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A MODEL FOR DWARF NOVAE AS PROGENITORS OF TYPE I SUPERNOVAE

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ABSTRACT

We propose that a Type I supernova event can be produced as a result of accretion at low rates, $\dot{M} < 10^{-10}\, M_\odot\, \mathrm{yr}^{-1}$, onto the white dwarf component of a dwarf-nova close binary. At these low rates, diffusion of the CNO nuclei out of the accreted hydrogen envelope can occur on the accretion time scale, and nuclear burning will occur mainly by the proton-proton chain. Studies of this process show that, when the CNO abundance in the envelope is less than 2.5×10^{-3} of solar, no thermonuclear flash occurs and no mass is lost. The result of the evolution is a gradually increasing layer of helium beneath the hydrogen-burning shell.

Subject headings: stars: accretion — stars: dwarf novae — stars: evolution — stars: supernovae — stars: white dwarfs

I. INTRODUCTION

The detailed nature of the progenitors of Type I supernovae (SN I's) has yet to be clearly established. The fact that, to date, only SN I's have been observed in elliptical galaxies (Tammann 1974, 1977) has been interpreted as strong evidence for their identification with an older stellar population. This has led a number of researchers to consider that the evolution of low-mass binary systems can yield presupernova configurations (Truran and Cameron 1971; Whelan and Iben 1973; Warner 1974; Shklovskii 1978). Evidence suggesting that SN I's belong, rather, to a younger stellar population has recently been emphasized (Tinsley 1975; Oemler and Tinsley 1979).

The common thread seems to have been provided by recent, detailed, theoretical models of the light curves of SN I's. Guided by the finding that ^{56}Ni represents the dominant product of "silicon burning" to iron-peak elements in supernova environments (Truran, Arnett, and Cameron 1967), the possible effects of the energy provided by the decay chain $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ were first examined by Colgate and McKee (1969; see also Leventhal and McCall 1975). Arnett (1979; see also Colgate, Petschek, and Kriese 1980) has recently provided a consistent modeling of the SN I light curve: the decay of ^{56}Ni powers the peak of the light curve, while the exponential tail is powered by kinetic energy from positron emission by ^{56}Co. General energetic requirements are satisfied if the ejected mass is less than 1.0 $M_\odot$, of which $\sim$0.25 $M_\odot$ is in the form of ^{56}Ni.

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Given these considerations, there exist several evolutionary paths capable of providing presupernova configurations compatible with SN I's. The study by Arnett (1979) dealt specifically with low-mass helium stars, which are assumed to be the product of the evolution of massive close binaries (van den Heuvel 1977). The growth of the degenerate carbon-oxygen cores of intermediate-mass stars ($5\, M_\odot \lesssim M \lesssim 8\, M_\odot$) to the Chandrasekhar limit is also expected to provide a presupernova configuration which can lead to SN I's associated with a younger stellar population. Discussions of diverse problems associated with the carbon-detonation model (Arnett 1969) are myriad (Buchler, Mazurek, and Truran 1974). The complexity of this problem was emphasized by the calculations of the onset of carbon ignition by Iben (1978).

An alternative evolutionary path to SN I's, and that most likely relevant to Population II systems, involves the growth of a white dwarf in a binary system to the Chandrasekhar limit. The presupernova configuration in this case is essentially a bare white dwarf. It has been argued (Lasher, Karp, and Chan 1977; Oemler and Tinsley 1979) that the early phases of the light curves of SN I's demand envelopes of up to $\sim M_\odot$ and radii $> 10^{13}$ cm, and therefore that SN I's are incompatible with exploding white dwarfs. This conclusion is questionable: the relevant consideration would appear rather to be that the dynamics provide ejection of a sufficient mass of matter at a sufficient velocity to ensure that the optical photosphere reaches $\sim 10^{14}$–10^{15} cm at visual maximum. Assuming $\mathcal{V}_{\mathrm{ejection}} \approx 10^4\ \mathrm{km\ s^{-1}}$, a radius $\sim 5 \times 10^{14}$ cm is indeed reached in $\sim$5 days. The implied kinetic energy, $\sim 5 \times 10^{50}$ ergs, is compatible with the view that much of the initial shock energy is expended in matter acceleration.

