THE ASTROPHYSICAL JOURNAL, 448:L119–L122, 1995 August 1

THE INFRARED SPECTRUM OF THE OPTICALLY THIN DUST SHELL OF V705 CASSIOPEIAE (NOVA CASSIOPEIAE 1993)

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Received 1995 March 23; accepted 1995 May 12

ABSTRACT

We report 1.25 to 18 μm infrared photometry spectroscopy of the optically thin dust shell of V705 Cassiopeiae (Nova Cas 1993) between 330 and 418 days after the outburst. The measurements show that the dust shell, which had been optically thick until at least day ≈131, now shows the spectral signatures of optically thin astrophysical silicate grains at 10 and 20 μm and hydrocarbons at 3.2–3.4 and 11.3 μm. The 1–8 μm continuum which is due to carbon dust is still present, although it no longer has a blackbody spectral energy distribution. We estimate mass of silicate grains required to produce the observed visual extinction and conclude that the condensible elements in the silicate grains may be overabundant with respect to hydrogen.

Subject headings: circumstellar matter — dust, extinction — infrared: stars — stars: individual (V705 Cassiopeiae)

1. INTRODUCTION

Infrared (IR) observations of classical novae have established that dust grains condense in the circumstellar shells ejected by thermonuclear runaways (TNRs) on the surfaces of white dwarfs (WDs) accreting matter in close binary systems. These measurements have defined the physical properties and mineral composition of the grains in the ejecta of more than a dozen recent dusty novae (see the review articles by Bode & Evans 1989; Gehrz 1988, 1990, 1993, 1995; Gehrz, Truran, & Williams 1991). IR emission signatures from all varieties of astrophysical dust known at present have been observed in various novae, and several novae have shown the signatures of several types of dust during their development scenarios. Most dust-forming novae condense amorphous carbon which produces a featureless gray body or blackbody spectral energy distribution (SED) from 2 to 23 μm. These appear to result from TNRs on low-mass, carbon-oxygen (CO) WDs (see Gehrz et al. 1995) and are typified by NQ Vul (Ney & Hatfield 1978), LW Ser (Gehrz et al. 1980a), and V1668 Cyg (Gehrz et al. 1980b). A growing number of novae are providing evidence that other types of common astrophysical dust can grow in nova ejecta. Dust formation behaviors in these novae have included the appearance of strong optically thin 11.3 μm silicon carbide (SiC) and/or 9.7 and 20 μm silicate emission features in V1370 Aql (Bode et al. 1984; Gehrz et al. 1984) and QU Vul (Gehrz et al. 1986), the appearance of 3.2–3.4 μm and 11.3 μm hydrocarbon emission features and 10 μm silicate emission in V842 Cen (see Gehrz 1990), and the sequential appearance of the emission signatures of four types of astrophysical dust in QV Vul (Gehrz, Grasdalen, & Hackwell 1992). In QV Vul, an optically thick carbon dust continuum evolved through a phase with superimposed 3.2–3.4 μm hydrocarbon and 11.3 μm SiC features to a late phase characterized by optically thin 9.7 and 20 μm silicate emission. The case of QV Vul was particularly interesting because it raised the possibility that different types of dust may have formed at different times in ejecta having large velocity and/or chemical gradients.

We recently obtained a series of IR photometric and spectroscopic measurements of the CO nova V705 Cassiopeiae (Nova Cas 1993) that show the temporal evolution of a shell that containing a complex mixture of grain materials similar to that seen in the case of QV Vul. Our measurements document an optically thin phase in the development of the dust shell following the recovery from the deep visible transition associated with the dust formation event (see Fig. 1). We show that the spectral changes can be modeled by the transition of an optically thick shell of "astrophysical silicates" to an optically thin phase caused by the expansion of the ejecta. The observations suggest that the dust formation process in some novae may be significantly more complex than was previously realized.

