NUCLEAR THERMOMETERS FOR CLASSICAL NOVAE

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ABSTRACT

Classical novae are stellar explosions occurring in binary systems, consisting of a white dwarf and a main-sequence companion. Thermonuclear runaways on the surface of massive white dwarfs, consisting of oxygen and neon, are believed to reach peak temperatures of several hundred million kelvin. These temperatures are strongly correlated with the underlying white dwarf mass. The observational counterparts of such models are likely associated with outbursts that show strong spectral lines of neon in their shells (neon novae). The goals of this work are to investigate how useful elemental abundances are for constraining the peak temperatures achieved during these outbursts and determine how robust “nova thermometers” are with respect to uncertain nuclear physics input. We present updated observed abundances in neon novae and perform a series of hydrodynamic simulations for several white dwarf masses. We find that the most useful thermometers, N/O, N/Al, O/S, S/Al, O/Na, Na/Al, O/P, and P/Al, are those with the steepest monotonic dependence on peak temperature. The sensitivity of these thermometers to thermonuclear reaction rate variations is explored using post-processing nucleosynthesis simulations. The ratios N/O, N/Al, O/Na, and Na/Al are robust, meaning they are minimally affected by uncertain rates. However, their dependence on peak temperature is relatively weak. The ratios O/S, S/Al, O/P, and P/Al reveal strong dependences on temperature and the poorly known $^{30}$P($p, \gamma$)$^{31}$S rate. We compare our model predictions to neon nova observations and obtain the following estimates for the underlying white dwarf masses: $1.34–1.35 \ M_\odot$ (V838 Her), $1.18–1.21 \ M_\odot$ (V382 Vel), $\leq 1.3 \ M_\odot$ (V693 CrA), $\leq 1.2 \ M_\odot$ (LMC 1990#1), and $\leq 1.2 \ M_\odot$ (QU Vul).

Key words: novae, cataclysmic variables – nuclear reactions, nucleosynthesis, abundances – stars: abundances

Online-only material: color figures

1 INTRODUCTION

Classical novae are stellar explosions occurring in binary systems consisting of a white dwarf and a close companion star (Bode & Evans 2008). When the stellar companion expands beyond its Roche lobe, a mass transfer episode ensues. This matter possesses angular momentum due to the system’s rotation and forms an accretion disk, falling onto the surface of the white dwarf. At some point, matter from the underlying white dwarf is mixed with the accreted material, and this mixture is heated and compressed until a thermonuclear runaway takes place, ejecting matter into the interstellar medium. The ejected material consists of a mixture of white dwarf and accreted materials that has been processed by explosive hydrogen burning (Starrfield et al. 2008; Shara et al. 2010; Yaron et al. 2005, and references therein). Spectroscopic studies have identified two distinct white dwarf compositions, carbon–oxygen (CO) and oxygen–neon (ONe). Nova shells rich in CNO material point to an underlying CO white dwarf, which represents the evolutionary fate of a low-mass star after core helium burning. On the other hand, element enrichments6 in the range of Ne to Ar have been attributed to underlying, massive ONe white dwarfs ($M_{WD} \gtrsim 1.1 \ M_\odot$), representing the evolutionary fate of stars ($M \approx 9–11 \ M_\odot$) after completion of core carbon burning (Althaus et al. 2010, and references therein). The latter explosions, which are often referred to as neon novae, tend to be much more energetic than CO novae (Starrfield et al. 1986) and are the main interest of the present work.

The study of classical novae is of significant interest for several reasons. Spectroscopic studies, after proper interpretation, constrain stellar evolutionary models by revealing the composition of the underlying white dwarf. Observed elemental abundances also provide a record of the thermonuclear runaway, including peak temperatures and expansion timescales, and have been used to constrain stellar explosion models (Starrfield et al. 2000). Classical novae are noteworthy contributors to the chemical evolution of the Galaxy because they are major sources of $^{13}$C, $^{15}$N, and $^{17}$O (Kovetz & Prihalov 1997; José & Hernanz 1998; José et al. 2006; Starrfield et al. 2008). Significant efforts have been undertaken to detect $\gamma$-rays from novae as well. Although no nuclear $\gamma$-rays from classical novae have been observed by any satellite observatory (Hernanz 2008), it has been proposed that $\gamma$-rays should be present in these novae due to the decay of radioactive $^{18}$F.

Although theoretical models of classical novae are successful in reproducing the overall characteristics of the observed outbursts, several key issues remain unexplained and call for improved observations, simulations, and nuclear laboratory measurements. First, the masses of ONe white dwarfs are poorly constrained by observations. Models of intermediate-mass stars predict values in the range of $\sim 1.1–1.4 \ M_\odot$ (see discussion in Doherty et al. 2010). Clearly, accurate white dwarf mass determinations are highly desirable. Second, hydrodynamic simulations undervalue the observed ejecta masses by an order of magnitude or more (Starrfield et al. 2008). Third, although it is sometimes claimed in the literature that theoretical models more...
influenced by reaction cycles at $^{23}$Na, $^{27}$Al, $^{31}$P, and $^{35}$Cl (Iliadis et al. 2010a, 2010b, 2010c), obtained from a Monte Carlo sampling of experimental nuclear physics observables, and provides for the first time statistically meaningful reaction rates and associated uncertainties.

