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HELIUM ABUNDANCE IN EJECTA FROM CP LACERTAE AND V446 HERCULIS

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ABSTRACT

Published emission-line intensities are used in this paper to measure the helium abundances in ejecta from the novae CP Lacertae and V446 Herculis. Recombination lines of hydrogen and helium indicate the helium abundance directly if corrections for unseen stages of ionization and recombination-line self-absorption are unimportant. These corrections are minimized by considering only spectra obtained during the late nebular phase of the outburst, when models show that ionization corrections are small and when self-absorption affects only certain lines. The physical conditions in the gas need not be accurately measured since ratios of recombination lines are only slightly affected by the density-temperature structure of the ejecta.

Ejecta from the fast nova CP Lac (1936) have a nearly cosmic helium abundance (He/H = 0.11 ± 0.02), but ejecta from V446 Her (1960) are enhanced (He/H = 0.19 ± 0.03). Previous studies have found high (He/H = 0.2) abundances of helium in ejecta from HR Del, V544 Her, RR Pic, and RR Tel. Three novae are now known to have nearly cosmic helium abundances (CP Lac, V1500 Cyg, and DQ Her). No evidence for extreme overabundances of helium (He/H ≥ 0.3) is found. The range in helium abundances in nova ejecta is similar to the range in planetary nebulae, but the sample of novae seems to be more clustered toward higher helium abundances. Cosmic or nearly cosmic helium abundances are probably an indication that the majority of the matter ejected in the nova outburst originated in the cool companion rather than in the white dwarf. There is no tight correlation between helium abundances and other properties of the nova outburst, but high helium abundances tend to occur in slower novae.

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

I. INTRODUCTION

The chemical composition of the material ejected during the nova outburst is an important clue to both the origin of the outburst and the nature of the system. Novae are generally believed to occur in close binaries where a cool star is transferring material onto an accretion disk surrounding a white dwarf. Under some conditions the accreted material can mix with the carbon core of the white dwarf (Colvin *et al.* 1977) to create a region with enhanced abundances of some heavy elements. Starrfield, Sparks, and Truran (1972, 1974) have shown that a thermonuclear runaway will occur if the hot, degenerate material at the base of the envelope has such enhanced abundances. Sparks, Starrfield, and Truran (1978) have suggested that the amount of CNO enrichment could determine some characteristics of the outburst.

Accurate measurements of the chemical abundances in ejecta from novae are required if we are to understand both the differences and similarities among the various classes of novae. The purpose of this paper is to measure helium abundances in ejecta from CP Lacertae and V446 Herculis using published data. Section II outlines the method and its assumptions, and § III gives results for individual novae. A critique of several studies which reported anomalous He/H ratios is also presented. The last section summarizes our results.

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II. METHOD

A nova outburst is the violent expulsion of 10^{-4}–10^{-3} $M_{\odot}$ from a close binary system (see Gallagher and Starrfield 1978). The ejected material is optically thick to continuum photons during the rise to maximum light, and the spectrum is similar to that of an A or B supergiant (Payne-Gaposchkin 1957). As the ejecta expand and become more dilute, the column density falls and the spectrum eventually comes to be dominated by emission lines.

The helium abundance in the ejected matter can be deduced from recombination-line ratios without a detailed analysis of the physical conditions in the nebula since the conversion from recombination-line ratio to ionic-abundance ratio is independent of the electron density and nearly independent of electron temperature. (A slight dependence on electron temperature and density remains because of *l*-mixing during the cascades following recombination, but this correction amounts to less than 10%.) Fine structure in the nebula will not affect the analysis.

In general, the equation to convert a recombination-line ratio to an abundance ratio takes the form:

$$\frac{N(\mathrm{He}^i)}{N(\mathrm{H}^+)} = \frac{I(\mathrm{He}^i\ \mathrm{line})\,\lambda(\mathrm{H}^+\ \mathrm{line})\,\alpha(\mathrm{He}^i, T_e, N_e)}{I(\mathrm{H}^+\ \mathrm{line})\,\lambda(\mathrm{He}^i\ \mathrm{line})\,\alpha(\mathrm{H}^+, T_e, N_e)}, \quad (1)$$

where α(line) is the effective recombination coefficient (see Osterbrock 1974). A temperature of 10^4 K and the effective recombination coefficients tabulated by Brocklehurst (1971, 1972) will be assumed.

a) Ionization Structure

It is now commonly believed that ejecta from novae are photoionized by the radiation field of the central object during the nebular phase of the outburst (McLaughlin 1960; Gallagher and Starrfield 1976, 1978). This hypothesis receives strong support from satellite observations of strong ultraviolet continua during late phases of the nova outburst (e.g., Gallagher and Holm 1974; Wu and Kester 1977). An even stronger case for photoionization is presented by the simultaneous continuum and emission-line variations of V1500 Cyg (Campbell 1976; Hutchings, Bernard, and Margetish 1978), which demand that the ionization of the nebula be coupled to the radiation field of the central object.

