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CARBON MONOXIDE EMISSION AND THE η CARINAE STAGE OF NOVA NQ VULPECULAE

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ABSTRACT

This paper announces the detection of CO emission from Nova NQ Vul. First-overtone vibration-rotation bands were detected in a 1.6–2.2 μm spectrum obtained 19 days after outburst, ~20 days before the large visual fading. The absence of detectable ^{13}CO bands sets the limit $^{12}C/^{13}C > 3$. CO emission at 4.8 μm is predicted to be ~40 times stronger than the 2.2 μm emission and easily accounts for the 5 μm emission feature discovered by Ney and Hatfield. This identification implies that CO emission persisted for 3 weeks in NQ Vul and that it was also present in FH Ser.

Photoionization equilibrium calculations were performed to deduce the physical conditions in the ejecta on day 19. The H^+ Strömgren sphere extends to only a small fraction of the radius of the nebula. A largely neutral region, which is heated by photoionization of heavy elements, extends to the outer edge of the ejecta. Strong Fe II, Mg II, and C I emission, a characteristic of the η Car phase of the nova outburst, originates here. This region may provide an auspicious site for both molecule and grain formation.

Subject headings: molecular processes — stars: abundances — stars: individual — stars: novae

I. NQ VULPECULAE—A DQ HERCULIS–TYPE NOVA

Infrared photometry of recent novae has provided new insights into the physics of novae shells. Discovery of a broad, strong infrared excess in the spectrum of FH Ser (Hyland and Neugebauer 1970; Geisel, Kleinmann, and Low 1970) led to the realization that dust grains could form in the ejecta. In addition to the thermal emission by warm dust grains, narrower infrared excesses have been identified. In particular, an excess of 5 μm was seen in both FH Ser (Geisel, Kleinmann, and Low 1970) and the recent nova NQ Vul (Ney and Hatfield 1978). The origin of this excess has not been identified. Clearly, infrared photometry over an extended wavelength interval and, in particular, spectroscopy should be undertaken for more novae in order to define the spectrum and to disentangle the contributions of the gas and the dust. This paper discusses infrared observations of NQ Vul, a recent nova of the DQ Herculis type.

Yamashita *et al.* (1977) outline the early development of NQ Vul which was discovered on 1976 October 21.7 by Alcock (1976). Between the discovery and early November, the nova varied erratically between about $V = 6.3$ and 8.5. The erratic decline continued after an initial sharp drop of 2 mag on 1976 November 3. A second drop of 3 mag, which occurred between about December 25 and 31, is probably the true signature of a DQ Herculis type. The nova was in the η Car phase, characterized by prominent Fe II, Ca II, and Na I emission, throughout 1976 November.

Ney and Hatfield (1978) discuss broad-band photometry at wavelengths of 0.5–12.5 μm for the period 3–235 days after outburst. The December drop in visual magnitude was accompanied by an infrared excess from 1 to 12.5 μm which can be interpreted as emission from an isothermal ($T \approx 900$ K) dust shell. A quite different infrared spectrum was found to be associated with the first drop in visual magnitude in early 1976 November. Ney and Hatfield interpret the spectrum as the result of free-free emission on which is superposed a contribution at 5 μm from an unidentified source; they note a suggestion that C_3 molecules may account for the 5 μm emission. The profile of the 5 μm feature on 1976 November 5 (Merrill 1977) is similar to the fundamental CO band.

In this paper, the detection of first-overtone vibration-rotation emission bands of CO at 2.3 μm is announced; a 1.6–2.4 μm spectrum was obtained on 1976 November 8, shortly after the first sharp drop in visual magnitude. It is suggested that the 5 μm excess can be identified with emission in the stronger fundamental CO bands. Although this is the first detection of the CO molecule in a nova spectrum, the CN radical has been detected earlier on rare occasions. The outstanding detection of CN occurred with DQ Her when the CN violet system was seen in absorption for about

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3 days near maximum. The CN absorption bands were not seen in either NQ Vul or FH Ser (Yamashita *et al.* 1977; Hutchings 1970). The conditions favoring the detection of CO are verified in the Appendix.

II. THE INFRARED SPECTRUM

NQ Vul was observed at the Kitt Peak National Observatory with the 4 m Mayall reflector and a Fourier transform spectrometer (Ridgway and Capps 1974; Hall 1976). Two spectra were obtained on 1976 November 8, or 19 days after outburst. The spectra representing a total of 3 hours of observation time were co-added to improve the signal-to-noise ratio and apodized to a resolution of 1 cm^{-1}; the original spectra are at a resolution of up to 0.15 cm^{-1}. A first-order correction for the telluric absorption lines was attempted by dividing the nova spectrum by a solar spectrum obtained with the same instrument. The final nova spectrum is shown in Figure 1. Regions of strong telluric absorption are not plotted.

