Synthesis of radioactive nuclei and gamma-line radiation from novae

A.D.Kudryashov\textsuperscript{1}, N.N.Chugai\textsuperscript{2}, and A.V.Tutukov\textsuperscript{2}

\textsuperscript{1}VINITI, Moscow, Russia
\textsuperscript{2}Institute of Astronomy of the RAS, Moscow, Russia

Abstract

We carried out kinetic calculations of thermonuclear burning in the hydrogen-rich matter to simulate nucleosynthesis yields in nova outbursts. These results are used to calculate the light curves of annihilation gamma-ray line from N, O and F radioactive isotopes.

Thermonuclear runaway on accreting white dwarfs (WD) is a conventional model of nova outbursts. High temperature hydrogen burning converts most of initial CNO nuclei to radioactive isotopes $^{13}\text{N}$, $^{14}\text{O}$, $^{15}\text{O}$, $^{17}\text{F}$ and $^{18}\text{F}$ (NOF isotopes); their presence in novae may be evidenced by 511 keV annihilation emission (Clayton & Hoyle 1974; Leising & Clayton 1987). Radioactive $^{22}\text{Na}$ also synthesized in novae may be detected in 1.275 MeV line. Furthermore, galactic $^{26}\text{Al}$ already observed in 1.809 MeV line may be also contributed by novae. Here we concentrate only on the synthesis of short-lived NOF isotopes and computation of annihilation line flux from novae.

Following Kudryashov & Tutukov (1995) we calculate nucleosynthesis in novae using one-zone model. Temperature and density are assumed constant during the burning which is terminated with an exhaustion of the hydrogen fraction $\Delta X=0.1$. The temperature is taken from the range $(1-3) \cdot 10^8$ K, while density is $10^4$ g cm$^{-3}$ in all cases. The adopted composition of CO dwarf is $X(^{12}\text{C})=0.49$, $X(^{16}\text{O})=0.49$, $X(^{22}\text{Ne})=0.01$, $X(^{25}\text{Mg})=0.01$, while for ONeMg dwarf the composition is $X(^{16}\text{O})=0.3$, $X(^{20}\text{Ne})=0.5$, $X(^{24}\text{Mg})=0.2$. Mixing parameter $q$ (mass fraction of the WD matter in the total envelope mass) is varied in the range 0.1–0.9. A kinetic network adopted in this paper is an updated version of that from Kudryashov & Tutukov (1995). Apart from H and He, it includes nuclei from C to Ca and all nuclear reactions with charged particles.

The obtained amount of NOF isotopes in both types of WD is roughly equal to total mass of admixed CO matter of WD in the envelope and thus is proportional to the mixing parameter $q$ (Fig. 1). The fraction of $^{18}\text{F}$ in most cases is within the range $10^{-3} - 10^{-2}$. The mass fraction of $^{22}\text{Na}$ in ONeMg WD envelopes exceeds 1% in a certain region of $T-q$ plane, while in CO dwarf envelopes the fraction of $^{22}\text{Na}$ is usually lower than $10^{-3}$. The fraction of $^{26}\text{Al}$ on ONeMg WD for reasonable values of $T$ and $q$ is between $10^{-4} - 10^{-2}$, while on CO WD $^{26}\text{Al}$ content is in the range $10^{-5} - 10^{-3}$.

We summarize some results of nucleosynthesis computations in Table 1, where compositions of major radioactive isotopes are given for average values.
Table 1: Isotope composition for typical ($T_{8} = 2, q = 0.5$, top) and optimistic
($T_{8} = 1, q = 0.7$, bottom) cases

| WD  | $\epsilon$, 10^17 | $^{12}$N | $^{13}$O | $^{14}$O | $^{18}$F | $^{22}$Na | $^{26}$Al |
|-----|------------------|---------|---------|---------|---------|--------|---------|
| CO  | 4.5              | 4.8e-4  | 2.1e-1  | 2.5e-1  | 8.4e-2  | 2.4e-3 | 2.3e-4  |
| ONeMg | 5.6         | 1.6e-4  | 1.1e-2  | 8.1e-2  | 6.0e-2  | 1.7e-3 | 1.6e-2  |
| CO  | 6.1              | 1.0e-1  | 2.1e-2  | 5.8e-2  | 5.4e-3  | 7.4e-3 | 2.0e-4  |
| ONeMg | 6             | 2.3e-2  | 4.2e-3  | 1.4e-2  | 1.0e-3  | 3.9e-2 | 2.0e-4  |

