OF GALACTIC NOVAE

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1. Introduction

The classical nova outburst is the second most violent explosion that occurs in a galaxy and its violence is exceeded only by a supernova explosion. However, novae are relatively nearby and a nova outburst occurs much more frequently than a supernova outburst so that there are more than 200 outbursts tabulated and discussed by Payne-Gaposchkin (1957) and McLaughlin (1960). The first ultraviolet (hereafter: UV) study of a nova was that of the 1970 outburst of F H Ser (Gallagher and Code, 1974) and that was broad band photometry done by the OAO—A2 satellite. The first UV spectroscopic study was that of V1500 Cyg 1975 done with Copernicus (Jenkins et al., 1977) but it was such a fast nova that the only line visible when the spectrum was taken was Mg II λ2800. Nova Cyg was also studied with the ANS satellite (Wu and Kester, 1975).

The whole picture changed with the launch of the International Ultraviolet Explorer satellite (hereafter: IUE) in 1978. Almost immediately after launch it began obtaining both low and high dispersion spectra of novae in outburst and old novae in quiescence. These data, taken over the last 8 years, have markedly increased our understanding of the nova outburst. Each outburst has proved to be unique and valuable and the IUE observations have shown that it is as important to obtain UV as optical, radio, and IR data. The data are complementary and all are necessary to understand the characteristics of the outburst.

The importance of the IUE data is that there are spectral lines in the 1200 Å to 3300 Å wavelength range that come from elements which do not have analyzable (or any) lines in the optical. In addition, the number of available diagnostic emission line ratios has been greatly expanded through the combination of optical and UV data. These lines can be used to determine elemental abundances, expansion velocities, and the amount of mass ejected. Many of these lines are the

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commonly observed and well understood medium ionization UV resonance and intercombination lines observed in most emission line objects. However, their time-dependant behavior in novae can be used to constrain the abundances that are determined for the ejected material. A table of such lines and the time variations of their fluxes for both a normal nova and also a ‘neon’ nova can be found in Stickland et al. (1981) and in Williams et al. (1985). Because of IUE data, we have recently been able to identify a new class of novae (Starrfield et al., 1986). Finally, continuum flux distributions can be used to determine temperatures and compare the observations with predictions of accretion disc theory.

The classical reviews of the observed behavior of a nova in outburst are those of Payne-Gaposchkin (1957) and McLaughlin (1960). Reviews of novae in quiescence are Gallagher and Starrfield (1978; quiescence plus outburst), Cordova and Mason (1983), and Bode and Evans (1986). A compilation of the abundances of novae can be found in Truran and Livio (1986). The existence of these reviews allows us to skip the basic optical data and concentrate only on the observations from IUE.

2. The Cause of the Outburst

In this review we assume the commonly accepted model for a nova: a close binary system with one member a white dwarf and the other member a larger, cooler star that fills its Roche lobe. Because it fills its lobe, any tendency for it to grow in size because of evolutionary processes or for the lobe to shrink because of angular momentum losses (by some, as yet unknown, mechanism) will cause a flow of gas through the inner Lagrangian point into the lobe of the white dwarf. The size of the white dwarf is small compared to the size of its lobe and the high angular momentum of the transferred material causes it to spiral into an accretion disk surrounding the white dwarf. Some viscous process, as yet unknown, acts to transfer mass inward and angular momentum outward through the disk so that a fraction of the material lost by the secondary ultimately ends up on the white dwarf. Over a long period of time, the accreted layer will grow in thickness until the bottom reaches a temperature that is high enough to initiate thermonuclear burning of hydrogen. The further evolution of nuclear burning on the white dwarf now depends upon the mass and luminosity of the white dwarf, the rate of mass accretion, and the chemical composition of the reacting layer.

Given the proper conditions, a thermonuclear runaway (hereafter: TNR) will occur, and the temperature in the accreted envelope will grow to values exceeding $10^8$ K. At this time the positron decay nuclei become abundant which strongly affects the further evolution of the outburst. Theoretical calculations demonstrate that this evolution will release enough energy to eject material with expansion velocities that agree with observed values and that the predicted light curves produced by the expanding material can agree quite closely with the observations (Sparks et al., 1978; Starrfield et al., 1978; Starrfield et al., 1974a, b, 1985, 1986; Prialnik et al., 1978, 1979; MacDonald, 1980; Prialnik et al., 1982).

