How much can supernova fall-back invade newborn pulsar wind and magnetosphere?

Yici ZHONG (THE UNIV. OF TOKYO)
With Kazumi KASHIYAMA, Toshikazu SHIGEYAMA and Shinsuke TAKASAO

Introduction

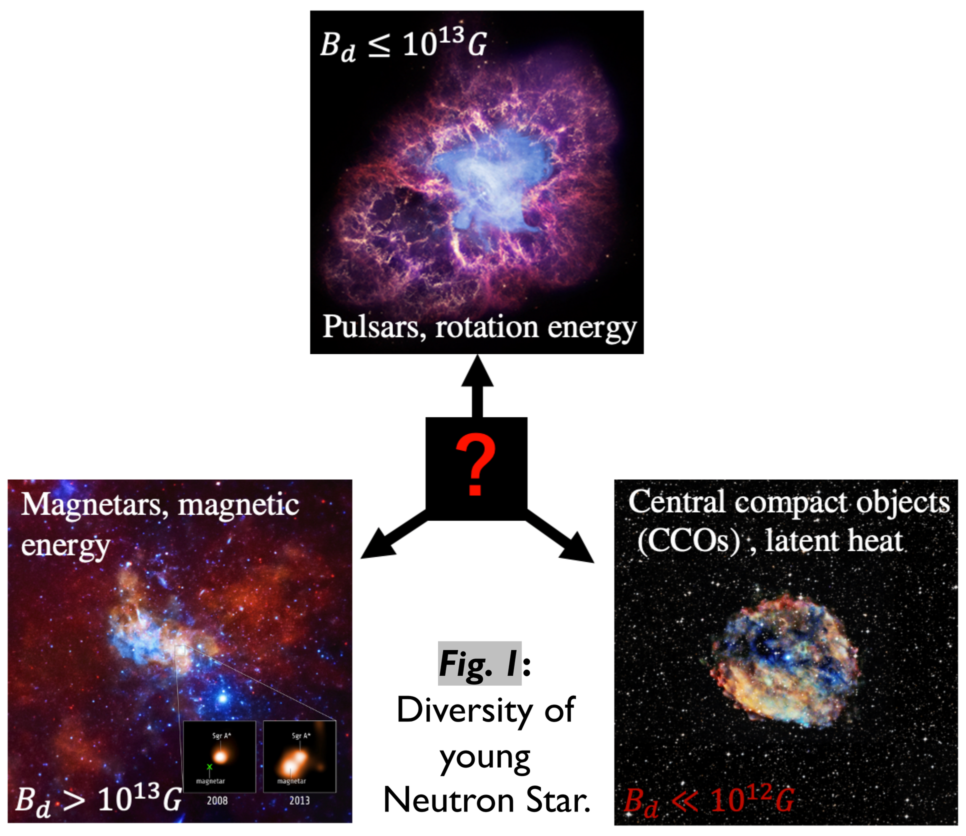

Fig. 1: Diversity of young Neutron Star.

- Young NSs in the Galaxy with ages of 1-10 kyr are categorized into three classes: non-recycled pulsars, magnetars, and central compact objects (CCOs) (e.g., *Enoto et al. (2019)*). Their main energy sources are considered to be different, and the surface magnetic field significantly vary. The origin of the diversity is still unknown.
- Fall-back accretion was suggested to be important for forming this diversity (e.g., *Muslimov & Page (1995)*)
- To study this diversity, we investigate a collision between a marginally bounded inflow and a relativistic fireball outflow, resembling to supernova fall-back accretion onto newborn pulsar wind through 1-D Relativistic Hydrodynamics simulation in Athena++

