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IUE AND OPTICAL SPECTRA OF AL COMAE BERENICES DURING A RARE SUPEROUTBURST

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ABSTRACT

We present optical spectra from 3 to 21 days and *IUE* spectra at 10 and 19 days following the outburst of the extreme amplitude, very short orbital period cataclysmic variable AL Com after a 20 yr quiescent interval. The *IUE* spectra have no evidence of P Cyg profiles and show an early presence of Lyα absorption, which may be indicative of a 25,000 K white dwarf. The optical spectra show only weak Balmer absorption throughout this interval, with no dramatic changes within the 3 weeks. The spectra are compared to those available for the few other systems that had similar long outbursts following a long quiescence (WZ Sge, WX Cet, SW UMa). © *1996 American Astronomical Society.*

1. INTRODUCTION

AL Comae Berenices has been known to be an eruptive variable since 1961 (Rosino 1961) but its faintness at quiescence (V=20.1) prevented much detailed information, other than the determination of the existence of large (8 mag) amplitude outbursts in 1961, 1965, 1974, 1975 (Bertola 1964; Moorehead 1965; Scovil 1975). With the advent of efficient CCDs, photometry at quiescence was accomplished during 1987–1989 (Howell & Szkody 1988; Szkody *et al.* 1989; Howell & Szkody 1991; Abbott *et al.* 1992), which revealed periodic modulations near 41 and 80–90 min. Since the minimum period for nondegenerate secondaries is near 80 min, and the spectrum of AL Com at quiescence shows strong hydrogen emission lines (Mukai *et al.* 1990), the 41 min period cannot be the orbital period. Howell & Szkody (1991) and Abbott *et al.* (1992) suggested the possibility of AL Com being a close binary with an orbital period of 80 min and the presence of one/two active accreting poles on a magnetic white dwarf which is spinning at the 41 min period. However, the lack of precise stability in the periods is a problem for this type of model.

In 1995, after 20 yrs, AL Com again went into outburst, reaching a peak magnitude of 11.9 on April 6. The light curve from the AAVSO measurements is shown in Howell *et al.* (1996). The outburst was very long, taking 2 months to return to quiescence. During the outburst, periods near 79.3, 81.6, and 40.5 min were present early in the outburst, followed by a periodicity at 82.5 min in the later stages (Nogami & Kato 1995; Patterson 1995; DeYoung 1995; Pych & Olech 1995; Howell *et al.* 1996). The 82.5 min period was identified with a superhump period, the 79.3/81.6 min period with the orbital period, while the 40.5 min period was suggested to be a disk resonance or stream overflow phenomenon.

In the characteristics of shortness of orbital period, amplitude of outburst, length of time since the last outburst, and outburst length, AL Com lies at the extreme limits of the dwarf novae (Warner 1995). Its characteristics place it in the category of objects labelled SU UMa stars, which have superoutbursts about 0.7 mag brighter than normal dwarf novae outbursts, superhumps in the light curves during superoutburst and orbital periods less than 2 hrs. The systems with

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extreme outbursts (large amplitude and long interoutburst time scale) have sometimes been separated out as WZ Sge stars (Bailey 1979), or as TOADs (Howell *et al.* 1995), although arguments can be made as to whether these should be a separate class of objects (O'Donoghue *et al.* 1991). Irrespective of the classification details, it is fundamental to understand the physical properties leading to the extreme ranges. Observational data have shown that long quiescent intervals are linked to long outburst lengths (Szkody & Mattei 1984) and outburst instability calculations (Howell *et al.* 1995) have shown that the extreme amplitudes and long intervals can only be produced in systems with very low-mass transfer and viscosity values. Thus, these systems provide a means to study the effects of accretion in its most extreme mode. The study of white dwarfs that are apparent in systems like U Gem (Kiplinger *et al.* 1991; Long *et al.* 1994) has revealed that the white dwarf is affected by the outburst and subsequently cools. The extreme duration of the outburst in these special systems provides the ideal laboratory to pursue the effect of this heating.

