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INFRARED OBSERVATIONS OF DUST FORMATION AND CORONAL EMISSION IN NOVA AQUILAE 1995

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ABSTRACT

We report 1.25–18.5 μm infrared spectrophotometric measurements of Nova Aquilae 1995. Photometric measurements were obtained over a four month period following the formation of an optically thin dust shell. Hydrogen and helium emission lines were evident throughout this period, along with strong near-infrared coronal line emission that appeared approximately 120 days after outburst. Both the photometric and the spectroscopic data suggest that the ejecta were clumpy, and that they contained both a dust component and a hot gas component. The outflow velocity of the ionized ejecta was observed to be $\sim$1365–1600 km s^{-1} (FWHM), and no appreciable deceleration of the ejecta was observed over the duration of these observations. Based on a M_V-t_2 light decline relationship, we calculate a distance of $\sim$3.6–4.8 kpc.

Subject headings: dust, extinction — infrared: stars — novae, cataclysmic variables — stars: individual (Nova Aquilae 1995)

1. INTRODUCTION

Originally, infrared (IR) observations of novae demonstrated that there were two distinct types of postejection shell evolution dependent on nova speed class (Warner 1990; Gehrz 1990). Slow novae, typified by DQ Herculis, exhibit a deep visual transition phase and form optically thick (at $V = 0.55$ μm) circumstellar dust shells. Fast novae, such as V1500 Cygni and V1974 Cygni, produce very little if any dust, do not display a visual transition, and have been observed to produce strong coronal line emission (Grasdalen & Joyce 1976; Woodward et al. 1995). The 1978 discovery of V1668 Cygni revealed evidence that a nova may have characteristics that lie between those of the slow and fast novae. V1668 Cygni was shown to be an intermediate speed nova that formed a relatively small amount of dust in an optically thin shell and exhibited no transition in the visible light curve (Gehrz et al. 1980).

On 1995 February 7.84 UT, K. Takamizawa discovered Nova Aquilae 1995 (Nakano 1995). A subsequent study of Nova Aquilae 1995 suggests that it may be similar to V1668 Cygni in its postoutburst evolution. The novae are quite comparable in visible evolution, outflow velocity, and dust shell formation. Our IR photometric observations revealed the existence of a dust shell that we conclude to be optically thin. However, unlike V1668 Cygni, Nova Aquilae 1995 displayed several strong coronal emission lines that were first observed approximately 120 days past outburst. Nova Aquilae 1995 is the first thoroughly documented case of overlap between dusty novae and novae that produce strong coronal lines. This suggests that there is a continuum in the evolutionary behavior of novae.

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2. OBSERVATIONS

We obtained 1.25–18.5 μm IR photometric and spectroscopic observations of Nova Aquilae 1995 on several occasions between 1995 February 16.6 UT ($\sim$day 23) and 1995 June 20.3 UT ($\sim$day 146). The photometry we report on was obtained from 1995 March 23.6 UT ($\sim$day 58) to 1995 June 20.3 UT. Observations were acquired at both the 1.52 m University of Minnesota (UM)/University of California at San Diego (UCSD) Mount Lemmon Observing Facility (MLOF; 10″ beam, 27″ throw) and the 2.34 m University of Wyoming (UW) Wyoming Infrared Observatory (WIRO; 10″ beam, 37″ throw) using UM bolometer and InSb radiometers. The filter bandpasses, calibrations, and operational characteristics of the UM bolometer are described by Hanner et al. (1990) and Gehrz & Ney (1992). Bergstrom (1991) and Bergstrom, Gehrz, & Jones (1992) have described the characteristics and calibrations of the broadband filters of the UM InSb. Zero magnitude flux densities for the calibration stars were derived using the WIRO photometric system (Gehrz, Hackwell, & Jones 1974; Gehrz, Grasden, & Hackwell 1992). Table 1 summarizes the broadband IR photometry of Nova Aquilae 1995 obtained with these instruments.