Coronal emission lines are often present in spectra of novae (McLaughlin 1953), and this suggests that a shock-ionized region ($T_e \geq 10^6$ K) must also exist (Wallerstein 1961; Collin-Souffrin 1976; Shields and Ferland 1978). Estimates of the physical conditions in the coronal-line region of V1500 Cygni (Shields and Ferland 1978) show that emission from these shocks is too feeble to affect the ionization of the nebular line-emitting region.

Line emission from the accretion disk dominates spectra of novae at minimum light but should be insignificant during the outburst for several reasons. Emission from the accretion disk should be largely unobservable during the outburst since the luminosity of the system increases by 10–15 mag. The mass-transfer rate must increase by a similar factor if accretion disk emission is to be observable. Observationally, a detailed study of emission-line profiles shows that all strong lines have characteristic castellated profiles and hence a common origin in the ejected material (Payne-Gaposchkin 1957).

Corrections for unseen stages of ionization must be applied if one element remains ionized in a region in which the other has become neutral. This type of correction is important if the ionizing radiation field has very few helium ionizing photons and an $\mathrm{He}^0/\mathrm{H}^+$ zone exists (Hummer and Seaton 1964), or if the radiation field has many energetic photons which produce an outer $\mathrm{He}^+/\mathrm{H}^0$ zone (Shields 1974). Model calculations show that neither correction is larger than a few percent when the temperature of the central star is between 6×10^4 K and 2.3×10^5 K. Nebulae which are ionized by blackbodies within this temperature range show weak to moderately strong He II λ4686 emission (Hummer and Seaton 1964), and the presence of this emission line is an indication that corrections for a partially neutral zone will be small.

b) Balmer Self-Absorption

Balmer decrements of novae deviate from theoretical predictions in a time-dependent manner (Payne-Gaposchkin 1957), and this has been attributed to Balmer self-absorption caused by Lα trapping (Strittmatter *et al.* 1977; Ferland, Netzer, and Shields 1979). The largest Lyman-continuum (λ912) optical depth through an H^+ Strömgren sphere is ~ 10 for a nebula ionized by a hot blackbody (Hummer and Seaton 1964). The optical depth will be less if the outer edge of the ionized zone is defined by the edge of the material (matter-bounded) rather than by the exhaustion of the ionizing radiation field (radiation-bounded). Since the ratio of opacities of Lα to the Lyman continuum is $\sim 10^4$ for thermal broadening ($T_e = 10^4$ K), the total optical depth to Lα through the highly ionized Strömgren sphere is $\lesssim 10^5$. (The inequality holds if the nebula is matter-bound or if turbulence is present.) The Lα optical depth through the transition zone will be $\leq 10^7$.

Under some conditions the trapped Lα photons can create a significant population in the first excited state and the transfer of Balmer quanta will be affected. Each Lα will scatter $\sim \tau_0$ times before escaping from the nebula (Osterbrock 1962). The level 2 population of hydrogen is set by the equilibrium between processes which populate level 2 (capture-cascade and Lα scattering) and those which depopulate level 2 (the slow leakage of Lα from the shell). The balance equation becomes (Osterbrock 1964):

$$N_e N_p \alpha_B(T_e, 2p) = \tfrac{2}{3}\alpha_B(T_e) N_e N_p = N_{2p}\epsilon_{21} A_{2p\to 1s} \quad (2)$$

where ϵ_{21} is the mean escape probability for Lα. Effectively, there are ${\epsilon_{21}}^{-1}$ scatterings per recombination (the effects of dust are ignored).

Detailed calculations (Ferland and Netzer 1979) show that $\epsilon_{21} \approx 10^{-6}$ (incomplete redistribution and thermal broadening), so

$$\tau_{\mathrm{H}\alpha} \lesssim 10^{-16.3}\frac{Q(\mathrm{H})}{r^2}, \quad (3)$$

where Q(H) is the ionizing photon flux (S^{-1}) and r is the separation between the central object and the nebula. Self-absorption should be most important during the earliest stages of the nova outburst when Q(H) is large and the radius of the ejecta small, but will be unimportant during the late nebular phase.

Self-absorption degrades Hβ and higher Balmer quanta into Hα and Paschen photons. As a result, the Balmer decrement is steeper [I(Hα)/I(Hβ) larger than expected for case B conditions; Hα/Hβ = 2.8]. Netzer (1975) has computed Balmer-line intensities under conditions of self-absorption and finds that the strength of Hα is never enhanced by more than 20%, but that Hβ can be weakened by over 50%. An abundance analysis should employ Hα if the physical conditions (and hence $\tau_{\mathrm{H}\alpha}$) cannot be accurately estimated.

