NEW RESULTS ON \(^{26}\text{Al}\) PRODUCTION IN CLASSICAL NOVAE

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ABSTRACT

The production of \(^{26}\text{Al}\) by explosions of classical novae has been computed by means of a hydrodynamic code that follows both the accretion and the explosion stages. A special emphasis has been put on the analysis of the influence of the initial abundances of the accreted envelope, as well as on the nuclear reaction rates involved. With the most recent values of chemical composition and reaction rates available, \(^{26}\text{Al}\) production is lowered with respect to previous computations. According to our results, the final contribution of novae to the Galactic \(^{26}\text{Al}\) is at most 0.4 \(M_\odot\), which is a small part of the estimated \(^{26}\text{Al}\) in the Galaxy derived from COMPTEL observations of the 1809 keV emission.

Subject headings: gamma rays: theory — novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

The discovery of \(^{26}\text{Al}\) in the interstellar medium by the HEAO 3 satellite, through the detection of the 1809 keV \(\gamma\)-ray line (Mahoney et al. 1982; Mahoney et al. 1984), has raised the interest on potential \(\gamma\)-ray diagnostics of nucleosynthesis in several scenarios. This \(\gamma\)-ray line is produced by the decay (\(\tau \approx 10^7\) yr) from the ground state of \(^{26}\text{Al}\) to the first excited state of \(^{26}\text{Mg}\), which de-excites to its ground-state level by emitting a 1809 keV photon. This detection has been confirmed by other space missions like the Solar Maximum Mission \(\gamma\)-ray spectrometer (Share et al. 1985) or several balloon-borne experiments.

Recent measurements made with the COMPTEL instrument on board the Compton Gamma Ray Observatory have provided a map of the 1809 keV emission in the Galaxy. This map shows an extended diffuse emission along the Galactic plane, with a peculiar large-scale asymmetry about the Galactic center and a clumpy structure with several noticeable hot spots (Diehl et al. 1995). The first interpretations of this map have suggested that novae and low-mass stars cannot be the major contributors to the 1809 keV emission, because their low individual yields and their high frequency should provide a smooth distribution, in contradiction with the irregular appearance of the emission (see Prantzos & Diehl 1996 for a review). The general model suggested considers a two-component origin of the emission: a global component following the spiral pattern of the Galaxy (a presumed site of massive star formation) on which several localized regions of intense activity, such as the Vela region, are superimposed (Chen, Gehrels, & Diehl 1995). However, observations of four nearby supernova remnants with COMPTEL do not provide evidence for the 1809 keV emission, although the uncertainties in the distances do not allow us to put severe constraints on \(^{26}\text{Al}\) production by supernovae (Knödlseder et al. 1996b). Finally, recent attempts to understand the 1809 keV map of the sky have analyzed in more detail its correlation with the spiral structure (Knödlseder et al. 1996a). They derive a total \(^{26}\text{Al}\) mass of 2.5 \(M_\odot\), from which at least 0.7 \(M_\odot\) can be attributed to massive stars, stressing that they cannot exclude that a large fraction of \(^{26}\text{Al}\) is produced by novae or low-mass asymptotic giant branch stars. Therefore, with this still unclear panorama, it is worth studying the role played by classical novae in the synthesis of Galactic \(^{26}\text{Al}\).

As pointed out by Ward & Fowler (1980), \(^{26}\text{Al}\) production requires moderate peak temperatures, of the order of \(T_{\text{peak}} \approx 2 \times 10^8\) K, and a fast decline from maximum temperature, conditions that are commonly achieved in nova outbursts. In the early 1980s, one-zone model calculations of explosive hydrogen-burning nucleosynthesis by Hillebrandt & Thielemann (1982) and Wiescher et al. (1986) suggested that classical novae might produce sufficient amounts of \(^{26}\text{Al}\) to account for some of the observed meteoritic anomalies but would not represent major Galactic sources. But these calculations used only solar or CNO-enhanced envelopes. New one-zone model calculations by Weiss & Truran (1990) and Nofar, Shaviv, & Starrfield (1991), on the basis of ONeMg white dwarf stars, produced large amounts of long-lived radioactive nuclei, such as \(^{22}\text{Na}\) and \(^{26}\text{Al}\), concluding that these novae might represent important (though not dominant) sources of the Galactic \(^{26}\text{Al}\). However, according to Nofar, Shaviv, & Starrfield 1991, no \(^{26}\text{Al}\) production results for models with \(T_{\text{peak}} \geq 2.7 \times 10^8\) K. Recent calculations have refuted this result (Politano et al. 1995; Starrfield et al. 1993), demonstrating the crucial role played by convection to carry some \(^{26}\text{Al}\) to the outer, cooler layers of the envelope, where its destruction through proton captures is prevented. But these fully hydrodynamical calculations involving ONeMg white dwarfs assume a composition for the white dwarf core (which is partially mixed with the envelope) based on old calculations of C-burning nucleosyn-
thesis by Arnett & Truran (1969) that need to be updated. Since the resulting nucleosynthesis is very sensitive to the envelope’s composition, it is important to adopt a more realistic one. On the other hand, there are large uncertainties on some crucial reactions involving $^{26}$Al production. Thus, it is important to analyze the influence of the different prescriptions available on the final $^{26}$Al yields in the ejecta of classical novae. With this aim, we have computed a series of hydrodynamic models of nova outbursts for several white dwarf masses and accretion rates, adopting updated initial chemical compositions and recent prescriptions for the crucial reaction rates.