The K-band spectrum presented in Figure 1 was obtained on 1995 June 15.3 UT ($\sim$day 141) on the Kitt Peak National Observatory (KPNO) 2.1 m telescope using the CRyogenic imaging SPectrometer (CRSP) with a 256×256 InSb focal plane array (Joyce, Fowler, & Heim 1994) and a 1″.7 slit. Multiple spectra using a single grating setting and spectral resolution ($R = \Delta\lambda/\lambda = 2.56 \times 10^{-3}$ μm pixel^{-1}) were obtained by stepping the source along the slit at 20″ intervals. Photometric standards were observed in a similar manner. The two-dimensional spectral images of both the nova and the photometric calibration stars were processed using standard IR techniques (cf. Joyce 1992).

TABLE 1

IR Photometric Magnitudes of Nova Aql 1995

1995 UT Date (μm)	March 23.6	April 14.7	May 9.4	June 15.5	June 17.5	June 20.3
1.2 (*J*)	8.00 ± 0.13	...	≥8.87	≥9.06	...	10.71 ± 0.02
1.6 (*H*)	7.21 ± 0.03	...	8.73 ± 0.24	≥9.31	≥9.90	10.54 ± 0.02
2.2 (*K*)	5.17 ± 0.02	...	8.11 ± 0.19	≥8.99	≥9.54	9.66 ± 0.01
3.6 (*L*)	2.79 ± 0.04	4.54 ± 0.02	5.81 ± 0.04	7.53 ± 0.14	7.56 ± 0.11	...
3.8 (*L′*)	...	...	...	...	...	7.42 ± 0.04
4.9 (*M*)	1.76 ± 0.05	3.58 ± 0.03	4.60 ± 0.06	≥5.97	5.92 ± 0.21	...
10 (*N*)	0.75 ± 0.20	...	3.18 ± 0.08	≥3.44	≥3.99	...
7.8	0.84 ± 0.06	2.72 ± 0.17	3.39 ± 0.13	...	≥4.03	...
8.7	1.37 ± 0.09	2.55 ± 0.15	3.03 ± 0.09	≥3.67	≥4.54	...
9.8	0.90 ± 0.19	2.21 ± 0.22	2.92 ± 0.14	3.72 ± 0.26	≥3.34	...
10.3	1.58 ± 0.15	2.33 ± 0.17	3.10 ± 0.16	≥3.29	≥3.86	...
11.6	...	≥2.08	2.63 ± 0.16	2.83 ± 0.19	3.30 ± 0.25	...
12.5	...	0.62 ± 0.27	2.04 ± 0.25	≥2.74	≥3.05	...
18.5	...	...	...	...	≥1.08	...

Background images used for the first-order removal of the night-sky emission from individual source images were generated by median-filtering all images in a given observational set. Individual one-dimensional spectra were subsequently extracted from each image using the IRAF APEXTRACT package. Final spectra were generated by averaging the extracted spectra and scaling each spectrum to the median of the total co-added data set.

Flux calibration of the spectrum was performed by using the spectrum of the photometric standard star HD 161903 ($m_K = -7.020$; Elias et al. 1982), which was normalized using a blackbody source function appropriate to its spectral type (A2). The blackbody was normalized to the 2.2 μm flux density derived from a Kurucz (1979) model atmo-

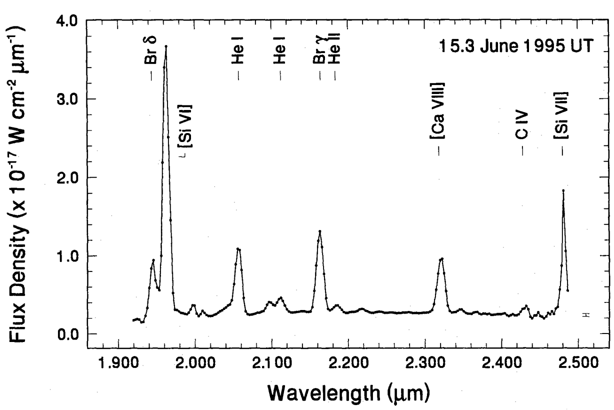

Fig. 1.—The moderate spectral resolution 1.91–2.49 μm spectrum (*K* band) of Nova Aquilae 1995 obtained on 1995 June 15.3 UT. Hydrogen and helium recombination lines are prominent, as well as coronal line emission from silicon and calcium. A representative 1-σ error bar is given in the lower right of the panel, and a cubic spline had been drawn through the data points as a visual aid.

