Effects of a New Triple-α Reaction on X-Ray Bursts of a Helium-Accreting Neutron Star

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The effects of a new triple-α reaction (OKK) rate on a helium flash of a helium-accreting neutron star in a binary system have been investigated. Since ignition points determine the properties of a thermonuclear flash of type I X-ray bursts, we examine the cases of different accretion rates, \( \frac{dM}{dt} (\dot{M}) \), of helium from \( 3 \times 10^{-10} M_\odot \text{yr}^{-1} \) to \( 3 \times 10^{-8} M_\odot \text{yr}^{-1} \), which could cover the observed accretion rates. We find that, at low accretion rates, nuclear burning occurs at the helium layers of rather low densities. As a consequence, helium deflagration would be triggered at accretion rate lower than \( \dot{M} \simeq 3 \times 10^{-8} M_\odot \text{yr}^{-1} \). We find that the OKK rate is consistent with the available observations of X-ray bursts on a helium-accreting neutron star. We advocate that the OKK rate is better than the previous rate for the astrophysical phenomena of X-ray burst due to helium accretion.

Subject Index: 423, 425, 481

1. Introduction

A new challenge has been raised in the study of the triple-α (3-α) reaction rate, which has been calculated by Ogata et al.1) and found to be very large compared with the previous rate used.2)–5) As a consequence, the new rate results in helium \( (^4\text{He}) \) ignition at a lower density/temperature on the stellar evolution of low-, intermediate-, and high-mass stars,6)–7) accreting white dwarfs,8)–9) and accreting neutron stars.10)–12) Therefore, it is urgent to quantitatively clarify how the new rate affects the above astrophysical phenomena, because the rate plays a most fundamental role in the nuclear burning in heavenly bodies and some role in the early universe, where terrestrial experiments on the 3-α reaction are very difficult. In the present study, we investigate the effects of a newly calculated 3-α reaction (OKK) rate1) on helium flashes that occur at bottom layers inside an accreting envelope of a neutron star. We can use the ignition curves to roughly determine when nuclear ignition occurs. We note that X-ray bursts, which have been extensively studied so far, are limited to the combined burning of hydrogen and helium13) and observational features such as light curves and burst energy have been qualitatively explained well. Fujimoto et al.14) have succeeded in simulating X-ray bursts by solving whole-structure equations and clarified for the first time the importance of heat flow from the bottom of an accumulated layer. The application has been carried out for several X-ray burst observations of combined H and He burnings.15)–17) However, a detailed

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comparison between observations and calculations related to successful bursts, very low accretion rates, or superbursts remains to be performed (e.g., 13, 18)).

Fynbo et al.\textsuperscript{19}) (we call the reference Fynbo) revised the $3\alpha$ rate of NACRE\textsuperscript{3} on the basis of new experiments at high temperatures of $T > 10^9$ K and with an artificial extrapolation up to the very low temperature region toward $T \sim 10^7$ K. However, in the present case of accreting neutron stars, we can regard the differences between NACRE and Fynbo as unimportant, because the OKK rate is much larger at temperatures less than $10^8$ K than the difference between NACRE and Fynbo.

Note that, although nuclear burning strongly depends on temperature, the density becomes very important at high densities of $\rho \geq 10^6$ g cm$^{-3}$ and at low temperatures of $T \leq 10^8$ K owing to the screening effects.\textsuperscript{8}

The new rate has been found to significantly affect the evolution of low- and intermediate-mass stars,\textsuperscript{4, 5} where the evolutions from the zero-age main sequence through the core He flash/burning from 1 $M_\odot$ to 10 $M_\odot$ have been investigated. From the HR diagram obtained with the OKK rate, the results are clearly in disagreement with the observations. If the OKK rate in the temperature range of $10^8$ K $< T < 2 \times 10^8$ K is precisely correct, we must invoke some new physical processes such as rotational mixing and convection mechanism.

