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THE PECULIAR INFRARED TEMPORAL DEVELOPMENT OF NOVA VULPECULAE 1987 (QV VULPECULAE)

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ABSTRACT

We report 1.25–19.5 μm infrared photometry and optical/infrared spectroscopy of Nova QV Vul (1987) from 1987 November through 1989 September. The measurements show that an optically thick carbon dust shell formed within 83 days of the outburst, and that the spectral signatures of four types of astrophysical grains appeared at various times during a 2 year period following the eruption. Carbon, SiC, and hydrocarbons formed first; oxygen-rich silicates formed later. The ejecta in which the optically thick carbon grain shell condensed were apparently moving at nearly 3 times the velocity of the principle ejecta responsible for the early emission from the hot gas pseudophotosphere. We suggest the possibility that the carbon dust components formed in fast-moving polar plumes, and that the silicates formed in a slow-moving equatorial ring. Mass estimates from the infrared photometry and optical spectroscopy confirm that grain condensation in both the slow and fast ejecta of QV Vul is consistent with constraints established by previous observations of other dusty novae. The physical properties of the dust condensation zones are discussed, and numerical estimates of the dust mass are given for carbon and silicates. We conclude that the condensible elements in these grains were present in approximately solar abundance.

Subject headings: circumstellar matter — dust, extinction — novae, cataclysmic variables — stars: individual (QV Vul)

1. INTRODUCTION

Two decades of infrared observations of classical nova outbursts have established that substantial amounts of dust can condense in the ejecta (see Gehrz 1988, 1990; Gehrz, Truran, & Williams 1991). The nucleation and growth of the grains have been documented by their obscuration of the central engine and their reradiation of the absorbed radiation as thermal infrared emission. Infrared spectroscopy in the 1–23 μm region has been used to identify gas phase atoms, molecules, and mineral dust grain materials in the ejecta of more than a dozen recent novae.

Most dust-forming novae produce amorphous carbon. Typical examples are NQ Vul (see Ney & Hatfield 1978; Gehrz et al. 1992), LW Ser (Gehrz et al. 1980a), and V1668 Cyg (Gehrz et al. 1980b), where the infrared continuum of the carbon dust emission was that of a smooth, featureless graybody from 2 to 23 μm. There is recent evidence that other types of common astrophysical dust can grow in nova ejecta. For example, a 10 μm emission feature in V1370 Aql suggested the presence of SiC or a mixture of silicates and SiC in addition to the carbon (Bode et al. 1984; Gehrz et al. 1984; Williams & Longmore 1984). Gehrz et al. (1986) showed that silicates condensed in the ejecta of QU Vul after about 140 days. QU Vul never developed the smooth near-infrared continuum characteristic of carbon dust. Recently a 3.28 μm emission feature was reported in the spectrum of Nova V842 Cen (Hyland & McGregor 1989), suggesting that the dust in its ejecta contained hydrocarbon grains similar to those seen in other stellar sources, in the ISM, and in comet dust (see Gehrz 1991).

We report here infrared and optical measurements that define the temporal development of an optically thick carbon dust shell in the ejecta of Nova QV Vul (1987), and provide evidence for the presence in the ejecta of the four primary astrophysical grain materials.

2. OBSERVATIONS

Nova Vul 1987 (QV Vul) was discovered independently by American amateur astronomers K. Beckmann and P. Collins within a three-hour period on 15 November 1987 UT (Beckmann & Collins 1987). Beckmann's initial discovery on 15.042 November (JD 2,447,114.5) occurred when the object had reached its visual maximum of $m_v = 7.0$ and appears to have been made within a few hours of the moment of mass ejection ($t = 0$).

We obtained infrared photometric and spectrophotometric observations of QV Vul (Table 1, and Figs. 1 and 2) during the period from 1987 November 18 UT to 1989 September 16 UT with the Wyoming Infrared Observatory (WIRO) 234 cm infrared telescope and the University of Minnesota (UM) O'Brien Observatory 76 cm infrared telescope. Detection systems used at WIRO were the Wyoming multifilter bolometer (UW 15), the UM 15 filter uplooking bolometer (UM Up 1), the UW InSb spectrophotometer, and the UM InSb spectrophotometer. Beam sizes for the WIRO observations were 5″ for the bolometers and 6″.8 for the InSb

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TABLE 1

INFRARED MAGNITUDES AND PHYSICAL PARAMETERS OF NOVA QV VUL

Parameter Wavelength[a]	Day 3.25 (1987 Nov 18)	Day 4.25 (1987 Nov 19)	Day 10.4 (1987 Nov 25)	Day 20.3 (1987 Dec 4)	Day 82.8 (1988 Feb 5)	Day 102 (1988 Feb 24)	Day 103 (1988 Feb 25)
JD	7117.5	7118.5	7124.6	7134.5	7197	7216	7217
Site	O'Brien	O'Brien	WIRO	O'Brien	WIRO	WIRO	WIRO
System	UM Up 2	UM Up 2	UM Up 1	UM Up 2	UW InSb	UM Up 1	UM Up 1
U	...	$+5.49 \pm 0.53$	...	...	...	...	...
R	...	$+6.22 \pm 0.17$	...	...	...	...	...
I	...	$+5.38 \pm 0.21$	...	...	...	...	...
1.25	$+5.37 \pm 0.10$	$+5.34 \pm 0.09$	$+4.25 \pm 0.15$	$+5.85 \pm 0.29$	...	...	...
1.6	$+5.43 \pm 0.08$	$+4.99 \pm 0.05$	$+3.82 \pm 0.15$	$+5.03 \pm 0.09$	...	...	$+8.90 \pm 0.02$
2.3	$+4.59 \pm 0.06$	$+4.64 \pm 0.03$	$+3.96 \pm 0.15$	$+4.80 \pm 0.08$	$+4.40 \pm 0.01$	$+5.82 \pm 0.02$	$+5.67 \pm 0.02$
3.6	$+4.33 \pm 0.08$	$+4.51 \pm 0.09$	$+3.57 \pm 0.19$	$+4.60 \pm 0.07$	$+1.60 \pm 0.01$	$+2.37 \pm 0.02$	$+2.36 \pm 0.02$
3.8	...	...	...	...	...	...	...
4.9	$+3.62 \pm 0.25$	$+4.09 \pm 0.25$	$\geq \pm 2.42$ (31)	$+2.34 \pm 0.10$	$+0.60 \pm 0.05$	$+0.93 \pm 0.05$	$+0.85 \pm 0.05$
N	...	...	...	...	...	-0.87 ± 0.03	-1.00 ± 0.03
7.8	...	...	...	...	...	-0.44 ± 0.03	-0.66 ± 0.03
8.7	...	...	...	...	$+1.11 \pm 0.20$	-0.67 ± 0.03	-0.87 ± 0.03
9.8	...	...	...	...	...	-0.83 ± 0.03	-1.01 ± 0.03
10.0	...	...	...	...	...	...	...
10.3	...	...	...	...	...	-1.02 ± 0.03	-1.08 ± 0.03
11.4	...	...	...	...	...	...	...
11.6	...	...	...	...	...	-1.41 ± 0.03	-1.27 ± 0.03
12.5	...	...	...	...	...	-1.35 ± 0.03	-1.48 ± 0.03
12.6	...	...	...	...	...	...	$+0.57 \pm 0.08$
18.5	...	...	...	...	...	-1.54 ± 0.04	-1.78 ± 0.05
19.5	...	...	...	...	...	...	-0.42 ± 0.12
T_{BB}	6637	5825	3863	...	781	633	667
$(\lambda F_\lambda)_{max}$	7.5×10^{-15}	8×10^{-15}	9.5×10^{-15}	...	6.5×10^{-15}	4.6×10^{-15}	4.8×10^{-15}
θ_r	0.196	0.266	0.542	...	13.35	17.09	15.72

