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HYDRODYNAMIC MODELS FOR NOVAE WITH EJECTA RICH IN OXYGEN, NEON, AND MAGNESIUM[1]

SUMNER STARRFIELD[2]
Group T-6, Los Alamos National Laboratory
WARREN M. SPARKS
Group X-5, Los Alamos National Laboratory
AND
JAMES W. TRURAN
Department of Astronomy, University of Illinois
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ABSTRACT

In this *Letter* we identify and seek to explain the characteristics of a new class of novae. This class consists of those objects that have been observed to eject material rich in oxygen, neon, magnesium, and aluminum at high velocities. We propose that for this class of novae the outburst is occurring not on a carbon-oxygen white dwarf but on an oxygen-neon-magnesium white dwarf which has evolved from a star which has a main-sequence mass of $\sim 8\ M_\odot$ to $\sim 12\ M_\odot$. We have simulated such an outburst by evolving 1.25 $M_\odot$ white dwarfs accreting hydrogen-rich material at various rates. The effective enrichment of the envelope by ONeMg material from the core is simulated by enhancing oxygen in the accreted layers. The resulting evolutionary sequences are the most violent that we have yet studied and can eject the entire accreted envelope plus core material at high velocities. They can also become super-Eddington at maximum bolometric luminosity. The expected frequency of such events ($\sim 1/4$) is in good agreement with the observed numbers of these novae.

Subject headings: hydrodynamics — stars: evolution — stars: novae

I. INTRODUCTION

Over the past 10 yr, at least four out of the 12 well-studied nova outbursts have been found to have ejecta rich in neon and other intermediate-mass elements. These four novae are Nova V1500 Cygni 1975 (Ferland and Shields 1978), Nova V1370 Aql 1982 (Snijders *et al.* 1984), Nova V693 CrA 1981 (Williams *et al.* 1985), and Nova Vul Number 2 1984 (Gehrz, Grasdalen, and Hackwell 1985; Starrfield *et al.* 1986; Andrillat and Houziaux 1985). The most striking recent discovery was that of Gehrz, Grasdalen, and Hackwell (1985) who found the [Ne II] 12.8 μ emission line in Nova Vul Number 2 to be very strong. Although they conservatively state in their paper that neon could have a solar abundance if it were all Ne II (see also Ferland and Shields 1978), nearly simultaneous spectra obtained with the *IUE Satellite* show very strong emission from both Ne III and Ne IV ions (Starrfield *et al.* 1986) and the Mg II lines are very strong both in the *IUE* and optical spectra (Andrillat and Houziaux 1985). In fact, the UV spectra of Nova Vul Number 2 are quite similar to those taken of Nova V693 CrA 1981 in which neon was found to be ~ 100 times overabundant (Williams *et al.* 1985), providing further support for our claim that neon is also overabundant in this nova. They have also discovered that this nova has formed SiO_2 dust (R. D. Gehrz 1985, private communication). All of the other novae that have formed dust have formed carbon dust except for Nova V1370 Aql 1982, which formed dust of an unidentified material (Gehrz *et al.* 1984).

The distributions of abundances in these novae, especially that of Nova V693 CrA 1981, strongly suggest that we are observing core material from an oxygen-neon-magnesium (hereafter ONeMg) white dwarf that has been mixed through a hot hydrogen burning region and then ejected into space by the explosion (Williams *et al.* 1985; Wiescher *et al.* 1985; Truran 1985). Law and Ritter (1983) have already proposed that a fraction of the accreting white dwarfs in nova systems could be ONeMg white dwarfs. Nomoto (1983) has performed evolutionary calculations which show that ONeMg white dwarfs can arise from single stars that were originally about 8 $M_\odot$ to 12 $M_\odot$ on the main sequence. This high a mass is necessary to ensure that core carbon burning occurs under nondegenerate conditions which requires that the core mass exceed $\sim 1.2\ M_\odot$.

These data indicate that there may exist two distinct classes of nova outbursts: those that occur on CO white dwarfs and those that occur on ONeMg white dwarfs. The most obvious difference concerns the relative abundances of carbon, nitrogen, oxygen, neon, sodium, magnesium, and aluminum in the ejected material. It is already established that several of the other recent nova outbursts show CNO enrichment but no evidence for enhanced neon. In addition, an examination of

[1]Supported in part by National Science Foundation grants AST83-14788 to Arizona State University and AST83-14415 to the University of Illinois and by the DOE.
[2]Permanent address: Department of Physics, Arizona State University.

the spectra of novae show that the velocities of the ejecta are higher in the ONeMg novae than in the CO novae. It may be possible that other differences will become apparent, if one searches for them. The existence of ONeMg white dwarfs in close binary systems clearly implies both that a significant amount of mass and angular momentum must be lost and also that these systems began their evolution as very widely separated binaries (see, for example, Iben and Tutukov 1985).

