THE ASTROPHYSICAL JOURNAL, 448:807–821, 1995 August 1

HYDRODYNAMIC STUDIES OF ACCRETION ONTO MASSIVE WHITE DWARFS: ONeMg-ENRICHED NOVA OUTBURSTS. I. DEPENDENCE ON WHITE DWARF MASS

M. POLITANO,[1] S. STARRFIELD,[1] J. W. TRURAN,[2] A. WEISS,[3] AND W. M. SPARKS[4]
Received 1993 August 13; accepted 1995 February 10

ABSTRACT

Hydrodynamic studies have been performed of accretion onto 1.00 $M_\odot$, 1.25 $M_\odot$, and 1.35 $M_\odot$ oxygen-neon-magnesium (ONeMg) white dwarfs at a rate of 10^{17} g s^{-1}. The material from the companion star is expected to be of solar composition but is assumed to be mixed with material from the underlying white dwarf during accretion, such that the accumulating envelope material is enriched in oxygen, neon, and magnesium to fifty percent by mass. A new, expanded nuclear reaction network, utilizing up-to-date reaction rates and including 78 nuclei up to ^{40}Ca, has been used in combination with the hydrodynamics for the first time in this study.

We again find that the outbursts become more violent as the assumed white dwarf mass is increased. Burning temperatures, nuclear energy generation rates, and ejecta velocities all increase significantly with mass. A peak burning temperature of 356×10^6 K is reached in the 1.35 $M_\odot$ sequence, allowing significant nucleosynthesis of intermediate-mass elements to occur. We find that as we increase the white dwarf mass, the abundance of ^{26}Al decreases (by about a factor of 3 for our range of white dwarf masses), and the abundances of ^{22}Na and the majority of nuclei in the Si-Ca range increase significantly (by 2 orders of magnitude or greater). Our simulations indicate that nova outbursts which occur on ONeMg white dwarfs having a mass of 1.25 $M_\odot$ or greater produce sufficient amounts of ^{22}Na such that γ-rays from the decay of ^{22}Na should be detectable with the *Compton Gamma Ray Observatory*, if the nova is nearby ($D \sim 1$ kpc). Our simulations also confirm that nova outbursts occurring on ONeMg white dwarfs are an important source of ^{26}Al nuclei in the Galaxy. We further examine whether such outbursts can fully account for the reported ~ 3 $M_\odot$ of ^{26}Al needed to explain the Galactic 1.809 MeV γ-ray line emissions. We estimate that a minimum mass of 1.2 $M_\odot$ for ONeMg white dwarfs in binaries is needed in order for nova outbursts to be able to produce the observed ~ 3 $M_\odot$ of ^{26}Al over the mean lifetime of this nucleus. However, this estimate is based on the particular initial conditions we have chosen for the sequence of models presented in this paper, and on the assumption that the production of cataclysmic variables with ONeMg white dwarfs is not significantly less than that assumed for CO white dwarfs in the same mass range.

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

1. INTRODUCTION

Recent observations of classical novae indicate the existence of a class of novae, the "neon novae," whose ejecta show strong emission lines in Ne, Na, Al, and Mg (Starrfield, Sparks, & Truran 1986; Starrfield et al. 1992b). Of the well-studied Galactic novae for which reliable abundance determinations exist, approximately one-third are neon novae (e.g., Truran 1990). As *significant* production of heavy elements is not expected to occur as a result of nuclear burning of hydrogen-rich material over the course of the nova outburst, the enrichments of these elements are believed to indicate that material from the underlying white dwarf has been mixed into the accreted envelope (e.g., Starrfield, Sparks, & Truran 1974a; Truran & Livio 1986). Historically, this has been interpreted as indicating that the outbursts have occurred on ONeMg white dwarfs (Truran & Livio 1986; Starrfield et al. 1986). Recently, however, Livio & Truran (1994) have noted that since neon abundance enrichments less than approximately 8 times solar may be understood on the basis of the prior evolution of a carbon-oxygen (CO) white dwarf, only novae for which the ejecta reveal neon enrichments well in excess of this *demand* the presence of an underlying ONeMg white dwarf. On the basis of this criterion, they argue that, of the classical novae for which detailed abundance analyses are available (see Table 4), only three seem *unambiguously* to demand the presence of an underlying ONeMg white dwarf: V693 CrA 1981, V1370 Aql 1982, and QU Vul 1984. Consequently, some neon novae may have occurred on CO white dwarfs; at the moment, this is not clear. We emphasize that, in this paper, we are specifically attempting to model nova outbursts which occur on ONeMg white dwarfs. When we are specifically referring to such events, we shall designate them as "ONeMg novae," to distinguish them from neon novae in general.

It is believed that ONeMg novae may be an important source of ^{26}Al and ^{22}Na in the Galaxy (Weiss & Truran 1990; Nofar, Shaviv, & Starrfield 1991). In their study of nova nucleosynthesis, Weiss, & Truran (1990) constructed and used

[1] Department of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504.

[2] Department of Astronomy and Astrophysics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

[3] Institut für Astrophysik, Max-Planck-Institut für Physik und Astrophysik, Karl-Schwarzschild-Strasse 1, D-85748 Garching bei München, Germany.

[4] Applied Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545.

the same nuclear reaction network that has been used in this study, but they did not couple it directly to a hydrodynamic stellar evolution code. Rather, they used temperature-density profiles chosen to be representative of classical novae and which are generally compatible with those of Starrfield, Truran, & Sparks (1978). Nofar et al. (1991) used a nuclear reaction network that is similar to the one used in this calculation, but again they did not couple it to a hydrodynamic code. They used temperature-density profiles from Starrfield, Sparks, & Shaviv (1988). In both studies, the authors concluded that nova outbursts occurring on ONeMg white dwarfs, when the accreted hydrogen envelope material has been enriched in oxygen, neon, and magnesium, can be significant ^{26}Al contributors in the Galaxy. Weiss & Truran also concluded that this type of nova can produce detectable amounts of ^{22}Na.

A major aim of the present study has been to determine if these conclusions are correct by performing more realistic calculations in which the nuclear reaction network is coupled directly to the hydrodynamics. We are particularly interested in providing improved quantitative estimates of the amounts of ^{26}Al and ^{22}Na that are produced in nova outbursts on ONeMg white dwarfs. We should note here that some of us have previously evolved models of ONeMg novae (Starrfield et al. 1986). However, our earlier models were calculated using a significantly smaller nuclear reaction network, appropriate for the treatment of pure CNO burning sequences, which did not include either Ne or Mg. While the results were illustrative and perhaps provided reasonable estimates of the energetics of the runaways, the present models are more realistic, particularly with respect to their predictions for nucleosynthesis.

In this paper, we present model calculations of thermonuclear runaways initiated by accretion onto white dwarfs of 1.00 $M_{\odot}$, 1.25 $M_{\odot}$, and 1.35 $M_{\odot}$. We have utilized an implicit, hydrodynamic stellar evolution code that includes an expanded nuclear reaction network of 78 nuclei. In the next section, we briefly describe the hydrodynamic code and assumed starting conditions. We focus our discussion on the expanded nuclear network, since this is the major modification to an existing evolutionary code which has been described extensively in the literature (e.g., Kutter & Sparks 1972; Starrfield & Sparks 1987). In § 3, we present the results of the evolutionary calculations. A discussion of the results and our conclusions then follow.

2. EVOLUTIONARY CODE AND STARTING CONDITIONS

2.1. *Nuclear Reaction Network*

The crucial distinction between this study and our own previous examination (Starrfield et al. 1986) of thermonuclear runaways in heavy-element enriched envelopes on ONeMg white dwarfs is our use of a greatly expanded nuclear reaction network in the present work. We found this to be essential to proper treatments of both the nuclear energy generation and the nucleosynthesis. In particular, at the temperatures exceeding 350×10^6 K achieved in thermonuclear runaways on very massive white dwarfs (see below), and in the presence of substantial enrichments of neon and magnesium nuclei, proton captures on Ne and Mg nuclei and their progeny can provide significant energy generation. We are also now able to provide far more realistic estimates of nucleosynthesis associated with this class of nova outburst, including, specifically, the production of the interesting radioactive nuclear species ^{22}Na and ^{26}Al.

The reaction network used in this study, and now coupled consistently with the hydrodynamic equations, is entirely equivalent to that utilized by Weiss & Truran (1990; Fig. 1 in their paper). It includes 78 nuclei ranging from hydrogen to calcium and includes the triple-alpha reaction, as well as all reactions involving neutrons, protons, alpha particles, and photons, and all relevant weak interactions. Reaction rates for these various cases were taken either from the recent compilation of experimental rates by Caughlan & Fowler (1988) or from theoretical estimates (Thielemann, Arnould, & Truran 1987, 1988), as provided in the reaction library of F.-K. Thielemann (see, e.g., Cowan, Thielemann, & Truran 1991). The exploratory study of nucleosynthesis accompanying nova explosions by Weiss & Truran (1990) has established that this network is quite sufficient to provide an accurate determination of energy generation and nucleosynthesis in these environments.

The upper extent of this network is taken to be at ^{40}Ca. For peak burning temperatures up to $\sim 350\text{–}400 \times 10^6$ K and dynamical timescales characteristic of nova explosions, this network provides a satisfactory treatment of nuclear energy generation and nucleosynthesis (see, e.g., Weiss & Truran 1990). It also allows for an accurate determination of the abundances of such elements as silicon, sulfur, and argon, which have been found to be overabundant in the ejecta of some neon novae (see, e.g., Truran 1990). At higher peak temperatures, consistent for example with hydrogen runaways on neutron stars, extension of the network through the iron-peak region would be necessary. In our program, such an extension of the network would be effected automatically, if the temperature was to reach these higher values. This was not necessary for the physical conditions achieved by the models discussed in this paper.

2.2. *Initial Model Parameters*

Our calculations were performed with 95 zone white dwarf models with initial luminosities of 10^{-2} $L_{\odot}$. We considered the characteristics of the thermonuclear runaways resulting from accretion onto white dwarfs of three different masses: 1.00 $M_{\odot}$, 1.25 $M_{\odot}$, and 1.35 $M_{\odot}$. For all three cases, an accretion rate of 10^{17} g s^{-1} (1.6×10^{-9} $M_{\odot}$ yr^{-1}) was assumed. The initial radii and effective temperatures of these white dwarfs were: 5.38×10^8 cm and 2.1×10^4 K, 3.50×10^8 cm and 2.6×10^4 K, and 2.49×10^8 cm and 3.0×10^4 K, respectively.

We assume the material from the donor star has a solar composition. However, we also assume that mixing of the accreted material with matter from the underlying white dwarf occurs, such that the composition of the accreted material is enriched in oxygen, neon, and magnesium nuclei to approximately 50% by mass, for all three white dwarf masses. The exact composition of the accreted material that we used for these calculations is given in Table 1 and is derived from the carbon-burning nucleosynthesis calculations of Arnett & Truran (1969; see also Weiss & Truran 1990).

3. RESULTS

Significant features of our calculated models are summarized in Table 2, which lists, for each mass sequence, the total amount of mass accreted and ejected, the peak temperature and luminosity achieved, the peak energy generation rate, and the maximum velocity of ejection. Theoretical light curves for each sequence are shown in Figures 1–3.

