AN EXTENDED GRID OF NOVA MODELS. II. THE PARAMETER SPACE OF NOVA OUTBURSTS

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ABSTRACT

This paper is a sequel to an earlier paper devoted to multiple, multicycle nova evolution models (Prialnik & Kovetz, Paper I), which showed that the different characteristics of nova outbursts can be reproduced by varying the values of three basic and independent parameters: the white dwarf mass, \( M_{\text{WD}} \), the temperature of its isothermal core, \( T_{\text{WD}} \), and the mass transfer rate, \( \dot{M} \). Here we show that the parameter space is constrained by several analytical considerations and find its limiting surfaces. Consequently, we extend the grid of multicycle nova evolution models presented in Paper I to its limits, adding multicycle nova outburst calculations for a considerable number of new parameter combinations. In particular, the extended parameter space that produces nova eruptions includes low mass transfer rates down to \( 5 \times 10^{-11} \, M_{\odot} \, \text{yr}^{-1} \) and more models for low \( T_{\text{WD}} \). Resulting characteristics of these runs are added to the former parameter combination results to provide a full grid spanning the entire parameter space for carbon-oxygen white dwarfs. The full grid covers the entire range of observed nova characteristics, even those of peculiar objects, which have not been numerically reproduced until now. Most remarkably, runs for very low \( \dot{M} \) lead to very high values for some characteristics, such as outburst amplitude \( A \gtrsim 20 \), high super-Eddington luminosities at maximum, heavy element abundance of the ejecta \( Z_{\text{ej}} \approx 0.63 \), and high ejected masses \( m_{\text{ej}} \approx 7 \times 10^{-4} \, M_{\odot} \).

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — white dwarfs

Online material: color figures

1. INTRODUCTION

The realization that classical novae (CNs) are due to thermonuclear runaways (TNRs) on the surfaces of white dwarf (WD) stars in close, mass-transferring binary systems (Starrfield et al. 1972) is now three decades behind us. Direct observations of novae (summarized in, e.g., Payne-Gaposchkin 1957) had already demonstrated that large ranges in ejecta velocity and metallicity occur in novae, and later interpretations of the data suggested that ejecta masses varied strongly from object to object. The first simulations by nova theorists, trying to make sense of these observations, involved much groping into various corners of parameter space. Early triumphs included an explanation of the UV emission and high bolometric luminosities of novae after eruption (Starrfield et al. 1976), fast and moderately slow nova models (Prialnik et al. 1978), natural enrichment of ejecta in heavy elements via diffusion (Prialnik & Kovetz 1985) and via mixing from the underlying WD (MacDonald 1983; Kutter & Sparks 1987), the realization that nuclear burning with EUV emission could occur without mass ejection (perhaps leading to Type Ia supernova [SN Ia] or super soft X-ray sources; Shara et al. 1977), and novae recurring on timescales as short as a few years (Starrfield et al. 1987).

The first decade of nova simulations crystallized the understanding that a space of three independent parameters controls the behavior of a CN eruption: the WD mass, the WD temperature (or luminosity), and the mass accretion rate from the companion (Shara et al. 1980; Prialnik 1995). Increased computer power and codes including better physics lead to an ever-increasingly sophisticated series of eruption simulations. Once multicycle simulations became possible, the arbitrariness of initial conditions could be eliminated, and systematic surveys throughout the three-dimensional space became a real possibility. These culminated in an extended grid of multicycle nova evolution models (Prialnik & Kovetz 1995, hereafter Paper I) that have been used extensively by researchers.

While Paper I covered virtually all of the \( (M_{\text{WD}}, T_{\text{WD}}, \dot{M}) \) space then thought likely to be reached by novae, more recent work (Hurley & Shara 2003) has shown that cataclysmic variables (CVs) are likely to evolve considerably beyond the boundaries of their calculations. Remarkably, we find in this study that some of these systems (parameter combinations) still produce nova eruptions. Among these are models with extreme values of \( M_{\text{WD}}, T_{\text{WD}}, \) and \( \dot{M} \), which can give rise to “extreme novae” — objects with eruption luminosities, metallicities, and/or ejecta masses and velocities significantly larger or significantly smaller than any yet predicted by simulations.

The existence of very unusual eruptive systems like the “red variable” in M31 (Mould et al. 1990) or V838 Mon (Bond et al. 2003) are already sufficient justification for extending nova simulation grids to cover all conceivable cases. Each of these unusual variables has properties (particularly luminosity) reminiscent of novae, and we will examine possible connections in a future paper. But of equal interest is the physical insight that these new simulations can provide as important input in trying to determine the very long term evolution of cataclysmic binaries and relationships between the various subclasses of CVs. Most surprising of all is the nonlinear behavior of some of the most extreme new nova models. Simple extrapolations from previous simulations give answers that may be wrong by large factors. This is because dominance of competing timescales and physical effects changes with movement through the three-dimensional nova parameter space.

It is perhaps not too surprising that \( \dot{M} \) lower than \( 10^{-11} \, M_{\odot} \, \text{yr}^{-1} \) (the lowest values considered in Paper I) can occur, especially as a mass-accreting WD whittles down its donor companion...
Table 1

| Time (Myr) | M1    | M2    | Types\(^a\) | Separation (AU) | R1/R1L | R2/R2L | Comment         |
|-----------|-------|-------|-------------|-----------------|--------|--------|----------------|
| 0.000     | 2.809 | 0.196 | MS, MS      | 110.363         | 0.03   | 0.01   | Initial        |
| 450.482   | 2.809 | 0.196 | HG, MS      | 110.363         | 0.07   | 0.01   | Ev change      |
| 453.303   | 2.809 | 0.196 | GB, MS      | 110.408         | 0.19   | 0.01   | Ev change      |
| 456.049   | 2.808 | 0.196 | GB, MS      | 49.259          | 1.03   | 0.01   | Begin RLOF     |
| 456.049   | 0.14   | 0.196 | HeMS, MS    | 0.854           | 1.01   | 0.03   | Common envelope|
| 758.047   | 0.413 | 0.196 | HeGB, MS    | 0.782           | 0.25   | 0.92   | Ev change      |
| 786.929   | 0.412 | 0.196 | CO WD, MS   | 0.765           | 0.05   | 0.94   | Ev change      |
| 1010.000  | 0.412 | 0.196 | CO WD, MS   | 0.718           | 0.05   | 1.01   | Begin RLOF\(^b\) |
| 12000.000 | 0.412 | 0.040 | CO WD, MS   | 0.841           | 0.03   | 1.06   | Max time       |

\(^a\) MS: main sequence; HG: Hertzsprung gap; GB: giant branch.

