2. MODELS OF OBSERVATIONS

THE IONIZATION OF NOVAE EJECTA

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ABSTRACT. Novae ejecta pass through four distinct phases of evolution of the emission-line spectrum, caused by different ionization characteristics of the shell. These include a neutral (I), an auroral (II), a coronal (III), and a nebular (IV) phase. Photoionization from the contracting photosphere of the hot white dwarf is the source of the ionization, including the highly ionized coronal phase. Changing emission line ratios in certain novae that develop dust are caused by condensation of grains from the gas, and can be used to determine the composition of the dust. In V1370 Aql, substantial silicate grain formation appears to have taken place, probably within the ionized gas.

INTRODUCTION

Novae outbursts are among the few astronomical events that evolve in a time-scale over which they can be studied directly. The evolution of most other phenomena requires the study of many objects, each at a different stage of evolution, from which the evolution of a single object is then pieced together. Thus, novae offer an opportunity to directly observe certain processes which otherwise might remain poorly misunderstood, e.g., the evolution of surface nuclear reactions, and the formation of dust. Relatively few novae have been followed systematically over a long period of time after outburst because of the persistence required to consistently obtain data for many years. So, although the fundamentals of ejecta ionization are understood, there are very few studies in which detailed physical conditions have actually been calculated for different times.

Novae eject a shell of material with mass $M_{sh} \sim 3\text{x}10^{-5}\ M_\odot$ (Cohen and Rosenthal 1983), leaving behind a hot degenerate primary which continues to experience mass loss. The nuclear reactions do not shut down immedidiately because the initial mass ejection does not completely remove the energy-producing layer on the white dwarf surface. Thus, continued energy generation occurs near the Eddington luminosity (Sparks, Starrfield, and Truran 1978), and drives a wind which in turn serves to remove the outer layers until a shut down of the nova reactions eventually occurs (Bath and Shaviv 1976). The turn-off time varies widely for novae, from months to years, and is determined by parameters such as the white dwarf mass and the composition and mass of the unejected outer envelope (Starrfield et al. 1989).

After the outburst, the degenerate primary is left with a photosphere that is initially much larger than the white dwarf radius, but which gradually shrinks toward the surface from the effect of the continued mass loss (Prialnik 1986). Until the nova terminates nuclear burning and the luminosity drops below $L \sim L_{edd}$, the usual definitional relationship between luminosity, photospheric radius R, and effective temperature T_{rad} of the remnant requires that

$$T_{rad} \approx 9 \times 10^4 \left(\frac{R}{R_\odot}\right)^{-1/2} \mathrm{K}. \qquad (1)$$

Thus, as the photosphere approaches the degenerate surface at $R \sim 10^{-2}\ R_\odot$, the ionizing radiation is characterized by temperatures near $T_{rad} \sim 10^6$ K (MacDonald, Fujimoto, and Truran 1985). Normally, nova turn-off does not occur until such temperatures are achieved, which explains the common appearance of coronal emission lines in novae. However, novae can turn-off while the photosphere is still extended. Such was likely the case with V1668 Cyg 1978, which showed little evolution in the emission line spectrum and did not show evidence for particularly high ionization (Stickland et al. 1981).

The basic ionization characteristics of novae ejecta derive from the constantly expanding shell of decreasing density which is photoionized by a central radiation source whose temperature steadily increases from the constant luminosity and decreasing radius until it turns off. Thus, the level of ionization generally increases with time until the luminosity drops, at which point the emission spectrum of the ejecta becomes difficult to detect against the continuum of the remnant. There is little convincing evidence that collisional ionization is important in novae ejecta. The shell around GK Per may be an exception to this in that it has a spectrum similar to that of an old supernova remnant.