Of the roughly 40 SU UMa stars listed in Warner (1995), there are only 5 (WZ Sge, WX Cet, LL And, SW UMa, and HV Vir) that have timescales between outbursts of more than 3 yrs and corresponding outburst durations of more than 2 weeks. Of these, only WZ Sge has been closely followed during its outburst (1978 Dec 1 after 32 yrs at quiescence) and decline with *IUE* and optical spectra (Fabian *et al.* 1980; Ortolani *et al.* 1980; Patterson *et al.* 1981; Holm 1988; Szkody & Sion 1989). For WX Cet (a superoutburst after 26 yrs at quiescence), there are only *IUE* spectra at 14 days past outburst (Downes 1990) and optical spectra from days 6–11 (O'Donoghue *et al.* 1991). Lastly, SW UMa has been observed with *IUE* at days 5 and 9 in relatively short superoutbursts after quiescent intervals of only 1 yr (Szkody *et al.* 1988; Howell *et al.* 1995). Thus, there is a lack of a good database of what actually happens during the long outbursts and decline of the extreme systems. This is especially frustrating since the results for WZ Sge have turned out to be so intriguing.

While the optical flux of WZ Sge reached quiescence in 4 months, the UV flux decreased by an order of magnitude in 2 weeks but took more than 3 yrs to stabilize at a quiescent value. Near outburst, the spectra were similar to optically thick disks, but as the UV flux declined, a strong Lyα feature appeared, as well as the H2 quasi-molecule at 1400 Å, which could be fit to white dwarf models. These fits showed a decreasing temperature of the white dwarf, which could be modelled by equatorial accretion that included the angular momentum of the accreted material (Sparks *et al.* 1993).

In order to further study these characteristics of the outburst and cooling of extreme systems like WZ Sge, we obtained *IUE* and optical spectra during the first 3 weeks following the outburst of AL Com. We compare its UV and optical spectra to those available for WZ Sge, WX Cet, and SW UMa. Table 1 summarizes how the basic properties of AL Com compare to those for other dwarf novae and to the 3 systems mentioned above.

TABLE 1. Comparison of normal and extreme dwarf novae.

Object	Orb P (hr)	Out P	Out Amp (mag)
U Gem[a]	3.7–137.1	14–300 d	3.7±1.0
Z Cam[a]	3.6–9.1	13–27 d	3.5±1.0
SU UMa[a]	1.4–2.8	45–500 d	5.0±1.2
AL Com	1.36	1–20 yr	8.2
WZ Sge	1.36	33 yr	7.7
WX Cet	1.32	3–26 yr	8.0
SW UMa	1.36	1–4 yr	9.5

Notes to TABLE 1

[a] The range of characteristics for the whole category of this type of dwarf nova as compiled from the tables in Warner 1995.

2. OBSERVATIONS

Optical spectra were obtained using the facilities at CTIO, APO, and MDM from 3 to 21 days following the outburst peak.

The APO data were obtained on the 3.5 m telescope with the double imaging spectrograph (DIS), which uses a 512 ×512 UV-coated Tek CCD in the blue (1.09″/pixel in imaging mode) and an 800×800 TI CCD in the red (0.61″/pixel in imaging mode). In spectroscopic mode, a 1.5″ slit was used with a medium resolution pair of gratings on April 12 (830.8/1200 lines/mm in the blue and red, respectively, giving a resolution of 2–3 Å over the regions 4300–5100 and 5800–6800 Å), and with a lower resolution pair of gratings on April 26 (150/300 lines/mm with a resolution of about 12 Å) over the region from 3900–9000 Å. On April 12, spectra were obtained over a 1.75 hr interval in order to search for radial velocity variations, but lack of a guider and poor telescope tracking, combined with refraction effects, resulted in large light losses, especially in the blue portion of the spectra, for many of the spectra.

