THEORETICAL IMPLICATIONS OF NOVA ABUNDANCES

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ABSTRACT

Abundance determinations for the ejected shells of classical novae are reviewed. Substantial enrichments (relative to hydrogen) of helium, the CNO elements, and elements in the range from neon to aluminum are found to be characteristic of nova ejecta. The source of these enrichments is believed to be the dredge-up of underlying white dwarf core matter, thus reflecting the white dwarf composition and confirming the presence of oxygen-neon-magnesium (ONeMg) as well as carbon-oxygen (CO) degenerate dwarfs in cataclysmic variable systems. The implications of these abundance enrichments, for the behavior of nova systems in outburst and for nucleosynthesis, are examined.

I. INTRODUCTION

The outbursts of the classical novae are now known to be attributable to thermonuclear runaways proceeding in the accreted hydrogen-rich envelopes of the white dwarf components of nova binary systems. For the conditions which are expected to obtain in this environment, nuclear burning will proceed by means of the carbon-nitrogen-oxygen (CNO) cycle hydrogen burning reactions. The energetics of the critical stages of these runaways are severely constrained by the characteristics of the CNO burning sequences: in particular, the rate of nuclear energy generation at high temperatures is limited by the time scales of the slower and temperature insensitive positron decays of ^{14}O and ^{15}O (see, for example the discussion by Truran (1982)). This feature holds important implications for the nature and consequences of classical nova outbursts: it provides a physical basis for distinguishing between "fast" and "slow" novae, it allows an understanding of the super-Eddington luminosities achieved in the outbursts of very fast novae, and it provides a constraint on the contributions of classical novae to galactic nucleosynthesis.

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Our theoretical understanding of these features of nova explosions has been influenced significantly by observations of the abundance patterns characterizing nova ejecta. Abundance determinations for the ejected shells of classical novae, indicating the presence of significant enrichments relative to solar abundances, are reviewed in the following section. Possible models for the source of these enrichments are identified. We then examine the general implications of these abundance enrichments both for theoretical models of the outburst and for galactic nucleosynthesis.

II. HEAVY ELEMENT ABUNDANCES IN NOVAE

Recognition of the fact that nova ejecta can exhibit unusual abundance features dates back many years (Payne-Gaposchkin 1957; Mustel 1974; Williams 1977; Gallagher and Starrfield 1978). The suggestion that enhanced concentrations of CNO elements are generally required to explain the rapid development and dynamical characteristics of fast novae has motivated detailed abundance studies of a number of novae. Most recent determinations of heavy-element abundances in the ejecta of classical novae have been based either upon emission-line analyses during decline or on analyses of the resolved nebular shells observed for a few older novae.

The available elemental abundance data, reviewed most recently by Williams (1985) and Truran (1985a,b), is summarized in Table 1. Here we present, specifically, the mass fractions (where known) in the form of the elements hydrogen, helium, carbon, nitrogen, oxygen, neon, sodium, magnesium, aluminum, silicon, sulphur, and iron, adapted from the indicated references. Table 2 provides helium to hydrogen ratios for a somewhat larger sample of novae. Here again, where known, the total mass fractions Z in the form of heavy elements are also tabulated. For purposes of comparison, we note that solar system matter is characterized by a helium to hydrogen ratio by number He/H = 0.08 and a heavy element mass fraction Z_{SOLAR} = 0.019 (Anders and Ebihara 1982; Cameron 1982).

