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ON THE INTERPRETATION AND IMPLICATIONS OF NOVA ABUNDANCES: AN ABUNDANCE OF RICHES OR AN OVERABUNDANCE OF ENRICHMENTS

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ABSTRACT

We reexamine the question of the frequency of occurrence of oxygen-neon-magnesium (ONeMg) degenerate dwarfs in classical nova systems, in light of recent observations which have been interpreted as suggesting that "neon novae" can be associated with relatively low mass white dwarfs. Determinations of heavy-element concentrations in nova ejecta are reviewed, and possible interpretations of their origin are examined. We conclude that, of the 18 classical novae for which detailed abundance analyses are available, only two (or possibly three) seem unambiguously to demand the presence of an underlying ONeMg white dwarf: V693 CrA 1981, V1370 Aql 1982, and possibly QU Vul 1984. Three other novae which exhibit significant neon enrichments, relative to their total heavy-element concentrations, are RR Pic 1925, V977 Sco 1989, and LMC 1990 No. 1. This result is entirely consistent with present frequency estimates, and our interpretation of the lower levels of enrichment in other systems explains, in a natural way, the existence of relatively low mass white dwarfs in some of the "neon" novae.

Subject headings: novae, cataclysmic variables — stars: abundances — white dwarfs

1. INTRODUCTION

The outbursts of classical novae are now understood to result from the occurrences of thermonuclear runaways in accreted hydrogen-rich envelopes on the white dwarf components of close binary systems (see, e.g., the reviews by Truran 1982, Starrfield 1989; Livio 1993). In early discussions of this problem, it was generally assumed that the degenerate dwarf was a carbon-oxygen (CO) white dwarf. This was consistent with the finding that the nebular ejecta of many novae were enriched in carbon, nitrogen, and oxygen (see, e.g., the review of nova abundances by Truran 1990). The existence of a distinct subclass of the classical novae which are associated with an underlying oxygen-neon-magnesium (ONeMg) white dwarf, the possibility of which was first discussed by Law & Ritter (1983), is generally considered to have been confirmed by spectroscopic observations of Nova V693 CrA 1981 (Williams et al. 1985) and Nova V1370 Aql 1982 (Snijders et al. 1987). For both of these novae, analyses of the ultraviolet spectra revealed significant overabundances of the intermediate-mass nuclei neon, sodium, magnesium, aluminum, and silicon. Since it is generally believed that in situ nuclear processing associated with the outburst itself cannot explain such patterns of abundance enrichment, either of CNO or of ONeNaMgAl nuclei, it is assumed that the observed enrichments in these systems must arise from material that has been dredged up from the core of the underlying dwarf (see, e.g., the discussion by Truran & Livio 1986). It follows that the large ONeNaMgAl enrichments demand an underlying ONeMg white dwarf.

Recent observations have certainly *appeared* to confirm the existence of systems which contain ONeMg white dwarfs: indeed, a combination of detailed abundance analyses and observations of "strong neon features" in the UV spectra have been interpreted as suggesting that perhaps as many as one-half of the recent classical nova outbursts, both in the Galaxy and in the Large Magellanic Cloud, may involve such systems. This result alone is not terribly surprising. Stellar evolution theory predicts that CO white dwarfs are the expected remnants of the evolution of stars in the mass range 1–8 $M_{\odot}$, while ONeMg white dwarfs arise from stars in the mass range $\sim$8–12 $M_{\odot}$ (a narrower range is predicted when effects of binary evolution are considered, e.g., Iben & Tutukov 1985). On the assumption of a Salpeter (1955) initial mass function alone, the relative frequencies of CO to ONeMg white dwarfs is approximately 30 to 1. Truran & Livio (1986) demonstrated, however, that selection effects associated with the fact that the more massive ($M > 1.2\ M_{\odot}$) ONeMg white dwarf remnants require less accreted envelope matter to initiate thermonuclear runaway, greatly favor their occurrence in nova systems observed in outburst. Ritter et al. (1991) performed a more detailed study of the selection effects and have shown that *assuming that the enrichments observed in the so-called neon novae indeed represent material that has been dredged up from an underlying* ONeMg *white dwarf*, then neon novae are expected to represent 25%–57% of all novae.

