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Ultraviolet spectral evolution and heavy element abundances in Nova Coronae Austrinae 1981

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Summary. Nova CrA 1981, a moderately fast galactic nova, was systematically observed over a period of seven months with the *IUE* satellite. The initial evolution of the UV spectrum was similar to that of previously observed novae; however, several months after maximum, weak emission due to very high ionization forbidden lines of Na, Mg, Al, and Si appeared, eventually decreasing in strength over the next two months. The spectral development of the lines is consistent with the photoionization of an expanding shell; a high-temperature 'coronal' origin is ruled out. Abundances deduced from the spectra show that most of the observed heavy elements in the ejected material are enhanced with respect to helium, with neon the most abundant of these. In addition, there are substantial deviations of the Na/Mg/Al/Si abundance ratios from solar values. This is interpreted as evidence for the mixing of core material with the accreted envelope on a massive O–Ne–Mg (as opposed to a C–O) white dwarf. Furthermore, the proportion of core material in the ejecta implies that the mass of the white dwarf decreased as a consequence of the outburst.

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1 Introduction

Nova CrA 1981 was discovered by Honda (1981) on 1981 April 2 near maximum light, at apparent brightness $m_V=7$. The nova was not studied extensively at optical wavelengths because of its southern declination ($\delta=-38°$), which made observations from northern latitudes difficult. Brosch (1982) has discussed the spectrum obtained on one date a week after discovery, and we also show an optical spectral scan taken near maximum light. However, little other optical spectral data have been published.

The nova was declared a target of opportunity by the *International Ultraviolet Explorer (IUE) Observatory*, and ultraviolet spectra were obtained systematically following the outburst for a period of seven months, beginning 1981 April 10. The spectra were all taken at low dispersion (~6 Å resolution), on 12 separate dates. Initially, during the immediate post-maximum period, the interval between observations was several days. Eventually, as the rate of decline slowed, the scans were obtained approximately monthly. On each date, four scans were usually acquired: two with the short-wavelength camera ($\lambda\lambda$ 1200–1950 Å) and two with the long-wavelength camera (1900–3200 Å). Because of the decreasing intensity of the nova and the changing strengths of the emission lines relative to the continuum, proper exposure times had to be guessed, with the result that the signal-to-noise ratios of the spectra varied widely. On a number of dates, even the best scans were quite noisy and showed only the strongest lines. The scans were all reduced at Goddard Space Flight Center using the *IUE* data reduction package to obtain flux calibrated spectra, and integrated line fluxes were determined for the emission lines.

The nova displayed three distinct stages of spectral development. The first consisted of emission lines of different excitation mechanisms, but not forbidden lines. The second stage was characterized by the presence of high-ionization, collisionally-excited forbidden lines from non-CNO elements, and the third stage consisted primarily of the more commonly observed medium-ionization UV resonance and intercombination lines observed in most emission-line objects. We show the best scans obtained during each of these stages in Figs 1–3. As is usually the case with novae in decline, the spectra consist of very broad emission lines formed in the high-velocity ejecta, and therefore some of the line identifications could be incorrect. In particular, Nova CrA 1981 displayed a number of UV lines that we were not able to find identified previously in any nova, but which have been observed in the solar corona (Jordan 1971; Sandlin, Brueckner & Tousey 1977; Sandlin & Tousey 1979). For these lines, we have attempted to make identifications which are consistent with the presence of the other more definite transitions, within the framework of a low-density astronomical plasma. All of the line identifications for which we have some confidence have been labelled in the figures. In addition, we have listed in Table 1 the emission fluxes for the lines identified in the spectra shown in the figures, corresponding to the dates 1981 April 12, June 13, and September 13. For completeness, we have also denoted with a ‘P’ or an ‘S’ those lines which were either ‘present’ and/or ‘strong’ on other dates. Since the quality of the spectra varied considerably, the absence of a P is not necessarily significant, i.e. the line might have appeared on a higher signal-to-noise spectrum.

The fluxes in Table 1 are only given to the nearest 0.1 dex because the measurement accuracy for all but a few of the stronger, unblended lines is of the order of 25 per cent. The observed intensities differ from the actual emitted strengths by an unknown reddening correction which we believe is not substantial. First, there is no evidence for the λ 2200 Å interstellar absorption feature in the continuum, consistent with the galactic latitude ($b=-15°$) of the nova, which causes the line-of-sight to leave the galactic plane within about 0.5 kpc from the Sun. Secondly, there are five globular clusters within ~7° of the nova for which reddening measurements take on the range of values $0.03 \leqq E(B-V) \leqq 0.20$ (Burstein & Heiles 1978), with the cluster closest to the nova having reddening at the lower limit. If the upper limit were to apply, several of the line ratios we subsequently use for calculations could be affected by as much as a factor of 1.4. However, the

Table 1. Emission-line fluxes for Nova CrA 1981.

LINE	10 Apr	12 Apr	21 Apr	2 May	13 June	17 July	18 Aug	13 Sept	5 Oct	14 Nov
Ly-α		S	S	S	P					
N V 1240		-9.1	S		-9.5	S	S	-11.7	S	S
Si II 1263		-9.6								
O I 1304		-9.1	S	P						
C II 1335		-9.4	S	P						
O V 1371		-9.8	S	P						
Si IV 1397		}-9.2	}S	P						
O IV] 1402				S	-10.3	S	S	-12.1	P	P
N IV] 1486		-9.6	S	S	-9.9	S	S	-11.7	S	S
C IV 1549		-9.5	S	S	-10.2	S	S	-12.1	P	P
[Ne V] 1575					-10.9					
[Ne IV] 1602					-10.6	S	S	-12.0	P	P
He II 1640		-9.7	P	P	-10.7	P	P	-12.2	P	P
O III] 1663		}-9.9	}S	S	-10.6	P	P	-12.7	P	P
Al II 1671										
N IV 1719		-9.6	P							
N III] 1750		-9.3	S	S	-10.3	S	S	-12.2	P	P
[Mg VI] 1806					P	P	P			
Si II 1814		-10.0	P							
[Ne III] 1815				P	-11.2	P	P	-12.5		
Al III 1857		-9.4	S	P	-11.1					
Si III] 1892		}-9.6	}S							
C III] 1909	S			S	-10.7	P	P	-12.6		
[Na V] 2069					-11.4					
N II] 2142	P	-9.8	P							
[Si VII] 2147					}-11.4					
[Si IX] 2150										
C II] 2326	P	-10.5								
[Al VIII] 2367					-11.4					
[Ne IV] 2422							S	-12.1		
[Al VI] 2431					-11.3					
[Mg VII] 2510					-11.1					
[Al VI] 2604					P					
[Mg VII] 2629					-10.7		P			
Al II] 2670	P	-9.7	P							
[Mg V] 2783					-10.8					
Mg II 2798	S	-9.3	S	S	-10.6		S	-12.0		
[Mg V] 2929					-11.3		P			
[Na VI] 2974					}-11.0					
[Ne V] 2976							P			
O III 3133					-10.9		P			