The ionization evolution of ejecta is deduced directly from the emission line spectrum, and since different types of lines are seen in the various regions of the spectrum, it is important to observe the UV, optical, and IR spectra together. This coordination of satellite and ground-based observations is essential because reliance on just one of the spectral regions gives an incomplete picture of what is happening. All of the low-excitation lines of C, N, O, Ne, Mg, etc., which appear in the optical are forbidden lines, thus their presence is strongly dependent upon the shell density. The low-excitation IR lines are high ionization forbidden fine-structure transitions from heavy elements, so they are sensitive to both the ionization and density of the ejecta. The lowest excitation permitted lines of most elements occur in the ultraviolet, and these are not affected by collisional de-excitation. On the other hand, lines of the very highly ionized species (which are forbidden lines) are not as common in the UV as in the optical or IR, and so highly ionized elements are best monitored at the longer wavelengths. The most valid study is therefore one which follows all three spectral regions in time through the decline.

The study of novae ejecta has intensified since the interest generated by the bright outburst of V1500 Cyg in 1975, and by the opening up of the UV spectral region shortly thereafter by the IUE satellite. Spectral studies have been made of many of the brighter novae since that time, mainly to determine element abundances, and these are reviewed elsewhere in this volume. Most of the abundance studies have concentrated on the spectra for a single date, analyzing in detail the state of a nova at one particular epoch. Thus, actual time-dependent calculations of the ionization of novae ejecta have been performed for only very few objects. The most notable exceptions are (a) the analysis of V1500 Cyg by Ferland and Shields (1978), who had no UV information available since it was before the launch of IUE; (b) the Stickland et al. (1981) study of V1668 Cyg during the first year after its outburst; and (c) the Snijders et al. (1987) study of V1370 Aql, although they analyze optical data on only one date. Following its outburst in 1983, the nova GQ Mus has been followed in detail in the optical, UV, and IR by Krautter and co-workers (Krautter et al. 1984; Krautter and Williams 1989). Its development has been very interesting, and a description of the evolution of the nova is in progress.

PHASES OF SPECTRAL EVOLUTION

The emission spectra of post-outburst novae pass through several characteristic phases which reflect the changing conditions in the ejecta. When ejecta become optically thin in the continuum in a wavelength region, the spectrum changes to an emission-line spectrum. This usually occurs within a few days of the outburst at shell densities of $N_e \sim 10^{11-12}$ cm^{-3}, although it is dependent on the wavelength regime and ejecta mass. Since optical forbidden transitions suffer collisional de-excitation for electron densities $N_e \geq 10^8$ cm^{-3}, they are usually not initially present in the spectrum. Rather, optical and UV permitted lines and UV intercombination lines appear first, until the shell density drops.

The nova shells are initially ionization-bounded because of high density, i.e., they are optically thick and completely absorb all ionizing radiation, so the ionization is stratified, and an outer zone of neutral gas exists early after the outburst. Neutral and low-ionization permitted lines are prominent at this time, such as O I λ1302, C II λ1335, and optical Fe II lines, although ionized lines such as C IV λ1549 are also present. The condition that a nova shell be surrounded by an outer neutral zone requires that it absorb all ionizing photons from the central remnant, or that (Osterbrock 1989)

$$\int_{\nu_H}^{\infty} \frac{L_\nu}{h\nu}\, d\nu < N_e N_{H^+}\ \alpha_B^H \epsilon \tfrac{4}{3}\pi R_s^3 \ , \qquad (2)$$

where L_ν is the ionizing luminosity, α_B^H is the hydrogen excited-state recombination coefficient, ϵ is the volume filling factor, and R_s is the ejecta shell radius. If we assume that the white dwarf radiates at the Eddington luminosity with an effective temperature $T_{rad} \geq 6\text{x}10^4$ K, so that much of the radiation is above the H ionization limit, and that the ejecta mass is