TABLE 2

Summary of Derived Physical Parameters

Parameter	Relationship	Nova Aql 1995
Day 0..........	Discovery date	JD 2,449,742.5 ± 4.0
t_2	Visible light curve	11 days
V_0	Spectra	1365–1600 km s^{-1}
$(m_V)_{max}$	...	5.9–6.5
A_V	$E(B-V)$[a]	≥1.7
M_V	Eq. (1)	−8.6
D	...	3.6–4.8 kpc
$L_{outburst}$	...	(0.6–1.7) × 10^{32} W
L_{IR}(max)	...	(3.0–6.1) × 10^{30} W
τ_V	L_{IR}(max)/$L_{outburst}$	0.04–0.06
M_{dust}	Eq. (4)	(1.7–8.0) × 10^{-7} $M_\odot$
M_{gas}	Eq. (5)	(2.1–3.2) × 10^{-4} $M_\odot$
M_{dust}/M_{gas}	...	(8.3–24.8) × 10^{-4} $M_\odot$

[a] Greeley et al. 1995.

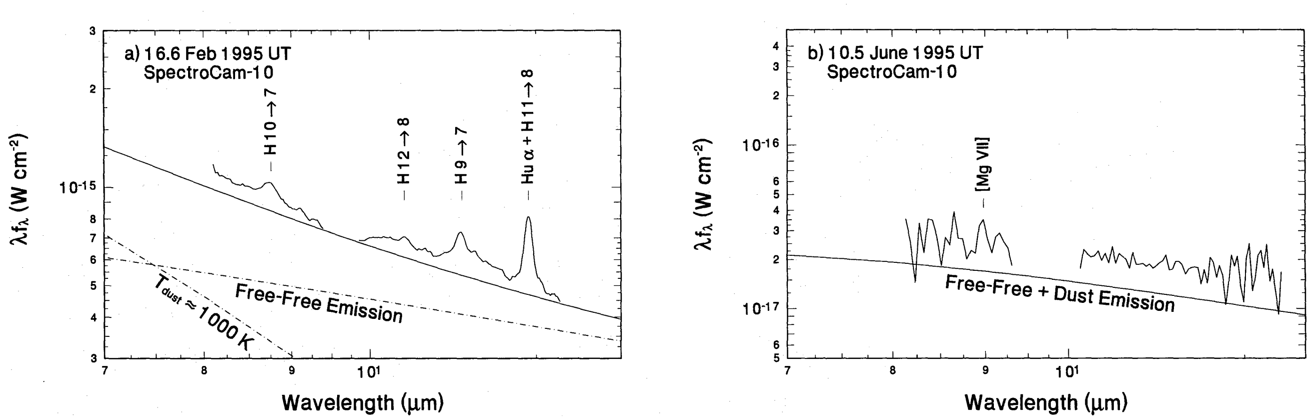

Fig. 2.—Low-resolution 8–13 μm SC-10 spectra obtained on 1995 February 16.6 and June 10.5 UT. (*a*) The February spectrum reveals several hydrogen recombination lines and is fitted to a SED composed of free-free and $T_{dust} \sim 750$ K dust emission. The free-free emission fit is used to estimate the ejected gas mass in § 3.4. (*b*) The June spectrum shows the existence of [Mg vii] at 8.99 μm and is fitted to a free-free and dust emission SED.

sphere. Residual absorption from hydrogen recombination lines in the stellar spectrum were removed by a linear interpolation of the continuum adjacent to the feature prior to division of the object spectrum. Precise wavelength calibration was determined using the strong, unresolved emission lines present in the spectrum of the planetary nebula NGC 7027 observed with the same grating parameters. No atmospheric extinction corrections were applied to the data, since Nova Aquilae 1995 and the comparison photometric standard were observed at similar air masses. The K-band spectrum (Fig. 1) exhibits hydrogen and helium recombination lines, several coronal emission lines from metals, and an underlying thermal dust continuum.