Parameter Wavelength[a]	Day 242 (1988 Jul 13)	Day 244 (1988 Jul 15)	Day 278 (1988 Aug 18)	Day 279 (1988 Aug 19)	Day 561 (1989 May 28)	Day 612 (1989 Jul 18)	Day 613 (1989 Jul 19)	Day 672 (1989 Sep 16)
JD	7365	7358	7392	7393	7675	7726	7727	7786
Site	WIRO	WIRO	WIRO	WIRO	WIRO	WIRO	WIRO	WIRO
System	UW 15	UW 15	UM Up 1	UM Up 1	UM Up 1	UM Up 1	UM InSb	UM InSb
U	...	...	...	...	...	...	...	...
R	...	...	...	...	...	...	...	...
I	...	...	...	...	...	...	...	...
1.25	...	...	$+9.37 \pm 0.33$	$+8.29 \pm 0.43$	...	...	...	$+14.62 \pm 0.03$
1.6	...	...	$+9.40 \pm 0.27$	$+8.66 \pm 0.33$	...	...	...	$+14.29 \pm 0.06$
2.3	$+6.97 \pm 0.10$	$+6.71 \pm 0.09$	$+7.64 \pm 0.07$	$+7.23 \pm 0.24$	...	...	$+12.98 \pm 0.15$	$+13.05 \pm 0.03$
3.6	$+4.16 \pm 0.01$	$+3.98 \pm 0.02$	$+4.61 \pm 0.01$	$+4.30 \pm 0.06$	$+8.65 \pm 0.34$	...	...	...
3.8	...	...	...	...	...	...	...	$+10.60 \pm 0.20$
4.9	$+2.96 \pm 0.01$	$+2.81 \pm 0.05$	$+3.53 \pm 0.01$	$+3.27 \pm 0.05$	$+7.46 \pm 0.35$	...	...	...
N	$+1.16 \pm 0.07$	$+0.85 \pm 0.01$	$+1.22 \pm 0.01$	$+0.94 \pm 0.02$	$+3.48 \pm 0.02$	$+3.40 \pm 0.09$	...	...
7.8	...	...	$+1.52 \pm 0.01$	$+1.39 \pm 0.06$	$+4.53 \pm 0.42$	...	...	...
8.7	$+0.66 \pm 0.02$	$+0.92 \pm 0.01$	$+1.40 \pm 0.02$	$+0.76 \pm 0.04$	$+3.69 \pm 0.31$	...	...	...
9.8	...	...	$+1.30 \pm 0.04$	$+0.93 \pm 0.05$	$+3.08 \pm 0.25$	$+3.20 \pm 0.24$	...	...
10.0	$+0.56 \pm 0.06$	$+0.68 \pm 0.05$	...	...	...	...	...	...
10.3	...	...	$+1.18 \pm 0.06$	$+1.49 \pm 0.14$	$+3.14 \pm 0.24$	$+3.70 \pm 0.25$	...	...
11.4	$+0.66 \pm 0.08$	$+0.72 \pm 0.07$	...	...	...	...	...	...
11.6	...	...	$+1.61 \pm 0.07$	$+1.04 \pm 0.05$	$+3.00 \pm 0.26$	$+3.79 \pm 0.34$	...	...
12.5	...	...	$+1.13 \pm 0.03$	$+0.96 \pm 0.14$	$+3.04 \pm 0.15$	...	...	...
12.6	$+0.63 \pm 0.05$	...	...	...	...	...	...	...
18.5	...	...	-0.13 ± 0.12	-0.03 ± 0.22	$+1.99 \pm 0.26$	...	...	...
19.5	$+0.32 \pm 0.17$	...	...	...	...	...	...	...
T_{BB}	633	655	667	667	422	...	...	...
$(\lambda F_\lambda)_{max}$	1.1×10^{-15}	1×10^{-15}	4.8×10^{-16}	6.8×10^{-16}	...	4.2×10^{-17}	...	1.5×10^{-18}
θ_r	8.36	7.44	4.97	5.92	3.67	...	...	...

[a] JD = 2,440,000+; wavelengths in units of μm; T_{BB} in units of K; $(\rho F_\lambda)_{max}$ in units of W cm^{-2} and determined for days 3, 4, and 10 by correcting the data for interstellar extinction using $A_v = 1$ mag; θ_r in units of milli-arcsec; UT dates are given in headings.

systems. The reference beams were typically 10″–20″ north and south of the source beams during chopping for background cancellation. The O'Brien observations were made with the UM 10 filter uplooking bolometer (UM Up 2) with a 20″ square beam and a 30″ throw. QV Vul was a point source with respect to our beams, so that the variations in beam size and throw did not introduce any systematic effects in the photometry. The bandpasses, calibrations, and operational characteristics of our detection systems are discussed elsewhere (UW 15: Gehrz, Hackwell, & Jones 1974; UM Up 1: Hanner et al. 1990; UW InSb: Greenhouse et al. 1988, 1990; UM InSb: Bergstrom 1991, Bergstrom, Gehrz, & Jones 1991; UM Up 2:

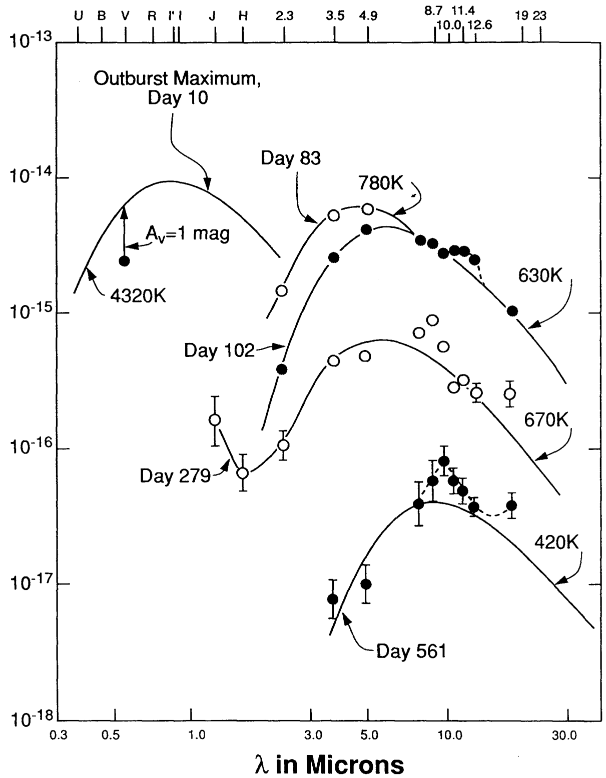

FIG. 1.—Development of the optical/infrared energy distribution of QV Vul showing the expanding pseudophotosphere (day 10) and thermal emission during the dust formation phase (days 83–561). Thermal emission from three types of dust grains are evident. All of the dust phase energy distributions show 2–8 μm continuum radiation from carbon dust. SiC emission at 11.3 μm was evident on day 102, and the 9.7 and 19.5 μm silicate emission features dominated the thermal infrared on day 561. The outburst energy distribution was derived by applying a correction of $A_v = 1$ mag.

Ney & Hatfield 1978). The position for QV Vul, derived by averaging the infrared photometric coordinates (Gehrz 1987) and the astrographic coordinates (Klemola 1987), is $\alpha(1950) = 19^h02^m32^s.20 \pm 0^s.05$ and $\delta(1950) = +21°41'39''.5 \pm 0''.4$.