$$M_{sh} = N_{H^+} m_H \epsilon \tfrac{4}{3}\pi R_s^3 \ , \qquad (3)$$

then the condition for an ionization-bounded shell is

$$\frac{L_{edd}}{h\nu_H} \leq N_e \alpha_B^H \frac{M_{sh}}{m_H} \ , \qquad (4)$$

which requires that $N_e \geq 10^9$ cm^{-3} for an ejecta mass of $M_{sh} = 3\text{x}10^{-5}\ M_\odot$. This indicates that novae lose their neutral outer layer, becoming less stratified and more highly ionized, at about the same densities at which optical forbidden lines appear, for typical ejecta masses. The strongest indicator of the optically thick, ionization-bounded phase of nova shells is the presence of the O I $\lambda\lambda$1302, 8446 lines in emission, which are usually strong early in novae spectra because they are excited by resonance fluorescence of Ly-β photons trapped by the neutral hydrogen zone (Strittmatter et al. 1977).

As the shell expands, decreasing density causes the ionized fraction of the ejecta to increase until the neutral zone disappears. This typically occurs near the critical densities of forbidden lines, i.e., those densities for which radiative and collisional de-excitations of the transitions are comparable. Auroral transitions between the excited levels of terms of the p^2, p^3, and p^4 electronic configurations have higher transition probabilities, and therefore critical densities, than the corresponding nebular transitions involving the ground states. Thus, as the density decreases, auroral lines such as [O I] λ5577, [N II] λ5755, [O III] λ4363 appear with greater strength than nebular transitions such as [O I] λ6300, [N II] λ6584, and [O III] λ5007, even though the latter lines have lower excitation potentials. This auroral phase of the spectra usually lasts a relatively short time, as the auroral lines steadily weaken relative to the nebular lines. The differences between the critical densities of nebular and auroral transitions become smaller at higher effective nuclear charge, so the presence of strong auroral lines is a feature that occurs at low-to-moderate levels of ionization.

For all ejecta densities less than $N_e \approx 10^7$ cm^{-3}, the optical and IR spectra of novae are dominated by forbidden lines. The IR lines are generally fine-structure transitions among the ground states of the p, p^2, p^4, and p^5 electron configurations, e.g., [Ne II] λ12.8μ, [Si VI] λ1.96μ, whereas the optical and UV forbidden lines are transitions involving excited levels, e.g., [O III] λ5007, [Ne III] λ1815. If the ionization is high, some of the transitions are similar to those seen in the solar corona. This occurs when the ionizing radiation is characterized by temperatures $T_{rad} \geq 10^6$ K. For lower temperatures the ionization level is similar to that found in planetary nebulae. During both the coronal and nebular phases collisionally excited permitted lines are also prominent, and these occur primarily in the UV. Resonance and intercombination lines such as N V λ1240, C IV λ1549, and O III] λ1663 appear shortly after the outburst and usually remain strong through all of the different spectral phases.

The level of ionization and the nature of the emission spectrum are dependent upon T_{rad} and the shell density N more than any other parameters, so it is instructive to describe the evolution of the ejecta in terms of these quantities. The degree of ionization is determined primarily by T_{rad} of the central remnant, while the types of emission transitions observed are dependent upon the gas density. Fig. 1 describes the evolution of several novae from shortly after outburst to turn-off in terms of these paramaters. Each of the four spectral phases occupies a distinct region in the diagram. Normally, ionization is moderate when emission lines first appear, with permitted and intercombination lines being dominant: O I, C II, C IV, N IV], N V, and Fe II (Phase I: neutral phase). As the density decreases, the ejecta become completely ionized, and lines such as [N II] λ5755 appear (Phase II: auroral phase). As the density drops further, other forbidden