Given the existence of a new class of novae, we have performed numerical calculations in order to explore the characteristics of the outbursts that occur on ONeMg white dwarfs, just as we have done previously for CO white dwarfs. In the course of this investigation, we have found that these outbursts may be extremely violent compared to outbursts on CO white dwarfs, just as has been observed. It is the purpose of this *Letter* to demonstrate that there are differences in the gross features of the ONeMg and CO outbursts and to show that hydrodynamic simulations of outbursts involving ONeMg white dwarfs are in good agreement with the observations.

II. EVOLUTIONARY CALCULATIONS

We use a Lagrangian, hydrodynamic, one-dimensional computer code that incorporates a nuclear reaction network (Starrfield, Sparks, and Truran 1985, and references therein). Accretion is included via a fast rezoning technique (Starrfield, Sparks, and Truran 1986). For this study, we utilize 1.25 $M_\odot$, 95 zone, complete white dwarf models with initial luminosities of 10^{-2} $L_\odot$. We accreted hydrogen-rich material onto the surface at three different mass accretion rates and varied the assumed abundances of hydrogen, helium, carbon, and oxygen in the accreted matter. For speed of calculation, we used our small nuclear reaction network and simulated ONeMg material by enhancing only oxygen. This provides a good approximation to the energy production since a significant fraction of the energy will come from the $^{16}O(p, \gamma)^{17}F$ reaction. This does preclude the evolution to higher mass nuclei through the $^{17}F(p, \gamma)^{18}Ne$ reaction, but since the rate of the $^{17}F(p, \alpha)^{14}N$ reaction is much larger, this will have only a minor effect on the nucleosynthesis (Wiescher *et al.* 1985). Our opacities and equations of state are obtained from Los Alamos (we thank A. N. Cox for providing them to us), and for these calculations we used the Aller mixture.

The radius of the 1.25 $M_\odot$ white dwarf configuration, which provided the initial model for all of our evolutionary calculations, was 4.04×10^3 km and its luminosity and effective temperature were 10^{-2} $L_\odot$ and 2.4×10^4 K, respectively. We chose accretion rates of 10^{16} g s^{-1} (1.6×10^{-10} $M_\odot$ yr^{-1}), 10^{17} g s^{-1} (1.6×10^{-9} $M_\odot$ yr^{-1}), and 10^{18} g s^{-1} (1.6×10^{-8} $M_\odot$ yr^{-1}). For each rate we evolved sequences with four different compositions: (1) a solar mixture with $X = 0.72$, $Y = 0.26$, and $Z = 0.02$ (all abundances are quoted as mass fraction); (2) a mixture with $X = 0.365$, $Y = 0.133$, $X(^{12}C) = 0.5$; (3) a mixture with $X = 0.365$, $Y = 0.133$, $X(^{12}C) = 0.25$, and $X(^{16}O) = 0.25$; and (4) a mixture with $X = 0.365$, $Y = 0.133$, and $X(^{16}O) = 0.5$. The other light nuclei were present in solar proportions. Mixture 4 is our simulation of accretion onto an ONeMg white dwarf. In the last three cases we are assuming that mixing occurs between the accreted matter and the underlying core material.

The results of these calculations are given in Table 1 for the various possible choices of the accretion rates and the compositions. We list the mass of the accreted envelope (ΔM_e), the evolution time to reach that amount of mass at the given accretion rate (τ), the temperature and pressure at the end of the accretion phase, and the peak values of $\varepsilon_{\rm nuc}$, T, M_B, and M_v. We also list the amount of mass ejected and the velocity range of the ejected material. A theoretical light curve for an oxygen-enhanced model is shown in Figure 1.

