HYDRODYNAMIC STUDIES OF THE NOVA OUTBURST

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I. Introduction

Over the past few years, significant advances have been made in our understanding of the nova outburst. The theoretical studies have shown not only that a thermonuclear runaway in the envelope of a white dwarf reproduces the gross features of the nova outburst (c.f.; Starrfield, Sparks, and Truran 1978, Sparks, Starrfield, and Truran, 1978, Gallagher and Starrfield 1978), but also made important predictions regarding the observed behavior of the outburst itself. The observational studies have provided us with new data concerning the evolution of the bolometric light curve of a nova during outburst, the elemental abundances in the ejecta, the formation of dust during the outburst, and the structure of nova binaries (c.f., Gallagher and Starrfield 1978).

The thermonuclear runaway theory of the outburst is based on the observed characteristics of the novae binary systems: a large, cool component that fills its Roche Lobe and a much smaller star which is presumably a degenerate dwarf. The large star is transferring material through the inner Lagrangian point into the lobe surrounding the white dwarf and this material spirals into an accretion disc which acts to transfer angular momentum outward and mass inward allowing a layer of hydrogen-rich material to be gradually accumulated on the surface of the degenerate star (Warner 1976, Robinson 1976). The observed mass accretion rates are on the order of 10^{-9} to 10^{-10} $M_\odot$ yr^{-1} or less (Wade 1979; Cordova, Mason, and Nelson 1980; Bath, Pringle, and Whelan 1980) implying that a layer with a mass of 10^{-4} $M_\odot$ can be built up on the dwarf on time scales of 10^5 to 10^6 yr. Hydrostatic studies have shown that a thermonuclear runaway will occur in such an envelope (Taam and Faulkner 1976). We have used the results of their studies to obtain initial models for calculations which show that the resulting thermonuclear runaway produces a nova outburst (Starrfield, Sparks, and Truran 1978; Sparks, Starrfield, and Truran 1978); the characteristics of this outburst depending upon the carbon-oxygen abundance in the envelope.

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II. Thermonuclear Runaways and the Nova Outburst

As was shown in our first paper (Starrfield, et.al. 1972) the nova outburst is a thermonuclear phenomena and a direct result of the properties of the four β^+ unstable nuclei: ^{13}N, ^{14}O, ^{15}O, and ^{17}F. These nuclei act both to limit the maximum rate of energy generation during the outburst and as a source of energy at late times. Convection during the early stages carries them to the surface where they decay and enhance the mass ejection process. They then decay at a time when the envelope temperatures are too cool for further proton captures so that the final isotopic ratios are unusual for an astrophysical process. Finally, it is because of their properties that we have been forced to require enhanced CNO abundances in the envelope in order to produce a fast nova outburst.

The β^+-unstable nuclei first become important in the last stages of the rise of the shell source temperature to maximum deep in the envelope. This is just at the time that the bolometric magnitude begins its steep rise. This phase is very rapid for all novae (it takes about a day or less) and is caused by convection in the envelope of the white dwarf carrying the β^+-unstable nuclei to the surface on a rapid ($\sim 10^3$s) time-scale. Their decay in the uppermost layers of the accreted envelope causes the rate of energy generation to reach values exceeding 10^{12} to 10^{13} erg gm^{-1} sec^{-1} which results in luminosities of at least 10^4 $L_\odot$. However, the envelope cannot begin to expand on such a short time scale and radii for white dwarfs of 10^9 cm imply effective temperatures of 10^5 K or larger at bolometric maximum.

The intense heating throughout the envelope causes a hydrodynamic ($U > C_s$) expansion of the hydrogen layers which will reach a radius of $\sim 10^{12}$ cm before becoming optically thin. If we assume that the luminosity is at least 10^4 $L_\odot$, then the effective temperature at maximum visible light will be about 10^4 K. The mass fraction in the optically thin shell remains virtually constant until the temperature has dropped to $\sim 10^4$ K, and then, as the opacity drops, the optically thin region moves inward in mass but remains virtually constant in radius. The time to reach visual maximum varies from nova to nova, caused by the differences in the rate of expansion speeds of novae. This in turn must depend on the rate of the energy released in the envelope from nuclear reactions to the total binding energy of the envelope which in turn depends upon white dwarf mass. The total binding energy of the envelope is largest for the smallest mass white dwarfs (even though the binding energy per gram is largest for the most massive white dwarfs) because a 0.5 $M_\odot$ white dwarf require more envelope mass ($\sim 10^{-3} M_\odot$) to produce a runaway than a 1.25$M_\odot$ white dwarf ($\sim 10^{-5} M_\odot$). This effect will cause an outburst on a low mass white dwarf to appear slow no matter how large the degree of CNO enhancement (Truran 1980, Shara, Prialnik, and Shaviv 1980).

