ON THE EFFECT OF EXPLOSIVE THERMONUCLEAR BURNING ON THE ACCRETED ENVELOPES OF WHITE DWARFS IN CATACLYSMIC VARIABLES

Edward M. Sion1 and Warren Sparks2,3

1 Astrophysics and Space Sciences, Villanova University, Villanova, PA 19085, USA; edward.sion@villanova.edu
2 Los Alamos National Laboratory, 701 Meadow Lane, Los Alamos, NM 87544, USA; warrensparks@comcast.net

ABSTRACT

The detection of heavy elements at suprasolar abundances in the atmospheres of some accreting white dwarfs in cataclysmic variables (CVs), coupled with the high temperatures needed to produce these elements, requires explosive thermonuclear burning. The central temperatures of any formerly more massive secondary stars in CVs undergoing hydrostatic CNO burning are far too low to produce these elements. Evidence is presented that at least some CVs contain donor secondaries that have been contaminated by white dwarf remnant burning during the common envelope phase and are transferring this material back to the white dwarf. This scenario does not exclude the channel in which formerly more massive donor stars underwent CNO processing in systems with thermal timescale mass transfer. Implications for the progenitors of CVs are discussed and a new scenario for the white dwarf’s accretion–nova-outburst is given.

Key words: novae, cataclysmic variables – white dwarfs

1. INTRODUCTION

Approximately 10% of the cataclysmic variables (CVs) reveal large abundance ratios of nitrogen to carbon, most commonly from the ratio of intensities of N v (1238, 1242) to C iv (1548, 1550) resonance doublet emission lines in the far-ultraviolet (Gänsicke et al. 2003). The units of the emission lines are erg cm−2 s−1 Å−1. The N v emission is typically very strong and the C iv emission is very weak or absent. This enhancement of nitrogen and depletion of carbon is the hallmark of CNO processing during hydrogen burning via the CNO bi-cycle. The emission lines almost certainly arise from the accretion disk (or boundary layer) that forms when the Roche-lobe filling donor secondary transfers gas to the white dwarf (WD) primary star. The N/C abundance anomaly has also been seen in magnetic CVs such as AE Aqr (Mouchet et al. 2003), BY Cam (Mouchet et al. 2003), V1309 Ori (Szkody & Silber 1996), and MN Hya (Schmidt & Stockman 2001).

A less common manifestation of the N/C abundance anomaly is seen in a few cases where detected N and C absorption lines form in the exposed WD photosphere itself. The two best examples are the WDs in VW Hyi (Sion et al. 1995, 1997, 2001; Long et al. 2009) and U Gem (Sion et al. 1998; Long et al. 2006). Typical values of the N/C ratio from studies of the WDs in VW Hyi and U Gem range from 5 to 41 times solar with C abundances of 0.1–0.3 solar (Sion et al. 2001; Long et al. 2006, 2009). Does the N/C abundance anomaly arise from a formerly more massive secondary star (capable of CNO burning) having been peeled away by mass transfer down to its CNO-processed core, due to mass transfer? Or does the N/C anomaly originate in the WD itself due to unstable CNO burning associated with nova explosions and remnant burning and possibly dredge-up and mixing as a consequence of a dwarf nova (DN) outburst?

The question of which star, the WD or the donor main-sequence star, is responsible for the N/C anomaly is critical. If the N/C anomaly originated in the donor, then the donor had to be more massive than its present value to sustain CNO burning. This could be the case if the CVs with a N/C anomaly are the descendants of supersoft X-ray binaries where the formerly more massive donor in the system underwent thermal timescale mass transfer at a high rate, thus driving steady thermonuclear burning on the WD at the accretion supply rate. In this Letter, we present evidence that, for at least a fraction of the CVs that reveal a N/C anomaly, the origin of the CNO-processed abundances lies with the WD, which subsequently contaminated the secondary donor star with the ejecta from the previous nova explosion and remnant burning.

The problem of contamination of a secondary star by novae ejecta has been considered by Marks et al. (1997), Marks & Sarna (1998), Scott et al. (1994), and more recently by Sengupta et al. (2013). All of these studies relied on a simple geometric treatment to quantify the amount of ejected matter that would be accreted by the donor and re-accreted by the WD. Spherically symmetric ejection is assumed with a geometric factor that quantifies the fraction of the nova ejecta intercepted by the donor secondary. This is taken to be the ratio of the cross-sectional area of the secondary star to the area of a sphere having a radius equal to the binary separation. In addition to the problem of this small fraction of nova ejection that is intercepted (~2%–4% for nova systems) by the donor secondary, very little carbon has been converted to nitrogen at the time of interception. It has long been known (Starrfield et al. 1974) that the nova outburst must occur on a carbon-enhanced envelope of a CO WD. (The less rare ONeMg novae on more massive WD are not considered here because the vast majority of the WDs in DN systems are less than 1.25 \( M_\odot \).) Thus, the material intercepted is very N/C poor! Therefore, the observed N/C enhanced material must come from a different phase of the nova outburst.