In light of these considerations, the high frequency of occurrence of neon novae, alone, is not a cause for concern. The rather large inferred masses of nebular ejecta for several of these systems are, however, inconsistent with this model. In all of the theoretical studies of occurrence frequencies, the selection effect that operates is based upon the assumption that ONeMg white dwarfs have high masses, typically larger than 1.2 $M_{\odot}$. For these conditions, runaways occur more frequently simply because less accreted matter is required to trigger outbursts. Recent observational results have begun, however, to raise some doubts as to whether the commonly accepted interpretation of the abundance data indeed represents the true physical situation. We note, in particular, that the mass of the ejecta of the alleged neon nova QU Vul 1984 was determined to be between 10^{-4} and $4 \times 10^{-3}\ M_{\odot}$ (Saizar et al. 1992). Similarly, for another alleged neon nova, Nova Her 1991, the

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ejected shell mass was estimated to be $(6.4\text{–}9) \times 10^{-5}$ (Woodward et al. 1992). Such a high envelope mass is normally expected to correspond to a white dwarf that is considerably less massive than typical ONeMg white dwarfs (see e.g., Truran 1982; Livio 1993). Nevertheless, observations of Nova Her 1991 appear to show that sulfur is highly overabundant compared to solar values (Williams, Phillips, & Hamuy 1993; Matheson, Filippenko, & Ho 1993).

In the present paper, we therefore reexamine the question of the abundances in nova ejecta and their interpretation. The basic question we address is whether the various identified "neon novae" necessarily *all* demand the presence of an underlying ONeMg white dwarf, or whether, rather, there might possibly be an alternative explanation of neon enrichments, particularly in systems involving lower mass white dwarfs. The current state of our knowledge of abundances in nova ejecta is reviewed in § 2. Problems associated with the interpretation of these nova abundance determinations, and possible alternative solutions, are considered in § 3. A discussion and conclusions follow.

2. ABUNDANCES IN NOVA EJECTA

Table 1 presents a summary of the available data on abundances in nova ejecta (for previous reviews, see e.g., Williams 1985; Truran 1990). We present, specifically, the mass fractions (where known) of hydrogen, helium, carbon, nitrogen, oxygen, neon, and the sodium-iron elements, adapted from the references that are identified in the table. Also tabulated are the total mass fraction in heavy elements, Z, and its ratio to the solar value. In the last two columns of the table, we give, respectively, the ratio of the observed neon abundance to the solar value and the ratio Ne/Z, relative to the "expected" value for solar system matter (this issue will be discussed further in § 3).

The following features of this abundance compilation should be noted.

1. *Abundance determinations are characterized by large uncertainties.* This is clearly exemplified by the fact that independent determinations of the total metallicity, Z, in V1500 Cyg, V693 CrA, QU Vul and, in particular, PW Vul, resulted in very different values (Table 1). The helium abundances determined for some of these cases also show considerable scatter.

2. To the extent that abundance determinations can be considered reliable, *enhanced conentrations of heavy elements seem to be characteristic of all nova ejecta.* The average Z for the 18 novae in Table 1 (we averaged individually over different values obtained for the same object) is $\langle Z \rangle = 0.31$, compared to the solar value of 0.019 (Anders & Grevesse 1989), indicating a mean enrichment relative to solar by a factor ~ 16.

3. *High helium-to-hydrogen ratios are also a general characteristic of nova ejecta.* The average ratio He/H for the 18 novae in Table 1 (we again averaged individually over different values obtained for the same object) is $\langle \mathrm{He/H} \rangle = 0.88$, compared to the solar value of 0.39, indicating a helium overabundance relative to solar by a factor ~ 2.3. Additional novae (not included in Table 1, because there exists no information on their heavy-element abundances) for which helium abundances (He/H by mass) have been determined (Ferland 1979) include CP Lac (0.44), RR Tel (0.76), DK Lac (0.88), V446 Her (0.76), and V533 Her (0.72).

