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The contribution of O-Ne-Mg novae to the ^{26}Al production in the Galaxy

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Abstract. Recent COMPTEL observations revealed inhomogeneities in the spatial distribution of the Galactic ^{26}Al 1.809 MeV γ-ray emission, which reduces the required amount of ^{26}Al in a homogeneous background from ~ 3 $M_\odot$ (the value assuming *all* of the radiation is from a homogeneous background) to ~ 1 $M_\odot$. Using recent nova population models and simulations of classical nova outbursts we reinvestigate the question of whether nova outbursts on oxygen-neon-magnesium white dwarfs (ONeMg WDs) contribute significantly to the production of ^{26}Al in the Galaxy. We find an upper limit of $\sim 3\,M_\odot$ for the amount of ^{26}Al produced by ONeMg novae in the Galaxy, if we adopt a value of 30% for the fraction f_{ONeMg} of novae in our models that are ONeMg novae and choose optimal models and parameter values. Uncertainties in both observations and theory do not allow us to quote a lower limit with any confidence at this time. Choosing models and parameter values that are more consistent with independent observational quantities gives an ^{26}Al production of $\sim 0.15\,M_\odot$, again for an assumed f_{ONeMg} of 30%. However, this value is dependent on our assumption of choosing the same amount of mixing between the underlying WD material and the accreted companion material for the entire population. If the mean amount of mixing in ONeMg novae is $\sim$a factor of 2 higher than the mean maximum amount of mixing for all novae, then we estimate that ONeMg novae can produce a sufficient amount of ^{26}Al ($\sim 1\,M_\odot$) to account for the entire diffuse background emission observed by COMPTEL. We explore to what extent ejecta abundances in well-studied novae support this possibility.

Key words: novae, cataclysmic variables – stars: evolution – stars: white dwarfs – gamma-rays: theory – nuclear reactions, nucleosynthesis, abundances

1. Introduction

From observations with the HEAO γ-ray satellite it has been known for more than a decade that there is a noticeable γ-ray line emission at an energy of 1.809 MeV attributed to the decay ^{26}Al $(\beta^+,\gamma)^{26}$Mg of the radioactive isotope ^{26}Al on a mean lifetime of 1.05×10^6 yr (Mahoney et al. 1984). The Galaxy is optically thin to these 1.8 MeV photons, which interact with matter mainly via Compton scattering, so that the ^{26}Al emission can be seen from the entire Galaxy. As the angular resolution of HEAO was very poor, no information about the spatial distribution of the 1.8 MeV emission could be extracted. Assuming that the emission is diffuse but concentrated towards the Galactic plane, a total amount of $3\,M_\odot$ ^{26}Al homogeneously distributed in the Galactic disk was derived to account for the observed intensity at 1.8 MeV (e.g., Mahoney et al. 1984).

Only recently, with the successful operation of the imaging γ-ray telescope COMPTEL aboard the COMPTON Gamma Ray Observatory, has it been been possible to make a detailed investigation of the angular distribution of the 1.8 MeV emission on the sky. From data obtained during the first (all-sky survey) mission phase, Diehl et al. (1995) compiled a 1.8 MeV map along the Galactic plane revealing an unexpected clumpiness and asymmetry relative to the Galactic center. This finding was confirmed by Oberlack et al. (1996a, b) who combined 3.5 years of observations to construct the first all-sky map of the ^{26}Al decay line. No emission was found at high galactic latitudes $|b| \gtrsim 30°$, rejecting a purely local origin. Although the maximum entropy method used to create the ^{26}Al map may exaggerate the clumpiness, it seems now well-established that at least part of the 1.8 MeV emission comes from localized regions. This imaging technique does not allow a positive identification of individual 1.8 MeV sources with counterparts in other wavebands, but there are unambiguous hotspots close to the Galactic center in the Vela, Carina and Cygnus regions (see the summary by Oberlack et al. 1996a, b). A number of authors find a resemblance between the structure in the ^{26}Al map and tracers of rather close-by regions of recent star formation (Diehl et al. 1995, Timmes et al. 1995), and Chen et al. (1995) argue that the observed asymmetry could be explained by the local spiral structure and the existence of a central stellar bar. An important further consequence of these new data is that the amount of ^{26}Al in a diffuse background may be much less than previously thought. Diehl et al. (1995) derive an upper limit of $\sim 1\ M_\odot$, although more recent reinvestigations indicate that a somewhat larger value cannot be excluded (Oberlack, priv. comm).

Several astrophysical environments have been proposed as sites for the production of ^{26}Al in the Galaxy, all related to either explosive nucleosynthesis or hydrostatic hydrogen burning: besides oxygen-neon-magnesium novae (ONeMg novae) which are discussed below, these are, core-collapse supernovae (SNe; e.g, Timmes et al. 1995), Wolf-Rayet stars (e.g., Pranztos & Cassé 1986, Meynet 1994, Langer et al. 1995) and asymptotic giant branch (AGB) stars (e.g., Guélin et al. 1995, Forestini et al. 1991). Estimates have been made which suggest that each of these source groups alone could potentially account for all of the observed 1.8 MeV emission. However, the emission from individual nova outbursts or AGB stars is expected to be too weak to be detected as isolated sources, rather the corresponding population would create a diffuse background radiation at 1.8 MeV. In contrast, SNe and Wolf-Rayet stars are thought to produce 10 to 100 times as much ^{26}Al per event/object, so that they would not only contribute to a background, but could also appear as individual sources. Moreover, as they are the youngest objects, and therefore are more closely associated with regions of recent star formation, they appear to be the best candidates to explain the observed clumpiness at 1.8 MeV. For a detailed overview of relevant observations and a critical discussion concerning suggested sources of interstellar ^{26}Al, we refer the reader to the very nice review by Prantzos & Diehl (1996).

In this paper, we specifically investigate ONeMg novae as sites of ^{26}Al production in the Galaxy. An ONeMg nova is believed to be a classical nova system in which the thermonuclear runaway (TNR) occurs on an ONeMg WD. The numerous observations of classical novae whose ejecta show significant enrichments in intermediate-mass elements, particularly neon, in the last ten years strongly support the existence of such systems (e.g., Politano et al. 1995; Starrfield et al. 1996 and references therein), although there is some question as to how much neon *demands* the presence of an underlying ONeMg WD (e.g., Livio & Truran 1994). Essential for significant production of ^{26}Al during the TNR is the presence of a sufficient amount of ^{24}Mg seed nuclei (e.g., Weiss & Truran 1990), which is believed to enter the envelope from the underlying WD material through some mixing process or processes.

Previous estimates of the amount of ^{26}Al produced by ONeMg novae range from $\sim 0.4\,M_\odot$ (Weiss & Truran 1990) to the full $3\,M_\odot$ assuming the lower limit to the WD mass of ONeMg WDs in cataclysmic variables (CVs) is $1.2\,M_\odot$ (Politano et al. 1995). However, there are problems with each calculation. Weiss & Truran based their estimate purely on average values of quantities such as the amount of material ejected in an ONeMg nova, the mass fraction $X(^{26}\mathrm{Al})$ of ^{26}Al in the ejecta of an ONeMg nova and the fraction of novae which are ONeMg, neglecting any detailed dependence of $X(^{26}\mathrm{Al})$ on these parameters. Politano et al. (1995) calculated the amount of ^{26}Al from an integral over WD mass but still relied on a mean accretion rate in nova systems based on the nova rate in the Galaxy. Moreover, their ^{26}Al mass fractions are based on the particular accretion rate chosen for their models.

Our purpose in this paper is therefore twofold: (1) to improve on earlier estimates of ^{26}Al production in ONeMg novae and compare the improved estimate with the recent COMPTEL data, and (2) to investigate how the new, tighter observational constraints on the ^{26}Al background may help to constrain free parameters in our theoretical understanding of both the galactic population of CVs and the nucleosynthesis during the TNR in classical nova outbursts.

In particular, we improve on earlier estimates in two regards. First, we obtain the ^{26}Al mass fraction in nova ejecta as a function of WD mass, initial enrichment of the accreted envelope, and accretion rate from a grid of detailed ONeMg nova models, calculated with a 1-dimensional hydrodynamic code coupled to an extended nuclear network (Politano et al. 1995, 1996), thereby exploring a greater range of parameter space than was done in Politano et al. (1995). Second, we combine these data with a detailed background model for the Galactic CV population (Kolb 1993a). As a result we come up with the first self-consistent prediction for the ^{26}Al production in ONeMg novae solely from theoretical models.

We present data from the TNR simulations which are important for this study in Sect. 2. The CV population models and their relationship to the classical nova population are described in Sect. 3. We show and discuss our results in Sects. 4 and 5, respectively. Main conlusions follow at the end of the paper.

2. The ^{26}Al abundance in the ejecta of O-Ne-Mg novae

In order to calculate the amount of ^{26}Al produced by ONeMg novae in the Galaxy, we need to know how much ^{26}Al is produced by an ONeMg nova of a given set of parameters and then how such novae are distributed over those parameters. We discuss the latter point in Sect. 3.

2.1. Computation of a production function

To determine the mass fraction of ^{26}Al in the ejecta of ONeMg novae, we use the results of recent hydrodynamic studies of accretion onto massive (ONeMg) WDs by Politano et al. (1995, 1996). These computations use an implicit, 1-D hydrodynamic stellar evolution code to follow the TNR. The code is coupled to an extended nuclear reaction network, including 78 nuclei ranging from H to ^{40}Ca. The nuclear network is described in Politano et al. (1995) and Weiss & Truran (1990). The hydrodynamic code to which the network is coupled has been described extensively in the literature (e.g., Kutter & Sparks 1972; Starrfield & Sparks 1987). We refer the reader to these papers for further details.

