Explosive nucleosynthesis in ONeMg novae

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A quasi-analytic study on ONeMg novae is performed to examine explosive nucleosynthesis in wide range of white dwarf and envelope masses. Comparing our results with recent observations enables us to constrain those two parameters. About a half of observed ONeMg novae may have attained high envelope masses such as $\sim 10^{-4}\ M_\odot$, then obtained high burning temperatures ~ 3–4×10^8 K. Those may have produced significant amount of ^{22}Na. Leakage out of CNO material via alpha captures of ^{14,15}O is not of importance in our results but initially enhanced neon in the envelope must be seed nuclei for heavy element production by the rp-process.

1. Introduction

Recent observations show that ~ 25 % of well-studied novae are classified to *ONeMg novae*, occurrences of outbursts with underlying ONeMg white dwarfs. As seen in Table 1, they are characterized by highly enhanced neon and CNO/Ne–Fe ~ 1, which comes from the core-material mixing on ONeMg white dwarfs [8]. Table 1 also shows that the novae enhanced with sulfur deplete oxygen in their ejecta. They may have achieved rather high temperatures during outbursts, which require massive white dwarfs or ignition envelopes [7]. There is, however, a serious disagreement on envelope masses between observations and current theory [2]. The estimated ejecta masses for QU Vul and V1974 Cyg are $\sim 10^{-4}$–$10^{-3} M_\odot$, 10–100 times larger than theoretical estimates [3,4].

ONeMg novae may be important targets for the γ-ray detection of ^{22}Na by *CGRO* and *INTEGRAL*, as well as the sources of *Ne-E* in certain primitive meteorites. The production of ^{22}Na must, however, highly depend on the burning temperatures, therefore, the white dwarf and envelope masses [7].

It has been suggested that HCNO breaking via alpha captures of ^{14,15}O leads to heavy element production by the rp-process nucleosynthesis [6]. These reactions, however, need quite high temperatures such as $\geq 5 \times 10^8$ K. Thus it may be more plausible to consider that the rp-process nucleosynthesis starts from proton captures of initially enhanced ^{20}Ne. This reaction takes place for lower temperature $\sim 4 \times 10^8$ K.

The purpose of this paper is to report our results of nucleosynthesis calculations on ONeMg novae in terms of two parameters, i.e., white dwarf and envelope masses. It enables us to constrain these parameters through comparison of element production with observational estimates. The detectability of ^{22}Na γ-rays and the rp-process nucleosynthesis in ONeMg novae are then discussed.

2. A quasi-analytic study of ONeMg novae

The nova model applied in this work is a quasi-analytic approach for hydrogen shell flashes on accreting white dwarfs [1]. The structure of an envelope is determined uniquely when a white dwarf mass ($M_{\rm WD}$) and an envelope mass ($M_{\rm env}$) are specified, in assumption that the spatially adiabatic envelope expands spherically in hydrostatic equilibrium. We have calculated ~ 50 sequences of $M_{\rm WD}$ ($= 1.1$–$1.4\ M_\odot$) and $M_{\rm env}$ ($= 10^{-6}$–$10^{-3}\ M_\odot$).

The progress of an envelope is derived from the energy generation rate by nuclear reactions involved. The nuclear reaction network used here contains 77 stable and proton-rich isotopes from hydrogen to calcium, including all relevant nuclear reactions. We adopted the up-to-date nuclear reaction rate data [5]. The initial composition in the envelope is assumed to be a mixture of the solar composition gas and the dredge-up matter from the surface of an ONeMg white dwarf. The mixing ratio of the core-surface matter is assumed to be 0.5 by mass, reflecting the average metalicity of $\langle Z \rangle \sim 0.45$ in the ejecta for recent ONeMg nova observations (Table 1).

Comparison of our results with hydrodynamic calculations [2] shows there are no significant differences between them for most element production [7].

Table 1
Heavy element mass fractions in ONeMg novae

Object	Year	O	Ne	S	CNO/Ne-Fe	Z
V693 CrA[1]	1981	0.12	0.17		1.3	0.39
V1370 Aql[2]	1982	0.051	0.52	0.10	0.36	0.86
QU Vul[3]	1984	0.017	0.086	0.012	0.67	0.40
V351 Pup[4]	1991	0.19	0.11		2.5	0.38
V838 Her[5]	1991	0.0032	0.068		0.57	0.11
V1974 Cyg[6]	1992	0.25	0.10	0.011	2.3	0.54
This work*		0.28	0.17	0.0002	1.4	0.51

