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TITLE NOVA OUTBURST MODELING AND ITS APPLICATION TO THE RECURRENT NOVA PHENOMENON

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NOVA OUTBURST MODELING AND ITS APPLICATION TO
THE RECURRENT NOVA PHENOMENON

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ABSTRACT

The thermonuclear runaway (TNR) theory for the cause of the common novae is reviewed. Numerical simulations of this theory were performed using an implicit hydrodynamic Lagrangian computer code. Relevant physical phenomena are explained with the simpler envelope-in-place calculations. Next the models that include accretion are discussed. The calculations agree very well with observations of common novae. The observational differences between common novae and recurrent novae are examined. We propose input parameters to the TNR model which can give the outburst characteristics of RS Ophiuchi and discuss the implications. This review is concluded with a brief discussion of two current topics in novae research: shear mixing on the white dwarf and Neon novae.

1. INTRODUCTION

In this review we present and discuss theoretical calculations of the thermonuclear runaway (TNR) model for a nova outburst. We start with the canonical model of a cataclysmic binary (see figure 1) consisting of a hot white dwarf and a cooler companion (Kraft 1964). The cool companion overflows its Roche lobe and supplies hydrogen-rich material to an accretion disk around the white dwarf. This material eventually accretes onto the white dwarf, forming a hydrogen-rich envelope whose base is electron-degenerate. As the accretion proceeds, the temperature at the base of this envelope increases, which increases the thermonuclear energy generation. The thermonuclear energy, in turn, increases the temperature. However, because the material is degenerate it does not expand and so the

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CATAclysmic BINARY

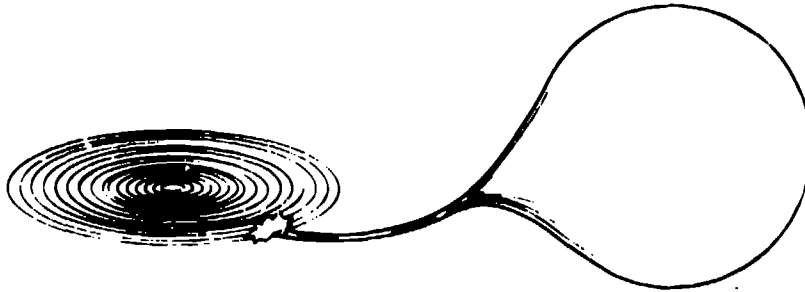


Figure 1. Canonical picture of a cataclysmic binary.

temperature continues to rise. This positive feedback loop leads to a TNR, which Kraft (1963) proposed as the cause of the nova outburst. Under the proper conditions the released energy will be sufficient to eject part or all of the accreted envelope.

2. HYDRODYNAMIC CALCULATIONS

We have used the implicit hydrodynamic Lagrangian computer code developed by Kutter and Sparks (1972). This code solves the conservation of mass, momentum and energy equations and the energy transport equation, simultaneously. An implicit solution is necessary because the Courant time for a zone in the degenerate region is less than 1 second, while the required evolution time to the runaway is thousands of years. The necessity of a hydrodynamic treatment is obvious. The addition of an artificial viscosity pressure is necessary to handle shock waves.

2.1. Evolution of envelope-in-place models

In our earlier model calculations (Starrfield *et al.* 1978, and references therein) the hydrogen-rich envelope was initially on the white dwarf in hydrostatic and thermal equilibrium. Because these models are somewhat simpler than the accreting models, we will use them to discuss some of the physics involved in the evolution. Calculations by Pringle *et al.* (1978) and MacDonald (1979) showed

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similar results. Figure 2 shows the behavior of the temperature of the envelope as a function of mass at significant times in its evolution. Curve 1 on the graph is the initial temperature distribution of the envelope. Curve 2 represents the distribution when the CNO reactions first become dominant at $\sim 2 \times 10^7$ K. The time between these first two curves is usually many thousands of years and is very strongly dependent on the white dwarf's intrinsic luminosity and to a lesser extent on the CNO abundance of the envelope's matter and the white dwarf's mass. The next significant event as the temperature continues to rise is at $\sim 3 \times 10^7$ K when convection begins in the region above the maximum temperature (curve 3). This convective region will continue to extend outward until it reaches the surface layers near peak temperature. When the maximum temperature (#4) reaches 10^8 K two significant circumstances occur. First, the temperature exceeds the Fermi temperature and the electron degeneracy is lifted. At this point a hydrodynamic treatment becomes necessary, and mass motions on a dynamical time scale must be included. Second, the proton capture rates on the CNO nuclei become shorter than the β^+ decay rates.