Three sets of model sequences were calculated by Politano et al. (1995, 1996). In the first set of sequences, the dependence of the outburst on the mass of the WD was investigated. In the second set of sequences, the dependence of the outburst on the amount of enrichment of the accreted material in O, Ne, and Mg

Table 1. ^{26}Al and ^{22}Na abundance, $X(^{26}\mathrm{Al})$ and $X(^{22}\mathrm{Na})$, in the ejecta of ONeMg nova models for different white dwarf masses M_1, enrichments d of the accreted material in O, Ne and Mg, and mass accretion rates $\dot{M}$. The sixth column provides an estimate for the total mass of ^{26}Al ejected into the interstellar medium per TNR for the corresponding nova model. Eq. (12) was used to estimate the total ejected mass.

Set	$M_1/\mathrm{M}_\odot$	d	$\log \dot{M}$ (in $\mathrm{g s^{-1}}$)	$X(^{26}\mathrm{Al})$	est. $\Delta M_{\mathrm{Al-26}}$ (in $10^{-8}\,\mathrm{M}_\odot$)	$X(^{22}\mathrm{Na})$
I	1.00	50 %	17	1.96×10^{-2}	412	4.94×10^{-5}
	1.25	50 %	17	9.45×10^{-3}	60.5	7.64×10^{-4}
	1.35	50 %	17	7.54×10^{-3}	22.6	5.54×10^{-3}
II	1.35	25 %	17	3.87×10^{-3}	7.73	1.53×10^{-5}
	1.35	50 %	17	1.05×10^{-2}	31.5	2.52×10^{-4}
	1.35	75 %	17	9.41×10^{-3}	56.5	1.32×10^{-2}
III	1.35	75 %	16	4.79×10^{-4}	2.88	8.58×10^{-3}
	1.35	75 %	17	9.41×10^{-3}	56.5	1.32×10^{-2}
	1.35	75 %	18	2.77×10^{-2}	166	3.97×10^{-2}

was investigated. Finally, in the third set of sequences, the dependence of the outburst on the accretion rate was investigated. For a given set of sequences, only one parameter was varied, the other two remaining fixed. In all three sets, an initial WD luminosity of $\sim 10^{-2}\,\mathrm{L}_\odot$ was used. Initial model parameters and ^{26}Al mass fractions in the ejecta for all three sets of sequences are shown in Table 1, together with an estimate for the total mass of ^{26}Al ejected per nova event by the corresponding model.

Here, we model the mass fraction of ^{26}Al in the ejecta of ONeMg novae by assuming it can be approximated by a product function of the three parameters investigated by Politano et al. (1995, 1996). Accordingly, we obtain as a production function

$$X(^{26}\mathrm{Al}) = X_0\, f_{\mathrm{m}_1}(M_1)\, f_{\dot{\mathrm{m}}}(\dot{M})\, f_\alpha(\alpha)\,, \tag{1}$$

where M_1 is the mass of the WD, $\dot{M}$ is the accretion rate, and α is the ratio of the mass ejected in a given nova outburst to the mass accreted by the WD between outbursts. We have normalized the factors f_{m_1}, $f_{\dot{\mathrm{m}}}$ and f_α to unity for the nova model with $M_1 = 1.25\,\mathrm{M}_\odot$, $\dot{M} = 10^{17}\ \mathrm{g s^{-1}}$, and $\alpha = 2$ (which we will hereafter refer to as our "standard" nova model). The normalization factor, X_0, is then simply the ^{26}Al abundance in the ejecta of this standard model (see below). Before discussing the individual functions in (1), we first discuss the parameter α, and its relationship to the assumed amount of enrichment of the accreted material in O, Ne, and Mg.

The presence of significant enrichments of CNO or intermediate-mass elements in the ejecta of most classical novae suggests that the WD mass is being eroded. Such significant amounts of enrichment are very difficult to understand unless material from the underlying WD is being mixed into the accreted envelope material (e.g., Truran 1990). Unless essentially all of the enriched envelope (i.e., accreted hydrogen-rich companion material *and* dredged-up WD material) is ejected during the explosion, there would remain on the WD some hydrogen-rich material. During the constant bolometric phase, this hydrogen would be burned to helium. If this process continued, then, over the course of several outbursts, eventually the composition of the underlying WD would be masked by the build-up of remnant helium in the envelope. Since we *do* observe substantial enrichments of CNO or intermediate-mass elements in the ejecta of novae, we conclude that not only must an amount of mass equal to the accreted companion mass be ejected, but also an amount of mass equal to the amount of WD material that was mixed into the envelope. This gives us a relationship between α, the ratio of the ejected mass, ΔM_{env}, to the accreted mass, ΔM_{acc}, and d, the amount of enrichment (by mass) of the accreted material in O, Ne, and Mg:

$$\alpha = \frac{\Delta M_{\mathrm{env}}}{\Delta M_{\mathrm{acc}}} = \frac{1}{1-d}\,. \tag{2}$$

In order to construct the functions, $\mathrm{f}_{\mathrm{m}_1}$, $\mathrm{f}_{\dot{\mathrm{m}}}$, and f_α, we have made analytic fits to the data in Table 1 for the separate dependencies on M_1, $\dot{M}$, and α. These analytic fits are given below and the corresponding functions, along with Politano et al.'s data, are shown in Fig. 1.

$$f_{\mathrm{m}_1} = 0.212 + \frac{1.861}{(M_1/\mathrm{M}_\odot)^{3.85}}\,, \tag{3}$$

$$f_{\dot{\mathrm{m}}} = \begin{cases} \exp(2.9779\,\dot{m}) & \text{for } \dot{m} \le 0 \\ -1.0342\,\dot{m}^2 + 2.9779\,\dot{m} + 1 & \text{for } 0 < \dot{m} \lesssim 1.5\,, \end{cases} \tag{4}$$

where $\dot{m} = \log(\dot{M}/10^{17}\mathrm{g s^{-1}})$, and

$$f_\alpha = \begin{cases} 0 & \text{for } \alpha \le 1 \\ \alpha - 1 & \text{for } 1 < \alpha < 2 \\ 1 - 0.052 \times (\alpha - 1) & \text{for } \alpha \ge 2\,. \end{cases} \tag{5}$$

In the enrichment and accretion rate sequences the pre-runaway abundances were computed differently than in the WD mass sequences. As a result of this, the ^{26}Al mass fraction is $\sim 40\%$ higher in the 50% enrichment sequence than in the $1.35\,\mathrm{M}_\odot$ WD mass sequence, even though these two sequences were computed for identical sets of parameters ($1.35\,\mathrm{M}_\odot$, 50% enrichment, $10^{17}\mathrm{g\,s^{-1}}$). To compensate for this inconsistency between the WD mass sequences and the rest of the sequences, we have increased all of the ^{26}Al mass fractions in the WD

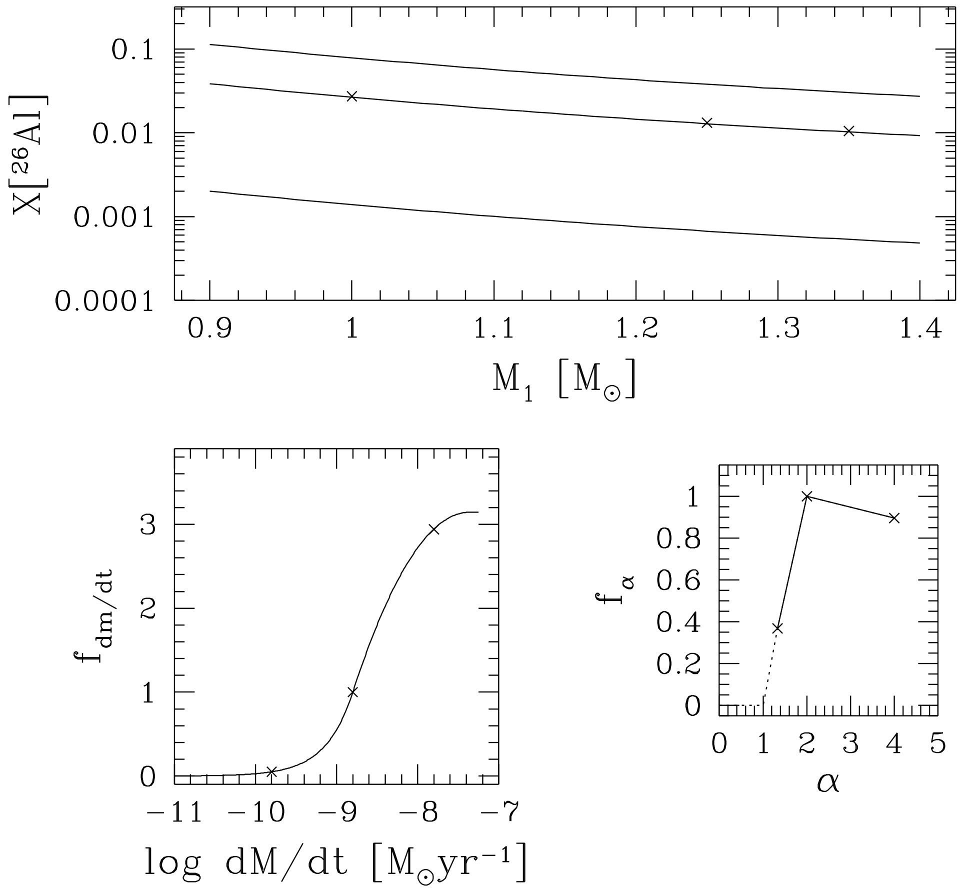

Fig. 1. a (upper panel): ^{26}Al abundance in nova ejecta as a function of WD mass, M_1, computed according to (1) with $\alpha = 2$. The curves correspond to log $\dot{M}$[M$_\odot$yr^{-1}] = −9.8, −8.8 and −7.8 (from bottom to top); **b** (lower panel, left): $f_{\dot{m}}$ from Eq. (4); **c** (lower panel, right): f_α from Eq. (5). Crosses mark the results from actual model calculations by Politano et al. (1995, 1996), see Table 1.

mass sequences listed in Table 1 by 40%. In particular, we adopt X_0 = 0.01316 for the normalization in (1). We note that Hernanz et al. (1996) investigated the TNR on a 1.25 M$_\odot$ ONeMg WD using similar techniques and input physics as Politano et al. (1995, 1996) and find an ^{26}Al output consistent with (1).