Additional 8–13 μm spectra of Nova Aquilae 1995 were obtained with the Cornell University SpectroCam-10 (SC-10) infrared spectrometer (Hayward et al. 1993) on the 200 inch (5.1 m) Hale telescope.[8] Low-resolution ($R \sim 100$) mid-IR spectra of the nova were obtained at two different epochs, 1995 February 16.6 and June 10.5 UT ($\sim$day 137), while a single high-resolution 12.3–12.9 μm spectrum ($R \sim 2000$) was obtained on 1995 February 16.6 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 band and several telluric water lines. The February observations were calibrated using α Boo for the low-resolution spectrum and α CMa for the high-resolution spectrum. For the June observations, α Lyr was observed as a standard. The ratio of α Boo to α Lyr was obtained by interpolating broadband photometry derived from images; α CMa was assumed to be $m_V = -1.35$ at all wavelengths. In all cases, the zero-magnitude flux was taken to be a 9600 K blackbody (Hanner et al. 1993) normalized to the absolute fluxes for α Lyr given by Cohen et al. (1992). The low-resolution spectra from 1995 February 16.6 UT and June 10.5 UT are shown in Figures 2*a* and 2*b*, respectively.

A summary of the ejecta outflow velocity and other physical parameters derived from our observations is presented in Table 2.

3. RESULTS

3.1. *Ejecta*

The approximate outburst time (day 0) must be known in order to determine the mass of the ejecta and to evaluate the temporal evolution of other physical parameters that characterize the development of the ejecta. For several days after outburst, a nova radiates like a hot blackbody due to an optically thick pseudophotosphere. The blackbody angular radius of the expanding pseudophotosphere can be used to extrapolate to day 0 (cf. Gehrz 1988). Because the ejecta of Nova Aquilae 1995 were optically thin at the time of our observations, this technique cannot be used. Instead, we will assume that the postmaximum optical evolution of Nova Aquilae 1995 is similar to that of V1668 Cygni (Kato 1994). Utilizing the visible light-curve decline of V1668 Cygni as a template (Fig. 3), we infer a day 0 of JD 2,449,742.5$\pm$4.0 (1995 January 21–29 UT) for Nova Aquilae 1995. The uncertainty in day 0 is due to the spread in the visible data (Fig. 3). Our estimate of day 0 is consistent with optical

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

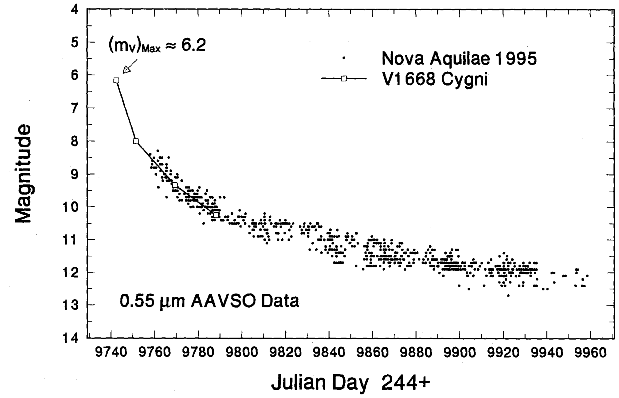

FIG. 3.—Visible light curve of Nova Aquilae 1995 (AAVSO data; Mattei 1995) fitted to the visible light curve of V1668 Cygni (Kato 1994). The extrapolation of the light curve leads to a day 0 of JD 2,449,742.5 $\pm$ 4.0 and a maximum apparent magnitude of $(m_V)_{max} \sim 6.2$.

spectra obtained on 1995 February 10.2 UT that exhibit prominent H I and Fe II emission lines without P Cygni profiles (Iijima, Esenoglu, & Rosino 1995). The lack of P Cygni profiles suggests that the nova was already 2–4 weeks past outburst (Martin 1989; Williams 1995).