Setup

$$\zeta = \frac{L_{\rm out}}{\dot{M}_{\rm fb}(t=0)c^2}$$

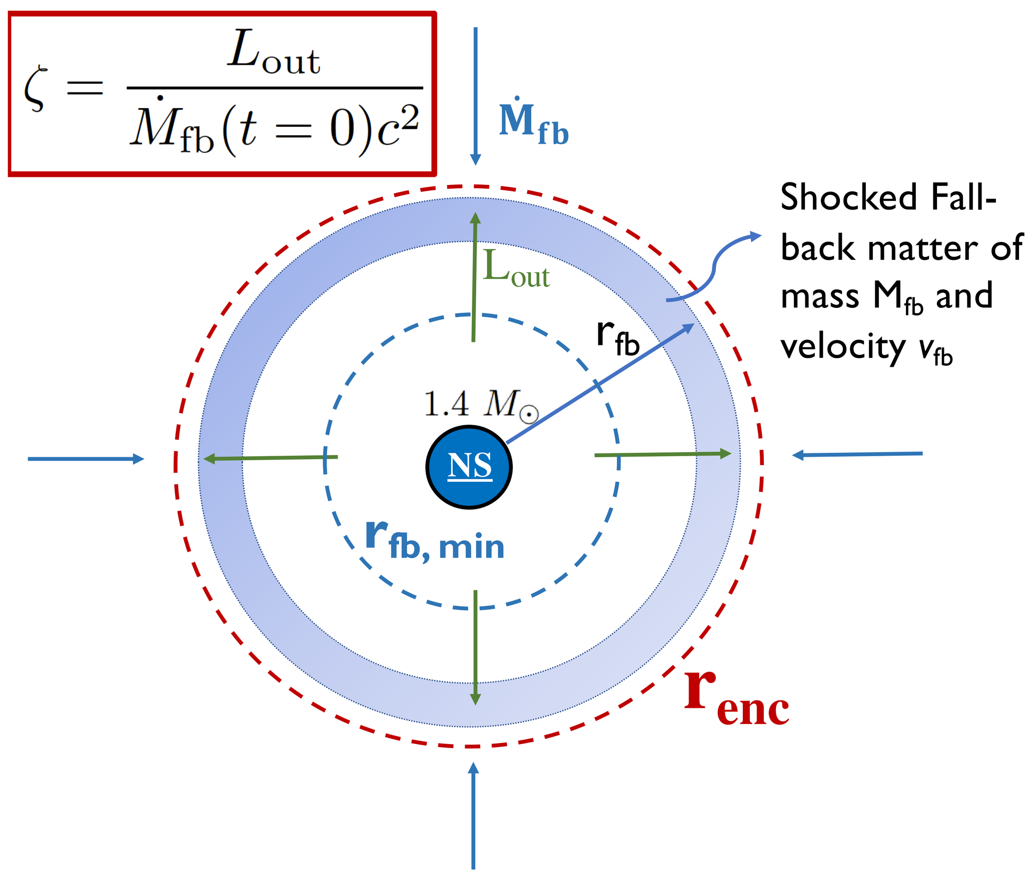

Fig. 2: Schematic picture of a fall-back accretion onto a relativistic outflow from a newborn neutron star with energy flux ratio ζ at encounter radius $r_{\rm enc}$

Analytical model of fall-back accretion

The thin shell approximation

(Validity has been verified)

A simplified ver. of hydro Eqs. for the contact surface

$$\frac{dM_{\rm fb}}{dt} = -4\pi r^2 \rho (v - v_{\rm fb}),$$

$$\frac{d}{dt}(M_{\rm fb}v_{\rm fb}) = 4\pi r_{\rm fb}^2 P - \dot{M}(v - v_{\rm fb}),$$

$$3\frac{d}{dt}(PV) + P\frac{dV}{dt} = L,$$

$v_{\rm fb,0} = (GM/r_{\rm enc})^{1/2}(\sqrt{\zeta/\zeta_{\rm cri}} - 1)$
$4\pi r_{\rm enc}^2 P_0 = L/c$
$M_{\rm fb,0} = 0$
can be integrated analytically till $v_{\rm fb} = 0$
$V = 4\pi r_{\rm fb}^3/3$
$r_{\rm fb,0} = r_{\rm enc}$