Resolution $\lambda/\Delta\lambda = 75$ *L*-band circular variable filter wheel (CVFW) observations of QV Vul were made at WIRO on 1988 April 21 UT (day 157) using the Wyoming InSb. The resulting spectrum is shown in Figure 2. Absolute flux calibration was determined using Vega (α Lyrae), and zero magnitude flux densities were derived from the WIRO photometric system (Gehrz, Grasdalen, & Hackwell 1987). Wavelength calibration of the CVF was determined to an accuracy of ± 0.01 μm by observation of NGC 7027, HD 19793, and IRAS 21282+5050 (see, respectively, Smith, Larson, & Fink 1981; Lambert & Hinckle 1984; de Muizon et al. 1986). The CVF spectrum was spectrally oversampled by a factor of 4. Each spectral element was integrated for 40 s, and the telescope was recentered periodically using a software peaking routine. A gap in the data between 3.45 and 3.5 μm resulted from a guiding error that was not detected until the data were under analysis.

Optical spectrophotometric observations of QV Vul were obtained on 1987 November 23 (day 7) and 1990 August 29 (day 1017–1018). The 1987 observations were obtained using the Ohio State University image dissector scanner (Byard et al. 1981) attached to the 1.8 m Perkins telescope of the Ohio Wesleyan and Ohio State Universities at the Lowell Observatory. Dual 7'' diameter entrance apertures and a 600 line mm^{-1} grating blazed at 5500 Å covered about 2600 Å of the spectrum at 10 Å resultion. Two different grating tilts were required to cover the spectral region 3700–8600 Å. The spectrum of a quartz-halogen lamp was observed to remove pixel-to-pixel variations in response, and the spectrum of an FeNe-He source provided wavelength calibration. The observation of one or more standard stars from Stone (1977) permited the removal of the instrumental response and provided absolute photometric calibration. The reduction procedures are described in Wagner (1986). The 1990 observations were obtained using the University of Arizona Steward Observatory 2.3 m telescope located on Kitt Peak and the Boller and Chivens CCD spectrograph. A 300 mm^{-1} grating and 1''.5 wide slit were employed which covered 3000 Å of the spectrum, also at 10 Å resolution. As in the Flagstaff observations, two grating tilts were required to cover the entire spectral region between 3200 and 8800 Å. For the Steward observations, the slit was aligned along the parallactic angle to avoid variable light loss with wavelength due to atmospheric refraction. The spectrum of a quartz-halogen lamp and HeAr lamp were obtained to remove flat-field variations and determine the wavelength response, respectively. The spectrum of BD +28°4211 was obtained to remove the instrumental response function. The CCD spectra were reduced in IRAF using standard routines.

Figure 3 shows the optical spectra of QV Vul that we obtained on 1987 November 23 (day 7) and 1990 August 28–29 (day 1017). The early spectrum is dominated by permitted lines arising from the Balmer series of hydrogen, Fe II multiplets 42 and 48, Na D λ5890, λ5896, Ca II H and K and the near-infrared Ca II triplet, and O I λ7774 and λ8446. The Balmer lines Ca II, Na D, and O I exhibit striking P-Cygni profiles. These features are the characteristics of the ejection of the dense cool envelope. Gaussian deconvolution of some selected emission lines in the early spectrum give the following line strengths and widths (FWHM), respectively: Hα, 7.8×10^{-10} ergs cm^{-2} s^{-1} (920 km s^{-1}); Hβ, 1.9×10^{-10} ergs cm^{-2} s^{-1} (1300 km s^{-1}); O I λ7774, 1.2×10^{-10} ergs cm^{-2}

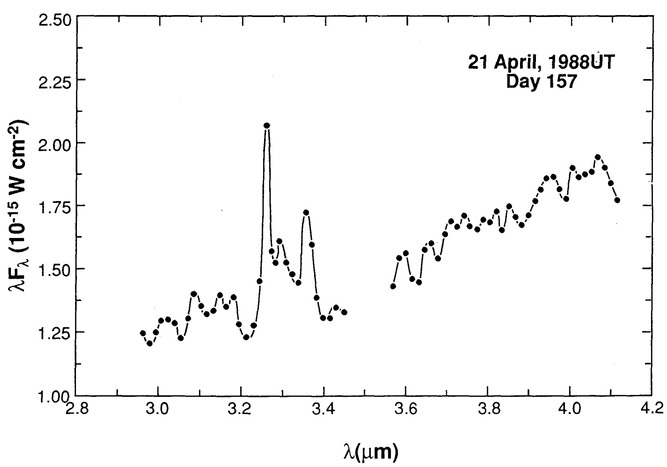

FIG. 2.—A resolution $\lambda/\Delta\lambda = 75$ *L*-band spectrum of QV Vul showing strong 3.28 μm and 3.3–3.4 μm emission from hydrocarbon grains. Statistical error bars are smaller than the plotting symbols. The gap from 3.45 to 3.55 μm was caused by a telescope tracking error. Four data points per spectral resolution element are shown. A cubic spline has been interpolated between them as a visual aide.

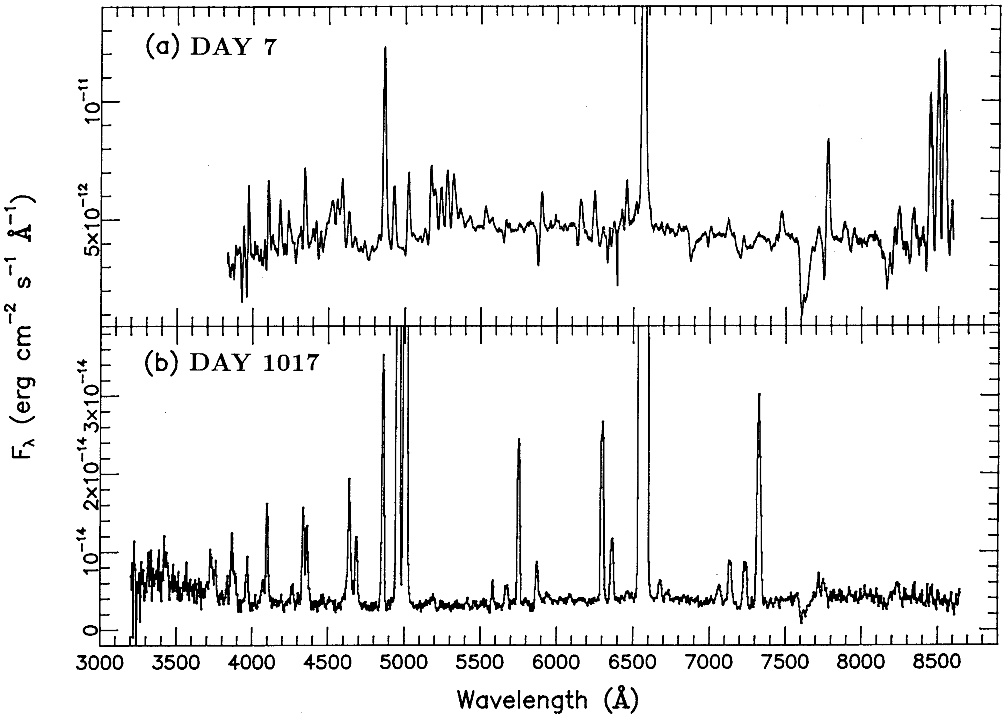

FIG. 3.—Optical spectra of Nova QV Vul obtained 7 days (*a*) and 1017 days (*b*) after the outburst. Note the relatively cool continuum and low ionization of the spectrum on day 7.

s^{-1} (950 km s^{-1}). The P-Cygni absorption components have terminal velocities that extend up to 1500 km s^{-1}.