4. An important conclusion to be drawn from these abundance considerations (Truran & Livio 1986) is the fact that *all*

TABLE 1

HEAVY ELEMENT ABUNDANCES IN NOVAE

Object	Year	Ref.	Mass Fractions H	He	C	N	O	Ne	Na-Fe	Z	($Z/Z_\odot$)	($Ne/Ne_\odot$)	(Ne/Z)
T Aur	1891	4	0.47	0.40		0.079	0.051			0.13	6.8		
RR Pic	1925	13	0.53	0.43	0.0039	0.022	0.0058	0.011		0.043	2.3	6.3	13.5
DQ Her	1934	15	0.34	0.095	0.045	0.23	0.29			0.57	30.		
DQ Her	1934	7	0.27	0.16	0.058	0.29	0.22			0.57	30.		
HR Del	1967	12	0.45	0.48		0.027	0.047	0.0030		0.077	4.1	1.7	2.0
V1500 Cyg	1975	3	0.49	0.21	0.070	0.075	0.13	0.023		0.30	16.	13.	4.0
V1500 Cyg	1975	6	0.57	0.27	0.058	0.041	0.050	0.0099		0.16	8.4	5.6	3.3
V1688 Cyg	1978	11	0.45	0.23	0.047	0.14	0.13	0.0068		0.32	17	3.9	1.1
V1688 Cyg	1978	1	0.45	0.22	0.070	0.14	0.12			0.33	17.		
V693 CrA	1981	14	0.29	0.32	0.0046	0.080	0.12	0.17	0.016	0.39	21.	97.	23.
V693 CrA	1981	1	0.16	0.18	0.0078	0.14	0.21	0.26	0.030	0.66	35.	148.	21.
V1370 Aql	1982	10	0.053	0.088	0.035	0.14	0.051	0.52	0.11	0.86	45.	296.	32.
V1370 Aql	1982	1	0.044	0.10	0.050	0.19	0.037	0.56	0.017	0.86	45.		34.
GQ Mus	1983	5	0.27	0.32	0.016	0.19	0.19	0.0034	0.0068	0.41	22.	1.9	0.073
PW Vul	1984	8	0.69	0.25	0.0033	0.049	0.014	0.00066		0.067	3.5	.38	0.52
PW Vul	1984	5	0.54	0.28	0.032	0.11	0.038			0.18	9.5		
PW Vul	1984	1	0.47	0.23	0.073	0.14	0.083	0.0040	0.0048	0.30	16.	2.3	0.70
QU Vul	1984	9	0.30	0.60	0.0013	0.018	0.039	0.040	0.0049	0.10	5.3	23.	21.
QU Vul	1984	1	0.33	0.26	0.0095	0.074	0.17	0.086	0.063	0.40	21.	49.	11.
V842 Cen	1986	1	0.41	0.23	0.12	0.21	0.030	0.00090	0.0038	0.36	19.	.51	0.13
V827 Her	1987	1	0.36	0.29	0.087	0.24	0.016	0.00066	0.0021	0.35	18.	.38	0.099
QV Vul	1987	1	0.68	0.27		0.010	0.041	0.00099	0.00096	0.053	2.8	.56	0.98
V2214 Oph	1988	1	0.34	0.26		0.31	0.060	0.017	0.015	0.40	21.	9.7	2.2
V977 Sco	1989	1	0.51	0.39		0.042	0.030	0.026	0.0027	0.10	5.3	15.	14.
V443 Sct	1989	1	0.49	0.45		0.053	0.0070	0.00014	0.0017	0.062	3.3	.80	0.12
LMC	1990A	2	0.37	0.59	0.00058	0.0072	0.0059	0.013	0.012	0.039	2.1	7.4	18.

REFERENCES.—(1) Andrea 1992; (2) Dopita et al. 1992; (3) Ferland & Shields 1978; (4) Gallagher et al. 1980; (5) Hassall et al. 1990; (6) Lance et al. 1988; (7) Petitjean et al. 1990; (8) Saizar et al. 1991; (9) Saizar et al. 1992; (10) Snijders et al. 1987; (11) Strickland et al. 1981; (12) Tylenda 1978; (13) Williams & Gallagher 1979; (14) Williams et al. 1985; (15) Williams et al. 1978.

novae for which reasonable abundance data exist appear to be enriched in either helium or heavy elements or both.