III. CO EMISSION

The infrared spectrum contains very few emission lines; a line list (Table 1) is discussed later. A cluster of four "lines" attracted attention because they coincided closely with the CO first-overtone band heads which are a prominent feature in the absorption spectra of cool stars. Their identification as emission bands of the CO molecule is supported by a synthetic spectrum calculation. Figure 2 shows the nova spectrum around the CO bands. This is the first detection of carbon monoxide in the spectrum of a nova.

The synthetic spectrum was calculated on the assumption that the CO emission was produced in an optically thin layer in local thermodynamic equilibrium. CO line positions and intensities are well known; a procedure described by Hinkle, Lambert, and Snell (1976) was adopted. The line profile of a single CO line was assumed to match the observed profile of the Bγ line. The agreement between the synthetic and observed spectra suggests that the CO emission originates within or near the nova ejecta; the velocity of the CO and Bγ line cannot differ by more than 300 km s^{-1}. The shape of the CO contour is temperature-sensitive; a temperature $T = 3500 \pm 750$ K is derived. The CO mass is $10^{25.5\pm0.5}$ g ($d = 1.5$ kpc). For comparison, the carbon and oxygen mass of ejecta from V1500 Cyg was $10^{28.4\pm0.3}$ g (Ferland and Shields 1978). Sample synthetic spectra with the addition of ^{13}CO to the line list set a lower limit $^{12}\mathrm{C}/^{13}\mathrm{C} > 3$ to the isotopic abundance ratio. Positions of the ^{12}CO and ^{13}CO band heads are marked in Figure 2. The $^{12}\mathrm{C}^{17}\mathrm{O}$ 2–0 band head lies at 4306 cm^{-1}. A lower limit of $^{16}\mathrm{O}/^{17}\mathrm{O} > 3$ is set.

Identification of CO emission near 2.3 μm provides a straightforward explanation for the 5 μm excess observed by Ney and Hatfield. Emission in the first-overtone ($v' \rightarrow v'' = v' - 2$) bands near 2.3 μm must be accompanied by stronger emission in the fundamental ($v' \rightarrow v'' = v' - 1$) bands near 4.8 μm. For a typical vibration-rotation level, the ratio of the Einstein A values $A(v', J' \rightarrow v' - 1, J' - 1)$ and $A(v', J' \rightarrow v' - 2, J' - 1)$ is approximately 60. In the optically thin limit, the synthetic spectrum calculations predict the CO emission at 4.8 μm to be approximately 40 times stronger than at 2.3 μm. The predicted CO emission provides about a factor of 10 more flux than is required to account for the observed 5 μm excess. A part of this discrepancy is probably attributable to the crude modeling of the 5 μm filter bandpass used by Ney and Hatfield. It is difficult to estimate the effective bandwidth of the 5 μm filter because telluric absorption is quite strong. The discrepancy may also indicate that the CO fundamental lines are optically thick. The 5 μm band profile is similar to fundamental CO band profiles in cool stars (Merrill 1977).

IV. OTHER EMISSION LINES

The emission lines (see Table 1) in the 1.6–2.2 μm spectrum are recombination lines of hydrogen, carbon, and sodium.

The strongest line is Bγ with an equivalent width $W_\sigma \sim 75\ \mathrm{cm}^{-1}$ corresponding to a flux of 4.5×10^{-10} ergs $\mathrm{s}^{-1}\ \mathrm{cm}^{-2}$. The flux was estimated by normalizing the infrared spectrum to the flux at 2.2 μm given by Ney and Hatfield. This procedure is probably accurate to $\pm 30\%$. Other members of the Brackett series are identified in Figure 1.

Calculations show the Bα flux to be about 2.7 times stronger than the Bγ flux. The estimated Bα flux of 1.2×10^{-9} ergs $\mathrm{s}^{-1}\ \mathrm{cm}^{-2}$ accounts for the excess flux which was apparently present in the bandpass of the 3.8 μm filter.

V. THE NOVA SHELL

In this section a model of the ionization structure of the ejecta is presented. The goals are to determine whether conditions amenable to molecule formation, survival, and heating are present. The ejecta are assumed to be in photoionization equilibrium around a central object radiating as a blackbody.

