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INFRARED OBSERVATIONS OF NOVA CYGNI 1975

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ABSTRACT

Infrared photometry from 1 to 20 μm and spectroscopy at $\sim 2\,\mu$m are presented for Nova Cygni 1975 for the period from 2 days before to 1 yr after maximum light. The data can be explained by a simple model in which the expanding gas expelled during the explosion is always a plasma at $\sim$10,000 K. Initially the gas is optically thick; this phase clearly defines the time of onset of the nova. Later, as the gas continues to expand, it becomes optically thin. The temporal dependence of the observed flux suggests that in this phase the expanding cloud is in the form of a shell. After $\sim$300 days, long wavelength emission which may be attributable to thermal reradiation from dust is observed.

Subject headings: infrared: sources — stars: novae

I. INTRODUCTION

Recently, extensive 1–10 μm photometry which delineates the early behavior of Nova Cygni 1975 has been published by Gallagher and Ney (1975), and 1–3 μm photometry has been published by Kawara *et al.* (1976). Limited 2–4 μm spectroscopic measurements of the nova have been published by Grasdalen and Joyce (1976) and discussed by Black and Gallagher (1976). Prior to these investigations, detailed study of the development of infrared radiation from novae has been reported for only one object—Nova Serpentis 1970 (Hyland and Neugebauer 1970; Geisel, Kleinmann, and Low 1970). Those observations began 19 days after discovery, and so nothing was known of the behavior near maximum light.

This paper presents a series of infrared measurements of Nova Cygni 1975, both broad-band photometric from 1.2 μm to 20 μm and spectroscopic at 2.2 μm ($\Delta\lambda/\lambda \sim 0.015$) which began 2 days before visual maximum and continued for 1 yr. The data agree with the previous measurements of this time-varying object but extend the temporal coverage to earlier and later times than other published reports. The combination of spectral and photometric data leads to a particularly simple self-consistent model of the gross geometry and history of the nova.

II. OBSERVATIONS

The observations were made between 1975 August 30 UT and 1976 September 08 UT using indium antimonide photovoltaic detectors and germanium bolometers at the 0.6 m, the 1.5 m, and the 2.5 m telescopes at Mount Wilson, and the 5 m telescope at Palomar Mountain. The central wavelengths and widths of the photometric bands are 1.25 μm ($\Delta\lambda = 0.3\,\mu$m), 1.65 μm (0.3 μm), 2.2 μm (0.4 μm), 3.5 μm (0.6 μm), 4.8 μm (0.6 μm), 8.7 μm (1.2 μm), 9.5 μm (1.5 μm), 10 μm (5 μm), 11.2 μm (1.5 μm), 12.5 μm (1.3 μm), and 20 μm (7 μm). The 2 μm spectra were obtained with an indium antimonide detector and a nitrogen-cooled circular variable filter-wheel spectrometer having a resolution of $\Delta\lambda/\lambda \sim 0.015$. Measurements were made several times per night before and at maximum light, and less frequently during decline, as dictated by the rate of change in the nova and by the weather. Because the nova is a unique time-varying object, low-accuracy data, which would otherwise be improved at a later time, are retained in these results.

III. RESULTS

Figure 1 shows the 1–20 μm energy distribution of the nova on each of 6 days around maximum and at 14, 31, and 43 days after maximum, and Table 1 summarizes all the photometric data obtained. Figure 2 shows a comparison between a portion of the present photometric data and those of Gallagher and Ney (1975) and Kawara *et al.* (1976). It is seen that there is excellent agreement among all three sets of data.

Figure 3 shows a portion of the 2 μm spectrum of the nova on each of 5 days around maximum and 44 days after maximum; the equivalent width of the Brackett-γ line of hydrogen ($\lambda = 2.17\,\mu$m; $n = 7 \rightarrow 4$) is included in Table 1. The wavelength coverage was dictated by the desire to observe the development of the Brackett-γ line, and many spectra were restricted to wavelengths near that line. The spectra are consistent with those of Grasdalen and Joyce (1976) when adjusted to the same dates.

The photometric data shown in Figure 1 show a striking change in the characteristic shape of the energy distribution of the nova at about the time of maximum light from that of a Rayleigh-Jeans spectrum ($S_\nu \propto \nu^2$) to that of thermal bremsstrahlung emission ($S_\nu \sim$ constant). This transition takes on the order of

