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TIME DEVELOPMENT OF RECURRENT NOVA CI AQUILAE'S 2000 OUTBURST BETWEEN 0.8 AND 2.5 MICRONS

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ABSTRACT

We report 0.8–2.5 μm spectrophotometry of CI Aquilae at eight epochs between 2000 May 9 and 2001 June 2 UT, corresponding to approximately 3 and 391 days after peak brightness. Near peak brightness, the spectra showed emission lines that were characteristic of a low-excitation, nitrogen-rich shell. Within a few weeks, the spectra began to show higher excitation/ionization emission lines indicative of a harder illuminating source: the neutral metal lines faded, leaving only lines of H I, He I, and He II and the emerging coronal lines. A month after peak brightness, the [Ca VIII] coronal line at 2.3205 μm appeared and persisted until the last of our observations, on day +391. From the O I line ratios, we deduced a reddening of $E_{B-V} = 1.5 \pm 0.1$ and a visual extinction of $A_V = 4.6 \pm 0.2$. Along with the rate of decline from the light curve (t_2), we derived a distance of 2.6 ± 1.3 kpc. The frequently observed unidentified novae lines were present in CI Aquilae along with a potentially new member of the group at 2.425 ± 0.002 μm.

Key words: infrared radiation — novae, cataclysmic variables — stars: individual (CI Aquilae)

1. INTRODUCTION

Recurrent novae (RNe) are thought to be progenitors of Type Ia supernovae (Nomoto 1982; Nomoto, Thielemann, & Yokoi 1984; Hachisu & Kato 2001). A number of different types of white dwarf (WD) scenarios are under consideration including merging double WDs (e.g., Iben & Tutukov 1984; Webbink 1984), recurrent novae (e.g., Starrfield, Sparks, & Truran 1985), symbiotic stars (e.g., Munari & Renzini 1992), and so on (see Livio 2000, for recent summary).

Type Ia supernovae are the primary nonredshift cosmological distance indicators (Riess et al. 1998; Schmidt et al. 1998; Perlmutter et al. 1999). In the supernova scenario, the CO WD accumulates more material during its quiescent phase than it ejects during the subsequent outburst. In this way, the WD gains mass until it reaches the Chandrasekhar limit of 1.44 $M_\odot$, at which time it collapses and initiates carbon burning, which explosively disrupts the star, leading to the supernova. In both its nova and supernova phase, the ejection of material increases the abundance of heavy elements in the interstellar medium (ISM), although by vastly different amounts. Thus the study of novae and how they relate to Type Ia supernovae and the ISM abundances are a fundamental issue in astronomy.

CI Aquilae (CI Aql) is a recurrent novae in the U Sco subclass (Warner 1995). U Sco stars have slightly evolved dwarf secondaries, and in general their novae shells do not appear to be significantly enriched in heavy elements. This suggests that little if any material from the WD is being ejected and therefore it is likely that the WD is gaining mass from the accretion disk in the long run (Starrfield et al. 1985). CI Aql is also an eclipsing binary (Mennickent & Honeycutt 1995) with a period of $P = 0.618355$ days and an amplitude variation of about 0.2–0.6 m_V (Schaefer 2001a).

CI Aql's first recorded outburst was in 1917 (Reinmuth 1925; Duerbeck 1987). Since that time, there have been several outbursts, but these were not recognized until recently (Schaefer 2001b). CI Aql's quiescent brightness is thought to be $m_V = 17$–18. Observations in 1992–1993 by Greiner, Alcala, & Wenzel (1996) revealed some minor variability in the [O I] nebular line at 0.6302 and 6364 μm and a *ROSAT* upper limit of 7×10^{-4} counts s^{-1} in the 0.1–2.4 keV band.

The most recent outburst of CI Aql was first reported by Takamizawa et al. (2000) at $18^{h}52^{m}03\overset{s}{.}57$, $-01°28'39\overset{\prime\prime}{.}4$ (J2000.0). Its AAVSO light curve is shown in Figure 1. From the light curve, we estimate the date of peak brightness as JD 2,451,671 (2000 May 6.5 UT) with $m_V = +9.2$, and t_2 and t_3 (the time taken to drop by 2 and 3 mag, respectively) as 27 and 33 days, respectively. These values are in good agreement with those of Kiss et. al. (2001, hereafter K01), who used the VSNET light curve to find peak brightness on 2,451,669.5 ± 0.1 (2000 May 5.0 UT) t_2 and t_3 of 30 ± 1 and 36 ± 1 days, respectively. Thus, CI Aql is a "moderately fast" nova (Payne-Gaposchkin 1957), although the object's

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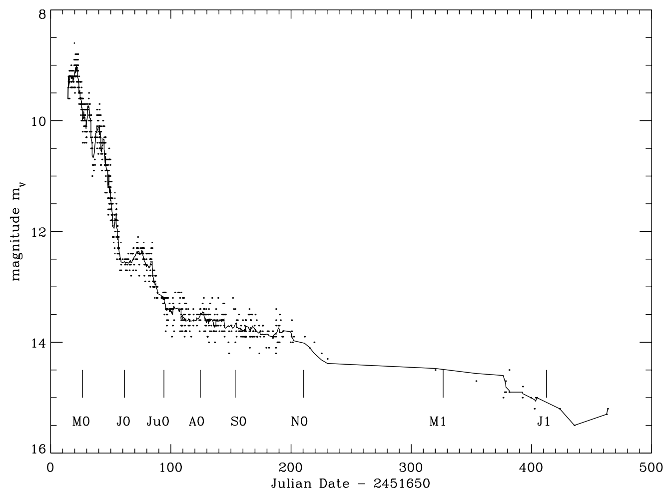

