Influence of magnetic field on beta-processes in supernova medium

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Supernova

- Core-collapse supernova is the final stage of evolution for stars with masses
$$M_{\rm star} \gtrsim 10\, M_\odot$$
- SN matter is opaque for neutrinos $\Rightarrow$ neutrino interaction with SN matter is important ingredient of core-collapse supernova models
- β-processes are dominant neutrino processes in the SN matter:
$$\begin{aligned} 1:&\ p + e^- \to n + \nu_e \\ 2:&\ n + \nu_e \to p + e^- \\ 3:&\ n + e^+ \to p + \bar{\nu}_e \\ 4:&\ p + \bar{\nu}_e \to n + e^+ \end{aligned}$$

Supernova with magnetic field

- 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 core-collapse supernovae:
  $B \sim (10^{9} - 10^{10})$ G at pre-supernova stage $\Rightarrow$
  $B \sim (10^{12} - 10^{13})$ G at post-bounce stage

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

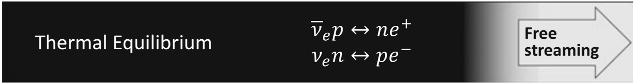
  [G. S. Bisnovatyi-Kogan, Sov. Astron. 14, 652 (1971);
  G. S. Bisnovatyi-Kogan et al, Atom. Nucl. 81, 266 (2018)]

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 medium $\Rightarrow$ extend to partially transparent medium

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 in 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)]

$$f(\omega) \approx \left(\frac{\omega}{\omega_1}\right)^{\alpha - 3} e^{-\alpha\, \omega / \omega_1}$$

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 (anti)neutrinos to the medium
- Momenta transferred from (anti)neutrinos to the medium are oriented in radial direction

$$\mathcal{F}_r^{(1)} = G^2 N_p N_0\, n_\nu\, \varepsilon_1^3\, s^s\, \Gamma^{-1}(s)\big[\chi_1\, I_1(s+\alpha-3, s+\gamma\alpha, \beta) + (g_{va}/2)(1-3\chi_2)\, I_2(s+\alpha-3, s+\gamma\alpha, \beta)\big]$$

$$\mathcal{F}_r^{(2)} = G^2 N_n N_0\, n_\nu\, \varepsilon_1^3\, e^{-a}\, s^s\, \Gamma^{-1}(s)\big[\chi_1\, I_1(s+\alpha-3, s+\gamma\alpha-\gamma_t, \beta) + (g_{va}/2)(1-3\chi_2)\, I_2(s+\alpha-3, s+\gamma\alpha-\gamma_t, \beta)\big]$$

$$\mathcal{F}_r^{(3)} = G^2 N_n \bar{N}_0\, n_{\bar\nu}\, \bar\varepsilon_1^3\, \bar{s}^{\bar{s}}\, \Gamma^{-1}(\bar{s})\big[\bar\chi_1\, \bar{I}_1(\bar{s}+\bar\alpha-3, \bar{s}+\bar\gamma\bar\alpha, \beta) + (g_{va}/2)(1-3\bar\chi_2)\, \bar{I}_2(\bar{s}+\bar\alpha-3, \bar{s}+\bar\gamma\bar\alpha, \beta)\big]$$

$$\mathcal{F}_r^{(4)} = G^2 N_p \bar{N}_0\, n_{\bar\nu}\, \bar\varepsilon_1^3\, e^{a}\, \bar{s}^{\bar{s}}\, \Gamma^{-1}(\bar{s})\big[\bar\chi_1\, \bar{I}_1(\bar{s}+\bar\alpha-3, \bar{s}+\bar\gamma\bar\alpha-\bar\gamma_t, \beta) + (g_{va}/2)(1-3\bar\chi_2)\, \bar{I}_2(\bar{s}+\bar\alpha-3, \bar{s}+\bar\gamma\bar\alpha-\bar\gamma_t, \beta)\big]$$

