THEORY AND OBSERVATIONS OF CLASSICAL NOVAE IN OUTBURST

S. STARRFIELD

> I have become convinced that the whole nova phenomenon must be studied; the variations of total light and continuum, of radial velocity, and the intensities and profiles of absorption and emission lines must be seen as connected parts of one physical phenomenon, rather than as isolated data that can be understood separately.
>
> – C. Payne-Gaposchkin (1957)

1. Introduction

Novae in outburst have been the object of intense study for more than 100 years but it is only in the last two decades that we have begun to make serious progress in understanding the cause of both their outbursts and the extraordinary phenomena that they display during their outbursts. The multiwavelength observations of these fascinating objects exhibit such a diversity of behavior, both in outburst and in quiescence, that virtually all of the techniques and analyses of modern astronomy must be used to understand the observations. Our advances in understanding the classical novae outburst have come about because of observations with digital detectors, satellite observations at wavelengths unobservable from ground based observatories, and theoretical studies with large computers. For example, as a direct result of studies done with both the IUE and EXOSAT satellites we have:

1. been able to identify two major classes of outburst, one that occurs on an oxygen, neon, magnesium white dwarf and one that occurs on a carbon, oxygen white dwarf;
2. obtained abundances for a large number of recent novae;
3. identified and studied at least two classes of recurrent nova, one that has a giant for the mass-losing companion and one that has a compact but evolved companion;
4. found evidence at late times for a high temperature ($T > 3 \times 10^5$ K) source within the system;
5. found that the outburst lasts longer in the ultraviolet than in the optical; and
6. found that the outbursts of the fastest classical and recurrent novae exceed the Eddington luminosity, for a 1.0 $M_\odot$ white dwarf, at maximum light.

Studies of the infrared emission of novae done over the past two decades have shown that novae form grains during their outbursts and it has been possible

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to actually observe the grains form and follow the changes in their emission characteristics over time. These same studies have shown that all types of grains, found in the ISM (carbon, silicates, SiC, and PAH), are produced in the ejecta of novae. In addition, Nova QV Vul 1987 formed all four types of grain during the course of its outburst which seriously constrains the theories of grain formation. Infrared observations of novae have also been used to obtain black body expansion parallaxes twice during the outburst providing improved distance estimates to galactic novae.

As a result of theoretical hydrodynamic studies done over the last two decades, the nova outburst is now thought to be the result of a thermonuclear runaway (TNR) which occurs in the accreted hydrogen rich envelope of a white dwarf in a close binary system. The hydrodynamic simulations of the growth of the accreted layer on the white dwarf have been very successful in reproducing the gross features of the nova outburst: the amount of mass ejected, the kinetic energies of the ejecta, and the optical light curves. These studies have also shown that it is necessary to include both a nuclear reaction network and the physics of the infalling material in the calculations. More important, these calculations *predicted*: (1) that enhanced CNO nuclei would be found in the ejecta of fast novae, (2) that the isotopic ratios of the CNO nuclei would be far from solar, (3) that there should be a post maximum phase of constant luminosity lasting for years, (4) that fast classical novae would have larger CNO enhancements than typical slow classical novae, and (5) that the observed features of the outburst would be strong functions of the mass of the underlying white dwarf.

The most important summaries of the nova phenomena can be found in Payne-Gaposchkin (1957) and McLaughlin (1960). References to previous studies can be found in these publications and will not be repeated here. Reviews can also be found in articles by Gallagher and Starrfield (1978), Starrfield and Snijders (1987; reprinted in 1989); Starrfield (1986, 1987, 1988, and 1990), Gehrz (1988), and Shara (1989). More recently, a book has appeared which was edited by Bode and Evans (1989) and which discusses the behavior of classical novae both in outburst and quiescence. The two most recent IAU Colloquia devoted entirely to the nova phenomena were in Paris in 1976 (Friedjung 1977) and Madrid in 1989 (Cassatella and Viotti 1991). Bode (1987) edited a book on the 1985 RS Oph outburst and there were many papers on the nova outburst in the 1986 Bamberg Workshop on Cataclysmic Variable Stars (Drechsel, Kondo, and Rahe 1987).

2. Observations of the Outburst

2.1. PREMAXIMUM

A nova outburst is classified, according to the rate of decline from maximum, as either 'fast' or 'slow'. The initial eruption of a fast nova is very rapid, with the major part of the rise to visual maximum taking place in a day or less. During the rising branch of the light curve, a classical carbon, oxygen (CO) nova exhibits spectral features corresponding to an optically thick, expanding shell (Stryker *et al.* 1988; Starrfield 1990). The first spectra obtained in the optical are usually dominated by broad absorption lines and emission lines are either weak or absent. Spectral types are B to A, although some novae have been observed to have a later spectral class; for example, RR Pic was listed as having a class of F and Nova QV Vul 1987 was probably G or K (Gehrz and Starrfield 1992, in preparation). In addition, the optical spectrum of V1500 Cyg 1975, one day before maximum, was that of a B2Ia star with unusual absorption line strengths for the C, N, and O elements (Boyarchuk *et al.* 1977; Ferland, Lambert, and Woodman 1986a,b; Lance, McCall, and Uomoto 1988). The unusual strengths, as compared to normal stars, of the C, N, and O lines seen in Nova V1500 Cygni 1975, are rather common (McLaughlin 1960). Spectra obtained in the ultraviolet show a cool continuum but usually the FeII "forest" is superimposed on this continuum (Wehrse *et al.* 1990, 1991).

As the expansion is very rapid and the bolometric luminosity is either nearly constant or still rising, the effective temperature of a CO classical nova declines until it reaches a value of $\sim 4 \times 10^3$ K to 7×10^3 K at visual maximum (Gallagher and Ney 1976; Gallagher and Starrfield, 1978). However, this is not the case for the fastest recurrent (RN) or oxygen, neon, magnesium (ONeMg) novae which reach maximum with their effective temperatures exceeding 10^4 K (Shore, Sonneborn, and Starrfield 1990; Shore *et al.*, 1991). The most probable explanation for this difference in behavior is that considerably less material is ejected by these novae during their outbursts as compared to the other classes of novae (Starrfield, Sparks, and Truran, 1985; Starrfield, Sparks, and Shaviv, 1988).

If a nova is caught early enough in the outburst, an IUE spectrogram will show a continuum rising to the red broken both by emission and absorption lines (see, for example, Starrfield *et al.* 1988b, Stryker *et al.* 1988; Starrfield 1990). An important advance in our understanding of the spectra of novae at maximum, occurred when it was realized that the first UV spectra of SN 1987A strongly resembled early UV spectra of novae; except that the lines were much broader in the supernova. As a result, it was apparent that modern techniques in spherical, expanding, stellar atmospheres, developed to treat SN II (Hauschildt, Shaviv, and Wehrse 1989), could be applied to novae (Wehrse *et al.* 1990, 1991).

The first results of these studies are now being applied to the IUE spectra of novae at maximum. The initial results have shown that the actual effective temperature cannot be determined from the observed continuum but must be obtained from continuum fitting to a very broad region of the spectrum. This is because the expanding atmosphere of a nova has a very large extension and the observed continuum is formed by overlapping lines of FeI, II, and III. The initial analyses have found that a nova with an effective temperature of 25,000 K mimics the continuum of a more normal star with an effective temperature below 10,000 K. The intent of these analyses is to perform spectral syntheses of the observed spectra and determine elemental abundances. These data can then be compared, at a later time,

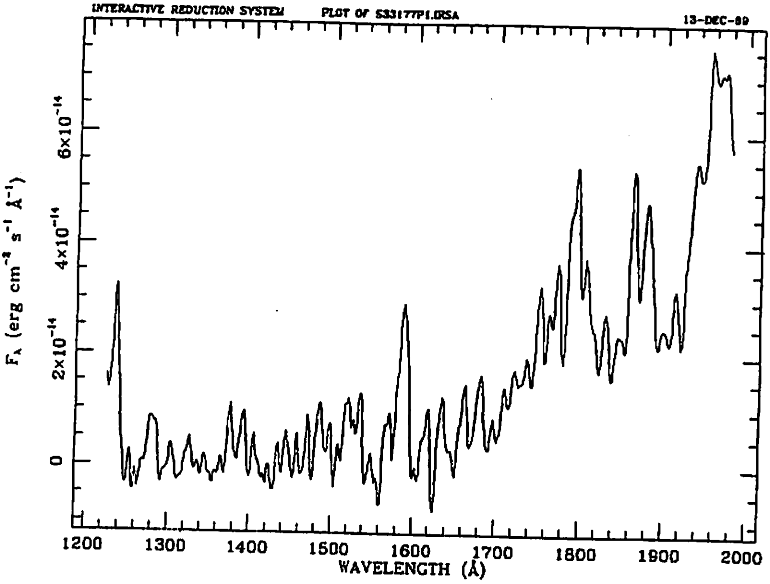

Fig. 1. Low dispersion IUE SWP spectrum obtained of LMC 1988 #1 on day 1988/64. This was a 30 minute exposure. Note the strength of the feature at 1590 Å.

with abundances determined from nebular emission line analyses, and, thereby, both methods can be checked (Wehrse *et al.*, 1990, 1991).

In order to illustrate the early spectral development of a classical CO nova, in the first few figures, I show the evolution over the first few weeks of the outburst of LMC 1988 #1. Figure 1 shows one of the first spectra that was obtained for this nova. It was a 30 minute SWP exposure obtained on March 30, 1988. Figure 2 shows the SWP spectrum of the nova obtained on April 8, 1988 (a 45 minute exposure). This nova continued to brighten in the ultraviolet for sometime after it had reached maximum light in the optical (Austin *et al.* 1990). This can be seen by noting the flux levels in the two spectra. An ultraviolet light curve can be found in Austin et al. (1990) and in Figure 10. This nova did not reach maximum ultraviolet light until about April 25, 1988 while it reached maximum light in the optical around the end of March 1988. This is characteristic of the light curves for all novae: optical maximum occurs before the maximum in the ultraviolet.

Figure 2 also shows the typical emission lines produced by a gas expanding and beginning to go optically thin. [NIII] 1750 Å and [OIII] 1660 Å, 1666 Å are present as is [CIII] 1909 Å. These lines are not generally seen in the ultraviolet spectrum this early in the evolution of a nova. The ultraviolet spectrum continued to evolve rapidly and Figure 3 (April 15, 1988: a 60 min. exposure) is very different from the spectrum shown in Figure 2. Note the strength of [NIII] 1750 Å as compared to all of the other lines that were present in the spectrum. [NIV] 1486 Åis now strong

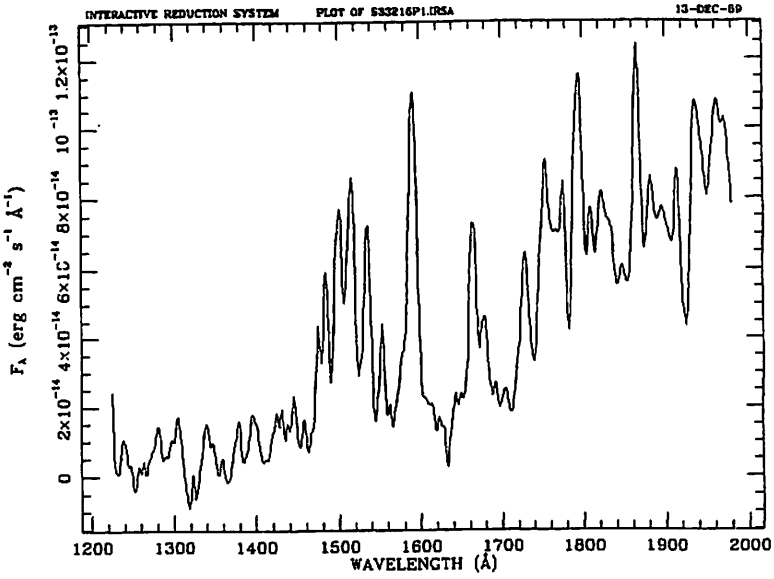

Fig. 2. A low dispersion IUE SWP spectrum obtained of LMC 1988 #1 on day 1988/97. This was a 45 minute exposure. NIII] 1750 Å is now present.

and CIV 1550 Å is present and exhibits a P-Cygni profile indicating mass outflow.

The last spectrum that I show for this nova was obtained on May 16, 1988 (Figure 4) and one can see by the marked change in the lines and their strengths that, in the month since Figure 3 was obtained, the densities in the nova ejecta have dropped considerably. Although a strong blue continuum is still present, emission lines from an optically thin gas are obviously present and strong. [NIII] 1750 Å has dropped in strength, relative to OI 1304 Å. HeII 1640 Å is now clearly present and CIV 1550 Å shows a strong P-Cygni profile indicating that mass is still being lost. For comparison, in Figure 5, I show a 2 minute SWP spectrum of OS And 1986 obtained on 14 December 1986. Note the strong resemblance of this spectrum to Figure 2. The strong feature at ~1590 Å is unidentified.

