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A MODEL FOR THE 1987 OUTBURST OF THE RECURRENT NOVA U SCORPII[1]

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ABSTRACT

U Sco is a recurrent nova that has suffered a series of outbursts of which the last occurred in 1987 May. This makes it the recurrent nova with the shortest known recurrence time (8 yr). This time is so short that it severely constrains the thermonuclear runaway theory for the nova outburst as applied to recurrent novae. Therefore, we have simulated the outburst of U Sco by accreting material, with a solar abundance of the CNO nuclei, at a rate of $1.1 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ onto a $1.35\ M_{\odot}$ white dwarf. These calculations incorporated both new theoretical developments of Shaviv and Starrfield on boundary layer heating and, also, the expansion opacity caused by a velocity gradient in optically thin material. One of our most important results is that it takes this evolutionary sequence only ~ 2.6 yr to reach runaway conditions and ultimately eject $4 \times 10^{-7}\ M_{\odot}$ moving with speeds exceeding $\sim 400\ \mathrm{km\ s^{-1}}$. We found that ejection occurred by radiation pressure rather than explosive CNO burning. Although the observed velocities in the 1979 outburst exceeded the above values, we describe the cause of the discrepancy and why our predictions are lower limits. A major fraction of the accreted material remains on the surface of the white dwarf so that it must be growing toward the Chandrasekhar limit at virtually the rate of accretion and will ultimately suffer a supernova explosion. This result again shows that massive white dwarfs in recurrent novae systems are increasing in mass with time.

Subject headings: stars: accretion — stars: mass loss — stars: novae

I. INTRODUCTION

Recurrent novae are a small subclass of cataclysmic variables with multiple outbursts that resemble those of classical novae but are of lesser magnitude (see Kenyon 1986; Webbink *et al.* 1987 for recent reviews, hereafter WLTO). One member of this class is U Sco whose last two outbursts occurred in 1979 June and 1987 May. An interoutburst time of 8 yr is not only the shortest yet known but is shorter than previously thought possible to attain within the framework of the thermonuclear runaway (TNR) theory of the recurrent nova outburst (Starrfield, Sparks, and Truran 1985). Its observed properties are extremely unusual both during outburst (Barlow *et al.* 1981; Williams *et al.* 1981) and quiescence (Hanes 1985) and WLTO claim that it is one of only two recurrent novae that could occur as a result of a TNR (see also Starrfield *et al.* 1984; Starrfield, Sparks, and Truran 1985; Truran *et al.* 1988). While U Sco is considered to be a unique member of the class of recurrent novae, in 1987 August V394 CrA went into outburst and its ultraviolet spectrum closely resembles that of U Sco taken on 1979 June 30 (S. Starrfield *et al.* 1988, in preparation).

The principal observational results are that U Sco displays large ejection velocities, H/He ≈ 2 (by number) in the ejecta, a solar abundance of the CNO nuclei, a very small mass for the ejected shell: $\sim 10^{-7}\ M_{\odot}$, and a very rapid rate of decline. In addition, there is no convincing evidence for H in the quiescent spectrum (Williams *et al.* 1981; Hanes 1985) which sets an upper limit to the H/He ratio in the (assumed) accretion disk of ~ 1 (by number). However, Hanes has identified absorption features that he attributes to a G0 star and WLTO conclude that we are observing an accretion disk plus G giant. It is perplexing, however, that a G giant would be transferring material that is so very hydrogen poor.

Starrfield, Sparks, and Truran (1985) investigated the consequences of accreting mass onto a $1.38\ M_{\odot}$ white dwarf and were able to reproduce the light curve, ejected mass, and CNO abundance in the ejecta for U Sco even though they used a solar ratio for H/He. The runaway occurred after only ~ 30 yr of evolution in excellent agreement with the observed recurrence time of U Sco (at that time). This work was recently extended by Truran *et al.* (1988) who utilized a large range in input H/He ratios (plus solar CNO) and found that unless H/He > 1 (by mass) they could not obtain an optically bright outburst and eject material. The difficulty with their sequences with lower hydrogen abundance was that there was not enough nuclear energy released, on a short enough time scale, to cause the envelope to expand past radii of $\sim 10^{10}$ cm. With this small a radius, only a small fraction of the radiated energy was emitted in the optical.

