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THE EARLY INFRARED DEVELOPMENT OF NOVA CYGNI 1975

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ABSTRACT

Broad-band infrared photometry of Nova Cygni is presented for 50 days following discovery. During the first three days, the energy distribution is approximately that of a blackbody. A distance of 1.5 ± 0.5 kpc is derived from a measurement of the blackbody-expansion parallax. After the fourth day, the energy spectrum is close to F_ν = constant. A possible mechanism for producing this rapid change is discussed. Although the nova is unusual in several respects, the physical parameters derived from the observations are about normal for a very fast galactic nova.

Subject headings: infrared: general — stars: individual — stars: novae

I. INTRODUCTION

Within 3 hours of being informed of the appearance of a bright nova, an infrared photometric program was under way with the O'Brien Observatory 76 cm telescope. Our initial goal was to monitor Nova Cygni for an epoch of dust formation (cf. Hyland and Neugebauer 1970; Geisel, Kleinmann, and Low 1970). However, the unusual character of this nova soon became apparent (i.e., peculiar light curve, lack of bright prenova), and it is now likely that the most interesting infrared evolution occurred within 10 days of the initial discovery.

In this *Letter* we present infrared light curves obtained during this time period. The nova shows a rapid and dramatic change in properties following visual maximum. The infrared data provide the basis for a preliminary discussion of this spectacular change in terms of the intrinsic physical properties of the nova system.

II. OBSERVATIONS

Broad-band photometric measurements of Nova Cygni at wavelengths of V through 12.5 μ were obtained with a liquid-helium–cooled bolometer on the O'Brien Observatory 76 cm telescope. A 27″ diaphragm was used and the measurements reduced to standard magnitudes through observations of α Lyr and α Boo. Table 1 lists the results; the estimated uncertainty is ±0.2 mag unless otherwise noted.

The infrared energy spectra fall into two distinct classes. Before 1975 September 1 the spectra closely approximate a blackbody while by September 2 the blackbody is gone and is replaced by a complex spectrum. Figure 1 shows infrared energy distributions from the first epoch. In addition to our observations, the early photometry of Martynov (1975) and Shenavrin (1975) have been included. For comparison, a spectrum of α Cyg obtained at O'Brien Observatory is also plotted.

Figure 2 gives data from the second stage of development. The spectra resemble those usually ascribed to free-free sources (F_ν = constant). The comparison spectrum is that of the old nova RR Tel obtained by Gehrz *et al.* (1973). Like the declining Nova Cygni, the infrared luminosity of RR Tel appears to be primarily due to free-free and free-bound transitions in the nova ejecta (Glass and Webster 1973). However, RR Tel is an extremely slow nova which is now 30 years past visual maximum while Nova Cygni is a young, rapidly evolving object.

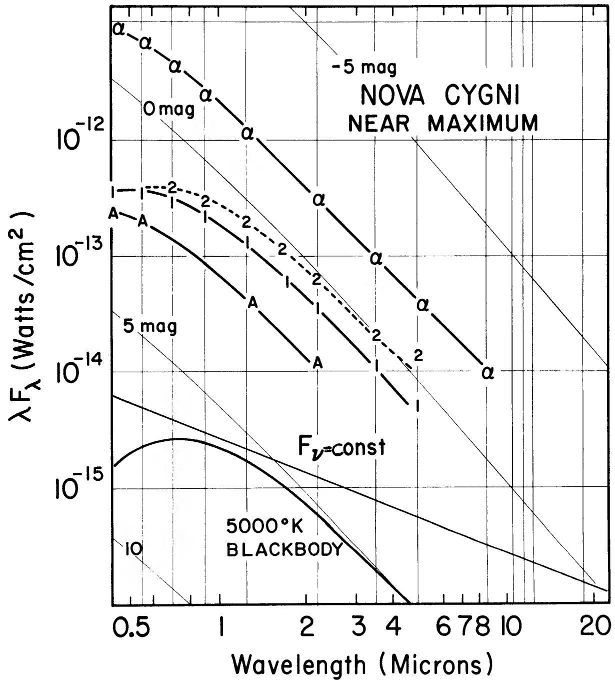

FIG. 1.—Energy spectra for Nova Cygni near maximum light. The observations correspond to those listed in Table 1. In each case the spectra are well fitted with blackbodies. For comparison, O'Brien photometry of α Cygni (α) shifted by −2.5 mag is also shown.

