CARBON–NITROGEN–OXYGEN “BREAKOUT” AND NUCLEOSYNTHESIS IN CLASSICAL NOVAE

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ABSTRACT

For very slow white dwarf accretors in cataclysmic variables, Townsley & Bildsten found a relation between the accretion rate \( \dot{M} \) and the central temperature \( T_c \) of the white dwarf. According to this relation, for \( \dot{M} \) less than \( 10^{-10} M_\odot \text{yr}^{-1} \), \( T_c \) is much lower than \( 10^7 \text{K} \). Motivated by this study, we follow the thermonuclear runaway on massive white dwarfs (\( M_{\text{WD}} = 1.25–1.40 M_\odot \)) with \( T_c \) lower than \( 10^7 \text{K} \), accreting matter of solar composition. We demonstrate that in this range of the relevant parameter space (\( T_c, M_{\text{WD}}, \text{and} \ M \)), the slope of the relation between the peak temperatures achieved during the runaway and \( T_c \) becomes much steeper than its value for \( T_c \) above \( 10^7 \text{K} \). The peak temperatures we derive can lead to nuclear breakout from the conventional “hot carbon–nitrogen–oxygen” cycle. When breakout conditions are achieved the heavy-element abundances can show a much wider variety than what is possible with the common enrichment mechanisms.

Key words: binaries: close – novae, cataclysmic variables – stars: abundances – white dwarfs

1. INTRODUCTION

Classical nova explosions are a consequence of the unstable ignition of hydrogen in accreted envelopes on white dwarfs in close binary systems. Peak temperatures in the range \( \approx 200–350 \text{ million K} \) achieved in the ensuing thermonuclear runaway yield burning of hydrogen to helium by means of the hot carbon–nitrogen–oxygen (CNO) cycles, with the associated nuclear energy release \( \approx 5 \times 10^{18} \text{erg g}^{-1} \) powering the outburst. One-dimensional numerical simulations (Starrfield et al. 1974, 1985; MacDonald 1980, 1983; Narita et al. 1980; Prialnik et al. 1978; Prialnik 1986; Iben 1982; Truran 1982; Jose & Hernanz 1998) have established that many features of classical novae in outburst can be understood on this model for representative choices of white dwarf mass (\( M_{\text{WD}} \approx M_\odot \)) and the accretion rate (\( \dot{M} \approx 10^{-10}–10^{-9} M_\odot \text{yr}^{-1} \)). More details can be found in a review by Starrfield (2002).

Observational studies of novae reveal that while the composition of the accreted matter is consistent with solar abundances, the ejecta are characterized by high concentrations of heavy elements (e.g., C, N, O, Ne, Mg) relative to solar abundances (Gehrz et al. 1998). For most nova models, numerical simulations predict that peak temperatures achieved in the runaways do not exceed the critical value (\( T_{\text{eu}} \approx 4 \times 10^6 \text{K} \)) at which “breakout” from the hot CNO cycles can occur (Wiescher et al. 1986; Yaron et al. 2005). This has led to the conclusion accepted by most nova theorists that the observed enhancements reflect the effects of “dredge-up” of CO- or O-, Ne-, and Mg-rich matter from the underlying white dwarf star (Livio & Truran 1990). We show here that in a restricted, and therefore rare, region of the relevant parameter space (\( T_c, M_{\text{WD}}, \text{and} \ M \)), breakout burning can lead to heavy-element enrichment caused only by breakout burning.

In a recent exploration of the thermal state of accreting white dwarfs experiencing classical nova explosions, Townsley & Bildsten (2004) have demonstrated that there exists a population of massive white dwarfs (\( M > 1.2 M_\odot \)) accreting at rates as low as \( 10^{-11} M_\odot \text{yr}^{-1} \), with central temperatures \( T_c \) of \( \approx 5 \times 10^6 \text{K} \). The combination of cold white dwarfs with low accretion rates leads to novae runaways with massive envelopes and exceptionally high peak temperatures. We show here that for a significant part of the relevant parameter space (\( T_c, M_{\text{WD}}, \text{and} \ M \)), the peak temperature at runaway, \( T_{\text{peak}} \), is well above the minimum value for CNO “breakout.”