higher colour correction is probably larger than the actual extinction for the nova, and is comparable to the uncertainties in the measured fluxes and the atomic parameters required for the calculations, and therefore we have not attempted to arrive at a more specific reddening correction.

2 Spectrum development

The time evolution of the UV spectrum of Nova CrA is well represented by the scans in Figs 1–3. Every UV line which was observed in the nova appears in one of these three spectra, and all of the other scans are essentially minor variants of these scans. The initial development of the nova spectrum was roughly the same as that of other novae which have been studied in the ultraviolet, e.g. U Sco (Williams *et al.* 1981) and V1663 Cyg (Stickland *et al.* 1981). Strong emission lines were already present on our first scans, obtained roughly one week after maximum light. Weak absorption appears to be present blueward of Si IV+O IV] λ 1400, C IV λ 1549, N IV λ 1719, and Al III λ 1857, and it persisted for several weeks. The emission lines are primarily the principal resonance lines and the lowest lying intercombination lines connected to the ground states of cosmically abundant elements. The only exceptions to this are He II λ 1640, N IV λ 1719, and O V λ 1371, which are formed by two-body and dielectronic recombination (Stickland *et al.* 1981; Storey 1981). We suspect that dielectronic recombination is also largely responsible for the intensities of C II λ 1335, Si II λ 1263 and Si II λ 1814 (*cf.* Storey 1981). The considerable strength of the O I λ 1304 emission feature is caused by Lyβ resonance fluorescence excitation (Strittmatter *et al.* 1977).

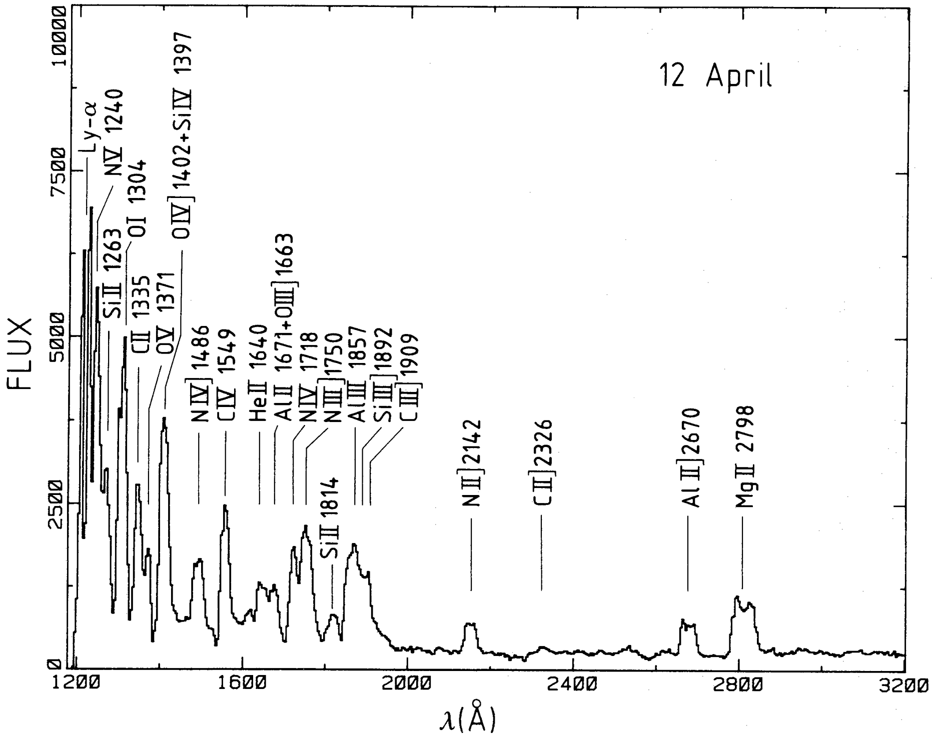

Figure 1. Low-dispersion *IUE* ultraviolet spectrum of Nova CrA 1981 on 1981 April 12. Flux is in units of $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Å^{-1}}$.

During the month following outburst, the general appearance of the nova spectrum remained the same. Both the lines and continuum decreased in flux during this time, with the line intensities diminishing less rapidly, so that the lines became relatively more prominent, increasing in equivalent width. On 1981 May 25, the spectrum underwent its first significant change with the