\(^b\) From this stage onward, CV behavior, continuous mass loss from secondary to binary with periodic mass ejections. RLOF: Roche-lobe overflow.

to the brown dwarf mass range. Equally understandable is that WD core temperatures can drop to or below \(10^7\) K for WDs accreting at very low rates for many Gyr, whereas Paper I considered only hot WDs accreting at the lowest rate. Both these effects—low mass accretion rate and cold WDs—are extensively studied in this work. What is less intuitively obvious is that CO WDs with masses well under \(6.5 \times 10^{-3}\) \(M_\odot\) (the lower limit of the Paper I study) are also expected. Mass stripping via common envelope evolution can produce a naked helium star, which evolves to the helium giant branch and then becomes a low-mass CO WD, as illustrated by the example of a long-term binary evolution track summarized in Table 1 (J. Hurley 2004, private communication). The existence of low-mass (\(\leq 0.50 \times 10^{-3}\) \(M_\odot\)) WDs resulting from close binary evolution was also discussed by Marsh et al. (1995) and Althaus et al. (2004 and references therein). The behavior of such low-mass CO WDs accreting hydrogen-rich material is also examined, for the first time, in this work.

The methods of numerical computation, the grid of results, and the range of nova parameter space covered are discussed in § 2. In § 3 we discuss the existence of a confined region of the three-dimensional parameter space within which conditions for nova outbursts are satisfied. A brief summary and conclusions are given in § 4.

2. NUMERICAL COMPUTATIONS

The hydrodynamic Lagrangian stellar evolution code by which the present study was performed is the code presented in Paper I. It includes OPAL opacities, an extended nuclear reactions network comprising 40 heavy element isotopes, and a mass-loss algorithm that applies a steady, optically thick supernova wind solution (following the phase of rapid expansion). In addition, diffusion is computed for all elements, accretional mass-loss algorithm that applies a steady, optically thick superwind solution (following the phase of rapid expansion). The behavior of such low-mass CO WDs accreting hydrogen-rich material is also examined, for the first time, in this work.

The methods of numerical computation, the grid of results, and the range of nova parameter space covered are discussed in § 2. In § 3 we discuss the existence of a confined region of the three-dimensional parameter space within which conditions for nova outbursts are satisfied. A brief summary and conclusions are given in § 4.

First, the general tendency of decreasing nova characteristics displayed in Table 3 are the maximal expansion velocity \(v_{m\|}\) its average over the whole mass-loss phase \(v_{m,\|}\), the maximal luminosity attained during the burning shell \(L_{m,\|}\) the time of decline of bolometric luminosity by 3 mag: \(t_{3, bol}\), the duration of the mass-loss phase \(t_{ml}\), and the recurrence period of the outbursts \(P_{rec}\) for all values of WD mass and temperature, and we have added calculations for \(M_{WD} = 0.4 \, M_\odot\), amounting to about 30 new parameter combinations in all.

Tables 2 and 3 list the results of our complete grid of parameter combinations. The tables are presented in a manner similar to those of Paper I: Table 2 lists properties that are related to the accretion phase and the onset of the outburst, while Table 3 presents characteristics of the outburst itself. The properties displayed in Table 2 are the accreted and ejected masses \(m_{acc}\), \(m_{ej}\), the helium mass fraction of the envelope and the ejecta \(Y_{env}, Y_{ej}\); the heavy element mass fractions \(Z_{env}, Z_{ej}\); and the maximum temperature attained in the burning shell \(T_{max}\). The characteristics displayed in Table 3 are the maximal expansion velocity \(v_{max}\), its average over the whole mass-loss phase \(v_{m,\|}\), the maximal luminosity attained during the outburst \(L_{4,\|}\), the amplitude of the outburst in magnitudes, and three typical timescales, the time of decline of bolometric luminosity by 3 mag: \(t_{3, bol}\), the duration of the mass-loss phase \(t_{ml}\), and the recurrence period of the outbursts \(P_{rec}\) for all values of WD mass and temperature, and we have added calculations for \(M_{WD} = 0.4 \, M_\odot\), amounting to about 30 new parameter combinations in all.

Some parameter combinations yield peculiar results, such as the speeds of such low-mass CO WDs accreting hydrogen-rich material are also examined, for the first time, in this work.

The method of numerical computation, the grid of results, and the range of nova parameter space covered are discussed in § 2. In § 3 we discuss the existence of a confined region of the three-dimensional parameter space within which conditions for nova outbursts are satisfied. A brief summary and conclusions are given in § 4.
### Table 2: Complete Grid Results: Characteristics of the Nova Envelope

| Parameter Combinations | Nova Envelope Characteristics |
|-------------------------|-------------------------------|
| $M_{WD}$ ($M_\odot$) | $T_{WD}$ (10^6 K) | $\log M$ ($M_\odot$ yr$^{-1}$) | $m_{ac}$ ($M_\odot$) | $m_{ej}$ ($M_\odot$) | $Y_{ac}$ | $Y_{ej}$ | $Z_{ac}$ | $Z_{ej}$ | $T_{ke}$ max (10^6 K) |
| 0.40 | 10 | -9 | 4.12E-04 | 4.55E-04 | 0.2568 | 0.2579 | 0.1154 | 0.1204 | 0.90 |
| | -6 | 5.62E-04 | 6.76E-04 | 0.2358 | 0.2364 | 0.1832 | 0.1893 | 0.98 |
| | -11 | 5.87E-04 | 6.96E-04 | 0.2444 | 0.2222 | 0.1539 | 0.2075 | 0.95 |
| 0.65 | 10 | -6 | 8.35E-06 | 0.00E+00 | 0.2830 | ... | 0.0208 | ... | 0.81 |
| | -7 | 2.45E-05 | 0.00E+00 | 0.3434 | ... | 0.0203 | ... | 1.10 |
| | -8 | 1.01E-04 | 1.03E-04 | 0.3754 | 0.3865 | 0.0207 | 0.0215 | 1.34 |
| | -9 | 1.61E-04 | 1.63E-04 | 0.2540 | 0.2650 | 0.1201 | 0.1350 | 1.39 |
| | -10 | 2.55E-04 | 2.76E-04 | 0.2407 | 0.2498 | 0.1637 | 0.1786 | 1.67 |
| | -11 | 2.58E-04 | 2.37E-04 | 0.2570 | 0.2538 | 0.1233 | 0.1847 | 1.39 |
| | -12 | 3.94E-04 | 6.66E-04 | 0.2660 | 0.1799 | 0.0500 | 0.4458 | 1.59 |
| | -12.3 | 5.40E-04 | 5.04E-04 | 0.2644 | 0.2723 | 0.0504 | 0.0733 | 1.51 |
| 1.00 | 10 | -6 | 8.94E-06 | 0.00E+00 | 0.2860 | ... | 0.0206 | ... | 0.80 |
| | -7 | 2.66E-05 | 0.00E+00 | 0.3497 | ... | 0.0203 | ... | 0.97 |
| | -8 | 1.06E-04 | 9.88E-05 | 0.3669 | 0.3774 | 0.0207 | 0.0212 | 1.31 |
| | -9 | 7.41E-05 | 9.16E-05 | 0.2556 | 0.2584 | 0.2098 | 0.2208 | 1.16 |
| | -10 | 5.23E-05 | 6.72E-05 | 0.2549 | 0.2570 | 0.2442 | 0.2551 | 1.20 |
| | -11 | 3.86E-05 | 5.36E-05 | 0.2480 | 0.2550 | 0.3109 | 0.3160 | 1.09 |
| | -12 | 4.54E-05 | 1.11E-04 | 0.1320 | 0.1347 | 0.6049 | 0.6170 | 1.60 |