TABLE 1

INFRARED PHOTOMETRY

Observation	Date	Day	V	R	I	1.2 μ	1.6 μ	2.2 μ	3.6 μ	4.8 μ	8.5 μ	10.6 μ	12.5 μ
A........	8/29.8	0.8*	2.6	...	...	2.0	...	1.8	...	...	...	...	...
1.........	8/30.3	1.4	1.9	1.5	1.3	1.1	0.9	0.8	0.8	0.4	...	...	...
2.........	9/1.1	3.2	2.3†	...	...	0.5	0.3	0.1	−0.4	−0.7	...	...	...
3.........	9/2.0	4.2	3.8	2.7	1.9	1.3	1.3	0.8	0.0	−0.4	−1.0	−1.2	−1.4
4.........	9/2.4	4.6	4.6	3.1	2.4	1.9	1.8	1.4	0.5	0.1	−0.7	−0.6	−1.4
5.........	9/4.0	6.0	5.2	3.7	3.2	2.6	2.6	2.1	1.0	0.4	−0.3	−0.5	−1.1
6.........	9/6.1	8.1	5.6	4.3	3.8	3.2	3.3	2.8	1.5	1.2	0.3	−0.3	−0.8
7.........	9/9.1	11.2	6.5±0.3	4.6	4.5	3.8	4.0	3.4	2.2	1.5	0.9	0.1±0.5	−0.6
8.........	9/16.2	18.3	6.8‡	6.3	6.0	4.8	5.1	4.6	3.5	2.5	1.3±0.5	0.8±0.5	...
9§........	9/24–25	26	8±0.5	6.4±0.1	6.4	5.4±0.1	5.6±0.1	5.1±0.1	4.1±0.1	3.1	1.9	1.7	1.3
10‖.......	10/18–21	51	9.2	7.8±0.1	8.0±0.1	7.3±0.1	7.2±0.05	6.5±0.04	5.3±0.04	4.9±0.1	3.5±0.1	3.4±0.1	2.0±0.1

* Magnitudes from Martynov 1975 and Shenavrin 1975.

† V is Sept. 1.3 value of Strittmatter 1975.

‡ V is Sept. 16.2 visual estimate by Maley 1975.

§ Mean of two observations.

‖ Mean of four observations obtained with the UM–UCSD Mount Lemmon 1.5 m telescope.

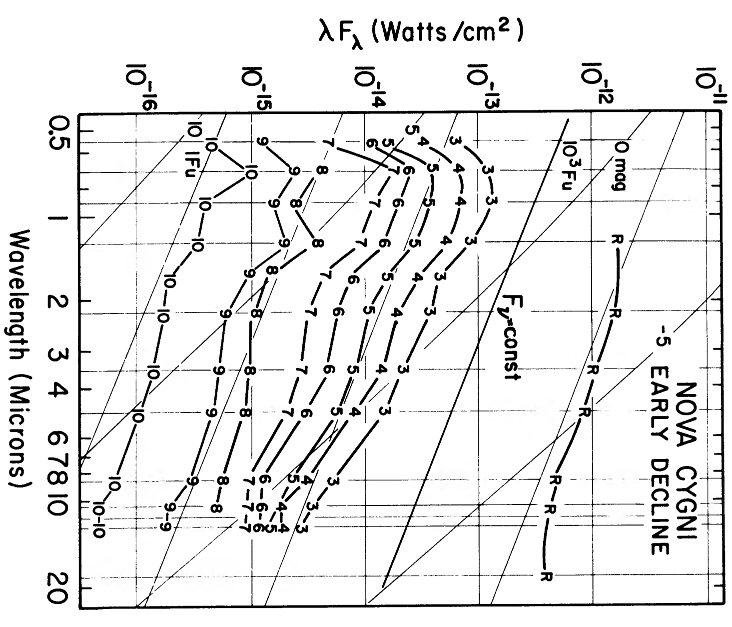

FIG. 2.—Energy spectra for Nova Cygni during the early decline. The time interval between observation 2 in Fig. 1 and observation 3 in this figure is 1 day (see Table 1). The comparison spectrum (R) is that of RR Tel as given by Gehrz *et al.* (1973) shifted by −7.5 mag.