These theoretical studies have involved hydrodynamic calculations of TNR's in the accreted hydrogen rich envelopes of white dwarfs which are assumed to be the
compact components of nova binary systems. This work has been extremely successful in reproducing the gross features of the nova outburst: ejected masses, kinetic energies, and light curves. More importantly, 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 months, or longer, and (4) that the properties of the outburst should be strong functions of the mass of the white dwarf. As discussed in Starrfield (1986a, b), observational confirmation of each of these points has now appeared in the literature. The theoretical studies of the nova outburst have also identified a number of parameters that strongly influence the characteristics of the outburst. These are: (1) the white dwarf mass, (2) the envelope mass, (3) the white dwarf luminosity, (4) the rate of mass accretion, and (5) the chemical composition of the envelope (see MacDonald, 1983; Paczynski 1983).

The nucleosynthesis that occurs during the outburst will produce $^{13}\text{C}$, $^{14}\text{N}$, $^{15}\text{N}$, and $^7\text{Li}$ and these nuclei will be ejected by the nova explosion (Starrfield et al., 1978; Lazareff et al., 1979; Starrfield et al., 1978; Audouze et al., 1979; Wallace and Woosley, 1981; Hillebrandt and Thielemann, 1982; Wiescher et al., 1985). It has also been predicted that the $^{26}\text{Al}$ anomaly could be a result of nuclear burning during the nova outburst (Arnould et al., 1980) and the recent discovery of ONeMg novae (Starrfield et al., 1986) strengthens this prediction. These predictions, along with the observational confirmation of nonsolar CNO abundances in nova ejecta, demand that novae be included in studies of galactic nucleosynthesis.

The prediction that the ejecta of novae would be enhanced in CNO nuclei has been confirmed by a number of observational studies (Sneden and Lambert, 1975; Williams et al., 1978, 1981, 1985; Williams and Gallagher, 1979; Ferland and Shields, 1978; Tylenda, 1978; Gallagher et al., 1980; Stickland et al., 1981; Snijders et al., 1984). In addition, Sneden and Lambert (1975) determined that the $^{12}\text{C}/^{13}\text{C}$ isotopic ratio (in combination with the extreme overabundance of carbon) in DQ Her strongly supported a TNR as the cause of the outburst.

Studies of recent novae have reported very large enhancements of neon (V1500 Cyg: Ferland and Shields, 1978; V693 CrA: Williams et al., 1985; V1370 Aql: Snijders et al., 1984). Now, Gehrz, et al. (1985) have reported the discovery of [Ne II] emission at 12.8 µ in Nova Vul #2 1984 and Gehrz et al. (1986) report the condensation of SiO$_2$ grains in the same nova. These results, in combination with the IUE spectra that also show strong neon lines (Starrfield et al., 1987, in prep.; Snijders et al., 1986, in prep.; and this review), imply that at least four of the recent nova outbursts have ejecta rich in neon. The most likely explanation is that some novae are ejecting material which has been processed to neon and beyond during the prior evolution of the white dwarf (as suggested by Law and Ritter, 1983 and confirmed and expanded by Starrfield et al., 1986).

UV and IR studies confirm that most novae exhibit a phase of constant luminosity following the initial rise to maximum (Wu and Kester, 1977; Ney and Haffield, 1978; Stickland et al., 1981; Sparks et al., 1982; Snijders et al., 1984; Williams et al., 1985; Snijders, 1986). This phase occurs because not all of the accreted material is ejected during the burst phase of the outburst and the radiated
energy, the effective temperature, and the time scale of this phase of the outburst provide fundamental data about the white dwarf (Gallagher and Starrfield, 1976, 1978; Starrfield, 1979, 1980, 1986a; Truran, 1982; Sion and Starrfield, 1986; MacDonald et al., 1985). These data have been used to show that the masses of white dwarfs in binary systems range from $\sim 0.6 \, M_\odot$ (DQ Her 1934) to $\sim 1.2 \, M_\odot$ or even higher (Nova V1500 Cyg 1975 and U Sco 1979). The inferred mass for DQ Her appears to be in substantial agreement with the values determined from radial velocity studies (Smak, 1980; Young and Schneider, 1980).