Netzer's (1975) Figure 2 shows computed Balmer decrements for a variety of optical depths. If the shell

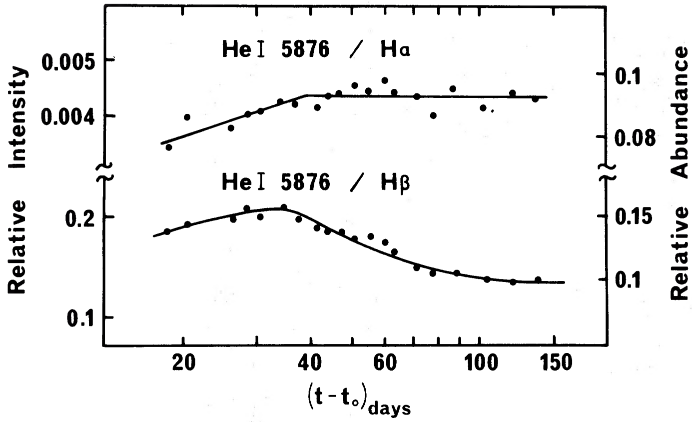

FIG. 1.—Intensity of He I λ5876 relative to both Hα and Hβ during the η Car (days 10–30) and nebular phases of nova V1500 Cygni's outburst. The reddening corrected intensity ratio is indicated on the left, and the corresponding ionic (He^+/H^+) abundance ratio is indicated on the right. The He I/Hα data are plotted on an extended scale. The He I/Hβ ratio suggests an enhanced, time-dependent helium abundance while the He I/Hα ratio indicates a time-steady cosmic abundance. Hβ is a poor abundance indicator because its intensity is weakened by Balmer self-absorption, which degrades Hβ photons into Hα and Pα. The He^+/H^+ ionic abundance increased before day 30 because the nebula contained an extensive He^0, H^+ zone which diminished as the central object grew hotter.

is radiation-bounded and turbulence is constant, then the optical depth to Lα will be nearly constant throughout the outburst. The Balmer optical depth will decrease rapidly (eq. [3]), and a nova will follow an arc in the (α, β, γ)-plane, eventually approaching case B predictions.

If the initial Hα optical depth is large and $\tau_0 \approx 10^5$, then the (α, β)-ratio first increases to ~6, and then approaches case B predictions. This behavior is commonly observed in novae [see Fig. 6 of Meinel [1963] and Fig. 2 of Ferland (1978)]. Figure 1 shows the intensity of He I λ5876 relative to both Hα and Hβ as observed during the nebular phase of V1500 Cygni (Tomkin, Woodman, and Lambert 1976). The total helium abundance would have appeared to decrease from 0.18 to 0.11 if helium lines had been compared with Hβ and no correction for self-absorption made. A nearly cosmic helium abundance would have been measured at all times had helium lines been referred to Hα and no correction applied.

c) *Collisional Excitation of* Hα

Novae Balmer decrements have long been known to deviate from pure recombination values (Payne-Gaposchkin 1957), and this has frequently been interpreted as evidence for collisional excitation of Hα by thermal electrons. This is easily shown to be unimportant within a Strömgren sphere. The ratio of the recombination rate to the collisional excitation rate from the ground state will be

$$\frac{R_{\rm rec}}{R_{\rm col}} = \frac{N_e N_{\rm H^+} \alpha_{\rm H\alpha}{}^{\rm eff}(N_e, T_e)}{N_e N_{\rm H^0} q_{13}(T_e)} = 7.13 \frac{N_{\rm H^+}}{N_{\rm H^0}} , \quad (4)$$

where we have assumed the excitation rates of Burke, Ormonde, and Whitaker (1967) and $T_e = 10^4$ K. The ratio $N(H^+)/N(H^0)$ is model-dependent, but models show that a typical value is $\sim 10^4$ (see Osterbrock 1974). Recombination clearly dominates over collisional excitation because of the fairly low kinetic temperature and high ionization.

Collisional excitation of Hα from level 2 is proportional to $N_e \tau_{\rm H\alpha}$ (Ferland and Netzer 1979). Their equation (20) predicts that collisional excitation of Hα by this process will also be negligible when $N_e \lesssim 10^9$ cm^{-3}.

d) He *Line Transfer*

Robbins (1968*a*, *b*), Brocklehurst (1972), Netzer (1978), and Feldman and MacAlpine (1978) have studied the He I emission spectrum. Optical singlet lines have very high excitation potentials (≥20 eV) so collisional excitation and line trapping are not likely to be important. Under some circumstances certain triplet lines (2^3S–N^3P) will be optically thick because the metastable 2^3S state often has a large population. Some lines (e.g., λ7065 2^3P–3^3S) may be strengthened at the expense of other quanta (λ3888 2^3S–3^3P). Lines which are not connected directly to a 2^3S–N^3P transition, and which arise from 2^3P or a higher level will be unaffected. Robbins (1968*a*, *b*) stressed that the strength of both λ4471 and λ5876 will not be affected by this process under most conditions.

In this paper the strong He I line λ5876 (2^3P–2^3D) will be used to measure the He^+ abundance. Collisional excitation of λ5876 from the metastable 2^3S state will be unimportant since the collision strength is small, but excitation from 2^3P could be important if a significant fraction of the neutral helium atoms are in the 2^3P state (MacAlpine 1976; Netzer 1978). Trapped λ10,830 (2^3S–2^3P) photons will be the main agent populating 2^3P for densities smaller than $\sim 10^{13}$ cm^{-3} (Osterbrock 1974).

