

NEAR-INFRARED SPECTROPHOTOMETRY AND THE CO EMISSION IN V2274 CYGNI (NOVA CYGNI 2001 No. 1)

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ABSTRACT

Infrared spectroscopy of V2274 Cygni (=Nova Cygni 2001 No. 1) is presented for two widely separated epochs, 17 and 370 days after discovery. In addition to the Paschen and Brackett series of H I, the early-time spectrum shows strong emission lines of C I and N I, fluorescently excited lines of O I, and emission from the first overtone of carbon monoxide. Because the initial data were probably acquired no more than 18 days after outburst, CO molecule formation occurred remarkably quickly in the dense, cool, carbon and oxygen rich ejecta. Rapid formation was also seen in NQ Vul, V842 Cen, and V705 Cas, three other novae in which first-overtone CO emission has been detected. Formation of the CO molecule may occur chemically in a process that requires H₂ as a precursor or directly through radiative association. The overtone emission of V2274 Cyg indicates a temperature of ~2500 K. The vibrational levels show no obvious departures from thermal equilibrium, which may indicate high optical depths in the fundamental. A large ¹³C/¹²C ratio (0.83 ± 0.3) is also indicated by the observations, consistent with the fast CNO burning expected in novae explosions. By the time of the second epoch observations, the emission lines of the neutral C, N, and O had disappeared. He I λ10830 was the dominant emission feature in the spectrum. In addition to the hydrogen lines, recombination features of He II were also strong. The common nebular lines of [S III] were seen but only two coronal line, [S VIII] λ9911 and [Si VI] λ19645, were detected. The CO emission had disappeared, but a strong thermal dust component was present. The interstellar reddening for the system was found to be $E(B-V) = 1.3$. This extinction, together with the absolute magnitude derived from the rate of decline of the light curve, suggest a distance of ~10.8 kpc. This places V2274 Cyg well out of the Galactic plane. The small number of novae with spectroscopic detections of carbon monoxide all have prominent C I lines, moderate speed classes and ejection velocities, exhibit marked dust formation events, and result from an explosion on a CO-type white dwarf. Based on these similarities, the spectrum of V2274 is proposed as a likely near-infrared spectral template for other novae that display carbon monoxide emission.

Subject headings: infrared: stars — novae, cataclysmic variables — stars: individual (V2274 Cygni) — techniques: spectroscopic

1. INTRODUCTION

At first glance, novae shells would appear to be ideal regions for molecules to form. The enrichment of the heavy elements C and O (e.g., Livio & Truran 1994; Jose & Hernanz 1998) in the ejected material, plus the high density of the ejecta provide the necessary conditions for the incubation of molecules. It is thus surprising that carbon monoxide has been detected previously in only a few novae. Ferland et al. (1979) made the initial discovery of CO in a nova with a measurement of the first overtone in the bright nova NQ Vul. They also associated the large mid-infrared flux detected by Ney & Hatfield (1978) in the same object with emission of the CO fundamental. Subsequently, first-

overtone CO emission was observed in V842 Cen (Nova Cen 1986) by Hyland & McGregor (1989) and Wichmann et al. (1990), and in V705 Cassiopeiae (Nova Cas 1993) by Evans et al. (1996). Lynch et al. (1997) tentatively identified a weak feature at 4.6 μm with the CO fundamental in the latter object.

The presence of CO in novae is of interest for reasons in addition to its novelty. (1) It can provide insight into the formation process for molecules. (2) Molecule formation is itself a precursor to the formation of dust. (3) The vibrational-rotational lines could be an important coolant for the dense, warm portions of the ejecta, particularly the fundamental at 4.6 μm. (4) The lines provide a probe of conditions (density and temperature) within the molecular regions. (5) And finally, the CO emission provides a means for assessing the isotopic abundances, particularly the ¹²C/¹³C ratio, but also ¹⁶O/¹⁷O. The last point is relevant, since it is in the form of such isotopes that novae make their most significant contribution to the interstellar medium (Pagel 1997, p. 149). Moreover, because the ¹²C/¹³C ratio of the synthesized material varies according to the composition of the white dwarf and the degree of mixing of the white dwarf surface and accreted material (Jose & Hernanz 1998), measuring its value can provide information about both.

In this paper we present near-infrared spectra of V2274 Cygni (Nova Cygni 2001 No. 1) from 17 and 370 days after discovery. V2274 Cyg was discovered by Y. Nakamura on

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July 13.65 UT (Sato et al. 2001). Outburst probably occurred within a day of discovery, and the nova was at or very near maximum light at the time of discovery (Sato et al. 2001). Iijima (2001) reported the presence of broad emission lines of H I and Fe II and a P Cygni profile on H α and suggested that the outburst had already reached maximum light, a fact that was supported by subsequent photometry (Waagen 2001). The visible light curve showed a steep decline around 40 days after maximum due to dust formation. At the time of our first observations, the nova had already formed large amounts of carbon monoxide. We analyze the CO emission and discuss the conditions that gave rise to the CO. In addition, we compare properties of V2274 Cyg such as its spectrum, rate of decline, expansion velocity, time for dust formation, and presence of C I lines to the same parameters in other novae that have manifested CO emission.

2. OBSERVATIONS

The initial infrared spectrophotometric data were acquired on the night of 2001 July 29 (UT) with the 1.5 m reflector of Palomar Observatory. The instrument used was the Cornell Massachusetts Slit Spectrograph (CorMASS), which is described in detail by Wilson et al. (2001b). CorMASS is a compact, low-resolution ($R \sim 300$), double-pass prism cross-dispersed near-infrared (NIR) spectrograph. It uses six separate spectral orders to cover the wavelength range between 0.75 and 2.5 μm . The detector is a 256×256 NICMOS3 device. A slit width corresponding to $2''$ was employed for the measurements of V2274 Cyg. The slit length was $15''$, and the source was switched between two positions along the slit to provide for background subtraction. The slit orientation was north-south.

The infrared spectrophotometric data from 2002 July 18 (UT) were acquired using the Shane 3 m reflector of Lick Observatory. For these data, the instrument employed was Aerospace Near-Infrared Imaging Spectrograph (NIRIS; Rudy, Puetter, & Mazuk 1999), a long-slit spectrograph that uses two channels to provide nearly continuous coverage between 0.8 and 2.5 μm . A beam splitter that switches from reflection to transmission at 1.38 μm separates the channels. The focal plane arrays, which employ HgCdTe as the detector material, are two-quadrant Hawaii devices that each provide 1024 channels in the spectral dimension and 300 in the spatial direction. The spatial resolution is 0.44 pixel $^{-1}$. The spectral resolution is constant over each channel and is determined by the width of the entrance slit. It was 16 \AA for the blue channel and 37 \AA for the red, with the $3''$ slit width employed for our observations of V2274 Cyg.