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Table 1

Infrared Flux Densities for Nova Cygni 1975

Day	JD(244+)	Date (UT)	Flux Density (Jy) 1.2 μm	1.6 μm	2.2 μm	3.5 μm	4.8 μm	8.7 μm	9.5 μm	10.0 μm	11.2 μm	12.5 μm	20 μm	W(μm)′
1.65	2654.65	1975 Aug 30.15	460 ±40	360 ±40	230 ±20	110 ±10	50 ±20							
1.70	2654.70	1975 Aug 30.20	480 ±40	360 ±40	240 ±20	120 ±10	70 ±20							
1.74	2654.74	1975 Aug 30.24	560 ±50	410 ±40	270 ±20	130 ±10	80 ±20							
1.82	2654.82	1975 Aug 30.32	600 ±60	430 ±40	290 ±20	140 ±10	90 ±30	29 ± 6	23 ± 5	22 ± 5	16 ± 4	14 ± 3	9 ± 3	
1.86	2654.86	1975 Aug 30.36	590 ±60	460 ±50	290 ±20	160 ±20	70 ±20							
1.90	2654.90	1975 Aug 30.40	600 ±60	440 ±40	290 ±20	160 ±20	90 ±30							
1.94	2654.94	1975 Aug 30.44	660 ±70	480 ±50	330 ±30	170 ±20								
2.55	2655.55	1975 Aug 31.05	840 ±80	700 ±50	490 ±50	270 ±30								
2.72	2655.72	1975 Aug 31.22	970 ±90	750 ±70	550 ±50	310 ±30	150 ±40							
2.80	2655.80	1975 Aug 31.30	990 ±90	720 ±70	570 ±50	310 ±30	190 ±30	70 ±15	55 ±10	50 ±10	45 ± 8	33 ± 6	15 ± 4	
2.90	2655.90	1975 Aug 31.40	990 ±90	740 ±70	600 ±60	340 ±30	190 ±30							
3.9	2656.9	1975 Sep 01.4	900 ±150	790 ±100	680 ±100	470 ±70	340 ±80	160 ±30	120 ±20	110 ±20	95 ±20	85 ±20	30 ±10	0.005
4.8	2657.8	1975 Sep 02.3	340 ±50	280 ±40	240 ±40	260 ±40	200 ±40	150 ±30	130 ±30	120 ±30	100 ±20	90 ±20		0.018
5.8	2658.8	1975 Sep 03.3	190 ±30	140 ±15	130 ±15	160 ±20	140 ±30							0.028
6.8	2659.8	1975 Sep 04.3	130 ±15	90 ±10	85 ±10	100 ±10	100 ±20	110 ±20	80 ±10	75 ±10	70 ±10	78 ±10		0.037
7.9	2660.9	1975 Sep 05.4	110 ±10	73 ± 7	70 ± 7	87 ±10	100 ±20	68 ±15	58 ±15	61 ±12	54 ±15	53 ±15		0.043
9.0	2662.0	1975 Sep 06.5	92 ±14	50 ± 7	54 ± 7	63 ± 8	60 ±12							0.055
9.7	2662.7	1975 Sep 07.2	74 ±10	44 ± 6	45 ± 6	55 ± 7	52 ±10							0.052
10.7	2663.7	1975 Sep 08.2	64 ± 9	35 ± 5	35 ± 5	39 ± 6	46 ±10							
11.9	2664.9	1975 Sep 09.4	51 ± 7	27 ± 3	29 ± 3	40 ± 6	42 ± 7			28 ± 5				
12.8	2665.8	1975 Sep 10.3	47 ± 6	25 ± 3	27 ± 3	36 ± 5	35 ± 6			31 ± 6				
13.8	2666.8	1975 Sep 11.3	40 ± 5	21 ± 2	23 ± 2	30 ± 4	30 ± 5			23 ± 4				
14.7	2667.7	1975 Sep 12.2	33 ± 4	17 ± 2	19 ± 2	26 ± 3	27 ± 4							
15.7	2668.7	1975 Sep 13.2	29 ± 4	16 ± 2	17 ± 2	23 ± 3	21 ± 3	19 ± 3	16 ± 3	18 ± 3	17 ± 3	25 ± 4	19 ± 8	0.060
16.7	2669.7	1975 Sep 14.2	26 ± 3	14 ± 2	15 ± 2	24 ± 3	23 ± 3	15 ± 2	13 ± 2	14 ± 2	10 ± 2	17 ± 3	12 ± 6	0.059
17.7	2670.7	1975 Sep 15.2	24 ± 3	13 ± 1	14 ± 1	20 ± 2	18 ± 3	14 ± 2	12 ± 2	15 ± 2	13 ± 2	18 ± 3	15 ± 4	0.068
18.6	2671.6	1975 Sep 16.1	20 ± 2	10 ± 1	12 ± 1	16 ± 2	14 ± 2	10 ± 2	9 ± 2	10 ± 2	10 ± 2	14 ± 3		
28.8	2681.8	1975 Sep 26.3	8.8 ± 0.9	5.1 ± 0.5	5.6 ± 0.6	11 ± 5				9 ± 4				
29.8	2682.8	1975 Sep 27.3	7.8 ± 0.8	4.7 ± 0.5	5.3 ± 0.5	7 ± 1	8 ± 4							0.068
32.8	2685.8	1975 Sep 30.3	6.5 ± 0.7	3.6 ± 0.4	4.0 ± 0.4	5.2 ± 0.5	4 ± 1	5 ± 2	4 ± 1	6 ± 1	4 ± 1	9 ± 2		
33.7	2686.7	1975 Oct 01.2	6.5 ± 0.7	3.5 ± 0.4	3.9 ± 0.4	5.3 ± 0.6	5 ± 1			5 ± 1				0.062
34.8	2687.8	1975 Oct 02.3	5.8 ± 0.6	3.2 ± 0.4	3.6 ± 0.4	5.1 ± 0.6	4 ± 1	5 ± 1	5 ± 1	5 ± 1	3 ± 1	6 ± 1		
36.8	2689.8	1975 Oct 04.3	5.5 ± 0.6	3.0 ± 0.3	3.4 ± 0.4	4.7 ± 0.5	3 ± 1			4.1 ± 0.5				
41.5	2694.5	1975 Oct 09.0	4.0 ± 0.6	2.3 ± 0.3	2.6 ± 0.3	3.7 ± 0.4	2.7± 0.5			3.7 ± 0.8				
47.6	2700.6	1975 Oct 15.1	2.8 ± 0.3	1.8 ± 0.2	2.0 ± 0.2	2.8 ± 0.3	3.3± 0.6							0.057
48.7	2701.7	1975 Oct 16.2					1.9± 0.4	2.2± 0.3	2.1± 0.3	2.4 ± 0.3	1.7± 0.2	2.5± 0.3	2.1± 0.5	
49.6	2702.6	1975 Oct 17.1					1.9± 0.4			2.0 ± 0.3			1.7± 0.4	
56.5	2709.5	1975 Oct 24.0	1.7 ± 0.2	1.0 ± 0.1	1.2 ± 0.1	1.8 ± 0.2				1.7 ± 0.4				
57.5	2710.5	1975 Oct 25.0			1.2 ± 0.1					1.0 ± 0.5				
61.5	2714.5	1975 Oct 29.0	1.4 ± 0.2	0.84 ± 0.1	1.0 ± 0.1	1.6 ± 0.2	1.5± 0.4			1.1 ± 0.4				0.042
82.5	2735.5	1975 Nov 19.0	0.58 ± 0.07	0.41 ± 0.06	0.50 ± 0.07									
87.5	2740.5	1975 Nov 24.0	0.52 ± 0.07	0.39 ± 0.06	0.43 ± 0.07									
90.5	2743.5	1975 Nov 27.0								0.7 ± 0.2				
94.7	2747.7	1975 Dec 01.2								0.6 ± 0.1				
96.5	2749.5	1975 Dec 03.0	0.34 ± 0.04	0.23 ± 0.03	0.28 ± 0.04									
115.6	2768.6	1975 Dec 22.1								0.31± 0.04				
203.0	2856.0	1976 Mar 18.5	0.06 ± 0.01	0.036± 0.006	0.045± 0.008	0.11 ± 0.02								0.035
205.1	2858.1	1976 Mar 20.6								0.19± 0.05				
224.0	2877.0	1976 Apr 08.5	0.043± 0.005	0.029± 0.003	0.035± 0.003					<0.3				
280.0	2933.0	1976 Jun 03.5	0.029± 0.003	0.020± 0.002	0.023± 0.002									
294.1	2947.1	1976 Jun 17.6	0.022± 0.003	0.015± 0.002	0.019± 0.002	0.087± 0.009								
303.9	2956.9	1976 Jun 27.4								0.26± 0.08				
364.8	3018.8	1976 Aug 28.3	0.017± 0.002	0.012± 0.001	0.014± 0.001									
375.8	3029.8	1976 Sep 08.3								0.33± 0.06				