The color temperature of the central object must be determined. The absence of detectable He I lines sets an upper limit to T_*, since the radiation field can contain few photons capable of ionizing He^0. The upper limit $I(\mathrm{He\ I}\ 1.70\ \mu\mathrm{m})/I(\mathrm{H\ I}\ 1.68\ \mu\mathrm{m}) < 0.2$ sets the limit $N(\mathrm{He}^+)/N(\mathrm{H}^+) < 0.04$. If the total helium abundance is cosmic or enhanced (He/H ≥ 0.11), then $T_* < 30{,}000$ K (Hummer and Seaton 1964).

The Bγ Zanstra temperature provides a lower limit to T_* (Harmon and Seaton 1966); H$^+$ continuous emission accounts for approximately half of the continuum at 2.1 μm. This contribution was predicted from the strength of Bγ and an electron temperature of 7500 K. The equivalent width of Bγ ($W_\sigma = 75\ \mathrm{cm}^{-1}$) sets a limit $T_* > 26{,}000$ K. The covering factor, which accounts for the fraction of ionizing photons intercepted by the ejecta, is unknown, so the Zanstra

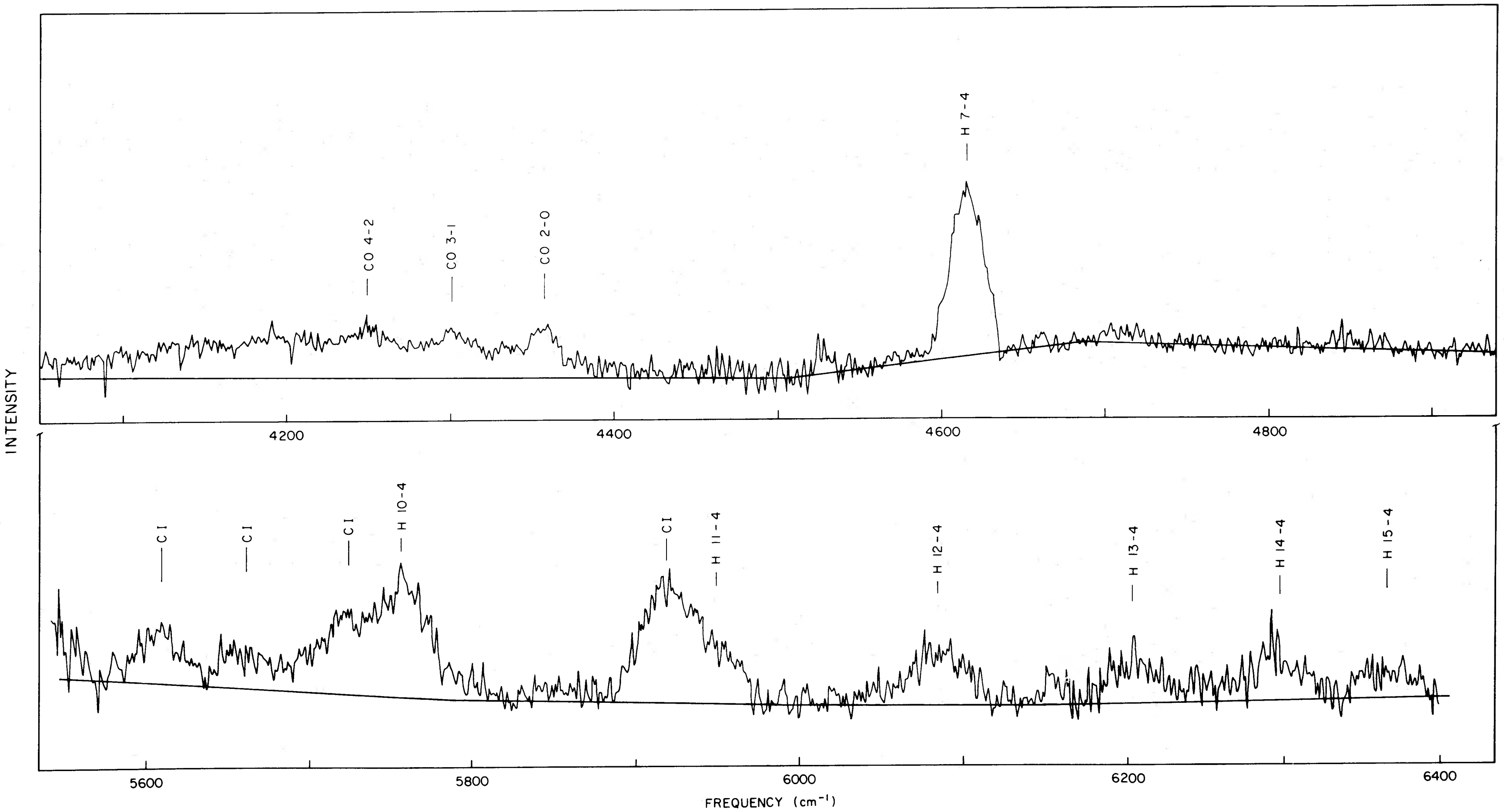

FIG. 1.—1.6 μm–2.2 μm spectrum of NQ Vul obtained with the 4 m Mayall reflector at the Kitt Peak National Observatory. The data have been apodized to a resolution of 1 cm^{-1} and divided by a solar spectrum to remove the effects of telluric absorption and the instrumental sensitivity function. Identifications of the stronger lines are marked. Hydrogen and carbon recombination lines dominate the near-infrared spectrum of this DQ Herculis–type nova. The hydrogen line Bδ at 5138 cm^{-1} is not shown. An interpolated continuum is drawn as a light line.