Our observations of Nova Aquilae 1995 suggest an elementary model for the ejecta, with two distinct components contributing to the IR spectral energy distribution (SED). These are an optically thin dust shell and a hot ionized gas region. Figures 4*a*–4*d* show the SEDs derived from IR broadband photometry. The resulting SEDs are combinations of emission from both regions. Free-free emission arises from the hot ionized gas. The emission from the dust shell is attributed to carbon grains. Most novae have been observed to form carbon dust (Gehrz et al. 1995) that results in a smooth Planckian-type IR SED, as shown in Figures 4*a*–4*d*. The dust emission conforms to the Planck function multiplied by the dust emissivity. The dust emissivity is calculated using the absorption efficiencies of Draine (1985) for 0.5 μm graphite grains (Draine & Lee 1984). Dust grains of this size are on the order of those observed in other novae (Gehrz 1988) and result in the best fit to the broadband photometry. The SC-10 data (Fig. 2*a*) suggest that dust may have formed as early as 1995 February 16.6 UT. These data are fitted to $T_{\rm dust} \sim 1000$ K. The dust temperature is difficult to constrain at this epoch due to the narrow spectral range of the data, but it is consistent with the 1000–1200 K dust grain condensation temperature range observed in other novae (Gehrz 1988, 1990). The dust shell temperature decreased steadily through our last measurement on 1995 June 20.3 UT, where $T_{\rm dust} \sim 375$ K.

Analysis of the SEDs suggests that the dust shell of Nova Aquilae 1995 is optically thin at visible wavelengths. From Figure 3, we infer a visible outburst luminosity, $L_{\rm outburst} = (0.6\text{–}1.7) \times 10^{32}$ W, while the maximum observed IR luminosity derived from fitting the 1995 March 23.6 UT data with a $\sim$750 K dust continuum is $L_{\rm IR}({\rm max}) = (3.0\text{–}6.1) \times 10^{30}$ W (Fig. 4*a*). Thus, we derive a lower limit to the visible optical shell depth of $L_{\rm IR}({\rm max})/L_{\rm outburst} = \tau_V = 0.04\text{–}0.06$ (Fig. 5). Optically thick nova dust shells have $\tau_V \geq 0.50$ (Gehrz 1995). The spread in luminosities and optical depth is the result of uncertainties in the visible data and dust temperature. The decline of the visible light curve of Nova Aquilae 1995 also suggests that the dust shell is optically thin. Novae that form optically thick shells, such