Photometric data for Nova Cygni 1975. Time is expressed relative to the epoch JD 2,442,653.0 (1975 August 28.5 UT) which is taken as the time of onset of the nova. The uncertainty in the equivalent width of the Brackett-γ line, W, is ~15%.

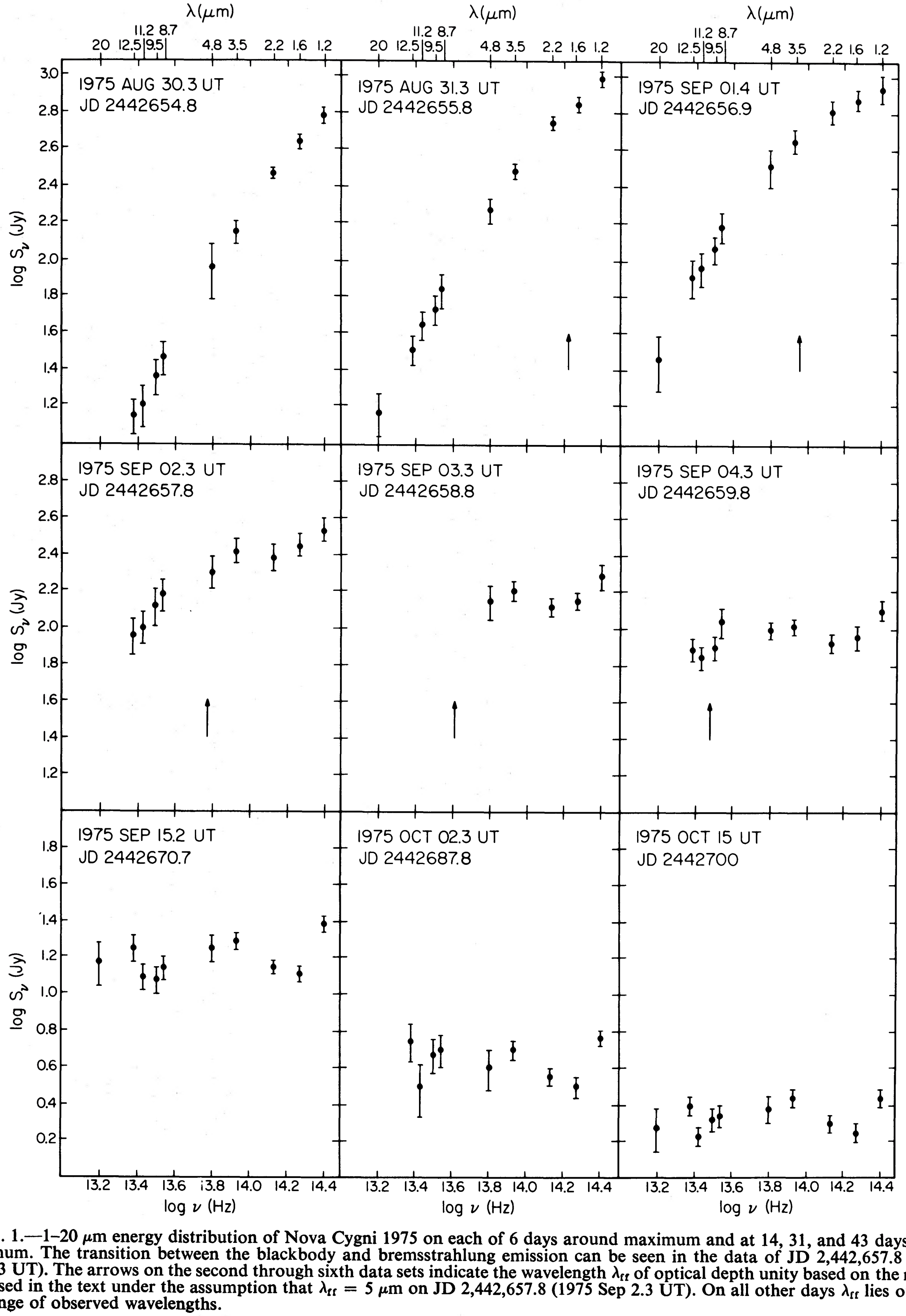

FIG. 1.—1–20 μm energy distribution of Nova Cygni 1975 on each of 6 days around maximum and at 14, 31, and 43 days after maximum. The transition between the blackbody and bremsstrahlung emission can be seen in the data of JD 2,442,657.8 (1975 Sep 2.3 UT). The arrows on the second through sixth data sets indicate the wavelength λ_{ff} of optical depth unity based on the model discussed in the text under the assumption that λ_{ff} = 5 μm on JD 2,442,657.8 (1975 Sep 2.3 UT). On all other days λ_{ff} lies outside the range of observed wavelengths.