The processing of the observations to obtain absolute spectrophotometry involved the division of the raw spectra of V2274 Cyg by that of a comparison star. This process removes the instrumental response and reduces the effects of atmospheric absorption. For both the 2001 and 2002 observations the comparison star was HD 191854. HD 191854 is a solar analog with $V = 7.45$. To remove its intrinsic spectrum from this ratio, a solar model from Kurucz (1994) was used. The absolute flux level for each spectrum was determined from the K magnitude of HD 191854. The K magnitude (5.95) was calculated from the V magnitude and the $V-K$ color for a G3 dwarf from Koorneef (1983). The resulting 0.8–2.5 μm spectrum for the 2001 July data is shown in Figure 1. Identifications and measured line fluxes

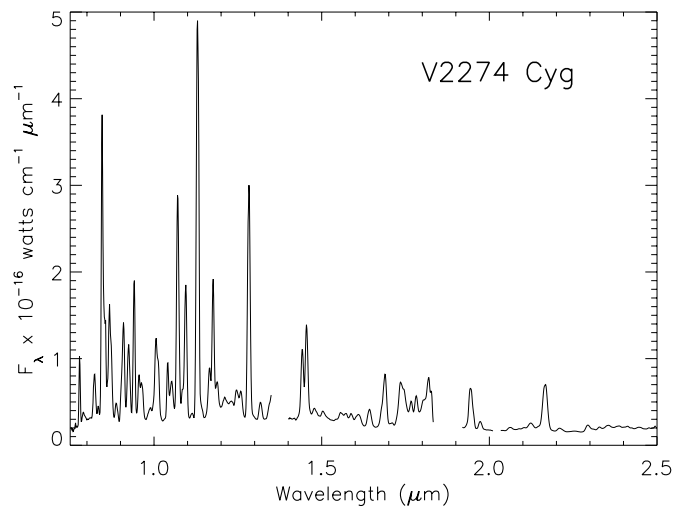


FIG. 1.—V2274 Cyg (Nova Cyg 2001 No. 1) 0.75–2.5 μm spectrum from 18 days after outburst. Identifications for the emission lines are provided in Figs. 2 and 3. The two strongest lines in the spectrum, O I $\lambda\lambda 8446$ and 11287 , are excited primarily by Ly β fluorescence. The noticeably greater strength of O I $\lambda 11287$ indicates that the nova is significantly reddened. These data were acquired prior to the formation of dust, so the reddening is interstellar in origin.

for the emission features in the 2001 spectrum are given in Table 1; values for the 2002 data are presented in Table 2.

3. RESULTS

3.1. Early Spectrum Atomic Lines

The near-infrared spectrum from approximately 18 days after outburst is very rich in low-excitation emission lines. It shows the usual recombination lines of H I (the Paschen and Brackett series), numerous permitted lines of C I and N I, and a few very strong, fluorescently or collisionally excited, lines of O I. Figures 2 and 3 present enlarged views of the spectrum with the emission lines labeled. The average FWHM (full width at half maximum) of the hydrogen lines, corrected for instrumental resolution, is 1600 km s^{-1} . The excitation is so low that helium is not significantly ionized—He I $\lambda 10830$ is probably present but is weak. It is frequently the strongest infrared line in the spectra of novae and will become so for V2274 Cyg (see § 3.3 below). Its apparent weakness in Figure 2 is consistent with the fact that no other He I lines are detected in the early-time spectrum.

The low excitation of the spectrum is manifest in the lines of neutral carbon and nitrogen. The higher abundances of carbon and nitrogen that typically occur in nova ejecta (Jose & Hernanz 1998), in conjunction with the low-excitation, high-density conditions that are prevalent shortly after outburst, lead to strong emission lines of C I and N I. These features are not uncommon in novae (e.g., Evans et al. 1990; Rossano et al. 1994; Lynch et al. 1995), but are rarely observed in other astronomical environments. The N I emission lines include transitions from both doublet and quartet levels, indicating that recombination is the principal mechanism for line formation. Similarly, singlet as well as triplet transitions are seen from carbon, underscoring the importance of recombination in forming the C I features.

In contrast, the strongest features of oxygen in the near-infrared are excited primarily by fluorescence, and in the

TABLE 1
LINE FLUXES FOR V2274 CYGNI (2001 JULY 29 UT)

Line	Laboratory Wavelength ^a (Å)	$F/F(\text{Pa}\beta)^b$
O I.....	7774	0.135 ± 0.02
N I, Na I?.....	8185–8200, 8183–8195	0.060 ± 0.02
N I.....	8216, 8223, 8242	0.066 ± 0.02
C I.....	8335	0.028 ± 0.007
O I.....	8446	0.744 ± 0.05
Ca II.....	8498	0.213 ± 0.04
Ca II.....	8542	0.193 ± 0.04
Ca II.....	8662, 8665	0.274 ± 0.04
N I.....	8680–8729	0.182 ± 0.04
Pa I.....	8863	0.030 ± 0.007
Pa 10.....	9015	0.102 ± 0.03
C I.....	9061–9111	0.288 ± 0.04
Pa 9, O I.....	9229, 9261–9266	0.258 ± 0.03
C I, N I.....	9406; 9387, 9393	0.429 ± 0.03
Paε.....	9545	0.139 ± 0.03
C I.....	9603–9658	0.118 ± 0.03
N I.....	9777–9872, 9883–9969	0.026 ± 0.007
Fe II.....	9998	0.034 ± 0.01
Paδ.....	10049	0.261 ± 0.05
C I, N I.....	10124, 10105–10165	0.183 ± 0.04
[N I].....	10400	0.201 ± 0.03
Fe II, N I.....	10501,	0.160 ± 0.04
C I.....	10683–10754	0.860 ± 0.06
He I, Fe II.....	10830, 10863	0.095 ± 0.02
Paγ.....	10938	0.503 ± 0.05
Fe II.....	11126	0.009 ± 0.003
O I.....	11287	1.15 ± 0.10
C I, N I.....	11330, 11266–11323	0.510 ± 0.10
Na I?.....	11381, 11404	0.032 ± 0.014
C I.....	11600–11674	0.160 ± 0.025
C I.....	11748–11823	0.456 ± 0.025
C I.....	11819–11896	0.106 ± 0.025
N I.....	12074, 12187, 12204	0.080 ± 0.02
N I.....	12289, 12299; 12289, 12329, 12382	0.056 ± 0.02
N I.....	12461, 12470	0.110 ± 0.03
C I.....	12549–12614	0.100 ± 0.03
Paβ.....	12818	1.000
O I.....	13165	0.071 ± 0.009
C I.....	14420–14472	0.288 ± 0.04
C I.....	14542	0.392 ± 0.04
C I.....	14738–14852	0.044 ± 0.005
Mg I?.....	15025–15048	0.029 ± 0.004
Br 17.....	15439	0.009 ± 0.004
Br 16.....	15556	0.053 ± 0.012
Br 15.....	15701	0.052 ± 0.012
Br 14.....	15881	0.054 ± 0.012
?.....	16030 ± 15	0.033 ± 0.013
Br 13.....	16109	0.048 ± 0.013
Br 12.....	16407	0.093 ± 0.010
Br 11.....	16807	0.072 ± 0.020
C I.....	16890	0.248 ± 0.025
Mg I?.....	17109	0.010 ± 0.003
Br 10.....	17362	0.273 ± 0.04
C I.....	17449	0.209 ± 0.04
? + C I.....	17662 ± 12, 17685–17857	0.192 ± 0.04
? + C I.....	17820 ± 12, 17685–17857	0.246 ± 0.04
O I?, C I.....	18021–18022, 17859–18140	0.235 ± 0.04
Br 9.....	18174	0.314 ± 0.04
O I?.....	18229–18230	0.243 ± 0.05
Brε.....	19446	0.259 ± 0.27
C I.....	19722	0.038 ± 0.006
?.....	20620 ± 8	0.023 ± 0.004
C I.....	21023	0.023 ± 0.004
?.....	21232 ± 9	0.063 ± 0.01