FIG. 1.—Aql's light curve from the AAVSO along with a 10 day moving average. The dates of our observations reported here are shown as vertical lines along the bottom of the chart. M0 = 2000 May, J0 = 2000 June, Ju0 = 2000 July, etc. (see Table 1). In 2000 June, there was a sudden drop in brightness followed by a small brightening, suggestive of a minor dust-producing episode. Our last observation was taken when the object had nearly reached its quiescent brightness. We estimate the date of peak brightness as JD 2,451,671 (2000 May 6.5 UT) with $m_V = +9.2$ and t_2 and t_3 as 27 and 33 days, respectively. Based on Payne-Gaposchkin's classification, CI Aql's 2002 outburst was "moderately fast."

subsequent behavior indicated a relatively slow evolution. Based on optical photometry, Matsumoto et al. (2003) regard the unusually long plateau phase as indicating that CI Aquilae is intermediate in nature between classical and recurrent novae.

Optical spectroscopy was reported by Takamizawa et al. (2000), Liller (2000), and K01. This early spectroscopy indicated the shell to be characteristic of a low and increasing excitation shell with near-solar abundances. Neutral species of H, He, C, N, and O were evident. Also present were the interstellar Na I lines and diffuse interstellar bands at 5847 and 6613 Å. Observations between 2000 May and October by Burlak & Esipov (2001) indicated a significant helium enrichment. Of particular interest was K01's monitoring of the Hα profile that began before peak brightness. The line shape started out roughly Gaussian with a P Cygni profile and evolved into a well-separated, double-peaked profile, with each component being highly non-Gaussian. The profile and its changes are readily understood as emission from an expanding, asymmetric optically thick shell that became optically thin about a month after peak brightness.

In this paper we present and analyze near-IR spectra obtained from near peak brightness in 2000 May to the star's near return to quiescence. Near-infrared spectroscopy provides a wealth of diagnostic detail about novae and the evolution of their shells because of the number and variety of special utility lines that are available. Low-excitation hydrogen Paschen and Brackett lines provide a background against which to assess abundances, electron densities, and temperatures. They also reveal information about the shell geometry, kinematics, and optical depths (Lynch et al. 2000). The intrinsic flux ratio of the O I lines at 0.8446 μm and 1.1287 μm is well known and therefore any departure from it is usually a good indicator of interstellar reddening (Rudy et al. 1991b). Neutral and low ionization permitted lines of nitrogen, oxygen, carbon, phosphorus, silicon, calcium, magnesium, and iron often provide crucial abundance information, which in turn can be related to the initial composition, evolutionary state, and surface mixing of the WD before the outburst. As the ejecta cools and thins to reveal the hot WD, higher ionization forbidden "coronal" lines such as [S VIII] 0.9913 μm, [Fe xiii] 1.0747 μm, [S IX] 1.2523 μm, [Al IX] 2.0469 μm, [Ca VIII] 2.3214 μm, and [Si VII] 2.4827 μm begin to appear. By noting their relative strengths, time of emergence, and critical densities, much can be learned about the conditions in the shell (Rudy et al. 2002b). The unprecedented near-IR spectral coverage presented below has allowed us a good deal more confidence in identifying lines, as well as overall insight into the evolution of novae than we have ever had before.

2. OBSERVATIONS

Most of the observations were made with the Palomar 1.52 m telescope using the Cornell Massachusetts Slit Spectrograph (CorMASS), an IR spectrograph operating from 0.8 to 2.5 μm with a resolving power ($\lambda/\Delta\lambda$) of about 300 (Wilson et al. 2001). One of the spectra was taken with the Lick 3 m telescope and the Aerospace Corporation's Near Infrared Imaging Spectrograph (NIRIS; Rudy, Puetter, & Mazuk 1999). NIRIS operates in roughly the same wavelength region as CorMASS, but with a resolving power closer to 700. A log of the observations is given in Table 1.

Observations were made in the usual nodding mode for background subtraction. The Palomar calibrator was SAO 142777, a K2 star presumed to be a giant because of the absence of an *Hipparcos* parallax. The flux model for a K2 III star was obtained from Kurucz (1991). It was scaled to match the K magnitude of SAO 142777's V magnitude from the Yale Bright Star Catalog (Hoffleit & Warren 1995) and using the $V-K$ value for a K2 III from Koorneef (1983).

With widths (FWHM) in the neighborhood of 3000 km s^{-1}, CI Aql's emission lines are resolved in our spectra. The Palomar and Lick spectral resolutions of about 400 and 1000 km s^{-1}, respectively, are small but not insignificant compared with the line widths. CI Aql's lines are so broad that it is often not possible to separate the many blends that we encountered. This leads to difficulties in isolating single lines, and, as a result, line flux determinations were in many cases compromised.

3. THE SPECTRA

3.1. *General Aspects of the Spectra*

Figures 2 and 3 show all of our spectra, arranged with earliest spectrum on top and descending downward through the latest on the bottom. The earliest spectra (2000 May) are indicative of low-excitation conditions in the shell. Lines of H I, He I, N I, and O I dominate the 2000 May spectrum (Table 2), with N I being the most frequent line from a heavy element. As time goes on, the neutral and singly ionized lines fade away almost completely except for He I 1.0830 μm, Brγ and Paβ. As early as 2000 August and certainly by 2000 September, the [Ca VIII] coronal line at 2.3205 μm appeared and persisted to very late times. The [Si VI] 1.9641 μm line appeared in 2000 November. There was no evidence of thermal emission from dust at anytime during the observation period.