On the other hand, Saruwatari and Hashimoto\textsuperscript{20}) have shown the important difference between the ignition points calculated using the two rates for a helium-accreting carbon-oxygen white dwarf. They have concluded that at all accretion rates, nuclear fuel ignites at the accumulated layers of helium and the scenario of type Ia supernovae changes for low accretion rates of $\dot{M} < 4 \times 10^{-8}$ $M_\odot$ yr$^{-1}$. Related to this study, since the progenitor of type Ia supernovae has been constructed with the use of the previous reaction rate, discussions concerning the origin of the supernovae being the binary between a white dwarf and red giant could change.\textsuperscript{21}

Furthermore, a simple helium ignition model of an accreting neutron star has been investigated.\textsuperscript{12}) It is concluded that the OKK rate does not fit the observations of X-ray bursts owing to the pure helium accretion but that the previous rate is in agreement with the observations. However, their model is based on a model of one variable of column density, and only a steady state has been monitored until the ignition. Note that the whole structure from the center to the surface of a neutron star must be solved to discuss the thermal evolution of accreting neutron stars. This has been stressed by Fujimoto et al.\textsuperscript{14}) Therefore, it is desirable to include the whole structure and monitor the evolution of accreting neutron stars with physical processes included,\textsuperscript{14}) if we try to elucidate the effects of the OKK rate on the evolution and compare the results with the available observations. We note that, for the combined burning of H and He, no difference between Fynbo and OKK rates appears since the burst is triggered at higher temperatures of $T > 5 \times 10^8$ K.\textsuperscript{22}) In this paper, we present the results of the evolutionary calculation beyond the helium ignition of a helium-accreting neutron star. We will show the important role of both the $3\alpha$ reaction rates in the low-temperature region and the properties of crustal heating.\textsuperscript{23, 24}}
2. Evolution toward the explosive helium burning on the accreting neutron star

Accreting neutron stars are considered to be the origin of type I X-ray bursts.\(^{14}\) Accreting materials are usually hydrogen and helium. Since hydrogen is converted to helium through steady hydrogen burning, helium gradually accumulates on the neutron star and deep layers become hot and dense. Helium flashes triggered in the region composed of degenerate electrons could develop up to the dynamical stage, depending on the accretion rate \(\dot{M}\).\(^{21}\) The properties of ignition are determined from the thermal structure around the bottom of accreting layers. It has been found that unstable helium burning after the exhaustion of hydrogen results if helium accretes in the range of \(2 \times 10^{-10} M_\odot \text{ yr}^{-1} < \dot{M} < 10^{-9} M_\odot \text{ yr}^{-1}\).\(^{18}\)

We have computed the evolution of an accreting neutron star by the Henyey-type implicit-explicit method\(^{14}\) during the hydrostatic evolutionary stage of the accretion of helium, where the full set of general relativistic equations of spherically symmetric stars is based on the formulation by Thorne.\(^{25}\) Physical inputs are the same as those in Ref. 14) except for the network of nuclear burning and additional heating from the crust. We note that, under the assumption of a spherical symmetry, the basic four equations of neutron star evolution become the same as those of an ordinary stellar evolution except for the effects of general relativity.

Initial models are constructed by accreting helium on a neutron star, the gravitational mass and radius of which are \(M = 1.3 M_\odot\) and \(R = 8.1\) km, respectively. We can obtain the initial models for each constant accretion rate shown in Table I, after the steady state has been achieved, as in Ref. 14): the integrated energy flux of the nonhomologous part for the gravitational energy release becomes negligible and therefore the thermal structure almost does not change. The masses gradually increase during the accretion toward the steady state and the amounts are less than 1% of the total mass when the steady state has been achieved.

To monitor nuclear burning, the alpha network has been implemented to obtain the nuclear energy generation rate:\(^{26}\) the network consists of \(^4\text{He}, ^{12}\text{C}, ^{16}\text{O}, ^{20}\text{Ne}, ^{24}\text{Mg}, ^{28}\text{Si}, ^{32}\text{S}, ^{40}\text{Ca}, ^{44}\text{Ti}, ^{48}\text{Cr}, ^{52}\text{Fe},\) and \(^{56}\text{Ni}\). We include and examine the two reaction rates of Fynbo and OKK for the \(3\alpha\) reaction, and the other reaction chain is selected from the faster reaction of either \((\alpha, \gamma)\) or \((\alpha, p)\) followed by the \((p, \gamma)\) reactions. After the calculations for the stellar structure have been converged, the iteration of this network is operated to obtain the nuclear energy generation rate to calculate the next stellar structure as in Ref. 17). The nuclear energy generation rate of the \(3\alpha\) reaction is crucial in determining the ignition conditions and is proportional to \(T_9^{-3} \exp(-44.0/T_9)\) in the high-temperature region of \(T_9 > 0.1\). However, the temperature dependence cannot be written using a simple analytical formula, that is,

\[
\varepsilon_{3\alpha} \propto \rho^2 \left(\frac{Y}{4}\right)^3 f\langle 3\alpha\rangle(T),
\]