5. Several novae appear to be enriched in neon. However, while two of them (V693 CrA and V1370 Aql) show extremely large neon abundances ([Ne/Ne$_\odot$] $\gtrsim$ 100), a few others (e.g., QU Vul, V1500 Cyg, V977 Sco, Nova LMC 1990 No. 1, and V2214 Oph) show a more modest overabundance ([Ne/Ne$_\odot$] $\lesssim$ 20). Some of these "neon" novae (e.g., V693 CrA, V1370 Aql, and QU Vul) appear also to show large concentrations of sodium, magnesium, aluminum, and sulfur.

In order to provide an observational framework within which to discuss these abundance determinations, we suggest that, broadly speaking, the novae in Table 1 can be divided into three groups, as follows.

1. Novae which appear to show a modest enrichment in CNO nuclei ($Z \lesssim 0.1$) but a large enrichment in helium (e.g., T Aur, RR Pic, HR Del, V977 Sco, V443 Sct, and LMC 1990 No. 1). A modest enrichment in neon appears also in some of these novae (e.g., RR Pic, V977 Sco, and LMC 1990 No. 1). We further note that QV Vul may also be associated with this group, although its quoted He concentration is approximately solar, relative to H.
2. Novae which appear to show a considerably higher CNO enrichment and sometimes a modest enrichment in neon (e.g., DQ Her, V1500 Cyg, V1688 Cyg, GQ Mus, PW Vul, V842 Cen, V827 Her, and V2214 Oph). These systems display a range in helium concentration, from approximately solar to approximately twice solar.
3. Novae which appear to show extreme enhancements of neon and heavier nuclei (e.g., V693 CrA, V1370 Aql, and possibly QU Vul). This group also shows the highest He/H ratios, averaging ~3.8 times solar.

As explained in the Introduction, our aim in this paper is to reexamine the question as to whether abundance determinations in general, and those for the neon novae in particular, indeed imply/demand the occurrence of mixing from an underlying CO or ONeMg white dwarf. In order to accomplish this, we must be able to cleanly identify the members of and thereby define the class of "neon novae." In the course of our subsequent discussions, we will be led to the conclusion that it is the third class identified above for which we can make the strongest case that its members must indeed involve an underlying ONeMg white dwarf.

3. POTENTIAL PROBLEMS WITH THE INTERPRETATION OF NOVA ABUNDANCES AND POSSIBLE ALTERNATIVE SOLUTIONS

Previous studies of abundances in novae reached the conclusion that these have to represent dredged-up material from the underlying white dwarfs. In view of the problems described in the Introduction we would like to examine possible alternative interpretations. In general, the following possibilities exist.

1. Photoionization model analyses do not produce correct determinations of abundances and/or ejecta masses.
2. Heavy-element enrichments are produced by mass transfer from the secondary star.
3. Heavy-element enrichments are produced by nuclear transformations associated with the thermonuclear runaway (TNR).
4. Neon enrichments are produced in prior evolution.
5. The heavy-element enrichments are indeed produced by dredge-up from the underlying white dwarf.

Let us now investigate each of these possibilities.

3.1. *Uncertainties in Abundance Determinations*

As noted previously, a significant level of uncertainty in the heavy-element abundance determinations is clearly reflected in Table 1. The three independent determinations of the total metallicity, Z, for PW Vul span a range of a factor ~4. Similarly, the two quoted values for the novae V1500 Cyg, V693 CrA, and QU Vul differ by factors ~2–4. The agreement between the quoted values for both V1688 Cyg and V1370 Aql may simply be a consequence of the fact that essentially the same (photoionization) program and analysis was employed. In all cases but these last two, the helium abundances also show considerable scatter. Based upon these very general considerations alone, we believe that a factor ~2–4 uncertainty is reasonably to be associated with any classical nova abundance determination.

Furthermore, a recent and quite detailed photoionization model analysis of the nebular phase in Nova LMC 1990 No. 1 (Dopita et al. 1993a), gave much lower enrichment levels of intermediate elements than those previously obtained for the "remarkably similar" nova V693 CrA, for which an ionization correction factor (ICF) analysis has been used. Since the electron temperature in the highly ionized zone is not measured directly, and because of the fact that ICF analyses do not treat the energy balance fully self-consistently, it is quite possible that all of the previous abundance estimates gave systematically too large values. If this assessment is true, it may mean that all the novae which show only moderate neon abundances (e.g., V1500 Cyg, V2214 Oph, Nova LMC 1990 No. 1) are not true "neon" novae, but rather represent admixture with CO white dwarf material. Such a mixture, containing ~30% material which has undergone prior helium burning, can be expected to produce a moderate enrichment in neon (e.g., Arnett & Thielemann 1985; Wiescher et al. 1986).