TABLE 1—Continued

Line	Laboratory Wavelength ^a (Å)	$F/F(\text{Pa}\beta)^b$
Brγ.....	21655	0.360 ± 0.03
Na I?.....	22056, 22084	0.024 ± 0.006
C I.....	22906	0.021 ± 0.006
CO ($\Delta\nu = 2$).....	22932–24800	0.423 ± 0.045

^a Wavelengths in air.^b $F(\text{Pa}\beta) = 2.55 \times 10^{-11}$ ergs cm⁻² s⁻¹.

case of one line, by collisions. Prominent in Figure 2 are four lines of neutral oxygen: $\lambda\lambda 7774$, 8446, 11287, and 13165. The quintet line $\lambda 7774$ has the 5S_o state as its lower level, which is the lowest lying of all the quintet levels. As such, the strength of this feature is augmented by cascades from the many higher quintet levels that are populated by recombinations. Moreover, because the lower level is metastable, it can support a substantial population, so collisional excitation can further enhance the strength of $\lambda 7774$.

The only other O I quintet lines that might be expected to contribute substantially are $\lambda 9263$ (actually a multiplet of nine separate lines from 9261 to 9266 Å) and, perhaps, $\lambda 11299$ (three lines at 11295, 11298, and 11302 Å). We cannot resolve O I $\lambda 9263$ from the broad, blended feature that centers around Pa9, but its strength, relative to $\lambda 7774$, can be estimated from the spectrum of V1419 Aql (Nova Aql 1993) presented by Lynch et al. (1995). In that object, O I $\lambda 9263$ could be as large as one-third of the strength of

TABLE 2
LINE FLUXES FOR V2274 CYGNI ON 2002 JULY 18 (UT)

Line	Laboratory Wavelength ^a (Å)	$F/F(\text{Pa}\beta)^b$
He II + ?.....	8237	0.130 ± 0.030
[S III].....	9069	0.079 ± 0.020
Pa 9.....	9229	0.136 ± 0.025
[S III], Pa 8.....	9532, 9545	0.373 ± 0.035
[S VIII].....	9911	0.130 ± 0.040
Paδ.....	10049	0.215 ± 0.040
He II 5–4.....	10124	0.298 ± 0.040
[N I].....	10400	0.413 ± 0.020
He I.....	10830	3.46 ± 0.080
Paγ.....	10938	0.353 ± 0.035
? ^c	11114	0.079 ± 0.020
He II.....	11636, 11675	0.171 ± 0.030
? ^c	11900	0.123 ± 0.020
Paβ.....	12818	1.000
He II 9–6.....	14760	0.100 ± 0.050
? ^c	15545	0.105 ± 0.020
Br 12.....	16407	0.102 ± 0.025
Br 11.....	16807	0.111 ± 0.035
He I.....	17002	0.069 ± 0.025
Br 10, [P VIII]?.....	17362, 17356	0.270 ± 0.025
Br 8.....	19446	0.25 ± 0.08 ^d
[Si VI].....	19645	0.19 ± 0.06 ^d
?.....	20020 ± 14	0.107 ± 0.020
He I.....	20581	0.147 ± 0.020
He I, ? ^c	21120, 21132; 20996	0.148 ± 0.035
Brγ.....	21655	0.361 ± 0.035

^a Wavelengths in air.^b $F(\text{Pa}\beta) = 2.72 \times 10^{-13}$ ergs cm⁻² s⁻¹.^c Unidentified line seen in other novae (see Rudy et al. 2002).^d Affected by telluric absorption.

$\lambda 7774$. If this limit were applicable to V2274 Cyg as well, O I $\lambda 9263$ could have ~ 0.05 the flux of Pa β . O I $\lambda 11299$, whose components have smaller transition probabilities than those of the components of $\lambda 9263$, is expected to be significantly smaller. An additional group of quintet transitions centered at $1.8021 \mu\text{m}$ is expected to be even weaker than O I $\lambda 11299$.

In contrast to the quintet transitions, the triplet lines $\lambda\lambda 8446, 11287, \text{ and } 13165$ are fluorescently excited from the 3P ground state. For the first two of these, the principal agent is Ly β , which excites the O I $^3D^o$ level directly from the ground state in the familiar Bowen process (Bowen 1947; Haisch et al. 1977). A de-excitation from this level produces $\lambda 11287$, and the subsequent cascade gives rise to $\lambda 8446$. Thus, $\lambda 8446$ and $\lambda 11287$ are produced in equal photon numbers by this mechanism. The triplet $\lambda 13165$ is also excited by fluorescence, but in its case the exciting flux is provided by the ultraviolet continuum (Grandi 1975, 1976). This same mechanism also enhances $\lambda 8446$ and, to a much lesser extent, $\lambda 11287$. It may also give rise to the feature at $1.8229 \mu\text{m}$.

By using the strength of $\lambda 13165$ to correct both $\lambda 8446$ and $\lambda 11287$ for the contribution from continuum fluorescence, the ratio of the latter two can be used to estimate the reddening (Rudy et al. 1991; Kastner & Bhatia 1995). An additional complication in the case of V2274 Cyg is that O I $\lambda 11287$ is blended with features of C I and N I. The C I line is the $^1P-^1D^o$ transition at $1.1330 \mu\text{m}$. Its strength is approximately 10 times that of $\lambda 19722$, with which it shares a common upper level. This indicates a flux that is approximately 0.38 that of Pa β . The contribution from N I is due to several transitions between 1.1266 and $1.1323 \mu\text{m}$. These descend from levels within the 4P term with energies ranging from 103622 to 103735 cm^{-1} . Their total flux can be estimated from the N I lines between 1.2130 and $1.2299 \mu\text{m}$ that also originate from the 4P term. The value is found to be ~ 0.13 that of Pa β , and these corrections have been incorporated into Table 1. Using the fluxes in Table 1 for the three O I lines yields $E(B-V) = 1.30 \pm 0.20$ for the reddening, assuming that the reddening law is as described by Draine (1990).