In contrast to the spectral development of a moderate speed CO nova like LMC 1988 #1, fast ONeMg novae show a very hot continuum at maximum plus emission lines characteristic of a low density gas. In fact, maximum light in the ultraviolet occurs very soon after maximum optical light. This implies that fast ONeMg nova outbursts occur on very massive white dwarfs with small envelope masses. This same behavior is also seen in RN which eject much less mass than a classical CO nova.

The most recent ONeMg nova studied in outburst occurred in the LMC in 1990 and exhibited outburst behavior very similar to that of the galactic ONeMg nova V693 CrA 1981 (Williams *et al.* 1985). In the next few paragraphs, I discuss the

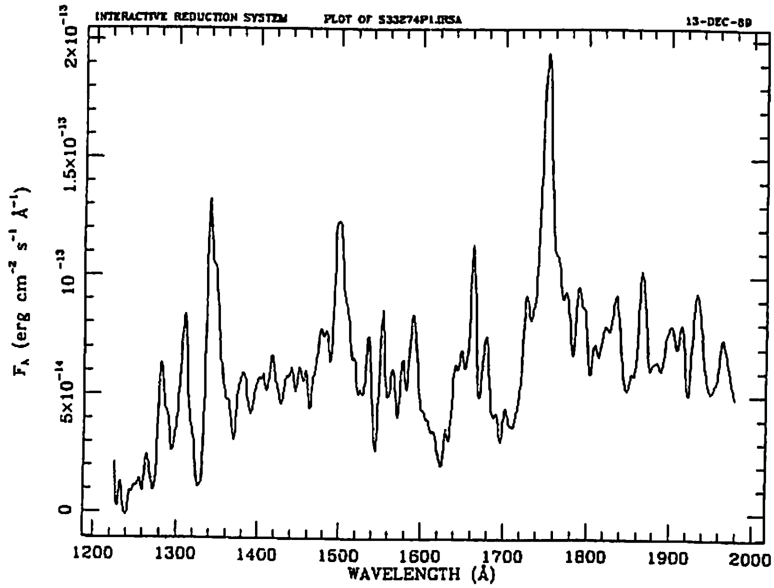

Fig. 3. A low dispersion IUE SWP spectrum of LMC 1988 #1 on day 1988/104. It was a 60 minute exposure. The continuum has begun to flatten but NIII] 1750 Å is still very strong.

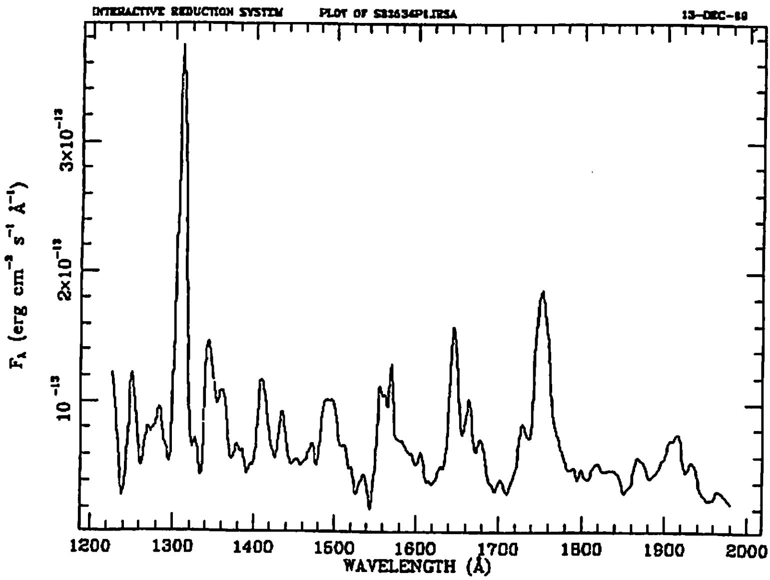

Fig. 4. A low dispersion IUE SWP spectrum of LMC 1988 #1 on day 1988/136. The nova has begun to fade and this was a 100 minute exposure. Note that OI has become the strongest line in the spectrum and that a number of low density lines have begun to appear.

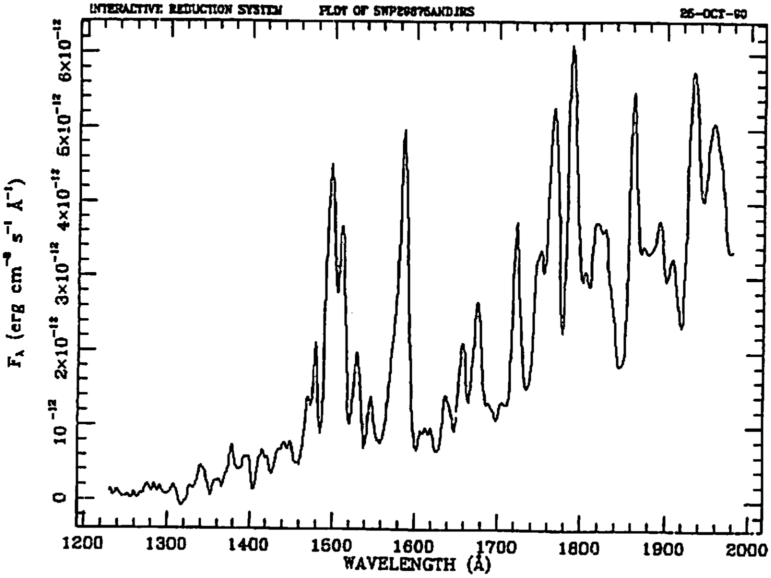

Fig. 5. This is a low dispersion IUE SWP spectrum of Nova OS And 1986 obtained on day 1986/348 which was shortly after discovery. It is a 2 minute exposure. It strongly resembles the spectrum shown in Figure 2.

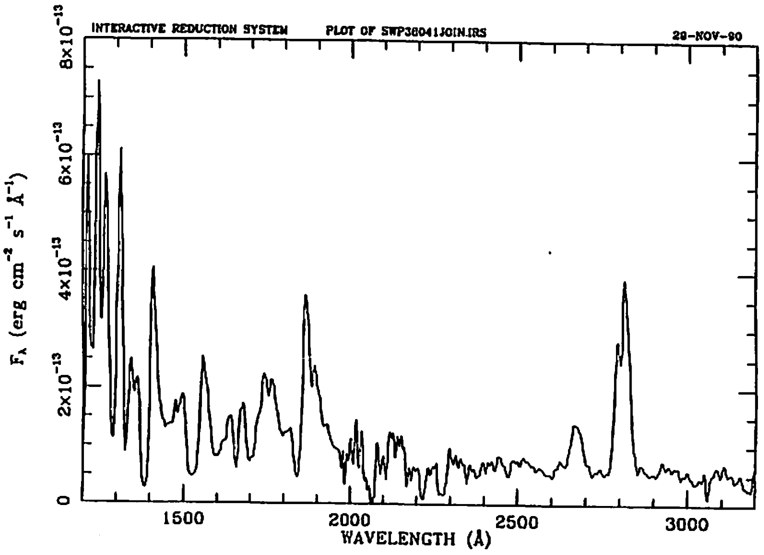

Fig. 6. This was the first IUE low dispersion SWP+LWP spectrum obtained of LMC 1990 #1 and was obtained on day 1990/18. The SWP spectrum was a 30 minute exposure.

observations of the outburst of this nova which is called LMC 1990 #1 because there was a second nova found in outburst in the LMC in 1990. This nova was discovered on 16.47 January 1990 at a visual magnitude of 11.5 and IUE observations began on 17.95 January, within hours of the announcement of the discovery. The initial IUE spectrum (Figure 6) showed a hot continuum and strong emission lines from NV, Si IV, C IV, and AlIII. As can be seen in Figure 6, they all exhibited P-Cygni profiles with flat-bottomed absorption troughs extending to more than -6000 km s^{-1}. There is no resemblance, whatsoever, to early spectra of slow CO novae. However, there is a strong resemblance to spectra of RN such as U Sco suggesting that fast ONeMg novae do not eject much material and the expanding shell has gone nearly optically thin at maximum light in the optical.

The optical spectra obtained by Dopita and Rawlings provided additional evidence that LMC 1990 #1 was an extragalactic analog of V693 CrA (IAUC 4964; note that this same circular also contained the announcement of the discovery of LMC 1990 #2 by Liller) and, thereby, an ONeMg nova. They reported that [NeIII] 3868 Å appeared on 22 January, and [Ne V] 3426 Å on 29 January. By 13 February 1990 [NeV] was the strongest emission feature in the optical spectrum. The ultraviolet forbidden neon lines seen at late stages in other ONeMg novae ([Ne IV] 1602 Å and 2420 Å) were not detected in the IUE spectra but this is not surprising since they did not appear in either V693 CrA or QU Vul until well into the nebular stage when the densities in the ejecta had dropped by a large factor from the values determined at maximum light. In Figures 7 and 8, I show spectra of LMC 1990 #1 obtained on 25 January and 4 February 1990. Note the marked change in the spectrum over this last time interval. In fact, the IUE spectra showed that the expanding shell became optically thin in the Lyman continuum about 30 January or a little over two weeks into the outburst. Analysis of these spectra indicated that about $10^{-5}M_\odot$ to $10^{-6}M_\odot$ were ejected during the outburst of LMC 1990 #1. This is in reasonable agreement with the results for V693 CrA (Williams *et al.* 1985).

Finally, the ultraviolet light curve suggests that the luminosity in the wavelength region from 1200 Å to 3300 Å reached a value of 3×10^{38} erg s^{-1} at maximum brightness. This value assumes a distance to the LMC of 55 kpc [E(B-V)=0.15, non-30 Dor extinction] and shows that the luminosity in this nova exceeded the Eddington luminosity for a $1.0M_\odot$ white dwarf. Finally the nitrogen abundance appears to be larger than normal for the LMC. Spectra of a galactic fast ONeMg nova can be found in Williams *et al.* 1985. In order to demonstrate the difference between a fast ONeMg nova and a galactic *slow* ONeMg nova, in Figure 9 I show an early spectrum of QU Vul 1984 #2. It was a 15 minute exposure obtained on 11 January 1985 which was about two weeks after discovery. This nova is clearly still in the optically thick phase and more closely resembles the slower CO novae than the fast ONeMg novae. It clearly ejected more material than the fast ONeMg novae.

Infrared observations, when obtained early in the outburst, show that it is radiating like a black body expanding with time. Because it is optically thick in the

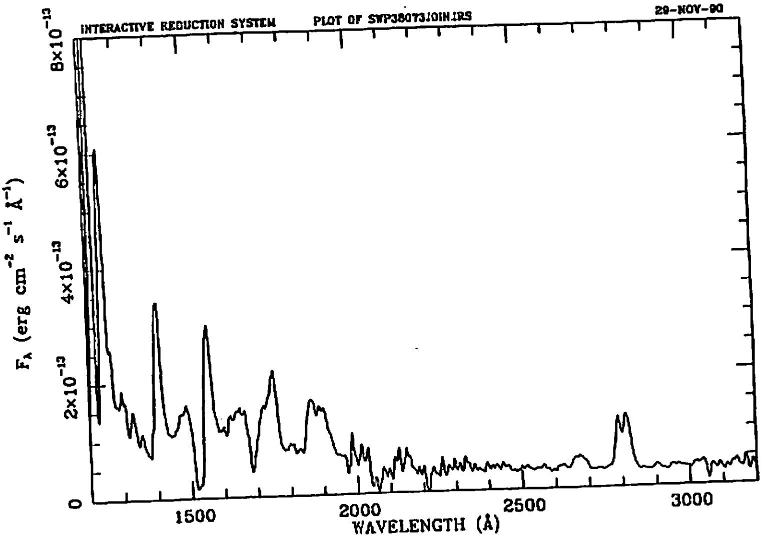

Fig. 7. This low dispersion IUE SWP+LWP spectrum was obtained on day 1990/25. The SWP spectrum was a 48 minute exposure. Note the prominent P-Cygni feature at CIV 1550 Å.

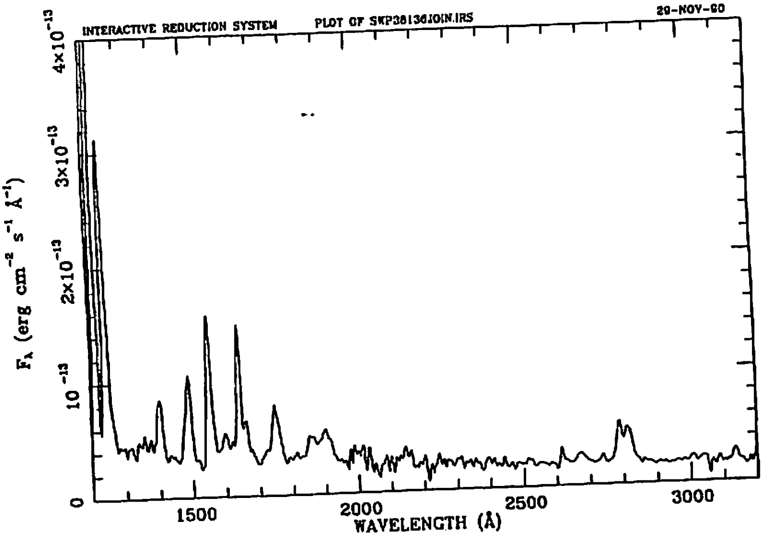

Fig. 8. This low dispersion IUE SWP+LWP spectrum was obtained on day 1990/36 and the SWP spectrum was an 85 minute exposure. The expanding material became optically thin some time between this spectrum and that shown in Figure 7.