2. MODEL AND RESULTS

A one-dimensional, Lagrangian, implicit hydrodynamic code has been developed, in order to follow both the hydrostatic accretion phase and the resulting hydrodynamic explosion (José 1996 and José & Hernanz 1997). A time-dependent formalism for convective transport has been included (Wood 1974), where partial mixing in convective shells is treated by means of a diffusion equation (Priailnik, Shara, & Shaviv 1979). With this code, we have performed a series of computations of the complete evolution of accreting white dwarfs with masses ranging from 1 to 1.35 $M_\odot$, accreting at rates between $2 \times 10^{-3}$ and $2 \times 10^{-1} M_\odot$ yr$^{-1}$, and with an initial luminosity of $10^{2} L_\odot$ (see Hernanz et al. 1996 for an application of this code to the study of ‘Li synthesis in novae). The matter transferred from the companion is assumed to be solar-like, but some process of mixing between the envelope and the outermost shells of the underlying core (shear mixing, diffusion) is assumed to take place. This assumption is based on the current prediction that enhanced CNO or ONeMg abundances are required in order to power the nova outburst and also to explain some of the observed abundances (Livio & Truran 1994; see also Priailnik & Kovetz 1995 and Politano et al. 1995 for recent calculations of CO and ONeMg novae, respectively). The problem of the initial composition of nova envelopes is complicated and far from being understood. A compromise solution is to adopt a mixture with 50% by mass of core abundances. This may be considered as representative of the degree of mixing, in view of the mean metallicity observed in the ejecta of ‘true’ ONeMg novae (Livio & Truran 1994; see Kolb & Politano 1997 for an analysis of the influence of the degree of mixing in the synthesis of $^{26}$Al). The composition of the underlying core has been taken from recent detailed evolutionary models, specially for the case of ONeMg white dwarfs, which are the main contributors to $^{26}$Al production. These stars are made basically of $^{20}$O and $^{20}$Ne (Domínguez, Tornambè, & Isern 1993 and Ritossa, García-Berro, & Iben 1996), since magnesium is almost absent (so we will call them ONe models). We want to stress that this issue has important consequences on the final yields of some species, like $^{26}$Al.