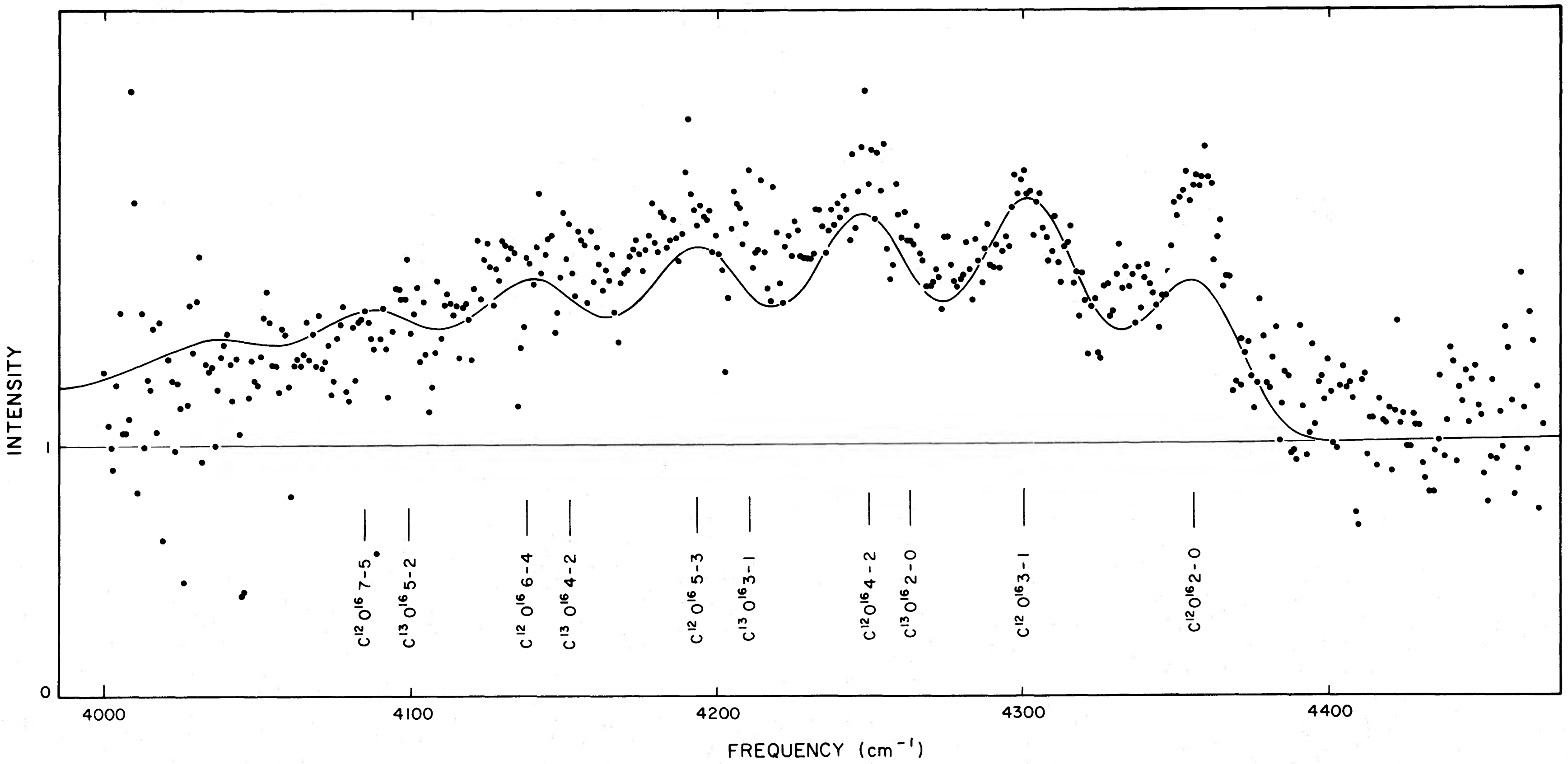

FIG. 2.—CO emission bands in the spectrum of NQ Vul. The synthetic spectrum (*solid line*) shows the emission predicted for an optically thin layer at $T = 3500$ K. The interpolated continuum is shown by the thin horizontal line. Positions of the ^{12}CO and ^{13}CO *R*-branch band heads are marked.

TABLE 1

NQ VUL LINE LIST

ν_σ* (cm^{-1})	W_σ (cm^{-1})	Ion	Transition	$I/B\gamma$†
4528.........	15	Na^0	$4s\,^2S$–$4p\,^2P^o$	0.12
4615.........	75	H^0	7–4	1.0
5138.........	63	H^0	8–4	1.0
5608.........	18	C^0	$3d\,^3D^o$–$4f[2\frac{1}{2}]$	0.4
5660.........	12	C^0	$3d\,^3D^o$–$4f'[3\frac{1}{2}]$	0.2
5715.........	29	C^0	$3d\,^3F^o$–$4f[3\frac{1}{2}]$	0.6
5760.........	57	H^0 C^0	10–4 $3d\,^3F^o$–$4f'[4\frac{1}{2}]$	1.2
5919.........	58	C^0	$3p\,^1D$–$3d\,^1F^o$	1.3
5950.........	27	H^0	11–4	0.6
6090.........	36	H^0	12–4	0.8
6206.........	25	H^0	13–4	0.6
6292.........	26	H^0	14–4	0.6
6360.........	21	H^0	15–4	0.5

* Vacuum wavenumber ($\Delta\sigma \pm 3\ \mathrm{cm}^{-1}$) uncorrected for a radial velocity displacement.

† Approximate intensity, computed by assuming that the continuum is Rayleigh-Jeans ($B_\nu \propto \nu^2$).

method provides only a lower limit. The agreement between the He^+ upper limit and the Zanstra temperature lower limit suggests that the covering factor is large ($\Omega/4\pi \sim 0.3$–1.0).