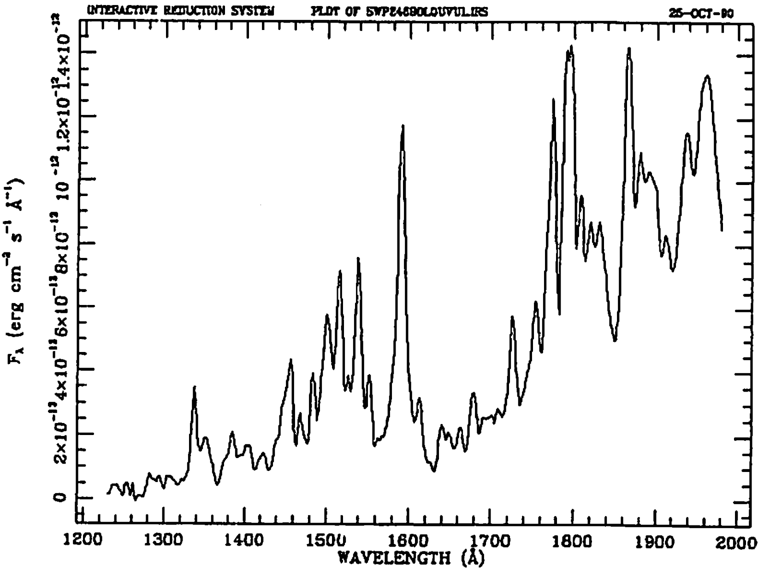

Fig. 9. This IUE SWP low dispersion spectrum was taken of nova QU Vul 1984 #2 on day 1985/11. It was a 15 minute exposure. This was a slow ONeMg nova and early spectra more closely resemble CO novae such as OS And 1986 and LMC 1988 #1 than fast ONeMg novae such as LMC 1990 #1 or V693 CrA 1981.

infrared, Ney and Hatfield (1978) refer to this as the pseudo-photospheric expansion phase. An excellent review of the infrared emission of novae can be found in Gehrz (1988). Gallagher and Ney (1976) used the existence of this phase to determine the distance to V1500 Cyg by measuring the rate of the angular expansion of the photosphere and combining that rate with the doppler velocity of the lines observed at that time. Given both that the measured velocities correspond to the material that is producing the black body emission and that this material is ejected with spherical symmetry, one can determine a very accurate distance. This expansion parallax method has now been applied to all novae that were observed early enough in the outburst to detect the expanding photosphere (Gehrz 1988).

At some time after the expanding material begins to go optically thin at infrared wavelengths, the nova enters the free-free expansion phase (Gallagher and Starrfield 1978). Gehrz *et al.* (1974), Ennis *et al.* (1977), Gehrz *et al.* (1980a,b), and Gehrz (1988) show that the density of the expanding shell can be determined from the wavelength where the optically thin free-free emission turns over into the Rayleigh-Jeans tail. This result is also well known from radio studies (Hjellming 1990).

2.2. MAXIMUM

The maximum in optical light occurs when the opacity in the outer layers of the expanding (and cooling) gas declines to a value where they begin to go optically thin and the pseudo-photosphere moves inward in mass as the material continues its expansion. Because the deeper layers, which are now becoming visible are hotter, the bolometric correction increases and the optical brightness declines. Although originally thought to occur because of the recombination of hydrogen, which would produce the required decrease in the opacity, it is now known that the presence of numerous lines of FeI, FeII, and similar ions in the ultraviolet are as least as important as hydrogen in determining the location of the photosphere in the expanding gas (Wehrse *et al.* 1990).

In addition, because the opacity is lower longward of the Balmer discontinuity at 3647 Å, radiation preferentially escapes there. This causes the expanding layers to cool rapidly and as the temperatures decline below $\sim 1.2 \times 10^4$ K important changes occur in the emergent spectrum. The most striking change is the appearance of strong absorption from FeII which acts to increase the opacity and shift the peak of the emitted radiation to about 2800 Å. Therefore, the ultraviolet spectra of novae obtained at or near maximum show, in general, a cool continuum with strong evidence for FeII features. In fact, it is not clear that any of the sharp "emission" features seen in the IUE spectra are really emission lines; they may only be regions of transparency between overlapping absorption lines. For example, the prominent feature at $\sim$ 1590 Å in Figures 1, 2, 5, and 9 is ubiquitous in early spectra of optically thick nova shells but cannot be identified with any abundant element. In addition, at virtually the same time, nearly all of the Balmer lines develop P-Cygni profiles indicating that a large amount of material has been ejected during the outburst.

At maximum the Principal Spectrum (see McLaughlin 1960) appears in the optical. The features that are seen evolve continuously in velocity as the receding photosphere moves inward in mass and many of the absorption lines seen at maximum can eventually be identified with the emission lines in the nebular shell (McLaughlin 1960; Gallagher and Starrfield 1978). As the nova begins its decline, the continuum declines more rapidly than the emission lines and the P-Cygni profiles slowly disappear. After a short time, the emission lines dominate the spectrum. They have rather complex profiles and suggest that material has been ejected in clouds, blobs, or rings (Gallagher and Starrfield 1978). As was predicted in the mid-1970's (Gallagher and Starrfield 1976; Bath and Shaviv 1978); the fading continuum has now been shown, by ultraviolet observations done with the IUE satellite, to be caused by the hardening of the emergent intensity as the pseudo-photosphere moves inward to deeper and hotter layers (Austin *et al.* 1990).

For a typical classical nova, where the mass of the ejecta may range from $10^{-6}M_\odot$ to as large a value as $10^{-5}M_\odot$, the duration of the photospheric phase depends upon the speed class of the nova. In fast, optically luminous, novae the ejected shell may become optically thin in a few days; thereafter, the optical is dominated by bremsstrahlung and hydrogen bound-free emission (Gallagher and Ney 1976; Ennis *et al.* 1977; Gehrz 1988; Martin 1989). In slower, lower optical brightness novae, continuous mass loss can maintain a low temperature photosphere for several months to years (Bath 1978; Ney and Hatfield 1978). For example, LMC 1988 #1 took nearly two months for the expanding envelope to become optically thin while LMC 1990 #1 became optically thin within a few weeks of maximum light (Sonneborn, Shore, and Starrfield 1990). For smaller values of ejected mass, $10^{-7}M_{\odot}$, which is typical of RN and the fastest of the ONeMg novae, the optically thick phase is severely curtailed and may last only a few days if it occurs at all.

2.3. POST-MAXIMUM DECLINE

The post-maximum decline in the optical is the result of the relaxation of the hydrostatic remnant to a stable luminosity and the gradual redistribution of the luminosity into the UV and EUV as the shrinking photosphere moves inward in mass. The stable luminosity is set by the core mass of the underlying white dwarf and can be estimated from the core-mass luminosity relationship (Paczynski 1971). For the most massive white dwarfs the luminosity predicted from this relationship will nearly equal that of the Eddington luminosity (Starrfield *et al.* 1990a):

$$L_{\mathrm{Edd}} = \frac{4\pi c G M_{WD}}{\kappa_{es}}$$

for pure electron scattering opacity. When expressed in magnitudes, L_{Edd} has a value of $M_{\mathrm{Bol}} \cong -7$ for a typical nova near maximum. When this limit is applied to novae in outburst, it implies that nova systems contain massive white dwarfs.

It is now clear that the bolometric luminosities of the fastest and brightest novae initially exceed the Eddington luminosity (see for example, V1500 Cyg: Wu and Kester 1976; LMC 1988 #2: Austin *et al.* 1990; LMC 1990 #1: Sonneborn, Shore, and Starrfield 1990; LMC 1990 #2: Shore *et al.* 1991), they drop to the core-mass luminosity soon after maximum. In Figure 10, taken from Austin *et al.* 1990, I show the ultraviolet light curves of LMC 1988 #1 and #2 obtained from integrating under SWP+LWP IUE spectra. In order to obtain the luminosity, they assumed a distance to the LMC of 55 kpc. The depression in the light curve of LMC 1988 #1 was caused by the formation of dust. In contrast, novae with maximum absolute visual magnitudes fainter than -7 show little change in M_{Bol} after maximum; the initial decline in the visual is caused by flux redistribution into the UV (Bath and Shaviv 1978). At this time mass is being ejected from the white dwarf by a radiation pressure driven wind (Starrfield *et al.* 1990b) which will continue until most of the remaining accreted material (plus some core material from the white dwarf) on the white dwarf is lost.

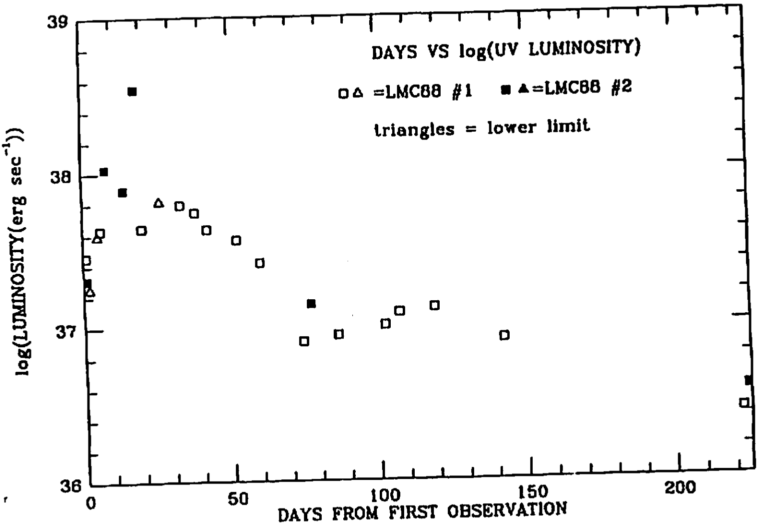

Fig. 10. This figure was taken from Austin *et al.* (1990) and shows the ultraviolet light curves of LMC 1988 #1 and #2. Each point is obtained by integrating under a combined SWP + LWP spectrum (minus Lα) and was put on an absolute scale by assuming a distance of 55 kpc to the LMC. LMC 1988 #2 clearly exceeds LEd at maximum. The depression in the decline of the light curve of LMC 1988 #1 marks the formation of dust.

During the declining branch of the light curve, novae undergo important changes in physical conditions. Because the hardening of the radiation field from the central source produces an ionization front moving out through the expanding ejecta, because the density of matter is high compared to most nebulae, and because the process is time dependent; the spectrum can become exceedingly complex, especially for novae with significant post-maximum stellar winds (Gallagher and Starrfield 1978). In addition, optical high-dispersion spectra (1 Å to 3 Å or less) show that the material is ejected in a very inhomogeneous fashion (Wagner *et al.* 1992; in preparation). Figures 11 and 12 are taken from this paper and show, respectively, the Hα profile (resolution 3 Å) for OS And 1986 and QV Vul 1987. These spectra were obtained in November 1990 with the Perkins 1.8-m telescope at Lowell Observatory using the Ohio State CCD spectrograph. It is interesting that the profiles for these two novae seem to show the same general shape.

New absorption line systems now appear (in the optical) at high velocities compared to the principal absorption line system. These systems are called the diffuse enhanced and consist of broad features that may separate (as time passes) into many sharp components. At still later times in many novae, very highly ionized features appear in absorption at even larger velocities than the diffuse enhanced systems. These systems are collectively called the Orion spectrum (based on their similarity to features seen in OB stars) and are optical analogues of the 'sharp, narrow, absorption' components seen in the ultraviolet spectra of the most luminous O and B stars which also exhibit strong stellar winds. However, the Orion features always seem to remain broad and do not separate into sharp components.

During this stage the ionization increases to levels of 50–60 eV and the electron densities decrease to values of 10^8 to 10^{10} cm^{-3}. We can now use the techniques developed for the analysis of planetary nebulae and quasars to determine the variation of electron density and temperature with time and, also, the elemental abundances (Ferland and Shields 1978; Ferland, Lambert, and Woodman 1986a,b; Lance, McCall, and Uomoto 1988). Since novae are time dependent, this phase represents an interesting exploration of nebular physics and allows us to use the time variation as an additional constraint in determining the abundances.