**Source:** The image represents a table from a document, detailing various parameters and their corresponding values for the nova envelope characteristics. The table includes columns for different parameters such as the mass of the white dwarf ($M_{WD}$), the temperature of the white dwarf ($T_{WD}$), the logarithm of the mass accretion rate ($\log M$), the masses of the accretion column ($m_{ac}$) and the ejecta ($m_{ej}$), and the abundances of various elements like $Y_{ac}$, $Y_{ej}$, $Z_{ac}$, and $Z_{ej}$. Each row provides specific values for these parameters across different columns, indicating a grid of results for the nova envelope characteristics.
Table 2—Continued

| Parameter Combinations | Nova Envelope Characteristics |
|-------------------------|-------------------------------|
| $M_{WD}$ ($M_\odot$)    | $T_{WD}$ ($10^6$ K) | log $M$ | $m_{a_{ej}}$ ($M_\odot$) | $m_{i_{ej}}$ ($M_\odot$) | $T_{env}$ | $T_{ej}$ | $Z_{nv}$ | $Z_{ej}$ | $T_{e_{max}}$ ($10^6$ K) |
| 1.25                    | 30                | $-6$   | 3.82E-07 | 0.00E+00 | 0.3299 | ... | 0.0203 | ... | 1.23 |
| 1.40                    | 30                | $-6$   | 1.06E-06 | 1.86E-06 | 0.3374 | ... | 0.0218 | 0.0269 | 1.67 |
| 1.75                    | 30                | $-6$   | 1.18E-06 | 2.16E-06 | 0.3027 | ... | 0.0996 | 0.1037 | 1.92 |
| 2.35                    | 30                | $-6$   | 3.21E-06 | 5.28E-06 | 0.2730 | ... | 0.1305 | 0.1359 | 2.05 |
| 3.05                    | 30                | $-6$   | 5.35E-06 | 8.32E-06 | 0.2423 | ... | 0.2380 | 0.2480 | 2.05 |
| 3.85                    | 30                | $-6$   | 7.55E-06 | 1.15E-06 | 0.1676 | ... | 0.4733 | 0.4931 | 1.99 |
| 4.75                    | 30                | $-6$   | 9.79E-06 | 1.38E-06 | 0.1421 | ... | 0.5747 | 0.5725 | 2.01 |
| 5.85                    | 30                | $-6$   | 1.20E-06 | 1.62E-06 | 0.1858 | ... | 0.5548 | 0.5401 | 2.84 |
| 7.15                    | 50                | $-6$   | 1.41E-06 | 1.61E-06 | 0.3148 | ... | 0.0205 | ... | 1.26 |
| 9.00                    | 50                | $-6$   | 1.71E-06 | 1.81E-06 | 0.3374 | ... | 0.0218 | 0.0269 | 1.67 |
| 11.50                   | 50                | $-6$   | 3.12E-06 | 3.52E-06 | 0.2904 | ... | 0.1498 | 0.1583 | 1.86 |
| 16.00                   | 50                | $-6$   | 6.35E-06 | 6.85E-06 | 0.2584 | ... | 0.2523 | 0.2663 | 1.78 |
| 21.00                   | 50                | $-6$   | 9.60E-06 | 1.01E-06 | 0.2210 | ... | 0.3930 | 0.3970 | 1.76 |
| 27.00                   | 50                | $-6$   | 1.29E-06 | 1.34E-06 | 0.3387 | ... | 0.3356 | 0.3264 | 2.12 |
| 34.00                   | 50                | $-6$   | 1.66E-06 | 1.72E-06 | 0.4400 | ... | 0.3346 | 0.3169 | 2.46 |

$^a$ log $M$ of $-12.3$ stands for $M = 5 \times 10^{-11}$.

Parameters have been selected, whereas at the same time, the weaker gravitational potential enables more massive ejecta, despite the typically lower outburst intensity. In Figure 2c we show the maximum expansion velocities $v_{max}$, which exhibit a similar behavior to that of the maximum luminosity surface. While the low-$M_{WD}$, high-$M$ domain is that of the weakest novae, the high-$M_{WD}$, low-$M$ corner can be identified as the domain of the most powerful outbursts. The time of bolometric decline, as shown in Figure 2d (the trend being very similar to that of $t_{max}$, which is not displayed here), clearly exhibits, in conjunction with Figures 2a and 2c, the correlation between decline time (speed class) and outburst intensity. The slowest novae (longest decline times) occupy the domain of weakest outbursts and vice versa.