The results of the nucleosynthesis accompanying the evolution are given in Table 3, which lists the mean composition of

TABLE 1

INITIAL COMPOSITION OF THE ACCRETED MATERIAL

Nucleus	Mass Fraction	Nucleus	Mass Fraction
H	0.36500	^{26}Al	0.
^{4}He	0.13300	^{26}Al*	0.
^{2}D	0.	^{27}Al	1.6102E-05
^{3}He	5.7953E-06	^{24}Si	0.
^{7}Li	0.	^{25}Si	0.
^{7}Be	0.	^{26}Si	0.
^{8}B	0.	^{27}Si	0.
^{12}C	9.4408E-04	^{28}Si	1.8134E-04
^{13}C	1.1506E-05	^{29}Si	9.5133E-06
^{14}C	0.	^{30}Si	6.5327E-06
^{13}N	0.	^{27}P	0.
^{14}N	2.3209E-06	^{28}P	0.
^{15}N	9.1248E-07	^{29}P	0.
^{14}O	0.	^{30}P	0.
^{15}O	0.	^{31}P	2.2647E-06
^{16}O	0.15036	^{29}S	0.
^{17}O	8.5263E-07	^{30}S	0.
^{18}O	4.8553E-06	^{31}S	0.
^{17}F	0.	^{32}S	1.0992E-04
^{18}F	0.	^{33}S	8.9477E-07
^{19}F	1.1251E-07	^{34}S	5.1828E-06
^{18}Ne	0.	^{32}Cl	0.
^{19}Ne	0.	^{33}Cl	0.
^{20}Ne	0.24883	^{34}Cl	0.
^{21}Ne	8.9983E-07	^{35}Cl	9.7605E-07
^{22}Ne	2.8280E-05	^{36}Cl	0.
^{20}Na	0.	^{37}Cl	3.3008E-07
^{21}Na	0.	^{33}Ar	0.
^{22}Na	0.	^{34}Ar	0.
^{23}Na	9.2090E-06	^{35}Ar	0.
^{21}Mg	0.	^{36}Ar	1.9168E-05
^{22}Mg	0.	^{37}Ar	0.
^{23}Mg	0.	^{38}Ar	3.7905E-06
^{24}Mg	0.10010	^{36}K	0.
^{25}Mg	1.8791E-05	^{37}K	0.
^{26}Mg	2.1551E-05	^{38}K	0.
^{23}Al	0.	^{39}K	9.6323E-07
^{24}Al	0.	^{39}Ca	0.
^{25}Al	0.	^{40}Ca	1.6634E-05

the ejecta for each sequence. In calculating the mean abundances, we have assumed that any material which reaches a radius greater than the orbital separation of the binary will escape from the system. Theoretical studies of the common envelope phase of evolution of a classical nova in outburst (MacDonald 1980; Livio et al. 1990; Shankar, Livio, & Truran 1991) support this assumption. An orbital separation of 10^{11} cm, typical of a classical nova system, was chosen for the ejection radius. We emphasize that the results in Table 3 are not sensitive to the choice of ejection radius, as long as it is of the same order of magnitude as observed CV semimajor axes.

3.1. *Energetics of the Outbursts*

Inspection of Table 2 reveals that the outburst becomes more violent as the mass of the white dwarf in our models is increased. As some of us have found previously (Starrfield, Sparks, & Truran 1974b), this results from the fact that, all other factors being kept equal, runaways on more massive

TABLE 2

MODEL PARAMETERS AND OUTBURST CHARACTERISTICS

Initial white dwarf mass ($M_\odot$)	1.00	1.25	1.35
Initial white dwarf luminosity (10^{-3} $L_\odot$)	9.40	9.70	9.60
Initial white dwarf effective temperature (K)	20,500	25,700	30,300
Initial white dwarf radius (km)	5379	3496	2488
Time to reach runaway (10^3 yr)	73.1	20.3	8.7
Total mass accreted (10^{-5} $M_\odot$)	10.5	3.2	1.5
Ignition pressure (10^{19} dyn cm^{-2})	2.5	5.2	10.
Peak nuclear energy generation rate (10^{17} erg gm^{-1} s^{-1})	0.21	1.0	1.9
Peak burning temperature (10^6 K)	224	290	356
Peak surface luminosity (10^5 $L_\odot$)	0.22	0.43	1.63
Peak surface effective temperature (10^5 K)	3.40	6.42	9.02
Model ejected mass (10^{-6} $M_\odot$)	0.0	0.0	6.2
Maximum velocity of ejected material (km s^{-1})	45	560	2320

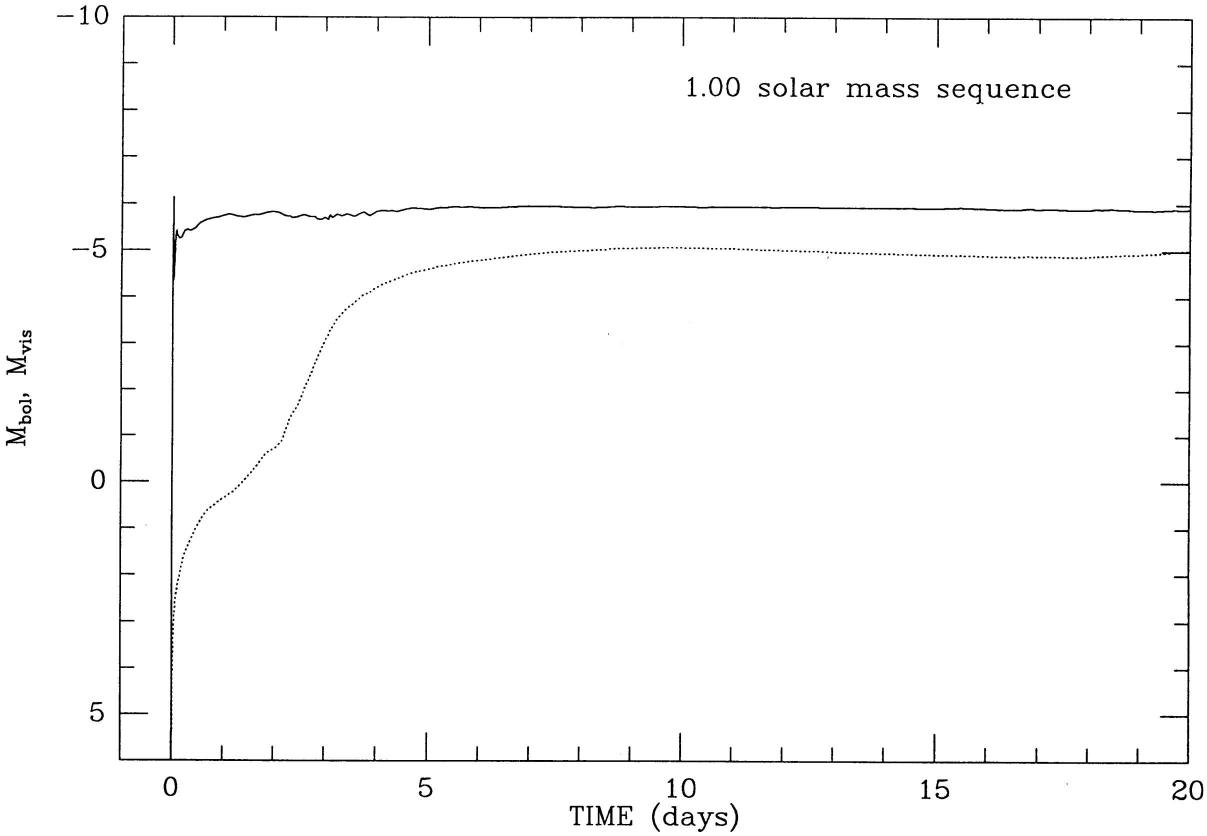

FIG. 1.—Variation with time of the bolometric (*solid curve*) and visual (*dashed curve*) luminosities for the 1.00 $M_\odot$ sequence. In this and all subsequent figures, $t = 0$ is the time at which the bolometric luminosity begins to increase as a result of the runaway in the interior.

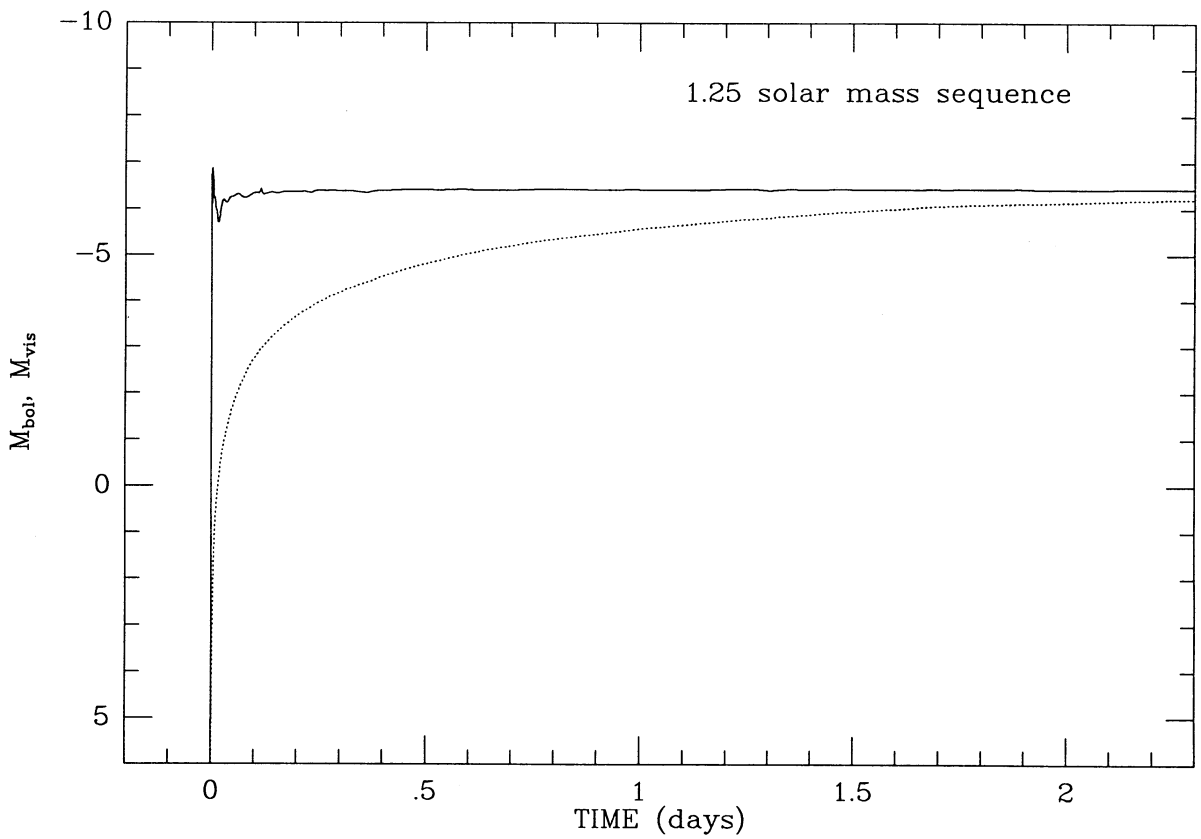

FIG. 2.—Variation with time of the bolometric (*solid curve*) and visual (*dashed curve*) luminosities for the 1.25 $M_\odot$ sequence

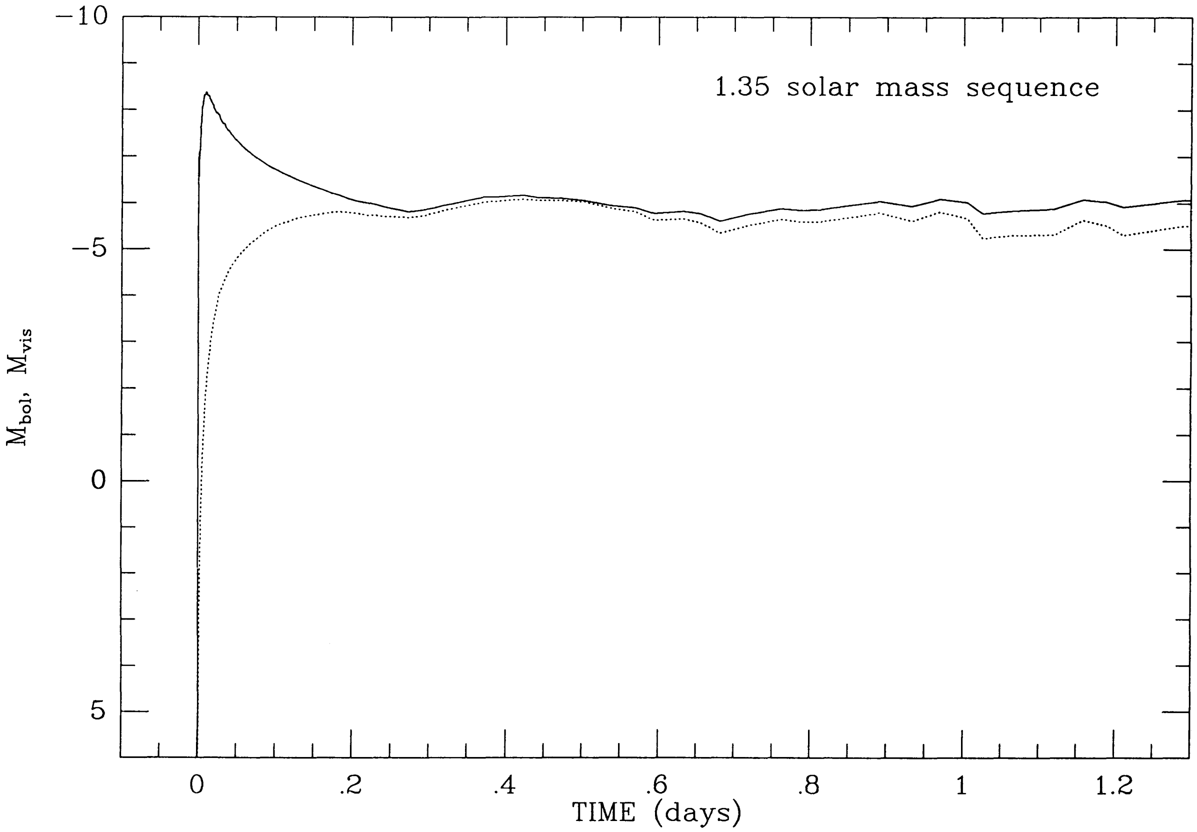

FIG. 3.—Variation with time of the bolometric (*solid curve*) and visual (*dashed curve*) luminosities for the 1.35 $M_\odot$ sequence