Once the burst ejection phase of the outburst is complete, the nova settles into a constant luminosity phase. The luminosity comes from nuclear burning in the envelope material that was not ejected during the burst phase and has returned to hydrostatic equilibrium. Most of the envelope is convective and an intense (T $\sim$ 5 x 10^7 K) nuclear burning shell source is located at the bottom. A core-mass luminosity relationship (Paczynski 1971) holds for the remnant allowing us to calculate that the mass of the white dwarfs in novae are $\sim$ 1.0$M_\odot$ (Truran 1980). During this state the envelope continues to lose mass, presumably by a wind (Bath 1978), and its effective temperature slowly climbs to values exceeding 10^5 K (Gallagher and Starrfield 1976, Starrfield 1979).

The final phase is the turn-off of the nuclear reactions and the return to minimum (so that the process may begin again). Numerical calculations (Starrfield 1979) show that virtually the entire accreted envelope must be ejected in order for the active phase of the outburst to end. The outburst should be over one to 10 years after peak brightness. This stage is not very well known for any nova, and observations are required to understand just now and when a nova turns off.

III. The Abundances in the Ejecta

One of the first pedictions of the hydrodynamic studies was that the CNO nuclei had to be enhanced in the envelope in order to produce a fast nova outburst. Concomitant with this prediction was the calculated result that the CNO abundances also would be enhanced in the ejecta. However, the difficulty of obtaining accurate abundances for emission or absorption line spectra of novae (Williams 1977) prevented confirmation of this prediction. The recent studies have now taken advantage of the fact that a number of old novae have resolved shells and that techniques developed for analyzing planetary nebula shells can also be applied to novae ejecta. A summary of these results appears in Truran (1980). Another study by Ferland and Shields (1978) of Nova Cygni 1975 showed that one could determine the abundance of the emission lines during the early stages of the outburst if one used modern digital detectors and observed the nova for a long period of time. The results of these studies showed that all nova had either enhanced CNO or non-solar H/He or both. These studies also showed that the enhancement increased with speed class although DQ Her 1934 was anomalous in that it had the largest CNO enhancement of any nova studied; and, yet, it has been classes as a slow nova (Williams, et.al. 1978). Nevertheless, this is not in disagreement with the theoretical calculations if one considers white dwarf mass in addition to enhancement, as discussed in the previous section. Support for our argument comes from a study of Smak (1979, preprint) who finds a white dwarf mass of 0.5$M_\odot$ for DQ Her. This is in contrast to the assumed white dwarf mass of other novae of $\sim$ 1.0$M_\odot$ (Warner 1976, Robinson 1976). In fact, a low mass white dwarf will always produce a "slow" outburst no matter what the enhancement because the envelope will not be as degenerate as it would be for a more massive white dwarf (Starrfield 1971). In addition, a low mass white dwarf requires more envelope mass to produce a runaway so that the total binding energy of the envelope is larger than for a more massive white dwarf (Truran 1980, Shara, Prialnik, Shaviv 1980) and even a large enhancement of the CNO nuclei will produce a "slow" outburst.

Another problem with abundances and the hydrodynamic studies is that the new observations have shown that fast novae do not need as great an enhancement of the CNO nuclei as our calculations predict. However, we have been redoing some of our older calculations with the new Los Alamos Opacity tables and find that we can decrease the carbon abundance from $X(^{12}C) = 0.5$ to $X(^{12}C) = 0.2$ and still produce a fast novae (Starrfield, Truran, and Sparks 1980, in preparation). Therefore, it now appears that both observations and theory are in agreement about the enhancement necessary to produce a nova outburst - either fast or slow.

IV. Dwarf Novae and Elemental Diffusion

In this section I will consider the effects of the settling of the CNO nuclei out of the accreted hydrogen envelope into the core on thermonuclear runaways in the envelope. This process has not been considered in previous studies of the nova phenomena, because the problem has always been to enhance the CNO nuclei in the envelope rather than deplete them. Here I restrict the discussion to the dwarf novae systems where the accretion rate is presumably lower than in the common novae and there is no evidence for mass loss during the outburst (c.f.; Starrfield, Truran, and Sparks 1980). In addition, it now seems likely that the dwarf nova outburst is caused by either an instability in the rate of mass transfer from the secondary or by an instability in the accretion disc and <u>not</u> by a thermonuclear runaway in the accreted envelope. Nevertheless, there is still a flow of hydrogen-rich material onto the dwarf and one must be concerned with the ultimate fate of this gas. The observations imply that $\dot{M}$ for dwarf novae is about 10^{-10} $M_\odot$ yr^{-1} or less (Bath, Pringle, or Whelan 1980) requiring at least 10^6 years to build-up an envelope of $\sim 10^{-4} M_\odot$. This time-scale is comparable to the time scale for gravitational settling to completely empty the accreted envelope of the CNO nuclei (Fontaine and Michaud 1979, Vauclair, Vauclair, and Greenstein 1979, Alcock and Illarionov 1980). As a result, when the bottom of the accreted layer reaches the conditions necessary for thermonuclear burning in the envelope, no flash will occur; only a phase of slow, steady nuclear burning from p-p reactions. Since the temperature dependence of these reactions is only $\propto T^4$, they do not even produce enough energy per gram to expand the envelope. Instead, recent calculations (Starrfield and Sparks 1979, Starrfield, Truran and Sparks 1980) have shown that the luminosity of the white dwarf increases to only a few $L_\odot$ while the effective temperature never exceeds 5×10^5 to 6×10^5 K. These values imply that a p-p burning white dwarf will be indistinguishable from a hot, cooling, white dwarf. The configuration resulting from this evolution will be a massive white dwarf with a thickening helium layer underlying the hydrogen-rich layer on the surface. It has recently been predicted that the end result of this process will be a Type I supernova explosion (Starrfield, Truran, and Sparks 1980, Taam 1980).