(1)

where \(Y\) is the helium mass fraction and \(f\) is the screening factor, which is included in the same formula given in Ref. 2). As a function of \(T\), \(\langle 3\alpha\rangle(T)\) was obtained from the thermal average using the Maxwell-Boltzmann distribution concerning the product of the cross section and the relative velocity.\(^{1}\)
The importance of crustal heating during the thermal evolution of neutron stars has been pointed out. The heating rates are tabulated in Ref. 27), and the heating rate is determined using

$$Q_i = 6.03\dot{M}_{10}q_i \frac{q_i}{1\text{MeV}} 10^{33} \text{erg s}^{-1},$$

(2)

where $\dot{M}_{10}$ is the accretion rate in units of $10^{-10} \ M_\odot \ yr^{-1}$ and $q_i$ is deposited heat in MeV/nucleon, whose representative value within the present accretion rate in this paper is evaluated to be 0.012 MeV/nucleon from the obtained average heating rate:

$$\langle Q_i \rangle = \frac{\int_{\text{crust}} Q_i dm}{\Delta M}, \quad \Delta M = \int_{\text{crust}} dm,$$

(3)

where $dm = 4\pi r^2 \rho dr$ and the integral covers the crust of the density range $10^{11} - 10^{13} \ g \ cm^{-3}$ and $\Delta M \simeq 1.2 \times 10^{-4} \ M_\odot$ with a thickness of 1 km. We can easily include it just as the neutrino energy loss rates and/or nuclear generation rates, that is, the rate of the crustal heating is added in addition to the nuclear energy generation rate, where we write the energy equation in Newtonian approximation for simplicity:

$$\frac{\partial L_r}{\partial \dot{M}_r} = \varepsilon^*_{n} - \varepsilon_\nu - T \left( \frac{\partial s}{\partial t} \right)_{M_r},$$

where $L_r$ is the energy flow and $\varepsilon^*_{n}$ includes both the nuclear energy generation rate and crustal heating rate. $\varepsilon_\nu$ is the neutrino energy loss rate and $s$ is the specific entropy.

We have selected six cases of accretion for two reaction rates (see Table I), where the height of the accreted layer is at most 10 m during shell flashes. We have shown the evolutionary tracks in Fig. 1 for the OKK rate (left panel) and Fynbo rate (right panel) with solid lines. The tracks correspond to the bottom of the accretion layers, where the maximum temperature results and shell flashes are triggered in the neighborhood of the region.

Let us define the ignition and deflagration and/or detonation curves to clearly show the points of helium ignition and the development of shell flashes. The density and temperature in Eqs. (4)–(8) must correspond to the bottom of the burning layer and/or around that of the accreted layer. The energy conservation law can be written as

$$c_P \frac{dT}{dt} = \varepsilon_n - \varepsilon_{\text{rad}},$$

(4)

where $c_P$ is the specific heat at a constant pressure and $\varepsilon_n$ is the nuclear generation rate of the 3-\(\alpha\) reaction. We approximate the radiative loss in simple form as

$$\varepsilon_{\text{rad}} = \frac{4\kappa c T^4}{3\kappa \sigma^2},$$

(5)

where $\kappa$ is the opacity, $\sigma$ is the column density, $\alpha$ is the radiation constant, and $c$ is the speed of light. The column density can be obtained from the pressure and gravitational acceleration for a neutron star model (see Eq. (9)). The ignition curve
Fig. 1. Evolutionary track of the temperature against the density at the bottom of the burning layer in $\dot{M} = 3 \times 10^{-10} M_\odot \text{yr}^{-1}$ for the 3-$\alpha$ reaction rate of OKK (left panel) and Fynbo (right panel). The ignition and deflagration curves are defined by $\varepsilon_n = \varepsilon_{\text{rad}}$ and Eq. (8), respectively. is defined on the plane of $(\rho, T)$ to satisfy the equality $\varepsilon_n = \varepsilon_{\text{rad}}$. The ignition curves are drawn in Fig. 1 for the OKK and Fynbo rates, where we can infer that helium ignition is triggered at a much lower density.

