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NUCLEOSYNTHESIS IN CLASSICAL NOVAE: CO VERSUS ONe WHITE DWARFS

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ABSTRACT

Detailed nucleosynthesis in the ejecta of classical novae has been determined for a grid of hydrodynamic nova models. The reported 14 evolutionary sequences, followed from the onset of accretion up to the explosion and ejection stages, span a range of CO and ONe white dwarf masses (0.8–1.35 $M_{\odot}$) and mixing levels between the accreted envelope and the underlying white dwarf core (25%–75%). The synthesis of each isotope from ^{1}H to ^{40}Ca is discussed, along with its sensitivity to model parameters. Special emphasis is placed on isotopes such as ^{13}C, ^{15}N, and ^{17}O, whose synthesis may account for a significant fraction of their Galactic content. Production of the radioactive isotopes ^{7}Be, ^{22}Na, and ^{26}Al is also analyzed, since they may provide a direct test of the thermonuclear runaway model through their γ-ray emission. The resulting elemental yields reproduce the spectroscopic abundance determinations of several well-studied classical novae fairly well.

Subject headings: novae, cataclysmic variables — nuclear reactions, nucleosynthesis, abundances — white dwarfs

1. INTRODUCTION

Classical novae release dramatic amounts of energy. According to the widely accepted scenario, classical novae are close binary systems consisting of a white dwarf and a large main-sequence star. The companion overfills its Roche lobe, and matter flows outward through the inner Lagrangian point, leading to the formation of an accretion disk around the white dwarf. Some fraction of this H-rich matter ultimately ends up on top of the white dwarf, where it is gradually compressed by more material that is still being accreted. This compression heats the envelope up to the point at which the ignition conditions for driving a thermonuclear runaway (hereafter TNR) are reached.

Over the last 25 years many hydrodynamic computations of nova outbursts have pointed out that an important fraction of the formerly accreted envelope is ejected. Since the temperatures attained in the envelope during the explosion are rather high, with typical peak values of ~ 2–3×10^{8} K, the ejecta show significant nuclear processing (Starrfield et al. 1997; Kovetz & Prialnik 1997; José, Hernanz, & Coc 1997, and references therein). Abundance levels of the intermediate-mass elements in the ejecta are significantly enhanced, in general agreement with spectroscopic abundance determinations (Livio & Truran 1994). This raises the issue of the potential contribution of classical novae to the Galactic abundances, assuming the solar abundance levels. The total mass ejected by classical novae over the Galaxy's history may be estimated by the product of the Galactic nova rate (~ 30 events yr^{-1}), with the Galaxy's lifetime ($\sim 10^{10}$ yr) and the average ejected mass per nova outburst ($\sim 2 \times 10^{-5}$ $M_{\odot}$). This gives $\sim 6 \times 10^{6}$ $M_{\odot}$, which accounts for only $\sim 1/3000$ of the Galactic disk's gas and dust content. This order of magnitude estimate suggests that, despite their large occurrence rate in the Galaxy, novae scarcely contribute to the Milky Way's overall metallicity, as compared to other major sources, such as supernovae or asymptotic giant branch stars (Woosley 1986). However, classical novae can account for a significant fraction of the abundance levels of individual nuclei, especially those with overproduction factors $f \geq 1000$ ($f \equiv X_i/X_{i,\odot}$, where X_i and $X_{i,\odot}$ are the mass fractions of species i in the ejected envelope and the solar value, respectively). Many numerical models of nova outbursts have shown significant overproduction of several species, such as ^{7}Li (see Starrfield, Truran, & Sparks 1978; Hernanz et al. 1996), ^{13}C, ^{15}N, or ^{17}O (Starrfield et al. 1972; Sparks, Starrfield, & Truran 1976; Prialnik 1986; Politano et al. 1995; Kovetz & Prialnik 1997; Starrfield et al. 1997; José & Hernanz 1997). In particular, Galactic ^{15}N and ^{17}O have been strongly supported as being produced during nova outbursts (see Woosley et al. 1997). Significant production of radioactive nuclei like ^{22}Na and ^{26}Al (Weiss & Truran 1990; Nofar, Shaviv, & Starrfield 1991; Coc et al. 1995; Politano et al. 1995; José et al. 1997; José & Hernanz 1997; Starrfield et al. 1997) and even heavier species, such as ^{31}P, ^{32,33}S, and ^{35}Cl, have also been reported (Politano et al. 1995; José & Hernanz 1997; Starrfield et al. 1997).

Despite the availability of several determinations of the nucleosynthetic yields in classical novae, extended analyses through a representative number of isotopes and nuclear reactions, directly linked to the hydrodynamical models, for both CO and ONe novae have only scarcely been reported. Kovetz & Prialnik (1997) have recently published detailed multicycle calculations of nova outbursts for CO white dwarf masses ranging from 0.65 to 1.4 $M_{\odot}$. However, according to stellar evolution, massive white dwarfs are expected to be made of ONe instead of CO. Moreover, observations of some nova systems, such as V693 CrA 1981, QU Vul 1984 No. 2, V838 Her 1991, or V1974 Cyg 1992, reveal the presence of an underlying ONe white dwarf. It is also worth noticing that the nuclear reactions library used by Kovetz & Prialnik (1997) has been taken from the

Caughlan & Fowler's (1988) compilation, and hence does not take into account the different updates of some crucial rates that may influence their nucleosynthesis results. On the other hand, Starrfield et al. (1997) have used fully updated physics in the modeling of the neon nova V1974 Cyg 1992. The analysis is limited, however, to 1.25 $M_{\odot}$ white dwarfs, for which a fixed 50% degree of mixing between core and envelope is systematically adopted.

In this paper we reinvestigate the role played by classical nova outbursts in the synthesis of chemical species, comparing CO and ONe novae, for a wide range of white dwarf masses (0.8–1.35 $M_{\odot}$) and degrees of mixing between core and envelope (25%–75%), using a hydrodynamic code with a fully updated nuclear reaction network. Special emphasis is placed on the comparison with available observations of several nova systems. In § 2 we briefly describe the method of computation, the input physics, and the initial models adopted. Results from the different evolutionary computations and comparison with observations are given in § 3. A summary of the most relevant conclusions of this paper is given in § 4.

2. MODEL AND INPUT PHYSICS

Following the method described in Kutter & Sparks (1972, 1980), a one-dimensional implicit hydrodynamical code (SHIVA), in Lagrangian formulation, has been developed to analyze the course of nova outbursts from the onset of accretion up to the expansion and ejection stages. The code solves the standard set of differential equations for hydrodynamical evolution: conservation of mass, momentum, and energy; energy transport by radiation and convection; and the definition of the Lagrangian velocity. In order to treat the long-term evolution of the system, when the expanding nebula becomes optically thin, we have added a term that obeys Kirchhoff's law to the equation of radiation transport in the diffusion approximation (see Larson 1972; Starrfield, Sparks, & Truran 1974). A time-dependent formalism for convective transport has been included whenever the characteristic convective timescale becomes larger that the integration time step (Wood 1974). Partial mixing between adjacent convective shells is treated by means of a diffusion equation (Prialnik, Shara, & Shaviv 1979). The equation of state includes contributions from the electron gas (with different degrees of degeneracy), the ion plasma, and radiation; Coulomb corrections to the electronic pressure are also taken into account. Models make use of Iben's (1975) opacity fits. However, the effect of Iglesias & Rogers (1993) radiative opacities has also been tested. Calculation of evolutionary sequences systematically including the radiative opacities from Iglesias & Rogers (1993) is currently in progress. The code has been linked to a reaction network that follows the detailed evolution of 100 nuclear species, ranging from ^{1}H to ^{40}Ca through 370 nuclear reactions, with updated rates and screening factors from Graboske et al. (1973) and DeWitt, Graboske, & Cooper (1973). The code has already been used for the specific analysis of the contribution of novae to the Galactic content of ^{7}Li (Hernanz et al. 1996) and ^{26}Al (José et al. 1997), as well as for the γ-ray emission from nearby novae (see Hernanz et al. 1997; Gómez-Gomar et al. 1997).