One of the central factors which determines the behavior of f_{m_1}, $f_{\dot{m}}$, and f_α is the peak burning temperature achieved during the runaway. High peak temperatures (T $\gtrsim 100 \times 10^6$ K) are needed to produce the ^{26}Al via the reaction sequence: ^{24}Mg(p,γ)^{25}Al(β^+)^{25}Mg(p,γ)^{26}Al. However, once the temperature exceeds $\sim 200 - 250 \times 10^6$ K, destruction of ^{26}Al via the reaction, ^{26}Al(p,γ)^{27}Si, competes favorably with production mechanisms (e.g., Nofar et al. 1991; Politano et al. 1995). In the case of the WD mass sequences, as the WD mass increases, the outburst becomes more violent. The peak temperature increases from 224 $\times 10^6$ K in the 1.00 M$_\odot$ sequence to 356 $\times 10^6$ K in the 1.35 M$_\odot$ sequence. Correspondingly, the mass fraction of ^{26}Al decreases monotonically by a factor of ~ 3. In the enrichment sequences, it may first appear unusual that the mass fraction of ^{26}Al doesn't increase monotonically as the pre-runaway envelope becomes more enriched in O, Ne and Mg. After all, it is proton captures on ^{24}Mg which are ultimately responsible for the production of ^{26}Al during the runaway. However, as the enrichment in O, Ne, and Mg increases, the mass fraction of carbon decreases. Proton captures on ^{12}C are responsible for initiating the runaway. Therefore, a reduction in the ^{12}C abundance in the envelope delays the runaway, and this allows the envelope material to become more degenerate. Once the runaway occurs, the higher degeneracy causes the outburst to be more violent and higher peak temperatures are reached. Peak temperatures increase from 257 $\times 10^6$ K in the 25% enrichment sequence to 390 $\times 10^6$ K in the 75% enrichment sequence. Thus, there are two competing effects as the enrichment is increased: more ^{24}Mg is available, which means that more ^{26}Al can be produced, but higher peak temperatures are achieved, which means that more ^{26}Al can be destroyed. These competing effects result in a maximum in f(α) near α = 2 (50% enrichment). Finally, in the accretion rate sequences, as the accretion rate decreases, longer and longer periods of time are required in order to achieve a runaway. This allows the accreted material to become more and more degenerate, and the ensuing runaway more and more violent. This effect is very prominent; peak temperatures increase to $\sim 700 \times 10^6$ K in the 10^{16} g/s sequence. The mass fraction of ^{26}Al in the ejecta shows a correspondingly sizable decrease.

Several factors in the model calculations can cause uncertainties in the corresponding mass fraction of ^{26}Al. First, the initial WD temperature in all of the models is probably too high. Studies of WD temperatures in dwarf novae soon after outburst suggest that the WD is cooler than expected (Long et al. 1994). Second, the opacities are still uncertain. Even with the newer (OPAL) opacities, there are still some problems. In particular, because the material is partially degenerate, at certain points in the evolution extrapolations must be made to the opacities where the temperature and density values are outside of the range of the tables. Third, modeling convection is problematic since the nuclear burning time scale can be comparable to or shorter than the convective turn-over time. As with all other 1-dim. nova simulations that we are aware of, we use a mixing length description for convection, adapted to the physical situation under consideration as described in Starrfield et al. (1978). Convective mixing is handled by solving the diffusion equation at the end of each time step for each isotope over the convective region. A closer inspection of the interplay between convective turbulent motion and nuclear burning similar to the case of Type Ia supernovae (e.g. Niemeyer & Hillebrandt 1995) would require a 2-D or 3-D hydrodynamic model which is beyond the scope of this study. Nevertheless, we believe that the implemented procedure represents a satisfactory description of convection and convective mixing in the context of a TNR in a classical nova. Fourth, the luminosity due to accretion was not included in the models. Fifth, and probably most importantly, while the most up-to-date reaction rates were used at the time of the calculations, some of the rates particularly relevant to ^{26}Al production were uncertain. More accurate reaction rates have been published recently by Herndl et al. (1995). Very recent calculations similar to Politano et al. (1995) have been performed by Starrfield et al. (1996) using the newer rates. A comparison for a $1.25\,M_\odot$ WD sequence suggests that the ^{26}Al mass fraction may be reduced by as much as a factor of ~ 10, although one must be careful in making a direct comparison since other factors (e.g., opacities, WD temperature) were also varied.

2.2. A parameterized production function

In view of these uncertainties, we wish to investigate the importance of each of the factors f_{m_1}, $f_{\dot m}$, and f_α individually for the predicted overall Galactic ^{26}Al production. To do this, we consider an artificial production function similar to (1), but containing adequately chosen free parameters. The first free parameter is the absolute calibration X_0 of the standard model. Since this represents only an overall scaling factor, its actual value has no influence on our differential study, and for consistency we simply use the same value as in (1), i.e., $X_0 = 0.01316$. From the considerations in the previous section, we expect that any production function obeys similar differential trends as expressed in Eqs. (3)-(5), i.e. that $X(^{26}\mathrm{Al})$ decreases with increasing WD mass, increases with increasing accretion rate, and that $X(^{26}\mathrm{Al})$ reaches a maximum value for an intermediate degree of envelope/core mixing values (α in the vicinity of $\simeq 2$). Hence, we adopt

$$f_{m_1} = \left(\frac{M_1}{1.25\,M_\odot} \right)^{-\beta}, \tag{6}$$

as a generalized form for f_{m_1}, with $\beta \geq 0$ as a free parameter. The functional dependence expressed in (3) corresponds roughly to $\beta \simeq 3$; in Sects. 4 and 5 we vary β, the steepness of the decrease in $X(^{26}\mathrm{Al})$ with increasing WD mass, from 0 to 8.

To find a generalized $f_{\dot m}$, we first note that within standard models for CV evolution the mean mass transfer rate in CVs is in the range $-9 \lesssim \log(\dot M/\,M_\odot\mathrm{yr}^{-1}) \lesssim -7.5$ for long-period systems above the so-called CV period gap ($P \gtrsim 3$ h), and $\log(\dot M/\,M_\odot\mathrm{yr}^{-1}) \lesssim -10$ for short-period CVs below the gap ($P \lesssim 2$ h; see e.g., Kolb 1993a). If the accretion rate is on the average the same as the transfer rate, then (4) suggests that the contribution of systems below the gap is negligible. Detailed population models (see the discussion in Sect. 5.1) with the production function derived in Sect. 2.1 confirm this expectation. Assuming the same property for the generalized $f_{\dot m}$, we use the expression

$$f_{\dot m} = \begin{cases} 0 & \text{for } \dot m \leq -0.2 \\ 1 + \gamma \dot m & \text{for } \dot m > -0.2\,, \end{cases} \tag{7}$$

with $\gamma \geq 0$ as a free parameter. Eq. (4) is equivalent to $\gamma \simeq 2$. In Sects. 4 and 5, we explore the influence of γ, which measures how steeply $X(^{26}\mathrm{Al})$ increases with increasing accretion rate, on our results as γ is varied between 0 and 8.

Finally, we note that f_α plays no role in the differential comparison presented below. We assume that α has a fixed value, α_i, for a given nova population model (i), and the amount of ^{26}Al produced scales linearly with $f_\alpha(\alpha_i)$.

Results of model computations using this generalized production function are shown in Sect. 4 and discussed in Sect. 5.2.4.

3. Nova population models

In addition to knowledge of how much ^{26}Al is produced by an ONeMg nova of a given set of parameters, an estimate of the total amount of ^{26}Al produced by ONeMg novae in the Galaxy requires knowledge about how novae are distributed in the Galaxy. Previous work (Weiss & Truran 1990) relied on observational estimates of the total Galactic nova rate and could not account for the dependence of $X(^{26}\mathrm{Al})$ on nova parameters as expressed in Eq. (1). A first step towards a more consistent estimate for the overall ^{26}Al production in novae was attempted by Politano et al. (1995) who combined their findings for the mass dependence of $X(^{26}\mathrm{Al})$ with a theoretically computed WD mass distribution in novae (Ritter et al. 1991; Politano 1996a).

In our study, we extend this procedure by using a much more detailed, theoretically-predicted Galactic population of classical novae which has been derived from population models for CVs. Such population models (Kolb 1993a) essentially describe the distribution of the present-day Galactic population of CVs in a 4-dimensional configuration space defined by WD mass M_1, secondary mass M_2, mass transfer rate $\dot M$ and orbital period P and, therefore, provide self-consistently the framework necessary to take advantage of the full, explicit dependencies of $X(^{26}\mathrm{Al})$ on M_1 and $\dot M$ expressed in Eq. (1).