2. OBSERVATIONS

We obtained 1.25–18 μm IR photometric and spectrophotometric observations of V705 Cas on several occasions between 1994 April 22 UT (day 131) and 1995 February 4 UT (day 418) using Cassegrain instrumentation at the University of Minnesota (UM) O'Brien Observatory (OBO) (0.76 m aperture, 25″ beam, 35″ throw), the UM/University of California at San Diego Mount Lemmon Observing Facility (MLOF) (1.52 m aperture, 10″ beam, 27″ throw), the NASA Infrared Telescope Facility (IRTF) (3 m aperture, 6″ beam, 15″ throw), and the Hale Telescope at Palomar Observatory[6] (PO; 200 inch = 5.1 m aperture). Table 1 and Figure 2 summarize the results of the photometry. Days past outburst are reckoned from visual maximum on JD 2,449,334.5 (1993 December 13.0 UT). The filter bandpasses, calibrations, and operational characteristics of the UM bolometer are described by Hanner

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[6] Observations at the Palomar Observatory were made as part of a continuing collaborative agreement between the California Institute of Technology and Cornell University.

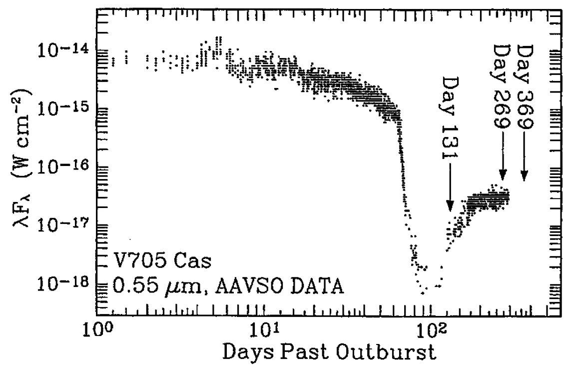

FIG. 1.—Visible light curve of V705 Cas (AAVSO data; Mattei 1995).

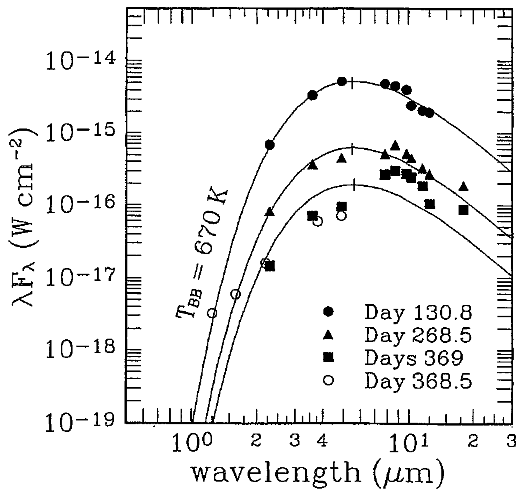

FIG. 2.—IR SED of V705 Cas at three epochs showing the transition from optically thick (day 130.8; data from OBO) to optically thin (day 369). The transition was barely evident by day 268.5 (data from IRTF).

et al. (1990) and Gehrz & Ney (1992), and those for the NASA IRTF bolometer by Tokunaga et al. (1986, 1988). Bergstrom (1991) and Bergstrom, Gehrz, & Jones (1992) have described the characteristics and calibration of broadband filters and the $R = \lambda/\Delta\lambda = 75$ 2–3.7 μm circular variable filter wheel (CVFW) of the UM InSb system.

The near-IR CVFW spectrum (see Fig. 3) of V705 Cas was obtained with the UM InSb at MLOF on 1994 December 16 UT and 1995 February 4 UT. The calibration stars for the two days were α And and 4 Pup, respectively, and the zero-magnitude flux densities were derived from the WIRO photometric system (Gehrz, Grasdalen, & Hackwell 1992). The wavelength calibration of the CVF was determined to an accuracy of ±0.04 μm using atmospheric transmission curves obtained from observations of α And and α Leo and laboratory measurements of the CVFW using a Beckman, Inc., Acculab 1 IR spectrophotometer. A small gap in the data between 3.07 and 3.12 μm is due to a crack in the CVFW.

We used the Cornell University SpectroCam-10 (SC-10) infrared imaging spectrometer (Hayward et al. 1993) on the 200 inch Hale telescope to acquire an $R = \lambda/\Delta\lambda = 100$ 8–13 μm spectrum of V705 Cas (Fig. 4 and 5) on 1994 November 15 UT. The slit width was 1″, and the sky background was canceled by the standard IR beam-switching technique using a chopper throw of 20″. The wavelength scale was calibrated to an accuracy of 0.024 μm from the 9.5 μm ozone and several telluric water lines. The data were calibrated into flux units using similar observations of β Peg, the spectrum of β Peg relative to α Lyr given by Hanner et al. (1993), and by assuming that α Lyr is a 9600 K blackbody normalized to the absolute fluxes from Cohen et al. (1992). The flux calibration is uncertain by ~15% because of relatively poor 1″ seeing at 10 μm, but the nova and standard star spectra were taken close in time at air masses 1.10 and 1.05, respectively, so we are confident that the overall shape and slope of the reduced spectrum is considerably more accurate.

