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THE SHELL PHASE IN NOVA CYGNI (1975)

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ABSTRACT

We report optical energy distributions during the early decline, and infrared photometry during later phases, for the fast nova V1500 Cyg (Nova Cyg 1975). Combined with published data, these enable us to follow the changes in the relative contributions of the expanding shell and central object to the optical continuum. The early infrared and optical energy distributions are consistent with optically thin free-free and free-bound emission. As the shell expanded, the flux in the optical continuum increased relative to that expected from the infrared free-free emission. We attribute this optical flux increase to the appearance of a hot central object which contributed ~60% of the flux observed in the Strömgren *y* filter bandpass in mid-1976. The appearance of this excess optical flux was contemporaneous with the start of the periodic photometric variations discovered by Tempesti.

Subject headings: stars: novae

I. INTRODUCTION

Nova Cygni 1975 (V1500 Cyg) is the first bright nova to occur since the development of modern electronic astronomical techniques. As a result of improved instrumentation its evolution has been traced with an unprecedented precision and spectral coverage. The infrared photometry of Gallagher and Ney (1976, hereafter GN) and Ennis *et al.* (1976) has demonstrated that the expanding shell was optically thick for the first 3 days after discovery, becoming an optically thin free-free source when the shell density became sufficiently tenuous. Early multichannel Reticon observations by Campbell (1976) demonstrated that emission from the expanding shell was modulated with a 0.14 day period. This was followed by the observations of Tempesti (1975) which revealed photometric variations which increased in amplitude.

Observations presented by Ferland, Tomkin, and Woodman (1976) showed the continuum to be the source of photometric activity nearly a year after outburst. Here we combine optical and infrared photometry to differentiate between sources of flux in different regions of the spectrum at different times. During early stages, hydrogen continuous emission was the dominant source of flux in the optical and infrared spectrum (GN). Near the time when photometric variations began, an excess of blue light appeared in the energy distribution. We believe that a central object is the source of this blue light and that the photometric variations originate in this object.

II. OBSERVATIONS

Observations from four sources are analyzed in this paper. Absolute spectrophotometry was obtained by one of us (G.J.F.) on the McDonald Observatory 92 cm reflector using a conventional single-channel rapid-scanning spectrophotometer. Blue (0.3–0.7 μm) observations were made with RCA 31034A (GaAs photocathode) and red (0.6–1.1 μm) data with FW118 (S-1 photocathode) photomultiplier tubes, both refrigerated to dry ice temperatures. Both tubes were used in a pulse counting mode; the spectrophotometer was operated under computer control.

The secondary standards of Hayes (1970) were observed frequently during the night at varying air masses to obtain both the atmospheric extinction and system sensitivity function. The observations were reduced using the color calibration of Vega reported in Hayes and Latham (1975). The absolute calibration of our relative spectrophotometry was obtained from the *uvby* observations of Lockwood and Millis (1976) using the Hayes and Latham calibration of Vega to convert magnitudes to fluxes. The blue data have 20 Å resolution and are accurate to 5% while the red data have 40 Å resolution and are accurate to 10%. The data are presented as dereddened fluxes in Figure 1. We have chosen an $E(B - V)$ of 0.47 mag following Ferland (1977); this is probably accurate to 0.03 mag.

We have also used the extensive set of spectroscopic scans obtained by Dr. J. Woodman using the coudé scanner of the 2.7 m reflector. Some of these observations have been reported in Tomkin, Woodman, and Lambert (1976).

The infrared photometry of V1500 Cyg was done by H.A.W. using the InSb photometry system of the 1.3 m telescope of Kitt Peak National Observatory on the night of 1976 May 25/26. A 30″ aperture was used with a reference beam 100″ away in declination. The nova was observed at 2.4 air masses immediately after an observation of α Cyg at 2.3 air masses. The infrared magnitudes were determined using standard α Cyg magnitudes (Strom, private communication) after cor-

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recting for extinction. The data are presented in Table 1 as magnitudes; absolute fluxes were calculated using Wilson *et al.*'s (1972) values of fluxes for α Lyr.