3.1. Model assumptions for CV populations

We emphasize at this point that our calculations are based on the widely-accepted standard models for formation and evolution of CVs (e.g. King 1988, Politano 1996a, Kolb 1995b, 1996). Although we test the influence of certain parameters on our results within this standard model, no attempt is made to introduce non-standard effects during or immediately after the common envelope phase (e.g. Terman & Taam 1996), or frictional angular momentum loss during the CV evolution (Schenker, Kolb & Ritter 1996; Kolb et al. 1996). We briefly summarize the physical assumptions and techniques used to calculate the CV model population below.

Main-sequence binaries are assumed to form continuously at a constant rate according to certain given distributions of the primary mass M_p, the mass ratio $q = M_2/M_p$ (M_2 being the secondary mass, $M_2 < M_p$) and the orbital separation. Applying simple analytical fits of single star evolutionary calculations, their evolution is followed up to the point when the primary fills its Roche lobe for the first time. In CV progenitors at this stage the primary is a giant, while the secondary is still an unevolved, low-mass main-sequence star. The ensuing mass transfer is dynamically unstable, leading to a common envelope (CE) phase during which the orbital separation is reduced considerably. Released orbital energy is consumed to eject the primary envelope, leaving behind a WD (the exposed core of the giant), and the secondary, which is basically unaffected by the CE evolution. The post-CE orbital separation is computed in the usual way with the common envelope efficiency, $\alpha_{\rm CE}$, set to 1 (we use the definition of $\alpha_{\rm CE}$ given in deKool 1992). Gravitational radiation and magnetic stellar wind braking shrink the orbit of the post-CE binaries further, bringing the secondary into contact with its Roche lobe, and drive the subsequent semi-detached CV evolution. Magnetic braking is computed according to Verbunt & Zwaan (1981). The braking is calibrated so as to reproduce the width of the CV period gap, and is assumed to be effective only as long as the secondary retains a radiative core. An isotropic stellar wind from the WD is used to approximate the effect of nova outbursts on the long-term evolution of CVs. This wind carries the WD's specific angular momentum and a mass per unit time, $\alpha(-\dot{M}_2)$, so that $\dot{M}_1 = (\alpha - 1)\dot{M}_2$, where α is the parameter introduced in Eq. (2) and is assumed to be constant.

To create the population models, we started from calculations for the formation rate of newborn CVs by deKool (1992) and Politano (1996a) and computed the present, evolved state of the CV population with the CV population synthesis technique described by Kolb (1993a). In this procedure it is assumed that the CV formation rate has remained constant during the past 10^{10} yr, the assumed age of the Galaxy. Test calculations in which the explicit time dependence of the CV formation rate was taken into account show that the error introduced by this assumption is small, and altogether negligible for a calculation of ^{26}Al production since the relevant high-mass WD CVs are the first in the CV population to reach a stationary state (e.g. Politano 1996a). The evolved population is obtained by combining a large number of CV evolutionary sequences computed with the generalized and calibrated bipolytrope code (Kolb & Ritter 1992) which cover the initial configuration space on a sufficiently dense grid. The sum over all initial configurations is then weighted according to the formation rate and integrated over the star formation history in the Galaxy (e.g. Kolb 1993a).

Of the parameters which enter into a calculation of the formation rate of CVs, the initial distribution of the mass ratio, q, in main-sequence binaries is the most controversial, yet is the one with the most significant influence on the final CV population (e.g., deKool 1992; Kolb 1993a; Politano 1994). Thus, we test two somewhat extreme cases, one with a very strong correlation between primary and secondary mass, and one without any correlation at all (see Sect. 4).

The ratio of the ejected mass to the accreted mass, specified by the global parameter α in Eq. (2), is the key parameter needed to compute the amount of ^{26}Al produced by the corresponding CV population. The mass transfer rate and the ^{26}Al mass fraction from Eq. (1) then determine the mass of ^{26}Al a given system ejects per unit time:

$$\Delta M_{\rm Al-26} = \alpha \, \dot{M} \, X(^{26}{\rm Al}) \, . \tag{8}$$

Assuming that ^{26}Al has an equilibrium abundance (i.e., decays as fast as it is replenished by nova outbursts), the total mass of ^{26}Al, $M_{\rm Al-26}$, presently existing in the Galaxy that is produced by ONeMg novae is the sum of $\Delta M_{\rm Al-26}$ for all systems in the population containing an ONeMg WD, multiplied by the mean lifetime, $\tau = 1.05 \times 10^6$ yr, of ^{26}Al:

$$M_{\rm Al-26} = \sum_{\rm ONeMg\ WDs} \Delta M_{\rm Al-26} \, \tau \, . \tag{9}$$

We note that $M_{\rm Al-26}$ in Eq. (9) is *independent* of the nova outburst frequency. The mass ejected within a time, τ, is determined by the mean mass transfer rate $\dot{M}$ during τ; it doesn't matter if the outburst frequency is high with a correspondingly small ejected mass per outburst, or low with a large envelope mass. This is important since, as a result, our prediction for the ^{26}Al production by ONeMg novae is not affected by either the uncertainty in the predicted ejecta masses from nova models or by the uncertainty in the ignition condition in TNR models for nova outbursts which we discuss below.

Whenever results from population synthesis calculations similar to the one used here are given as absolute numbers, they appear either as the local mid-plane space density, n_0, the surface density, Σ (the space density integrated in the z-direction, i.e., perpendicular to the Galactic plane), or as a total number of systems in the Galaxy. To prevent any confusion, we note that our models are normalized either in terms of n or Σ, and we convert n into Σ by assuming an exponential drop-off in z direction $n(z) = n_0 \exp\{(z/H)^2/2\}$ with a scale height H = 250 pc, i.e. $\Sigma = \sqrt{2\pi} H n_0 \simeq n_0\, 630$ pc. The total number of systems in the Galaxy is then $N = \Sigma A$, where A is the area of the Galactic disk; we choose A = 850 kpc^2 (Ratnatunga & van den Bergh 1989). We emphasize that these normalizations matter only if one is interested in absolute numbers, and authors preferring a different normalization or conversion may simply renormalize our results accordingly.

3.2. From CVs to novae

The CV population models discussed above can be used to predict the distribution of the nova outburst frequency

$$\nu = \frac{\dot{M}}{\Delta M_{\rm acc}} = \alpha \frac{\dot{M}}{\Delta M_{\rm env}} \qquad (10)$$

over system parameters (e.g., the orbital period), and the total Galactic nova rate given some ignition criterion determining the envelope mass $\Delta M_{\rm env} = \Delta M_{\rm ign}$ at ignition. A comparison with observed collective properties of novae could, in principle, serve as an independent check of the models (Kolb 1995a). However, the sample of novae with determined orbital periods is small (e.g. Ritter & Kolb 1995), and observational selection effects may influence the distribution considerably.

As we shall see later, for our purposes in this paper, it is nevertheless interesting to determine the Galactic nova rate predicted by our CV population models. We do this according to three different prescriptions for $\Delta M_{\rm ign}$: First, we adopt the "classical" criterion according to which the TNR ignites when the pressure at the base of the accreted envelope surpasses a critical value $P_{\rm ign} \simeq 2 \times 10^{19}$ dyn cm^{-2} (Truran & Livio 1986). This criterion gives

$$\frac{\Delta M_{\rm ign}}{\rm M_\odot} = 2.24 \times 10^4 \left(\frac{R}{\rm R_\odot}\right)^4 \left(\frac{M_1}{\rm M_\odot}\right)^{-1} . \qquad (11)$$

Second, we use an approximation for the actual ignition masses based on the models of Politano et al. (1995) for the case of accretion onto massive WDs,

$$\frac{\Delta M_{\rm ign}}{10^{-4}\,{\rm M_\odot}} = 8.327 - 10.763 \frac{M_1}{\rm M_\odot} + 3.486 \left(\frac{M_1}{\rm M_\odot}\right)^2 . \qquad (12)$$

We note that this fit to their data is strictly valid only for $M_1 \geq 1.0\,{\rm M_\odot}$. Finally, we also test the predicted nova rate by applying results of an extended grid of nova models by Prialnik & Kovetz (1995). Following Kolb (1995a), we approximate their tabulated values of ignition masses for cold WDs ($T_{\rm WD} = 10^7$K) by $\Delta M_{\rm ign} = f \Delta M_{\rm ign_0}$, where $\Delta M_{\rm ign_0}$ is the canonical value for $\Delta M_{\rm ign}$ given by Eq. (11), and

$$\log f \simeq 2 \log \left(\frac{M_1}{\rm M_\odot}\right) - \frac{1}{3} \log \left(\frac{\dot{M}}{\rm M_\odot yr^{-1}}\right) - \frac{4}{3} , \qquad (13)$$

(typically $f \simeq 0.1 - 1$). We emphasize that the computations by Politano et al. (1995, 1996) do not form a consistent set with TNR models by Prialnik & Kovetz, which rely on different assumptions. In particular the latter adopt a diffusion-convection mechanism to determine the degree of mixing between envelope and WD material, and the criterion for mass ejected from the system is different.

Integrating the distribution of ν over the total present CV population yields the predicted total Galactic nova rate ν_Σ. Table 2 lists the nova rate we obtain for the population models discussed in Sect. 4. We note that the observed value for the Galactic nova rate is subject to considerable uncertainties and the quoted value varies from author to author (see e.g. the discussion in Della Valle & Duerbeck 1993). The major uncertainty is the unknown fraction of outbursts that are missed due to interstellar (or intergalactic) absorption. In comparing our population models to observations, we use the most recent value for the Galactic nova rate, $\nu_\Sigma = 20$ yr^{-1}, obtained by Della Valle & Livio (1994). They extrapolated the observed nova frequency in galaxies of different Hubble type to the Milky Way.