Recent calculations have demonstrated that a recurrent nova outburst can occur as a result of a TNR by examining the consequences of accretion of hydrogen rich material, with a solar abundance of the CNO nuclei, onto a massive white dwarf (Starrfield et al., 1985). They found that a TNR resulted after $\sim 33 \, yr$ of evolution and the evolution resembled that of U Sco. Sion and Starrfield (1986) have also modeled the observed behavior of Z And. Finally, a calculation of accretion onto ONeMg white dwarfs has produced extremely violent outbursts in which the entire accreted envelope was ejected at high velocities (Starrfield et al., 1986). This study was an attempt to simulate the novae that are ejecting enhanced neon.

### 3. IUE Studies of Classical Novae in Outburst

In this section we review the published studies of novae in outburst as a function of the date of outburst. Table I gives a list of the novae studied by IUE.

#### TABLE I

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<th>Name const.</th>
<th>Outburst year</th>
<th>R. A. (hr:mn:sec)</th>
<th>Dec. (deg:mn:sec)</th>
<th>$l$ (deg)</th>
<th>$b$ (deg)</th>
<th>$V_{\text{max}}$ (mag)</th>
<th>$V_{\text{min}}$ (mag)</th>
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<td>Muscae</td>
<td>(1983)</td>
<td>11h 49m 35s</td>
<td>$-66^\circ 55' 43''$</td>
<td>297.2</td>
<td>-05.0</td>
<td>6.5</td>
<td>14.5</td>
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<tr>
<td>U Sco</td>
<td>(1979)</td>
<td>16h 19m 37s</td>
<td>$-17^\circ 45' 43''$</td>
<td>357.7</td>
<td>+21.9</td>
<td>9.0</td>
<td>14.3</td>
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<td>(1985)</td>
<td>17h 47m 31s</td>
<td>$-06^\circ 41' 47''$</td>
<td>19.8</td>
<td>+10.4</td>
<td>6.5</td>
<td>11.7</td>
</tr>
<tr>
<td>Ser</td>
<td>(1983)</td>
<td>17h 53m 24s</td>
<td>$-14^\circ 00' 56''$</td>
<td>14.1</td>
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<tr>
<td>Sgr</td>
<td>(1982)</td>
<td>18h 31m 33s</td>
<td>$-26^\circ 28' 25''$</td>
<td>7.4</td>
<td>-08.3</td>
<td>8.0</td>
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<tr>
<td>V693 CrA</td>
<td>(1981)</td>
<td>18h 38m 30s</td>
<td>$-37^\circ 34' 59''$</td>
<td>357.8</td>
<td>-14.4</td>
<td>7.0</td>
<td>14.0</td>
</tr>
<tr>
<td>V1370 Aql</td>
<td>(1982)</td>
<td>19h 20m 50s</td>
<td>$+02^\circ 24' 00''$</td>
<td>38.8</td>
<td>-05.9</td>
<td>6.5</td>
<td>13.0</td>
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<tr>
<td>PW Vul</td>
<td>(1984)</td>
<td>19h 24m 3s</td>
<td>$+27^\circ 15' 54''$</td>
<td>61.1</td>
<td>+05.2</td>
<td>6.5</td>
<td>12.8</td>
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<td>RR Tel</td>
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<td>20h 00m 18s</td>
<td>$-55^\circ 52' 00''$</td>
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<td>-32.2</td>
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<td>WZ Sge</td>
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<td>20h 05m 18s</td>
<td>$+17^\circ 32' 56''$</td>
<td>57.5</td>
<td>-07.9</td>
<td>8.1</td>
<td>14.0</td>
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<tr>
<td>Ser</td>
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<td>$-14^\circ 43' 08''$</td>
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<td>-26.2</td>
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<tr>
<td>Vul #2</td>
<td>(1984)</td>
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<td>$+27^\circ 40' 40''$</td>
<td>68.5</td>
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<tr>
<td>V1668 Cyg</td>
<td>(1978)</td>
<td>21h 40m 38s</td>
<td>$+43^\circ 48' 00''$</td>
<td>90.8</td>
<td>-06.8</td>
<td>6.5</td>
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</table>