Our optical photometry was obtained through a conventional Strömgren y filter together with a RCA 8850 photomultiplier tube on the 76 cm reflector of the McDonald Observatory. The optical continuum is highly variable (Tempesti 1975; Ferland, Tomkin, and Woodman 1976), and we have used the mean measured brightness. We have estimated the 1976 May y magnitude by interpolating between our August observations and the 1976 January observations of Lockwood and Millis (1976), assuming an exponential decline. This interpolation should not contribute more than a 0.05 mag error.

III. RESULTS

Nova Cygni has displayed a quasi-periodic light modulation since shortly after its eruption (Tempesti 1975). Ferland, Tomkin, and Woodman (1976) have recently reported that the continuum is the source of this variation. To discover the nature of the continuum source, we have investigated the temporal development of the nova's energy distribution, making use, in part, of the infrared photometry of Gallagher and Ney (1976) and Ennis *et al.* (1976), and the Strömgren four-color photometry of Lockwood and Millis (1976). As the

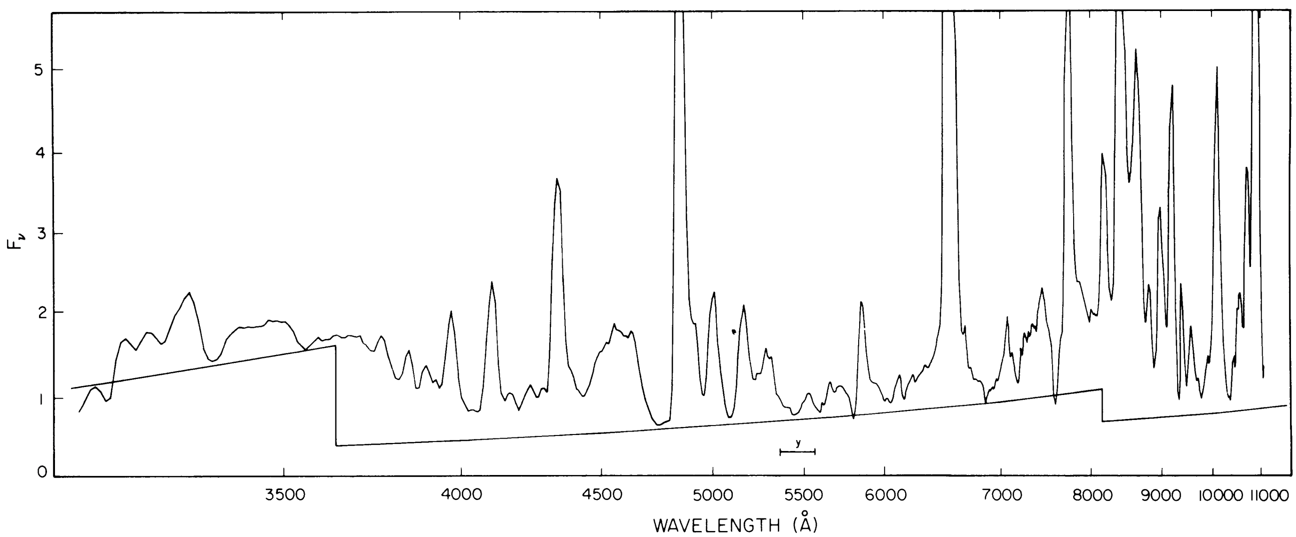

FIG. 1.—Spectrophotometry of V1500 Cyg obtained on 1975 September 5 at 20–40 Å resolution. The data have been dereddened assuming $E(B - V) = 0.47$ and standard interstellar extinction curves. The continuum emission from hydrogen free-free and free-bound has been predicted from the infrared magnitudes of Gallagher and Ney (1976) assuming $T_e = 2 \times 10^4$ and the absence of optical depth in the continuum. One unit on the flux axis represents 1.92×10^{-22} ergs s^{-1} cm^{-2} Hz^{-1}.