In principle, the energy distribution should provide another temperature indicator. However, the interstellar reddening of NQ Vul is poorly determined. The equivalent widths of interstellar CH, CH^+ lines indicate $E_{B-V} = 1.2 \pm 0.2$ (Carney 1977), but Yamashita *et al.* (1977) find that the object's galactic position would suggest a reddening of 0.8. The 0.5–10 μm energy distribution can be fitted with a combination of Rayleigh-Jeans blackbody and H^+ continuous emission if the reddening is 1.2 mag, i.e., the shape is temperature-independent. If the reddening is smaller then a poorer fit with a lower temperature blackbody can be obtained, e.g., $T_* \sim 6000$ K for $E_{B-V} = 0.8$. This point is not critical because the gross features of the ionization structure are not sensitive to T_*.

A temperature of $T_* = 27{,}000$ K will be assumed for our model. The blackbody radius and luminosity are $R_* = 0.1$ AU and $M_{\mathrm{bol}} = -8 \pm 2$ mag ($d = 1.5$ kpc).

A constant-pressure photoionization equilibrium model was computed with a computer program described by Baldwin and Netzer (1978). The model parameters and composition are listed in Table 2. The radius of the ejecta was computed from the elapsed time and expansion velocity (Ney and Hatfield 1978). The chemical composition of V1500 Cygni was assumed (Ferland and Shields 1978); i.e., C, N, and O are overabundant relative to a solar composition. This composition is similar to that found by Williams *et al.* (1978) in ejecta from DQ Her. The model is not sensitive to the assumed density, $N_{\mathrm{H}} = 10^{12}\ \mathrm{cm}^{-3}$, a typical density near maximum light (Mustel 1964).