$^a$ $V_{\text{max}}$ and $V_{\text{min}}$ refer to the maximum and minimum brightness of the nova at the times of IUE exposures.
3.1. V1668 Cygni

This was the first classical nova to be studied with the IUE satellite. It was a moderately ‘fast’ nova which reached a $V_{\text{max}}$ of $\sim 6.2$ on September 12, 1978. A brief review of the IUE data can be found in Sparks et al. (1980) who also present data on the outbursts of WZ Sge and U Sco. There were 194 spectra obtained for this nova during its outburst and these data consist of both low and high dispersion SWP and LWR images. The first spectrum was taken on day 1978/254 and the last on day 1980/363 (our dating system is year/day number). During this time the visual magnitude declined to $\sim 14$. Cassatella et al. (1979) also presented early spectra of this outburst. The data have been analyzed by Stickland et al. (1979, 1981). They restricted their analysis mainly to the nebular phase and found that the total CNO abundance in the ejecta was about 30 times solar and that nitrogen alone was about 200 times solar. They report an expansion velocity $\sim 800$ km s$^{-1}$, an ejected mass of $\sim 6 \times 10^{-5} M_\odot$, and a kinetic energy of $6 \times 10^{44}$ ergs. These results are in close agreement with calculations of Starrfield et al. (1978) for a CNO outburst on a 1.0 $M_\odot$ white dwarf.

3.2. WZ Sge

This object has had at least two prior recorded outbursts and, because its rise is from $\sim 14$ to $\sim 8$ mag, it is often referred to as a recurrent nova. In fact, both the optical and IUE data obtained during this outburst confirm that it is a dwarf nova with a very long interoutburst period (Sparks et al., 1980; Fabian et al., 1980). There were 76 spectra obtained during the outburst. The first was taken on day 1978/335 and the last on day 1981/326 (at least a year after its return to minimum). The analysis of the IUE data was done by Fabian et al. (1980) and Friedjung et al. (1980) who reported that the IUE data did not show strong emission lines as is normally seen in the outburst of a classical nova. They found that very little material was ejected, the UV spectra were characteristic of an accretion disk, and during the outburst it continued to show variations in the line profiles with phase. The line widths gave velocities expected for material orbiting in keplerian velocities at the outer edge of an accretion disk around the white dwarf.

3.3. U Sco

This was the first recurrent nova to be studied by the IUE and the analysis of its outburst has provided us with some very unusual findings. There were 18 spectra obtained for this nova from day 1979/179 to day 1979/237. Optical data for this outburst were analyzed by Barlow et al. (1981) who found that H/He in the ejecta was $\sim 1/2$. The analysis of the IUE spectra is in Williams et al. (1981) who report that nitrogen was overabundant while carbon and oxygen probably were not. In fact, the CNO abundances could be explained by solar CNO material being processed through a hot hydrogen burning region. The first spectra taken with the IUE showed P Cygni type profiles which upon analysis implied an ejected mass of $\sim 10^{-7} M_\odot$ to $\sim 10^{-8} M_\odot$. This low a value, plus the rapidity of the decline, suggests strongly that the outburst occurred on a very massive white dwarf.
(Starrfield et al., 1985). They evolved TNR's on 1.38 $M_\odot$ white dwarfs and found reasonably good agreement with the observations. One difficulty is that studies of the accretion disk, both before and after the outburst (Barlow et al., 1981; Williams et al., 1981; Hanes, 1985) show only lines due to helium. This nova appears to be transferring helium and ejecting both hydrogen and helium!

3.4. V693 CrA

This classical nova was discovered at $\sim$7 mag. Optical spectra are published by Brosch (1982). There were 42 IUE spectra obtained during the outburst (day 1981/100 to day 1981/318). Williams et al. (1985) analyzed the IUE data and presented both a UV line list and line fluxes over the duration of the outburst. Brosch (1982) determined an ejection velocity of $\sim$2200 km s$^{-1}$ from the FWHM of the hydrogen lines. This high a value is also derived from low dispersion IUE data. In addition, a recent analysis of a high dispersion SWP image (13712) taken on day 1981/122 shows C IV 1550 with the blue edge of the P Cygni profile extending to a velocity of almost 8000 km s$^{-1}$ (Sion et al., 1986; and Figure 1).

