ELEMENT ABUNDANCE ANALYSES OF NOVAE

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ABSTRACT

The different methods by which element abundances in novae have been determined are reviewed. Curve of growth studies of novae at maximum light have indicated CNO nuclei to be greatly enhanced with respect to hydrogen in certain objects. These results are questionable because they depend upon an assumed temperature distribution in the photosphere which is probably too steep to be realistic. Emission line analyses of novae, generally obtained in the period of early decline, also indicate possible heavy element enhancement, however these results are tentative because of uncertainties in the parameters of the emitting gas. It is suggested that useful abundance determinations of nova ejecta might be obtained from studies of old, extended nova shells.

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1. INTRODUCTION

Much of the interest in novae is generated by the possibility that they may contribute to the enrichment of the Galaxy in certain elements. The exact role of novae in the build-up of heavy elements is unclear because of large uncertainties in the abundances and masses of nova ejecta and the relative importance of competing objects and processes which also contribute to chemical enrichment. However, if the nova outburst is due to explosive nuclear energy generation in an advanced phase of stellar evolution, the material returned to the interstellar medium is almost certainly depleted in hydrogen and enriched in other elements.

In the past several years, a renewed interest in the nova phenomenon has occurred as a result of theoretical studies which have shown that certain characteristics of the outburst can be accounted for by the nuclear burning of material which has accreted onto a degenerate white dwarf. Starrfield, Truran, and Sparks (1977, and references therein) have published a series of papers in which they have modelled the nova outburst in terms of an evolving member of a close binary system which overfills its Roche lobe and loses mass onto a companion white dwarf. The gas spirals in toward the star, forming an accretion disk around it. A certain fraction of the disk material reaches the surface of the degenerate star (assumed to be a carbon-oxygen white dwarf), building up a layer of hydrogen-enriched material on the surface. Eventually, compression of the accreting gas causes heating to temperatures at which nuclear burning commences, and an outburst occurs. According to the calculations, the rate of the nuclear burning is sensitive to the CNO abundances on the surface of the white dwarf. If the CNO nuclei are enhanced in the envelope, a thermonuclear runaway occurs, producing a fast nova. If the CNO abundances are more nearly normal, a slow nova results.

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The thermonuclear reactions of the CNO cycle do not produce an enrichment of CNO nuclei, however they do cause a redistribution of the isotopes if the reactions do not occur in equilibrium. The CNO enrichment required for a thermonuclear runaway to occur must have already been present before the outburst, having been produced by the earlier evolution of the binary system. The nova models of Starrfield et al. (1977) specifically predict the isotopic ratios of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ to exceed solar values by factors of $\sim$100. Sneden and Lambert (1975) have pointed out that a spectroscopic determination of isotope ratios is possible from an analysis of molecular absorption in novae, such as the CN bands that were observed in Nova DQ Her 1934 near maximum light. Assuming different isotopic compositions, they computed synthetic spectra and compared them with the observed profiles of the CN bands in DQ Her, and concluded that the evidence supported an appreciable enhancement of ^{13}C, and probably ^{15}N also. If this result applies to other novae, then novae are probably an important source of ^{13}C and ^{15}N in the Galaxy.

Clearly, a knowledge of element abundances in novae is essential to our understanding of the nature of the outburst and late stages of stellar evolution, and also the role that novae may play in the chemical evolution of the Galaxy.

2. CHARACTERISTICS OF THE SPECTRUM AND SHELL GEOMETRY

One of the most difficult aspects of abundance determinations of novae is that they must be made from the analysis of a spectrum which is continually changing (sometimes rapidly) with time. From the time of the initial rise in luminosity from the outburst, it is questionable whether many of the processes producing the observed spectrum achieve an equilibrium. Thorough phenomenological descriptions of the development of novae spectra have been given by Payne-Gaposchkin (1957) and McLaughlin (1960), with individual objects showing such diversity and complexity that it is difficult to conveniently summarize the results. Generally, novae initially show an absorption spectrum accompanied by emission features which tends to become later in spectral type as time progresses. The blueward displacements of the absorption lines become progressively larger with time, and the lines tend to become more diffuse. As a nova declines in brightness, the absorption lines gradually weaken in contrast to the emission lines, which become more prominent relative to the continuum.

Permitted emission lines first appear immediately after maximum brightness, and almost always have associated absorption components. The Balmer lines, and Ca II, Na I, and Fe II lines are usually seen near maximum, and are followed by the appearance of various forbidden lines, such as [O I], [N II], and [O III]. The emission line profiles frequently show a blue/red symmetry which indicates that the radiation is originating in material which is symmetrically distributed in velocity about a central point of expansion. Some emission lines, such as [O III] λ4363, appear and then gradually fade away; however, most nebular lines continually strengthen in time relative to the underlying continuum. Actually, except for the brief period when they first appear, the lines steadily decrease in absolute intensity, however they do so slower than the declining continuum.

The final stage in the spectral development of a nova is one in which all absorption has faded away, and the stellar remnant emits an essentially continuous spectrum, upon which are superimposed the emission lines characteristic of a nebula. Typically, the continua are indicative of temperatures of $\gtrsim$ 20000 K. For most novae, the emission from the ejected shell fades from visibility before the disk becomes resolvable, however, there are a few nova shells, almost all associated with the nearer novae, which have persisted long enough to allow study of their spatial structure (Mustel and Boyarchuk 1970).

The structure of the material ejected by novae may be probed in two ways: (a) spectroscopy at high dispersion allows the velocity distribution of the gas to be determined from analysis of line profiles, and (b) measurements of

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emission line fluxes from novae which have developed extended disks enable the density distribution of the gas to be determined. It appears from both types of investigation that many nova shells have a common basic structure. Mustel and Boyarchuk (1970) found from a study of photographs of the shells around DQ Her and V603 Aql 1918 taken by Baade over a long period of time that the structure of the gas was symmetrical. From a comparison of the images of each object in the emission lines of Hα, [N II] λ6584, and [O III] λ5007, they concluded that the morphology of both shells could be explained in terms of an equatorial ring (or rings) of gas and polar condensations which lie on an axis perpendicular to the plane of the ring. The ring of emitting material was assumed to lie in the plane of the binary orbits and accretion disk on the basis of symmetry. This conclusion has been confirmed for DQ Her, where the ring orientation is edge-on, in the same plane as the accretion disk, which is periodically eclipsed (Walker 1954, Kraft 1959).

