Asymmetric neutrino transport in strong toroidal magnetic field

Tomoyuki Maruyama (Nihon Univ.)
Toshitaka Kajino(NAOJ, Univ. of Tokyo)
Nobutoshi Yasutake (Chiba Inst. Tech.)
Yung-ki Cheoun (Soongsil Univ.)
Chung-Yeol Ryu (Hanyang Univ.)
Jun Hidaka (NAOJ)
Grant J. Mathews (Univ. of Notre Dome)
Takami Kuroda (NAOJ)

Motivation :

Nuclear spin & neutrino
➔ asymmetric cross-section (parity violation)

Nuclear matter in B
➔ Nuclear spin : partially polarized

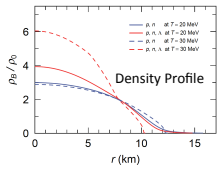
Net effect can be observed by asymmetric neutrino emission

How asymmetric neutrino transport affects dynamics of PNS at birth ?

ex) Pulsar Kick / Spin-down of Pulsar rotation

PNS Model

$$\begin{cases} M = 1.68 M_\odot \\ Y_L = 0.4 \\ T = 20\mathrm{MeV} \\ \text{w/o Hyperon (Lambda)} \end{cases}$$



Nuclear Matter

$$\mathcal{L}_{\rm tot} = \mathcal{L}_{\rm Nucl(RMF)} + \mathcal{L}_{\rm Lep} + \mathcal{L}_{\rm B\text{-}Mag.} + \mathcal{L}_{\rm e\text{-}Mag.} + \mathcal{L}_{\rm Weak}$$

$\psi_N \; \psi_\Lambda$

$\sigma \quad \omega$

Numerical Scheme of Neutrino Transport

Boltzmann eqn. : $\left(\frac{\partial}{\partial t} + \hat{k}_\nu \cdot \frac{\partial}{\partial \vec{r}}\right) f_\nu(\vec{r}, \vec{k}_\nu) = I_{\rm coll}$

Assume:
- steady state
- absorption (omitting scattering)
- ➔ trajectory of neutrino : straight line

$f_\nu(\vec{r}, \vec{k}_\nu) = f_\nu^{(0)}(\vec{r}, \vec{k}_\nu) + \Delta f_\nu(\vec{r}, \vec{k}_\nu)$ (Fermi-Dirac distribution + Asymmetric component)

$$\hat{k}_\nu \cdot \frac{\partial \mu_\nu}{\partial \vec{r}} \frac{\partial f_\nu^{(0)}}{\partial \mu_\nu} + \hat{k}_\nu \cdot \frac{\partial \Delta f_\nu}{\partial \vec{r}} = -\frac{\sigma_A}{V} \Delta f_\nu$$

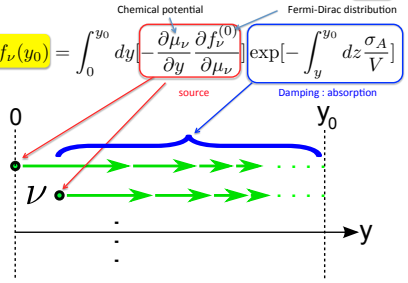
Solution of Botzmann eqn : straight line

$$\Delta f_\nu(y_0) = \int_0^{y_0} dy \left[-\frac{\partial \mu_\nu}{\partial y} \frac{\partial f_\nu^{(0)}}{\partial \mu_\nu}\right] \exp\left[-\int_y^{y_0} dz \frac{\sigma_A}{V}\right]$$

Solution of Boltzmann eqn. : $f_\nu = f_\nu^{(0)} + \Delta f_\nu$

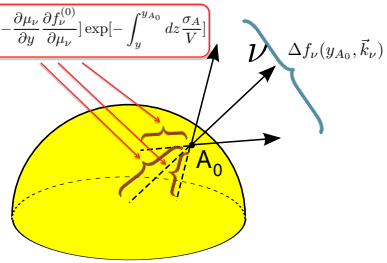
$$\Delta f_\nu(y_0) = \int_0^{y_0} dy \left[-\frac{\partial \mu_\nu}{\partial y} \frac{\partial f_\nu^{(0)}}{\partial \mu_\nu}\right] \exp\left[-\int_y^{y_0} dz \frac{\sigma_A}{V}\right]$$