It is the purpose of this *Letter* to consider the response of a white dwarf to hydrogen mass accretion and its implied growth toward the Chandrasekhar limit. We must, therefore, be concerned with those systems known to have white dwarfs accreting hydrogen from a close companion—the cataclysmic variables. Included in this class of objects are the dwarf novae, the recurrent novae, and the classical novae. The relevant properties of these systems will be examined in the next section (§ II). A model for the core growth in dwarf novae is then presented.

II. ACCRETION AND CATACLYSMIC VARIABLES

The outburst mechanism appropriate to the recurrent novae has not been unambiguously identified (see, for example, Truran 1980). It is possible that both thermonuclear runaway events (Shara 1980) and accretion events (Bath 1975; Webbink 1976) are relevant to one or another of these systems. In view of these uncertainties, the question as to whether significant growth of a white dwarf component will occur cannot, at present, be answered.

The two most commonly identified members of the class of cataclysmic variables are the dwarf and classical novae. Both are found generally to consist of short-period ($\sim$4 hr) binary systems in which a low-mass main-sequence star transfers mass to a white dwarf. The luminosities of these systems at minimum light are compatible with accretion occurring at rates $10^{-10}\,M_\odot$ yr^{-1} and $10^{-9}\,M_\odot$ yr^{-1}, respectively, for dwarf and classical novae. Taken at face value, these estimates imply that a significantly more rapid growth of the white dwarf component toward the Chandrasekhar limit will occur in classical nova systems.

That this is not the case follows from the fact that the classical novae, because of the relative violence of their outbursts, are inefficient in preserving this accreted material. This conclusion follows from straightforward considerations. Both hydrostatic studies (Giannone and Weigert 1967; Taam and Faulkner 1975; Taam 1979) and hydrodynamic studies (Truran *et al.* 1977) reveal that thermonuclear ignition will occur only after $\gtrsim 10^{-4}\,M_\odot$ of hydrogen-rich matter has been accreted by a typical 1.0 $M_\odot$ white dwarf. In contrast, the integrated bolometric light curve of a classical nova, the kinetic energy of the ejected shell, and the energy required to unbind the envelope indicate an energy output of $\sim 5 \times 10^{46}$ ergs, which can be provided by the burning of only $\sim 4 \times 10^{-6}\,M_\odot$ of hydrogen to helium. Since the turnoff of a nova and its return to minimum demand the exhaustion of the nuclear fuel, these numbers imply that most of the accreted material is lost during the course of the outburst. This is compatible with the finding that the light curves of classical novae can be modeled consistently in terms of optically thick winds driven at near Eddington luminosities (Bath 1978; Bath and Shaviv 1976; Ruggles and Bath 1980). We conclude that less than 10% of the accreted matter is retained by the white dwarf. Effective accretion rates $\sim 10^{-10}\,M_\odot$ yr^{-1}, compatible with those inferred for dwarf novae, are thus implied. Note, however, that an increase of the white dwarf core of $\sim$0.2 $M_\odot$ would require transfer of $\sim$2 $M_\odot$ of matter: the typical companion stars in nova binary systems clearly cannot satisfy these demands. The observations also show that large amounts of CNO nuclei are present in the ejected matter, implying that significant amounts of core material are present. This fact suggests that for some systems the white dwarf may actually be decreasing in mass as a result of the nova outburst.