TABLE 1

MAGNITUDES OF NOVA CYGNI

Date (month/day) (1)	Age (days) (2)	y (3)	H (4)	$y - H$ (5)	$(y - H)$ (6)	$H - K$ (7)	$J - H$ (8)	R (9)
9/2.0	4.2	1.0	1.3	2.7	3.0	0.5	0	1
9/6.1	8.1	6.0	3.3	2.7	3.0	0.5	−0.1	1
9/9.1	11.2	6.5	4.0	2.5	2.7	0.6	−0.2	1.3
9/12.2	14.7	7.1	4.4	2.7	2.9	0.6	−0.2	1.1
9/16/2	18.3	7.5	5.1	2.4	2.6	0.5	−0.3	1.45
9/26.3	28.8	8.3	5.7	2.6	2.8	0.6	0	1.2
10/1.2	33.7	8.5	6.1	2.4	2.6	0.6	−0.1	1.4
10/4.3	36.8	8.6	6.3	2.3	2.5	0.6	−0.1	1.6
10/12.0	43.5	9.1	6.7	2.4	2.5	0.6	0.0	1.6
10/18–21	51	9.4	7.2	2.2	2.3	0.7	+0.1	1.9
10/24.0	56.5	9.7	7.5	2.2	2.3	0.7	0.0	1.9
11/19.0	82.5	10.8	8.4	2.4	2.4	0.6	+0.2	1.7
11/24.0	87.5	10.9	8.5	2.4	2.4	0.6	+0.3	1.7
12/3.2	96.7	11.1	9.1	2.0	2.0	0.7	+0.1	2.5
5/26/76	280	12.9*	11.0	1.9	1.9	0.5	+0.5	2.8
8/24/76	361	13.1	12.3	0.8	0.8	0.7	+0.2	7.6

* Interpolated.

free-free and free-bound emission from the nova envelope decays, the nova progenitor is expected to reappear. Since the envelope emission is expected to dominate the infrared energy distribution while a hot central object might dominate the optical, we have formed the $y - H$ colors displayed in Figure 2. We discuss the spectrophotometry and photometry before interpreting these colors.

a) The Spectrophotometry

Figure 2 shows the optical energy distribution obtained on 1975 September 5. The stronger emission lines are off-scale to allow close examination of the continuum. The predicted energy distribution for the optical continuum is from the tables of Osterbrock (1974) for optically thin material at 2×10^4 K neglecting two-photon emission. The flux ratio of the IR photometry of GN to our optical spectrophotometry was predicted from theory (Kaplan and Pikel'ner 1970) under the same assumptions. We stress that the optical continuum shown is the theoretical hydrogen emission spectrum fitted to the observed infrared spectrum of the nova.

Considering the enormous complexity of the spectrum, the predicted hydrogen continuum is in reasonable agreement with the observed nova continuum. Unfortunately line blending prevents a more definitive statement. The region longward of the Balmer jump is elevated because of the convergence of the Balmer series and the presence of other emission lines. The Paschen slope near Hβ is fairly well matched, as is the region longward of the Paschen jump.

We believe that the successful prediction of the gross nature of the optical continuum from the infrared fluxes attests well to the assumption of their hydrogen free-free free-bound character. Thus, unlike RR Tel (Glass and Webster 1973), the early optical energy distribution of V1500 Cyg is well understood as hydrogen free-free and free-bound emission.