References: [1]Williams et al. 1985, [2]Snijders et al. 1987, [3]Andreä et al. 1994, [4]Saizar et al. 1996, [5]Vanlandingham et al. 1996, [6]Austin et al. 1996.
*Initial composition

3. Results and conclusions

Our results show that there exist two types of elements based on their production patterns in the $M_{\rm WD}$–$M_{\rm env}$ plane [7]. The first, which shows a clear correlation between the element production and the burning peak temperatures, includes oxygen, neon, and sulfur. Oxygen and neon are much enhanced in the initial gas (Table 1), but decrease significantly by proton captures when the burning temperature exceeds $\sim 3 \times 10^8$ K, and $\sim 4 \times 10^8$ K, respectively. In contrast, sulfur increases substantially over $\sim 3 \times 10^8$ K. Consequently, we can constrain the peak burning temperatures ($T_{\rm peak}$) for the observed six ONeMg novae listed in Table 1, considering that neon may not be depleted significantly for all novae: $T_{\rm peak} \sim 3$–4×10^8 K for sulfur-enhanced or oxygen-depleted novae, V1370 Aql, QU Vul, V838 Her, and V1974 Cyg, and $\leq 3 \times 10^8$ K for V693 CrA and V351 Pup.

The second type of elements, correlated with the burning timescale like carbon and magnesium, helps us to constrain the parameter ranges in the $M_{\rm WD}$–$M_{\rm env}$ plane, coupled with the above results [7]. Finally, we get the ranges of these parameters for each nova: ($M_{\rm WD}/M_\odot$, $M_{\rm env}/M_\odot$) = (1.23–1.3, 3–6$\times 10^{-5}$) for V1370 Aql, ($M_{\rm WD}/M_\odot$, $M_{\rm env}/M_\odot$) = (1.18–1.27, 1–5$\times 10^{-4}$) for QU Vul, ($M_{\rm WD}/M_\odot$, $M_{\rm env}/M_\odot$) = (1.15–1.22, 0.3–5$\times 10^{-4}$) for V1974 Cyg. Indeed, these results suggest that these systems had massive envelopes, in good agreement with observational estimates [3,4], *without* theory. We cannot constrain these parameters strictly for the other three novae because of the lack of heavy element data.

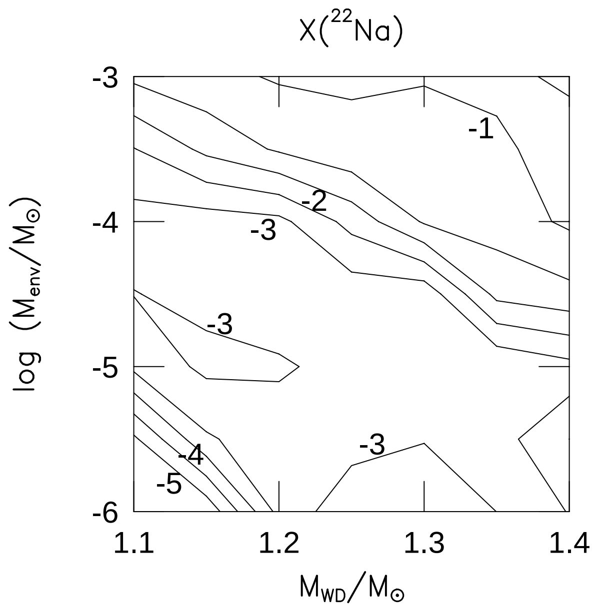

Figure 1. Final production of ^{22}Na by mass fraction in logarithmic scale.

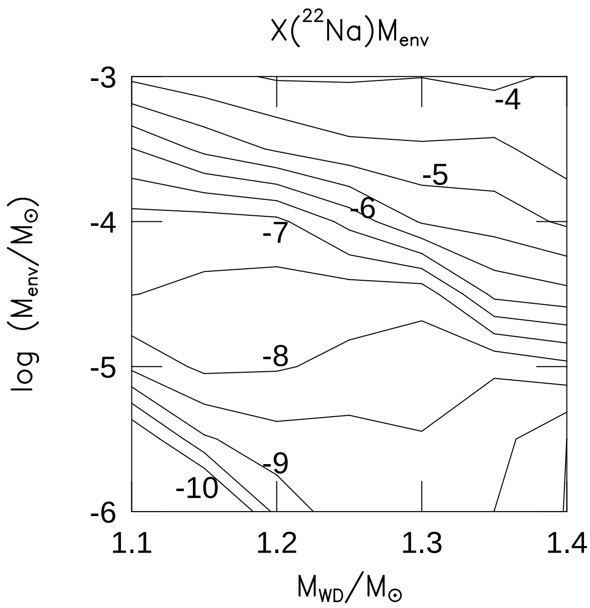

Figure 2. Total amount of ^{22}Na per nova event in logarithmic scale.

