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A HOT NEON NOVA: OPTICAL SPECTROPHOTOMETRY AND THE PHYSICS OF NOVA CYGNI 1992

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ABSTRACT

We present the results of low-resolution optical spectrophotometric observations of Nova Cygni 1992 obtained at the Pine Bluff Observatory between 8 and 450 days after outburst. The early emission spectra show the Balmer spectrum of H I, Fe II lines, and some He I lines. As the nova declines, the continuum fades rapidly, and the emission lines become dominant. The decreasing densities in the expanding shell and the hardening of the nova's radiation field lead to the emergence by 1993 April 30, of the nebular lines [O III] λ4363, [O II] λ5007, and [Ne III] λ3869. By August 21 the [Ne III] λλ3869, 3968 and [Ne V] λλ3346, 3426 emission lines have become the main features of the nebular spectrum and establish Nova Cygni as a neon nova. The unusual strength of [O III] λ4363 is attributed to high densities collisionally deexciting the nebular lines, while the extreme [Ne V] intensity during late phases suggests a very high temperature photosphere for the nova. A wide ionization range also implies high electron densities as compared to normal nebulae.

Subject headings: stars: circumstellar matter — stars: novae, cataclysmic variables

1. INTRODUCTION

Nova Cygni 1992 was discovered by Collins (1992) on 1992 February 19.07 UT, and reached a maximum of $V = 4.4$ on 1992 February 22.0 UT, which we take as $t = 0$ of the outburst. Using a light curve of Nova Cygni compiled from observations reported in the IAU Circulars, we find that Nova Cygni was a fast type of classical nova (Payne-Gaposchkin 1957). Hjellming (1993) finds the distance to the nova to be 2.1 kpc based on a radio angular diameter measurement of 0\".36 obtained on day 309, assuming a velocity spread in the shell of 3800 km s^{-1}.

The rich spectra of optical nebular lines observed in Nova Cygni make it an ideal nova for studying physical properties of the ejecta (Starrfield et al. 1993; Shore et al. 1993). Of particular interest is the tremendous strength of its forbidden neon emission lines (see also Hayward et al. 1992). This is a characteristic of neon novae (Gehrz, Grasdalen, & Hackwell 1985; Starrfield, Sparks, & Truran 1986; Williams et al. 1991; Williams, Phillips, & Hamuy 1994).

2. OBSERVATIONS

Twenty-nine optical spectrophotometric observations of Nova Cygni 1992 were obtained with a spectropolarimeter attached to the 0.9 m telescope at the Pine Bluff Observatory (PBO) of the University of Wisconsin–Madison. The data were taken in an identical way with the same instrument during the Nova Cygni observations. These data comprise a homogeneous set and represent a valuable collection of broad-wavelength coverage, low-resolution spectra for studying the evolution of the optical spectrum. Our observations were made from 1992 March 1 through 1993 May 17, covering the 3200–7600 Å wavelength interval. The slit width was 12\" for all spectra in order to improve the photometric accuracy. The spectra have a resolution of 25 Å. Bjorkman et al. (1993) provide further details on the instrumentation and discuss the polarization data. Spectrophotometry was calibrated using flux standards and a mean atmospheric extinction curve, which may result in a 25% overestimate of the atmospheric extinction correction at $\lambda < 3500$ Å. Intensity calibration errors are < 10%.

3. RESULTS

3.1. *Late Decline and Early Nebular Phases*

The data record the optical spectral evolution of Nova Cygni from about 1 mag below visual maximum through the nebular phase (Fig. 1). Relative to the continuum, the emission-line intensities increase smoothly over time, and the main characteristics of the data are consistent with the steady luminosity evolution of a classical nova in outburst (Gallagher & Starrfield 1978; Starrfield 1988), as shown by Figure 2. The decreasing density of the circumstellar matter implies that the radius of photoionization is decreasing. Both the lower density and harder photons cause the ionization to increase with time. Physically these effects lead to systematic variations of optical depths in both the continuum and permitted lines as the nova declines.