This knowledge of the reddening, together with the maximum visible magnitude and the rate of decline, can be used to estimate the distance. Both the maximum visible magnitude and the rate of decline can be derived from the light curve (Fig. 4). Their values are $m_V = 11.8$ and $t_2 = 33 \pm 4$ days. For this value of t_2 (the time, measured from maximum light, for the nova to decline by 2 mag in the V band), the relationship between the maximum magnitude and the rate of decline (MMRD) of Della Valle & Livio (1995) gives $M_V \sim -7.34$. With allowance for the reddening, this value yields a nominal distance of 10.8 kpc . Uncertainties in the reddening and in the value of t_2 result in distance estimates as small as 7.7 kpc and as large as 15 kpc , and that does not include the fact that the MMRD technique is only an approximate relation.

The early-time infrared spectrum also hosts a number of unidentified features. For these, the measured wavelengths and uncertainties for the line centers are presented in Table 1. Those that are relatively unblended include lines at 2.0620 and $2.1232 \mu\text{m}$, and a feature near $2.209 \mu\text{m}$ that is tentatively associated with Na I. The atomic line list of the University of Kentucky was searched for identifications for these features, with particular emphasis given to transitions of C I.

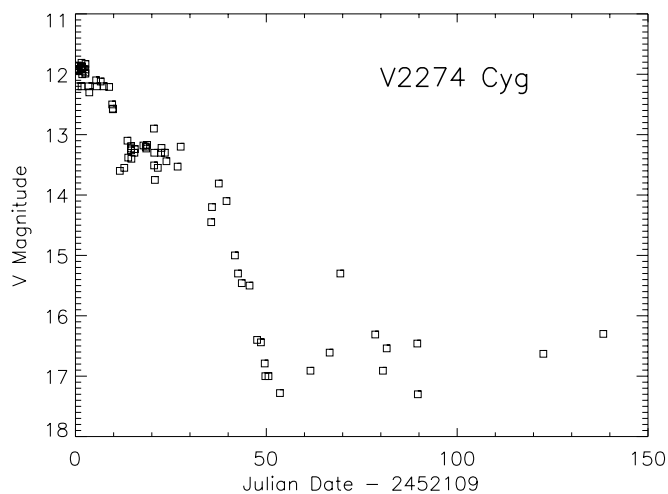


FIG. 4.—Visible light curve for V2274 Cyg. Data are all V-band CCD observations, and were provided by the AAVSO. Note the sharp drop in the visible brightness at around day 40 as a result of the onset of dust formation. This sort of massive dust formation is also characteristic of the small number of novae that have shown emission from CO.

There were no transitions of C I that matched with the feature at $2.0620 \mu\text{m}$. Candidate transitions from neutral Si, Al, V, and Fe were considered and rejected because of the absence of stronger transitions from the same species. Moreover, the transition is too far to the red to be associated with the He I singlet at $2.0581 \mu\text{m}$.

It is possible that the feature at $2.2084 \mu\text{m}$ is produced by a combination of two or more C I transitions among high energy levels. However, the strongest of these, the $^3D-^3D^o$ transitions at 2.2089 and $2.2091 \mu\text{m}$, are expected to be significantly weaker than the $2.1023 \mu\text{m}$ line, which is barely detectable. A more likely identification is with the Na I doublet ($\lambda\lambda 22056$ and 22084). Evans et al. (1996) identified these features in their higher resolution observations of V705 Cas (Nova Cas 1993). The $^2P^o$ upper term of these lines can be reached by two resonance transitions, so excitation by continuum fluorescence is possible. Additional Na I transitions at ~ 0.819 and $1.14 \mu\text{m}$ (see Table 1) may be present but are masked by stronger features. These lines have transition probabilities comparable to or stronger than the $2.2 \mu\text{m}$ lines and originate from levels of lower energy, but cannot be excited directly from the ground state.

For the feature at the nominal wavelength of $2.1232 \mu\text{m}$, we considered an identification with the $S(1)$ transition of molecular hydrogen. However, both the wavelength disparity with the observed feature and the absence of the $Q(1)$ and $Q(3)$ transitions at 2.4059 and $2.4231 \mu\text{m}$ argued against this association.

3.2. CO Emission

3.2.1. CO Characteristics

The first overtone of carbon monoxide, formed from the $\Delta\nu = 2$ vibrational transitions, is seen in Figure 3. The level of the emission is slightly greater than half that of the underlying continuum. As noted in the § 1, the observations were acquired 17 days after the nova was discovered and probably within 18 days of outburst (Sato et al. 2001). As such, it was very similar to the nova NQ Vul, in which CO was detected 19 days after outburst

(Ferland et al. 1979). The 2–0, 3–1, and 4–2 bandheads at 2.2929, 2.3220, and 2.3518 μm (air wavelengths), respectively, are all distinct in the spectrum. Higher bands at longer wavelengths are present but are not as well defined. This is due partially to the lower signal-to-noise ratio (S/N) of the data beyond 2.4 μm , where both the rising thermal background and increased telluric absorption affect the quality of the measurements.

To model the CO emission of V2274 Cyg, we first removed the underlying continuum and the contribution for the C I line at 2.2906 μm . The former, as gauged from Figure 3, was taken to be constant in F_λ at a level $1.5 \times 10^{-17} \text{ W cm}^{-2} \mu\text{m}^{-1}$. The strength of the C I line was estimated from that of a companion feature at 1.7749 μm that shares the same upper level. Using the measured strength for the latter and the known values for the Einstein A -values, and correcting for the different reddening experienced by the two lines, the flux for C I $\lambda 22906$ was found to be $9.4 \pm 2.0 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The line profile was assumed to be Gaussian in shape with a FWHM derived from the width of the C I $\lambda 14542$ singlet and the instrumental resolution at 2.29 μm . Its contribution to the CO overtone is shown in Figure 5.

After removal of the continuum and C I the carbon monoxide emission was modeled as follows. A theoretical spectrum was generated for optically thin emission from $^{12}\text{C}^{16}\text{O}$ in thermal equilibrium at a specified temperature using a band model. The spectrum was smoothed to $\sim 140 \text{ \AA}$ resolution to account for the expansion velocity of the emitting material and the spectral resolution of the CorMASS instrument. The intensity was scaled and redshifted 24 \AA , so that the first-overtone 3–1 (second) band-head height would match the measured spectrum at 2.327 μm . The 2–0 (first) band head was not used because of the uncertain contribution from C I $\lambda 22906$. Spectral features at longer wavelengths were also considered less reliable because of poorer S/N and contamination from $^{13}\text{C}^{16}\text{O}$. The model spectrum for $^{13}\text{C}^{16}\text{O}$ was generated,

shifted, and smoothed in an identical manner to that of $^{12}\text{C}^{16}\text{O}$. It was added to the $^{12}\text{C}^{16}\text{O}$ spectrum in the amount required to match the peak near 2.355 μm in the measured spectrum. (Note that possible contributions from $^{12}\text{C}^{17}\text{O}$ and $^{13}\text{C}^{17}\text{O}$ were not modeled; the data were not of sufficient quality to make a meaningful estimate. Moreover, nucleosynthesis models of novae explosions on CO-type white dwarfs generally indicate $^{16}\text{O}/^{17}\text{O} < 0.1$; Jose & Hernanz 1998). This entire procedure was then repeated for several different temperatures.

