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AN X-RAY MODEL FOR THE NEBULA OF NOVA DQ HERCULIS 1934

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ABSTRACT

A model for the nebula of DQ Her is presented which is built upon the assumption that the power is provided by an X-ray source. The X-ray and UV energy spectra recently calculated by Kylafis and Lamb for the case of spherical accretion onto degenerate dwarfs are modified to take account of the geometry of the system. The influence of a low frequency cutoff is considered: the column density we find to be consistent with our model falls nicely in the range inferred for nova systems by recent observations of Cordova, Mason, and Nelson. The effects of the radiation field upon the envelope ejected in the 1934 outburst were determined with a photoionization program which includes all X-ray heating and ionization processes known to be important (Compton recoil by both bound and free electrons, the Auger effects, and secondary ionization by suprathermal electrons). Our calculations show that many observed features of the nebula follow as a very natural consequence of this model. Specifically, the nebula is expected to be very cool, ~300 K, and to show extremely strong recombination lines of ionized carbon, nitrogen, and oxygen, as previously reported by Williams *et al.* Time variations of the inferred nebular composition are to be expected, as the reestablishment of accretion flows, formation of a disk, and the ensuing emergence of an X-ray flux must follow upon the turnoff of the underlying white-dwarf nova remnant. Scrutiny of the spectroscopic data for DQ Her suggests that this turnoff occurred in the late 1940s, and that the nebula cooled rapidly in this stage. The relevance of our results to studies of other nova nebular remnants is briefly examined.

Subject headings: nebulae: individual — stars: individual — stars: novae — X-rays: sources

I. INTRODUCTION

Observational studies of the nebula surrounding the old nova DQ Herculis 1934 have, through the years, revealed a number of interesting and yet unexplained features. Mustel and Boyarchuk (1970) noted that the [O III] λλ4959, 5007 emission lines (usually the dominant features in nebula spectra) weakened throughout the 1940s, and had virtually disappeared by 1950. This weakening must have been caused by a dramatic decrease in the temperature of the shell, since it was not accompanied by a corresponding decrease in the emission measure of the nebula, as indicated by Hβ. The fact that the nebula had grown quite cool was confirmed by the identification by Williams *et al.* (1978) of a strong sharp Balmer jump, indicating $T_e \leq 500$ K. The gas appears to have been this cool for at least 25 years, since the sharp Balmer jump is evident in old spectroscopic observations (Greenstein and Kraft 1959).

The emission line spectrum presents two further puzzles. Strong [O II] λ3727 and [N II] λλ6548, 6584 forbidden lines are present together with strong recombination lines of C^{+2}, N^{+2}, and O^{+2}. If the forbidden lines are collisionally excited, then a second, warm, region ($T_e \gtrsim 6000$ K) would appear to be required. The strengths of the recombination lines are surprising, since taken at face value they indicate that the nebula is presently ~6 times more enriched in carbon that it was in 1935 (although the He/H ratio may have decreased) and that the degree of the carbon enrichment varies across the face of the nebula (Williams *et al.* 1978; Ferland and Truran 1980). Ferland and Truran (1980) have also noted that these large abundance variations cannot be understood in the context of current theoretical models of the outbursts of classical novae. The fact that the present data indicate that fully half the observed mass is in the form of carbon, nitrogen, and oxygen clearly distinguishes DQ Her with respect to other slow novae (Truran 1980).

The fact that the nebula has remained in its present state for several decades while, simultaneously, the C^{++}/H^{+} ratio has increased suggests that the nebula continues to be ionized by a source of hard radiation, and that this ionic abundance ratio may not reflect the true composition of the shell. In this paper we consider Ferland and Truran's (1980) contention that the physical conditions in the shell of DQ Her can be

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understood in terms of steady state X-ray photoionization. We assume an X-ray source attributable to steady state accretion onto the white dwarf. In the next section, we discuss the likely form of the X-ray continuum; in § III, photoionization models of the nebula are presented. An X-ray continuum with a low frequency cutoff and a luminosity of only $\sim 10^{34}$ ergs s^{-1} can produce many of the observed properties, and is consistent with a heavily obscured accretion shock, similar to those considered by Fabian, Pringle, and Rees (1976) and Kylafis and Lamb (1979). A discussion of the significance of these results is presented in § IV. The predicted evolution of the nebula in the context of a "frozen-in ionization" model is illustrated in an appendix.

II. THE X-RAY SPECTRUM

X-radiation resulting from accretion onto degenerate dwarfs has recently been examined in some detail by Kylafis and Lamb (1979; see also Kylafis 1978). These authors considered, specifically, the case of spherical accretion onto nonmagnetic white dwarfs. The X-ray and UV spectra they have calculated provide the basic input to our present study. Direct application to the case of DQ Her is of course inappropriate, since we are dealing with a binary system for which accretion is expected to occur via a disk in a manner which is strongly influenced by the presence of a magnetic field. It is straightforward, however, to scale the Kylafis and Lamb spectra in a manner consistent with considerations of the overall geometry. Here, we follow the analysis of disk accretion onto a magnetized white dwarf given by Fabian, Pringle, and Rees (1976).