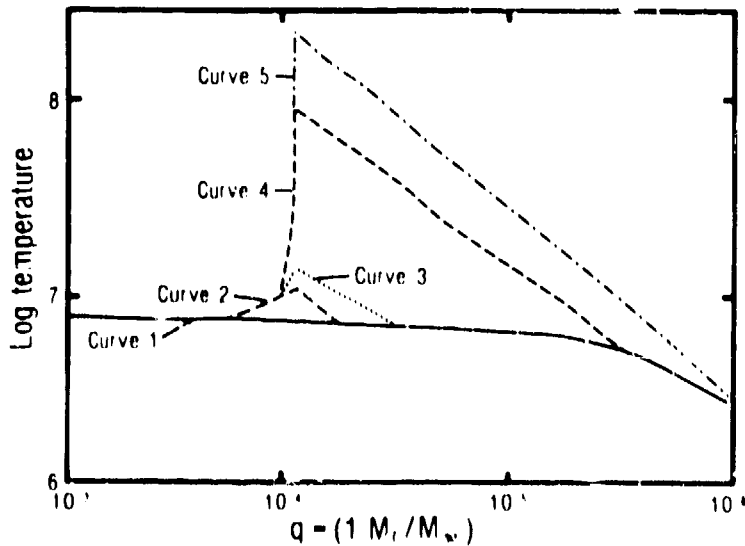


Figure 2. Log temperature of a Hydrogen-rich envelope vs. mass during its evolution on a white dwarf. See text for a description of the various curves.

Thus, the β^+ -unstable nuclei and their rates must be included both in the nuclear reaction network and in the energy generation calculation (Starrfield et al. 1972). As the temperature increases, the CNO reactions are controlled by the β^+ decay rates, and the energy generation rate briefly becomes independent of temperature and density and dependent only on the CNO abundances.

The last curve (#5) shows the time of peak temperature, which is reached only a few seconds after curve 4. The dynamic time scale is now of the order of one second while the nuclear burning time scale is given by $C_p T / \epsilon_{\text{nuc}}$. If the CNO abundance is solar then the nuclear burning time scale is also of the order of one second. This allows the envelope to expand before a strong TNR can develop. Under these conditions little or no material is ejected by the expansion. The now rekindled hydrogen burning shell source may eject the envelope by radiation pressure and produce a slow nova (Sparks et al. 1978). If the initial CNO abundances are increased above solar, the nuclear burning time scale becomes shorter than the dynamic time scale. For large CNO overabundances the TNR becomes strong enough to eject a portion of the hydrogen-rich envelope and produce a fast nova (Starrfield et al. 1978). The peak temperature is also strongly dependent on the CNO abundances. At peak temperature the convective time scale is of the order of 100 sec. This is also the decay time scale of the β^+ -unstable nuclei. Therefore, a sizeable fraction of the β^+ -unstable nuclei will be convected to the outer layers before they decay. When they decay in the outer layers, they provide an additional energy source for ejection at a relatively low gravity. This complexity of physical phenomena shows why it is necessary to use an implicit hydrodynamics code with time-dependent convection and a nuclear reaction network which includes the β^+ -unstable nuclei.

Because of the strong dependence of the outburst on the abundances of the CNO nuclei, we will digress at this point to discuss their observed abundances. Table 1 shows the element abundances of various novae. In general there is an increase in the speed of the nova as the CNO abundances increase which is predicted by the calculations. DQ Her and U Sco are the two notable exceptions to

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Table 1. Nova Ejecta Abundance Data

	Speed Class	H	He	C	N	O	Ne	"Z"	Ref
Solar		0.76	0.22	0.0034	0.0013	0.0083	0.0015	0.018	
HR Pic	Slow	0.53	0.43		0.022	0.0058	0.011	0.039	a
HR Del	Slow	0.45	0.48		0.027	0.047	0.003	0.077	b
T Aur	Med	0.47	0.40		0.079	0.051		0.13	c
V1500 Cyg	Fast	0.55	0.15	0.064	0.095	0.12	0.022	0.30	d
Cyg 1978	Med Fast	0.47	0.22	0.04	0.14	0.13		0.31	e
DQ Her	Slow	0.34	0.095	0.045	0.23	0.29		0.56	f
V Sco	Very Fast	0.32	0.64					0.03	g