Most of the line profiles are not Gaussian or Lorentzian, but rather display structure that is indicative of doubling (Fig. 4). The FWHM of the lines is about 3000 km s^{-1}, and the separation of the peaks is about 1500 km s^{-1}. In view of the

TABLE 1

Observation Log of CI Aquilae

Date (UT)	JD	Instrument/Observatory	Days after Peak
2000 May 9	2,451,673.5	CorMASS/Palomar	3
2000 May 12	2,451,676.5	CorMASS/Palomar	6
2000 May 14	2,451,678.5	CorMASS/Palomar	8
2000 Jun 14	2,451,709.5	CorMASS/Palomar	39
2000 Jun 16	2,451,711.5	CorMASS/Palomar	41
2000 Jul 18.80	2,451,744.29	NIRIS/Lick	73
2000 Aug 18	2,451,774.5	CorMASS/Palomar	104
2000 Sep 14	2,451,801.5	CorMASS/Palomar	131
2000 Sep 16	2,451,803.5	CorMASS/Palomar	133
2000 Sep 18	2,451,805.5	CorMASS/Palomar	135
2000 Nov 12	2,451,860.5	CorMASS/Palomar	190
2001 Mar 8	2,451,976.5	CorMASS/Palomar	306
2001 Jun 2	2,452,062.5	CorMASS/Palomar	391

Notes.—The date of peak brightness was taken as JD 2,451,671 = 2000 May 6.5 UT based on the AAVSO light curve. The "Days after Peak" were rounded up to the nearest whole day.

fact that a spherical expansion generates a flat-topped profile, the presence of two major components of roughly equal strength suggests that the expanding shell was nonspherical and very likely composed of two lobes, probably the polar components.

3.2. *The Early Spectrum*

The spectrum obtained on 2000 May 9 (about 3 days after peak brightness) is shown in Figure 5 (0.8–1.4 μm) and Figure 6 (1.4–2.5 μm), along with the line identifications. Table 2 lists the lines in these spectra and their strengths relative to Paβ. The most striking aspect of the spectrum is the large number of permitted N I lines. This almost certainly indicates an overabundance of nitrogen in the emitting shell. Also present are the Lβ-fluoresced lines of O I (discussed below in connection with reddening) and a few Fe II lines. The Paschen and Brackett lines of H I dominate the spectra and the He I lines at 1.0830 and 2.0581 μm both show P Cygni profiles. Virtually all of the lines show evidence of doubling, i.e., having two distinct velocity components.

While the presence of many N I lines was evident, identifying them was problematic because of the large line widths. In many cases the indicated N I lines are blended with H I lines or other N I lines and therefore cannot be specified with complete certainty. Most of the N I lines had disappeared by June, so there was no opportunity to monitor their changes and learn from their relative rates of decline. Our final conclusion that N I lines were abundantly present was based on the large number of N I coincidences in the earliest spectrum and the absence of the other lines of the CNO cycle, primarily C I.

The He I lines were surprisingly weak in all of the spectra. Even though He I 1.0830 μm was the strongest line in the spectrum in 2000 July, it only exceeded the Paβ line flux by a factor of 3. A factor of a 10–20 is more common (Rossano et al. 1994; Rudy et al. 2002b; Venturini et al. 2002).

The Lyβ-fluoresced lines of O I were observed and one nonfluoresced O I line was seen at 0.9262 μm. The O I and N I line profiles matched the line profiles of the H I lines, i.e., they

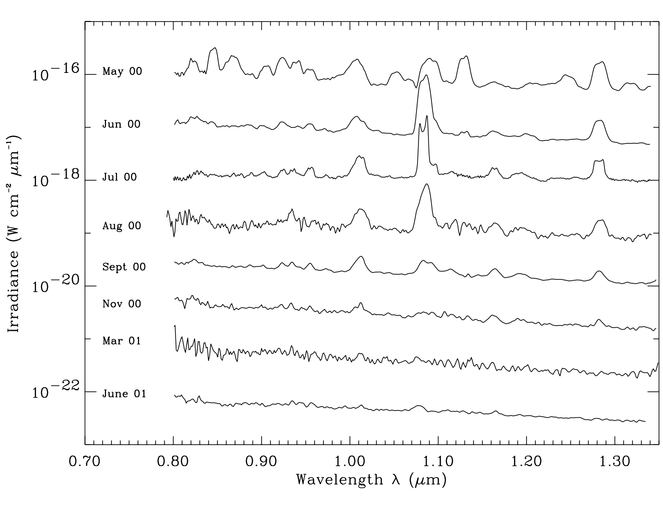

Fig. 2.—Time sequence of CI Aquilae's near-infrared spectra from 0.8 to 1.34 μm. The spectra are arranged from earliest (*highest*) to latest (*lowest*). The radiances scale refers only to the 2000 July spectrum. The other spectra have been scaled up or down for convenient viewing.

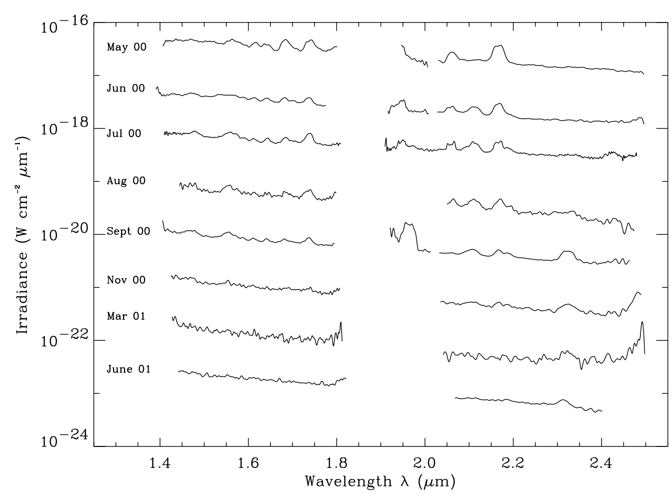

Fig. 3.—Time sequence of CI Aquilae's near-infrared spectra from 1.4 to 2.5 μm. The spectra are arranged from earliest (*highest*) to latest (*lowest*). The radiance scale refers only to the 2000 July spectrum. The other spectra have been scaled up or down for convenient viewing. We did not plot the regions of the spectrum where the atmosphere is opaque (1.82–1.92 μm).