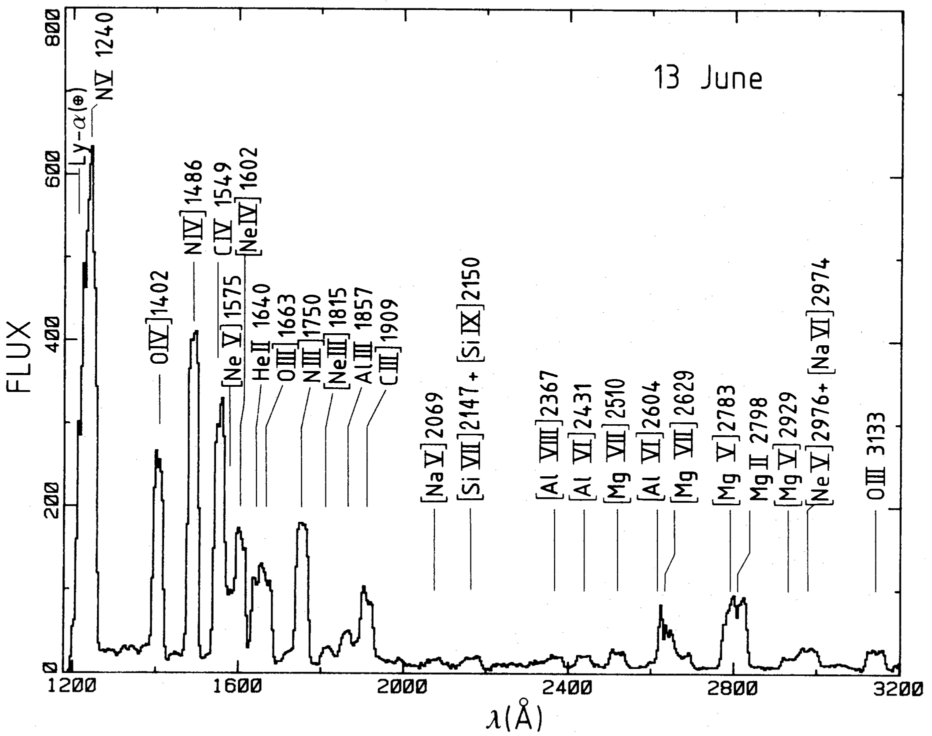

Figure 2. UV spectrum of Nova CrA on 1981 June 13. Units of flux are same as in Fig. 1.

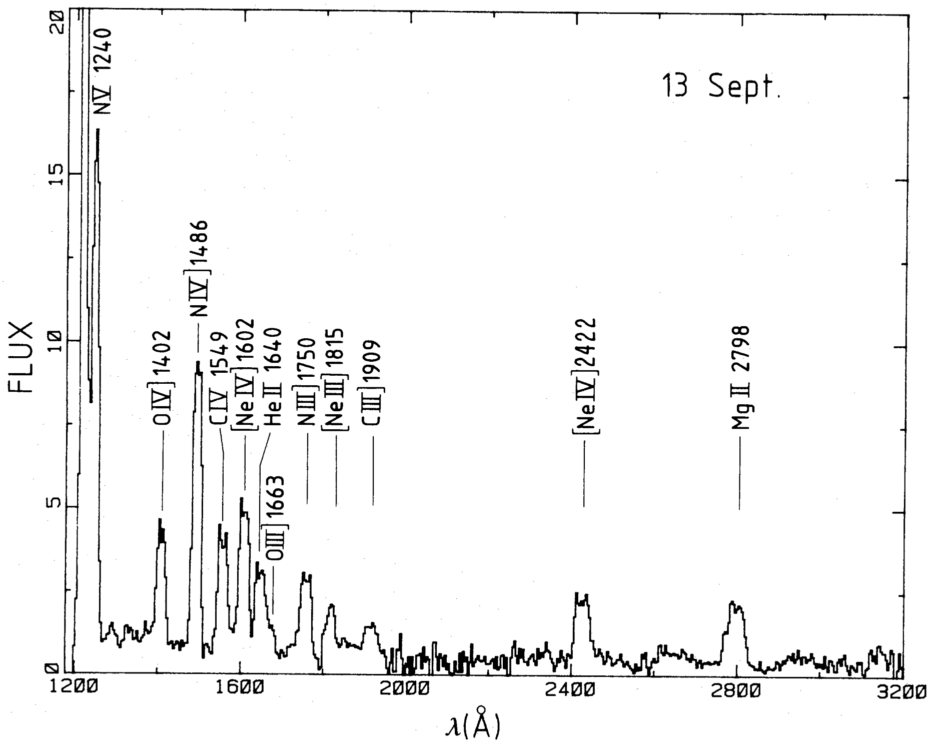

Figure 3. UV spectrum of Nova CrA on 1981 Sept 13. Flux units are the same as Figs 1 and 2.

initial appearance of highly-ionized forbidden lines. By this time, except for He II λ1640 all transitions other than those to the ground states of ions had disappeared, implying that the observed emission lines were caused by collisional excitation from the ground state.

The forbidden-line phase of the spectrum was most pronounced in June, as shown in Fig. 2. Most of the forbidden lines occur in the interval λ2000–3000 Å, and belong to moderately high ionization states. The gradual appearance of these lines is due to the decreasing density of the nova ejecta, which results in less collisional de-excitation for these transitions and also in increasing ionization. This ‘quasi-coronal’ phase in the nova spectrum is almost certainly due to photoionization rather than collisional ionization because of the absence of high-excitation ‘auroral’ transitions which would be observable if high temperature were the cause of the ionization.

The high-ionization forbidden lines gradually weaken relative to the permitted lines, and disappear into the continuum by August. During this time, the lower-ionization CNO resonance and intercombination lines maintain roughly the same strengths relative to each other. By mid-September (Fig. 3), the relative emission line fluxes have stabilized, and thereafter do not undergo any substantial changes through 1981 November, the date of our last spectral scan, when the visual brightness as indicated by the *IUE* Fine Error Sensor was $m_V \gtrsim 16$.

There are several possible causes for the eventual weakening of the Na, Mg, Al, and Si forbidden lines with respect to the other emission lines. However, consistent with the expectations for an expanding gas with decreasing density, collisional de-excitation is not a cause, since [Ne IV] λ2422 remains strong after the other forbidden lines have disappeared, yet the [Ne IV] line has the lowest critical density of any of the lines observed. Nor is it due to a general lowering of the ionization level of the gas, since the strength of N V λ1240 relative to other lines such as N IV] λ1486, C IV λ1549, and N III] λ1750 remains relatively constant during this time. However, if the ejecta are photoionized by relic thermal radiation from the outburst or from the re-established accretion disc, there is likely to be a sharp high-frequency turnover to the ionizing flux which is very temperature-dependent. It is quite plausible then that a decrease in the temperature of the stellar remnant causes the high-frequency cut-off to pass from higher energies down to frequencies near the ionization edge of N^{+4}. This would explain why all the lines from ions with ionization potentials of Ne^{+4} and greater disappeared, without appreciably affecting any line strengths from ions with ionization potentials lower than N^{+4}.