The MDM data were obtained on the 2.4 m Hiltner telescope with the Modular spectrograph, using a 600 lines mm^{-1} grating (4300–6900 Å; 1.2 Å/pixel), a 1.2″ slit and a Loral 2048×2048 CCD. In all cases, multiple (3 or 4) separate exposures were co-added into a final spectrum.

The CTIO data were taken on the 1.5 m telescope with the Cassegrain Spectrograph, using a GEC CCD, a 300 lines mm^{-1} grating, and a 3″ slit, resulting in coverage from 4650 to 7100 Å, with a resolution of about 8.4 Å.

All optical data were reduced using IRAF software to extract the spectrum, subtract sky and calibrate the wave-

TABLE 2. Spectra of AL Com.

1995 Date	Obs	Start UT	Exp(min)	*V* mag	Days past outburst
April 9	CTIO	4:08	10	12.8	3
April 10	CTIO	3:30	10	12.9	4
April 12	APO	6:52	13x6.7	13.0	6
April 16	*IUE*	18:22	75	13.5	10
April 24	MDM	5:24	3x6.7	14.4	18
April 25	MDM	5:42	3x10	14.5	19
April 25	*IUE*	22:48	110	14.5	19
April 26	APO	3:57	5	14.6	20
April 27	MDM	5:27	4x15	14.6	21