Our attempts to understand the outburst of U Sco were then complicated by its outburst in 1987, only 8 yr after its last outburst. While it initially seemed almost impossible to produce a TNR after 8 yr of accretion, in the past year we have made important additions both in our hydrodynamic stellar evolution code and in our physical understanding of the accretion process. In addition, observations of novae at maximum show that there is a great deal more ultraviolet opacity present

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than is predicted by the normal stellar evolution opacity tables. Thus, it seemed worthwhile to redo our study of U Sco with the updated computer program and use both a higher $\dot{M}$ and H/He ratios in better accord with the observations. In addition, the fact that its companion was recently identified as a giant allows us to utilize higher accretion rates than we have used previously (Plavec, Ulrich, and Polidan 1973). As a result of these new calculations, we report that we have now been able to produce a TNR in less than 3 yr and, in addition, eject material with nearly the observed H/He ratio. In the next section we briefly report on the changes to the computer code. In § III we report the results of the calculations, and end, in § IV, with a summary and discussion.

II. THE HYDRODYNAMIC CODE

We continue to use the Lagrangian, one-dimensional, hydrodynamic computer code as originally described by Kutter and Sparks (1972). It has been updated continuously over the past 17 yr and the various changes have been reported in our papers on the nova outburst (see Starrfield and Sparks 1986 for a recent review). Recently, we added a very fast rezoning technique to treat mass accretion (Starrfield, Sparks, and Truran 1986), new equation of state and opacity tables based on those of Iben (see Iben and Renzini 1983 and references therein), and boundary layer heating of the star caused by the accretion process (Shaviv and Starrfield 1987, 1988). We have also added the expansion opacity (Karp *et al.* 1977) whenever the expanding zones became optically thin and have a velocity gradient.

We use the observations of novae, Type I supernovae, and SN 1987a to justify this last addition to our code. It is clear from the ultraviolet studies of these objects (Panagia 1987; Kirshner *et al.* 1987; S. Starrfield *et al.* 1988, in preparation) that there are significant sources of opacity present that severely depress the ultraviolet continuum to a level far below what would be predicted from assuming that electron scattering, for fully ionized material, is the only opacity source. In addition, the Rosseland mean opacities commonly used in stellar interior codes such as ours do not include all of the possible sources of opacity in expanding and cooling material. For example, one effect that is neglected is the expansion opacity as described by Karp *et al.* (1977) who also found that its importance is largest for supernova and nova shells. In addition, Wehrse and Shaviv (1987) find that the iron group nuclei, as well as Mg, have an extremely large number of lines in the UV around 2000 Å (the iron forest) which also produces a major increase in the opacity. Therefore, in order to reproduce the observations of novae, we can *very conservatively* increase the opacity, over that of pure electron scattering for a completely ionized gas, by a factor of 2 or more (factors of 5–10 may be reasonable) in the optically thin region with a large velocity gradient (see also Ferland and Younger 1981). Finally, we note that our evolutionary sequences always reach luminosities within a factor of 2 of the Eddington luminosity so that doubling the opacity is sufficient to produce a stellar wind and drive ejection by radiation pressure.

III. THE NUMERICAL CALCULATIONS

We have simulated the observed outbursts of U Sco, T Pyx, and V394 CrA by accreting material at high rates onto 1.35 $M_\odot$ complete white dwarfs. The initial conditions for all of our sequences are: $L = 0.148\ L_\odot$, $T_e = 53{,}000$ K, $R = 3200$ km, $M_{\rm bol} = 6.8$, and $M_V = 11.6$. We use $1/H_p = 2$ in all of our calculations (Cox *et al.* 1987). Various other input parameters are given in Table 1 which also gives the results of the evolution. The input parameters for model C was chosen to represent the outbursts of T Pyx and V394 CrA while that of D was chosen for U Sco. In both cases we have successfully reproduced the short interoutburst times which were strong constraints on the TNR theory for the outburst.