TABLE 2
2000 MAY LINE LIST

Air/Lab Wavelength (μm)	Measured Wavelength (μm)	ID	$F/F_{\mathrm{Pa}\beta}$	Comments
0.8216, 0.8223, 0.8242	0.8221	N I	0.472	
0.8446	0.8453	O I	1.017	
0.8656, 0.8665	0.8662	H I Pa13 + N I	0.819	
0.9015, 0.9061–0.9112	0.9044	H I Pa10 + Fe II?	0.301	
0.9229	0.9241	H I Pa9 + Fe II?	0.729	
0.9387, 0.9393	0.9396	N I	0.559	
0.9545	0.9545	H I Paϵ	0.235	
0.9777–1.0003	0.9879	N I	0.163	
1.0049, 1.0105–1.0165	1.0052	H I Paδ + N I	1.027	
1.0500–1.0563	1.0529	N I	0.286	
1.0684	1.0672	C I	0.043	
1.0830, 1.0938	1.0911	He I + H I Paγ	1.301	
1.1287	1.1281	O I	1.068	
1.1566, 1.1625, 1.1651	1.1627	N I	0.139	
1.1998, 1.2074, 1.2187–1.2329, 1.2289–1.2329	1.2056	N I	0.049	
1.2461, 1.2470	1.2450	N I	0.317	
1.2818	1.2832	H I Paβ	1.000	
1.3165	1.3172	O I	0.127	
1.5557, 1.5701	1.5645	H I Br16 + H I Br15 + ?	0.151	
1.6109	1.6157	H I Br13	0.048	
1.6407	1.6406	H I Br12	0.058	
1.6806	1.6855	H I Br11 + ?	0.230	
1.7362	1.7404	H I Br10 + ?	0.225	
1.9446	1.9487	H I Br8	0.119	Affected by atmosphere
2.0581	2.0634	He I	0.114	
2.1655	2.1645	H I Brγ	0.282	

showed approximately the same width and doubled structure. There was an unusual number of N I lines, probably indicating an overabundance of nitrogen. Weak or absent from the early spectra were the Ca II infrared triplets, C I, and Fe II, most of which are frequently seen in novae. The 1 μm Fe II lines (see Rudy et al. 2001 and references therein) are probably present but are weak. These lines are frequently the strongest Fe II features in the near-infrared and have been seen previously in novae (e.g., Rossano et al. 1994; Lynch et al. 1995). The lines at 1.6873 and 1.7414 μm that were recently identified by Rudy et al. (2002a) with Fe II transitions from the $c\ ^4F$ term may also be present in Figure 6.

3.3. *Time Evolution of the Spectra*

Figure 7 shows the 0.8–1.4 μm spectra for 2000 May, June, July, and September, and Figure 8 shows the 1.4–2.5 μm spectra for the same dates. The August data were not included here because of the lower signal-to-noise ratios, although we saw nothing unusual in the spectral lines that were present. CI Aql's broad lines made it difficult to identify and separate blended features, so we have listed the lines for each epoch

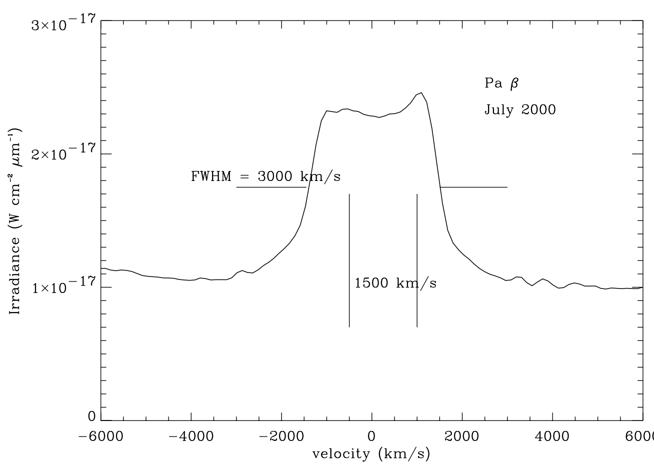

FIG. 4.—All of the line profiles show somewhat flattened top with evidence of doubling. Paβ is typical with a FWHM of about 3000 km s^{-1} and a splitting separation of around 1500 km s^{-1}. Lines of both high and low excitation are similar.

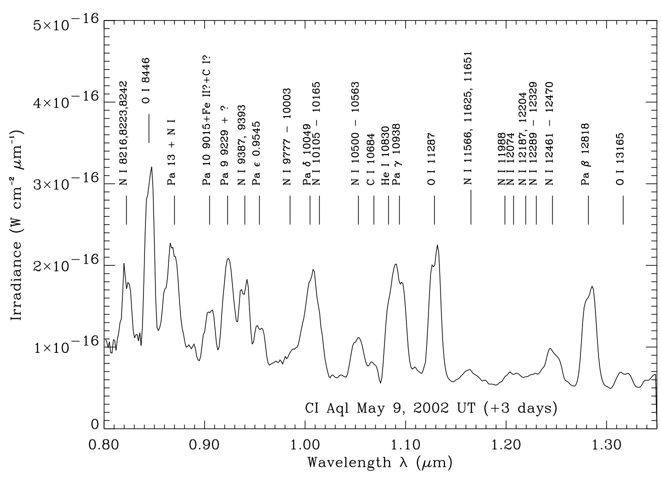

FIG. 5.—The 2000 May spectrum between 0.8 and 1.34 μm with identifications.

