:* $t = 13$ sec.
The dashed parts of the lines correspond to supernova regions where the electron-positron plasma is no longer ultrarelativistic.

Conclusion

Analytical expressions for reaction rates of β-processes as well as energy and momentum transferred from neutrinos and antineutrinos to the matter are obtained. Details of these calculations can be found in [2]. Modifications of the macroscopic quantities by the magnetic field with the strength $B \sim 10^{15}$ G are of a few percents only $\Rightarrow$ magnetic-field effects can be safely neglected, considering neutrino interaction and propagation in a supernova matter.

References

[1] M.T. Keil, G.G. Raffelt, and H.-T. Janka. *ApJ*, 590(2):971–991, 2003.

[2] A. Dobrynina and I. Ognev. *Phys. Rev. D*, 101(8):083003, 2020.

[3] L. Hüdepohl. *PhD thesis, Technische Univ. München*, 2014.

Acknowledgements

The work was supported by the Russian Science Foundation (Grant No. 18-72-10070). We are thankful to H.-T. Janka and his group for providing us with the data of the supernova explosions and for helpful discussions.

Contact Information

- Email: dobrynina@uniyar.ac.ru
- Email: ognev@uniyar.ac.ru