THE ASTROPHYSICAL JOURNAL, **224**:171–181, 1978 August 15

THE SHELL AROUND NOVA DQ HERCULIS 1934

R. E. WILLIAMS, N. J. WOOLF, E. K. HEGE, R. L. MOORE, AND D. A. KOPRIVA
Steward Observatory, University of Arizona

Received 1978 January 25; accepted 1978 March 3

ABSTRACT

Spectral scans have been obtained of different regions of the extended nova shell surrounding DQ Her, using an intensified Reticon detector. The spectra show unusually strong recombination lines of ionized carbon, nitrogen, and oxygen which indicate enhancements of the CNO with respect to H over solar values of roughly a factor of 100 in parts of the shell. In addition, a strong, broad emission feature at $\lambda 3644$ is identified as the Balmer continuum, formed at a very low temperature ($\lesssim 500$ K). Most of the hydrogen emission and CNO recombination lines originate in the cold, ionized gas. However, forbidden lines of [N II] and [O II] are also observed that indicate the presence of a hotter component of gas.

Subject headings: nebulae: individual — stars: novae

I. INTRODUCTION

There are at present fewer than 10 old novae which are known to possess observable extended shells or filaments of material that were ejected from the outburst. Past interest in old nova shells has primarily concerned their rates of angular expansion, which have been used together with the expansion velocities deduced from emission lines to derive distances to the novae. Distances to eight novae have been determined by this method, and these are considered to have yielded among the most reliable determinations of the absolute magnitudes of novae (Payne-Gaposchkin 1957; McLaughlin 1960). The more or less constant expansion of nova envelopes causes the emission measure of the shells to continually decrease, making detection difficult after a period of time. Consequently, almost all of the novae which have developed detectable spatially resolved shells have been among the closer, brighter novae.

The structure of selected nova shells when still bright, and therefore young and only barely resolved spatially, has been studied independently by Hutchings (1972), Weaver (1974), and Soderblom (1976) by means of the analysis of high dispersion spectra with different slit orientations, which makes possible the reconstruction of the geometry of the shells. They have found that a number of the shells show a moderate degree of symmetry, with gas concentrated in "equatorial" rings and "polar" condensations. This finding is consistent with the analysis of Mustel and Boyarchuk (1970), who studied the morphology of extended nova shells from monochromatic photographs obtained at Mount Wilson and Palomar Observatories and in the Soviet Union by different observers over a long period of time. Mustel and Boyarchuk noted variations in the relative brightness of different regions of several shells in the light of the [O III] and [N II] emission lines, and they used this information to make very rough estimates of the ionization and density in the shells. However, monochromatic photographs such as these represent the extent of the data obtained from old shells; virtually no published spectroscopic data exist on the radiation from extended shells because of their low surface brightnesses.

On the other hand, a wealth of spectroscopic data exist on novae in their "nebular" phase, during the period of decline, because of the brightness of novae during this stage. Unfortunately, because the novae and associated ejecta are generally still point sources until some years after the outburst, during this period the spectrum is a mixture of emission from different components of the system: stellar remnant, accretion disk, and ejected shell. The severe inhomogeneities that exist in the ejecta following the outburst and the confusion of emission from different members of the system make interpretation of the spectrum during this time very difficult (Gallagher and Anderson 1976; Ferland, Lambert, and Woodman 1977; Gallagher 1978). Spectroscopic analysis of old shells where spatial resolution is possible and conditions have stabilized would allow a more straightforward determination of certain parameters, such as chemical composition, to be made. Although such shells usually have very low surface brightness, linear detectors which allow accurate sky subtraction can be used to obtain reliable line fluxes. Current models of the nova outburst make specific predictions regarding element abundances (Starrfield, Truran, and Sparks 1977), and a study of the extended envelopes around novae might yield information regarding the element abundances in novae which could be used to discriminate between various theories of the nova phenomenon. In order to resolve these questions, we have begun a systematic study of physical conditions in old nova shells.

II. OBSERVATIONS

Photographs of the shell of DQ Her in the light of Hα show it to have an ellipsoidal shape with an angular size of roughly 15″ × 20″, as shown in Figure 1. Spectra were obtained of four regions of the shell at points which correspond to the ends of the major and minor axes of the ellipse. The sizes of the areas sampled, which are illustrated in Figure 1, were 5″ in diameter for regions A and C, and 3″.5 for regions B and D. The spectra were obtained with the Steward Observatory 2.3 m telescope and the Cassegrain spectrograph, using as the detector an intensified two-line Reticon system that has been under development at the observatory. Both blue and red scans were obtained for each region at a dispersion of 95 Å mm^{-1}, providing a resolution of 6 Å and a spectral coverage of approximately 1800 Å per scan.

A detailed description of the intensified Reticon system will appear in a separate publication; however, a brief summary of its salient features is appropriate here. The system is used in the analog mode to record and display spectra. The spectrum is initially imaged onto an RCA two-stage 40 mm magnetically focused image tube, and the phosphor output of the tube is reimaged, using an f/1.0 Nikkormat transfer lens, onto a Vargo two-stage 40 mm intensifier. The output of the Varo tubes is coupled to the surface of a Reticon CP1001 silicon photodiode array by fiber optics. The Reticon array consists of two parallel adjacent rows of 936 diodes each, upon which are imaged the "sky" and "object" spectra. The diodes are 30 μm wide (in the direction of dispersion) and 375 μm long, with a total array length of 28 mm.

The Varo tubes are magnetically shielded from the RCA tube, and the final stage ofthe Varo tubes is equipped with a pair of coils which translate the spectrum along the photodiode array in order to oversample the spectrum. Deflection of the spectrum by one-half diode width, i.e., 15 μm, comfortably oversamples the 60 μm resolution obtained with a 2″.5 entrance slit. With an f/2.8 relay lens setting, approximately 3×10^4 electrons are produced for each photoelectron, as compared with the diode saturation charge of $\sim 2 \times 10^7$ electrons. The readout noise is about 700 electrons, so individual photoelectrons can be detected readily.