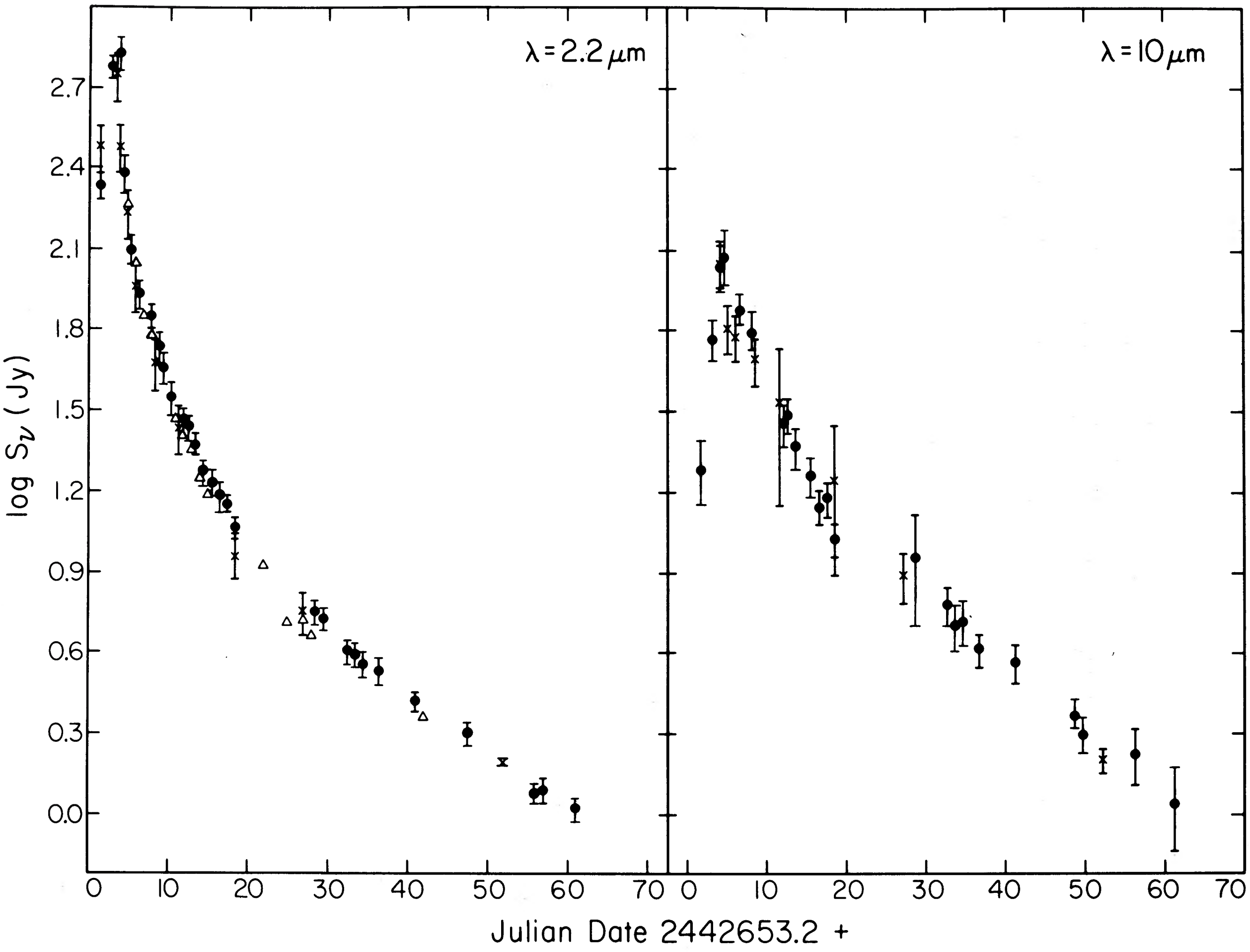

FIG. 2.—Comparison with the published photometric data for Nova Cygni 1975 at 2.2 μm and 10.1 μm. The legend is: ● = this paper; x = Gallagher and Ney 1975; △ = Kawara *et al.* 1976.

2 days. The subsequent changes in the gross shape of the spectrum are small; the detailed shape is affected by the presence of emission lines. Initially the Brackett-γ line, seen in Figure 3, is in absorption when the 1–20 μm spectrum is that of a blackbody. The line is seen in emission as the 1–20 μm continuum spectrum starts to become predominantly that of bremsstrahlung radiation, confirming this mechanism for the 2 μm radiation. About 3 days after maximum, the equivalent width of the Brackett-γ line assumes a value near 0.05 μm (Table 1).

IV. DISCUSSION

The present data lend themselves to a simple model in which the nova consists throughout its lifetime of an expanding mass of ionized gas. Initially the gas is optically thick at infrared wavelengths, and absorption lines are produced at the front edge of the cloud. Later, as the gas continues to expand, it becomes optically thin, resulting in a bremsstrahlung spectrum with hydrogen and helium lines in emission. The data can be interpreted without any temporal variations in temperature, and so for simplicity the temperature is taken constant at 10,000 K throughout. This temperature is typical of that in an ionized plasma (Osterbrock 1974) and is consistent with the equivalent width (Hilgeman 1970) of the Brackett-γ line measured 3 days after maximum. Also for simplicity the expansion velocity is assumed constant.

In this picture, the observed increase in total flux of the nova at all wavelengths during the optically thick phase is caused simply by the change in size of the object; specifically, the flux is proportional to the angular size of the nova. If, therefore, the expansion velocity is constant, a plot of $(\text{flux})^{1/2}$ versus time will be a straight line, and an extrapolation to zero angular size will give the time of the explosion. Figure 4 shows that the present data during the time the nova is optically thick (see discussion below) are consistent with the onset of rapid expansion at JD 2,442,653.0 ± 0.5 (1975 August 28.5 UT). It should be noted that the data, to the extent they define a straight line, confirm the plausibility of the simplifying assumptions. The