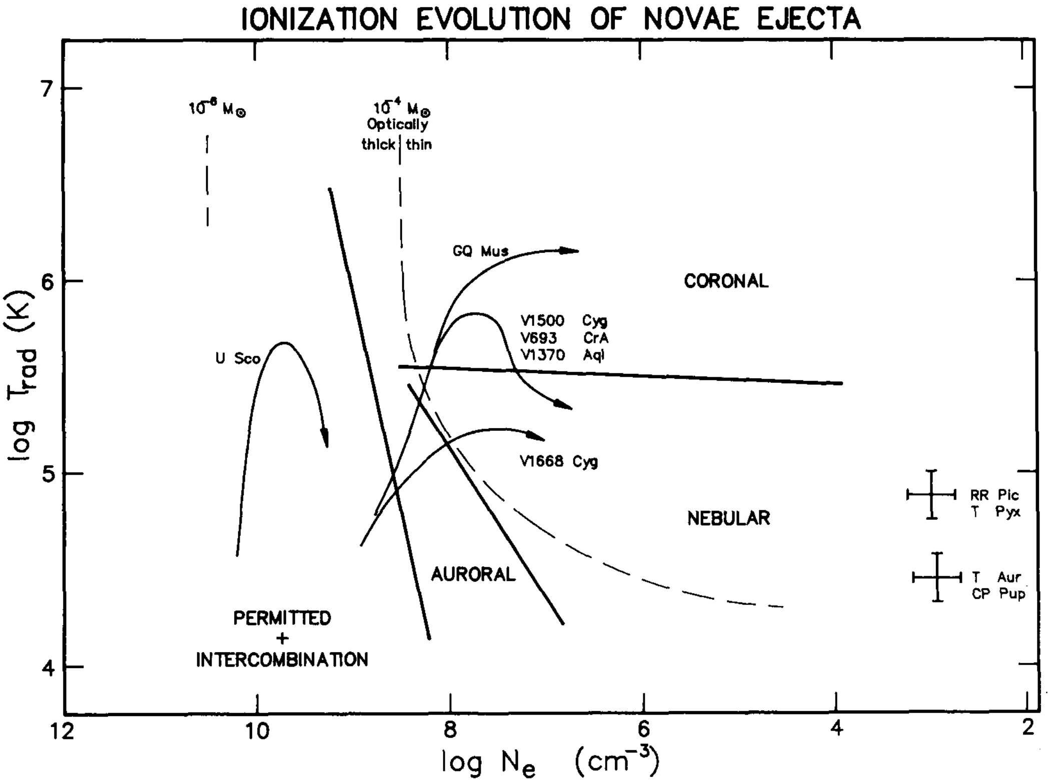

Fig. 1 - Schematic representation of novae ejecta evolution in terms of the ionization and the emission spectrum. The different phases of evolution which characterize the emission spectra are demarcated. The dashed lines denote the boundary at which the ejecta change from being optically thick to being optically thin to ionizing radiation , i.e., from having an outer neutral zone to being fully ionized. The densities at which this occurs depend on the shell mass (eqn. [4]). Some novae (U Sco) evolve so fast that return to quiescence occurs before forbidden lines are observed. Most nova remnants achieve sufficiently high photospheric temperatures and low shell densities that coronal lines appear (V1370 Aql, GQ Mus). Others do not achieve high temperatures, and have a line spectrum more characteristic of galactic nebulae (V1668 Cyg). Old novae with spatially resolved shells (T Pyx, CP Pup) are observed to have low to moderate ionization, which is either a relic of the outburst or excited by the continuum from the re-established accretion process.

lines appear and these frequently include UV, optical, and IR coronal lines, such as [Fe X] λ6374, [Al IX] λ2.04μ, [Mg IX] λ2953 (Phase III: coronal phase). However, if the white dwarf photospheric temperature remains below $T_{rad} \sim 10^5$ K, the stronger lines more closely resemble those of planetary nebulae: [O III] λ5007, [Ne V] λ3426 (Phase IV: nebular phase). The spectra retain this character as the novae decline until the termination of nuclear burning.

IONIZATION OF CORONAL LINES

Many novae pass through a phase in which they emit some of the highly ionized emission lines seen in the solar corona, such as [Fe X] λ6374 and, less frequently, [Fe XIV] λ5303 (McLaughlin 1953). The development of IR detectors has enabled the coronal phase of novae to be followed via fine-structure transitions from ions which do not emit in the optical. Emission from [Mg VIII], [Si IX], and [Al IX] was originally discovered in V1500 Cyg by Grasdalen and Joyce (1976), and the same lines have again been detected in QU Vul by Greenhouse et al. (1987). With the advent of the IUE the UV has also become accessible, and ultraviolet emission lines from [Al VIII] and [Si IX] were observed in V693 CrA (Williams et al. 1985).

