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R-Process Nucleosynthesis in Alfvén Wave-driven Proto-Neutron Star Winds

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We propose magnetic proto-neutron star (PNS) winds driven by Alfvén waves as well as the neutrino heating as an appropriate site for the r-process nucleosynthesis. Alfvén waves excited by surface motions of a PNS propagate outwardly, and they heat and accelerate the wind by dissipation. In the Alfvén wave-driven wind, larger entropy per baryon and shorter dynamical time scale are achieved, which favors the r-process. A PNS with surface $B_0 \gtrsim 5 \times 10^{14}$G, gives suitable wind properties for the r-process in a typical case. We also perform nuclear reation calcuations and confirm this result; the 3rd peak elements are sufficiently synthesized in the Alfvén wave-driven wind in such a condition.

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1. Introduction

A neutrino-driven wind is probably the most promising site of the rapid neutron capture process (r-process). However, it is difficult to realize the suitable condition for the r-process in the wind of the standard proto-neutron star (PNS) (*e.g.* [1]). Recently roles of magnetic fields are highlighted to suitable circumstances for the r-process, namely short dynamical timescale, $t_{\rm exp}$, and large entropy per baryon, S. Thompson (2003) [2] considered large-scale scale magnetic fields which confine the plasma to achieve enough S. As another possibility, Suzuki & Nagataki [3] proposed that Alfvén waves generated from magnetic PNS give faster acceleration (smaller $t_{\rm exp}$) and larger heating (larger S) in the wind by the additional momentum and energy inputs. In this contribution, we firstly introduce basic properties of Alfvén wave-driven winds, and then, present results of nucleosynthesis calculations.

2. Model

We consider steady-state winds from PNSs with radius, $R_{\rm NS} = 10$ km, under the Newtonian gravity. We assume radial expansion of magnetic flux tubes in which the winds flow out, giving magnetic flux conservation, $Br^2 = B_0 r_0^2$, where B_0 is the surface magnetic field strength. Difference from the standard neutrino-driven wind is that we take into account the acceleration by the wave pressure, P_w, in the momentum equation and the heating, $\dot{q_w}$, by the wave dissipation in the energy equation which are

$$v\frac{dv}{dr} = -\frac{GM}{r^2} - \frac{1}{\rho}\frac{dP}{dr} - \frac{1}{\rho}\frac{dP_w}{dr} \tag{2.1}$$

and

$$\dot{q_\nu} + \dot{q_w} = v\left(\frac{d\mathscr{E}}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right), \tag{2.2}$$

respectively, where $\dot{q_\nu}$ is cooling/heating by neutrino and the other variables have the usual meanings. The acceleration ($\frac{dP_w}{dr}$) and heating ($\dot{q_w}$) by the Alfvén wave are determined by a suitable dissipation model. Here, We assume wave action, defined as $H_w \equiv \frac{\delta B^2}{8\pi}\frac{(v_{\rm A}+v)(v_{\rm A}+v)}{v_{\rm A}}$ which is an adiabatic constant in unit of energy flux, follows an exponential decay on r with dissipation length, l:

$$H_w = \frac{R_{\rm NS}^2}{r^2} H_{w,0} \exp\left(\frac{R_{\rm NS} - r}{l}\right), \tag{2.3}$$

We inject Alfvén waves with initial amplitude, $\delta B_0/B_0 = 0.1$ at the surface, and we construct transonic wind solutions (see [3] for more detailed setting of the model and subsonic cases.) We only consider strong magnetic field cases, $B_0 = 10^{14} - 10^{15}$G, because otherwise the Alfvén waves only give a tiny effect on the winds. l can be estimated from the solar wind studies by one of the authors [4 – 6], in which weakly nonlinear ($\delta B_0/B_0 \sim 0.1$) waves dissipate typically after propagating ~ 10 wavelengths, corresponding to $l \lesssim 10 R_{\rm NS}$ in the present PNS conditions.

3. Results

Figure 1 shows the structures of the Alfvén wave-driven winds. The left panels present dependence on surface magnetic field, B_0, and the right panels present dependence on dissipation length,