In Section 2, we present updated observed abundances in neon nova shells. It will become clear that it is advantageous to focus the discussion on elemental abundance ratios rather than the abundance of one element. Our methods and results are presented in Sections 3 and 4, respectively. First, we computed four new hydrodynamic models of classical novae, with peak temperatures in the range of 228–313 MK. The subset of elemental abundance ratios revealing the steepest dependence on peak temperature, that is, with the promise of potential use as a thermometer, was considered for further inspection. Then, suitable post-processing calculations were performed, demonstrating that the final predicted elemental abundances approximately agree with those from the self-consistent hydrodynamic model. In a final step, many post-processing network calculations were performed by varying one reaction rate at a time within its current uncertainty. The impact of this sensitivity study on potential classical nova thermometers was then investigated. Our results are compared to observations in Section 5. A summary and conclusions are given in Section 6.

2. OBSERVED ABUNDANCES

Before discussing our new simulations, we will summarize the abundances observed in neon nova shells. Compilations of classical nova abundances (expressed as mass fractions) can be found, for example, in Gehrz et al. (1998), Starrfield et al. (1998), and Wanajo et al. (1999). First, these compilations reveal that in several cases, even for identical events, different authors report rather different elemental abundances, with differences amounting up to an order of magnitude for some elements. Second, no uncertainties are provided with the listed abundances, making it difficult to assess the significance of a given element observation. Third, some of the compilations provide only the mass fraction sum for elements between Ne and Fe. As will become apparent later, when modeling neon novae the individual observed abundances of intermediate-mass elements (Ne, Mg, Al, Si, and S) are extremely important. Fourth, for several novae listed in the above compilations, the mass fraction sum differs significantly from unity, reflecting errors in the reported values. Since all of these reasons could contribute to the mistaken impression that reported nova abundances are highly uncertain and scatter widely, we felt compelled to present updated abundances.

It is difficult to determine reliable abundances from observed nova ejecta. For example, the derived abundances are model dependent since most analyses assume spherical shells although there is evidence that the ejecta are not spherically symmetric (Casanova et al. 2011). Furthermore, the ejecta are potentially chemically inhomogeneous, adding substantially to the complexity of the problem. Also, the filling fraction (i.e., the fraction of the shell volume occupied by gas) is poorly constrained. Finally, the abundance analysis must account for the (sometimes substantial) fraction of unobserved ionization states. These and other difficulties have been discussed in more detail by José & Shore (2008).

In the past different authors have used different procedures in the analysis of optical, infrared, and ultraviolet spectra.

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7 The operation of the $^{22}$Na($p$, $\alpha$)$^{20}$Ne reaction also contributes to the survival of $^{20}$Ne.
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### Table 1

| LMC 1990#1 | V4160 Sgr#2 | V838 Her#2 | V382 Vel#3 | QU Vul#4 | V693 Cta#5 | V1974 Cyg#6 | V1085 Cen#7 | Solar#8 |
|-------------|-------------|------------|------------|---------|-----------|------------|------------|--------|
| X_{He}/X_H  | 4.8(8)E-01  | 7.1(4)E-01 | 5.6(4)E-01 | 4.0(4)E-01 | 4.6(3)E-01 | 5.4(22)E-01 | 4.8(8)E-01 | 5.4(10)E-01 | 3.85E-01 |
| X_C/X_H     | 3.7(15)E-02 | 1.43(7)E-02 | 2.28(23)E-02 | 2.6(13)E-03 | 9.5(9)E-04 | 1.06(44)E-02 | 3.1(9)E-02 | 3.1(9)E-03 | 3.31E-03 |
| X_S/X_H     | 1.48(42)E-01 | 1.27(8)E-01 | 3.29(47)E-02 | 2.28(54)E-02 | 1.61(10)E-02 | 1.84(67)E-01 | 6.0(15)E-02 | 1.40(33)E-01 | 1.14E-03 |
| X_O/X_H     | 2.8(10)E-01 | 1.35(9)E-01 | 1.42(36)E-02 | 4.13(38)E-02 | 3.2(14)E-02 | 1.63(60)E-01 | 1.55(85)E-01 | 4.7(15)E-01 | 9.65E-03 |
| X_Na/X_H    | 1.61(10)E-01 | 1.38(5)E-01 | 1.22(5)E-01 | 4.0(7)E-02 | 5.1(4)E-02 | 6.7(3)E-01 | 9.7(40)E-02 | 5.34(98)E-01 | 2.54E-03 |
| X_Mg/X_H    | 1.37(7)E-02 | 8.4E-03 | 1.2(7)E-03 | 2.45(14)E-03 | 1.02(49)E-02 | 9.7E-03 | 4.3(28)E-03 | 4.4(13)E-03 | 9.55E-04 |
| X_Si/X_H    | 2.3(11)E-02 | 1.8(13)E-03 | 1.63(16)E-03 | 4.1(11)E-03 | 5.0(46)E-03 | >7.8E-05 | ... | ... | 8.74E-05 |
| X_S/X_H     | 4.8(39)E-02 | 1.09(6)E-02 | 7(2)E-03 | 5(3)E-04 | 2.4(18)E-03 | 2.4(18)E-02 | ... | ... | 1.08E-03 |
| X_Fe/X_H    | ... | 1.48(15)E-02 | ... | ... | ... | ... | 2.3(13)E-02 | 5.17E-04 |
| X_C/X_H     | ... | ... | ... | ... | 4.0(3)E-05 | ... | 4.6(17)E-03 | 1.29E-04 |
| X_Fe/X_H    | 2.4(8)E-03 | 2.35(63)E-03 | ... | 9.53(54)E-04 | ... | 8.8(72)E-03 | 1.16(40)E-02 | 1.81E-03 |
| X_N     | 4.7(9)E-01 | 4.65(37)E-01 | 5.63(36)E-01 | 6.64(6)E-01 | 6.3(3)E-01 | 3.81(40)E-01 | 5.5(8)E-01 | 3.6(10)E-01 | 7.11E-01 |