TABLE 2

MODEL PARAMETERS

R_{ejecta}....	7×10^{13} cm	He/H	0.1
$Q(\mathrm{H})$.....	2.9×10^{49} photons s^{-1}	C/H	1.2×10^{-2}
$F_\nu(912)$...	8.1×10^{23} ergs $\mathrm{s}^{-1}\,\mathrm{Hz}^{-1}$	N/H	1.1×10^{-2}
N_{H}.......	$10^{12}\ \mathrm{cm}^{-3}$	O/H	1.7×10^{-2}
T_*.......	27,000 K	Fe/H	1.0×10^{-4}

The ionization structure is shown in Figure 3. Three distinct regions are present. The hydrogen Strömgren sphere extends to 2.5×10^9 cm and is characterized by fairly high ionization (H^+, C^+, O^+, Fe^{++}, Mg^{++}). Hydrogen ionizing photons do not penetrate beyond the H^+ Strömgren radius, so only ions with ionization potentials less than 1 rydberg exist. A region characterized by N^0, O^0, C^+, Fe^+, and Mg^+ extends out to $r_c = 5 \times 10^{11}$ cm, where carbon ionizing photons are exhausted. The outer C^0, N^0, O^0, Fe^+, Mg^+ zone extends to the edge of the nebula, $r_{\mathrm{neb}} \sim 2 \times 10^{12}$ cm. This largely neutral region is heated to 4000 K by photoionization of the metals (Mg, Fe, etc.).

A large neutral hydrogen ionized metal zone exists because the ionizing radiation field peaks longward of the ionization limit of hydrogen. This is a characteristic of all models with $T_* \lesssim 40{,}000$ K. The ionization structure shown in Figure 3 is a general property of metal-rich nebulae ionized by a fairly cool radiation field and is not sensitive to the details of the model.

This model accounts for several important characteristics of the η Car phase of the nova outburst. During the period just after maximum light, novae display strong emission lines of Fe II and Mg II. Thackeray (1978) noted that the strengths of Fe II lines relative to hydrogen lines appear to indicate $\mathrm{Fe}^+/\mathrm{H}^+ \approx 1$. This ionic ratio is achieved by the model with a solar iron abundance. The Fe II emission is the result of collisional excitation in the hot C II–O I zone. The model predicts that the Mg II 2798 doublet should be the strongest nebular line during the η Car stage. Other strong predicted lines are NaD (recombination) and Ca II (K, H, and infrared triplet). Gallagher and Code (1974) and Jenkins *et al.* (1977) found very strong Mg II during the η Car phases of FH Ser and V1500 Cyg.

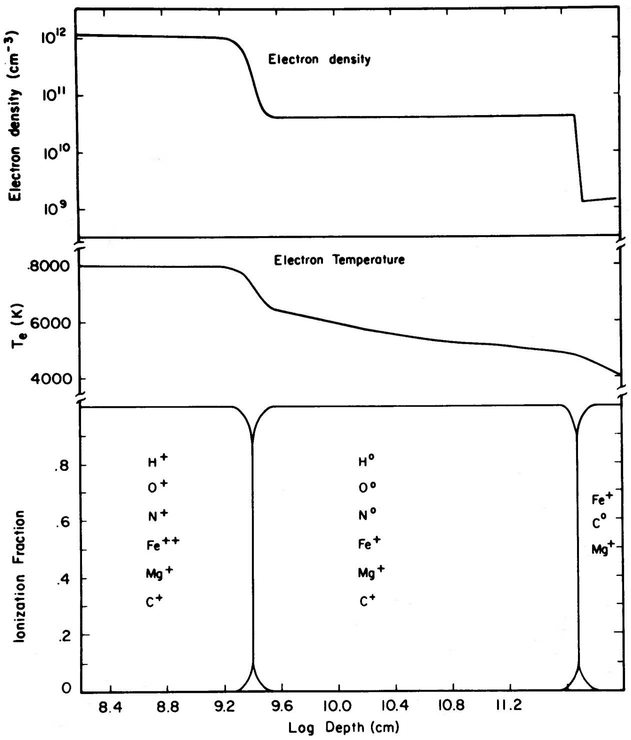

FIG. 3.—Ionization structure of NQ Vul computed with the parameters in Table 2. The abscissa is marked in depth from the inner face of the cloud. An extensive H^0, Fe$^+$, Mg$^+$ region exists because the ionizing radiation field peaks below the H^0 ionization limit. This neutral zone is heated to $T_e \sim 4000$ K by photoionization of heavy metals (e.g., Fe$^+$, Mg$^+$). The maximum thickness shown represents the physical edge of the nebula if the total mass is 4×10^{29} g $(\Omega/4\pi)$.

