Modification of beta-processes by magnetic field in core-collapse supernova

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Introduction

- SN matter is opaque for neutrinos ⇒ neutrino interaction with SN matter is important ingredient of core-collapse supernova models
- β-processes are dominant neutrino processes in the SN matter:

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

- Magnetars (SGRs and AXPs) with $B \sim 10^{15}$ Gauss

  [S. A. Olausen and V. M. Kaspi, Astrophys. J. Suppl. 212, 6 (2014)]
- Magnetohydrodynamical (MHD) simulations of pre-supernova core collapse: $B \sim (10^9 - 10^{10})$ G at pre-supernova stage ⇒ $B \sim (10^{12} - 10^{13})$ G at post-bounce stage

  [A. Heger et al, ApJ 626, 350 (2005);
  M. Obergaulinger et al, MNRAS 445, 3169 (2014)]
- SN magnetorotational model ⇒ $B \sim (10^{14} - 10^{15})$ Gauss

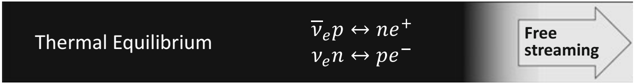
  [G. S. Bisnovatyi-Kogan, Sov. Astron. 14, 652 (1971);
  G. S. Bisnovatyi-Kogan et al, Atom. Nucl. 81, 266 (2018)]

β-processes in magnetic field

- Magnetic field can influence not only supernova dynamics, but also modify the neutrino processes
- Investigations of the magnetic field influence on β-processes have a long history
  - L.I. Korovina, Izv. Vyssh. Uchebn. Zaved., Fiz. 6, 86 (1964)
  - L. Fassio-Canuto, Phys. Rev. 187, 2141 (1969)
  - A.I. Studenikin, Sov. J. Nucl. Phys. 49, 1031 (1989)
  - L.B. Leinson and A. Perez, JHEP 9809, 020 (1998)
  - A.A. Gvozdev and I.S. Ognev, JETP Lett. 69, 365 (1999)
  - D.A. Baiko and D.G. Yakovlev, Astron. Astrophys. 342, 192 (1999)
  - D.G. Yakovlev et al, Phys. Rept. 354, 1 (2001)
  - H. Duan and Y.Z. Qian, Phys. Rev. D 72, 023005 (2005)
  - V.L. Kauts et al, Phys. Atom. Nucl. 69, 1453 (2006)
  - ...
- I.S. Ognev, JETP 123, 643 (2016): influence of magnetic field on β-processes in transparent for neutrino matter $\Rightarrow$ extend to partially transparent matter

Region of neutrino interaction with matter for β-processes

Electron flavor (ν_e and $\overline{\nu}_e$)



[G. Raffelt, arXiv:1201.1637]

Analysis of results of 1D PROMETHEUS-VERTEX simulations

[L. Huedepohl, PhD thesis, Technische Univ. (2014)]

Let us put the following conditions on the SN matter:

- Nucleons are non-degenerate: $R \gtrsim R_{PNS}$, R_{PNS} is the proto-neutron star radius
- $e^- e^+$-plasma is moderately degenerate: $\mu_e / T \lesssim 10 \Rightarrow R \gtrsim 16$ km
- $e^- e^+$-plasma is ultra-relativistic: $T \gg m_e \Rightarrow R \lesssim 500$ km
- SN explosion is spherically symmetric $\Rightarrow$ neutrinos propagate along a radial direction of the SN

$$16 \text{ km} \lesssim R \lesssim 500 \text{ km}$$

Distribution functions of $e^-, e^+, \nu_e, \bar{\nu}_e$ can be approximated by "α-fit":

[M.T. Keil et al, Astrophys. J. 590, 971 (2003)]

$$\omega^2 f(\omega) \sim \left(\frac{\omega}{\omega_1}\right)^{\alpha - 1} e^{-\alpha\,\omega/\omega_1}$$