The accretion luminosity is given generally by

$$L=\frac{GM}{R}\dot{M}=2.66\times 10^{34}\left(\frac{M}{M_\odot}\right)\left(\frac{R}{5\times 10^{8}\ \mathrm{cm}}\right)^{-1} \times\left(\frac{\dot{M}}{10^{17}\ \mathrm{g\ s^{-1}}}\right)\mathrm{ergs\ s^{-1}},$$

where we have normalized to the case of a solar mass white dwarf and an accretion rate 10^{17} g $s^{-1} \equiv 1.6\times 10^{-9} M_\odot$ yr^{-1}. Funneling of the accretion flow down the field lines onto the magnetic poles of the white dwarf occurs over a fraction f of the stellar surface area which is dependent upon the strength of the surface magnetic field. Assuming the mass flux to be uniform and radial over the accreting area, the density is then given by

$$\rho=4.2\times 10^{-11}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{R}{5\times 10^{8}\ \mathrm{cm}}\right)^{3/2} f^{-1} \times\left(\frac{\dot{M}}{10^{17}\ \mathrm{g\ s^{-1}}}\right)\mathrm{g\ cm^{-3}}.$$

The calculated spectra of Kylafis and Lamb (1979) are parametrized by the ratio of the accretion rate to the Eddington value:

$$\dot{M}_{\mathrm{E}}=\frac{4\pi cR}{\kappa_0}=5.36\times 10^{20}\left(\frac{\mu_e}{1.14}\right)\left(\frac{R}{5\times 10^{8}\ \mathrm{cm}}\right)\mathrm{g\ s^{-1}},$$

where the choice $\mu_e=1.14$ corresponds to matter of solar composition. The appropriate spectrum to choose is that for which the effective rate of accretion over the accreting area $4\pi R^2 f$ is compatible with our model:

$$\left(\frac{\dot{M}}{\dot{M}_{\mathrm{E}}}\right)_{K-L} =1.83\times 10^{-4}\left(\frac{R}{5\times 10^{8}\ \mathrm{cm}}\right)^{-1}\left(\frac{\dot{M}}{10^{17}\ \mathrm{g\ s^{-1}}}\right)f^{-1}.$$

The results of our analysis of the nebula of DQ Her are particularly sensitive to the character of the emergent energy spectrum. It is therefore important to examine carefully the consequences of absorption of the outgoing radiation by the accreting matter. These effects are again dependent upon the geometry of the system. The accretion shock is situated at a distance D above the surface of the star which is dependent upon the cooling time scale for the infalling matter below the shock. The radius of the accretion column is given approximately by $d=(2f)^{1/2}R$. In general, when $D \gg d$, absorption effects are not important whereas for $D \lesssim d$ the emergent radiation will encounter a column density N of absorbing matter given by (Fabian, Pringle, and Rees 1976; equation 49)

$$N\approx 1.4\times 10^{22}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{R}{5\times 10^{8}\ \mathrm{cm}}\right)^{1/2} \times f^{-1/2}\left(\frac{\dot{M}}{10^{17}\ \mathrm{g\ s^{-1}}}\right)\mathrm{cm^{-2}}.$$

We have performed detailed calculations of the absorption attributable to this column density of accreting material, for choices of $\dot{M}$ and f compatible with our model for DQ Her. We find that this matter is sufficiently strongly photoionized to ensure that no appreciable absorption occurs; therefore, for our parameter regime the energy spectra they have calculated on the assumption of complete ionization are appropriate.

Modification of the emergent energy spectra is nevertheless possible, if there should exist any appreciable amount of cooler matter within the system. As noted by Fabian, Pringle, and Rees (1976), such is suggested by evidence that much of the light in the system is due to reflection effects. In order to determine the effects of such material, we parametrize our models presented in

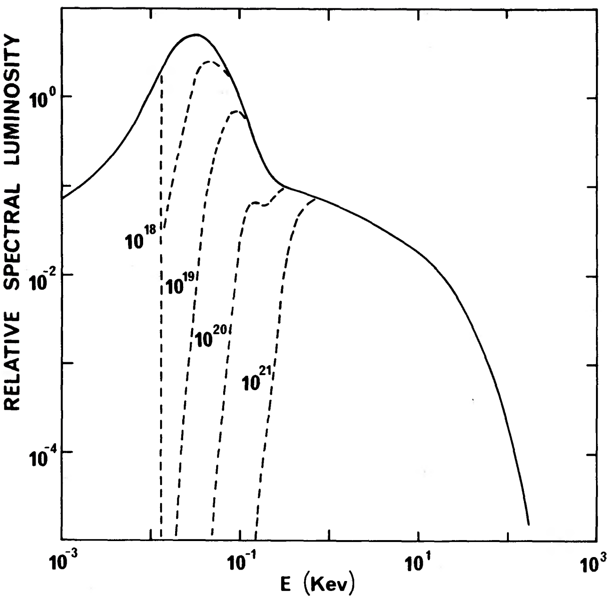

FIG. 1.—Ionizing continuum. The heavy curve shows the intrinsic energy distribution of the accretion shock, as computed by Kylafis and Lamb. The dashed curves show the continua actually used in our calculations. These continua have been extinguished by an amount given by the neutral hydrogen column density indicated, together with the extinction curves of Cruddace *et al.* (1974).

the next section by an effective column density of (assumed) cool matter. The low frequency absorption is taken to be that defined by the extinction curves of Cruddace *et al.* (1974) for our effective column density. The altered energy spectra determined by this procedure, illustrated in Figure 1, have important effects on the surrounding nebula and the associated line strengths.

The mass of the white dwarf in the DQ Her system is estimated to be $1\ M_\odot$ (Robinson 1976), the corresponding radius being 5×10^8 cm. We assume an accretion rate 3×10^{16} g s^{-1}, consistent with the observed speedup of the rotation rate, giving $L_{\rm acc}\sim8\times10^{33}$ ergs s^{-1}. The magnetic field is assumed to be of appropriate strength to funnel the matter accreting from the disk into an essentially radial flow over a fractional surface area $f=0.05$ at the magnetic poles. Our chosen accretion rate implies $\dot{M}/\dot{M}_{\rm E}=5.5\times10^{-5}$; the energy spectrum appropriate to our study is, however, that provided by Kylafis and Lamb (1979) for $(\dot{M}/\dot{M}_{\rm E})f^{-1}$ or 1.1×10^{-3}. Unless otherwise noted, the calculations presented below were performed for these stated assumptions regarding the DQ Her system.

III THE NEBULA

Williams *et al.* identify three distinguishing properties of the shell surrounding DQ Her. Perhaps the most outstanding property of the shell is its low temperature: the sharp Balmer jump indicates $T_e\lesssim500$ K. Despite this low temperature, the nebula must still be moderately ionized since C II, N II, and O II recombination lines are strong and indicate metal enrichments of several hundred times solar. Finally, [O II] λ3727 and [N II] λλ6548, 6584 are seen, and may require on their model a hot ($T_e\gtrsim4000$ K) region.