In Section 2, we briefly describe the hydrodynamic solver and the reaction network. Section 3 presents the main results of our models. We conclude (Section 4) with a discussion of the possible observational consequence of our results and of their consistency with previously published models.

2. THE HYDRODYNAMIC SOLVER

The accretion process and the runaway are studied with a one-dimensional Lagrangian implicit code that integrates the equations of momentum and energy conservation assuming spherical symmetry. The energy transfer includes a radiative term and a convective term. The radiative component is a diffusive flux. The radiative diffusion coefficient is determined according to the Iglasias & Rogers opacity tables (Iglasias & Rogers 1996) for temperatures above \( \log(T) = 3.75 \text{K} \) and according to the Alexander fit for lower temperatures. Electron conductive opacities are computed according to the Itoh fit (Itoh et. al. 1983). The convective energy flux is computed according to the mixing length theory (Spiegel 1963). Within a convective zone, the matter is mixed using a diffusion coefficient that takes into account both the local convective velocity and the mixing length (which is taken to be two pressure scale heights):

\[
D_c = v_c l/3,
\]

where \( D_c \) is the diffusion coefficient, \( v_c \) is the one-dimensional convective velocity derived from the mixing length theory, and \( l \) is the effective mixing length.

In the present survey, we ignore element settlement by diffusion and undershoot mixing. The equation of state employed to derive the energy and pressure for given temperature density and chemical abundances is an ideal gas for the ions and involves a table fit for the numerical integration of the Fermi integrals for the electrons (and positrons). The rate of nuclear energy production and the abundance changes is calculated with a 160 nuclei network. The electron capture channel in the PP cycle (called
the PeP reaction) takes into account the extra electron density term (Bahcall & May 1969). The chemical elements included in the network were chosen in a proper way to provide an accurate history of the proton-rich composition of the accreted envelope.

Accreted material is added in each time step to the outermost zone as dictated by the accretion rate and the size of the time step. The outermost zone in the numerical grid is divided into two grid zones whenever the mass of the zone is greater than a specified value (taken to be twice the specified mass resolution in the envelope). The mass is added with the instantaneous thermodynamic properties of the outermost grid zone. The same one-dimensional solver was used in order to produce the initial models for all our two-dimensional novae studies (Glasner & Livne 1995; Glasner et al. 1997, 2007). More details about the solver and its abilities will be given in a forthcoming paper.

3. MAIN RESULTS

In this Letter, we follow the accretion process and the ensuing runaway for cold massive white dwarfs accreting at very low rates. Under such conditions, the peak temperature achieved in the runaway is expected to be quite high. In order to trace the nucleosynthesis history, we solve the hydrodynamic equations coupled with a nuclear reaction network that includes 160 nuclei up to $^{64}$Ni. As we noted in Section 1, our interest in this poorly explored region of the nova parameter space was motivated by the results published by Townsley & Bildsten (2004). In our survey, we include white dwarf cores in the mass range 1.2–1.4 $M_{\odot}$ accreting matter of solar composition (Anders & Grevesse 1989) at rates ranging from $10^{-11} M_{\odot}$ yr$^{-1}$ to $10^{-10} M_{\odot}$ yr$^{-1}$. The initial models are cold white dwarf cores in hydrostatic and thermal equilibrium characterized by their central temperature ($T_c$) with values ranging from $T_c = 4 \times 10^6$ K to $2 \times 10^7$ K.

The combination of very low central temperatures $T_c$ and very slow accretion rates, which demands the use of a greatly expanded nuclear reaction network, is the unique feature of this survey. In this Letter, we therefore focus on the main outcome: the extremely high peak temperatures achieved in the runaway and the induced nucleosynthesis. The main features of the time history of the total burning rate, the bolometric luminosity, and the peak temperature at the base of the envelope are quite similar for all studied models.