By analogy with the solar corona, it has often been assumed that the coronal lines in novae originate in a hot ($T_e \approx 10^6$ K) gas. There are no compelling reasons that this is the case. On the contrary, there are several facts that suggest that the coronal gas is photoionized to its high ionization state, while retaining a relatively low nebular electron temperature of $T_e \sim 10^4$ K. A priori, ionization by either collisions or photoionization from the nova remnant are capable of causing high ionization. The ejecta are expelled at velocities of $\sim 10^3$ km/sec which through interaction with surrounding interstellar medium can generate temperatures of the order of $T_e \geq 10^7$ K. This is in excess of that needed to produce the coronal lines, and would certainly cause [Fe XIV] to appear as often and as strong as [Fe X]. Alternatively, the fact that the degenerate remnant continues to radiate near the Eddington luminosity provides an explanation for a hot, central ionizing source with $T_{rad} = 10^6$ K [cf. eqn (1)], as the photosphere contracts toward the white dwarf surface. This, also, can explain the steady increase in ionization experienced by most novae ejecta until a coronal phase is arrived at.

Although both collisional ionization from hot plasma and photoionization from a central source are capable of producing the coronal phase, there are important differences in the characteristics of each. Since photoionization can only achieve $T_{rad} \sim 10^6$ K, the exponential drop-off in the Planck function at higher frequencies than $h\nu \approx kT_{rad}$ should produce a well defined upper limit to the ionization near 10^2 eV, whereas collisional ionization should occur to energies $\sim 10^3$ eV. More importantly, the excitation and ionization temperatures should be similar from collisional ionization, whereas they are not coupled in photoionization. Thus, collisional ionization of the coronal lines should excite emission lines with $\chi_{exc} \geq 10^2$ eV, as is the case in the solar corona, where some of the stronger lines have upper levels ~ 50 eV above the ground state. On the other hand, photoionization usually results in kinetic gas temperatures around $T_e \sim 10^4$ K. In this case, collisional excitation does not produce strong lines from upper levels greater than 10 eV above ground state, and this fact can be used as a discriminant between the two alternatives.

There are only two novae for which coronal lines have been observed sufficiently well to provide information on the temperature of the emitting gas. V693 CrA briefly passed through a coronal phase in which [Mg VII] λ2629 appeared with sufficient strength such that if it were collisionally ionized, the higher excitation auroral transition [Mg VII] λ2262 should also have been detected. It was not detected, and its absence requires that $T_e \leq 5\times10^4$ K (Williams et al. 1985). More recently, GQ Mus has developed very strong coronal lines in the visible, such that [Fe X] λ6374 is now the strongest line in the spectrum (Krautter and Williams 1989). In the solar corona a higher excitation line [Fe X] λ3454 appears at roughly 20% the intensity of λ6374 (Mason and Nussbaumer 1977; Jefferies et al. 1971; Magnant-Crifo 1973), and therefore it should be one of the stronger lines in GQ Mus if the ionization and excitation are both collisionally caused. It is not observed, and its absence requires that $T_e \leq 2\times10^5$ K, which although not a low upper limit, is still sufficient to rule out a thermal origin for the Fe^{+9} ionization.

The evidence in favor of photoionization of the coronal line region thus consists of (a) the presence of a central ionizing radiation field with $T_{rad} = 10^6$ K; (b) the general weakness of [Fe XIV] together with the strength of [Fe X], which is difficult to explain from collisional ionization but a natural consequence of (a); and (c) the low gas temperatures required by the absence of any collisionally excited lines with $\chi_{exc} \geq 10$ eV. Thus, in spite of the high velocities of the ejecta, there is no solid evidence that this energy of expansion is converted into thermal energy in the gas.