From the models at the different temperatures, the one that best matched the observations was chosen by inspection. The temperature associated with this model was 2500 K. Models at 2000 and 3500 K resulted in noticeably poorer fits, whereas a model at 3000 K was only slightly worse. Models were also considered that allowed the vibrational levels to fall out of thermal equilibrium while retaining thermal populations for the rotational levels. This is physically plausible, since pure rotational lifetimes are typically 10^4 – 10^5 longer than their vibrational-rotational counterparts (Chandra, Maheshwari, & Sharma 1996). Under such conditions, the widths of the band heads are sensitive to the rotational temperature, while their relative intensities are determined primarily by the populations of the vibrational levels. (See the models of Liu, Dalgarno, & Lepp [1992] for examples of how the shape of the first CO overtone emission varies with temperature, density, and outflow velocity.) However, such non-LTE models did not result in a measurably better fit to the observations, so we adopted the LTE model and used it to estimate physical parameters such as the mass incorporated into CO and the $^{13}\text{C}/^{12}\text{C}$ value.

The level populations may be entirely determined by collisions, but it is also possible that they are sustained by significant optical depths in the transitions of the fundamental. Although our data do not distinguish between the two cases, concurrent measurements of future novae in the shortwave and midwave infrared should do so. Because of the great strength of the fundamental under optically thin, LTE conditions (>25 times that of the first overtone at $T = 2500 \text{ K}$), those conditions should be readily identifiable.

Based on the assumptions of LTE level populations and that the first-overtone emission is optically thin, the mass of the emitting CO can be estimated. For the derived temperature of 2500 K, the value is $\sim 7 \times 10^{-11} D^2 M_\odot$, where D is the distance in kpc. For the value of 10.8 kpc predicted from the light curve, this indicates a mass of $\sim 8 \times 10^{-9} M_\odot$ for the CO. For a total ejected mass of $4 \times 10^{-5} M_\odot$ that is 25% carbon and oxygen by weight (Jose & Hernanz 1998), this would imply that only about 0.0008 of the available carbon and oxygen is incorporated into CO. A low-mass carbon-oxygen white dwarf might eject an order of magnitude more material than this (Gehrz et al. 1998). If this were the case for V2274 Cyg, it would imply that less than 0.01% of the carbon and oxygen is incorporated into CO.

Of the carbon that is present in carbon monoxide, a significant fraction is ^{13}C . The result from the fit to the observed spectrum is $^{13}\text{C}/^{12}\text{C} > 0.83 \pm 0.3$. The error is large, reflecting the approximate nature of the model, noise in the observations, and possible contamination by ^{17}O . Nevertheless, the result does indicate a significant overabundance of ^{13}C compared to the solar value of 0.011 (Smith & Suntzeff 1991). This is not surprising given that

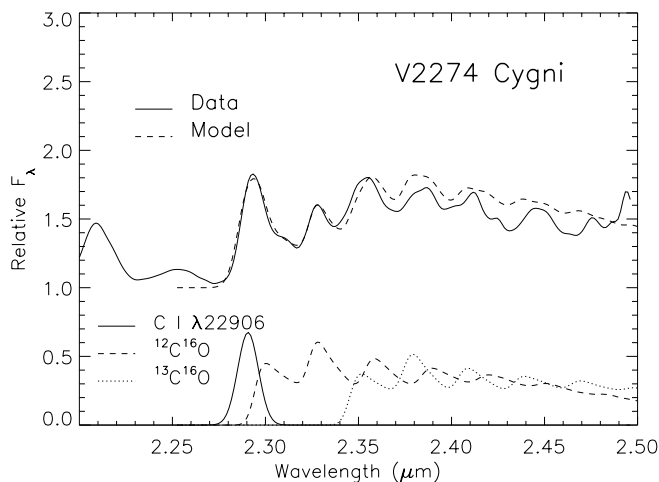


Fig. 5.—Fit to the CO emission of V2274 Cyg. The best-fit temperature of 2500 K was derived from a model that assumed thermal populations for both the rotational and vibrational levels. The decomposition shows contributions from a single atomic line, C I $\lambda 22906$, and both $^{12}\text{C}^{16}\text{O}$ and $^{13}\text{C}^{16}\text{O}$. The latter is substantial, accounting for $\sim 45\%$ of the emission. See the text for additional discussion.

fast CNO burning produces large amounts of ^{13}C . In fact, all the models of Jose & Hernanz (1998) that treat nucleosynthesis in novae explosions involving CO white dwarfs predict $^{13}\text{C} > ^{12}\text{C}$, although mixing with unburned material and material swept up from the atmosphere of the companion can reduce this value.

3.2.2. CO Formation

As noted in § 1, during the thermonuclear runaway, nucleosynthesis enhances the carbon and oxygen in the material that will be ejected. The presence of strong C, N, and O lines indicating this enrichment in V2274 Cyg was reported in a preliminary summary of these data by Wilson et al. (2001a), and is manifest in the strength of the many C I lines (see Figs. 2 and 3). Thus, the ingredients to make carbon monoxide are present, but this alone does not guarantee its formation. The formation of CO in novae ejecta has been treated by Rawlings (1988) and Evans et al. (1996). CO can form through a number of chemical reactions or through direct radiative association. (In the interstellar medium CO can also form on dust grains, but in the ejecta of V2274 Cyg CO formation preceded dust formation.) The chemical reactions are the faster mechanisms, but are dependent on the formation of intermediate molecules, namely H_2 and OH. Unlike CO, the dissociation energies of H_2 (4.48 eV) and OH (4.39 eV) are significantly less than the ionization potential for neutral carbon (11.26 eV) and thus are not shielded from the nova's radiation field inside the C I region. Nevertheless, only a very small fraction of the available hydrogen needs to be in the forms of H_2 and OH for chemical formation to dominate. For this reason, Evans et al. (1996) favored the chemical process as the source of CO in V705 Cas, even though there were no detectable H_2 features with which to gauge its presence. The same is also true for V2274 Cyg, where we cannot associate any of the emission line features with H_2 . We can check to see if H_2 had to be present by computing the formation time due to radiative association alone. If this value is greater than the 18 day constraint mandated by the observations, then a more efficient process than radiative association must also be active. Dalgarno, Du, & You (1990) have studied radiative association of CO in SN 1987A and found that the dominant reaction at temperatures greater than 600 K is $\text{C} + \text{O} \rightarrow \text{CO} + h\nu$. (At lower temperatures most CO forms from a two-step process, $\text{C}^+ + \text{O} \rightarrow \text{CO}^+ + h\nu$ followed by the charge exchange reaction $\text{CO}^+ + \text{O} \rightarrow \text{CO} + \text{O}^+$.) They calculate association rates as a function of temperature and find, for 3000 K, a value of $\sim 2.2 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}$. Taking mass fractions of 0.10 and 0.15 for carbon and oxygen, respectively (these values were selected from Jose & Hernanz [1998] and are representative values for explosions involving carbon-oxygen WD primaries), and assuming a neutral particle density of $\sim 10^{12} \text{ cm}^{-3}$ (the value found by Ferland et al. [1979] in analyzing the CO formation in NQ Vul), radiative association can produce the small fractional CO abundance estimated above (~ 0.0008) in less than an hour. For a much lower particle density of 10^{10} cm^{-3} the formation would take ~ 4.4 days. Thus, radiative association is viable alternative to chemical processes for CO formation in V2274 Cyg.