In Table 4 the range of variation of some of the main nova properties is displayed, according to the new extended grid of results (for WD-mass range of $0.65-1.00 M_\odot$). The parameter combination for which each maximum and minimum value was
| Parameter Combinations | Complete Grid Results: Characteristics of the Outburst | Outburst Characteristics |
|------------------------|--------------------------------------------------------|--------------------------|
|                        | $r_{\text{max}}$ (km s$^{-1}$) | $r_{\text{avg}}$ (km s$^{-1}$) | $L_{\text{4 max}}$ ($10^4 L_\odot$) | $t_{\text{bol}}$ (days) | $t_{\text{ml}}$ (days) | $P_{\text{rec}}$ (yr) |
| $M_{\text{WD}}$ | $T_{\text{WD}}$ | $\log M_{\text{WD}}$ | $v_{\text{max}}$ (km s$^{-1}$) | $v_{\text{avg}}$ (km s$^{-1}$) | $L_{\text{max}}$ ($10^4 L_\odot$) | $A$ | $t_{\text{ml}}$ (days) | $P_{\text{rec}}$ (yr) |
| 0.40 | 10 | –9 | 234 | 149 | 7.03 | 15.6 | 1.10E+04 | 4.96E+01 | 4.12E+05 |
| 0.65 | 10 | –6 | 203 | 97 | 11.90 | 18.2 | 8.06E+03 | 6.19E+01 | 5.62E+06 |
| 0.65 | 30 | –6 | 156 | 122 | 1.52 | 9.4 | 2.93E+04 | 1.17E+03 | 1.01E+04 |
| 0.65 | 50 | –6 | 2590 | 2150 | 4.76 | 13.2 | 3.83E+04 | 2.64E+02 | 4.96E+01 |
| 1.00 | 10 | –9 | 203 | 97 | 11.90 | 18.2 | 8.06E+03 | 6.19E+01 | 5.62E+06 |
| 1.00 | 30 | –9 | 156 | 122 | 1.52 | 9.4 | 2.93E+04 | 1.17E+03 | 1.01E+04 |
| 1.00 | 50 | –9 | 2590 | 2150 | 4.76 | 13.2 | 3.83E+04 | 2.64E+02 | 4.96E+01 |
| 1.25 | 10 | –6 | 414 | 346 | 4.84 | 6.5 | 2.59E+02 | 6.51E+01 | 1.92E+01 |
| 1.25 | 30 | –6 | 414 | 346 | 4.84 | 6.5 | 2.59E+02 | 6.51E+01 | 1.92E+01 |
| 1.25 | 50 | –6 | 414 | 346 | 4.84 | 6.5 | 2.59E+02 | 6.51E+01 | 1.92E+01 |
obtained is indicated next to the value. We note that most of the maximum values result from the new, lower \( \dot{M} \) runs.

In Table 5 we present observed ranges of several nova characteristics (cf. Prialnik 1995) together with the ranges obtained from the full grid, for comparison. The ranges resulting from model calculations overlap and completely cover the observed ranges.

3. THE CONSTRAINED PARAMETER SPACE

As the extension of the three-dimensional parameter space for novae has resulted in the emergence of new features, the question arises: where do we stop, if at all, extending each one of the parameters' ranges? In other words, is the parameter space limited? We examine this question based on analytical considerations, verified by the results of numerical modeling.

3.1. Heating versus Cooling

The characteristic timescale for cooling of a WD, \( \tau_{\text{cool}} \), is basically a function only of the WD temperature (Mestel 1952). On the other hand, the accretion timescale \( \tau_{\text{acc}} \) is directly determined by the accretion rate and indirectly affected by the other parameters through their influence on the mass required to ignite hydrogen, \( \tau_{\text{acc}} = \frac{m_{\text{acc}}(M_{\text{WD}}, \dot{M})}{\dot{M}} \).

A nova outburst can take place only if \( \tau_{\text{cool}} > \tau_{\text{acc}} \); otherwise the temperature cannot rise to the point of thermonuclear instability. A limiting surface is thus obtained by equating these timescales:

\[
\tau_{\text{cool}}(T_{\text{WD}}) = \tau_{\text{acc}}(M_{\text{WD}}, \dot{M})/\dot{M} = 0.
\]

Following Mestel (1952), if we use the Kramer’s opacity law for the WD atmosphere, the cooling timescale of a CO WD may be approximated by

\[
\tau_{\text{cool}} \approx 2.5 \times 10^6 \left( \frac{M/M_{\odot}}{L/L_{\odot}} \right)^{5/7} \text{ yr},
\]

while the core temperature is approximated by

\[
T_{\text{WD}} \approx 4 \times 10^7 \left( \frac{L/L_{\odot}}{M/M_{\odot}} \right)^{2/7} \text{ K}.
\]

| Parameter Combinations | \( \tau_{\text{max}} \) (days) | \( \tau_{\text{avg}} \) (days) | \( L_{\text{max}} \) (10^3 \( L_{\odot} \)) | \( A \) | \( t_{\text{bol}} \) (days) | \( t_{\text{rec}} \) (days) | \( P_{\text{rec}} \) (yr) |
|------------------------|--------------------------|--------------------------|---------------------------------|-----|--------------------------|--------------------------|--------------------------|
| 1.25 30 0 11.5          | 0 0                      | 6.07                     | 1.01                            | 0.00| 9.04                     | 1.8                     | 0.01                     |
| 1.25 50 0 11.5          | 0 0                      | 6.07                     | 1.01                            | 0.00| 9.04                     | 1.8                     | 0.01                     |
| 1.40 10 0 11.5          | 0 0                      | 6.07                     | 1.01                            | 0.00| 9.04                     | 1.8                     | 0.01                     |
| 1.40 30 0 11.5          | 0 0                      | 6.07                     | 1.01                            | 0.00| 9.04                     | 1.8                     | 0.01                     |
| 1.40 50 0 11.5          | 0 0                      | 6.07                     | 1.01                            | 0.00| 9.04                     | 1.8                     | 0.01                     |

TABLE 3—Continued
On this approximation then,

$$\tau_{\text{cool}}(T_{WD}) \approx 8 \times 10^7 \left( \frac{10^7 \text{ K}}{T_{WD}} \right)^{2.5} \text{ yr.} \quad (4)$$

An approximation to the accreted mass can be derived from the requirement that the pressure at the base of the envelope

$$P_b = \frac{G M_{WD} m_{\text{acc}}}{4 \pi R_{WD}^4 (M_{WD})}$$

exceeds a critical prescribed value, say, $P_{\text{crit}} \approx 10^{19} \text{ dyn cm}^{-2}$, in order to obtain a TNR (Fujimoto 1982). Figure 3, based on grid results, presents yet another numerical validation of $P_{\text{crit}}$ having values of the order of $10^{18} \sim 10^{19} \text{ dyn cm}^{-2}$. We note that at low-WD temperatures the range of $P_{\text{crit}}$ values is wider, the critical pressure changing with both $M$ and $M_{WD}$. Finally, using the Nauenberg (1972) approximation to the Hamada-Salpeter (1961) WD mass-radius relation,

$$\frac{R_{WD}}{R_{\odot}} \approx 1.12 \times 10^{-2} \left[ \left( \frac{M_{WD}}{M_{\odot}} \right)^{-2/3} - \left( \frac{M_{WD}}{M_{\odot}} \right)^{2/3} \right]^{1/2}, \quad (6)$$

we obtain $m_{\text{acc}} = m_{\text{acc}}(M_{WD})$. Substitution of the analytic relations into equation (1) yields the desired surface.

