ON THE TIME-SCALE FOR TURN-OFF OF A NOVA AFTER THE OUTBURST*

Sumner Starrfield

Theoretical Division
Los Alamos Scientific Laboratory
University of California

and

Department of Physics
Arizona State University

I. INTRODUCTION

It is now generally accepted that a nova outburst is caused by a thermonuclear runaway (TR) in the accreted hydrogen rich envelope of a carbon white dwarf. Over the past few years we have studied the evolution of such runaways and have shown that the calculated evolutionary sequences are in substantial agreement with the observations (Starrfield, et. al. 1978; Sparks, et. al. 1978). In the published work we have varied the white dwarf mass, the envelope mass, the accreted envelope mass, and the chemical composition in the envelope (Starrfield, et. al. 1976; Gallagher and Starrfield 1978). In all cases we find that a TR results in mass ejection and the luminosity variations of this ejected material can reproduce the observed light curves of the fast and slow novae.

In addition to our other results, very early in our studies we predicted that not all of the accreted envelope would be ejected in the initial "burst" stage of the outburst. A major fraction of the envelope would remain on the white dwarf in the form of a hot, luminous, extended, completely convective remnant which was evolving on a nuclear burning time scale. This prediction was in close agreement with the satellite observations of Nova FH Ser 1970 (Gallagher and Code 1974) which showed that a hot, constant luminosity, source of UV photons existed in this nova for some months after the outburst.

While the prediction, and nearly simultaneous, detection of the remnant has been one of the more important results of our theory for the outburst, the calculated evolution of the remnant has caused one of the few remaining discrepancies between our theory and the observations. Our evolutionary sequences predict that the remnant continues to evolve on a nuclear burning time scale and since the envelope has a mass of

* Supported in part by the National Science Foundation under Grant AST77-23190 to Arizona State University.

https://doi.org/10.1017/S0252921100076041 Published online by Cambridge University Press

~ 10^{-4} $M_\odot$ and the luminosity is about 10^4 $L_\odot$, the remnant can be expected to take 10^3 years to convert the remaining hydrogen in its envelope to helium before returning to minimum.

It is the purpose of this paper to review the evidence, both theoretical and observational, for this remnant and then describe its evolution to burnout. I then proceed by discussing various physical mechanisms which can lead to an extended period of mass loss.

II. THE HYDROSTATIC REMNANT

Although it had long been noticed that there was a gradual rise in the state of ionization of the expanding nebula at late stages in the outburst (c.f., McLaughlin 1960), it was not until the observations of Nova FH Ser 1970 by OAO-2B (Gallagher and Code 1974) that it was realized that the post maximum stages of the optical outburst marked the beginning of a UV bright, constant luminosity, phase of the nova outburst. An analysis of the increasing ionization and excitation of the light ions present in the nebulae showed that such a phase must exist for all novae (Gallagher and Starrfield 1976; see also Gallagher and Starrfield 1978). This result has since been borne out by satellite observations of Nova V1500 Cygni 1975 (Wu and Kester 1977) and Nova Cygni 1978 (Sparks 1978; private communication) and by the infra-red observations of Nova NQ Vulpeculae 1976 (Ney and Hatfield 1978). In addition, Thackeray (1977) has shown that as RR Tel has evolved with time the level of ionization has increased in the expanding nebula. Therefore, it seems reasonable to expect that this constant luminosity, UV bright, phase exists in all novae.

We have already proposed that this phenomenon is caused by the radiation from the hydrostatic remnant which is a characteristic of all of our evolutionary sequences. First discovered in our initial calculations at 1.0 $M_\odot$ (Starrfield, et. al. 1974), we have confirmed these predictions with our studies at a variety of white dwarf masses, envelope masses, and chemical compositions (Starrfield, et. al. 1978, Sparks, et. al. 1978). However, our most recent results demonstrate that the fraction of the envelope that remains on the white dwarf is a strong function of the initial conditions and the evolution of the outburst. For example, the initial 1.00 $M_\odot$ studies had an envelope mass of 10^{-3} $M_\odot$ and ejected only ten percent of the accreted envelope, while models with envelope masses of 10^{-4} $M_\odot$ (Starrfield, et. al. 1978) ejected nearly half of the accreted envelope. More recent studies at 1.25 $M_\odot$ (Sparks, et. al. 1978, Truran, et. al. 1979, in preparation) show that anywhere from zero to eighty percent will be ejected depending upon the carbon enhancement.