white dwarfs occur at higher pressures and higher degeneracy, leading to more energetic outbursts. The peak nuclear energy generation rate achieved during the runaway increases from 2.1×10^{16} ergs g^{-1} s^{-1} in the 1.00 $M_\odot$ sequence to 1.9×10^{17} ergs g^{-1} s^{-1} in the 1.35 $M_\odot$ sequence. The peak temperature achieved during the runaway similarly increases with white dwarf mass. A peak temperature in excess of 350×10^6 K was achieved in the 1.35 $M_\odot$ sequence. At such high temperatures, reactions involving intermediate-mass nuclei proceed on timescales compatible with the dynamical timescale. Consequently, our results concerning the nucleosynthesis accompanying the explosion are quite interesting. We will discuss these results extensively in a later section.

We find that the maximum velocities achieved in our models are a strong function of white dwarf mass. V_{max} increases from 45 km s^{-1} in the 1.00 $M_\odot$ sequence to 2320 km s^{-1} in the 1.35 $M_\odot$ sequence. In fact, only in the 1.35 $M_\odot$ sequence is matter ejected in the explosive phase of the outburst, and only in this sequence are ejection velocities typical of fast novae achieved. We expect the envelope material in the other sequences to be ejected via a combination of common-envelope-driven mass loss and radiation pressure (Hauschildt et al. 1994).

In the 1.35 $M_\odot$ sequence, super-Eddington luminosities are reached for 1.75 hr during the peak of the outburst. We note that the Eddington limit is given by

$$L_{Edd} = (4\pi c G M)/\kappa_{es} = 4.6 \times 10^4 L_\odot (M/M_\odot) , \quad (1)$$

where κ_{es} is the electron scattering opacity and we have assumed a solar composition. The bolometric luminosity in this sequence reached a maximum of $4L_{Edd}$ during the outburst. It is clear that the radiation pressure in the outermost zones during the super-Eddington phase is sufficient (see Hauschildt et al. 1994) for the ejection of matter from the surface of the white dwarf in this sequence. The 1.25 $M_\odot$ sequence reaches peak surface luminosities near or slightly above L_{Edd}, while the peak luminosity in the 1.00 $M_\odot$ sequence is only about $0.5L_{Edd}$. It appears, at first glance, that radiation pressure is insufficient to accelerate the envelope material to escape velocity in these sequences. We note, however, that our Rosseland mean opacities are obtained from Iben's (1975) analytic fits to the opacity tables of Cox & Stewart (1970a, b), and that the opacities of Cox & Stewart are smaller than recent opacity calculations which are more accurate (see, e.g., Iglesias, Rogers, & Wilson 1992 and references therein). Therefore, it seems likely that for more modern opacities, radiation-pressure-driven mass loss would be very important for thermonuclear runaways on low-mass white dwarfs (Starrfield et al. 1988). Calculations to test this hypothesis are currently underway.

In both the 1.25 $M_\odot$ and 1.00 $M_\odot$ sequences, a significant fraction of the accreted material expands past the orbital radius of the binary as a result of the outburst, although velocities exceeding escape velocity were not achieved. Novae are binary systems, and for the separations normally measured for such systems, the secondary is now orbiting within the extended layers of the white dwarf envelope. As we have previously mentioned, a phase of common envelope evolution is expected to ensue, and the gravitational dynamical friction of the secondary moving through these layers provides an additional heat source that is more than capable of ejecting all of the layers that lie outside the radius of the binary (MacDonald 1980; Livio et al. 1990; Shankar et al. 1991). Therefore, while in

TABLE 3

MEAN COMPOSITION OF EJECTA ASSUMING AN EJECTION RADIUS OF 10^{11} cm

Sequence	$1.00\,M_{\odot}$	$1.25\,M_{\odot}$	$1.35\,M_{\odot}$
Nucleus		Mass Fraction	
H	3.28E-01	2.98E-01	2.69E-01
^{4}He	1.66E-01	1.95E-01	2.04E-01
^{3}He	4.15E-09	1.02E-09	3.89E-10
^{7}Be	1.75E-10	1.28E-08	5.21E-08
^{12}C	5.97E-03	2.89E-02	2.29E-02
^{13}C	3.37E-03	1.43E-02	1.22E-02
^{14}N	1.97E-02	1.23E-02	1.03E-02
^{15}N	1.20E-04	1.20E-02	7.58E-02
^{16}O	9.47E-02	2.49E-02	4.60E-03
^{17}O	2.28E-02	4.49E-02	6.54E-03
^{18}O	5.79E-04	1.43E-03	5.91E-04
^{19}F	2.47E-05	2.37E-05	4.51E-05
^{20}Ne	2.47E-01	2.31E-01	1.74E-01
^{21}Ne	5.87E-06	4.25E-05	5.56E-05
^{22}Ne	2.29E-05	2.43E-06	7.56E-07
^{22}Na	4.94E-05	7.64E-04	5.54E-03
^{23}Na	4.78E-04	5.55E-03	2.89E-02
^{24}Mg	8.88E-04	8.41E-04	1.39E-03
^{25}Mg	5.84E-02	3.66E-02	3.86E-02
^{26}Mg	7.99E-05	1.15E-03	3.69E-03
^{26}Al	1.96E-02	9.45E-03	7.54E-03
^{27}Al	1.42E-02	1.64E-02	1.93E-02
^{28}Si	1.61E-02	4.55E-02	3.15E-02
^{29}Si	7.87E-05	2.53E-03	4.13E-03
^{30}Si	4.06E-05	9.98E-03	1.74E-02
^{30}P	1.41E-11	7.39E-05	1.02E-03
^{31}P	1.82E-06	3.99E-03	2.02E-02
^{32}S	1.10E-04	2.98E-03	2.90E-02
^{33}S	2.99E-06	1.64E-04	4.14E-03
^{34}S	1.45E-07	1.18E-06	3.40E-05
^{35}Cl	6.25E-06	3.94E-05	2.65E-03
^{37}Cl	3.27E-07	2.32E-07	3.82E-08
^{36}Ar	1.92E-05	2.14E-05	4.10E-04
^{38}Ar	3.78E-06	3.29E-06	1.14E-06
^{39}K	9.78E-07	1.47E-06	2.39E-06
^{40}Ca	1.66E-05	1.67E-05	1.82E-05

Table 2 we list the amount of mass ejected in the 1.00 $M_{\odot}$ and 1.25 $M_{\odot}$ sequences as 0.0, in fact, at the time we ended our calculations, $\sim 10^{-5}$ $M_{\odot}$ lies beyond a radius of 10^{11} cm in both of these sequences and will ultimately be ejected in a slow nova outburst.

3.2. *Light Curves*

In Figures 1–3, we show the variations of the bolometric and visual luminosities from our models. Previous calculations of classical nova outbursts on CO white dwarfs have shown that a phase of constant bolometric luminosity occurs for a period of several months to several years past the outburst (Starrfield et al. 1974a; Truran 1982; Starrfield 1989). As expected, we also find this constant luminosity phase in these ONeMg models. Except for the initial super-Eddington phase in the 1.35 $M_{\odot}$ sequence, the bolometric luminosity remains essentially constant at a level consistent with the core mass-luminosity relations for hydrogen burning shells on degenerate cores for the time period shown in these figures.

3.3. *Abundances in the Nova Ejecta*

Because our calculations are the first to combine a large nuclear reaction network involving intermediate-mass nuclei with a hydrodynamic stellar evolution code for the study of classical novae, the nucleosynthesis results are those which we shall emphasize in this study. Table 3 lists the mean composition of the ejecta, calculated for an assumed ejection radius of 10^{11} cm. Recall that the envelope abundances prior to runaway were identical in the three cases (see Table 1).

One dominant trend in the abundance pattern is the increase in the mass fractions of heavier nuclei with increasing white dwarf mass. Note, for example, the increased concentrations of the silicon, sulfur, and argon isotopes in the ejected matter for the case of a nova outburst on a 1.35 $M_{\odot}$ white dwarf. This is a direct consequence of the progressive decrease in the CNO and neon abundances as burning proceeds at higher temperatures. Note that while the initial CNO mass fraction in the envelope was $X_{\rm CNO} = 0.151$ (see Table 1), the mass fractions in the ejecta for the 1.00, 1.25, and 1.35 $M_{\odot}$ cases are 0.147, 0.139, and 0.133, respectively. The ^{20}Ne mass fraction also decreases, from 0.247 at 1.00 $M_{\odot}$ to 0.174 at 1.35 $M_{\odot}$. Upward flows in the network thus explain the large overabundances of Si, S, and Ar achieved in the 1.35 $M_{\odot}$ sequence.

We now examine the abundances in Table 3 in more detail, beginning with the nuclei that are of special interest for this study. Of particular concern here are trends in the abundance levels of nuclear species with white dwarf mass.

1. ^{26}Al.—The abundance of this nucleus in the nova ejecta decreases with increasing white dwarf mass. Specifically, the mass fraction of ^{26}Al decreases by a factor of 3 over the range of white dwarf masses considered in this study. This decrease is a consequence of the fact that the peak temperature achieved

during nuclear burning increases with white dwarf mass. High temperatures are needed to create the ^{26}Al. However, if the temperature becomes too high, destruction mechanisms begin to dominate over production mechanisms, and the abundance of ^{26}Al begins to decrease. This behavior was also encountered in the one-zone nucleosynthesis study of Weiss & Truran (1990) and was discussed in detail by Nofar et al. (1991).

2. ^{22}Na.—The amount of ^{22}Na in the ejecta depends even more strongly on the mass of the underlying white dwarf. We find that the amount of ^{22}Na produced increases by 2 orders of magnitude as the mass of the white dwarf increases from 1.00 $M_\odot$ to 1.35 $M_\odot$. A mass fraction in the ejecta of 5.5×10^{-3} for ^{22}Na was found in the 1.35 $M_\odot$ sequence. Such a high concentration of ^{22}Na is not expected, even at the high burning temperatures achieved in the 1.35 $M_\odot$ sequence, unless these high temperatures are of very short duration. The variation of the temperature of the deepest (hottest) hydrogen-rich zone near the peak of the outburst is shown for each sequence in Figures 4–6. We see from Figure 6 that exactly such a condition is present in the 1.35 $M_\odot$ sequence. The temperature in the hottest burning zone remains high (above 300×10^6 K) for only 17 s and then falls rapidly. A significant amount of the ^{22}Na produced at the highest temperature survives as a consequence of this rapid temperature decrease. Furthermore, convection transports ^{22}Na to the cooler, outer regions of the envelope on a rapid timescale.

3. Ne.—In contrast to ^{26}Al and ^{22}Na, the abundance of neon (almost exclusively in the form of ^{20}Ne) remains approximately constant for the three sequences. Although a peak burning temperature of 356×10^6 K was achieved in the 1.35 $M_\odot$ sequence, temperatures of at least 400×10^6 K are needed for significant destruction of ^{20}Ne to occur. The mass fraction of ^{20}Ne in the envelope of the 1.35 $M_\odot$ white dwarf is reduced only slightly from its pre-runaway value of 0.25 to 0.17.