A complete reaction network has been directly coupled to the code in order to follow the detailed evolution of 100 nuclear species, ranging from $^1$H to $^{40}$Ca, linked through more than 370 updated nuclear reactions. Both the ground and the isomeric states of $^{26}$Al have been included ($^{26}$Al$^*$ and $^{26}$Al, respectively). The influence of nuclear uncertainties in $^{26}$Al yields has been investigated by Coc et al. (1995), with the use of the semianalytical model of MacDonald (1983), for the cases considered by Politano et al. (1995) (which have a high initial content of $^{24}$Mg, ~0.1 by mass). They stressed the importance of the $E_x = 188$ keV resonance in $^{26}$Al$(p, \gamma)$Si, which is not included in the Caughlan & Fowler (1988) rate (but whose strength was measured by Vogelaar 1989), and also of the large uncertainties still affecting the $^{25}$Al$(p, \gamma)$Si rate. When $^{24}$Mg is the primary source of $^{26}$Al, the formation of $^{26}$Al through $^{25}$Mg$(p, \gamma)$Al$(\beta^-)$Mg$(p, \gamma)$Al is bypassed by $^{25}$Al$(p, \gamma)$Si$(\beta^-)$Al*, at high temperature. Another important reaction for $^{26}$Al production is $^{26}$Al$(p, \alpha)$Mg, which competes with $^{27}$Al$(p, \gamma)$Si to partially recycle the initial MgAl material. While the $^{26}$Al$(p, \gamma)$Si rate is sufficiently known in the temperature range of interest, the $^{26}$Al$(p, \alpha)$Mg one is still uncertain but appears to be lower than the one found in Caughlan & Fowler (1988). Since then, the resonances affecting this rate in the domain of temperatures of novae have been studied by Timmermann et al. (1988) and Champagne et al. (1988). Using two different techniques, they derive similar upper limits for the strengths that are several orders of magnitude lower than those used by Caughlan & Fowler (1988). Instead of being recycled in the MgAl region, the nuclear flow mainly leaks out toward higher Z elements, with the result of a reduced $^{26}$Al production. Concerning the importance of the initial chemical composition, we stress that the sum $X(^{20}\text{Mg}) + X(^{24}\text{Mg})$, and not only $X(^{25}\text{Mg})$, has to be considered as a seed for $^{26}$Al production: $^{25}$Mg is readily transformed into $^{25}$Mg by the fast $^{25}$Mg$(p, \gamma)$Al reaction followed by the beta decay of $^{25}$Al, provided that the leak through $^{26}$Si can be neglected. Furthermore, unlike the CNO cycle, neither the NeNa nor the MgAl cycles are expected to be closed, and part of the initial neon and sodium will be transferred to the MgAl region. Indeed, in the temperature range $1.5 \leq T_\infty \leq 4$, the rate of the reaction $^{23}$Na$(p, \alpha)$Ne is approximately equal to that of $^{23}$Na$(p, \gamma)$Mg according to Caughlan & Fowler (1988) or up to an order of magnitude lower following a recent reevaluation by El Eid & Champagne (1995). Hence, a fraction of the initial $X(^{23}\text{Na})$ will reach the MgAl region, providing additional seeds, while the rest ends up as $^{20}$Ne. A fraction of $^{20}$Ne can also be transformed into $^{20}$Na. At the temperatures prevailing in nova outbursts, the rate of $^{20}$Ne$(p, \gamma)$Ne is low, and most of the initial $^{20}$Ne remains unburned. However, in classical novae involving massive white dwarfs, a significant fraction of $^{20}$Ne can be transformed through the $\text{NeNa}$ cycle and via $^{23}$Na$(p, \gamma)$Mg into $^{25}$Mg. Accordingly, even in the absence of magnesium in the initial composition, $^{26}$Al can be produced from $^{20}$Na, $^{22}$Ne, or even some $^{20}$Ne in the most extreme cases.

Snapshots of the evolution of several isotopes relevant to the $^{26}$Al synthesis ($^{23}$Na, $^{24}$Mg, $^{25}$Mg, $^{26}$Al, $^{26}$Al$^*$, and $^{27}$Al) are shown in Figure 1, for a $1.25 M_\odot$ ONe nova with an accretion rate of $2 \times 10^{-3} M_\odot$ yr$^{-1}$. The upper (first) panel corresponds to the time when the temperature at the burning shell has already reached $10^8$ K. Nearly flat abundance profiles along the accreted envelope are found, since the convective timescale is similar to the characteristic timescale of most of the dominant nuclear reactions. Proton capture reactions on $^{24}$Mg and $^{25}$Mg provide the main source of the Al-group nuclei, which increase their initial abundances. When the temperature in the burning shell rises up to $2.1 \times 10^8$ K (second panel), the nuclear timescale becomes much shorter than the convective timescale. Hence, only partial mixing between adjacent convective shells occurs, and nonflat profiles are obtained. At this time, the abundance of $^{26}$Al in the burning shell attains its maximum value, $X(^{26}\text{Al}) \sim 7.7 \times 10^{-3}$ by mass; $^{26}$Al is being
and 25Mg have almost been exhausted. The final abundances in the accreted envelope, for a 1.25 M\textsubscript{\textit{J}} envelope has already expanded to a size of \( R \). Transport, which carries 26Al isotopes to the outer, cooler layers of the envelope, where they can avoid destruction through \((p, \gamma)\) reactions.

The 26Al yields obtained in all models computed are summarized in Table 1. All 26Al production appears in its ground state, since the isomeric state does not play any role. ONe novae are more important producers than CO ones, because of the fact that peak temperatures attained during CO nova outbursts are not high enough to break the CNO cycle. Therefore, the production of 26Al comes from the initial 23Na, 24Mg, and 25Mg. It is worth noting that the initial abundance of 24Mg is much lower than the one adopted in the calculations performed by Politano et al. (1995), which were based on the old nucleosynthesis computations of carbon burning by Arnett & Truran (1969). However, according to the above discussion, the presence of 25Mg, 23Na, and 22Ne partially compensates for this absence.