Another possible explanation for the decline of some of the forbidden lines is condensation into grains. The sudden increase in the infrared flux of certain novae some months after outburst accompanied by a simultaneous decrease in optical brightness has generally been acknowledged as due to the formation of dust (*cf.* Gallagher & Starrfield 1978; Ney & Hatfield 1978). Although no such drop in the visible brightness of Nova CrA was reported, some grain formation may nevertheless have contributed to the decrease in the Na, Al, and Si line strengths.

3 Spectral analysis

The presence of emission lines in the Nova CrA spectrum from elements not normally seen in novae affords an excellent opportunity to determine abundances and physical conditions in the gas which underwent outburst. We will apply standard emission-line analysis to the nova spectra, incorporating some of the processes described by Stickland *et al.* (1981) for this situation. We confine our attention to the three dates for which we were able to obtain high-quality spectra over the entire UV wavelength region accessible to the *IUE* satellite.

3.1 1981 APRIL 12

A moderate range of ionization (O I to N V) exists on this date, and a number of different modes of excitation operate to produce the lines observed, including (1) simple two-body recombination (Lyα, He II λ 1640), (2) collisional excitation (C IV λ 1549, N III] λ 1750, Al II] λ 2670, etc.), (3) dielectronic recombination to autoionizing levels, followed by radiative decay (O V λ 1371, N IV λ 1719, C II λ 1335, Si II $\lambda\lambda$ 1263, 1814), and (4) resonance fluorescence (O I λ 1304).

Stickland *et al.* (1981) have used an excellent method for determining the kinetic temperature of an emitting gas using relative fluxes of lines excited by different processes (collisional excitation versus dielectronic recombination), and which therefore have different temperature dependences. They recommend using the line ratios C II λ 1335/C III] λ 1909, C III λ 2297/C IV λ 1549, and N IV λ 1719/N V λ 1240 in situations where the lower ionization line is excited entirely by recombination, and the higher ionization line is due to collisional excitation. In Nova CrA, we suspect that λ 1335 may have some contribution from collisional excitation, and λ 1909 may be contaminated by dielectronic recombination (Storey 1981); therefore we have not used this ratio. We were not able to detect C III λ 2297, and therefore the λ 1719/λ 1240 ratio is our only viable alternative. Ignoring any collisional excitation of N IV λ 1719 because of its very high excitation potential, one has

$$\frac{F(\mathrm{N\,IV}\,\lambda\,1719)}{F(\mathrm{N\,V}\,\lambda\,1240)}=\frac{N_e N(\mathrm{N}^{+4})\alpha^{\mathrm{di}}(\lambda\,1719)\ (1240/1719)}{N_e N(\mathrm{N}^{+4})\times 8.63\times 10^{-6}\ \Omega_{12}/(\omega_1 T_e^{1/2})\ \exp\,(-\chi_{12}/kT_e)}, \tag{1}$$

where Ω_{12}, ω_1, and χ_{12} are the collision strength, statistical weight, and excitation potential for λ 1240, and $\alpha^{\mathrm{di}}(\lambda\,1719)$ has been tabulated by Storey (1981) and is insensitive to temperature in the regime $T_e \sim 10^4$ K. Using the cross-sections tabulated in Mendoza (1983), one has

$$T_e=\frac{116100}{11.65+\ln[T_4^{-1/2}\ F(\lambda\,1719)/F(\lambda\,1240)]}\ \mathrm{K}, \tag{2}$$

where $T_4 \equiv T_e/10^4$, and this expression must be solved iteratively to obtain T_e. On April 12, the observed ratio is roughly $F(\lambda 1719)/F(\lambda 1240) \sim 0.3$, which leads to the electron temperature $T_e = 11000$ K. The upper limit to the intensity of C III λ 2297 requires $T_e \gtrsim 10000$ K.

Relative ion abundances which are rather insensitive to the electron density and temperature can be determined for emitting ions from a comparison of relative line intensities for lines which are excited by the same process, e.g. collisional excitation. Due to the more severe degree of line blending evident in April, as compared with June, and the considerable likelihood that some of the lines are collisionally de-excited at this earlier date, any derived abundance ratios are likely to be less reliable than those determined for June. However, the calculations are useful as an order of magnitude comparison with those to be computed for June. For two lines excited by collisions, the relative ion abundances are

$$\frac{N_k}{N_l} = \frac{\lambda_k F_k}{\lambda_l F_l} \frac{\Omega_l/\omega_l}{\Omega_k/\omega_k} \exp\left[(\chi_k - \chi_l)/kT_e\right], \tag{3}$$

where F_k/F_l is the line flux ratio. It is assumed that the ions occupy the same emitting volume, which is likely to be reasonable if they have similar ionization potentials. Acknowledging that in April the intercombination lines probably suffer collisional de-excitation, e.g. O III] λ 1663 is less intense than Al III λ 1857, whereas in June and thereafter, the O III]/Al III ratio is reversed, the following abundances are deduced (using the line ratios given in parentheses):

$$\begin{aligned} &\frac{\mathrm{C}^{+3}}{\mathrm{N}^{+3}} \simeq 0.2 \quad (\lambda 1549/\lambda 1486),\\ &\frac{\mathrm{Al}^{+2}}{\mathrm{C}^{+3}} \simeq 0.1 \quad (\lambda 1857/\lambda 1549),\\ &\frac{\mathrm{Al}^{+}}{\mathrm{Mg}^{+}} \simeq 1.4 \quad (\lambda 2670/\lambda 2798). \end{aligned} \tag{4}$$

The collision strengths used in the calculations were taken from Osterbrock & Wallace (1977), and for the Al transitions the relation was used that collision strengths vary as $\Omega \propto Z^{-2}$ for the same transition along an isoelectronic sequence (Layzer 1959; Seaton 1971), where Z is the the atomic number of the element. These ion ratios must be regarded as only very approximate because of the use of the intercombination lines. Unfortunately, no collisionally excited lines of O or Ne are sufficiently free from blending with strong transitions of other elements to be useful, and so no indication of oxygen or neon ion abundances can be obtained from the April data.