Weaver (1974) has studied the time development of the shell around V603 Aql in detail from a series of spectra of the object taken at Lick and Mt. Wilson Observatories in the years following the outburst. When the disk was resolved, slit spectra were obtained of the nova at different position angles, enabling the velocity and intensity distribution of the gas along the slit to be determined. Sufficient data exist to allow a reconstruction of the shell to be made, and Weaver found that material was ejected radially from V603 Aql in truncated cones which were roughly symmetrical about the plane of the binary system. The bulk of the material was directed into a small angle centered on the accretion disk, forming an equatorial ring of material. Another concentration of material was ejected into a small cone perpendicular to the equator, forming a polar condensation.

Subsequent analyses of other nova shells have established that the equatorial ring/polar condensations geometry applies in a general sense to other objects.

Hutchings (1972) has interpreted emission line profiles of the novae HR Del 1967, Nova Vul 1968 No. 1, and FH Ser 1970 in terms of a model in which material is ejected outward in conical shells. He was able to produce acceptable fits to the data by varying the velocity and amount of material ejected as a function of polar angle, and varying the orientation of the system with respect to the sun. The distribution of material in the shells was such that in each case there was a concentration of matter in equatorial rings and/or polar blobs. Soderblom (1976) has recently obtained Coude spectra of the just resolvable disk ($\sim 2''$) of HR Del in certain emission lines, and has verified the basic geometry suggested by Hutchings for this object. A schematic representation of the nova shells is shown in Fig. 1, from the papers of Hutchings, and Mustel and Boyarchuk.

When conditions can be established in the shells from emission lines, it is usually found that the density of the material in the equatorial rings exceeds that of the polar condensations. Also, the outward velocities of the polar ejecta are normally larger than the equatorial gas. Sparks and Starrfield (1973) have proposed that both of these situations occur naturally as a result of the collision between gas ejected by the white dwarf during the outburst and the accretion disk surrounding the star, which slows the expansion in the equatorial plane.

Exceptions do occur to the shell structure discussed above. Nova GK Per 1901 is a well-known example of a nova having a very assymetric geometry; photographs by Baade demonstrated that most of the material was directed into one quadrant. Hutchings (1972) discovered that the equatorial gas is moving away from HR Del at a velocity (500 km/sec) much faster than that of the polar condensations (200 km/sec). In addition, Soderblom (1976) found that the relative intensities of the emission lines in the shell indicated a higher ionization, and therefore perhaps a lower density, in the equatorial gas. What causes this

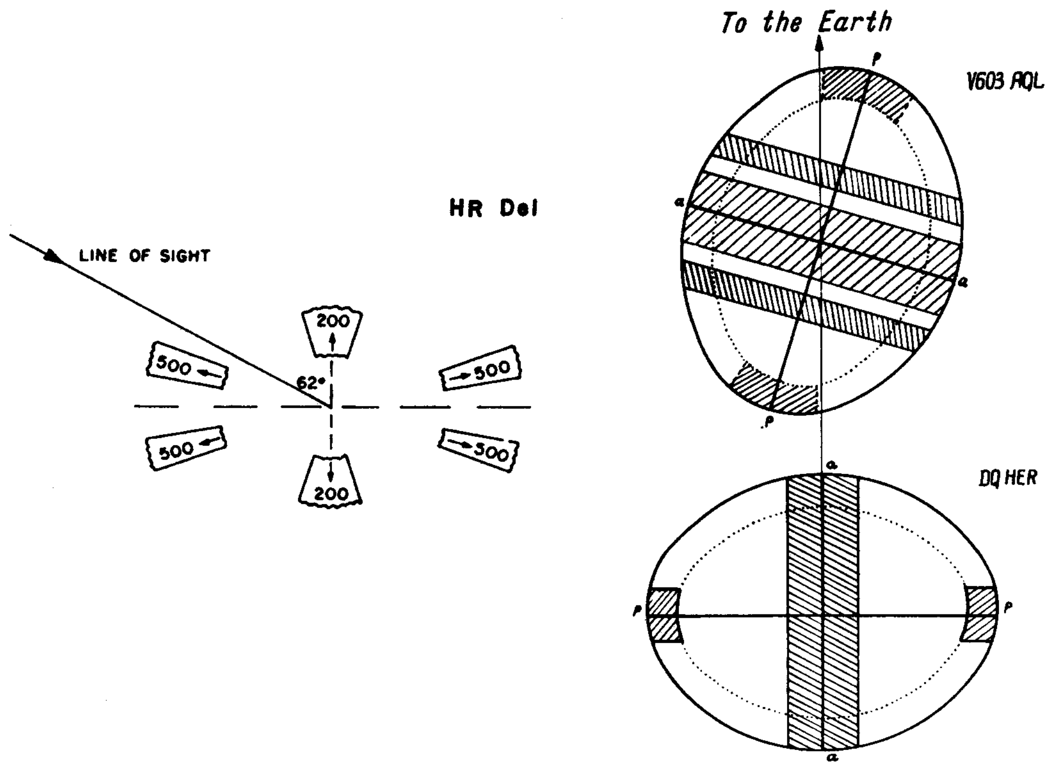

Fig. 1. Schematic representation of the geometry of nova shells. The models for V603 Aql and DQ Her are based upon monochromatic photographs, from Mustel and Boyarchuk (1970). The model of HR Del is based upon an analysis of emission line profiles, from Hutchings (1972).

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behavior in HR Del is not known. Two contrasting types of nova shells are illustrated in Fig. 2. The shell of DQ Her is very symmetrical, and completely surrounds the binary system, whereas the ejecta of the recurrent nova T CrB consist simply of two small condensations on either side of the stellar system.

3. ELEMENT ABUNDANCE ANALYSES

For objects such as novae, which show both an emission and absorption spectrum, there are two independent methods of determining element abundances: (1) a curve of growth can be constructed from the absorption lines, and (2) emission line fluxes can be computed from nebular theory according to some assumed model, and the chemical composition deduced for the emitting ions. There are many uncertainties associated with each type of analysis as applied to novae. Curve of growth analyses require at least a rough knowledge of the temperature and velocity structure of the line formation regions, and are dependent upon the validity of equilibrium relations governing excitation and ionization of the gas, such as the Boltzmann and Saha equations. Furthermore, equivalent widths of saturated lines, which are on the flat part of the curve of growth, must be determined accurately, free of any effects of blending or emission features, because small errors in the line strengths of such lines can lead to very large errors in the derived column densities. In a situation where uncertain conditions prevail, it is particularly important that equivalent width ratios of lines arising from common lower levels, i.e., multiplets, be used to establish the proper position of each line on the curve of growth.