Table 2. Predicted Galactic nova rate ν (in yr^{-1}) for models of set A (high correlation of component masses in ZAMS progenitor binaries) and set B (no correlation). ν_1, ν_2 and ν_3 were obtained using Eqs. (11), (12) and (13) as ignition criterion, respectively. The column entitled "model" gives an internal model number.

Set	model	α	ν_1	ν_2	ν_3
A	m069	1	0.87	0.87	2.4
A	m065	1.2	0.67	0.88	2.4
A	m068	4/3	0.60	0.89	2.4
A	m071	2	0.36	0.67	1.6
B	m066	1	10	8.0	17
B	m072	1.2	8.3	8.5	17
B	m073	4/3	7.7	8.6	17
B	m074	2	6.0	9.0	14

In contrast to the total nova rate, the fraction $f_{\rm ONeMg}$ of novae which occur on a ONeMg WD,

$$f_{\rm ONeMg} = \frac{\sum_{\rm ONeMg\ WDs} \nu}{\sum_{\rm all\ WDs} \nu} . \qquad (14)$$

is independent of the normalization chosen for the population model. Since ONeMg novae contain high-mass WDs, the quantity $f_{\rm ONeMg}$ is very sensitive to the ignition criterion close to the Chandrasekhar mass. Both the simple analytic form (11) and the approximate correction factor (13) are no longer valid in that regime. Rather, to compute $f_{\rm ONeMg}$ we use (12) as the actual result of detailed models of a TNR on ONeMg WDs for high-mass WDs, and (11) for low-mass WDs. We change from (11) to (12) at $M_1 \simeq 0.93\,{\rm M_\odot}$, where both criteria give the same ignition mass. An added complexity is that not all outbursts which occur on ONeMg WDs may result in an ONeMg novae. It is believed thermonuclear-powered recurrent novae must of necessity occur on WDs with masses very close to the Chandrasekhar limit because of their very short recurrence times, yet the ejecta in these systems show *no* evidence of enrichment in heavy elements (e.g., Starrfield et al. 1985; Webbink et al. 1987; Selvelli et al. 1992). The small number of well-studied novae with reliable abundance determinations leaves the "observed" value for $f_{\rm ONeMg}$ also uncertain (cf. the discussion in Livio & Truran 1994). In the recent compilation by Starrfield et al. (1996), 5 out of 19 well-studied novae have neon abundances $\gtrsim 35\times$ solar and may safely be considered as ONeMg novae. This sample, to which Nova Her 1991 (another ONeMg nova, e.g., Matheson et al. 1993; Vanlandingham et al. 1996) may now be added, suggests that $\sim$ 30% of all observed novae occur on ONeMg

WDs. This fraction could be even higher if those systems with "marginal" neon abundances are included (i.e., marginal in the sense that the observed neon abundance is only $\sim 10\times$ solar so that the presence of an underlying ONeMg WD cannot be unambiguously deduced; e.g., Livio & Truran 1994). Additional problems arise from selection effects not taken into account by our models; see the discussion in Sect. 5.2.3.

3.3. Uncertainties

Before proceeding to our results we wish to emphasize that the largest uncertainties in computing $M_{\rm Al-26}$ according to (9) come from two quantities:

First, the detailed WD mass distribution for CVs containing ONeMg WDs is unknown. In particular, for WDs formed in binaries, there is no agreement on the critical WD mass, $M_{\rm 1,lim}$, separating the less massive carbon-oxygen (CO) WDs from the more massive ONeMg WDs. An often-quoted value is 1.1 $M_\odot$ (e.g., Iben & Tutukov 1985; Nomoto & Hashimoto 1987).

This uncertainty in $M_{\rm 1,lim}$ arises chiefly because of the lack of detailed model calculations which follow the evolution of intermediate-mass stars beginning when they have hydrogen-rich envelopes through to the formation of an ONeMg WD. All studies begin with the star already in the core-helium burning phase. Indeed, the strongest inference that ONeMg white dwarfs can be formed does not come from theoretical models, but from the observed, large enrichments of intermediate-mass elements in neon novae. We, therefore, have approximated the WD mass spectrum of ONeMg WDs in newly-formed CVs with the WD mass spectrum of CO WDs in newly-formed CVs for the appropriate mass range. If the formation rate of CVs containing ONeMg white dwarfs and its associated distribution over WD mass is significantly different than that for CVs with high-mass CO white dwarfs, then this could have a significant effect on our predicted values for ^{26}Al production from ONeMg novae. A more detailed consideration of the formation of CVs with ONeMg WDs is currently in progress (Politano 1996b). In our calculations, we deal with the uncertainty in $M_{\rm 1,lim}$ by showing all results as a function of this parameter.

Second, the degree of mixing between the accreted companion material and the underlying WD material, quantified by the parameter α in Eq. (2), is essentially unknown. Although it appears clear that the observed abundance of heavy elements in nova envelopes requires some mixing to take place, the physical mechanism responsible for this mixing – diffusion, shear mixing and convective mixing have been suggested – is poorly understood. The degree of mixing plays a major role for determining the ^{26}Al yields since, for $\alpha \leq 1$ (i.e. no enrichment and thus no seed nuclei for ^{26}Al), ^{26}Al is produced in only negligible amounts (Hillebrandt & Thielemann 1982; Wiescher et al. 1986; Weiss & Truran 1990). Again, we treat α as a free parameter and show the results as a function of α. We further assume that α is the same for the entire population.

4. Results

Below we present in detail the resulting ^{26}Al production for two sets of population models. The sets differ only in the assumed initial mass ratio distribution $dN = g(q)\mathrm{d}q$ in main-sequence binaries. Set A assumes $g(q) \propto q^\gamma$, with $\gamma = 1$, and predicts a value $b = 1.05 \times 10^{-12}\mathrm{pc}^{-2}\mathrm{yr}^{-1}$ for the present CV formation rate (Politano 1996a). This corresponds to a total number of CVs in the Galaxy of $\sim 8.9 \times 10^6$. Set B was obtained using CV formation calculations by deKool (1992) where the component masses in main-sequence binaries were picked independently from the same IMF. The resulting present CV birthrate is $1.84 \times 10^{-14}\mathrm{pc}^{-3}\mathrm{yr}^{-1}$, which corresponds to $\sim 9.8 \times 10^7$ CVs in the Galaxy. For each set, population models were computed for 4 different values of the mixing parameter α: α = 1, 1.2, 4/3, and 2.

Models of set B produce roughly ten times as many CVs as models of set A. This is understood easily from the fact that the progenitor main-sequence binaries are required to have a mass ratio, M_2/M_p, less than $\simeq 0.3$ in order to avoid an unstable configuration at turn-on of mass transfer as a CV (Politano 1996a). Since set A strongly favors equal component masses ($M_2 = M_p$), fewer binaries in the corresponding population are successful in becoming CVs. The two sets represent rather extreme cases as far as the degree of correlation of the component masses is concerned (strong correlation [set A] versus no correlation at all [set B]); generally the total number of CVs in a population increases with decreasing γ (de Kool 1992; Politano 1994).

The $\alpha = 1$ models in sets A and B are identical to models pm3 and pm5 in Kolb (1993a), respectively. We note that, from an evolutionary point of view, models with $\alpha = 2$ are somewhat extreme, since the WD loses twice as much mass through nova outbursts as it gains via accretion and therefore is eroded substantially (e.g., the WD in a CV born at an orbital period of 6 hr would have lost $\simeq 0.5\,M_\odot$ when the system detaches at the upper edge of the period gap).

For three values of α (α = 1.2, 4/3, and 2), we plot the amount $M_{\rm Al-26}$ of ^{26}Al produced by ONeMg novae as a function of the critical WD mass, $M_{\rm 1,lim}$, for population models of sets A and B using the production function computed in Sect. 2.1 in Figs. 2 and 3, respectively. (As we noted previously, a negligible amount of ^{26}Al is produced for $\alpha = 1$.)

The fraction $f_{\rm ONeMg}$ of neon novae introduced in Eq. (14) depends on $M_{\rm 1,lim}$, but turns out to change very little with α. Representative plots of $f_{\rm ONeMg}$ with $M_{\rm 1,lim}$ are shown as the dotted lines in Figs. 2 and 3.