In model D we chose a mass accretion rate of 7×10^{19} g s^{-1} in order to guarantee a short recurrence time. We could have reduced this rate by a factor of 2–3 and still achieved runaway within the observed time of 8 yr for U Sco. This high an accre-

TABLE 1

MODEL PROPERTIES AND RESULTS

PARAMETER	MODEL			
	A	B	C	D
$L_{\rm ACC}/L_\odot$	0.0	3.59+1	7.22+2	2.53+3
$\dot{M}$ ($M_\odot$ yr^{-1})	1.6–8	1.6–8	1.6–7	1.1–6
α	0.	0.5	1.0	0.5
X	0.49	0.49	0.49	0.20
Y	0.49	0.49	0.49	0.78
Z	0.02	0.02	0.02	0.02
τ (yr)	354.9	357.4	23.8	2.6
$M_{\rm env}$ ($M_\odot$)	5.6–6	5.7–6	3.8–6	2.9–6
$\tau_{\rm peak}$ (s)	2.5+3	3.6+3	6.3+3	1.1+4
$\epsilon_{\rm nuc}$ (peak: ergs g^{-1} s^{-1})	1.3+14	1.3+14	1.2+14	8.6+13
$T_{\rm ss}$ (peak: K)	2.2+8	2.2+8	2.0+8	1.9+8
T_e (peak: K)	8.7+5	8.5+5	8.7+5	1.0+6
$M_{\rm bol}$ (max)	−7.0	−6.9	−7.1	−7.3
$M_{\rm ej}$ (mass ejected: $M_\odot$)	~1.0–9	~1.0–9	3.7–7	4.3–7
$f(M_{\rm ej}/M_{\rm env})$	1.0–3	1.0–3	0.10	0.15
$V_{\rm min}$ (km s^{-1})	29.	0.4	40.	35.
$V_{\rm max}$ (km s^{-1})	290.	247.	389.	407.
X (ejected)	...	...	0.41	0.125
Y (ejected)	...	...	0.57	0.856
C (^{12}C + ^{13}C: ejected)	...	...	1.1–3	1.4–3
N (^{14}N + ^{15}N: ejected)	...	...	9.6–3	9.2–3
O (^{16}O + ^{17}O: ejected)	...	...	6.0–5	1.8–4

1988ApJ...325L..35S

tion rate can be understood if the secondary of U Sco is a giant. Because of the small radius of a 1.35 $M_\odot$ white dwarf, most of the accretion luminosity is emitted in the far-UV and not the optical. The parameter, α, in Table 1 is the numerical coefficient which determines the fraction of the boundary layer accretion luminosity that is radiated into the star (Shaviv and Starrfield 1987): i.e.,

$$L_{\mathrm{Acc}} = \alpha \frac{1}{2} \frac{GM}{R} \dot{M} . \tag{1}$$

In this *Letter* we will discuss only sequence D in any detail; we will present the other sequences elsewhere. In model D we assume that half of the accretion energy ($\alpha = 0.5$) is directed into the interior of the white dwarf. We also computed a companion model to D with $\alpha = 0$ but the results were so close to those of D that we do not discuss it here. After 2.6 yr of evolution the shell source temperature T_{ss}, has reached 6.7×10^7 K and we end accretion because the nuclear burning time scale is now shorter than the accretion time scale. By this time the convective region has formed and now extends over nearly the entire accreted envelope reaching to within 100 km of the surface.