Emission line analyses pose problems that are different from those relevant to curves of growth. A knowledge is required of every important atomic process that contributes to the excitation of a level or ionization of an element. The temperature, radiation field, and density distribution of emitting material, i.e., geometry, must be known in order to compute line

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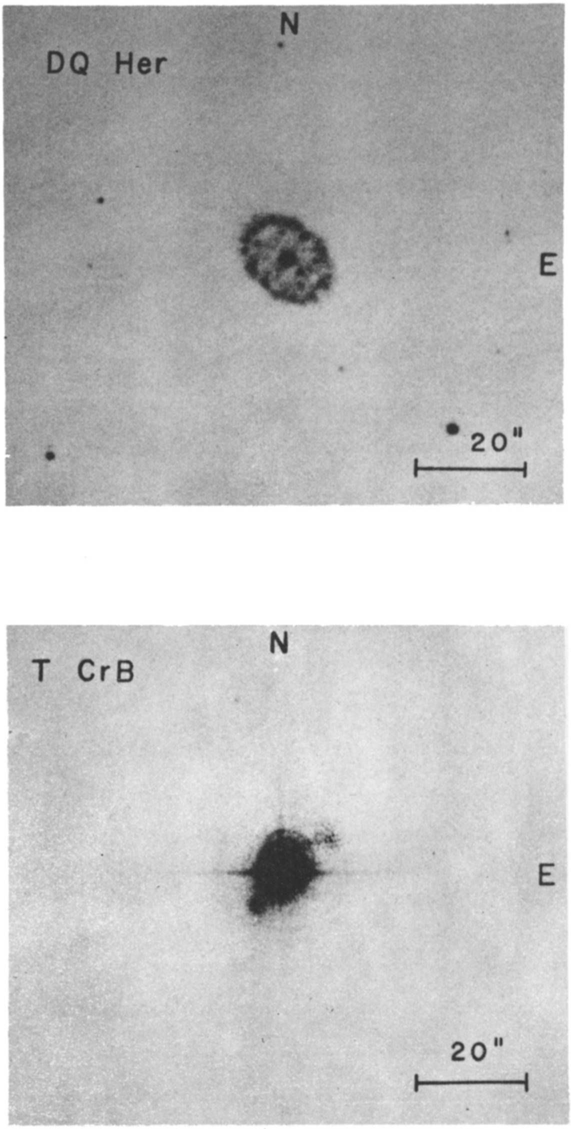

Fig. 2. Hα + N II interference filter photographs of DQ Her and the recurrent nova T CrB. The photographs were obtained with the Steward Observatory 2.3m telescope and an ITT 40-mm image tube in June 1977.

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intensities. Inhomogeneities can have a large effect upon the physical conditions and chemical composition deduced from the emission lines, and are difficult to probe in a spatially unresolved source. As a result of these complicating factors, the determination of element abundances in novae must be approached cautiously.

A. Curve of Growth Analyses

Curve of growth studies of novae have been published for the slow novae DQ Her and HR Del by Soviet astronomers, primarily by E. R. Mustel and co-workers. The most thorough analyses have been made of DQ Her, the impetus for which was an observation by McLaughlin (1937) that during a 24-hour period near maximum light, the spectrum of DQ Her resembled that of the F-type supergiant ϵ Aur. It is generally true that for a brief period near maximum light, when the absorption spectrum is changing from the pre-maximum to the principal absorption systems (nomenclature of McLaughlin), the nova spectrum does resemble that of an A or F supergiant, with the absorption lines of C I, N II, O I, and O II frequently appearing abnormally strong (McLaughlin 1960).

Abundance determinations from curves of growth for DQ Her have been obtained by Mustel and Boyarchuk (1959), Mustel and Baranova (1965), and Mustel and Antipova (1971). Additional discussions of the results and methods used in these studies are given by Antipova (1974) and Mustel (1974). The investigations are all based upon the same observational data, photographic spectra of DQ Her obtained at maximum light (22 December 1934) by G. Shain at a dispersion of 36 A/mm. Data for the comparison star, ϵ Aur, were obtained later using different instrumentation, at 24 A/mm. After corrections were made for effects which produced systematically smaller equivalent widths for the weaker lines in DQ Her because of the lower dispersion used, equivalent widths of all unblended absorption lines in each object were determined, and the lines were

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then fitted to a theoretical curve of growth computed by Minnaert and Unsöld for normal stars.

Several departures from normal procedures were required in all of the DQ Her curve of growth studies because of the relatively low dispersion used to observe the complicated spectrum. Normally, the equivalent widths of individual lines of each muliplet observed are used to construct a curve of growth for that multiplet, since the relative optical depths of all lines of a multiplet are directly proportional to their f-values. In this way the shape of the curve of growth is established for the star. Saturated lines which fall on the flat part of the curve of growth enable the microturbulent velocity V_t of the absorbing material to be determined in the region where the multiplet is formed. The curves of growth for all of the multiplets of an ion are then superposed to form a combined curve of growth which gives the strengths of all the lines of an ion in terms of the column density of that ion. This is accomplished by relating the populations of the different excited levels to the ground state through the excitation temperature T_{exc}, using the Boltzmann equation. Generally it is found that a small range of values of T_{exc} will suffice to produce a satisfactory combined curve of growth for all multiplets of all ions, unless complicating factors like non-LTE effects are present (Mihalas 1970).

In the case of Nova Herculis there were insufficient unblended lines of multiplets to allow multiplet curves of growth to be determined for most of the elements. Only for the ions Fe I, Fe II, Ti II, and Cr II were there enough lines to allow curves of growth to be constructed for an individual ion. Even then, when all the lines for each of these ions were combined into a single curve, large scatter resulted unless it was assumed that T_{exc} was not constant, but took on a large range of values depending upon the excitation potential χ

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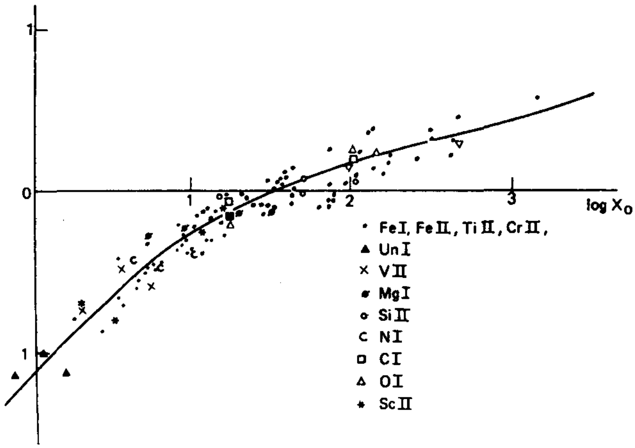

Fig. 3. The curve of growth for absorption lines in DQ Her at maximum light, from Mustel (1974).