3.2.3. CO Survival

The destruction of CO in V2274 Cyg could have been predicted from the studies of Shore & Braine (1992) and

Ferland et al. (1979). The former searched for CO emission at radio wavelengths in three nova shells but found none. The latter inferred, from infrared photometry, that the CO they observed 19 days after outburst in NQ Vul had disappeared by about a month later. While allowing for the possibility that some CO had been incorporated into dust grains, they noted that the growth of the Strömberg sphere that resulted from the hardening of the ionizing spectrum would have destroyed the remaining CO. The evolutionary stages of a nova present increasingly harsher environments for CO survival. In addition to photodissociation and photoionization, processes that can destroy CO include several charge transfer reactions (Rawlings 1988; Liu, Dalgarno, & Lepp 1992) and dissociation by He^+ (Lepp, Dalgarno, & McCray 1990). A glance at the late-time spectrum (Figs. 6 and 7) shows that the CO of V2274 Cyg did succumb to one or more of these processes, as did the CO in V705 Cas (Evans et al. 1996, 1997).

3.3. Late-Time Spectrum

By the time of the second observation, acquired slightly over a year after outburst, the permitted lines of neutral carbon, nitrogen, and oxygen had all disappeared (Figs. 6 and 7). $\text{He I } \lambda 10830$, which was weak or absent from the early measurements, had become the dominant emission line in the spectrum. The excitation of the system was also sufficient to produce emission lines of He II. Interestingly, some of the common coronal lines (e.g., $[\text{Ca VIII}] \lambda 23205$) were not seen and either had disappeared or were never present. (This is discussed further in § 3.5.) The only coronal features detected were $[\text{S VIII}] \lambda 9911$ and $[\text{Si VI}] \lambda 19645$. Four of the unidentified features ($\lambda 11114$, $\lambda 11900$, $\lambda 15545$, $\lambda 20996$) discussed by Rudy et al. (2002) and seen in several other novae (Williams, Longmore, & Geballe 1996; Lynch et al. 2001; Venturini et al. 2002) are present, but these appear to require only moderate excitation to exist. (Williams, Longmore, & Geballe [1996] identified the feature at $1.5545 \mu\text{m}$ with the hydrogenic 10–9 transition of N v, but

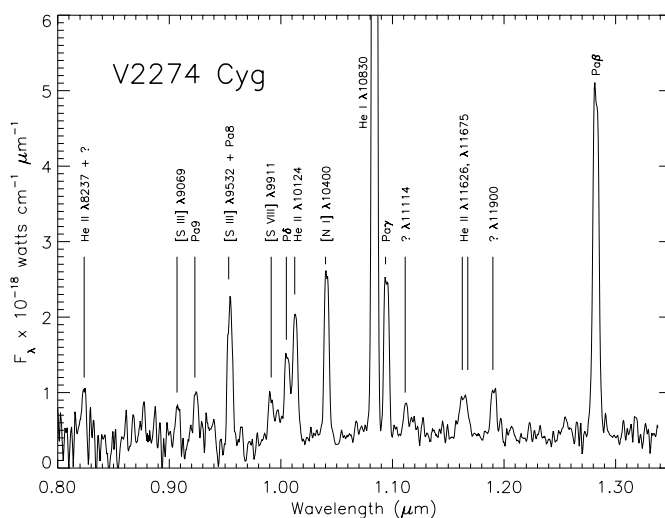


FIG. 6.—V2274 Cyg 0.8–1.35 μm spectrum from 371 days after outburst. The emission lines have narrowed slightly, and all of the permitted lines of the neutral metals have disappeared. $[\text{S VIII}] \lambda 9911$ is the only coronal line definitely detected. The lower excitation forbidden lines, $[\text{S III}] \lambda 9069$ and $\lambda 9532$, which are common in planetary nebulae, are present.

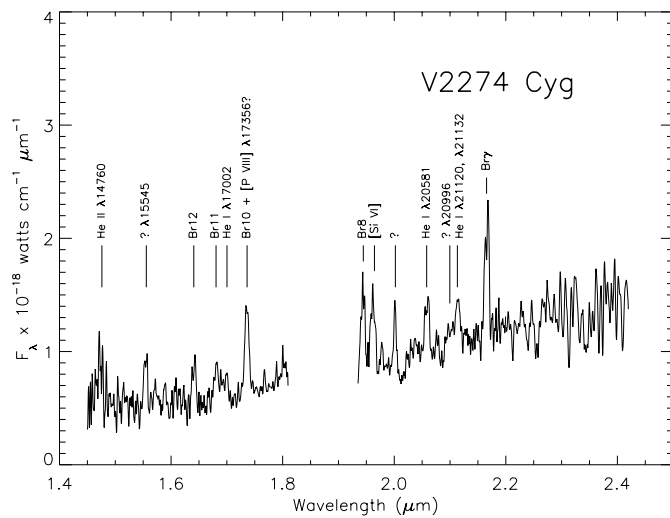


FIG. 7.—V2274 Cyg 1.4–2.5 μm spectrum from 371 days after outburst. The first overtone emission from CO has disappeared, and a strong thermal dust emission component is now present.

Rudy et al. [2002] rejected this identification based on the width of the feature, and the absence of the 9–8 multiplet and several other transitions from lower levels.) There is an additional feature at $\sim 2.0020 \mu\text{m}$ that is unidentified. [S III] $\lambda 9532$, a forbidden line that is common to planetary nebulae and H II regions, is present, as is [N I] $\lambda 10400$, which is nearly ubiquitous in novae spectra. The hydrogen lines have narrowed measurably, but not substantially, from 1600 to 1340 km s^{-1} .

Two other important characteristics of the late-time spectrum are the absence of CO emission and the rise in the infrared continuum toward longer wavelengths. The former is consistent with the destruction of CO by any or all of the mechanisms discussed in § 3.2.3. The rise in the continuum, which was not present in the early-time data, is indicative of thermal emission from dust. It is similar to that seen in the spectrum of V705 Cas (Evans et al. 1997) after dust formation occurred in that nova. Note that the rise is too steep to be either continuum emission from the hot gas or the photospheric emission from a late-type companion.