Not all of the material involved in the nova outburst is ejected. The remnant material forms a common envelope around the binary system. The bottom of the envelope that underwent thermonuclear runaway continues to burn, converting the hydrogen to helium and carbon to nitrogen until it runs out of fuel. This common envelope is convective which produces material with a high N/C ratio. Shara et al. (1986) have calculated that the Roche lobe of the secondary increases following a nova outburst, causing the secondary to lose contact with its Roche lobe. This occurs during the common envelope phase. It is reasonable...
and probably expected that this high N/C material would be accreted onto the secondary. Unless the secondary is convective, this high N/C material forms an outer layer, which will be transferred first when WD accretion begins again. Moreover, there is plenty of common envelope material available since, on average, 25% of the nova ejecta consist of WD remnant burnt material from the previous nova (Priplak 1989) and the secondary donor star with remnant burnt material during the common envelope phase.

2. CHEMICAL ABUNDANCES

For the vast majority of the CVs that exhibit a N/C anomaly, the highly non-solar abundances of N and C are inferred qualitatively from emission line intensity ratios and no other atomic species are used. There have been no reported abundances of N and C determined ab initio from fitting emission line profiles to date. However, a handful of DNe, all but one of which are below the CV period gap with orbital periods below 2 hr, were observed during DN quiescence when the accretion rate is very low and the WD completely dominates the far-ultraviolet band. These systems are BW Scl, SW UMa, BC UMa, and VW Hyi while U Gem is the only system above the period gap. The chemical abundances of their accreted metals have been derived largely from high-quality Hubble Space Telescope (HST) and Far-Ultraviolet Spectroscopic Explorer (FUSE) spectra by fitting the observed metal lines with rotationally broadened theoretical line profiles using TLUSTY and SYNSPEC (Hubeny 1988; Hubeny & Lanz 1995). In three SU UMa-type CVs—BW Scl, SW UMa, and BC UMa—the detected photospheric features reveal aluminum abundances of $3.0 \pm 0.8$, $1.7 \pm 0.5$, and $2.0 \pm 0.5$, respectively (Gänsicke et al. 2005).

The DN VW Hydi’s WD is also detected during DN quiescence, is modestly hotter than the WDs in the three systems above, and has a slightly longer orbital period. A plethora of photospheric absorption features due to metals have been detected in the VW Hyi WD. The derived abundances (relative to solar values) from profile fitting are AI 3, Si 0.3, C 0.3, O 3, N 3.0, Al 2.0, P 20, and Mn 50 (Sion et al. 1997). Large suprasolar phosphorus abundances result from thermonuclear runaways on ONeMg WDs (Starrfield et al. 2006; Etoj et al. 2006).

The exposed WD in the DN U Gem also exhibits a rich array of absorption features due to metals in both IUE and FUSE spectra (Sion et al. 1995). From HST and FUSE spectra, the U Gem WD has the largest photospheric N/C ratio of any CV WD (Sion et al. 1997; Long et al. 2006).

3. EXPLOSIVE CNO BURNING AND THE ABUNDANCES OF ELEMENTS IN THE MASS RANGE $A > 20$

It is well known that hydrostatic hydrogen burning via the CNO bi-cycle powers upper-main-sequence stars with masses $M > 1.3 M_\odot$ and the reactions are highly temperature sensitive. It is equally clear that CNO burning depletes the abundance of carbon while increasing the abundance of nitrogen. Hence, the CNO burning of a previously more massive CV secondary star could produce the large N/C abundance ratios that one observes in $\sim 10\%$ of the CV population. However, even in main-sequence stars as massive as $5 \rightarrow 10 M_\odot$, the core temperatures do not exceed $\sim 5 \times 10^7$ K.