The arrays are scanned sequentially, each array being read out in two analog channels through low noise charge-sensitive FET-input preamplifiers. To further minimize readout noise, the arrays are scanned at a maximum rate of 4 kHz (250 μs per diode), allowing analog filtering to a 20 kHz bandwidth yet permitting an 8 kHz data rate, since odd and even diodes are read simultaneously. This procedure sets a lower limit of 0.25 s for minimum integration time. The entire system is cooled to about −15° C to minimize dark current from the intensifiers and Reticon. The maximum integration time is presently limited to about 30 s by temperature-induced fluctuations in the Reticon dark current. Although the system is strictly speaking an analog system, it is nevertheless possible to clean the data by removing large spikes caused by ion events. A typical ion event produces a signal 10 to 100 times that of a photoelectron. Since phosphor afterglow associated with an ion event may still produce a signal comparable to a photoelectron in the scan following the one in which the ion event occurred, a given scan is compared to the ones immediately preceding and following it, and spikes greater than 3 σ are removed. Variations in diode-to-diode sensitivity of the Reticon are uniform to about $\pm 5\%$ rms, and are calibrated in the usual way by exposure to a continuum lamp.

The observing procedure used to obtain spectral scans of DQ Her consisted of placing the object in one of two identical diaphragms, spaced 20″ apart, and recording the spectra of the sky and object + sky on each of the arrays. Automatic beam-switching occurred by moving the telescope back and forth every 15 s, so scans of the object were alternately recorded on each array for equal lengths of time. Total integration times for each scan of a region of the DQ Her shell varied from 30 to 60 minutes. The wavelength calibration for the scans was obtained from a He-Ar lamp, and is accurate to about ±1 Å. Diode-to-diode variations and the instrumental response function and relative flux calibration were determined from observations of a quartz lamp and the standard stars BD +33°2642 and BD +40°4032 (Stone 1977). The resulting scans of the nova shell, which were obtained in 1977 June in 2–3″ seeing, are shown in Figures 2 and 3. Although the spectra were originally calibrated in terms of absolute flux, we have presented the results only in terms of relative flux because the nova shell is an extended source, and the surface brightness varies from point to point. Furthermore, the blue and red scans of each region were obtained on different nights, under somewhat different conditions, and slightly different areas of the shell were probably sampled on the different nights. Consequently, the only relative line strengths that are reliable are those from the same scan.

III. LINE IDENTIFICATIONS

The problem of obtaining correct identifications for the emission lines in novae is a difficult one. The lines are intrinsically very broad, so identifications cannot usually be made on the basis of wavelength agreement alone. Although the spectra of novae in the period of late decline are generally similar to those of gaseous nebulae, conditions in novae show such extremes and variations (Ferland *et al.*) that it is risky to anticipate the presence of specific lines. For example, the line that appears near λ5005 from regions A and C in the shell of DQ Her is not [O III] λ5007, because [O III] λ4959 is absent, and it must appear with one-third the strength of λ5007. We have not indicated the noise level of the scans in Figures 2 and 3 because it varies with wavelength due to the changing instrumental response. Furthermore, the signal-to-noise ratio of the different scans varies considerably because of the different integration times used. An estimate of the noise has been made by comparing the scans from the two independent Reticon arrays, and requiring all real features to appear on both arrays. We have used this criterion in making line identifications, and a line

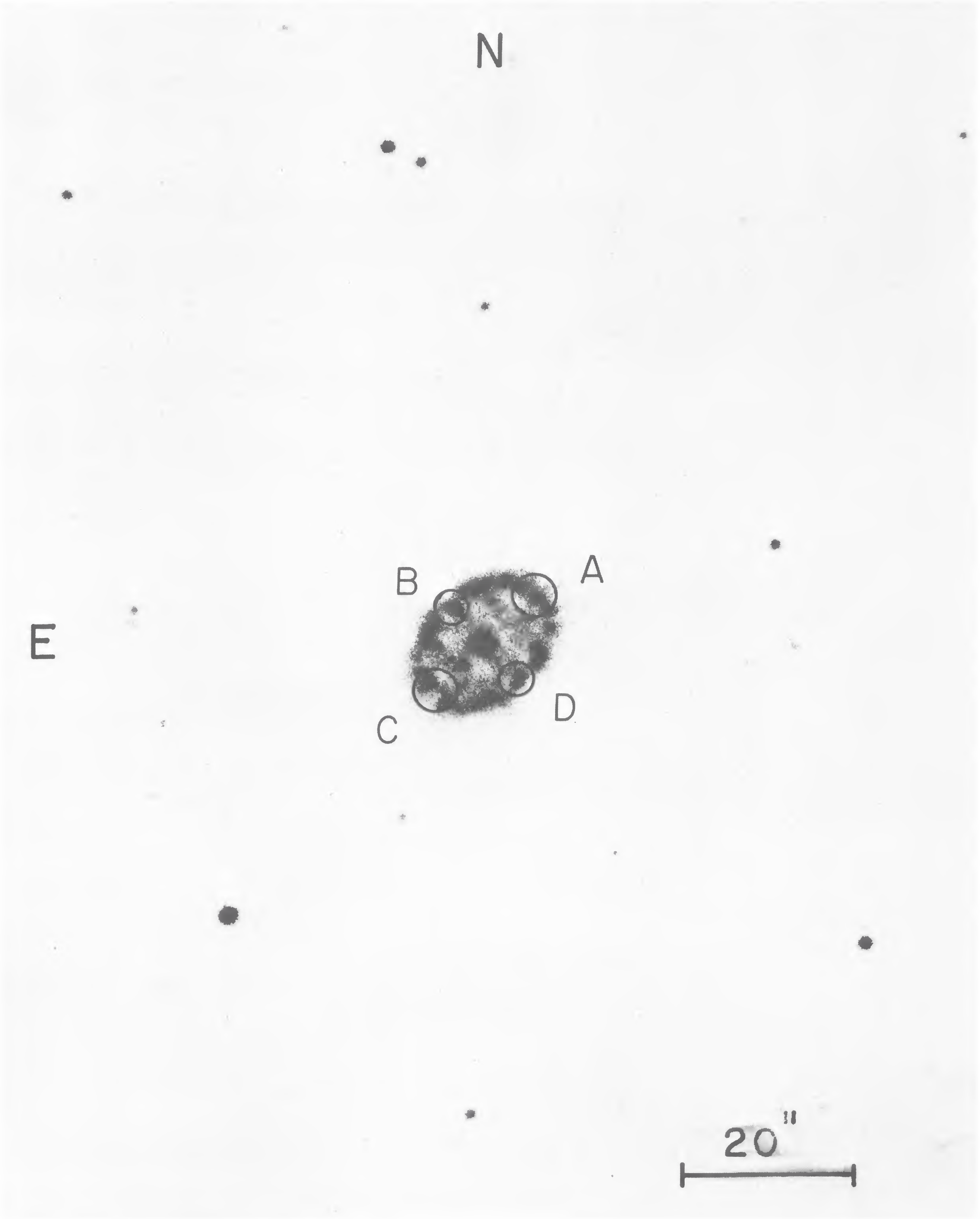

FIG. 1.—Monochromatic photograph of the nova shell surrounding DQ Her, obtained with an ITT 40 mm image tube in the light of Hα. The circles denote the regions of which spectra were obtained.