It takes this sequence another 1.5 days of evolution for T_{ss} to reach 10^8 K, and 3 hr later the rate of energy generation in the shell source peaks at 8.6×10^{13} ergs $\mathrm{g}^{-1}\,\mathrm{s}^{-1}$. Because of both compressional heating from the high rate of mass accretion and, also, heat radiating inward from the boundary layer, this sequence accretes the lowest amount of mass and is the least degenerate at runaway of all four models. That is why ϵ_{nuc}(peak) and T_{ss}(peak) are the lowest for the four sequences. Peak T_{ss} occurs 923 s after peak ϵ_{nuc} and the peak T_e of 10^6 K ($kt \approx 0.08$ keV) occurs at the same time. Again, because of the small radius of this white dwarf, it emits most of its energy in the EUV and not the visible. This is in contrast to supernovae which have an effective temperature at maximum light of $\sim 10^4$ K. Therefore, the effects of the Fe group lines will be more important for novae than for supernovae (Wehrse and Shaviv 1987).

The intense heat source in the envelope causes the accreted layers to begin expanding, and 7.5 hr later a peak bolometric luminosity of 6.4×10^4 $L_\odot$ is reached. This occurs at a radius of 1.5×10^9 cm with the layers expanding at 0.4 km s^{-1}. For our composition the luminosity exceeds 80% of L_{ED} (for electron scattering opacity) which causes the layers to be slowly but continuously accelerated as they move out of the potential well of the white dwarf. Four hours later the layers are expanding at 23 km s^{-1} and have reached a radius of 10^{10} cm. The surface layers now begin a short period of oscillation which is damped by the expansion of the deeper, hotter layers.

The region where the expanding envelope becomes optically thin begins to move inward in mass from the surface ~ 7 hr later. At this time the luminosity is 5×10^4 $L_\odot$, and the surface is expanding at 163 km s^{-1}. If we were to now assume that the only source of opacity was electron scattering, the material velocities would slowly increase to ~ 200 km s^{-1} and about 10^{-9} $M_\odot$ would be ejected (see the results for models A and B). However, at this time, but only for those zones which are optically thin and in which a velocity gradient exists, we double the opacity. This causes the luminosity to exceed L_{ED} by less than 50% but is sufficient to slowly drive the expanding envelope to velocities of 360 km s^{-1} before the surface has attained a radius of 10^{12} cm. This sequence ejects 4.3×10^{-7} $M_\odot$ moving with velocities from 30 to 400 km s^{-1}. The light curve is displayed in Figure 1.

The amount of mass ejected in our simulated outburst is in excellent agreement with the 1979 outburst (Williams *et al.* 1981). While our peak expansion velocity is lower than the observed value and the optical light curve does not drop as fast as is observed, the agreement would have been improved significantly if we had chosen a larger (and more realistic) coefficient with which to multiply the opacity. For example, we evolved a companion sequence to Model D but used an opacity multiplier of 4 instead of 2. In this sequence, the expanding layers reached a peak velocity of 716 km s^{-1} and 10^{-6} $M_\odot$ were ejected. Therefore, we also conclude that the amount of mass ejected is a very sensitive function of how the