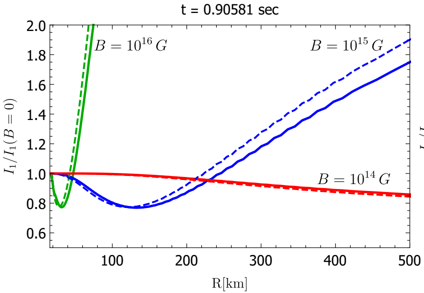
- 10 matter parameters + 8 neutrino parameters + magnetic field strength
- PROMETHEUS-VERTEX code developed by H.-T. Janka and his collaborators: $M_{progenitor} = 27\ M_\odot$, $M_{PNS} = 1.76\ M_\odot$
- All parameters reduce to t + R + B

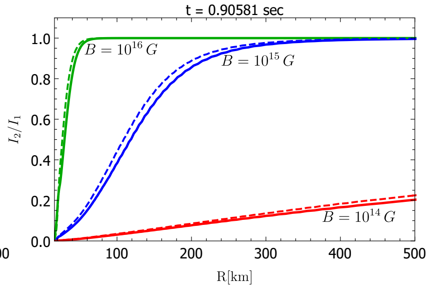
Magnetic field

- Magnetic field strength is included only in functions I_1 and I_2
- Dependence on magnetic field is defined by

$$\beta \sim \frac{m_e}{\varepsilon_1}\sqrt{\frac{2B}{B_e}}$$

- Significant modification of I_1 and I_2 at $B \gg B_e = m_e^2/e = 4.41 \times 10^{13}$ Gauss
- Ultrarelativistic matter decreases the influence of magnetic field
- Properties of I_1 and I_2



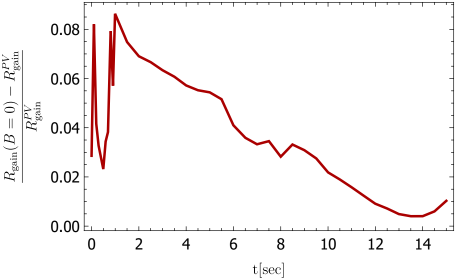


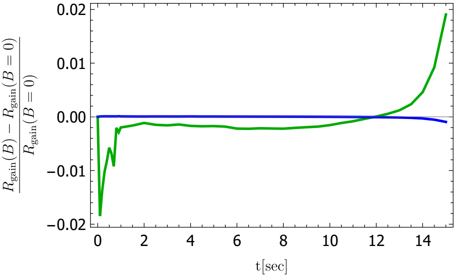
Dashed line: neutrino
Solid line: antineutrino