EMISSION LINES AND DUST FORMATION

The precipitation of dust from the gaseous ejecta of novae during the months after outburst is well documented (Gehrz 1988), in spite of the apparently hostile environment. Dust usually forms soon after the outburst when the ejecta have a substantial neutral component, although IR emission has been observed to appear suddenly more than a year after outburst, and it could in some cases represent the illumination of pre-existing dust. The chemical composition of dust is difficult to ascertain, but observed emission features in the IR have been interpreted either in terms of carbon/graphite grains or silicates. Changes in the emission line intensities during the formation of the dust may provide a direct means of determining which elements are condensing out of the gas. Thus, novae may offer the best means of observing the composition and process of formation of dust grains.

The largest effects of dust formation are likely to be found in those novae which have developed optically thick dust shells. Of the five such novae known, only one has occurred within the last decade and was well observed in both the optical and the UV: V1370 Aql (Rosino et al. 1983; Snijders et al. 1987). On the basis of their emission-line analysis, Snijders et al. concluded that the ejecta gas had very enhanced N and Ne abundances 156 days after the outburst, but that C, O, Mg, Si, and Fe were depleted from their solar values with respect to the N and Ne. These elements were assumed to have condensed into grains.

IR data over the period 50-276 days following outburst indicated strong 3μ and 10μ emission features with luminosities roughly equal to the luminosity of the nova at outburst (Gehrz et al. 1984; Williams and Longmore 1984). Gehrz et al. rejected silicate grains because of the absence of a 20μ stretching feature, and concluded that the 10μ peak was due to SiC grains, which tend to condense in a carbon-rich environment ($C/O > 1$). On the other hand, Williams and Longmore (1984), Bode et al. (1984), and Roche et al. (1984) ascribed the IR emission bumps to silicates. Whatever the grain composition, considerable formation had already occurred by day 50 after outburst, and therefore the gas phase abundances derived by Snijders et al. on day 156 could indeed reflect the effects of grain formation.

Extensive gas phase depletions might be detectable during the condensation process from changes in line fluxes, although care must be taken to distinguish between changes due to ionization, density, and temperature of the gas, and those due to decreased gas abundances from dust formation. A comparison of relative line intensities of similar transitions from different ions is useful in this regard. Such data exist for the optical from days 37-240 (Rosino et al. 1983) and for the ultraviolet from days 29-156 (Snijders et al. 1987). Since extensive dust formation had already occurred by day 37, the available optical and UV spectra could only show evidence for additional dust condensation past this time.

From studying the series of optical spectra presented by Rosino et al., there is nothing striking about the spectral changes, although the spectra are uncalibrated density tracings of photographic spectra so they do not have uniform signal-to-noise. There is a suggestion of a gradual weakening in time of [O III] λ5007 with respect to [Ne III] λ3869, but this is not established with certainty because of noise in the data. On the other hand, the UV spectra from IUE presented by Snijders et al. (1987) are more uniform in quality, and one can see a definite trend in several line ratios that is unusual in novae. Specifically, the relative intensities of Si IV + O IV] λ1402/N IV] λ1486 and O III] λ1663/N III] λ1750 decrease markedly with time over the interval day 29-156 (cf. Snijders et al. 1987, Fig. 1). This is in contrast to other novae for which UV data have been obtained. These two line ratios usually appear to be more constant as the spectra evolve in novae which did not form optically thick dust shells, as was observed in V1668 Cyg (Stickland et al. 1981), GQ Mus (Krautter et al. 1984; Krautter and Williams 1989), PW Vul and QU Vul (Starrfield and Snijders 1987).