Only some combinations of peak temperatures around \( T_{\text{peak}} \approx 1 - 2 \times 10^8 \) K and rapid evolution from maximum favor 26Al generation. In this sense, explosions in low-mass ONe white dwarfs, where the lower gravity provides softer explosions with lower peak temperatures, favor 26Al production. Our calculations (see Table 1) show a minimum in the 26Al production near \( M_{\text{red}} = 1.25 M_{\text{\textit{J}}} \), which fairly agrees with the trend obtained in the semianalytical analysis of Coc et al. (1995), but does not follow the monotonic decrease in the 26Al production as the white dwarf mass increases reported by Politano et al. (1995). We point out, however, that the amount of 26Al ejected into the interstellar medium decreases as the white dwarf mass or the mass accretion rate increases, because of the fact that the mass of the envelope is smaller. It is also worth noting that the amount of 26Al present in the ejecta of the models described in this Letter is systematically lower than the mean values obtained by Politano et al. (1995). Two main effects influence this result: first, a different initial composition (mainly the lower initial content of Mg in our calculations), and second, the specific prescriptions adopted for the reaction rates of interest for the 26Al synthesis. The effect of the nuclear reaction rates has been checked by means of two models of 1.25 M\textsubscript{\textit{J}} ONeMg white dwarfs, accreting mass at a rate \( 2 \times 10^{-9} M_{\text{\textit{J}}} \) yr\(^{-1}\), which are similar to one of the models analyzed by Politano et al. (1995). Both models differ in the specific rates adopted for the reactions 26Al\((p, \gamma)\)Si and 24Mg\((p, \alpha)\)2Al. Since these reactions play no role during the accretion phase, the total amount of mass accreted as well as the proper pressure at the onset of the explosive phase are the same in both models. Hence, the differences obtained in the final yields reflect exactly the different prescriptions for the reaction rates adopted. When the rates from Vogelaar (1989) and Champagne et al. (1988) are used, we obtain a mean value of \( X(\text{26Al}) = 1.4 \times 10^{-3} \) by mass in the ejected shells, whereas \( X(\text{26Al}) = 4.8 \times 10^{-3} \) is found when the Caughlan & Fowler (1988) rates are used (Politano et al. 1995).

**TABLE 1**

| Composition | \( M_{\text{red}} \) (M\textsubscript{\textit{J}}) | \( M \) (M\textsubscript{\textit{J}} yr\(^{-1}\)) | \( \dot{X}(\text{26Al}) \) | \( M_{\text{\textit{J}}}(\text{26Al}) \) (M\textsubscript{\textit{J}}) |
|-------------|-----------------|---------------------|-----------------|-------------------|
| CO........... | 1.0 | \( 2 \times 10^{-10} \) | \( 1.6 \times 10^{-7} \) | \( 3.5 \times 10^{-10} \) |
| ONe........... | 1.15 | \( 2 \times 10^{-10} \) | \( 4.7 \times 10^{-7} \) | \( 6.3 \times 10^{-10} \) |
| ONe........... | 1.15 | \( 2 \times 10^{-10} \) | \( 9.3 \times 10^{-7} \) | \( 1.7 \times 10^{-10} \) |
| ONe........... | 1.25 | \( 2 \times 10^{-10} \) | \( 4.7 \times 10^{-7} \) | \( 7.7 \times 10^{-9} \) |
| ONe........... | 1.25 | \( 2 \times 10^{-8} \) | \( 1.7 \times 10^{-7} \) | \( 4.7 \times 10^{-9} \) |
| ONe........... | 1.35 | \( 2 \times 10^{-10} \) | \( 7.2 \times 10^{-7} \) | \( 3.1 \times 10^{-9} \) |

**FIG. 1.**—Snapshots of the evolution of 23Na, 24Mg, 25Mg, 26Al, \( m \), and 27Al along the accreted envelope, for a 1.25 M\textsubscript{\textit{J}} ONe novae accreting at a rate \( M = 2 \times 10^{-10} M_{\text{\textit{J}}} \) yr\(^{-1}\). The successive panels, from top to bottom, correspond to the time for which the temperature at the burning shell reaches 10\(^8\), 2.1 \times 10\(^8\), \( T_{\text{max}} = 2.44 \times 10\(^8\), plus an additional case for which the white dwarf envelope has already expanded to a size of \( R_{\text{red}} \approx 10\(^{22}\) cm. The arrow indicates the base of the ejected shells.
obtained \(X^{(26)\text{Al}} = 9.45 \times 10^{-3}\) by mass for a similar model. In addition, the ratio \(26\text{Al}/27\text{Al}\) increases from 0.4 to 3.0 in the second model. This result is a direct consequence of the differences between the two prescriptions for the rate of \(27\text{Al}(p, \alpha)24\text{Mg}\); the lower cross section reported by Champagne et al. (1988) results in a less efficient recycling of \(27\text{Al}\) into \(24\text{Mg}\), which essentially will end up in the form of \(26\text{Al}\).