In addition to the Brackett series of hydrogen, strong C I recombination lines are present. The strongest, $3p\,^1D$–$3d\,^1F^o$, 1.69 μm, is twice as strong as the adjacent hydrogen lines. The effective recombination coefficient for C I 1.69 μm was computed by scaling from hydrogen Paschen lines. One-quarter of recombinations were assumed to be to C I singlet states, and transition probabilities were taken from Wiese, Smith, and Glennon (1966). The result is $\alpha_{1.69\,\mu\mathrm{m}}{}^{\mathrm{eff}} = 2.4 \times 10^{-16}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}$ ($T_e = 10^4$ K), probably accurate to a factor of 4. The observed C I/H I intensity ratio corresponds to $N(\mathrm{C}^+)/N(\mathrm{H}^+) = 5.3$, while the value predicted by the model is 3.8. The agreement is not surprising; the ratio is mainly sensitive to the shape of the ionizing radiation field rather than to the C/H abundance because both the C$^+$ and H$^+$ Strömgren spheres extend to the position where ionizing photons are exhausted.

The outer zone of the model is an attractive site for molecule formation. At the assumed density ($N_{\mathrm{H}} \sim 10^{12}\ \mathrm{cm}^{-3}$), molecule formation probably occurs on a satisfactorily short time scale; a chain of ion-molecule reactions should guarantee this provided that the initial molecules for the chain can be formed. In the outer zone, CO molecules should be stable against photodissociation and photoionization. Furthermore, the vibration-rotation temperature is close to the equilibrium temperature.

The 5 μm excess which is a monitor of the CO emission was present for about 1 month. Several possibilities can be invoked to explain the disappearance of the CO emission. The molecules may have amalgamated into larger molecules and dust grains. Ney and Hatfield detected thermal emission from dust within 30 days of the disappearance of the 5 μm excess.

Another contributing factor may be a temperature increase of the central ionizing source. Novae grow hotter as they fade (McLaughlin 1960; Gallagher and Starrfield 1976). A temperature increase will lead to an expansion of the Strömgren sphere into the warm H^0, Fe$^+$, Mg$^+$ zone. The result will be an increase in the 5 μm bremsstrahlung radiation and a decrease in the total CO content of the outer zone. Therefore the CO emission will contribute a smaller fraction of the total 5 μm radiation; i.e., the 5 μm excess will diminish. A trial model for day 40 with $T_* = 60{,}000$ K (assuming $N_e \propto \mathrm{time}^{-2}$ and the initial conditions) shows that the H$^+$ Strömgren radius is indeed near the outer edge of the cloud. Of course, these effects, which result from a change in the central source, can occur at the same time as dust grains soak up CO in the outer portions of the H^0, Fe$^+$, Mg$^+$ zone.

VI. CONCLUSIONS

A simple model of the NQ Vul shell explains in a semiquantitative way several important features of the spectrum. The absence of the He I recombination lines and the equivalent width of the Bγ line suggest that the central ionizing source had a temperature $T_* \sim 27{,}000$ K and that the covering factor, $\Omega/4\pi$, was fairly large (0.3–1.0). A calculation shows that this source can ionize H only in the inner regions of the ejecta. However, species with ionization potentials less than that of H are ionized over a larger region. In particular, Fe$^+$ and Mg$^+$ exist throughout the region in which H is neutral. Photoionization of Fe, Mg, and other metals heats this outer region to about 4000 K. This zone is responsible for the strong emission lines of Fe II and Mg II which are an outstanding characteristic of the η Car phase of the nova outburst. The model also accounts for the strong infrared C I recombination lines.

The outer zone appears to be the site for the CO emission whose discovery is announced in this paper. The infrared spectrum of NQ Vul obtained about 6 weeks before the DQ Her drop shows the bands of CO emission at 2.2 μm. The excitation temperature is consistent with the predicted equilibrium temperature for the outer zone. A previously reported 5 μm excess for NQ Vul and also FH Ser (a similar DQ Herculis-type nova) can also be attributed to CO emission. CO as monitored by the 5 μm excess was present for about 3 weeks. Disappearance of CO may be attributable to the incorporation of the molecules into dust grains or to an increase in the temperature of the ionizing source with a resultant reduction in the size of the outer H^0, Fe$^+$, Mg$^+$ zone.

It is hoped that the detection of CO emission from novae ejecta will stimulate observers to obtain infrared spectrophotometry with moderate resolution at closely spaced time intervals in order to define the CO emission phase for a sample of novae. A high-quality spectrum would provide useful excitation temperature and velocity information for the CO layer as well as an estimate for the isotopic C and O ratios. A search of the infrared spectrum may reveal other molecular lines.