3. THE DEVELOPMENT AND SPECTRAL MORPHOLOGY OF THE OPTICALLY THIN DUST EMISSION PHASE

IR photometry (Fig. 2) clearly shows that the dust evolved from an optically thick phase on day 131, on which the 2.3 to

TABLE 1

RECENT INFRARED PHOTOMETRY FOR V705 CASSIOPAIAE[a]

Parameter	UT Date: 1994 December 15.0	UT Date: 1994 December 16.5	UT Date: 1994 December 19.1
Julian day	2,449,701.5	2,449,703	2,449,705.6
Days past outburst	367.0	368.5	371.1
Telescope/detector	MLOF/Bolo	MLOF/InSb	MLOF/Bolo
1.25 μm (*J*)	···	+12.49 ± 0.22	≥+7.62
1.6 μm (*H*)	···	+11.28 ± 0.01	≥+7.91
2.2 μm (*K*)	···	+9.42 ± 0.03	···
2.3 μm (*K*)	···	···	+9.37 ± 0.23
3.6 μm (*L*)	+6.09 ± 0.05	···	+6.61 ± 0.05
3.8 μm (*L*′)	···	+6.32 ± 0.09	···
4.9 μm (*M*)	+5.12 ± 0.08	+5.36 ± 0.09	+4.96 ± 0.07
10 μm (*N*)	···	···	···
7.8 μm	+2.48 ± 0.08	···	+2.39 ± 0.05
8.7 μm	+1.95 ± 0.03	···	+1.96 ± 0.07
9.8 μm	+1.68 ± 0.07	···	+1.76 ± 0.05
10.3 μm	+1.68 ± 0.06	···	+1.62 ± 0.05
11.6 μm	+1.68 ± 0.12	···	+1.50 ± 0.06
12.5 μm	+1.95 ± 0.15	···	+1.95 ± 0.09
18 μm (*Q*)	+1.19 ± 0.24	···	+0.82 ± 0.10
f_{IR} (W cm^{-2})	6.8×10^{-16}	···	6.8×10^{-16}

[a] Data in magnitudes.

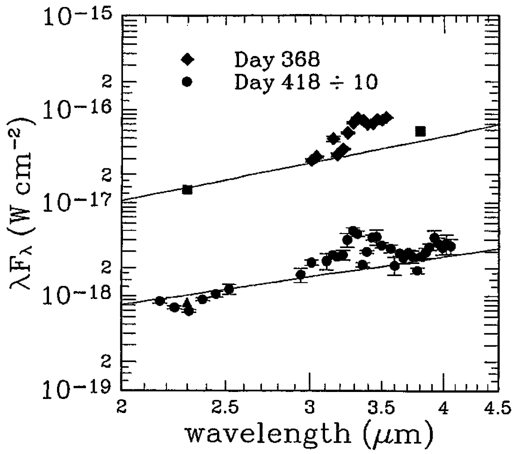

FIG. 3.—Near-IR SED of V705 Cas showing the 3.28 and 3.4 μm hydrocarbon emission features. Filled squares and triangles are broadband photometric data.

12.5 μm SED resembled that of a blackbody, to an optically thin phase on day ≈370, on which the SED is characteristic of thermal emission from optically thin dust. Examination of the behavior of the visual light curve (Fig. 1) shows that the shell became optically thin at short wavelengths as well. On day 131, the visible light was still in transition as a result of the visual extinction event caused by the dust formation. At this time, the visual optical depth of the shell was $\tau_v \approx 2$. By day 369, the visual light had recovered from transition sufficiently that $\tau_v \ll 1$.

The general shape of the SED during the optically thin phase departs significantly from that of a blackbody. Emission features at 10 and 20 μm from astrophysical silicates and 3.3, 3.4, and 11.3 μm emission features from hydrocarbon grains are superimposed on the carbon dust continuum. Near-IR hydrocarbon emission features may have been present as early as 1 month after outburst (Scott, Evans, & Geballe 1994).