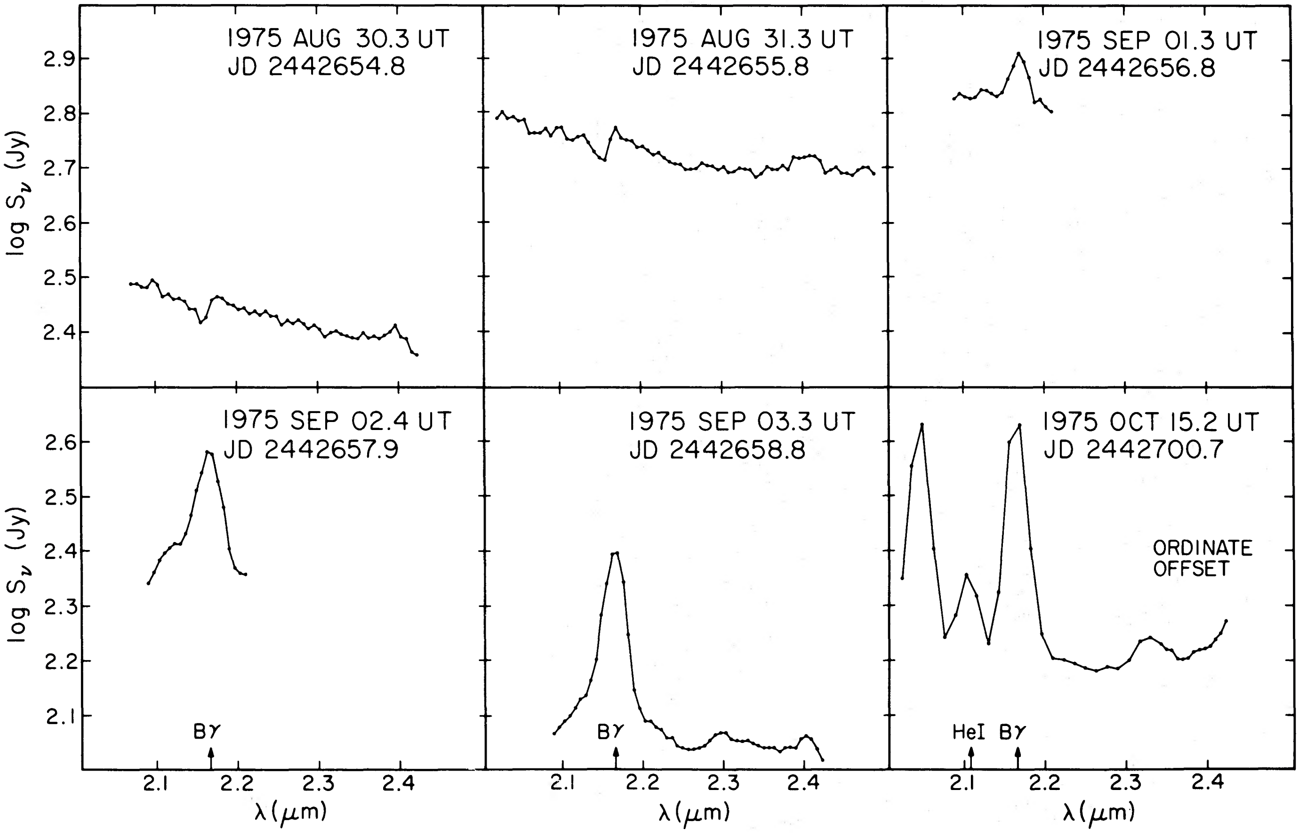

FIG. 3.—Spectra of Nova Cygni 1975 in 2 μm region on each of 5 days around maximum and 44 days after maximum. The data of 1975 Oct 15.2 UT have been multiplied by 100 in order to appear on the ordinate shown. The emission line at 2.04 μm in this spectrum has been identified with [Al IX] by Grasdalen and Joyce (1976) and with He I by Black and Gallagher (1976). The typical relative uncertainty in the spectral data is 2%.

epoch of onset is relatively insensitive to details of the model as long as the spectrum is in the Rayleigh-Jeans domain.

The slopes of Figure 4 can also be used to determine the distance to the nova if a value of the expansion velocity is assumed. The expansion velocity for Nova Cygni 1975 obtained from optical spectra lies in the range 1300–2500 km s^{-1} (Woszczyk, Krawczyk, and Strobel 1975; Preston, private communication; Leparskas 1976; Campbell 1976 and references therein); together with the mean observed angular expansion rate obtained from Figure 4, this range implies a distance D to the nova of $1.3 < D < 2.5$ kpc, in good agreement with distances obtained by other means (see, e.g., McLean 1976; McLaughlin 1960; and de Vaucouleurs 1975).

By approximately 4 days after the onset of the nova the expansion had caused the material to become optically thin. As discussed below, the wavelength at which the plasma has optical depth unity increases with time after the onset. The Brackett-γ line is seen in emission rather than absorption after the third day. The continuum shows a transition between an optically thick spectrum and an optically thin thermal bremsstrahlung spectrum on the third and fourth days and remains optically thin for the next several months.

It is possible to make an estimate of the mass of the ejected material from the data of Figure 1. For an optically thin plasma at a temperature 10,000 K, the optical depth $\tau(\lambda)$ at a wavelength λ in μm can be written

$$\tau(\lambda) \sim 10^{-18}\, \lambda^2 n_e^{\,2} l \qquad (1)$$

(Kaplan and Pikel'ner 1970), where n_e is the electron density (cm^{-3}) and l is the mean path length (pc). The data of JD 2,442,657.8 (1975 September 2.3 UT) show a clear transition at $\lambda \sim 5$ μm (see Fig. 1), and in the present interpretation the optical depth at 5 μm is assumed to be unity at that time. From equation (1), this implies that at that time $n_e^{\,2} l \sim 4 \times 10^{16}$ pc cm^{-6}. Arguments presented below indicate that the line-of-sight extent of the object lies between 10^{13} cm, the inferred thickness in an expanding shell model, and 10^{14} cm, the inferred outer radius of the gas on the date in question; thus $\langle n_e^{\,2}\rangle^{1/2} \approx 5 \times 10^{10}\ \mathrm{cm}^{-3}$. The resultant mass of the ejected material, which depends only slightly on the assumed model, is then $\sim 10^{-4}\, M_\odot$,

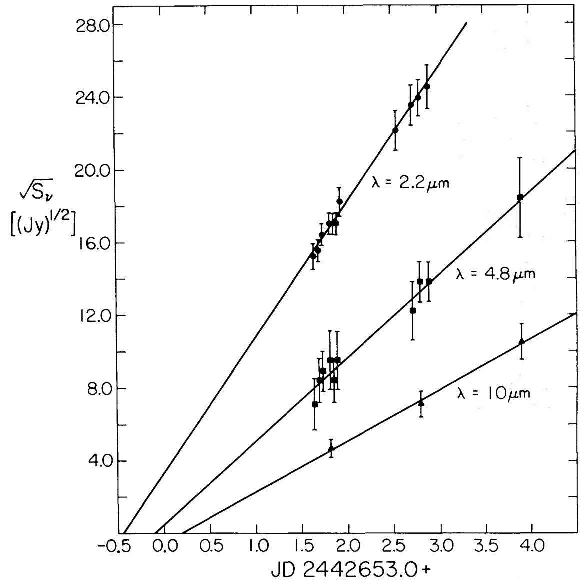

FIG. 4.—$S_\nu^{1/2}$ versus time for Nova Cygni 1975. As explained in text, a linear extrapolation of this quantity to zero gives the time of the onset of the explosion if the emission is from an optically thick gas at a constant temperature and if the expansion velocity is constant. This time is determined from an average of least squares fits at 2.2, 4.8, and 10 μm to be JD 2,442,653.0 ± 0.5 (1975 August 28.5 UT). The uncertainties shown include the uncertainty due to the absolute calibration of the photometry.

typical of ejecta masses calculated from visual data for other novae (Payne-Gaposchkin 1957). It is interesting to note that at the density derived above, the recombination time for the plasma is $\sim\frac{1}{2}$ minute (see, e.g., Spitzer 1968). The primary star must therefore continue to emit enough ultraviolet radiation to maintain the ejecta in an ionized condition.