Finally, Fig. 4 shows how $M_{\rm Al-26}$ varies in models of set B with the free parameters β and γ when the parameterized ^{26}Al production function introduced in Sect. 2.2 is used. For this purpose we compute $M_{\rm Al-26}$ for the value of $M_{\rm 1,lim}$ which results in $f_{\rm ONeMg} = 0.3$ (here $M_{\rm 1,lim} = 1.15\,M_\odot$). Plotted in Fig. 4 is the change of $M_{\rm Al-26}$ relative to M_0 as a function of β. M_0 is the value of $M_{\rm Al-26}$ for the "standard model" with $\beta = 3$ and $\gamma = 2$. Recall that (6) and (7) with $\beta = 3$ and $\gamma = 2$ closely mimic the results obtained with (3) and (4), so

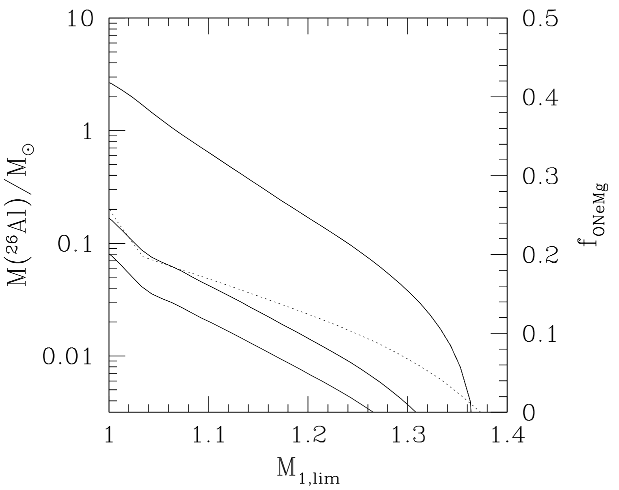

Fig. 2. Galactic ^{26}Al produced by ONeMg novae in models of set A as a function of the lower limiting mass for ONeMg white dwarfs (solid lines) for α = 1.2, 4/3 and 2 (from bottom to top, scale on the left). The dotted line shows the predicted fraction $f_{\rm ONeMg}$ of ONeMg novae (scale on the right), which is almost independent of α.

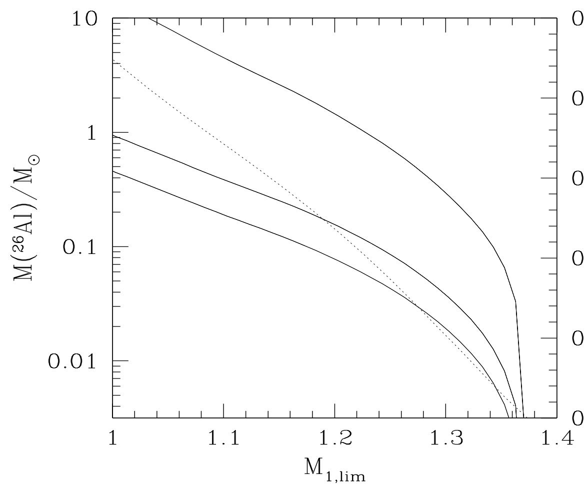

Fig. 3. The same as in Fig. 2, but for models of set B.

that the normalization to M_0 allows for an easy comparison with the production function in Sect. 2.1. The solid curves refer to models with α = 2 and to γ = 0, 2, 4, 8 (from bottom to top), the dashed curves to models with α = 1.2 and γ = 0, 2, 8 (from bottom to top), respectively. Necessarily, the lines for γ = 2 intersect at β = 3, $M_{\rm Al-26}/M_0$ = 1.

5. Discussion

A main goal of the present study is to derive limits on the ^{26}Al production by ONeMg novae from standard models for the formation and evolution of CVs, and explore to what extent the observed upper limit of $\simeq 1\,M_\odot$ of ^{26}Al in a homogeneous background puts constraints on free parameters in these standard models.

From our main results, which are depicted in Figs. 2 and 3, we first note two obvious trends:

1) Within a given set of models the amount of ^{26}Al produced increases with increasing α as long as $\alpha \lesssim 2$, where f_α reaches a maximum (Fig. 1c). Hence we expect that the curves in Figs. 2 and 3 for α = 2 are close to an upper limit for the ^{26}Al production in the corresponding population. This is true even if α is not a constant but depends on system parameters. 2) A comparison of the models in sets A and B which belong to the same value of α shows that models from set B produce typically 5-10 times more ^{26}Al than models from set A, consistent with the larger number of systems in set B.

Moreover, from Fig. 1b it can be seen that CVs with high mass transfer rates dominate the ^{26}Al production not only via the factor $\dot{M}$ in Eq. (8), but also due to the relative preference of these systems by $f_{\dot{M}}$. Therefore, the ^{26}Al is almost exclusively produced by systems above the period gap. Note that this is a non-trivial result: although most classical novae are indeed found to have periods above the period gap, these systems comprise only $\simeq$ 1% of the total intrinsic population (Kolb 1993a). Long-period nova systems have a greater detectability since the mass transfer rate, and consequently the outburst frequency, is a factor 10 to 100 higher than for short-period ones. The mass transfer rate above the gap, on the other hand, can't be very different from the values obtained from the specific formulation of magnetic stellar wind braking used here, since the width of the period gap alone requires that $\dot{M} \simeq 10^{-9}\,M_\odot{\rm yr}^{-1}$ at the upper edge of the gap (Stehle, Ritter & Kolb 1996, see also Kolb 1995b, 1996; this is one of the most robust predictions of the standard model of CV evolution), suggesting that the precise form of the magnetic braking is to zeroth order not important. We also note that the ^{26}Al production curve obtained from a test calculation with a smaller common envelope efficiency ($\alpha_{\rm CE}$ = 0.3) was very close to the curve for $\alpha_{\rm CE}$ = 1, confirming again the finding by Kolb (1993a) that $\alpha_{\rm CE}$ plays only a minor role in determining the present CV population.

5.1. Population models

Before proceeding further, it is desirable to test predictions from the CV population models we are using against observations not related to ^{26}Al. These independent tests will allow us to better constrain some of the uncertain parameters, particularly $g(q)$ and α, which enter into our investigation of ^{26}Al production from ONeMg novae.

One such test is to compare a visual magnitude-limited sample drawn from the computed population with the observed orbital period distribution of (non-magnetic) CVs, thereby neglecting further selection effects (a more detailed discussion is given in Kolb 1996). Population models with small or no correlation between the component masses in main-sequence binaries, similar to models of set B, tend to agree better with the observed fraction of CVs found below the period gap. Such models are also favored by a comparison of observed post-CE binaries (detached WD/main sequence stars, binary central stars of planetary nebulae, binary subdwarf O and B stars, barium

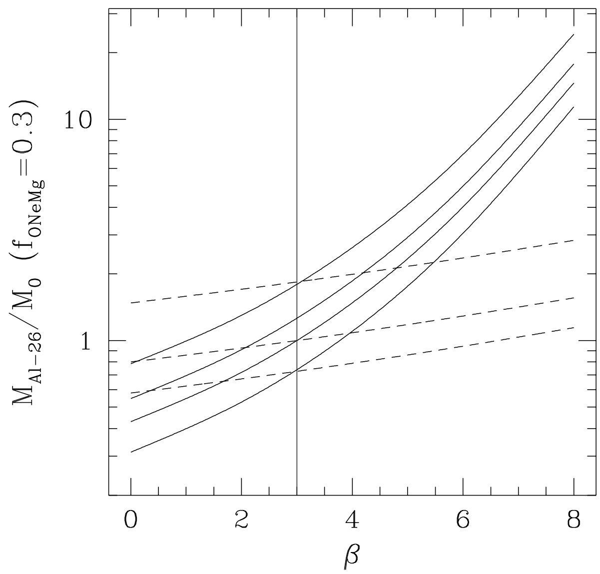

Fig. 4. ^{26}Al production in models of set B when the parameterized production function introduced in Sect. 2.2 is used. M_{Al-26} is determined for values of $M_{1,lim}$ which result in f_{ONeMg} = 0.3, normalized to M_0, the value of M_{Al-26} for the "standard" model (see Sect. 2.1) with $\beta = 3$, $\gamma = 2$, and plotted as a function of β. The solid curves denote models with $\alpha = 2$ and to $\gamma = 0, 2, 4, 8$ (from bottom to top). The dashed curves denote models with $\alpha = 1.2$ and $\gamma = 0, 2, 8$ (from bottom to top).

stars) with calculated distributions obtained from the same initial set of main-sequence binaries (e.g. deKool & Ritter 1993).

A second test is a comparison of the observed mean WD mass in CVs ($\simeq 0.8\,M_\odot$, e.g. Ritter & Kolb 1995) with the value calculated from the above-mentioned visual magnitude-limited samples. As was pointed out by Ritter & Burkert (1986), and confirmed by Dünhuber 1993 (see also Dünhuber & Ritter 1993), selection effects in favor of the high-mass WDs are responsible for the fact that the observed mean value is significantly above the mean WD mass observed in isolated WDs ($\simeq 0.6\,M_\odot$, Schmidt & Smith 1995). Dünhuber finds no clear preference for a particular population model. However, his investigations were based on models where the WD mass was held constant during the secular evolution of CVs, i.e $\alpha = 1$. If α is different from 1, as is the case in our models, the mean WD mass becomes a function of α. Kolb (1993b) derives $d\langle M_1\rangle/d\alpha \simeq 0.3$. In this case, the computed mean WD mass is sufficiently close to the observed value only for $0.8 \lesssim \alpha \lesssim 1.2$. We note that this limit applies only for a global value of α, that is, only under the assumption that α is the same for the entire population. However, α may depend on the mass of the WD and therefore the mean α may be different for different subsets of the population (e.g., for CVs with CO WDs as opposed to ONeMg WDs; see the discussion in Sect. 5.2.3. below).

