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ON THE CARBON COMPOSITION OF THE EJECTA OF DQ HERCULIS

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ABSTRACT

We call attention to the fact that existing spectrophotometric data for Nova DQ Herculis 1934, spanning virtually its entire postoutburst history, reveal a time dependence of the inferred nebular composition. The observed trends may suggest that the intrinsic carbon abundance is log C/H ≈ −1.7, and that the nebula has grown progressively cooler over the past 45 yr. The presence of a source of hard radiation in the DQ Herculis system is suggested. We stress the importance of similar long-term studies of recent novae.

Subject heading: stars: novae

I. INTRODUCTION

The evolution of the slow nova DQ Herculis 1934 has been documented by an unprecedented set of spectrophotometric observations extending over the past 45 yr (Payne-Gaposchkin and Whipple 1939; Swings and Struve 1940; Swings and Struve 1942; Swings and Jose 1949; Williams *et al.* 1978). The most recent spectra of the diffuse nebula reveal a strong, sharp Balmer jump (indicating $T_e \lesssim 500$ K) and strong recombination lines of carbon, nitrogen, and oxygen, which imply enhancements of roughly a factor 100 relative to hydrogen (Williams *et al.* 1978). The abundances of these elements are of particular interest since their isotopes play a catalytic role in the conversion of hydrogen to helium in the thermonuclear runaway generally believed to power the nova outburst.

As is well known, it is of the nature of the CNO-cycle hydrogen-burning sequences that significant redistribution of the nuclear constituents will occur. This will be reflected in both the isotopic and the elemental abundance patterns. Determinations of the abundances in nova ejecta, if they are to provide an accurate measure of the total concentration of CNO nuclei and establish whether the predicted distinction between fast and slow novae (Starrfield, Truran, and Sparks 1978; Sparks, Starrfield, and Truran 1978) indeed exists, must therefore sample carbon, nitrogen, and oxygen. While nitrogen and oxygen data exist for a number of novae, to date, accurate carbon abundances have been measured for only two cases: DQ Her and the very fast nova V1500 Cygni (Ferland and Shields 1978). Both the recent study of DQ Her (Williams *et al.* 1978) and that of V1500 Cygni indicate substantial enrichments of the nebular matter in carbon, nitrogen, and oxygen.

In this paper, data obtained during the first 15 yr following the outburst of DQ Her are used to deduce the carbon abundance at an epoch comparable to that for which the McDonald data for V1500 Cyg was obtained. These data are reviewed in § II, and estimates of the abundances are presented in § III. Discussion of suggestive trends in the data follows.

II. DATA

The Harvard data presented by Payne-Gaposchkin and Whipple (1939) are probably the most accurate of the early studies. Their data cover the early nebular phase of the outburst, beginning just after the recovery from the great minimum and continuing for 120 days. They used a photoelectric microdensitometer to place the data on a linear intensity scale, and the flux calibration was performed by reducing a set of comparison stars on the same plate. The logarithmic mean of the intensities of C II 4267, C III 4187, He I 4471, and He II 4686, relative to Hβ, are listed in Table 1. The data were arranged into two groups, each with five points. The C III line was weaker and measured on a total of only five spectra; all were averaged as a single group.

A second set of data was obtained by Struve and Swings at McDonald Observatory during the 1940s (Swings and Struve 1940; Swings and Struve 1942; Swings and Jose 1949). These spectra were mainly intended for a radial velocity study and for general reconnaissance, but relative intensities of the stronger emission lines are also indicated. The relative intensities of C II 4267 and Hγ should be fairly accurate, since the lines are close together and are of similar strengths ($\langle \log \lambda 4267/\mathrm{H}\gamma \rangle = -0.35 \pm 0.1$). If the Balmer decrement is case B, then $\langle \log \lambda 4267/\mathrm{H}\beta \rangle = 0.67 \pm 0.1$. The intensities of λ4471 and λ4686 were estimated similarly, and the results are entered in Table 1. Unfortunately, C III 4187 was not measured on these spectra.

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TABLE 1

EMISSION LINE INTENSITIES

$(t - t_0)$ Days	C II 4267	C III 4187	He I 4471	He II 4686	C/H	He/H
			DQ Herculis			
155–209	−1.15 ± 0.1	−1.20 ± 0.2	−1.27 ± 0.1	−0.63 ± 0.1	−1.7 ± 0.2	−0.89 ± 0.1
215–276	−1.02 ± 0.2		−1.09 ± 0.26	−0.59 ± 0.1	−1.6 ± 0.2	−0.74 ± 0.3
2–5 × 10^3	−0.6 ± 0.1	. . .	−1.10 ± 0.3	−0.13 ± 0.2	−1.5:	−0.7 ± 0.4
1.6 × 10^4	−0.3 ± 0.1	. . .	−1.15 ± 0.3	−0.88 ± 0.2	−1.2 ± 0.2	−1.02
			V1500 Cygni			
. . .	−1.3 ± 0.2	−2.0 ± 0.3	−1.3 ± 0.2	∼ −0.7	−2.1 ± 0.3	−0.96 ± 0.1