4. Si–Ca.—A trend with mass similar to that for ^{22}Na is found for the majority of nuclei in the Si–Ca range. As the white dwarf mass is increased, increases in abundance by several orders of magnitude are found for a number of nuclear species in this element range. Significant overabundances of these elements relative to solar in the ejecta of observed novae may then be an indication that the underlying white dwarf is very massive. The observed enrichments are a direct consequence of the fact that nucleosynthesis of the more massive nuclei via (p, γ) reactions occurs at the highest temperatures achieved in the 1.35 $M_\odot$ sequence.

5. CNO *nuclei.*—We find in our models that the abundance of ^{16}O in the ejecta is strongly dependent upon the white dwarf mass. The mass fraction of ^{16}O decreases by a factor of 20, from about 0.1 in the 1.00 $M_\odot$ sequence to about 0.005 in the 1.35 $M_\odot$ sequence. This is entirely a consequence of the fact that ^{16}O is more readily destroyed at the higher temperatures characteristic of the more massive sequences. The abundances of ^{17}O and ^{18}O show a slight maximum for the 1.25 $M_\odot$ sequence. The abundance of ^{14}N also decreases with white dwarf mass, but much less dramatically; the difference in mass fraction between the 1.00 and 1.35 $M_\odot$ sequences is only a factor of 2. However, the abundance of ^{15}N substantially increases with white dwarf mass; the difference in mass fraction between the 1.00 and 1.35 $M_\odot$ sequences is nearly 3 orders of magnitude. As a result, the total nitrogen abundance shows an

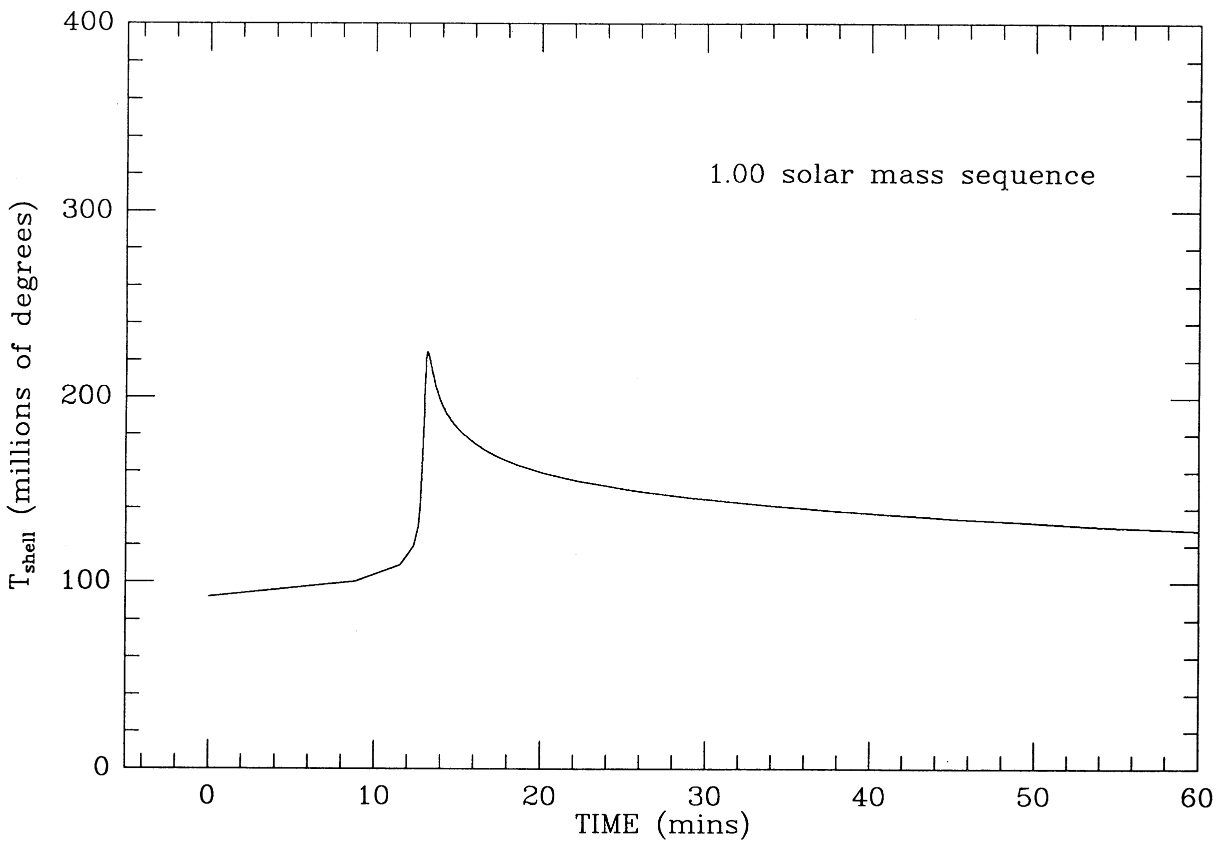

FIG. 4.—Variation with time of the temperature in the hottest hydrogen-rich burning zone near the peak of the outburst for the 1.00 $M_\odot$ sequence

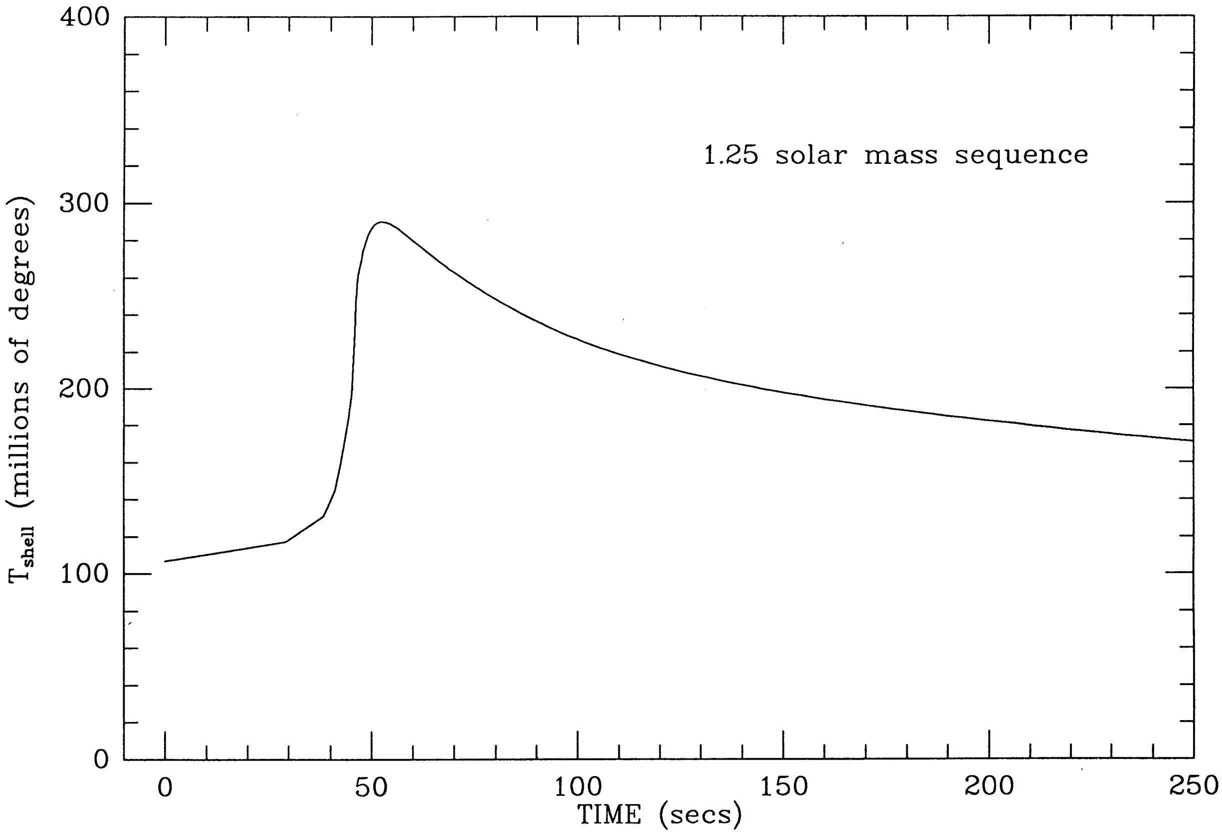

FIG. 5.—Variation with time of the temperature in the hottest hydrogen-rich burning zone near the peak of the outburst for the 1.25 $M_{\odot}$ sequence

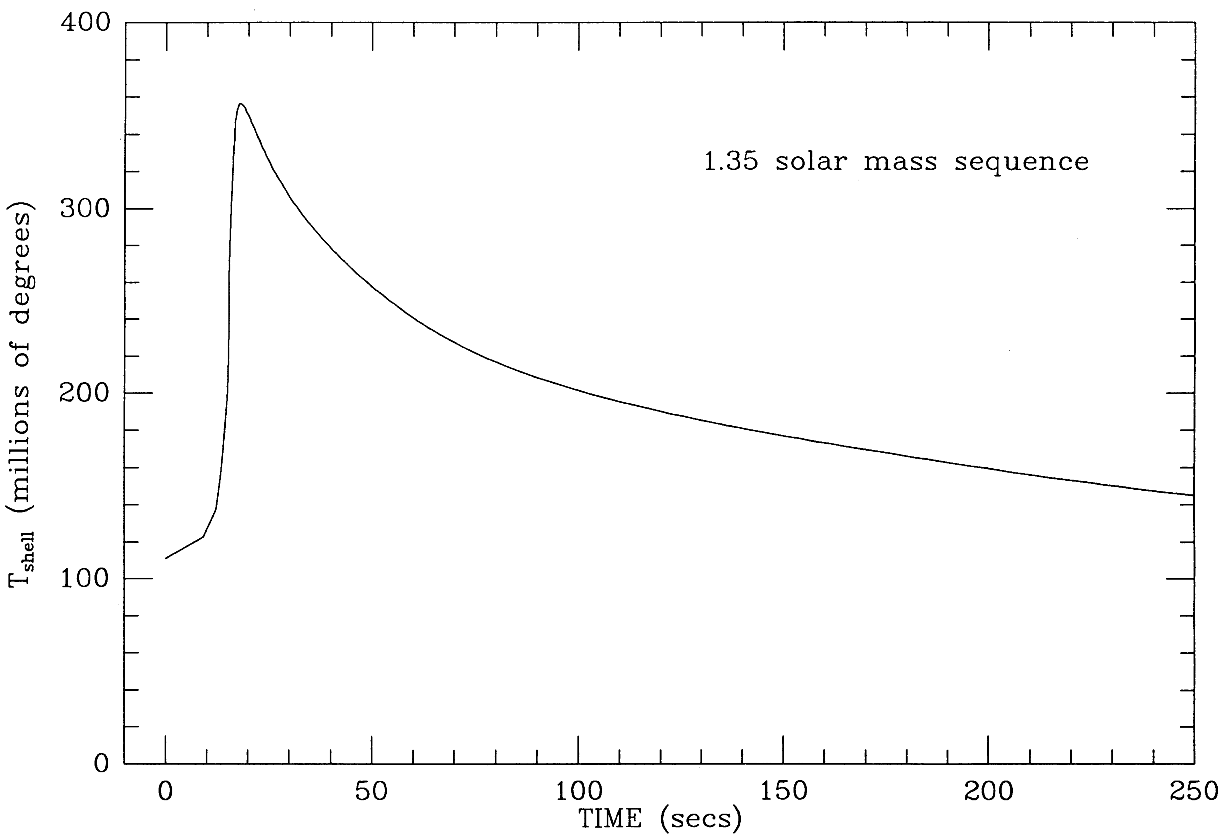

FIG. 6.—Variation with time of the temperature in the hottest hydrogen-rich burning zone near the peak of the outburst for the 1.35 $M_{\odot}$ sequence

overall increase with white dwarf mass (by about a factor of 4–5 for the mass range we considered). Looking at the O/N ratio in our three sequences, we see then that this ratio inverts somewhere between 1.25 and 1.35 $M_\odot$. That is, for our lower mass sequences, oxygen is more abundant than nitrogen in the ejecta, but for our highest mass sequence, nitrogen is more abundant than oxygen. We predict that a decreased oxygen abundance in the ejecta of a ONeMg nova, or an O/N abundance ratio that is less than 1, may be an indication that the nova contains a very massive ($\sim 1.35\ M_\odot$) white dwarf. This may be especially relevant to V838 Her 1991 and V1370 Aql 1982 (see § 4.2). The ^{12}C abundance is about 0.03 in the 1.25 $M_\odot$ sequence. It decreases by a factor of 5 to 0.006 in the 1.00 $M_\odot$ sequence, and, more modestly, to 0.02 in the 1.35 $M_\odot$ sequence. The trend for ^{13}C is similar. As we noted previously, the total mass fraction of CNO elements decreases by approximately 10% for the 1.35 $M_\odot$ sequence, due to leakage out of the CNO cycles at higher temperatures.