III. PHYSICAL PROPERTIES OF NOVA CYGNI

a) *Distance and Luminosity*

Since the energy distributions in Figure 1 are close to blackbodies, it is possible to combine these data with observed radial velocities to obtain a blackbody-expansion parallax for the nova. This procedure for determining distances to novae is closely related to Baade's (1926) method for finding the radii of Cepheid variables. At each date, we have a measurement of the temperature (found by fitting a blackbody curve) and the flux at the Earth. Since for each temperature T (kelvins) a blackbody has a unique surface brightness, we can find the angular radius of the source. For θ in arcseconds and $(\lambda F_\lambda)_{\max}$ in watts cm^{-2}, we have

$$\theta = 1.0 \times 10^{11} (\lambda F_\lambda)_{\max}{}^{1/2} T^{-2} . \qquad (1)$$

Then since $d\theta/dt = D^{-1} dR/dt = v/D$, the distance D may be found if the expansion velocity v is known. Figure 3 shows angular radii and temperatures for Nova Cygni based on the observations from Figure 1. The value of $d\theta/dt$ has been found by the linear fit shown in Figure 3. Velocities in Nova Cygni range from 1300 to 2500 km s^{-1}; thus $1.2 < D < 2.3$ kpc. For this discussion a conservative distance estimate of 1.5 kpc is adopted. We have also used the angular expansion to estimate the time of the initial explosion to be August 28.9. Dates are given relative to this day zero in the remainder of the paper.

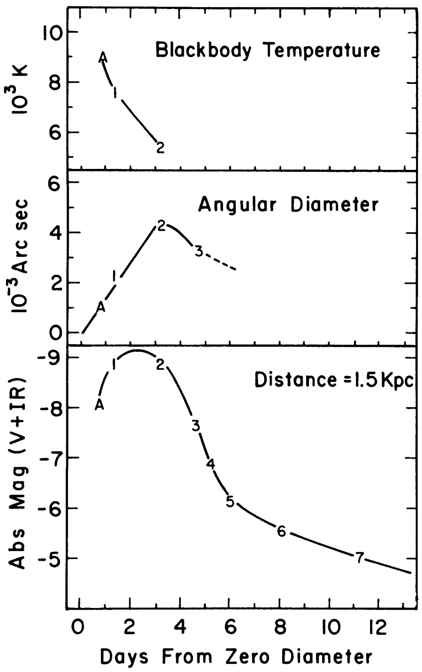

FIG. 3.—Physical properties of Nova Cygni are plotted in terms of the zero expansion date (1975 August 28.9). Temperatures and angular sizes are from the blackbody fits discussed in the text. The absolute magnitudes are based on a distance of 1.5 kpc and include both the visual and infrared luminosity. Unlike other nova, Nova Cygni so far displays similar light curves at all measured wavelengths and thus the integrated and visual light curves have the same characteristics.

The relatively low distance estimate is supported by two other points: (1) Nova Cygni cannot be heavily reddened by interstellar dust and retain the observed energy distributions. For an object at this location ($l = 99$, $b = -0.1$), low reddening is unlikely for distances greater than about 2 kpc (R. M. Humphreys, private communication). (2) The initial decline rate is 0.7 mag per day. Using the relationship for novae between rate of decline and maximum absolute magnitude given by Rosino (1965), we predict $M \approx -8.5$. For a distance of 1.5 kpc and no extinction correction, $M \approx -9$. Nova Cygni appears to be closely related to normal galactic novae.