Table 2: Parameters of novae and annihilation line flux ($d = 1$ kpc)

| Model | WD  | $M$, 10^-5$M_{\odot}$ | $V_{\text{max}}$, km s^{-1} | $f_{\text{mix}}$ | $\psi$, 10^{-4} | $F$, cm^{-2} s^{-1} | $\Phi$, cm^{-2} | $\Delta t$, 10^4 s |
|-------|-----|------------------------|-----------------------------|------------------|-----------------|-------------------|-------------|----------------|
| HP    | CO  | 2                      | 2500                        | 1                | 0.31            | 19                | 53          | 2.8            |
| HH1   | CO  | 2                      | 2500                        | 1                | 0.34            | 33                | 107         | 3.2            |
| W     | CO  | 2                      | 2500                        | 1                | 0.28            | 1                 | 2.6         | 2.6            |
| HH2   | CO  | 2                      | 2500                        | 0.34             | 0.3             | 3                 | 1           | 3.7            |
| HH3   | CO  | 2                      | 2500                        | 0.99             | 0.34            | 28                | 85          | 3.1            |
| HH4   | CO  | 10                     | 2500                        | 1                | 0.34            | 34                | 116         | 3.4            |
| HH5   | CO  | 2                      | 3500                        | 1                | 0.38            | 70                | 214         | 3              |
| HH6   | ONeMg | 2                  | 2500                        | 1                | 0.25            | 17                | 56          | 3.2            |
| HH7   | CO  | 2                      | 2500                        | 1                | 0.34            | 83                | 280         | 3.4            |
| HH8   | ONeMg | 2                  | 2500                        | 1                | 0.25            | 400               | 1300        | 3.3            |

of $T$ and $q$ parameters (typical case) and for parameters, which favour the maximum production of $^{18}$F (optimistic case). We suggest that computed isotope composition refers to the burning zone, which presumably occupies a fraction $\psi$ of the envelope mass. This fraction is computed from the energy balance (nuclear energy is the sum of the gravitation binding and kinetic energy) for 1$M_{\odot}$ WD. Prior to the ejection, isotopes are presumably mixed in the inner fraction $f_{\text{mix}}$ of the envelope.

The flux in the annihilation line for adopted abundances of radioactive isotopes in the typical case (Table 1) is computed assuming that ejecta may expand either homologically ($v = r/t$) or in the form of wind outflow with constant velocity and mass-loss rate. The ejecta mass, velocity and $f_{\text{mix}}$ are free parameters. In the wind case the outflow kinetic luminosity is fixed at Eddington limit $L_{k} = \left[1/2\right]Mv^{2} = 10^{38}$ erg s^{-1}. The emergent annihilation luminosity is determined by the mass of a transparent outer layer ($\tau \leq 1$). The density dependence of a probability of the two-photon positronium annihilation is taken into account.

Given equal outer velocity of ejecta, the emergent luminosity of gammarays is determined by the density distribution of outer layers. The homologous homogeneous sphere (model HH1, see Table 2, Fig. 2a) produces slightly higher second maximum ($^{18}$F) compared to the homologous envelope with the power law density distribution $\rho \propto v^{-7}$ (model HP). This is caused by the lower transparent mass in HP model. The wind model W gives considerably lower flux due to the lower density.
The effect of variation of mass, velocity, composition (ONeMg WD vs. CO WD), and degree of mixing is displayed at Fig. 2b (HH1–HH6 models). The minimum mixing degree restricted by the burning zone \( f_{\text{mix}} = \psi = 0.34 \) severely suppresses both light curve maxima. Remarkably, the marginally incomplete mixing, \( f_{\text{mix}} = 0.99 \), with only 1% of unmixed outer shell results in the complete suppression of initial part \( t < 10^4 \) s of light curve. Therefore, the incomplete mixing, which is quite conceivable in realistic novae makes the detection of the first maximum \( t < 10^3 \) s very problematic.

The Table 2 shows also flux \( F \) (distance 1 kpc) in the second maximum \( t \approx 2 \cdot 10^4 \) s related to \(^{18}\text{F}\), integrated flux (fluence \( \Phi \)) and the characteristic width \( \Delta t = \Phi/F \). Summing up these numbers, for typical burning case the expected fluxes from novae at 1 kpc are in the range \( 3 \cdot 10^{-5} - 7 \cdot 10^{-3} \text{ cm}^{-2} \text{ c}^{-1} \). The upper limit exceeds by a factor of two the detection limit of BATSE for 0.5 day-long events (Smith et al. 1996). Given the fact that roughly every three year nova may occur at the distance \( d < 1 \) kpc the detection of annihilation line from novae seems quite plausible. The flux from the optimistic ONeMg case (HH8, Table 2), may be as high as \( 4 \cdot 10^{-2} \text{ cm}^{-2} \text{ c}^{-1} \) making such events mostly favorable for detection.

References

Clayton D.D., Hoyle F., 1974, ApJ, 187, L101
Leising M.D., Clayton D.D., 1987, ApJ, 323, 159
Kudryashov A.D., Tutukov A.V., 1995, Astron. Reports, 39, 482
Smith D.M., Leventhal M., Cavallo R., et al., 1996, ApJ, 471, 783
Figure 1: Radioactive isotope mass fractions in the envelopes of CO WD (top) and ONeMg WD (bottom). On the left panel is the temperature dependence for $q = 0.5$, while shown on the right panel is the mixing parameter dependence for $T_8 = 2$. 
Figure 2: Annihilation line flux from model novae. The left panel (a) shows the effect of different kinematics and density distribution for homologous models HH1 (solid line) and HP (dotted), as well as for the wind outflow model W (dashed). The right panel (b) shows the effect of the variation of parameters and composition compared to the template model HH1 (thick solid line), viz. model with no mixing (HH2, short dashes), marginally homogeneous mixing (HH3, thin solid line), higher ejecta mass (HH4, long dashes), higher velocity (HH5, dash-dotted), ONeMg WD (vs. CO WD) composition (HH6, dotted).