Test of results

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

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

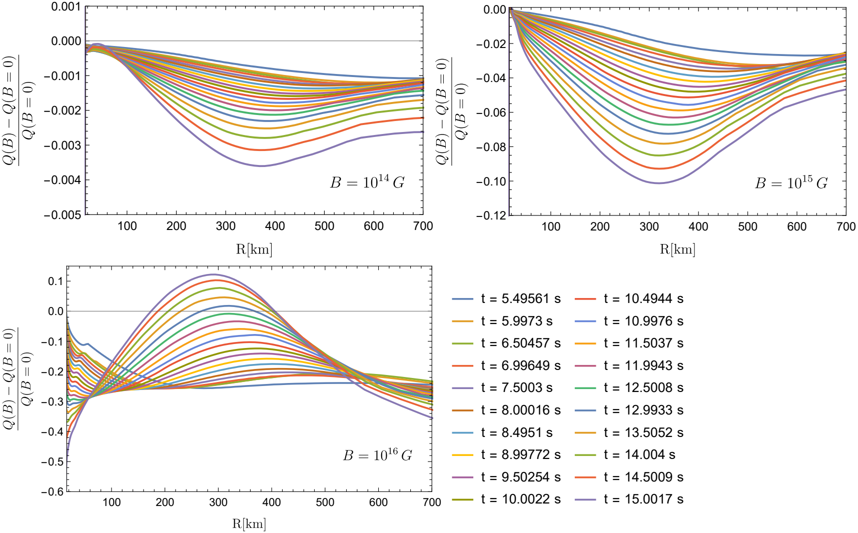




Blue line: $B = 10^{15}$ G

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

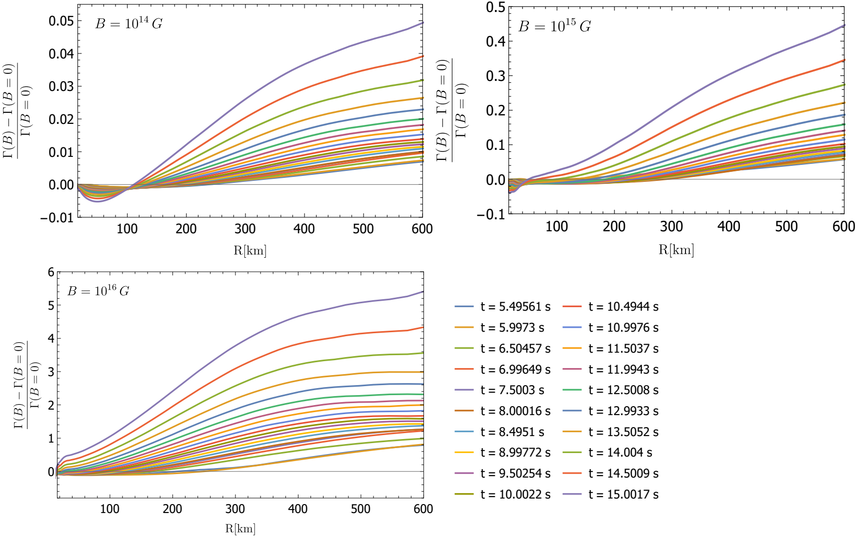
Total energy $Q(B) = \sum_{i=1}^{4} Q^{(i)}(B)$ transferred from (anti)neutrinos to the medium



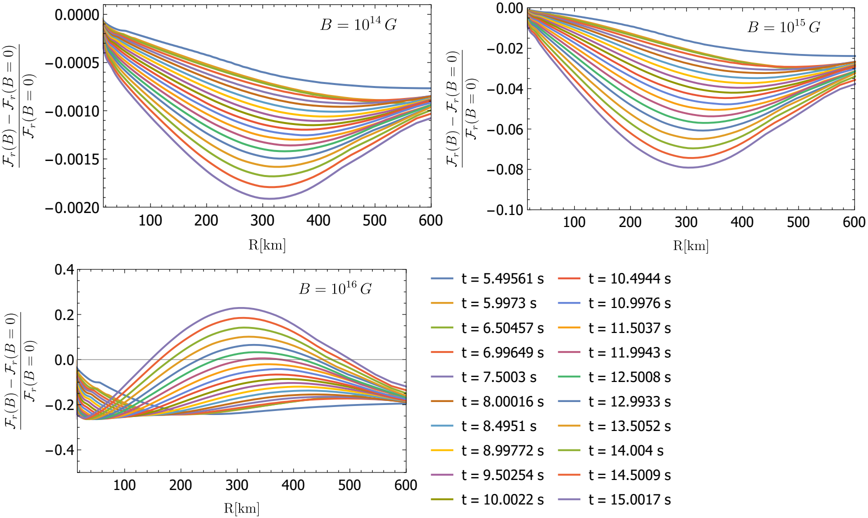
Conclusions

- Simple analytical expressions for reaction rates of beta-processes as well as energy and momentum transferred from (anti)neutrinos to the medium are obtained for an arbitrary strength of magnetic field in SN conditions
- With the averaged energy of electrons and positrons in plasma increased, the influence of magnetic field on Γ, Q and $\mathcal{F}_r$ is decreased
- Using of results of SN simulations allows to reduce a vast amount of necessary parameters to three and perform an analysis of magnetic field influence on quantities specified
- Magnetic field $B \sim 10^{14}$ G modifies quantities on several percents. To get a more significant effect requires a more stronger magnetic field up to 10^{16} G