The suprasolar chemical abundances of nuclides with $A > 20$ that have been detected in the photospheres of the accreting WDs in several DNe (e.g., AI, P, Mn) present a serious problem for any previously more massive CV secondary. First of all, there is virtually no leakage of material from the CNO mass region to the $A > 20$ mass range. Therefore, the nucleosynthesis must start from pre-existing seed nuclei with masses of $A > 20$ (Iliadis 2007). For example, the suprasolar abundance of $^{27}$Al must be formed in proton-capture reactions starting with seed $^{24}$Mg (Iliadis 2007) and so on. At temperatures below $5 \times 10^7$ K, it is not possible for $^{27}$Al to be produced from pre-existing $^{24}$Mg. The Coulomb barrier is simply far too high for such proton-capture reactions. Indeed, to build up the $^{27}$Al by depleting $^{24}$Mg through proton-capture reactions, the temperature of a main-sequence star would have to be $\sim 7.5 \times 10^7$ K, which corresponds to a $25 M_\odot$ star, to explain the observed Mg–Al anti-correlation observed in globular cluster stars (Prantzos et al. 2007).

4. SUMMARY OF CONCLUSIONS

The production of $A > 20$ nuclides during hydrogen burning requires temperatures between 100 million and 400 million K to affect the needed transmission through the Coulomb barriers of these heavier nuclei. The only thermonuclear environment that reaches these temperatures is during explosive hydrogen burning, e.g., a classical nova thermonuclear runaway. Hence, the detection of such nuclei as P and Al at suprasolar abundance in the surface layers of accreting WDs in DNe implies their origin within the WD. In the absence of mixing of the accreted material with the nucleosynthetic products in the transition region at the base of the accreted envelope where thermonuclear burning occurs, the matter flowing over from the secondary star to the WD would cover its surface layers. Hence, for some fraction of the CVs exhibiting a N/C anomaly, the donor secondary star’s large N/C abundance ratio arose from nova contamination. This conclusion is supported by the following considerations.

1. During the hydrostatic hydrogen burning of a $2 \rightarrow 3 M_\odot$ main-sequence star, the central temperature, while on the main sequence, reaches approximately $2.2 \times 10^7$ K, generating nuclear energy via the CNO reactions which convert hydrogen into helium. Thus, since the most likely mass range for a formerly more massive CV secondary is $2 \rightarrow 3 M_\odot$, the core temperatures of such stars are far too small to allow the formation of nuclei in the mass range $A > 20$. Thus, the detection of odd-numbered nuclides like AI, P, and Mn implies that the WD, not the secondary, is responsible for these nuclides. Since these heavy nuclei were accreted, the implication is that the secondary star, at least in the DNe that are cited above, was contaminated by nova ejecta and WD remnant burning and is transferring this nova-polluted material back to the WD via Roche-lobe overflow.

2. IR spectroscopy of VW Hyi’s secondary star appears to have solar abundance (Hamilton et al. 2011) but the accreting WD in the system, detected during quiescence, has a large N/C ratio in its surface layers (Sion et al. 1995, 1997, 2001). If the IR spectroscopic result of Hamilton et al. (2011) is confirmed, then this result suggests that the large N/C ratio originated in the WD, the same origin as the nuclides in the mass range $A > 20$. It also implies that there was mixing between the accreted material and the WD remnant burnt material but this mixing does not extend down to the WD’s CO core.

3. The FUSE spectra of U Gem’s WD photosphere reveals absorption features of P vs during quiescence, weeks after a DN outburst would have dredged it up. Phosphorus is a
The Astrophysical Journal Letters, 796:L10 (3pp), 2014 November 20

leaving a layer with high nitrogen and high helium abundances on the WD. When the donor star starts to overflow its Roche lobe, its partially burnt high N/C layer is accreted onto the WD first.

Afterward (many DN events later), the original donor star material is accreted. This scenario (while based upon DNe that eventually become novae) is probably applicable to all accreting WDs in CV systems. The abundances in the accreting layer of the WD are thus more complex than has been modeled. The lower H abundance in the high N/C material will decrease the burning at the bottom of the accreted material, delay the nova outburst, increase the total accreted material, and may strengthen the nova outburst.

E.M.S. is deeply indebted to Jim MacDonald for referring his queries on nuclear reaction networks to the superb book by Christian Iliadis and to Christian Iliadis for illuminating discussions. This work is supported by NASA grant NNX13AF12G to Villanova University.