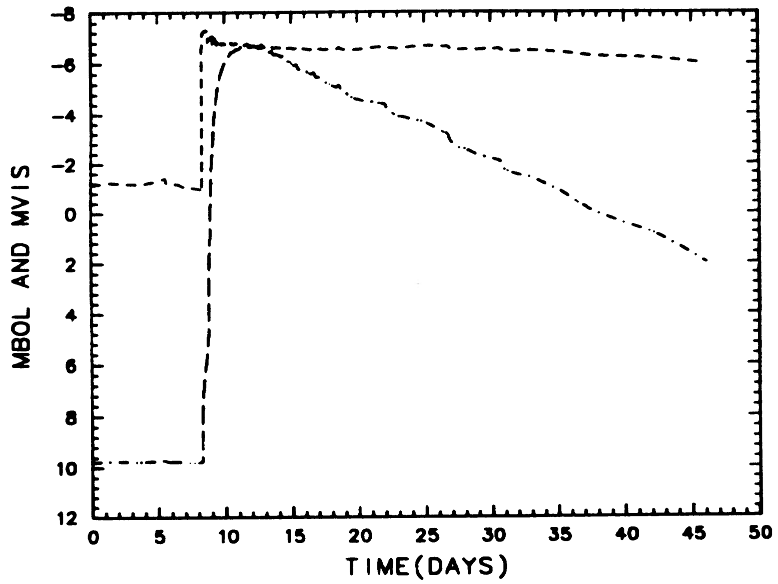

FIG. 1.—The variation of the bolometric magnitude (*dashed curve*) and the visual magnitude (*dot-dash curve*) as a function of time for model D

expansion opacity is included. In order to determine a realistic value for the expansion opacity in a nova envelope, it will be necessary to compute expanding, spherical atmospheres for novae using observed abundances and physical parameters as constraints (R. Wehrse, G. Shaviv, and P. Hauschildt 1988, in preparation). The abundances in the ejecta are given in Table 1. We find that the H/He ratio in our calculation agrees quite well with the observations and so do the abundances of the CNO nuclei.

Even with our opacity increase, this sequence ejected only 15% (f in Table 1) of its accreted envelope. The other 85% was burnt to helium over the next 10 yr. Therefore, the ultimate effect of mass accretion onto this massive white dwarf is for it to grow toward the Chandrasekhar limit at a rate that is almost the rate of mass accretion. We claim that the white dwarf component of U Sco must be very close to the Chandrasekhar limit and that if its mass exceeds 1.35 $M_\odot$ and the accretion rate exceeds 10^{-6} $M_\odot$ yr^{-1}, then it could suffer a SN I explosion within the next 5×10^4 yr (see also Starrfield, Sparks, and Truran 1985).

IV. SUMMARY AND DISCUSSION

We have investigated the evolution of a 1.35 $M_\odot$ white dwarf which was accreting mass at a rate of 1.1×10^{-6} $M_\odot$ yr^{-1} and found that it reached the peak of the TNR in 2.6 yr. As a result of the TNR, this sequence ejected more than 4×10^{-7} $M_\odot$ moving with speeds of up to 400 km s^{-1}. The amount of ejected mass and shape of the light curve are in good agreement with the observations. The predicted velocities are lower than those observed but a higher, and more realistic, opacity in the ejecta can easily increase their velocities.

It is appropriate to comment on whether or not such a high rate of accretion could be observed in U Sco. Since its companion appears to be a G giant, such high rates of mass accretion are more than possible (Plavec, Ulrich, and Polidan 1973). While the accretion luminosity is very large and exceeds 10^3 $L_\odot$, the radius of the star is so small that most of the accretion energy is radiated in the EUV. WLTO have claimed that, in spite of the large bolometric correction expected for accretion onto a white dwarf at high rates, evidence for a hot source in the system will be provided by the presence, or absence, of strong He II λ4686. In fact, U Sco does show strong He II λ4686 at minimum. However, we feel that the connection between the presence or absence of He II λ4686 and a high rate of mass accretion is not yet proven. In fact, the old novae or nova-like variables that show strong He II λ4686 have also turned out to be the (magnetic) AM Her variables (this now includes V1500 Cygni [Chlebowski and Kaluzny 1987]), and we do not feel that there is any observational evidence that argues against a high mass accretion rate in U Sco.

We have also found that the mass of the white dwarf in U Sco must be growing toward the Chandrasekhar limit at a rate equivalent to the rate at which it is accreting mass. It should become a SN I in a very short time.