Finally, the intensities reported by Williams *et al.* (1978) are listed, together with typical intensities during the early nebular phase of the very fast nova V1500 Cyg (Ferland and Shields 1978). It is interesting to note that the internal scatter in the photographic Harvard data is smaller than that of the modern photoelectric data on V1500 Cyg, mainly because the emission lines of the slow nova DQ Her are sharper and easier to measure than those of V1500 Cyg. The consistency of the Harvard and McDonald data in indicating that the C II 4267 line was weak prior to 1950 argues against the existence of any gross systematic errors in these earlier studies.

III. CHEMICAL COMPOSITION

Ionic abundance ratios are related to intensity ratios of optically thin recombination lines through a ratio of atomic constants (see Osterbrock 1974, § 5.8). Using the tables of Brocklehurst (1971, 1972) for $T_e = 10^4$, we obtain the helium abundances from

$$\frac{N(\mathrm{He}^+)}{N(\mathrm{H}^+)} = 2.04\,\frac{I(4471)}{I(4861)}\left(\frac{T_e}{10^4}\right)^{0.16},$$
$$\frac{N(\mathrm{He}^{++})}{N(\mathrm{H}^+)} = 0.078\,\frac{I(4686)}{I(4861)}\left(\frac{T_e}{10^4}\right)^{0.16}. \qquad (1)$$

No corrections for unseen stages of ionization are necessary during the early nebular phase, since the $\lambda4686/\lambda4471$ ratio indicates a stellar temperature between 6×10^4 and 2.5×10^5 K (Harmon and Seaton 1966).

The carbon recombination coefficients used by Ferland and Shields (1978) will be used here:

$$\frac{N(\mathrm{C}^{+2})}{N(\mathrm{H}^+)} = 0.11\,\frac{I(4267)}{I(4861)}\left(\frac{T_e}{10^4}\right)^{0.166},$$
$$\frac{N(\mathrm{C}^{+3})}{N(\mathrm{H}^+)} = 0.23\,\frac{I(4187)}{I(4861)}\left(\frac{T_e}{10^4}\right)^{-0.09}. \qquad (2)$$

Both are based on the effective recombination coefficients derived by Pengelly (1963), together with those of Brocklehurst (1971) at $T_e = 10^4$ K. Photoionization models (Shields 1978; Ferland and Shields 1978) show that nearly all carbon will be either doubly or triply ionized under normal conditions; so we set $\mathrm{C/H} = (\mathrm{C}^{+2} + \mathrm{C}^{+3})/\mathrm{H}^+$. The validity of this assumption will be discussed later. Abundances are listed in the last two columns of the Table assuming $T_e = 10^4$ K.

IV. DISCUSSION

Taken at face value, the data herein reviewed indicate a time dependence of the nebular abundances of DQ Her: the helium abundance appears to have decreased slightly from ∼1.5 times solar to about solar, while the carbon abundance has increased over the same interval from ∼40 times solar to ∼130 times solar. This behavior cannot be readily attributed to the effects of Balmer self-absorption (see Strittmatter *et al.* 1977; Ferland and Netzer 1979), since the C/He ratio has itself changed by a factor of 4. Recombination lines from ions of C and He should not be affected by radiative transfer effects, because their resonance lines are capable of ionizing hydrogen and, hence, are destroyed before many scatterings.

Perhaps the most straightforward interpretation of this behavior is that there exists a stratification of the heavy element (carbon) composition within the ejected envelope. With this picture we are able to view this spacial variation rather as a time variation of the abundances, because observations at any given epoch sample only the ionized region of the nebula. The depth of the ionized region will vary in response to the demand that equilibrium be maintained; for instance, for both HR Delphini and V1500 Cyg the ionized mass grew smaller as the nebula aged, indicating that spectra obtained at later times sampled progressively lower regions of the envelope.

It follows that the observed increase in the carbon abundance with time in DQ Her implies an increase with depth in the nebula. This behavior cannot readily be understood in terms of thermonuclear properties of the runaway alone. Indeed, assuming an initially uniform composition for the nebula, we would anticipate that the innermost regions of the envelope would be carbon depleted as a consequence of the conversion of carbon into nitrogen occurring in the CN-cycle hydrogen burning. The He/H ratio should be increasing as well in the deeper layers of the envelope, as a result of the burning of hydrogen into helium. The sense of the observed abundance changes, thus, is entirely in opposition to that which one would expect on the basis of the nuclear evolution. If it is indeed a stratification effect which we are observing, it must reflect composition gradients preexisting in the white dwarf envelope, which have somehow managed to persist through the outburst. This, too, is difficult to understand, given the convective character of the envelope, found in all theoretical studies to follow upon thermonuclear runaway.