Lastly, we test our population models against observations of novae. As can be seen from Table 2, models of set B predict a nova rate that is roughly 10 times higher than models of set A, reflecting the different number of CVs in the population. The nova rate is only a weak function of α, despite the apparent proportionality to α in Eq. (10). This can be understood from Eq. (11) which shows that high-mass WDs contribute quite significantly to the nova rate since ΔM_{ign} formally approaches 0 when the WD mass gets close to the Chandrasekhar mass. In populations with $\alpha > 1$, the WDs shrink in mass throughout their evolution, reducing the high-mass WD contribution to ν_Σ. Using (12) instead of (11) results in essentially the same Galactic nova rate, confirming that the prescription given in (11) reproduces the ignition mass fairly well (except for WDs very close to the Chandrasekhar mass). The extrapolation of (12) to WD masses much smaller than $1\,M_\odot$ is of course without physical significance and yields ignition masses a factor $\simeq 10$ higher than (11) for $M_1 = 0.3\,M_\odot$. This failure for low-mass WD systems does not propagate into the predicted nova rate since that is completely dominated by higher-mass WD CVs. The nova rates computed according to Prialnik & Kovetz (1995) lie generally slightly above the rates computed with the canonical ignition mass and this difference increases with increasing α. However, we note that deducing the nova rate from our population models using (13) as the ignition criterion introduces an inconsistency since the underlying nova models for this criterion do not belong to a constant value of α, rather α depends on the corresponding WD mass, mass accretion rate and WD temperature (typically $1.0 \lesssim \alpha \lesssim 1.2$, except for very high accretion rates $\gtrsim 10^{-7}\,M_\odot yr^{-1}$ where $\alpha < 1$). Indeed, the motivation to use an ignition condition based on these latter models at all is to demonstrate that the predicted Galactic nova rate is not very sensitive to the precise ignition condition, so that, in this context, (11) is a satisfactory approximation for it.

Concerning this last test, we note that a direct comparison with the value deduced from observations of 20 novae per year in the Galaxy must be taken with care because of the considerable uncertainties in both the computed and observed values. Nevertheless, models with uncorrelated main-sequence masses and small values for α seem to match the observations best. Given the fact that the computed nova rate is not very sensitive to the ignition criterion, the predicted total nova rate may well prove to be a major constraint on the models. We, therefore, emphasize the need for more reliable observational determinations of the nova rate in our Galaxy.

5.2. Predicted ^{26}Al production

In the light of the above considerations, we proceed to discuss limits and constraints that can be placed on the ^{26}Al production in ONeMg novae.

We begin by first discussing estimates for global upper and lower limits to ^{26}Al production in ONeMg novae. We then discuss likely regimes for ^{26}Al production. Finally, we close this section by discussing the effects of using the parameterized production function (see Sect. 2.2) on our results.

5.2.1. Global upper limit

Since models of set B produce more ^{26}Al than models of set A, we use set B to establish our upper limit. Further, since f_α reaches a maximum near α = 2, we can use the α = 2 curve in Fig. 3 to estimate an upper limit to ^{26}Al production as a function of $M_{1,\rm lim}$ for this population. Inspection of Fig. 3 shows that if $M_{1,\rm lim} \lesssim 1.25\,{\rm M}_\odot$, the resulting upper limit surpasses the COMPTEL upper limit of $\simeq 1\,{\rm M}_\odot$ ^{26}Al in the homogeneous background. To establish a global upper limit for ^{26}Al from ONeMg novae, we must eliminate the dependence on $M_{1,\rm lim}$ by finding a reasonable value for $M_{1,\rm lim}$. As we have said, stellar and binary evolution calculations are of little help in this regard. Instead, we will use a comparison of the observed fraction of ONeMg novae with our predicted fraction, $f_{\rm ONeMg}$, for this purpose. While we recognize the uncertainties in both the observed and predicted values of $f_{\rm ONeMg}$ (see Sect. 3.2), we feel that this will give at least a reasonable estimate for $M_{1,\rm lim}$. We also note that advantages of this approach are that our predicted $f_{\rm ONeMg}$ is insensitive to α and, since it is a relative quantity, we avoid any uncertainty related to the normalization of a population model. Choosing $f_{\rm ONeMg}$ = 0.3 to agree with observations (see Sect. 3.2), we find $M_{1,\rm lim} = 1.15\,{\rm M}_\odot$. From Fig. 3, this translates into an estimate of $M_{\rm Al-26} \lesssim 3\,{\rm M}_\odot$ (α = 2) as a global upper limit for ^{26}Al production from ONeMg novae.

5.2.2. Global lower limit

While the property of f_α that it reaches a global maximum near α = 2 allowed us to establish reasonably straightforwardly an estimate for a global upper limit, the situation is more complex for a global lower limit. As we discussed in Sect. 2.1, observed heavy element enrichments in nova ejecta almost inescapably suggest that $\alpha > 1$ for most classical novae: the question is how much greater? Population models which take into account a secular decrease of the WD are only able to constrain a mean or global value of α for the population to the range $\alpha \lesssim 1.2$. Ejecta abundances determined from observations, even in well-studied systems, are fraught with uncertainties and show a large scatter in Z across the board (i.e, for both CO and ONeMg systems; see Starrfield et al. 1996). While these abundance determinations may be used with some confidence to distinguish CO novae from ONeMg novae, they do not allow a firm determination of α for each system. Finally, the gist of the problem with quoting a lower limit really lies with our uncertain knowledge of mixing as we discussed in Sect. 3.3. Until our understanding of the physical mechanism responsible for mixing in classical novae improves, it will be very difficult to quote a global lower limit to ^{26}Al production in ONeMg novae (other than zero) with any confidence.

5.2.3. Constraints on ^{26}Al production

In this section we will use observational and theoretical constraints to attempt to establish likely values for ^{26}Al production in ONeMg novae. The observational constraints we use are: (1) the amount of ^{26}Al from diffuse sources based on the recent COMPTEL observations; (2) the fraction of ONeMg novae among novae that have been observed in outburst; and (3) ejecta abundances determined from well-studied novae. Before proceeding further, a few words about the uncertainties in these quantities is in order. The value of $\sim 1\,{\rm M}_\odot$ for ^{26}Al from diffuse sources is probably the most secure of the three. While a somewhat higher value cannot be excluded and while some ONeMg novae may possibly be associated with regions of isolated emission, using $1\,{\rm M}_\odot$ to place an upper limit on the amount of ^{26}Al from ONeMg novae is probably correct to within less than a factor of 2. While the current value of 30% for the observed fraction of ONeMg novae is a bit more uncertain, it has only fluctuated between $\sim$25% and 50% (the latter including systems with marginal neon abundances) as more and more ONeMg novae have been observed over the past ten years. We therefore would estimate that the *observed* value for $f_{\rm ONeMg}$ is good to within a factor of 2. However, there is a further uncertainty: how to translate the *observed* value of $f_{\rm ONeMg}$ into the quantity $f_{\rm ONeMg}$ we predict theoretically. Our models properly take into account the main reason for the prevalence of ONeMg novae – the higher outburst frequency on high-mass WDs (e.g., Ritter et al. 1991, Kolb 1995a). But there may be additional selection effects favoring the observation of ONeMg novae: nova outbursts on high-mass WDs are likely to be brighter than outbursts on lower-mass WDs (e.g. Livio 1994). This would imply that our predicted $f_{\rm ONeMg}$ corresponds to somewhat lower values of the observed $f_{\rm ONeMg}$. Finally, the most uncertain of the three constraints is the abundances of the ejected material in novae. While independent determinations of the ejecta abundances for the same system agree quite well in some cases (e.g., V1668 Cyg, V1370 Aql), there is disagreement in other cases, for the same system, by factors of 4 to 5 (e.g., QU Vul, PW Vul), making precise constraints from a single system unwise (see Starrfield et al. 1996). Instead, in the following we will use trends common to several systems or trends which require less precision (e.g., such as distinguishing ONeMg novae from CO novae) to place constraints.

The greater agreement between observations and predictions of post-CE and CV population models with weakly-correlated or uncorrelated progenitor primary and secondary masses, as discussed in Sect. 5.1, leads us to favor using models of set B to estimate likely values of ^{26}Al production from ONeMg novae. Fig. 3 shows that a value of $f_{\rm ONeMg}$ = 0.3 corresponds to $M_{1,\rm lim} = 1.15\,{\rm M}_\odot$. Assuming a constant or mean value of α for the entire population, as we have done in this study, we may use the constraint $\alpha \lesssim 1.2$, in order to remain consistent with the mean WD mass in CVs as derived from observations (see Sect. 5.1). Looking at the α = 1.2 curve in Fig. 3, for $M_{1,\rm lim} = 1.15\,{\rm M}_\odot$, we have a corresponding ^{26}Al production of $M_{\rm Al-26} \simeq 0.15\,{\rm M}_\odot$.

We emphasize that this value depends greatly on the assumption that α is the same for the entire population. If, for example, the mean α in ONeMg novae is higher than the mean α for all novae, then a larger ^{26}Al production is allowed. In order for ONeMg novae to account for the entire $1\,{\rm M}_\odot$ of ^{26}Al in a diffuse background implied by the COMPTEL observations, models of set B require that the mean α in ONeMg systems be ~ 1.6 (for $M_{1,\rm lim} = 1.15\,{\rm M}_\odot$). This implies a mean mixing of $\sim 40\%$ in ONeMg systems, as compared with a maximum mean mixing of $\sim 20\%$ for the entire population implied by the constraint of $\alpha = 1.2$ discussed above. We explore below to what extent a higher degree of mixing in ONeMg novae is supported by ejecta abundances in novae.