3.2. *The Transferred Material*

The possibility that nuclear-processed material is transferred from an evolved secondary has been suggested by Williams & Ferguson (1983). They examined spectra of a number of novae in quiescence and concluded from the strength of C II λ4267 and C III λ4650, as well as from the presence of N III λ4640 (but absence of O III), that nonsolar CNO enhancements exist in the transferred material.

Similarly, the fact that He II λ4686 is much stronger than Hβ in the quiescent spectra of the recurrent nova U Sco (with V394 CrA and Nova LMC 1990 No. 2 showing similar spectra), may indicate an overabundance of helium relative to hydrogen in the transferred material in these systems (Hanes 1985; Duerbeck & Seitter 1990; Williams et al. 1981; Sekiguchi et al. 1990). It should be noted, however, the hydrogen was detected in absorption (Johnston & Kulkarni 1992), indicating that the secondary is *reasonably* normal.

In spite of the abovementioned observations, it seems unlikely (if not impossible) that the extreme CNO and in particular neon enrichments observed in some novae (if true) result from the transferred material. The low-mass main-sequence companions of the white dwarfs in "typical" classical nova systems simply cannot be the source of such large CNO and ONeMg enrichments as are found in a number of cases.

3.3. *Enrichments Produced in the Thermonuclear Runaway*

We would now like to examine the possibility that the enrichments are produced by nuclear transformations in the TNR itself. This question was also addressed by Truran & Livio (1986). It was noted that helium flashes cannot readily explain the observed enrichments of neon, sodium, magnesium, and aluminum. The question of explosive hydrogen burning requires greater consideration.

One of the important results of explosive hydrogen burning calculations is the general conclusion that *substantial carbon or oxygen enrichment can only be obtained by mixing with white dwarf material containing these elements.* This is a consequence of the fact that carbon does not survive in the hot CNO cycle and it is converted to nitrogen. Peak temperatures achieved in the hydrogen burning shells on nova white dwarfs are found typically to lie in the range $\sim 150\text{–}300 \times 10^6$ K. These are already sufficiently high to allow for an *rp*-process production of nuclei heavier than neon (the formation of Ca and possibly even Fe is not excluded). If peak temperatures higher than 3.5×10^8 K are realized, a breakout from the hot CNO cycle is obtained, which merges with the *rp*-process and can lead to the synthesis of heavy nuclei from preexisting carbon and oxygen nuclei (Wallace & Woosley 1981; Wiescher et al. 1986). Such high temperatures, however, can be expected only for very massive WDs ($M_{WD} \gtrsim 1.2\ M_\odot$; e.g., Sugimoto et al. 1980; Starrfield, Sparks, & Truran 1985). Thus, this path of neon formation while possibly realizable in some systems, cannot explain the existence of high envelope masses (which are associated with relatively low mass WDs) discussed in the introduction.

3.4. *Neon Enrichments Arising from* ^{22}Ne *Production*

It is perhaps most relevant to note that a very significant source of *elemental* neon enrichment can be associated with prior production of the neutron-rich isotope ^{22}Ne, alone. The realization of a significant concentration of ^{22}Ne occurs as a natural consequence of the evolution of the cores of intermediate-mass stars to carbon-oxygen degenerate cores. The operation of the CNO cycles during hydrogen burning first acts to convert most of the initial carbon, nitrogen, and oxygen isotopes into ^{14}N. During the ensuing helium-burning phase, this ^{14}N is readily transformed into ^{22}Ne by ^{14}N(α, γ)^{18}F($e^+\nu$)^{18}O(α, γ)^{22}Ne. Such a concentration of ^{22}Ne is then expected to characterize the underlying CO core of the nova. If outward mixing of core material is indeed the source of the heavy-element enrichments observed in nova ejecta, *then a* ^{22}Ne *enrichment should accompany any* CNO *enrichment.*