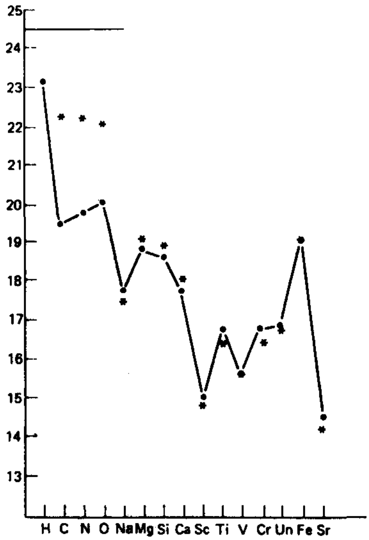

Fig. 4. Element abundances in DQ Her (asterisks) as determined from the curve of growth, compared with solar abundances. From Mustel (1974).

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of the line. An average value of V_t determined from Fe, Ti, and Cr was assumed to apply throughout the atmosphere (V_t = 19 km/sec), and the relationship between T_{exc} vs. χ deduced from these ions was assumed to apply to all other ions, and from this information the lines of all ions were used to construct a single curve of growth for the nova, as shown in Fig. 3. After allowances were made for ionization stages of elements for which no lines were observed, using Saha's equation, the chemical composition of the gas was determined. The results obtained from this procedure by Mustel and collaborators for DQ Her are presented in Fig. 4, together with solar abundances. The salient features of the graph are the large CNO abundances, relative to hydrogen for the nova, and the normal heavier element abundances. The large CNO enhancement in DQ Her is certainly a very important result, particularly if it is typical for other novae.

Element abundances in the nova HR Del have also been determined from curve of growth studies by Ruusalepp and Luud (1970), Antipova (1974), and Yamashita (1975). Little information is given in any of these papers concerning the detailed procedures used. In each case, a brief discussion of the curve of growth technique as applied to novae emphasizes the fact that the analysis is similar to that performed by Mustel and Baranova (1965) for DQ Her. The abundances derived for HR Del in the three investigations are all similar to those deduced for DQ Her, in that CNO are found to exceed solar values by substantial amounts, whereas the heavier element abundances are roughly normal. It must be noted, however, that the scatter in the results of the different investigators for the same object is appreciable, amounting to factors of over 10 for certain elements.

Critique. The conclusion from curves of growth that CNO nuclei are enhanced in novae with respect to H, whereas most heavier elements have solar abundances is a significant one. How valid is this result for the two novae that have been studied so extensively? It is the opinion of this reviewer that the curve of growth abundances published for novae must be accepted with great reservations. In the past decade, similar studies of normal F-supergiants have shown that small variations in certain parameters can have large effects on the interpretation of the curve of growth (Searle, Sargent, and Jugaku 1963, Parsons 1967, Osmer 1972). Confining our attention to the most thorough published curve of growth for DQ Her (Mustel and Baranova 1965), there are several troublesome features of it. First of all, the CNO abundances were derived from very few lines. According to Fig. 3, at most five lines were used for any of these elements, and none of the lines belong to the same multiplet. Consequently, there must be considerable uncertainty as to the correct position of the lines on the curve of growth. Most of the lines appear near the flat part of the curve, so the derived column densities are very sensitive to the assumed turbulent velocity. The value of V_t used in the calculations was derived from Fe I, Fe II, Ti II, and Cr II, and therefore may not be applicable to the lines of C I, N I, and O I, since V_t has been shown to vary with height in the atmosphere of F-supergiants (Parsons 1967).

The most critical parameter affecting the abundance analyses is the excitation temperature, particularly for those ions having observed lines originating entirely from levels with high excitation potentials (H, C, N, and O). At the temperatures characteristic of the photospheres of novae near maximum ($T \sim 7000$ K), small changes in T_{exc} can lead to very large differences in the population ratio of excited to ground levels. The absorption lines of most ions lead to column densities for the excited states only, and the correction factor necessary to provide the total ion population is a very large one for some elements. The values of T_{exc} found by Mustel and Baranova from the Fe, Ti, and

Cr lines varied from 5000 K for Fe I to 8000 K for Fe II and Cr II. They felt the evidence suggested a systematic variation of T_{exc} with the excitation potential of the level, although most of the levels of Fe, Ti, and Cr used to calibrate the relationship have $\chi \lesssim 4$ eV, so there is large uncertainty in T_{exc} for levels with larger χ. For the elements H, C, N, and O, for which all observed lines have $\chi > 8$ eV, assumed values of T_{exc} exceeded 9000 K. Lines of elements arising from levels near the ground state (mostly metals) were assigned values of $T_{exc} \sim 4500$ K. This large variation in T_{exc} is central to the analyses of abundances, since the derived ion column densities depend so sensitively upon T_{exc}. Yet, the assumed relation between T_{exc} and χ cannot be considered to have a solid basis. Not only does its validity rest upon levels with only a limited range in χ (primarily $\lesssim 4$ eV), but it has also been shown that such a steep gradient in the temperature is ruled out for normal F-supergiants. In a detailed study of F-supergiant atmospheres, Osmer (1972) found that the temperature distribution closely approximates a gray-body $T(\tau)$ relation. Assuming the effective temperature of the nova during maximum to be 7000 K, the gray-body relation would lead to a surface temperature of 5900 K, whereas the temperature at a point where the continuum optical depth is unity, above which most lines must be formed, would be $\sim$7400 K. This argues against the large temperature variations assumed by Mustel and Baranova (1965) for DQ Her, and apparently also by Antipova (1974) for HR Del. A more moderate range of values for T_{exc} would have the effect of increasing the abundances of those ions with lines with high excitation potential. In fact, precisely such an analysis was originally carried out on DQ Her by Mustel and Boyarchuk (1959), and they deduced CNO abundances _in excess of_ H.

It is difficult to evaluate just how reliable the published curve of growth abundances for novae are. It is not even clear how accurate the column densities are for the reference element H, since they were not obtained from the curve of growth, but from an independently derived relationship involving equivalent widths of the Balmer lines, electron density, and column density. Because the Balmer lines are saturated, the column density for H is sensitive to assumed broadening mechanisms for the lines, such as the Stark effect (Parsons 1967, Antipova 1971). An extensive literature exists on the subject of curves of growth for normal F-supergiants. It has been shown previously for these stars that analyses which initially indicated abundance anomalies could usually be interpreted more straightforwardly in terms of normal abundances and some previously neglected effect (Greenstein 1948; Searle, Sargent, and Jugaku 1963). This situation must certainly be applicable to novae, where the basic structure of the atmosphere is not known, in addition to being strongly time-dependent. Until such time as the absorption spectra and atmospheres of novae have been studied as extensively as those of normal supergiants, curve of growth abundance determinations, whether indicating solar or non-solar abundances, must be regarded as being very tentative.