The optical spectra have been integrated to yield a total observed optical flux $f_{\rm opt}$ for the 3200–7600 Å region. If $f_{\rm opt}$ is in ergs cm^{-2} s^{-1} and d is the day number, these data can be fitted to within 20% by two functions $f_{\rm opt} = C_1 e^{-0.0310d}$ for $d \le 68$ and $f_{\rm opt} = C_2 e^{-0.00918d}$ for $68 < d \le 450$. The observed optical luminosity uncorrected for interstellar extinction is then $L_{\rm opt}^{\rm obs} = 5 \times 10^{37} (D/2.1\ {\rm kpc})^2 f_{\rm opt}(d)/f_{\rm opt}(0)$ ergs s^{-1}, which will be about a factor of 2 less than the interstellar corrected value. As we are still not certain of the interstellar extinction correction (see below), we defer a final determination of $L_{\rm opt}$ until later. The e-folding times are 32 and 109 days for the early decline and nebular light curves, respectively. These two segments of the optical light curve correspond to the optically thick early decline during the first 68 days and the subsequent appearance of the nebular phase.

Line fluxes were measured by numerically integrating continuum-subtracted emission lines. The line strengths and equivalent widths of Hα and Hβ were determined for the

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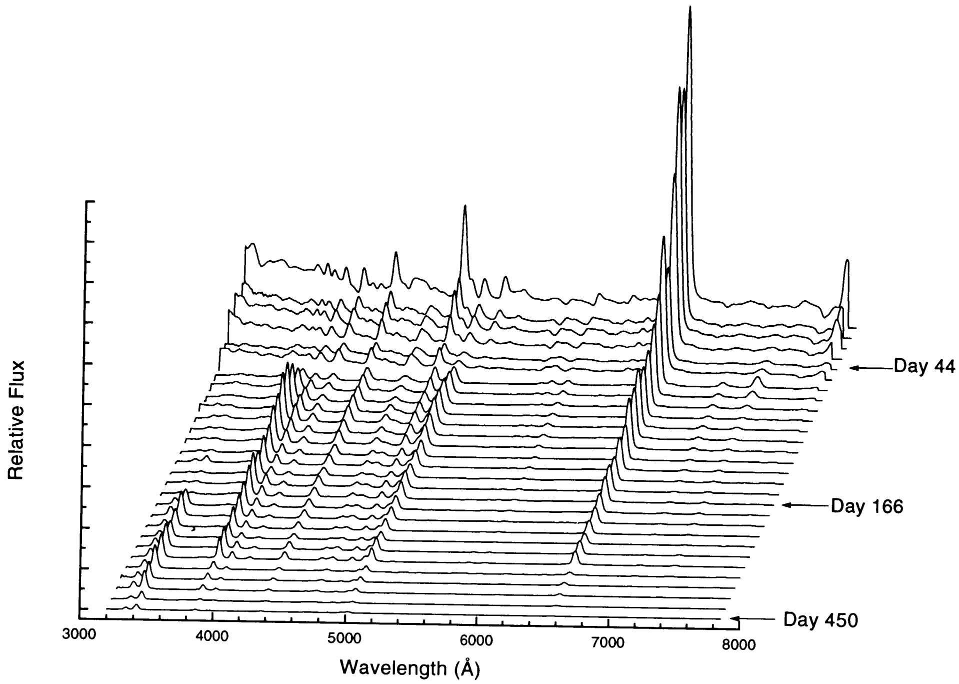


FIG. 1.—Time series of the 29 Nova Cygni 1992 optical spectra. The first spectrum observed, 1992 March 1 (day 8), is plotted at the back. The spectra progress forward in time on the plot, but they are not spaced according to real time intervals between observations. The front spectrum was the last spectrum observed, 1993 May 17 (day 450). The three labeled spectra are shown in greater detail in Fig. 2. Note the early decline in the continuum and the rapid rise in the forbidden neon lines.

spectra from day 8 to day 450, of the permitted line He I λ5876 from day 68 to day 450, and of the permitted line He II λ4686 (possibly blended with [Ne IV] λ4720, but other blends through day 112 were subtracted) from day 74 to day 450. Similar determinations were made for [O III] λ5007 (with early blending from iron and later blending from [O III] λ4959) from day 8 to day 450, [Ne III] λλ3869, 3968 from day 68 to day 450, and [Ne IV] λλ3346, 3426 (with early blends) from day 140 to day 450.

The flux of Hα contrasts with the continuum in approximately following exponential decline for all of our data (Fig. 3 [*top*]). This is interesting since a rapid evolution in the $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ ratio occurs around day 68 (Fig. 3[*center*]), behavior which is consistent with initially high optical depths in Hα. The increase in $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ which occurs during the transition to the nebular phase can then be identified with the overpopulation of the $n = 3$ state of hydrogen by trapped Lyman-β radiation (Strittmatter et al. 1977). The rapid drop in the $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ ratio thus coincides with the photoionization of the bulk of the ejecta and reduction in trapped Lyman-β. The slow decline of this ratio toward late phases of the decline can be understood if the ejecta contains clumps which remain optically thick well into the nebular phase.