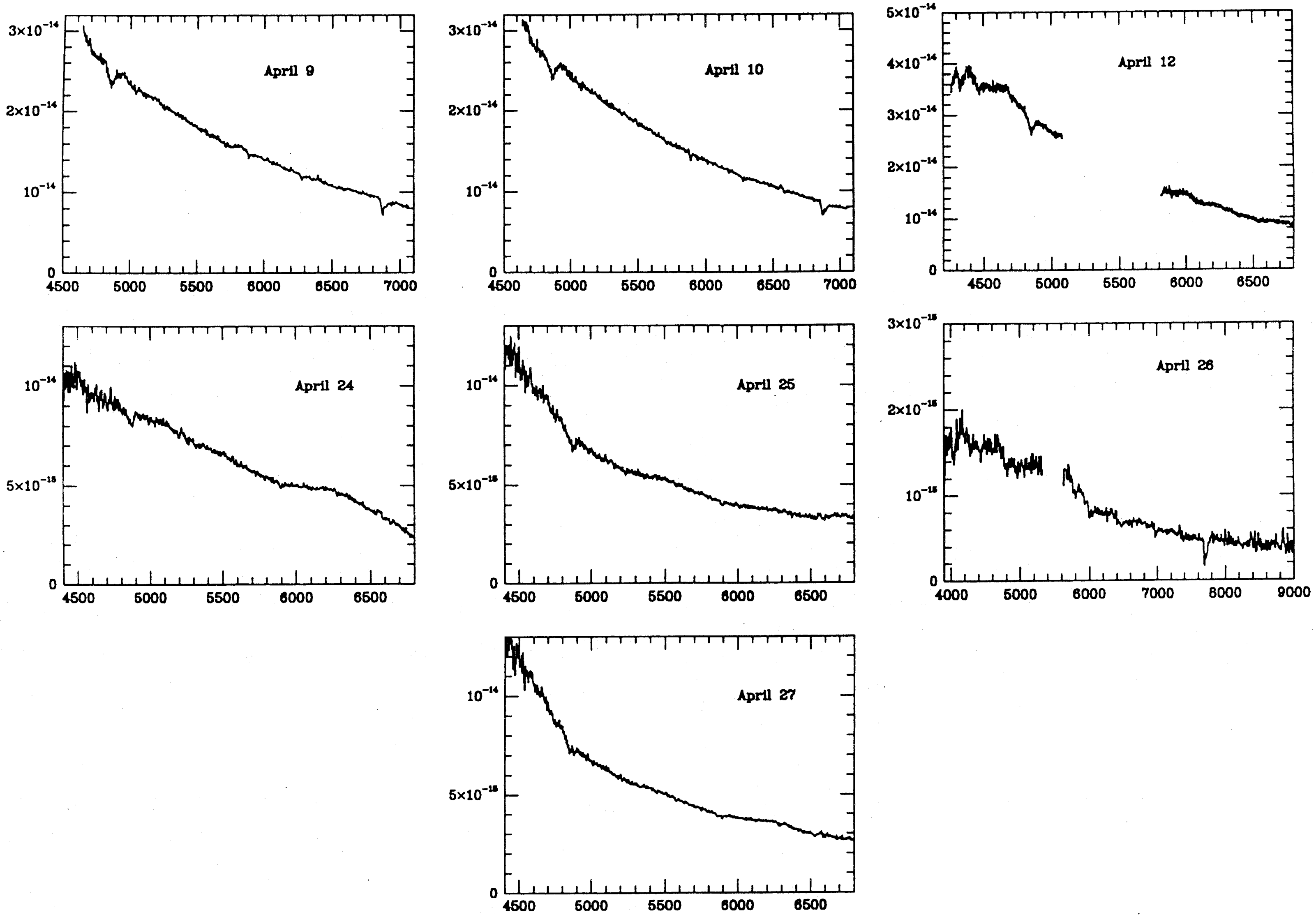

FIG. 1. Optical spectra from 3 to 21 days after outburst. The flux units are ergs cm^{-2} s^{-1} $Å^{-1}$. The peculiar flux distributions in the April 24 and 27 data are likely due to instrumental effects.

length and flux scales from comparison lamp images and spectrophotometric standards obtained on the same nights.

The *IUE* spectra were obtained in low resolution and with the large aperture using the short wavelength camera on 1995 April 16 and 25. The April 16 exposure (SWP 54446) was badly saturated in the region from 1650 to 2000 Å, but most of the shorter wavelengths were usable. The April 16 spectrum (SWP 54505) was a good exposure.

The observations are summarized in Table 2, while the optical spectra are shown in Fig. 1 and the *IUE* spectra in Fig. 2. Tables 3 and 4 summarize the line measurements.

3. OPTICAL RESULTS

As Table 3 and Fig. 1 show, the Balmer absorption lines decrease in strength, with corresponding increase in Hα emission and core emission within Hβ throughout the interval from April 9 through 21. This behavior is typical of dwarf novae during the transition from a hot, optically thick disk at outburst to a quiescent state disk (Clarke *et al.* 1984). Unfortunately, the optical spectra for WX Cet and WZ Sge are only described qualitatively in the literature, so only general comparisons can be made. The AL Com spectra are similar to that of WX Cet during its outburst after a 26 yr interval of quiescence (O'Donoghue *et al.* 1991). There is no evidence for the normal or inverse P Cygni profiles that were observed for the Hβ and Hγ lines in WZ Sge near outburst (Gilliland & Kemper 1980). However, as the inverse P Cygni profiles were only observed in WZ Sge for one day (22 days after outburst), it is possible that this phase was missed in AL Com due to the gap in optical coverage between day 6 and day 18 past outburst. Overall, there is less emission present in AL Com than is evident for WZ Sge at comparable stages past outburst. Ortolani *et al.* (1980) describe declining emission for WZ Sge during the first few weeks after outburst, with Hα, Hβ, and He II 4686 in emission and the He I and higher order Balmer lines in absorption during the first week after outburst, followed by Hβ in absorption the following week until, by 3.5 weeks past outburst, Hα had disappeared and the H and He I absorption had weakened. At times, the spectra appeared basically featureless. This behavior of weak lines is apparent in our spectra and in the time-resolved data obtained on April 12, where the sharp cores apparent in Fig. 1 disappeared from one spectrum to the next.