Prior to the runaway, some of the considered models accrete exceptionally high envelope masses $\delta M_{\text{ignite}}$. The ensuing thermonuclear runaways are characterized by very high peak temperatures, $T_{\text{peak}}$. In Figure 1, we present the relation between $T_{\text{peak}}$ and $T_c$ for white dwarf masses and accretion rates ($M$) that are relevant to this work; in Figure 2, we show the dependence of $\delta M_{\text{ignite}}$ on the same variables. The common feature for all the considered models is the increase of $T_{\text{peak}}$ with decreasing $T_c$: $T_{\text{peak}}$ is greater than $T_{\text{crit}}$ only for very cool white dwarfs ($T_c \lesssim 5 \times 10^6$–$7 \times 10^6$).

The high temperature and high density at the bottom of the accreted envelope and the comparatively long timescale for which these conditions prevail, defined as $\delta t_{\text{break}}$, allow a significant epoch of explosive hydrogen burning. In Table 1, we

![Figure 1](image1.png)

**Figure 1.** Peak temperature achieved in the runaway as a function of the central temperature $T_c$ of the white dwarf.

![Figure 2](image2.png)

**Figure 2.** Accreted mass at ignition as a function of the central temperature $T_c$ of the white dwarf.

| Model | $M_{\text{WD}}$ ($M_{\odot}$) | $T_c$ (10$^6$ K) | $M$ ($10^{-11} M_{\odot}$ yr$^{-1}$ | $\delta M_{\text{ignite}}$ ($10^{-5} M_{\odot}$) | $T_{\text{peak}}$ (10$^6$ K) | $\delta t_{\text{break}}$ (s) |
|-------|-----------------|-----------------|-------------------|-----------------|-----------------|-----------------|
| s135u | 1.35            | 4.00            | 1                 | 6.38            | 5.14            | 14500           |
| m135k | 1.35            | 5.88            | 1                 | 3.90            | 4.57            | 12000           |
| m135j | 1.35            | 7.65            | 1                 | 2.70            | 4.23            | 9500            |
| m135i | 1.35            | 9.03            | 1                 | 2.06            | 4.00            | 7000            |
| m135r | 1.35            | 4.00            | 10                | 3.40            | 4.42            | 11000           |
| m135q | 1.35            | 5.88            | 10                | 2.63            | 4.16            | 9000            |
| m135p | 1.35            | 7.65            | 10                | 2.01            | 3.92            | 7000            |
| m135o | 1.35            | 9.03            | 10                | 1.61            | 3.51            | 1000            |
| m13k  | 1.30            | 4.00            | 1                 | 9.62            | 4.29            | 7000            |
| m13ed | 1.30            | 6.00            | 1                 | 5.41            | 3.82            | 4250            |
| s125y | 1.25            | 4.00            | 1                 | 13.02           | 3.68            | 3000            |
present the main input parameters of our models—$M_{WD}$, $T_{c}$, and $M$—together with the major hydrodynamic outcome quantities that are relevant to the burning: $\delta M_{\text{gntm}}$, $T_{\text{peak}}$, and $\delta_{\text{break}}$.

As expected, hydrogen burning under such extreme conditions yields “breakout” from the conventional “hot CNO” cycle. During most of the time that the temperature stays above $T_{\text{crit}}$, the envelope is fully convective. Therefore, the nuclei produced in the burning are spread homogeneously over the entire envelope. Once the shell temperature falls below $T_{\text{crit}}$, the overall abundance of heavy nuclei is not expected to change during the later stages of the runaway. We selected one representative model from Table 1 (s135u for $M = 1.35 \, M_{\odot}$) and present its initial and final abundance patterns as a function of mass number ($A$) in Figure 3. We note that both the mass of heavy elements ejected and their distribution depend on the details of the mass ejection mechanism; we will present a study of the ejection phase in a forthcoming paper.