Nearly all λ10,830 photons are produced by collisional excitation under nebular conditions (Osterbrock 1974), and each photon will scatter $s \sim 10^{2\pm1}$ times (Netzer 1978). The balance equation becomes

$$N_{2^3P} A_{10,830} = N_{2^3S}\, s\, q_{10,830} N_e \,. \quad (5)$$

Assuming the collision rates q, and transition probabilities A, quoted by MacAlpine (1976), equation (5) becomes

$$R = \frac{N_{2^3P}}{N_{2^3S}} \sim 10^{-11.5\pm1} N_e \,. \tag{6}$$

The population of 2^3S is set by the balance between recombinations to the triplets and $2^3S \rightarrow 2^1S + 2^1P$ exchange collisions, for electron densities greater than $N_c \sim 10^4$ cm^{-3} (Osterbrock 1974). The balance equation becomes

$$\alpha_{\text{trip}} N_{\text{He}^+} N_e = N_{2^3S} q_{2^3S \rightarrow 2^1S + 2^1P} N_e \tag{7}$$

or

$$\frac{N_{\text{He}^+}}{N_{2^3S}} = 10^{5.1} \,.$$

The ratio of the recombination to collisional excitation intensity of λ5876 will be

$$\frac{I_{\text{rec}}}{I_{\text{coll}}} = \frac{N_{\text{He}^+}}{N_{2^3S} R} \frac{\alpha_{\text{eff}}^{5876}}{q_{2^3P-3^3D}} = 10^{-1.1} R^{-1} \sim 10^{10.3\pm1} N_e^{-1} \,. \tag{8}$$

The electron density must be much less than 10^9 cm^{-3} because [O III] λ5007 + λ4959 are present during the nebular phase. Recombination will clearly dominate over collisional excitation throughout the nebular phase.

III. INDIVIDUAL NOVAE

a) *CP Lacertae* (*1936*)

The outburst of this fast nova was similar to those of CP Pup (1942) and V1500 Cyg (1975). The decline was smooth and rapid. Popper's (1940) absolute spectrometry was relative to π^1 Cyg, which he took as a 16,500 K blackbody. Kodaira's (1972) energy distribution of π^1 Cyg shows that Popper's assumption was valid. Popper estimated the color excess of CP Lac to be $E(B - V) = 0.12$ by considering the object's galactic position.

The data pertaining to the hydrogen and helium emission spectra are shown in Figures 2 and 3. The β/γ ratio is from Payne-Gaposchkin (1957), and α/β was taken from Popper (1940). The α/β ratio is fairly noisy, and the strength of Hα in the last observations is probably affected by [N II] λλ6548, 6584 emission.

The He λ5876/Hα ratio is constant between days 25 and 100. This is expected since self-absorption increases the strength of Hα only slightly, and He^+ remains the dominant stage of ionization for any plausible radiation field. The mean ratio $[I(\lambda5876)/I(\lambda6563) = 0.44 \pm 0.04]$ corresponds to $He^+/H^+ = 0.093 \pm 0.01$.

Doubly ionized helium emission was observed after day 32. Figure 3 also shows the ratio I(He II λ4686)/I(He I λ5876). This ratio increases since the ionization of the shell increases as the radiation field of the central object shifts into the ultraviolet (Gallagher and Starrfield 1976). The mean $I(\lambda4686)/I(\lambda4861)$ ratio is 0.27 ± 0.06, and corresponds to $He^{++}/H^+ = 0.02$. The total helium abundance is $He/H = 0.11 \pm 0.02$.

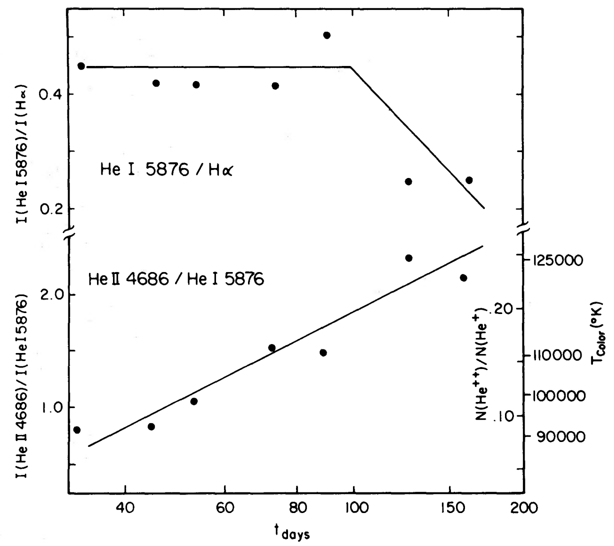

FIG. 3.—Intensities of hydrogen and helium emission lines of CP Lac taken from Popper (1940). Hα is blended with the [N II] λλ6548, 6584 doublet after day 100, but a nearby cosmic helium abundance is indicated by the He I 5876/Hα ratio before day 100. The lower panel shows the ratio of doubly to singly ionized helium, a measure of the ionization of the shell. If the shell is radiation-bound, then the He^{++}/He^+ ratio is proportional to the color temperature of the central object. This ratio has been matched to predictions of the Hummer-Mihalas model atmosphere to derive the color temperatures indicated on the right of the figure. The actual color temperature is uncertain since these model atmospheres may not be applicable to nova remnants, but both the level of ionization and its increase with time are typical of the nebular phase of the outburst.