B. Emission Line Analyses

Emission features initially appear in the spectra of novae around the time of visual maximum. At this time they are usually components associated with the stronger absorption lines, in the form of P Cygni profiles. Forbidden emission lines, which originate in the ejected envelope, appear after the visual brightness has dropped by about a magnitude. A wide range of ionization conditions is commonly observed, including the lines [O I] λ6300, [Fe VII] λ6087, and [Fe X] λ6374. Because of the large ejection velocities of the material, emission line widths are generally large, typically 15 A or so, making definite line identifications based solely on wavelength agreement a problem. Because of the extreme conditions associated with novae, it is difficult to evaluate supposed line identifications on the basis of astrophysical reasonableness.

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Consequently, numerous controversies exist over many of the lines observed. An example of this problem concerns the existence of a so-called "coronal" phase in certain novae one or two months after the outburst.

Grasdalen and Joyce (1976) monitored the 2 - 3μ spectral region of Nova V1500 Cygni 1975 after the outburst at irregular intervals. Initially, this region showed recombination lines of H and He normally expected from an ionized gas of temperature $\sim 10^4$ K. However, one month after the outburst, additional lines became visible, and within another month's time became so strong as to dominate the near-IR spectrum. It was discovered that all of these lines could be identified as highly ionized forbidden lines, similar to and including some lines seen in the solar corona. Suggested identifications included lines from the ions [Ca VIII], [Al IX], [Mg VIII], and [Si IX]. The most convincing argument in favor of these identifications was the fact that every collisionally excited fine-structure line that could be present in the spectral region observed, from any highly ionized state of an element having a normal abundance $> 10^{-6}$ that of H, was in fact observed. Grasdalen and Joyce concluded that the evidence supported the existence of a hot ($T \sim 10^6$ K), tenuous gas which developed in the nova after the outburst.

The suggestion of lines from highly ionized species occurring in novae is not new; many novae have had lines in the visible attributed to the ions [Fe VII], [A X], and [Fe X] (Payne-Gaposchkin 1957, Andrillat and Collin-Souffrin 1974). In fact, counterparts to the IR coronal lines were identified in the visible spectrum of Nova Cyg by Fehrenbach and Andrillat (1976), who observed transitions they attributed to [Fe X] λ6374, [Fe XI] λ7892, and [S VIII] λ9911. Nevertheless, Black and Gallagher (1976) disagreed with the infra-red coronal line identifications, pointing out that the observed lines could be explained without having to postulate the existence of 10^6 K gas.

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They maintained that the lines could, within the uncertainties of the wavelength measurements (due to low resolution), virtually all be identified as He I triplet transitions. They further asserted that the observed line intensities were roughly what one would expect if the He I triplet levels were populated by recombination at temperatures of $T \sim 10^5$ K, and that the evidence did not indicate the presence of a hotter gas.

More recently, Ferland, Lambert, and Woodman (1977) have reported the results of a study of V1500 Cyg in the region $0.3 \lesssim \lambda \lesssim 1\mu$, obtained with a resolution (4 A) which was capable of resolving structure in the emission lines. They confirmed the coronal identifications of Fehrenbach and Andrillat, and found that [Fe X] λ6374, [Fe XI] λ7892, and [S VIII] λ9911 all had identical profiles, which differed from the profiles of other (nebular) forbidden lines such as [O I] λ6300, [O III] λ5007, etc. Also, the time variations of these high ionization lines were all very similar, appearing and disappearing again within a several months time interval, as did the near-IR coronal lines observed by Grasdalen and Joyce. Since no alternative identifications for the lines seemed plausible, Ferland et al. concluded that the evidence strongly supported the existence of highly ionized lines which originated in a very hot component of gas early in the development of Nova Cygni.

The controversy over the existence of a coronal-type medium in Nova Cygni is a typical illustration of just one of the problems facing any emission line analysis of novae. The complexity of the spectra and large line widths make line identifications uncertain, particularly during the period of early decline. Furthermore, the envelopes do not become spatially resolved until at least several years past the outburst, making it difficult to establish a realistic geometry for the gas and properly account for the large inhomogeneities that are likely to exist in the emitting material. Because of these problems, relatively few attempts have been made to determine abundances in nova envelopes from emission lines, in spite of the wealth of data that has been acquired in recent years.

The procedure used to determine the chemical composition of nova shells from their emission spectrum is essentially the same as that employed in abundance analyses of planetary nebulae, and this subject has been reviewed recently by Collin-Souffrin (1977). Pottasch (1959) was the first to apply this now commonly used technique to nova shells. He considered the line intensities published by different observers for all novae prior to that time for which the nebular spectrum had been well-studied: V603 Aql, RR Pic 1925, GK Per, CP Lac 1936, and DQ Her. Lacking a specific knowledge of the structure of the emitting gas, Pottasch made simplifying assumptions about the conditions under which the spectrum was formed in each of the shells, and then deduced corresponding abundances for a number of elements. The heavy elements, with the possible exception of carbon, were found to be more abundant by a factor of about five relative to H, than in the sun. The helium abundances took on a range of values, $0.06 \lesssim \mathrm{He/H} \lesssim 0.32$, showing depletion in some of the novae, and enrichment in others. Subsequent to this study, Pottasch (1967) performed a similar, but much more detailed, analysis of the emission spectrum of the recurrent nova RS Oph, based upon spectra obtained at Mt. Wilson and Palomar Observatories after the 1958 outburst. The results obtained for the composition of RS Oph were consistent with those determined previously for the five novae; N/H and O/H exceeded the cosmic abundance by roughly an order of magnitude.

The spectrum of Nova Herculis 1963 was studied in its nebular phase by Doroshenko (1968). He computed the stellar temperature T_*, and the electron density and temperature as a function of time, finding that in the months following the outburst, $T_* \sim 100000$ K, $N_e \sim 10^7$ cm^{-3}, and $T_e \sim 12000$ K. These values are similar to those found by Pottasch (1959) for the five novae he studied. Doroshenko then used relations between line intensities and ion abundances derived for planetary nebulae to calculate the chemical composition of the envelope. His results showed Nova Her 1963 to have enhanced N and O abundances relative to H. A similar result was obtained by Ruusalepp and Luud (1970) from their analysis of emission lines in HR Del; they found N/H and O/H to be ten times higher than in planetary nebulae.