Several interesting and important conclusions may be drawn from the abundance data collected in these tables. (1) Enhanced concentrations of heavy elements are characteristic of nova ejecta; the average mass fraction for the ten nova in Table 1 is 0.33, a factor ~17 high compared to the solar value of 0.019. (2) High helium to hydrogen ratios are characteristic of nova ejecta: the average ratio for the 15 novae in Table 2 is He/H = 0.20, to be compared with a solar value 0.08. This is compatible with the burning of hydrogen to helium in approximately 20 percent of the envelope matter. (3) The ejecta of faster novae tend to be characterized by substantial heavy-element enrichments (viz. V1500 Cyg, V1668 Cyg, V693 Cr A, V1370 Aql, and GQ Mus). One must be cautious here, however, for the large Z determined for the "moderately fast" nova DQ Her 1934 indicates that a

Table 1

Heavy Element Abundances in Novae

Object	Year	Ref.	Mass Fractions											
			H	He	C	N	O	Ne	Na	Mg	Al	Si	S	Fe
RR Pic	1925	1	0.53	0.43	0.0039	0.022	0.0058	0.011						
HR Del	1967	2	0.45	0.48		0.027	0.047	0.0030						
T Aur	1891	3	0.47	0.40		0.079	0.051							
PW Vul	1984	4	0.54	0.28	0.032	0.11	0.038							
V1500 Cyg	1975	5	0.49	0.21	0.070	0.075	0.13	0.023						
V1668 Cyg	1978	6	0.45	0.23	0.047	0.14	0.13	0.0068						
V693 CrA	1981	7	0.29	0.32	0.0046	0.080	0.12	0.17	0.0016	0.0076	0.0043	0.0022		
GQ Mus	1983	4	0.27	0.32	0.016	0.19	0.19	0.0034		0.0014	0.00056	0.0028	0.0016	0.00047
DQ Her	1934	8	0.34	0.095	0.045	0.23	0.29							
V1370 Aql	1982	9	0.053	0.088	0.035	0.14	0.051	0.52		0.0067		0.0018	0.10	0.0045

References. - (1) Williams and Gallagher 1979. (2) Tylenda 1978. (3) Gallagher et al. 1980. (4) Hassal et al. 1989. (5) Ferland and Shields (1978). (6) Stickland et al. 1981. (7) Williams et al. (1985). (8) Williams et al. 1978. (9) Snijders et al. 1987.

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Table 2

Helium and Heavy-Element Abundances in Novae

Nova		He/H	Z	Reference	Enriched Fraction
T Aur	1891	0.21	0.13	b	0.36
RR Pic	1925	0.20	0.039	a	0.28
DQ Her	1934	0.08	0.56	a	0.55
CP Lac	1936	0.11 ± 0.02		a	0.08
RR Tel	1946	0.19		a	0.24
DK Lac	1950	0.22 ± 0.04		a	0.30
V446 Her	1960	0.19 ± 0.03		a	0.24
V553 Her	1963	0.18 ± 0.03		a	0.23
HR Del	1967	0.23 ± 0.05	0.077	a	0.35
V1500 Cyg	1975	0.11 ± 0.01	0.30	a	0.34
V1668 Cyg	1978	0.12	0.32	c	0.38
V693 Cr A	1981	0.28	0.38	d	0.61
V1370 Aql	1982	0.40	0.86	e	0.93
GQ Mus	1983	0.29	0.42	f	0.64
PW Vul	1984	0.13	0.18	f	0.27
V1819 Cyg	1986	0.19		g	0.24

References - (a) Ferland (1979). (b) Gallagher et al. (1980). (c) Stickland et al. (1981). (d) Williams et al. (1985); Williams (1985). (e) Snijders et al. (1987). (f) Hassal et al. (1989). (g) Whitney and Clayton (1989).

high CNO abundance is not an unambiguous or unique signature of extremely fast novae. In general, the available data presented in Table 3 reveals no clear correlation of abundance enrichment with speed class. This is suggestive of the fact that additional factors, such as the white dwarf mass and luminosity, must also be taken into consideration. (4) Two of the ten novae included in Table 1 (V693 Cr A and V1370 Aql) show large concentration of neon, as well as of the elements Na, Mg, Al, and S (suggesting, as we will discuss in the next section, the presence of an underlying ONeMg white dwarf). (5) All of the fifteen novae included in Tables 1, 2, and 3, which constitute all of the novae for which reasonable abundance data are available, appear to be enriched in either helium or heavy elements, or both. This suggests that envelope enrichment is a very general phenomenon. The implications of these abundance patterns for the (yet unidentified) mechanism of nova envelope enrichment are discussed in the next section.