Some of the input parameters with a deep influence on the nova nucleosynthesis are the chemical composition of the envelope and the mass of the underlying white dwarf. The problem of the chemical composition of nova envelopes is complex and far from being understood. Whereas Prialnik & Kovetz (1995) strongly support the diffusion-convection mechanism as responsible for the mixing, recent two-dimensional calculations by Glasner, Livne, & Truran (1997) suggest a very efficient dredge-up of matter from the outermost shells of the core into the solarlike accreted envelope, induced by convection. The question deserves further attention—probably fully three-dimensional calculations from the onset of accretion. As suggested by Politano et al. (1995), the matter transferred from the companion is assumed to be solarlike and is mixed in a given fraction with the outermost shells of the underlying core by means of an unknown mechanism (either shear mixing, diffusion, or a convective multidimensional process). This assumption is based on the enhanced CNO or ONeMg abundances required by theoretical nova models both to power the explosion and to account for the spectroscopic abundance determinations (Livio & Truran 1994). In most of the calculations performed by Starrfield's group, they adopt a 50% degree of mixing between core and envelope. This may be considered as a representative mixing level, in view of the mean metallicities observed in the ejecta of "true" ONeMg novae (Livio & Truran 1994). In our models, we have considered different mixing levels ranging from 25% to 75%, in order to be consistent with the wide spread of metallicities reported from observations. The composition of the underlying core has been taken from recent detailed evolutionary models, specially in the case of ONe white dwarfs, which are the main contributors to heavy isotopes. These stars are made basically of ^{16}O and ^{20}Ne (Domínguez, Tornambé, & Isern 1993; Ritossa, García-Berro, & Iben 1996), since Mg is almost absent. This issue plays a crucial role in the resulting nucleosynthesis, and it should be taken into account in comparing previous estimates by different groups. In particular, the ONeMg models by Starrfield et al. (1997) have an initial composition of the white dwarf core based on old nucleosynthesis calculations of C burning from Arnett & Truran (1969). As stated in their paper (Starrfield et al. 1997), the use of the new abundances by Ritossa et al. (1996) may provide quite different results. For the CO models we have assumed a core composition of $X(^{12}\mathrm{C}) = 0.495$, $X(^{16}\mathrm{O}) = 0.495$, and $X(^{22}\mathrm{Ne}) = 0.01$.

The effect of the white dwarf mass has been tested through a number of simulations involving both CO white dwarfs ($M_{\mathrm{wd}} = 0.8$, 1.0, and 1.15 $M_{\odot}$) and ONe ones ($M_{\mathrm{wd}} = 1.0$, 1.15, 1.25, and 1.35 $M_{\odot}$). The overlapping between both intervals results from the uncertain exact upper (lower) limit for CO (ONe) degenerate cores. We would like to stress that the mass accretion rate and the initial white dwarf luminosity (or temperature) may also influence the results. In particular, more violent outbursts are obtained when lower mass accretion rates or lower initial luminosities are adopted, since the higher degeneracy attained in the more massive accreted envelopes leads to more violent outbursts. The expected effect on the resulting nucleosynthesis is an extension of the nuclear activity toward heavier species as the mass accretion rate or the initial luminosity decrease, because of the higher temperatures achieved in the envelope. In this paper we have adopted a mass accretion rate of 2×10^{-10} $M_{\odot}$ yr^{-1} (though other values have also been tested) and an initial luminosity of 10^{-2} $L_{\odot}$, rather typical values, in order to limit the parameter space.

TABLE 1

INITIAL PARAMETERS AND MAIN CHARACTERISTICS OF ONe NOVA MODELS

Parameter	ONe1	ONe2	ONe3	ONe4	ONe5	ONe6	ONe7
M_{wd} ($M_\odot$)	1.00	1.15	1.15	1.15	1.25	1.35	1.35
Mixing (%)	50	25	50	75	50	50	75
ΔM_{env} (10^{-5} $M_\odot$)	6.4	3.2	3.2	3.5	2.2	0.54	0.58
t_{acc} (10^5 yr)	3.3	1.9	1.9	2.1	1.3	0.31	0.33
t_{rise} (10^6 s)	20	46	13	11	6.8	2.5	2.1
$\epsilon_{nuc,max}$ (10^{16} ergs g^{-1} s^{-1})	0.29	0.36	0.76	2.4	2.1	19	14
T_{max} (10^8 K)	1.98	2.21	2.19	2.48	2.44	3.24	3.32
t_{max} (s)	768	828	540	305	380	150	108
ΔM_{ejec} (10^{-5} $M_\odot$)	4.7	2.3	1.9	2.6	1.4	0.44	0.34
v_{ejec} (km s^{-1})	1600	2100	2400	2500	3100	4100	6000
K (10^{45} ergs)	1.3	1.1	1.2	1.9	1.4	0.9	1.3

3. RESULTS AND DISCUSSION

The main properties of the initial models for the 14 evolutionary sequences presented in this paper, as well as a summary of the most relevant characteristics of the evolution, are given in Tables 1 and 2: the initial white dwarf mass M_{wd} and the adopted mixing level between core and envelope are input parameters; ΔM_{env} is the envelope's mass at the end of the accretion stage; t_{acc} is the duration of the accretion phase; t_{rise} is the time required for a temperature rise from $T_{bs} = 3 \times 10^7$ to 10^8 K at the burning shell; $\epsilon_{nuc,max}$ and T_{max} are peak nuclear energy generation rate and maximum temperature at the burning shell, respectively; t_{max} is the time required to reach peak temperature from $T_{bs} = 10^8$ K; ΔM_{ejec}, v_{ejec}, and K represent the total mass, the mean velocity, and the mean kinetic energy of the ejected envelope, respectively. The mean composition of the ejecta is given in Tables 3 and 4 in mass fractions.

3.1. *Theoretical Nova Outbursts: From the Onset of Accretion to Mass Ejection*

In this section we will focus on the main characteristics of the computed models. As a framework for the analysis, we will describe the detailed evolution of model CO5 (a 1.15 $M_\odot$ CO white dwarf with a 50% mixture with core material, accreting mass at a rate of 2×10^{-10} $M_\odot$ yr^{-1}).

The early accretion phase is dominated by p–p chains [mainly ^{1}H(p, $e^+\nu_e$)^{2}H], as well as by the CNO-cycle reaction ^{12}C(p, γ)^{13}N, followed by ^{13}N β^+ decay into ^{13}C. As soon as the temperature at the burning shell reaches 2.4×10^7 K, the nuclear timescale becomes shorter than the accretion timescale, and accretion becomes negligible. The mass piled up in the envelope at the end of the accretion phase (which lasts $\sim 10^5$ yr) is 1.8×10^{-5} $M_\odot$. The rate of nuclear energy generation has risen to $\sim 10^8$ ergs g^{-1} s^{-1}.

The beginning of the TNR is accompanied by the development of a convective zone just above the burning shell, which rapidly expands toward the outer envelope. When T_{bs} reaches 5×10^7 K, convection extends already through a region of 125 km above the ignition shell. The release of nuclear energy is fully dominated by the cold CNO cycle, mainly through ^{12}C(p, γ)^{13}N(β^+)^{13}C(p, γ)^{14}N, and no significant activity in the NeNa and MgAl cycles is found. A similar behavior is found at $T_{bs} = 10^8$ K, when convection has already extended through the whole envelope ($\tau_{conv} \sim$ 0.6 s). The model has spent $t_{rise} \sim 7.2 \times 10^5$ s to rise from $T_{bs} = 3 \times 10^7$ to 10^8 K. When the temperature reaches 2×10^8 K, the star achieves a maximum rate of nuclear energy generation of $\epsilon_{nuc,max} = 1.1 \times 10^{16}$ ergs g^{-1} s^{-1}. At this time, significant energy production comes from the hot CNO cycle [initiated when ^{13}N(p, γ)^{14}O becomes faster than ^{13}N(β^+)^{13}C], mainly through ^{12}C(p, γ)^{13}N(p, γ)^{14}O, ^{14}N(p, γ)^{15}O and ^{16}O(p, γ)^{17}F. Leakage from the MgAl cycle through proton captures on ^{27}Si and ^{27}Al becomes progressively important. A peak temperature of $T_{max} = 2.1 \times 10^8$ K is attained 65 s after the ignition shell reaches 10^8 K. As a result of the violent TNR, 1.3×10^{-5} $M_\odot$ are ejected (72% of the formerly accreted envelope), with a mean velocity of ~ 2700 km s^{-1} (see Table 2 for a summary of these results).