A more accurate result is obtained numerically. First, we calculate cooling curves $T_{WD}(t)$ for all the WD masses of the grid (indeed, they are almost independent of $M_{WD}$). We define the cooling timescale at any point by $\tau_{\text{cool}} = (d \ln T/dt)^{-1}$ and calculate it for the $T_{WD}$ values of the grid. Then, for each pair $(T_{WD}, M)$, we solve $m_{\text{acc}}(M_{WD}, T_{WD}, M) = M_{WD}$ to obtain $M_{WD}$ by interpolation on the grid results. We thus obtain the points that satisfy equation (1), defining a surface within the parameter space. It is the bottom surface shown in Figure 4. The surface exhibits a monotonic decline in $M_{WD}$ for each $T_{WD}$, from lower to higher $M$, but also some decline of $M_{WD}$ at the same accretion rate from higher to lower $T_{WD}$. As mentioned earlier, the cooling timescales increase with decreasing temperatures. Because longer $\tau_{\text{cool}}$ (relative to $\tau_{\text{acc}}$) is what we require for a nova outburst to develop, the WD mass restriction is weaker for lower temperatures. In principle, if $m_{\text{acc}}$ were mainly a function of $M_{WD}$, the condition for a nova outburst to occur would be eventually satisfied for any WD and accretion rate, because $\tau_{\text{cool}}$ would increase, while $\tau_{\text{acc}}$ would remain fixed. However, calculations show that as $T_{WD}$ decreases, $m_{\text{acc}}$ becomes ever more strongly dependent on $T_{WD}$, increasing steeply as the WD cools. Thus, below a certain value of $T_{WD}$, the relation $\tau_{\text{cool}} < \tau_{\text{acc}}$ is maintained while both timescales increase (cf. Schwartzman et al. 1994). In other words, when mass accumulates slowly as the WD cools down, the accreted mass remains below the critical value while both increase with time.

The cooling time constraint is clearly illustrated in Figure 5, where examples of the evolution of two characteristics are shown: the maximum temperature within the burning envelope $T_{\text{max}}$ and the total luminosity $L$ for two-parameter combinations. A range of accretion rates is displayed, following the evolution over a period of one full cycle, from the beginning of accretion through outburst and decline. The lowest accretion rate for which a “true” mass-ejecting nova is obtained is $M = 5 \times 10^{-13} M_{\odot} \text{ yr}^{-1}$ (and even then, not for all parameter combinations, as seen in the results grid). We see in Figure 5 that for a slightly lower accretion rate value $2.5 \times 10^{-13} M_{\odot} \text{ yr}^{-1}$, the WD cools down faster than it is able to accrete sufficient mass to reach TNR conditions. This is clearly seen in the $T_{\text{max}}(t)$ plot; the curve gradually declines, without having reached an outburst. Equally, the luminosity curve remains flat for the lowest $M$. The curves for the higher accretion rates exhibit outburst events in which $T_{\text{max}}(t)$ exceeds $10^8$ K and the bolometric luminosity increases above $(4-5) \times 10^4 L_{\odot}$. Note also the obvious but nicely demonstrated fact that as we move from lower to higher accretion rates, the outburst occurs earlier on the timeline; hence, the recurrence period becomes shorter.

### 3.2. Nuclear versus Gravitational Energy

The source of energy for CN outbursts is nuclear energy released during the TNR, by burning a fraction $f$ of the hydrogen content of the accreted mass. Thus

$$E_{\text{nuc}} = f X m_{\text{acc}} Q, \quad (7)$$

where $X \approx 0.7$ is the hydrogen mass fraction in the outer layers of the nova companion star and $Q \approx 6 \times 10^{18}$ ergs g$^{-1}$ is the energy released per gram of burnt hydrogen.

The greatest part of the energy released at outburst is used in lifting the ejected shell from the gravitational potential well of the WD. This gravitational energy may be roughly approximated by

$$E_{\text{grav}} = \frac{G M_{WD} m_{\text{ej}}}{R_{WD}}. \quad (8)$$

Obviously, a mass-ejecting outburst can take place only if $E_{\text{nuc}} > E_{\text{grav}}$. Therefore, a limiting surface may be defined by requiring $E_{\text{nuc}} = E_{\text{grav}}$,

$$\frac{m_{\text{acc}}(M_{WD}, M, T_{WD})}{m_{\text{ej}}(M_{WD}, M, T_{WD})} = \frac{G M_{WD}}{f X Q R_{WD}} = 0. \quad (9)$$

As a rough analytical estimate, the difference between $m_{\text{acc}}$ and $m_{\text{ej}}$ may be neglected, in which case equation (9) simply imposes an upper limit on $M_{WD}$ for a given value of $f$ (e.g., $1.22 M_{\odot}$ for...
Fig. 2.—Three-dimensional plots of four major properties out of the complete result grid. Each plot represents the property as function of $[\dot{M}, M_{\text{WD}}]$ for a representative WD temperature (stated in units of $10^6$ K). In (a), the white surface represents the critical Eddington luminosity, emphasizing the domains where the luminosity either surpasses or is lower than $L_{\text{Edd}}$.