The He II λ 1640 line is due to recombination, and therefore the relative strength of He II to CNO collisionally-excited lines is very temperature-sensitive. Although λ 1640 is blended with Al II λ 1671 in April, the temperature is known to better accuracy than on succeeding dates, and so we have computed the $\mathrm{N}^{+4}/\mathrm{He}^{+2}$ abundance ratio as a rough indicator of the relative abundance of helium with respect to the heavy elements. We find that $\mathrm{N}^{+4}/\mathrm{He}^{+2} \sim 0.15$, assuming optically-thin lines and no collisional de-excitation.

3.2 1981 JUNE 13

By two months after the outburst, the nova spectrum has changed. Most of the lines formed by processes other than collisional excitation have disappeared, and in the wavelength interval longward of 2000 Å a number of emission lines have appeared at wavelengths which are different from those normally seen in the UV spectra of emission-line objects, but which have been identified in the solar corona (*cf.* Jordan 1971; Sandlin, Brueckner & Tousey 1977). The lines are weak, but definitely present since they are confirmed in several of our spectra during the interval

June–August. The transitions responsible for the lines are less certain, since the emission cannot be due to the common ionization stages of the more abundant elements such as C, N, or O, as they do not have transitions in this wavelength region. In assigning identifications, we were guided by the fact that the strongest features in the spectrum are collisionally excited transitions, and thus we attempted to find similar transitions from other elements. In fact, there are few reasonable alternatives possible other than those transitions at the same wavelengths which have been identified in the solar corona. Consequently, we have some confidence that the emission which appears in Nova CrA in June consists of the forbidden lines from highly ionized ions of Na, Mg, Al, and Si that are listed in Table 1.

This situation is reminiscent of the similar behaviour of Nova V1500 Cyg1975, which was discovered by Grasdalen & Joyce (1976) to have very highly ionized 'coronal' forbidden lines from some of the same elements in the near-infrared about one month after outburst. It should be noted that virtually all of the possible UV transitions from the lowest excited levels to the ground states of moderately to highly ionized species of Ne, Al, Mg, and Si are identified in the spectrum. The fact that several stages of ionization are observed for these elements is very important for our abundance determinations.

The level of ionization in the gas is much higher in June, and the density much lower. The critical collisional de-excitation densities for several of the observed lines are low due to small transition probabilities, particularly the p^3 transitions such as [Na v] λ 2069, for which $N_e^c=6\times10^5\,\mathrm{cm}^{-3}$. The presence of these lines at intensities comparable to the other lines suggests that $N_e\leq10^6\,\mathrm{cm}^{-3}$.

A definite value of the electron temperature cannot be established in June because of the absence of appropriate temperature-sensitive line pairs. N IV λ 1719 is no longer detectable, and the observed limit to the line ratio $F(\mathrm{N\,IV}\,\lambda\,1719)/F(\mathrm{N\,V}\,\lambda\,1240)\leq0.02$ requires $T_e\gtrsim15\,000\,\mathrm{K}$. On the other hand, the absence of detectable [Mg V] λ 2418 and [Mg VII] λ 2263 auroral transitions together with the presence of strong [Mg V] λ 2783 and [Mg VII] λ 2629 nebular lines requires that $T_e\lesssim50\,000\,\mathrm{K}$, since the difference in excitation potentials of the lines is 5 eV. We shall conservatively adopt the lower limit as the most realistic provisional value of T_e in the abundance calculations that follow. This limit to the temperature effectively rules out collisional ionization as the cause of the high ionization level of the gas.

Because of (1) the wider variety of ion species, which makes ionization corrections less uncertain, (2) the higher temperature, which makes the relative line fluxes less sensitive to T_e, and (3) the lower density, which causes the effects of collisional de-excitation to be minimal for all but a few lines, the chemical composition of the nova ejecta is best determined from the spectrum obtained on this date. The presence of different multiplets of Ne, Mg, Al, and Si is fortuitous because it enables the abundances of these elements to be established for the nova.

A very broad range of ionization is present in June, ranging from Mg II and Al III to Al VIII and Si IX, and so there is likely to be a fairly smooth distribution of each element among its ionization states, with no single ion predominating. Therefore, in the absence of more detailed information, we will take abundance ratios of ions having similar ionization potentials to be representative of the relative elements' abundances. We define the (arbitrarily normalized) abundance of an ion in terms of its collisionally-excited emission-line flux to be given by

$$N_i=\frac{\lambda F_\lambda}{\Omega/\omega}\exp(\chi_i/kT_e), \tag{5}$$

where the parameters of the transition are as defined for equation (3). Application of this equation to CNO and Ne ions is straightforward since their collision strengths have all been computed, and are tabulated by Mendoza (1983). However, excitation cross-sections for the Na, Mg, and Al ions have not yet been determined. Fortunately, most of the observed transitions from the latter ions belong to the same $2p^2$, $2p^3$, and $2p^4$ electronic configurations as well-studied

CNO lines, and the appropriate collision strengths for the quasi-coronal forbidden lines can be calculated from the corresponding CNO transitions via the relation $\Omega=\Omega_0/Z^2$ between the same levels in an isoelectronic sequence. Ion abundances have been derived using this information together with the observed relative line intensities given for June in Table 1 and the assumed temperature $T_e=15000$ K, and these are listed in Table 2.

Table 2. Relative ion abundances.

Ion	Line	Flux (erg/cm^2 sec)	Abundance (cf. eqn. 5)
He^{+2}	1640	2.0×10^{-11}	5.6×10^{-3}
C^{+2}	1909	2.0×10^{-11}	4.1×10^{-6}
C^{+3}	1549	6.3×10^{-11}	1.1×10^{-5}
N^{+2}	1750	5.0×10^{-11}	6.6×10^{-5}
N^{+3}	1486	1.3×10^{-10}	1.5×10^{-4}
N^{+4}	1240	3.2×10^{-10}	2.7×10^{-4}
O^{+2}	1663	2.5×10^{-11}	9.2×10^{-5}
O^{+3}	1402	5.0×10^{-11}	1.9×10^{-4}
Ne^{+2}	1815	6.3×10^{-12}	1.2×10^{-4}
Ne^{+3}	1602	2.5×10^{-11}	1.7×10^{-4}
Ne^{+4}	1575	1.3×10^{-11}	4.4×10^{-4}
Na^{+4}	2069	4.0×10^{-12}	3.6×10^{-6}
Mg^{+4}	2783	1.6×10^{-11}	1.6×10^{-5}
Mg^{+6}	2633	2.0×10^{-11}	1.8×10^{-5}
Al^{+5}	2431	5.0×10^{-12}	8.4×10^{-6}
Al^{+7}	2367	4.0×10^{-12}	5.6×10^{-6}
Si^{+6}	2148	4.0×10^{-12}	1.0×10^{-5}
Si^{+8}	2150		