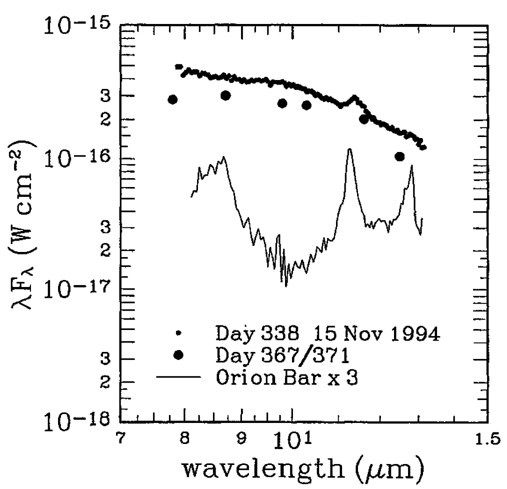

FIG. 4.—SC-10 spectrum of V705 Cas showing the 9.7 μm silicate emission feature and superimposed 11.3 μm hydrocarbon emission. Large filled circles are silicate filter photometry. Shown for comparison is an SC-10 low-resolution spectrum of the Orion bar, made during the 1994 November observing run with the same 1″ slit and observing techniques used for the nova. The Orion bar hydrocarbon feature is at 11.3 μm, in excellent agreement with the wavelength of the feature in the spectra of planetary nebulae (Witteborn et al. 1989), while that of the nova feature is about 11.4 μm. No 8.5 μm feature appears in the nova spectrum.

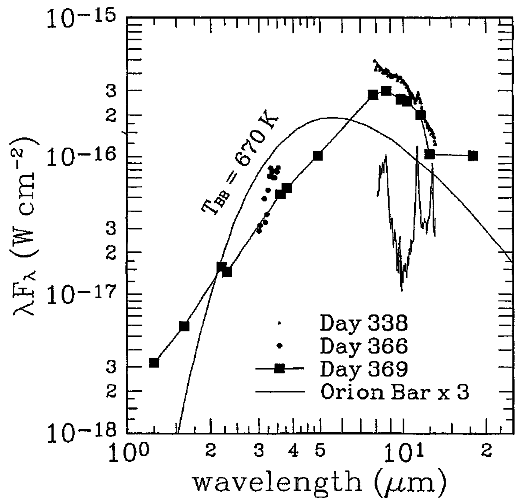

FIG. 5.—Composite showing the optically thin SED of V705 Cas from 1.25 to 18 μm. The 9.7 and 18 μm silicate and the 3.28 and 3.4 μm hydrocarbon emission features are superimposed on an optically thin dust emission continuum.

Comparing the power emitted in the 2.3–5 μm carbon continuum with the power emitted at wavelengths dominated by silicate emission, we conclude that 70% of the visual extinction in the shell is due to absorption by silicates. V705 Cas is the second nova to show an optically thin emission spectrum in which all these emission features were present at approximately the same epoch. The other was V842 Cen (Gehrz 1990). We conclude that the dust shells of these novae contain a complex mixture of both carbon and silicate-rich grains.

There are some important differences between the hydrocarbon emission from nova dust and the dust in regions of star formation. The long-wavelength hydrocarbon features in V705 Cas and V842 Cen both occur at 11.4 μm, about 0.1 μm longer than the 11.3 μm interstellar hydrocarbon feature seen in emission in the Orion Bar. Also, the 8.5 μm hydrocarbon emission feature seen in the Orion Bar is noticeably absent in the nova spectra. One obvious difference between novae and other objects is that the central engines of novae become exceedingly hot so that they can subject circumstellar dust to high fluxes of UV light (see the reviews by Gehrz 1988, 1990, 1993, 1995). Allamandola (1984) and Allamandola, Tielens, & Barker (1989) have suggested that the 11.3 μm feature can shift to the slightly higher wavelength we have observed when the hydrocarbons are subjected to such high-energy UV radiation.