Williams *et al.* model the nebula in terms of "frozen-in ionization", an approach first discussed by Mustel and Boyarchuk (1976) in which the nebula is assumed to expand more rapidly than it recombines. This model, however, does not appear capable of explaining Ferland and Truran's (1980) determination that a significantly lower carbon abundance characterized the early nebular phase. The straightforward explanation of Ferland and Truran's results is that the C^{++}/H^+ ratio has increased by a factor of ~6 over the past 40 years. Such an increase would demand a continuing source of ionization, since C^{++} should recombine $\sim Z^2\sim4$ times faster than H^+ in a time-dependent model. This ionizing continuum cannot be a moderately hot blackbody ($T_*\sim10^5$ K) because such a radiation field would heat the gas too efficiently: $C^{++}/H^+\gtrsim C/H$ and $T_e<500$ K are mutually exclusive. We shall show in this section that photoionization by a moderately absorbed X-ray source can explain many observed features of the shell. The frozen-in ionization model is discussed in further detail in the Appendix.

a) *Model Calculations*

A model photoionization program is used to study the thermal and ionization structure of a nebula surrounding the X-ray source discussed in § II. Calculations are performed with a newly developed computer program similar to those described by Williams (1967), Davidson (1972), MacAlpine (1972), Shields (1976), Netzer (1976), and Péquignot, Aldrovandi, and Stasinska (1976). The nebula is divided into a set of thin concentric zones, and the equations of statistical and thermal equilibrium are solved in the standard manner. The ionizing continuum is then extinguished by the photoelectric optical depth of that zone, and the conditions in the next zone are determined.

All known processes involving X-ray interaction with neutral material have been explicitly included (see Dalgarno and McCray 1972 and Davidson and Netzer 1979 for reviews). Inner-shell photoionization cross sections are taken from Daltabuit and Cox (1972) and Weisheit (1974). All inner-shell vacancies are assumed to be filled following ejection of one Auger electron, and the equations of statistical equilibrium were modified as discussed by Weisheit.

Both the primary and Auger electron have energies much larger than the ambient electron temperature. These suprathermal electrons can cause several collisional ionizations before being thermalized when the gas is largely neutral (see Spitzer and Tomasko 1968; Habing and Goldsmith 1971; Shull 1979). Accordingly, Shull's (1979) Monte Carlo results have been incorporated into both the heating and ionization rates. The effects of the suprathermal electrons upon heavy elements were included by scaling Shull's prediction for hydrogen by the collisional ionization cross sections of Lotz (1967).

Valence shell photoionization cross sections are largely taken from Henry (1970), Seaton (1958), Brown (1971), and Reilman and Manson (1979). We have explicitly included production of [O II] $\lambda 3727$ and $\lambda 7325$ by photodestruction of O^0 using Henry's cross sections. At energies near threshold, $\sim 76\%$ of O^0 photoionizations populate excited states of O^+. The interpolation formulae given by Henry are valid only near threshold, so the curves of Cruddace *et al.* (1974) were used for large energies.

Radiative recombination coefficients are taken from Aldrovandi and Péquignot (1973), Summers (1974), and Gould (1978). The power law temperature dependences given by Aldrovandi and Péquignot were used and should be valid for $T_e \geq 10^2$ K. All known charge exchange reactions have been included in these calculations (Dalgarno 1978; Butler, Bender, and Dalgarno 1979; Butler and Dalgarno 1979; Butler, Heil, and Dalgarno 1980; Butler and Dalgarno 1980*a*, *b*). Charge exchange will proceed faster than radiative recombination when the exchange rate δ is larger than $\alpha N_e / N_{H^0} \sim 10^{-14}$ cm^3 s^{-1}, where $\alpha \sim 10^{-12}$ cm^2 s^{-1} is a typical radiative recombination rate and $N_e/N_H \sim 10^{-2}$ is typical of our models. Charge exchange rates are generally poorly known, and many important reactions may have been overlooked. These uncertainties could introduce order-of-magnitude errors into our calculations, but our results should remain qualitatively valid.

Effective recombination coefficients for Balmer lines at low temperatures were taken from Ferland (1980). The Hβ emissivity over the interval 500 K $\leq T_e \leq 10^4$ K can be expressed within 10% as

$$4\pi j(H\beta) = 1.74 \times 10^{-22} T_e^{-0.787} \text{ ergs cm}^3 \text{ s}^{-1}$$

Since effective recombination coefficients have not been computed for lines of other ions over the temperature range of interest, we have used the following expressions, which are valid over 5000 K $\leq T_e \leq 10^4$ K:

$$4\pi j(\text{He I } 4471) = 2.42 \times 10^{-22} T_e^{-0.9} \text{ ergs cm}^3 \text{ s}^{-1},$$

$$4\pi j(\text{C II } 4267) = 1.20 \times 10^{-20} T_e^{-1} \text{ ergs cm}^3 \text{ s}^{-1},$$

$$4\pi j(\text{N II } 5680) = 1.82 \times 10^{-24} T_e^{-0.83} \text{ ergs cm}^3 \text{ s}^{-1},$$

$$4\pi j(\text{O II } 4651) = 3.4 \times 10^{-22} T_e^{-0.64} \text{ ergs cm}^3 \text{ s}^{-1}.$$

The expressions for the He I, C II, and O II lines are from Brocklehurst (1972), Pengelly (1963), and Williams *et al.* (1978), respectively, while the N II rate is deduced by isoelectronic extrapolation from O III $\lambda 3760$ (Burgess and Seaton 1960). Extrapolation of these coefficients to $T_e \lesssim 500$ K may introduce a factor-of-2 error. Temperature-dependent collision strengths for lines of C^0, N^0, and O^0 are taken from Péquignot and Aldrovandi (1976).

b) Model Parameters

We model the nebula as a spherically symmetric homogeneous shell with an inner radius of $10^{16.7}$ cm, which follows from the expansion velocity of 350 km s^{-1} given by McLaughlin (1960) and the elapsed time since outburst. Direct photographs (Williams *et al.* 1978) show the nebula to have a relative thickness of $\Delta R/R \sim 0.3$. Visually, the nebula appears to be quite clumpy; accordingly, we have assumed a covering factor of $\Omega/4\pi = 0.3$ and a filling factor of 0.3. If $\sim 10^{-4} M_\odot$ was ejected in the 1934 outburst, then the hydrogen density is presently $\sim 10^{3\pm1}$ cm^{-3}.