In order to check the effect of the white dwarf core composition, we have evolved model ONe3, an ONe white

TABLE 2

INITIAL PARAMETERS AND MAIN CHARACTERISTICS OF CO NOVA MODELS

Parameter	CO1	CO2	CO3	CO4	CO5	CO6	CO7[a]
M_{wd} ($M_\odot$)	0.8	0.8	1.0	1.15	1.15	1.15	1.15
Mixing (%)	25	50	50	25	50	75	50
ΔM_{env} (10^{-5} $M_\odot$)	9.7	8.8	3.9	2.1	1.8	1.8	0.9
t_{acc} (10^5 yr)	3.1	2.6	1.7	1.2	1.0	1.0	0.4
t_{rise} (10^6 s)	2.8	1.8	1.1	0.43	0.72	0.48	1.7
$\epsilon_{nuc,max}$ (10^{16} ergs g^{-1} s^{-1})	0.05	0.1	0.3	0.5	1.1	1.9	0.2
T_{max} (10^8 K)	1.45	1.51	1.70	2.03	2.05	2.08	1.73
t_{max} (s)	454	199	152	147	65	51	200
ΔM_{ejec} (10^{-5} $M_\odot$)	7.0	6.4	2.3	1.5	1.3	1.3	0.63
v_{ejec} (km s^{-1})	800	1200	1900	2200	2700	2900	2700
K (10^{45} ergs)	0.6	1.1	0.9	0.8	1.0	1.3	0.45

[a] Model with Iglesias & Rogers (1993) opacities.

dwarf with the same input parameters as model CO5. The lower amount of ^{12}C present in its envelope reduces the role played by the CNO cycle, and less nuclear energy is released at the same temperature. Therefore, model ONe3 accretes a more massive envelope before the TNR begins (3.2×10^{-5} $M_{\odot}$). Since the ignition density (and hence the degeneracy) is also higher, a higher peak temperature is attained ($T_{max} = 2.2 \times 10^8$ K). The net effect is a partial extension of the nuclear activity toward higher Z nuclei, both because of the different peak temperature and the different chemical composition of the envelope. In particular, model ONe3 shows the dominant role played by some reactions of the MgAl cycle at peak temperature that are absent in model CO5. A second feature, which turns out to be crucial, is the different timescales of the TNR: model ONe3 requires $t_{rise} \sim 1.3 \times 10^7$ s to increase the temperature at the burning shell from $T_{bs} = 3 \times 10^7$ to 10^8 K, plus $t_{max} \sim 540$ s to reach peak value (see Table 1 for a summary of the results). These larger times deeply influence the final abundances in the ejecta (see § 3.2).

In order to mimic the uncertain process of mixing between the solarlike accreted material and the outermost layers of the underlying CO or ONe white dwarf, we have adopted different degrees of mixing, ranging from 25% to 75%. Computations with 1.15 $M_{\odot}$ ONe white dwarfs (i.e., models ONe2, ONe3, and ONe4) show that a more massive envelope is accreted when a higher degree of mixing is adopted, leading to a more violent outburst. For instance, model ONe4 (with 75% mixing) attains a peak temperature of $T_{max} = 2.5 \times 10^8$ K and ejects matter with a mean kinetic energy of $K = 1.9 \times 10^{45}$ ergs, as compared to model ONe2 (with only 25% mixing), for which $T_{max} = 2.2 \times 10^8$ K and $K = 1.1 \times 10^{45}$ ergs (see Table 1). A similar trend is found for models ONe6 and ONe7, involving 1.35 $M_{\odot}$ ONe white dwarfs with 50% and 75% mixing, respectively. We have also performed several computations involving 1.15 $M_{\odot}$ CO white dwarfs (i.e., models CO4, CO5, and CO6, with 25%, 50%, and 75% mixing, respectively), as well as 0.8 $M_{\odot}$ CO white dwarfs (models CO1 and CO2, with 25% and 50%, respectively). Contrary to the ONe models, the most massive envelopes are accreted on top of white dwarfs with 25% mixing, with a minimum mass around 50% mixing. However, the strength of the explosion, as indicated by a higher peak temperature and a higher mean kinetic energy, increases with the mixing level (see Table 2).

As shown in Tables 1 and 2, massive white dwarfs develop a TNR after a shorter accretion phase (and hence accrete less mass), as compared to lighter white dwarfs, because of the higher surface gravity. Also, the evolution toward peak temperature takes place with a shorter timescale. The most relevant outcome is the increase of the peak temperature attained during the TNR as the mass of the white dwarf increases. We stress that this is especially noticeable for model ONe6 (with $M_{wd} = 1.35$ $M_{\odot}$), which attains a maximum temperature of 3.2×10^8 K.

Two different prescriptions for the radiative opacities have been considered in order to estimate their potential effect on the progress of the outburst and on the resulting nucleosynthesis: model CO5 has been evolved using Iben's (1975) fits to the opacity tables of Cox & Stewart (1970a, b), whereas Iglesias & Rogers (1993) opacities have been adopted in model CO7. As shown by José (1996), the use of Iglesias & Rogers (1993) opacities reduces the mass of the accreted envelope, leading to a softer explosion. The reason is that the Iglesias & Rogers opacities are larger than the Iben ones. Therefore, a significant temperature increase in the envelope of model CO7 ensues, reducing the time required to achieve the critical conditions for a TNR (see Table 2). A similar trend has been recently pointed out by Starrfield et al. (1997). Nucleosynthesis results from model CO7 do not reveal large differences from those of model CO5 (see Table 4).

3.2. *Nucleosynthesis*

In this section we will examine the yields of our numerical nova models. Tables 3 and 4 list the mean chemical composition of the ejecta in mass fractions a few days after the explosion, resulting from our evolutionary sequences of ONe and CO novae, respectively. Overproduction factors, relative to solar abundances, for models CO5, ONe3, and ONe6 are displayed in Figures 1–3.

3.2.1. *Synthesis of* ^{7}Be–^{7}Li

The synthesis of ^{7}Li in classical novae has been recently analyzed in detail by Hernanz et al. (1996), who have confirmed that the *beryllium transport* mechanism can efficiently lead to large amounts of ^{7}Li. In that paper we showed that lithium production is favored when CO novae are adopted, instead of ONe novae. The faster evolution of CO novae allow photodisintegration of ^{8}B through ^{8}B(γ, p)^{7}Be to prevent ^{7}Be destruction [synthesized in the first part of the TNR by means of ^{3}He(α, γ)^{7}Be].

Ejected masses of ^{7}Li in the CO models are almost an order of magnitude larger than in the ONe ones, with a maximum production for a 50% mixing. Because of the higher degeneracy attained in massive white dwarfs, which results in stronger outbursts with shorter evolutionary timescales, production is enhanced when the initial mass of the underlying white dwarf is increased. Although large overproduction factors are obtained for most of the CO models (up to $f \sim 900$; see Fig. 1), classical novae can only account for $\sim 10\%$ of the Galactic ^{7}Li content, assuming the solar system level. This result is similar to the estimates given by Starrfield et al. (1978) in the framework of hydro-

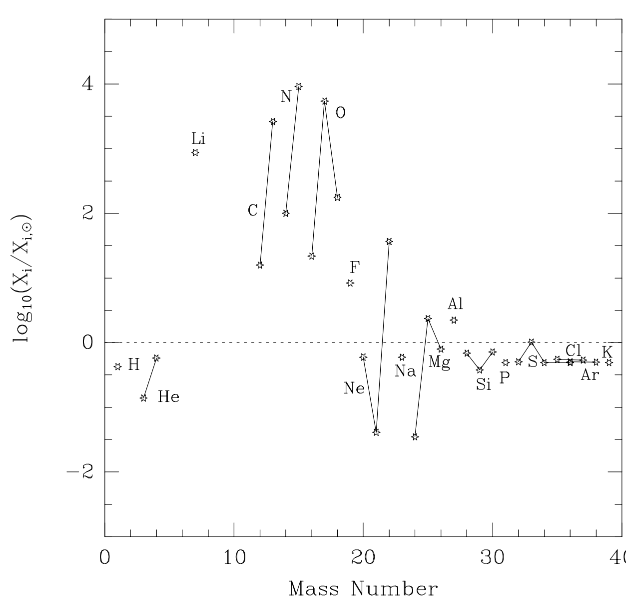

FIG. 1.—Overproduction factors relative to solar abundances vs. mass number for model CO5 (1.15 $M_{\odot}$ CO white dwarf with 50% mixing).