Table 3

Abundance Enrichment and Nova Speed Class

Nova	Year	$< t_3 >$	Speed Class	$< Z >$
HR Del	1967	230	Slow	0.077
RR Pic	1925	150	Slow	0.039
T Aur	1891	100	Moderately Fast	0.13
PW Vul	1984	97	Moderately Fast	0.18
DQ Her	1934	94	Moderately Fast	0.56
GQ Mus	1983	45	Moderately Fast	0.42
V1668 Cyg	1978	23	Fast	0.32
V693 CrA	1981	12	Very Fast	0.38
V1500 Cyg	1975	3.6	Very Fast	0.30

III. THE ENVELOPE ABUNDANCE ENRICHMENT MECHANISM

The occurrence of significant enrichments of helium and heavy elements in the ejecta of the classical novae is thus established. Possible sources of these abundance enrichments include: (i) mass transfer from the secondary star; (ii) nuclear transformations associated with the thermonuclear outburst itself; and (iii) outward mixing or "dredge-up" of matter from the underlying white dwarf. While Williams and Ferguson (1983) have suggested the possibility of mass transfer on the basis of observations of CNO emission line strengths in nova systems at quiescence, the extreme CNO and neon-to-aluminum abundances recently observed in nova systems are unlikely to have resulted from such transfer.

Nuclear reactions accompanying nova outbursts also appear to be incapable of explaining the large observed abundance anomalies, for the conditions which are expected to obtain in the burning shells of the classical novae in outburst. We recall that it is necessary to explain the presence of substantial enrichments of the elements carbon, nitrogen and oxygen and/or of the elements neon, sodium, magnesium, and aluminum, in one or another of the well observed novae. Significant production of heavy nuclei cannot result from CNO cycle hydrogen burning at the temperatures 150-250 x 10^6 K which are characteristic of nova shells (Truran 1982; Starrfield, Sparks, and Truran 1985; Starrfield 1989). For these conditions, the controlling CNO cycle reactions act only to rearrange existing CNO elemental and isotopic abundance patterns, but not to increase the total number of CNO nuclei. Breakout of the CNO hydrogen burning sequences via $^{15}O(\alpha,p)^{19}Ne(p,\gamma)^{20}Na$ can occur at higher temperatures ($T \gtrsim 400 \times 10^6$ K), yielding

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neon and heavier nuclei (Wallace and Woosley 1981; Wiescher et al. 1986), but even for these more extreme conditions (characteristic of thermonuclear runaways on neutron stars rather than white dwarfs) the total number of heavy nuclei is not greatly increased. In any case, the observed enrichments of carbon, nitrogen, and oxygen cannot be explained in this manner. The realization of large carbon and oxygen concentrations via nuclear processing requires helium burning. However, helium burning episodes driven by weak helium shell flashes on white dwarfs, which might serve to provide surface enrichments of carbon and oxygen, are predicted not to occur in the presence of the lower accretion rates $\lesssim 10^{-8}$ $M_{\odot}$/yr (Patterson 1984) characteristic of classical nova systems. Alternatively, the accretion rate range $\gtrsim 4 \times 10^{-8}$ $M_{\odot}$/yr compatible with weak helium shell flashes does not give rise to strong hydrogen flashes. Thus, for accretion rates low enough to allow strong hydrogen shell flashes like those of classical novae, either helium flashes do not occur at all or the first flash results in a supernova event (see, e.g., the discussion by MacDonald (1984)).