| Parameter Combinations | Characteristic | Max Value | Min Value |
|-------------------------|---------------|-----------|-----------|
| $m_{\text{acc}}$       | 5.40E−04     | 0.65      | 10        | $-12.3$ | 6.83E−08 | 1.40 | 50 | $-11$ |
| $m_{\text{ej}}$       | 6.66E−04     | 0.65      | 10        | $-12$   | 5.31E−08 | 1.40 | 10 | $-7$ |
| $Z_{\text{ej}}$       | 0.63         | 0.65      | 30        | $-12.3$ | 0.02    | 1.00 | 50 | $-7$ |
| $X_{\text{ej}}$       | 0.61         | 1.40      | 50        | $-12$   | 0.12    | 0.65 | 30 | $-12.3$ |
| $T_{\text{max}}$      | 4.7          | 1.40      | 10        | $-11$   | 1.1     | 0.65 | 50 | $-11$ |
| $v_{\text{max}}$      | 5270         | 1.40      | 10        | $-10$   | 139     | 0.65 | 30 | $-8$ |
| $v_{\text{avg}}$      | 3860         | 1.25      | 10        | $-11$   | 122     | 0.65 | 10 | $-8$ |
| $L_{\text{4, bol, max}}$ | 90          | 1.00      | 50        | $-12.3$ | 1.5     | 0.65 | 10 | $-8$ |
| $M_{\text{bol, max}}$ | $-10.2$     | 1.00      | 50        | $-12.3$ | $-5.7$ | 0.65 | 10 | $-8$ |
| $R_{\text{bol}}$      | 20.9         | 0.65      | 10        | $-12.3$ | 5.8     | 1.40 | 50 | $-7$ |
| $J_{3, \text{bol}}$   | 120 yr       | 0.65      | 50        | $-8$    | 3.05 days | 1.40 | 30 | $-12$ |
| $t_{\text{fil}}$      | 67 yr        | 0.65      | 10        | $-11$   | 0.68 days | 1.40 | 10 | $-10$ |
| $P_{\text{osc}}$      | 1.08E+09 yr  | 0.65      | 10        | $-12.3$ | 281 days | 1.40 | 10 | $-7$ |
$f = 0.1$ and $1.42 \, M_\odot$ for $f = 0.3$), a flat surface parallel to the [$T_{\text{WD}}, \dot{M}$] plane in the parameter space. This is already a more severe constraint than just the Chandrasekhar mass limit. Using the results of the numerical computations and taking $f = 0.3$ for illustration, we obtain a more significant constraint in the form of a slightly curved surface, the top surface in Figure 4.

### 3.3. Accretion versus Eddington Luminosity

For the nova progenitor to be able to accrete material during the quiescence phase, the accretion luminosity $L_{\text{acc}}$ must be lower than the Eddington critical luminosity $L_{\text{Edd}}$. Otherwise, radiation pressure would push away and dissipate the accreted material. In fact, the total (net) luminosity of the accreting star should be lower than the Eddington limit, but in most cases the WD intrinsic luminosity is negligible compared with $L_{\text{acc}}$. The accretion luminosity is given by

$$L_{\text{acc}} = \alpha \, G M_{\text{WD}} \dot{M} / R_{\text{WD}},$$

(10)

where $\alpha \approx 0.15$, taking into account accretional heating (Regev & Shara 1989) and again using equation (6) for $R_{\text{WD}}(M_{\text{WD}})$. Thus, a third limiting surface, obtained by equating $L_{\text{acc}}$ and $L_{\text{Edd}},$

$$\dot{M} = \frac{4\pi c}{\alpha \kappa_e} R_{\text{WD}}(M_{\text{WD}}) = 0$$

(11)

(where $\kappa_e$ is the electron scattering opacity coefficient), is shown in Figure 4. We note that the result, which in this case relies solely on analytical considerations, is independent of the WD temperature, although it might be indirectly affected by it to some extent through a more realistic opacity coefficient. It is not surprising that the allowed accretion rates decrease with increasing $M_{\text{WD}}$.

### 3.4. Degeneracy and the WD Core Temperature

According to Figure 4, the relevant region in parameter space in which nova eruptions can occur is tube-shaped. Our calculations assumed that the relevant range of WD core temperatures is $(10 - 50) \times 10^6 \, \text{K}$, taking the discrete representative values of 10, 30, and $50 \times 10^6 \, \text{K}$. In fact, the WD temperature is restricted from above and below, as we now show.

We can obtain a rough estimate for the upper limit on $T_{\text{WD}}$ by setting the Fermi parameter $\varepsilon_f \propto (\ln P - 2.5 \ln T)$ to zero at the base of the accreted layer, where the pressure, approximately given by equation (5), is of the order of $10^{19} \, \text{dyn cm}^{-2}$. Thus, assuming that $T_{\text{WD}} \approx T_{\text{nuc}}$, we have

$$T_{\text{WD}} \approx 4.7 \times 10^7 \left( \frac{P_{\text{nuc}}/10^{19} \, \text{dyn cm}^{-2}}{e^{\varepsilon_f}} \right)^{2/5} \, \text{K},$$

(12)

![Figure 3](image3.png)

**Figure 3.**—Values of the pressure at the base of the envelope prior to the TNR, grouped by the three main $T_{\text{WD}}$ values as function of the accretion rate calculated from grid results (according to eq. [5]). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 4](image4.png)

**Figure 4.**—Combined restricting surfaces, confining a volume within the three-dimensional parameter space in which conditions for nova outbursts are satisfied. The bottom surface corresponds to the heating vs. cooling criterion (§ 3.1); the top WD mass-limiting surface corresponds to the nuclear vs. gravitational energy considerations (§ 3.2); the left mass transfer rate–limiting surface relates to the accretion vs. Eddington luminosity (§ 3.3). Positions of the grid parameter combinations that successfully produced nova eruptions are plotted within the confined volume.

### Table 5

| Characteristic | Observed Ranges | Observed Exceptions | Calculated Ranges |
|---------------|-----------------|---------------------|-------------------|
| $M_{\text{max}}$ | $-6$ to $-9$ | $-10$ (V1500 Cyg) | $-5.7$ to $-10.2$ |
| $A$ | $7$–$16$ | $19.3$ (V1500 Cyg) | $5.8$–$20.9$ |
| $t_1$ | $4$–$300$ days | SymN: more | $0.76$ days to $67$ yr |
| $m_{\text{ej}}$ | $(1$–$30)\times 10^{05} \, M_\odot$ | RN: less | $5.3E$–$08$ to $6.6E$–$04$ |
| $Z_{\text{ej}}$ | $0.04$–$0.41$ | $0.86$ (V1370 Aql) | $0.02$–$0.63$ |
| $Y_{\text{ej}}$ | $0.21$–$0.48$ | $0.1$ (V1370 Aql) | $0.12$–$0.60$ |
| $v_{\text{exp}}$ | $350$–$2500$ km s$^{-1}$ | SymN: $\sim 100$ km s$^{-1}$ | $122$–$3860$ |

* Average expansion velocities.
where $P_e$ is the electron pressure. Hence, if the condition of strong electron degeneracy is expressed as $\epsilon_f \succeq 0$, it results in the requirement $T_{WD} \leq 5 \times 10^7$ K. Therefore, the tube of Figure 4 has a high-temperature end at a $T_{WD}$ of about 50 million degrees. Does it have a low-temperature end?