Since the ionization distribution of the elements is quite broad, rather large ionization corrections would be required to determine the total abundance of an element from any single ion. Therefore, the procedure we have used to find relative abundances is simply to take the ratios of as many ions of similar ionization potential as possible. A more elaborate procedure is probably not justified in view of our rough analysis which utilizes only one value of N_e and T_e for the emitting gas. The resultant abundance ratios we derive for the ejecta in June are

$$\frac{C}{N}=\frac{C^{+2}+C^{+3}}{N^{+2}+N^{+3}}=0.070, \qquad \frac{N}{O}=\frac{N^{+2}+N^{+3}}{O^{+2}+O^{+3}}=0.77,$$

$$\frac{Ne}{N}=\frac{Ne^{+3}+Ne^{+4}}{N^{+3}+N^{+4}}=1.45, \qquad \frac{Al}{Mg}=\frac{Al^{+5}+Al^{+7}}{Mg^{+4}+Mg^{+6}}=0.41, \tag{b}$$

$$\frac{Si}{Al}=\frac{Si^{+6}+Si^{+8}}{Al^{+5}+Al^{+7}}=0.71, \qquad \frac{Na}{Mg}=\frac{Na^{+4}}{Mg^{+4}}=0.23,$$

$$\frac{Mg}{Ne}=\frac{Mg^{+4}}{Ne^{+4}}=0.036.$$

The accuracy of these numbers is probably no better than a factor of about 2 or 3, particularly for an element like Na for which only one stage of ionization is observed.

The only hydrogen emission accessible at *IUE* wavelengths is Lyα, and it is strongly affected by scattering in the interstellar medium and by geo-coronal emission. Little can thus be inferred from our UV spectra concerning the hydrogen content of Nova CrA. We do have one optical spectral scan of the nova, obtained several days after outburst, and it is shown in Fig. 4. The spectrum is typical of the early decline period of a nova, being dominated by extremely broad Balmer lines, so it seems plausible to assume that this nova ejected a characteristic amount of hydrogen for a classical outburst, i.e. hydrogen may be the most abundant element in the ejected material.

In the absence of UV information regarding hydrogen, the heavy element abundances are determined with respect to helium, since the He II λ 1640 line is observed on most of our scans. The relatively high level of ionization in June suggests that most of the helium is He^{+2}, and one can roughly take $N/He \simeq (N^{+3}+N^{+4})/He^{+2}$ because N^{+2} has an ionization potential similar to that of He^{+}. An expression similar to equation (5) can be derived for the abundance of He^{+2}, involving the Case A hydrogenic recombination coefficient for λ 1640 rather than the collisional excitation coefficient [*cf.* Williams *et al.* 1981, equation (4)], and it leads to a suitable normalized abundance of $He^{+2}=5.6\times10^{-3}$, which corresponds to an abundance ratio of N/He=0.075.

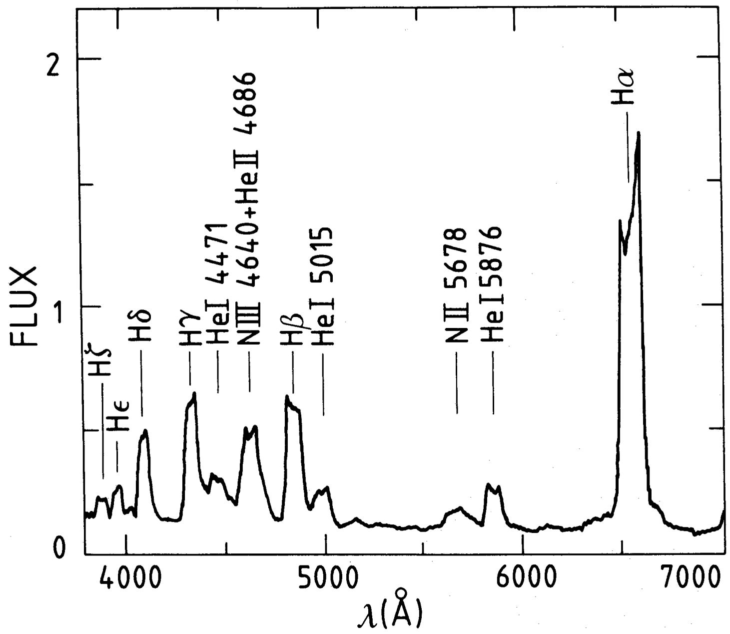

Figure 4. Spectral scan of Nova CrA on 1981 April 14 at optical wavelengths, obtained with the Steward Observatory 2.3-m telescope and the intensified Reticon system. Units of flux are 10^{-11} erg cm^{-2} s^{-1} Å^{-1}.

We have plotted the relative abundances of all the elements in Fig. 5, together with a plot of solar abundances for comparison. As is normal for novae ejecta, the CNO elements are enhanced relative to He, and presumably therefore to H also. What is surprising, however, is the very high enrichment of neon, in addition to that of Mg and Al. The implications of this result for the outburst and for the structure and evolution of the white dwarf will be considered in the following section.

