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# THE INTERSTELLAR REDDENING AND DISTANCE OF NOVA CYGNI 1975 (V1500 Cygni)

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## ABSTRACT

McDonald Observatory spectrophotometric scans, combined with published photometry, are used to study the interstellar reddening of Nova Cygni 1975 (= V1500 Cygni). The early blackbody energy distribution, the later free-free and free-bound energy distribution, the hydrogen Paschen to Balmer emission-line ratios, and the He triplet spectrum imply a color excess, $E(B - V)$, of 0.50 ± 0.05 mag. This value is consistent with the interstellar line strengths and polarization measurements of other observers. We combine our results with those of Schild to derive an independent measure of the distance, 1.95 ± 0.2 kpc.

*Subject heading:* stars: novae

## I. INTRODUCTION

The exceptionally fast nova V1500 Cyg (Nova Cygni 1975) has been observed over a broad range of wavelengths (Gallagher and Ney 1976; Ennis *et al.* 1977; Jenkins *et al.* 1977; Wu and Kester 1977). Interpretation of these data requires an accurate estimate of the amount of interstellar reddening along the line of sight. Unfortunately, published values range from a color excess, $E(B - V)$, of 0.12 ± 0.01 mag (Schild 1976) derived from a distance-reddening relationship, to 0.69 ± 0.03 mag (Wu and Kester 1977) estimated from the strength of the 2200 Å graphite feature. In this paper we study energy distributions and emission-line ratios to compare observed and theoretical fluxes to obtain measures of the color excess, which we estimate to be 0.50 ± 0.05 mag. We then combine our color excess with the distance-reddening law derived by Schild to obtain a distance of 1.95 ± 0.2 kpc. This distance and reddening correspond to a progenitor absolute magnitude of $M_B > 7.5$, within the range of preoutburst nova magnitudes, and to an absolute magnitude at maximum of $M_V = -11.0 \pm 0.2$ mag, making Nova Cygni the brightest well-observed nova of recent times.

## II. DATA

McDonald observations of V1500 Cyg with the coudé scanner of the 272 cm reflector began on 1975 August 30.3 and are continuing at regular intervals. Tomkin, Woodman, and Lambert (1976) have discussed the data obtained during the first 20 days.

Contemporaneous spectrophotometric observations were obtained with the 91 cm and 76 cm reflectors using a conventional single-channel scanner. The Hayes (1970) secondary standards were frequently observed, allowing us to derive nova energy distributions reduced to the Hayes and Latham (1975) absolute calibration of Vega. These low-resolution (20–40 Å) spectrophotometric scans were used to calibrate the higher (4–8 Å) resolution coudé data by assuming that the function required to bring the coudé data onto the Hayes and Latham calibration consisted of a constant system sensitivity function together with a variable extinction term. Comparison of the derived coudé scanner energy distributions with the calibrated spectrophotometric observations shows that this technique is accurate to 3% longward of 4000 Å, with the error increasing to 15% at 3300 Å. These data will be presented in detail in a later paper (Woodman *et al.* 1977). These scans, together with published photometry, will be used to derive the color excess of the nova.

## III. THE REDDENING

We shall use the numerical form of the Whitford (1958) interstellar reddening curve given in Miller and Mathews (1972)

$$\delta m = E(B - V) * 2.128\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right),$$

where $\lambda$ is in micrometers and both wavelengths are greater than 0.4367 $\mu$m. For one wavelength shortward of 0.4367 $\mu$m

$$\delta m = E(B - V) * (2.042 + 1.236\lambda_{\text{blue}}^{-1} - 2.128\lambda_{\text{red}}^{-1}),$$

where

$$\lambda_{\text{blue}} < 0.4367\ \mu\text{m} \quad \text{and} \quad \lambda_{\text{red}} > 0.4367\ \mu\text{m}.$$

The color excess is given in magnitudes, and the isophotal wavelengths of the $B$ and $V$ filters are assumed to be 2.30 $\mu\text{m}^{-1}$ and 1.83 $\mu\text{m}^{-1}$, respectively. These expressions are good below 1.1 $\mu$m. Their extrapolation to 1.6 $\mu$m should not add significant error.

We shall derive our estimate of the selective extinction by measuring quantities whose theoretical unreddened values can be estimated. These quantities include energy distributions and flux ratios of unsaturated emission lines from the expanding shell.

### *a*) *The Early Blackbody Energy Distribution*

Gallagher and Ney (1976) found that V1500 Cyg radiated as a blackbody during the rise to maximum luminosity. We shall use the published photometry of Ennis *et al.* (1976), Gallagher and Ney, and Lockwood and Millis (1976) to derive the color excess during this stage by assuming that the color temperature of the expanding shell is equal to the ionization temperature. The 1975 August 30.3 McDonald scan (0.5 days before optical maximum) in Tomkin, Woodman, and Lambert shows lines of H, He, C II, N II, and O II. This ionization corresponds to a spectral class of B3 or B5, in fair agreement with the average premaximum value of B9 for very fast novae (Payne-Gaposchkin 1957).