ω_1 is an average energy and α is a numerical parameter

Analytical results

- Reaction rates of beta-processes Γ, energy Q and momentum $\mathcal{F}$ transferred from neutrinos and antineutrinos to the matter
- For reaction rates, we have

$$\begin{aligned}
\Gamma^{(1)} = \;& G^2 N_p N_0\, \varepsilon_1^2\, s^s\, \Gamma^{-1}(s)\Big[I_{s-1,s}(\varepsilon_1, b) - n_\nu\, I_{s+\alpha-4,s+\gamma\alpha}(\varepsilon_1, b) \\
& + g_{va} \cos\beta\, \chi_1\, n_\nu\, J_{s+\alpha-4,s+\gamma\alpha}(\varepsilon_1, b)\Big], \\
\Gamma^{(2)} = \;& G^2 N_n N_0\, \varepsilon_1^2\, s^s\, e^{-\tau}\, \Gamma^{-1}(s)\Big[n_\nu\, I_{s+\alpha-4,s+\gamma\alpha-\gamma_t}(\varepsilon_1, b) \\
& - g_{va} \cos\beta\, \chi_1\, n_\nu\, J_{s+\alpha-4,s+\gamma\alpha-\gamma_t}(\varepsilon_1, b)\Big] \\
\Gamma^{(3)} = \;& G^2 N_n \bar{N}_0\, \bar{\varepsilon}_1^2\, \bar{s}^{\bar{s}}\, \Gamma^{-1}(\bar{s})\Big[I_{\bar{s}-1,\bar{s}}(\bar{\varepsilon}_1, b) - \bar{n}_\nu\, I_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}}(\bar{\varepsilon}_1, b) \\
& + g_{va} \cos\beta\, \bar{\chi}_1\, \bar{n}_\nu\, J_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}}(\bar{\varepsilon}_1, b)\Big], \\
\Gamma^{(4)} = \;& G^2 N_p \bar{N}_0\, \bar{\varepsilon}_1^2\, \bar{s}^{\bar{s}}\, e^{\tau}\, \Gamma^{-1}(\bar{s})\Big[\bar{n}_\nu\, I_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}-\bar{\gamma}_t}(\bar{\varepsilon}_1, b) \\
& - g_{va} \cos\beta\, \bar{\chi}_1\, \bar{n}_\nu\, J_{\bar{s}+\bar{\alpha}-4,\bar{s}+\bar{\gamma}\bar{\alpha}-\bar{\gamma}_t}(\bar{\varepsilon}_1, b)\Big] .
\end{aligned}$$

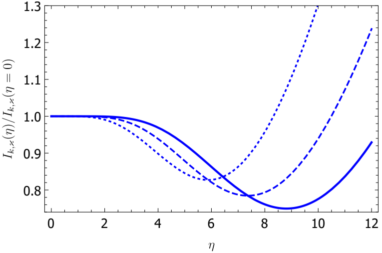
- 12 matter parameters + 8 neutrino parameters + magnetic field strength + angle between magnetic-field vector and star radial direction
- PROMETHEUS-VERTEX code developed by H.-T. Janka and his collaborators: $M_{progenitor} = 27\ M_\odot$, $M_{PNS} = 1.76\ M_\odot$
- All parameters reduce to t + R + b + $\cos\beta$

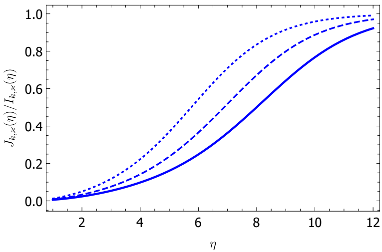
Magnetic field

- Magnetic field strength is included only in functions $I_{k,\varkappa}$ and $J_{k,\varkappa}$
- Significant modification of $I_{k,\varkappa}$ and $J_{k,\varkappa}$ at $B \gg B_e = m_e^2/e = 4.41 \times 10^{13}$ Gauss
- Dependence on magnetic field is defined by

$$\eta = \varkappa(m_e/\varepsilon_1)\sqrt{2b} = \varkappa(m_e/\varepsilon_1)\sqrt{\frac{2B}{B_e}}$$

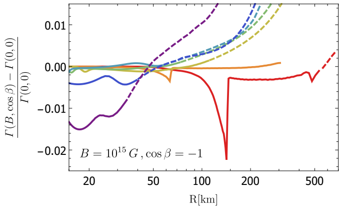
- The increase of average energy of $e^- e^+$-plasma reduces the parameter η
- Parameter η increases with a growth of the magnetic field B and the degeneracy of leptons $\varkappa$
- Properties of $I_{k,\varkappa}$ and $J_{k,\varkappa}$

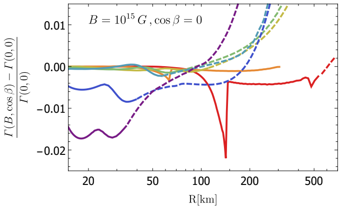


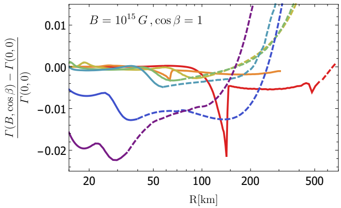


Dotted line: $k = 3$. *Dashed line:* $k = 4$. *Solid line:* $k = 5$.