The level of such an enrichment is itself an interesting number. Using the abundance table of Anders & Grevesse (1989), the implied total level of enrichment of neon by mass is given by (^{22}Ne[C + N + O])/Ne = 10. The significance of this number lies in the fact that it is quite comparable to the levels of neon enrichment, relative to solar (Ne/Ne$_\odot$), seen even in many identified "neon novae," as can be seen in our Table 1 (group 2 in our discussion in § 2). Even when account is taken of dilution via mixing, a level of neon enrichment of a factor $\sim 3\text{–}4$ is possible. As we will emphasize in our subsequent discussion, it is thus necessary to be careful in assuming that a neon enrichment necessarily implies the presence of an underlying ONeMg white dwarf.

It is very important to recognize that this (^{22}Ne) source of neon enrichment will be realized only in the heavy-element–rich component of the nova ejecta—that component which is presumed to represent dredged-up CO or ONeMg white-dwarf-core matter. The factor ~ 10 neon enrichment that can be achieved here is *relative to the total heavy-element concentration Z.* It is therefore most appropriate to consider, not the ratio (Ne/Ne$_\odot$), but rather the ratio $\text{Ne}/Z = (\text{Ne}/Z)_{\text{nova}}/(\text{Ne}/Z)_{\text{CO}}$, where $(\text{Ne}/Z)_{\text{CO}}$ is the predicted post-helium burning ratio of neon to heavy elements (C + O) in the underlying degenerate core matter. For stars which contain initially a solar distribution of heavy elements, the achievable ^{22}Ne mass function is such that $(\text{Ne}/Z)_{\text{CO}} \sim 10$. This measure of neon enrichment is presented in the last column of the table as (Ne/Z).

A further point to be considered with respect to the interpretation of neon enrichments, is the matter of gravitational settling in cooling white dwarfs. Calculations to date suggest that the settling of neon (primarily ^{22}Ne) in CO white dwarfs can occur on a rapid timescale, relative to the white dwarf cooling timescale. This effect could also hold important implications for the interpretation of high neon concentrations in the ejecta of novae for which the presence of an underlying CO white dwarf seems to be demanded.

4. DISCUSSION AND CONCLUSIONS

Based upon the various observational and theoretical considerations discussed in this paper, we draw the following conclusions.

1. For the purpose of emphasis and of clarification, we first repeat the critical conclusions drawn from our previous study of nova occurrence frequencies (Truran & Livio 1986) that all novae for which reasonable abundance data are available appear to be enriched in either helium or heavy elements or both and that the levels of enrichment of He, and in particular CNO nuclei are sufficiently high that they can only reasonably be explained by the dredge-up of underlying white dwarf core matter. In this context, *a true "neon nova" is one in which the concentration of* ONeMg *nuclei is sufficiently high, that it demands an underlying* (*and presumably massive*) ONeMg *white dwarf.*

2. The 18 individual nova events included in Table 1, those for which there exist detailed spectroscopic abundance analyses, may conveniently be grouped into three classes, on the basis of their abundance characteristics: class 1 novae that show a modest enrichment in heavy elements but a large enrichment in helium; class 2 novae that show a high enrichment in CNO nuclei and sometimes a modest enrichment in neon; and class 3 novae which show quite extreme enrichments in both neon and heavier elements.

3. It is the members of only one of these three classes, class 3, involving the novae V693 CrA 1981, V1370 Aql 1982, and perhaps QU Vul 1984, which we believe *unambiguously* warrant the designation "neon novae," as defined above. Only for these systems is the magnitude of the neon enrichment sufficiently large, in our opinion, to demand dredge-up from an underlying ONeMg white dwarf. Some questions concerning even V1370 Aql still remain. For example, while V693 CrA shows enrichments only in N, O, Ne, Na, Mg, Al, and Si, V1370 Aql shows also an enhancement of carbon. As we explained in § 3, an enrichment in carbon can be obtained by dredge-up of white dwarf material, only in the case of an underlying CO white dwarf. At the same time, the strong enhancements seen in V1370 Aql through S and Fe argue for an ONeMg white dwarf (either providing dredged-up material, or in order to obtain temperatures in excess of 3.5×10^8 K for

a break-out off the CNO cycle). The recent calculations of Politano et al. (1993) indeed confirm the general character of such enrichments to be associated with ONeMg white dwarfs, but also reveal that, for some burning conditions on ONeMg white dwarfs, the final concentrations of C, N, and O can include both an enrichment of carbon (even C/O > 1) and a high nitrogen concentration. Alternatively, the solution to this problem may lie in the fact that ONeMg white dwarfs are expected to have a thin CO shell ($\sim 10^{-2}$ $M_\odot$; Nomoto 1984).