2.4. INFRARED EMISSION AND GRAIN FORMATION

Some two to three months into the outburst, most novae begin to develop a second phase of infrared emission. The assumption commonly made is that this excess is caused by the formation and growth of grains in the expanding shell which then reradiate the ultraviolet energy from the hot, luminous white dwarf (see Gehrz 1988 and Gehrz, Truran, and Williams 1991). When first detected, the infrared excess attributed to grains exhibits a continuum black body temperature slightly exceeding 10^3 K. If this material has just formed, then this temperature is considerably below $\sim 2 \times 10^3$ K at which the grains are normally expected to form. As time passes, the temperature of the grains slowly decreases to ~800 K. One explains the variation in temperature by the formation of small particles which are inefficient radiators. They then slowly grow to a size that exceeds that of normal interstellar particles (0.01μm–0.03μm).

Until recently, the composition of the grains was thought to be amorphous carbon since the infrared excess failed to show any features (Gehrz 1988). However, infrared studies of V1370 Aql 1982, already known from IUE studies to be unusual because it ejected material with very strange abundances (Snijders *et al.* 1987), found an infrared excess with a broad continuum peaked at about 8μm. Superimposed on this very broad feature was narrow emission at 10μm that was attributed to SiC (Gehrz 1988). Two years later Nova QU Vul 1984 #2 was observed to form silicate grains since its infrared emission showed both the 10μm and 20μm features characteristic of SiO_2. It showed no continuum excess and its infrared emission never became optically thick (Gehrz *et al.* 1986). Since that time infrared features attributed to PAH's have been detected in Nova QV Vul 1987 (Gehrz 1990). This nova was extremely cool at maximum light and formed an extremely thick dust shell about six weeks into the outburst. Over the course of the next few months, it proceeded to exhibit infrared emission features characteristic of all of the four types of dust detected in the ISM and previously seen in other novae. However, current theories of grain formation predict that at most one type of grain can be formed in material of a given composition and the type of grain depends on the abundance ratio of carbon to oxygen in the ejecta since equilibrium condensation calculations indicate that carbon grains condense in a carbon rich environment and silicates condense if the material is oxygen rich. The nova observations are perplexing.

Another interesting result of the infrared studies of novae is that some novae show optically thick infrared emission from grains while others exhibit only optically thin emission. In both cases they develop the infrared emission that is characteristic of grain formation but, in the optically thin case, the amount of energy radiated by the grains never approaches the energy emitted in the optical at maximum. In contrast, in the optically thick case, the infrared emission in the novae increases until it is radiating the same amount of energy as was observed in the optical early in the outburst. In addition, an optically thick nova exhibits a very steep decline in the optical light curve, at the time of grain formation, with a slow recovery as the grains absorb less energy. This feature is called the transition phase in the optical. Optically thin emitting novae do not show a pronounced transition and sometimes the optical light curve shows no indication that dust has formed. A possible explanation for this phenomenon is that the region where the dust is forming has been ejected asymmetrically and does not completely block the ultraviolet light from the central source (Gehrz 1988). Both Nova V842 Cen 1986 and QV Vul 1987 formed optically thick dust shells with deep transition regions in their optical light curves. However, in contrast to other novae observed in the infrared, QV Vul emitted more energy from grains in the infrared than was seen in the optical at maximum (Gehrz 1989; private communication). A very thick expanding envelope, which reached radii of 10^{13} cm before becoming optically thin, would explain this observation.

Finally, Ney and Hatfield (1978), observing NQ Vul 1976, used the gradual growth in size of the dust forming region to apply the black body expansion parallax method to this nova. Since that time, it has been applied to all novae that showed an infrared excess characteristic of grain formation. Although one is still faced with the problem of determining the appropriate doppler velocity to use in the calculation, it is a very accurate technique for determining nova distances. It will be interesting to check the values determined from this method with the nebular expansion studies done in the optical (Cohen and Rosenthal 1983; Cohen 1985) when the expanding shells of these novae are finally resolved.

2.5. FINAL DECLINE

As the nova begins its final decline, the ionization level in the ejecta increases to moderately high levels and the electron density decreases to values approaching those found in planetary nebulae. This means that the analysis techniques used to obtain abundances in planetary nebulae can also be used for novae ejecta at late times (Williams *et al.* 1981, 1985; Williams 1990; Stickland *et al.* 1981; Snijders *et al.* 1987; Saizar *et al.* 1991; Austin *et al.* 1991, in preparation; Andrea *et al.*

1990). It is not known when or how a nova ends its outburst, but on a time scale of (at most) a few years, mass loss decreases and the nova returns to its quiescent luminosity (Starrfield 1979; MacDonald, Fujimoto, and Truran 1985; Starrfield 1989; Starrfield *et al.* 1990a,b). It is at this time that coronal line emission is seen in the infrared spectra of novae.

It has been known for decades that the optical spectra of novae show coronal line emission but such lines were not detected in the infrared until the outburst of V1500 Cygni. Since that time other novae have been found to exhibit coronal line emission with the most notable case being Nova QU Vul 1984 #2 (Greenhouse *et al.* 1988). Greenhouse *et al.* (1990) have also found coronal line emission from [CaVIII], [SiVI], and [SiVII] in Nova V1819 Cyg 1986 and Nova V827 Her 1987. Benjamin and Dinerstein (1990) report that they found coronal line emission in V2214 Oph 1988 and they confirmed the emission already reported by Greenhouse *et al.* for V1819 Cyg and V827 Her. Gehrz (1988) speculates that coronal line emission is probably ubiquitous in novae but is generally hidden by the grain emission. The lines have an excitation temperature of $\sim 10^6$ K and their presence constrains the modeling of the physical conditions in the gas at the time that they are seen. Although Benjamin and Dinerstein (1990) discuss the possibility that the source of the coronal line emission is collisional ionization in a shock, the most likely explanation is photoionization by the hot central source. Numerical simulations of the turn-off of a nova show that the underlying white dwarf can approach temperatures of 10^6 K which seems a likely source of the photoionization (see Figure 18). In their successful attempts to model the outburst of the RN LMC 1990 #2, Shore *et al.* (1991) found that it was necessary to assume that the underlying white dwarf had a temperature exceeding 2×10^5 K a few days after maximum light. Source temperatures below 10^5 K were prohibited by the observations (see Section 4.2).

The requirements for a hot source are also strongly supported by the X-ray observations of novae in outburst. Novae were first detected in outburst at X-ray wavelengths by EXOSAT which discovered emission from Nova GQ Mus 1983 (Ögelman, Beuermann, and Krautter 1984). This result was followed shortly thereafter by detections of Nova PW Vul 1984 #1, QU Vul 1984 #2, and the recurrent nova RS Oph 1985 (Ögelman, Krautter, and Beuermann 1987; Mason *et al.* 1986). Clearly, an object radiating at a luminosity $\sim L_{\mathrm{Edd}}$ with a radius of $\sim 10^9$ cm, will be emitting copious amounts of soft X-rays. Therefore, the observations of the three classical novae are best understood if we assume that the X-ray flux is coming from the white dwarf which, according to the X-ray observations, has a temperature of $\sim 3 \times 10^5$ K and a luminosity which corresponds to a $\sim 1.0 M_\odot$ white dwarf radiating at the Eddington limit (Ögelman, Krautter, and Beuermann 1987). Recent optical spectra of GQ Mus suggest that the central source has continued to increase in temperature but the luminosity is uncertain (Krautter and Williams 1989).

The X-rays detected during the outburst of RS Oph were thought to come from the interaction of a blast wave with the wind from the red giant secondary (Mason *et al.* 1986; Bode and Kahn 1985). RS Oph is a RN which has outbursts about every 18 years. The system contains a white dwarf and a red giant that is losing mass both into the Roche lobe of the compact star and, in addition, into the region surrounding the binary. Unlike the classical nova systems, in which there appears to be little gas surrounding the system, the gas ejected from the compact object in RS Oph must penetrate the circumbinary material which comes from the red giant wind. As the ejected gas collides with the circumbinary material, a shock forms and will produce X-rays if the velocity of the expanding material is large (Bode and Kahn 1985; O'Brien, Kahn, and Bode 1986). In fact, the material ejected during the RS Oph outburst was found to be expanding with velocities exceeding 10^3 km s^{-1} (Shore, Sonneborn, and Starrfield 1992; in preparation) which is sufficient to produce X-rays from shock emission. Ultraviolet emission from this interaction can be seen in the high dispersion IUE observations obtained during the 1985 outburst of RS Oph (Shore, Sonneborn, and Starrfield 1990a,b; 1992 in preparation, see Figures 19, 20, and 21 which are obtained from that paper). Optical spectra also indicated expansion velocities for the ejected gas of $\sim 3 \times 10^3$ km s^{-1} (Bruch 1986) and exhibited coronal line emission from [FeX] 6374 Å and [FeXIV] 5303 Å which indicated temperatures of nearly 1 keV. At late times the observed X-ray flux fell more rapidly than predicted by Bode and Kahn (1985) and Mason *et al.* suggested that they had observed the breakout of the shock from the red giant wind. This suggestion is strongly supported by the changes in the CIV 1550 Å line strength with time (Shore, Sonneborn, and Starrfield 1992, in preparation).

The final EXOSAT X-ray data point for RS Oph was obtained more than 200 days after the optical outburst and showed that, at that time, the source still had a temperature $\sim 3 \times 10^5$ K. This is in excellent agreement with the temperatures measured for the three classical novae and is strong evidence for the existence of a white dwarf in this system. However, the X-ray luminosity of RS Oph was less than expected for a massive white dwarf radiating at the Eddington limit and suggests that the white dwarf had finally ejected all of the accreted layers and was now cooling back to quiescence. This determination of a cooling time scale for the white dwarf provides a strong constraint for calculations of TNRs on massive white dwarfs.

Finally, Ögelman, Krautter, and Beuermann (1987) may have measured the turn off time scale for Nova GQ Mus 1983 since their last observation, 900 days after maximum light, suggests that its X-ray flux had decreased by more than a factor of two from maximum. If correct, this is an important measurement because, previously, we could only guess how long the nova would take to turn off.

3. Explosions in Cataclysmic Variable Systems

In the previous section, I have described the observations of the outburst and implicitly assumed the model to be presented in this section. In the first part of this section I will discuss the structure of the nova binary system and then proceed to describe the current ideas about the cause of the nova outburst.

3.1. A NOVA AS A CATACLYSMIC VARIABLE BINARY

As has been known since the early 1960's, novae are members of the class of cataclysmic variable stars (Kraft 1964). These systems contain a cool secondary and a white dwarf primary. The secondary fills its Roche lobe and material is lost through the L_1 point into the lobe surrounding the white dwarf. This material forms an accretion disk and ultimately falls onto the white dwarf. The rate at which the secondary is losing mass is unknown but recent work by Shara (1989) and his collaborators suggests that this rate is time variable (see also Shaviv and Starrfield 1987b). For a number of reasons, discussed in the review by Shara (1989), he proposed that mass lost by the secondary could decline to very low levels between outbursts on the white dwarf. He refers to this time as the period of hibernation. Observational support for this hypothesis has been provided by Vogt (1990). In addition, Shara and his collaborators have been searching historical records for candidates for very old novae with some success. For example, he has recovered CK Vul and WY Sge, two novae that exploded more than 300 years ago and which are now much fainter than more recent old novae (Shara 1989). Shara has also been involved in an unsuccessful search for other historical old novae which implies that they are now very faint as compared to novae with more recent outbursts and, therefore, must have evolved to very low mass transfer rates. However, there are novae that exploded more than 150 years ago which are still bright (V841 Oph and Q Cyg for example) and it is not clear for how long after an outburst that the binary system exhibits a high mass transfer rate onto the white dwarf. At some time after the outburst the old nova must begin its slide into obscurity. Hibernation cannot last forever and after some time has elapsed a high rate of mass transfer begins again and the nova evolves to another outburst (Ford 1978).

Given that material is lost from the secondary and enters the accretion disk, the viscous process by which this material moves through the accretion disk and actually reaches the white dwarf surface is also unknown (Pringle 1981). In addition, it is not clear at what rate mass is being transferred from the accretion disk onto the white dwarf or whether it arrives vertically or nearly horizontally. For example, the theoretical studies done assuming purely spherical accretion show that if the rate of accretion onto the white dwarf is too high, then a nova outburst will probably not occur since thermonuclear burning starts when the envelope is not very degenerate (Prialnik *et al.* 1972). However, there are direct predictions of the energy that should be emitted when the gas falls onto the surface of the white dwarf and neither ultraviolet nor X-ray observations confirm these predictions (Cordova and Howarth 1987).

The masses of the white dwarfs are also not very well known but theoretical studies now require that these systems contain very massive white dwarfs in order to produce either a fast classical nova or RN outburst (Starrfield 1986). The cause of this requirement is that the more massive a white dwarf, the more degenerate the bottom of the accreted hydrogen rich envelope at the time of runaway. This will produce higher peak temperatures and a more explosive event as is observed for fast classical novae. Slow novae may have lower masses and DQ Her, for example, is thought to have a mass of $\sim 0.6M_{\odot}$ (Young and Schneider 1980).