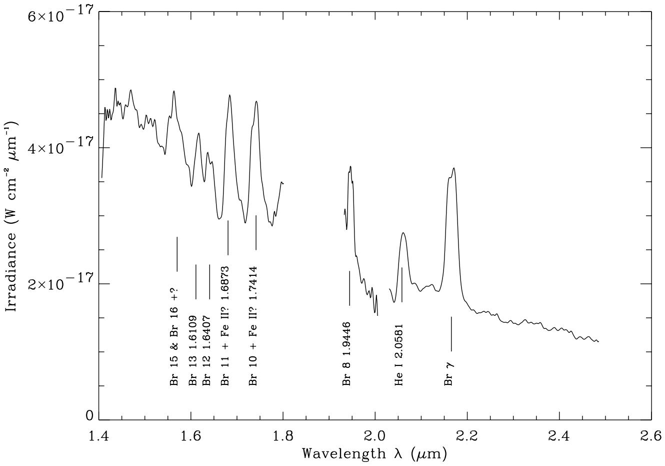

FIG. 6.—The 2000 May spectrum between 1.4 and 2.5 μm with identifications.

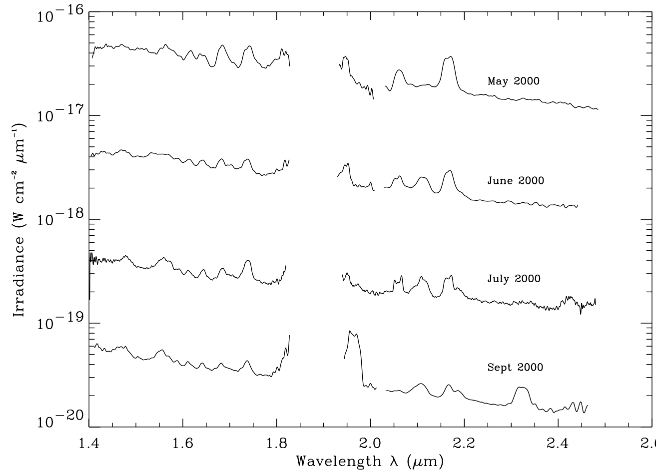

FIG. 8.—Long-wavelength spectral evolution of the 2000 May, June, July, and September spectra.

separately (2000 May, Table 1; 2000 June, Table 3; 2000 July, Table 4; and 2000 September, Table 5). The region around 1 μm in Figure 7 is a good example. The prominent feature at 1.01 μm in the 2002 May spectrum is actually a blend of Paδ and N I lines, with N I dominating. In the June spectrum when the excitation had increased, Paδ and the N I lines had weakened, and the He II 1.0124 started to become apparent on the red wing of the feature. By 2000 September, the N I was completely gone and the broad feature was comprised of Paδ and He II, the latter accounting for most of the line flux. Such an evolution could not be easily accommodated in a single table showing the lines for all the epochs.

The H I lines were present early in the nova's life, but weakened with time and were almost gone a year later. We did not observe P Cygni profiles on any of the H I lines of either the Paschen or Brackett series. All of the unblended H I lines showed doubled profiles. As distance indicators, the H I lines are useful only if there are a sufficient number of them that are unblended and if there is some degree of confidence that the excitation conditions in the shell are known. Furthermore, the lines must be optically thin. None of these conditions were met in CI Aql.

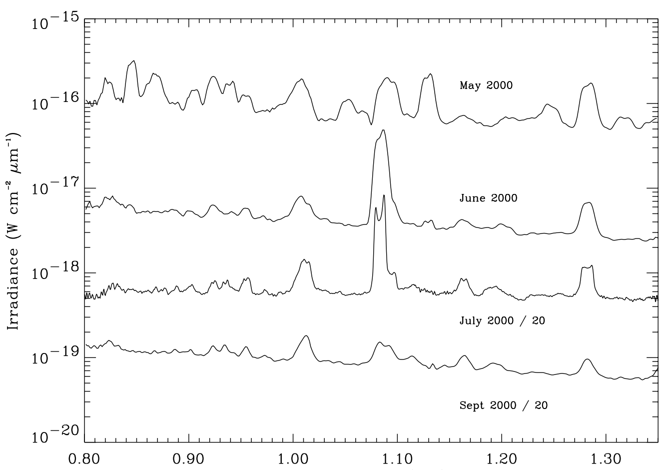

FIG. 7.—Short-wavelength spectral evolution of the 2000 May, June, July, and September spectra.

It is worth noting that Hachisu, Kato, & Schaefer (2003) reported that the optically thick winds stopped in early 2000 November and ceased completely in May of 2001. Unfortunately, by 2000 November the object had faded to the point where we could no longer measure the H I lines accurately.

During the observation period, we detected the He I singlet at 2.0581 μm and triplet at 1.0830 μm. Both lines have metastable lower levels and are excited by collisions and recombinations. These lines are almost always seen in novae spectra. The He I 1.0830 μm line persisted throughout the observation period but its singlet counterpart at 2.0581 μm did not.

In 2002 May both lines showed weak P Cygni profiles with an absorption component at around -2200 km s^{-1}. The P Cygni profiles were gone a month later and, as expected, did not show up in any subsequent spectra. K01 reported complex P Cygni profiles in a number of lines with blueshifted components in the range of -1700 to -2400 km s^{-1}.

Many novae show some of the higher He I lines such as 1.2528, 1.2785, and 1.2790 μm. We probably did not detect them because they were too weak. For example, based on Nova Sgr 1998 = V4633 Sgr (Lynch et al. 2001), the ratio of 1.0830 to 1.2528 μm was around 50. This would mean that 1.2528 μm would have had a strength of around 0.09 W cm^{-2}, close to our detection limit.