If we assume the Balmer lines approach the case B approximation, then we can use the last observed $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ ratio and the mean interstellar extinction law of Cardelli, Clayton, & Mathis (1989) to estimate the color excess. The estimate will be an upper limit since $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ may continue to decline. The derived mean extinction law only depends on the parameter $R_V[=A(V)/E(B-V)]$. In our reddening corrections we used $R_V = 3.2$:

1. In examining the Palomar Observatory Sky Survey plates, we found that the nova was located in a clear field with only subtle evidence for patchiness. The value $R_V = 3.2$ is typical of a diffuse sight line (Cardelli 1993).

2. Several longer distance stars located within 10° of the nova have R_V values of ~ 3.2 (Cardelli & Sembach 1993). The color excess for the nova using $R_V = 3.2$ is $E(B-V) \leq 0.20$. However, as the possibility of a slightly higher reddening exists, we also quote the color excess for $R_V = 4.2$ of $E(B-V) \leq 0.18$.

3.2. *Nebular Phase: A Neon Nova*

Near the end of the early decline phase, Fe II and [Fe II] suggest the shell is optically thick in Lyman continuum so that few H-ionizing photons are getting through. The transition to the nebular spectrum occurs as the shell ionizes. The break in the optical light curve slope near day 50 coincides with rapid development of nebular emission, and by day 74 the nova has a nebular spectrum. Characteristics at that time are strong [Ne III], strong [O III], and enhanced [O III] λ4363. The latter is due to high densities in the nebula. The permitted recombination spectrum consists mainly of He I and H I lines.

After day 150 we see the rapid appearance of [Ne V], which requires photons with $E > 126$ eV for its production in a photoionized model. This is consistent with a steady increase in the level of ionization as indicated by $I(\mathrm{He\ II})/I(\mathrm{H}\alpha)$ in Figure 4 (*left*). Forbidden Fe VII also follows this trend in a manner consistent with a photoionization driven process. Figure 4 (*right*) shows the emergence and evolution of the nebular spectrum. By the latest phase, Nova Cygni is completely dominated by [Ne V] at optical wavelengths (Fig. 2 [*bottom*]). [Ne V]/Hβ is used as a measure of the excitation classes of planetary nebulae. If we compare the highest excitation class 10 planetary nebulae (Aller 1956) with Nova Cygni, we find that the [Ne V] (3346+3426)/Hβ ratio is considerably smaller in the planetary nebulae (Kaler 1976).