3.3 1981 SEPTEMBER 13

By five months after the outburst, the UV spectrum has simplified considerably. The very high ionization lines have virtually all disappeared, and the spectrum has evolved towards that of a

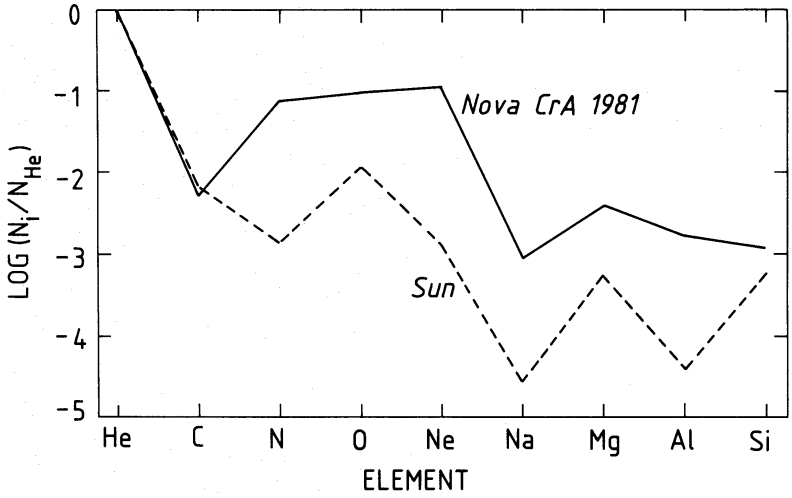

Figure 5. Abundances of the elements in the ejecta of Nova CrA, relative to helium, as determined from the emission-line spectrum. Solar composition is also shown for reference.

typical quiescent emission-line cataclysmic variable (Krautter *et al.* 1981). The range of ionization is narrower, probably because decreasing density eventually drives the gas optically thin, so less stratification occurs. The strongest lines are from doubly and triply-ionized ions. As the nova brightness declines, an increasing contribution to the spectrum must eventually be made by the re-established accretion disc, and some of the emission from Nova CrA on this date may possibly be due to a disc caused by mass transfer from the secondary.

No lines are visible which allow a direct determination of the electron temperature, and the poorer signal-to-noise ratios of the scans on this date do not provide for interesting limits. If a temperature in the range of $T_e=1.5-2.0\times10^4$ K is assumed, the line ratios of the collisionally-excited lines lead to ion abundance ratios similar to those derived from the June data.

Two short-wavelength *IUE* scans were obtained of the nova after September. Single spectra in October and November, the last dates for which we have data, showed the spectrum to be essentially the same as that observed in September, with both lines and continuum fainter. No new features were observed, and all the lines identified in September could still be discerned in November.

4 Discussion

The heavy element enrichment we have deduced for the nova ejecta is a normal feature of classical novae. Specifically, it has been found to be a consistent trait of galactic novae that they are enhanced in CNO elements, especially nitrogen, relative to H and He (Williams 1982). Marginal enrichments of neon, of the order of a factor of 10, have previously been reported for several novae, including V1500 Cyg (Ferland & Shields 1978) and RR Pic (Williams & Gallagher 1979); however, the recent novae studied in the UV have now established very large Ne enhancements as a common occurrence in the ejecta. In their thorough combined optical/UV analysis of Nova Aquila 1982, Snijders *et al.* (1984, in preparation) have found neon to be almost as abundant as helium, corresponding to an enhancement over solar values of a factor of $\geq10^3$. In Nova CrA, we have found Ne to be more abundant than C, N or O, with an enrichment with respect to helium exceeding 100 times the solar value.

Of major significance to theoretical models of the nova outburst is the information we have been able to gather regarding the elemental abundances of Na, Mg, Al, and Si. With the exception of Mg II λ 2798, emission lines from these elements are generally not observed in novae ejecta, so little information regarding their abundances or ionization distribution has been available. The higher ionization stages have a richer spectrum in the UV and IR, and Grasdalen & Joyce (1976) did detect highly-ionized coronal fine-structure transitions of post-Ne elements in V1500 Cyg; however they did not derive abundances from their data. Care must be exercised in interpreting element enhancements, which are generally expressed relative to hydrogen, since virtually *all* heavy elements have been found to be enriched in novae ejecta, i.e. hydrogen is almost always found to be depleted with respect to the solar composition. This finding is consistent with the interpretation of the outburst in terms of a CNO-cycle runaway (Gallagher & Starrfield 1978). A somewhat different question is what the relative CNO abundances are among themselves, and what the combined abundance of the CNO group is relative to other heavy elements. Summarizing the results of recent abundance determinations of ejecta, Truran (1982) noted the generally high abundance of nitrogen and discussed this characteristic in terms of the CNO runaway models. The CNO cycle essentially conserves the CNO/(H+He) nuclear ratio by mass, since the CNO nuclei are simply redistributed among themselves. Therefore, any marked CNO/(H+He) enrichments in nova shells require an origin prior to the outburst. A normal C–O white dwarf provides a natural reservoir for the enriched material if mixing from the interior can bring processed material up to the surface. Shear mixing during the accretion process is the most promising mechanism for mixing large amounts of white-dwarf material with accreted gas (Kippenhahn & Thomas 1978; Sparks & Kutter 1979). However, irrespective of whether mixing in a C–O white dwarf can yet be accounted for theoretically, the CNO enhancements observed in novae are generally believed to require it.

On the other hand, enhancements of Ne, Na, Mg, and Al relative to H, He, and CNO nuclei, as observed in Nova CrA 1981, cannot easily be accounted for within the framework of the current nova models if the degenerate star is a C–O dwarf. The source of the post-neon heavy element enrichments must be either (1) mass transfer from the secondary star, (2) the outburst, or (3) mixing in the white dwarf. There are difficulties with each of these alternatives according to current thinking, and so a major modification to some basic facet of our understanding of CVs or the nova outburst is clearly required. For example, the first alternative is unlikely because available evidence does not indicate that the secondary stars are sufficiently evolved to provide the Ne and Al enhancements observed. Alternative (2) encounters the difficulty that nova outburst calculations have indicated that degeneracy is lifted, and the nuclear runaway halted, before temperatures are achieved which produce substantial formation of neon (Starrfield, Sparks & Truran 1984).