We are thus led to the conclusion that nuclear processes accompanying nova outbursts cannot alone provide a consistent explanation of the abundance patterns that are observed in nova ejecta. It would appear, rather, that some fraction of the envelope matter and ejecta represents material which must have been dredged up in some manner from the core of the underlying white dwarf. Possible mechanisms for such mixing include: (i) shear-induced turbulent mixing between the white dwarf and the accreted material (Kippenhahn and Thomas 1978; MacDonald 1983; Livio and Truran 1987; Sparks and Kutter 1987; Fugimoto 1987); (ii) diffusion-induced convection (Prialnik and Kovetz 1984); and (iii) convective overshooting subsequent to runaway (Woosley 1986). It is not established which, if any, of these mechanisms is indeed the appropriate one. The shear mixing model is challenged by the finding that Nova V1500 Cyg 1975 (an extremely fast nova, the ejecta of which has been found to be strongly enriched in heavy elements) has a strong magnetic field which can channel the accreting material onto the polar caps, while the diffusion mechanism may not be capable of providing the necessary mixing on the shorter inter-outburst timescales characteristic of the more massive white dwarfs which appear to be present in many nova systems.

It should be noted that, quite independent of which mechanism is responsible for the mixing, the conclusion that the observed enrichments represent white dwarf core matter holds interesting implications for the origin and evolution of classical nova systems. High He/H ratios (beyond that consistent with the conversion of H to He accompanying the runaway) can be achieved when the accreted hydrogen-rich matter mixes with helium-shell matter on white dwarfs. Enrichments of CNO may be similarly understood on the basis of mixing which penetrates through to the underlying carbon-oxygen core, perhaps after a series of nova outbursts for which the ejecta showed only helium enrichments. The realization of large overabundances of the carbon-burning products Ne, Na, Mg, and Al, in this context,

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can only be understood if one assumes the presence of an underlying oxygen-neon-magnesium (ONeMg) white dwarf (Law and Ritter 1983; Truran 1985b; Williams et al. 1985; Truran and Livio 1986). This further implies both the presence of a substantial number of relatively massive white dwarfs in observed nova systems and the conclusion that the white dwarfs are slowly eroded by sequences of nova outbursts, such that the net result is a decrease of the white dwarf mass. The expected frequency of occurrence of events involving ONeMg white dwarfs is discussed in the next section.

IV. THEORETICAL PERSPECTIVE

We have seen that it is now firmly established that classical nova ejecta is characterized by substantial overabundances of heavy elements relative to solar matter. These must have arisen due to some yet unidentified mechanism of mixing of core matter and accreted hydrogen-rich matter. Quite independent of the mode of mixing, the observed abundance patterns hold important implications for the evolution of classical nova systems and the nature of the outburst itself. We note, in particular, the very encouraging consistency that exists with respect to abundance enrichments, the expected masses of the nova white dwarf components, and the characteristics of extremely fast novae. The physical basis for this consistency is briefly reviewed in this section.

Estimates of the relative frequencies of occurrence of different white dwarf masses in classical nova systems (Truran and Livio 1986, 1989; Politano et al. 1989) reveal that the mean mass for systems observed in outburst is $M_{WD} \sim 1.1$-1.2 $M_{\odot}$. This high realization frequency for massive white dwarfs is a straightforward consequence of a selection effect. Thermonuclear runaways are initiated on massive white dwarfs in the presence of much lower accreted envelope masses; hence, with the assumption of a constant accretion rate, it follows that massive white dwarfs will experience outbursts at much shorter intervals. The relative frequencies and recurrence timescales as a function of white dwarf mass are presented in Table 4, from both the Truran and Livio (TL) and Politano et al. (PLTW) calculations. We note, particularly, the general agreement between the results of the two studies and the necessary conclusion that approximately one quarter of all observed classical nova systems should involve ONeMg white dwarfs. In this context, the large concentrations of neon and heavier nuclei observed for two (V693 CrA and V1370 Aql) of the ten novae included in Table 1 may be understood, assuming that these enrichments are due to outward mixing of core matter.