**Notes.** All abundances are given here in terms of mass fraction ratios, X_{el}/X_H (or mass fraction for hydrogen; see last row), by converting the “number abundances relative to hydrogen relative to solar” from the original literature (references provided below). The abundance uncertainties are given in parentheses.

1. From Vanlandingham et al. (1999).
2. From Schwarz et al. (2007).
3. From Shore et al. (2003).
4. From Schwarz (2002).
5. From Vanlandingham et al. (1997).
6. From Vanlandingham et al. (2005); solar abundances assumed in their analysis are not listed; their adopted values were log ([N/Fe]) = −1.0 (He), −3.45 (C), −4.03 (N), −3.53 (O), −3.93 (Ne), −4.42 (Mg), −5.53 (Al), −4.45 (Si), −4.79 (S), −4.49 (Fe) (K. M. Vanlandingham 2012, private communication).
7. From Helton et al. (2010).
8. From Lodders et al. (2009).
9. Calculated from X_{el} = [1 + X_{He}/X_H + X_{C}/X_H + ··· + X_{Fe}/X_H]^{-1}.

However, over the past 15 years many nova ejecta have been analyzed using consistent techniques, and the situation has improved significantly. In particular, we list all known neon novae in Table 1, with the exception of V1370 Aql and U Sco.9 For these eight neon novae listed, the abundances were analyzed using the photoionization code CLOUDY (Ferland 2003) coupled to the least-squares minimization code MINUIT, adopted from the CERN library. In this manner, the intensities of all spectral lines are determined together via successive iterations during the minimization, while in addition uncertainties of the line intensities can be quantified in a meaningful way.

Nova abundances are usually presented in the literature as “relative to hydrogen relative to solar,” i.e., the quantity

\[ \xi = \frac{(N_{el}/N_H)}{(N_{el}/N_H)_\odot}, \]

where[N_{el}] refers to the number abundance. However, the “solar” abundances have undergone significant revision over the past two decades (see discussion in José & Shore 2008), so observations were normalized to the solar abundances of Lodders et al. (2009). In order to compare the observations to our simulations (discussed below) in a meaningful way, we first calculated, from the values of \( \xi \) reported in the literature, the quantity \( N_{el}/N_H \) and, subsequently, converted the results to the elemental mass fraction ratio, \( X_{el}/X_H \). In some instances, the abundances presented in the literature had asymmetric uncertainties. For the sake of simplicity, the uncertainties in these cases were symmetrized by adopting the central value between the upper and lower bounds as the recommended value. The resulting mass fraction ratios for elements between He and Fe are listed in Table 1. The hydrogen mass fraction is then obtained from

\[ X_H = \left[ 1 + \frac{X_{He}}{X_H} + \frac{X_C}{X_H} + \cdots + \frac{X_{Fe}}{X_H} \right]^{-1} \]

and is listed in the last row.

The individual mass fractions can be easily calculated from the values of \( X_{el}/X_H \) and \( X_H \). Note, however, that the values of \( X_{el} \) derived in this manner are sensitive to the abundance fraction missed in the spectral line analysis, such as missing elements or unaccounted-for ionization states. The ratio \( X_{el}/X_H \) is expected to be less susceptible to systematic errors than \( X_{el} \); therefore, we focus in the following sections on mass fraction ratios rather than mass fractions.