The data of Figure 1 are numerically consistent with the model presented above. From equation (1), the wavelength at which the plasma has decreased in density to have optical depth of unity is given by $\lambda_{\rm ff} \propto (\text{time})^P$. The value of the exponent P depends on the model chosen for the expanding mass, but lies in the range 2–2.5 for any simple geometry (see below). In Figure 1, $\lambda_{\rm ff}$ is identified on the assumption that on JD 2,442,657.8 (1975 September 2.3 UT) $\lambda_{\rm ff} = 5$ μm and $\lambda_{\rm ff} \propto (\text{time})^2$. Clearly, the continuum energy distributions shown are consistent with this interpretation. Furthermore, with this assumption $\lambda_{\rm ff} \approx 2.2$ μm 3.2 days after the onset, i.e., on JD 2,442,656.2 (1975 August 31.7 UT). Figure 3 shows that before that date the Brackett-γ line is observed in absorption while later it is seen in emission.

Finally, the temporal dependence of the flux during the optically thin phase gives an indication that the spatial distribution of the expanding gas is in the form of a shell. If no extra mass is ejected after the initial outburst and if no significant clumping occurs, the electron density of the optically thin plasma varies inversely as the volume of the plasma. For an expanding shell of initial thickness H, the total volume at a time t will be given by

$$4\pi v^2 t^2 (H + 2c_s t)\,,$$

where v is the expansion velocity and $2c_s$ is the rate of increase in the shell thickness; c_s should be roughly equal to the sound speed in the plasma. The time dependence of the flux is then given approximately by

$$S_\nu \propto t^{-2}(1 + 2c_s t/H)^{-1}\,,$$

and in the early stages of expansion the flux will be proportional to t^{-2}, while at later times in the expansion the flux is more closely proportional to t^{-3}.

The 1–2 μm data of Figure 5 may be fitted initially with a t^{-2} dependence with an indication of a change in slope at ~60 days after the outburst. Thus a plausible model is that the initial expansion is as a shell. The apparent change between the two simple expansion laws at $t \sim 60$ days indicates that, if $c_s \sim 10$ km s^{-1}, $H \sim 10^{13}$ cm. If the expansion velocity is taken to be ~2000 km s^{-1}, this thickness corresponds to a very reasonable time of expulsion of $\sim\frac{1}{2}$ day. Clearly, these latter details and interpretations are still more speculative than those relating to the simple shell structure. The data can also be consistently fitted with a single slope with a power law intermediate between -2 and -3 which could indicate that a more complicated model of the nova obtains.

The time dependence of the 10 μm flux shown in Figure 5 shows a departure from the time dependences discussed above after ~300 days. This departure may be indicative of the beginning of thermal emission from dust grains similar to that observed in Nova Serpentis 1970, although numerous other explanations are possible. The study of this phase in the development of Nova Cygni 1975 is left for a future paper.

A comparison with the other published models of the nova is appropriate. The present model differs only in technical detail from that of Gallagher and Ney (1975). Specifically, those authors attribute the early increasing redness at visual wavelengths to the cooling of neutral material rather than to the expansion of an initially optically thick plasma. As a result, the times of onset differ slightly between the two models. A more significant difference (3.7 days) exists between our time of onset and that of Campbell (1976) who derives an outburst time of JD 2,442,649.3 ± 0.2 (1975 August 24.8 UT) based on observations of the Hα line; the difference can only reflect a real inconsistency in the two models.

V. CONCLUSIONS

The development of the infrared emission from Nova Cygni 1975 can be understood in terms of a simple model in which $\sim 10^{-4}\,M_\odot$ of ionized gas is expelled in an explosive event. Initially the plasma is optically thick in the infrared, but as it expands it becomes optically thin. A plausible geometry which is suggested by the subsequent temporal behavior of the observed