The occurrence of large initial carbon and/or oxygen concentrations in the burning shells of classical novae also holds important implications for the light curves and dynamics of fast novae. The rate of nuclear energy generation at high

Table 4

Relative Frequencies and Recurrence Time Scales

$M_{WD}/M_{\odot}$	T_{rec}(yr)	f$(M_{WD})_{TL}$	f$(M_{WD})_{PLTW}$
CO White Dwarfs:			
0.6	1.29×10^6	0.103	0.035
0.7	7.31×10^5	0.053	0.087
0.8	4.16×10^5	0.042	0.076
0.9	2.36×10^5	0.040	0.060
1.0	1.20×10^5	0.046	0.058
1.1	6.39×10^4	0.062	0.069
1.2	2.81×10^4	0.100	0.098
1.3	9.02×10^3	0.232	0.212
ONeMg White Dwarfs			
1.35	3.98×10^3	0.322	0.306

temperatures via the CNO cycles is constrained by the positron decay lifetimes of ^{14}O (102 s) and ^{15}O (176 s). The fact that these lifetimes are long compared to the hydrodynamic timescale, $\tau_{HYD} \lesssim 10$ s, imposes a constraint on the total energy available on this dynamical timescale (Truran 1981, 1982):

$$E_{nuc}/\rho \sim 2 \times 10^{15} \text{ erg g}^{-1} \left(\frac{n_{CNO}}{n_{CNO}(\odot)}\right)$$

where n_{CNO} is the number density of CNO nuclei in the shell and $n_{CNO}(\odot)$ is the corresponding value for matter of solar compositions. The binding energy per gram of nova envelope matter, alternatively, is $GM/R \sim 2 \times 10^{17}$ erg g^{-1}. It follows that increased concentrations of carbon and/or oxygen are demanded to reproduce the rapid light curve evolution, high expansion velocities, and particularly the super-Eddington luminosities of the fast novae. In this regard, we note that twelve out of the fifteen novae for which reliable distances have been determined utilizing expansion parallaxes or interstellar line intensities (de Vaucouleurs 1978) reach absolute magnitudes brighter than $M_{bol} = -7.1$, the Eddington luminosity for a Chandrasekhar mass white dwarf. Recent calculations by Truran et al. (1989) have shown that the achievement of luminosities exceeding this value demands the presence of initial carbon and/or oxygen concentration substantially above those of solar system matter. A relatively high white dwarf mass, M ~ 1.1-1.2 $M_{\odot}$, consistent with the mean values reflected in Table 4, is also an essential ingredient (Truran and Livio 1989). The relatively slow evolution of Nova DQ Her

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1934 (see Table 3), even in the presence of high levels of carbon and oxygen abundances, is very likely attributable to the fact that the underlying white dwarf has a mass less than one solar mass.

V. NUCLEOSYNTHESIS IN CLASSICAL NOVA OUTBURSTS

The occurrence of significant concentrations of heavy elements in the ejecta of novae may at first suggest the possibility that novae may make an important contribution to Galactic nucleosynthesis. In fact, it is unlikely that this is true. Nucleosynthesis directly associated with nova events is limited to the effects of the proton-induced reactions which can proceed at the temperatures ~ 10^8 to 3×10^8 K achieved in the hydrogen burning shells on the dynamical timescale. The CNO and/or neon-sodium cycles will act to redistribute these nuclei and thereby alter the isotopic and elemental abundances, but the formation of increased concentrations of heavy elements is not expected to occur. It is also important to note in advance both that the integrated contribution of novae to Galactic nucleosynthesis is expected to be small and that detailed predictions regarding their contributions are highly uncertain. We do not know with sufficient confidence such critical parameters as the rate of nova outbursts over the course of Galactic history, the average mass ejected per outburst, and the abundance pattern emerging from a particular fast or slow nova event.