![Graph](image)

Fig. 1. The region around CIV 1550 taken from a high dispersion spectrum of V693 CrA. We point out the very narrow interstellar absorption lines which have recently been analyzed (Sion et al., 1986). Note also the large blueward extent, $\sim$8000 km s$^{-1}$, of the P Cygni absorption profile.

The most important finding of the IUE analysis (Williams et al., 1985) is that the abundances of all of the intermediate mass elements from nitrogen to aluminum are enhanced over a solar mixture by a factor of about 100 (by number). This implies that $Z$ for the ejected material is $\sim$0.4 (Truran and Livio 1986). V693 CrA is now identified as a member of a new class of novae which must be occurring on ONeMg white dwarfs (see Starrfield et al., 1986, where the implications of this result are discussed).
3.5. V1370 Aql

This nova was discovered in outburst on January 28, 1982. The IUE spectra (22 from 1982/55 to 1982/181) have been analyzed by Snijders, et al. (1982, 1984). This nova was also observed in the optical by Andrillat (1983) and Rosino et al. (1983) and in the IR by Gehrz et al. (1984), Williams and Longmore (1984), and Bode et al. (1984). Snijders, et al. (1984) report that this nova ejected \(5 \times 10^{-6} M_\odot\) with expansion velocities of \(\sim 4000\) km s\(^{-1}\). A high velocity component with velocities up to \(10000\) km s\(^{-1}\) was present for at least 35 days after the outburst (Snijders et al., 1982, 1986a). The abundances determined for the ejecta were as reported for V693 CrA. Neon was the most abundant element in the ejecta and elements up to sulfur were enhanced. Truran and Livio (1986) calculate a Z for the ejecta of \(\sim 0.86\). Starrfield et al. (1986) explain this as an outburst on an ONeMg white dwarf (but see Wiescher et al., 1986). The IR data showed an excess at \(\sim 10\) \(\mu\) but no excess at \(\sim 20\) \(\mu\) (Gehrz et al., 1984). Snijders et al. (1984) reported a grain mass of the same order of magnitude as the gas mass so that this material is an important part of the ejecta.


These novae had 13 IUE spectra (1982/291 to 1982/304) and three spectra (day 1983/64) taken respectively. A discussion of these spectra can be found in Dreichsel and Rahe (1982) and Dreichsel et al. (1984).


There were 55 spectra obtained for this nova from day 1983/63 to day 1985/215. The analysis of the early IUE spectra can be found in Krautter et al. (1984) who also reported optical and IR data. They found a distance of \(\sim 5\) kpc and noted that it was radiating at \(\sim L_\odot\) for a \(1.0 M_\odot\) white dwarf in agreement with the TNR predictions. An abundance analysis showed that He/H was enhanced over solar, N/C was \(\sim 20\), and N/O was \(\sim 2.4\). These values are characteristic of hot hydrogen burning. Pacheco and Codina (1985) determined an expansion velocity of \(\sim 1000\) km s\(^{-1}\) and confirmed, from optical spectra, the overabundance of He, and CNO. They also found an overabundance of Fe which is difficult to understand in terms of the TNR theory although iron enhancements have been suggested for other novae (V1500 Cygni: Ferland and Shields, 1978; V1370 Aql: Snijders et al., 1984).

This nova was also detected by Exosat in the low energy detectors by Ogelman et al. (1984) who reported the discovery of a source with \(T \sim 3 \times 10^5\) K at a late stage of the outburst. This is exactly what would be expected from a white dwarf which is finally burning out the remaining hydrogen envelope on its surface (Starrfield 1979; MacDonald et al., 1985).

3.8. PW Vul (1984 No. 1)

This slow nova was discovered to be in outburst in July 1984 and the IUE began taking spectra almost immediately on day 1984/175. We have continued to obtain spectra up to the present time. Optical and IR data for this nova are presented in
Kenyon and Wade (1986) who find a distance of \( \sim 1.2 \) kpc and \( M_s \sim 5.5 \). They also report He/H of \( \sim 0.13 \) and that oxygen is enhanced in the ejecta but neon was not enhanced. The IUE data are currently being reduced and analyzed (Cassatella et al., 1986, in prep.; Starrfield et al., 1987, in prep.). We show, in Figure 2, spectra of PW Vul taken on June 24, 1985 and March 31, 1986.