We shall assume that DQ Her has a chemical composition identical to that of V1500 Cyg (Ferland and Shields 1978), with the exception of a carbon abundance as deduced from data obtained in 1935 (Ferland and Truran 1980). The specific abundances used were (He : C : N : O : Ne : Mg : Si : S : Ar : Fe) $\times 10^4$/H = 10^3: 118 : 250 : 174 : 22 : 0.26 : 0.33 : 0.16 : 0.063 : 0.4. The abundances of C, N, O, and Ne represent enhancements by factors of 53, 110, 21, and 20, respectively, over the solar values (Lambert 1978; Allen 1973).

The nebula is illuminated by the ionizing continuum described in § II. A variety of low frequency cutoffs, parametrized by an effective absorbing column density and the curves of Cruddace *et al.* (1974), will be employed. Since other physical characteristics (luminosity, shell density, and chemical composition) have been set by other considerations, the value of this low frequency cutoff is the only remaining free parameter.

c) Results

The results of a large number of model calculations are summarized in Table 1. The inner, outer, and mean (weighted with respect to the proton density) temperatures of the nebula for a variety of extinguishing column densities and nebular hydrogen densities are given, along with the total power in Hβ and the intensities of several emission lines. Observed intensities are summarized at the bottom of the table. The differences between the various models are largely caused by the effective hardening of the ionizing radiation field as the low frequency cutoff increases. For small column densities, the gas is mainly ionized by valence electron photoabsorption, and the models are quite similar to standard models of low ionization H II regions. For

TABLE 1

SUMMARY OF MODEL CALCULATIONS

log Column Density	log N_H	T_{in}	T_{out}	$\langle T \rangle$	$P(H\beta)$ $\times 10^{-30}$	He I 4471	He II 4686	C II 4267	N I 5200	N II 6584	O I 6300	O II 3727
0........	2	476	2065	1170	2.9	0.063	0.142	0.19	0	0.02	0	0.60
	3	3470	167	3180	6.0	0.134	0.145	0.10	0.11	8.41	0.29	1.32
	4	2915	130	1400	10.6	0.175	0.046	0.03	0.04	1.03	0.12	0.65
18........	2	4260	3661	4120	0.6	0.062	0.437	0.21	0.11	25.9	0.48	3.25
	3	4126	198	3290	3.4	0.208	0.292	0.12	0.46	16.3	0.99	2.49
	4	3051	132	1190	7.9	0.234	0.079	0.03	0.06	0.71	0.16	0.90
19........	2	5062	2640	4130	0.1	0.134	1.090	0.194	1.23	39.2	2.46	3.16
	3	4332	367	2980	1.1	0.374	0.579	0.135	1.92	10.5	2.53	1.83
	4	2236	147	695	6.1	0.230	0.054	0.025	0	0.002	0	0.58
20........	2	3831	68	2660	0.08	0.101	0.026	0.22	0.12	1.97	0.18	0.31
	3	579	52	178	1.1	0.125	0.004	0.20	0	0	0	0.19
	4	339	155	266	6.0	0.106	0	0.03	0	0	0	0.19
20.5	2	4180	62	2560	0.09	0.082	0.011	0.22	0.19	2.89	0.25	0.14
	3	452	60	204	0.3	0.092	0.002	0.19	0	0	0	0.03
	4	324	130	234	5.8	0.086	0.001	0.04	0	0	0	0.02
21........	2	4405	880	2900	0.05	0.062	0	0.070	0.73	4.0	0.98	0.13
	3	144	43	72	0.9	0.097	0	0.137	0	0	0	0
	4	178	139	199	4.6	0.087	0	0.023	0	0	0	0
22........	2	<100	...	...	...	...	...	...	...	...	...	...
	3	$\ll 100$	...	...	...	...	...	...	...	...	...	...
	4	$\ll 100$		...	...	...	...	...	...	...	...	...
Observed	...	...	...	$\lesssim 500$	2.8	0.07	0.1	~ 0.5	...	~ 1	<0.05	~ 1

column densities larger than $\sim 10^{20}$ cm^{-2} the ionizing radiation field peaks shortward of 0.2 keV, and inner-shell photoionization of CNO, followed by several collisional ionizations by suprathermal electrons, becomes extremely important. The heating rate falls as the gas grows more neutral, since much of the energy of the primary and Auger electrons goes to ionization rather than heating.

The rapid fall in the electron temperature is also the result of the form of the cooling curve for the gas. Figure 2 shows the cooling rate for a gas of density 10^3 cm^{-3}, ionized by a source extinguished by a column of $10^{20.5}$ cm^{-2}. For $T_e \lesssim 10^{3.5}$ K, the infrared fine-structure lines carry most of the cooling and a broad plateau centered on $T \sim 10^3$ K exists because the Boltzman factors for these lines have reached unity. The cooling rate rises dramatically at $T \sim 10^4$ K when optical forbidden lines become strong. The effect of the plateau centered on 10^3 K is to cause clouds to equilibrate at either $T_e \leq 10^{2.4}$ K or $T_e \geq 10^{3.6}$ K.[3]

Several of the models are in fair agreement with observations. The model parametrized by no extinction and a density of $N = 10^2$ cm^{-3} matches the helium and oxygen lines quite well, but predicts too high a temperature. The model with $N_H = 10^3$ cm^{-3} and a column of 10^{20} cm^{-2} is in best overall agreement, and will be considered in greater detail. The ionization and thermal structure of this model is shown in Figure 3; Table 2 lists some emission line intensities and Table 3 gives the mean fractional ionizations for lower stages of ionizations of some common elements.