All of the emission studies discussed above were performed on spatially unresolved novae at moderate resolutions, and are therefore subject to the uncertainties of unknown stratification effects. The only practical way of disentangling separate emission components from different regions of an apparent point source is to use sufficiently high dispersion such that the velocity structure of the individual lines is resolved. Although this procedure does not guarantee that physically distinct regions of the gas can be identified, if a resolution can be achieved which is less than the thermal velocity of the gas individual components of emission lines at the same velocity are likely to originate from the same region. In order to resolve the separate emitting regions, Gallagher and Anderson (1976) observed the emission lines of HR Del at high dispersion, using an echelle format, and determined the relative intensities of the individual components of Hα, [N II] λ6584, and [O III] λ5007 in the (spatially unresolved) nova remnant, as shown in Fig. 5, from their paper. The basic structure of the lines consists of several velocity groupings of features, a trait common to novae, which is attributed to several major distinct emitting shells (Hutchings 1972, Malakpur 1973), as was discussed previously. Each shell consists of a number of different components (condensations), and it is clear from the data that the relative line intensities differ between the shells and condensations of gas. Gallagher and Anderson considered the various

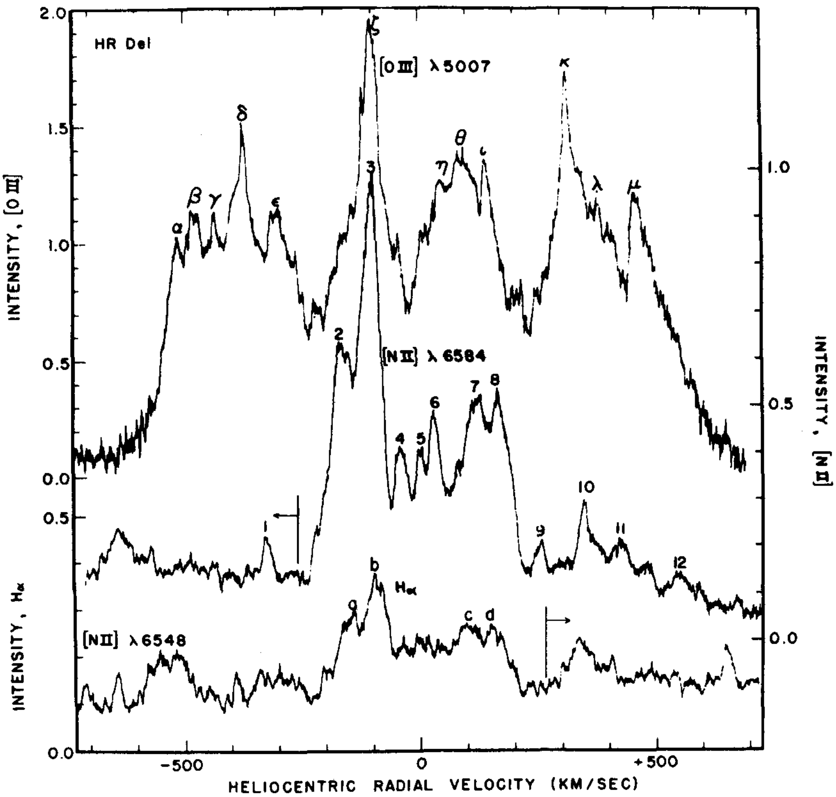

Fig. 5. Emission line profiles for HR Del, obtained at high dispersion with an echelle spectrograph/image tube combination. Note the four major velocity groupings of the lines, and the individual narrow emission components common to all of the lines. From Gallagher and Anderson (1976).

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possible conditions of density, temperature, and composition which would produce the observed fluxes, and concluded the evidence was suggestive of a nitrogen overabundance in HR Del by a factor of at least 2, compared with the solar value.

More recently, attention has focused on the He/H ratio in novae, as deduced from the recombination spectrum during the period of early decline. Collin-Souffrin (1977) has summarized the results of several investigations in which the fluxes of H and He lines were used to arrive at the helium abundance, from which she has derived an average value of He/H = 0.25, by number. Most of the work she discussed was performed without consideration of the effects of collisions or high optical depth on the line strengths. A subsequent study of the H and He lines in V1500 Cyg by Ferland (1977) has demonstrated that the Balmer lines are almost certainly influenced by strong self-absorption for months after the outburst. Not until the nova declined by 8 magnitudes did the Balmer decrement approach its purely radiative value. At that time, a solar abundance of He/H = 0.11 was derived for Nova Cyg. Prior to that time, any analysis not taking hydrogen self-absorption into account would have erroneously arrived at an anomalously high helium abundance, similar to those considered by Collin-Souffrin. A similar effect was apparently observed by Gallagher (1977) in Nova Scuti 1975, where relatively high He/H line intensity ratios occurred in the months following the outburst. Gallagher found the Balmer decrement to be non-radiative, and he speculated that the seemingly high He/H abundance that the line ratios indicated might, in fact, be normal if self-absorption were responsible for producing the non-radiative decrement.

Critique. The chemical abundances in nebulae have been studied thoroughly for many years, and are considered among the more reliably determined for objects in the Galaxy. However, there are certain differences between nebulae

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and nova envelopes which cause the composition determinations in the latter objects to be more problematical. The excitation and ionization processes in nebulae are reasonably well known, and the time-scale of nebular evolution is sufficiently long that these processes occur at equilibrium. Densities are sufficiently low that optical depths for all lines in the visible are negligible. Internal gas velocities are low, so line blending is usually not a problem. Also, gaseous nebulae are spatially resolved, so inhomogeneities can be observed and accounted for. For these reasons, it is generally believed that the composition of the more abundant elements in planetaries are known to better than factors of two. However, almost none of these conditions are applicable to novae in the period of decline. The large line widths and blending cause a situation in which as many as four different identifications are suggested for a given emission feature (cf. Gallagher 1977, Table 1). Physical conditions in the envelope change so rapidly that many of the ionization and excitation processes probably do not establish an equilibrium. Self-absorption certainly affects the intensities of prominent hydrogen and helium lines, and the high gas and radiation densities in certain lines may give rise to unusual excitation processes, as for example has been suggested for O I lines in V1500 Cyg (Strittmatter _et al_. 1977). And, as has been mentioned, the extent of inhomogeneities in density, temperature, and ionization is unknown, but they must be great, particularly when lines of ions such as [O I] and [Fe X] appear simultaneously in the spectrum.