The light curve for the integrated visual and infrared luminosity is shown in Figure 3. This light curve is somewhat abnormal and in fact is closer in form to that of a Type I supernova than most very fast galactic novae (Payne-Gaposchkin 1957).

b) *The Blackbody Stage*

During the initial expansion, the shell of Nova Cygni remained optically thick until approximately day 3.2 (see Figs. 2 and 3). At this time the required blackbody photosphere radius is $R \approx 3$ AU and the corresponding surface area is 3×10^{28} cm^2. If σ is the mass above each cm^2 of photosphere, then for an optically thick sphere with mean opacity κ we require $\tau \sim \kappa\sigma \sim 1$. Thus the mass of the ejected shell must be greater than $3 \times 10^{28}/\kappa$. For the low temperatures ($T \lesssim 5400$ K) expected above the photosphere and for densities greater than 10^9 cm^{-3}, Rosseland mean opacities for reasonable abundances are typically $\kappa < 0.1$, and a good estimate would be $\kappa \sim 0.01$ (Merts and MaGee 1975). If the outer part of the shell were ionized, then κ rises to be ~ 2. Thus we expect the mass of ejecta to be $2 \times 10^{28} < M < 3 \times 10^{30}$ g, and the kinetic energy of the nova is then more than 4×10^{44} ergs. These values are rather typical of those found for galactic novae.

Since a large, cool gas mass is present at the end of the blackbody stage, the rapid transformation in the form of the energy distribution between days 3 and 4 is remarkable. However, the relaxation time for matter in the optically thick shell is on the order of minutes, and this material can rapidly readjust to changes in physical conditions. For temperatures near 6000 K, the Merts and MaGee (1975) opacities give

$$\kappa \propto \left(\frac{T}{7000}\right)^{\sim 13} \propto (L)^{\sim 3} . \qquad (2)$$

A small decrease in luminosity could enable the outer ejecta to become optically thin. The inner, hotter regions of the ejecta would then be revealed, giving rise to a dramatic change in observable properties.

c) *Constant F_ν*

Following day 4 the infrared spectrum closely follows F_ν = constant, and it is therefore possible that we are dealing with a free-free source. Emission lines are also expected to be important in the infrared (Fink, Larson, and Gautier 1975). Spectra obtained at Minnesota and the photometry of Kemp and Rudy (1975) indicate that the R magnitudes are strongly affected by Hα emission. A conservative estimate is that Hα contributes 25 percent of the flux F_R at R. The I filter is similarly contaminated by the strong O I λ8446 emission line.

Assuming that the nova is a free-free source, the approximate physical characteristics of the emitting region can be modeled. For this discussion we have taken $T = 10^4$ K. Since the source appears to be optically thin to at least 10 μ, the requirement that the free-free optical depth be less than 1 can be utilized to estimate the density. We have used the expression for free-free optical depth given by Allen (1973) to find an upper limit to $\langle N_e N^+ \rangle X$, where X is the path length through the nova. The physical size of the nebula is taken to be the expansion radius, $X = vt$, and we have assumed that $v = 2000$ km s^{-1}. Similarly, the total free-free power L(ff) is related to the density and volume of the source through $L(\text{ff}) = G(T)\langle N_e N^+ \rangle V$, where $G(T)$ is a function of temperature. The Hα flux is also proportional to $\langle N_e N^+ \rangle V$, and we have assumed $F_{\text{H}\alpha} = 0.25\, F_R$ for comparison with the free-free model. The results of these calculations are shown in Table 2. The tabulated free-free masses were found by taking V to be given by the expansion volume and $N_{\text{H}} = (\langle N_e N^+ \rangle)^{1/2}$. The day 4.7 data require a volume whose