Dwarf novae are observed to undergo periodic outbursts of low intensity which are thought to arise as a consequence of either a mass-transfer instability in the secondary or an instability in the accretion disk (cf., Warner 1976; Robinson 1976). Recent observational studies indicate that rates of mass transfer $\sim 10^{-10}\,M_\odot$ yr^{-1} are typical (Wade 1979; Cordova, Mason, and Nelson 1980; Bath, Pringle, and Whelan 1980). The observational evidence also suggests that little mass is lost from the system in these less-violent outbursts (Robinson 1976). While continued accretion of matter at $\sim 10^{-10}\,M_\odot$ yr^{-1} is sufficient to ensure growth of the white dwarf to the Chandrasekhar limit in some fraction of these systems, burning episodes associated with the hydrogen shell must also be expected. At first glance, it would therefore appear that the efficiency factor inferred for classical novae with respect to the retention of accreted material is relevant for dwarf novae.

A crucial difference here is the rate of mass transfer. For a time-averaged accretion rate of $\sim 10^{-10}\,M_\odot$ yr^{-1}, a time of $\sim 10^6$–10^7 yr is required for the dwarf to accumulate an envelope $\gtrsim 10^{-4}\,M_\odot$ sufficient to initiate a thermonuclear runaway. This is now comparable to the estimated time scale for diffusion effects to be important (Fontaine and Michaud 1979; Vauclair, Vauclair, and Greenstein 1979; Alcock and Illarionov 1980), which can result in the carbon, nitrogen, and oxygen nuclear catalysts settling out of the hydrogen envelope. The initiation of hydrogen burning in the absence of a substantial CNO concentration should be less violent, since the rate of energy release from the proton-proton chain reactions alone is far less sensitive to temperature: a quite different response to accretion can be expected.

III. THERMONUCLEAR BURNING IN DWARF NOVAE

We have studied the onset of thermonuclear burning in degenerate accreted hydrogen envelopes on 0.6 $M_\odot$ and 1.0 $M_\odot$ white dwarfs, for various choices of the intrinsic white dwarf luminosity and of the mass fraction of CNO nuclei ($Z_{\rm CNO}$). A detailed description of these evolutionary sequences will be reported elsewhere; here, we will be concerned only with inferences with regard to the ultimate fate of the white dwarfs in dwarf nova systems. Our hydrodynamic studies begin with the envelope in place and in equilibrium. Complete white dwarf models are utilized in order to ensure a correct measure of the influence of heat transport into the interior. For both white dwarf masses, we chose the minimum envelope mass necessary to initiate a thermonuclear runaway: $7.6 \times 10^{-4} M_{\odot}$ ($0.6 M_{\odot}$) and $1.3 \times 10^{-4} M_{\odot}$ ($1.0 M_{\odot}$). We did not follow the diffusion of the CNO nuclei in these calculations, but rather assumed a uniform distribution in abundance throughout the envelope. Calculations including both accretion and diffusion effects are in progress.

Representative results of our calculations are presented in Table 1. For both dwarf masses, a range of luminosity was explored. The composition of the envelope, in all cases shown, was taken to be $Z_{\rm CNO} = 0$. The evolution of a hydrogen-rich envelope characterized by $Z_{\rm CNO} = 0$ was found to be very different from that for the case $Z_{\rm CNO}$ (solar): for the conditions studied, no flash to high luminosities and associated high effective temperatures occurred. Rather, independent of the initial white dwarf luminosity, the controlling *p-p* chain reactions provide only enough energy release per gram per second to raise the luminosity to $2 L_{\odot}$ and the effective temperature to ~50,000 K. The rapid realization of high rates of energy generation ($\epsilon_{\rm nuc} > 10^{13}$ ergs g^{-1} s^{-1}) and high shell source temperatures ($T_{\rm sh} > 10^8$ K) in response to the thermonuclear runaway, typical of nova models (Starrfield, Truran, and Sparks 1978; Sparks, Starrfield, and Truran 1978), is not seen here; instead a very slow rise to temperatures of $\sim 2 \times 10^7$ K and energy generation rates $\sim 10^4$ ergs g^{-1} s^{-1} results. This rate of energy generation is sufficiently low to ensure that convection never develops. The evolution time to peak temperature, given in the Table, is on the order of 10^6 yr for all sequences. A significant fraction of the H in the deepest layers is consumed during the rise to maximum; in fact, the decline from maximum is found to be attributable to the declining abundance of H in these layers, rather than to expansion and cooling as in standard nova models. We also note that, since no substantial envelope expansion occurs, the effective temperature at maximum remains high.