Inspection of Table 1 reveals large overabundances relative to the solar \( X_{el}/X_H \) values, listed in the last column. For some neon novae, N, O, Ne, Mg, Al, Si, S9 and Ar are enriched by factors of 160, 50, 260, 50, 260, 40, 40, and 40, respectively. In the following sections, we will discuss the abundances predicted by models of neon novae.

### 3. METHOD

Our nuclear reaction network followed the evolution of 117 nuclides in the range from H to Ti through 635 nuclear processes, including weak interactions, reactions of type \((\beta, \gamma)\), \((\alpha, \beta)\), and \((\alpha, \alpha)\), with \( \alpha \) and \( \gamma \) as indicated. For example, a few abundances, such as O and Ne, are discussed in Mason (2011).
(α, γ), and their reverse reactions. The rates of these interactions are adopted from a next-generation library, called STARLIB (Iliadis et al. 2011). A detailed account of this library will be given in a forthcoming paper. In brief, STARLIB is a tabular library, listing the rates and corresponding uncertainties on a temperature grid between 1 MK and 10 GK for each nuclear interaction. For 62 of the nuclear reactions in the A = 14–40 mass range contained in STARLIB (among them most of the reactions important for nova nucleosynthesis), experimental rates are based on the 2010 Monte Carlo evaluation of thermonuclear reaction rates (Longland et al. 2010; Iliadis et al. 2010a, 2010b, 2010c). The Monte Carlo reaction rates and associated uncertainties are obtained from sampling randomly over uncertainties of (input) nuclear physics observables and are derived from the 0.16th, 0.50th, and 0.84th quantiles of the cumulative distribution of the (output) reaction rates (for a coverage probability of 68%). The information on rigorously defined reaction rate uncertainties was not available previously and opens interesting possibilities for nucleosynthesis studies.

We generated a series of new hydrodynamic models using the code SHIVA (José & Hernanz 1998) with reaction rates adopted from STARLIB. The different models were generated for a range of white dwarf masses (1.15–1.35 M⊙). Information on derived parameters of our models, specifically peak temperature (Tpeak), ejected mass (Mej), and initial white dwarf radius (RWD ini), is given in Table 2. Each model included 45 envelope zones. Test calculations performed with 500 zones provided essentially the same results. The peak temperatures achieved in the hottest zone in our simulations, ranging from 228 MK to 313 MK depending on the model, can be regarded as typical for models of thermonuclear runaways involving ONe white dwarfs (for models that achieve higher peak temperatures; see Starrfield et al. 2009). We assumed a mixing fraction of 50% between accreted matter of solar composition and white dwarf matter prior to the outburst. The solar abundances are adopted from Lodders et al. (2009), while the latter abundances are taken from the evolution of a 10 M⊙ star from the main sequence to the end of core carbon burning (Ritossa et al. 1996). The initial envelope composition for our nova simulations is presented in Table 3. 

Table 2: Properties of Evolutionary Nova Models

| Property | Model |
|----------|-------|
| Mej (M⊙) | J115  | 1.15 |
| Mej (M⊙) | J125  | 1.25 |
| Mej (M⊙) | J130  | 1.30 |
| Mej (M⊙) | J135  | 1.35 |
| RWD ini (km) | J115 | 4326 |
| RWD ini (km) | J125 | 3788 |
| RWD ini (km) | J130 | 3297 |
| RWD ini (km) | J135 | 2255 |

Table 3: Initial Envelope Composition (Mass Fractions) of Present Nova Simulations

| Isotope | Mass Fraction |
|---------|--------------|
| 1H      | 3.56E-01     |
| 3He     | 4.23E-05     |
| 4He     | 1.37E-01     |
| 6Li     | 3.44E-10     |
| 7Li     | 4.91E-09     |
| 8Be     | 7.51E-11     |
| 10B     | 5.05E-10     |
| 11B     | 2.26E-09     |
| 12C     | 5.74E-03     |
| 13C     | 1.42E-05     |
| 14N     | 4.04E-04     |
| 15N     | 1.59E-06     |
| 16O     | 2.59E-01     |
| 17O     | 1.37E-06     |
| 18O     | 7.72E-06     |
| 19F     | 2.08E-07     |
| 20Ne    | 1.57E-01     |
| 21Ne    | 2.99E-03     |
| 22Ne    | 2.22E-03     |
| 23Na    | 3.22E-02     |
| 24Mg    | 2.77E-02     |
| 25Mg    | 7.94E-03     |
| 26Mg    | 4.98E-03     |
| 27Al    | 5.43E-03     |
| 28Si    | 3.51E-04     |
| 29Si    | 1.85E-05     |
| 30Si    | 1.26E-05     |
| 31P     | 3.50E-06     |
| 32S     | 1.74E-04     |
| 33S     | 1.42E-06     |
| 34S     | 8.24E-06     |
| 35Cl    | 1.87E-06     |
| 37Cl    | 6.29E-07     |
| 38Ar    | 3.84E-05     |
| 39Ar    | 7.40E-06     |
| 39K     | 1.86E-05     |
| 40Ca    | 3.18E-05     |