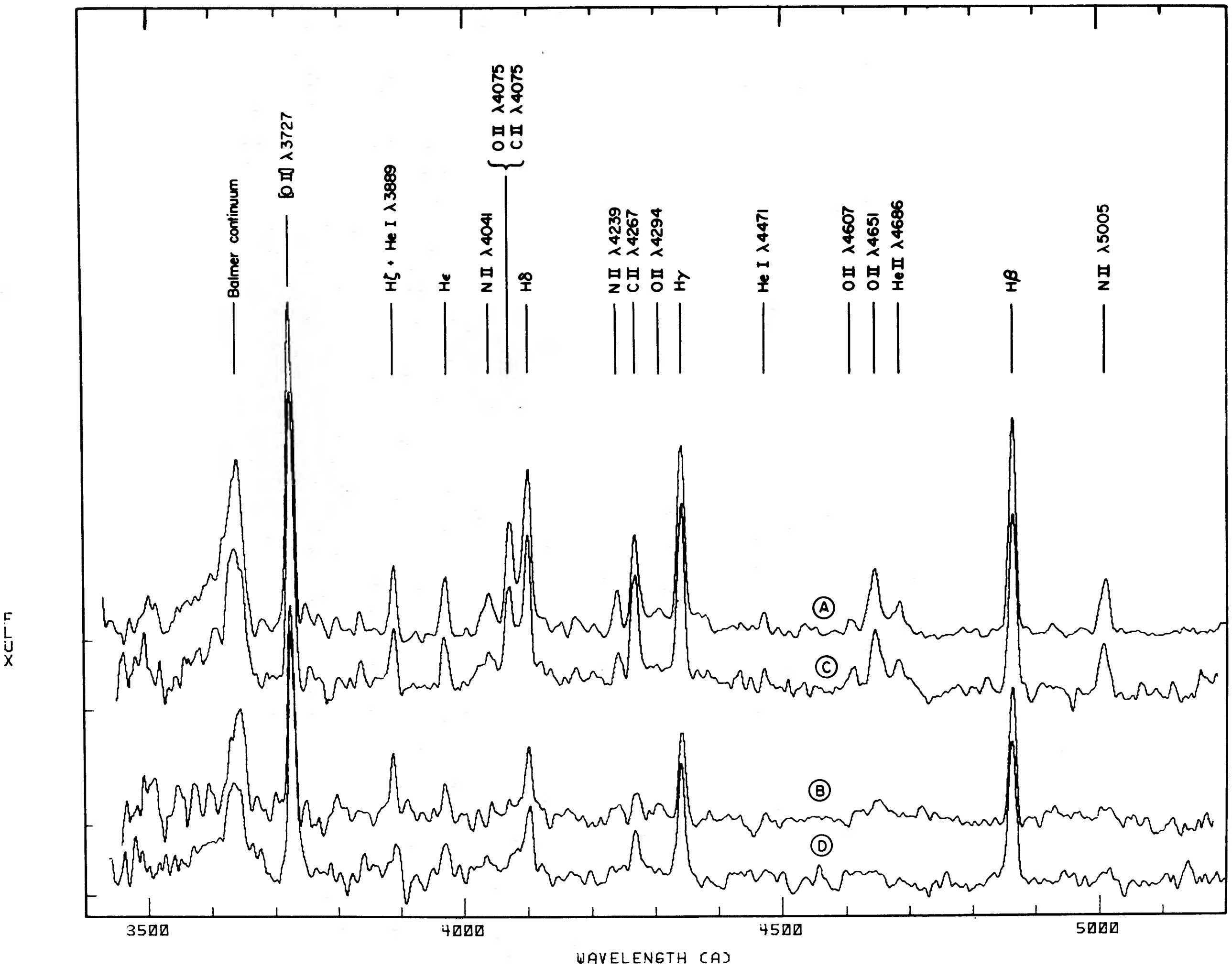

FIG. 2.—Blue spectral scans of the shell of DQ Her. The two upper scans are of regions A and C, at the ends of the major axis. The bottom two scans are of the regions at the ends of the minor axis. All of the scans are shown to the same scale. The signal-to-noise ratios of the scans vary considerably because different aperture sizes and integration times were used for different scans.

at λ4959 having one-third the flux of the line at λ5005 would definitely appear on the blue scan of region A. Numerous controversies exist over the proper identification of specific features in novae (Grasdalen and Joyce 1976; Black and Gallagher 1976; Ferland *et al.*), and it is common for as many as four different transitions to be suggested as the identification for a given line (Gallagher 1978). The best that can be done under these circumstances is to consider all transitions that give acceptable wavelength agreement, and choose the most likely identification on the basis of astrophysical reasonableness and consistency, i.e., other lines that one would or would not then expect to see.

In Table 1 we have listed the measured wavelengths of all definite emission features in the spectra of the nova shell, and what we believe to be the most reasonable line identifications. The suggested identifications also appear in Figures 2 and 3. In judging the reality of the weaker features, we have relied only upon the blue and red scans of the NW portion of the shell (region A). The signal-to-noise ratios of these scans are higher than those of the other regions because of longer integration times. It should be noted that, following normal nomenclature, the wavelength listed for each multiplet is the weighted (by the statistical weights of the upper levels) mean of the wavelengths of all lines of the multiplet (Wiese, Smith, and Glennon 1966), not the wavelength where peak emission of the multiplet occurs. The latter is determined by the relative transition probabilities of the individual lines. The multiplet numbers are given in parentheses.