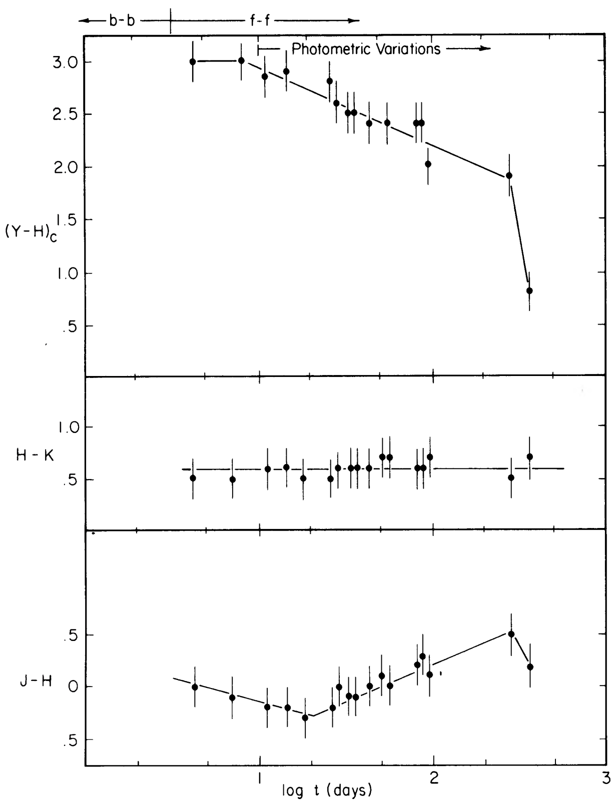

FIG. 2.—Photometry of V1500 Cyg; the $(y - H)_c$, $H - K$, and $J - H$ colors are shown. The $H - K$ color demonstrates that the free-free shell dominated this spectral region. The $J - H$ color was affected by O I fluorescence and may be affected by the central object at present. The $y - H$ color has been corrected for the presence of Fe II lines in the y filter and demonstrates that the central object now dominates the optical continuum.

b) The Photometry

To study the temporal development of the nova's energy distribution we shall make use of published photometry. The spectrum of the nova during the first month of decline displayed Fe II emission. A strong set of Fe II lines (most notably $\lambda\lambda$5362, 5534) contaminate the y magnitudes during this period. To correct the y magnitudes for this effect, a local continuum has been fitted to smooth regions of the coudé scanner data near the y filter, and emission-line contamination estimated and removed. Some contamination remains due to the pseudo-continuum formed by the many blended lines. Column (6) of Table 1 shows the $y - H$ color after this correction, and Figure 1 is a plot of the corrected $y - H$. The $H - K$ and $J - H$ colors are also shown.

Gallagher and Ney (1976) found that the infrared energy distribution of Nova Cygni closely followed $F\nu$ = constant and could be explained by free-free emission shortly after outburst. Our 1976 May data and the Ennis *et al.* data show that this was true until about 1976 July. The $H - K$ color (Fig. 1) was stable to 0.1 mag from the first appearance of the free-free spectrum to roughly 1976 July, indicating that the envelope was the dominant source of the infrared emission. Some explanation must be found, however, for the behavior of the $(J - H)$ color. For a free-free spectrum the theoretical color $[E(B - V) = 0.47]$ is 0.6 mag, consistent with the 1976 May observations. After this, the flux from the central object dominates the J and H passbands. During the early observations there appears to have been an excess of flux in the J filter. This excess is also evident in the GN energy distributions.

We propose to explain this excess flux by O I fluorescence. As shown in Tomkin, Woodman, and Lambert (1976) the nova showed strong O I λ8446, probably due to Lβ pumping. Two related transitions occur in the J bandpass: $2p^4$–$3d$ λ1025 of O I is nearly coincident with Lβ; decays from $3d$ to $3p$ produce a λ11287 photon, then $3p$–$3s$ λ8446 follows. A competing pumping mechanism is $2p$–$4s$ λ1039, which is 4000 km s^{-1} from Lβ. An O I atom on one side of the nova shell will see Lβ photons produced on the opposite side since the expansion velocity is of order 2000 km s^{-1}. This transition results in a $4s$–$3p$ λ13155 photon, followed by $3p$–$3s$ λ8446. Both the

$3d$–$3p$ and $4s$–$3p$ transitions occur in the J filter bandpass.

We can estimate the flux in these lines from our absolute spectrophotometric scans. A scan similar to the one displayed in Figure 2 was obtained on 1975 September 16, the night of minimum $J - H$ color. From this scan we estimate $F(8446) = 5.4 \pm 0.5 \times 10^{-12}$ W m^{-2}. Assuming $E(B - V) = 0.47$, we estimate the flux in the infrared lines to be 5.2×10^{-12} W m^{-2} by assuming that all λ8446 photons originate in one of these lines. Estimating the amount of hydrogen continuous emission in J from the H flux, we find that the flux from the continuum in J is 1.3×10^{-11} W m^{-2}. The 40% additional flux from the fluorescing O I lines accounts well for the 40% deviation observed in J. Further support for this interpretation is the behavior of the deviation in J which closely mimics O I λ8446. We have not attempted to estimate the effect of telluric H_2O absorption in the band at 1.1 μm which lowers atmospheric transmission in the region of the λ11287 line.