Note. Values are obtained assuming 50% mixing of solar accreted matter with white dwarf material (see the text).
Figure 1. Comparison of final elemental abundances from a full hydrodynamic model to results from post-processing calculations. Abundance ratios are displayed vs. atomic number, Z. The nova model assumes accretion onto a 1.25 M⊙ ONe white dwarf (Table 2). The three panels are obtained for three different mixing assumptions in the post-processing calculations. Top panel: instant-mixing; middle panel: no-mixing; bottom panel: geometric mean of abundances from the top and middle panels. See the text for details. Elements of interest in this work are displayed in color. Note the good agreement between hydrodynamic and post-processing results in the bottom panel. Similar plots are obtained for all other nova models explored in this work.

(2002) and will be referred to as the “no-mixing approximation.” In the second case, the post-processing calculation is performed by replacing each local thermonuclear rate by its mass-weighted average over the convective region, implying that the turnover time is faster than the nuclear burning time. This assumption has been made, for example, by Prialnik (1986) in the framework of a hydrodynamic model and will be referred to in the following as the “instant-mixing approximation.” The actual behavior probably lies somewhere between these prescriptions. Therefore, a third set of elemental abundances was derived from the post-processing calculations, simply by computing the geometric mean of the abundances resulting from the no-mixing and instant-mixing approximations. Representative results are shown in Figure 1, comparing the final elemental abundances from a full hydrodynamic simulation with the three sets of final post-processing abundances described above. It is especially encouraging that the geometric mean abundance values seem to reproduce the stellar model elemental predictions rather well, especially for the elements of interest in this work.

More than 7000 multi-zone network calculations for all four classical nova hydrodynamic models were performed by independently varying the rates of 214 reactions, that is, the most important nuclear reactions in our network. For each reaction, the rates were multiplied by factors of 100, 10, 5, 2, 0.5, 0.2, 0.1, and 0.01 in successive network calculations. Final elemental abundances were adopted from the mixing prescription (instant-mixing, no-mixing, or geometric mean) that best approximated the results of a given hydrodynamic model using recommended reaction rates. Final elemental abundances are then linearly interpolated between the above variation factors to determine the impact of the actual reaction rate uncertainties, which were adopted from the STARLIB library.

4. RESULTS

We start with the results from our hydrodynamic simulations using the code SHIVA. Figure 2 displays the final elemental abundances, normalized to initial abundance adopted in the simulation, versus atomic number, Z, for all four nova models (see Table 2). It is apparent that certain elements are overproduced (N, Si, P, and S), while others are depleted (O, Na, Mg). We are particularly interested in final elemental abundances that show a steep dependence on peak temperature. We find that N, Na, P, and S monotonically increase with peak temperature while O and Al decrease. Note that F, Cl, and Ar also show strong trends, but their absolute predicted final abundances are very small (i.e., $10^{-7}$ to $10^{-5}$ by mass). Therefore, they were deemed

Figure 2. Final elemental abundances from all four hydrodynamic models explored in this work, normalized to initial abundances, vs. atomic number. Some elements are overproduced (N, Si, P, S), while others are underproduced (O, Na, Mg). Of interest here is the monotonic dependence of certain elements on the white dwarf mass or, equivalently, peak temperature, resulting in a color sequence of red, blue, green, black, or vice versa.

(2002) and will be referred to as the “no-mixing approximation.”

(A color version of this figure is available in the online journal.)
Infrared coronal lines from phosphorus, \[ P \], show a steep dependence on peak temperature, i.e., by at least an order of magnitude. These ratios are prime candidates for nova thermometers.

(A color version of this figure is available in the online journal.)

Figure 3. Ratios of eight elemental abundances (mass fractions), derived from hydrodynamic nova models, that show a steep and monotonic dependence on peak temperature, i.e., by at least an order of magnitude. These ratios are prime candidates for nova thermometers.

The sensitivity of the nova thermometers to the nuclear physics input is shown in Figure 4. Elemental abundance (mass fraction) ratios are displayed versus peak temperature, for the four nova models explored here (see Table 2). Shown on the left-hand side are abundance ratios involving elements that have been observed in neon nova shells (N, O, Al, S), and dashed lines denote ratios involving elements (Na, P) for which reliable abundances have not been reported in shells of classical novae yet.\(^\text{10}\) The elemental abundance ratios O/S (decreasing) and S/Al (increasing) display the strongest variation between peak temperatures of 228 MK and 313 MK, amounting to about three orders of magnitude. Following closely are the abundance ratios O/P (decreasing) and P/Al (increasing), which vary by more than two orders of magnitude. The other ratios shown in Figure 3 (O/Na, N/Al, N/O, Na/Al) show variations by about one order of magnitude. The next step was to investigate how robust these element ratios are with regard to thermonuclear reaction rate variations.