All of the [O II] λ3727 emission is produced by photoionization of O^0 into excited states of O^+. The importance of this effect, which is negligible in classical H II regions, underscores the possibility that several other important physical processes have been neglected. The strong [N II] emission, which our models do not reproduce, may result from some such process, since our models show that significant [O I] λ6300 emission, which is not observed, is produced when the gas is warm enough to produce significant [N II] emission (Table 1). Over a third of the Lα and two-photon continuum emission is produced by collisional excitation by suprathermal electrons. The C I λ1656 line is produced by recombination. The strength was predicted by assuming that each singlet recombination ($\frac{1}{4}$ of all C^+ recombinations) produces a λ1656 photon. The models predict essentially no N II or O II recombination emission, because N and O are rapidly neutralized by very fast charge exchange reactions with hydrogen.

[3] We limit ourselves to single phase models in this discussion. The flat portion of the cooling curves suggests that, under some circumstances, both hot and cold phases could coexist in pressure equilibrium. Such models are now under consideration.

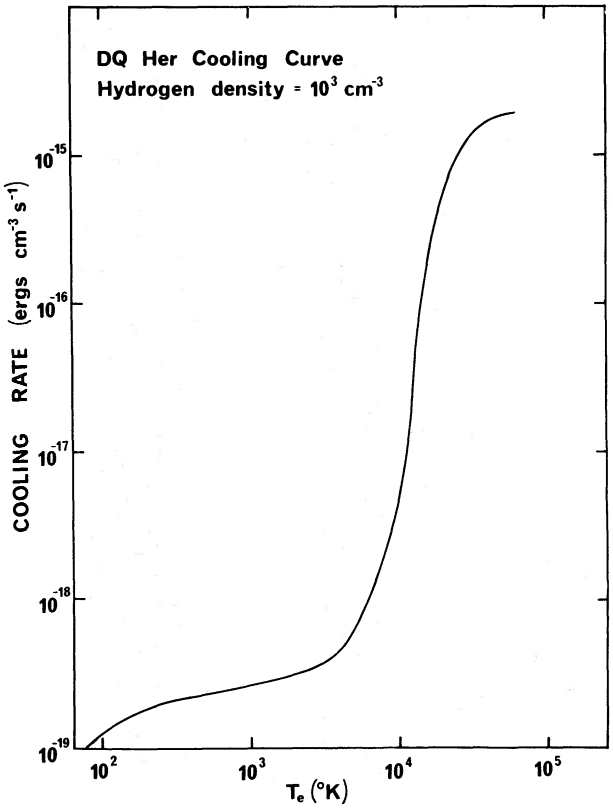

FIG. 2.—Cooling curve. This figure shows the cooling rate (ergs s^{-1} cm^{-3}) for the nebula surrounding DQ Her. This curve was computed for a gas of density $N_H = 10^3$ cm^{-3}, ionized by a continuum extinguished by a neutral hydrogen column density of $10^{20.5}$ cm^{-2}. The rapid increases in the cooling rate near $\sim 10^2$ K and $\sim 10^4$ K are caused by the rapid increase in the Boltzman factors for fine structure and forbidden lines at these temperatures. For a variety of heating rates the gas will tend to equilibrate at either $T_e < 10^{2.5}$ K or $T_e > 10^{3.5}$ K because of the plateau at $T_e = 10^3$ K.

Either these reactions are much slower at $T \sim 10^2$ K than has been predicted for 10^4 K, or the features identified as N II and O II lines have been misidentified. Nonetheless, we consider these results to be very encouraging, especially in the light of very large uncertainties inherent in our calculations.

IV. DISCUSSION

Diverse observations of the nebular shell of DQ Her have brought to light a number of features which cannot readily be understood in "conventional" terms. We note, in particular, the seemingly contradictory findings that the gas is relatively cool, $T_e \lesssim 500$ K, while the spectrum shows strong recombination lines of several doubly ionized elements (Williams *et al.* 1978) and the evidence that the heavy-element "content" of the nebula, as inferred from the C^{++}/H^+ ratio, has increased with time following the 1934 outburst (Ferland and Truran 1980). Motivated by these considerations, we have investigated, in this paper, an alternative model for the nebula: one in which it is powered by an X-ray source, presumed to result from accretion of matter onto the white dwarf component of the DQ Her system. The physical parameters of our model—viz., the accretion rate and associated X-ray and UV energy spectrum and the nebular characteristics—were chosen consistent with existing observations of DQ Her.

Our model calculations show that the postulated X-ray source can maintain the shell in a fairly low level of ionization ($H^+/H^0 \sim 10^{-3}$). The dominant heating and ionization mechanism is through inner-shell photoionization of CNO elements, and we find specifically that carbon can remain doubly ionized while the electron temperature remains below 500 K. Significant [O II] λ3727 emission is produced by photoionization into excited states of O^+. These three features represent the main successes of our model. We do not obtain detailed agreement with all observed line strengths; in particular, we predict the C II and N II lines to be ~ 2 times weaker than observed, He I λ4471 ~ 1.5 times stronger than observed, and virtually no O II recombination emission. The latter results from the fact that O^{++} and O^+ undergo rapid charge exchange reactions with hydrogen. This last problem is the most serious, and will be encountered by any model involving either time-dependent effects or a large neutral fraction of hydrogen. Either the $O^{++} + H^0 \rightarrow O^+ + H^+$ reaction is much slower at $T_e \sim 200$ K than has been estimated for $\sim 10^4$ K, or the features at 4610 and 4645 Å are not O II lines. As our calculations are necessarily only approximate, because of substantial uncertainties in the atomic physics at these temperatures, we find the general success encouraging.