Our calculations show that this remnant, which can be strongly enhanced in the CNO nuclei, expands to radii of 10^{10} to 10^{12} cm just after the burst ejection phase of the outburst. At this time nuclear burning is still proceeding in the envelope at a rate of 10^8 to 10^9 erg gm^{-1} sec^{-1}. This intense energy generation raises the temperature throughout the envelope so that the pressure support comes mainly from radiation pressure and the envelope becomes completely convective. Since the support of the envelope depends upon radiation pressure, the luminosity quickly climbs to nearly the Eddington luminosity for an object with the mass of the dwarf. This point will be emphasized by Truran (1979). Over the next few days to weeks the envelope slowly shrinks and its effective temperature climbs to values exceeding 10^5 K. In fact, as the envelope loses mass, as it must, its effective temperature will increase. This result is in close agreement with the observations which suggest that the temperature of the source which heats the nebula is also increasing with time. However, even if no mass were lost, as the nuclear reactions convert hydrogen to helium, the radius of the envelope shrinks at constant luminosity producing an increase in the effective temperature.

Nevertheless, the theoretical calculations predict that the remnant is evolving on a nuclear burning time scale. The velocities of the envelope are less than meters/second and, in fact, the structure resembles that of a star on the asymptotic giant branch (without the helium burning shell). Given this structure, how can one expect it to return to minimum on the observed time scale of 1 to 2 years?

One suggestion to resolve this problem was made by Nariai (1974) who followed (with a series of quasi-static models) the evolution of the remnant envelope assuming no energy generation present. He found that the envelope returned to minimum on a time scale of one to two years. We redid this study using actual remnants and turning off the nuclear reactions just after ejection was complete (Truran, et. al. 1979, in preparation). We found that as the envelope collapsed, the gravitational energy release produced both an increase in the effective temperature (to ~ 2 to 3×10^5 K) and an increase in the collapse time (to about 10 years). Since these results strongly disagree with the observations and since one cannot simply "turn-off" the nuclear energy generation, it appears that other mechanisms must act to return the nova to minimum on a short time scale.

III. EVOLUTION TO BURN-OUT

We have also considered the possibility that the surface conditions at late stages in the evolution of the remnant would actually be different from what one would predict from simple arguments about hydrogen burning in the shell. We were also interested in determining at what value of X the envelope will actually begin its decline. In order to answer these questions, we chose a 1.00 $M_\odot$ dwarf with an envelope mass of 10^{-4} $M_\odot$, a luminosity of 1.0 $L_\odot$, and an initial hydrogen abundance of X = 0.2. We did not enhance the CNO nuclei because we did not want to produce an outburst and eject material.

This model takes 20 years to reach a peak ε_{nuc} of 3.4×10^{14} erg gm^{-1} sec^{-1} and a peak temperature in the shell source of 1.57×10^8 K. These values are in reasonable agreement with our low envelope mass studies (Starrfield, et. al. 1978). Over the next few hours the effective temperature reaches 5×10^5 K and then begins to decrease as the luminosity climbs to 5.4×10^4 $L_\odot$ (see Figure 1). This value is nearly the Eddington luminosity for a 1.0 $M_\odot$ model with our surface conditions. The radius increases continuously over this interval until it slightly exceeds 10^{10} cm at which point quasi-periodic oscillations set in and we are forced to reduce the size of the time steps. The structure of this model now closely resembles that of the hydrostatic remnants in the nova-like evolutionary sequences and we feel confident that our neglect of the evolution time for the remnant to reach X = .2 will not affect our conclusions. Since this evolutionary sequence shows that it takes 10^2 years for the hydrogen in the envelope to reach $X = 10^{-4}$ and during this time the envelope stays hot and luminous, we are forced to conclude that the nova does not return to minimum through a nuclear evolution process and the remnant must eject its envelope in order to return to minimum.