Once the material has arrived in the accretion disk, it must still be accreted onto the surface of the white dwarf. Although, it is still moving in Keplerian or near-Keplerian orbits close to the surface of the white dwarf, the actual disk-star interaction is not understood at all for the normal classical nova. In the case of V1500 Cyg, now known to be an AM Her variable (Stockman, Schmidt, and Lamb 1988), hydrogen rich material is predicted to arrive at the poles on trajectories that are nearly normal to the surface. This is because the magnetic field strength in an AM Her variable is high enough to prevent an accretion disk from forming and material flows directly from the secondary to the white dwarf. On the other hand, if the disk extends to the surface of the white dwarf, then spherical inflow cannot take place and there must be some kind of boundary layer where the infalling gas actually interacts with the outer layers of the white dwarf.

Nevertheless, most of the simulations of accretion onto a white dwarf have assumed spherical inflow because that is the simplest process to treat in a one-dimensional computer code. In contrast, Sparks and Kutter (1987) and Kutter and Sparks (1987) have tried to simulate the disk-star boundary by including shear instabilities in their calculations. They simulated the accretion of material with angular momentum onto the white dwarf but assumed no mechanism for removing the angular momentum of the accreted material. While this resulted in mixing of accreted material with core material, the added centrifugal pressure support from the material moving at large tangential speeds on the white dwarf produced only very weak outbursts. The material was not very degenerate at the time of the TNR.

Finally, if one assumes that the accretion disk has an inner boundary that lies above the surface of the white dwarf and that all material arrives vertically onto the white dwarf, then the spherical accretion studies are useful. However, there is a further complication pointed out by Shaviv and Starrfield (1988) which is that the infalling material contains gravitational potential energy. The infalling material must release an energy of:

$$L = \frac{GM}{R} \dot{M}$$

Because the binding energy for material in an orbit just above the surface of the white dwarf is $0.5GM/R$, half of this energy must be released in the accretion disk and half must be released at the boundary between the disk and the star (King 1989). The calculations of spherical accretion onto white dwarfs show that the boundary layer consists of an accretion shock at the surface of the white dwarf and the virial theorem states that half of the remaining energy is radiated and half is transported into the interior of the white dwarf (Shaviv and Starrfield 1987a). In addition, the internal energy of the infalling material is GM/R when it arrives on the surface. These two effects have only recently been included in the spherical inflow calculations and are important (Shaviv and Starrfield 1987b).

3.2. THE CAUSE OF THE OUTBURST

The theoretical studies indicate that the accreted layer grows in thickness until it achieves a temperature at its base that is high enough for thermonuclear burning of hydrogen to begin. The further evolution of nuclear burning on the white dwarf then depends upon the mass and luminosity of the white dwarf, the rate of mass accretion, and the chemical composition of the reacting layer (Truran 1982; Starrfield 1989). Since there is observational evidence that the infalling material is mixed with the core (Starrfield 1988; Truran 1990), the chemical composition must also be a function of the above parameters. The simulations show that, if the material is sufficiently degenerate, a thermonuclear runaway (TNR) occurs, and the temperatures in the accreted envelope grow to values exceeding 10^8 K. The studies of mass accretion onto a white dwarf, under a variety of conditions, imply that sufficiently degenerate means that the pressure at the base of the accreted layer must reach values of about 10^{19} dynes cm^{-2} to 10^{20} dynes cm^{-2} prior to the TNR (MacDonald 1983).

During the early phases of nuclear burning, most of the energy comes from the proton-proton chain ($T_b < 10^7$ K; where T_b is the temperature at the base of the accreted layer) but once the temperature exceeds about 10^7 K, more energy is obtained from the CNO reactions. Note, however, that this is a composition dependant statement. Since the $^{12}C(p,\gamma)^{13}N$ reaction rate is dependent on the abundance of ^{12}C in the envelope, the temperature at which this reaction begins to produce a significant amount of energy depends on the amount of ^{12}C present in the envelope. During the early stages of the evolution to a TNR, the lifetimes of the CNO nuclei against proton captures are very much longer than the decay times for the β^+-unstable nuclei: ^{13}N (863 s), ^{14}O (102 s), ^{15}O (176 s), and ^{17}F (92 s), which insures that these nuclei can decay and their daughters can capture another proton in order to keep the CNO reactions cycling. As the temperatures increase in the shell source, the lifetimes of the CNO nuclei against proton captures continuously decrease until, at temperatures $>10^8$ K, they become shorter than the β^+-decay lifetimes; for these conditions, the β^+-unstable nuclei will become abundant as the rate of nuclear energy generation is constrained. All of the computer simulations further indicate that, during the evolution to peak temperature, a convective region forms just above the shell source and grows until it includes the entire accreted envelope. It follows that, at the peak of the outburst, the most abundant of the CNO nuclei in the envelope will be the β^+-unstable isotopes.

It also follows that the time to peak temperature is a function both of the initial luminosity of the white dwarf and the initial abundances of the CNO elements. This is because the nuclear burning time scale decreases for increased energy generation. A luminous white dwarf is hotter at the composition interface then a cool white dwarf which increases the rate of energy generation and enhancing the numbers of CNO nuclei in the envelope also increases the rate of energy generation. For a given accretion rate the envelope mass at runaway is a function of the time scale to runaway, so if the accretion time is short, then the envelope mass is small (Starrfield 1989).

The rapid rise to temperatures above 10^8 K has several effects on the subsequent evolution. First, since the energy production in the CNO cycle arises from proton captures followed by β^+-decays, the rate at which energy is produced at maximum temperature depends on both the half-lives of the β^+-unstable nuclei and the abundances of the CNO nuclei initially present in the envelope. Second, since the convective turn-over time scale is about 10^2 sec, near the peak of the TNR, a significant fraction of the β^+-unstable nuclei can reach the surface before decaying (Starrfield 1989).

Once peak temperature is reached and the envelope begins to expand, the rate of energy generation in the surface regions declines only as the abundances of the β^+-unstable nuclei decline, since their decay is neither temperature nor density dependent (Truran 1982; Starrfield 1989). Numerical simulations performed with enhanced abundances of the CNO nuclei show that these decays will release more than 10^{46} erg into the envelope after it has begun to expand and the envelope will reach radii of more than 10^{10} cm before all of the ^{13}N has disappeared (Starrfield, Truran, and Sparks 1978). Therefore, the decays of the β^+-unstable nuclei provide a delayed source of energy which is responsible both for assisting in the ejection of the shell and for powering the super-Eddington luminosity phase of the outburst.

Both optical and ultraviolet observations of novae ejecta indicate that there is mixing of a significant amount of core material into the accreted layer, such that the chemical composition determined for the ejected material will reflect a combination of core and accreted material. This implies that, for those novae which show the most extreme levels of abundance enrichments of CNO and ONeMg nuclei in the ejecta, the white dwarf must be losing mass as a result of the outburst. These same abundance studies further show that the core material must come from either a CO or ONeMg white dwarf. It now seems possible that some of the ONeMg novae may be responsible for synthesizing the ^{26}Al that is thought to be responsible for heating of the small bodies in the early solar system (Nofar, Shaviv, and Starrfield 1991; Weiss and Truran 1991).

3.3. THE THEORETICAL PHASES OF THE OUTBURST

Using the theoretical development presented in the previous paragraphs, it is possible to separate the outburst into four phases each of which marks an important change in the observable characteristics of the nova. These four phases are

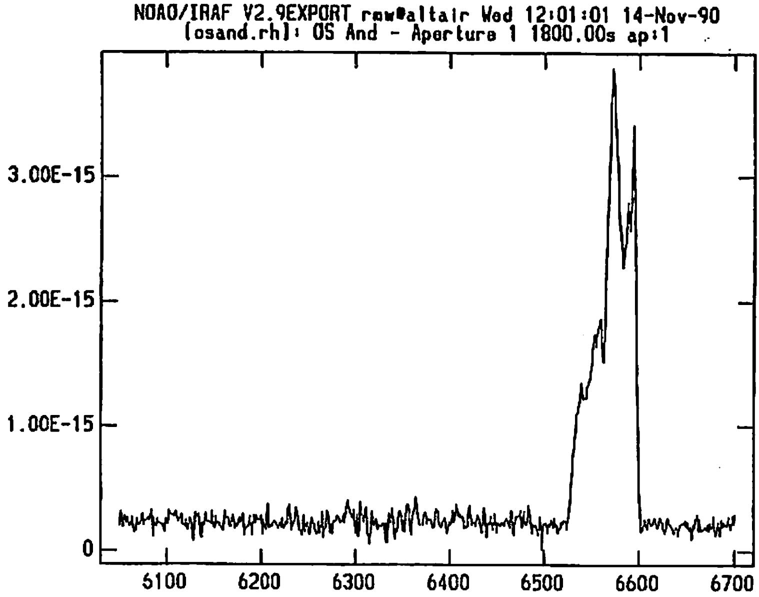

Fig. 11. This is a high dispersion (3 Å) optical spectrum taken at the Perkins 1.8-m telescope at Lowell Observatory. It shows the region around Hα for OS And 1986 and was taken in November 1990. Note the very castellated structure of this emission line.

1. the rise to bolometric maximum which occurs on a convective tun [illegible]ver time scale,
2. the rise to optical maximum which occurs on t[illegible] scale for the outer layers of the expanding envelope to reach a radius of $\sim 10^{12}$ cm,
3. the constant luminosity phase which lasts for a significant part of the remaining evolution of the nova, and
4. the turn-off phase in which nuclear burning ends and the nova returns to quiescence. In the following subsections I discuss each phase in turn.

3.3.1. The Rise to Bolometric Maximum

Although Robinson (1975) found that some novae do show evidence for the growing TNR at their surfaces, in most novae there is very little indication that anything unusual is occurring in the interior until the β^+- unstable nuclei reach the surface. At this time their decays cause the luminosity to rise to the Eddington luminosity, or even beyond (Austin *et al.* 1990), and the layers begin to expand. Since this rise is occurring on the convective turn-over time scale, 10^2 sec to 10^3 sec, it must be very fast and, because the radius of the white dwarf is still small, the effective temperature of the white dwarf can exceed 10^5 K for a very short time (Starrfield *et al.*, 1990a,b). It has been predicted that there will be a brief but intense period of EUV or soft X-ray emission at this time (Starrfield *et al.* 1990a). In Figure 13,

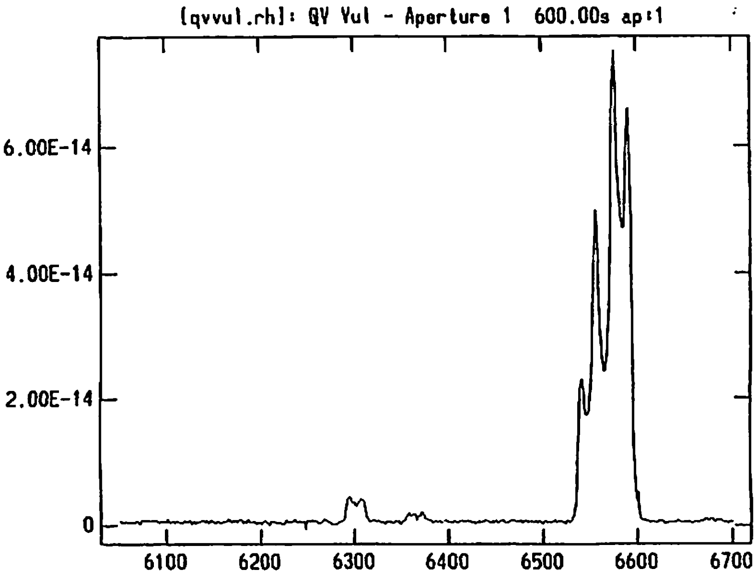

Fig. 12. This is a spectrum obtained for Nova QV Vul 1987 with the same equipment as was used for the spectrum shown in Figure 11. It also shows Hα with a 3 Å resolution. It is very interesting that it shows four major features with similar line ratios to the Hα profile of OS And.

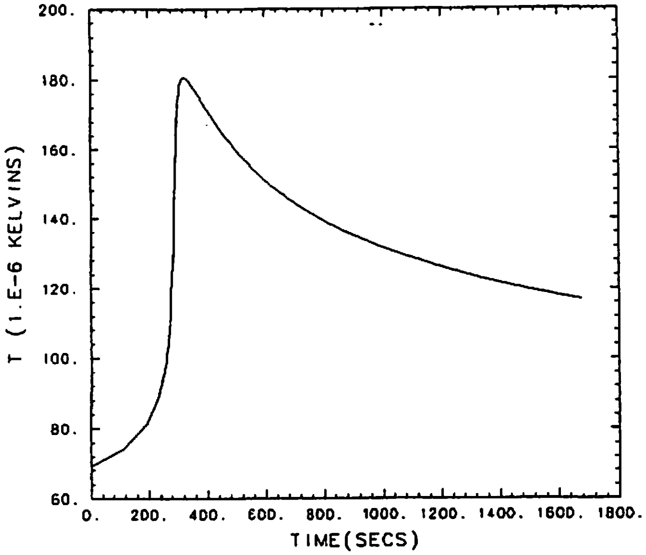

Fig. 13. The variation with time of the temperature in the shell source for a simulation with a white dwarf mass of 1.25 $M_{\odot}$. Note the steep rise and slower decline.