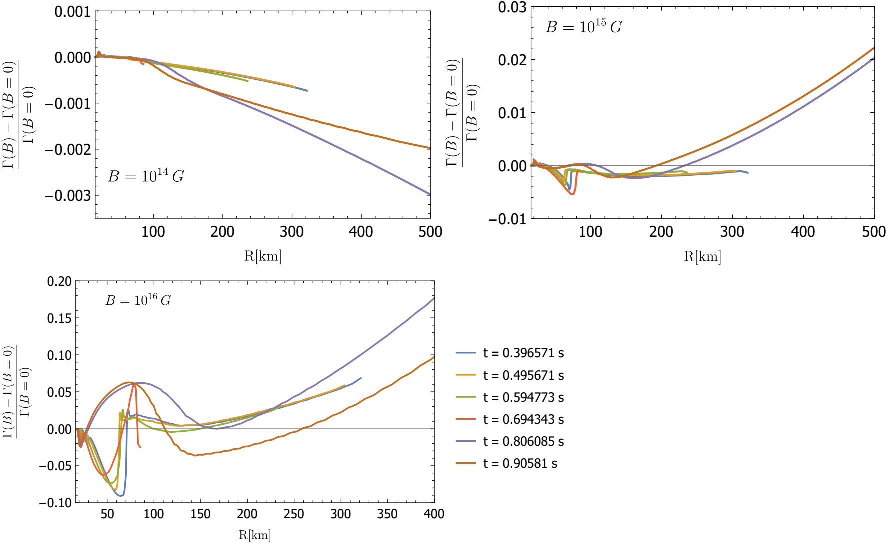
Total reaction rate $\Gamma_{p\to n}(B) = \sum_{i=1}^{4} \Gamma_{p\to n}^{(i)}$



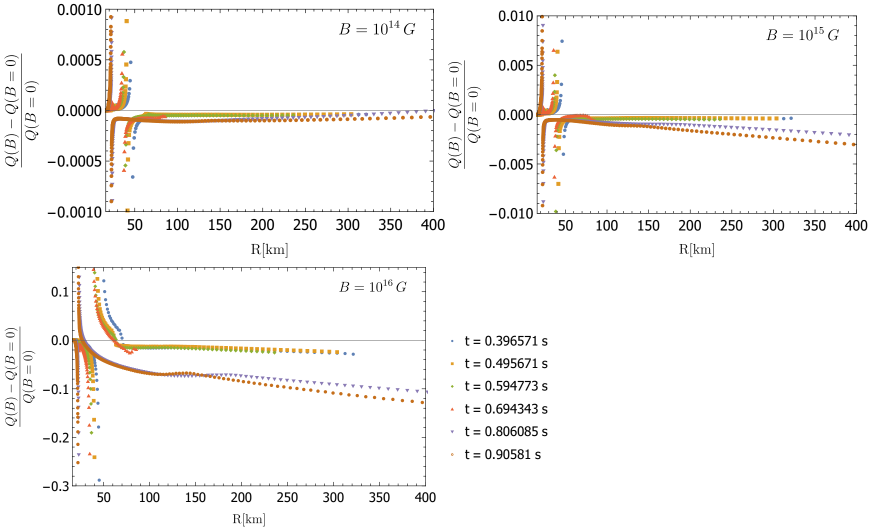
Total radial momentum $\mathcal{F}_r(B) = \sum_{i=1}^{4} F_r^{(i)}(B)$ transferred from (anti)neutrinos to the medium



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



Total energy $Q(B) = \sum_{i=1}^{4} Q^{(i)}(B)$ transferred from (anti)neutrinos to the medium



Total radial momentum $\mathcal{F}_r(B) = \sum_{i=1}^{4} F_r^{(i)}(B)$ transferred from (anti)neutrinos to the medium