The dashed lines in each panel of Figure 4 display the change of predicted elemental abundance (mass fraction) ratios caused by varying individual reaction rates within their uncertainties (defined by a coverage probability of 68%; see Longland et al. 2010; Iliadis et al. 2010c). Interestingly, four of the thermometers (N/O, N/Al, O/Na, and Na/Al) reveal rather robust abundance ratios, with an uncertainty of less than 30%. Consequently, these ratios represent currently useful nova thermometers, without the immediate need for improved nuclear laboratory measurements. However, only the first two (N/O and N/Al) involve elements that have so far been observed in neon nova shells. The last two involve sodium, which has been searched for in infrared spectra but not yet detected (S. N. Shore 2012, private communication).

The use of the other four predicted elemental ratios (O/S, S/Al, O/P, and P/Al) as nova thermometers is somewhat limited. The first two of these ratios (O/S and S/Al) involve elements observed in neon nova shells (Table 1), while the other two ratios (O/P and P/Al) involve phosphorous, which has not been observed. Thus, our results call for improved observations and spectral analysis of neon nova ejecta (i.e., for phosphorous). These ratios are also uncertain by factors of 3–6, so future laboratory measurements of nuclear reactions would clearly improve their utility as nova thermometers. However, these four ratios also demonstrate the strongest temperature dependence of the potential thermometers, which mitigates the effect of reaction rate uncertainties. Therefore, the two currently observed ratios (O/S and S/Al), despite their large uncertainties, can be effectively used to narrow the range of white dwarf mass for a nova, as will be shown in Section 5 for V838 Her (Figure 6).

Detailed information on our results is provided in Table 4. The first four entries (N/O, N/Al, O/S, and S/Al) relate to nova thermometers involving elements observed in neon nova shells, while the last four involve sodium and phosphorous, which have not been observed. Column 2 lists the maximum range of a given elemental abundance ratio versus peak temperature from our post-processing analysis. Recall that the larger this value...
Figure 4. Eight ratios of elemental abundances (mass fractions), prime candidates for nova thermometers, that show a steep and monotonic dependence on peak temperature. Solid black and red lines correspond to element ratios obtained from our post-processing and hydrodynamic simulations, respectively. Dashed lines indicate the uncertainty bands obtained by independently varying all relevant nuclear reaction rates within their uncertainties. Broad uncertainty bands call for future laboratory measurements of nuclear reactions (Table 4). All ratios shown in the left column involve elements that have been observed in neon nova shells (see Table 1). All ratios shown in the right column involve elements (Na and P) that have not been observed in neon nova shells (see Table 1).

(i.e., the steeper the dependence on temperature), the more useful a ratio will be as a nova thermometer.

The next columns list the two reactions whose current rate uncertainties most significantly influence a given elemental abundance ratio. A number of important conclusions can be drawn from this information. First, the “second-most important reactions” (Columns 5 and 6) give rise to very small elemental abundance ratio variations (less than 30%), a number that is small compared to the uncertainty in observed elemental abundances (Table 1). Second, the nova thermometers O/S, S/Al, O/P, and P/Al, which have the steepest dependence on peak temperature (by factors of 220–540; see Column 2), also show the largest sensitivity to current reaction rate uncertainties (by factors of 3–6; see Column 4). Third, the latter four nova thermometers are mainly sensitive to current rate uncertainties of a single reaction, $^{30}\text{P}(p, \gamma)^{31}\text{S}$. This reaction involves a short-lived nuclide ($t_{1/2} = 2.498$ minutes) and has not been measured directly yet because a sufficiently intense $^{30}\text{P}$ beam is currently lacking. Indirect nuclear structure studies, in order to improve the reaction rate, have been reported (Doherty et al. 2012; Parikh et al. 2011; Wrede et al. 2009). At present, the spin and parity assignments for some of the important threshold states in the $^{31}\text{S}$ compound nucleus are ambiguous. In addition, none of the proton partial widths for these levels are known experimentally. Therefore, we did not estimate the rates using the Monte Carlo procedure described in Section 3. In the absence of more reliable information, we adopted the Hauser–Feshbach (statistical model) estimate of Rauscher & Thielemann (2000), assuming a factor of 10 uncertainty in the classical nova temperature range. Our adopted rates for this reaction agree within their uncertainties with those of Parikh et al. (2011), which were obtained using a different procedure.

The influence of the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ rate on the abundances in the mass region above Si has already been pointed out by José...
et al. (2001) and, more recently, by Parikh et al. (2011). We have quantified its impact on nova thermometers in the present work. Therefore, our results provide additional motivation for new laboratory measurements at radioactive ion beam facilities.