These results hold interesting implications for the long-term evolution of dwarf nova systems. Steady accretion at a rate $\sim 10^{-10} M_{\odot}$ yr^{-1} must ultimately yield hydrogen envelope masses compatible with thermonuclear ignition. If diffusion can act to settle the heavy nuclei out of this envelope prior to ignition, then an extended phase of nuclear burning at low luminosity will ensue. Continued accretion will serve to replenish the supply of nuclear fuel, further extending the duration of the burning epoch. In fact, since the luminosities $\sim 2 L_{\odot}$ achieved in our studies are less than, but comparable with, the nuclear luminosity $\sim 8 L_{\odot}$ expected for steady burning of matter accreting at $10^{-10} M_{\odot}$ yr^{-1}, the achievement of steady state burning configurations seems likely. Studies of the response of a white dwarf to thermonuclear ignition with accretion and diffusion effects included will clarify this issue.

Growth of the underlying white dwarf configuration at a rate of $\sim 10^{-10} M_{\odot}$ yr^{-1} seems generally to be expected. The increased dwarf mass is realized here as an expanding helium layer above a carbon-oxygen core of $\sim 1.0 M_{\odot}$. Growth of the white dwarf to the Chandrasekhar limit should occur on a time scale of billions of years. The response of such configurations to the growth of this helium layer on a $1.2 M_{\odot}$ carbon/oxygen core has recently been explored by Taam (1980*a*, *b*). At accretion rates above $5 \times 10^{-10} M_{\odot}$ yr^{-1}, a helium runaway occurs at the base of the helium zone. For lower accretion rates, carbon ignition in the core is the likely consequence. If carbon ignites at a density less than $\sim 10^{10}$ g cm^{-3}, then a deflagration front will likely occur as has been discussed for the evolution of intermediate-mass stars. For higher densities at ignition, neutronization may lead to core collapse and the formation of a neutron star, as is also the case for electron captures in an oxygen-neon-magnesium core (Nomoto 1980).

In all of the above cases we are provided with a promising SN I presupernova configuration: the ejecta will be hydrogen deficient and contain the products of explosive burning (carbon and helium) which should include a substantial mass in the form of iron-peak nuclei. Of special interest to our hypothesis, are the evolutionary processes which result in the formation of a neutron star remnant, since such an evolution would produce a neutron star in a close binary with a low-mass red companion as has been proposed for V616 Mon (Oke 1977) and Cen X-4 (S. Wyckoff, private communication).

Our model also predicts observable consequences for dwarf novae systems with low accretion rates. Note

TABLE 1

RESULTS OF THE EVOLUTION

Model	White Dwarf Mass ($M_{\odot}$)	$L/L_{\odot}$ (begin)	$L/L_{\odot}$ (peak)	T_e (peak) ($\times 10^4$)	R(peak)/ R (begin)	τ (peak in yr) ($\times 10^5$)	τ (end in yr)	$T_{\rm sh}$ (peak) K ($\times 10^7$)	$\epsilon_{\rm nuc}$ (peak) ($\times 10^4$)
1.	0.6	2.3×10^{-1}	1.3	4.6	1.04	12	4.3×10^{7}	2.6	0.65
2.	0.6	1.9×10^{-2}	2.9	5.6	1.11	2.6	2.4×10^{8}	3.1	1.4
3.	0.6	5.3×10^{-3}	2.6	5.8	1.13	3.0	6.0×10^{8}	3.2	1.7
4.	0.6	1.5×10^{-3}	2.3	6.0	1.15	4.7	1.4×10^{9}	3.3	1.8
5.	1.0	2.4×10^{-1}	0.7	5.4	1.01	3.1	1.4×10^{7}	2.6	1.5
6.	1.0	7.1×10^{-2}	0.4	4.9	1.01	7.3	5.3×10^{7}	2.4	1.3
7.	1.0	2.1×10^{-2}	0.4	4.8	1.02	6.4	1.1×10^{8}	2.4	1.3
8.	1.0	6.4×10^{-3}	0.3	4.6	1.02	7.6	3.2×10^{8}	2.4	1.2