The late spectrum is dominated by features characteristic of the nebular phase of the development of a nova shell. These features include the Balmer series; He I λ4471, λ5876, λ6678, λ7065; He II λ4686; [N II] λ5755, λ6548, λ6584, N III λ4640; [O III] λ4363, λ4959, λ5007, [O II] λ7320, λ7330; [O I] λ6300, λ6363; [Ne III] λ3869, λ3968; [Ar III] λ7136; and weaker emissions due to [Fe II]. In addition, forbidden lines arising from [O I] λ3727, λ3729 and [S II] λ4070, λ6717, λ6731 also are present, indicating the presence of very low density gas. Coronal lines such as [Fe VII] λ6087 are weak or absent. This is the first nova in which we have detected [S II] emission in the optical spectrum. Line strength measurements with respect to Hβ for the prominent lines in the nebular spectrum on day 1017 are given in Table 2.

3. PHYSICAL CHARACTERISTICS OF THE ERUPTION OF QV VUL

Our data show that QV Vul exhibited three classic phases (see Gehrz 1988) in its infrared development. Pseudophotospheric emission from the optically thick gaseous ejecta was present for at least 10 days following the outburst. An optically thin infrared emission phase was observed on day 20. Finally, an optically thick carbon dust shell formed in the ejecta. This shell apparently became optically thick in the visible about 10–20 days before we first observed it on day 83. The energy distribution of the nova was that of a blackbody during the pseudophotospheric expansion and the optically thick dust phases (see Fig. 1). During these phases, the blackbody angular radius θ_r of the source is given by (Gehrz 1988)

$$\theta_r \approx 1.01 \times 10^{14} \frac{[(\lambda f_\lambda)_{\max}]^{1/2}}{T_{BB}^2} \text{ milli-arcsec} , \quad (1)$$

where T_{BB} is the blackbody temperature of the source in K and $(\lambda f_\lambda)_{\max}$ is the apparent maximum of the energy distribution in W cm^{-2}. Values of θ_r for dates when equation (1) can be applied to the data are given in Tables 1 and 4 and are plotted in Figures 4*e* and 5.

Because we were able to begin measurements of QV Vul

TABLE 2

LINE IDENTIFICATIONS FOR THE NEBULAR PHASE OF QV VUL

Wavelength (Å)	Species	$F/F(H\beta)$	$I/I(H\beta)$ $A_v = 1$	$I/I(H\beta)$ $A_v = 3.5$
3869.0........	[Ne III]	0.25	0.32	0.60
3969.8........	[Ne III]	0.10	0.13	0.22
4071.4........	[S II]	0.11	0.13	0.22
4099.6........	Hδ + N III	0.35	0.42	0.66
4339.0........	Hγ	0.33	0.37	0.50
4362.9........	[O III]	0.31	0.35	0.46
4638.7........	N III	0.56	0.59	0.65
4683.8........	He II	0.30	0.31	0.34
4859.6........	Hβ	1.00	1.00	1.00
4958.4........	[O III]	11.93	11.61	10.83
5008.3........	[O III]	36.93	35.40	31.85
5752.0........	[N II]	0.75	0.58	0.31
5874.2........	He I	0.17	0.13	0.06
6087.0........	[Fe VII]	0.02	0.02	0.01
6300.9........	[O I]	0.74	0.53	0.23
6364.5........	[O I]	0.27	0.19	0.08
6544.2........	[N II]	2.66	1.86	0.76
6562.8........	Hα	12.53	8.75	3.56
6578.1........	[N II]	8.06	5.61	2.27
6678.2........	He I	0.08	0.06	0.02
6717.0........	[S II]	0.03	0.02	0.01
6731.0........	[S II]	0.03	0.02	0.01
7135.0........	[A III]	0.22	0.14	0.05
7325.3........	[O II]	0.99	0.63	0.20

NOTE.—$F(H\beta) = 7.26 \times 10^{-13}$ ergs cm^{-2} s^{-1}.

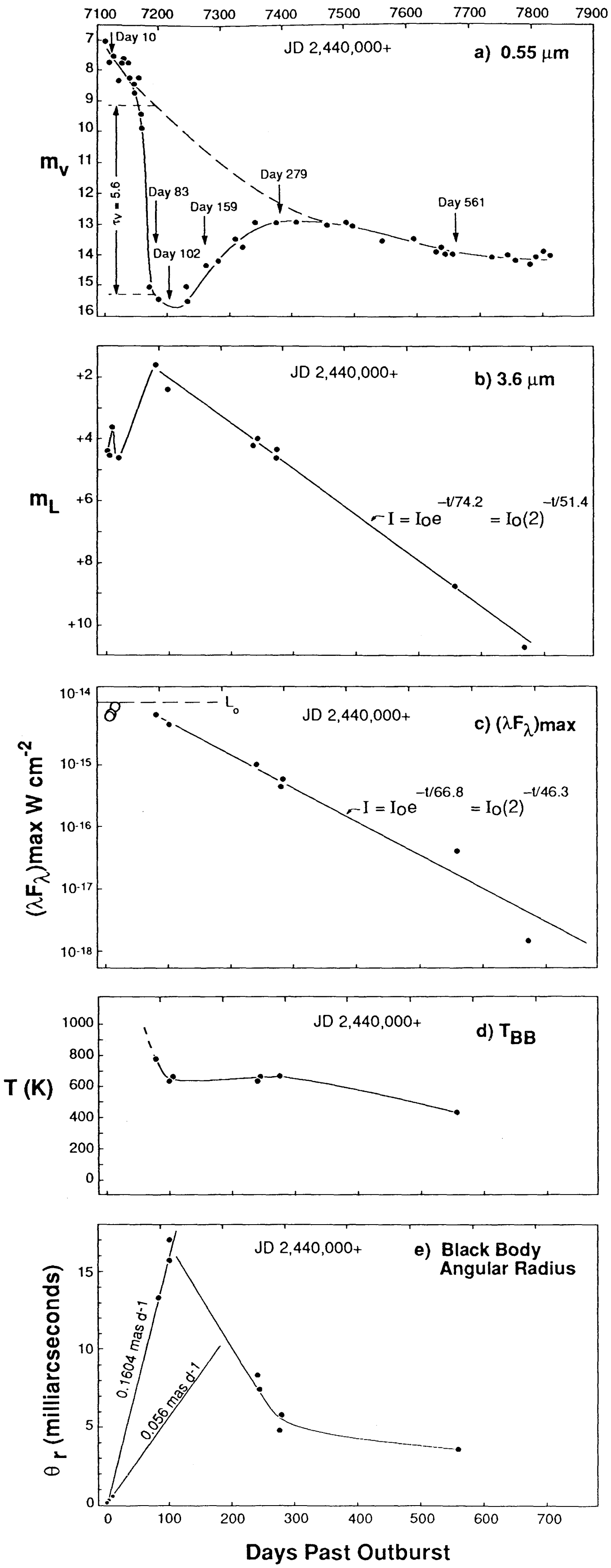

FIG. 4.—Temporal development of QV Vul showing (*a*) the visible light from data provided by the AAVSO (J. A. Mattei 1989, private communication), (*b*) the infrared 3.6 μm light, (*c*) the apparent integrated optical/infrared luminosity as measured by $(\lambda F_\lambda)_{max}$, (*d*) the blackbody temperature of the carbon dust continuum radiation, and (*e*) the blackbody angular radius of the optical/infrared energy distribution for all times when the energy distribution was black. Note that the infrared monochromatic flux at 3.5 μm and the total flux as measured by $(\lambda F_\lambda)_{max}$ both decay exponentially with time. As shown in (*e*), a comparison of the expansion rates of the blackbody angular radius of the nova remnant during the psuedophotospheric and optically thick dust phases leads to the conclusion that the ejecta from which the carbon dust condensed were apparently moving at nearly 3 times the velocity of the primary ejecta responsible for the early pseudophotosheric emission. The carbon dust shell reached a visual optical depth of $\tau_v = 5.6$, 33 days after the onset of the visual transition.