REFERENCES

Gänsicke, B. T., Szkody, P., de Martino, D., et al. 2003, ApJ, 594, 443
Gänsicke, B. T., Szkody, P., Howell, S. B., & Sion, E. M. 2005, ApJ, 629, 451
Hamilton, R., Harrison, T. E., Tappert, C., & Howell, S. B. 2011, ApJ, 728, 16
Hubeny, I. 1988, CoPhC, 52, 103
Hubeny, I., & Lanz, T. 1995, ApJ, 439, 875
Iliadis, C. 2007, Nuclear Physics of Stars (Weinheim, Germany: Wiley)
Jose, J., Hernanz, M., & Iliadis, C. 2006, NuPhA, 777, 550
Long, K., Brammer, G., & Froning, C. 2006, ApJ, 648, 541
Long, K. S., Gänsicke, B. T., Knigge, C., Froning, C. S., & Monard, B. 2009, ApJL, 697, L1512
Marks, P. B., & Sarna, M. J. 1998, MNRAS, 301, 699
Marks, P. B., Sarna, M. J., & Priolnik, D. 1997, MNRAS, 290, 283
Mouchet, M., Bonnet-Bidaud, J.-M., Roueff, E., et al. 2003, A&A, 401, 1071
Paquette, C., Pelletier, C., Fontaine, G., & Michaud, G. 1986, ApJS, 61, 197
Prantzos, N., Charbonnel, C., & Iliadis, C. 2007, A&A, 470, 179
Priolnik, D. 1989, in IAU Colloq. 122, Madrid, Spain, Physics of Classical Novae, ed. A. Cassatella & R. Vietti (Berlin: Springer), 351
Schmidt, G., & Stockman, H. 2001, ApJ, 548, 410
Scott, A. D., Rawlings, J. M. C., Krautter, J., & Evans, A. 1994, MNRAS, 268, 749
Sengupta, S., Izzard, R., Lau, H., et al. 2013, A&A, 559, 66
Shara, M., Livio, M., Moffat, A. F. J., & Orio, M. 1986, ApJ, 311, 163
Sion, E. M., Cheng, F. H., Sparks, W. M., et al. 1997, ApJL, 480, L17
Sion, E. M., Cheng, F., Szkody, P., et al. 1998, ApJ, 496, 449
Sion, E. M., Cheng, F., Szkody, P., et al. 2001, ApJL, 561, L127
Sion, E. M., Szkody, P., & Huang, M. 1995, ApJL, 444, L97
Starrfield, S., Hix, W. R., & Iliadis, C. 2006, in Classical Novae, ed. M. Bode & A. Evans (Cambridge: Cambridge Univ. Press)
Starrfield, S., Sparks, W. M., & Truran, J. W. 1964, ApJS, 28, 247
Szkody, P., & Silber, A. 1996, AJ, 112, 289

nuclide that should be produced in high abundance at the very high temperatures of classical nova explosions and is seen in the surface layers of the WDs in both VW Hyi and U Gem. In the atmosphere of U Gem’s WD, with a quiescent surface temperature of ~30,000 K, the diffusion timescale for a phosphorus ion is shorter than three days (Paquette et al. 1986). Hence, the photospheric P v had to be accreted from the secondary. Thus, this implies that the donor star was contaminated by material that underwent explosive CNO burning of elements beyond A > 20. The secondary star in U Gem has a large N/C ratio (Hamilton et al. 2011). While we cannot exclude the possibility that the large N/C ratio originated in its formerly more massive secondary star, this would mean that the detected nuclide 31P originated in the WD but that the large N/C ratio originated separately in the secondary star.

4. To date, no pre-CV WD or pre-CV secondary star has yet been found to have surface abundances indicative of prior CNO processing. Even so, it is the pre-CVs that are thought to be the immediate progenitors of the CVs.

As can be seen, these abundences can give information about the transfer of material in DN systems, the nova common envelope phase, and the mixing during the accretion onto the WD. Ten percent of the DNs have a large N/C ratio that indicates the accreted nova remnant material is not mixed throughout the donor star. Otherwise, the donor star would contain more accreted novae remnant material than the original donor star material. Thus, if no mixing occurs in the donor star and if the 10% represents a random sampling of DNs, then on average, 10% of the donated material is N/C-enhanced and is donated first.

An explanation of these abundances leads to the following scenario of a nova binary system. During a nova outburst on the WD, the secondary captures only a small amount of the carbon-rich nova ejecta (~2%–4%). The loss of mass from the WD causes an increase in the binary separation and the Roche-lobe volume (Shara et al. 1986). This volume increase prompts the secondary to lose contact with its Roche lobe. In the meantime, remnant material from the nova outburst forms a common envelope around the binary system. The WD burns this envelope, converting hydrogen into helium and carbon into nitrogen. This high N/C material will fill the space between the secondary and its Roche-lobe volume.

As the common envelope shrinks down to the WD’s Roche lobe, it leaves a partially burnt high N/C layer on the donor. The rest of the remnant layer within the WD’s Roche lobe is burnt,