Apart from changes in the gas phase abundances, the Si IV + O IV]/N IV] and O III]/N III] ratios should not vary with changes in temperature, density, or ionization. The lines in each ratio have similar excitation potentials, collisional de-excitation critical densities, and ionization potentials, so there is no other straightforward reason to account for substantial variations with time. This is consistent with the general evolution of these line ratios in other novae, where no large variations have been observed. Of all the novae studied in the UV, only in V1370 Aql is there a clear, systematic decrease in the two line ratios. Since this nova is the only one of those studied to have developed an optically thick dust shell, the systematic decline in the strengths of Si IV + O IV] and O III] with respect to the nitrogen lines can be attributed to the precipitation of these elements into dust grains -- presumably, silicates.

Dust first appeared in V1370 Aql near day 40, as evidenced by strong IR emission. At this early date, substantial condensation of either carbon-rich (Gehrz et al. 1984) or oxygen-rich (Roche et al. 1984) gas, including Fe (Snijders et al. 1987) had already occurred. Whatever the composition of the early dust, the subsequent decline in the Si and O lines relative to N and C suggest substantial silicate formation after that time. The fact that moderately ionized species such as Si^{+3}, O^{+3}, and O^{+2} showed the decline indicates that the dust may have condensed within the ionized gas and not in neutral, sheltered regions, although alternative explanations are possible.

Different scenarios to explain the changing line fluxes can be constructed in which the dust forms in either the neutral or the ionized region of the ejecta. Consider first the situation in which the grain condensation occurs in the neutral gas, as one would a priori expect to be the case. The ejecta at day 30 might be very much ionization-bounded such that the ionized gas comprises only a small fraction, say 15%, of the entire ejecta. Suppose dust formation takes place only within the neutral gas, and not in the ionized region where the emission lines are formed. As decreasing density and increasing radiation temperature cause the ionized regions to expand into the neutral gas, dust enriched, gas depleted material is increasingly incorporated into the emitting gas, causing decreasing Si IV + O IV]/N IV] and O III]/N III] ratios. When the ejecta eventually become completely ionized, e.g., around day 156, the elements depleted by the grains would then exhibit decreased intensities by a factor of around 5, which is the order of the changes observed in the above line ratios (Snijders et al. 1987).

Although tractable, the above picture should also possess certain other characteristics. First, one would expect a strong O I λ1302 line that slowly decreases in intensity. In fact, the O I is never strong, but perhaps its excitation is prevented because Ly-β scattering is quenched by absorption by the dust. Secondly, in order to maintain the depletions, the dust must obviously survive once it becomes immersed in the ionized gas. Thirdly, if the luminosity remains near L_{edd} with increasing radiation temperature, one should see an increasing equivalent width of He II λ1640 since the ejecta are absorbing all of the incident ionizing radiation (Zanstra 1931). This is not what is observed for the first 3 months, since λ1640 weakens until day 115. This latter point is especially bothersome for any model in which the V1370 Aql ejecta are required to have a neutral component as the Si and O lines decrease relative to the N lines.

The alternative possibility is that the ejecta are fully ionized during the period of dust formation, and therefore the grains precipitate out of the ionized gas. Apart from requiring the condensation to take place in a more hostile environment, this picture offers the more straightforward interpretation of the line ratios. The absence of strong O I λ1302 and the steady decline in the equivalent width of He II λ1640 do suggest that the ejecta lack a neutral zone and are optically thin to ionizing radiation, absorbing a decreasing fraction of the radiation as they expand. As Si and O condense into grains, the line fluxes from these elements decrease. The increasing equivalent width of λ1640 after day 100 can be attributed to either a hardening radiation field which causes a higher level of ionization of He^+, or to a lower luminosity which allows the ejecta to absorb a larger fraction of the ionizing radiation.

Without more detailed models of the evolution of the ejecta, it is difficult to establish with certainty whether the dust is formed in neutral or in the ionized gas. However, the behavior of He II λ1640 does not support the presence of a substantial component of neutral gas in V1370 Aql, and therefore the emission line behavior in this nova may be a signal that the formation of dust within ionized gas is a possibility that should be considered seriously in astronomical environments.