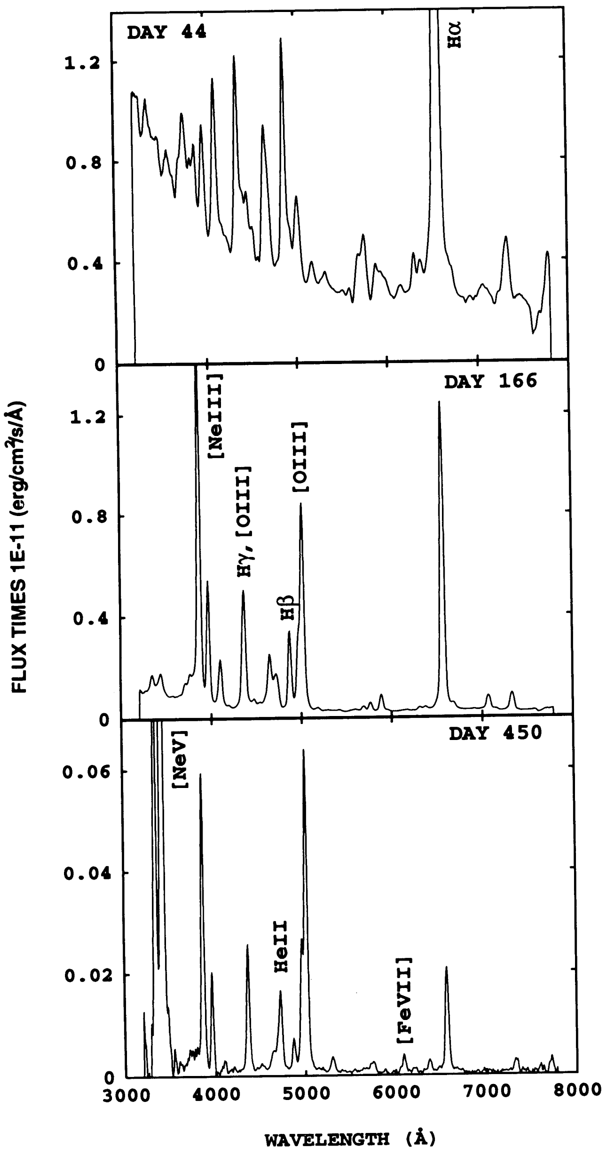


FIG. 2.—Flux vs. wavelength plots selected to illustrate key features in the evolution of the nova. The spectrum in Fig. 2 (*top*) was observed on 1992 April 6 (day 44), before the appearance of the nebular spectrum. By the 1992 August 6 (day 166) spectrum, Figure 2 (*center*), the [Ne III] λλ3869, 3968 lines are easily visible. Figure 2 (*bottom*) shows the 1993 May 17 (day 450) spectrum, where the [Ne V] λλ3346, 3426 lines optically dominate the nova. (See text for comments on the UV flux calibration.) The vertical scale in Fig. 2 (*bottom*) has been reduced to enlarge some emission-line features.

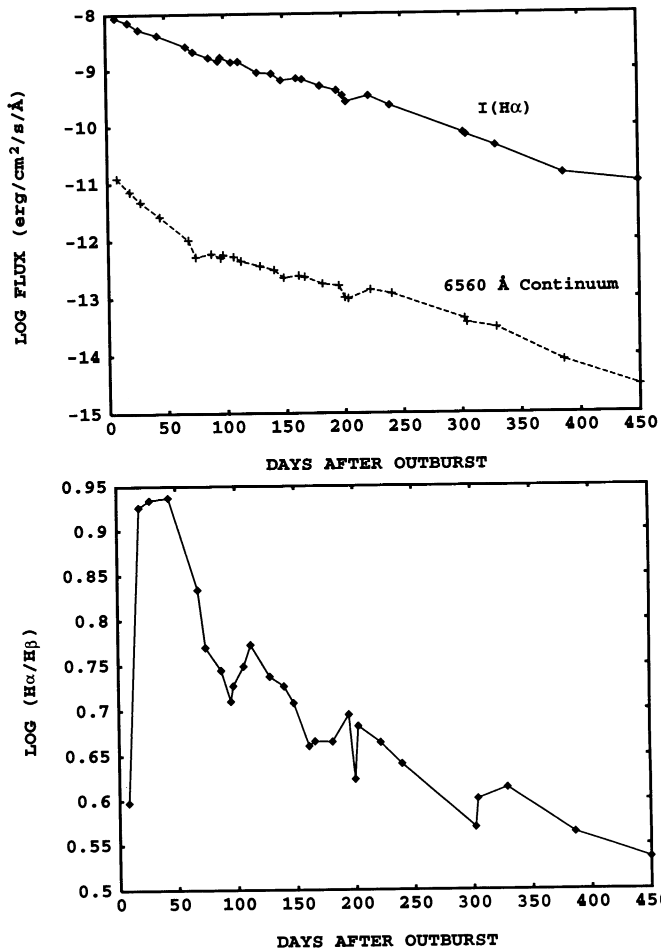
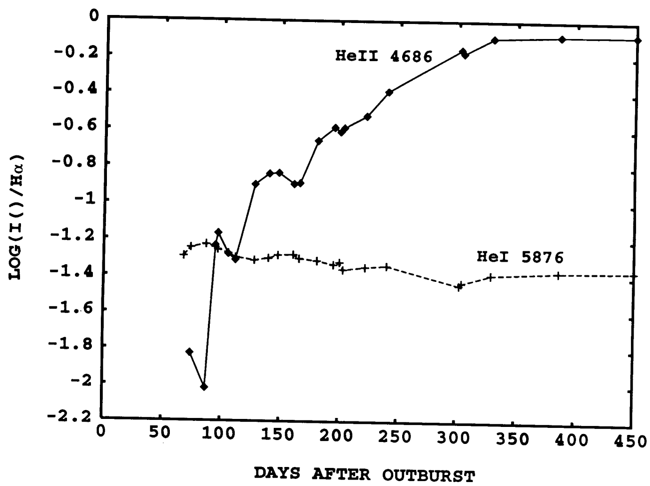


FIG. 3.—Figure 3 (*top*) shows the logarithm of the $I(\text{H}\alpha)$ flux and $I(\text{H}\alpha)$ continuum flux vs. days after outburst. In Figure 3 (*bottom*), the logarithm of the $I(\text{H}\alpha)/I(\text{H}\beta)$ ratio vs. days after outburst changes dramatically in the early stages of nova evolution but begins to level off at later times as the nova passes through an optically thick phase. Points are connected in this and later figures to show trends in the data and do not imply strict continuity in the time-dependent behavior of the nova. Line ratios are accurate to $\pm 20\%$.