He II lines were seen at 0.9345, 1.0124, 1.1626, and 1.476 μm. As the excitation in the spectra increased, the He I lines fade and the He II lines began to strengthen. There was also a number of probable He II lines whose certainty could not be fully established owing to the broad line widths.

Only two coronal lines are evident in CI Aql: [Ca VIII] 2.3205 μm and [Si VI] 1.9641 μm, with ionization potentials (IPs) of 127 and 167 eV, respectively. There is some evidence that the [P VIII] line at 1.7356 μm is present (IP = 264 eV). Some other common coronal lines that were absent were [S VIII] 0.99111 μm (IP = 281 eV), [S IX] 1.2520 μm (IP = 328 eV), and [Si VII] 2.4826 μm (IP = 205 eV), although the latter line may have appeared 10 months after outburst (Tables 2–6). All of the coronal lines had line widths and shapes that were similar to the lower excitation permitted lines.

Novae frequently show a number of the same unidentified lines at 0.8926, 1.1110, 1.1900, 1.5545, and 2.0996 μm (Lynch et al. 2001; Rudy et al. 2002b). A subset of these (0.8926 and 1.5545 μm) were first reported by Williams, Longmore, &

TABLE 3

2000 JUNE LINE LIST

Air/Lab Wavelength (μm)	Measured Wavelength (μm)	ID	$F/F_{Pa\beta}$	Comments
0.8242	0.8244	N I	0.342	Blended
0.8413 or 0.8438	0.8427	H I Pa19 or H I Pa18	0.059	
0.8863	0.8846	H I Pa11	0.121	
0.9015	0.9013	H I Pa10	0.109	
0.9229, 0.9261	0.9249	H I Pa9 + O I ?	0.263	
0.9393	0.9409	N I	0.078	
0.9545	0.9539	H I Paϵ	0.200	
0.9708	0.9714	N I	0.041	
1.0049, 1.0105	1.0087	H I Paδ + N I	1.081	Blended
1.0830, 1.0844, 1.0938	1.0879	He I + N I + H I Paγ	9.868	
1.1287, 1.1291	1.1283	O I + N I	0.108	
1.1626	1.1641	He II?	0.243	
1.1998	1.2015	N I	0.120	
1.2818	1.2807	H I Paβ	1.000	
	1.4335	?	0.067	
1.4760	1.4716	He II?	0.110	
1.5538, 1.5545	1.5493	UNL + ?	0.150	Blended
1.5881	1.5874	H I Br14	0.015	
1.6109	1.6133	H I Br13	0.035	
1.6407	1.6407	H I Br12	0.069	
1.6806	1.6818	H I Br11	0.091	
	1.7001		0.030	
1.7362	1.7352	H I Br10	0.124	
1.9446	1.9424	H I Br8	0.306	Affected by atmosphere
2.0581	2.0582	He I	0.084	
2.1120	2.1084	He I	0.145	
2.1655	2.1679	H I Brγ	0.287	

TABLE 4

2000 JULY

Air/Lab Wavelength (μm)	Measured Wavelength (μm)	ID	$F/F_{Pa\beta}$	Comments
0.8237	0.8292	He II + ?	0.219	
0.8863	0.8881	H I Pa11	0.053	
0.9015	0.9020	H I Pa10	0.100	
0.9229	0.9239	H I Pa9	0.189	
0.9345	0.9354	He II	0.198	
0.9545	0.9543	H I Paϵ	0.281	
	0.9737	?	0.063	
1.0049	1.0101	H I Paδ	1.344	
1.0830, 1.0938	1.0861	He I + H I Paγ	6.406	
1.1114	1.1146	UNL	0.091	Blended
1.1626, 1.1673	1.1632	He II	0.393	
1.1969	1.1924	UNL	0.341	
	1.2560	?	0.024	
1.2818	1.2810	H I Paβ	1.000	
1.4760	1.4763	He II	0.118	
1.5557	1.5575	H I Br16 + ?	0.282	Blended
1.6109	1.6124	H I Br13	0.049	
1.6407	1.6422	H I Br12	0.089	
1.6806, 1.6918, 1.7002	1.6840, 1.6968, 1.7057	H I Br11 + He II, + He I	0.151	
1.7362	1.7341	H I Br10 + ?	0.295	Blended
1.9446	1.9476	H I Br8	0.134	
1.9641	1.9715	[Si VI]	0.062	
2.0581	2.0598	He I	0.135	
2.0996	2.0932	UNL	0.050	
	2.1111	?	0.206	
2.1655	2.1671	H I Brγ	0.227	
2.1885	2.1874	He II	0.083	
2.3205, 2.3214	2.3270	[Ca VIII]	0.050	
	2.4248	?	0.117	

TABLE 5

2000 SEPTEMBER LINE LIST

Air/Lab Wavelength (μm)	Measured Wavelength (μm)	ID	$F/F_{Pa\beta}$	Comments
0.8237	0.8236	He II + ?	0.752	
0.8665	0.8670	H I Pa13	0.034	
0.8750	0.8754	H I Pa12	0.049	
0.8863	0.8861	H I Pa11	0.138	
0.9015	0.8990	H I Pa10	0.144	
0.9229	0.9242	H I Pa9	0.428	
0.9345	0.9341	He II	0.459	
0.9545	0.9546	H I Paϵ	0.417	
0.9735	0.9737	?	0.159	
1.0049, 1.0124	1.0102	H I Paδ + He II	2.308	
1.0830	1.0864	He I	1.650	
1.0938	1.0936	H I Paγ	1.171	
1.1114	1.1131	UNL	0.674	
1.1626	1.1626	He II	0.730	
1.1901, 1.1969	1.1923	UNL + He I	0.750	
1.2818	1.2814	H I Paβ	1.000	
1.4760, 1.4879	1.4686	He II	0.640	
1.5557	1.5554	H I Br16 + ?	0.587	Blended
1.5881	1.5859	H I Br14	0.038	
1.6109	1.6133	H I Br13	0.107	
1.6407	1.6407	H I Br12	0.143	
1.6806	1.6818	H I Br11	0.256	
1.7362, 1.7356	1.7337	H I Br10 + [P VIII]?	0.319	
1.9641	1.9622	[Si VI]	2.933	
2.0996, 2.1120, 2.1132	2.1023	UNL + He I + ?	0.373	
2.1655	2.1679	H I Brγ	0.242	
2.1885	2.1846	He II	0.133	
2.3205, 2.3214	2.3217	[Ca VIII]	0.683	