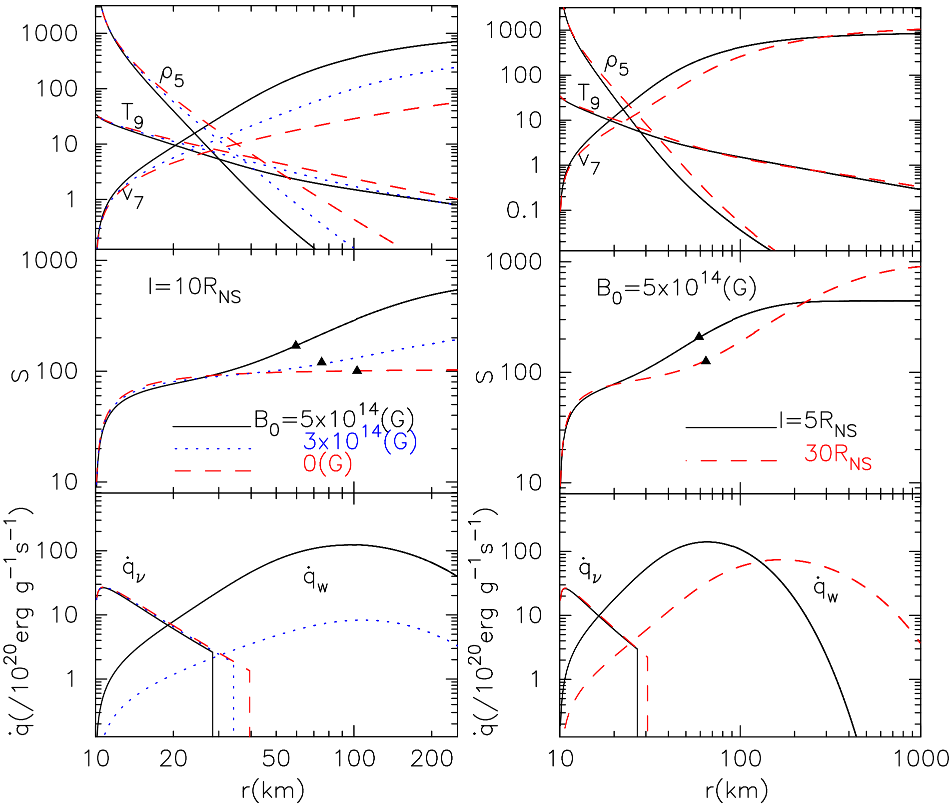

Figure 1: Structures of Alfvén wave-driven winds. The top panels show density in unit of 10^5 g cm^{-3}, ρ_5, temperature in 10^9 K, T_9, and velocity in 10^7 cm s^{-1}, v_7. The middle panels exhibit entropy per baryon, S. The bottom panels show the heating by waves, $\dot{q_w}$, and by neutrinos, $\dot{q_\nu}$. The left panels show dependence on B_0 ($= 5 \times 10^{14}$ G; solid, 3×10^{14} G; dotted, 0 G; dashed) for fixed $l = 10R_{\rm NS}$ and the right panels show dependence on l ($= 5R_{\rm NS}$; solid, $30R_{\rm NS}$; dashed) for fixed $B_0 = 5 \times 10^{14}$ G.

l. Thanks to the wave pressure, the wind is accelerated faster as B_0 increases. The heating due to the wave dissipation also gives larger S in the larger B_0 case. Therefore, the conditions in the Alfvén wave-driven winds are favorable for the r-process. Faster dissipation (smaller l) leads to more rapid increase of S, which is also better for the r-process.

In Figure 2 we compare the results of $t_{\rm exp}$ and S with the r-process condition[1] by [1],

$$S \gtrsim 2 \times 10^3 Y_e \left(\frac{t_{\rm exp}}{s}\right)^{1/3}, \tag{3.1}$$

where Y_e is electron fraction which our model does not explicitly include. For standard $Y_e (= 0.4 - 0.5)$, Alfvén -driven winds of PNSs with $B_0 \gtrsim 5 \times 10^{14}$ G satisfy the condition, provided $l < 10R_{\rm NS}$.

Next, we calculate the actual nucleosynthesis in the Alfvén wave-driven winds [8]. We perform nuclear reaction network calculations by adopting the physical conditions (ρ and T) which change with time according to the outward velocities along with the flows. Figures 3 and 4 show the dependences of the synthesized elements on B_0 and l, where we assume electron fraction $= 0.4$.

[1] This is strictly the condition for α-process [7] which determines a neutron-to-seed ratio before the neutron capture occurs.

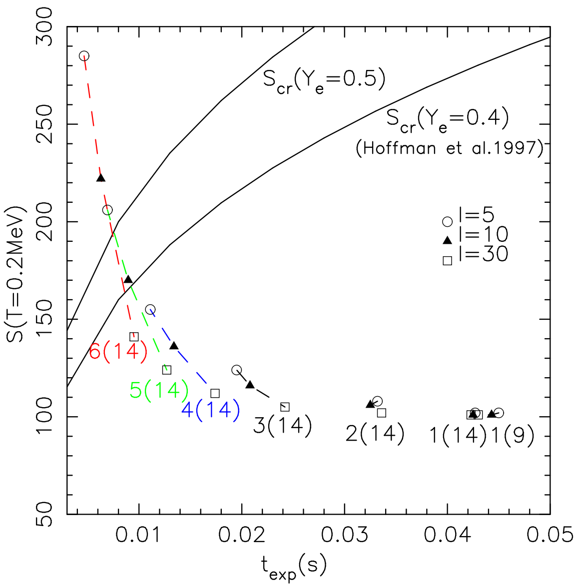

Figure 2: $t_{\rm exp}$(s) (X-axis) and S at $T = 0.2$MeV (Y-axis) for various parameters of Alfvén waves. Open circles, filled triangles, and open squares are results with $l = 5$, 10, & 30, respectively. Numbers denote magnetic field strength at the surface. For example 6(14) indicates $B_0 = 6 \times 10^{14}$G. Results with the same B_0 are connected by dashed lines. Solid lines are the conditions for the r-process by [1] for $Y_e = 0.4$ & 0.5.