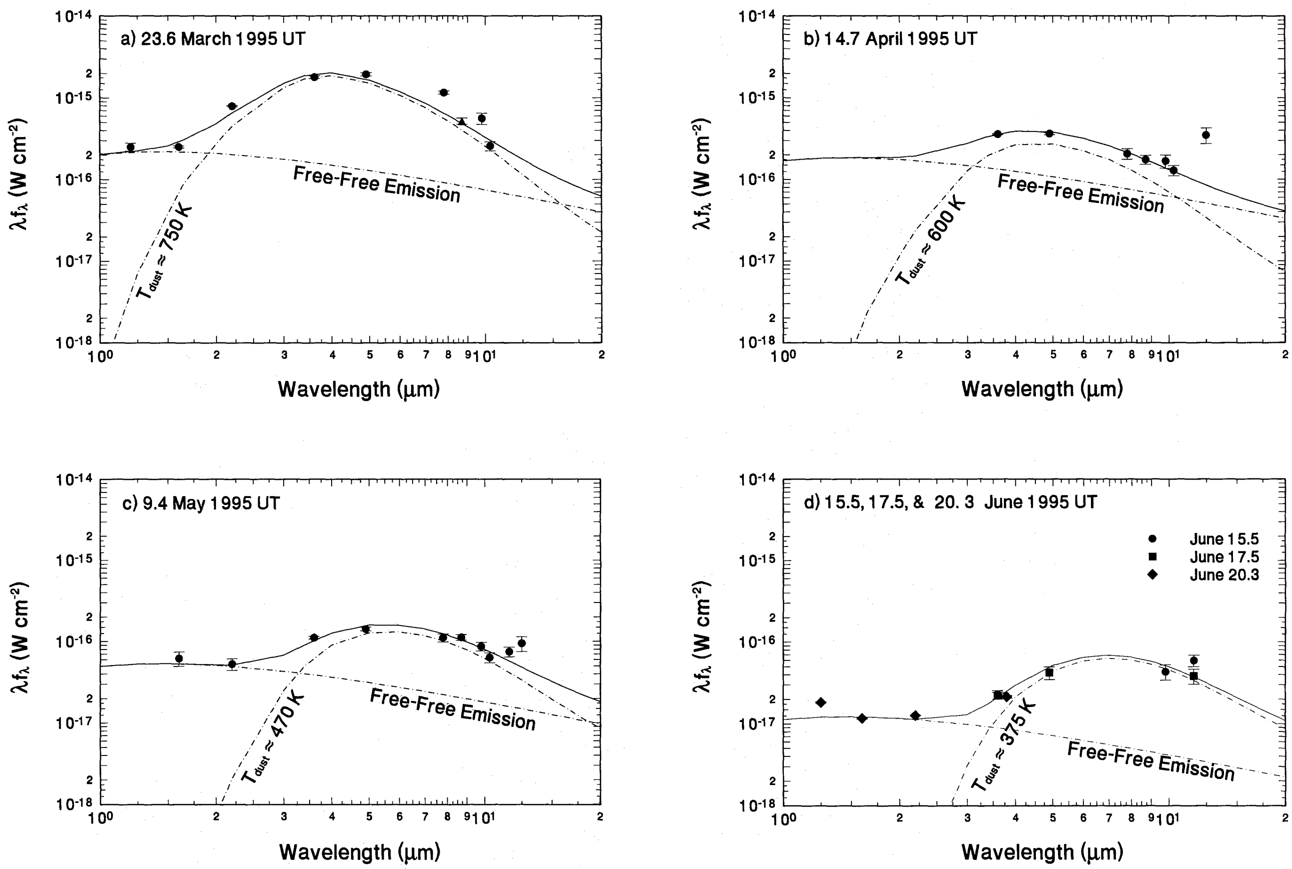

FIG. 4.—(*a–d*) IR temporal development of Nova Aquilae 1995 spanning from 1995 March 23.6 to June 20.3 UT. The smooth SED is attributed to carbon dust and free-free emission. [The elevated points at *J* (1.25 μm), *H* (1.6 μm), and *K* (2.2 μm) observed on 1995 May 9.4 and June 15.5 and 17.5 UT are due to hydrogen and helium recombination and coronal line emission.] For (*a*), the 8.7 μm point (*solid triangle*) has been corrected for a faulty calibration.

as DQ Herculis, show marked transitions (of 0.5–7 mag) in their visible light curves, with a corresponding rise in the IR light curves at the onset of dust condensation in the ejecta. During the first 220 days, no transition in the visible light curve of Nova Aquilae 1995 was evident.

In addition to thermal emission from the optically thin dust shell, observations show emission from a hot gas component. In addition to free-free emission, several emission lines are produced in this region. The 1995 February 16.6 UT SC-10 spectrum (Fig. 2*a*) exhibits several hydrogen and helium emission lines from a hot gas component superposed above the free-free and dust continua. Using SC-10 high-resolution spectra taken at the same epoch, an ejecta expansion velocity (FWHM) of $\sim$1600 km s^{-1} is derived from the Humphreys α (Hydrogen 7 $\rightarrow$ 6, 12.37 μm) emission line. The day 1995 June 10.5 UT SC-10 spectrum (Fig. 2*b*) shows a feature (2–3 σ detection) tentatively identified as [Mg VII] (Hayward et al. 1996). The 1995 June 15.3 UT CRSP *J*-, *H*-, and *K*-band spectra continued to show hydrogen and helium recombination lines as well as emission from oxygen, nitrogen, and carbon (Woodward et al. 1996). In addition, the *K*-band spectrum (Fig. 1) revealed several strong coronal lines of silicon and calcium. At this epoch (1995 June 15.3 UT), the expansion velocity (FWHM) was $\sim$1365 km s^{-1}, utilizing the Brackett γ (Hydrogen 7 $\rightarrow$ 4, 2.166 μm) emission line.