TABLE 6

2000 NOVEMBER LINE LIST

Air/Lab Wavelength (μm)	Measured Wavelength (μm)	ID	$F/F_{Pa\beta}$	Comments
0.8237	0.8221	He II + ?	7.787	
0.8665	0.8655	H I Pa13	0.292	
0.9015	0.8983	H I Pa10	1.095	
0.9229	0.9204	H I Pa9	1.246	
0.9345	0.9325	He II	1.396	
0.9545	0.9508	H I Paϵ + ?	1.600	Blended
1.0049, 1.0124	1.0110	H I Paδ + He II	4.876	Blended
1.0830	1.0864	He I + ?	3.163	Blended
1.1114	1.1123	UNL + ?	1.496	Blended
	1.1337	?	0.637	
1.1626	1.1618	He II	2.041	
1.1901, 1.1969	1.1923	UNL + He I?	1.806	
1.2818	1.2837	H I Paβ	1.000	
1.4760, 1.4879	1.4640	He II	1.271	
1.5557	1.5463	H I Br16 + ?	0.833	
1.6109	1.6072	H I Br13	0.544	
1.7362, 1.7356	1.7352	H I Br10 + [P VIII] ?	0.496	
2.0996, 2.1120, 2.1132	2.1069	UNL + He I + ?	0.537	
2.1655	2.1648	H I Brγ	0.368	
2.1885	2.1861	He II	0.213	
2.3205, 2.3214	2.3248	[Ca VIII]	1.544	
2.4827	2.4848	[Si VI]	0.905	Line cutoff

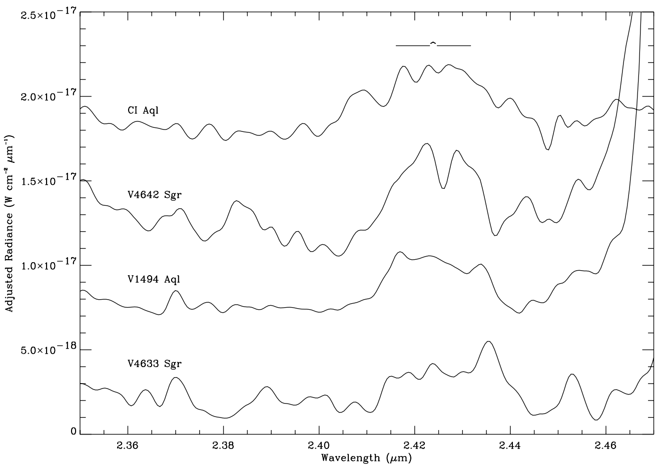

FIG. 9.—Enlarged region around 2.4 μm showing the unidentified emission feature at 2.425 ± 0.002 observed in the 2000 July (Lick) spectrum. The central wavelength and approximate width are indicated above the spectra. The feature is weak and is in a spectral region affected by water vapor and as a result the signal-to-noise ratio is low.

Geballe (1996). These authors associated these lines with hydrogenic transitions of N V. Based on observations of V723 Cas (Nova Cas 1995), Rudy et al. (2002b) disputed this identification based on absence of other, stronger transitions from the same ion. They also exploited the comparatively narrow line widths of V723 Cas to provide the precise wavelengths quoted above. This is true for all features except that at 1.1110 μm. In V723 Cas, that feature appeared to resolve into two features, at approximately 1.1107 and 1.1132 μm, respectively. These unidentified novae lines (UNL) have been seen in several other novae (e.g., Lynch et al. 2001), and they are rarely, if ever, present during the early, low-excitation stage. They first appear about the same time as the He II lines but usually before any of the coronal lines become evident. In 2000 June some of these lines may have been present. By July, they were clearly visible, and they persisted until the very latest stages of our observations. The relatively late appearance of the UNL may indicate that they are of medium to high excitation (tens of eV) and require relatively low electron densities.

The 2000 July spectrum from Lick showed an unidentified line at 2.425 ± 0.002 μm (Figs. 8 and 9). This line was first detected by Evans et al. (1997) who observed it in the late time spectrum of V705 Cas (Nova Cas 1995). It has also been seen before in V4633 Sgr (Lynch et al. 2001), V1494 Aql (=Nova Aquilae 1999 No. 2; Venturini et al. 2000; Rudy et al. 2001), and V4642 Sgr (=Nova Sagittarii 2000; Lynch et al. 2000), but we have thus far been unable to identify it.

The line was present the following month but seems to have largely disappeared by 2000 November. It has the about same width as the rest of the lines in the spectrum, i.e., 3000 km s^{-1}. The feature does, however, appear in four different novae and seems to follow the behavior of the previous unidentified lines in the sense that it does not appear until the shell has entered a medium excitation stage. Evans et al. (1997) tentatively identified the feature with the 9–8 transitions of C IV. The absence of transitions at 2.08 μm makes this unlikely.