6. H *and* He.—As expected, with the higher burning temperatures achieved as the white dwarf mass is increased, the hydrogen abundance decreases with increasing white dwarf mass and the helium abundance increases.

3.4. *Model Evolution in the* 1.00 $M_\odot$ *Sequence*

We wish to discuss the results for the 1.00 $M_\odot$ evolutionary sequence in more detail, since this sequence produced the largest amount of ^{26}Al. This sequence accretes at 10^{17} g s^{-1} for about 7×10^4 yr in order to establish an envelope of $\sim 10^{-4}$ $M_\odot$. We terminate the accretion phase when the temperature at the interface between the core and the envelope (hereafter, CEI) has reached 45×10^6 K and the rate of energy generation has reached $\sim 1.0 \times 10^9$ ergs g^{-1} s^{-1}. At this time, the mass fraction of ^{26}Al, which was zero in the initial model, has increased to 5.15×10^{-7}. The abundance of ^{27}Al, which was initially 1.61×10^{-5}, has not changed. We also find that the convective region, which first appeared when $T_{\rm CEI}$ reached about 30×10^6 K, has now grown to a layer which extends 200 km above the CEI, and whose upper boundary is within 75 km of the surface. It takes about 27 days for $T_{\rm CEI}$ to climb to 10^8 K, at which time the nuclear energy generation rate at the CEI is 2.3×10^{13} ergs g^{-1} s^{-1}, and the nuclear energy generation rate at the surface has increased to 3×10^{12} ergs g^{-1} s^{-1}. By the time $T_{\rm CEI}$ has reached 2×10^8 K, about 200 s later, the abundance of ^{26}Al has increased to 1.3×10^{-2} at the CEI and, to 3×10^{-4} at the surface. It is being produced by the reaction sequence: ^{24}Mg(p, γ)^{25}Al($\beta^+\nu$)^{25}Mg(p, γ)^{26}Al. The isomeric state of ^{26}Al is not important. The peak nuclear energy generation rate at the CEI is 2.1×10^{16} ergs g^{-1} s^{-1}, and the peak temperature is $T_{\rm CEI} = 2.24 \times 10^8$ K. At this time, the outer layers are expanding at ~ 150 km s^{-1}, but the outer radius has not yet reached 10^9 cm.

Since most of the ^{26}Al comes from the decay of ^{25}Al followed by the proton capture on ^{25}Mg, its abundance continues to increase even after the peak temperature has been reached. The expansion of the nova envelope gradually slows until, after a few hours, the surface layers are moving at speeds of only a few km s^{-1}. As we have said earlier, it is clear that the energy production during the runaway was insufficient to explosively eject the shells.

4. DISCUSSION

Recent observations have shown that a significant fraction of the nova systems seen in outburst contain ONeMg white dwarfs. The strongest evidence arises from detailed abundance analyses of the ejecta in these systems, which reveal levels of enrichment of the intermediate-mass elements neon, sodium, magnesium, aluminum, silicon, and sulfur that cannot be explained solely on the basis of explosive hydrogen burning, either in material of solar abundances or in CNO-enriched matter. Our aim in this paper has been to begin to explore the implications of this conclusion for the characteristics of classical novae in outburst and, particularly, for nucleosynthesis associated with the thermonuclear runaways that define these events.

In the following discussions, we will first compare the nucleosynthesis predictions emerging from our detailed hydrodynamic calculations with the results of earlier nucleosynthesis studies. In § 4.2, we review recent nova abundance analyses and discuss these in light of the abundance trends with white dwarf mass that we have identified in our calculations. We specifically discuss ^{26}Al and ^{22}Na nucleosynthesis in ONeMg novae in §§ 4.3 and 4.4. In § 4.5, we examine the spatial distribution of neon novae in our Galaxy and make some remarks concerning nova speed class in neon novae. We close with a discussion of ONeMg novae versus recurrent novae.

4.1. *Comparison with Nucleosynthesis in One-Zone Models*

Previous one-zone nucleosynthesis studies of nova explosions that involve the presence of significant initial enrichments of intermediate-mass elements in the white dwarf envelopes (Weiss & Truran 1990; Nofar et al. 1991) have suggested that such novae can be an important source of intermediate-mass isotopes, particularly ^{22}Na and ^{26}Al, in the Galaxy. The results of the models presented in this paper have conclusively demonstrated that this is true. There are, however, some interesting and important differences between our models and the one-zone nucleosynthesis calculations which we would like to identify in this section.

We first note that the ^{22}Na and ^{26}Al abundances calculated for the ejecta of our models are higher than those found by Weiss & Truran. Similarly, the ^{26}Al abundances in our models are generally higher than those of Nofar, Shaviv, & Starrfield. An essential distinction between the calculations of Weiss & Truran and Nofar, Shaviv, & Starrfield and the hydrodynamic calculations we have presented here is that the previous authors have assumed a single mass zone for the white dwarf envelope and have evolved it through a temperature-density-time profile, whereas we have subdivided the envelope into approximately 30–40 mass zones. This allows for temperature and density stratification within the envelope and, more importantly, for mixing of material via convection within these stratifications. Because of the short turnover time ($\tau_{\rm conv} \sim 10^2$–$10^3$ s), convection is able to transport ^{22}Na and ^{26}Al from deep within the envelope to zones near the surface, where the temperature is far too low for these nuclei to be rapidly destroyed. This mixing, therefore, acts to increase the levels of abundance of these nuclei.

A further important difference is that, contrary to the results of Weiss & Truran (1990), our results do *not* indicate that there should exist a strong correlation between ^{26}Al and ^{22}Na overproduction in nova outbursts. We find, instead, that the mass fraction of ^{26}Al remained rather constant, falling by only a factor of ~ 3 as the mass increased from 1.00 $M_\odot$ to 1.35 $M_\odot$, while the ^{22}Na concentration increased dramatically over this range. The ^{22}Na mass fractions for the 1.00, 1.25, and 1.35 $M_\odot$ sequences were, respectively, 4.9×10^{-5}, 7.6×10^{-4}, and 5.5×10^{-3}.

4.2. *Comparison with Observations*

At present, seven neon novae have been studied in detail. Six are within our Galaxy: V1500 Cyg 1975, V693 CrA 1981, V1370 Aql 1982, QU Vul 1984, V838 Her 1991, and V1974 Cyg 1992. The remaining one is in the Large Magellanic Cloud: LMC 1990 No. 1. Other neon novae have been discovered (LMC 1988 No. 2, Nova Oph 1988, and Nova Pup 1991), but the data reductions and analyses are still in progress. Observed neon novae range in speed class from moderately fast to very fast (see § 4.5), with velocities of ejection ranging from 2300 km s^{-1} to as high as 10,000 km s^{-1} (V1370 Aql; Snijders et al. 1984). The masses of the ejected material in neon novae range from $\sim 10^{-5}$ $M_\odot$ to possibly as high as 10^{-3} $M_\odot$ in QU Vul (Taylor et al. 1987; Greenhouse et al. 1988; Saizar et al. 1992).

The 1.35 $M_\odot$ sequence we have calculated ejected 1.0×10^{-5} $M_\odot$, and the velocity of the ejecta reached a maximum of 2300 km s^{-1}. These values are consistent with observed results for the faster neon novae. The masses of the ejecta in the 1.00 and 1.25 $M_\odot$ sequences are consistent with observed neon novae, but the ejection velocities are not in agreement with the observations. Higher ejection velocities have been achieved for sequences with a lower accretion rate (Starrfield et al. 1992a; Politano et al. 1995).

The nova, QU Vul, merits some further comment. If the mass of the ejected material in QU Vul is indeed as high as some observational estimates suggest, 10^{-3} $M_\odot$, then this is ~ 10 times greater than the mass ejected in the 1.00 $M_\odot$ sequence and ~ 30–100 times greater than the mass ejected in the 1.25 and 1.35 $M_\odot$ sequences, assuming these sequences will eventually eject their entire accreted envelopes. A value of 10^{-3} $M_\odot$ for the ejected mass in QU Vul is difficult to reconcile with our current theoretical nova models. (We also note that the mass of the ejecta in V1974 Cyg 1992, another "slower" neon novae, is also high, $> 10^{-4}$ $M_\odot$; see Shore et al. 1993.) This is an important issue which must be resolved if we wish to provide realistic estimates of the consequences of nova nucleosynthesis.

A summary of abundances for some well-studied novae, for which reliable abundance estimates exist, is given in Table 4. Four neon novae are included in this table. Let us compare the ejecta abundances from our models (Table 3) with these observed abundance estimates. Recall that we have *assumed* that the abundances of the carbon-burning products, oxygen, neon, and magnesium, comprise 50% by mass of the envelope matter.

The reported mass fractions of neon in the ejecta of observed neon novae range from as low as 0.023 in V1500 Cyg to as high as 0.52 in V1370 Aql. The mass fraction of magnesium determined for the neon novae range from $\sim 2 \times 10^{-3}$ to $\sim 7 \times 10^{-3}$. We note that the novae which have higher magnesium abundances also have a high neon abundance. This presumably reflects a higher degree of mixing between the envelope material and the white dwarf material in these cases. Also, we predict from our simulations that, while ^{24}Mg is the dominant magnesium isotope in the envelope prior to runaway, much of this isotope is burned to ^{25}Mg and ^{26}Al during the runaway. ^{25}Mg is predicted to be the most abundant isotope of magnesium in the ejecta. In general, the ranges of magnesium, aluminum, and silicon mass fractions calculated in our models are systematically higher than the observed mass fractions by approximately a factor of 5–10. Finally, sulfur abundances have been determined for both V1370 Aql and V838 Her (Matheson, Filippenko, & Ho 1993; Vanlandingham et al. 1995). The observed mass fractions are on the order of 0.10, which is quite high, nearly 200 times solar. Nonetheless, the abundance of sulfur in the ejecta of our 1.35 $M_\odot$ sequence is 0.033, which is lower than the observed value in V1370 Aql by only a factor of three, indicating that such a high sulfur abundance is not unreasonable from a theoretical viewpoint.