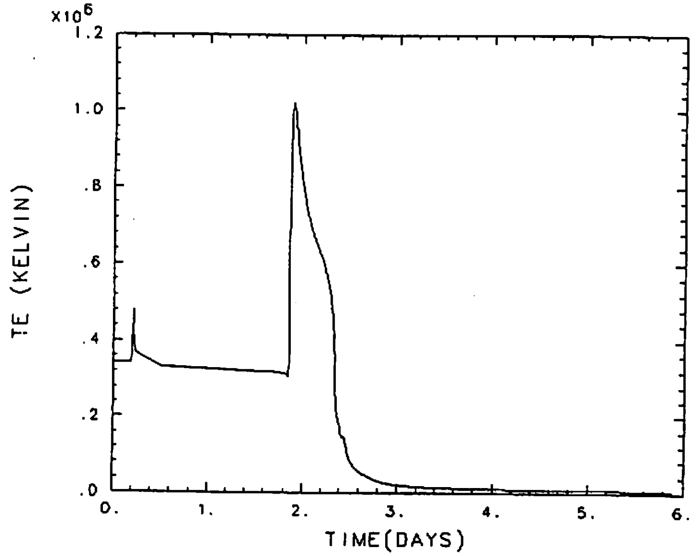

Fig. 14. The variation of T_e with time near the time of peak M_{Bol} for a simulation of a TNR on a 1.35 $M_\odot$ white dwarf. The rapid decrease after maximum is caused by the expansion of the outer layers.

I show the variation of temperature in the shell source (deepest hydrogen rich zone) with time for a TNR on a 1.25 $M_\odot$ white dwarf. The entire accreted shell is convective during the time displayed in this figure. Figure 14 shows the effective temperature as a function of time for a TNR on a 1.35 $M_\odot$ white dwarf. The details of the evolution are presented in Starrfield, Sparks, and Shaviv (1988). It can be seen that peak effective temperature exceeds 10^6 K. A compilation of results for a variety of white dwarf masses is given in Figure 18 where it can also be seen that the peak value of the effective temperature at this time is a measure of the mass of the white dwarf. The large amount of energy deposited in the outer layers on a short time scale, plus the fact that the luminosities can reach or exceed the Eddington luminosity, causes the outer layers to begin expanding and the effective temperature rapidly declines.

3.3.2. *Rise to Maximum in the Optical*

Once the layers begin expanding and the effective temperature starts to drop, the bolometric correction decreases until the time when the radius has reached about 10^{12} cm. If we assume that the luminosity has remained virtually constant or even increased slightly, then the temperature in the outer layers must have declined to a value around 10^4 K and hydrogen begins to recombine. This produces a drop in the opacity and the pseudo photosphere moves inward in mass. We have yet

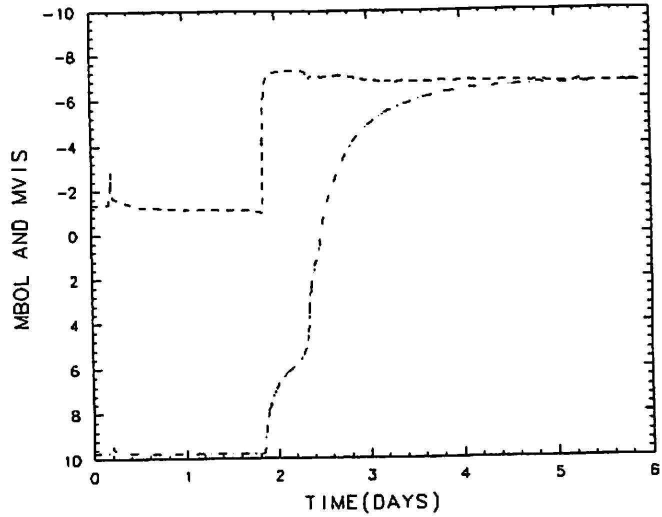

Fig. 15. This figure shows the early light curve for a simulation of a TNR on a 1.35 $M_\odot$ white dwarf. The upper curve is as a function of time and the lower curve is M_{vis} as a function of the same time. Note that M_{Bol} rises very rapidly as the β^+ unstable nuclei reach the surface and then stays virtually constant.

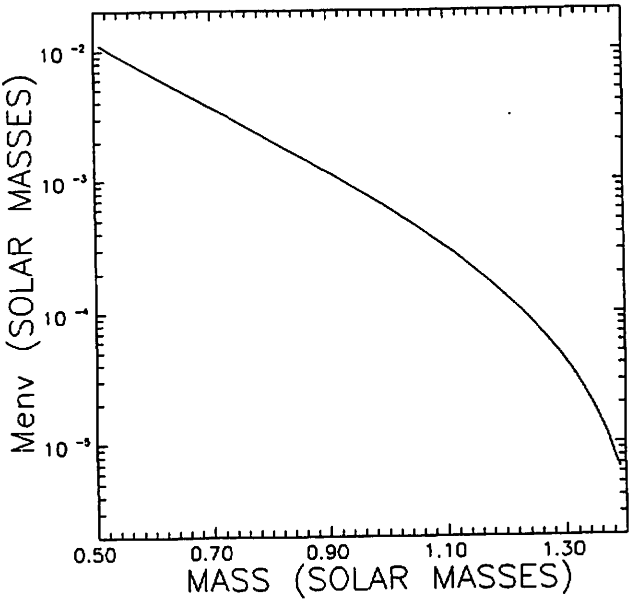

Fig. 16. This figure shows the variation in the envelope mass necessary to ignite a TNR on a white dwarf as a function of the mass of the white dwarf. It assumes a constant pressure at the base of the accreted envelope of 10^{19} dynes cm^{-2} (MacDonald 1983).

to determine what the principal source of opacity is at this time and it could be either hydrogen or low ionization metals such as iron. Nevertheless, whatever is providing the opacity at this time, maximum brightness in the optical is an opacity effect. In the ultraviolet, where the opacity is higher, we find that maximum light occurs after maximum light in the optical (Austin *et al.* 1990). In Figure 15, I show the light curve for one evolutionary sequence with the upper curve being the bolometric light curve and the lower curve the visual light curve.

The time scale for this phase of the outburst depends on the expansion velocity of the outer layers. The velocity must depend on the ratio of the total energy released into the shell, around the time of maximum energy generation, to the binding energy of the shell. The time scale must also depend on the mass of the envelope which is dependant on the mass of the white dwarf and the rate of accretion (Starrfield 1986). Since the mass of the envelope is much smaller for massive white dwarfs (this is shown in Figure 16), the expanding envelope should reach higher velocities for the same input energy. Therefore, it must be the case, if the abundances are enhanced, then more energy is produced at maximum temperature in the shell source and the accreted layers are ejected with higher velocities then if the abundances are not enhanced. I identify fast novae as those with large enhancements of core material in the envelope and slow novae as those with smaller or no enhancement of the envelope (for white dwarfs of mass greater than 1.0 $M_\odot$).

The effective temperature reached at optical maximum must also be a strong function of the mass of the expanding envelope. For low mass white dwarfs, with massive envelopes, we can expect that the expanding layers will reach radii of 10^{12} cm to 10^{13} cm before going optically thin. For example, in Nova QV Vul 1987 the spectral energy distribution fit a black-body curve of ~4000 K (Gehrz 1989; private communication). In contrast, for RN which probably occur on very massive white dwarfs, the envelope masses are very small and the luminosities are either close to, or exceed, the Eddington luminosity so that the material is ejected at very high speeds. In this case, the effective temperature at maximum can exceed 10^4 K (Wehrse *et al.* 1990a,b; Shore *et al.* 1991). This can be seen in the ultraviolet spectra of RN (Shore, Sonneborn, and Starrfield 1990; Shore *et al.* 1991). Up to now all RN with compact secondaries, observed in the ultraviolet, show a very hot continuum at maximum light indicative of a small amount of mass being ejected.

3.3.3. Constant Bolometric Luminosity

This phase of the outburst was one of the first predictions of the TNR theory of the outburst. It arises because not all of the accreted material is ejected during the burst or explosive phase of the outburst and anywhere from 10% to 90% will remain on the white dwarf in hydrostatic equilibrium. For some years there have been problems with the life time of this phase. For 1.0 $M_\odot$ white dwarfs, the nuclear burning time scale for the envelope can be as long as 400 years (Truran 1982) which, obviously, disagrees with the observations that imply that most novae

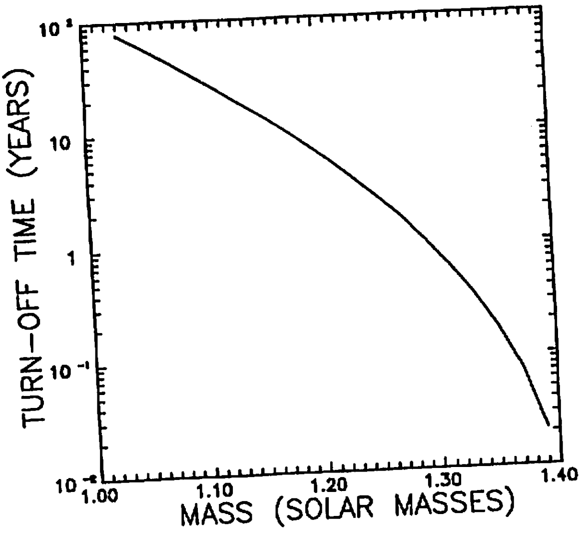

Fig. 17. This figure shows the time necessary to eject the entire accreted shell via a radiation pressure driven wind. It is a steep function of white dwarf mass because the equilibrium core mass luminosity of a white dwarf approaches L_{Edd} as the mass approaches the Chandrasekhar Limit. In addition, the envelope mass that must be ejected is a decreasing function of white dwarf mass as can be seen in Figure 16.

return to quiescence within 10 years.

However, the theoretical studies of this phase of evolution show that the equilibrium radius of the hydrostatic remnant is about 10^{11} cm, which is larger than the Roche Lobe radii of some cataclysmic variable stars. Therefore, slightly after the peak of the outburst, the binary will be revolving within the extended radius of the white dwarf. This cannot be a stable situation and Livio *et al.* (1990) have examined the consequences of the dynamical friction that arises from the motion of the binary within the extended envelope of the white dwarf. Dynamical friction seems capable of ejecting that part of the envelope that extends past the Roche Lobe of the secondary on short timescales (MacDonald 1980; Livio *et al.* 1990).

There is another process that must be acting at this time: radiation pressure driven mass loss. Not only is it driving mass off the remnant, it must also be acting on a short time scale. The studies of this phenomenon in novae imply very short time scales for ejecting the remaining material (Starrfield *et al.* 1990a,b). For white dwarf masses in excess of 1.2 $M_\odot$, the constant bolometric luminosity phase should last no longer than about 10 years. In Figure 17, I show the turnoff time as a function of white dwarf mass. The calculations upon which this figure is based (Starrfield *et al.* 1990a,b) assume both mass loss via the Castor, Abbott, and Klein (1975) theory and also that the envelope mass versus white dwarf mass relationship shown in

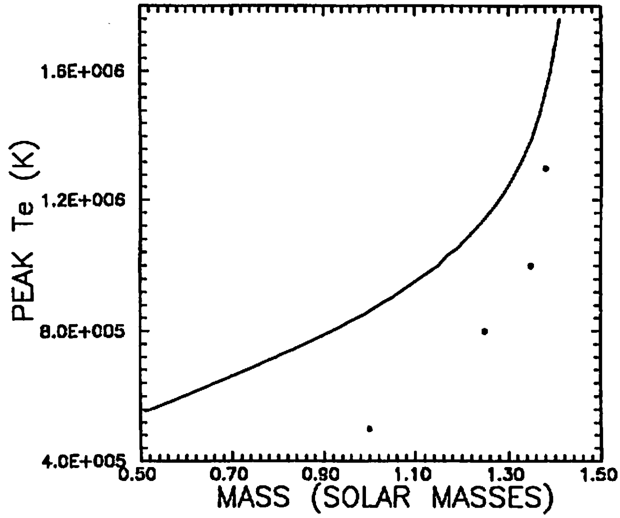

Fig. 18. This figure shows the peak effective temperature as a function of white dwarf mass. The curve is obtained by assuming the core mass luminosity (Paczynski 1971) and the equilibrium white dwarf radius as a function of mass. The points are from actual simulation of TNRs on white dwarfs of masses 1.0 $M_\odot$, 1.25 $M_\odot$, 1.35 $M_\odot$, and 1.38 $M_\odot$ and show that some expansion has occurred at the time of the first phase of Peak T_e.

Figure 16 is valid. The turnoff times shown in Figure 17 are probably upper limits for low mass white dwarfs since this calculation neglects the dynamical friction of the binary. On the other hand, the theory also breaks down for the most massive white dwarfs where the luminosity is very close to the Eddington luminosity. The recent ultraviolet observations of RN, which are predicted to occur on very massive white dwarfs (Starrfield, Sparks, and Truran 1985; Starrfield, Sparks, and Shaviv 1988), imply that the mass is ejected by a wind and the outburst is over within weeks after maximum light has occurred (Shore *et al.* 1991) as one would expect for white dwarfs with masses near the Chandrasekhar limit.