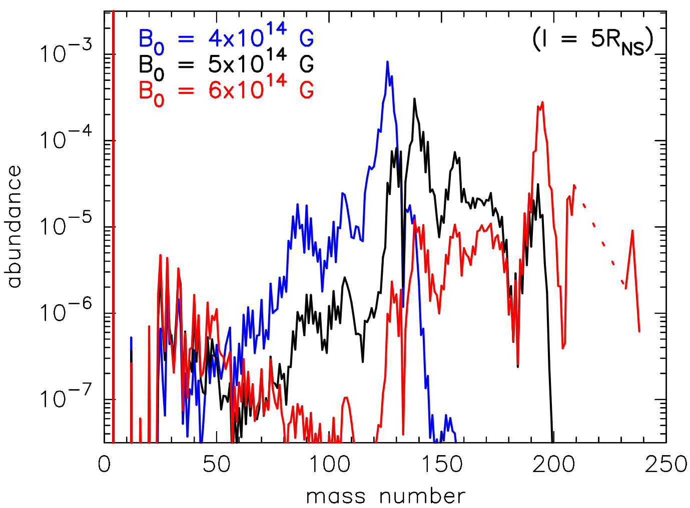

Figure 3: Results of the synthesized elements in the Alfvén wave-driven winds. The red, black, and blue lines correspond to $B_0 = 6 \times 10^{14}$ G, 5×10^{14} G, and 4×10^{14} G, respectively, where we adopt constant $l = 5R_{\rm NS}$.

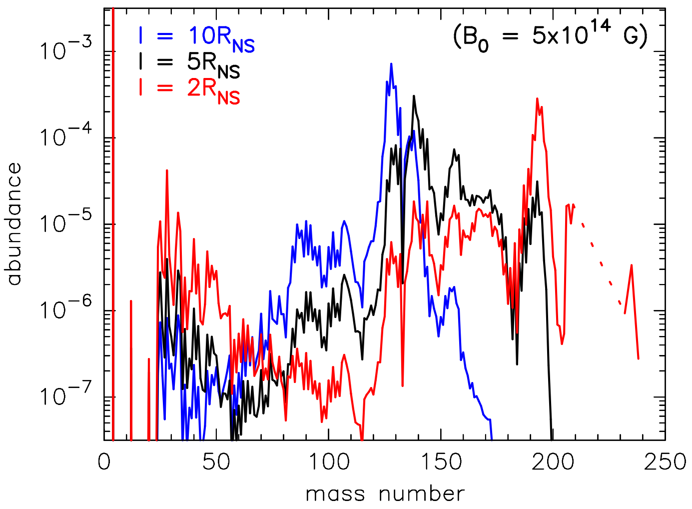

Figure 4: The same as Figure 3 but for the ł dependence. The red, black, and blue lines correspond to $l = 2R_{\rm NS}$, $5R_{\rm NS}$, and $10R_{\rm NS}$, respectively, for $B_0 = 5 \times 10^{14}$ G.

Figure 3 illustrates that larger B_0 favors the r-process. While the 3rd peak elements (mass number, $A \approx 195$) are not produced in the $B_0 = 4 \times 10^{14}$ G case (see [8] for non magnetic field case), they are synthesized in the $B_0 = (5,6) \times 10^{14}$ G cases. In the $B_0 = 6 \times 10^{14}$ G case, sizable amounts of elements with $A = 230 - 240$ are also synthesized. This is because the nonequilibrium circumstances with small $t_{\rm exp}$ and large S are achieved in larger B_0, which is suitable for the r-process.

Figure 4 exhibits that smaller l is favorable to the synthesis of the r-process elements; the 3rd peak elements are produced in the cases with $l = (2,5)R_{\rm NS}$, while they are not in the case with $10R_{\rm NS}$. This is because S should be large in the inner region where the α-process [7] takes place to give a sufficiently large neutron-to-seed ratio, which requires small l. Otherwise if l is large, the wave heating occurs in the outer region and the increase of S is a little to slow; in the case with $l = 10R_{\rm NS}$, the 3rd peak elements are not synthesized.

References

[1] Hoffman, R. D., Woosley, S. E., & Qian, Y.-Z. 1997, ApJ, 482, 951

[2] Thompson, T. A. 2003, ApJ, 585, L33

[3] Suzuki, T. K. & Nagataki, S. 2005, ApJ, 628, 914

[4] Suzuki, T. K. 2004, MNRAS, 349, 1227

[5] Suzuki, T. K. & Inutsuka, S. 2005, ApJ, 632, L49

[6] Suzuki, T. K. & Inutsuka, S. 2006, JGR, 111, A06101

[7] Woosley, S. E. & Hoffman, R. D. 1992, ApJ, 395, 202

[8] Wanajo, S., Suzuki, T. K. & Nagataki, S. 2006, submitted to ApJL