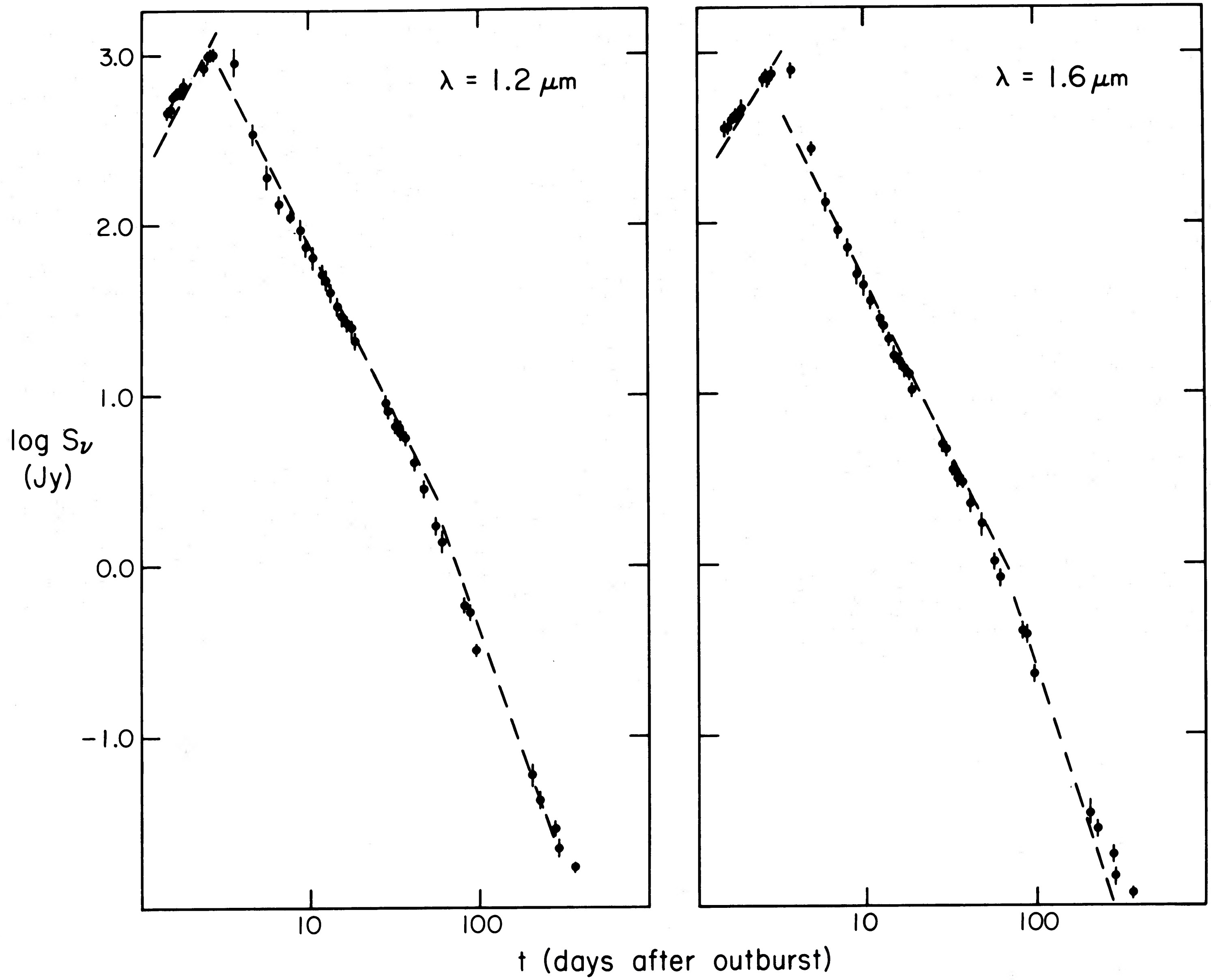

FIG. 5*a*.—Temporal dependence of the flux density from Nova Cygni 1975. The zero of time is taken from Fig. 4 to be JD 2,442,653.0 (1975 August 28.5 UT). The dashed lines show expansions at a constant velocity for an optically thick blackbody ($\propto t^2$), an optically thin shell ($\propto t^{-2}$), and a free expansion of the plasma ($\propto t^{-3}$). Uncertainties less than 10% are not displayed.