We shall consider the $y - H$ color, where $y$ is the Strömgren intermediate bandpass filter centered on 0.545 $\mu$m, a region fairly clear of emission lines, and $H$ is the 1.6 $\mu$m broad bandpass filter. The $y$ photometry is from Lockwood and Millis while the infrared photometry is from Gallagher and Ney and Ennis *et al.* The $y - H$ color observed on 1975 August 30.3 was $1.00 \pm 0.09$ mag while $V - H$ (interpolated) for a mid-B supergiant is $-0.28 \pm 0.2$ (Johnson 1966). The error represents a B2–B6 uncertainty in spectral class. We shall neglect the slight differences between the $y$ and $V$ filters. The color excess, $E(V - H)$ of $1.3 \pm 0.2$ mag corresponds to a color excess, $E(B - V)$, of $0.50 \pm 0.08$ mag.

### *b*) *The Free-Free Energy Distribution*

Gallagher and Ney found that the energy distribution of the nova during the decline was similar to that of an optically thin thermal bremsstrahlung source. Kaplan and Pikel'ner (1970) give a flux ratio of

$$\frac{F_\nu(y)}{F_\nu(H)} = 0.77$$

for hydrogen free-free and free-bound at $T_e = 2 \times 10^4$ K, the temperature derived by Ferland and Wootten (1977) from the amplitude of the Balmer jump.

The $y$ filter bandpass is unfortunately affected by strong Fe II $\lambda\lambda$5362, 5534 emission. We have removed the energy due to these lines by drawing a local continuum through the region and performing a numerical integration of an analytic fit to the $y$ filter function, $\phi(\lambda)$,

$$\phi(\lambda) = \exp \llbracket \{-[5470 - \lambda(\text{Å})]/138\}^{-2} \rrbracket$$

over the coudé data within the $y$ bandpass. The ratio

$$R = \frac{\int_0^\infty f_\lambda(\lambda)\phi(\lambda)d\lambda}{\int_0^\infty c_\lambda(\lambda)\phi(\lambda)d\lambda} = 1.39\,,$$

where $f_\lambda(\lambda)$ is the flux of the line-contaminated data and $c_\lambda(\lambda)$ is the flux of the interpolated continuum gives the excess flux in the $y$ bandpass due to line contamination. The Gallagher and Ney energy distributions do not show an excess of energy above the free-free continuum in the $H$ bandpass so we shall assume that the line contribution to this filter is negligible.

The observed mean flux ratio for 1975 September 2 and 1975 September 6 (after correction) is $0.24 \pm 0.02$ which corresponds to a color excess of $E(B - V) = 0.49 \pm 0.03$.

### *c*) *The* He *Triplet Spectrum*

Robbins (1968) found that the He triplet line ratio

$$\frac{F(5876)}{F(4471)} = 2.9$$

is not sensitive to radiative transfer effects. This ratio was measured on six nights approximately 1.5 months after discovery (1975 September 28, October 2, 5, 9, 12, and 19) to derive a ratio of $5.9 \pm 1.2$. This corresponds to a reddening, $E(B - V)$, of $0.6 \pm 0.2$ mag. This color excess is inaccurate because of both the small baseline and the weakness of the 4471 Å line.

### *d*) *The Balmer Decrement*

The hydrogen recombination spectrum may be used to estimate the reddening in the absence of self absorption. Payne-Gaposchkin (1957) has pointed out that nova Balmer decrements vary with time, probably because of optical depth effects. We would expect that as the shell expands and becomes more dilute, the Balmer decrement should approach the case B value. Osterbrock (1974) lists

$$\frac{F(6563)}{F(4861)} = 2.8$$

for $10^4$ K and $10^6$ cm$^{-3}$. The ratio is not sensitive to the assumed temperature.

The McDonald data show that this ratio reached its greatest value (9.8) on day 16, then monotonically decreased until day 140 when it reached 5.25. H$\alpha$ line blending with [N II] 6548, 6584 prevented further measurements of this ratio. If we assume that the terminal value of the Balmer decrement is $< 5.25$, then the reddening is $E(B - V) < 0.57$ mag.