SUMMARY

Ionization calculations of individual novae ejecta have been used to derive element abundances from the emission line spectra. From these a general picture of the evolution of post-outburst novae has emerged. More detailed information awaits the construction of a series of models over time for particular objects including calculations during each of the four major phases of the emission spectrum. The available evidence points to photoionization as the cause of the coronal lines in novae, a natural outcome of Planckian radiation at the Eddington luminosity on the surface of a white dwarf. The changes in line fluxes in novae which form dust offer the possibility of direct observation of condensation into grains. The next nova which develops an optically thick shell should be observed extensively in all spectral regions in order to see if element depletions occur and if further evidence indicates that grain formation occurs within ionized gas.

REFERENCES

Bath, G.T., and Shaviv, G. 1976, MNRAS, **175**, 305.

Bode, M.F., Evans, A., Whittet, D.C.B., Aitken, D.K., Roche, P.F., and Whitmore, B. 1984, MNRAS, **207**, 897.

Cohen, J.G., and Rosenthal, A.J. 1983, Ap.J., **268**, 689.

Ferland, G.J., and Shields, G.A. 1978, Ap.J., **226**, 172.

Gehrz, R.D. 1988, Ann. Rev. Astr. Ap., **26**, 377.

Gehrz, R.D., Ney, E.P., Grasdalen, G.L., Hackwell, J.A., and Thronson, H.A. 1984, Ap.J., **281**, 303.

Grasdalen, G.L., and Joyce, R.R. 1976, Nature, **259**, 187.

Greenhouse, M.A., Grasdalen, G.L., Hayward, T.L., Gehrz, R.D., and Jones, T.J. 1987, Astron.J., **95**, 172.

Jefferies, J.T., Orrall, F.Q., and Zirker, J.B. 1971, Solar Phys., **16**, 103.

Krautter, J. et al. 1984, Astr.Ap., **137**, 307.

Krautter, J., and Williams, R.E. 1989, Ap.J., **341**, in press.

MacDonald, J., Fujimoto, M.Y., and Truran, J.W. 1985, Ap.J., **294**, 263.

Magnant-Crifo, F. 1973, Solar Phys., **31**, 91.

Mason, H.E., and Nussbaumer, H. 1977, Astr.Ap., **54**, 547.

McLaughlin, D.B. 1953, Ap.J., **118**, 27.

Osterbrock, D.E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: University Science), p. 21.

Prialnik, D. 1986, Ap.J., **310**, 222.

Roche, P.F., Aitken, D.K., Whitmore, B. 1984, MNRAS, **211**, 535.

Rosino, L., Iijima, T., and Ortolani, S. 1983, MNRAS, **205**, 1069.

Snijders, M.A.J., Batt, T.J., Roche, P.F., Seaton, M.J., Morton, D.C., Spoelstra, T.A.T., and Blades, J.C. 1987, MNRAS, **228**, 329.

Sparks, W.M., Starrfield, S.G., and Truran, J.W. 1978, Ap.J., **220**, 1063.

Starrfield, S.G., and Snijders, M.A.J. 1987, in Exploring the Universe with the IUE Satellite, ed. Y. Kondo (Dordrecht:Reidel), p. 377.

Starrfield, S.G., Truran, J.W., Sparks, W.M., and Krautter, J. 1989, in EUV Astronomy, ed. R. Malina (in press).

Stickland, D.J., Penn, C.J., Seaton, M.J., Snijders, M.A.J., and Storey, P.J. 1981, MNRAS, **197**, 107.

Strittmatter, P.A. et al. 1977, Ap.J., **216**, 23.

Williams, P.M., and Longmore, A.J. 1984, MNRAS, **207**, 139.

Williams, R.E., Ney, E.P., Sparks, W.M., Starrfield, S.G., Wyckoff, S., and Truran, J.W. 1985, MNRAS, **212**, 753.

Zanstra, H. 1931, Pub. Dom. Ap. Obs., **4**, 209.