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References

Alcock, C. and Illarionov 1980, Ap. J., 235, 534.
Bath, G. T. 1978, MNRAS, 182, 35.
Bath, G. T., Pringle, J. E., and Whelan, J. A. J. 1980, MNRAS, 190, 185.
Cordova, F. A., Mason, K. O., and Nelson, J. G. 1980, preprint.
Ferland, G. J. and Shields, G. A. 1978, Ap. J., 226, 172.
Fontaine, G. and Michaud, G. 1979, Ap. J., 231, 826.
Gallagher, J. S. and Starrfield, S. 1976, MNRAS, 176, 53.
Gallagher, J. S., and Starrfield, S. 1978, Ann. Rev. Astr., and Ap., 16, 171.
Paczynski, B. 1971, Acta Astron., 21, 417.
Robinson, E. L. 1976, Ann. Rev. Astr. and Ap., 14, 119.
Shara, M., Prialnik, D., and Shaviv, G. 1980, Ap. J., in press.
Sparks, W. M., Starrfield, S., and Truran, J. W. 1978, Ap. J., 220, 1073
Starrfield, S. 1971, MNRAS, 152, 307.
Starrfield, S. 1979, in IAU #53: White Dwarfs and Variable Degenerate Stars, ed. H. M. Van Horn and V. Weidemann (University of Rochester Press), p. 274.
Starrfield, S. and Sparks, W. M. 1979, B.A.A.S., 11, 663.
Starrfield, S., Truran, J. W., and Sparks, W. M. 1978, Ap. J., 226, 186.
Starrfield, S., Truran, J. W., Sparks, W. M., and Kutter, G. S. 1972, Ap. J., 176, 169.
Starrfield, S., Truran, J. W., and Sparks, W. M. 1980, Ap. J. Lett., in press.
Taam, R. E. 1980, Ap. J., in press.
Taam, R. E. and Faulkner, J. 1975, Ap. J., 198, 435.
Truran, J. W. 1980, preprint.
Vauclair, G., Vauclair, S., and Greenstein, J. L. 1979, Astr. Ap., 80, 79.
Wade, R. A. 1979, A. J., 84, 562.
Warner, B. 1976, in Structure and Evolution of Close Binary Systems, ed. P. Eggleton, S. Mitton, and J. Whelan (Dordrecht: Reidel), p. 119.
Williams, R. E. 1977, IAU #42: Interaction of Variable Stars with their Environments, ed. R. Kippenhahn, J. Rahe, and W. Strohmeier (Bamberg: Remeis-Sternwarte), p. 242.
Williams, R. E., Woolf, N. J., Hege, R. L., Moore, R. L., and Kopriva, D. A. 1978, Ap. J., 224, 171.

DISCUSSION

A. COX: What is the cause of the slow rise?

STARRFIELD: We know that white dwarfs have very thin convection zones. In models using the HE5C5 Los Alamos opacities, we get another convection zone that is being driven by the nuclear reactions at the bottom. As the runaway down below proceeds and as the temperature increases, the convective region reaches upward and actually penetrates into the surface convection zone. It just penetrates right to the top and the rise goes off.

SIMON: What is the contribution to the enrichment of the interstellar medium in the elements that are most abundant?

STARRFIELD: It looks as though the ones we can predict the best are lithium 7 and ^{13}C and is perhaps 10%. This is from looking at twenty novae per year per 10^9 years and at how much mass is going to recycle in the interstellar medium.

SIMON: I was asking whether the novae then become the dominant source of the enrichment of those elements.

STARRFIELD: Probably not, but they are important.

SIMON: What is the source then?

STARRFIELD: I would guess red giants.

FERNIE: An observational feature is the fact that the absolute magnitude at maximum is a function of the rate of decline, or is it the other way around?

STARRFIELD: Yes, as a matter of fact, Mike Shara has a paper in press in which he gives an explanation of that particular feature based on theoretical studies.