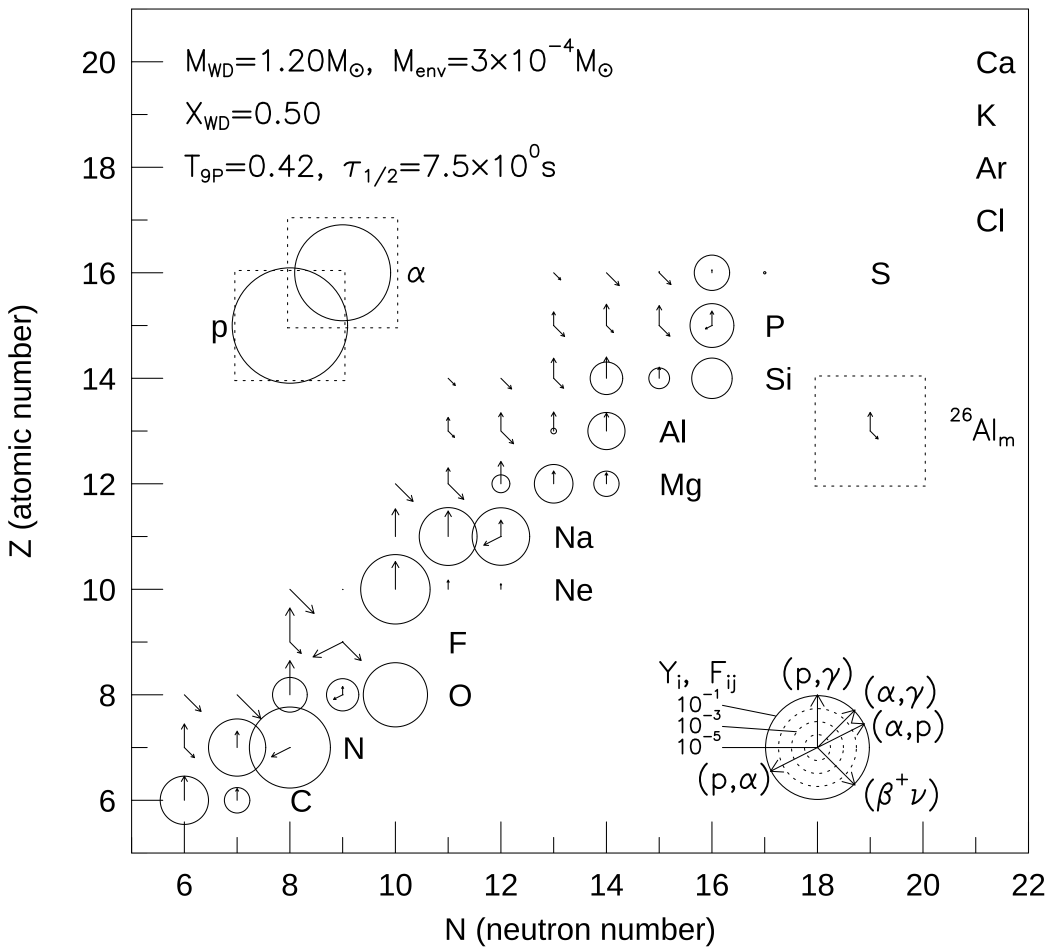

Figure 3. A nuclear chart for $(M_{\rm WD}/M_\odot,\, M_{\rm env}/M_\odot) = (1.2,\, 3\times10^{-4})$. The size of a circle indicates the yield at the final stage, and the length of an arrow the net nuclear flow in the same scale.

Figure 1 shows the final mass fraction of ^{22}Na in the $M_{\rm WD}$–$M_{\rm env}$ plane. ^{22}Na is greatly enhanced when the burning temperature exceeds 4×10^8 K and the burning timescale is comparable to the beta-decay lifetime of ^{22}Mg ($\sim$ 6 s). It is due to the substantial nuclear flux from ^{20}Ne, and the $A = 22$ progenitors that survive proton captures of ^{22}Na, as seen in Figure 3. This is a possible explanation for QU Vul. The resulting γ-ray line flux is detectable for a nova producing $\sim 10^{-7}M_\odot$ of ^{22}Na within the distance of $\sim$ 3 Kpc, with the sensitivity of *CGRO*. Figure 2 shows the total amount of ^{22}Na par event in the $M_{\rm WD}$–$M_{\rm env}$ plane. Assuming that most part of the envelope is eventually blown away, $M_{\rm env} \sim 10^{-4}M_\odot$ is needed for the γ-ray detection. The γ-ray flux from V1974 Cyg might have been just under the sensitivity, which is consistent with the COMPTEL result. However, QU Vul must have produced $\geq 10^{-7}M_\odot$ of ^{22}Na, though it appeared too early for the *CGRO* survey. The next nearby ONeMg nova enhanced with sulfur in the ejecta will be a promising target for ^{22}Na γ-ray line detection by *CGRO* or *INTEGRAL*.