As a result of the difficulties in interpreting the emission spectra of novae, the analyses must be considered to be suggestive of certain heavy element enhancements, but not yet conclusive. Studies of the He/H ratio give divergent results. An added complication that must be taken into account when considering the He abundance involves the discovery by Greenstein and Kraft

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(1959) that in DQ Her, He II λ4686 and the higher lines of the Balmer series go into eclipse, whereas the fluxes of the lower Balmer lines remain relatively constant in time, indicating that the He II and higher Balmer lines originate in the accretion disk rather than in the nova shell (Kraft 1959). This situation is not unlikely to also occur in other novae, and therefore the He II and some H I lines could come from entirely different components of the gas than other lines. Unless this fact is properly accounted for, spurious abundances will be deduced.

At the present time, almost no effort has been given to the study of old nova shells which are spatially resolved as a means of determining the composition of novae. Although most nova shells become too faint to study spectroscopically before they develop a resolved disk, there are several notable exceptions among some of the closer novae: DQ Her, GK Per, T Aur, and RR Pic being among them. Spectrophotometry of isolated regions in such shells is possible with modern digital photon-counting systems which allow accurate sky-subtraction, and the physical situation is perhaps more straightforward to interpret than that which prevails immediately after the outburst. By this time, shell densities are low, so self-absorption and collisional de-excitation should be unimportant. The distance between the shell and the stellar remnant and accretion disk eliminates confusion between these dissimilar environments, and the time-scale for changes in excitation and ionization is long, so conditions have stabilized, even though a true ionization equilibrium may not exist because of the low gas densities.

At Steward Observatory, we have recently begun a systematic spectroscopic study of old nova shells. An example of the data that has so far been obtained appears in Fig. 6, which shows a spectral scan of a 5" diameter region of the shell of DQ Her at the NW end of the ellipsoidal shell (cf. Fig. 2). The scan

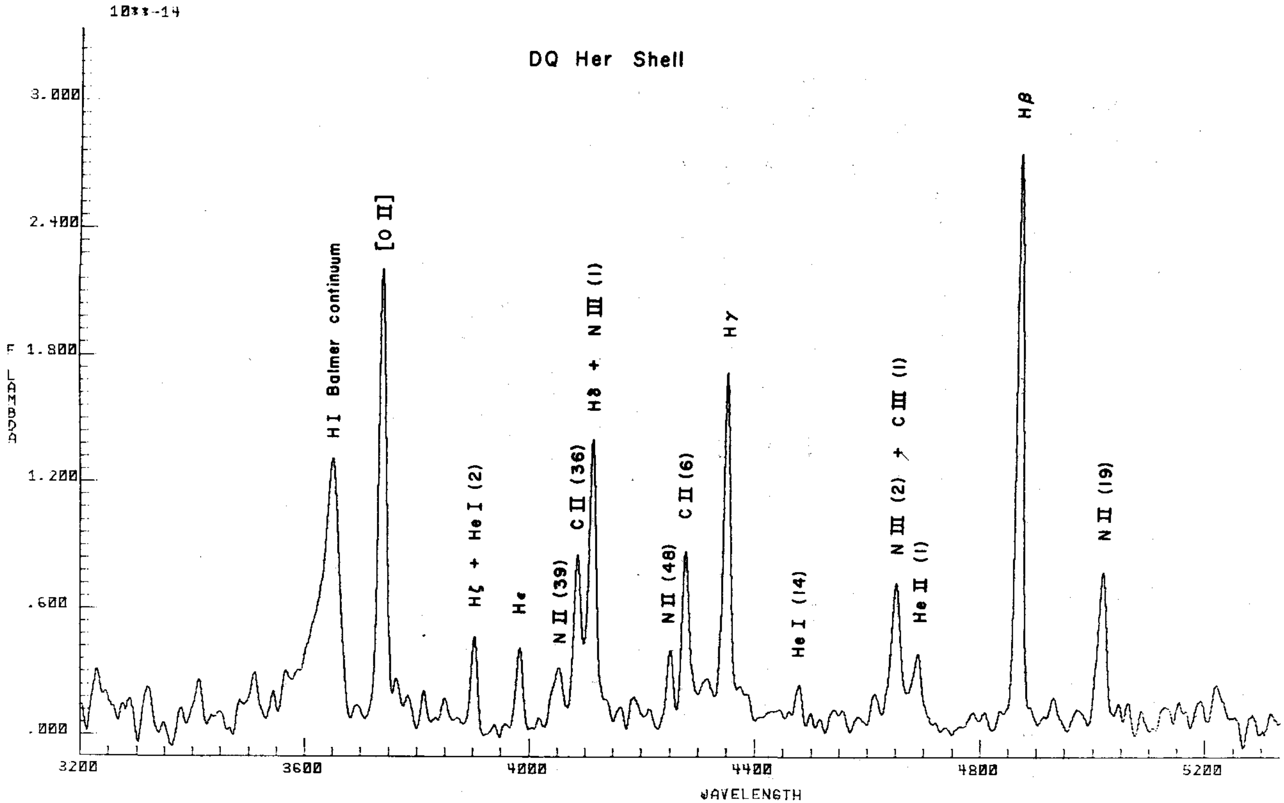

Fig. 6. A blue spectral scan of a 5" region of the NW portion of the shell of DQ Her. The spectrum was obtained with the Steward Observatory 2.3m telescope using the intensified Reticon system, and has a resolution of 6 A. Suggested line identifications are given, including the multiplet number. The most puzzling feature is the broad emission centered at ∿λ3645 A, due either to Balmer continuum emission at a very low temperature, or a line not normally seen in gaseous nebulae. The wavelength scale is not exact.

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has a resolution of 6 A, and was obtained with the Steward 2.3m telescope Cassegrain spectrograph, using the intensified Reticon detector system that has been developed by E. K. Hege and N. J. Woolf. The data reduction is still in a preliminary stage, and a detailed description will appear elsewhere in a separate publication, so only a few comments on the spectrum will be made here. The spectrum of the DQ Her shell shows some similarity to the emission spectrum of a nebula, in that the Balmer series and [O II] λ3727 are prominent, however there are also some notable differences. Specifically, certain permitted recombination lines of C and N are unusually strong, and [O III] λ5007 is absent because the observed feature at λ5005 is not accompanied by the required emission of λ4959. In addition, a strong emission feature is seen near λ3645, which is attributed to the Balmer continuum formed at a very low temperature ($T_e \sim 500$ K). It therefore appears that the spectrum of the nova shell must be produced by a moderately ionized gas having both hot (10^4 K) and cold (500 K) components.