We are particularly encouraged by the extent of the agreement between our model and the overall properties of the nebula, since we have made no attempt to search parameter space for the best fit. Rather, we have largely constrained our model to be compatible with other inferred properties of the DQ Her system. We note, nevertheless, that the column density $N_H \sim 10^{20}$ cm^{-2}, determined from our calculations to be required to effect the low-energy cutoff, is close to the mean of those determined by Cordova, Mason, and Nelson (1980) for several cataclysmic variable systems. The nature of the source of this obscuring material is not established. The existence of an opaque shell of matter at the Alfvén radius (McCray and Lamb 1976) could provide such a column density. The total mass of matter involved would be extremely small; the possibility also exists that distinguishing coronal features would result under these circumstances. Further work on this question is clearly required.

Severe observational limits on the X-ray flux from DQ Her have recently become available. We note that,

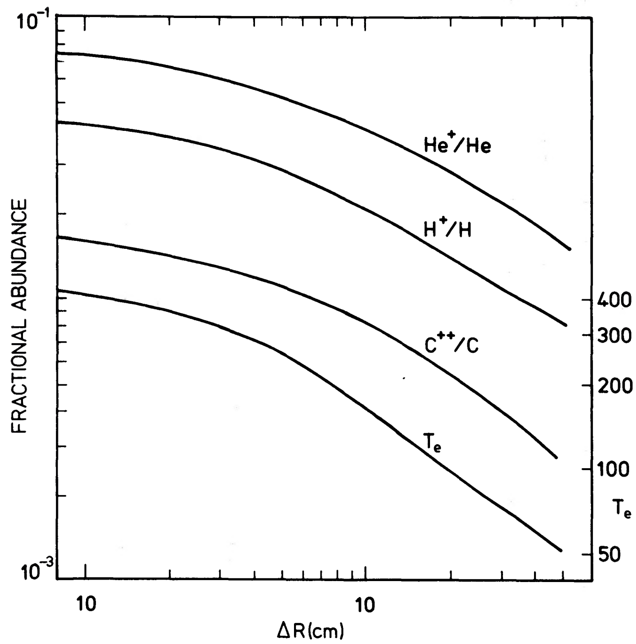

FIG. 3.—Ionization and temperature structure of the nebula. The fractional abundance of H^+, He^+, and C^{++}, and the electron temperature are shown as a function of depth into the cloud.

for a total luminosity of 10^{34} ergs s^{-1} and a distance of 420 pc, the 2–10 keV flux predicted by our model is 2×10^{-10} ergs s^{-1} cm^{-2} $\sim$12 *Uhuru* counts: this source should certainly be detectable with modern instruments. The nondetection reported by Cordova, Mason, and Nelson (1980) would therefore appear to present difficulties. Their result can, however, be understood if it is assumed that the X-ray source is significantly obscured by interactions with the disk. This is consistent with the fact that, since eclipses are observed, we know we are viewing the DQ Her system from in or near the orbital plane.

Apart from considerations of the X-ray flux, there does exist another possible observational test of our model. A distinguishing feature of all cases considered is a particularly strong C I λ1656 recombination line. The predicted strength of this line is roughly 7 times that of Hβ and implies a total intensity of $\sim 10^{31}$ ergs s^{-1}. At a distance of 420 pc, this feature should have a strength of $10^{-12\pm1}$ ergs cm^{-2} s^{-1}, quite accessible

TABLE 2

EMISSION LINE INTENSITIES

Ion	λ	I
H I.....	4861	1.00
H I[a]....	1216	37.2
H I[a]....	2ν	18.6
He I....	4471	0.125
He II...	4686	0.004
C I.....	1656	7.71
C II....	1335	0.38
C II....	4267	0.20
N II....	122 μm	1.53
O I.....	63 μm	0.39
O II[b]...	3727	0.19
O II[b]...	7325	0.05
Ne II...	12.8 μm	0.19
Si II....	35 μm	1.72

[a]Includes a 39% contribution from collisional excitation by suprathermal electrons.

[b]Produced by photoionization into excited states.

TABLE 3

MEAN IONIZATION FRACTIONS

ATOM	IONIZATION STAGE I	II	III
Hydrogen	0.984	0.016	...
Helium.......	0.975	0.025	2.9 (−5)
Carbon.......	0.323	0.673	0.005
Nitrogen	0.974	0.026	1.2 (−5)
Oxygen.......	0.997	0.003	4.1 (−5)
Neon	0.939	0.059	2.6 (−3)
Magnesium...	0.740	0.241	0.018
Silicon	0.123	0.877	1.7 (−5)
Sulfur........	0.354	0.616	0.030
Argon........	0.846	0.139	0.014
Iron	0.317	0.675	6.4 (−3)

with current UV facilities. The alternative interpretation of the nebular characteristics, based upon a model of frozen-in equilibrium (Williams *et al.* 1978), carries rather the prediction of strong C III λ1909 and C IV λ1550 lines. UV observations of the nebula of DQ Her can therefore potentially serve to discriminate between these two models and thus provide significant constraints on theoretical models of classical nova systems.

We note as well that, for the inferred gas temperatures $\lesssim 500$ K, the bulk of the radiation from the nebula should be in the infrared. Several significant spectral features are identified in Table 2. Unfortunately, the predicted fluxes seem yet too low to allow detection with current IR facilities.

The observations of Williams *et al.* (1978) provide a further piece of information which lends itself to interpretation in the context of our model. Variations in the heavy-element to hydrogen recombination line strengths through the nebula were identified, in the sense that the CNO lines are relatively weaker at the ends of the minor axis of the ellipsoidal shell than at the ends of the major axis. Differential obscuration of the X-ray flux with position in the nebula could in principle explain these observations. The disk can be expected to be optically thick to X-rays and thus shield a band of nebular matter lying in or near the orbital plane. We note that this behavior would characterize any model involving a source of hard radiation to explain the observed nebular features. If this effect is indeed responsible for the abundance variations noted by Williams *et al.*, the orientation of the system within the ellipsoidal nebula then follows: the plane of the disk (orbital plane) is that of the minor axis. This conclusion is at odds with the interpretation of the shapes of nova nebular remnants in general (and that of DQ Her in particular) as oblate, due to the effects of the rapid rotation of the parent star (Fiedler and Jones 1979).