Minimum radius the fall-back matter could reach

$$r_{\rm fb,min} = r_{\rm enc}\zeta^{2/3}\left(\frac{r_{\rm enc}}{r_{\rm Sch}}\right)^{1/3} f(t_{\rm min})$$

$$f(t_{\rm min}) = \left[1 + \frac{c\int_0^{t_{\rm min}} dt' r_{\rm fb}(t')^3}{r_{\rm enc}^4}\right]^{2/3}$$

Can be fitted by numerical results

- $r_{\rm fb,\,min} < r_0$ gives the **criterion that fall-back matter invades down to the radius r_0**

Results

- Time evolution of accretion shock with different $\zeta = \frac{L_{\rm out}}{\dot{M}_{\rm fb}(t=0)c^2}$

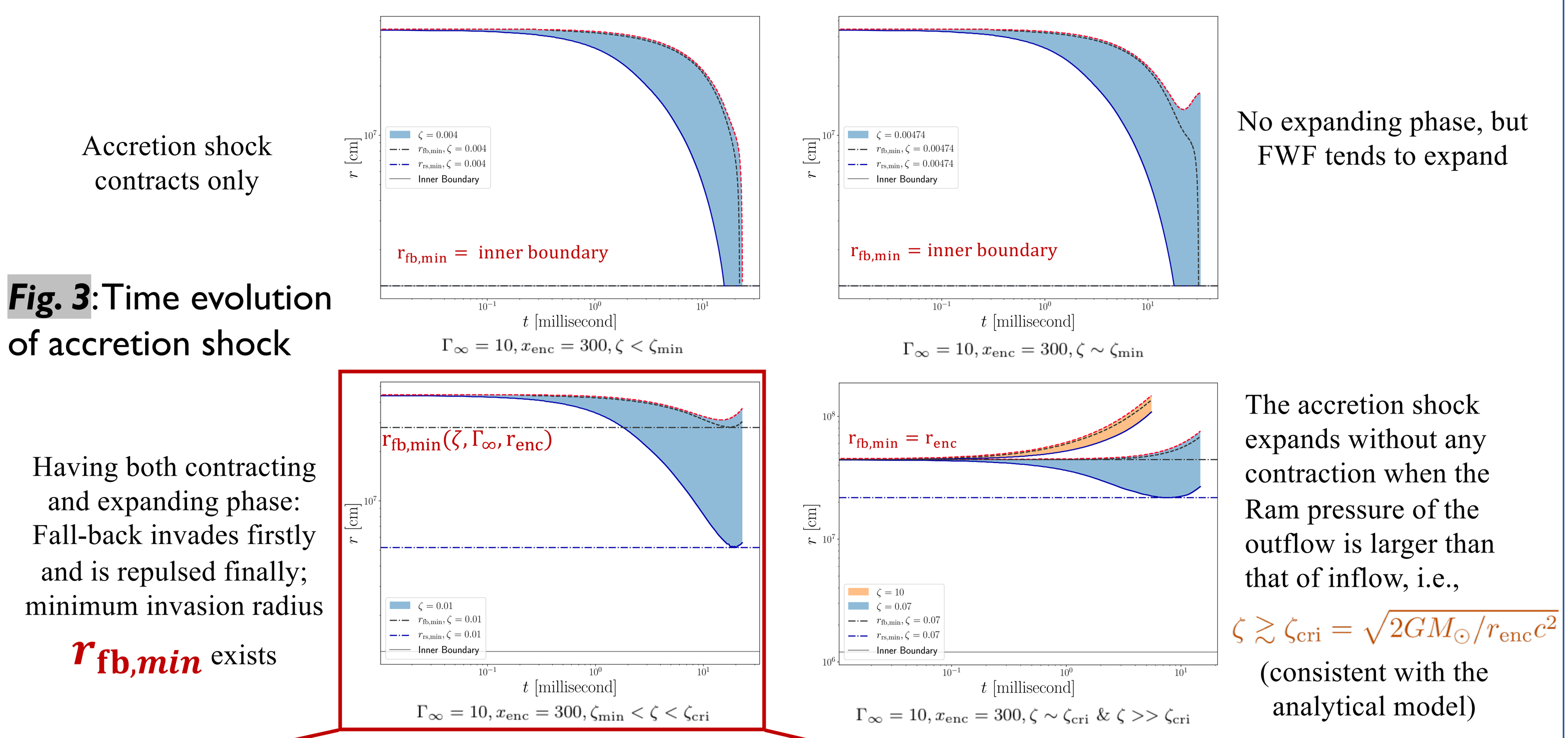

Fig. 3: Time evolution of accretion shock

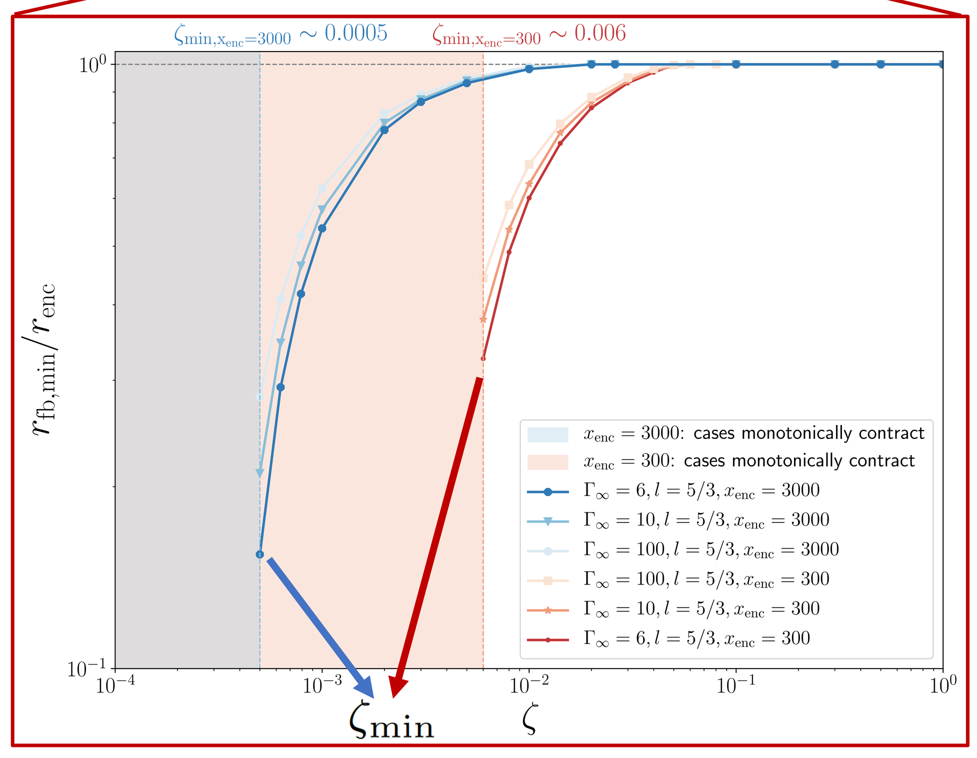

Fig. 4: Dependence of $r_{\rm fb,min}$ on energy ratio ζ

Existing a minimum energy flux ratio $\zeta_{\rm min}$! Fall-back matter reaches the NS surface successfully in cases with ζ smaller than it