- a. Williams and Gallagher 1979
- b. Tylenda 1978
- c. Callagher *et al.* 1980
- d. Ferland and Shields 1978
- e. Stickland *et al.* 1981
- f. William *et al.* 1978
- g. William *et al.* 1981

this pattern. DQ Her has a very high overabundance of CNO elements but is classified as "slow", while U Sco has nearly solar CNO abundances but is "very fast". While various observers have quoted a wide range of mass for the white dwarf component of DQ Her, it may be anomalously low, $\sim 0.5 M_{\odot}$ (Smak 1980). This might allow us to understand its slow evolution in spite of its high CNO concentration. From numerical calculations (Starrfield *et al.* 1974), it is known that such a low white dwarf mass will produce a weak TNR. Conversely a high white dwarf mass ($1.38 M_{\odot}$) produces a strong runaway and a rapid development of a light curve, even without CNO enhancement. This model has been proposed for the recurrent nova U Sco (Starrfield *et al.* 1985) and will be discussed later.

Now we return to the calculations with the in-place envelopes. Figure 3 shows a comparison of the observed light curve of HR Del with the calculated visual light curve (M_{vis}) of a $1.25 M_{\odot}$ white dwarf with a hydrogen-rich envelope (Sparks *et al.* 1978) where we have assumed a distance of 750 kpc. The agreement is excellent. The nearly constant calculated bolometric luminosity (M_{BOL}) is a result of the rekindled hydrogen-burning shell source ($M_{\dot{g}}$). This shell source produces a surface luminosity close to the Eddington limit. Sparks *et al.* (1976) have predicted that constant bolometric luminosity will occur after the outburst while the visual

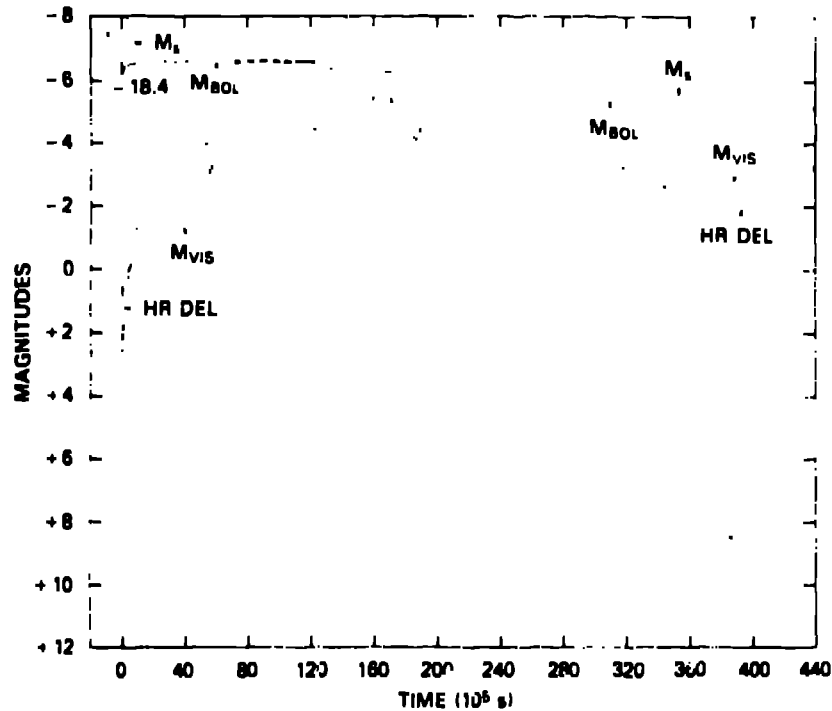


Figure 3. The absolute bolometric (M_{BOL}), visual (M_{VIS}), and energy generation (M_E) magnitudes as functions of time. The absolute visual magnitude of HR Del assuming a distance of 750 kpc is also plotted.

luminosity declines because the peak of the radiation is shifting into the ultraviolet. The multifrequency observation of FH Ser (Geisel *et al.* 1970, Gallagher and Code 1974) and V1500 Cygni (Wu and Kester 1977) confirm this behavior. The theoretical models also predict that part of the hydrogen-rich envelopes will be ejected with velocities of 100-2000 km s⁻¹, which agree with general observation of novae.