Even considering the Doppler width contribution to the uncertainty in the wavelength of the 2.425 μm line, it is unlikely to be confused with the H_2 1–0 $Q(5)$ line that is located at 2.4548 μm. The H_2 1–0 $Q(3)$ line falls at 2.4237 μm, but the absence of other H_2 lines makes this line seem like a remote possibility. It would also be extraordinarily unlikely that a molecular line would suddenly appear, while the rest of the shell was showing unmistakable evidence of an increasingly hardening spectrum from the WD, i.e., emerging He II lines.

3.4. *Late Time Spectra—2000 Nov to 2001 June*

After 2000 September, CI Aql was becoming so faint as to render high signal-to-noise spectra difficult to obtain. It appeared that the coronal lines continued to dominate the spectrum, and the changes in the spectra from month to month were becoming less significant. Most lines weakened and ultimately became undetectable. By 2001 June, the only two lines that we could reliably identify were He I 1.0830 μm and [Ca VIII] 2.3205 μm. This behavior is typical of most novae.

4. REDDENING AND DISTANCE

The intrinsic flux ratios of the Lyβ-fluoresced O I lines at 0.8446 and 1.1287 μm are precisely known and therefore any departure from them is usually a good indicator of interstellar reddening and continuum fluorescence, the latter of which is estimable from the strength of the O I 1.3165 μm line (Rudy et al. 1991a). Based on CI Aql's O I line ratios, we find that $E(B-V) = 1.50 \pm 0.15$, assuming Lyβ fluorescence is the main contributor to the O I lines 0.8446 and 1.1287 μm with corrections for continuum fluorescence (Rudy et al. 1991a, 1991b). This value is higher than, but still consistent with, K01's finding of $0.8 < E_{B-V} < 1.5$. For an assumed value of $A_V/E_{B-V} = 3.1$, we find the visual extinction $A_V = 4.6 \pm 0.5$. The absolute visual magnitude at peak brightness was obtained by using Della Valle & Livio's (1995) relation between t_2 and M_v, resulting in $M_v = -7.55 \pm 0.5$. Using the standard expressions relating M_v, m_v, A_v, and distance, we find the distance of CI Aql is then 2.6 ± 1.3 kpc. Based on colors, Hachisu, Kato, & Schaefer (2003) estimate the distance at 1.6 kpc. Using a photometric model of the system, Lederle & Kimeswenger (2003) find the distance and the interstellar foreground extinction to be 1.55 kpc and $E_{B-V} = 0.98$, respectively.

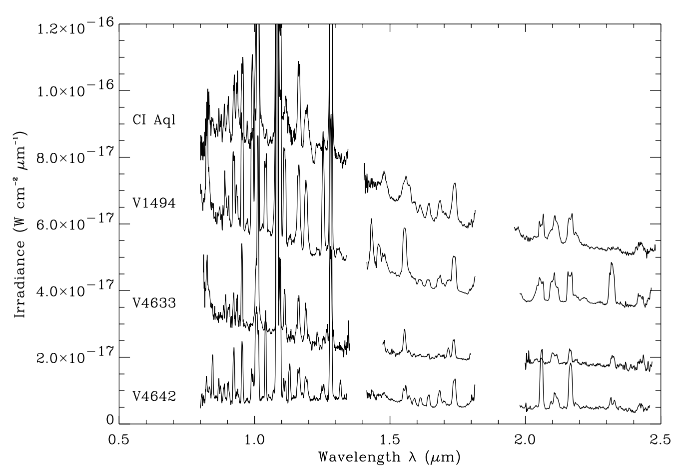

FIG. 10.—CI Aql's early spectra are similar to those seen previously in V4642 Sgr = Nova Sagittarii 2000 (Lynch et al. 2000), V1494 Aql = Nova Aquilae 1999#2 (Venturini et al. 2000; Rudy et al. 2001), and V4633 Sgr = Nova Sgr 1998 (Lynch et al. 2001). Except for the line widths and continua shapes, the spectra have nearly the same emission lines. Although the age and speed class of the novae shown here vary, all are in the early to intermediate excitation stage.

5. DISCUSSION

CI Aql's early spectra (2000 May and June) are similar to those seen previously in V4642 Sgr (=Nova Sagittarii 2000; Lynch et al. 2000), V1494 Aql (=Nova Aquilae 1999 No. 2; Venturini et al. 2000; Rudy et al. 2001), and V4633 Sgr (=Nova Sgr 1998; Lynch et al. 2001). In Figure 10, we show all four spectra. Note that except for the line width and continuum shapes, the spectra have nearly the same emission lines. Most of the lines are from permitted H I Paschen and Brackett series, and some of the stronger He I and He II lines are also present. He I 1.0830 μm is clearly present, but is not as strong as we have seen in other novae. The Lyβ-fluoresced O I lines at 0.8446 and 1.1287 μm are prominent in May but have all but vanished by June.

The strength of the N I lines suggests that CI Aql's shell is overabundant in nitrogen. This may mean that mixing is taking place and some of the WD intrinsic (as opposed to accreted) material is being ejected: This is somewhat at variance with the idea that the ejecta of U Sco–type RNe have nearly solar abundances. The same can be said about the elevated helium abundance noted earlier by Burlak & Esipov (2001).

6. CONCLUSIONS

We presented an unusually complete time series of infrared spectra of CI Aql's 2000 outburst. With many spectra taken only weeks apart for many months, lines that have previously passed unnoticed or which were judged questionable can now be confirmed. In CI Aql's case, these included weak N I and He I and He II lines.

The most interesting finding about CI Aql is that it appeared to be overabundant in nitrogen. It also showed an unidentified feature at 2.425 ± 0.002 μm that may have a similar origin similar to the five previously unidentified novae lines. This feature has now been observed in several other novae.

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