Inspection of ejecta abundances in well-studied novae (see Table 1 in Starrfield et al. 1996) reveals that the mean Z in systems which are unambiguously ONeMg novae ($X_{\rm Ne}/X_{{\rm Ne}_\odot} \gtrsim 35$) is 0.52 compared with a mean Z for all well-studied novae of 0.34. Care must be taken in interpreting this point, however, since in order for a system to be unambiguously considered as a ONeMg nova, the enrichment in neon over solar must be well in excess of 10 × solar (see Sect. 3.2), biasing the mean Z in ONeMg nova systems to be high. If one includes novae with $X_{\rm Ne}/X_{{\rm Ne}_\odot} \sim 10$ (V977 Sco, V2214 Oph and V1500 Cyg), then the mean Z is reduced to 0.42. Nevertheless, it does appear that the neon abundances in two ONeMg novae are quite high (V693 CrA, $X_{\rm Ne} \sim 0.2$ and V1370 Aql, $X_{\rm Ne} \sim 0.5$; we note that two independent abundance determinations were made for each system and the values for $X_{\rm Ne}$ agree to within 40% for V693 CrA and to within 10% for V1370 Aql.) Comparison with the nova models of Politano et al. (1995, 1996) suggests that the level of mixing is of order 50% or greater for these systems.

Finally, we close by noting that the null detection of ^{22}Na γ-ray emission from nearby ONeMg novae (Iyudin et al. 1995) imposes constraints on the amount of ^{22}Na produced in ONeMg novae. The authors estimate an upper limit for the ejected ^{22}Na mass for such novae within the Galactic disk of $3.7 \times 10^{-8}\,{\rm M}_\odot$. However, this constraint does not necessarily restrict α to small values. Politano et al. (1996) produce models with very high mass WDs ($1.35\,{\rm M}_\odot$) where the ^{22}Na mass fraction is low even for moderate values of α (of order 50%), cf. last column of Table 1. Nova outbursts on lower mass ONeMg WDs ($\sim 1\,{\rm M}_\odot$) are not expected to produce significant amounts of ^{22}Na because the peak temperature is too low (e.g., Politano et al. 1995). In addition, the unusually high ejecta masses in a number of ONeMg novae (e.g., QU Vul [Taylor et al. 1988], V838 Her [Woodward et al. 1992]), V1974 Cyg [Pavelin et al. 1993]) pose difficulties for standard models of nova outbursts on high-mass WDs, which predict much lower ejecta masses (e.g., Starrfield 1989; Politano et al. 1995). These latter two points make it imperative for observers to obtain reliable WD masses for ONeMg nova systems, particularly those with high ejected masses (see the discussion in Misselt et al. [1995]). If such determinations reveal WD masses of $\sim 0.8\,{\rm M}_\odot$ in these systems, then either alternative mechanisms for producing ONeMg-rich WDs in binary systems with lower-mass WDs (~ 0.75-$1.0\,{\rm M}_\odot$ at birth) must exist (e.g., Shara & Prialnik 1994; Shara 1994), or the mean amount of mixing in ONeMg novae *is* significantly higher than for novae in general, leading to substantial erosion of the WD during the system's lifetime. Either case would have important implications for ^{26}Al production in novae.

5.2.4. Effects of the parameterized production function on ^{26}Al production

Our motivation for using a parameterized production function is to attempt to estimate the effects of the uncertainties in the nova models on ^{26}Al production (see Sects. 2.1 and 2.2). Recall from Sect. 2.2 that we generalized the production function in Sect. 2.1 (which we will hereafter refer to as our "standard" production function), while keeping the same differential trends, using simple parameters, β and γ, to explore a greater range of dependencies on M_1 and $\dot M$. In particular, β and γ were varied from 0 to 8, probing stronger and stronger dependencies on WD mass and accretion rate, respectively. Our standard production function corresponds approximately to $\beta = 3$ and $\gamma = 2$. Thus, for $\beta \lesssim 3$, we have a weaker (flatter) dependence on WD mass than in our standard production function for f_{m_1} (Eq. [3]), whereas $\beta \gtrsim 3$ corresponds to a stronger (steeper) dependence on WD mass. Similarly, for $\gamma \lesssim 2$, we have a weaker (flatter) dependence on accretion rate than in our standard production function for $f_{\dot m}$ (Eq. [4]), whereas $\gamma \gtrsim 2$ corresponds to a stronger (steeper) dependence on accretion rate.

The results of using the parameterized production function are shown in Fig. 4. As noted previously, the ^{26}Al production in this figure is normalized to M_0, the ^{26}Al production in our "standard" model. The qualitative dependencies on β and γ expressed by these curves are as expected from the functional form of the parameterization: namely ^{26}Al production increases with both increasing β and γ. It is interesting, however, to note that the influence of γ is rather modest (a factor of 2 change at most), whereas the influence of β can be substantial (factors of 2-30) especially for larger values of α. This shows that the influence of the accretion rate dependence is weaker than the influence of the WD mass dependence on ^{26}Al production for a given population.

Of the uncertainties in the nova models discussed in Sect. 2.1, the greatest concern is the potential influence of the new reaction rates described in Herndl et al. (1995) on ^{26}Al production in novae, and we would like to discuss this briefly here. Since the dependence on γ is small (at least of the same order as the uncertainties in the observational quantities we used to place constraints on ^{26}Al production in the first place), we focus on how the new rates may affect the dependence on β. Network calculations by Herndl et al. (1995) show that the new reaction rates result in a decreased ^{26}Al production compared with the rates used by Politano et al. (1995, 1996). However, Herndl et al. point out that the new rates will only affect the production of ^{26}Al for temperatures greater than $\sim 250 \times 10^6$ K. From the WD mass sequence (Politano et al. 1995), this peak temperature corresponds to a WD mass between $1.00\,{\rm M}_\odot$ ($T_{\rm peak} = 224 \times 10^6$ K) and $1.25\,{\rm M}_\odot$ ($T_{\rm peak} = 290 \times 10^6$ K). This will tend to steepen the dependence on WD mass compared with the standard production function based on Politano et al.'s data, so that β should be somewhat larger than 3. However, the new rates will not only affect the differential trends with WD mass, accretion rate, etc., but also the absolute amount produced by a given model. In particular, therefore, the value of M_0 (the amount of ^{26}Al produced from our standard model) will presumably be smaller and hence the normalization used in Fig. 4 be different. While preliminary calculations using the new rates performed by Starrfield et al. (1996) on a $1.25\,M_\odot$ WD indicate that the ^{26}Al production is reduced by a factor of ~ 10, we emphasize that several other factors (such as the initial WD luminosity, opacities, etc.) were also varied compared with Politano et al.'s models, so that one cannot directly infer that the effect of the new rates was of the same amount. Even assuming it were, the drop by a factor of $\sim$ 10 would be weakened by the effect of the simultaneous increase of β. Hence this seems to suggest an overall modest reduction of the ^{26}Al output in models with the new rates. However, we cannot make a definitive statement until detailed comparison models which use the new rates are calculated for several WD masses.

6. Conclusions

Applying Galactic nova population models and recent 1-dim. hydrodynamical nucleosynthesis calculations for ONeMg novae, we have examined the ^{26}Al production by ONeMg novae in the Galaxy. We summarize our key conclusions below.

(1) The amount of ^{26}Al produced by our model populations is strongly dependent on the assumed mass ratio distribution in ZAMS binaries. Populations of CVs which evolve from progenitor ZAMS binaries in which the masses of the primary and secondary stars are uncorrelated produce ~ 5 to 10 times more ^{26}Al than those in which there is a strong correlation between progenitor primary and secondary masses. This is a direct consequence of the fact that populations of ZAMS binaries with un- or weakly-correlated primary and secondary masses produce more CVs than those with strongly correlated primary and secondary masses.

(2) ^{26}Al production is also a strong function of the amount of mixing which occurs between material accreted from the donor star and material from the underlying white dwarf. For a given population, maximum ^{26}Al production is achieved for a level of mixing of $\sim 50\%$ ($\alpha = 2$).

(3) ^{26}Al is produced almost exclusively from systems with high mass transfer rates in our model populations and, therefore, systems with orbital periods above the period gap. We note that this is not a trivial result, since such systems comprise only $\sim 1\%$ of the entire population.

(4) Choosing optimal models and parameter values, we estimate an upper limit for ^{26}Al production from ONeMg novae of $\sim 3\,M_\odot$. In estimating this number, we have taken the fraction of ONeMg novae in our population to be equal to 30%, the current value deduced from observations. This choice constrains the least massive ONeMg WD (at birth) in our population to a value of $M_{1,\rm lim} = 1.15\,M_\odot$.

Uncertainties in both theory and observations, particularly our lack of understanding of the physical mechanism responsible for mixing in classical novae, preclude us from placing a lower limit on ^{26}Al production from ONeMg novae (other than zero) with any confidence at this time.

(5) Selecting models and parameter values that are the most consistent with observational quantities independent of ^{26}Al production (e.g., fraction of CVs below the period gap, properties of post-CE binaries, mean WD mass in CVs, etc.), we find a value of $\sim 0.15\,M_\odot$ for ^{26}Al production from ONeMg novae (again for $f_{\rm ONeMg} = 0.3$). However, we emphasize that this value is strongly dependent on our use of a single value of α for the entire population. If the mean amount of mixing in ONeMg novae is approximately $\simeq$ 40%, a factor of two greater than the maximum mean amount of mixing for all novae, then our results suggest that ONeMg novae could produce enough ^{26}Al ($\sim 1\,M_\odot$) to account for the entire diffuse 1.8 MeV emission seen by COMPTEL. Ejecta abundances in well-studied novae do not preclude this possibility, and are perhaps (weakly) in support of the possibility that the mean level of mixing in ONeMg novae is higher than that for all novae.

We note that the specific values quoted in points (4) and (5) above are predicated on our assumption that the formation of CVs with ONeMg WDs is quantitatively similar to the formation of CVs with high-mass CO WDs. If detailed models of the formation of CVs with ONeMg WDs suggest otherwise, then our predictions would need to be re-evaluated in light of these more accurate models.

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