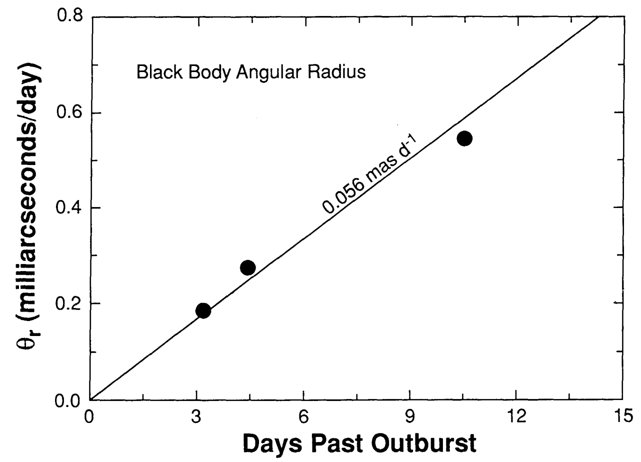

FIG. 5.—Detail of Fig. 4*e* showing the expansion of the blackbody angular radius of the pseudophotosphere.

shortly after outburst and its development was fairly slow, our data present an excellent opportunity to estimate nearly all of the critical parameters of its outburst. We state below the arguments leading to the results summarized in Table 3 and Figures 4 and 5.

3.1. *Reddening*

Estimation of most physical parameters of the outburst requires an assessment of the visible interstellar extinction coefficient, A_v. Zissel (1987a) reported a color index of $B-V = +1.18$ on 1987 November 16.99, 2.25 days after the outburst. Comparison of this with color with the average intrinsic color of $B-V \approx +0.2$ exhibited by a typical classical nova near maximum (Allen 1973) suggests a visual interstellar extinction of $A_V \approx 3$ mag. There is evidence that this very red color was an intrinsic peculiarity of the ejecta during the early development phase, and that the actual interstellar reddening is much lower. First, this extinction is somewhat large given QV Vul's rather high Galactic latitude ($b^{II} = +7.0°$) and wide separation from the Galactic center ($l^{II} = 54°$). Second, $B-V$ had decreased to $+0.64$ mag (Zissell 1987b) by 22.97 November (day 8.72) when the nova was still clearly in the pseudophotospheric expansion phase, implying a reddening of only $A_v \approx 1.3$ mag. The infrared luminosity observed on day 83 sets a lower limit of $A_v \approx 0.7$ mag on the visual extinction, assuming that the central engine maintained a constant luminosity during this period (see Gehrz 1988).

Additional constraints on the amount of interstellar extinction toward QV Vul can be derived by considering the optical

TABLE 3

SUMMARY OF PHYSICAL PROPERTIES OF QV VUL

Parameter	Relationship	Value of QV Vul
RA (1950)	...	$19^h02^m32\overset{s}{.}20 \pm 0\overset{s}{.}05$
Decl (1950)	...	$+21°41'39\overset{''}{.}5 \pm 0\overset{''}{.}4$
Day 0	$(d\theta/dt)_{phot}$	JD 2,447,114.25 ± 1.0
V_0	Hα FWHM	460 km s^{-1}
V_0	P-Cygni lines	900–1300 km s^{-1}
$(m_v)_{max}$	...	+7.0
A_v	...	1.0 mag
t_2, t_3	V light curve	50, 60 days
M_v	t_2 and t_3	−7.25 ± 0.2
$D_{2,3}$	Distance modulus	4.47 kpc
D_{exp}	Early photosphere, V_0	4.72 kpc
$(\lambda F_\lambda)_{max}$, V	...	1×10^{-14} W cm^{-2}
$(\lambda F_\lambda)_{max}$, IR	...	6.5×10^{-15} W cm^{-2}
L_0	M_v and BC = 0.0	$6.3 \times 10^4\ L_\odot$.
$(L_0)_v$	$(\lambda F_\lambda)_{max}$ at V, D	$8.6 \times 10^4\ L_\odot$
$(L_0)_{IR}$	$(\lambda F_\lambda)_{max}$ in IR, D	$5.6 \times 10^4\ L_\odot$
M_{gas}	(slow, fast) shell	$(2.3, 10) \times 10^{-5}\ M_\odot$
M_{dust}	Carbon optical depth	$3.0 \times 10^{-7}\ M_\odot$
M_{dust}	Silicate optical depth	$1.5 \times 10^{-7}\ M_\odot$
t_d	Transition, IR max	≤83 days
V_d	$(d\theta/dt)_{dust}$	1318 km s^{-1}
ρ_c	$M_{gas}/4\pi R_c^2 \Delta R$ for (slow, fast) shells	$\approx(1.5, 6.5) \times 10^{-16}$ g cm^{-3}

spectra. Comparison of the nebular phase spectrum observed on day 1017 with a model spectrum calculated based on the photoionization model indicate very poor agreement of the relative strengths of the Balmer and He lines if 1 mag of visual extinction is assumed. Detailed examination of the spectrum revealed the presence of the interstellar λ4430 absorption band with an equivalent width of about 2.4 Å. Using the calibration by Herbig (1975), this equivalent width correlates with $A_v \approx 3$ mag. Furthermore, if we assume that the intrinsic ratio of the Balmer lines is given by their case B values, then their observed ratios suggest that there are about 4 mag of visual extinction along the line of sight. A final constraint on the amount of visual extinction along the line of sight during the nebular phase was obtained by performing continuum fitting of the optical spectrum as described by Wagner (1986) using 22 continuum points apparently free from emission lines. The results indicate that the optical continuum is best fitted by the Rayleigh-Jeans tail of a blackbody continuum with 3.5 ± 0.3 mag of visual extinction. Thus, for the late-time nebular phase spectrum, three independent measurements yields 3–4 mag of visual extinction along the line of sight. However, there appears to be strong evidence from the day 7 spectrum that a large component of this extinction is intrinsic to the circumstellar rather than interstellar material. Correction of the spectrum taken on day 7 for 3.5 mag of visual extinction yields a continuum that suggests that there should have been a strong ultraviolet excess. This excess does not appear in the photometry taken by others during this period and is inconsistent with the cool continuum, observed ionization, and absence of higher ionization lines such as He I. It seems apparent that the observed line spectrum and continuum are strongly affected by dust in the ejecta even more than 1000 days after the initial outburst.

We conclude that the true interstellar extinction in the direction of QV Vul is $A_v = 1$ mag, and we apply this correction in the analysis that follows.

3.2. *Distance and Luminosity*

The distance and luminosity of QV Vul can be determined from the decline rate and the angular expansion rate of the early pseudophotosphere. The average absolute visible magnitude of QV Vul calculated from the decay rate of the visible light curve (Canterna & Schwartz 1977; Cohen 1985) is $M_v = -7.25 \pm 0.2$ mag, leading to a distance of 4.47 kpc. A comparable distance of 4.72 kpc results from the observed 0.056 milliarcsec day^{-1} angular expansion rate of the pseudophotosphere (Table 4, Fig. 5) and the 460 km s^{-1} expansion velocity of the principle ejecta derived from the FWHM of the Hα emission lines (Wagner 1987 and data presented in this paper). We have assumed here that the slow-moving principle ejecta represent the material that defines the surface of the pseudophotosphere observed between days 3 and 10. There are several strong high-velocity components in the spectrum of QV Vul (Andrillat 1987; Wagner 1987) that suggest the presence of material moving as fast as 900–1240 km s^{-1}. We argue below that the optically thick carbon dust shell probably formed in these fast-moving ejecta. Presumably, these fast ejecta had already gone optically thin in the gas phase by day 3.