In general, two different techniques can be used to study the impact of reaction-rate variations on nucleosynthesis: variation of individual rates, as done in the present work, and simultaneous variation of all rates using a Monte Carlo approach. The advantage of the first method is that the impact of a specific reaction can be quantified in a straightforward manner, whereas the second technique allows for the influence of correlations between interactions in the network to be taken into account automatically. While our results indicate that primary sources of uncertainty, such as uncertainty in the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ rate, overwhelm the effects of any secondary source of uncertainty, we chose to verify our individual variation method. A recently implemented Monte Carlo reaction network, which included the instant-mixing and no-mixing approximations, was used to reproduce the nuclear thermometers and their uncertainties. This approach supports the results of individual reaction rate variation when correlation effects are taken into account, similar to the work of Parikh et al. (2008).

5. COMPARISON WITH OBSERVATION

We will now compare the abundances from our simulations with observations (Table 1). A first general impression can be obtained from the top panel of Figure 5, showing a three-element abundance plot involving N, O, and Al, i.e., N/O versus N/Al. Our model predictions are shown as thick and thin solid black lines (see Figure 4). As already discussed in Section 4, the simulated N/O and N/Al abundance ratios have relatively small uncertainties, which is reflected by the narrow region between the two thin solid lines. These abundance ratios represent useful thermometers since they are not significantly affected by current reaction rate uncertainties. The elements N, O, and Al have been simultaneously observed in five neon novae, according to Table 1, and their abundance ratios are displayed as data points. It is apparent that in this case the uncertainties in the observational data, with the exception of V382 Vel (green), far exceed those in the simulations. We conclude that the N/O and N/Al abundance ratios will become more useful thermometers for a number of novae when more reliable abundances can be determined from UV, IR, and optical spectra. A three-element abundance plot involving O, Al, and S, i.e., O/S versus S/Al, is shown in the bottom panel of Figure 5. We previously mentioned in Section 4 that the predicted O/S and S/Al abundance ratios have rather large uncertainties, which is reflected by the broad region between the two thin solid lines. These uncertainties originate from the poorly known $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate (Figure 4 and Table 4). Only for a single neon nova, V838 Her (blue), have all three elements been observed simultaneously (Table 1). It is apparent in this case that the observational uncertainties are relatively small compared to the stellar model results. We conclude that the O/S and S/Al abundance ratios will become more useful thermometers for neon novae when the $^{30}\text{P}(p, \gamma)^{31}\text{S}$ reaction rate can be determined experimentally and Al and S are simultaneously observed in additional novae.

A more detailed comparison between prediction and observation can be made by comparing observed abundance ratios to two or more corresponding nuclear thermometers. We are interested to find out if, for a given neon nova, the derived peak temperatures from two or more nuclear thermometers are in mutual agreement. Only nova V838 Her exhibits observed elemental abundance ratios corresponding to all four currently observable nuclear thermometers (N/O, N/Al, O/S, and S/Al), while observed abundance ratios corresponding to two nuclear thermometers (N/O and N/Al or N/O and O/S) are available for five other neon novae (Table 1). Thus, we are disregarding in the following discussion neon novae V4160 Sgr and V1974 Cyg, for which only a single nuclear thermometer (N/O) is available.
Nova V838 Her. Predicted and observed values for nova V838 Her are presented in Figure 6. The observed N/O and O/S abundance ratios strongly restrict the peak temperature to a range of $T_{\text{peak}} = 0.30-0.31$ GK, corresponding to a white dwarf mass of $M_{\text{WD}} = 1.34-1.35 M_\odot$. For this temperature range, the observed N/Al abundance ratio barely misses the predicted values, although it is clear that the uncertainty of the observed value is too large for the observation to be of any use. An improved estimate of the white dwarf mass range could be obtained by reducing the nuclear uncertainties in the O/S and S/Al thermometers.

Our above estimate supports the suggestion of Politano et al. (1995) that the white dwarf in this system “is very massive.” On the other hand, our estimate significantly exceeds the result of Wanajo et al. (1999), which suggests a value of $M_{\text{WD}} = 1.05 M_\odot$. Note that our simulations reproduce the observed abundance ratios in the narrow peak temperature range shown in Figure 6, although no “breakout” of matter from the CNO mass range to heavier masses has occurred in any of our nova models. Thus, we find no compelling evidence for a breakout in V838 Her, contrary to previous results (Schwarz et al. 2007).

Nova V382 Vel. The N/O and N/Al thermometers, which exhibit relatively small nuclear uncertainties, restrict the peak temperature to a narrow range of $T_{\text{peak}} = 0.23-0.24$ GK, corresponding to a white dwarf mass of $M_{\text{WD}} = 1.18-1.21 M_\odot$. For this relatively low peak temperature range, only a modest overproduction (factor 2) of sulfur is expected (Figure 2), consistent with its lack of observation in this neon nova.