We may summarize the above discussion of nova abundances with the following comments: (1) Our model ejecta abundances for neon and sulfur are in agreement with observational estimates for the better-studied ONeMg systems. This lends support to the scenario which we have attempted to model in these evolutionary calculations, namely that these outbursts occurred on ONeMg white dwarfs. (2) Our predicted abundances for Al, Mg, and Si are all about a factor of 10 higher than the observational estimates. We note, however, that the present evolutionary sequences were calculated for one particular choice of accretion rate and level of mixing. We have performed evolutionary calculations for other choices of these parameters and will report on their influence on the composition of the ejecta in later papers in this series. (3) The trends with mass for the ejecta abundances in our models point

TABLE 4

HEAVY ELEMENT ABUNDANCES IN CLASSICAL NOVAE

			Mass Fractions											
Object	Year	Ref.	H	He	C	N	O	Ne	Na	Mg	Al	Si	S	Fe
RR Pic	1925	1	0.53	0.43	0.0039	0.022	0.0058	0.011						
HR Del	1967	2	0.45	0.48		0.027	0.047	0.0030						
T Aur	1891	3	0.47	0.40		0.079	0.051							
PW Vul	1984	4	0.49	0.23	0.064	0.12	0.093	0.0019		0.00027		0.0058		0.00092
PW Vul	1984	5	0.69	0.25	0.0033	0.049	0.014	0.00066						
V1500 Cyg	1975	6	0.49	0.21	0.070	0.075	0.013	0.023						
V1668 Cyg	1978	7	0.45	0.23	0.047	0.14	0.013	0.0068						
V693 CrA	1981	8	0.29	0.32	0.0046	0.080	0.12	0.17	0.0016	0.0076	0.0043	0.0022		
GQ Mus	1983	9	0.27	0.32	0.016	0.19	0.19	0.0034		0.0014	0.00056	0.0028	0.0016	0.00047
DQ Her	1934	10	0.34	0.095	0.045	0.23	0.29							
V1370 Aql	1982	11	0.053	0.088	0.035	0.14	0.051	0.52		0.0067		0.0018	0.10	0.0045
QU Vul	1984	12	0.30	0.59	0.0010	0.021	0.041	0.044		0.0017	0.0021	0.00039		

REFERENCES.—(1) Williams & Gallagher 1979. (2) Tylenda 1978. (3) Gallagher et al. 1980. (4) Andreae & Drechsel 1990. (5) Saizar et al. 1991. (6) Ferland & Shields 1978. (7) Stickland et al. 1981. (8) Williams et al. 1985. (9) Hassal et al. 1990. (10) Williams et al. 1978. (11) Snijders et al. 1987. (12) Saizar et al. 1992.

toward the conclusion that the outburst in V1370 Aql took place on a very massive white dwarf (probably around 1.35 $M_\odot$). The unusually high sulfur abundance, relatively low oxygen abundance and relatively high nitrogen abundance all provide support for this conclusion. We note that the spectra of V838 Her 1991, which also shows enhanced sulfur and depleted oxygen, suggests that the white dwarf in this system is also very massive. (4) We wish that our models could shed some light on the mass of the white dwarf in QU Vul and V1974 Cyg. If the mass of the ejected material in these novae is indeed as high as 10^{-4} to 10^{-3} $M_\odot$, then one would expect the mass of the white dwarf in these systems to be unusually low, a situation that would be difficult to understand in the context of current theoretical models. Unfortunately, the observed ejecta abundances suggest no clear confirmation of this based on our model trends. In fact, the low oxygen abundances are more suggestive of a high-mass white dwarf. These are clearly interesting systems demanding further study. The helium abundances are quite high and, in the case of QU Vul, the silicon abundance is, in fact, below solar, yet the C, N, O, and Ne abundances are similar to those of V1500 Cyg, which was an extremely fast nova.

4.3. ^{26}Al *Production in* ONeMg *Novae*

Observations of ^{26}Al γ-ray line emission by Mahoney et al. (1984) are interpreted as requiring the presence of approximately 3 $M_\odot$ of ^{26}Al in the Galaxy, although recent COMPTEL observations suggest that the amount of ^{26}Al required in a homogeneous background is ~ 1 $M_\odot$ (Diehl et al. 1995). Weiss & Truran (1990) estimated the mass of ^{26}Al returned to the ISM by nova explosions on the basis of the following formula,

$$M_{26,\rm novae} = 0.4\ M_\odot (R_{\rm nova}/40\ {\rm yr}^{-1})(f_{26}/0.25) \times (M_{\rm ej}/2\times 10^{-5}\ M_\odot)(X_{26}/2\times 10^{-3})\ , \quad (2)$$

where $R_{\rm nova}$ is the nova rate in the Galaxy, f_{26} is the fraction of those novae which occur on ONeMg white dwarfs, $M_{\rm ej}$ is the average mass ejected per outburst, X_{26} is the mass fraction of ^{26}Al in the ejected mass and 0.4 includes the mean lifetime of ^{26}Al, 1.05×10^6 yr.

In the above formula, the quantities $M_{\rm ej}$ and X_{26} represent values which have been averaged over white dwarf mass. Our present models now provide data which allow us to estimate the dependence of the ^{26}Al mass fraction on white dwarf mass. We can, therefore, hope to provide a more sophisticated analysis of the amount of ^{26}Al produced in ONeMg nova outbursts. Such an analysis is further warranted in view of the possibility that ONeMg novae can eject masses as large as those inferred for QU Vul (10^{-3} $M_\odot$) and V1974 Cyg 1992 ($>10^{-4}$ $M_\odot$; see § 4.2). This raises concerns about the estimate used by Weiss & Truran for ONeMg novae, as well as the accuracy of using an average value, given the possibility that the range of ejected masses in ONeMg novae appears to be wider than previously anticipated.

We can replace Weiss & Truran's expression for the mass of ^{26}Al returned to the ISM by nova explosions with the following integral over white dwarf mass:

$$M_{26,\rm novae} = \tau_{26} \int_{M_{L,\rm ONeMg}}^{1.38 M_\odot} n(M)\nu_{\rm rec}(M)M_{\rm ej}(M)X_{26}(M)dM\ , \quad (3)$$

where $n(M)$ is the number distribution of nova systems with white dwarf mass, $\nu_{\rm rec}(M)$ is the frequency with which nova outbursts recur as a function of white dwarf mass, and $M_{\rm ej}$ and X_{26} have the same meaning as before, except that each is now a function of white dwarf mass. $M_{L,\rm ONeMg}$ is the lower limit to the mass of ONeMg white dwarfs in binaries, and τ_{26} is the mean lifetime of ^{26}Al.

The integrand in equation (3) is the total mass of ^{26}Al ejected per year from nova explosions on ONeMg white dwarfs whose masses are in an interval M to $M + dM$. Integration over the range of ONeMg white dwarf masses in classical nova systems then gives an estimate of the rate of injection of ^{26}Al into the ISM from novae. Multiplication by the mean lifetime of ^{26}Al gives the desired estimate of the mass of ^{26}Al returned to the ISM from nova explosions, $M_{26,\rm novae}$, which is contributing presently to the observed γ-ray flux.

We have taken the limiting stable ONeMg white dwarf mass to be 1.38 $M_\odot$, following Hamada & Salpeter (1961). The lower limit to the masses of single ONeMg white dwarfs is believed to be approximately 1.1 $M_\odot$ (Murai et al. 1968). A definite value for this lower limit in binary systems is not well known, however, because many of the quantitative effects of binary evolution on advanced phases of stellar evolution are not sufficiently well understood. Consequently, we cannot directly compute an estimate of the amount of ^{26}Al returned to the ISM by nova explosions from the integral in equation (3). However, all the terms in the integrand of equation (3) can be estimated for a given white dwarf mass. We can, therefore, determine the value of $M_{L,\rm ONeMg}$ for which $M_{26,\rm novae} = 3$ $M_\odot$ in equation (3).

We begin by rewriting equation (3) as

$$M_{26,\rm novae} = \tau_{26} \int_{M_{L,\rm ONeMg}}^{1.38 M_\odot} n(M)[\dot{M}/M_{\rm acc}(M)]M_{\rm ej}(M)X_{26}(M)dM\ . \quad (4)$$

Here we have replaced the recurrence frequency, $\nu_{\rm rec}$, by $\dot{M}/M_{\rm acc}$, where $\dot{M}$ is the accretion rate in the system and $M_{\rm acc}$ is the mass of material accreted prior to the outburst. The amount of accreted material required to initiate the thermonuclear runaway is a function of white dwarf mass (e.g., Truran & Livio 1986; Starrfield 1989). While, in general, the accretion rate is probably dependent upon white dwarf mass, the form of this dependence is not well known at all. We have, therefore, simply assumed a mean accretion rate for nova systems which is independent of white dwarf mass. We constrain this mean accretion rate by the total nova rate in the Galaxy in a self-consistent manner using the following expression:

$$\int_{M_{L,\rm all}}^{1.38 M_\odot} n(M)[\dot{M}/M_{\rm acc}(M)]dM = R_{\rm nova}\ , \quad (5)$$

where we have taken $M_{L,\rm all}$ as 0.55 $M_\odot$, the lowest mass carbon-oxygen white dwarf in newly forming cataclysmic variable systems (Politano 1988). Ritter et al. (1991) have shown that thermonuclear events on helium white dwarfs (0.27–0.46 $M_\odot$) would contribute less than 2% to the total nova rate.

The integrand in equation 4 contains the ratio of the ejected mass per outburst, $M_{\rm ej}$ to the accreted mass, $M_{\rm acc}$. Numerous observations of significant heavy element enrichments in nova ejecta argue that this ratio is greater than 1 for classical novae. Let us call the ratio of the ejected mass to the accreted mass, α. In order to be formally consistent with our choice for the amount of mixing between the accreted envelope and the underlying white dwarf in these models, we have chosen $\alpha = 2$.

(That is, in order for the pre-runaway material to be enriched in O, Ne, and Mg to 50% by mass, this material must contain equal amounts of white dwarf material and companion material.) Nevertheless, in rewriting equation (4), we will leave α unspecified because we will have cause to comment later on how $M_{L,\mathrm{ONeMg}}$ depends on α. We can then rewrite equation (4) as

$$M_{26,\mathrm{novae}} = \tau_{26}\,\dot{M} \int_{M_{L,\mathrm{ONeMg}}}^{1.38 M_\odot} \alpha(M) n(M) X_{26}(M) dM \,. \quad (6)$$

For $n(M)$, we have chosen the white dwarf mass distribution for newly forming cataclysmic variables calculated by Politano (1988, 1990). As an estimate for $X_{26}(M)$, we have simply linearly interpolated between the values from our models.

We find, given the choices we have made, that a value of 1.20 $M_\odot$ for $M_{L,\mathrm{ONeMg}}$ will give $M_{26,\mathrm{novae}} = 3\ M_\odot$. Although the effects of binary evolution regarding the production of ONeMg white dwarfs in binaries are not quantitatively well understood, some theoretical estimates of the range of ONeMg white dwarf masses in binaries have been put forth which place the lower limit to ONeMg white dwarf masses in binaries at approximately 1.1 $M_\odot$ (e.g., Iben & Tutukov 1985; Nomoto & Hashimoto 1987). We may provide some discussion of the uncertainty in our estimate for $M_{L,\mathrm{ONeMg}}$ by estimating the uncertainties in the quantities in equation (6).

There is no clear trend from observations to allow us to estimate the dependence of α on white dwarf mass. Given the large scatter in the total heavy element mass fractions (Z) for the well-studied CO and ONeMg novae (see Table 4), we do not suspect that the dependence of α on white dwarf mass is very strong. Therefore, we simply assume α is constant and take α outside of the integral so that $M_{26,\mathrm{novae}}$ depends linearly on α. Theoretical calculations which attempt to model the cataclysmic variable population and which include a secular decrease in the white dwarf mass suggest that α should be less than $\sim$1.2 in order to be consistent with the observed mean white dwarf mass in cataclysmic variable systems (see Kolb 1993). Choosing $\alpha = 1$ as a lower limit (this implies that the mass of the white dwarf does not change secularly) would then reduce our estimate of $M_{L,\mathrm{ONeMg}}$ to 1.13 $M_\odot$.

Because of our assumption of a *mean* accretion rate, $M_{26,\mathrm{novae}}$ depends linearly on $\dot{M}$. However, our choice for this mean accretion rate is constrained by the total nova rate in the Galaxy via equation (5). If we were to assume that the nova rate in our Galaxy is similar to that in M31, this would increase R_{nova} from 40 yr^{-1} to 100 yr^{-1} (Ciardullo et al. 1987). Such an increase in R_{nova} would increase our estimate of $M_{L,\mathrm{ONeMg}}$ to 1.28 $M_\odot$.