We now consider the development of the $(y - H)_c$ color shown in Figure 1. The color was stable near the value expected for pure hydrogen continuous emission until 1975 September 9 when an excess of flux in the y bandpass appeared. This bluing trend has continued up to the last observation, with the $(y - H)_c$ color changing by more than 2 mag. This change must be ascribed to a change in the continuous energy distribution since neither filter is strongly affected by line emission. The magnitude of the change, together with reasonable assumptions of the shell properties, rules out two-photon emission, a change in temperature of the plasma, and the presence of doubly ionized helium continuous emission as plausible sources of the change.

We conclude that the central object is the most plausible source of the excess blue flux, in agreement with Wu and Castor's (1976) suggestion that the central object is responsible for the UV flux. We offer the following interpretation of the secular change with $(y - H)_c$ color.

The early colors are consistent with a spectrum formed by free-free and free-bound hydrogen emission, as shown by our energy distribution. On the tenth day, two changes occurred in the character of the nova light: the color commenced a bluing trend; and the photometric variations (Tempesti 1975), which have been attributed to the central object (Ferland, Tomkin, and Woodman 1976), began. This marked the time when the optically thin shell became faint enough for flux contributions from the central object to be detected. The color became bluer and the amplitude of the variations increased as the contribution of the central object to the optical flux increased.

The continuous emission spectrum calculated for the optical continuum from the infrared fluxes fails to predict the correct optical flux by a large amount in mid-1976. We can estimate the contribution of the central object to the luminosity by assuming that the intrinsic energy distribution of the expanding material has not changed. Then the deviation of the color from the original value measures the central object contribution. The last column of Table 1 gives the amount of excess luminosity in y normalized to the flux observed in 1975 early September.

It is possible to calculate the true amplitude of the photometric variations by correcting for the contribution of the expanding shell. It is difficult to infer the amplitude of the continuum variation from broad-band photometry because of the uncertain contribution of the stable emission lines. We will consider two sets of narrow-band photometry, those of Young *et al.* (1976) and those of Ferland, Tomkin, and Woodman (1976). The former show that the y amplitude was 0.05 mag in 1975 October when the shell contributed approximately 50% of the flux in y. The latter data show the 1976 August amplitude to be nearly 0.5 mag while the shell contributes ~10% of the y filter flux. If we let

$$\delta f_y = f_{y\,\mathrm{max}} - f_{y\,\mathrm{min}}\,,$$

where f_y is y-filter flux, and define f_{yc} as the mean y flux due to the central object, then $\delta f_y/f_{yc}$ has changed from 10% in 1975 early October to 50% in 1976 August. Modulation of such a large amplitude places severe constraints on single-star models for Nova Cygni (Starrfield *et al.* 1976).

We offer a simple interpretation of this change in amplitude. Following Kemp, Sykes, and Rudy (1977), we ascribe the photometric variations to eclipses of the luminous star, presumably a white dwarf. The change in amplitude of the eclipse could be due to a change in the diameter of the photosphere of the white dwarf, which occurred because of the decreasing energy output of the remnant during the decline.

The sudden decrease in $(y - H)_c$ evident in the August data deserves some comment. The y magnitude has continued following the decline rate evident in earlier data, and the continuum has become quite blue. The $H - K$ color has remained characteristic of hydrogen free-free emission. Ennis *et al.* (1976) have noted the appearance of an excess 10 μm flux which they attribute to dust formation. If present, the dust formation has not caused noticeable attenuation of the blue continuum flux. Important changes are clearly still occurring in V1500 Cyg, but the stage in which the free-free emission from the expanding shell dominates the optical and infrared continuum is ending. With the central object still 7 mag above minimum, we infer that enhanced energy generation is still taking place in the system. The need for further observation is obvious: V1500 Cyg presently offers a rare opportunity for the study of a still-active nova.

IV. CONCLUSIONS

We have shown that the optical continuum is presently (mid-1976) originating mainly in the central object. The central object first became visible in the optical on the tenth day after discovery when photometric variations first began. As the expanding envelope grew fainter, the relative contribution of the central object increased, but the infrared continued to be dominated by the hydrogen free-free and free-bound emission from the ejected shell. The $J - H$ color shows that O I fluorescence contributed significant flux to the J filter in 1975 late September.

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