From $M_v = -7.25$ and a bolometric correction of BC = 0.0 (Allen 1983), we find on the basis of light decline rate considerations alone that the outburst luminosity of QV Vul is $L_0 \approx 6.3 \times 10^4\ L_\odot$. The mean distance of $D = 4.6$ kpc resulting from the determinations above and the integrated outburst energy distribution corrected for $A_v = 1$ mag give $L_0 = 4\pi D^2[1.35(\lambda F_\lambda)_{max}] = 8.6 \times 10^4\ L_\odot$. The same calculation for the infrared maximum yields $L_0 = 5.6 \times 10^4\ L_\odot$. All three values suggest that the outburst luminosity was somewhat higher than the Eddington luminosity for a 1.4 $M_\odot$ white dwarf. They are comparable to the outburst luminosities of other dusty novae.

3.3. *Outburst Time*

The outburst time (day 0) must be known to determine the mass in the ejecta and to evaluate the temporal evolution of other physical parameters that characterize the development of the ejecta. For QV Vul, day 0 can be deduced from our observations of the pseudophotospheric expansion during 1987 18–25 November UT. The expansion data (Table 4, Fig. 5) are consistent with the interpretation that the pseudophotosphere began its expansion on day 0 = JD 2,447,114.25 ± 1.0, about 6 hr before the first reported discovery of the visible light from the event (Beckmann & Collins 1987). All elapsed times given in the discussion refer to this zero point.

TABLE 4

EXPANSION OF THE ANGULAR DIAMETER OF QV VUL

JD 2,440,000+	Days Since Outburst	Blackbody Angular Radius (milli-arcsec)
Pseudophotospheric Expansion Phase		
7117.5	3.25	0.196
7118.5	4.25	0.266
7124.6	10.35	0.542
Optically Thick Dust Emission Phase		
7197	82.75	13.35
7216	101.75	17.09
7217	102.75	15.72

The angular expansion rate of the optically thick carbon dust shell between days 83 and 103 is consistent with the ejection of the dust-forming ejecta on day 0, but at a much higher velocity than that of the pseudophotospheric material. Given the distance of 4.6 kpc indicated by the pseudophotospheric expansion and light decline rate, the ejecta in which the carbon dust formed must have been expanding at 1320 km s^{-1}. This velocity is comparable to the highest velocity components observed in the optical spectra (Andrillat 1987; Wagner 1987).

3.4. *Mass of Gas in the Ejecta*

The mass of gas in the ejecta in the pseudophotosphere can be estimated from the fact that the photosphere had become optically thin by day 20. Assuming that Thompson scattering dominated the opacity at this time, and that the ejecta filled a constant density sphere, the gaseous mass M_g is given by

$$M_g \approx \frac{\pi R^2}{\kappa_T} , \qquad (2)$$

where $R = V_0 t$ is the shell radius for ejecta flowing outward at constant velocity $V_0 = 420$ km s^{-1} for an elapsed time t, and κ_T is the Thompson scattering opacity. Our data give $M_g \approx 2.3 \times 10^{-5}\ M_\odot$.

On day 7 the optical spectrum (Fig. 3*a*) arises from a cool, high-density, optically thick shell. Because of the high density, the shell is ionization bounded and completely absorbs all of the ionizing radiation. This results in a large outer neutral zone and an inner ionized zone. The presence of such a shell is indicated by the great strength of O I 8446 Å in emission. This line is excited by resonance fluorescence from Lyβ photons trapped by the neutral zone (Strittmatter et al. 1977). The absence of optical forbidden lines at this time indicates that $N_e \geq 10^8$ cm^{-3}, but the electron density is probably well in excess of this value, and perhaps as large as $\simeq 10^{11-12}$ cm^{-3}.

Detailed analysis of the expanding, optically thick atmospheres of novae during this phase of the outburst requires the construction of non-LTE, blanketed, expanding, model atmospheres such as those described by Hauschildt et al. (1992). These models are characterized by a slow decrease of the density with increasing radius leading to a large geometrical extension and a large temperature difference between the inner and outer parts of the line-forming region. Thus, in the absence of such a model, any conclusions regarding the physical properties of the envelope based on simple nebular considerations and estimates of the temperature and density are suspect.

An upper limit to the mass in the ejecta can also be derived from the optical spectrum obtained 1017 days after the outburst. First, an estimate of the mean electron density in the shell is required. An electron temperature of 10^4 K was assumed for the warm, dense phase of the gas which is typical of most nova ejecta this late in the outburst. The electron density was then calculated based on the extinction-corrected intensity ratio of [O III] $\lambda\lambda$4959, 5007 to [O III] λ4363 (Osterbrock 1989). The electron density was found to be $\simeq 10^5$ cm^{-3}. The mass of the ejected shell is given by

$$M \simeq \frac{\mu m_p L(H\beta)}{N_{neb}\, \gamma(H\beta)} , \qquad (3)$$

where μ is the mean molecular weight and is equal to 0.5 for a fully ionized hydrogen gas, m_p is the mass of the proton, $L(H\beta)$ is the luminosity in Hβ, N_{neb} is the density of the nebular gas, and $\gamma(H\beta)$ is the emissivity of Hβ appropriate for an electron density of 10^5 cm^{-3} and a temperature of 10^4 K. On day 1017, $L(H\beta) = 8.4 \times 10^{34}$ ergs s^{-1}, $N_{neb} \simeq 10^5$ cm^{-3}, and $\gamma(H\beta) = 1.2 \times 10^{-25}$ ergs cm^3 s^{-1}. The mass of the nebular gas is $\simeq 5 \times 10^{-3}\ M_\odot$.

This estimate of the ejecta mass should be considered an upper limit because the analysis does not take into account the filling factor of the gas which could be extremely small. The infrared and visible light development suggests that the carbon dust shell was optically thin by day 1017. Furthermore, the high-dispersion spectra of the emission lines after day 1000 show considerable structure, suggesting that the ejecta are very clumpy. These findings are consistent with the conclusion that the filling factor for the shell of QV Vul was small by day 1017. They also provide further evidence that circumstellar dust formation in novae ejecta is associated with a clumpy medium (see Gehrz 1988, 1990).

3.5. *Dust Formation Parameters*

A strong transition in the visible light curve beginning around day 50 and a corresponding rise in the infrared brightness (see Fig. 4) leave no doubt that dust condensed in the ejecta of QV Vul. The depth of the transition and the recovery of the infrared luminosity to nearly the outburst level suggest that the shell was optically thick in the visible and effectively covered the central engine. QV Vul appears to be another case in which the central engine maintained a constant luminosity for at least 100 days after the outburst. We first observed the carbon dust shell on day 83, when its temperature was $\approx$780 K. Since the shells of other dust-forming novae have temperatures of 1000–1200 K during the growth to maximum optical depth (Gehz 1988), we presume that the carbon dust formation phase was well underway by day 83.

The temporal development of QV Vul (Fig. 4) is nearly identical in detail to the two classic cases of optically thick dust shell formation, NQ Vul (Ney & Hatfield 1978) and LW Ser (Gehrz et al. 1980b). The transition in the visible light curve (Fig. 4*a*) shows that the dust in QV Vul reached an optical depth at V of $\tau_V \approx 5.6$ along the line of sight to Earth, making it the thickest dust shell produced among these three novae. The recovery of the visible light curve to the initial decline rate indicates that dust condensation was complete by day 250 and that the dust shell became optically thin as it continued to expand. QV Vul's infrared development exhibited three distinctive characteristics in common with the other two novae:

1. Both the 3.6 μm light (Fig. 4*b*) and the infrared luminosity $L_{IR} = 1.35(\lambda F_\lambda)_{max}$ (Fig. 4*c*) decayed exponentially following infrared maximum; for QV Vul, the meanlife of this decay was 74 days.
2. The grains cooled rapidly at first, and then became isothermal for several hundred days before resuming their cooling (Fig. 4*d*).
3. The angular radius of the shell declined rapidly as the visible light curve recovered, indicating that the grain growth had stopped (Fig. 4*e*).