TABLE 3

YIELDS FROM ONe NOVA MODELS (MASS FRACTIONS)

	MODEL						
NUCLEUS	ONe1	ONe2	ONe3	ONe4	ONe5	ONe6	ONe7
^{1}H	3.2E − 1	4.7E − 1	3.0E − 1	1.2E − 1	2.8E − 1	2.4E − 1	7.3E − 2
^{3}He	7.1E − 8	2.1E − 9	4.3E − 8	1.7E − 7	2.8E − 8	2.9E − 8	9.7E − 8
^{4}He	1.8E − 1	2.8E − 1	2.0E − 1	1.3E − 1	2.2E − 1	2.4E − 1	1.7E − 1
^{7}Be	2.3E − 7	4.6E − 8	6.0E − 7	1.2E − 6	6.9E − 7	1.3E − 6	2.4E − 6
^{11}B	8.8E − 13	4.0E − 13	4.4E − 12	1.7E − 11	1.2E − 11	2.5E − 10	1.9E − 9
^{12}C	1.3E − 2	1.8E − 2	2.3E − 2	2.2E − 2	2.8E − 2	2.1E − 2	2.6E − 2
^{13}C	1.7E − 2	2.3E − 2	2.8E − 2	2.7E − 2	3.2E − 2	1.5E − 2	2.5E − 2
^{14}N	2.6E − 2	3.0E − 2	2.2E − 2	2.7E − 2	3.2E − 2	4.6E − 2	3.5E − 2
^{15}N	7.7E − 3	1.7E − 2	2.3E − 2	2.4E − 2	4.2E − 2	1.2E − 1	1.4E − 1
^{16}O	1.7E − 1	2.4E − 2	1.2E − 1	2.3E − 1	7.1E − 2	2.2E − 2	9.1E − 2
^{17}O	1.8E − 2	1.1E − 2	2.8E − 2	4.1E − 2	3.9E − 2	1.7E − 2	5.1E − 2
^{18}O	8.2E − 3	2.4E − 3	6.0E − 3	7.3E − 3	4.2E − 3	9.8E − 4	1.8E − 3
^{19}F	8.5E − 6	4.7E − 6	8.9E − 6	1.2E − 5	1.3E − 5	2.2E − 5	4.0E − 5
^{20}Ne	1.8E − 1	9.0E − 2	1.8E − 1	2.6E − 1	1.8E − 1	1.5E − 1	2.4E − 1
^{21}Ne	1.9E − 5	1.3E − 5	3.0E − 5	4.0E − 5	3.5E − 5	5.1E − 5	8.4E − 5
^{22}Ne	2.0E − 3	5.9E − 4	1.7E − 3	2.5E − 3	1.0E − 3	1.5E − 4	4.2E − 4
^{22}Na	4.8E − 5	3.1E − 5	5.3E − 5	1.5E − 4	9.6E − 5	6.0E − 4	6.5E − 4
^{23}Na	1.2E − 3	3.6E − 4	7.5E − 4	3.6E − 3	1.4E − 3	6.6E − 3	7.9E − 3
^{24}Mg	2.5E − 4	1.6E − 5	1.0E − 4	1.5E − 3	2.0E − 4	3.6E − 4	1.2E − 3
^{25}Mg	1.0E − 2	7.8E − 4	2.9E − 3	7.4E − 3	2.4E − 3	4.2E − 3	6.6E − 3
^{26}Mg	9.4E − 4	7.8E − 5	3.4E − 4	1.0E − 3	2.8E − 4	5.9E − 4	1.0E − 3
^{26}Al	2.7E − 3	1.8E − 4	9.3E − 4	2.0E − 3	5.4E − 4	7.2E − 4	1.5E − 3
^{27}Al	1.2E − 2	7.6E − 4	4.5E − 3	9.2E − 3	2.0E − 3	1.8E − 3	4.5E − 3
^{28}Si	3.4E − 2	3.0E − 2	5.4E − 2	7.3E − 2	5.6E − 2	3.5E − 2	5.8E − 2
^{29}Si	8.7E − 5	3.1E − 4	4.2E − 4	7.8E − 4	8.8E − 4	1.7E − 3	2.7E − 3
^{30}Si	4.3E − 5	1.4E − 3	6.9E − 4	1.7E − 3	4.8E − 3	1.1E − 2	1.7E − 2
^{31}P	4.5E − 6	2.6E − 4	5.9E − 5	1.9E − 4	1.3E − 3	7.6E − 3	1.2E − 2
^{32}S	2.0E − 4	3.6E − 4	2.0E − 4	1.2E − 4	8.3E − 4	2.3E − 2	1.9E − 2
^{33}S	4.7E − 6	4.3E − 5	1.2E − 5	7.0E − 6	7.7E − 5	9.1E − 3	4.4E − 3
^{34}S	9.2E − 6	1.8E − 5	9.2E − 6	4.7E − 6	1.9E − 5	6.4E − 3	1.8E − 3
^{35}Cl	1.5E − 6	6.2E − 6	2.2E − 6	1.2E − 6	6.1E − 6	7.0E − 3	8.7E − 4
^{36}S	4.6E − 8	5.4E − 8	4.2E − 8	2.1E − 8	3.2E − 8	5.4E − 9	5.7E − 9
^{36}Ar	3.9E − 5	5.8E − 5	3.9E − 5	1.9E − 5	3.8E − 5	3.9E − 3	1.9E − 4
^{37}Cl	4.8E − 7	1.4E − 6	6.2E − 7	3.4E − 7	1.2E − 6	2.8E − 4	7.2E − 6
^{38}Ar	7.7E − 6	1.1E − 5	7.6E − 6	3.8E − 6	7.4E − 6	5.1E − 5	3.7E − 6
^{39}K	1.8E − 6	2.9E − 6	1.8E − 6	9.1E − 7	2.0E − 6	6.5E − 6	1.8E − 6

dynamic models of CO nova outbursts, but assuming an initial envelope already in place (hence neglecting the accretion phase and the building up of the envelope). In their most recent hydrodynamic nova models (Starrfield et al. 1997) they obtain lower overproduction factors of ^{7}Li than the ones reported from our evolutionary sequences. This is probably because of the different choice of initial abundances, and, to some extent, other differences in the input

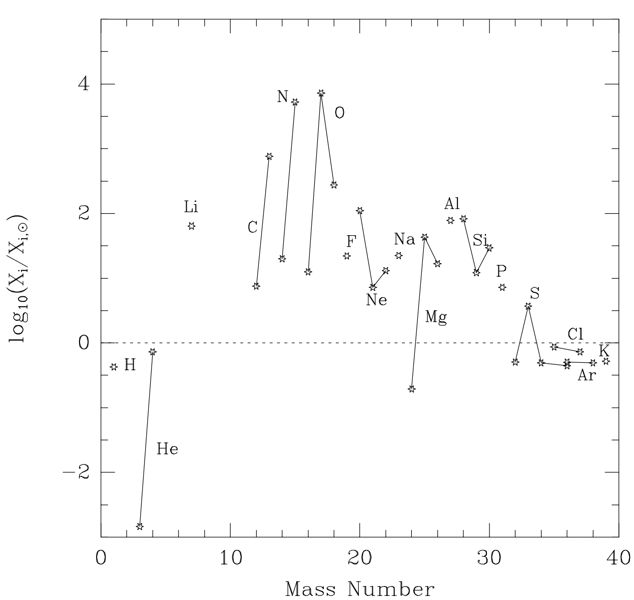

FIG. 2.—Same as Fig. 1, but for model ONe3 (1.15 $M_\odot$ ONe white dwarf with 50% mixing).

