Nuclear uncertainties in the NeNa-MgAl cycles and synthesis of $^{22}$Na and $^{26}$Al in classical novae

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Abstract. Classical novae eject significant amounts of matter into the interstellar medium, as a result of thermonuclear runaways. Nucleosynthesis associated with nova outbursts includes products from explosive H-burning, such as $^{17}$O, $^{15}$N and $^{13}$C, and also radioactive species like $^7$Be, $^{22}$Na and $^{26}$Al. In this paper we report on new hydrodynamic calculations of nova outbursts, from the onset of accretion to mass ejection. We stress the role played by the nuclear uncertainties associated with key reactions of the NeNa-MgAl cycles on the synthesis of $^{22}$Na and $^{26}$Al.

1 Introduction

The thermonuclear runaway model has been successful in reproducing the main observational properties of classical nova outbursts. According to this scenario, novae are produced by thermonuclear runaways located in the white dwarf component of a close binary system. The large, main sequence companion overfills its Roche lobe, providing matter outflows through the inner Lagrangian point that lead to the formation of an accretion disk around the white dwarf. A fraction of this H-rich matter lost by the companion ultimately ends up on top of the white dwarf, where it is gradually compressed as accretion goes on. The piling up of matter heats the envelope up to the point when ignition conditions to drive a TNR are reached.

An extended set of hydrodynamic computations of classical nova outbursts has been performed during the last 25 years (see [25], [17], [15], and references therein), for a wide range of white dwarf masses and initial luminosities, which have been able to identify two types of nova outbursts, those occurring in CO and in ONe white dwarfs. The latter ones have provided a framework for the origin of the high concentrations of Ne and more massive isotopes found in the spectra of some well-observed nova systems [19]. Among the isotopes synthesized in these so-called ONe novae (mainly $^{13}$C, $^{17}$O and $^{15}$N), two radioactive species have raised a particular astrophysical interest: $^{22}$Na and $^{26}$Al. In this paper we investigate the role played by the nuclear uncertainties associated with key reactions of the NeNa-MgAl cycles on the synthesis of $^{22}$Na and $^{26}$Al during classical nova outbursts.

2 Synthesis of $^{22}$Na and $^{26}$Al in nova outbursts

The role of $^{22}$Na as a diagnosis of a nova outburst was first suggested by [4]. In its decay to a short-lived excited state of $^{22}$Ne ($\tau \sim 3.75$ yr), $^{22}$Na emits a $\gamma$-ray photon of 1.275 MeV. Through this mechanism, nearby ONe novae within a few kiloparsecs
from the Sun may provide detectable γ-ray fluxes. Several experimental verifications of this γ-ray emission at 1.275 MeV from nearby novae have been attempted in the last twenty years, from which upper limits on the ejected 22Na have been derived. In particular, the observations performed with the COMPTEL experiment on-board CGRO of five recent neon-type novae [2], as well as observations of standard novae, have led to an upper limit of \(3.7 \times 10^{-8} \text{M}_\odot\) for the 22Na mass ejected by any nova in the Galactic disk. This limit has posed some constraints on pre-existing theoretical models of classical nova explosions.

\(^{26}\text{Al}\) is another unstable nucleus, with a lifetime of \(\tau = 1.04 \times 10^6\) years, that decays from ground state to the first excited level of \(^{26}\text{Mg}\), which in turn de-excites to its ground state by emitting a gamma-ray photon of 1.809 MeV. This characteristic gamma-ray signature, first detected in the Galactic Center by the HEAO-3 satellite, has been confirmed by other space missions. The most recent measurements made with COMPTEL have provided a map of the 1.809 MeV emission in the Galaxy ([15], [22]). The inferred 1 – 3 \(\text{M}_\odot\) of Galactic \(^{26}\text{Al}\) are, according to the observed distribution, mainly attributed to young progenitors, such as massive AGB stars, SN II and Wolf-Rayet stars. However, a potential contribution from novae or low-mass AGB stars cannot be ruled out.