We wish finally to comment upon possible implications of our results with regard to the thermonuclear runaway model for the classical novae. Many of the points considered in what follows are elaborated upon in a recent review by Truran (1980). The abundances inferred for DQ Her by Williams *et al.* (1978) imply that ~55% of the mass of the envelope is in the form of carbon, nitrogen, oxygen, and neon. This represents the most substantial enrichment yet determined for any nova system. For the extremely fast nova V1500 Cygni 1975, these heavy elements are found to constitute ~30% of the mass (Ferland and Shields 1978). On the basis of its rate of decline from visual maximum, DQ Her must be viewed rather as a "moderately fast" to slow nova. Our results indicate that, while the presence of an X-ray flux can introduce substantial distortions in abundance ratios, it cannot account entirely for the apparent high CNO content of the DQ Her nebula.

It would thus seem that the envelope composition cannot represent the unique factor determining the speed class of a nova. The mass of the underlying white dwarf (and the implied envelope mass requisite to initiate runaway) can also be critically important. The total binding energy of a $\sim 10^{-3} M_{\odot}$ envelope necessary to trigger runaway on a $\sim 0.6 M_{\odot}$ white dwarf is roughly 3 times that of a $\sim 10^{-5} M_{\odot}$ envelope on a $\sim 1.25 M_{\odot}$ white dwarf. Even a violent runaway proceeding at the base of such a relatively massive envelope may be insufficient to overcome this greater inertia: the early development of the light curve will therefore be less rapid and a smaller fraction of the envelope will be ejected during this phase. An extended epoch of shell hydrogen burning is therefore to be expected, presumably accompanied by significant wind-driven mass loss. That DQ Her quite likely behaved in this manner is suggested by the fact that significant powering of the nebula appears to have continued through the late 1940s, at which time the rapid decrease in the strength of the [O III] λλ4959, 5007 features probably reflected the extinguishing of the shell source. Subsequently the reestablishment of accretion flows onto the white dwarf surface could then yield an X-ray source of the form we have considered in this paper.

Our results also hold implications for the possible nature of the mechanism responsible for the heavy-element enrichment of the envelope matter. If, because of the presence of a strong magnetic field, accretion occurs largely over the magnetic polar regions of the white dwarf in the DQ Her system, then *at least for this case* the enrichment is unlikely to have resulted from shear-induced mixing attributable to the presence of an "accretion belt" over the equatorial region (Kippenhahn and Thomas 1978).

Smak (1980) has recently determined that a somewhat lower white dwarf mass ($0.5 \pm 0.2 M_{\odot}$) and higher accretion rate ($\sim 3 \times 10^{17}$ g s^{-1}) than we have assumed may be appropriate for the DQ Her system. While this would necessarily entail changes in the details of a model such as ours, it should not significantly influence the qualitative features which we have emphasized. We also note that a mass $\lesssim 0.8 M_{\odot}$ for the white dwarf is more consistent with the fact that, despite its extremely high abundance of CNO nuclei, DQ Her was not a particularly fast nova.

V. CONCLUSION

We have demonstrated that a number of observed and yet seemingly contradictory features of the nebula of DQ Her follow as a natural consequence of the presence of an X-ray source such as is predicted for accretion at a rate compatible with the measured decrease of the white dwarf rotation period. Independent of the degree of validity of our specific model for this system, it seems clear that X-ray photoionization effects must be carefully examined with regard to interpretation of nova spectra in general. The recent observations of Nova T Aur 1891 by Gallagher *et al.* (1980), for example, again reveal evidence both for cool gas and for strong N II and possibly O II recombination lines.

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APPENDIX

TIME-DEPENDENT IONIZATION

One attractive explanation for the present state of the nebula surrounding DQ Her is that no energy source presently powers the gas, and that the nebula is in a state of "frozen-in" ionization. This will be the case if the expansion time for the nebula is more rapid than the recombination time, and the effect would be to produce a cold but ionized gas. In this Appendix we examine the consequences of this model in greater detail, and present time-dependent models of the nebula which include all important physical processes.

Time-dependent ionization was discussed by Williams *et al.* (1978) with an assumption of constant temperature, and by Jura and Dalgarno (1972) in a different context. The program described in § III will be used here to follow the recombination and cooling of a metal-rich expanding nebula. The evolution of the nebula is followed by solving the equation of statistical and thermal equilibrium for the case of no photoionization or photoelectric heating. As an example, the balance equation for hydrogen may be written as

$$\frac{dN_{H^0}}{dt} = N_e N_{H^+}\alpha - N_e N_{H^0} C, \tag{A1}$$

where α and C are the recombination (both radiative and by charge exchange) and collisional ionization coefficients, and $N_{H^0}, N_{H^+}, N_e, N_H$ are number densities of the respective atoms and ions. Writing $N_H = N_{H^0} + N_{H^+}$, we find

$$\frac{dN_{H^0}}{dt} = N_e N_H \alpha - N_e N_{H^0}(\alpha + C). \tag{A2}$$

Time intervals will be chosen small enough to keep the electron and total hydrogen densities constant, so equation (A2) is a linear first order differential equation with constant coefficients, identical to the equation of radiative transfer. The solution is

$$N_{H^0}(t) = N_{H^0}(O)\exp[-tN_e(\alpha + C)] + \frac{N_H \alpha}{(\alpha + C)}\{1 - \exp[-tN_e(\alpha + C)]\},$$

where $t = 0$ is the start of the time step of length t. The time-dependent abundances of other ions are determined in a similar manner. The temperature is determined by solving

$$\frac{d}{dt}\left(\frac{3}{2}NkT\right) = -\Lambda(T_e)N_e^2 - P\,dV,$$

where $\Lambda(T_e)$ is the cooling rate due to both collisionally excited lines and radiative continuum processes. This cooling rate is evaluated for each time step assuming the ionization state and temperature as determined by the previous step. The adiabatic expansion term $-P\,dV$ is included since the gas is allowed to expand freely.