Because of our improved equation of state and our inclusion of the expansion opacity, we have been able to achieve mass ejection for accreted compositions where hydrogen is equal in abundance to helium by number. This is contrary to the findings of Truran *et al.* (1988) who used a simple argument to show that there was not enough nuclear energy to eject the *entire* accreted envelope from a massive white dwarf. We agree with their argument but point out that the available nuclear energy (plus the accretion energy) produced in the accreted layers needs to eject only a small fraction of the accreted material. Their expression should be multiplied by the ratio of the mass ejected to the mass burnt during the entire outburst. In addition, we also reduced the mass of the white dwarf to 1.35 $M_\odot$, from their value of 1.38 $M_\odot$, in order to decrease the gravitational binding energy.

Finally, it is also appropriate to point out that the calculations were initiated with no hydrogen on the surface of the white dwarf and, thereby, we were simulating what must be the first outburst on U Sco and not the "nth." Our evolutionary sequences took more than 10 yr to return to minimum and, in addition, left unburned hydrogen on their surfaces. If we assume that the actual white dwarf starts accreting when it is hot and has residual hydrogen on the surface, then we can reduce the rate of accretion to values that might be more acceptable. We shall do this in a succeeding paper.

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REFERENCES

Barlow, M. J., *et al.* 1981, *M.N.R.A.S.*, **195**, 61.
Chlebowski, T., and Kaluzny, J. 1987, *IAU Circ.* 4413.
Cox, A. N., Starrfield, S. G., Kidman, R. B., and Pesnell, W. D. 1987, *Ap. J.*, **317**, 304.
Ferland, G. J., and Younger, J. W. 1981, *Ap. J.* (*Letters*), **251**, L17.
Hanes, D. A. 1985, *M.N.R.A.S.*, **213**, 443.
Iben, I., and Renzini, A. 1983, *Ann. Rev. Astr. Ap.*, **21**, 271.
Karp, A. H., Lasher, G., Chan, K. L., and Salpeter, E. E. 1977, *Ap. J.*, **214**, 161.
Kenyon, S. J. 1986, *The Symbiotic Stars* (Cambridge: University Press).
Kirshner, R. P., Sonneborn, G., Crenshaw, D. M., and Nassiopolous, G. 1987, *Ap. J.*, **320**, 602.
Kutter, G. S., and Sparks, W. M. 1972, *Ap. J.*, **175**, 407.
Panagia, N. 1987, in *High Energy Phenomena Around Collapsed Stars*, ed. F. Pacini (Dordrecht: Reidel), p. 33.
Plavec, M., Ulrich, R. K., and Polidan, R. S. 1973, *Pub. A.S.P.*, **85**, 769.
Shaviv, G., and Starrfield, S. 1987, *Ap. J.* (*Letters*), **321**, L51.
Shaviv, G., and Starrfield, S. 1988, *Ap. J.*, submitted.
Starrfield, S., and Sparks, W. M. 1986, in *Cataclysmic Variables: Recent Multi-frequency Observations and Theoretical Developments*, ed. H. Drechsel, Y. Kondo, and J. Rahe (Dordrecht: Reidel), p. 379.
Starrfield, S., Sparks, W. M., and Truran, J. W. 1985, *Ap. J.*, **291**, 136.
———. 1986, *Ap. J.* (*Letters*), **303**, L5.
Starrfield, S., Sparks, W. M., Truran, J. W., and Sion, E. M. 1984, in *Future of Ultraviolet Astronomy Based on Six Years of IUE Research*, ed. J. M. Mead, R. D. Chapman, and Y. Kondo (NASA CP-2349), p. 313.
Truran, J. W., Livio, M., Hayes, J., Starrfield, S., and Sparks, W. M. 1988, *Ap. J.*, **324**, 345.
Webbink, R. F., Livio, M., Truran, J. W., and Orio, M. 1987, *Ap. J.*, **314**, 653 (WLTO).
Wehrse, R., and Shaviv, G. 1987, *Ap. J.* (*Letters*), submitted.
Williams, R. E., Sparks, W. M., Gallagher, J. S., Ney, E. P., Starrfield, S., and Truran, J. W. 1981, *Ap. J.*, **251**, 221.

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