Some of the effect of the lower emission line strength in AL Com than WZ Sge may be due to a lower inclination of AL Com, as a comparison of *IUE* spectra of dwarf novae at different inclinations has shown that high inclination systems have more prominent (or only) emission (La Dous 1993). WZ Sge has a very short (less than 4 min), shallow (0.15 mag) eclipse resulting in an estimated inclination of 75° (Gilliland *et al.* 1986). Since the best time-resolved data on AL Com (Abbott *et al.* 1992) has only 2–3 min time resolution, an eclipse like WZ Sge would not have been detected. However, the long data strings of Abbott *et al.* (1992) rule out the presence of deep eclipses of the white dwarf, and hence, the inclination is likely to be $\leqslant 75°$. A similar situation exists for WX Cet (Mennickent 1994). Since the WX Cet data over 6 days and our data over 18 days show little spectral variation while the optical magnitudes declined by 1.0 and 1.8 mag, respectively, the implications are that the optically emitting portions of the disk remain in a relatively similar condition while the overall flux declines.

4. *IUE* DATA

The two *IUE* spectra, at 10 and 19 days past outburst, show changes in both the continuum and lines. The first spectrum has a relatively flat continuum (slope of log F vs log λ near 1) with weak absorption of Si III, C II, and Si IV, and with C IV in weak emission (Table 4). Nine days later, when the optical flux had dropped by a factor of 2.5, the flux at 1900 Å dropped by a factor of 1.7 and the flux at 1150 Å had decreased by a factor of 1.2. The overall continuum slope of the *IUE* spectrum had steepened to $\simeq -2.3$. While C IV changed to weak absorption and the other absorption lines had weakened, a strong Lyα absorption feature appeared.

For comparison, the low resolution spectrum of WZ Sge obtained 14 days past outburst is also shown in Fig. 2 and its line measurements and those of WX Cet (Downes 1990) and SW UMa (Szkody *et al.* 1988; Howell *et al.* 1995) are listed in Table 4. As in the optical, the emission lines (of C IV and N V) in WZ Sge are stronger than for the other systems, while AL Com has weaker lines. The most interesting change concerns the broad Lyα absorption that becomes apparent in the second spectrum of AL Com and the steeply rising continuum blueward of Lyα. In contrast, the 2 *IUE* spectra of SW UMa at 5 and 9 days past outburst (Howell *et al.* 1995) show a decreasing depth of Lyα and a flatter continuum as a function of time, WX Cet has only one measurement at 14 days (showing Lyα), while the broad Lyα absorption did not appear in WZ Sge until 7 months after outburst (Holm 1988). However, there is no clear record of the onset since WZ Sge was too close to the sun for *IUE* observations from 1980 Jan to July (32–187 days after outburst). Since the Lyα feature in WZ Sge is consistent with the interpretation of an origin in the cooling white dwarf, it could also be the explanation for the sudden appearance at day 19 after the outburst of AL Com.

The e-folding time for the decline of the white dwarf temperature after the pulse of accretion involved with a dwarf nova outburst appears to roughly scale with the outburst duration (Sion & Szkody 1990). Since the outburst of AL Com lasted only half as long as in WZ Sge, we would expect that the cooling would progress at a faster pace, if the response of the white dwarfs to accretional heating is similar in the two systems. Thus, the Lyα feature could be the first clue that the inner disk was thinning out and the hot white dwarf was evident. This explanation would fit in with the scenario proposed to account for the outburst light curve (Howell *et al.* 1996) where there is a relatively slow decay for the first 3 weeks until a fast decay causes a cooling front to start, resulting in a rapid evacuation of the hot disk and corresponding optical decline. The fast optical drop actually occurs a few days after the *IUE* observations, but the UV may be revealing the inner disk changes first.