4. Neon novae can also show significant enrichments of heavier nuclei, as reflected in the high values of nuclei in the Na–Fe region (see Table 1). Indeed, Weiss & Truran (1990) found that large concentrations of S and Ar could be formed, for reasonable choices of the nuclear burning timescale and peak temperature, in envelopes initially enriched in O, Ne, and Mg. We also note that these novae may form significant concentrations of the interesting radioactive isotopes ^{22}Na and ^{26}Al (Weiss & Truran 1990; Nofar, Shaviv, & Starrfield 1991; Politano et al. 1993).

5. Nova QU Vul 1984 is a particularly interesting case. Its high neon abundance tentatively places it in class 3, with the designated "neon novae." This is also suggested by the fact that it shows enrichment of the heavier elements in the Na–Fe region. However, the large estimates of its envelope mass suggest that it may involve a less massive white dwarf than is readily compatible with standard models for ONeMg white dwarf configurations. Given the fact that (as we have shown) factors ∼2–4 uncertainties are associated with nova abundance determinations, it is possible that this nova should more appropriately be placed in class 2. Further critical analyses of the data regarding this nova are clearly required. We believe it to be unlikely that erosion of an ONeMg white dwarf via dredge-up and subsequent mass loss associated with the nova event can reduce the mass of an ONeMg white dwarf to below ~ 1 $M_\odot$, to allow us to understand an ejected envelope mass in excess of $\sim 10^{-4}$ $M_\odot$. Here too, we believe a careful examination of the methods by which the masses of nova ejecta are estimated is appropriate.

6. Scrutiny of the neon enrichments relative to the heavy-element concentration, reflected in the tabled values of (Ne/Z), reveals that the novae RR Pic, V977 Sco, and LMC 1990 no. 1 also show appreciable neon abundances, even though the total levels of heavy-element enrichments for these three cases are relatively small. Further examination of the abundance data for these interesting cases seems necessary.

7. Based upon our classification scheme and its implied demographics, the "neon novae" may constitute only 11%–17% (two to three) of 18) of the well-studied novae. This fraction is easily compatible with earlier frequency estimates for ONeMg white dwarfs in classical nova systems in outburst (Truran & Livio 1986; Ritter et al. 1991). The inclusion of the three novae RR Pic, V977 Sco, and LMC 1990 No. 1, which have been found to have high relative levels of neon enrichment in the presence of lower total heavy-element enrichments, would bring the count up only to six of 18, or ∼33%, again quite consistent with theoretical frequency estimates.

8. In light of the above considerations, and our restricted class of *true* "neon novae," we are led to conclude that no exotic models for the formation of low-mass ONeMg WDs are required (Shara & Prialnik 1993). Such models, while possibly interesting in their own right, are not dictated by the observations.