4. DISCUSSION

There is a well-established consensus in the nova research community that the relevant parameters that define the thermonuclear runaway are the white dwarf mass ($M_{WD}$), the central temperature ($T_{c}$), and the accretion rate ($M$), together with the composition of both the cold white dwarf and the accreted matter. This parameter space has been well explored by many researchers. Most of the previous studies were concerned with the range of central temperature above approximately $T_{c} = 10^{7} \, \text{K}$. But in a recent study, Townsley & Bildsten (2004) demonstrate that for very slow accretors there exists a steady state that determines a relation between $M$ and $T_{c}$. For $M$ less than $10^{-10} \, M_{\odot} \, \text{yr}^{-1}$, they find that $T_{c}$ is accordingly much smaller than $10^{7} \, \text{K}$. We therefore focused our study on massive white dwarfs with $T_{c}$ much lower than $10^{7} \, \text{K}$ and very slow accretion rates.

Since the expected temperatures at the runaway are above $T_{\text{crit}}$, the nuclear energetics and associated nucleosynthesis in our models were calculated with the use of an extended nuclear reaction network that included 160 nuclei up to $^{64}\text{Ni}$. Our results are generally consistent with those of the 1.3 $M_{\odot}$ model of Nariai et al. (1980), as is evident from Table 1. For $T_{c} = 10^{7} \, \text{K}$, both the accreted mass we obtain and the peak temperature $T_{\text{peak}}$ achieved during the runaway are consistent with the 1.35 $M_{\odot}$ model of Jose & Hernanz (1998) and with the 1.25 $M_{\odot}$ and 1.40 $M_{\odot}$ models of Yaron et al. (2005). For the conditions of central temperature and accretion rate, we took these from the results of Townsley & Bildsten (2004); the ignition mass we obtained is fully consistent with their stated results (compare our model s125y in Table 1 with their Figure 8).

Considering the dynamical aspects of our survey, we find a very steep dependence of the accreted mass and peak temperature at runaway on the central temperature $T_{c}$ below $T_{c} = 10^{7} \, \text{K}$. In contrast, the dependence in the more commonly studied region above $T_{c} = 10^{6} \, \text{K}$ is very shallow. This behavior can be understood on the basis of the well-known dependence of the burning rates on the temperature during the accretion stage. For the accreted matter of assumed solar composition, the slope of the logarithmic derivative of the burning rate changes in the vicinity of a temperature of $10^{7} \, \text{K}$ from four (PP cycle) to about 18 (CNO cycles). At central temperatures $T_{c} = 4 \times 10^{6} \, \text{K}$, relevant to cataclysmic variables below the period gap (Townsley & Bildsten 2004), the accreted envelope mass required to initiate runaway can be 4–5 times greater than for $T_{c} = 10^{7} \, \text{K}$ (Table 1). This result confirms that once the core of the white dwarf is sufficiently cool, massive hydrogen-rich accreted envelopes can exist at runaway even for very massive white dwarfs. Therefore, observational evidence for nova outbursts with massive accreted envelopes in the range of a few times $10^{-4} \, M_{\odot}$ cannot exclude very massive white dwarfs as the underlying core.

Most significant are the results we obtain for the nucleosynthesis occurring in our models. The high temperatures, far above $T_{\text{crit}}$, that can prevail for thousands of seconds lead to a very interesting path of nuclear burning up to the iron peak region. In order to identify the pattern of enrichment of iron group elements, we divided the elements included in our models into five groups: (1) hydrogen, (2) helium, (3) all the CNO cycle elements up to fluorine, (4) the elements from neon to calcium (the intermediate-mass elements), and (5) the iron group elements from titanium to nickel. For all the models reported in Table 1, the peak temperature in the runaway exceeds $T_{\text{crit}}$ and produces large concentrations of iron group elements. The concentrations of freshly synthesized iron group elements (relative to the original solar amounts) range from an increase by a factor of 1.75 for the less massive models (model s125y with $M = 1.25 \, M_{\odot}$) to an increase by a factor of 10.0 for the more massive models (model s135y with $M = 1.35 \, M_{\odot}$); this can be seen from the results presented in Table 2. Both CNO elements (from breakout) and intermediate-mass elements are seen to be transformed to the iron group elements. The outcome is a net decrease in the mass of hydrogen and CNO elements.
As one might expect, for the higher-mass cases (higher peak temperature), there is even a small decrease in the fraction of intermediate-mass elements and a significant production of iron group elements (see, e.g., Figure 3 and Table 2). For lower-mass white dwarfs (lower peak temperature), there is a slight increase in the mass fraction of intermediate-mass elements and a smaller level of production of the iron group elements (see, e.g., Table 2).