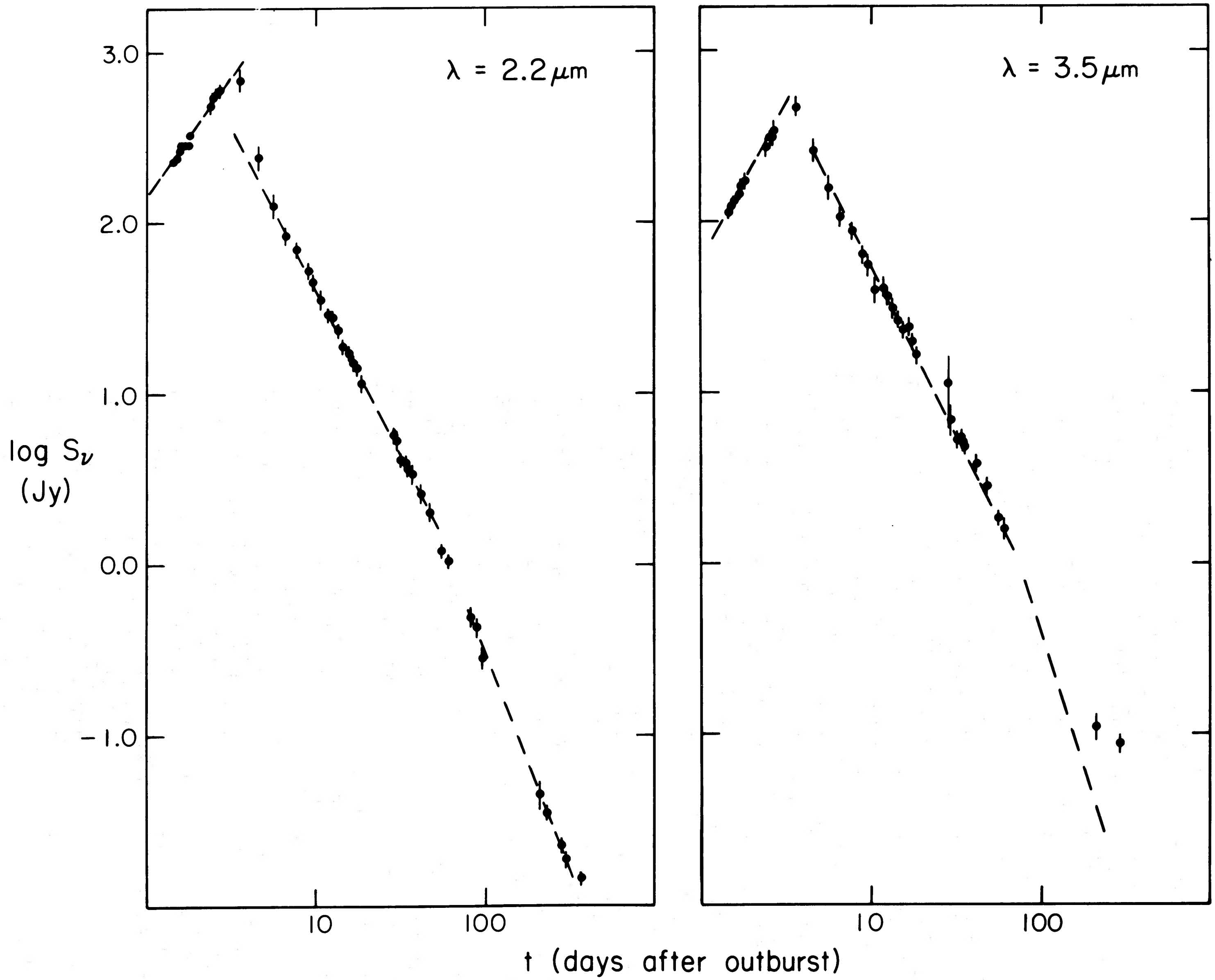

FIG. 5*b*.—Same as Fig. 5*a*

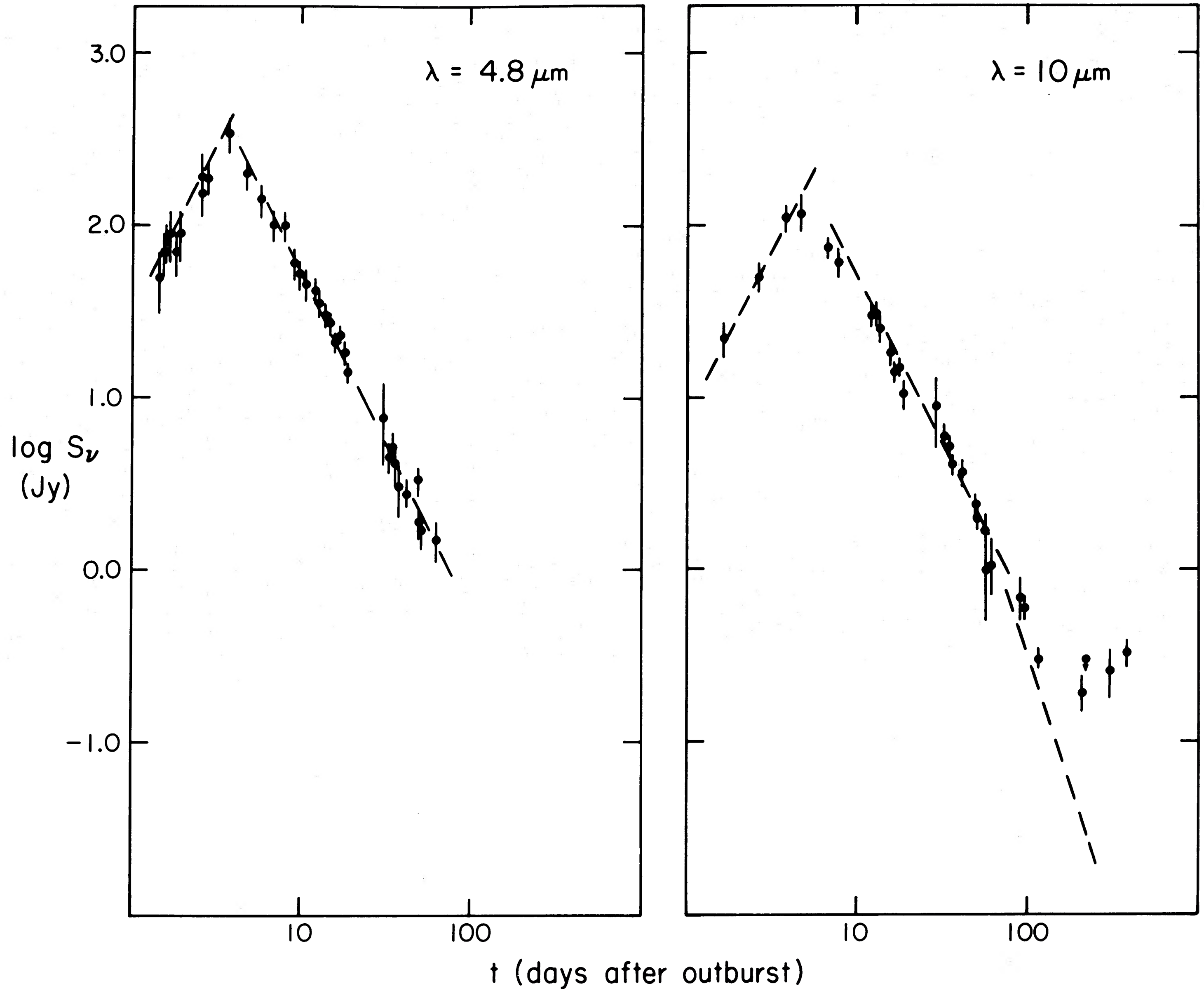

FIG. 5c.—Same as Fig. 5a

fluxes is that the ejecta are initially in the form of an expanding shell. The effects of the radial spreading in the thickness of this shell apparently become important after ~60 days when a change in the temporal behavior is seen. About 1 yr after the explosion, deviations from this simple development are seen; these may be related to the formation of dust grains.

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REFERENCES

Black, J. H., and Gallagher, J. S. 1976, *Nature*, **261**, 296.
Campbell, B. 1976, *Ap. J.* (*Letters*), **207**, L41.
de Vaucouleurs, G. 1975, *Sky Tel.*, **50**, 282.
Gallagher, J. S., and Ney, E. P. 1976, *Ap. J.* (*Letters*), **204**, L35.
Geisel, S. L., Kleinmann, D. E., and Low, F. J. 1970, *Ap. J.* (*Letters*), **161**, L101.
Grasdalen, G. L., and Joyce, R. R. 1976, *Nature*, **259**, 187.
Hilgeman, T. W. 1970, Ph.D. thesis, California Institute of Technology, p. 82.
Hyland, A. R., and Neugebauer, G. 1970, *Ap. J.* (*Letters*), **160**, L177.
Kaplan, S. A., and Pikel'ner, S. B. 1970, *The Interstellar Medium* (Cambridge: Harvard University Press).
Kawara, K., Maihara, T., Noguchi, K., Oda, N., and Sato, S. 1976, *Pub. Astr. Soc. Japan*, **28**, 163.
Leparskas, H. J. 1976, *Pub. A.S.P.*, **88**, 154.
McLaughlin, D. B. 1960, in *Stars and Stellar Systems*, Vol. **6**, ed. J. L. Greenstein (Chicago: University of Chicago Press).
McLean, I. S. 1976, *M.N.R.A.S.*, **176**, 73.
Osterbrock, D. E. 1974, *Astrophysics of Gaseous Nebulae* (San Francisco: Freeman).
Payne-Gaposchkin, C. 1957, *The Galactic Novae* (Amsterdam: North-Holland).
Spitzer, L. 1968, *Diffuse Matter in Space* (New York: Interscience).
Woszczyk, A., Krawczyk, S., and Strobel, A. 1975, *Inf. Bull. Var. Stars*, No. 1072.

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