Nova V693 CrA. The observed N/O and N/Al abundance ratios have relatively large uncertainties; consequently, the peak temperature is not well constrained. The best estimate, based on these two nuclear thermometers, results in an upper limit of $T_{\text{peak}} \leq 0.28$ GK, corresponding to a white dwarf mass of $M_{\text{WD}} \leq 1.3 M_\odot$. An improved estimate could be obtained with more reliable observed abundance ratios. Our result is significantly larger than that of Wanajo et al. (1999), who suggest a value of $M_{\text{WD}} = 1.05 M_\odot$.

Nova LMC 1990#1. The uncertainties of the observed N/O and N/Al elemental abundance ratios are too large to narrowly constrain the peak temperature range, and thus we only obtain an upper limit of $T_{\text{peak}} \leq 0.24$ GK, corresponding to a white dwarf mass of $M_{\text{WD}} \leq 1.2 M_\odot$. Improved observations would certainly result in a more reliable prediction.

Nova QU Vul. The observed N/O ratio hints at a low peak temperature. However, the observed N/Al abundance ratio is smaller than the predicted values over the entire peak temperature range explored in the present work. Therefore, we can only conclude that the peak temperature is $T_{\text{peak}} < 0.22$ GK, corresponding to a white dwarf mass of $M_{\text{WD}} < 1.2 M_\odot$. This value is near the lower limit for single ONe white dwarfs (Doherty et al. 2010). It also agrees with the suggestion of Wanajo et al. (1999), who report a range of $M_{\text{WD}} = 1.05-1.1 M_\odot$.

Nova V1065 Cen. In this case, observed N/O and O/S abundance ratios are available. However, no range of peak temperatures can be found that gives consistent results for these two nuclear thermometers.

The resulting peak temperature and white dwarf mass ranges for V838 Her, V382 Vel, V693 CrA, LMC 1990#1, and QU Vul are shown in Figure 7. Although these results are encouraging, it must be kept in mind that the present simulations are obtained for one particular choice of accretion rate, white dwarf luminosity, and mixing fraction between accreted and white dwarf matter. Evolutionary sequences for other choices of these parameters are in progress and will be presented in a forthcoming publication.

6. SUMMARY AND CONCLUSIONS

One goal of the present work was to investigate how useful elemental abundances are for determining the peak temperature, which is strongly correlated with the underlying white dwarf mass, achieved during neon nova outbursts. Another aim was to determine how robust such “nova thermometers” are with respect to currently uncertain nuclear physics input. To this end, we first presented updated observed abundances for several neon novae, and we performed new hydrodynamic simulations of neon novae, with peak temperatures in the range of 228–313 MK. We found that the most useful thermometers (i.e.,
those elemental abundance ratios with the steepest monotonic dependence on peak temperature) are N/O, N/Al, O/S, S/Al, O/Na, Na/Al, O/P, and P/Al. These vary by factors of 13, 6, 330, 530, 11, 7, 540, and 220, respectively, over the temperature range explored here (see Table 4).

Next, we investigated the sensitivity of these nova thermometers to thermonuclear reaction rate variations. The ratios N/O, N/Al, O/Na, and Na/Al are robust, in the sense that they are affected by uncertain reaction rates by less than 30%. At present, only the ratios N/O and N/Al are useful thermometers since these elements have been observed in neon nova (see Table 1). The last two ratios, O/Na and Na/Al, are not currently useful as sodium has not yet been detected in classical nova spectra. We also find that for these four elemental abundance ratios the dependence on peak temperature (factor variations of 6–13; Table 4) is not as strong as for some other ratios, mentioned below.

The thermometers O/S, S/Al, O/P, and P/Al reveal far steeper monotonic dependences on peak temperature, by factors of 220–540. However, their current drawback is the strong dependence on the uncertain $^{31}$S reaction rate. Thus, our study provides additional motivation for new laboratory measurements of this crucial nuclear reaction. In addition, the last two of these ratios, O/P and P/Al, involve phosphorus, another element for which reliable abundances have not yet been derived from classical nova spectra in outburst.

Finally, we compared our model predictions to elemental abundances observed in neon nova shells. Based on the present nuclear thermometers, we obtain the following estimates for the underlying ONe white dwarf masses: 1.34–1.35 $M_\odot$ (V838 Her), 1.18–1.21 $M_\odot$ (V382 Vel), $\leq 1.3 M_\odot$ (V693 CrA), $\leq 1.2 M_\odot$ (LMC 1990#1), and $\leq 1.2 M_\odot$ (QU Vul). Currently no white dwarf mass range based on elemental abundances can be derived for nova V1065 Cen. These predictions could be improved if more reliable abundances from the analysis of UV, IR, and optical spectra become available in the future. The present simulations were obtained for one particular choice of accretion rate, white dwarf luminosity, and mixing fraction between accreted and white dwarf matter. Evolutionary sequences for other choices of these parameters will be presented in a forthcoming publication.

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