Chemical potential; Fermi-Dirac distribution; source; Damping : absorption

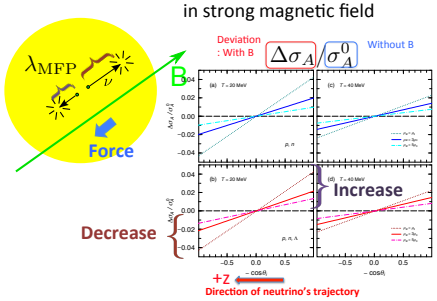


Distribution Function on the PNS surface

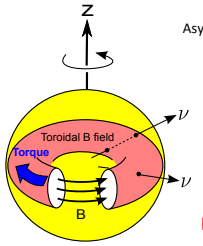
$$\int_0^{y_{A_0}} dy \left[-\frac{\partial \mu_\nu}{\partial y} \frac{\partial f_\nu^{(0)}}{\partial \mu_\nu}\right] \exp\left[-\int_y^{y_{A_0}} dz \frac{\sigma_A}{V}\right]$$



Asymmetric Absorption of Neutrino in strong magnetic field



Toroidal magnetic field inside PNS



Asymmetric absorption cross-section

Torque : opposite direction of B

Deceleration of PNS spin

Estimation of Spin-deceleration

$$f_\nu = f_\nu^{(0)} + \Delta f_\nu$$ (Asymmetric component)

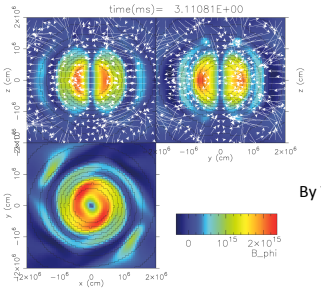
$$\int_s L_z^{(\nu)} \times \Delta f_\nu \qquad \int_s E^{(\nu)} \times \Delta f_\nu$$

Carrying away:Energy & L_z

$$\dot{\omega} = \frac{1}{I_{\rm PNS}} \frac{dL_z}{dt} = \frac{1}{I_{\rm PNS}} \frac{dE_{tot}}{dt} \quad \frac{dL_z/dt}{dE_{tot}/dt}$$

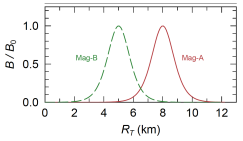
$3 \times 10^{52}\mathrm{erg/s}$

Numerical Example of the Toroidal Magnetic Field



By T. Kuroda

Numerical Results



$$\mathbf{B}(r_T, z) = B_0 G_T(r_T) G_L(z) \hat{e}_\varphi$$

$$\begin{cases} G_T(r_T) = \dfrac{16\exp[-(r_T - R_0)/\Delta r]}{\{1+\exp[-(r_T - R_0)/\Delta r]\}^2} \\ G_L(z) = \dfrac{\exp[-z/\Delta r]}{\{1+\exp[-z/\Delta r]\}^2} \end{cases}$$

Mag Distr.	Bary.	B [G] at $\rho_B = \rho_0$	$-\frac{cdL_z/dt}{dE_T/dt}$ (cm)	$-\dot{\omega}$	$\dot{P}/P$ ν emis.	$\dot{P}/P$ γ rad.
Mag-A	p,n	1.0×10^{16}	46.7	3.02×10^{-2}	4.82×10^{-2}	1.0×10^{-8}
R_0 = 8 (km)	p,n,Λ	1.6×10^{16}	70.6	5.19×10^{-2}	8.26×10^{-2}	2.6×10^{-8}
Mag-B	p,n	2.6×10^{13}	0.157	1.01×10^{-4}	1.61×10^{-4}	6.6×10^{-14}
R_0 = 5 (km)	p,n,Λ	4.2×10^{13}	0.259	1.90×10^{-4}	3.03×10^{-4}	1.7×10^{-13}

Conclusion

Asymmetric Neutrino emission from the PNS under strong toroidal magnetic field is an effective way to decelerate spin of PNS.

This affects the early stage of neutron star evolution considerably.

Future Work

Hydrodynamical Simulation by taking account of the symmetric neutrino interaction with the matter

☆ Maruyama's Talk
: Pulsar kick and RMFT for neutrino-hadron int. of SNe (Tomorrow: Wed. 16:30- 18:30)