The dynamical timescale $\tau_{\text{dyn}}$ is defined as

$$\tau_{\text{dyn}} = \frac{1}{\sqrt{24\pi G\rho}},$$

where $G$ is the gravitational constant. On the other hand, the time scale $\tau_n$ of the increase in temperature due to nuclear burning is defined as

$$\tau_n = \frac{c_p T}{\varepsilon_n}.$$  

The deflagration curve has been obtained using the condition below:\textsuperscript{8})

$$\tau_n = \tau_{\text{dyn}}.$$  

If $\tau_n < \tau_{\text{dyn}}$, a deflagration wave should arise, which could develop and burn out the previously accumulated layers. The deflagration curves are also drawn on the plane of $(\rho, T)$ in Fig. 1. We note that the curves depend significantly on the helium mass fraction designated by $Y$.

Figure 1 shows the evolutionary track on the plane of $(\rho, T)$ toward the helium ignition for the bottom of the burning layer (around the bottom of the accreted layer) and a subsequent helium flash beyond the deflagration curves, where the deflagration curves at two helium mass fractions ($Y = 0.1$ and 0.5) are drawn using the OKK and Fynbo rates. We can find that helium ignition occurs in lower-density regions by almost two orders of magnitude if the OKK rate is adopted. We note that, for $\dot{M} < 3 \times 10^{-8} M_\odot \text{yr}^{-1}$, a helium flash develops up to the dynamical stage. Therefore, our hydrostatic evolution code cannot follow the dynamical stage, which would lead to deflagration and/or detonation.

3. Comparison with the observations

It would be useful to determine which 3-$\alpha$ rate is more consistent with the available observations. In general, it is very difficult
Table I. Energy releases $E_{\text{burst}}$ per burst for a fixed accretion rate are given in two cases of OKK and Fynbo. The ignition pressure for each $\dot{M}$, $P_{\text{ign}}$, corresponds to the maximum temperature layer inside the accretion layers whose location is around the bottom of the accumulated ones.

| reaction rate | $M$ [$M_\odot$ yr$^{-1}$] | log $P_{\text{ign}}$ [dyn cm$^{-2}$] | $E_{\text{burst}}$ [erg] |
|---------------|-----------------|-----------------|-----------------|
| OKK           | $3 \times 10^{-10}$ | 24.34           | $4.98 \times 10^{40}$ |
|               | $8 \times 10^{-10}$ | 23.07           | $2.72 \times 10^{39}$ |
|               | $1 \times 10^{-9}$  | 23.04           | $2.52 \times 10^{39}$ |
|               | $5 \times 10^{-9}$  | 23.03           | $2.47 \times 10^{39}$ |
|               | $1 \times 10^{-8}$  | 22.90           | $1.80 \times 10^{39}$ |
|               | $3 \times 10^{-8}$  | 22.68           | $1.09 \times 10^{39}$ |
| Fynbo         | $3 \times 10^{-10}$ | 26.47           | $6.84 \times 10^{41}$ |
|               | $8 \times 10^{-10}$ | 24.35           | $5.13 \times 10^{40}$ |
|               | $1 \times 10^{-9}$  | 24.31           | $4.73 \times 10^{40}$ |
|               | $5 \times 10^{-9}$  | 23.83           | $1.51 \times 10^{40}$ |
|               | $1 \times 10^{-8}$  | 23.34           | $5.07 \times 10^{39}$ |
|               | $3 \times 10^{-8}$  | 22.68           | $1.09 \times 10^{39}$ |