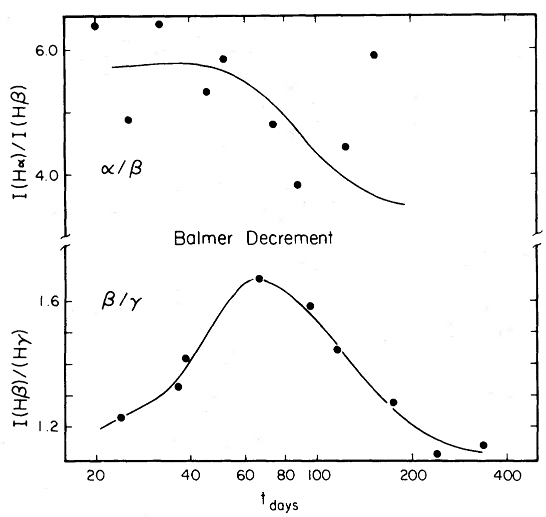

FIG. 2.—Balmer decrements of novae change with time in a typical manner. This figure shows the α/β ratio (Popper 1940) and β/γ ratio (Payne-Gaposchkin 1957) of the fast nova CP Lac. The changes in the Balmer decrement are quite similar to those which occurred during outbursts of V446 Her and V1500 Cygni, and are the result of extensive Lα trapping in the expanding shell.

Popper's data show that neutral oxygen was present throughout the decline, so the ejecta are probably radiation-bounded (O^0 and H^0 are coupled by charge exchange). The He^{++}/H^+ ratio may be used to measure the color temperature of the ionizing radiation field, if the shell is radiation-bounded, since

$$\frac{N(He^{++})}{N(He^+)} \approx \frac{Q(He^{++})}{Q(He^+)} = \frac{\int_{4\nu_0}^{\infty}(F_\nu/h\nu)d\nu}{\int_{1.8\nu_0}^{4\nu_0}(F_\nu/h\nu)d\nu} . \quad (9)$$

The right side of Figure 2 is calibrated in both $N(He^{++})/N(He^+)$ and color temperature, taken from the planetary nebula nuclei models of Hummer and Mihalas (1970). The temperatures are similar to those of V1500 Cyg (Ferland 1978).

b) *V446 Herculis* (*1960*)

Meinel's (1963) photoelectric spectrometry covers the outburst from the η Car stage through the nebular stage. The nova was not discovered until well after maximum, which may have been as bright as $V \lesssim$ 3 mag. The decline was smooth and fairly rapid, falling 3 mag in 30 days. The spectral evolution during the nebular phase was similar to that of V1500 Cyg (1975).

Meinel pointed out that the nova is probably only slightly reddened since the observed Balmer decrement approached case B during the late nebular phase, and the observed free-free, free-bound continuum was close to theoretical predictions. Low interstellar reddening is consistent with the object's position and distance.

Large variations in the Balmer decrement were observed as the nova evolved. The α/β ratio was shallow (2.2) in early March of 1960. It reached a maximum ($\sim$6) in early April, and approached case B predictions ($\sim$2.8) by late May. This behavior is nearly identical to that of V1500 Cyg (compare Meinel's [1963] Fig. 6 with Fig. 2 of Ferland 1978).

The He^+/H^+ ratio is measured from I(He I λ5876)/ I(H I λ6563). The presence of He II λ4686 during early April shows that an outer He^0/H^+ zone did not exist. The [N II] lines did not contribute to the flux in Hα since the Balmer decrement was nearly case B during late May and June. The mean λ5876/λ6583 ratio is 0.081 ± 0.01, which corresponds to $He^+/H^+ = 0.17 \pm 0.02$.

Meinel's low-resolution photoelectric data cannot separate He II λ4686 from the rest of the λ4640 blend, but a moderate-resolution, uncalibrated photographic spectrum (his Fig. 10) shows that He II λ4686 is present, and that it contributes about one third of the power in the blend. Then $I(\lambda4686)/I(\lambda4861) = 0.2$ and the He^{++}/H^+ ratio is 0.02 ± 0.01. The total helium abundance is 0.19 ± 0.03. Ejecta from this nova are clearly overabundant in helium.

No plausible physical process could make λ5876 abnormally strong during the late nebular stage. If the effects of Balmer self-absorption or interstellar reddening have been underestimated, then the helium abundance would also have been underestimated (and the Balmer decrement would not have approached case B). Since the data are likely to be reliable, it is difficult to escape the conclusion that helium is overabundant. A heavy-element abundance analysis would be especially interesting.