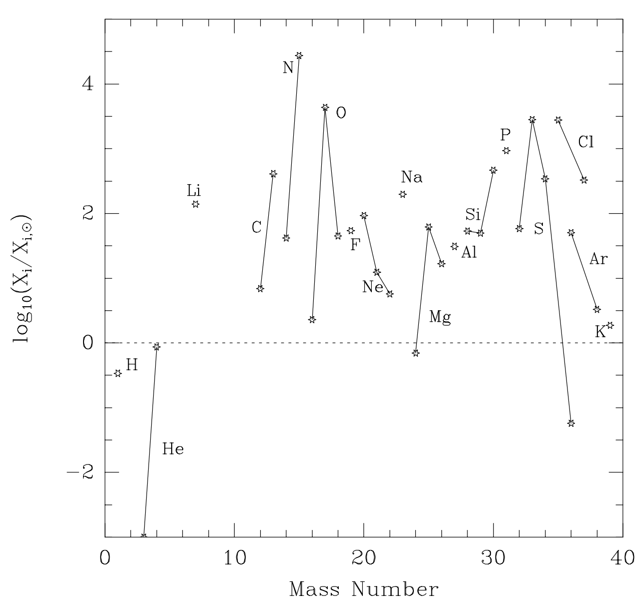

FIG. 3.—Same as Fig. 1, but for model ONe6 (1.35 $M_\odot$ ONe white dwarf with 50% mixing).

TABLE 4

Yields from CO Nova Models (Mass Fractions)

Nucleus	Model CO1	CO2	CO3	CO4	CO5	CO6	CO7[a]
^{1}H	5.1E − 1	3.3E − 1	3.2E − 1	4.7E − 1	3.0E − 1	1.2E − 1	3.0E − 1
^{3}He	7.0E − 6	9.2E − 6	6.1E − 6	1.5E − 6	4.1E − 6	2.8E − 6	3.7E − 6
^{4}He	2.1E − 1	1.4E − 1	1.5E − 1	2.5E − 1	1.6E − 1	9.0E − 2	1.6E − 1
^{7}Be	4.4E − 7	9.6E − 7	3.1E − 6	6.0E − 6	8.1E − 6	4.0E − 6	3.1E − 6
^{11}B	1.1E − 13	2.2E − 14	1.7E − 12	2.6E − 11	2.2E − 11	7.4E − 12	1.9E − 12
^{12}C	1.4E − 2	5.3E − 2	3.6E − 2	2.9E − 2	4.8E − 2	6.8E − 2	3.2E − 2
^{13}C	3.4E − 2	1.1E − 1	1.3E − 1	4.4E − 2	9.6E − 2	1.9E − 1	1.0E − 1
^{14}N	9.5E − 2	1.1E − 1	1.1E − 1	7.1E − 2	1.1E − 1	1.4E − 1	1.4E − 1
^{15}N	9.9E − 4	9.3E − 4	6.2E − 3	2.3E − 2	4.0E − 2	2.9E − 2	5.5E − 3
^{16}O	1.3E − 1	2.5E − 1	2.4E − 1	8.6E − 2	2.1E − 1	3.4E − 1	2.3E − 1
^{17}O	3.3E − 3	4.4E − 3	8.0E − 3	1.2E − 2	2.1E − 2	1.9E − 2	8.6E − 3
^{18}O	8.4E − 4	5.6E − 4	2.2E − 3	4.4E − 3	3.8E − 3	3.7E − 3	3.9E − 3
^{19}F	8.5E − 7	4.4E − 7	9.9E − 7	5.0E − 6	3.4E − 6	1.8E − 6	1.7E − 6
^{20}Ne	1.2E − 3	8.2E − 4	8.5E − 4	1.4E − 3	9.7E − 4	5.2E − 4	8.7E − 4
^{21}Ne	2.9E − 8	4.0E − 8	5.6E − 8	1.9E − 7	1.7E − 7	7.2E − 8	3.4E − 8
^{22}Ne	2.6E − 3	5.0E − 3	5.0E − 3	2.2E − 3	4.8E − 3	7.3E − 3	5.0E − 3
^{22}Na	3.4E − 7	3.0E − 7	1.6E − 7	3.8E − 7	2.9E − 7	1.1E − 7	8.5E − 8
^{23}Na	3.6E − 5	3.6E − 5	3.4E − 5	1.6E − 5	2.0E − 5	2.4E − 5	3.4E − 5
^{24}Mg	5.7E − 5	6.3E − 5	1.6E − 5	4.4E − 6	1.8E − 5	1.0E − 5	2.8E − 6
^{25}Mg	3.8E − 4	2.4E − 4	2.8E − 4	1.1E − 4	1.6E − 4	1.3E − 4	2.8E − 4
^{26}Mg	5.5E − 5	3.7E − 5	3.0E − 5	1.1E − 5	1.5E − 5	9.4E − 6	2.6E − 5
^{26}Al	8.1E − 6	3.4E − 6	1.6E − 5	3.1E − 5	4.7E − 5	3.3E − 5	2.4E − 5
^{27}Al	4.8E − 5	2.6E − 5	4.3E − 5	1.3E − 4	1.3E − 4	5.9E − 5	5.4E − 5
^{28}Si	4.9E − 4	3.3E − 4	3.3E − 4	9.4E − 4	4.5E − 4	1.9E − 4	3.4E − 4
^{29}Si	2.6E − 5	1.7E − 5	1.7E − 5	1.6E − 5	1.3E − 5	7.3E − 6	1.7E − 5
^{30}Si	1.8E − 5	1.2E − 5	1.2E − 5	3.2E − 5	1.7E − 5	7.5E − 6	1.2E − 5
^{31}P	6.1E − 6	4.1E − 6	4.1E − 6	6.2E − 6	4.0E − 6	2.0E − 6	4.0E − 6
^{32}S	3.0E − 4	2.0E − 4	2.0E − 4	2.9E − 4	2.0E − 4	9.8E − 5	2.0E − 4
^{33}S	2.5E − 6	1.7E − 6	1.8E − 6	8.6E − 6	3.3E − 6	1.3E − 6	1.9E − 6
^{34}S	1.4E − 5	9.3E − 6	9.3E − 6	1.4E − 5	9.2E − 6	4.6E − 6	9.3E − 6
^{35}Cl	1.9E − 6	1.3E − 6	1.3E − 6	2.4E − 6	1.4E − 6	6.7E − 7	1.3E − 6
^{36}S	7.0E − 8	4.7E − 8	4.7E − 8	6.8E − 8	4.6E − 8	2.3E − 8	4.7E − 8
^{36}Ar	5.8E − 5	3.9E − 5	3.9E − 5	5.8E − 5	3.9E − 5	1.9E − 5	3.9E − 5
^{37}Cl	6.4E − 7	4.3E − 7	4.3E − 7	7.4E − 7	4.6E − 7	2.2E − 7	4.3E − 7
^{38}Ar	1.2E − 5	7.7E − 6	7.7E − 6	1.2E − 5	7.7E − 6	3.8E − 6	7.7E − 6
^{39}K	2.6E − 6	1.7E − 6	1.7E − 6	2.6E − 6	1.7E − 6	8.7E − 7	1.7E − 6

[a] Model with Iglesias & Rogers (1993) opacities.

physics (such as reaction rates and equation of state) or even in the treatment of convection. Since CO novae dominate ^{7}Li synthesis, other calculations involving CO novae are needed in order to compare them to our results. In the recent analysis of CO novae by Kovetz & Prialnik (1997), the limited nuclear network, ranging from ^{12}C to ^{31}P, does not enable any study of light elements.

^{7}Be has another potential interest as a γ-ray signature of a nearby nova outburst (Clayton 1981; Harris, Leising, & Share 1991), since its decay to ^{7}Li, with the emission of a γ-ray photon of 478 keV, may be detected for CO novae within 0.5 kpc by the future *International Gamma-Ray Astrophysical Laboratory* (*INTEGRAL*) mission (Hernanz et al. 1997; Gómez-Gomar et al. 1997).

3.2.2. *Synthesis of the* CNO-*Group Nuclei*

The dominant nuclear reaction at the beginning of the TNR in a nova outburst is typically ^{12}C(p, γ)^{13}N, which is followed by a combination of β^{+} decays, or (p, γ) and (p, α) reactions, as a function of the local temperature. As pointed out by Starrfield et al. (1972), some of the most overabundant species at peak temperature, except hydrogen and helium, are the short-lived β^{+}-unstable nuclei ^{13}N, ^{14}O, ^{15}O, and ^{17}F, which decay releasing enough energy to account for the ejection of a fraction of the envelope. Therefore, their daughter nuclei ^{13}C, ^{14,15}N, and ^{17}O are among the main products in the ejecta of classical novae. Models presented in this paper show large overproduction factors of ^{13}C, ^{15}N, and ^{17}O with respect to solar abundances (see Figs. 1–3).