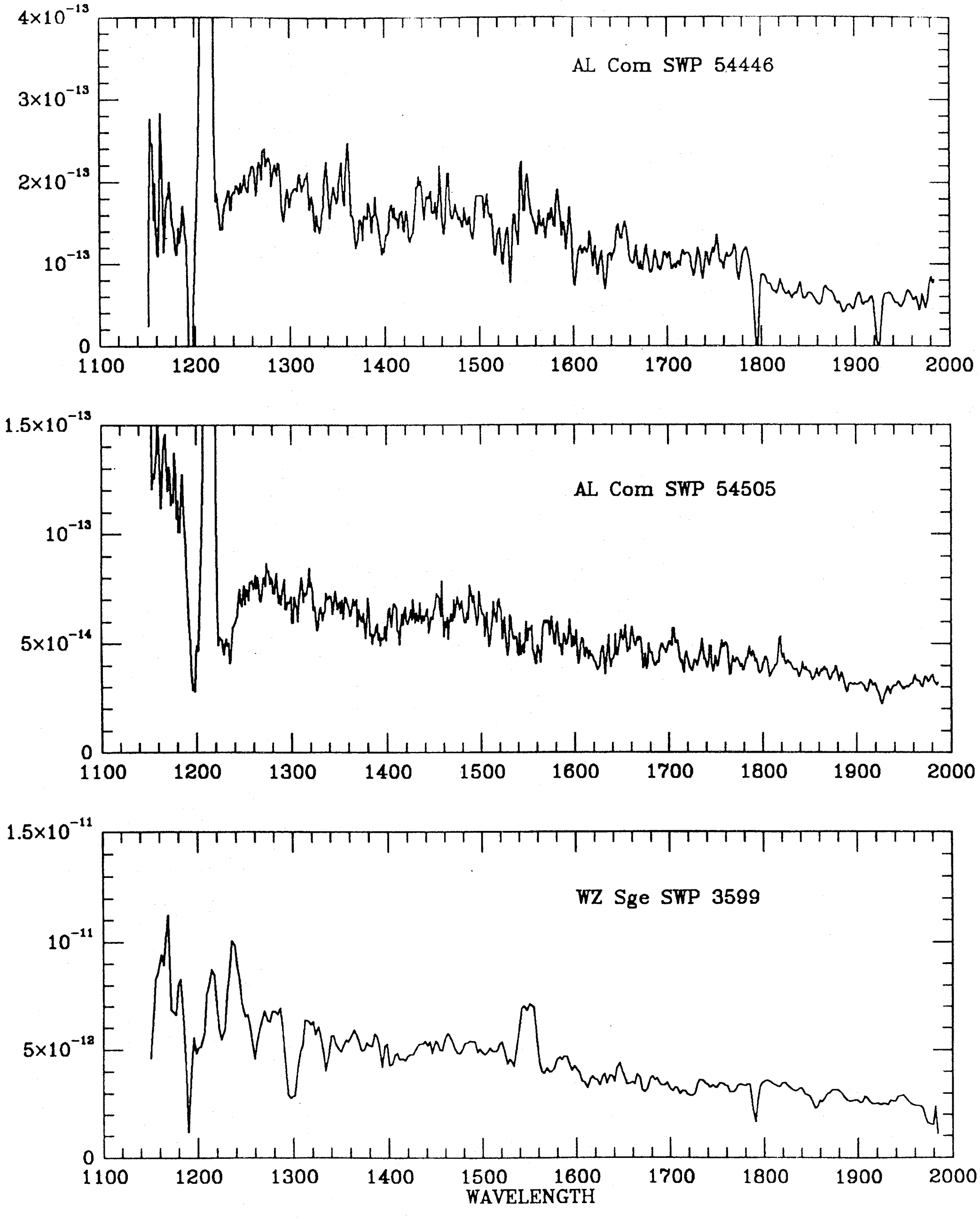

FIG. 2. *IUE* spectra obtained at 10 (SWP 54446) and 19 (SWP 54505) days past outburst. SWP 54446 has been smoothed by 3 and most of the spectrum is saturated longward of 1650Å . A spectrum of WZ Sge obtained 14 days past outburst (SWP 3599) is shown for comparison.