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APPENDIX

CO EMISSION AND CN ABSORPTION LINES IN NOVAE SPECTRA

Conditions favoring the detection of CO in emission are examined in this Appendix. The molecules are assumed to reside in a spherical shell of radius R_s and thickness H. CO molecules exist at density N_{CO}. The line width of a line in the shell spectrum is $\Delta\lambda_{\mathrm{CO}}$. The contrast of the CO emission-line peak relative to the stellar continuum (a correction may be added to account for the nebular emission) can be written

$$C_{\mathrm{CO}} = \frac{n'_{\mathrm{CO}} A_{\mathrm{CO}} h\nu_{\mathrm{CO}}}{\pi B_\lambda(T_*)\Delta\lambda_{\mathrm{CO}}} \frac{R_s{}^2 H}{R_*{}^2} ,$$

where n'_{CO} denotes the population of an excited state, A_{CO} is the transition probability for spontaneous emission, T_* and R_* are the temperature and radius of the central star. The shell is assumed to be optically thin to the CO emission.

The strength of the CN absorption lines in the blue part of the spectrum depends on the optical depth along the thickness H through the shell. Emission via collisional excitation at the low shell temperature ($T_s \sim 3500$ K) is unlikely to contribute significantly to the spectrum. The contrast factor for an optically thin absorption line can be written

$$C_{\mathrm{CN}} = \frac{n_{\mathrm{CN}}'' A_{\mathrm{CN}} \lambda_{\mathrm{CN}}{}^4 H}{8\pi c \Delta\lambda_{\mathrm{CN}}} ,$$

where n_{CN}'' is the number of CN molecules in the lower level. Statistical weights of upper and level are assumed equal.

On substitution of the Rayleigh-Jeans approximation for the Planck function $B_\lambda(T_*)$, the ratio of the contrast factors simplifies to

$$C' = \frac{C_{\mathrm{CO}}}{C_{\mathrm{CN}}} = \frac{n_{\mathrm{CO}}'}{n_{\mathrm{CN}}''} \frac{A_{\mathrm{CO}}}{A_{\mathrm{CN}}} \frac{\lambda_{\mathrm{CO}}{}^2}{\lambda_{\mathrm{CN}}{}^3} \frac{4hc}{kT_*} \frac{(R_s)^2}{(R_*)^2} .$$

For typical lines, $A_{\mathrm{CO}} \sim 20\ \mathrm{s}^{-1}$, $\lambda_{\mathrm{CO}} \sim 5\ \mu\mathrm{m}$, and $A_{\mathrm{CN}} \sim 1.5 \times 10^7\ \mathrm{s}^{-1}$ and $\lambda_{\mathrm{CN}} \sim 3890$ Å. The n_{CO}' and n_{CN}'', which here refer to vibrational levels $v = 1$ and $v = 0$, respectively, can be expressed in terms of the molecular partition functions. The central star of NQ Vul at the time of the CO observations had $T_* \sim 27{,}000$ K. Substitution in C' yields

$$C' \approx 1 \times 10^{-3} \frac{(R_s)^2}{(R_*)^2} \frac{n_{\mathrm{CO}}}{n_{\mathrm{CN}}} .$$

The small value for the numerical coefficient results from the large difference in the Einstein A coefficient between a vibration-rotation transition (CO) and an electronic transition (CN).

The stellar radius is $R_* \approx 10^{12}$ cm. The shell radius R_s can be as large as the outer extent of the ejecta, which is given by the velocity time since outburst product or $R_s \sim 7 \times 10^{13}$ cm (see Table 2). Then,

$$C' \sim 5 n_{\mathrm{CO}}/n_{\mathrm{CN}} .$$

Absence of CN absorption lines suggests $n_{\mathrm{CO}} > n_{\mathrm{CN}}$, which is not unexpected. Clearly, if molecules can form at an early stage in the outburst when R_s is smaller, CN detection may be favored. Their absence would imply $n_{\mathrm{CO}} \gg n_{\mathrm{CN}}$.

In the future, it should be possible to search for CO, CN, NO, SiO, CH, NH, OH, and other molecules in the 3–5 μm interval. Analysis of the emission lines should yield relative molecular, isotopic, and elemental abundances. A comparison with molecular absorption lines in the visible and ultraviolet will provide information on the radius of the molecular shell.

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