We see from Table 1 that the sequences which we identify as those characteristic of accretion onto an ONeMg white dwarf accrete the most mass and eject the most mass at all accretion rates. They also achieve the highest temperatures in the shell source, although the carbon-enhanced sequences reach the highest values of nuclear energy generation because carbon is so much more reactive than oxygen for the range of temperatures and densities obtained in nova environments. During the later stages of the outburst, the oxygen-enhanced sequences are brightest at visual maximum while the carbon-enhanced sequences are brightest at bolometric maximum and both sequences exceed $L_{\rm Edd}$ at maximum. Finally the pure oxygen enhanced sequences achieve ejection velocities that exceed 4×10^3 km s^{-1}, and these velocities are much larger than the carbon-plus-oxygen–enhanced sequences. Since the oxygen-enhanced sequences eject more mass than the carbon-plus-oxygen–enhanced sequences, it is clear that the material ejected during the oxygen-enhanced evolution carries a great deal more kinetic energy.

The oxygen-enhanced sequences are the most violent because they have the largest envelope masses, and the material at the composition interface is the most degenerate. What is more interesting is that they accrete more mass prior to runaway than even the sequences with a solar composition. This is because, for the same temperature and density, the rate of energy generation from the *p-p* chain is lowest in the oxygen-enhanced sequences (half the hydrogen has been replaced with oxygen, a less reactive element). Since the time scale to outburst depends on $\varepsilon_{\rm nuc}$, they take the longest time to reach runaway and, therefore, accrete the most mass. Once the temperatures in the shell source reach values for which the CNO reactions become dominant, the reduced proton abundance is still an important consideration, while the large oxygen abundance will not make a difference until the shell source temperature exceeds $\sim 5 \times 10^7$K.

One important characteristic of the oxygen-enhanced sequences is that, for 10^{16} g s^{-1} $< \dot{M} < 10^{17}$ g s^{-1}, the gross features are the same. This means that a very broad range of $\dot{M}$ will produce a similar evolution. On the other hand, once $\dot{M}$ reaches 5×10^{17} g s^{-1}, we find a large decrease in the ejected mass and in the velocity of the ejecta. Therefore, an accretion rate in this regime will still give a nova-like outburst but the evolution of the nova will be much slower; i.e., a "slow" nova involving an ONeMg white dwarf. In fact, Nova V693 CrA 1981 was a much "faster" nova than is Nova Vul 1984 Number 2, which has remained bright since 1984 December.

Finally, we note that a reasonable fraction of the oxygen initially present in the envelope can be converted to carbon during the outburst. Therefore, we expect the carbon abundances in ONeMg enriched novae to be enhanced along with

TABLE 1

RESULTS OF THE EVOLUTION

Parameter	Solar	Carbon	C + O	Oxygen
		Mass Accretion Rate = 10^{16} g s^{-1}		
$\Delta M_e(M_\odot)$	3.6E − 5	1.7E − 5	2.2E − 5	7.3E − 5
τ (yr)	2.3E + 5	1.0E + 5	1.4E + 5	4.6E + 5
P (dyn cm^{-2})	3.4E + 19	1.5E + 19	2.1E + 19	4.0E + 19
T max (K)	2.38E + 8	2.21E + 8	2.34E + 8	2.67E + 8
ϵ_{nuc} max (ergs g^{-1} s^{-1})	1.2E + 14	1.1E + 17	8.6E + 16	9.1E + 15
M_B (max)	−6.67	−11.50	−9.11	−10.46
M_v (max)	−6.60	−7.32	−6.52	−7.71
$M_{ej}(M_\odot)$	3.0E − 7	8.3E − 6	2.3E − 6	3.7E − 5
V max (km s^{-1})	158.	4245.	2721.	4214.
V min (km s^{-1})	0.	465.	130.	479.
		Mass Accretion Rate = 10^{17} g s^{-1}		
$\Delta M_e(M_\odot)$	2.9E − 5	1.2E − 5	1.6E − 5	4.5E − 5
τ (yr)	1.8E + 4	7.8E + 3	9.8E + 3	2.8E + 4
P (dyn cm^{-2})	2.6E + 19	1.2E + 19	1.4E + 19	4.2E + 19
T max (K)	2.23E + 8	2.06E + 8	2.15E + 8	2.69E + 8
ϵ_{nuc} max (ergs g^{-1} s^{-1})	1.2E + 14	4.7E + 16	3.3E + 16	5.0E + 15
M_B (max)	−6.73	−10.77	−7.79	−10.52
M_v (max)	−6.59	−6.52	−6.92	−7.76
$M_{ej}(M_\odot)$	3.0E − 8	4.3E − 6	1.8E − 6	3.8E − 5
V max (km s^{-1})	0.	3177.	1314.	4290.
V min (km s^{-1})	0.	63.	3.	341.
		Mass Accretion Rate = 10^{18} g s^{-1}		
$\Delta M_e(M_\odot)$	1.4E − 5	7.1E − 6	8.2E − 6	1.7E − 5
τ (yr)	9.1E + 2	4.5E + 2	5.2E + 2	1.1E + 3
P (dyn cm^{-2})	1.3E + 19	6.5E + 18	7.5E + 18	1.3E + 19
T max (K)	2.00E + 8	1.81E + 8	1.86E + 8	2.09E + 8
ϵ_{nuc} max (ergs g^{-1} s^{-1})	1.1E + 14	1.1E + 16	6.2E + 15	2.8E + 15
M_B (max)	−6.77	−7.07	−7.34	−7.35
M_v (max)	−6.58	−6.75	+1.53	−6.98
$M_{ej}(M_\odot)$	5.0E − 8	8.0E − 7	0.	2.0E − 6
V max (km s^{-1})	160.	2546.	0.	275.
V min (km s^{-1})	0.	11.	0.	10.