Since the dust presumably formed in the ejecta and is warmed by light from the nova photosphere, its presence can also be detectable as a drop in the visible light curve or as an increase in the measured extinction. The light curve for V2274 Cyg, as plotted in Figure 4, shows a decline around day 45 characteristic of the formation of dust. The O I lines are no longer present to estimate the reddening, but the late-time hydrogen line ratios should be well described by their case B values. Unfortunately, there are only four H I lines with sufficient S/N to be useful. These are Pa δ , Pa γ , Pa β , and Br γ . Assuming an electron temperature of 10^4 K and an electron density of 10^6 cm^{-3} , using the case B recombination coefficients of Storey & Hummer (1995) and again employing the reddening curve of Draine (1990) gives a value of $E(B-V) = 1.47 + 0.15$. Although the difference between this result and the early-time value (1.30) is not statistically significant, it does hint at a slight increase. Since the late-time observations are more than 320 days after the onset of dust formation, outflow of the ejecta may well have dissipated the dust along the line of sight and reduced the local extinction from its peak value.

3.4. Taxonomy

Classification of novae is important, since it matches or distinguishes observed properties of a specific nova with all of those that have been observed previously. This provides both a framework and an aid for investigating a specific nova. It is particularly important in the near-infrared, since classification of a nova can tie its properties in that wavelength region to those of the optical, where a wealth of past measurements exist.

Various methods for classifying novae exist. These include methods based on the shape of the light curve (Duerbeck 1981 and references therein), the relative strength of the nitrogen and helium emission lines relative to those of iron (Williams 1992 and reference therein), and the mass of the component white dwarf (Gehrz et al. 1998 and references therein). Of these three, the WD mass is the most fundamental, since it strongly influences such key aspects of the explosion as the amount of mass ejected, the outflow velocity, the total energy released, the recurrence time for future explosions, and the elemental abundances within the ejecta. These factors, in turn, influence the light curve and the resulting spectrum. Since the WD component may range in mass from 0.6 to 1.35 M_{\odot} , and because it is generally not possible to determine the mass precisely, an attempt is made to distinguish whether the mass is less or greater than 1.2 M_{\odot} . Below this value carbon-oxygen (CO) types are found, while oxygen-neon-magnesium (ONeMg) WDs predominate at higher masses. Although the higher mass (ONeMg) types are much rarer, their shorter recurrence times for outburst lead to an overrepresentation among novae. As such, they account for a quarter to a third of all novae explosions (Gehrz et al. 1998). Della Valle & Livio (1998) investigated the correlation of the component WD mass with location in the Galaxy. They find that novae with less massive CO WDs are typically members of the thick disk, while those with more massive ONeMg components tend to cluster along the plane (in the thin disk).

It is not always easy to distinguish CO from ONeMg WDs using near-infrared spectroscopy. Williams (1992) associated Fe II novae primarily with explosions on CO WDs, while ONeMg type WDs tended to produce He and N lines in their spectra. Emission lines of Fe II as well as He and N are present in V2274 Cyg, but neither are dominant. Explosions on ONeMg WDs are characterized by higher abundances of the elements from neon through sulfur (Livio & Truran 1994; Jose & Hernanz 1998), with the lines of neon being the most frequently exploited to identify ONeMg WDs. Its various ionization states form strong forbidden lines in the blue, and in the midwave and thermal infrared, but are absent in the near-infrared region.

There are other observational features besides the emission lines of a specific element that may help to distinguish between novae explosions involving lower mass, CO WDs and their higher mass, ONeMg counterparts. In V2274 Cyg these include the rate of decline, the expansion velocity, the presence of coronal lines, the location relative to the Galactic plane (as noted above), the formation of dust, the existence of C I lines, and, possibly, the presence of CO itself. All of these features indicate that the WD in V2274 Cyg is a CO type. The “moderately fast” speed class into which V2274 Cyg falls as well as the moderate ejection velocities that it exhibits are somewhat ambiguous, since they are intermediate between those expected from a low-mass CO

WD and a massive ONeMg type. Both characteristics are, however, similar to those of other novae with CO emission (see the following section), all of which have been associated with CO type WDs.

With regard to coronal emission lines, both Williams (1992) and Gehrz et al. (1998) have noted that while coronal lines are present in both types of novae, they tend to be both more prevalent and more prominent in those involving ONeMg WDs. The few coronal lines in V2274 Cyg and their weakness are more characteristic of a CO WD. This is also true of V2274 Cyg's location within the Galactic plane. Its Galactic latitude of $+1.99^\circ$, and the derived distance of 10.8 kpc, place V2274 Cyg approximately 370 pc above the Galactic plane. This is well beyond the ~ 100 pc value that Della Valle & Livio (1998) find for the massive ONeMg WDs that are predominantly members of the thin disk, but is commensurate with the novae with less massive CO WDs that are more apt to belong to the thick disk.

Similarly, the formation of dust following the outburst of V2274 Cyg is suggestive of a CO-type WD. Although dust formation is observed in novae with both WD types, it is significantly more common in systems with CO WDs (Gehrz et al. 1998). So too is the presence of C I lines, which is yet another feature that favors a CO component WD. While both types of WD produce ejecta with substantially enhanced carbon abundances, the enhancement can be as much as a factor of 3 greater for the CO type (Jose & Hernanz 1998). In addition, the more massive envelopes that are ejected at lower velocities by the CO WDs, together with their generally slower and less extreme ionization development, tend to produce and sustain the sheltered regions where carbon can survive in its neutral state. The formation and survival of CO is even more sensitive to the presence of these regions than is neutral carbon. While none of these criteria by themselves conclusively determine the nature of the WD present within the V2274 Cyg system, taken in sum they indicate strongly that the white dwarf is a CO type.

3.5. Similarities to Other Novae with CO Emission

Table 3 compares some of the properties of V2274 Cyg that may be relevant to CO formation to those of the three other novae in which the first overtone of CO has been observed spectroscopically. These other novae, listed in § 1, are NQ Vul (Ferland et al. 1979), V842 Cen (Hyland & McGregor 1989; Wichmann et al. 1990), and V705 Cas

(Evans et al. 1996). Also included in Table 3 is V1419 Aql (Lynch et al. 1995), a nova without CO observations but in which we suspect CO was present (see below).

What can be seen from Table 3 is that all the novae included have very similar properties. The existence of C I lines indicates the presence of the neutral carbon that is essential for the formation of CO (Rawlings 1988). (Note that since most of the C I lines are formed by recombination, it is possible that the regions of most active CO formation produce little C I emission). The existence of neutral carbon is a necessary but not sufficient condition for the formation of CO. While CO may be dissociated by processes that do not affect C I, a radiation field capable of photoionizing the latter will also destroy the former.

Another significant commonality among the novae of Table 3 is that all formed copious amounts of dust. All showed sharp drops in their visible light curves at the onset of dust formation. In the case of V705 Cas, this amounted to a decline of 8 mag in a period of approximately 1 week (Evans et al. 1997). This association of dust with CO is perhaps not surprising, given that CO formation may be a precursor for dust formation (Rawlings 1988), helping to cool the regions sufficiently that dust formation can occur. Moreover, the conditions that are necessary for the formation of CO (low temperature, high density, metal-rich material) are also favorable for the creation of dust. However, the one-to-one relation between the presence of CO shortly after outburst and the formation of dust several weeks later in the novae of Table 3 certainly solidifies this notion.