3.3.4. The Return to Quiescence

The final phase of the outburst marks the ejection (or conversion to helium) of all of the hydrogen in the accreted envelope and the cessation of nuclear burning on the white dwarf. It is not clear if this phase also marks the resumption of mass transfer by the secondary, if mass transfer has already resumed, or if it has been going on during the entire outburst. It is possible to make some predictions about the characteristics of the system during this phase since we can assume that the white dwarf is emitting at a constant (or near constant) luminosity and the radius is declining. Since it will eventually reach the equilibrium radius of the white dwarf, which is less than 10^9 cm, the most massive white dwarfs can reach temperatures exceeding 10^6 K during the last stages of the outburst (Starrfield *et al.* 1990a,b). This result can be seen in Figure 18 which shows the variation in effective temperature as a function of mass for white dwarfs that are radiating at a luminosity determined by the core mass-luminosity relationship (Paczynski 1971). In addition, their radius is obtained from the equilibrium radius for a white dwarf of a given mass. The four points plotted on this curve are taken from actual evolutionary sequences and show that some radius expansion has taken place.

Observational support for this prediction comes from the EXOSAT studies of GQ Mus, PW Vul, QU Vul, and RS Oph (Ögelman, Krautter, and Beuermann 1987; Mason *et al.* 1986). All four novae were observed to contain a hot source emitting at a temperature of $\sim 3 \times 10^5$ K. This value is somewhat low for a 1.25 $M_\odot$ white dwarf but calibration problems may have affected their temperature determinations. On the other hand, optical observations of GQ Mus in 1988 and 1989 (Krautter and Williams 1989) show that [FeX] 6374 Å is stronger than Hα which cannot occur unless there is a hot ($T > 5 \times 10^5$ K) photoionizing source inside the system. IUE observations of GQ Mus obtained in September, 1989, showed a very blue continuum with a number of features present in the spectrum (Krautter and Starrfield 1992; in preparation).

4. Recurrent Novae

The last few years have seen major advances in our understanding of the ultraviolet behavior of RN. In addition, in 1990 we observed a RN in the LMC (1990 #2: Shore, Sonneborn, and Starrfield 1990; Shore *et al.* 1991). LMC 1990 #1 was an ONeMg nova similar to Nova V693 CrA 1981 (Williams *et al.* 1985; Sonneborn, Shore, and Starrfield 1990).

RN are members of the nova subclass of cataclysmic variable stars. However, unlike classical novae which are observed to suffer only one major outburst on historical time scales, RN suffer less extreme (than classical novae) outbursts which repeat on observable timescales. Therefore, a nova will be classified as recurrent if it exhibits a second outburst and there are RN, such as T Pyx, U Sco, and RS Oph, that have experienced more than two outbursts in the last 100 years. I also note that the interoutburst time is not regular and can range from 9 years (U Sco) to longer than 50 years (T CrB). It is also possible that there are novae that can reoccur on time scales of 100 to 200 years and we have yet to observe the second outburst.

In order to understand the rapid recurrence time scale of these systems, it has been predicted: 1) that a RN system must contain an accreting white dwarf which is very near the Chandrasekhar mass limit so that the envelope mass required to reach runaway will be small; 2) that the white dwarf in RN binary systems must be more luminous than the white dwarfs in normal classical novae systems so that the evolution time to runaway will be short; and 3) that the secondary must be evolved so that the mass transfer rate onto the white dwarf will be higher for RN than for classical novae (Starrfield, Sparks, and Truran 1985; Starrfield, Sparks, and Shaviv 1988). These three conditions are necessary to produce TNRs that can reach maximum in less than 3 years.

There are interesting observational differences between RN and classical novae. For example, all well studied RN have evolved secondaries. This is very different from classical novae for which the secondary (mass loser) is commonly assumed to be on or close to the main sequence. In addition, the magnitude range during the outburst is much smaller for recurrent novae than for classical novae: about 8 to 10 mag. rather than 14 mag. or greater. Concomitant with this smaller range in brightness, a recurrent nova ejects less mass ($\sim 10^{-7}\ M_{\odot}$) during the outburst than does a classical nova ($\sim 10^{-5}\ M_{\odot}$). This is probably the cause of the smaller magnitude range in RN. They eject much less material and become optically thin before the outer layers have reached radii of 10^{12} cm. Therefore, most of the radiative energy will be emitted in the ultraviolet. This was certainly the case for LMC 1990 #2 and U Sco (Williams *et al.* 1981; Shore *et al.* 1991).

To complicate the situation even further, it turns out that there are at least two classes of RN. Those like U Sco and V 394 CrA, in which the secondary is small and the orbital periods are a few days or less (Schaefer 1990), and those like V745 Sco, T CrB, and V3890 Sgr in which the secondary is a giant (Starrfield and Wagner 1990). The differences in the size of the secondary will cause the observed characteristics of the outburst to differ even if the evolution of the white dwarfs are similar. Finally, there is RS Oph in which the secondary is not only a giant but it is losing mass in a dense wind so that the outburst takes place within the wind of the giant.

4.1. THE 1985 OUTBURST OF RS OPH

I will concentrate on the 1985 outburst of RS Oph because not only are there numerous high dispersion IUE data that have recently been analyzed and which are providing a great deal of information about the progress of the outburst (Shore, Sonneborn, and Starrfield 1992, in preparation), but RS Oph was also detected in outburst by EXOSAT. One of the most active of the RN, outbursts have been observed in 1898, 1933, 1958, 1967, and 1985. The 1985 outburst of RS Oph was exceptionally well covered in the ultraviolet with both low and high dispersion observations (Snijders 1986; see Bode 1986 for a complete discussion of the outburst behavior of this nova and data at a variety of wavelengths). Since the white dwarf is actually orbiting within the wind from the red giant companion, we must try to understand how the blast wave from the white dwarf will propagate through and interact with the red giant wind. Fortunately, we can compare the data for RS Oph with data for other RN, which have giants as secondaries but whose giants do not exhibit a thick wind, and then assume that any differences

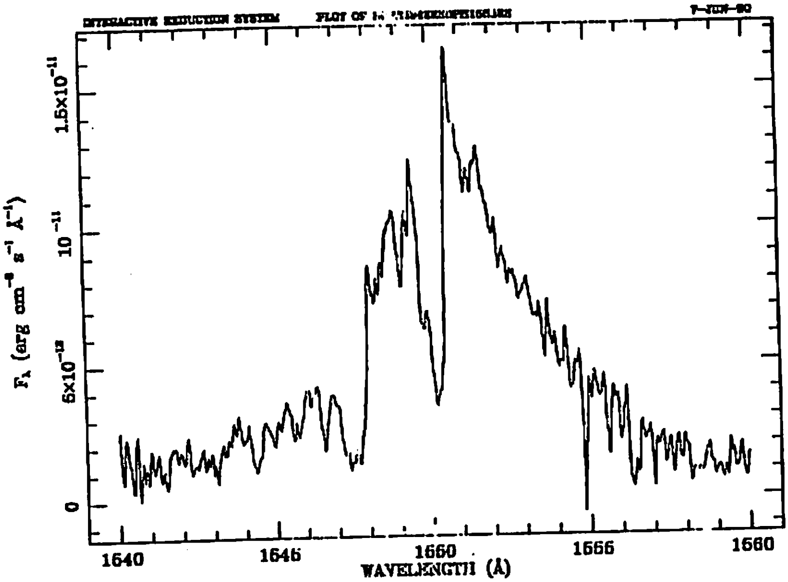

Fig. 19. This is a high dispersion IUE SWP spectrum of Nova RS Oph 1985 obtained on day 1985/45.5 and shows the CIV 1550 Å profile. The broad feature is from the expanding blast wave while the absorption comes from the ionized red giant wind of the companion.

in behavior are caused by the difference in the environment. Since a detailed discussion of the ultraviolet behavior of this recurrent nova will appear elsewhere (Shore, Sonneborn, and Starrfield 1992, in preparation), here I only present and discuss three high dispersion images that show some of the variation in the CIV 1550 Å profiles with time. Figure 19 shows the high dispersion profile of CIV obtained on 1985 day 45.5. There are two important features to be noticed in this spectrum which shows broad emission with superimposed absorption. First, the broad emission extends (FWHM) to velocities of about 1200 km s^{-1}, while FWZI is about 1900 km s^{-1}. This emission must be coming from the pseudo photosphere produced by the shock moving through the red giant atmosphere. The absorption components are much narrower and are probably coming from the photoionized wind from the red giant.

The presence of these absorption components, early in the outburst, has a very important implication. The material in a red giant wind should be too cool to have sufficient C^{+++} to produce the observed absorption unless it has been ionized to this stage by the outburst. It seems likely that the EUV phase at maximum M_{Bol} was the original cause of this ionization and precursor UV photons from the blast wave are maintaining the ionization (Shore, Sonneborn, and Starrfield 1992; in preparation). There are more than enough ionizing photons emitted during the rise to bolometric maximum to ionize the entire shell if the outburst occurs as a result of a TNR.

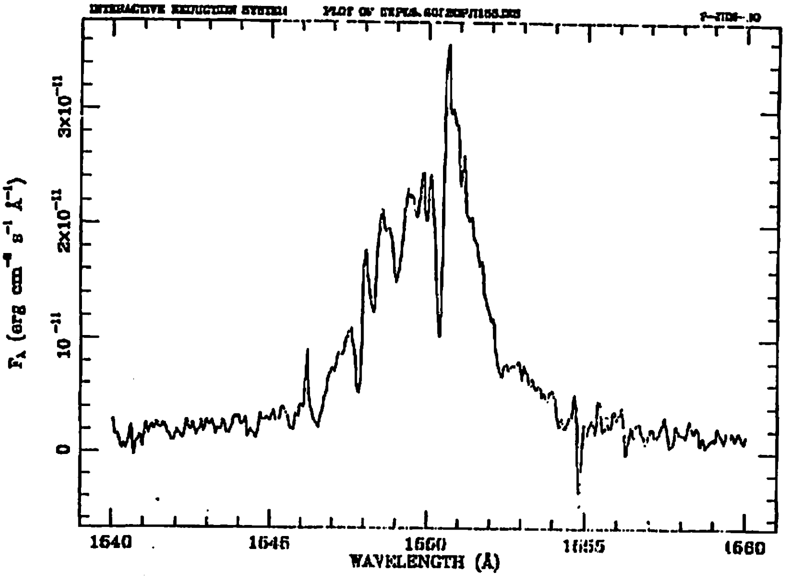

Fig. 20. This high dispersion IUE SWP spectrum of RS Oph 1985 was obtained on day 1985/52.5 and also shows the CIV profile. The expanding shock has continued to move through the envelope, which has caused the narrowing of the profile, and the absorption from the red giant wind has also narrowed because it is coming from farther out in the wind.

One of the differences between this nova and other RN is that the velocity of the blast wave is much smaller for RS Oph than was found for U Sco, V745 Sco, or V3890 Sgr. If we assume that the outburst has the same cause (a TNR), that the masses and luminosities of the white dwarfs are approximately equal, and the compositions are also about the same, then the lower velocities must be a direct result of the interaction of the blast wave with the red giant wind. We also expect the widths of the emission lines to narrow as the blast wave moves through the wind into lower velocity material. This can be seen in Figure 20 which shows the region around CIV on day 1985/52.5. The line has become narrower and the absorption is less pronounced since the blast wave has penetrated more of the shell.

The final high dispersion spectrum of RS Oph (Figure 21) was obtained on day 1985/82.3 and shows the emission from the red giant shell after the blast wave has reached the edge of the shell. We see the two components of the CIV doublet very clearly. I note that when the doublet was first seen, early in the outburst, both components were optically thick. As the outburst evolved, first the 1550 Å component became optically thin, then the 1548 Å component became optically thin.