The exponential decay of the monochromatic flux and the total infrared luminosity described in (1) is intriguing, because it is similar to the behavior associated with the light decline rate of supernovae where the ejecta are powered by radioactivity (see Gehrz & Ney 1990). To our knowledge there is no evidence that radioactivity is associated with the long-term behavior of the central engine in novae. The detailed behavior of the grain temperature and blackbody angular radius described in (2) and (3) has been discussed by Gehrz et al. (1980a, b) and Gehz (1988, 1990). These behaviors are expected for a dust shell that first becomes optically thick as grains grow to large radii, and later becomes optically thin as the grains sputter or evaporate in a constant velocity outflow.

The time of the appearance of the optically thick carbon dust shell in QV Vul is consistent with its production in the fast rather than the slow ejecta. Gehrz et al. (1980a, b), Gehrz & Ney (1987), and Gehrz (1988, 1990) have suggested that the time t_d for the ejecta to reach the condensation radius R_c,

$$R_c = \sqrt{\frac{L_0}{16\pi\sigma T_c^4}}\,, \quad (4)$$

at which the ejecta cool to the condensation temperature T_c = 1000 K will be

$$t_d = \frac{137}{V_0}\sqrt{\frac{L_0}{L_\odot}}\ \text{days}\,, \quad (5)$$

where L_0 is the outburst luminosity in solar units, and V_0 is the outflow velocity in km s^{-1}. The carbon dust condensation temperature of 1000 K is characteristic of every recent nova in which the dust formation process was well documented by infrared observations (Ney & Hatfield 1978; Gehrz 1988, 1990). Infrared data on M stars suggest that it is reasonable to presume that the 1000 K condensation point refers to silicate grains as well as to carbon grains (see the discussion in Ney & Hatfield 1978). For $L = 8.6 \times 10^4\ L_\odot$ and $V_0 = 1320$ km s^{-1}, $t_d = 30$ days. We have argued above that the carbon dust shell had formed well before day 83. In other cases of dust formation in classical novae, the onset of condensation precedes the infrared maximum by 20–30 days (Gehrz 1988). The onset of transition at around day 50 shows that this was the case for QV Vul as well. We conclude that the initial carbon dust condensation episode occurred in the high-velocity ejecta. We discuss in § 4 the probability that dust also condensed in the slow-moving ejecta.

Our analysis of the visible spectra, as discussed above, shows that there appears to be $\approx 10^{-4}\ M_\odot$ of gas above the pseudophotosphere. This result is consistent with the conclusion that there was a sufficient amount of mass in the fast ejecta to satisfy the condensation criterion established by Gehrz & Ney (1987),

$$\rho_c = 1.2 \times 10^{-4}\left[\frac{M_{\rm gas}}{M_\odot}\right]\left[\frac{L_\odot}{L_0}\right]^{3/2} \geq 3 \times 10^{-16}\ \text{g cm}^{-3}\,, \quad (6)$$

where ρ_c is the density of the gas at the condensation radius, M_g is the ejected gas mass, and L_0 is the outburst luminosity. We conclude that $\rho_c = 5\text{–}8 \times 10^{-16}$ g cm^{-3} for the ejecta above the photoshere of QV Vul, which places this novae firmly within the parameter space defined by previous dusty novae.

3.6. *Gradients in the Expansion Velocity of the Ejecta*

Our measurements during the pseudophotospheric expansion and carbon dust condensation phases (see Table 4 and Fig. 4*e*) strongly support the conclusion that the ejecta associated with the optically thick carbon dust zone are expanding nearly 3 times faster than those associated with the pseudophotosphere observed between days 3 and 10. In all other novae where the formation of optically thick carbon dust shells has been completely documented, the velocities of the pseudophotosphere and the dust shell appear to have been the same, and these two zones appear to have been associated with the low-velocity ejecta. The inference is that the carbon dust in other novae formed in the principle ejecta (Gehrz 1988).

QV Vul represents the first case in which optically thick carbon dust condensation apparently occurred in the fast ejecta. Gehrz et al. (1984) suggested that the optically thick carbon dust Shell of V1370 Aql formed in rapidly expanding ejecta, but no measurements of the period following the outburst exist to compare the behavior of the principle ejecta in the pseudophotosphere with that of the dust zone. QV Vul and V1370 Aql are similar in that both belong to only a small handful of novae that have produced silicate or SiC dust. Whether the formation of these materials is associated primarily with the fast ejecta or the slow ejecta is a matter that requires further investigation.

4. COMPOSITION OF THE EJECTA

Our data show that four types of astrophysical grains condensed in the ejecta of QV Vul over a 2 year period following the eruption (see Figs. 1 and 2). These are amorphous carbon, silicon carbide, hydrocarbons, and oxygen-rich silicates. All of the dust phase energy distributions (Fig. 1) exhibit 2–8 μm continuum radiation from carbon dust. SiC emission at 11.3 μm was evident on day 102, and the 9.7 and 19.5 μm silicate emission features dominated the thermal infrared on day 561. A key distinction between the silicate and SiC is that the latter does not produce a 20 μm emission feature. There is also a clear difference in the wavelength of the emission peak within the 7–14 μm window. The 2.9–4.2 μm spectrum of QV Vul (Fig. 2) demonstrates that there was strong 3.28 μm and 3.3–3.4 μm emission from hydrocarbons on day 157. The feature is very similar to those seen in sources like NGC 7027, the Orion Bar and IRAS 21282+5050 (Allamandola 1984; Allamandola, Tielens, & Barker 1987; Gehrz 1991; Russell, Soifer, & Willner 1977, Woodward et al. 1989). Although all of these grain materials have been detected before in other novae, *QV Vul represents the first case in which all of them have been detected in a single nova event.* The case is fascinating because the SiC formation preceded the formation of silicates by over 100 days.

It is difficult to reconcile the formation of both carbon-rich and oxygen-rich ejecta within ejecta with a single chemical composition. Assuming that CO formation goes to completion, carbon and SiC should condense in ejecta where C > 0 and silicates condense in ejecta where O > C (see Gehrz 1991). There appear to be several explanations for the multiplicity of grain types in the ejecta of QV Vul. One is that CO did not go to completion, and that C- and O-rich clumps in the same ejecta condensed grains of different compositions at different times. Another is that the ejecta of this nova had large density, temperature, and/or abundance gradients.

Our observations imply that the chemical compositions of the fast and slow ejecta may have been different. The transition in the visible light curve (Fig. 4*e*) shows that carbon dust condensation was substantial in the fast ejecta by day 50. Scaling by the ratio of the expansion velocities of the fast and slow ejecta using equation (4), we conclude that dust in the slow ejecta would have reached a comparable condensation stage by day 150. The sudden appearance of strong 10 and 19.5 μm silicate emission features sometime between days 102 and 279 implies that silicate dust condensed from the slow ejecta. The presence of these features indicates that the silicate emission was optically thin in the infrared. There is no evidence that the silicate dust shell became optically thick at visible wavelengths. The visible light curve (Fig. 4*a*) showed no sudden inflection between days 102 and 279 that might be interpreted as the formation of optically thick dust along the line of sight in the slow ejecta, nor was there a corresponding increase in the infrared luminosity (Fig. 4*c*) that would be expected from additional dust covering a large solid angle. Apparently, conditions in the slow ejecta were not favorable for the formation of a second optically thick dust shell even though the mass in the slow ejecta of $M_g = 2.3 \times 10^{-5}$ $M_\odot$ gives a value for ρ_c (1–2 $\times 10^{-16}$ g cm^{-3}) at the 1000 K condensation point that is close to the criterion stated by equation (5) for the condensation of optically thick shells in novae. One possibility is that hardening of the radiation field for the central engine caused ionization that suppressed dust formation in the slow ejecta (see Gallagher 1977).