Recognizing the limitations imposed by these uncertainties, we can nevertheless proceed to estimate the amount of processed matter contributed by novae to the interstellar medium of our Galaxy, on the basis of the following assumptions: (1) the current rate of nova events is 30 yr^{-1}, compatible with that observed for Andromeda (Arp 1956); (2) the rate of occurrence of classical novae has remained relatively constant over the ~ 10^{10} year lifetime of the Galaxy; and (3) the average mass ejected per nova event is ~ 3×10^{-5} $M_\odot$. These choices yield a total mass ~ 10^7 $M_\odot$ processed through nova shells over the lifetime of the Galaxy. This mass constitutes only a small fraction ~ 1/300 of the mass of the interstellar gas and dust in our Galaxy (~ 3×10^9 $M_\odot$). It follows that only nuclei enriched by factors $\gtrsim$ 300 in nova ejecta can contribute significantly to Galactic nucleosynthesis.

These galactic chemical evolution constraints imply that novae can potentially produce important concentrations only of the <u>rarer</u> isotopes of carbon, nitrogen, and oxygen: ^{13}C, ^{15}N, and ^{17}O. The models reviewed by Starrfield et al. (1978) and by Sparks, Starrfield, and Truran (1978) indicate that the concentrations of ^{13}C and particularly ^{15}N can be enhanced relative to solar by factors $\gtrsim 10^2$-10^3, hence novae may contribute significantly to their Galactic abundances. It is also recognized that novae can produce potentially interesting concentrations of ^7Li (Arnould and Norgaard 1975; Starrfield et al. 1978). ^7Li production in classical

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nova outbursts proceeds in a manner quite similar to that in red giants: ^7Be is formed via the ^3He + ^4He reaction and transported rapidly to the cooler surface regions by convection, before it can be destroyed via $^7Be(p,\gamma)^8B$. The total mass of ^7Li formed and/or ejected is a sensitive function of the temperature and convective histories of the nova envelope, hence reliable predictions of ^7Li production are not yet achievable. The initial concentration of ^3He is also an important consideration, since much of it may be transformed directly into ^7Be. Model calculations by Starrfield et al. (1978) indicated that ^7Li enrichments by factors up to $\gtrsim 10^2$ can be realized. While the integrated contributions of classical novae to Galactic nucleosynthesis are quite uncertain, the calculations performed to date do nevertheless provide a potentially interesting constraint on ^7Li production in novae: if the level of enrichment of ^7Li in novae is indeed typically less than that for the CNO isotopes ^{13}C and ^{15}N by factors ~ 3-10, it follows that novae can at most contribute only a fraction of the ^7Li present in galactic matter.

It is also recognized that the production of potentially interesting and detectable abundance levels of the radioactive isotopes ^{22}Na ($\tau_{1/2}$ = 2.6 years) and ^{26}Al ($\tau_{1/2}$ = 7.3 x 10^5 years) can occur in nova explosions. Calculations of nucleosynthesis accompanying nova explosions, for representative temperature histories extracted from hydrodynamic models, have been performed by Hillebrandt and Thielemann (1982), Wiescher et al. (1986) and most recently Truran and Weiss (1989). These various calculations are entirely consistent in their prediction that only relatively low levels of ^{22}Na and ^{26}Al can be achieved, for nova envelopes of initial composition similar to that of solar system matter.

Substantially increased ^{22}Na and ^{26}Al production can occur in envelope matter characterized by large initial concentrations of elements in the range from neon to aluminum, such as are found in the ejecta of several recent novae. This is apparent from the results presented in Table 5, where the mass fractions of ^{22}Na and ^{26}Al

Table 5

^{22}Na and ^{26}Al Production in Novae

	ABUNDANCES BY MASS FOR SPECIFIED COMPOSITIONS					
	SOLAR			(O+Ne+Mg)=0.25		
NUCLEUS	250*	200	150	250	200	150
^{22}Na	2.4(-8)	1.1(-6)	2.5(-6)	4.3(-6)	5.1(-5)	1.8(-4)
^{26}Al	5.0(-7)	2.0(-5)	1.3(-4)	1.1(-4)	1.9(-3)	5.1(-3)
^{27}Al	2.5(-7)	9.8(-6)	6.5(-5)	5.4(-5)	9.0(-4)	4.3(-3)