The synthesis of ^{13}C is initiated by ^{12}C(p, γ)^{13}N. Its evolution follows a competition between destruction through ^{13}C(p, γ)^{14}N near the burning shell and production by means of ^{13}N(β^{+})^{13}C in the outer envelope, where a fraction of ^{13}N has been carried out by convection. Our computations show that the synthesis of ^{13}C is favored in CO novae because of the higher initial content of ^{12}C. Hence, its final amount increases when higher degrees of mixing with the underlying core are adopted. Overproduction factors for the different CO models computed lay in the range $\sim$900–5200, with a maximum abundance of X(^{13}C) $\sim$ 0.2 by mass. Overproduction factors ranging from 400 to 900 are obtained in the ONe models.

The final amount of ^{15}N is related to the fraction of its parent nucleus ^{15}O [coming from ^{12}C(p, γ)^{13}N(β^{+})^{13}C(p, γ)^{14}N(p, γ)^{15}O] that is transported to the outer layers by convection before decaying. Its evolution follows a competition between destruction by proton captures [the closing CNO-cycle reaction ^{15}N(p, α)^{12}C] and creation through ^{15}O(β^{+})^{15}N. ^{15}N is overproduced for both CO ($f \sim$ 200–9200) and ONe models ($f \sim$ 1800–32,000). The higher abundances of ^{15}N found in the ONe models result from the higher peak temperatures achieved, which allow proton captures to proceed onto ^{14}N. Only some CO models show overproduction factors of ^{14}N larger than 100 ($M_{\rm wd} \sim 0.8$–$1.15\ M_\odot$ with 50%–75% mixing).

The synthesis of ^{17}O is dominated by $^{16}{\rm O}(p, \gamma)^{17}{\rm F}(\beta^+)^{17}{\rm O}$, whereas destruction results from both $^{17}{\rm O}(p, \alpha)^{14}{\rm N}$ and $^{17}{\rm O}(p, \gamma)^{18}{\rm F}$ (only at high temperatures). The last reaction is in turn responsible for the synthesis of ^{18}O from $^{18}{\rm F}(\beta^+)^{18}{\rm O}$. Our calculations show a significant overproduction of ^{17}O: $f \sim 900$–5500 in the CO models, and $f \sim 2900$–$13{,}000$ in the ONe ones. The increase of the final abundances with the white dwarf mass, and also when ONe cores are adopted, is a direct consequence of the higher peak temperatures achieved, which allow proton captures to proceed onto ^{16}O and initiate the chain.

Accurate estimates of the contribution of classical novae to the Galactic abundances of these CNO-group nuclei (or of any other species) require a model of chemical evolution of the Galaxy that properly takes them into account. Present models of chemical evolution include novae in a rather rough way, without taking into account the wide range of variation of the yields with nova properties (see, for instance, Woosley et al. 1997, in which the 1.35 $M_\odot$ ONeMg model from Politano et al. 1995 is adopted as representative). This can be partially caused by the fact that these yields were not available until very recently (i.e., Kovetz & Prialnik 1997 for CO novae, and the present work for CO and ONe novae). A detailed analysis is out of the scope of this paper, but a crude estimate of the Galactic production of some elements by novae can be obtained from our evolutionary sequences. We have derived upper limits to this production that may be useful in elucidating which elements deserve a careful analysis and which can be discarded as being produced by novae. Upper limits are obtained from the following expression:

$$M^i(M_\odot) = \tau_G({\rm yr}) M^i_{\rm ej}(M_\odot) \nu_{\rm nova}({\rm yr}^{-1}) ,$$

where τ_G is the age of the Galaxy, $\nu_{\rm nova}$ is the Galactic nova rate, and $M^i_{\rm ej}$ corresponds to the ejected mass of species i in the most favorable model. We have adopted $\tau_G \sim 10^{10}$ yr, and $\nu_{\rm nova} \sim 30\ {\rm yr}^{-1}$ (Shafter 1997).

Our estimates show that nova outbursts may account for 100% of the Galactic abundances of ^{13}C, ^{15}N, and ^{17}O, assuming solar system levels for the mean composition of the Milky Way. However, since the maximum production of ^{15}N is attained for massive ONe novae (which are less abundant than low-mass CO novae, according to stellar evolution), this upper limit is probably too high. As expected, novae scarcely contribute to the abundances of ^{14}N and ^{18}O (with upper limits around 10% and 25% of the Galactic abundances, respectively). As a summary, classical novae are likely sites for the synthesis of most (or all) of the Galactic ^{13}C and ^{17}O, and may contribute significantly to the amount of ^{15}N, though an extra source seems to be required. These results are in good agreement with the main conclusions of Kovetz & Prialnik (1997) in their analysis of the composition of the ejecta of CO novae.

Another important feature obtained in our calculations is that the ratios O/N and C/N decrease when the mass of the white dwarf increases. For instance, in our ONe models, the ratio O/N ranges from 3.3 (for a 1.15 $M_\odot$ white dwarf) to 0.2 (1.35 $M_\odot$), whereas C/N lies between 1.1 (1.15 $M_\odot$) and 0.2 (for a 1.35 $M_\odot$ white dwarf). Hence, high concentrations of N in the ejecta of a nova system may reveal the presence of a massive white dwarf. Our results also indicate that a decrease in the degree of mixing between core and envelope from 75% to 25% translates into lower ratios of O/N. No clear influence on C/N is found in the ONe models. The observed trend agrees with results from previous works (Politano et al. 1995 for ONeMg novae; Kovetz & Prialnik 1997 for CO ones).

3.2.3. *Synthesis of* ^{19}F

The nucleosynthetic origin of ^{19}F, by far the least abundant of all the stable $12 \leq A \leq 35$ nuclei, is still a matter of debate. A handful of astrophysical scenarios has been suggested, including explosive hydrogen-burning sites like classical novae (Woosley 1986; Wiescher et al. 1986; Truran 1986), thermal pulses in AGB stars (Forestini et al. 1992; Jorissen, Smith, & Lambert 1992; Mowlavi, Jorissen, & Arnould 1996), Wolf-Rayet stars (Meynet & Arnould 1993), proton ingestion into He-rich layers (Jorissen & Arnould 1989), and neutrino process during Type II supernovae (Woosley & Haxton 1988; Timmes, Woosley, & Weaver 1995; Woosley & Weaver 1995).

The mechanism responsible for the synthesis of ^{19}F in classical novae is the production of the short-lived, β^+-unstable nucleus ^{19}Ne through $^{17}{\rm O}(p, \gamma)^{18}{\rm F}(p, \gamma)^{19}{\rm Ne}$, which is partially transported by convection toward the outer cooler layers of the envelope, where it decays into ^{19}F, with a mean lifetime of $\tau(^{19}{\rm Ne}) \sim 25$ s. Our calculations show that ^{19}F production is more important in ONe than in CO novae. It increases as the white dwarf mass and the degree of mixing increase (see Table 3), with overproduction factors ~ 100 obtained for model ONe7 (a 1.35 $M_\odot$ white dwarf with 75% mixing). These values are not far from those found during thermal pulses in asymptotic giant branch stars (AGB; see Forestini et al. 1992; Jorissen et al. 1992). Nevertheless, since ^{19}F is only significantly synthesized in models involving 1.35 $M_\odot$ white dwarfs (see Fig. 3), which are very scarce in nature, we conclude that classical novae can be ruled out as dominant sources of the Galactic ^{19}F. The importance of ^{19}F lies in the fact that it provides a potential observational clue to the presence of a massive white dwarf.

3.2.4. *Synthesis of the* NeNa- *and* MgAl-*Group Nuclei*

Two isotopes of the NeNa and MgAl groups have a particular astrophysical interest: ^{26}Al and ^{22}Na. These nuclei are synthesized in significant amounts in ONe rather than in CO novae.