First estimates of the 22Na and 26Al production in novae were performed by different groups, using simplified one-zone models with representative temperature and density profiles (see [10], [31], [30], [20]), on the basis of ONeMg white dwarf stars. This scenario was revisited by [21] using hydrodynamic computations: the obtained 22Na yields range between \(5 \times 10^{-5}\) and \(5 \times 10^{-5}\), by mass. Assuming that the whole envelope (\(\sim 10^{-4} – 10^{-5} \text{M}_\odot\)) is ejected during the outburst, they derive peak fluxes of the 22Na 1.275 MeV line in the range \((2 – 30) \times 10^{-5}\) photons s\(^{-1}\) cm\(^{-2}\) (corresponding to ONeMg white dwarf masses between 1.00 – 1.35 \(\text{M}_\odot\), respectively) for classical novae exploding at 1 kpc. Their main conclusion, based on the reported 3σ line sensitivity of OSSE and COMPTEL, is that nearby classical novae involving ONeMg white dwarfs of \(M_{\text{wd}} \geq 1.25 \text{M}_\odot\) should produce detectable 22Na γ-rays for CGRO, a prediction not confirmed so far [12]. Their results showed also a significant production of 26Al (i.e., \((19.6 – 7.5) \times 10^{-5}\), by mass, for the same white dwarf mass range), which could account for a major fraction of the Galactic 26Al.

Recent hydrodynamic computations ([14], [4], [13]) using updated nuclear reaction rates have led to a significant reduction of both 26Al and 22Na ejected during nova outbursts. In particular, a mean mass fraction of \(1 \times 10^{-4}\) of 22Na is found in the 1.25 \(\text{M}_\odot\) ONe Model (with \(M_{\text{eject}}^{(22\text{Na})}=1.3 \times 10^{-9} \text{M}_\odot\)), whereas a maximum value of \(6 \times 10^{-4}\) results from the 1.35 \(\text{M}_\odot\) ONe Model (with \(M_{\text{eject}}^{(22\text{Na})}=2.6 \times 10^{-9} \text{M}_\odot\)). The corresponding peak fluxes in the 1.275 MeV 22Na line, below \(10^{-5}\) counts s\(^{-1}\) cm\(^{-2}\) for novae at 1 kpc, turn out to be too low to be detected with OSSE or COMPTEL but represent potential targets for the nearby future INTEGRAL mission [1]. Concerning 26Al, yields ranging from \(2 \times 10^{-3}\) to \(2 \times 10^{-4}\) by mass have been obtained in a series of ONe nova models with masses between 1.15 – 1.35 \(\text{M}_\odot\). Contribution of novae to the Galactic 26Al is limited to \(0.1 – 0.4 \text{M}_\odot\) [1].

Other hydrodynamic computations performed by [24] and [25], using also updated nuclear reaction rates and opacities, have modified previous estimates (i.e., [21]). The expected abundance of 22Na in the ejecta has risen up to \((2 – 3) \times 10^{-3}\), by mass, when 1.25 \(\text{M}_\odot\) ONeMg white dwarfs are adopted, high enough to be detected by
CGRO, provided that all the accreted envelope (∼3 × 10⁻⁵ M⊙) is ejected. On the other hand, the improved input physics translates into a factor of 10 reduction on the synthesis of ²⁶Al, in better agreement with the analysis of the 1.809 MeV emission map provided by COMPTEL, and also with the results previously reported by [16].

Since the synthesis of both ²²Na and ²⁶Al is very dependent on the adopted nuclear reaction rates, we have investigated the effect of the nuclear uncertainties accompanying reaction rates within the NeNa-MgAl cycles on the synthesis of ²²Na and ²⁶Al, using an updated version of the spherically symmetric, hydrodynamic SHIVA code [15]. In a first step, we have identified the most relevant reactions involved in the synthesis of such isotopes. Main results are summarized in Table 1. We stress the crucial role played by ²¹Na(p,γ)²²Mg: a reduction by a factor 100 of the rate given by [1] translates into an increase in the mean abundance of ²²Na in the ejecta by a factor between 1.2 and 3. An increase by a factor of 3 is also obtained when the rate given by [26], instead of that from [1], is adopted for ²²Na(p,γ)²³Mg. Worth noticing is also the increase in the final amount of ²⁶Al by a factor 2 when the term corresponding to the 0.188 MeV resonance, as measured by [29], is reduced by just a factor 1/3.