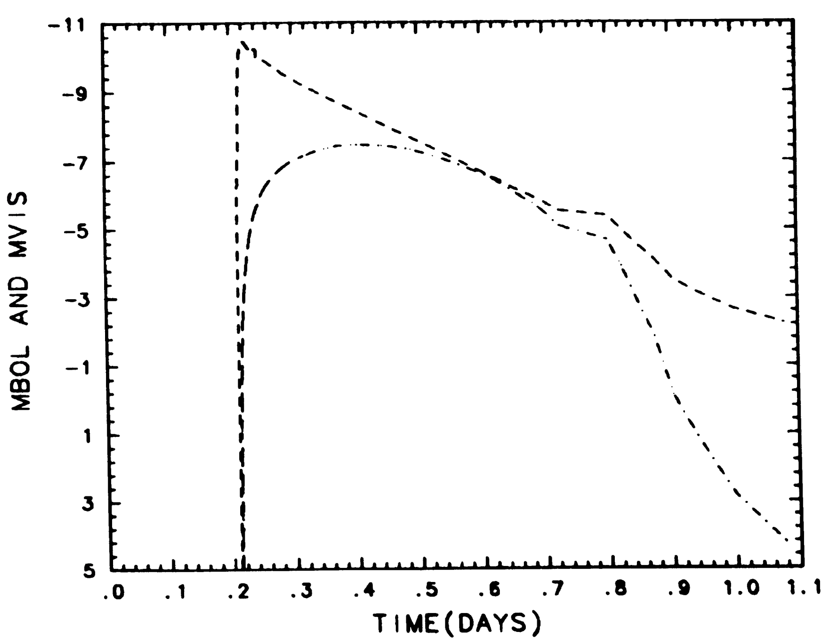

FIG. 1.—The variation of the bolometric magnitude (*dashed curve*) and the visual magnitude (*dot-dash curve*) as a function of time for the oxygen-enhanced model with $\dot{M} = 10^{16}$ g s^{-1}. The entire accreted envelope has become optically thin by the end of the figure. During most of the time shown on the plot, the luminosity was super-Eddington.

nitrogen and oxygen. The precise degree of enhancement cannot be accurately predicted until we rerun these sequences with a much larger and more complete nuclear reaction network; this study is now progress. Nevertheless, our calculations are in agreement with the observations which find that carbon is enhanced in the ejecta.