^{26}Al is an unstable nucleus, with a lifetime of $\tau = 1.04 \times 10^6$ yr, that decays from ground state to the first excited level of ^{26}Mg, which in turn de-excites to its ground state by emitting a γ-ray photon of 1809 keV. This characteristic γ-ray signature of ^{26}Al, first detected by the *HEAO 3* satellite (Mahoney et al. 1982, 1984), has been confirmed by other space missions, such as *SMM* (Share et al. 1985) and several balloon-borne experiments. Recent measurements made with the COMPTEL instrument on board the *Compton Gamma Ray Observatory* (*CGRO*) have provided a map of the 1809 keV emission in the Galaxy (Diehl et al. 1995; Prantzos & Diehl 1996). They derive a total ^{26}Al mass between 1 and 3 $M_\odot$, which, according to the observed distribution, is mainly attributed to young progenitors, such as massive AGB stars, Type II supernovae, and Wolf-Rayet stars. However, a potential contribution from novae or low-mass AGB stars has not been excluded. The synthesis of ^{26}Al in classical novae has been analyzed in a recent paper by José et al. (1997), who have shown that only some combinations of peak temperatures around $T_{\rm peak} \sim 1$–2×10^8 K and rapid evolution from maximum favor ^{26}Al generation in ONe novae. A crude estimate of the total production of ^{26}Al brings a maximum contribution of classical nova outbursts that is in the range 0.1–0.4 $M_\odot$. Although the contribution of the yields from model ONe1 (i.e., a 1.00 $M_\odot$ white dwarf with 50% mixing) would increase this range drastically, we point out that, according to the results from the theory of stellar evolution, 1.00 $M_\odot$ white dwarfs are expected to be made of CO instead of ONe. Therefore, model ONe1 should be considered as a test model rather than as a representative model for ONe novae.

The synthesis of ^{22}Na proceeds through ^{20}Ne$(p, \gamma)^{21}$Na [starting from either initial ^{20}Ne or from ^{23}Na, which can be transformed in the former by ^{23}Na$(p, \alpha)^{20}$Ne], which can either decay into ^{21}Ne (at low temperature), followed by ^{21}Ne$(p, \gamma)^{22}$Na, or capture another proton, leading to ^{21}Na$(p, \gamma)^{22}$Mg$(\beta^+)^{22}$Na (at high temperature). Since ^{20}Ne requires temperatures around $T \sim 4 \times 10^8$ K to burn, only massive white dwarfs, which attain higher peak temperatures close to that value, allow an efficient synthesis of ^{22}Na. Our models show that its final amount increases when the white dwarf mass or the degree of mixing with the core increase, in agreement with the anticorrelation between ^{22}Na and ^{26}Al production reported by Politano et al. (1995).

^{22}Na has a lifetime of $\tau \sim 3.75$ yr. In its decay to a short-lived excited state of ^{22}Ne, it emits a γ-ray photon of 1275 keV (Clayton & Hoyle 1974). A few experimental verifications of the γ-ray emission at 1275 keV from nearby novae have been attempted in recent decades, using balloon-borne experiments and several detectors on board *HEAO 3*, *SMM*, and *CGRO*, from which constraints on the maximum amount of ^{22}Na ejected into the interstellar medium have been derived (Leising et al. 1988; Harris et al. 1996). The most recent estimates are based on several measurements with the COMPTEL experiment on board *CGRO* of five recent Ne novae (Iyudin et al. 1995), which translate into an upper limit of the ejected ^{22}Na mass by any nova in the Galactic disk of the order of 3.7×10^{-8} $M_\odot$. The low ejected masses of ^{22}Na obtained in our ONe models agree fairly well with this upper limit. Moreover, our estimated γ-ray flux from a nearby nova (i.e., within 0.5 kpc) is too low to be detected by OSSE or COMPTEL, but may represent a good target for the future *INTEGRAL* mission (Hernanz et al. 1997; Gómez-Gomar et al. 1997).

^{22}Na has also been invoked to account for the abnormally high amount of ^{22}Ne in the Ne-E meteorites (Clayton 1975; Eberhardt et al. 1979; Lewis et al. 1979), in which the extremely high content of Ne (the possibility of pure ^{22}Ne is not excluded) is attributed to the β^+ decay of ^{22}Na. However, since the shells ejected during ONe nova outbursts are contaminated with large amounts of ^{20}Ne (and some ^{21}Ne), the ratio $(^{20}\text{Ne} + {}^{21}\text{Ne})/(^{22}\text{Ne} + {}^{22}\text{Na}) \gg 1$. Thus, it seems an unlikely explanation for the isotopic ratios found in the Ne-E meteorites, although some hypothetical mechanisms such as elemental fractionation have been invoked to reduce the ratio to the observed values. The problem of the isotopic ratio $(^{20}\text{Ne} + {}^{21}\text{Ne})/(^{22}\text{Ne} + {}^{22}\text{Na})$ has already been pointed out by Hillebrandt & Thielemann (1982) and by Wiescher et al. (1986), who also obtained ratios higher than 1 in their nucleosynthesis calculations with parameterized nova models.

Another isotope of the MgAl cycle, ^{27}Al, is also significantly synthesized during ONe nova outbursts. It is produced by means of ^{26}Mg$(p, \gamma)^{27}$Al. Near peak temperature, creation through ^{27}Si$(\beta^+)^{27}$Al dominates the destruction channel ^{27}Al$(p, \gamma)^{28}$Si. However, above 2×10^8 K, proton captures on ^{27}Si dominate its β^+ decay, and hence, only a rapid evolution from peak temperature avoids ^{27}Al destruction. The maximum production is attained in model ONe1 (1.0 $M_\odot$ white dwarf), which achieves the lowest peak temperature, $T_{\rm max} = 1.98 \times 10^8$ K, and also in model ONe4 (1.15 $M_\odot$ white dwarf with 75% mixing), which shows a fast decline from peak temperature. Even in the most favorable cases, contribution of novae to the Galactic ^{27}Al is limited to less than 15%.

3.2.5. *Synthesis of Heavier Species: From* Si *to* Ca

The nuclear activity in this range of isotopes is largely restricted to massive ONe white dwarfs, which achieve high enough temperatures to enable proton captures onto heavy nuclei. The most overproduced species are the odd nuclei ^{31}P, ^{33}S, and ^{35}Cl (see Fig. 3). Similar results were obtained by Starrfield et al. (1997; see their model 8, with 1.35 $M_\odot$). The significant synthesis of ^{35}Cl obtained in models ONe6 and ONe7 confirms the estimates given by Woosley (1986) with parameterized calculations. Significant detection of Cl in the ejecta of a nova outburst would therefore reveal the presence of a very massive ONe white dwarf. It is unlikely that classical novae play any role in the Galactic abundances of these elements: even the most favorable case accounts for less than 20% of the Galactic ^{33}S and $\sim$10% of ^{35}Cl and ^{31}P.

It is worth noticing that a recent spectrum of the dwarf nova VW Hydri, taken with the *Hubble Space Telescope* (Sion et al. 1997), has revealed the presence of P with an abundance 900 times solar, not far from the values obtained in model ONe6. This observation has raised the question of whether a thermonuclear runaway has occurred on that dwarf nova. Quite surprisingly, the estimated mass of the white dwarf in the nova system VW Hydri is around 0.86 $M_\odot$, which is too low to allow proton captures to proceed up to ^{31}P.

3.3. *The Ejecta of Classical Novae: A Comparison with Observations*

The comparison between observed and theoretical abundances is not straightforward for two reasons. On one hand, completely different yields have been derived for some systems, as for instance V693 CrA 1981 and QU Vul 1984. This fact points out the intrinsic difficulties in the accurate determination of the chemical abundances from observations. The extent to which the reported abundances are precisely known is somehow uncertain. On the other hand, one should bear in mind that numerical calculations lack an accurate description of some input physics: the mechanism responsible for metal enrichment of the accreted envelope, a self-consistent formulation of convection, and realistic prescriptions for the adopted nuclear reaction rates, to quote a few.