TABLE 1

HELIUM ABUNDANCE IN IV CEPHEI

Line (1)	Ratio (2)	He^+/H^+ (3)
λ6678/Hα	0.02 ± 0.01	0.15 ± 0.07
λ5876/Hα	0.06 ± 0.06	0.13 ± 0.13
λ4471/Hβ	0.06 ± 0.04	0.12 ± 0.08

IV. OTHER NOVAE

a) *IV Cephei* (*1971*)

Pacheco (1977) has derived He, O, and N abundances from the photographic data of Rosino (1975). He claimed that a large helium abundance (0.35) was indicated by the strength of λ5876. Table 1 lists several He/H indicators, chosen to minimize the effects of interstellar reddening. Column (1) lists the pair of lines, column (2) lists the observed line ratio, without correction for interstellar reddening, and column (3) gives the He^+/H^+ ratio. These values are the straight mean of all four Rosino observations

The data are consistent with a cosmic helium abundance. Little more can be said because the scatter is so large, but the data certainly do not demand a large overabundance of helium. More observations are required if the helium abundance of this object is to be measured.

b) *RS Ophiuchi*

Outbursts of this recurrent nova have been observed in 1898, 1933, 1958, and 1967. Tolbert, Pecker, and Pottasch's (1967) photographic spectrophotometry was obtained during the 1958 outburst. Pottasch (1967) analyzed this data and derived a helium abundance of $He/H = 0.43 \pm 0.06$ from the strengths of He I λ5876 and He II λ4686 relative to the Balmer lines. The analysis was straightforward, assuming that both the helium and hydrogen lines were optically thin recombination lines, and that the Balmer lines were formed under case B conditions.

If this assumption is valid, then the relative intensities of various helium lines should agree with the predictions of Brocklehurst (1972). Table 2 lists helium line intensities taken from Tolbert *et al.* The wavelength (column [1]) and transitions (column [2]) are given. Column (3) gives the mean intensity on days 9.5 and 10.5. The error is taken as half the spread. Brocklehurst's predictions are listed in column (4), and column (5) gives the ratio (observed/predicted). Column (6) gives other possible contributors to the line, and column (7) gives the half-width of the line in km s^{-1}. If the physical conditions estimated by Pottasch (1967) are correct, then none of the lines in the table should be affected by collisional excitation or self-absorption.

The scatter in the observed/predicted ratio suggests that the interpretation of this spectrum is not

TABLE 2

Helium-Emission Spectrum of RS Ophiuchi

Line (Å) (1)	Transition (2)	Mean* (3)	Theory (4)	Mean/Theory (5)	Breadth (km s^{-1}) (6)	Other Contribution (7)
4026.........	2^3P–5^3D	0.24 ± 0.7	0.474	0.51 ± 0.15	900	...
4144.........	2^1P–6^1D	0.37 ± 0.15	0.071	5.2 ± 2.1	1200	...
4388.........	2^1P–5^1D	0.42 ± 0.015	0.129	3.2 ± 0.1	1100	Fe II λ4385
4471.........	2^3P–4^3D	1.0 ± 0.15	1.00	1.0	1300	Fe II λλ4452, 4458
4713.........	2^3P–4^3S	1.04 ± 0.29	0.09	11.6 ± 3.4	1500	Fe II λλ4728, 4701
4922.........	2^1P–4^1D	1.32 ± 0.03	0.27	4.9 ± 0.11	900	Fe II λ4924
5016.........	2^1S–3^1P	3.0 ± 0.6	0.59	5.0 ± 1	1400	Fe II λ5018
5047.........	2^1P–4^1S	1.03 ± 0.15	0.039	26.4 ± 4	1100	Si II λ5041
5876.........	2^3P–3^3D	8.3 ± 1.5	2.76	3.0 ± 0.54	1800	NaD
6678.........	2^1P–3^1D	1.5 ± 1.0	0.78	1.87 ± 1.28	900	...

* Average of line intensity, relative to λ4471, for days 9.5 and 10.5.

straightforward. As an example, consider the two ratios I(He I λ5876)/I(He I λ4471) = 8.3 ± 0.1 and I(He II λ5412)/I(He II λ4686) = 0.43 ± 0.11. Both are often used as reddening indicators since neither is likely to be affected by self-absorption or collisional excitation. These ratios, together with their predicted values of 2.75 and 0.08, respectively, require reddening corrections of $E(B-V) = 1.1 \pm 0.1$ mag and 3.1 ± 0.2 mag. If the line intensities were corrected for the average color excess, $E(B-V) = 2$ mag, the Balmer decrement would be flat (Hα/Hβ/Hγ/Hδ = 1.0 ± 0.2/1.00/1.11 ± 0.5/0.90 ± 0.3). A nearly flat Balmer decrement is difficult to achieve in a photoionized nebula and is in serious disagreement with the assumption that the Balmer lines are formed under case B conditions. It is likely that the strengths of the helium lines are affected by mechanisms other than recombination.

The spectrum of RS Oph presents very broad emission lines. Interpretation is hampered because line blending is often serious, and may go unnoticed. Further, RS Oph was in the η Car stage of the outburst throughout most of Tolbert *et al.*'s data (Fe II emission was quite strong). Since Fe II has a particularly rich spectrum, it is likely that many of the He I features are blended with iron lines. The breadth of a feature and its intensity relative to other helium lines are good indicators of whether a line is blended. Column (6) of the table lists lines which lie within the observed breadth of the helium line. The strengths of the Fe II lines can be estimated by scaling Thackeray's (1977) Fe II intensities for RR Tel, to the strengths of unblended Fe II lines in RS Oph. The Fe II lines listed in Table 2 contribute significant fractions of the total power in the blend.