X-ray observation of this outburst, obtained with the EXOSAT satellite showed a

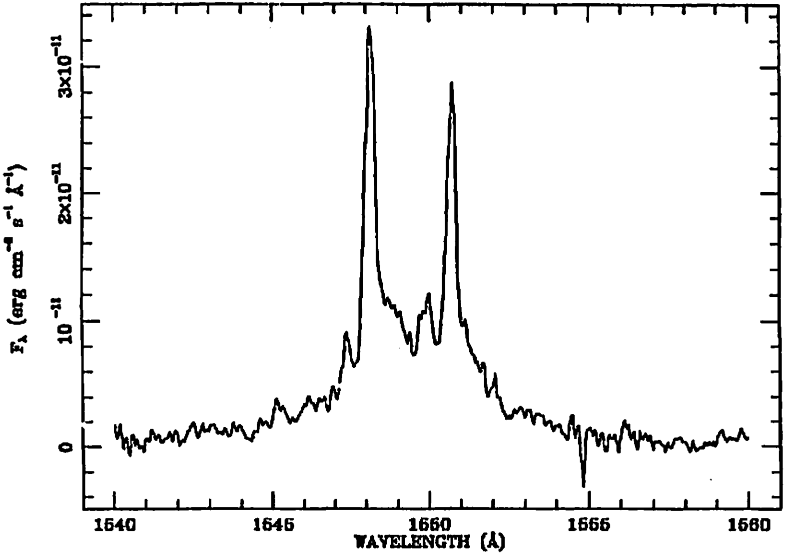

Fig. 21. This high dispersion IUE SWP image of RS Oph 1985 was obtained on day 1985/82.3 and shows the same region as in the previous two figures. This was taken about the same time as the EXOSAT X-ray data indicated that the blast wave had broken through the wind. In fact, the most prominent features are caused by the emission from the red giant wind.

strong decrease in emission beginning at about the same time as when the spectrum shown in Figure 11 was obtained. This behavior was also explained as break out of the shock at the edge of the red giant wind (Mason *et al* 1986; see Section 2.5).

4.2. THE OUTBURST OF THE RN LMC 1990 #2

Up to the time of the writing of this chapter there have been four novae in the LMC that have been studied in some detail with a variety of methods. In this subsection I will discuss the outburst of LMC 1990 #2 which was found to be a RN. Its outburst was very similar to the galactic RN: U Sco 1979, 1987 (Williams *et al.* 1981) and V394 CrA 1987. In contrast to RS Oph, T CrB, and other RN with giant secondaries, this class of objects have secondaries that are evolved but must be small in size since they have relatively short orbital periods (Schaefer 1990). The evidence for their secondaries being evolved is that U Sco, V394 CrA, and LMC 1990 #2 are transferring material that is hydrogen poor so that it must have undergone hydrogen nuclear fusion at some time in the past. In addition, LMC 1990 #2 has provided much important data about the RN class in general (Shore, Sonneborn, and Starrfield 1990; Shore *et al.* 1991). For the very first time, we know the distance to a RN and, thereby, can determine the energetics of the outburst to a high degree of accuracy. For example, as can be seen from the ultraviolet light curve presented in Shore *et al.* (1991), this nova radiated at super-Eddington luminosities at the peak of the outburst. Although predicted by the theoretical calculations (c.f., Starrfield, Sparks, and Shaviv 1988), this is the first observational confirmation of this prediction.

The optical outburst of Nova LMC 1990 # 2 was discovered on February 14.1 (UT) by Liller (1990) as the result of photographic nova patrol observations. In his announcement, Liller suggested a correspondence in position between this nova and one reported in the LMC in 1968 (Sievers 1970) which reached a maximum visual magnitude of about 10.7 mag. Shore *et al.* (1991) remeasured the original plates at Bamberg and found a coincidence in position to an acceptable degree of accuracy. They are extremely confident that it is recurrent. They also examined other plates of the area and were able to set limits on the brightness of the secondary that place it as fainter than the secondaries of galactic RN with *giant* secondaries.

Their principal result was that the luminosity in the ultraviolet exceeded $7 \times 10^4\ L_\odot$ during the first few days of the outburst. An ultraviolet light curve can be found in Shore *et al.* (1991). This value is greater than the Eddington luminosity of a $1.0\ M_\odot$ white dwarf, assuming a solar mixture of the elements and electron scattering as the opacity. The ultraviolet luminosity rapidly declined after the first day, which appears to have been at maximum brightness in the ultraviolet. However, the optical outburst was discovered two days prior to the first IUE observation and those observations (IAU Circular 4964) suggested that this nova had already reached optical maximum when first discovered. Since it was super-Eddington when first observed in the UV and a nova cannot remain that bright for more than a day or two, Shore *et al.* suggested that it was at maximum when first observed with the IUE satellite. Therefore, this RN shows the same behavior seen in other novae studied both in the optical and ultraviolet: the ultraviolet light maximum follows optical maximum (Austin *et al.* 1990). By 23 February, approximately one week after ultraviolet maximum, the integrated luminosity had fallen to approximately $6.3 \times 10^3\ L_\odot$

Analysis of the optical and IUE spectra of this RN provided some very interesting results. The mass of the ejecta was $\sim 10^{-7}\ M_\odot$ which is in good agreement with the ejected mass in U Sco (Williams *et al.* 1981). Models of the continuum and emission line fluxes were able to place good limits on the effective temperature of the underlying white dwarf. This is because the NV 1240 Å line is very sensitive to the flux emitted in the Lyman continuum and, therefore, is a very good thermometer. Shore *et al.* report that in those models where they decreased the Teff of the (underlying) ionizing source from 2×10^5 K to 10^5 K, the predicted NV line strength decreased by more than an order of magnitude. Therefore, for temperatures below $\sim 2 \times 10^5$ K, no reasonable match could be obtained for the observed nitrogen line strengths for any consistent set of abundances. Finally, they also found that helium and nitrogen were enhanced in abundance over solar material by significant factors.

5. Nucleosynthesis in Novae

As has been continuously emphasized in various studies of the nova outburst, a proper treatment of nuclear energy generation is essential to understanding the cause of the classical nova and RN outburst. The super-Eddington character of the bolometric luminosity at maximum of fast novae is dependent on the violence of the thermonuclear runaway, which in turn depends on the CNO nuclear reactions and the composition of the accreted nova envelope. In addition, novae may be important contributors to the galactic abundances of the rarer isotopes ^{13}C, ^{15}N, and ^{17}O, as well as ^{7}Li. I also note that the same novae whose ejecta are enhanced in intermediate mass nuclei (V693 CrA, V1370 Aql, QU Vul, LMC 1990 #1) exhibit velocities of ejection exceeding 8×10^3 km s^{-1} so that this material is well mixed in the ISM.

In order to determine the important nucleosynthesis regimes as a function of temperature, density, and time, Nofar, Shaviv, and Starrfield (1990) and Weiss and Truran (1990) have independently calculated the nucleosynthesis expected to occur in nova explosions. The results of both their studies can be summarized as follows: (1) They confirm earlier findings of Hillebrandt and Thielemann (1982) and Weischer *et al.* (1986) that extremely low levels of ^{26}Al and ^{22}Na are expected to be formed in nova envelopes with a solar initial heavy element composition. This result implies that slow CO novae and RN are not expected to contribute significantly to the abundance of ^{26}Al in the galaxy although it still might be possible for slow CO or RN to contribute to some of the abundance anomalies detected in meteorites. (2) Enhancing only the CNO nuclei does not guarantee significantly increased ^{22}Na or ^{26}Al although CO novae may be responsible for production of some rare light nuclei. (3) Greatly increased ^{22}Na and ^{26}Al production does result from envelopes with substantial initial enhancements of elements in the range from neon to aluminum. For example, for the choice of an initial composition consisting of matter enhanced to a level of $Z = 0.25$ in the products of stellar carbon burning (Arnett and Truran 1969), their calculations predict that the abundances of ^{22}Na and ^{26}Al can be one to two orders of magnitude larger than for equivalent models where the initial composition is solar. I note that large enhancements of nuclei from nitrogen to sulfur have been observed in novae ejecta (Sonneborn, Shore, and Starrfield 1990; Starrfield 1988; Truran 1990). (4) Novae with ejecta rich in material from an ONeMg white dwarf may represent an important source of ^{26}Al in our Galaxy. Order of magnitude estimates indicate that their integrated contribution is within a factor of 3 to 10 of what is observed implying that more detailed calculations are necessary. (5) The abundances of ^{22}Na predicted for the ejecta of novae involving ONeMg white dwarfs are sufficiently high that we may expect relatively nearby ONeMg novae to produce detectible flux levels of ^{22}Na decay γ-rays. (6) The calculations also indicate that there should be a strong anti-correlation between ^{22}Na and ^{26}Al overproduction in nova outbursts. (7) The degree of enhancement of ^{22}Na and ^{26}Al is a sensitive function of the temperature

TABLE I
Partial List of Recent Classical and Recurrent Novae.

Nova	Year	Dust	Class
V1668 Cyg	1978	Yes	CO
U Sco	1978	No	REC
V693 CrA	1981	No	ONeMg
V1370 Aql	1982	Yes[4]	ONeMg
GQ Mus	1983	No	CO
PW Vul	1984	Yes	CO
QU Vul	1984	Yes[4]	ONeMg
RS Oph	1985	No	REC[1]
OS And	1986	No	CO
V842 Cen	1986	Yes	CO
V394 CrA	1987	No	REC[1]
QV Vul	1987	Yes[3]	CO[4]
LMC 88 #1	1988	Yes	CO
LMC 88 #2	1988	?	CO
V745 Sco	1989	No	REC[1]
Sco 1989	1989	?	?[2]
LMC 90 #1	1990	?	ONeMg
LMC 90 #2	1990	?	REC[1]
V3890 Sgr	1990	No	REC[1]

[1] Recurrent nova

[2] Unknown
[3] No late time spectra
[4] Silicate dust

history (assuming the same initial concentration of nuclei) and, therefore, detection of ^{22}Na would provide useful constraints on the evolution of the thermonuclear runaway.

6. Conclusions

The studies of novae done over the past two decades have far advanced our understanding of the cause and evolution of the nova outburst. Nova outbursts are not rare phenomena as can be seen from Table I which shows all of the novae that have been studied in the past few years. The importance of satellite studies to novae can be understood if we note that the photospheres of novae are small and very luminous so that they emit most strongly in the ultraviolet and soft X-ray. As a direct result of IUE studies, we have discovered that there are two compositional classes of novae: those that occur on an ONeMg white dwarf and those that occur on a CO white dwarf. Theoretical studies, using the existence of ONeMg nova explosions, indicate that these novae are the source of ^{26}Al in the solar system. In studies of recurrent novae, we have found evidence for the passage of a blast wave through the envelope of a red giant and can show that the luminosities of both fast classical novae and recurrent novae are super-Eddington at maximum brightness.

Given the successes in the studies of novae, what are the reasons for continued observations of novae. Although we have identified broad classes of novae, detailed studies of novae have shown that every well studied outburst is unique and the expanding, optically thin shell in each object samples a different regime of electron density and electron temperature parameter space. This is to be expected since we must realize that the explosions take place on white dwarfs with a range in masses, luminosities, accretion rates, and compositions. Continual studies of novae are improving and expanding our knowledge of the plasma diagnostics that can be applied to other objects (symbiotic variable stars and AGN's are two important examples) which exhibit evidence for expanding gas. Finally, we remind the reader that studies of novae provide time-dependant information about the evolution of stellar winds, grain growth, emission lines, and stellar atmospheres that can be compared with objects whose features do not change rapidly with time.

It is clear that obtaining high quality data on novae at maximum, or before maximum, can provide very important information about the outburst. Unfortunately, such data have been obtained for only a few novae and recent studies of nova spectra in the IUE archives have shown that it is very easy to overexpose the continuum of a nova and render the exposure useless. Observations of novae require very broad wavelength coverage and early spectra show that the nova evolves very rapidly near maximum. It is necessary to obtain numerous spectrophotometric data over the first few days of the outburst. It is also important to follow the evolution of the spectra as the nova evolves from optically thick to optically thin. Such an observing campaign requires repeated observations and very broad wavelength coverage over a long period of time

In the past two years, we have obtained important data for novae in the Large Magellanic Cloud. Their brightnesses at maximum are well suited for multiwavelength studies with a variety of ground based and satellite telescopes. Obtaining the distance to the LMC, by as many different methods as possible, is one of the fundamental steps in determining the size scale of the Universe. One of the fundamental indicators is the brightnesses of novae a few days past maximum. We have found that novae exhibit a variety of brightnesses at maximum and detailed study of each outburst is required to make them useful as distance indicators.

The studies of these 4 novae in the LMC show that both classical and recurrent novae can become super-Eddington at maximum but that it should still be possible to obtain a very good determination of the rate of decline-absolute magnitude relationship. However, up to the present there have been only 4 novae that have been studied with the IUE satellite and each of them has suffered a unique outburst (a slow CO nova, a fast CO nova, an ONeMg nova, and a recurrent nova).

The explosion of a recurrent nova in the LMC has provided us with an unparalleled opportunity to understand the outbursts of these enigmatic objects. As a direct result of knowing the distance to the LMC, from other techniques, we can firmly state that the peak luminosity of this nova exceeded the Eddington limit for a 1.0 $M_\odot$ white dwarf with solar abundances. Its luminosity becomes even more super-Eddington if we note that the ejected abundances were not solar, but helium (He/H$\sim$1) and nitrogen (N $\sim 30\times$ solar), at least, were enhanced over an equivalent solar mixture by large factors. In addition, the actual opacity in the shell probably far exceeded the electron scattering opacity which is usually used to calculate the Eddington luminosity. Unfortunately, because of the differences in the outbursts of the 4 novae in the LMC, we must obtain more data on such novae in order to not only obtain more information on these distance indicators but, in addition, to obtain abundances for objects that are sampling the interiors of white dwarfs in an external galaxy.

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