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 reaction calculations 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, $t_{\text{exp}}$, 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 $t_{\text{exp}}$) 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, $R_{\text{NS}} = 10$ 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, $q_w$, by the wave dissipation in the energy equation which are

$$\frac{dv}{dr} = \frac{GM}{r^2} - \frac{1}{\rho} \frac{dP}{dr} - \frac{1}{\rho} \frac{dP_w}{dr},$$ (2.1)

and

$$q_{\text{v}} + q_{\text{w}} = v \left( \frac{d\varepsilon}{dr} - \frac{P}{\rho^2} \frac{d\rho}{dr} \right),$$ (2.2)

respectively, where $q_{\text{v}}$ is cooling/heating by neutrino and the other variables have the usual meanings. The acceleration ($\frac{dv}{dr}$) and heating ($q_{\text{w}}$) by the Alfvén wave are determined by a suitable dissipation model. Here, We assume wave action, defined as $H_w \equiv \frac{1}{8\pi} \frac{\delta B_0^2}{\rho^2} (v_A + v)(v_A + v)$ which is an adiabatic constant in unit of energy flux, follows an exponential decay on $r$ with dissipation length, $l$:

$$H_w = \frac{R_{\text{NS}}^2}{l^2} H_{w,0} \exp \left( \frac{R_{\text{NS}} - r}{l} \right).$$ (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 $\sim 10$ wavelengths, corresponding to $l \approx 10R_{\text{NS}}$ 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 $10^5 \text{g cm}^{-3}$, $\rho$, temperature in $10^9 \text{K}$, $T$, and velocity in $10^7 \text{cm s}^{-1}$, $v_7$. The middle panels exhibit entropy per baryon, $S$. The bottom panels show the heating by waves, $q_w$, and by neutrinos, $q_\nu$. The left panels show dependence on $B_0 (= 5 \times 10^{14} \text{G}; \text{solid}, 3 \times 10^{14} \text{G}; \text{dotted}, 0 \text{G}; \text{dashed})$ for fixed $l = 10R_{\text{NS}}$ and the right panels show dependence on $l (= 5R_{\text{NS}}; \text{solid}, 30R_{\text{NS}}; \text{dashed})$ for fixed $B_0 = 5 \times 10^{14} \text{G}$.

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 $t_{\text{exp}}$ and $S$ with the r-process condition\(^1\) by [1],

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

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

Next, we calculate the actual nucleosynthesis in the Alfvén wave-driven winds [8]. We perform nuclear reaction network calculations by adopting the physical conditions ($\rho$ 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 $\alpha$-process [7] which determines a neutron-to-seed ratio before the neutron capture occurs.
Figure 2: \( t_{\text{exp}}(s) \) (X-axis) and \( S \) at \( T = 0.2 \text{MeV} \) (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 \( B_0 = 6 \times 10^{14} \text{G} \). 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 \( B_0 = 6 \times 10^{14} \text{G}, 5 \times 10^{14} \text{G}, \) and \( 4 \times 10^{14} \text{G} \), respectively, where we adopt constant \( l = 5 R_{\text{NS}} \).
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 $t_{\text{exp}}$ 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 $l = (2, 5) R_{\text{NS}}$, while they are not in the case with $10 R_{\text{NS}}$. This is because $S$ should be large in the inner region where the $\alpha$-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 $l = 10 R_{\text{NS}}$, the 3rd peak elements are not synthesized.

References