The deviation in the SED from a blackbody shape suggest that the grains are individually optically thin beyond $\lambda \approx 3$ μm. Nonetheless, the contrast of the hydrocarbon and silicate emission features in V705 Cas is fairly low. Laboratory measurements (Rose 1979) and observations of comet dust (Gehrz & Ney 1992) show that this behavior is characteristic of grains with fairly large radii. Previous analyses of the extinction at UV (Shore et al. 1994) and visible (Gehrz 1995) wavelengths during the early transition phase have already established that the circumstellar grains causing the visual extinction event in V705 Cas grew to radii as large as 0.2–0.5 μm quite quickly.

4. ABUNDANCE OF SILICATE DUST IN THE EJECTA

A quantitative estimate of the silicate dust mass and the abundance of the condensed material in the ejecta of V705

Cas can be made from our observations. Assuming that the central engine maintained constant luminosity from day 131 to day 369 and that 70% of the visual extinction was due to silicates, the silicate visual absorption optical depth τ_v of the silicate dust at time t after outburst during the optically thin dust emission phase is

$$\tau_v = \frac{NQ_{\rm abs}a^2}{4R^2} = 0.7\frac{f_{\rm thin}}{f_{\rm thick}}, \qquad (1)$$

where N is the total number of grains in the shell, $R = V_0 t$ is the shell radius at time t given a constant shell expansion velocity V_0 in km s^{-1}, $Q_{\rm abs}$ is the grain absorption efficiency at 0.55 μm, and a is the grain radius. The right-hand relation in equation (1) is the ratio of the apparent shell IR fluxes during the optically thick and optically thin dust emission phases, respectively; note that this ratio is independent of the distance to the nova. The flux $f_{\rm thick}$ measures the luminosity of the central engine as described by Gehrz (1988, 1995). The total silicate grain mass $M_{\rm sil}$ in the shell is

$$M_{\rm sil} = N\frac{4\pi}{3}a^3\rho_{\rm gr}, \qquad (2)$$

where $\rho_{\rm gr} \approx 3$ g cm^{-3} is the density of typical silicate rocks. Combining equations (1) and (2) and substituting, we find that

$$M_{\rm sil}(M_\odot) = 4.4 \times 10^{-17}\frac{a\pi_{\rm gr}}{Q_{\rm abs}}V_0^2 t^2\frac{f_{\rm thin}}{f_{\rm thick}}, \qquad (3)$$

where a is in microns, t is in days, and f is in W cm^{-2}. The IR measurements on days 131 and 369 give $f_{\rm thin}/f_{\rm thick} \approx 0.1$, and IR spectra by Woodward & Greenhouse (1993) give a shell expansion velocity of $V_0 \approx 840$ km s^{-1}. Using the values of $Q_{\rm abs}$ for astrophysical silicate spheres with radii in the range 0.2–0.5 μm (Draine & Lee 1984; Draine 1985, 1995), we find from equation (3) that $M_{\rm sil} \approx 7 \times 10^{-7}$ $M_\odot$. We note that $Q_{\rm abs}$ for 0.2–0.5 μm grains does not vary strongly with temperature for the likely range of temperatures of the central engine (20,000–100,000 K) between days 130.8 and 369. The mass we derive is comparable to the silicate dust mass derived by Shore et al. (1994) using UV data. Gehrz (1995) argued from early IR measurements that an upper limit to the hydrogen mass in the ejecta was $M_{\rm gas} \leq 1.3 \times 10^{-5}$ $M_\odot$. Assuming that the dust condensed from the same gas, we conclude that $M_{\rm gas}/M_{\rm sil} \geq 18.6$, which is $\sim$15 times higher than solar abundance of the condensible elements by mass. We conclude that the ejecta of V704 Cas may therefore contain significant overabundances of such elements as O, Mg, and Si. Hauschildt et al. (1995) found evidence for very large enhancements of gas-phase C and O from UV spectra taken shortly after outburst.

B. T. Draine contributed useful comments and recent calculations of $Q_{\rm abs}$ for astrophysical grains. R. D. G. and C. G. M. thank A. Knutson for assistance with observations at MLOF. The UM IR Group is supported by the NSF, NASA, and the UM Graduate School. C. E. W. acknowledges support from the NSF. D. Shupe permitted us to use his Orion bar spectrum. Cornell observations were supported by NASA (NAGW-2551), the Cornell Department of Astronomy, and the NASA SIRTF detector development program (NAGW-2870).

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