To follow in hydrodynamical calculations a helium flash until the fuel of helium is depleted, as described in the previous section. However, using the results of evolutionary calculations obtained in a previous section, we can qualitatively compare the theoretical calculations with the observations. We choose the layer of the helium ignition from which the pressure, density, temperature, and composition of helium are obtained. We define the density $\rho_{\text{ign}}$ and the pressure $P_{\text{ign}}$ for the layer when helium ignition occurs. We can obtain $\rho_{\text{ign}}$ from the crossing point between the evolutionary track of the bottom of the accreting layer and the ignition curve. As a consequence, $P_{\text{ign}}$ is obtained using the equation of state. Since the accumulated layers are well approximated using the plane parallel model, we can adopt the approximation to estimate the accumulated mass with sufficient accuracy. It is written in the spirit of the plane parallel model that (29)–(31)

$$P_{\text{ign}} = g_s \sigma_{\text{ign}},$$

where $g_s$ is the gravitational acceleration and $\sigma_{\text{ign}}$ is the the column density at the ignition point. The energy release $E_{\text{burst}}$ can be obtained under the assumption that the accumulated layers on the ignition layer are completely burnt out:

$$E_{\text{burst}} = \Delta M_{\text{ign}} Q_{\text{nuc}} / (1 + z_s),$$

$$= 4\pi R^2 \sigma_{\text{ign}} Q_{\text{nuc}} / (1 + z_s).$$

Here, $\Delta M_{\text{ign}}$ is the total rest mass of the accreted layers, the gravitational redshift, $z_s = (1 - 2GM_t/c^2R)^{-1/2} - 1 \approx 0.38$, and $Q_{\text{nuc}}$ is the nuclear energy release per nucleon ($Q_{\text{nuc}} = 1.6$ MeV/nucleon), where all the helium fuel is assumed to be burnt into iron. For our model of the neutron star, since $g_s = GM(1 + z_s)/R^2$, we obtain $\log g_s = 14.56$.

In Table I, we show $P_{\text{ign}}$ and $E_{\text{burst}}$ in each accretion rate in the cases of OKK and Fynbo. In Fig. 2, we show $E_{\text{burst}}$ as a function of the accretion rate $\dot{M}$; we also show the two observations of type I X-ray bursts; 4U1820-30 (labeled 4U1820-30), SLX 1737-282, SLX 1735-269, and 2S 0918-549 (labeled intermediate long bursts).
Fig. 2. Energy release of $E_{\text{burst}}$ against the accretion rate $\dot{M}$ in two cases of OKK and Fynbo. Observed values from different astrophysical objects, which have been identified to cause type I X-ray bursts due to pure helium accretion, are plotted as was done in Ref. 12).

Their accreted matter from their companions is pure helium.\textsuperscript{32)–37)} As is mentioned in Ref. 12), the uncertainties of accretion rates and burst energies are indicated by boxes. For these three observations, we can see from Fig. 2, that the results obtained using OKK are consistent with the observations if we choose the accretion rate of $\dot{M} \leq 3 \times 10^{-10} M_\odot \text{ yr}^{-1}$.

4. Discussion and conclusions The ignition densities that determine the triggering mechanism on helium-accreting neutron stars will change significantly if we adopt the new $3\alpha$ reaction rate for the low accretion rate of $\dot{M} < 10^{-8} M_\odot \text{ yr}^{-1}$. Until the OKK rate has been presented, the method by Nomoto\textsuperscript{8)} has been used, of which the simple extrapolation of the Breit-Wigner type function up to the low-temperature side is adopted, where it has been advocated that the nonresonant $3\alpha$ reaction is crucial in determining the helium ignition of compact stars for a low accretion rate. However, the microscopic calculation to solve the three-body problem has been found to be crucial in evaluating the $3\alpha$ reaction rate. In the present study, we have examined the effects of the OKK rate on the very low temperature site of astrophysics. Although our results seem to contradict those of Peng and Ott,\textsuperscript{12)} we may ascribe it to the following. First, we have cited the rate of crustal heating from Ref. 27). Second, they have used the mass of $1.4 M_\odot$ and the radius of 10 km for a neutron star. Third, although we have followed the evolution of an accreting neutron star from the center to the surface of the star, they have solved only steady-state equations above the crust as a function of a single dependent variable of the column density. As a consequence, it has been written that the outward energy release due to the crustal heating was taken to be a free parameter as a boundary condition, which would be inappropriate in the calculations of accreting neutron stars.