**Table 1. Test Models**

| Nuclear reaction       | Old rate | Test rate       | X(²²Na)ₜₚₑₓₜ | X(²⁶Al)ₜₚₑₓₜ |
|------------------------|----------|-----------------|----------------|---------------|
| ²¹Na(p,γ)²²Mg           | CF88     | CF88/100        | 2.3            | 1.1           |
| ²⁵Al(p,γ)²⁶Si           | Wie86    | Coc95, case A   | 1              | 1.2           |
|                        | Wie86    | Coc95, case C   | 1              | 0.5           |
| ²³Na(p,γ)²⁴Mg           | CF88     | CF88+Gor89      | 1.2            | 1.3           |
| ²⁶Al(p,γ)²⁷Si           | Vog89    | Vog89           | 1              | 1.9           |
| ²⁶Al⁹(p,γ)²⁷Si          | CF88     | CF88×100        | 1              | 1             |
| ²⁶Si(p,α)²⁷P            | Wie86    | Her95           | 1              | 1             |
| ²⁷Al(p,α)²⁴Mg           | Cha88    | Cha88+Tim88     | 1              | 1             |
| ²⁶Mg(p,γ)²⁷Al           | Ili90    | Ili90+Cha90     | 1              | 1             |

**1.15 M⊙ ONe**

| Nuclear reaction       | Old rate | Test rate       | X(²²Na)ₜₚₑₓₜ | X(²⁶Al)ₜₚₑₓₜ |
|------------------------|----------|-----------------|----------------|---------------|
| ²¹Na(p,γ)²²Mg           | CF88     | CF88/100        | 3              | 1.1           |
| ²²Na(p,γ)²³Mg           | CF88     | Ste96           | 3              | 1.2           |
| ²³Mg(p,γ)²⁴Al           | Wie86    | KUb95           | 1.1            | 1.1           |

**1.25 M⊙ ONe**

| Nuclear reaction       | Old rate | Test rate       | X(²²Na)ₜₚₑₓₜ | X(²⁶Al)ₜₚₑₓₜ |
|------------------------|----------|-----------------|----------------|---------------|
| ²¹Na(p,γ)²²Mg           | CF88     | CF88/100        | 1.2            | 1             |
| ²³Al(p,γ)²⁴Si           | Wor94    | Sch97           | 1              | 1             |

In a second step, a series of hydrodynamic nova models has been computed assuming upper, recommended and lower estimates of the reaction rates, from which limits on the production of both ²²Na and ²⁶Al are derived (see [13] for details). Main results are summarized in Table 2. Large differences in the ²²Na and ²⁶Al yields have been obtained: in particular, a factor ∼ 4 in the ²²Na production for the 1.15 M⊙ ONe Model, and a factor ∼ 7 in the case of ²⁶Al production (1.35 M⊙ ONe Model) when either the upper or the lower estimates are adopted. These differences are too large to accurately predict the contribution of classical novae to the Galactic ²⁶Al, or to...
determine the maximum distance to a classical novae for a potential detection of the 1.275 MeV $^{22}$Na $\gamma$-ray line.

**Table 2.** Ranges of $^{22}$Na and $^{26}$Al production

| Model | Network | $X(\text{^{22}Na})$ | $X(\text{^{26}Al})$ | $X(\text{^{22}Na})_{\text{upper}}$ | $X(\text{^{22}Na})_{\text{lower}}$ | $X(\text{^{26}Al})_{\text{upper}}$ | $X(\text{^{26}Al})_{\text{lower}}$ |
|-------|---------|---------------------|---------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| $1.15 \, M_\odot$ ONe | Lower | 1.2E-4 | 3.3E-4 | 3.8 | 3.6 |
| Upper | 4.6E-4 | 1.2E-3 |
| $1.25 \, M_\odot$ ONe | Lower | 1.9E-4 | 2.0E-4 | 3.2 | 4.4 |
| Upper | 6.0E-4 | 8.7E-3 |
| $1.35 \, M_\odot$ ONe | Lower | 7.7E-4 | 1.5E-4 | 1.8 | 7.3 |
| Upper | 1.4E-3 | 1.1E-3 |

Therefore, we stress the need of new nuclear physics experiments to reduce the uncertainties associated with some key reactions of the NeNa-MgAl cycles, in particular $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$, $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ and $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$. A verification of the yet unpublished values corresponding to the 0.188 MeV resonance of $^{26}\text{Al}^9(p,\gamma)^{27}\text{Si}$, measured by [29], is also recommended.

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