We now consider a specific model for the DQ Her nebula. We assume that the nebula was initially in equilibrium with the radiation field from the central object, and that this field was extinguished ~15 years after outburst. This is consistent with the disappearance of the [O III] λλ4959, 5007 lines in ~ 1950. The central object is assumed to have been initially a black body of temperature 2×10^5 K and luminosity 0.1 $L_{\rm Edd}$ for a $1 M_\odot$ white dwarf. The nebula is given an inner radius of 2×10^{16} cm at the time when the radiation field ceased.

We assume that the gas is in free expansion, so that $N(t)=N(0)(t-t_0)^{-3}$. This rate is faster than was found by Ferland and Shields (1978) in their study of the fast nova V1500 Cygni, so the effects of frozen-in ionization will be overestimated. The present density of $10^{3.5\pm0.5}$ cm^{-3} corresponds to a density of $\sim10^{5\pm0.5}$ cm^{-3} in 1950 if this expansion law is assumed.

Figure 4 shows the evolution of the nebula as it recombines and cools. Time is reckoned from the turnoff in 1950. Figure 5 shows the intensities of several of the stronger optical emission lines relative to Hβ.

The frozen-in ionization model encounters several difficulties. The calculations predict that very little C^{++} will be present after $(t-t_0)=\frac{1}{3}$ yr, whereas C II lines are presently quite strong. Essentially no He II emission is predicted after the first $\frac{1}{2}$ yr, although the observed He^+/H^+ ratio remains close to the intrinsic He/H ratio. Like the X-ray models discussed in § III, this model predicts no permitted O II or forbidden [O II] λ3727 emission after the first 1/10 year because of the very fast oxygen-hydrogen change exchange reactions. Essentially no line emission other than H I and He I lines is predicted after the first year.

Although these calculations do not reproduce the present state of the DQ Her nebula, they do underscore the importance of continued, long term, monitoring of old novae. The results of this Appendix and of § III suggest that the nebula will change quickly when the shell source turns off and accretion becomes the dominant heating agent. In particular, the easily measured [O III] λ5007/Hβ ratio will change over time scales ~1 week, and should follow the evolution of the shell source quite closely.

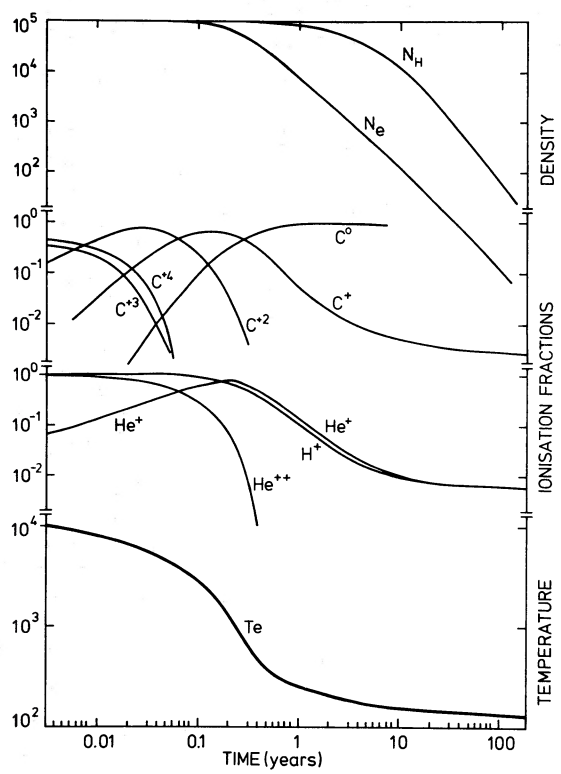

FIG. 4.—Time-dependent ionization.—This figure shows the physical conditions in an expanding metal rich nebula with no source of ionization. The ionizing continuum was assumed to be instantaneously extinguished at $(t-t_0)=0$, and the recombination and cooling of the nebula is followed as described in the text. The initial conditions were chosen to mimic those in 1950 when the [O III]λλ5007, 4959 lines disappeared. The gas is largely neutral within a year.

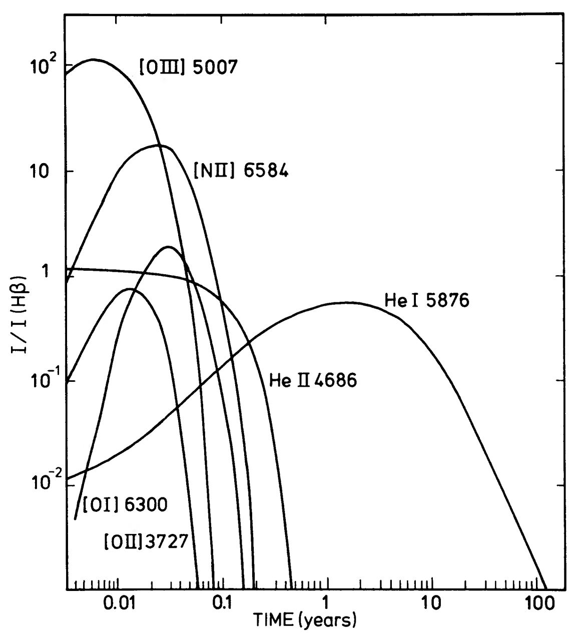

FIG. 5.—Time-dependent emission line intensities.—This figure shows the intensities of several of the stronger emission lines relative to Hβ. These lines correspond to the physical conditions in Fig. 4. Essentially all emission lines vanish within a few months of the continuum vanishing. The optical forbidden lines respond very quickly to changes in the ionizing continuum and should be monitored frequently to establish changes in the character of the radiation field from the central object.

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