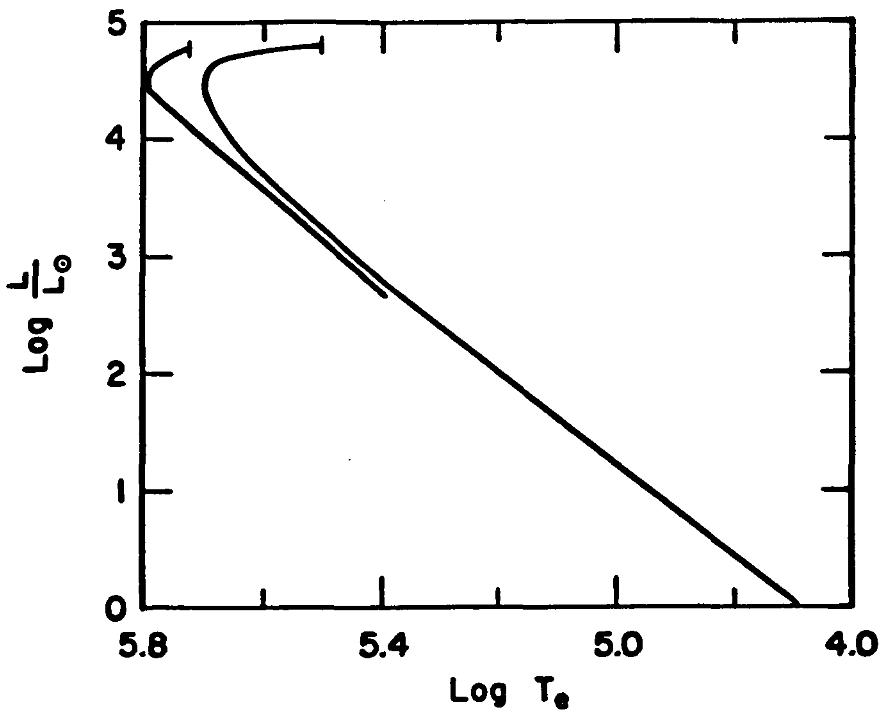

Figure 1. The evolution of a 1.00 $M_\odot$ model with a helium rich envelope from X = 0.02 to $X = 1 \times 10^{-4}$. The break in the curve marks a region of pulsation in this sequence.

IV. MECHANISMS FOR MASS LOSS

The results of the previous section indicate that it is extremely unlikely that a nova can return to minimum without ridding itself of its entire accreted envelope. We have, therefore, examined three possible mechanisms for driving the remaining hydrogen off of the white dwarf on a time scale of months to years. All of these mechanisms have been proposed to explain mass loss in other kinds of stars and it seems reasonable to extend them to the nova outburst. These mechanisms are radiation pressure driven mass loss in the O stars (Lucy and Solomon 1967; Castor, Abbot, and Klein 1975), gravitational stirring in close binaries (Paczynski 1976), and mass loss from red giants (c.f., Hagen 1978, Reimers 1975).

https://doi.org/10.1017/S0252921100076041 Published online by Cambridge University Press

The theory of radiation pressure driven mass loss has been developed in some detail by Castor, et. al. (1975). In essence, ions which have resonance lines at wavelengths near the peak in the energy distribution of a star can become very efficient at absorbing momentum from the radiation field and imparting it to the gas producing an expanding atmosphere. The ions that they found important were carbon, nitrogen, and oxygen, just the elements that we expect to find enhanced in the novae remnants. In addition, it is clear that the luminosities of these remnants are already near the Eddington limit and they should be prime candidates for mass loss due to radiation pressure. If we use the equations derived in Castor, et. al. (1975) for a solar mixture, we predict mass loss rates of 10^{-6} to 10^{-7} $M_{\odot}$/year. It is not completely clear by how much the enhanced abundances will increase these rates; nevertheless, rates exceeding 10^{-5} $M_{\odot}$/year are certainly possible for material as enriched in the CNO nuclei as the remnants will be. It appears, therefore, that radiation pressure driven mass loss is an important part of the late stages of the nova outburst.

Another important mass loss mechanism is gravitational stirring (Paczynski 1976; Taam, Bodenheimer, and Ostriker 1978). As has been pointed out in earlier work (Starrfield, et. al. 1974; 1976; 1978), the radii of many of the calculated remnants is larger than the Roche lobes of the shorter period cataclysmic variables. This suggests that the secondary will actually be moving through the outer layers of the remnant and dynamical friction can occur. We can estimate the importance of this process by calculating the energy that will be released per gram in a given layer in the star. Using reasonable values for the parameters taken from our models, we obtain a "drag" rate of $\sim 10^{7}$ erg gm^{-1} sec^{-1}. For those models which have large radii, we find ε_{nuc} (β^{+}-decays) in the surface regions to be 14 orders of magnitude below this value. Calculations to determine the effect of this energy production on the structure of the envelope are now in progress.