The lines CII λ4267 and N II λ4237,4242 are among the more definite identifications, and their strengths with respect to Hβ are roughly 1 to 2 orders of magnitude greater than normally observed in gaseous nebulae (Kaler 1976). Since these lines both originate in levels high above the ground state ($>$20 eV), and do not directly couple to the ground state by permitted transitions, direct radiative (fluorescent) or collisional excitation from the ground state is highly improbable, and the lines are probably due to recombination alone. The emission coefficients of the C II and N II lines have roughly the same temperature and density dependence as the Balmer recombination lines, and therefore the relative intensities depend only upon the abundances of the emitting ions integrated over the emitting volume. Making the simplifying assumption (perhaps unjustified) that throughout this region of the shell all H is ionized, and C^{+2} and N^{+2} are the dominant stages of ionization for these elements, leads to the result that the carbon and nitrogen abundances are $C/H \sim 7 \times 10^{-3}$ and $N/H \sim 2 \times 10^{-2}$. That is, based upon their line strengths, C and N appear to be enhanced relative to H by factors of roughly 20 and 100 from their solar values. The oxygen abundance is more difficult to establish since no recombination lines of O are seen, and forbidden line intensities are very sensitive to the assumed electron temperature. From He I λ4471, the helium abundance appears to be essentially solar.

The deduction of possible C and N overabundances in the shell of DQ Her from the relatively high intensities of the lines of these elements is not without question. The enhancements have been derived using assumptions of ionization and temperature which are appropriate for equilibrium conditions, even though the time-scale for ionization processes at the shell densities inferred from the presence of the [O II] line must be greater than the age of the shell. Alternative explanations might be possible in terms of plausible non-equilibrium models having solar abundances. To illustrate this point, consider a situation in which the ionization and heating in a nova shell occur over a relatively short period of time (say, a month or so) that follows the outburst. Suppose sufficient energy is available in the envelope, from radiation or collisions, to highly ionize the elements. Upon withdrawal of the ionizing source, the gas will cool by radiation and begin to recombine. After a given length of time, which depends upon the density, the gas will have decreased in ionization by several stages: much of the H will be neutral, but the CNO might still be moderately ionized. The time-scale for cooling by collisional excitation is much less than the recombination time, so the gas will be very cool at this point, radiating perhaps in the infra-red fine-structure lines, but not from higher levels which radiate in the visible. Thus, the spectrum one would see

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would consist of recombination lines of the heavier elements, and recombination lines of H at greatly reduced strength because of its low ionization, but no forbidden lines in the visible. If in addition there existed a source which heated some of the gas but produced little ionization, as might occur from X-rays or the accretion process, then a temperature could be produced which collisionally excites visible forbidden lines like [O II] and [N II], the latter of which appears on red scans. In short, a spectrum like that of the shell of DQ Her could possibly be produced in a gas with solar heavy element abundances if the ionization occurs near the time of the outburst, and steadily declines thereafter.

As with the other methods of determining novae abundances, the interpretation of the spectra of old nova shells requires more study before the derived compositions can be considered to be firmly established. Nevertheless, the analysis of the emission spectra of extended envelopes is capable of producing results which are as valid as those obtained by other methods, and should be pursued. Virtually all analyses of the chemical composition of novae have shown evidence for certain heavy element enrichment. More detailed investigations of the emission spectra of novae offer the best opportunity for determining the extent to which evolutionary processes in close binary systems may modify the cosmic element abundances.

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D I S C U S S I O N of paper by WILLIAMS:

SMAK: Can you say more about the differences between the spectra of the equatorial and polar regions of the envelope of DQ Her, particularly from the point of view of predictions by Starrfield et al.?

WILLIAMS: Yes. One of the purposes of our study of old nova shells is to determine possible differences between the polar and equatorial ejects. The spectra of the equatorial regions of the DQ Her shell differ from the polar regions in that the strengths of the C and R recombination lines are definitely weaker with respect to Hβ in the equatorial gas. This could be due to differences in ionization (caused perhaps by density), however, one would then expect to see other lines from C and N that are not observed. Since relative recombination line intensities are insensitive to density and temperature, the most straightforward interpretation of these observations is that the CNO abundances differ in the two regions of the shell. If so, the polar gas shows evidence for more CNO processing than the equatorial gas, which is probably mixed with gas from the accretion disk.

KRAFT: What effects are produced on the abundances by uncertainties in the input radiation field?

WILLIAMS: The radiation field of the star is certainly capable of having a considerable effect upon the ionization, and therefore the derived abundances, of the gas. However, the far-UV flux of DQ Her is probably not sufficient to produce the observed ionization of the shell. I think the OAO observations of old novae in the UV by Gallagher and Code are consistent with this fact. Therefore, the ionization observed in the shell of DQ Her is probably not very dependent upon the radiation field, but is largely a relic of the original ionization produced near the time of the outburst.

APPENZELLER: I have two questions: First, this morning we learned about the dust production in nova outbursts. Thus, part of the ejected matter will condense into grains, changing the composition of the remaining gas. Doesn't this affect your abundance determinations in old nova envelopes?

Second, is it safe to use a curve of growth analysis in a rapidly expanding shell, where presumably velocity gradients are not negligible?

WILLIAMS: 1. Clearly, the presence of large amounts of dust could affect the abundance determinations inasmuch as the emission lines are produced only by the gaseous component of matter. I might report here that I recently obtained spectral scans of the condensation 10" NE of T CrB that appears in Fig. 2 of the manuscript. It does not show an emission-line spectrum, but only a reflection spectrum of T Cr B (primarily TiO bands, with Balmer line emission). This indicates a large concentration of dust. The observation will be repeated next season because of the problem of scattered light in the telescope and spectrograph from T Cr B, which is bright. However, the indications are that some nova shells may have substantial amounts of dust, whereas others may be largely ionized gas.

2. As for your question concerning curves of growth, velocity gradients must be taken into account in such analyses. This is especially true of comparative curve of growth studies, such as the analyses of DQ Her and HR Del were. The novae almost certainly have a severe velocity structure, and this is another uncertainty that affects the abundance analyses.

FRIEDJUNG: The gas is expanding at maximum, but according to Mustel's analysis the absorption in a line at a certain observed radial velocity is only produced by gas with a small range in velocity. I was always skeptical about curve of growth analyses, and Dr. Williams has convincingly pulled them to pieces.

BOYARCHUK: Several years ago E.R. Mustel and I have published a paper in "Astrophysics and Space Science", containing a figure which showed the evolution of the envelope as observed in different spectral regions. At all times, the envelope looked completely different in [NII] and [OIII]. I cannot understand this difference, if I consider only excitation.

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