We are left with the conclusion that the carbon abundance has either been underestimated during the early nebula phase or overestimated at present. We feel that the carbon abundance in 1935–1950 is most secure, because the ionization in the shell seems well understood during the early outburst. The level of ionization, as indicated by line ratios such as He II 4686/Hβ, was similar to that at a similar phase of V1500 Cyg's outburst; so the model calculations presented by Ferland and Shields (1978) should apply. These show that much of the carbon is in the form C^{++}; so 4267/Hβ measures essentially all the carbon in the H^+ zone. A great difference between the two novae is that DQ Her evidently passed through an epoch of grain formation during its transition phase. The effects of dust on the ionization structure of model nebulae has been studied by Sarazin (1977) in the context of H II regions. His models, which probably overestimate the ultraviolet dust opacity, suggest that dust will have only a small effect on fractional abundances of the lower stages of ionization of metals. Unpublished models by Martin and Ferland (1980), which incorporate a more realistic grain opacity function, also show that dust has only small effects on the C^{++}/C fraction.

Another possibility is that ~90% of the carbon in the envelope condensed onto graphite grains during the transition phase, but that this graphite had been destroyed by 1977. This seems to be an unlikely explanation, since it requires that the fact that both DQ Her and V1500 Cyg appear to have similar carbon abundances be an accident. Further, we see no way to destroy the graphite in time for the Steward observations to measure C/H ≈ 130 times solar. Nonetheless, the question whether a significant fraction of the carbon condenses onto grains should receive high priority when the next DQ Her type nova appears.

The apparent change in the C/H ratio could be a consequence of a dramatic fall in the temperature of the nebula over the past 45 yr. Williams *et al.* (1978) deduced that the temperature in 1977 was less than 500 K, from the absence of collisionally excited forbidden lines and the presence of a strong, sharp, Balmer jump. Ratios of recombination lines have a weak temperature dependence because of the energy-dependent free-bound Gaunt factor; this dependence was estimated in equation (2) by fitting power laws to published values of $\alpha_{\rm eff}$ in the interval $5 \times 10^3\ {\rm K} \leq T_e \leq 2 \times 10^4\ {\rm K}$ (Pengelly 1963; Brocklehurst 1971). A temperature well below 10^2 K would be required to explain the changes in C/H as a temperature effect alone if the extrapolation to small T_e is valid. If this interpretation is correct, then the earliest carbon abundances, obtained when collisionally excited lines were strong and the nebula hot, are the most secure. Surprisingly, even this abundance is about twice that of the fast nova V1500 Cygni.

The heavy element composition determined for the shell around DQ Her (Williams *et al.* 1978) clearly distinguishes it among novae. Translating abundance ratios into mass fractions, we find that fully half the observed mass is in the form of carbon, nitrogen, oxygen, and neon. This is to be compared with inferred heavy element mass fractions of ~0.30 for the extremely fast nova V1500 Cyg (Ferland and Shields 1978) and of ~0.07 and ~0.04, respectively, for the slow novae HR Del 1967 (Tylenda 1978) and RR Pic 1925 (Williams and Gallagher 1979). The degree of heavy element enrichment is particularly uncharacteristic of slow novae, as is the approximately solar He/H ratio in DQ Her: slow novae tend to show helium enrichments (Ferland 1979). The large CNO enrichment poses a challenge to theoretical modeling as well, since it generally yields a more violent thermonuclear runaway and fast-nova-like light curve (Kenyon and Truran 1979). The apparent uniqueness of DQ Her is further emphasized by a recent study of the nebula of the DQ Her like nova T Aurigae 1891 (Gallagher *et al.* 1980), as they find both a substantially lower heavy element content and a helium-to-hydrogen ratio ≈0.20. Nevertheless, they note that the similarity of the outburst characteristics of T Aurigae and DQ Her, as reflected in their light curves, seems to have extended to the manner in which their ejecta have evolved.

The availability of the early data on DQ Her has provided a unique opportunity to trace the nebular composition over an extended period. The fact that the abundances vary with time in a manner which is not readily explained in the context of theoretical models of novae suggests that we may be neglecting something fundamental and that caution must be exercised in drawing conclusions from studies of the nebular phase. It is essential that recent well-observed novae (e.g., V1500, Cyg, FH Ser, HR Del, NQ Vul, Nova Cyg 1978) be studied during the late nebular phase to determine whether large apparent changes in the metallicity of the nebulae are common. A theoretical understanding of the present physical conditions in DQ Her's envelope is also important. The existence of ionization effects which act to misrepresent the true abundance ratios at present seems likely. We note that an appropriately tuned X-ray source in DQ Her, which could indeed exist and yet be obscured by the disk, is potentially capable of explaining these observations. We are currently undertaking to explore this possibility.

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