TABLE 2

FREE-FREE SOURCE CHARACTERISTICS

PARAMETER	DATE 4.7	 11.2	 26
X (cm)	8.1×10^{13}	1.9×10^{14}	4.5×10^{14}
Optical depth:			
$\langle N_eN^+\rangle V$ (cm^{-3})	$<2\times10^{62}$	$<1\times10^{63}$	$<8\times10^{64}$
Free-free:			
$\langle N_eN^+\rangle V$ (cm^{-3})	7×10^{62}	1×10^{62}	3×10^{61}
M(ff) (g)	6×10^{28}	9×10^{28}	2×10^{29}
Hα: $\langle N_eN^+\rangle V$ (cm^{-3})	3×10^{61}	7×10^{60}	1.4×10^{60}

radius is almost twice that of the day 3.2 photosphere, and even then the nova is on the verge of becoming optically thick. Masses found from the free-free models are in fair agreement with estimates based on the optically thick blackbody phase, but masses from Hα are systematically lower. This difference could result if the nova is optically thick in Hα or if discrete lines are contributing substantially to the infrared energy.

Another indication that the nova is not a simple, expanding nebula comes from the time-dependence of the free-free luminosity. For a simple expanding sphere with constant temperature, $L(\text{ff}) \propto t^{-3}$. However, from our last two observations we find $L \propto t^{-2}$. Since free-free emission is only weakly temperature dependent, this might imply either that the emission is mainly confined to clumps which are slowly expanding or that more optically thin material is being added to the nebula by some other means (e.g., continued mass loss). This hypothesis receives some support from the increasing free-free masses given in Table 2, although these are primarily due to the assumed uniform model. Whatever the cause, this type of behavior seems to be common in novae as similar effects have been observed in the radio spectra of Novae HR Del 1967 and FH Ser 1970 (Wade and Hjellming 1971; Hjellming and Wade 1970).

d) Energetics

Several methods have been used to show that the envelope mass is $M \sim 10^{28-29}$ g which leads to a kinetic energy $\epsilon(\text{KE}) \sim 10^{45}$ ergs. The measured optical and infrared luminosity during the first 11 days is approximately $\epsilon(V + \text{IR}) \sim 5 \times 10^{44}$ ergs. Models for mass ejection by novae (e.g., Sparks 1969) show that about 10 percent of the energy in a shock moving through a stellar atmosphere is converted into kinetic energy. We would therefore expect the total luminous energy to be $\epsilon(\text{rad}) \gtrsim 10^{45}$ ergs. This argument suggests that the envelope mass has been correctly estimated.

It is also useful to compare the free-free and bound-free radiation rates with the available energy reserves in the nebula. The recombination time for a typical nebula is $\tau_r = 1/N_e\alpha_A = 3 \times 10^{12}/N_e$ s. For our adopted density of $\gtrsim 10^9$ cm^{-3}, τ_r is less than a day. On day 11, the total free-free luminosity is $L(\text{ff}) \sim 2 \times 10^{39}$ ergs s^{-1}. The available internal energy of the envelope is about 2×10^{41} ergs; thus again the relevant time scale is $\tau_{\text{ff}} \sim 10^4$ s. A source must be continuing to energize the nova. A limit of $L \sim 10^{38}$ ergs s^{-1} is found by estimating the minimum energy required to maintain an ionized envelope on day 11. This corresponds to an apparent bolometric magnitude of less than 4 as compared to the observed value of ~5.5. It would therefore appear that Nova Cygni is maintaining a high luminosity, despite the apparent decline at visual and infrared wavelengths. However, preliminary results from OAO *Copernicus* indicate that there has been no dramatic rise at ultraviolet wavelengths (Snow 1975). The energy budget for the declining nova is not obvious at this time.

IV. DISCUSSION

Nova Cygni has several distinguishing characteristics. These include the lack of a prenova on Palomar Sky Survey prints (Samus 1975, S. R. B. Cooke, private communication), the overall shape of the visual light curve, and the apparent absence of diffuse enhanced or Orion absorption spectra during the early decline. In terms of intrinsic properties such as velocities, ejected mass, and maximum luminosity, Nova Cygni is a fairly typical galactic nova. This suggests that a relatively normal nova explosion occurred in uncommon circumstances.

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