Total reaction rate $\Gamma_{p\to n}(B, \cos\beta) = \sum_{i=1}^{4} \Gamma^{(i)}_{p\to n}(B, \cos\beta)$





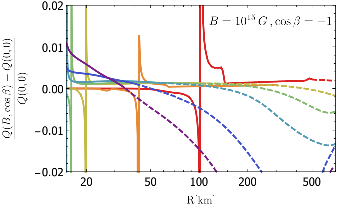


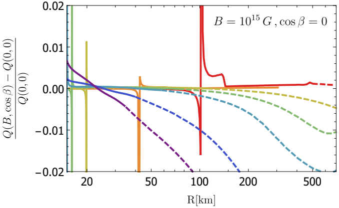
Red lines: $t = 0.1$ sec; *orange:* $t = 0.5$ sec; *yellow:* $t = 1.5$ sec; *green:* $t = 4$ sec; *cyan:* $t = 5.5$ sec; *blue:* $t = 10$ sec; *violet:* $t = 13$ sec.
The dashed parts of the lines correspond to supernova regions where the electron-positron plasma is no longer ultrarelativistic.

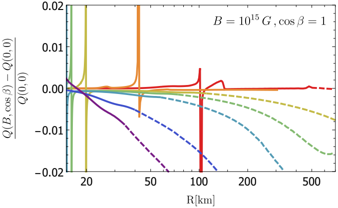
Conclusions

- Simple analytical expressions for reaction rates of beta-processes as well as energy and momentum transferred from neutrinos and antineutrinos to the matter are obtained for an arbitrary strength of magnetic field in SN conditions
- The influence of magnetic field on Γ, Q and $\mathcal{F}$ increase with growth of the lepton degeneracy while the increase of the averaged energy of electron-positron plasma reduce it
- Using of results of SN simulations allows to reduce a vast amount of necessary parameters to four and perform an analysis of magnetic field influence on quantities specified
- 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

Total energy $Q(B, \cos\beta) = \sum_{i=1}^{4} Q^{(i)}(B, \cos\beta)$







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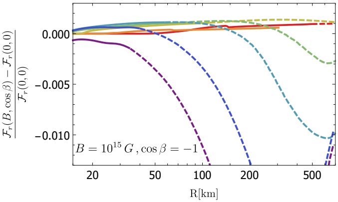
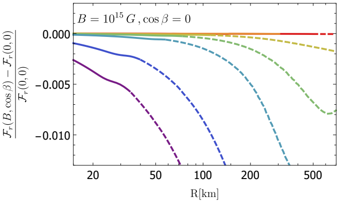
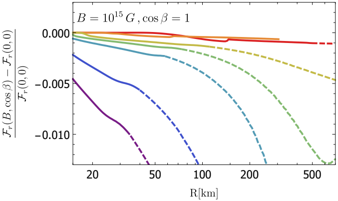
The dashed parts of the lines correspond to supernova regions where the electron-positron plasma is no longer ultrarelativistic.

Total radial momentum $\mathcal{F}_r(B,\cos\beta) = \sum_{i=1}^{4} \mathcal{F}_r^{(i)}(B,\cos\beta)$







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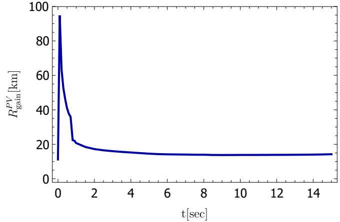
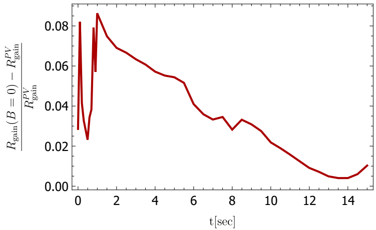
The dashed parts of the lines correspond to supernova regions where the electron-positron plasma is no longer ultrarelativistic.

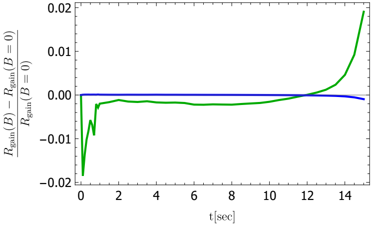
Test of results

$R_{gain}(B)$: gain radius from analytical equations, $Q_{total} = \sum_i Q^{(i)} = 0$

R^{PV}_{gain}: gain radius from PROMETHEUS-VERTEX simulations







Blue line: $B = 10^{15}$ G

Green line: $B = 10^{16}$ G