During the η Car stage, NaD emission is present in addition to the Fe II lines (see, e.g., spectra of nova V1500 Cygni between 1975 September 2 and 1975 September 10, Tomkin *et al.* 1976). It is likely that NaD affects the strength of λ5876 in RS Oph since (1) Na emission is expected during this stage of the outburst; (2) the breadth of the feature at λ5880 is large and includes the NaD doublet; and (3) the λ5880 feature is abnormally strong relative to λ4471, which is itself likely to be blended.

The He I lines λλ4026, 4144, and 6678 may be unblended. The intensity and abundance ratios are: I(λ4026)/I(Hδ) = 0.14 ± 0.3, $He^+/H^+ = 0.15 \pm 0.03$; I(λ4144)/I(Hδ) = 1 ± 0.5; $He^+/H^+ = 1.1 \pm 0.5$; and I(λ6678)/I(Hα), $He^+/H^+ = 0.18 \pm 0.12$. The very large scatter demands that these abundances be treated with caution, but the λ4026/Hδ and λ6678/Hα ratios may indicate $He^+/H^+ \sim 0.17 \pm 0.1$. He II λ4686 is present but weak at this time, so only a slight correction for He^{++} would be required ($He^{++}/H^+ = 0.02$).

The interpretation of the helium line intensities in RS Oph presents many serious problems. In particular, the entire He I emission-line spectrum cannot be interpreted in terms of an optically thin model. Either the emission mechanism is affected by an unknown process, or the photographic data are inaccurate. It seems premature to conclude that helium is extremely overabundant in RS Oph. This issue may be resolved shortly; RS Oph should undergo another outburst soon if its past behavior is continued.

c) *The Analysis of Ruusalepp and Luud*

Ruusalepp and Luud (1970) derived chemical abundances of 12 novae, and found a range of helium abundances between 0.19 and 0.53. Their analysis assumes that the ejecta from a nova are similar to the photosphere of a star; Saha's equation correctly describes ionization conditions and the level populations are as in LTE. It is much more likely that the ejecta are photoionized by the radiation field of the central object during the nebular phase (Gallagher and Starrfield 1976) since the ejecta radiate much more energy than can be stored in $10^{-4}\,M_\odot$. An energy source is required to explain the energetics.

The physical conditions within a photoionized nebula (Strömgren 1939) are quite different from those in an LTE stellar atmosphere. Since the kinetic temperature within nova ejecta is $T_e \sim 10^4$ K, Ruusalepp and Luud applied large corrections for He^0 (necessary because collisional ionization equilibrium was assumed), and a large helium abundance resulted. Since several key assumptions of their analysis are suspect, their results must be treated with extreme caution.

d) *Other Measurements*

Robbins and Sanyal (1978) and Tylenda (1977) have both found that ejecta from the very slow nova HR Del have an enhanced helium abundance. The mean of their measurements (He/H = 0.20 and 0.27, respectively) is He/H = 0.23 ± 0.05.

Collin-Souffrin (1976) reported the results of a study which found a similar helium abundance (He/H = 0.25) for the slow nova DK Lac. Her study employed Larsson-Leander's (1954) photographic data which extend over the first months of the nebular phase. Since the expansion velocity of the ejecta was fairly small and the emission lines sharp, several helium lines could be measured accurately. We have repeated her analysis and find essentially the same abundance, He/H = 0.22 ± 0.04.

The helium abundance of V544 Her (1963) has been measured by several authors (Andrillat and Collin-Souffrin 1979, He/H = 0.15; Bartasch and Boyarchuk 1965, 0.20; and Doroshenko 1968, 0.19). The mean is He/H = 0.18 ± 0.03. Glass and Webster (1973) found that ejecta from RR Tel had a helium abundance of He/H = 0.19, a value similar to the helium abundance of RR Pic found by Williams and Gallagher (1979, He/H = 0.23).

Williams *et al.* (1978) studied the nebula surrounding the old nova DQ Her and found an essentially solar helium abundance (He/H ~ 0.08). We can compare this abundance with that which would have been derived during the early nebular phase. Payne-Gaposchkin and Whipple (1939) published the results of observations made during the recovery from the great minimum. The data seem to be reliable since the [O III] λ5007/λ4959 doublet has the correct 3:1 ratio. The He I λ4471/Hγ intensity ratio can be measured on seven nights [$I(\lambda4471)/I(\lambda4363) = 0.18 \pm 0.06$] and apparently indicates a large abundance of singly ionized helium ($He^+/H^+ = 0.18 \pm 0.06$). Doubly ionized helium is observed, and the total helium abundance is ~0.20 ± 0.06. The Balmer decrement, however, is steep (Hγ/Hβ = 0.33 ± 0.04 as opposed to the case B prediction of 0.47), and it is likely that self-absorption affects the Balmer line strengths. This case illustrates the danger of using Balmer lines such as Hβ or Hγ as a hydrogen abundance indicator when the physical conditions in the ejecta are uncertain.