The 3.2–3.4 μm hydrocarbon features are believed to arise from hydrogenated amorphous carbon (HAC), polycyclic aromatic hydrocarbons (PAHS), or quenched carbonaceous composites (QCCs) that may exist either as grains or as mantles on more refractory grains (see Allamandola et al. 1989). In either case, processing by UV radiation may be important in producing and exciting these materials. The hard radiation known to be emitted by the central engine during the relaxation period following the thermonuclear runaway (Gallagher & Starrfield 1978) could provide these photons in the case of the classical nova.

5. A MULTIPLE SHELL EJECTION MODEL

We favor the interpretation that the carbon-based and silicate based-components condensed in two separate shells with distinctly different chemical compositions, with carbon condensing in the fast ejecta and silicates condensing later in the slow ejecta. Models that predict the ejection of multiple shells in nova eruptions have been proposed previously based on optical observations (see Gallagher & Starrfield 1978; Fiedler & Jones 1980; Solf 1983). Slit-spectroscopic observations of the elongated shell of HR Del are consistent with a model in which the thermonuclear runaway resulted in the ejection of fast-moving polar plumes and a slow-moving equatorial ring (Solf 1983). In this model the Plumes move at roughly 3 times the velocity of the equatorial ring, and the plumes are expected to be rich in products of the CNO runaway, whereas the chemical composition of the equatorial ring should be predominantly hydrogen-rich nonprocessed material. Observations of the shell of DQ Her (see Williams et al. 1978; Martin 1989) are consistent with a similar interpretation.

Our picture of the dust formation process in QV is remarkably consistent with the model proposed by Solf (1983). The carbon dust would be expected to form first in the fast-moving, CNO-rich polar plumes. Silicate dust would form later in the slow-moving, relatively underprocessed equatorial shell. The dust formation times we observed, as well as the expansion velocities we derived from our optical spectra, are consistent with the proposition that the fast ejecta were moving at nearly 3 times the velocity of the slow ejecta.

Our data provide some constraints on the geometry of the ejecta. For example, the polar plumes must have developed in such a way that the dust covered a very large solid angle, since the carbon dust eventually reradiated nearly the outburst luminosity. At the same time, these ejecta must have gone optically thin in the gas phase very rapidly to uncover the underlying pseudophotosphere by day 3. The equatorial ejecta must have covered a large solid angle early in the outburst to have produced the pseudophotospheric emission observed from days 3–10.

6. ABUNDANCES OF THE CONDENSABLE ATOMS

Numerical estimates of the dust mass for the carbon and silicate dust are useful for determining the abundances of metals in the nova ejecta. Assuming that the carbon dust shell that was optically thick at visible wavelengths formed in the fast ejecta, the shell size can be estimated at any time during the dust emission phase from $R = V_0 t$, where t is the time elapsed since outburst and $V_0 \approx 1320$ km s^{-1} is the outflow velocity. The dust mass M_d in a thin shell of radius R is given by

$$M_d = 4\pi R^2 \frac{\tau_\lambda}{\kappa_\lambda}, \qquad (7)$$

where τ_λ is the extinction optical depth to the center of the shell at the wavelength λ, κ_λ is the opacity of the dust at wavelength λ, and R is the shell radius at the time of the measurement. The dust opacity can be calculated from the relationship

$$\kappa_\lambda = \frac{Q_{\rm ext}(\lambda)\pi a^2}{(4\pi/3)\rho_{\rm gr} a^3} = \frac{3}{4} \frac{Q_{\rm ext}(\lambda)}{a \rho_{\rm gr}} \qquad (8)$$

where $Q_{\rm ext}(\lambda)$ is the extinction coefficient at the wavelength λ, a is the grain radius, and $\rho_{\rm gr}$ is the density of a grain.

The carbon dust shell reached a maximum extinction optical depth of $\tau_v \approx 5.6$ at $\lambda = 0.55$ μm (V) on day 83, when the shell radius for the fast ejecta was 9.5×10^{14} cm. We assume that the dust at this time was primarily carbon with perhaps a trace of SiC. Assuming that the grains have a radius $a \approx 0.1$ μm as in other dust-forming novae (Gehrz 1988), they will have $Q_{\rm ext}(\lambda) = 3.3$ at $\lambda = 0.55$ μm (Draine 1985) and $\rho_{\rm gr} = 2.25$ g cm^{-3}. The dust opacity at $\lambda = 0.55$ μm from equation (8) is 1.1×10^5 cm^2 g^{-1}, and the carbon dust mass follows from equation (7) to be $\approx 6 \times 10^{26}$ g, or 3×10^{-7} $M_\odot$. Assuming $\approx 10^{-4}$ $M_\odot$ is in the fast ejecta and that all the carbon is in grains, the gas-to-dust ratio for carbon is $\approx 330/1$ which is consistent with solar abundance for carbon. The abundance of the silicates can be estimated assuming that the central engine has maintained a constant luminosity through day 561. In this case, the shell optical depth on day 561 at 10 μm where the silicate opacity is 4350 cm^2 g^{-1} (Gilman 1974) is about 10^{-2}. The shell radius of 6.4×10^{15} cm on this date leads to a silicate mass of 6×10^{26} g, or 3×10^{-7} $M_\odot$, and a gas-to-dust ratio of $\approx 330/1$, again consistent with solar abundance of the condensables. We conclude that substantial enhancements of the condensable elements that form carbon and silicate dust are not necessarily required for copious dust production in novae.

7. CONCLUSIONS

Our 1.25–19.5 μm photometric and optical/infrared spectroscopic measurements of Nova QV Vul (1987) during a period of nearly 2 years following the outburst lead to several conclusions:

1. The nova exhibited three classic phases during the expansion of the ejecta: pseudophotospheric expansion, free-free emission, the optically thick carbon dust formation. The carbon dust shell apparently formed in "fast" ejecta that were expelled at 3 times the velocity of those characterizing the

development of the pseudophotosphere. Silicates formed later in the slow-moving ejecta. Our observations enabled us to derive a number of physical parameters describing the outburst (see Tables 3 and 4).

2. The infrared temporal development of the carbon dust shell was essentially identical to the carbon dust shell formation development scenarios followed by two other novae that condensed optically thick shells, NQ Vul and LW Ser.

3. Four types of astrophysical grains apparently condensed in the ejecta during the 2 year period following the eruption. These are amorphous carbon, silicon carbide, hydrocarbons, and oxygen-rich silicates. Such behavior has never been previously observed in a nova, nor in any other star.

4. QV Vul was unusual in that the expansion velocities of the gas pseudophotosphere and the optically thick carbon grain shell were distinctly different. The latter were moving at nearly 3 times the velocity of the principle ejecta. These two velocities have usually been the same in other novae that condense optically thick carbon dust shells. The amount of mass above the pseudophotosphere of QV Vul was sufficiently large to be consistent with the condensation of an optically thick shell of carbon dust in the fast ejecta.

5. The dust formation scenario suggests that QV Vul ejected two shells with distinctly different chemical compositions. A plausible model is one in which carbon species condense first in fast-moving, CNO-rich polar plumes, and silicate dust condenses later in slow-moving, underprocessed equatorial ejecta. Condensation in the fast ejecta was more efficient than in the slow ejecta. Numerical estimates of the dust mass for carbon and silicate dust show that the condensable elements were present in approximately solar abundance.

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