The spectrum of the shell of DQ Her shows some similarity to that of a nebula, in that lines which we identify as the Balmer series, [O II] λ3727, and [N II] λ6584 are prominent. However, there are a number of other lines which also appear with appreciable strength that are at best seen only very weakly in nebulae, and these we have identified as permitted recombination lines of carbon, nitrogen, and oxygen. With the exception of N II λ5005, which is normally hopelessly

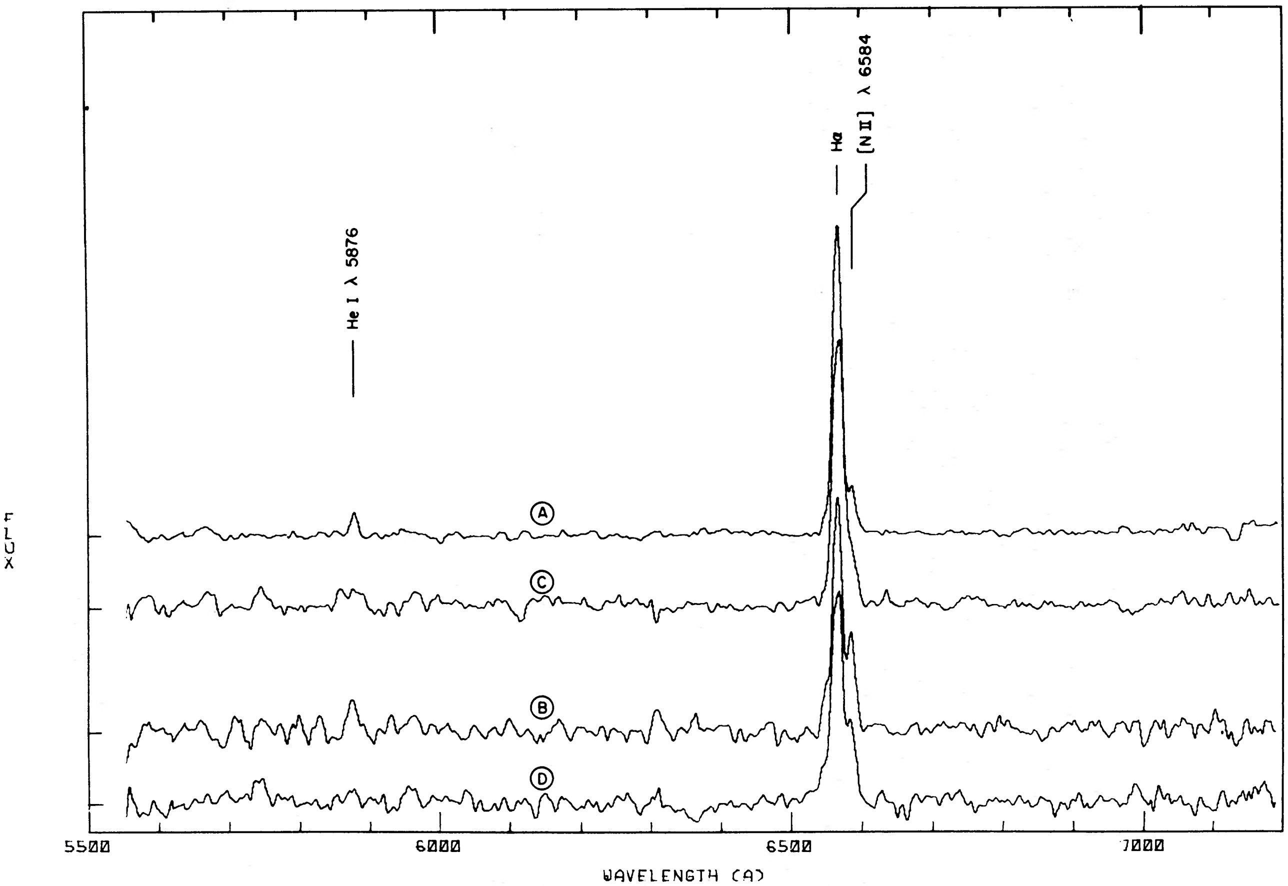

FIG. 3.—Red spectral scans of the DQ Her shell. The curves are labeled by the corresponding regions of the shell shown in Fig. 1.

TABLE 1

EMISSION LINES IN THE SHELL OF DQ HER

Measured Wavelength (Å)	Identification
3644	H I Balmer continuum
3727	[O II] λ3727
3889	Hζ + He I λ3889
3970	Hϵ
4038	N II λ4041 (39)
4072	O II λ4075 (10) + C II λ4075 (36)
4100	Hδ
4240	N II λ4239 (48)
4267	C II λ4267 (6)
4303	O II λ4294 (54)
4341	Hγ
4472	He I λ4471
4610	O II λ4607 (93)
4645	O II λ4651 (1)
4684	He II λ4686
4861	Hβ
5005	N II λ5005 (19)
5875	He I λ5876
6563	Hα
6584	[N II] λ6584

dominated by [O III] λ5007, all of the CNO permitted lines we have identified in DQ Her are among the stronger heavy-element recombination lines observed in planetary nebulae (Kaler 1976). The most puzzling feature in the spectrum is the very broad, asymmetric feature at λ3644. A search was made in Moore's (1959) *Multiplet Table* for all multiplets in the range $3615 \leq \lambda \leq 3655$ which might contribute to this feature, and the only plausible candidate was the Ca I λ3638 (9) multiplet. Emission of this multiplet populates the $4p\ ^3P^o$ level of Ca I, from which the only radiative decay is by emission of [Ca I] λ6572 to the ground state. Consequently, the two lines should appear with comparable strengths. In fact, emission in the red wing of Hα is evident on several scans in Figure 3; however, the measured wavelength of the line is λ6584, almost certainly requiring this to be [N II]. We have therefore rejected the Ca I identification for the λ3644 feature. The only alternative explanation for this feature which seems reasonable is that it is due to hydrogen Balmer-continuum emission. The presence of Balmer lines requires continuum emission also; however, an emission-line spectrum of this type generally originates in a gas of 10^4 K, so the Balmer continuum is normally emitted over a much larger wavelength interval. The emission coefficient for Balmer emission above the threshold (λ3648) has a frequency dependence given by $j_\nu \propto \exp(-h\nu/kT_e)$, where T_e is the electron temperature (Osterbrock 1974). Therefore, the fact that the Balmer-continuum radiation is confined to the relatively small wavelength interval indicated in Figure 2 requires the temperature of the ionized gas to be very low, $T_e \sim 450$ K.