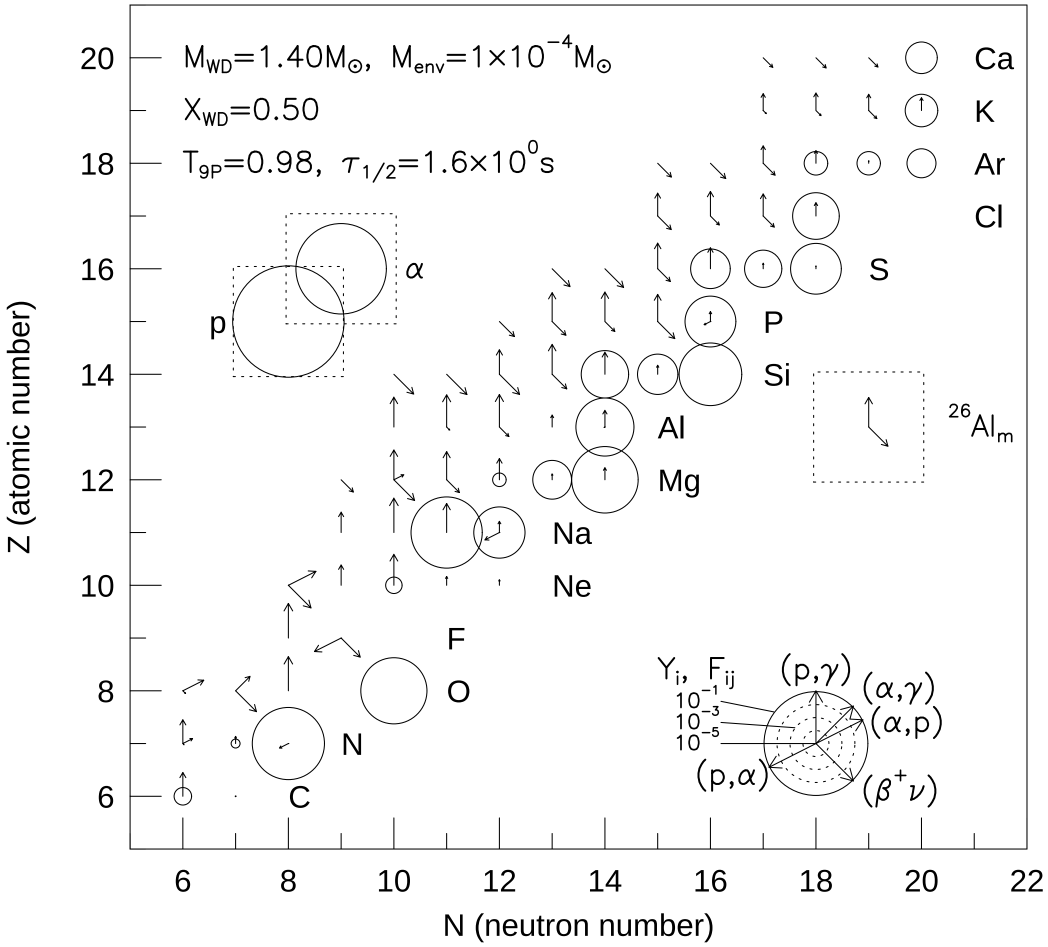

Figure 4. The same as Figure 3, but for $(M_{\rm WD}/M_\odot,\, M_{\rm env}/M_\odot) = (1.4,\, 1 \times 10^{-4})$.

Our results suggest that the HCNO breaking via alpha captures of ^{14,15}O is not of importance on heavy element production by the rp-process nucleosynthesis. The peak burning temperatures of $\sim$3–4 $\times$ 10^8 K is not enough to ignite these reactions. Even in a higher temperature case where the alpha captures of ^{14,15}O are effective, the contribution of nuclear flux via HCNO breaking is much smaller than that of ^{20}Ne(p,γ) as seen in Figure 4. Instead, the rp-process nucleosynthesis starts by the proton captures of ^{20}Ne as seen in Figure 3. The increasing nuclear energy generation fixes the progress of the shell flash to terminate the nuclear flow at sulfur.

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