3.9. NOVA VUL (1984 NO. 2)

This slow nova was discovered late in 1984 and the first IUE spectrum was obtained on day 1984/363. At the end of July 1986, it had declined only to \( \sim 10.8 \) mag and it is still being observed in the UV, optical, IR, and radio. More than 55 IUE spectra have been obtained, so far, and these data imply that the ejected material is very neon rich so that this must be a fourth member of the ONeMg class of outbursts (Starrfield et al., 1986). The IUE data show that \([\text{Ne} \, \text{V}] \lambda 3346\) appeared during the fall of 1985 and that at the present time \([\text{Ne} \, \text{IV}] \lambda 1602\) is the strongest line in the SWP spectral region (Figure 3). In addition, \([\text{Ne} \, \text{IV}] \lambda 2422\) is also present, which, in combination with the IR results (Gehrz et al., 1985; Gehrz et al., 1986) is strong evidence for enhanced neon in this nova.

3.10. RS OPH

This fact recurrent nova was discovered to be in outburst in January 1985. 73 spectra were obtained from day 1985/033 to day 1985/137. In addition, there are IUE images obtained, in quiescence, both before and after outburst. Preliminary results from the IUE observations are now available (Cassatella et al., 1985; Snijders, 1986; see also Bode, 1986). These data support TNR models for the outburst of this recurrent nova. A discussion of the relationship of this outburst to the outbursts of classical novae can be found in Sparks et al. (1986) and Starrfield et al. (1985; An alternative view is in Livio et al. [1986] but their hypothesis is in disagreement with the observations). A detailed analysis of the IUE observations is in progress (Snijders et al., 1986b).

3.11. RR TEL

We briefly mention this slow nova which has been in outburst for nearly 40 yr and for which 106 spectra have been obtained by IUE. The early data have been analyzed by Penston et al. (1983) who complement the optical analysis of Thackery (1977). The line strengths imply a source of ionizing radiation for the nebula. Spectra since then have been taken under the ID: ‘PHCAL’ and are used for wavelength calibration of the IUE; they do not appear under the class ‘55’ designation for classical novae in the IUE databank.

4. Novae at Quiescence

In this section we briefly discuss the IUE studies of old novae: those whose outburst began before the launch of the satellite and who have either returned to minimum or are on the way down. A list of these objects is given in Table II. A very wide range of nova speed class has been studied by IUE with a very broad range in time since outburst. The analysis of this data base should ultimately be
Fig. 2. The top plot shows low dispersion spectra taken of Nova PW Vul 1984 #1 on June 24, 1985 and the bottom plot shows spectra obtained on March 31, 1986. We were not able to plot Ly on the same scale as the rest of the lines in the bottom plot so the first line is actually N v 1240. The other two strong lines are N iv 1486 and C iv 1549, N iii 1750 and C iii 1909 are also present at both times. Note their peak fluxes have fallen by a factor of ~20 from June to March and that Mg ii 2800 is present in June but probably absent in March. The features longward of 3000 Å in March are probably noise.
Fig. 3. These two low dispersion spectra show Nova Vul 1984 #2 on June 24, 1985 and March 31, 1986. We have only outlined Mg II 2800 on the bottom spectrum so as to be able to show the other lines on the same scale. The strong line at 3346 is [Ne v]. The strong line at 1602 is [Ne iv] and [Ne iv] 2426 is present in the March spectrum. These spectra resemble those taken of V693 CrA 1981 (Williams et al., 1985) and a line list can be found in that paper.
### TABLE II

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<tr>
<th>Name</th>
<th>Outburst year</th>
<th>R. A.</th>
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<td>DO Her</td>
<td>(1934)</td>
<td>18h 06m 05s</td>
<td>+45° 51' 01&quot;</td>
<td>73.2</td>
<td>+26.4</td>
<td>14.0</td>
<td>14.8</td>
</tr>
<tr>
<td>V533 Her</td>
<td>(1960)</td>
<td>18h 12m 46s</td>
<td>+41° 50' 21&quot;</td>
<td>69.2</td>
<td>+24.3</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td>V603 Aql</td>
<td>(1918)</td>
<td>18h 46m 21s</td>
<td>+00° 31' 00&quot;</td>
<td>33.2</td>
<td>+00.8</td>
<td>11.0</td>
<td>12.0</td>
</tr>
<tr>
<td>CK Vul</td>
<td>(1670)</td>
<td>19h 45m 35s</td>
<td>+27° 11' 18&quot;</td>
<td>63.4</td>
<td>+01.0</td>
<td>16.0</td>
<td></td>
</tr>
<tr>
<td>HR Del</td>
<td>(1967)</td>
<td>20h 40m 00s</td>
<td>+18° 59' 00&quot;</td>
<td>63.4</td>
<td>-14.0</td>
<td>12.0</td>
<td>12.5</td>
</tr>
</tbody>
</table>