In order to ensure that we indeed achieved “breakout” from the conventional “hot CNO” cycle, we conducted a definite test. A model similar to s135u ($M = 1.35 \, M_\odot$), for which the accreted matter was assumed to include solar concentrations of nuclei only up to fluorine, was evolved. The energetics of this model are similar to those of model s135u (Table 1). With regard to the nucleosynthesis, the final concentration of iron group elements was determined to be comparable to that of model s135u. There is only a small concentration of intermediate-mass elements in the final stages, which confirms that indeed CNO nuclei were burned all the way to iron.

Our main conclusion concerning nucleosynthesis is that due to “breakout” from the conventional “hot CNO” cycle, the heavy-element abundances in the relevant novae ejecta can show a much wider variety than is possible with the conventional mixing mechanisms. Some rare cases could be enriched by breakout alone. Future work will therefore concentrate on the observational predictions that can be made about the time history of the ejected mass. In order to test this hypothesis, we will also consider the interpretation of observed abundance patterns in such nova systems as Nova Cygni 1992 and Nova Her 1991, in light of the possibility that they may well have experienced nuclear burning at temperatures approximating or above breakout leading to increased nucleosynthesis of intermediate-mass and heavy elements. In order to improve the accuracy of such predictions, we intend to follow the abundance history of the ejected matter all through the phase of nuclear burning and mass ejection.

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REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Bahcall, J. N., & May, R. M. 1969, ApJ, 155, 501
Gehrz, R. D., Truran, J. W., & Williams, R. E. 1998, PASP, 110, 3
Glasner, S. A., & Livne, E. 1995, ApJ, 445, L149
Glasner, S. A., Livne, E., & Truran, J. W. 1997, ApJ, 475, 754
Glasner, S. A., Livne, E., & Truran, J. W. 2007, ApJ, 665, 1321
Iben, I., Jr. 1982, ApJ, 259, 244
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943
Itoh, N., Mita, S., Iyetomi, H., & Ichimaru, S. 1983, ApJ, 273, 774
Joss, J., & Hernanz, M. 1998, ApJ, 494, 680
Livio, M., & Truran, J. W. 1990, in Nonlinear Astrophysical Fluid Mechanics, Ann. N.Y. Acad. Sci., Vol. 617, ed. J. R. Buchler & S. T. Gottesman (New York: New York Academy Sciences), 126
MacDonald, J. 1983, ApJ, 267, 732
Nairini, K., Nomoto, K., & Sugimoto, D. 1980, PASJ, 32, 473
Prihnik, D. 1986, ApJ, 310, 222
Prihnik, D., Shara, M. M., & Shaviv, G. 1978, A&A, 62, 339
Spiegel, E. A. 1963, ApJ, 138, 216
Starrfield, S. 2002, in AIP Conf. Proc. 637, Classical Nova Explosions, ed. M. Hernandez & J. Jose (New York: AIP), 89
Starrfield, S., Sparks, W. M., & Truran, J. W. 1974, ApJS, 28, 247
Starrfield, S., Sparks, W. M., & Truran, J. W. 1985, ApJ, 291, 136
Townsley, D. M., & Bildsten, L. 2004, ApJ, 600, 390
Truran, J. W. 1982, in Nuclear Theory of Nova—Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Schramm, & D. N. Clayton (Cambridge: Cambridge Univ. Press), 47
Wiescher, M., Gorres, J., Thielemann, F. K., & Ritter, H. 1986, A&A, 160, 56
Yaron, O., Prihnik, D., Shara, M. M., & Kovetz, A. 2005, ApJ, 623, 398