The most important difference comes from the treatment of crustal heating. In the present case, the energy flux (erg cm$^{-2}$s$^{-1}$) from the crust is shown in Fig. 3. The average energy per unit mass from the crust can be evaluated to be $\sim 0.01$ MeV/nucleon, as shown in the previous section. In contrast, the rate they...
Fig. 3. Energy flux in units of erg cm$^{-2}$s$^{-1}$ from the crust against accretion rates with use of the table$^{27}$ (solid line), and the two boxes are cited from Ref. 12).

have adopted was nearly 0.1 MeV/nucleon.$^{24}$ These differences reflect the calculations of the heat flux, as shown in Fig. 3, where the solid line represents the heat flux in our calculations and the two boxes are cited from Ref. 12). It is clear that the heat flux from the crust in the present study is 1–2 orders of magnitude lower than that in Ref. 12). As a consequence, our initial models just before accretion starts might have lower temperatures than those discussed in Ref. 12). The most significant difference would come from the initial model, and therefore from the location of the ignition point on the ($\rho, T$) plane. While the bottom of the accreted layers in our initial model for $\dot{M} = 3 \times 10^{-10} M_\odot$ yr$^{-1}$ has a temperature of $T = 1.6 \times 10^7$ K (see Fig. 1.), we can infer from Ref. 12) that the temperature could be rather high. From the column density obtained from the box of the observation of intermediate long bursts (see Fig. 2 in their paper), we can obtain the ignition temperature of $T = (1 - 2) \times 10^8$ K for the Fynbo rate. If the initial temperature of their calculation takes nearly the same temperature, which is a common feature of accreting compact objects before the beginning of shell flashes,$^{38}$ ignition density is found to be in the neighborhood of that at the OKK rate. In contrast to our calculations, which are the results of stellar evolution and include all the necessary physical processes, their calculations depend essentially on the numerically convenient boundary condition at the assumed surface of the crust.

We have shown that the OKK rate must change the scenario of type Ia supernovae and type I X-ray bursts for low accretion rates, where the temperature at the ignition is less than $10^8$ K. Since the rate was calculated under the situation of three-$\alpha$-particles in vacuum, the application of the OKK rate is doubtful against the high density. As seen from Fig. 3 in Ref. 1), the discretized continuum wave functions of the two-$\alpha$-particle system extend to $5 \times 10^5$ fm. Therefore, in the medium of stellar plasma, the effects of more than three $\alpha$-particles cannot be negligible for $\rho > 10^6$ g cm$^{-3}$. $^{39}$ For example, the reaction rate is to be calculated with the inclusion of an appropriate screening potential. If the effects of many-body interactions are included, the OKK rate should decrease by several orders of magnitude. We may
constrain the 3-α reaction rate from the astrophysical observations of type I X-ray bursts.

As an example of constraint for the OKK rate, if we adopt the upper values of the observational box of $E_{\text{burst}}$ in Fig. 2 for $M = 3 \times 10^{-10} M_\odot \text{ yr}^{-1}$, we obtain $\log P_{\text{ign}} \sim 24.9$ from Eqs. (9)–(11). Since the evolutionary paths are almost the same for the two 3-α rates up to the ignition points (see Fig. 1), the corresponding ignition density with the evolutionary paths of OKK becomes in the range of $\log \rho_{\text{ign}} = 7.7 - 7.8$ for the OKK rate reduced by a factor of $10^{2-3}$. We note that the properties of shell flash depend to some extent on the structure of a neutron star (mass and radius). Since $E_{\text{burst}}$ is proportional to $R^4/M$, a rather hard EOS ($R = 12 \text{ km}$ and $M = 2.0 M_\odot$) gives a three fold larger value than that in our case, which would be preferable for the OKK rate. On the other hand, it depends on nonstandard cooling processes: if we use nonstandard cooling processes such as a pion condensation, our estimates would change significantly.

In conclusion, we have found that the new rate affects helium ignition in accreting neutron stars, where for lower accretion rates helium burns at lower densities and temperatures, which should change the period of the formation of a helium deflagration wave and the modeling of type I X-ray bursts. In particular, we consider that crustal heating affects the ignition properties significantly. Furthermore, the mechanism behind superbursts should be studied again using the new rate, because the amount of $^{12}\text{C}$ could play a crucial role in inducing superbursts.