### *e*) *Paschen to Balmer Line Ratio*

The ratio of intensities of Paschen to Balmer lines with common upper levels may be used to estimate the reddening if the lines are optically thin. Paschen-$\gamma$ to Balmer-$\delta$ is most amenable to this technique with

$$\frac{F(10938)}{F(4101)} = 0.35$$

for $10^4$ K and $10^6$ cm$^{-3}$ (Osterbrock 1974). Balmer-$\delta$ is likely to be optically thin during 1975 October since H$\delta/\epsilon$ was within 10% of the case B predictions by late 1975 September. Paschen-$\gamma$ is partially blended with He I 10830 Å but is easily measured since only the wings overlap. The same is true for the slight contribution of N II 4041 Å to Bδ.

A more serious problem is N III λ4099 ($3s\ ^2S \rightarrow 3p\ ^2P^o$) which is coincident with Hδ. This doublet is emitted after λ4640 ($3p\ ^2P^o \rightarrow 3d\ ^2D$) which probably owes its great strength during the later nebular phase to a fluorescence mechanism (Bowen 1935; Swings 1948). We can estimate the strength of λ4099 by multiplying the observed number of λ4640 photons by the probability that an atom in $3p\ ^2P^o$ will decay via λ4099 (0.34, Mihalas and Hummer 1973). We find that λ4099 contributes approximately 37% of the power in the λ4101 complex on the five nights (1975 October 5, 9, 12, 19, and 27) for which we have the Pγ/Hδ ratio. The observed Pγ/Hδ ratio (1.09 ± 0.07), after this correction (1.75 ± 0.2), corresponds to a color excess of $E(B - V) = 0.56 \pm 0.07$ mag.

The results of this section are summarized in Table 1. A color excess of $E(B - V) = 0.50 \pm 0.05$ mag fits the most reliable techniques. This agrees with two other studies which have reported color excesses from spectroscopic or photometric measures of the nova. Tomkin, Woodman, and Lambert (1976) used the interstellar K I 7699 Å line to derive a color excess of 0.45 ± 0.07 mag while McLean (1976) derived $E(B - V) = 0.45 \pm 0.2$ from the optical polarization.

TABLE 1

RESULTS

| Technique | $E(B - V)$ |
|---|---|
| Blackbody | 0.50 ± 0.08 |
| Free-free | 0.49 ± 0.03 |
| Pγ/Hδ | 0.56 ± 0.07 |
| Terminal Hα/Hβ | < 0.57 |
| He triplet ratio | 0.6 ± 0.2 |
| Interstellar lines (Tomkin *et al.* 1976) | 0.45 ± 0.07 |
| Polarization (McLean 1976) | 0.45 ± 0.2 |

## IV. THE DISTANCE OF V1500 CYG

Distance moduli for novae are very difficult to obtain because of their great distances. Usually one must wait years or decades for the appearance of the ejected matter as a visible shell. The distance can then be derived from the relation between apparent size, linear size, and distance. This technique, although accurate, has the disadvantage that a great deal of time must pass before the distance can be measured.

Blackbody expansion parallaxes overcome this difficulty by inferring the diameter of the ejected shell from changes in the flux density and color temperature. Gallagher and Ney derived an expansion parallax of

$$1.2\ \text{kpc} < d < 2.3\ \text{kpc}$$

from their infrared photometry. The large uncertainty was due to the unknown expansion velocity. Barnes (1976) derived a smaller distance

$$0.8\ \text{kpc} < d < 1.4\ \text{kpc}$$

from a similar application of a $(V - R)$-surface brightness relationship to the rising branch of the light curve.

We can estimate the distance of this nova by combining our color excess with the distance-reddening law derived by Schild (1976) for the line of sight to the nova. Our reddening estimate, $E(B - V) = 0.50 \pm 0.05$ mag, corresponds to a distance of 1.95 ± 0.2 kpc from his Figure 1. This distance and reddening correspond to an absolute magnitude at maximum of $M_V = -11.0 \pm 0.2$, about $1^{\rm m}$ brighter than the fastest previous novae.

## V. DISCUSSION

Many novae have been observed to undergo an epoch of grain formation. Ennis *et al.* (1977) have evidence for an infrared excess possibly due to dust in V1500 Cyg at a much later time ($t \sim 300$ days) during the decline than the present data. Our estimates for the selective extinction in the nova do not show a trend with time for the first 100 days, but this can only rule out extensive early grain formation since the ratio of total to selective extinction for dust formed in nova shells tends to be large.

Wu and Kester (1977) derived a color excess of 0.69 ± 0.03 mag from the strength of the 2200 Å interstellar feature in observations made in 1975 December. Our contemporaneous observations of the Balmer decrement rule out a reddening larger than 0.57 mag unless too shallow a decrement is allowed. Optical depth effects tend to produce steeper, not shallower, decrements, so we are confident that 0.57 mag represents a good upper limit to the reddening. The cause of the discrepancy is not clear—perhaps line emission affects the channels used to measure the equivalent width of the 2200 Å feature.

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