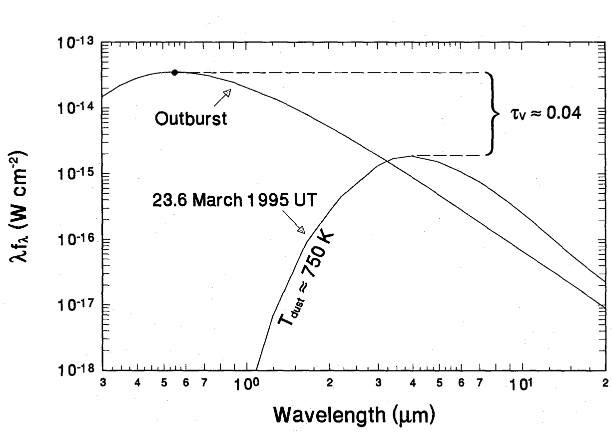

FIG. 5.—Visible outburst flux vs. the maximum observed IR flux. The outburst flux is extrapolated from the visible (0.55 μm) data point using an F star–type spectra, T_{BB} = 6700 K blackbody SED. The data result in an optical depth τ_V = 0.04–0.06, demonstrating the existence of an optically thin dust shell.

Within the uncertainties of our line width measurements, no appreciable deceleration of the ejected nova shell occurred as it expanded into the interstellar medium over the $\sim$120 day epoch covered by our spectra. This constant line width suggests that the bulk of the radiating gas had expanded at essentially constant velocity subsequent to being ejected from the white dwarf. The presence of a wide range of ionization states, including coronal line emission, observed in the near-IR spectra (cf. Fig. 1) suggests that the ejecta of Nova Aquilae 1995 were clumpy. The ejecta can be modeled to consist of dense, cool ($T_e \sim 10^4$ K) globules embedded in a hot ($T_e \sim 10^5$ K), tenuous confining medium

(Saizar & Ferland 1994). The coronal line–emitting region is believed to arise on the surfaces of cool globules that are photoionized by the nova remnant or by free-free radiation from the hot plasma. The photometric observations presented here and detailed analysis of the near-IR spectra of Nova Aquilae 1995 discussed in Woodward et al. (1996) support a two-phase model for the ejecta.

Photometry from 1995 June 20.3 UT shows the J-band energy flux elevated above the free-free continuum. The 1995 June 15.3 UT CRSP J-band spectrum shows several strong hydrogen, helium, and oxygen emission lines (Woodward et al. 1996). It is likely that the elevated bands are due to strong hydrogen, helium, and coronal emission.

3.2. *Distance*

A distance to Nova Aquilae 1995 can be calculated from a M_V-t_2 relationship (maximum magnitude rate of decline relationship), where t_2 is the time in days required for the nova to decrease 2 mag from visual maximum. Della Valle & Livio (1995) showed the relationship between M_V and t_2 to be

$$M_V = -7.92 - 0.81 \arctan \frac{1.32 - \log t_2}{0.23} , \qquad (1)$$

where the value of arctan is in radians.

Using the extrapolation of the visible light curve as described in § 3.1, we find $t_2 \sim 11$ days and $(m_V)_{\max} = 5.9$–6.5. From t_2, we calculate an absolute visual magnitude from equation (1) of $M_V = -8.6$. By applying 1.7 mag of visual extinction (Greeley, Blair, & Long 1995), we conclude a distance of $\sim$3.6–4.8 kpc to Nova Aquilae 1995.

3.3. *Dust Mass*

The IR luminosity of a shell composed of N spherical grains of radius a and temperature $T_{\rm dust}$ is given by

$$L_{\rm IR}(\max) = N 4\pi a^2 Q_e \sigma T_{\rm dust}^4 , \qquad (2)$$

where Q_e is the Plank mean emission cross section for a grain and σ is the Stefan-Boltzmann constant. The total dust grain mass in the shell is

$$M_{\rm dust} = N \frac{4\pi}{3} \rho a^3 , \qquad (3)$$

where ρ is the density of the condensed material. For a shell composed of carbon grains for which $a \leq 1\ \mu$m and $T_{\rm BB} \leq 1000$ K, $Q_e = 0.01 a T_{\rm dust}^2$ (Gilman 1974). Equations (2) and (3) may be combined, along with the above expression for Q_e, to yield the expression