A lower limit on $T_{WD}$ results from the following considerations. When material starts accumulating on the WD surface, its temperature is lower than the core temperature and also lower than the ignition temperature (otherwise hydrogen would ignite immediately and quietly, rather than explosively under degenerate conditions). As the material becomes compressed, it releases gravitational energy, which is absorbed, in part, by the accreted layer, while in part it is conducted into the core. If the absorption of heat is sufficiently effective to raise the temperature of the hydrogen-rich material, then eventually the temperature at the bottom of the hydrogen-rich layer will become high enough for hydrogen to ignite. The nuclear luminosity, low at first, will soon become the dominant energy source. Therefore, the restrictive condition for a nova outburst to occur is that compressional heating be sufficiently effective in order to raise the temperature to the ignition value of roughly $15 \times 10^6$ K required by the CNO cycle. The competition between compressional heating power and the rate of heat conduction can only be decided by solving the energy equation. Although it is reasonable to assume that accumulation of matter at a high rate and/or a massive WD will tip the scale in favor of heating, an accurate analytical result is difficult to obtain; it would require too many simplifying assumptions and approximations. We therefore resort to numerical modeling in order to obtain an estimate on the limiting temperature.

A few additional models beyond the grid described in § 2 were calculated for WDs cooler than $10^7$ K; indeed, very old WDs in binary systems may reach temperatures below $10^7$ K (Nelson et al. 2004). For high accretion rates ($M = 10^{-9} M_\odot$ yr$^{-1}$), we obtained nova outbursts even for $T_{WD} = 3 \times 10^6$ K, and the results were very similar to those obtained for $T_{WD} = 10^7$ K. At the other $M$ end, adopting $M = 10^{-12} M_\odot$ yr$^{-1}$ and $M_{WD} = 1 M_\odot$, we did not obtain an outburst for $T_{WD}/10^6 K = 5, 7,$ and 8; the accreted material cooled continuously. However, for $T_{WD} = 9 \times 10^6$ K a regular nova outburst was obtained. Thus, the lower limit for $T_{WD}$ is strongly dependent on $M$, as expected, and in agreement with the conclusions of Schwartzman et al. (1994). In the case of a very cold WD, heating is impeded by heat conduction into the hydrogen-depleted deep core and may be altogether suppressed. However, the impediment is less severe at high accretion rates as a result of the rapid supply of accretion energy.

We also checked the effect of $M_{WD}$. Taking $T_{WD}/10^6 K = 8$ (no nova for $M_{WD} = 1 M_\odot$) but increasing the WD mass to 1.25 $M_\odot$, we did obtain a nova outburst. In this case we found the lower limit to be below $8 \times 10^6$ K but above $7 \times 10^6$ K. Thus, a lower limit to the WD core temperature exists for any combination of WD mass and accretion rate, but for high accretion rates this limit is so low that it requires more than the age of the universe for a cooling WD to reach it. Hence, the constraint on $T_{WD}$ becomes significant only in the case of low accretion rates.

Finally, since it is not clear that erupting WDs may cool down to the theoretical lower limit, and since between the lower limit and $10^7$ K the results are not highly sensitive to the precise value of $T_{WD}$ (cf. Schwartzman et al. 1994), we chose $10^7$ K as the lowest $T_{WD}$ value in this study, as in Paper I. However, accretion on very cold WDs will be investigated further in a future paper, since it is this part of the parameter space that appears likely to shed light on the most peculiar observed novae, showing very high luminosities, relatively low expansion velocities, and, apparently, large ejected masses.

### 3.5. The Full Parameter Space

The three surfaces obtained so far and displayed in Figure 4 describe a restricted, tube-shaped region within the three-dimensional parameter space in which conditions for nova outbursts are expected to be satisfied. The additional constraints imposed by the electron degeneracy and mainly concerning the WD temperature determine the ends of the tube.

Hence, there appears to be a confined volume of parameter space in which conditions for classical nova outbursts are satisfied. Plotted on top of these surfaces are all of the parameter combination positions that produced “well-behaved” mass-ejecting nova outbursts in our runs (including the three runs for the lowest WD mass of 0.40 $M_\odot$ and two runs for WD temperatures lower than $10^7$ K, as analyzed in the previous section). There are six “mass-ejecting” parameter combinations that lie on the boundaries of the restricting volume denoted in Figure 4.

![Figure 5](image-url)

Fig. 5.—Evolution in time of two characteristics for different accretion rates: the maximum temperature (within the burning shells) $T_{\text{max}}$ and the luminosity $L$ for $M_{WD} = 1.00 M_\odot$, $T_{WD} = 30 \times 10^6$ K (left) and $M_{WD} = 1.25 M_\odot$, $T_{WD} = 50 \times 10^6$ K (right).
4. SUMMARY AND CONCLUSIONS

In the framework of this study we have extended the three-dimensional parameter grid of multicycle nova evolution to cover combinations with low accretion rates. The main results of this study may be summarized as follows:

1. The entire range of observed nova characteristics is thoroughly covered by the complete grid of models. Even exceptional observed values such as outburst amplitudes of over 19 mag and very high Z are covered by the new grid of results. The majority of the calculated maximum values for the various characteristics is obtained for the lower M runs, down to the lowest accretion rate value of $5 \times 10^{-13} M_{\odot}$ yr$^{-1}$.  

2. There has been a problem deriving ejected mass values as high as those deduced observationally. Moreover, a strong case has been made that much of the ejecta from each nova is missed by observers (Ferland 1998). We have managed to produce a notably high $m_{ej}$ value of $6.6 \times 10^{-4} M_{\odot}$, which is almost a factor of 3 greater than the maximum value obtained in the original grid (Paper I). This high $m_{ej}$ was produced for a low $M_{WD}$ at low M (combination 065.10.12). The former maximum $m_{ej}$ was obtained for the same $[M_{WD}, T_{WD}]$ combination but with $M$ of $10^{-10} M_{\odot}$ yr$^{-1}$.  

3. For the new runs of lower $M$ values we obtain maximum outburst luminosities surpassing the Eddington luminosities (calculated for electron scattering opacities) by factors of up to a few tens for the whole range of WD masses. The highest super-Eddington luminosities (with correspondingly highest derived outburst amplitudes) are obtained for fast to very fast novae.  

4. We predict the existence of remarkably small amplitude novae with decline times ranging from a week to over a year.  

5. In previous studies as well as this one, we have seen that by extending the parameter space new features emerge. That raised the question whether the parameter space is at all limited, and if so, what are the exact limits on the three basic independent parameters? Using both models and analytic relations, we derived a confining volume within the three-dimensional parameter space in which conditions for nova outbursts are satisfied. Thus, the parameter space is indeed limited. As the new grid of models now covers the entire parameter space (assuming WDs composed of CO, but see below), it should enable us to provide explanations for most (all?) novae, including the more peculiar objects among them. This, however, will be the subject of a later study. Of special significance is the existence of a critical accretion rate $M_{crit}(M_{WD}, T_{WD})$ below which conditions are not sufficient to trigger a TNR. The critical mass transfer rate is indeed very low but seems to be relevant for old close interacting binaries with very low mass companions. For cases like these, the determination of limits is important.  