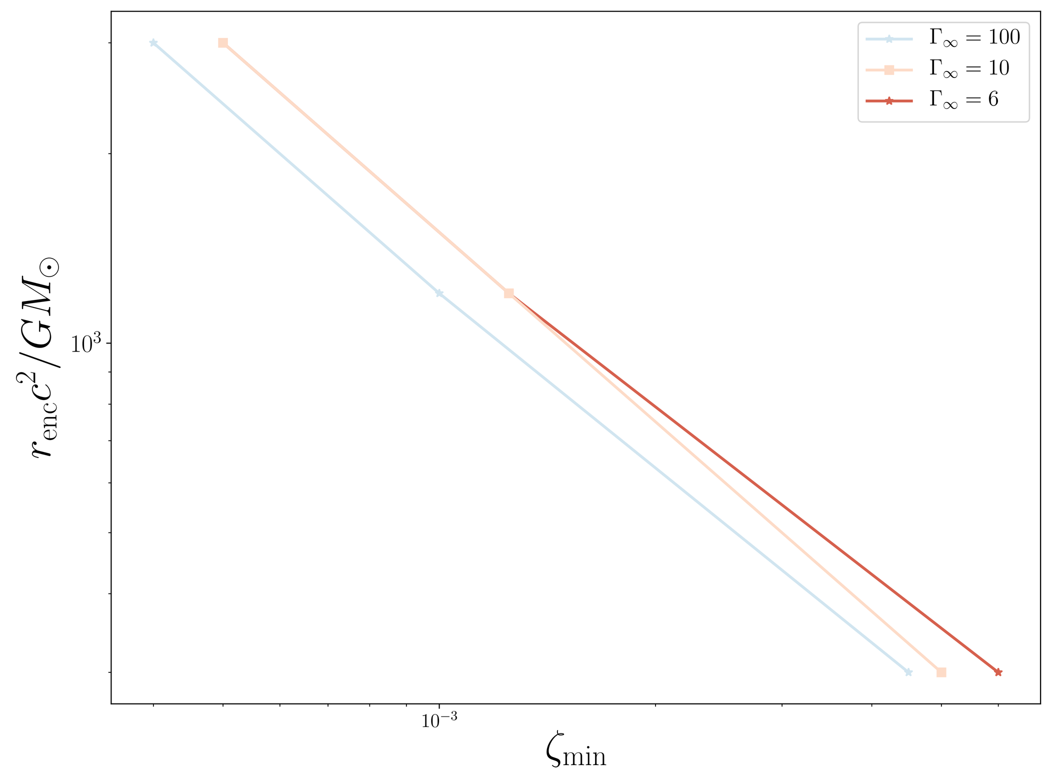

Fig. 5: dependence of $\zeta_{\rm min}$ on encounter radius $r_{\rm enc}$

I.e.

$$\zeta_{\rm min} \sim 1.5GM_\odot/r_{\rm enc}c^2$$

Conclusion and discussions

- Combining the analytical model based on thin shell approximation with numerical study, we are able to predict how much fall-back matter could successfully invade down to **magnetosphere** and **NS surface**, which gives implications about the diversity of NS as follows:

➤ *The invasion condition down to the* ***light cylinder***

$$r_{\rm fb,min} = r_{\rm enc}\zeta^{2/3}\left(\frac{r_{\rm enc}}{r_{\rm Sch}}\right)^{1/3} f(t_{\rm min}),\quad r_{\rm fb,min} < r_{\rm lc}$$

$$\Rightarrow \dot{M}_{\rm fb} > \dot{M}_{\rm fb,lc} \equiv 1.1\times10^{-7}\,M_\odot\,{\rm s}^{-1}\left(\frac{\xi_1}{10}\right) B_{13}{}^2 P_{-1}{}^{-11/2} t_{\rm fb,1}{}^{4/3}$$

$(\xi_1 = f(t_{\rm min})^{3/2})$ **B**: Surface dipole Magnetic field; **P**: Rotation period

e.g., the ***magnetosphere*** *of a Crab-like pulsar can be marginally invaded with a typical fallback*

➤ *The invasion condition down to the* ***NS surface*** *without bouncing back*

$$\zeta < \zeta_{\rm min} = \xi_2 GM_\odot/r_{\rm enc}c^2 \Rightarrow \dot{M}_{\rm fb} > \dot{M}_{\rm fb,R} \equiv 5.5\times10^{-7}\,M_\odot\,{\rm s}^{-1}\left(\frac{\xi_2}{1.5}\right)^{-1} B_{13}{}^2 P_{-1}{}^{-4} t_{\rm fb,1}{}^{2/3}$$

i.e., The ***Surface of NS*** *could be buried if the fall-back accretion rate is large enough, which indicates the bifurcation points between CCOs and Pulsars*

Contact

Yici ZHONG (ジョン　イチ)
Faculty of Science Bldg.1, the University of Tokyo
Email: zhong-yici@g.ecc.u-tokyo.ac.jp

東京大学
THE UNIVERSITY OF TOKYO

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