*Peak burning temperature in millions of degrees Kelvin.

realized in the burning shells of novae are tabulated for two specific compositions: matter of solar composition and matter characterized by an initial mass fraction 0.25 in the form of oxygen, neon and magnesium nuclei (in proportions compatible with carbon burning products). As described by Truran and Weiss (1989), these calculations were performed for representative temperature density profiles for the three choices of peak burning temperature shown in the table. Note the considerably higher concentrations produced for the case X(O+Ne+Mg) = 0.25. These models suggest that novae may represent an important source of ^{26}Al in the Galaxy and that some(nearby and O-Ne-Mg-enriched) novae may be expected to produce detectable flux levels of ^{22}Na decay gamma rays. The detection of ^{22}Na in novae would provide critical constraints both on their temperature and envelope convection histories and on their initial envelope compositions.

VI. CONCLUDING REMARKS

On the basis of the various considerations reviewed in this paper, several conclusions seem clear. Enrichments of some combination of helium, the CNO elements, and the elements from oxygen to aluminum characterize the ejecta of all studied novae (Table 2). The CO and ONeMg enrichments must certainly reflect the composition of the underlying white dwarf core, although the nature of the dredge-up mechanism is not yet clear. The presence of such heavy element enrichments is quite consistent both with estimates of the expected frequencies of occurrence (Table 4) of more massive CO and ONeMg white dwarfs in classical nova systems that are actually observed to erupt and with the dynamical characteristics of, particularly, the faster novae. In the nuclear processing of this heavy element enriched matter, classical novae may produce sufficient quantities of ^{13}C, ^{15}N, ^{17}O, and perhaps ^{7}Li, to make important nucleosynthesis contributions.

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REFERENCES

Anders, E., Ebihara, M.: 1982, Geochim. Cosmochim. Acta. 46, 2363

https://doi.org/10.1017/S025292110006886X Published online by Cambridge University Press

Arnould, W.D., Wefel, J.P.: 1978, Ap. J. (Letters) 224, L139

Arp, H.C.: 1956, Astr. J. 61, 15

Cameron, A.G.W.: 1982, in Essays in Nuclear Astrophysics, ed. C.A. Barnes, D.D. Clayton, and D.N. Schramm (Cambridge: Cambridge University Press), p. 23

de Vaucouleurs, G.: 1978, Ap. J. 223, 351

Ferland, G.J.: 1979, Ap. J. 231, 781

Ferland, G.J., Shields, G.A.: 1978, Ap. J. 226, 172

Fujimoto, M.Y.: 1987, Astr. Ap. 176, 53

Gallagher, J.S., Hege, E.K., Kopriva, D.A., Williams, R.E., Butcher, H.R.: 1980, Ap. J. 237, 55

Gallagher, J.S., Starrfield, S.: 1978, Ann. Rev. Astr. Ap. 16, 171

Hassall, B.J.M., Snijders, M.A.J., Harris, A.W., Cassatella, A., Dennefeld, M., Friedjung, M., Bode, M., Whitlet, D., Whitelock, P., Menzies, J., Evans, T.L., Bath, G.T.: 1989, these proceedings

Hillebrandt, W., Thielemann, F.-K.: 1982, Ap. J. 255, 617

Kippenhahn, R., Thomas, H.-C.: 1978, Astr. Ap. 63, 265

Law, W.Y., Ritter, H.: 1983, Astr. Ap. 123, 33

Livio, M., Truran, J.W.: 1987, Astrophys. J. 318, 316

MacDonald, J.: 1983, Ap. J. 273, 289

MacDonald, J.: 1984, Ap. J. 283, 241

McLaughlin, D.B.: 1960, in Stellar Atmospheres, ed. J.L. Greenstein (Chicago: University of Chicago Press), p. 585