Finally, another class of mass losing stars are the red giants. Although the mechanism for producing mass loss is unclear, it is probably associated with the deep convective zone and low surface gravity. Inasmuch as a nova has a deep convective zone (although not a low gravity), we can apply the usual formula to the remnant and obtain a mass loss rate. One commonly uses an equation of the form: $\dot{M} = \alpha \cdot RL/GM$; the problem being to determine α. Recently Reimers (1975) has obtained a value for α and we shall use it although there is some criticism of his value (Hagen 1978). For the luminosities and radii of the remnants, we obtain $\dot{M} \sim 10^{-7}$ to 10^{-8} $M_{\odot}$/year. These values are somewhat low for this process to be important in the novae.

V. DISCUSSION

The results presented in this paper demonstrate that some kind of mass loss mechanism must be acting in the late stages of the nova outburst in order to return it to minimum on the observed time scales. The most likely processes are radiation pressure driven mass loss in an envelope (and atmosphere) strongly enhanced in carbon and gravitational stirring. In fact, we expect both processes to act during the outburst with the latter mechanism more important when the outer radius of the

https://doi.org/10.1017/S0252921100076041 Published online by Cambridge University Press

remnant lies outside the Roche lobe of the binary and the former gradually becoming important as the remnant shrinks within the lobe and becomes hotter. Nevertheless, it is clear from the observations (Gallagher and Starrfield 1978) that some mass loss mechanism is operating to bring the nova back down to minimum on a time scale of years.

I would like to express my thanks to J. Gallagher, W. Sparks, J. Truran, R. E. Williams, and H. M. Van Horn for a number of useful conversations on the topic of this paper. I am grateful to P. Strittmatter for the hospitality of Steward Observatory where this work was begun. I am also grateful to P. Carruthers and A. N. Cox for the hospitality of the Los Alamos Scientific Laboratory and a generous allotment of computer time.

REFERENCES

Castor, J. I., Abbot, D. C., and Klein, R. I. 1975, Ap. J., 195, 157.
Gallagher, J. S., and Code, A. D. 1974, Ap. J., 189, 303.
Gallagher, J. S., and Starrfield, S. 1976, M.N.R.A.S., 176, 53.
Gallagher, J. S., and Starrfield, S. 1978, Annual Reviews Astr. and Astrophysics, 16, 171.
Hagen, W. 1978, Ap. J. Suppl., 38, 1.
Lucy, L. B., and Solomon, P. M. 1967, Ap. J., 159, 879.
McLaughlin, D. M. 1960, in Stars and Stellar Systems VI. Stellar Atmospheres, ed. J. L. Greenstein (Chicago: Univ. of Chicago Press), p.585.
Nariai, K. 1974, P.A.S. Japan, 26, 57.
Ney, E. P., and Hatfield, B. F. 1978, Ap. J. Lett., 219, L111.
Paczynski, B. 1976, in Structure and Evolution of Close Binary Systems, ed. P. Eggleton, S. Mitton, J. Whelan (Dordrecht: Reidel) p.75.
Reimers, D. 1975, in Problems of Stellar Hydrodynamics, ed. P. Ledoux, Mem. Roy. Soc. Sci. Liege, 8, 369.
Sparks, W. M., Starrfield, S., and Truran, J. W. 1978, Ap. J., 220, 1063.
Starrfield, S., Sparks, W. M., and Truran, J. W. 1974, Ap. J. Suppl., 28, 247.
Starrfield, S., Sparks, W. M., and Truran, J. W. 1976, in Structure and Evolution of Close Binary Stars, ed. P. Eggleton, et. al. (Dordrecht: Reidel) p.155.
Starrfield, S., Truran, J. W., and Sparks, W. M. 1978, Ap. J., 226, 186.
Taam, R. E., Bodenheimer, P., and Ostriker, J. P. 1978, Ap. J., 222, 269.
Thackeray, A. D. 1977, Mem. R.A.S., 83, 1.
Truran, J. W. 1979, in Proceedings of IAU Colloquium No. 53, White Dwarfs and Variable Degenerate Stars, ed. H. M. Van Horn and V. Weidemann.
Wu, C. C., and Kester, D. 1977, Astr. and Astro., 58, 331.