III. A NEW CLASS OF NOVA EVENTS

Given the existence of a newly identified class of novae, it is interesting to note several additional potential distinguishing features between this class and the CO class. Three of them seem to be at least moderately fast novae, which is compatible both with the presence of large overabundances of heavier elements and also with our findings that pure oxygen rather than pure carbon enrichments, together with low accretion rates, yield relatively more violent events. Additionally, several of these novae seem to be ejecting matter at extremely high velocities compared to typical "fast" novae. It now appears that three or four of the 12 well-studied novae in the past 10 yr occurred on ONeMg white dwarfs; this seems at first glance to be a rather high fraction. However, we note that stellar evolution calculations predict that stars in the mass range 1–8 $M_{\odot}$ will form CO degenerate cores while those in the mass range $\sim$ 8–12 $M_{\odot}$ will evolve to ONeMg degenerate dwarfs. If we assume that a Salpeter (1955) initial mass spectrum is appropriate, then these mass ranges imply that the ratio of single stars with CO cores to those with ONeMg cores is approximately 35. Truran and Livio (1985; see also Delbourgo-Salvador, Mochkovitch, and Vangioni-Flam 1985) have found that a strong selection effect (associated with the fact that ONeMg white dwarfs, being more massive on average, require less accreted envelope matter to initiate a thermonuclear runaway and, therefore, experience outbursts at shorter recurrence intervals) acts to ensure that the relatively small fraction of the systems in which ONeMg white dwarfs do occur can account for a significantly larger fraction (perhaps one-fourth) of the observed outbursts. Finally, it should also be noted that the oxygen-enhanced sequences are the brightest at visual maximum which will also influence selection effects.

IV. DISCUSSION AND SUMMARY

Our theoretical calculations predict that there should be identifiable, gross differences between nova outbursts which occur on CO white dwarfs and those that occur on ONeMg white dwarfs. For the same initial white dwarf mass, luminosity, and rate of accretion onto the white dwarf, we predict that an outburst on an ONeMg white dwarf will eject more mass at higher velocities than an outburst on a CO white dwarf. We also predict that the ONeMg outbursts will be brighter at visual maximum than CO outbursts. An obvious distinguishing feature of these classes is that neon and magnesium (at least) will be enhanced in the ejecta of the ONeMg outbursts and not in the ejecta of CO outbursts. We also predict that observable differences in outburst behavior can be produced by differences in $\dot{M}$, although for broad ranges of $\dot{M}$, the gross features of the outburst will be quite similar.

These results imply, therefore, that there are two distinct types of novae and that each type can exhibit variations consistent with different observed speed classes. They also imply that a significant amount of core material must be brought up into the accreted hydrogen envelope, in order to provide the levels of heavy element abundances seen in the ejected envelope. In those cases where a major fraction of the ejecta appears to be core material, then it must certainly be the case that the white dwarf is losing mass as a result of the outburst. This may not be true for those slow novae where the ejected abundances are nearly solar. However, even in those novae the hydrogen-to-helium ratio in the ejecta is far from solar and a significant fraction of the ejected helium may come from the white dwarf and not from nuclear burning during the thermonuclear runaway. Truran and Livio (1985) estimate, on the basis of existing data for well-studied novae, that $\sim$ 38% of the ejecta of novae represent matter enriched in helium or heavy elements.

We can assume, based on stellar evolution calculations, that the mass of the ONeMg white dwarf is larger than the mass of a CO white dwarf at the beginning of the nova phase. Studies of accretion onto white dwarfs show that the envelope mass necessary to reach a thermonuclear runaway is a decreasing function of white dwarf mass so that the mass ejected in an ONeMg outburst should be smaller than that of lower mass (presumably) CO white dwarfs. The ejected masses that we found in this study range from less than 10^{-5} $M_{\odot}$ to $\sim 4 \times 10^{-5}$ $M_{\odot}$. These values suggest that ejected masses should be determined for the ONeMg outbursts and that they will be found to be smaller than the canonical value of 10^{-4} $M_{\odot}$. This has implications as well for nucleosynthesis in novae. While several recent events suggest that very substantial neon and other heavy element enrichments can occur in nova ejecta, these very likely correspond to more massive systems for which the total masses of the ejecta are relatively small. Novae, therefore, are not expected to make a significant contribution to the abundances of these nuclei in galactic matter. It is possible, however, that such nova events can make important contributions to the levels of the radioactive nuclei ^{22}Na and ^{26}Al present in the interstellar medium.

In summary, our study of accretion onto 1.25 $M_{\odot}$ ONeMg white dwarfs shows that the class of novae thus defined will produce outbursts that are quite different from outbursts on CO white dwarfs. The ejected velocities will be higher and the ejected masses lower. Such novae will, on average, be brighter at visual maximum and the abundances in the ejecta will be very different from those of novae involving CO white dwarfs.

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WARREN M. SPARKS: Group X-5. MSF669, Applied Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545

SUMNER STARRFIELD: Joint Institute for Laboratory Astrophysics, Box 440, University of Colorado, Boulder, CO 80309

JAMES W. TRURAN: Department of Astronomy, University of Illinois, 1011 West Springfield, Urbana, IL 61801