2.2. Evolution of accreting models

Our computer code has now been modified to include the accretion of the hydrogen-rich material onto the white dwarf (Kutter and Sparks 1980). Therefore, the mass accretion rate is an input parameter instead of envelope mass. Calculations by Narial *et al.* (1980), Prialnik *et al.* (1982) and Starrfield *et al.* (1985, 1986b) show that the accreted envelope mass and the accretion time scale required for a TNR decrease as the white dwarf mass, accretion

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rate, white dwarf's intrinsic luminosity or CNO abundances increase. An increase in the mass accretion rate, the intrinsic luminosity or the CNO abundances all cause the temperature of the runaway region to increase, leading to a shorter runaway time and a lower accreted envelope mass. A larger white dwarf mass and the corresponding smaller white dwarf radius both cause the gravity to be larger. A larger gravity leads to a higher pressure at a given Lagrangian mass depth. Theoretical hydrodynamic calculations typically show that the runaway starts when the pressure reaches $\sim 2 \times 10^{19}$ d, cm^{-2} in the hydrogen-rich envelope. Thus the envelope mass is smaller for a more massive white dwarf.

Numerical studies have also shown that the strength of the outburst increases as the white dwarf mass or the CNO abundance increases and as the mass accretion rate or the white dwarf's intrinsic luminosity decreases. Generally speaking, the strength of a nova is taken to mean its peak luminosity and its rate of development and decline. For the case of a lower mass accretion rate or a lower white dwarf's intrinsic luminosity, the accreted envelope mass is large and the strength of the outburst stronger. A more massive white dwarf has a higher degree of degeneracy and, thus, a stronger outburst. The role of the CNO abundances on the outburst strength has been explained above.

With accretion rates of $10^{-10} - 10^{-8} M_{\odot} \text{ yr}^{-1}$, the theoretical calculations fit the observed characteristics of a nova.

3. APPLICATION OF TNR MODEL TO THE RECURRENT NOVAE

Let us now apply the TNR model to the recurrent novae. First we must examine the differences between the common novae and the recurrent novae as given in Table 2. The most difficult constraint recurrent novae impose on the TNR model is the short recurrence time. The recurrence time scale of a nova is equal to the accretion time scale plus the time for the remnant hydrogen envelope to be converted into helium. This means that an envelope massive enough to undergo a TNR must be accreted on a very short time scale. Starrfield et al. (1985) have demonstrated that a TNR model can occur on time scales as short as 33 years and applied this model

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to U Sco. The model investigated was a $1.38 M_{\odot}$ white dwarf with an intrinsic luminosity of $0.1 L_{\odot}$ and an accretion rate of $1.7 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. This white dwarf model accreted $5 \times 10^{-7} M_{\odot}$ in 32.7 yr before the runaway. It ejected $3 \times 10^{-8} M_{\odot}$ (6% of the accreted mass) with velocities ranging from 300 to 3000 km s^{-1} . The light curve, shown in figure 4, rises and falls very rapidly consistent with U Sco. It takes an additional 2 years to convert the remnant hydrogen envelope to helium.

Table 2. Common and Recurrent Nova Characteristics

	<u>Common Novae</u>	<u>Recurrent Novae</u>
Ejected Mass	$10^{-4} M_{\odot}$	$10^{-8} - 10^{-5} M_{\odot}$
Active Period	1 year	1 month
Velocity of Ejection	1000 km s^{-1}	5000 km s^{-1}
Kinetic Energy	10^{46} erg	10^{44} erg
Radiated Energy	10^{45} erg	10^{43} erg
He/H	~ 0.3	2
Range	> 14 mag	< 10 mag
Recurrence Time	$10^4 - 10^5 \text{ yr}$	30 year

A very similar model, with a higher accretion rate, can be applied to RS Ophiuchi. Such a model will have a rapidly rising and falling light curve, high velocity and short recurrence time scale characteristic of RS Ophiuchi. The observed X-rays (Mason et al. 1985) early in the outburst could possibly be due to the high velocity ejecta colliding with the slower wind-ejected material from the giant. E. M. Jones (1985, private communication) is currently modeling this mechanism to see if it can account for the X-rays. If the radiation observed in the X-rays - 8 months after the outburst is assumed to have a blackbody distribution on a 10^9 cm radius white dwarf at a distance of 1.6 kpc, then it represents a temperature of $3.5 \times 10^5 \text{ K}$ and a luminosity of $10^{37} \text{ erg s}^{-1}$ (Mason et al. 1985). These values are consistent with the constant luminosity from the rekindled hydrogen-burning shell source after the TNR.