$M_{26,\mathrm{novae}}$ is dependent upon the distribution of white dwarf masses in novae, $n(M)$. Two things should be noted in using Politano's distribution (Politano 1990) for $n(M)$ in equation (4). First, this distribution does not distinguish between ONeMg white dwarfs and CO white dwarfs, chiefly because of a lack of detailed binary evolutionary calculations which begin with hydrogen-rich envelopes and lead to the production of ONeMg white dwarfs. We expect the transition from CO white dwarfs to ONeMg white dwarfs to be continuous (e.g., Law & Ritter 1983), and we assume that the distribution of cataclysmic variables with ONeMg white dwarfs is similar to the calculated distribution of cataclysmic variables with CO white dwarfs in this mass range. If the production of cataclysmic variables with ONeMg white dwarfs is significantly less than that calculated assuming CO white dwarfs in this mass range, then Politano's distribution for $n(M)$ may overestimate the number of ONeMg white dwarfs in novae, and our estimate for $M_{L,\mathrm{ONeMg}}$ might be too high. This is an important consideration. Calculations are presently underway to produce model distributions of cataclysmic variables with ONeMg white dwarfs (Politano 1995). Second, Politano's distribution is for newly forming cataclysmic variables, whereas $n(M)$ is the present (secularly evolved) distribution of novae. In choosing Politano's distribution for $n(M)$ we have implicitly assumed that the white dwarf mass remains constant during the lifetime of a nova. This is inconsistent with our choice of $\alpha = 2$, although preliminary calculations using model distributions which include the secular decrease of the white dwarf mass suggest that using Politano's distribution for $n(M)$ introduces only a small error for $\alpha = 2$ (Kolb & Politano 1995).

We expect that the mass fraction of ^{26}Al in the ejecta depends both on the initial level of mixing between white dwarf and envelope material and on the accretion rate. Our calculations were performed for one particular choice of accretion rate and amount of mixing. This introduces a major uncertainty in X_{26}. The observational estimates of the aluminum abundance in the ejecta would seem to suggest that our model abundances for aluminum are too high (see § 4.2). These estimates are for the *total* aluminum abundance, not just ^{26}Al, and perusal of Table 3 shows that the mass fraction of ^{27}Al can be as much as 70% of the total aluminum mass fraction. If we reduce X_{26} by a factor of three, this would reduce our estimate of $M_{L,\mathrm{ONeMg}}$ to 1.09 $M_\odot$.

Our estimate of $M_{L,\mathrm{ONeMg}}$ and the uncertainties associated with its value appear to suggest that ONeMg novae can account for the Galactic ^{26}Al γ-ray line emission, provided that the production of cataclysmic variables with ONeMg white dwarfs is not drastically less than that calculated for CO white dwarfs in the same mass range. However, we wish to point out an important limitation of this estimate. Our estimate is based on the particular accretion rate and level of mixing we have chosen for these evolutionary sequences. The integral in equation (6) should really be a two-dimensional integral over M and $\dot{M}$. Both α and X_{26} are functions of $\dot{M}$, although the dependence of these quantities on $\dot{M}$ is not known at present. We have calculated evolutionary sequences for accretion onto ONeMg white dwarfs at different accretion rates, and we hope to readdress this issue in a later paper in this series. Preliminary calculations (Kolb & Politano 1995) which use these sequences and which use model distributions of cataclysmic variables over both white dwarf mass *and* accretion rate show good agreement with the present estimate for $\alpha = 2$. However, there are significant deviations from the simple one-dimensional estimate for smaller values of α (<1.2). Thus, for the moment, while ONeMg novae appear to be important contributors to the Galactic ^{26}Al γ-ray line emission, the question as to whether they can *fully* account for this emission remains unresolved.

We also wish to comment that recent COMPTEL observations of the ^{26}Al γ-ray line emission revealed unexpected inhomogeneities and asymmetries in the emission, suggesting that a significant fraction of the emission originates from localized regions and thereby reducing the required amount of ^{26}Al in a homogeneous background from $\sim 3\ M_\odot$ to $\sim 1\ M_\odot$ (Diehl et al. 1995). Such a reduction may possibly provide an upper limit to the amount of ^{26}Al produced by ONeMg novae in the Galaxy of $\sim 1\ M_\odot$ (this assumes that ONeMg novae are not associated with the localized emissions, and this is not clear, since ONeMg novae are expected to be from a young population). If such an upper limit is valid, it would provide further constraints on α and on the production of cataclysmic variables with ONeMg white dwarfs (see Kolb & Politano 1995).

4.4. ^{22}Na *Production in* ONeMg *Novae*

^{22}Na has a half-life of 2.6 yr. Its decay to ^{22}Ne produces a γ-ray with an energy of 1.275 MeV. Weiss & Truran (1990) estimated, on the basis of their nucleosynthesis studies, that nearby (~ 1 kpc) novae involving ONeMg white dwarfs may be able to produce ^{22}Na decay γ-rays at flux levels which are detectable with the *Compton Gamma Ray Observatory* (*CGRO*). Starrfield et al. (1992b), on the basis of the simulations presented in this paper, also reached this conclusion and predicted that ^{22}Na γ-ray emission from the ejecta of V838 Her 1991 should be detectable with the *CGRO*.

The flux of γ-rays from the decay of ^{22}Na may be calculated as

$$F_{\gamma, {}^{22}\mathrm{Na}} = 4 \times 10^{-5}(M_{\mathrm{ej}}/10^{-5}\ M_{\odot})(X_{{}^{22}\mathrm{Na}}/10^{-3}) \times (D/\mathrm{kpc})^{-2} e^{-t/3.75\,\mathrm{yr}}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ , \quad (7)$$

where M_{ej} is the mass of the ejecta, $X_{{}^{22}\mathrm{Na}}$ is the mass fraction of ^{22}Na in the ejecta, D is the distance to the nova in kiloparsecs, and 3.75 yr is the mean lifetime of ^{22}Na. The 3 σ line sensitivity for the *CGRO* is approximately 10^{-4} cm^{-2} s^{-1} (OSSE) and 6×10^{-5} cm^{-2} s^{-1} (COMPTEL).

Assuming that all the accreted material is eventually ejected, and assuming that the nova is nearby ($D \sim 1$ kpc), we can use equation (7) to estimate the peak flux of ^{22}Na γ-rays expected from each mass sequence, using the ^{22}Na mass fractions for each sequence in Table 3. These peak flux values are 3×10^{-4} cm^{-2} s^{-1} for the 1.35 $M_{\odot}$ sequence, 10^{-4} cm^{-2} s^{-1} for the 1.25 $M_{\odot}$ sequence, and 2×10^{-5} cm^{-2} s^{-1} for the 1.00 $M_{\odot}$ sequence. Although the ejected envelope will not immediately be transparent to γ-rays, the time it takes for this to happen (typically, a few weeks) is short compared to the mean lifetime of ^{22}Na, and thus the peak values are not significantly reduced.

For the initial conditions we have assumed for these sequences, our simulations indicate that nearby nova outbursts occurring on ONeMg white dwarfs with masses greater than $\sim 1.25\ M_{\odot}$ should produce ^{22}Na γ-rays at flux levels that are detectable with the *CGRO*. However, we expect that the amount of ^{22}Na produced in the outbursts will also depend on the initial amount of ONeMg enrichment in the accreted material and on the accretion rate. Thus, the detection limit may be reached for a white dwarf mass which is higher or lower than 1.25 $M_{\odot}$ for other choices of these parameters. We investigate this in subsequent papers in this series (Politano et al. 1995).

We note that Starrfield et al. (1992b) based their prediction for V838 Her 1991 on our 1.35 $M_{\odot}$ sequence. The extremely rapid decline of this nova, as well the enhanced sulfur and depleted oxygen in its ejecta, suggest that the mass of the white dwarf is very high, although see Szkody & Ingram (1994).

4.5. *The Spatial Distribution of Neon Novae and Nova Speed Class*

Scrutiny of the distribution of classical novae throughout the Galaxy reveals that fast novae are concentrated at low Galactic latitudes (only one fast nova with $\| b \| > 25°$; Warner 1989). Both semianalytical studies (e.g., MacDonald 1983; Fujimoto 1982) and detailed model calculations (Starrfield, Sparks, & Truran 1985, 1986) have indicated that fast novae require massive white dwarfs. Massive white dwarfs, and particularly ONeMg white dwarfs, have evolved from higher mass stars which are more likely to be found among a younger stellar population, such as the Galactic disk population. This, then, provides a reasonable, possible explanation for the concentration of fast novae within the Galactic disk.

Where do the neon novae fit into this picture? Of the seven known Galactic neon novae, three are very fast (V1500 Cyg, $t_3 = 4$ days; V838 Her 1991, $t_3 = 5$ days; V693 CrA, $t_3 = 12$ days), three are moderately fast (Nova Pup 1991, $t_3 = 30$ days; QU Vul, $t_3 = 40$ days; V1974 Cyg 1992, $t_3 = 40$ days), and the speed class for the remaining one (V1370 Aql) is unknown. Furthermore, this population of novae is more tightly concentrated toward the plane of the Galaxy than fast novae in general. All are found within 15° of the Galactic plane: $b = -0\overset{\circ}{.}07$ (V1500 Cyg), $-0\overset{\circ}{.}73$ (Nova Pup 1991), $-5\overset{\circ}{.}95$ (V1370 Aql), $-6\overset{\circ}{.}03$ (QU Vul), $+6\overset{\circ}{.}62$ (V838 Her) $+7\overset{\circ}{.}74$ (V1974 Cyg), and $-14\overset{\circ}{.}39$ (V693 CrA). Although we are clearly dealing with small number statistics, it is nonetheless relevant to note that these data are consistent with the view that ONeMg novae involve very massive white dwarfs. In fact, they support the hypothesis that neon novae contain ONeMg white dwarfs: (1) ONeMg white dwarfs are expected to evolve from stars in the 8–13 $M_{\odot}$ range (e.g., Nomoto & Hashimoto 1986), which are presumably the most massive stars capable of evolving into white dwarfs; one might thus expect that the Galactic distribution of ONeMg novae would be even more tightly concentrated toward the Galactic plane than fast novae showing only CNO element enhancements. (2) ONeMg white dwarfs are the most massive, stable white dwarfs capable of being formed; if there is a correlation of speed class with white dwarf mass, it therefore follows that ONeMg novae should be among the fastest. However, it must also be noted that speed class in novae is not solely dependent upon white dwarf mass, but it is also dependent on the level of heavy element enrichment of the envelope and on the accretion rate.

We see that three neon novae are "slower" than the rest of the group—QU Vul, V1974 Cyg 1992, and Nova Pup 1991. Observational estimates of the ejected mass in the first two novae ($> 10^{-4}\ M_{\odot}$) are higher than predicted by theory. If the mass of the white dwarf in a nova system is reduced as a result of the outburst, then one should expect to see a fraction of ONeMg novae occurring on white dwarfs with masses below 1.1 $M_{\odot}$, the estimated lower limit at birth. A possibility, then, is that what we are seeing in these "slower" neon novae are cases where the white dwarf mass has been significantly reduced over values typical for new ONeMg white dwarfs, as a result of erosion of core material by the nova explosion. Even in light of this, there is a significant discrepancy between observations and theory on the amount of mass ejected by some neon novae.

4.6. ONeMg *Novae versus Recurrent Novae*

The question of massive white dwarfs in classical novae prompts us to comment briefly on thermonuclear models for the recurrent novae. In order to explain the very short recurrence times characteristic of these systems, recurrent novae, for which a thermonuclear runaway is proposed as the outburst mechanism, must necessarily occur on white dwarfs whose masses are very near to the Chandrasekhar limit. Consequently, thermonuclear-powered recurrent novae should also occur on ONeMg white dwarfs. However, in contrast to ONeMg novae, recurrent novae show no firm evidence of significant heavy element enrichments in their ejecta (Webbink et al. 1987; Selvelli, Cassatella, & Gilmozzi 1992). An obvious possible explanation for this difference is simply that material from the underlying white dwarf is not mixed with accreted material from the donor star in the case of recurrent novae. Theoretical studies of thermonuclear models for recurrent novae are consistent with this view. Starrfield et al. (1985, 1988) reproduced the essential features of the light curve as well as the outburst recurrence time for the recurrent nova, U Sco, by accreting material of solar composition onto a 1.38 $M_\odot$ white dwarf at a high accretion rate (1.7×10^{-8} $M_\odot$ yr^{-1}), and assuming that no mixing occurred with the white dwarf material. Since it appears likely that material from the underlying white dwarf is dredged up as a result of accretion in ONeMg novae, and since it appears equally likely that mixing does not occur in recurrent novae (or is at least greatly reduced), even though the outbursts in both classes presumably occur on ONeMg white dwarfs, the interesting question arises as to what is the cause of this difference.