6. Although this study covers the entire range of WD masses, practically up to the Chandrasekhar limit, the assumed composition of the WD core is C and O (in equal mass fractions) for all models. At first glance, this might appear unrealistic; very massive WDs are believed to emerge after the carbon burning stage in the evolution of a star, and they should be composed of oxygen, neon, and magnesium (Gutiérrez et al. 1996). Although the mass fractions of these elements and their dependence on the WD mass are still uncertain issues, clearly such WDs should not contain carbon. On the other hand, our grid of models produces results that cover the entire range of observed characteristics (ignoring the breakdown of the total heavy element mass fraction $Z_{ej}$). This seems to indicate that they are more widely applicable than those imposed by the assumption on the WD composition. In fact, the mechanism of nova eruptions revolves around thermonuclear instability under conditions of electron degeneracy. Electron degeneracy, in turn, is determined by $\mu_e = (A/Z)$, which assumes the same value for helium- and carbon-burning products. In addition, the CNO cycle is not sensitive to the initial CNO breakdown. Consequently, we should not expect significant differences in the outburst characteristics of WDs that differ only in composition, except for the breakdown of $Z_{ej}$. In order to test this expectation, we have repeated the calculations for two illustrative models after replacing the carbon in the WD core by neon. The results are summarized in Table 6, and indeed they confirm our prediction. Thus, it is not surprising that the entire range of nova characteristics is reproduced by our CO models, and the results should be applicable to novae in general.  

7. An intriguing issue related to the investigation of novae is the question of the ultimate fate of the WD. Will it be losing or gaining mass after multiple successive cycles? Will it be able to reach $M_{ch}$, thus acting as a possible SN Ia precursor or not? The ratio $m_{ej}/m_{acc}$ is shown in Figure 6 for all parameter combinations. We note that it falls below unity only in a small region of the parameter space, thus strongly reducing the possibility of SNe Ia resulting from accreting WDs. Nevertheless, this region

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**Table 6**

|                | CO | ONe |
|----------------|----|-----|
| 1.25, 10, −11  |
| $m_{ej}$      | 3.6E−05 | 3.67E−05 | 4.74E−07 | 2.89E−07 |
| $y_{ej}$      | 0.3155 | 0.3123 | 0.4732 | 0.5129 |
| $z_{ej}$      | 0.2092 | 0.2179 | 0.1521 | 0.1508 |
| $C_{ej}$      | 3.35E−02 | 1.970E−02 | 2.430E−02 | 1.143E−02 |
| $C_{ej}$      | 3.13E−02 | 2.089E−02 | 2.485E−02 | 8.148E−03 |
| $N_{ej}$      | 6.545E−02 | 3.806E−02 | 9.392E−02 | 4.706E−02 |
| $O_{ej}$      | 6.660E−02 | 3.321E−02 | 4.191E−03 | 1.147E−03 |
| $O_{ej}$      | 1.165E−02 | 9.241E−05 | 2.092E−04 | 1.402E−04 |
| $O_{ej}$      | 6.157E−04 | 7.729E−05 | 1.342E−05 | 8.500E−06 |
| $N_{ej}$      | 3.38E−07 | 6.579E−02 | 1.372E−07 | 1.358E−03 |
| $N_{ej}$      | 3.53E−09 | 6.541E−04 | 1.047E−10 | 1.141E−06 |
| $M_{ej}$      | 2.861E−08 | 9.611E−03 | 5.238E−09 | 3.640E−05 |
| $A_{ej}$      | 2.09E−08 | 7.929E−03 | 6.355E−09 | 4.258E−05 |
| $A_{ej}$      | 1.027E−08 | 3.137E−03 | 1.251E−09 | 7.662E−06 |
| $Z_{ej}$      | 1.046E−07 | 2.600E−02 | 6.087E−07 | 8.147E−02 |

*a* Heavy elements $Z_{ej}$ breakdown.
does lead continuously from low mass to the Chandrasekhar limit provided the accretion rate remains very high all along. Therefore, it is possible, at least in principle, for a WD to grow by accretion up to $M_{\text{Ch}}$. In order to further investigate this problem, we need to consider the dynamic evolution of the binary system that determines the evolution of mass transfer rate. Given the accretion rate as a function of time $\dot{M}_{\text{acc}}(t)$, which changes with binary separation and masses, we can calculate the change of $M_{\text{WD}}$ with time,

$$M_{\text{WD}}(t) = \int \{M_{\text{acc}}(t) - \dot{m}_{\text{ej}} \dot{M}_{\text{WD}}(t)\} \, dt,$$

where

$$\dot{m}_{\text{ej}} \dot{M}_{\text{WD}}(t) = \frac{m_{\text{ej}}}{P_{\text{rec}}}$$

is obtained by interpolation on the grid. An example is shown in Figure 7, based on an evolving accretion rate kindly supplied by J. Hurley, for a binary system of initial masses $0.6 \, M_\odot$ (secondary) and $0.9 \, M_\odot$ (primary).

8. Finally, in a similar manner, the evolving luminosity of an accreting WD may be constructed as a quasi-periodic function of the variables $L_{\text{acc}}$, $L_{\text{max}}$, $T_{\text{WD}}$, and $P_{\text{rec}}$ supplied by the grid, all of which change with time as $M_{\text{WD}}$ and $\dot{M}_{\text{acc}}$ change. Thus, in the future, an important use of the nova grid will be the parameterization of nova evolution for long-term modeling of large stellar systems.

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Fig. 6.—Color maps displaying shades that correspond to values of the ratio $m_{\text{ej}}/m_{\text{acc}}$ in the [$M_{\text{WD}}$, log $M$] plane. A value of 1 corresponds to an unevolving WD mass, <1 an increase in $M_{\text{WD}}$, and >1 a decrease in $M_{\text{WD}}$. The three panels correspond to the three $T_{\text{WD}}$ values, 10, 30, and $5 \times 10^6$ K, from top to bottom.

Fig. 7.—Example calculation of $M_{\text{WD}}(t)$ based on an evolving $M$ for initial masses of 0.6 and 0.9 $M_\odot$ for the secondary (dashed line) and primary (solid line), respectively. [See the electronic edition of the Journal for a color version of this figure.]
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YARON ET AL.

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