If one accretes $1.7 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ onto a $1.38 M_{\odot}$ white dwarf then we expect a quiescent luminosity of several hundred solar

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luminosities radiated mostly in the unobservable extreme ultraviolet. The wind material around this binary may shift most of the luminosity to longer wavelengths. The detection of this luminosity during quiescence would be a strong support for this model. This and related constraints on any TNR model for PS Ophiuchi have been discussed by Livio *et al.* (1985) who have proposed an episodic accretion event from the giant onto a bloated main sequence star as a means of producing the outburst.

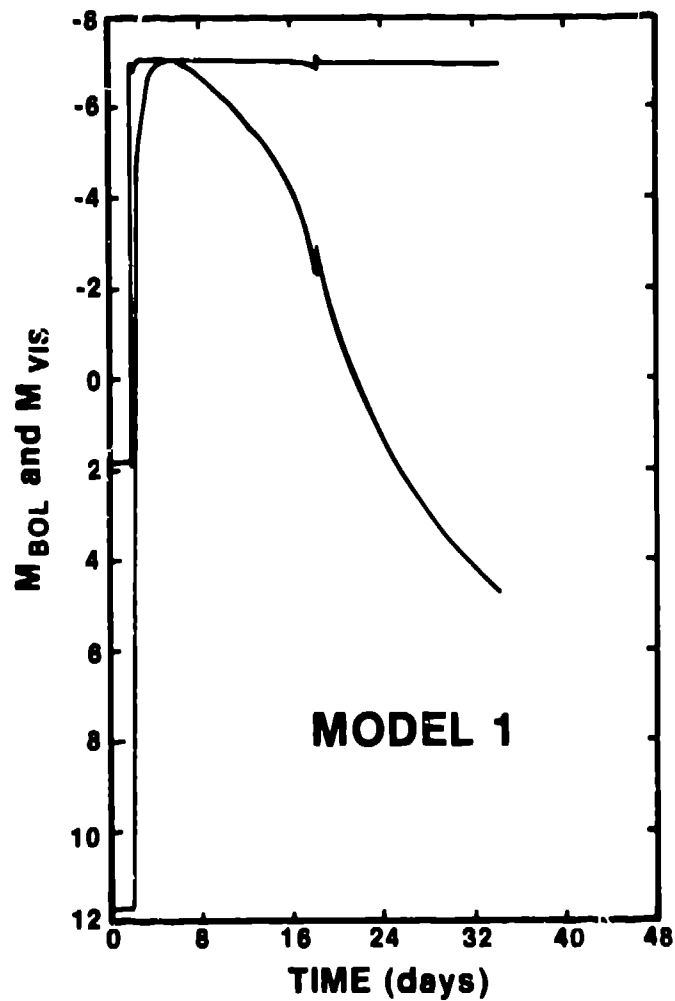


Figure 4. The visual and bolometric light curve of a rapidly accreting $1.38 M_{\odot}$ white dwarf. This model compares favorably with the recurrent nova U Sco.

4. OTHER CURRENT NOVA RESEARCH

We conclude with a short discussion of our other nova research projects. Spherical accretion is only an approximation to the true physical processes. The hydrogen-rich material arrives at the equator of the white dwarf from the accretion disk with nearly Keplerian angular momentum. Kippenhahn and Thomas (1978) have shown that by conserving angular momentum, assuming marginal stability and setting the Richardson number to $1/4$, shear instabilities mix the accreted material inward and toward the poles. The bulk of the accreted material remains in a wide belt at the equator. The large overabundances of He, C, N and O nuclei in nova ejecta (Table 1) must be caused by some type of mixing on the white dwarf. Shear mixing offers a natural mechanism for this and, indeed, because of the conservation of angular momentum is difficult to avoid. Thus, shear mixing opens up a wide range of situations depending on the type of white dwarf (e.g., He, C/N/O, O/Mg/Ne). Sparks and Kutter (1986) have recently calculated evolutionary models with shear mixing.