Perhaps the most likely candidate is the accretion rate. The accretion rate in recurrent novae must necessarily be high in order to produce outburst recurrence times on the order of decades, as are typical of these systems. The accretion rate used by Starrfield et al. (1985) to model U Sco was 10 times higher than the accretion rate we have used here to model classical nova outbursts on ONeMg white dwarfs. This may reduce the effectiveness of the mixing process (whatever it may be) between the accreted material and the white dwarf material (see, e.g., the review discussion by Livio & Truran 1990). To the extent that the high accretion rate used by Starrfield et al. (1985) in modeling recurrent novae is atypical of accretion rates in classical nova models, the difference in accretion rates may provide a natural distinction between the mixing behavior in the two classes of novae. Comparison of the characteristics of ONeMg novae and recurrent novae may therefore be expected to impose quite stringent constraints on the mixing mechanisms.

5. CONCLUSIONS

In this paper, we have reported on simulations of nova outbursts on ONeMg white dwarfs using a hydrodynamic code which is coupled, for the first time, to a nuclear reaction network capable of following the abundances of intermediate-mass elements, and we have specifically examined how the outburst depends on the mass of the white dwarf. To this end, we may summarize some of our key findings as follows:

1. As we have noted in the Introduction, the presence of substantial abundance enrichments of elements such as neon, magnesium, and sulfur in the ejecta of certain novae strongly suggests that the outbursts in those systems occurred on ONeMg white dwarfs in which material from the white dwarf was mixed into the accreted envelope. The calculations we have presented here, which have attempted to model the consequences of this mixing scenario, have successfully reproduced the typical outburst energetics and the compositions characteristic of the ejecta of ONeMg novae. They, therefore, provide further support for the hypothesis that material from the underlying white dwarf is indeed (somehow) dredged up during the accretion process.

2. Similar to the trend found for CO white dwarfs (Starrfield et al. 1974b), outbursts on ONeMg white dwarfs increase in violence as the mass of the white dwarf is increased. A peak temperature in excess of 350×10^6 K was reached in our 1.35 $M_\odot$ sequence, thus allowing significant nucleosynthesis of intermediate-mass elements to occur.

3. A dominant trend among the ejecta abundances in our models is the increase in the mass fractions of the heavier nuclei with increasing white dwarf mass. Table 3 shows the dramatic increase in the abundances of elements such as Na, Si, P, S, Cl, and Ar as the mass of the white dwarf is increased. Significant overabundances of these elements in the ejecta of a neon nova may, therefore, support the conclusion that the outburst took place on a very massive (~ 1.35 $M_\odot$) white dwarf.

4. We find that nova outbursts which occur in white dwarf envelopes that have been enriched in oxygen, neon, and magnesium are an important source of ^{26}Al in the Galaxy, and should produce detectable emission of ^{22}Na γ-rays in certain cases, confirming the conclusions reached by Weiss & Truran (1990) and Nofar et al. (1991), based on their one-zone nucleosynthesis calculations.

5. We predict that a nova outburst which occurs on an ONeMg white dwarf of mass ~ 1.25 $M_\odot$ or greater and which occurs at a distance of less than ~ 1 kpc can produce γ-ray emissions which are detectable with the *CGRO*. This prediction is in substantial agreement with the conclusion reached by Weiss & Truran (1990).

6. We further estimate that a minimum mass of 1.2 $M_\odot$ for ONeMg white dwarfs in binaries is needed in order for nova outbursts to produce the estimated 3 $M_\odot$ of ^{26}Al required to explain the γ-ray line emissions observed by Mahoney et al. (1984). We emphasize, however, that this estimate is based on the particular initial conditions we have chosen for this sequence of models, and on the assumption that the production of cataclysmic variables with ONeMg white dwarfs is not significantly less than that assumed for CO white dwarfs in the same mass range.

We wish to thank S. Shore, G. Sonneborn, and P. Szkody for useful discussions concerning this paper. One of us (M. P.) wishes to thank J. Chapyak, J. Hills, W. Zurek, and C. Keller for their hospitality and visitor support while at Los Alamos. We also thank an anonymous referee for a careful reading of our paper and for useful criticism. This research was supported in part by NSF grants AST 89-17442, AST 92-17969, and AST 93-96039 to the University of Chicago, and AST 88-19215 and AST 91-14917 to Arizona State University, by National Aeronautics and Space Administration grant NAGW 2628 to Arizona State University, by *Compton Gamma Ray Observatory* grant NAG 5-2081 to the University of Chicago, and by a Laboratory Directed Research and Development grant at Los Alamos National Laboratory.

REFERENCES

Andreae, J., & Drechsel, H. 1990, in IAU Coll. 122, The Physics of Classical Novae, ed. A. Cassatella & R. Viotti (Berlin: Springer), 204
Arnett, W. D., & Truran, J. W. 1969, ApJ, 157, 339
Caughlin, G. R., & Fowler, W. C. 1988, Atomic Data Nucl. Data Tables, 40, 283
Ciardullo, R., Ford, H. C., Neill, J. D., Jacoby, G. H., & Shafter, A. W. 1987, ApJ, 318, 520
Cowan, J. J., Thielemann, F.-K., & Truran, J. W. 1991, Phys. Rep., 208, 267
Cox, A. N., & Stewart, J. N. 1970a, ApJS, 19, 243
———. 1970b, ApJS, 19, 261

Diehl, R., Dupraz, C., Bennett, K., Bloemen, H., Hermsen, W., Knödlseder, J., Lichti, G., Morris, D., Ryan, J., Schönfelder, V., Steinle, H., Strong, A., Swanenburg, B., Varendorff, M., & Winkler, C. 1995, A&A, in press
Ferland, G. J., & Shields, G. A. 1978, ApJ, 226, 172
Fujimoto, M. Y. 1982, ApJ, 257, 767
Gallagher, J. S., Hege, E. K., Kopriva, D. A., Williams, R. E., & Butcher, H. R. 1980, ApJ, 237, 55
Greenhouse, M. A., Grasdalen, G. L., Hayward, T. L., Gehrz, R. D., & Jones, T. J. 1988, AJ, 95, 172
Hamada, T., & Salpeter, E. E. 1961, ApJ, 134, 683
Hassal, B. J. M., et al. 1990, in IAU Coll. 122, The Physics of Classical Novae, ed. A. Cassatella & R. Viotti (Berlin: Springer), 202
Hauschildt, P. H., Starrfield, S., Shore, S. N., Gonzalez-Riestra, R., Sonneborn, G., & Allard, F. 1994, AJ, 108, 1008
Iben, I., Jr. 1975, ApJ, 196, 525
Iben, I., Jr., & Tutukov, A. V. 1985, ApJS, 58, 661
Iglesias, C. A., Rogers, F. J., & Wilson, B. G. 1992, ApJ, 397, 717
Kolb, U. 1993, in Cataclysmic Variables and Related Physics, Annals of the Israel Physical Society, ed. O. Regev & G. Shaviv (Bristol: Institute of Physics), 294
Kolb, U., & Politano. M. 1995, in preparation
Kutter, G. S., & Sparks, W. M. 1972, ApJ, 175, 407
Law, W. Y., & Ritter, H. 1983, A&A, 123, 33
Livio, M., Shankar, A., Burkert, A., & Truran, J. W. 1990, ApJ, 356, 250
Livio, M., & Truran, J. W. 1990, in Ann. NY Acad. Sci. No. 617, Nonlinear Astrophysical Fluid Dynamics, ed. J. R. Buchler & S. T. Gottesman (New York: New York Academy of Sciences), 136
———. 1994, ApJ, 425, 797
MacDonald, J. 1980, MNRAS, 191, 933
———. 1983, ApJ, 267, 732
Mahoney, W. A., Ling, J. C., Wheaton, W. A., & Jacobson, A. S. 1984, ApJ, 286, 578
Matheson, T., Filippenko, A. V., & Ho, C. 1993, ApJ, 418, L29
Murai, T., Sugimoto, D., Hoshi, R., & Hayashi, C. 1968, Prog. Theor. Phys. 39, 619
Nofar, I., Shaviv, G., & Starrfield, S. 1991, ApJ, 369, 440
Nomoto, K., & Hashimoto, M. 1986, Prog. Part. Nucl. Phys., 17, 267
———. 1987, Ap&SS, 131, 395
Politano, M. 1988, Ph.D. thesis, University of Illinois
———. 1990, in Accretion-Powered Compact Binaries, ed. C. W. Mauche (Cambridge: Cambridge Univ. Press), 421
———. 1995, in preparation
Politano, M., Starrfield, S., Truran, J. W., & Sparks, W. M. 1995, in preparation
Ritter, H., Politano, M., Livio, M., & Webbink, R. F. 1991, ApJ, 376, 177
Saizar, P., Starrfield, S., Ferland, G. J., Wagner, R. M., Truran, J. W., Kenyon, S. J., Sparks, W. M., Williams, R. E., & Stryker, L. L. 1991, ApJ, 367, 310
———. 1992, ApJ, 398, 531
Selvelli, P. L., Cassatella, A., & Gilmozzi, R. 1992, ApJ, 393, 289
Shankar, A., Livio, M., & Truran, J. W. 1991, ApJ, 374, 693
Shore, S. N., Sonneborn, G., Starrfield, S., Gonzalez-Riestra, R., & Ake, T. B. 1993, AJ, 106, 2408
Snijders, M. A. J., Batt, T. J., Roche, P. F., Seaton, M. J., Morton, D. C., Spoelstra, T. A. T., & Blades, J. C. 1987, MNRAS, 228, 329
Snijders, M. A. J., Batt, T. J., Seaton, M. J., Blades, J. C., & Morton, D. C. 1984, MNRAS, 211, 7
Starrfield, S. 1989, in The Classical Nova, ed. N. Evans & M. Bode (New York: Wiley), 39
Starrfield, S., Politano, M., Sparks, W. M., & Truran, J. W. 1992a, in Second GRO Science Conf., ed. C. Shrader, N. Gehrels, & B. Dennis (NASA CP 3137), 377
Starrfield, S., Shore, S. N., Sparks, W. M., Sonneborn, G., Truran, J. W., & Politano, M. 1992b, ApJ, 391, L71
Starrfield, S., & Sparks, W. M. 1987, Ap&SS, 131, 379
Starrfield, S., Sparks, W. M., & Shaviv, G. 1988, ApJ, 325, L35
Starrfield, S., Sparks, W. M., & Truran, J. W. 1974a, ApJS, 28, 247
———. 1974b, ApJ, 192, 647
———. 1985, ApJ, 291, 136
———. 1986, ApJ, 303, L5
Starrfield, S., Truran, J. W., & Sparks, W. M. 1978, ApJ, 226, 186
Stickland, D. J., Penn, C. J., Seaton, M. J., Snijders, M. A. J., & Storey, P. J. 1981, MNRAS, 197, 107
Szkody, P., & Ingram, D. 1994, ApJ, 420, 830
Taylor, A. R., Seaquist, E. R., Hollis, J. M., & Pottasch, S. R. 1987, A&A, 183, 38
Thielemann, F.-K., Arnould, M., & Truran, J. W. 1987, in Advances in Nuclear Astrophysics, ed. E. Vangioni-Flam (Gif-sur-Yvette: Editions Frontières), 525
———. 1988, in Capture Gamma-Ray Spectroscopy, ed. K. Abrahams & P. Van Assche (Bristol: IOP), 730
Truran, J. W. 1982, in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Clayton, & D. N. Schramm (Cambridge: Cambridge Univ. Press), 467
———. 1990, in The Physics of Classical Novae, ed. A. Cassatella & R. Viotti (Berlin: Springer), 373
Truran, J. W., & Livio, M. 1986, ApJ, 308, 721
Tylenda, R. 1978, Acta Astron., 28, 333
Vanlandingham, K., et al. 1995, in preparation
Warner, B. 1989, in The Classical Nova, ed. N. Evans & M. Bode (New York: Wiley), 1
Webbink, R. F., Livio, M., Truran, J. W., & Orio, M. 1987, ApJ, 314, 653
Weiss, A., & Truran, J. W. 1990, A&A, 238, 178
Williams, R. E., & Gallagher, J. S. 1979, ApJ, 228, 482
Williams, R. E., Ney, E. P., Sparks, W. M., Starrfield, S. G., Wyckoff, S., & Truran, J. W. 1985, MNRAS, 212, 753
Williams, R. E., Woolf, N. J., Hege, E. K., Moore, R. L., & Kopriva, D. A. 1978, ApJ, 224, 171