Recombination theory can be used to determine the expected relative intensities of the Balmer lines to the continuum for a cold gas. Calculations have not been made for temperatures as low as 500 K; however, the Balmer line/continuum ratio should be fairly insensitive to T_e, and published calculations can be extrapolated to this temperature. The ratio of the integrated flux of the Balmer continuum to the flux of Hβ is $F_{\text{Bac}}/F_{\text{H}\beta} = \alpha_2\langle\nu_2\rangle/(\alpha_{\text{H}\beta}\nu_\beta)$, where $\alpha_{\text{H}\beta}$ and α_2 are the effective Hβ and level 2 recombination coefficients, and ν_β and $\langle\nu_2\rangle$ are, respectively, the average frequency of Hβ and Balmer-continuum photons. Extrapolating values of $\alpha_2/\alpha_{\text{H}\beta}$ (Osterbrock 1974) to 450 K leads to a predicted value of $F_{\text{Bac}}/F_{\text{H}\beta} \approx 1.2$, as compared with the observed ratio of $F_{\text{Bac}}/F_{\text{H}\beta} = 2.5$. The discrepancy between these numbers may simply be due to blending of other lines with the Balmer-continuum feature, or to uncertainties in extrapolating the recombination cross sections to low temperature. Alternatively, it could be due to the fact that processes other than pure recombination in an optically thin gas are important in the formation of the Balmer emission. The relative intensities of the Balmer lines seem to suggest the latter, in that the Balmer decrement is flatter than the normal radiative decrement at 10^4 K. Nevertheless, in spite of the difference between the predicted and observed ratio of $F_{\text{Bac}}/F_{\text{H}\beta}$, the calculations indicate that, if our identification of the λ3644 feature as the Balmer continuum is correct, essentially all of the Balmer line emission must also originate in the very cold gas.

The presence of [O II] λ3727 and [N II] λ6584 in the envelope of DQ Her is difficult to account for in terms of a cold gas, since these lines are normally collisionally excited at temperatures of around 10^4 K. Because they are the only forbidden lines in the spectrum, requiring higher temperature, it is tempting to try to identify them with possible recombination lines, which are preferentially formed at low temperature. We have searched for viable alternatives to the [O II] and [N II] identifications, but have found none. The wavelength agreement of the observed lines with these transitions is good, and on the red scans of the NW and SW portions of the shell (regions A and D), a line appears in the blue wing of Hα having a measured wavelength of λ6548 and an intensity less than half that of λ6584. This line is almost certainly [N II] λ6548, which must be present at one-third the strength of [N II] λ6584, and its presence confirms the identification of these lines with [N II].

It is conceivable that the [N II] and [O II] lines are formed by recombination rather than by collisional excitation. Most of the electron recaptures to levels of N II and O II go to the triplet and quartet states of these ions, respectively. However, as many as one-third of all recombinations go to the singlet levels of N II and the doublet levels of O II, followed by cascading down into the lowest singlet and doublet levels. The lowest singlet level of N II is $2p^2\ ^1D_2$, from which the only radiative route to the ground state is via emission of [N II] λλ6548, 6584. Similarly, the lowest doublet level of O II is $2p^3\ ^2D^o$, from which the only radiative transition to the ground state is by emission of the [O II] λ3727 doublet. Therefore, the large majority of all recombinations to N II singlet and O II doublet levels must eventually produce [N II] λλ6548, 6584 and [O II] λ3727. The expected intensities of the recombination contributions to these lines relative to the other N II and O II recombination lines we have identified are uncertain, but could be large. Nevertheless, we believe the data argue against the formation of the [N II] and [O II] by recombination because the strengths of these lines in different regions of the nova shell are not correlated with the strengths of the CNO permitted recombination lines. The CNO permitted lines are all substantially weaker relative to the Balmer lines on the minor axis of the shell (regions B and D) than on the major axis, whereas the [N II] and [O II] lines do not show this effect. Therefore, we believe the forbidden lines must be formed separately from the other heavy-element lines, and originate from a hot ($T_e \gtrsim 5 \times 10^3$ K) component of gas in the shell, which evidently contributes little to the Balmer emission.

IV. INTERPRETATION

The salient features of the spectra of the nova shell are (*a*) the heavy-element permitted line strengths are much greater, relative to the Balmer lines, than normally seen in H II regions or planetary nebulae; (*b*) the Balmer continuum and forbidden lines indicate the existence of both hot and cold components of gas in the shell; and (*c*) the spectra of regions A and C (on the major axis of the shell) are virtually the same, but differ from the spectra of regions B and D (on the minor axis). The relative strengths of the Balmer, [O II], and [N II] lines are all similar throughout the shell; however, the C II, N II, and O II lines which appear along the major axis are all much weaker or absent along the minor axis.

Excitation of the CNO permitted lines could occur by fluorescence, collisional excitation from the ground state, or recombination. Collisional excitation is unlikely because the upper levels of the transitions are all greater than 20 eV above the ground state, requiring very high temperatures. Fluorescent excitation is a possibility, although almost all of the observed heavy-element permitted lines originate in *F* and *G* states and do not directly couple to the ground states (which are all *S* and *P* terms) by permitted transitions. Therefore, direct excitation of these levels by scattering is not possible, although it could occur to higher levels, followed by cascading into the states from which lines are observed. We have searched for possible transitions by which the fluorescence of continuum or line photons could occur to produce the heavy-element permitted lines, but we have not found any reasonable fluorescent processes. The O II λ4651 line is unlikely to be contaminated by N III λ4634, which is strong in some planetary nebulae due to the Bowen fluorescence mechanism, because the N III lines that are excited by Bowen fluorescence must all have intensities substantially less than He II λ4686, which is weak in the DQ Her shell. As a result, we believe the CNO permitted lines are all almost certainly due to recombination. In addition, it appears that these lines must be emitted by the very cold component of gas which produces the Balmer emission, since the strength of the O II λ4651 line requires a substantial fraction of oxygen to be O^{+2}. If the gas producing this emission were not at a very low temperature, collisional excitation of the O^{+2} would produce very strong [O III] λ5007 emission in the nova shell, which is not observed.