4. SUMMARY

The dominance of the forbidden neon lines in the optical spectrum establish Nova Cygni 1992 as a neon nova (Austin et al. 1992; Shore et al. 1992; Hayward et al. 1992). Since the nova ejecta is very clumpy, a proper neon abundance determination requires careful modeling to account for ranges in density and ionization level within the ejecta. The following density-related issues may affect the derived neon abundance. The great strength of [O III] λ4363 even at late phases indicates a high electron density ($n_e > 10^6$ cm^{-3}). Similarly, the nearly constant $I(\text{He I})/I(\text{H}\alpha)$ ratio coupled with the steady increase of $I(\text{He II})/I(\text{H}\alpha)$ and $I([\text{Ne V}])/I(\text{H}\alpha)$ suggest a large range in ionization, and therefore considerable variation in density within the nova ejecta. Also, both [Ne V] λλ3346, 3426 and [Ne III] λλ3869, 3968 have a factor of ~10 higher critical densities for collisional deexcitation than the [O III] lines for levels that are most important in radiative cooling ($^1D_2$, $^3P_2$, and $^3P_1$ from Osterbrock 1989). We are modeling the nova to determine abundances.

Nova Cygni has been observed in many different wavelengths and thus provides an unparalleled opportunity for obtaining a self-consistent description of the underlying phenomena. The *ROSAT* X-ray detection of the nova during its [Ne V] phase indicates a photospheric temperature of $\sim 3 \times 10^5$ K (Ögelman 1993). Polarization data obtained with the spectropolarimeter at PBO show evidence for an asymmetric geometry of the explosion and clumping in the ejecta (Bjorkman et al. 1993). Optical spectrophotometry, such as the data presented here, will continue to be important in understanding physical conditions within the nova ejecta. Outside of the optical, the nebula can also be observed in the ultraviolet, the infrared, and the radio spectral regions, with each region providing unique diagnostics of physical conditions (e.g., Shore et al. 1993; Hayward et al. 1992; Hjellming 1993).



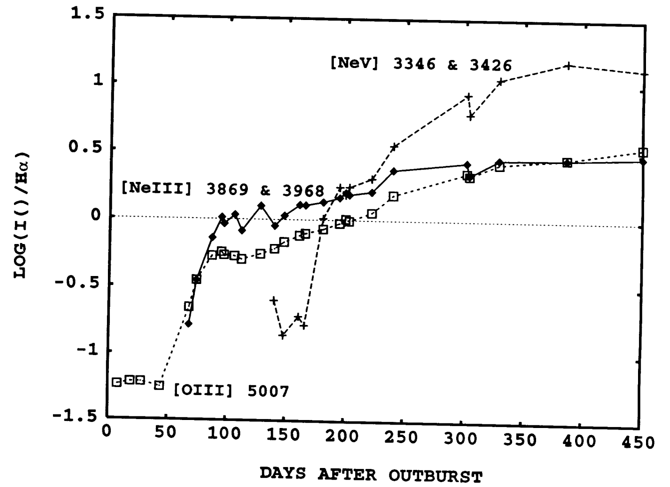


FIG. 4.—Permitted line flux ratios I(He I)/I(Hα) and I(He II)/I(Hα) are plotted vs. days after outburst in Fig. 4 (*left*). Forbidden line flux ratios I([O III])/I(Hα), I([Ne III])/I(Hα), and I([Ne V])/I(Hα), plotted vs. days after outburst in Fig. 4 (*right*), clearly show the emergence of the nebular spectrum.

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Note added in proof.—Chocol et al. (Chocol, D., Hric, L., Urban, Z., Kromži'k, R., Grygar, J., & Papoušek, J. A&A, 277, 103 [1993]) have also reported results from optical spectroscopy and photometry of Nova Cygni 1992. Their data are consistent with the neon nova interpretation, demonstrate the effects of clumping within the ejecta on optical emission-line profiles, and suggest that He [II] λ4686 is strongly blended with lines from [Ne IV] and [Ar IV].