* $V_{\text{max}}$ and $V_{\text{min}}$ refer to the maximum and minimum brightness of the nova at the time of IUE exposures.

very useful in determining the interoutburst characteristics of old novae. In this section, we order the discussion by right ascension and do not discuss those novae for which the IUE data have not been published. A description of the original outburst can usually be found in Payne-Gaposchkin (1957).

4.1. **GK Per**

This was a fast nova which showed pronounced oscillations during its decline. There were 34 spectra taken and some were obtained during a mini outburst which occurred in 1983. An analysis of the IUE data is in Bianchini and Sabbadin (1983) who found a UV continuum distribution characteristic of an accretion disk with a mass accretion rate of $\sim 2 \times 10^{16}$ gm s\(^{-1}\). However, the continuum slopes that they obtained do not agree with standard accretion disk predictions. Other UV studies have been reported by Selvelli and Hack (1983) and Rosino et al. (1982) who report a continuum fit that implies a temperature of $\sim 12000$ K and $E(B-V) \sim 0.1$.

4.2. **RR Pic**

There were 31 spectra taken from 1979 to 1982. Duerbeck et al. (1980) and Rosino et al. (1982) report that it shows very high ionization emission lines and that the continuum slope fits a temperature of $\sim 3 \times 10^4$ K. Their spectrum shows that the strongest lines in the UV are NV $\lambda$1240, CIV $\lambda$1550, and HeII $\lambda$1640. Other discussions of RR Pic in quiescence can be found in Selvelli (1982) and Selvelli and Cassatella (1982).
4.3. T CrB

There were 47 IUE spectra taken from 1979 until 1985. The UV spectra have been analyzed by Duerbeck et al. (1980) and Cassatella et al. (1982, 1986) who find large changes in the UV flux from one spectrum to another. The UV luminosity varies from about $5L_\odot$ to $40L_\odot$. Kenyon and Webbink (1984) attempted to fit the continuum by simulations of accretion onto main sequence stars at various rates. This binary system consists of an M giant and a massive (1.6 $M_\odot$; Kenyon and Garcia, 1986) compact component. The large mass of this star makes it unlikely that it is a white dwarf.

4.4. DQ Her

There were 15 IUE spectra obtained from 1979 to 1985. The early spectra have been analyzed by Lambert et al. (1981) and Ferland et al. (1984) who report $T_e < 500$ K, in agreement with the optical studies of the expanding nebula (Williams et al., 1978). The extremely low temperature is probably caused by cooling by the enhanced CNO nuclei (Williams et al., 1978).

4.5. V603 Aql

This is the brightest old nova in the sky and a prime target for both optical and UV studies. There were 32 IUE spectra taken in 1979 and 1980 and two were high dispersion. It is a strong X-ray source (Becker and Marshall, 1981). An interesting development is that Rahe et al. (1980) reported periodic light variations and, in addition, variations were found in the emission line strengths (Drechsel et al., 1981). The light variations were not confirmed in an optical study (Slovak, 1981). The IUE spectra show the presence of a strong UV continuum ($T \sim 25000$ K) which is attributed to an accretion disk (Lambert et al., 1981). Other IUE studies (Dultzin-Hacyan et al., 1980) find that it is impossible to make a simple fit to the continuum flux distribution and suggest that there are at least two sources. Ferland et al. (1982) show that the abundances in the accretion disk are quite close to solar implying that the material being transferred from the secondary is normal and, therefore, that the enhanced abundances seen in novae ejecta must come from the core of the white dwarf.