3. DISCUSSION AND CONCLUSIONS

The production of \(26\text{Al}\) by classical novae is very sensitive to the initial composition of the envelope and to the nuclear reaction rates adopted. ONe novae are more important \(26\text{Al}\) producers than CO ones, because seed nuclei for the NeNa and MgAl cycles are almost absent in the latter ones. For the same reason, the amount of \(26\text{Al}\) synthesized in ONe novae depends on the initial composition of the white dwarf core. When using the recently available chemical abundance profiles by Ritossa et al. 1996, a lower \(26\text{Al}\) production is obtained. Furthermore, some improvements in the nuclear reaction rates since Caughlan & Fowler (1988) also lead to a lower \(26\text{Al}\) production.

The amount of \(26\text{Al}\) injected into the interstellar medium by ONe nova events decreases as the mass of the underlying white dwarf increases. Hence, low-mass white dwarfs are most likely candidates for \(26\text{Al}\) production. Contribution from low-mass white dwarfs is favored by both the higher \(26\text{Al}\) production and the higher ejected mass. But white dwarfs of masses lower than \(\sim 1.1 M_\odot\) are expected to be CO white dwarfs, which are unable to produce important quantities of \(26\text{Al}\) (see Table 1). Also, the observations of some Ne novae, such as OU Vulpecula 1984, indicate high ejected masses \((\sim 10^{-3} M_\odot)\), unobtainable if a massive ONe nova is responsible for the explosion. This has led some authors to propose a new scenario (Shara 1994; Shara & Prialnik 1994): low-mass CO white dwarfs, undergoing episodic accretion phases at high rates, experience large metal enrichments from the ashes of He burning. The subsequent nova explosion, correlated with a phase of a lower accretion rate, produces, at the same time, high \(26\text{Al}\) abundances and high ejected masses. But these models require a fine-tuning of some parameters relative to the catastrophic variable, such as the mass accretion rate.

A crude estimate of the total production of \(26\text{Al}\) by nova can be computed by means of the expression from Weiss & Truran (1990):

\[
M^{(26)\text{Al}} = 0.4 \times \frac{X^{(26)\text{Al}} \cdot \text{frac(Ne)}}{2 \times 10^{-3} \cdot 0.25} \times \frac{M_\odot (M_\odot)}{R_{\text{ nova}} \text{(events yr}^{-1})} \times \frac{2 \times 10^{-5}}{40},
\]

where \(X^{(26)\text{Al}}\) represents the mean mass fraction of \(26\text{Al}\) in the ejecta, frac(Ne) the fraction of Ne novae over the total number of classical nova outbursts (between 0.25 and 0.53, but typically \(\sim 0.5\); see Truran & Livio 1986 and Livio & Truran 1994), \(M_\odot\) the amount of mass ejected in an outburst, and \(R_{\text{ nova}}\) the nova rate \((\sim 46 \text{ yr}^{-1})\) [Higdon & Fowler 1987] or \(\sim 20 \text{ yr}^{-1}\) [Della Valle & Livio 1994]. Adopting these estimates of \(R_{\text{ nova}}\) and frac(Ne) and our most favorable ONe nova case, for which \(M_\odot^{(26)\text{Al}} = 1.7 \times 10^{-8} M_\odot\), we derive a maximum contribution of classical nova outbursts to the Galactic \(26\text{Al}\) in the range 0.1–0.4 \(M_\odot\). Although higher abundances of \(26\text{Al}\) can be obtained for models with higher enrichment from core material (i.e., 75%), these may be considered as very extreme cases, in view of the typical metallicities observed in the ejecta of classical nova outbursts. In summary, the contribution of novae to Galactic \(26\text{Al}\) is small as compared with the one required to explain COMPTEL measurements (between 1 and 3 \(M_\odot\)). This is in agreement with the most accepted hypothesis of young progenitors as sources of Galactic \(26\text{Al}\).

We want to stress that the two aspects that are crucial for the final \(26\text{Al}\) yields are far from being understood; these are the process of mixing between the core and the envelope, which determines the initial chemical profile, and the exact rates of the nuclear reactions involved in \(26\text{Al}\) synthesis. This latter topic will surely be improved with the new compilation of nuclear reaction rates (NACRE Collaboration 1997).

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