The final alternative is that the enrichments are produced during an earlier stage of evolution of the white dwarf and then mixed to the surface during accretion. The evolution of stars which eventually end as massive O–Ne–Mg white dwarfs has been studied theoretically by Sugimoto & Nomoto (1980), van den Heuvel (1981), and Nomoto (1984). It is possible for white dwarfs with masses between ~ 1.2 and $1.35\,M_\odot$ to have processed nuclei beyond oxygen (Nomoto 1984). Law & Ritter (1983) have considered the most likely situations for which mass transfer could lead to the creation of O–Ne–Mg white dwarfs and they found that non-conservative mass transfer in very short period binaries will result in such objects. The nuclear evolution of these massive white dwarfs has not been studied in sufficient detail to know what the relative abundances should be of the heavier elements such as Ne, Mg, Al, and Si after the material has been processed through hot hydrogen burning but it is a tractable idea that enhancements such as we have found in Nova CrA 1981 may have originated in such a fashion. Nucleosynthetic calculations to study this problem are in progress. In fact, Law & Ritter (1983) anticipated this situation with their prediction that 'the presence of an O–Ne–Mg white dwarf in a close binary system could manifest itself via the peculiar chemical composition of the nova ejecta.'

The current situation regarding the post-CNO heavy element enrichments in novae can be summarized by the statement that Ne/CNO enhancements by a factor of 10 to 1000 over the solar abundance have clearly been established for different objects. In addition, the elements Mg, Al, and Si also have non-solar abundances with respect to both CNO and to each other in Nova CrA 1981. The most likely source of the nuclear processing is the interior of the white dwarf. If produced in the white dwarf and subsequently mixed to the surface, the relatively high percentage of O–Ne–Mg white dwarfs in CVs then requires an explanation. The main argument against massive white dwarfs as the source of the nova enrichments is a statistical one. The formation of O–Ne–Mg white dwarfs requires a narrow range of parameters, and should occur in only a small fraction [<1 per cent, according to Ritter (1983, private communication); or perhaps one in 25 CVs according to Iben & Tutukov (1983, private communication)] of cataclysmic systems. Yet, of the roughly ten novae for which ejecta abundances have been fairly well determined in the past decade, two have very large neon enrichments [Nova Aql 1982 (Snijders 1983; Snijders *et al.* 1984, in preparation), and Nova CrA 1981]. In addition, the shells of two other novae, V1500 Cyg and RR Pic, contain neon enhancements of an order of magnitude over the solar value. So, the enrichment of Ne in novae is apparently a common phenomenon, and would appear to require that O–Ne–Mg dwarfs be rather commonplace in CVs if they are the source of the neon and that these nova systems originally contained very massive white dwarfs. Our abundance results are further evidence that a significant amount of material is mixed up into the accreted envelope and ejected during the outburst. The degree of enhancement in the ejecta implies, therefore, that the mass of these white dwarfs is decreasing as a result of the nova phenomenon.

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References

Brosch, N., 1982. *Astr. Astrophys.,* **107,** 300.

Burstein, D. & Heiles, C., 1978. *Astrophys. J.,* **225,** 40.

Ferland, G. J. & Shields, G. A., 1978. *Astrophys. J.,* **226,** 172.

Gallagher, J. S. & Starrfield, S. G., 1978. *Ann. Rev. Astr. Astrophys.,* **16,** 171.

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

Honda, M., 1981. *IAU Circ. No. 3590.*

Jordan, C., 1971. *Solar Phys.,* **21,** 381.

Kippenhahn, R. & Thomas, H.-C., 1978. *Astr. Astrophys.,* **63,** 265.

Krautter, J., Klare, G., Wolf, B., Duerbeck, H. W., Rahe, J., Vogt, N. & Wargau, W., 1981. *Astr. Astrophys.,* **102,** 337.

Law, W. Y. & Ritter, H., 1983. *Astr. Astrophys.,* **123,** 33.

Layzer, D., 1959. *Ann. Phys.,* **8,** 271.

Mendoza, C., 1983. *Planetary Nebulae,* p. 143, ed. Flower, D. R., Reidel, Dordrecht, Holland.

Ney, E. P. & Hatfield, B. F., 1978. *Astrophys. J.,* **219,** L111.

Nomoto, K., 1984. *Astrophys. J.,* **277,** 791.

Osterbrock, D. E. & Wallace, R. K., 1977. *Astrophys. Lett.,* **19,** 11.

Sandlin, G. D., Brueckner, G. E. & Tousey, R., 1977. *Astrophys. J.,* **214,** 898.

Sandlin, G. D. & Tousey, R., 1979. *Astrophys. J.,* **227,** L107.

Seaton, M. J., 1971. *Highlights of Astronomy,* p. 503, ed. de Jager, C., Reidel, Dordrecht, Holland.

Snijders, M. A. J., 1983. *Observatory,* **103,** 141.

Sparks, W. M., & Kutter, G. S., 1979. *White Dwarfs and Variable Degenerate Stars, IAU Colloq. No. 53,* p. 294, eds Van Horn, H. M. & Weideman, V., University of Rochester.

Starrfield, S. G., Sparks, W. M. & Truran, J. W., 1984. *Astrophys. J.,* in press.

Stickland, D. J., Penn, C. J., Seaton, M. J., Snijders, M. A. J. & Storey, P. J., 1981. *Mon. Not. R. astr. Soc.,* **197,** 107.

Storey, P. J., 1981. *Mon. Not. R. astr. Soc.,* **195,** 27P.

Strittmatter, P. A., Woolf, N. J., Thompson, R. I., Wilkerson, S., Angel, J. R. P., Stockman, H. S., Gilbert, G., Grandi, S. A., Larson, H. & Fink, U., 1977. *Astrophys. J.,* **216,** 23.

Sugimoto, D. & Nomoto, K., 1980. *Space Sci. Rev.,* **25,** 155.

Truran, J. W., 1982. *Essay in Nuclear Astrophysics,* p. 467, eds Barnes, C. A., Clayton, D. D. & Schramm, D. N., Cambridge University Press.

van den Heuvel, E. P. J., 1981. *Pulsars, IAU Symp. No. 95,* p. 379, eds Sieber, W. & Wielebinski, R., Reidel, Dordrecht, Holland.

Williams, R. E., 1982. *Astrophys. J.,* **261,** L77.

Williams, R. E. & Gallagher, J. S., 1979. *Astrophys. J.,* **228,** 482.

Williams, R. E., Sparks, W. M., Gallagher, J. S., Ney, E. P., Starrfield, S. G. & Truran, J. W., 1981. *Astrophys. J.,* **251,** 221.