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1) K. Ogata, M. Kan and M. Kamimura, Prog. Theor. Phys. 122 (2009), 1055.
2) K. Nomoto, F.-K. Thielemann and S. Miyaji, Astron. Astrophys. 149 (1985), 239.
3) C. Angulo et al., Nucl. Phys. A 656 (1999), 3.
4) A. Dotter and B. Paxton, Astron. Astrophys. 507 (2009), 1617.
5) P. Morel, J. Provost, B. Pichon, Y. Lebreton and F. Thévenin, Astron. Astrophys. 520 (2010), A41.
6) K. Nomoto and M. Hashimoto, Phys. Rep. 163 (1988), 13.
7) M. Hashimoto, Prog. Theor. Phys. 94 (1995), 663.
8) K. Nomoto, Astrophys. J. 253 (1982), 798.
9) K. Nomoto, Astrophys. J. 257 (1982), 780.
10) M. Y. Fujimoto, T. Hanawa and S. Miyaji, Astrophys. J. 247 (1981), 267.
11) S. Miyaji and K. Nomoto, Astron. Astrophys. 152 (1985), 33.
12) F. Peng and C. D. Ott, Astrophys. J. 725 (2010), 309.
13) W. H. G. Lewin, J. van Paradijs and R. E. Taam, Space Sci. Rev. 62 (1993), 223.
14) M. Y. Fujimoto, T. Hanawa, I. Iben Jr. and M. B. Richardson, Astrophys. J. 278 (1984), 813.
15) T. Hanawa and M. Y. Fujimoto, Publ. Astron. Soc. Jpn. 38 (1986), 13.
M. Y. Fujimoto, M. Sztajno, W. H. Lewin and J. van Paradijs, Astrophys. J. 319 (1987), 902.

T. Hanawa and M. Y. Fujimoto, Publ. Astron. Soc. Jpn. 36 (1984), 199.

L. Bildsten, in NATO ASIC Proc. 515: The Many Faces of Neutron Stars, ed. R. Bucciero, J. van Paradijs and M. A. Alpar (Kluwer, Dordrecht, 1998), p. 419.

H. O. U. Fynbo et al., Nature 433 (2005), 136.

M. Saruwatari and M. Hashimoto, Prog. Theor. Phys. 124 (2010), 925.

K. Nomoto, F.-K. Thielemann and K. Yokoi, Astrophys. J. 286 (1984), 644.

R. K. Wallace and S. E. Woosley, Astrophys. J. 45 (1981), 389.

K. Sato, Prog. Theor. Phys. 62 (1979), 957.

A. Cumming, J. Macbeth, J. J. M. in’t Zand and D. Page, Astrophys. J. 646 (2006), 429.

K. S. Thorne, Astrophys. J. 212 (1977), 825.

R. Kuromizu, O. Koike, M. Hashimoto and K. Arai, Physics Reports of Kumamoto University 11 (2002), 197.

P. Haensel and J. L. Zdunik, Astron. Astrophys. 227 (1990), 431.

T. Hanawa, D. Sugimoto and M. Hashimoto, Publ. Astron. Soc. Jpn. 35 (1983), 491.

T. Hanawa and D. Sugimoto, Publ. Astron. Soc. Jpn. 34 (1982), 1.

T. Hanawa and M. Y. Fujimoto, Publ. Astron. Soc. Jpn. 34 (1982), 495.

M. Hashimoto, T. Hanawa and D. Sugimoto, Publ. Astron. Soc. Jpn. 35 (1983), 1.

F. Haberl, L. Stella, N. E. White, W. C. Friedhorsky and M. Gottwald, Astrophys. J. 314 (1987), 266.

J. J. M. in’t Zand et al., Astron. Astrophys. 389 (2002), L43.

M. Falanga, J. Chenevez, A. Cumming, E. Kuulkers, G. Trap and A. Goldwurm, Astron. Astrophys. 484 (2008), 43.

S. Molkov, M. Revnivtsev, A. Lutovinov and R. Sunyaev, Astron. Astrophys. 434 (2005), 1069.

J. J. M. in’t Zand, A. Cumming, M. V. van der Sluys, F. Verbunt and O. R. Pols, Astron. Astrophys. 441 (2005), 675.

J. J. M. in’t Zand, D. K. Galloway and D. Ballantyne, Astron. Astrophys. 525 (2011), A111.

D. Sugimoto and K. Nomoto, Space Sci. Rev. 25 (1980), 155.

K. Ogata, private communication.

A. Cumming and L. Bildsten, Astrophys. J. 559 (2001), L127.