The intensities of the recombination lines of most ions have essentially the same dependence upon density and temperature, and therefore relative strengths of the lines in the DQ Her envelope can be used to derive abundance ratios for the ions C^{+2}, N^{+2}, and O^{+2} with respect to H^+. Line identifications in which we have considerable confidence are C II λ4267, N II λ4239, and O II λ4651. The lines are all among the stronger heavy-element recombination lines that have been seen in gaseous nebulae (Kaler 1976), and in DQ Her they do not appear to be seriously affected by blending. The recombination spectrum of heavy elements in nebulae has been considered by Grandi (1976), and we have adopted his procedure to calculate the effective recombination coefficients for each of these lines. A comparison of Grandi's predicted line fluxes, from an ionization model of the Orion Nebula, with observations has indicated that the values of α^{eff} computed by his scaling procedure may be a factor of 3 too small for λ4267, and a factor of 2 too large for λ4651. Therefore, we have adjusted his computed coefficients for these lines by these amounts. The computed effective recombination coefficients for the multiplets C II λ4267, N II λ4239, and O II λ4651 at a temperature of 10^4 K are, respectively, 1.2×10^{-12}, 1.1×10^{-13}, and 2.2×10^{-13} cm^3 s^{-1}. The relative flux of a line with respect to Hβ is expressed in terms of α^{eff} through the relation

$$\frac{F_\lambda}{F_{\text{H}\beta}} = \frac{N_{l+1}}{N_{\text{H}^+}} \frac{\alpha_l^{\text{eff}}}{\alpha_{\text{H}\beta}} \frac{\nu_l}{\nu_\beta}, \tag{1}$$

where N_l is the number density of the emitting ion, and ν_l is the line frequency. We will assume that the CNO lines originate in the same region of gas as the Balmer emission. If this is not the case, derived abundances of the CNO will be lower limits. We will also assume that the H is completely ionized where the CNO are doubly ionized, as would be expected of the ionization in any equilibrium situation. The relative intensities of the lines in regions A and C (major axis) of the shell of DQ Her are roughly $F(\lambda4267)/F(\lambda4239)/F(\lambda4651)/F(\text{H}\beta) = 5/2/4/10$. Using the value of $\alpha(\text{H}\beta) = 3.0 \times 10^{-14}$ cm^3 s^{-1}, appropriate for a temperature of 10^4 K, and assuming the temperature dependence of all line recombination coefficients to be the same, leads to abundance ratios of $C^{+2}/N^{+2}/O^{+2}/H^+ = 1.1 \times 10^{-2}/4.8 \times 10^{-2}/5.2 \times 10^{-2}/1$ for these regions of the shell, irrespective of the temperature of the gas. This result must be considered to be only approximate because of the assumptions that have been made and the uncertainties in the recombination coefficients; however, it does appear that the CNO are enhanced in portions of the nova shell by factors of about 100 over solar values. If the CNO lines were to originate in substantially hotter gas than the Balmer emission, e.g., at 10^4 K, then the deduced CNO/H abundance ratios would be even higher, roughly 500 times above solar abundances. However, as stated previously, we believe this to be unlikely because of the absence of [O III] λ5007 emission.

The signal-to-noise ratio for the spectral scans of regions B and D, which were observed with smaller apertures, is not good, so the flux ratios on the minor axis of the shell are not well determined. The N II lines are at best only marginally detected in the noise, being 3 to 4 times weaker relative to the Balmer lines than on the major axis. C II λ4267 and O II λ4651 are about one-half and one-fourth as strong on the minor axis as on the major axis. The C^{+2}, N^{+2}, and O^{+2} abundances with respect to H^+ are correspondingly smaller in these regions. The variations in line strengths may reflect differences in ionization between different regions of the shell, or differences in element abundances. Unfortunately, no lines from other ions are definitely seen, and the recombination spectra of heavy-element ions are not known well enough to enable us to predict whether lines of other ions should be seen if the ionization were to vary and the heavy elements were predominantly singly or triply ionized in regions B and D. Whatever the cause of the variations in the line strengths in the nova envelope, the enhancements of CNO to H^+ are still at least a factor of 10 over solar values.

It is interesting to note that the present emission structure of the shell differs considerably from that shown in the monochromatic photographs published by Mustel and Boyarchuk (1970). In the period 1940–1950, there was very strong emission along the minor axis from [N II] λλ6548, 6584 + Hα, whereas [O III] λ5007 was strong at the ends of the major axis. The subsequent time development of the shell emission has been such that now there is no detectable [O III] emission, and [N II] + Hα have comparable intensities in each of the regions we have sampled.

Little can be inferred from the presence of the [N II] and [O II] lines, other than the fact that higher temperatures are required for the collisional excitation of these lines than indicated by the Balmer-continuum feature. If N and O are overabundant in the shell, one would expect [N II]/Hα and [O II]/Hβ ratios that are very much larger than observed in nebulae, unless the electron temperature is low in the component of gas where these lines are formed. In fact, empirically the forbidden line/Balmer line ratio does appear to be very high in the "warm" gas, since the Balmer continuum/Balmer line ratio requires the observed Balmer lines to originate in the cold gas. Furthermore, low T_e is unlikely in the warm component because of the strong [O II] line, which is much more sensitive to temperature than [N II] due to its higher excitation potential.

The He/H abundance appears to be essentially solar, based upon the intensities of He I λ4471 and He II λ4686 in regions A and C. The intensity ratio of λ4686/λ4471 is larger than one would expect given the fact that no C III, N III, or O III lines are observed in the shell. This may be due to nonequilibrium ionization, or perhaps the He II λ4686 identification is incorrect.

V. NONEQUILIBRIUM IONIZATION

The evidence for strong heavy-element enhancement in the shell of DQ Her is based upon the assumption that H is fully ionized in the gas when CNO are doubly ionized. In any equilibrium situation, this would almost certainly be the case. However, the time scale for ionization and recombination processes in DQ Her is longer than the age of the shell if the shell densities are $N_e \lesssim 10^3\ \mathrm{cm}^{-3}$, as seems likely from the presence of the strong [O II] λ3727 line which is collisionally deexcited at higher densities. Therefore, the shell ionization is probably not in equilibrium. A time-dependent picture of the ionization in nova shells has been suggested by Williams (1977) which could conceivably explain the comparable intensities of the heavy element and hydrogen recombination lines without requiring CNO enhancements. Basically, the hypothesis is that the initial ionization in nova shells is complete for the more abundant elements, and subsequently decreases with time. If the hydrogen recombines and becomes predominantly neutral during the time it takes the CNO ionization to drop from, say, C^{+6}, N^{+7}, and O^{+8} down to C^{+2}, N^{+2}, and O^{+2}, then the recombination lines of CNO will appear greatly enhanced with respect to the Balmer lines, even though the heavy-element to hydrogen abundance ratio is normal. Because of the importance of resolving the question of element abundances in nova shells, we have studied this problem quantitatively.