Interestingly, there does appear to be some difference in the $^{13}\text{C}/^{12}\text{C}$ value for the novae of Table 3. While we report a ratio of 0.83 for V2274 Cyg, and Wichmann et al. (1990) present 0.34 for V842 Cen, Evans et al. (1996), who had high-quality observations of V705 Cas, see no evidence of ^{13}C . They set an upper limit of 0.2 for $^{13}\text{C}/^{12}\text{C}$. Similarly, Ferland et al. (1979) established $^{13}\text{C}/^{12}\text{C} < 0.33$ while Sneden & Lambert (1975) estimated $^{13}\text{C}/^{12}\text{C} < 0.67$ in the related nova DQ Her. It is surprising that in systems that otherwise appear so similar, the nuclear processes would vary. Alternately, the $^{13}\text{C}/^{12}\text{C}$ variations may reflect variations in the amount of unprocessed material from the companion that is entrained in the ejecta.

With regard to the rate of brightness decline (t_2) and the expansion velocity, the grouping among the sample does not appear to be as tight as for the other parameters. How-

TABLE 3
PROPERTIES OF V2274 CYGNI AND OTHER NOVAE WITH CO EMISSION

Object	C I Lines?	t_2 (days)	CO Appearance (days after outburst)	Dust Formation (days after outburst)	$V_{\text{expansion}}$ (km s^{-1})
V2274 Cyg ^a	yes	33	<18	40	1600
NQ Vul ^b	yes	$\sim 50^f$	<19	50	1135–1350
V842 Cen ^c	yes	35	<25	39	1400
V705 Cas ^d	yes	45	<6	68	1600
V1419 Aql ^e	yes	17–22	?	~ 90 (~ 40 days after maximum light)	1500

^a This paper.

^b Ferland et al. 1979; Sato et al. 1978.

^c Hyland & McGregor 1989; Whitelock 1987; Sekiguchi et al. 1989; Wichmann et al. 1990; de Freitas Pacheco et al. 1989.

^d Evans et al. 1996.

^e Lynch et al. 1995; Munari et al. 1994.

^f Erratic light curve.

ever, t_2 is sometimes hard to determine, since light curves may be erratic. Similarly, different emission lines in the same object may manifest different widths, and those widths may vary somewhat as the nova evolves. Nevertheless, both t_2 and $v_{\text{expansion}}$ cluster well within the extreme values exhibited by novae.

A comparison of the infrared spectra of the novae of Table 3 is largely limited to the region between 2 and 2.5 μm . The overlap between our data and those of Evans et al. (1996) is confined to that spectral range. Wichmann et al. (1990) presented measurements only of the first-overtone emission, while Ferland et al. (1979) included some spectroscopic observations in the H -band atmospheric window. Nevertheless, the presence of strong C I lines in all of the objects, as well as similarities in spectral regions of overlap, suggest that the spectra of all of the earlier novae may have appeared quite similar to V2274 Cyg at shorter wavelengths. Lending support to this notion is the 0.8–1.35 μm spectrum of V1419 Aql (Lynch et al. 1995). As can be seen in Figure 8, it is virtually identical to that of V2274 Cyg. Since, in all other ways listed in Table 3, V1419 Aql is typical of novae with CO emission, we suspect that it was present in this nova as well.

Based on its spectral similarities to NQ Vul, V842 Cen, and V705 Cas from 2–2.5 μm , and its near identity to V1419 Aql in the near-infrared, we suggest that the measurements of V2274 Cyg represent a plausible template for the near-infrared spectra of novae with CO emission. Obviously, the spectra of novae develop rapidly, particularly in the period after outburst. Hence, a single nova can present many different spectral “looks,” depending on the epoch at which it is observed. However, the conditions necessary for forming and sustaining carbon monoxide are sufficiently short-lived that most of the other spectral properties probably change little during this period.

4. SUMMARY AND CONCLUSIONS

Near-infrared spectroscopy of V2274 Cyg (Nova Cyg 2001 No. 1) from 18 days after outburst reveal carbon monoxide overtone emission, the Paschen and Brackett series of H I, atomic emission from neutral carbon and nitrogen, and very strong, fluorescently excited emission from O I. The CO emission indicates a temperature of ~ 2500 K, with nearly half of the emission arising from $^{13}\text{C}^{16}\text{O}$. By the time of the second epoch observations a year later, the neutrals and CO had disappeared, lines of He I and He II had emerged, large amounts of dust had formed, and only a few weak coronal lines were present. The small number of novae in which CO emission has been observed spectroscopically have t_2 values between 30 and 50 days, moderate ejection velocities (1200–1600 km s^{-1}), form dust prolifically, and contain a CO white dwarf. C I emission lines will almost certainly be present if CO is detectable.

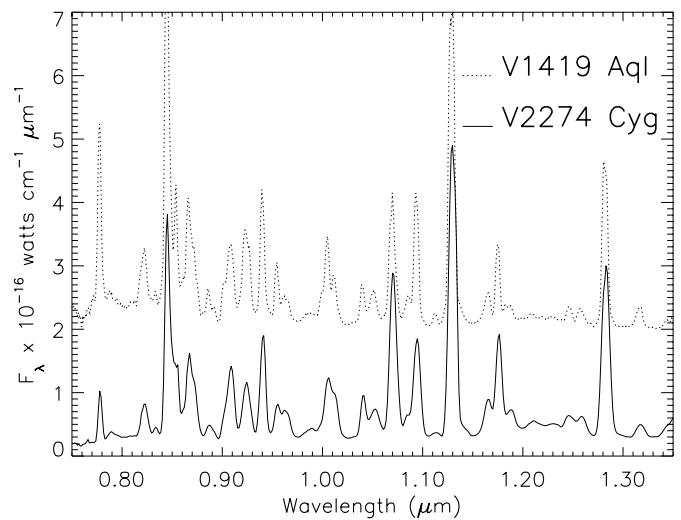


Fig. 8.—Comparison of the 0.75–1.35 μm portion of the early spectrum of V2274 Cyg with the spectrum of V1419 Aql (Nova Aql 1993), also from 18 days after outburst, from Lynch et al. (1995). To facilitate the comparison, the spectrum of the latter has been scaled and offset. Note that after allowing for the slightly higher resolution of the Lynch et al. observations, the spectra are nearly identical. Real differences between the spectra are subtle but include the slightly stronger O I $\lambda 7774$ line of V1419 Aql, and the somewhat greater reddening and stronger C I lines of V2274 Cyg. Like V2274 Cyg, V1419 Aql also formed large amounts of dust (Munari et al. 1994), and was similar to CO emitting novae in other ways (see text).

Based on spectral similarities with the small number of other novae, we suggest that these near-infrared observations of V2274 Cyg represent a plausible infrared spectral template for novae that manifest CO emission and that many aspects of future novae can be predicted if their spectra show CO emission.

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