4.6. HR Del

This old nova is a bright object that could use regular monitoring both in the UV and optical. There were 32 spectra taken in 1978, 1979, and 1980. These spectra have been analyzed by Hutchings (1979, 1980) who found a variable P Cygni profile for CIV $\lambda$1550 and a continuum slope that rises steeply to the blue. He argues, by analogy with O star winds, that this old nova is losing mass at $\sim 10^{-8}$ $M_\odot$ yr$^{-1}$. He also obtained a UV luminosity of $\sim 25L_\odot$. On the other hand, Andrillat et al. (1982) and Friedjung et al. (1982) interpret the steep UV continuum in terms of a disk accretion model and obtain a rate of mass accretion of $\sim 10^{-6}$ $M_\odot$ yr$^{-1}$. This value implies an accretion luminosity of better that 2500 $L_\odot$. In addition, another study of this nova by Dultzin-Hacyan et al. (1980) finds different temperatures from the previous authors. Finally, Wargau et al. (1982) do
continuum fits for a number of CV's and find that none of them fit steady-state optically thick accretion disk predictions. This seems like an interesting and useful problem to solve.

5. Summary and Discussion

- It is clear from this review of the IUE observations that the data from this satellite have been of paramount importance in extending our understanding of the characteristics and cause of the nova outburst and the structure of the nova binary. The ability of the satellite to make long, uninterrupted, exposures of a faint old nova or repeated exposures of a nova in outburst have allowed us to gather a wealth of material that is still being analyzed. Its ability to do Target-of-Opportunity observations on time scales of hours has made it possible to study some of these nova before maximum light when the expanding envelope is still optically thick. Finally, because all the data have been archived, IUE has provided material that will be useful for years.

The studies of old novae show that the continuum flux distributions fit power laws with some degree of accuracy. However, trying to estimate temperatures and mass accretion rates from these data is fraught with difficulties. The values of $10^{-8}$ to $10^{-9} \, M_\odot \, yr^{-1}$ that have been found do not seem unreasonable and are roughly equivalent to the values obtained for dwarf novae in outburst. Studies of old novae such as V603 Aql, HR Del, and RR Pic show that some of their UV emission lines have P Cygni profiles which implies that mass loss is occurring. However dwarf novae also show wind mass loss during some phases of their outburst cycle so this result is not too surprising.

Old novae such as GK Per, HR Del, and T CrB, show variations in continuum flux, line profiles, and luminosity with time. Of these objects, only T CrB has been observed since 1981 or 1982 but all are prime candidates for continuous monitoring (Cassatella et al., 1986). It will be important to learn if these changes are caused by variations in mass loss, mass accretion, or the temperature of the compact component. Finally, a study of V603 Aql (Ferland et al., 1984) has shown that the enhancement of the CNO nuclei cannot come from the secondary.

Observations of novae in outburst have allowed us to determine abundances of the elements, determine masses of the ejecta, rates of mass loss, velocities of ejecta, and continuum flux distributions. Because many elements are only observable in the UV, we have been able to determine abundances for many more elements than were possible with only optical data. In addition, while obtaining abundances from optical data during outburst has had a shaky history, with many claims that have not held up under close scrutiny (Williams, 1977), the combination of optical and UV data has proved to be reasonably easy to interpret. It is now clear that none of the novae studied with IUE have ejected material with a solar abundance.

- One of the most important recent results is the realization that three of the novae observed with the IUE (V693 CrA 1981, V1370 Aql 1982, and Nova Vul 1984 #2) are members of a class of novae in which the outburst is occurring on an ONeMg white dwarf rather than a CO white dwarf. The discriminating emission line is [Ne IV] $\lambda$1602. If it is present, at late times in the outburst, then the ejecta
are rich in neon. In Nova Vul 1984 #2, it is currently the strongest line in the SWP spectrum (Figure 3).

Ultraviolet data taken with IUE also confirm that the flux peaks at shorter and shorter wavelengths as time progresses. This is a confirmation of the TNR theory of the outburst and demonstrates that nuclear burning is still occurring in the extended envelope of the white dwarf and that mass loss must still be going on inside the ejected shell. Finally, each nova that has been studied in the optical, UV, and IR has proved to be unique. We have observed both slow and fast novae, both classical and recurrent, and both CNO and ONeMg outbursts. There will always be new novae to study and this review is only a progress report to be continued by data on new novae in outburst.

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