first that, if thermonuclear runaways in known dwarf nova systems were to give rise to classical nova-like outbursts, we would not expect to have yet witnessed such an occurrence (Bath and Shaviv 1978). If, on the other hand, ignition gives rise to an outburst of long duration or perhaps even to steady burning of the accreting matter, then some of the currently observed systems should exist in that state. How would these appear? For purposes of illustration, we consider the case of a 1 $M_\odot$ white dwarf of radius 5×10^8 cm which is burning in steady state at an accretion rate of $10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$: the implied nuclear-burning luminosity is 7.5 $L_\odot$ (whereas the accretion luminosity onto the white dwarf is only 0.4 $L_\odot$). Assuming no significant radial expansion, the effective temperature is $\sim$110,000 K, the associated bolometric correction is $\sim$7, and the visual magnitude of the white dwarf is $M_v \approx 9.5$. This is below the accretion-dominated level characteristic of dwarf nova systems at minimum and is consistent with observations. However, the presence of a relatively stronger blackbody UV source ($M_{\mathrm{UV}} \approx +2.5$) is also predicted. We note that this is consistent with recent *IUE* studies of SS Cyg and U Gem and explains the UV to visual luminosity ratio reported by Fabbiano *et al.* (1980).

IV. CONCLUSIONS

i) The low rates of mass accretion typical of dwarf novae imply a time scale of $\sim 10^{6-7}$ yr for the accumulation of a hydrogen envelope mass sufficient to induce runaway. On this time scale, gravitational diffusion may act to reduce the concentrations of the carbon, nitrogen, and oxygen nuclei which play a critical catalytic role in hydrogen burning. Thermonuclear ignition in matter devoid of these elements is not violent, because of the weak temperature sensitivity of the proton-proton chain, and an extended epoch of hydrogen burning at low luminosity ensues.

ii) Growth of the underlying white dwarf proceeds at a rate $\sim \dot{M} \times M_\odot\,\mathrm{yr}^{-1}$, forming an increasingly massive helium layer on top of a carbon-oxygen core. When the mass of the white dwarf reaches the Chandrasekhar limit, a viable presupernova configuration is realized.

iii) Identification of these events with Type I supernovae is suggested by the generally hydrogen-deficient character of this configuration, by the likelihood that a mass in the form of ^{56}Ni sufficient to power a SN I light curve will be ejected, and by the fact that the time scale for realization of this supernova event as a consequence of binary evolution—of order billions of years—is compatible with the predominance of SN I in elliptical galaxies.

iv) Further investigations of this problem which treat both accretion and diffusion effects with care are absolutely called for. Accretion heating can alter the runaway conditions and perhaps accelerate the approach to a configuration in which accretion occurs in a steady state with nuclear burning and diffusion. Diffusion effects must be explored in order to ensure that reactions involving the CNO nuclei, as they settle through the envelope, will not lead to a violent runaway. Note that the lifetime of ^{14}N against proton capture (the slowest reaction in the CN cycle) for a proton mass density $\rho = 10^2\,\mathrm{g\,cm^{-3}}$ is 10^6 yr and 10^3 yr at temperatures of 20^6 and 30^6 degrees, respectively. At the higher temperature, CNO cycling may thus provide a significant energy output on the diffusion time scale. This factor may act to restrict the accretion rate domain for which our model is applicable.

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