V. SUMMARY

In this paper we have measured the helium abundance in ejecta from the novae CP Lac (He/H = 0.11 ± 0.02) and V446 Her (He/H = 0.19 ± 0.03). Table 3 lists these results together with results of the studies discussed in the previous section.

The range of helium abundances in this sample is 0.08 ≤ He/H ≤ 0.23. This range is similar to the spread in helium abundances in planetary nebulae (Kaler 1978), although a larger fraction of novae have an enhanced abundance. It is interesting that the carbon composition of planetary nebulae indicated by optical recombination lines (Torres-Peimbert and Peimbert 1977) is also similar to that deduced for novae (Williams *et al.* 1978, Ferland and Shields 1978).

Starrfield *et al.* (1972, 1974) have shown that a fast nova outburst will occur if the carbon composition of the material at the base of the envelope of the white dwarf is enhanced by ~10–100 times the solar abundance. Envelopes with more nearly solar compositions will produce slow novae (Sparks *et al.* 1978). The carbon required for a fast nova outburst could be mixed up from the core of the white dwarf (Colvin *et al.* 1977), but the analogy with planetary nebulae suggests that the material transferred from the red star could already have been enriched in carbon and helium. An abundance analysis of the atmosphere of the companion in GK Per would be especially interesting.

Several correlations between various parameters of the nova outburst are well established (Payne-Gaposchkin 1957; McLaughlin 1960). For example, fast novae tend to have the most luminous maxima, the largest outburst ranges and expansion velocities, and the smoothest light curves. It is tempting to try to understand these systematics in terms of some fundamental quantity such as the mass or chemical composition of

TABLE 3

HELIUM ABUNDANCES

Nova	He/H
V1500 Cyg........	0.11 ± 0.01
HR Del...........	0.23 ± 0.05
DQ Her..........	0.08
V446 Her.........	0.19 ± 0.03
V544 Her.........	0.18 ± 0.03
CP Lac...........	0.11 ± 0.02
DK Lac..........	0.22 ± 0.04
RR Tel...........	0.19
RR Pic...........	0.20

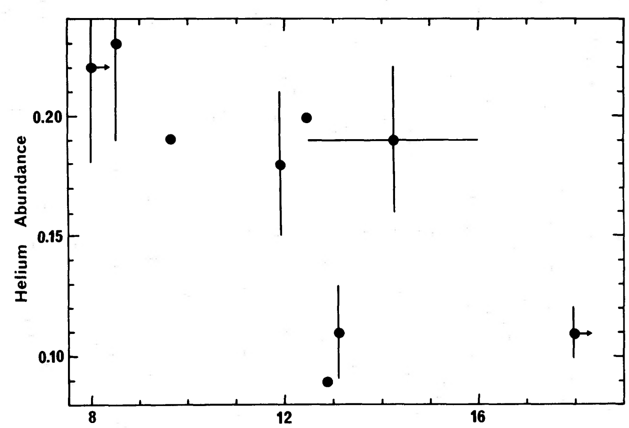

FIG. 4.—Helium abundances of novae plotted against the outburst range, as given by Payne-Gaposchkin (1957, 1977). The outburst range is an advantageous parameter since it can usually be measured unambiguously. Other parameters such as the luminosity at maximum light and the rate of decline show similar correlations but with more scatter. The points with rightward pointing arrows correspond to Dk Lac and V1500 Cyg and are lower limits to the range. The point at (14.0, 0.19) corresponds to V446 Her. The range is uncertain because the nova was not discovered until well after maximum light. The discovery magnitude corresponds to a range of 12.5 mag, but the nova could have been as bright as $V \sim$ 3 mag (Meinel 1963), making the range ~16 mag.

the envelope (Sparks *et al.* 1978). We have searched for correlations between the helium abundances of Table 3 and other features of the individual outbursts. Figure 4 shows the best correlation, that between helium abundance and outburst range. Novae with smaller outburst ranges tend to have enhanced helium abundances. (The novae with small outburst ranges also tend to be those with the most chaotic light curves, the slowest rates of decline, and the faintest luminosities at maximum.)

If the enhanced helium and CNO abundances in novae are to be attributed to enrichment from the core of the white dwarf, then the following scenario is possible. Stellar evolution calculations (Eggleton 1979) predict that the carbon core of a white dwarf will be surrounded by a 10^{-6}–10^{-1} $M_{\odot}$ helium shell. Each nova system undergoes $\sim 10^3$–10^4 outbursts (Ford 1978; Bath and Shaviv 1978). If some fraction of the outer layers of the white dwarf are removed during each outburst, then the first outbursts will eject comparatively more helium and less carbon than the later outbursts. If Sparks *et al.*'s (1978) ideas are correct and the carbon abundance affects the speed class of the outburst, then the first outbursts will resemble a slow nova. The speed class might grow faster on each subsequent outburst as the outer layers of the white dwarf are removed and as deeper, more carbon-rich layers become exposed. It is interesting that the total mass of helium beyond the cosmic abundance ejected in $\sim 10^3$ outbursts with He/H $= 0.2$ will be $\sim 10^{-2}$ $M_{\odot}$, within the range of helium shell masses. Alternatively, helium abundances of individual novae could be determined by the system's evolutionary history or by the outburst itself.

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