In Table 5 we compare spectroscopic abundance determinations (in mass fractions) and those obtained from our models for five novae that are particularly well fitted. Model ONe3 (1.15 $M_\odot$ white dwarf with 50% mixing) shows similar yields to those derived for the nova system V693 CrA 1981, according to the recent analysis by

TABLE 5

MODELS VERSUS OBSERVATIONS OF SOME CLASSICAL NOVA SYSTEMS

Model	Element							
	H	He	C	N	O	Ne	Na–Fe	Z
V693 CrA 1981								
Vanlandingham et al. 1997	0.25	0.43	0.025	0.055	0.068	0.17	0.058	0.32
Model ONe3	0.30	0.20	0.051	0.045	0.15	0.18	0.065	0.50
Andreä et al. 1994	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66
Model ONe4	0.12	0.13	0.049	0.051	0.28	0.26	0.10	0.75
Williams et al. 1985	0.29	0.32	0.0046	0.080	0.12	0.17	0.016	0.39
Model ONe5	0.28	0.22	0.060	0.074	0.11	0.18	0.071	0.50
V1370 Aql 1982								
Andreä et al. 1994	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86
Model ONe7	0.073	0.17	0.051	0.18	0.14	0.24	0.14	0.76
Snijders et al. 1987	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86
Model ONe7	0.073	0.17	0.051	0.18	0.14	0.24	0.14	0.76
QU Vul 1984								
Austin et al. 1996	0.36	0.19	…	0.071	0.19	0.18	0.0014	0.44
Model ONe1	0.32	0.18	0.030	0.034	0.20	0.18	0.062	0.50
Saizar et al. 1992	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10
Model ONe2	0.47	0.28	0.041	0.047	0.037	0.090	0.0035	0.25
PW Vul 1984								
Andreä et al. 1994	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30
Model CO4	0.47	0.25	0.073	0.094	0.10	0.0036	0.0017	0.28
V1688 Cyg 1978								
Andreä et al. 1994	0.45	0.22	0.070	0.14	0.12	…	…	0.33
Model CO4	0.47	0.25	0.073	0.094	0.10	0.0036	0.0017	0.28
Stickland et al. 1981	0.45	0.23	0.047	0.14	0.13	0.0068	…	0.32
Model CO1…	0.51	0.21	0.048	0.096	0.13	0.0038	0.0015	0.28

Vanlandingham, Starrfield, & Shore (1997), despite the intrinsic differences in the mean metallicity. The presence of an underlying ONe white dwarf can be inferred from the high amount of Ne in the ejecta, as well as from the moderately high concentration of nuclei in the range Na–Fe, ~ 0.06 by mass. Mass fractions of H, C, N, Ne, and Na–Fe agree quite well with the observed values (see Table 5). The largest difference is the final amount of O (with a mass fraction of ~ 0.07 derived from observations, compared to ~ 0.15 obtained in model ONe3). Our value is a direct consequence of mixing with the outer layers of an ONe white dwarf that is extremely enriched in ^{16}O, according to the adopted chemical composition of Ritossa et al. (1996). The second main difference is the He content: V693 CrA 1981 has an abnormally high concentration of this element, which, as suggested by Starrfield et al. (1997), may result from residual H-burning in the remaining shells of a previous outburst. Other spectroscopic abundance determinations of V693 CrA 1981 (Andreä, Drechsel, & Starrfield 1994; Williams et al. 1985) provide completely different results. In fact, the abundance distribution derived by Andreä et al. (1994), with nearly twice the metallicity obtained by Vanlandingham et al. (1997), is better fitted by model ONe4 (1.15 $M_{\odot}$ white dwarf with 75% mixing). Furthermore, model ONe5 roughly reproduces the distribution derived by Williams et al. (1985), with an excellent agreement in H, N, O, and Ne.

Another nova system, V1370 Aql 1982, shows low amounts of H and He, and a high concentration of Ne, in an envelope with a mean metallicity of ~ 0.86 (Andreä et al. 1994). This suggests a high mixing level with the Ne-rich shells of a massive white dwarf. Model ONe7, a 1.35 $M_{\odot}$ white dwarf with 75% mixing, fits the derived abundances appreciably well (see Table 5). It is worth noting that Snijders et al. (1987) inferred a high concentration of sulfur in the ejecta of V1370 Aql 1982, a determination that is still a matter of debate. We point out that similar amounts of sulfur are obtained in models ONe6 and ONe7.

The abundance distribution derived for another "neon" nova, QU Vul 1984 (Austin et al. 1996), is roughly similar to the mean composition obtained in model ONe1 (1.0 $M_{\odot}$ white dwarf with 50% mixing). This recent determination widely differs from previous estimates by Andreä et al. (1994) and Saizar et al. (1992).

Model CO4 (1.15 $M_{\odot}$ white dwarf with 25% mixing) also fits the composition derived for the classical nova PW Vul 1984 (Andreä et al. 1994) fairly well. The lack of heavy nuclei in the ejecta, specially Ne, suggests the presence of a low-mass CO white dwarf, a conclusion also supported by the moderately high amount of C in the ejecta. The total amount of nuclei in the range Na–Fe is slightly lower than the value derived from observations. This is a consequence of the adopted initial chemical composition, since the moderate temperatures achieved in low-mass white dwarfs do not allow significant nuclear flows toward this range of isotopes. Other abundance distributions for nova PW Vul 1984 have been obtained by different groups: Saizar et al. (1991) derived a much lower metallicity (~ 0.067, only twice solar), whereas the recent analysis by Schwarz et al. (1997), using another photoionization code, has provided a distribution that lies between the estimates by Saizar et al. (1991) and Andreä et al. (1994). In particular, the new determination of the C content is lower than the value obtained by Andreä et al. (1994).

Moreover, model CO4 also fits the chemical distribution derived for another nova system, V1688 Cyg 1978 (Andreä et al. 1994), the most relevant discrepancy being the absence of nuclei in the range Na–Fe.

4. CONCLUSIONS

We have computed 14 hydrodynamic models of nova outbursts from the onset of accretion up to the ejection stage for a range of CO and ONe white dwarf masses (0.8–1.35 $M_{\odot}$) and degrees of mixing between the accreted envelope and the outermost shells of the underlying white dwarf core (25%–75%). The main characteristics of the explosions, as well as a detailed nucleosynthesis for each model, are provided. These yields can be important for future detailed studies of the chemical evolution of the Galaxy that intend to include novae in an accurate way.

The role played by the different model parameters has been analyzed. Concerning the influence of the composition of the underlying white dwarf, we find that ONe novae accrete more massive envelopes than CO novae (if all the remaining input parameters are the same) because of the lower ^{12}C content in the envelope when the TNR develops. As a result of the higher degeneracy, a more violent outburst is found. Therefore, ONe models show a partial extension of the nuclear activity toward higher Z nuclei, owing to the higher peak temperature achieved in their envelopes.

More violent outburts also occur as the mass of the white dwarf increases, because of the larger surface gravity. The most relevant outcome is the synthesis of heavy nuclei, such as P, S, or Cl, as a result of the higher peak temperature attained in the envelope. However, since massive white dwarfs are very scarce in nature, their potential contribution to the Galactic abundances is rather small, despite the large overproduction factors of some particular isotopes.

In order to reproduce the wide spread of metallicities reported from observations, a range of mixing levels between the core and the envelope has been adopted. The general trend is an increase of peak temperature and mean ejection velocities as the degree of mixing increases. Higher degrees of mixing favor the synthesis of higher Z nuclei in ONe models, whereas a clear pattern is not found for the CO novae.

We have shown that classical novae are likely sites for the synthesis of most (or all) of the Galactic ^{13}C and ^{17}O (with maximum overproduction factors of ~ 5200 and $\sim 13{,}000$, respectively) and may also contribute significantly to the abundance of ^{15}N ($f_{\max} \sim 32{,}000$), though an extra source seems to be required. CO models produce significant amounts of ^{7}Be ($f_{\max} \sim 900$), which are large enough to be detected from nearby novae through its γ-ray emission, providing a potential observational clue to the presence of a CO white dwarf. Contribution of classical novae to the Galactic ^{7}Li, coming from ^{7}Be decay, is limited to ~ 10%.

The ejecta from ONe models show an important synthesis ^{22}Na. Its γ-ray emission might be detected by future space missions, according to the values obtained in our calculations, which are in good agreement with the upper limits derived from COMPTEL observations. Concerning ^{26,27}Al, ONe novae can account for less than 10%–15% of the Galactic content.

Our nova models show that massive ONe white dwarfs are characterized by low O/N and C/N ratios in the ejecta. Also, the presence of a massive ONe white dwarf could be inferred from a significant detection of ^{19}F, ^{35}Cl, and even ^{31}P and ^{33}S in ejected nova shells.

The elemental yields obtained in our grid of nova models fit the spectroscopic abundance determinations of the novae V693 CrA 1981, V1370 Aql 1982, QU Vul 1984, PW Vul 1984, and V1688 Cyg 1978 fairly well.

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