It is known that, in the period immediately following the outburst, the ionization in nova shells is very high. In Nova Cygni 1975, for example, lines of [Fe X] and [Fe XI] were seen several months after maximum (Ferland, Lambert, and Woodman 1977). The ionization generally decreases in the period of decline because the radiation field of the stellar remnant is incapable of sustaining the high ionization. Gallagher and Holm (1974) found from UV measurements of the stellar continua of old novae with the *OAO* satellite that color temperatures generally do not exceed 35,000 K. The probable history of the ionization is therefore one in which most of the low-*z* elements (H, He, C, N, O) are initially essentially completely ionized. After the initial ionization source associated with the outburst is withdrawn, subsequent ionization is governed by electron recapture by the ions. The steadily declining ionization distribution is determined by the electron density and temperature of the gas, which are also decreasing with time. Because of the decrease in the density due to the expanding gas, recombination times continually increase until the ionization eventually becomes "frozen in," to use the terminology of Mustel and Boyarchuk (1970).

We have computed the ionization of the elements H, He, C, N, and O as a function of time, beginning with an assumed ionization distribution. The equations governing the ionization in the situation described above are

$$\frac{dx_i}{dt} = N_e x_{i+1}\alpha_i(T_e) - N_e x_i \alpha_{i-1}(T_e)\,, \qquad (2)$$

where x_i is the fractional abundance of the *i*th ionization stage, N_e is the electron density, and $\alpha_i(T_e)$ and $\alpha_{i-1}(T_e)$ are the recombination coefficients for capture to ions i and $i - 1$. Analytic expressions for the $\alpha_i(T_e)$ were obtained from Aldrovandi and Péquignot (1973). The ionization equations (2) are identical in form to the equations describing the radioactive decay of an element, and we have solved them by using the analytic solutions to the nuclear radioactivity problem involving the recursion relations given by Leighton (1959). Charge exchange reactions have been neglected because they are important primarily for the lower ionization stages of the heavy elements, and we are interested in following the ionization only to the point where the C II, N II, and O II recombination lines are at maximum strength. The temperature of the gas was assumed to take on values between 10^4 and 10^2 K. This temperature range was selected because the time scale for cooling by collisional excitation is much shorter than the time scale for recombination, so T_e will drop from initial values, assumed to be $\sim 10^4$ K, to the point where the cooling can be sustained by the excitation of fine-structure lines, which is generally at temperatures around 10^2 K.

The importance of considering a nonequilibrium ionization distribution in the shell of DQ Her is that the apparent heavy-element enhancements required by the strengths of the CNO lines may instead be explained in terms of very low hydrogen ionization. We have attempted to consider the most favorable conditions for this situation to occur by assuming initial (at $t = 0$) complete ionization of all elements, in order to see whether the H would become neutral by the time the heavy-element ionization dropped to the point where the CNO were doubly ionized. The results of the calculations are presented in Figures 4 and 5 for different assumed temperatures. The comparative ionization distributions for each element are independent of density, and only weakly dependent upon T_e in the regime of interest. Calculations were also made for cases in which the temperature varied with time; however, the results were very similar to those shown. In order to present the results for all of the elements in each figure, we have chosen not to plot the individual ionization curves, $x_i(t)$, for every ion. Intead, we have plotted curves for several selected ions, and for the remaining ions have denoted the maximum value of

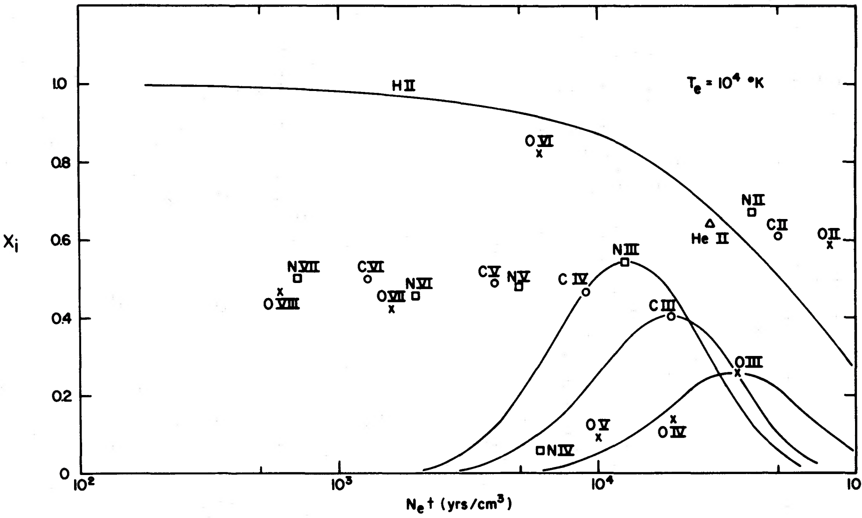

FIG. 4.—Distribution of ionization of the elements as a function of time, assuming initial complete ionization of all elements, followed by electron recapture at a temperature of 10^4 K. Ionization curves showing $x_i(t)$ are given only for H^+, C^{+2}, N^{+2}, and O^{+2}. For all other ions, the maximum value of the abundance attained by each ion is denoted at the time of occurrence.

the abundance attained by each ion at the time it occurs.

The most striking feature of the curves is the progressively longer time scales that are required for the recombination of lower stages of ionization. This is due to the larger recapture cross sections of ions with large effective nuclear charge, caused by their higher Coulomb fields. So pronounced is this effect that the recombination time for any given ion is generally greater than the sum of the combined recombination times for all higher stages of ionization of that element. The net result of this is that CNO recombine from even the highest possible stage of ionization down to C^{+2}, N^{+2}, and O^{+2} before the H has been substantially reduced in ionization. This fact makes it difficult to conceive of any realistic situation in which most of the H is neutral while the heavy elements remain ionized. Consequently, the interpretation of the relative intensities of the emission lines in DQ Her in terms of abundance enhancements is made more secure. We cannot think of any other alternatives that are plausible.