$$M_{\rm dust} = 1.15 \times 10^6 \rho L_{\rm IR}(\max) T_{\rm dust}^{-6} , \qquad (4)$$

where $M_{\rm dust}$ is given in $M_\odot$, ρ in g cm^{-3}, $L_{\rm IR}(\max)$ in $L_\odot$, and $T_{\rm dust}$ in kelvins. The density of condensed carbon is 2.25 g cm^{-3}. There is evidence that the dust mass may have increased slightly from March to June. By 1995 June 20.3 UT, the maximum dust mass of $M_{\rm dust} = (1.7$–$8.0) \times 10^{-7}$ $M_\odot$ is calculated. From our data, we are unable to conclude the physical relation between the dust shell and the hot gas region.

3.4. *Gas Mass*

Free-free emission from Nova Aquilae 1995 can be used to calculate an upper limit to the mass of ejected gas. For a plasma of temperature T in kelvins,

$$\lambda f_\lambda = 2.11 \times 10^{-18} T^{-1/2} N_e^2 \lambda^{-1} R^3 d^{-2} \times \exp(-1.44 \times 10^4/\lambda T) , \qquad (5)$$

where λf_λ is given in W cm^{-2}, λ in microns, shell radius R in parsecs, distance d in kiloparsecs, and the electron density N_e in cm^{-3} (Allen 1973). Free-free emission may arise from both regions of the hot gas component of the ejecta. For the observed free-free emission to arise entirely from the hot tenuous gas ($T \sim 10^5$ K), the gas density would have to be $\sim 10^9$ cm^{-3}. This density is 4 orders of magnitude larger than is expected for this region, $N_e \sim 10^5$ cm^{-3} (Saizar & Ferland 1994). Therefore, we conclude that the free-free emission arises from the cooler gas in the dense globules. For $T = 10^4$ K, $N_e \sim (0.7$–$1.5) \times 10^9$ cm^{-3} on 1995 February 16.6 UT. By 1995 June 20.3 UT, the gas density decreased to $(5.0$–$7.2) \times 10^6$ cm^{-3}. Assuming the gas ejecta is composed entirely of hydrogen, and that its contents fill a sphere of radius R, $M_{\rm gas} = (2.1$–$3.2) \times 10^{-4}$ $M_\odot$. Since the gas measured by this technique is located in concentrated knots, the gas mass will be a fraction of that calculated above. The resulting dust mass–to–gas mass ratio is $M_{\rm dust}/M_{\rm gas} \geq (8.3$–$24.8) \times 10^{-4}$. From this ratio, we cannot conclude that it is necessary for the carbon abundance to be greater than solar to explain the formation of the observed dust shell.

4. SUMMARY

Our observations of Nova Aquilae 1995 lead to the following conclusions:

1. Nova Aquilae 1995 is very similar to V1668 Cygni in its postmaximum evolution. We exploited this similarity to estimate an outburst date of JD 2, 449, 742.5 $\pm$ 4.0. This day 0 estimate allows us to calculate several physical parameters for the nova (Table 2).
2. A visually optically thin dust shell [$\tau_V = L_{\rm IR}(\max)/L_0 \geq 0.04$–$0.06$] formed, as indicated by the absence of a measurable transition in the visible light curve.
3. In addition to the dust shell, there also exists an ionized gas component of the ejecta. This component is responsible for the hydrogen, helium, and coronal emission lines observed.
4. The ejecta can be fitted to an elementary model involving the two components mentioned above. Our spectra suggest that the ejecta are clumpy due to the presence of emission lines from both highly ionized and neutral species at the same temporal epoch in the ejecta. We cannot conclude that a greater than solar abundance of carbon is necessary for the formation of the observed dust shell.
5. The nature of Nova Aquilae 1995 implies that there is a continuum in the evolution of novae that ranges from dusty DQ Herculis–type novae to the strong coronal V1974 Cygni–type novae.

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