9. A clear consequence of the above points is that we predict the WDs in V693 CrA and V1370 Aql to be massive.

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REFERENCES

Andrea, G. 1992, Ph.D. thesis, Univ. Nuremberg
Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arnett, W. D., & Thielemann, F.-K. 1985, ApJ, 295, 589
Della Valle, M., Bianchini, A., Livio, M., & Orio, M. 1992, preprint
Dopita, M. A., Meatheringham, S. J., Sutherland, R., Williams, R. E., Starrfield, S., Sonnenborn, G., & Shore, S. 1992, preprint
Dopita, M. A., Meatheringham, S. J., Sutherland, R. S., Ryder, S. D., Starrfield, S., Williams, R. E., Shore, S., & Sonneborn, G. 1993a, preprint
Dopita, M. A., Meatheringham, S. J., Sutherland, R. S., Williams, R. E., Starrfield, S., Sonneborn, G., & Shore, S. 1993b, in New Aspects of Magellanic Cloud Research, ed. G. Klare, in press
Duerbeck, H. W., & Seitter, W. C. 1990, in The Physics of Classical Novae, ed. A. Cassatella & R. Viotti (Berlin: Springer-Verlag), 425
Ferland, G. J. 1979, ApJ, 231, 781
Ferland, G. J., & Shields, G. A. 1978, ApJ, 226, 172
Fujimoto, M. Y., & Iben, I., Jr. 1992, ApJ, 399, 646
Gallagher, J. S., Hege, E. K., Kopriva, D. A., Williams, R. E., & Butcher, H. R. 1980, ApJ, 237, 55
Hanes, D. A. 1985, MNRAS, 213, 443
Hassall, B. J. M., et al. 1990, in Physics of Classical Novae, ed. A. Cassatella & R. Viotti (Berlin: Springer-Verlag), 202
Hayward, T. L., Gehrz, R. D., Miles, J. W., & Houck, J. R. 1993, preprint
Iben, I., Jr., & Tutukov, A. 1985, ApJS, 58, 661
Johnston, H. M., & Kulkarni, S. R. 1992, ApJ, 396, 267
Lance, C. M., McCall, M. L., & Uomoto, A. K. 1988, ApJS, 66, 151
Law, W. Y., & Ritter, H. 1983, A&A, 63, 265
Livio, M. 1993, in 22nd Saas Fee Advanced Course, Interacting Binaries, ed. H. Nussbaumer & A. Orr (Berlin: Springer), 135
Matheson, T., Filippenko, A. V., & Ho, L. C. 1993, ApJ, 418, L29
Nofar, I., Shaviv, G., & Starrfield, S. 1991, ApJ, 369, 440
Nomoto, K. 1984, ApJ, 277, 291
Petitjean, P., Boisson, C., & Pequignot, D. 1990, A&A, 240, 433
Politano, M., Starrfield, S., Truran, J. W., Weiss, A., & Sparks, W. M. 1993, preprint
Ritter, H., Politano, M. J., 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, 651
Salpeter, E. E. 1955, ApJ, 121, 161
Sekiguchi, K., Stobie, R. S., Buckley, D. H. H., & Caldwell, J. A. R. 1990, MNRAS, 245, 28p
Shara, M. M., & Prialnik, D. 1993, preprint
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
Starrfield, S. 1989, in Classical Novae, ed. N. Evans & M. Bode (New York: Wiley), 123
Starrfield, S., Sparks, W. M., & Truran, J. W. 1985, ApJ, 291, 136
Stickland, D. J., Penn, C. J., Seaton, M. J., Snijders, M. A. J., & Storey, P. J. 1981, MNRAS, 197, 107
Sugimoto, D., Fujimoto, M. Y., Norini, K., & Nomoto, K. 1980, in IAU Colloq. 53, ed. H. M. Van Horn & V. Weidemann (Rochester: Rochester Univ. Press), 280
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 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
Wallace, R. K., & Woosley, S. E. 1981, ApJS, 45, 389
Weiss, A., & Truran, J. W. 1990, A&A, 238, 178
Wiescher, M., Görres, J., Thielemann, F.-K., & Ritter, H. 1986, A&A, 160, 56
Williams, R. E. 1985, in Production and Distribution of CNO Elements, ed. I. J. Danziger (Garching: ESO), 225
Williams, R. E., & Ferguson, D. H. 1983, in Cataclysmic Variables and Related Objects, ed. M. Livio & G. Shaviv (Dordrecht: Reidel), 97
Williams, R. E., & Gallagher, J. S. 1979, ApJ, 228, 482
Williams, R. E., Ney, E. P., Sparks, W. M., Starrfield, S., Truran, J. W., & Wyckoff, S. 1985, MNRAS, 212, 753
Williams, R. E., Phillips, M. M., & Hamuy, M. 1993, ApJ, in press
Williams, R. E., Woolf, N. J., Hege, E. K., Moore, R. L., & Kopriva, D. A. 1978, ApJ, 224, 171
Williams, R. E., Sparks, W. M., Gallagher, J. S., Ney, E. P., Starrfield, S. G., & Truran, J. W. 1981, ApJ, 251, 221
Woodward, C. E., Gehrz, R. D., Jones, T. J., & Lawrence, G. F. 1992, ApJ, 384, L41