Mustel, E.R.: 1974, Vistas in Astronomy 16, 260

Patterson, J.: 1984, Ap. J. Suppl. 54, 443

Payne-Gaposchkin, C.: 1957, The Galactic Novae (Amsterdam: North Holland)

Politano, M., Livio, M., Truran, J.W., Webbink, R.F.: 1989, these proceedings

Prialnik, D., Kovetz, A.: 1984, Ap. J. 281, 367

Snijders, M.A.J., Batt, T.J., Roche, P.F., Seaton, M.J., Morton, D.C., Spoelstra, T.A.T., Blades, J.C.: 1987, M.N.R.A.S. 228, 329

Sparks, W.M., Kutter, G.S.: 1987, Astrophys. J. 321, 394

Sparks, W.M., Starrfield, S., Truran, J.W.: 1978, Ap. J. 220, 1063

Starrfield, S.: 1989, in Classical Novae, ed. N. Evans and M. Bode (New York: Wiley), p. 123

Starrfield, S., Truran, J.W., Sparks, W.M., Arnould, M.: 1978, Ap. J. 222, 600

Starrfield, S., Sparks, W.M., Truran, J.W.: 1985, Ap. J. 291, 136

Stickland, D.J., Penn, C.J., Seaton, M.J., Snijders, M.A.J., Storey, P.J.: 1981, M.N.R.A.S. 197, 107

Truran, J.W.: 1981, in Progress in Particle and Nuclear Physics, Vol. 5i, ed. D. Wilkinson (Oxford: Pergamon), p. 177

Truran, J.W.: 1982, in Essays in Nuclear Astrophysics, ed. C.A. Barnes, D.D. Clayton, and D.N. Schramm (Cambridge: Cambridge University Press), p. 467

Truran, J.W.: 1985a, in Production and Distribution of CNO Elements, ed. I.J. Danziger (Garching: ESO), p. 211

Truran, J.W.: 1985b, in Nucleosynthesis: Challenges and New Developments, ed. W.D. Arnett, and J.W. Truran (Chicago: University of Chicago Press), p. 292

Truran, J.W., Livio, M.: 1986, Astrophys. J. 308, 721

Truran, J.W., Weiss, A.: 1989, in preparation

Truran, J.W., Livio, M.: 1989, in White Dwarfs, ed. G. Wegner (Berlin: Springer-Verlag), p. 498

Truran, J.W., Hayes, J., Shankar, A., Livio, M.: 1989, preprint

Tylenda, R.: 1978, Acta Astron. 28, 333

Wallace, R.K., Woosley, S.E.: 1981, Ap. J. Suppl. 45, 389

Whitley, B.A., Clayton, G.C.: 1989, A. J., 98, 297

Wiescher, M., Görres, J., Thielemann, F.-K., Ritter, H.: 1986, Astr. Ap. 160, 56

Williams, R.E.: 1977, in The Interaction of Variable Stars with Their Environments, ed. R. Kippenhahn, J. Rahe, and W. Strohmeier (Bamberg: Remeis-Sternwarte), p. 242

Williams, R.E.: 1985, in Production and Distribution of CNO Elements, ed. I.J. Danziger (Garching: ESO), p. 225

Williams, R.E., Ferguson, D.H.: 1983, in Cataclysmic Variables and Related Objects, ed. M. Livio and G. Shaviv (Dordrecht: Reidel), p. 97

Williams, R.E., Gallagher, J.S.: 1979, Ap. J. 228, 482

Williams, R.E., Sparks, W.M., Starrfield, S., Ney, E.P., Truran, J.W., Wyckoff, S.: 1985, M.N.R.A.S. 212, 753

Williams, R.E., Woolf, N.J., Hege, E.K., Moore, R.L., Kopriva, D.A.: 1978, Ap. J. 224, 171

Woosley, S.E.: 1986, in Sixteenth Advanced Course of the Swiss Society of Astronomy and Astrophysics, ed. A. Maeder (Geneva: Geneva Observatory), p. 1

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