Another recent development are novae found to have large overabundances of Ne, Mg, Al and O, in their ejecta. These include Nova CrA 1981 (Williams et al. 1985), Nova Aqu 1982 (Snijders et al. 1984), Nova Vul II 1984 (Starrfield et al. 1986c) and possibly Nova Cyg 1975 (Ferland and Shields 1978). The implication is that the outburst occurs on an O/Ne/Mg white dwarf. Although the expected ratio of O/Ne/Mg white dwarfs to C/N/O white dwarfs is only $1/34$ to $1/47$ (Iben and Tutukov 1985), the more massive O/Ne/Mg white dwarfs will have more outbursts and the expected outburst ratio is $1/4$ (Truran and Livio 1985). This is comparable with the observations. Starrfield et al. (1986a) have recently evolved models to simulate these outbursts and found that these models are the most violent of any calculated models. We are currently expanding our nuclear reaction network to include the reactions on Ne, Al and Mg.

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REFERENCES

- Ferland, G. J., and Shields, G.A. (1978). *Ap.J.*, 226, 172.
Gallagher, J. S., and Code, A.D. (1974). *Ap.J.*, 189, 303.
Gallagher, J. S., Hege, E. K., Kopriva, D. A., Williams, R. E., and Butcher, H. R. (1980). *Ap.J.*, 237, 55.
Geisel, S. L., Kleinman, D.E., and Low, F. J. (1970). *Ap.J. Lett.*, 161, L101.
Iben, I., and Tutukov, A. (1985). *Ap.J. Suppl.*, 54, 335.
Kippenhahn, R., and Thomas, H.-C. (1978). *Astr. Ap.*, 63, 265.
Kraft, R. P. (1963). *Adv. Astr. Ap.*, 2, 43.
_____. (1964). *Ap.J.*, 139, 457.
Kutter, G. S., and Sparks, W. M. (1972). *Ap.J.*, 175, 407.
_____. (1980). *Ap.J.*, 239, 988.
Livio, M., Truran, J. W., and Webbink, R.F. (1985). preprint.
MacDonald, J. (1979). PhD thesis, University of Cambridge.
Mason, K. O., Cordova, F. A., Bode, M. F., and Barr, D. (1985). this meeting.
Narial, K., Nomoto, K., and Sugimoto, D. (1980). *P.A.S.J.*, 32, 473.
Priainik, D., Livio, M., Shaviv, G., and Koetz, A. (1982). *Ap.J.*, 257, 312.
Priainik, D., Shara, M. M., and Shaviv, G. (1978). *Astr.Ap.*, 62, 339.
Smak, J. (1980). *Acta Astron.*, 30, 267.
Snijders, M.A.J., Batt, T.J., Seaton, M.J., Blades, J.C., and Morton, D.C. (1984). *M.N.R.A.S.*, 211, 7p.
Sparks, W. M., and Kutter, G. S. (1986). submitted to *Ap.J.*
Sparks, W. M., Starrfield, G. S., and Truran, J. W. (1976). *Ap.J.*, 208, 819.
_____. (1978). *Ap.J.*, 220, 1063.
Starrfield, G. S., Sparks, W. M., and Truran, J. W. (1974). *Ap.J.*, 192, 647.
_____. (1978). *Ap.J.*, 226, 186.
_____. (1985). *Ap.J.*, 291, 136.
_____. (1986a). submitted to *Ap.J. Letters*.
_____. (1986b). in preparation
_____. (1986c). in preparation
Starrfield, G. S., Truran, J.W., Sparks, W. M., and Kutter, G. S. (1972). *Ap.J.*, 176, 169.
Stickland, D. J., Penn, C. J., Seaton, M. J. Snijders, M.A.J., and Storey, P.J. (1981). *M.N.R.A.S.*, 197, 107.
Truran, J. W., and Livio, M. (1985). submitted to *Ap.J.*

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- Tylenda, R. (1978). *Acta Astron.*, 28, 333.
- Williams, R. E., and Gallagher, J. S. (1979). *Ap.J.*, 228, 482.
- Williams, R. E., Ney, E. P., Sparks, W. M., Starrfield, S. G.
Wyckoff, S., and Truran, J. W. (1985). *M.N.R.A.S.*, 212, 753.
- Williams, R. E., Sparks, W. M., Gallagher, J. S., Ney, E. P.,
Starrfield, S. G., and Truran, J. W. (1981). *Ap.J.*, 251, 221.
- Williams, R. E., Woolf, N. J., Hege, E. K., Moore, R. L.,
and Kopriva, D. A. (1978). *Ap.J.*, 224, 171.
- Wu, C.-C., and Kester, D. (1977). *Astron. and Ap.*, 58, 331.