VI. SUMMARY

The spectra of different regions of the shell around DQ Her show carbon, nitrogen, and oxygen recombination lines which are much stronger relative to the Balmer lines than normally seen in nebulae. A broad emission feature at λ3644 Å appears in all spectra, which we attribute to the Balmer continuum from a cold gas ($\lesssim 500$ K). Variations in the heavy-element/hydrogen recombination line strengths occur

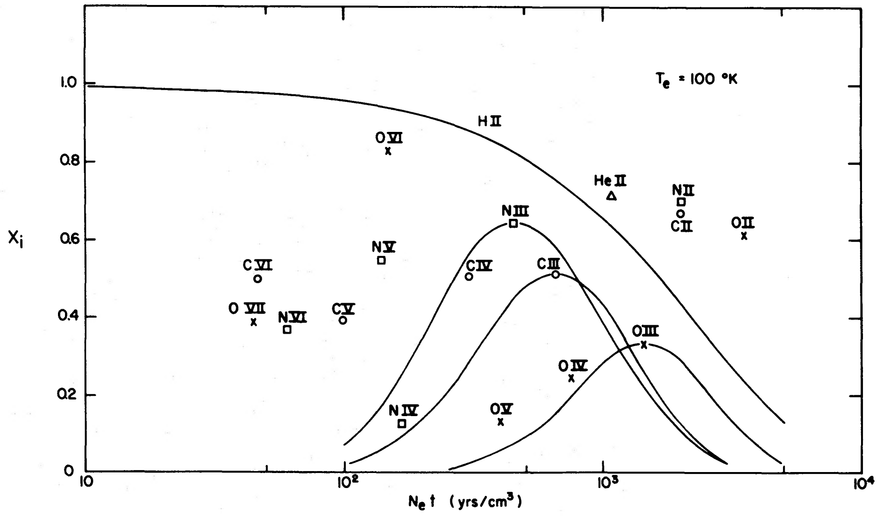

FIG. 5.—Same as Fig. 4, except that the assumed electron temperature is 10^2 K

in the sense that the CNO lines are weaker with respect to H at the ends of the minor axis of the ellipsoidal shell than at the ends of the major axis. Forbidden lines of [N II] and [O II] are present, which are probably formed by collisional excitation, and therefore require the presence of a hotter component of gas ($\gtrsim 5 \times 10^3$ K). It is possible that these lines might be produced by recombination, in which case the entire spectrum of the shell could be explained in terms of a cold gas, as would be expected if the source of ionization and heating of the shell were very strong near the time of the nova outburst, but declined thereafter. It is difficult to escape the conclusion that the total CNO abundance in the shell relative to H is two orders of magnitude above the solar value. The variations in the line strengths are consistent with lower heavy-element abundances in parts of the shell or differences in the ionization, although in the latter instance one might expect lines from other ions of CNO to become visible.

In spite of the many uncertainties surrounding the identification and interpretation of the line spectrum of the shell of DQ Her, the evidence suggests heavy-element abundance enhancements in the nova ejecta. It is unclear how this result is to be understood in the context of current ideas concerning the nova outburst, since recent models of Sparks, Starrfield, and Truran (1977) have shown that slow novae, like DQ Her, may be produced by CNO burning with solar abundances. Similar investigations of the shells around fast novae are planned in order to determine what differences might exist in the envelopes of fast and slow novae.

This research has been supported by the National Science Foundation through grant AST 77-15865.

REFERENCES

Aldrovandi, S. M. V., and Péquignot, D. 1973, *Astr. Ap.*, **25**, 137.

Black, J. H., and Gallagher, J. S. 1976, *Nature*, **261**, 296.

Ferland, G., Lambert, D. L., and Woodman, J. H. 1977, *Ap. J.*, **213**, 132.

Gallagher, J. S. 1978, *Ap. J.*, **221**, 211.

Gallagher, J. S., and Anderson, C. M. 1976, *Ap. J.*, **203**, 625.

Gallagher, J. S., and Holm, A. V. 1974, *Ap. J.* (*Letters*), **189**, L123.

Grandi, S. A. 1976, *Ap. J.*, **206**, 658.

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

Hutchings, J. B. 1972, *M.N.R.A.S.*, **158**, 177.

Kaler, J. B. 1976, *Ap. J. Suppl.*, **31**, 517.

Leighton, R. B. 1959, *Principles of Modern Physics* (New York: McGraw-Hill), p. 519.

McLaughlin, D. B. 1960, in *Stellar Atmospheres*, ed. J. L. Greenstein (Chicago: University of Chicago Press), p. 585.

Moore, C. E. 1959, *A Multiplet Table of Astrophysical Interest* (rev. ed.; NBS Tech. Note 36).

Mustel, E. R., and Boyarchuk, A. A. 1970, *Ap. Space Sci.*, **6**, 183.

Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).

Payne-Gaposchkin, C. 1957, *The Galactic Novae* (Amsterdam: North-Holland).

Soderblom, D. 1976, *Pub. A.S.P.*, **88**, 517.

Sparks, W. M., Starrfield, S. G., and Truran, J. W. 1977, in *Novae and Related Stars*, ed. M. Friedjung (Dordrecht: Reidel), p. 219.

Starrfield, S. G., Truran, J. W., and Sparks, W. M. 1977, in CNO *Isotopes in Astrophysics*, ed. J. Audouze (Dordrecht: Reidel), p. 49.

Stone, R. P. S. 1977, *Ap. J.*, **218**, 767.

Weaver, H. F. 1974, in *Highlights of Astronomy*, ed. G. Contopoulos (Dordrecht: Reidel), Vol. **3**, p. 509.

Wiese, W. L., Smith, M. W., and Glennon, B. M. 1966, *Atomic Transition Probabilities I* (NSRDS-NBS 4).

Williams, R. E. 1977, in *IAU Colloq. No. 42*, *The Interaction of Variable Stars with Their Environment*, ed. R. Kippenhahn, J. Rahe, and W. Strohmeier (Bamberg: Remeis-Sternwarte), p. 242.

E. K. Hege, D. A. Kopriva, R. L. Moore, R. E. Williams, and N. J. Woolf: Steward Observatory, University of Arizona, Tucson, AZ 85721