To test this conjecture, we have carried out preliminary synthetic disk and photosphere spectral fits to the *IUE* spectrum of AL Com obtained 19 days post outburst (SWP 54505). Due to the relatively low signal to noise of this spectrum, the absorption features due to transitions of metals are only marginally identifiable. Our synthetic spectra were constructed with the codes TLUSTY, SYNSPEC, and DISKSYN (Hubeny *et al.* 1994). Three models with $T_{\rm eff}$=30,000, 25,000, and 20,000 K, each with log g=8 and solar abundances, were compared with the *IUE* data. The Lα profiles of the models at $T_{\rm eff}$=30,000 K and $T_{\rm eff}$=20,000 K are, repectively, far too narrow and far too broad compared to the observed profile. The model with $T_{\rm eff}$=25,000 K agrees very well with the width of the observed profile and with the observed continuum slope (Fig. 3). There is some evidence for Si III (1300 Å), Si IV (1393,1402 Å), Si II (1260,1265 Å), C II (1335 Å), and C IV (1550 Å) absorption in the data, all of which are also present in the 25,000 K solar composition model. However, the synthetic Si II lines are much deeper than observed, while the observed Si IV is stronger than the model predicts. Of course, since a single temperature white dwarf synthetic spectrum was used in our preliminary fits,

TABLE 3. Equivalent widths of Balmer lines.

Line	April Date 9	10	12	24	25	26	27
Hβ abs	3.7	2.9	2.8	2.4	1.5	1.3	0.7
Hα em	0.5	1.1	0.4	2.3	1.5	–	2.2

TABLE 4. Equivalent widths of *IUE* lines.

Object	SWP	Si III	C II	Si IV	C IV	Days[a]	Slope[b]
AL Com	54465	1.9	3.1	2.6	3.9em	10/60	− 1.0
AL Com	54505	1.7	1.5	2.6	2.3	19/60	−2.3
WZ Sge	3599	8.5	1.6	3.3	13.6em	14/120	−2.0
WX Cet[c]	36511	3.4	0.6	6.3	6.5(0.6em)	14/21-70	−2.2
SW UMa[d]	44266	3.8	2.1	3.0	1.4(1.9em)	9/14	−2.0

Notes to TABLE 4

[a] Days past outburst/Total length of optical outburst.

[b] Continuum slope between 1200 and 2000 Å for log F vs log λ.

[c] Values taken from Downes 1990.

[d] Values taken from Howell *et al.* 1995.

the photospheric properties should be viewed as being ''average'' since the white dwarf may be hotter in the equatorial region where the disk matter first accretes tangentially. Moreover, the silicon line strengths may manifest an abundance gradient with latitude with equatorial abundances from the freshly accreted matter being different from the abundances at higher latitudes. However, without higher signal-to-noise spectra, we cannot carry out a detailed composite spectral analysis with the inclusion of an accretion belt and/or inner disk contribution.

As a check on the white dwarf interpretation, we used the normalization between the model and observed flux, and assumed a reasonable white dwarf to calculate a distance ($d^2 = 4\pi r^2$/norm). For a normalization of 2.7×10^{-23} at 1450 Å and a 0.6 $M_\odot$ white dwarf having $T_{\rm eff}$=25,000 K and radius of 7×10^8 cm, the white dwarf would have a distance of 155 pc and an observed V mag of 16.0. The error bar on our distance from the temperature fits alone is on the order of 60 pc. Our value for the distance is comparable to that determined by Sproats *et al.* (1996) from fitting a secondary to the observed K band magnitudes (190–260 pc). The observed V mag of 14.5 at the time of the *IUE* spectrum would also mean that the accretion disk can dominate the optical flux (to account for the superhumps that are still apparent on the 25th of April; Pych & Olech 1995; Howell *et al.* 1996). In addition, since we know the quiescent V mag and since, as in WZ Sge, the available quiescent spectrum does not show a dominant H absorption feature from the white dwarf around Hα (Mukai *et al.* 1990), we can make some estimate of the changes to this white dwarf fit that would be needed to be compatible with AL Com at quiescence. If the white dwarf at

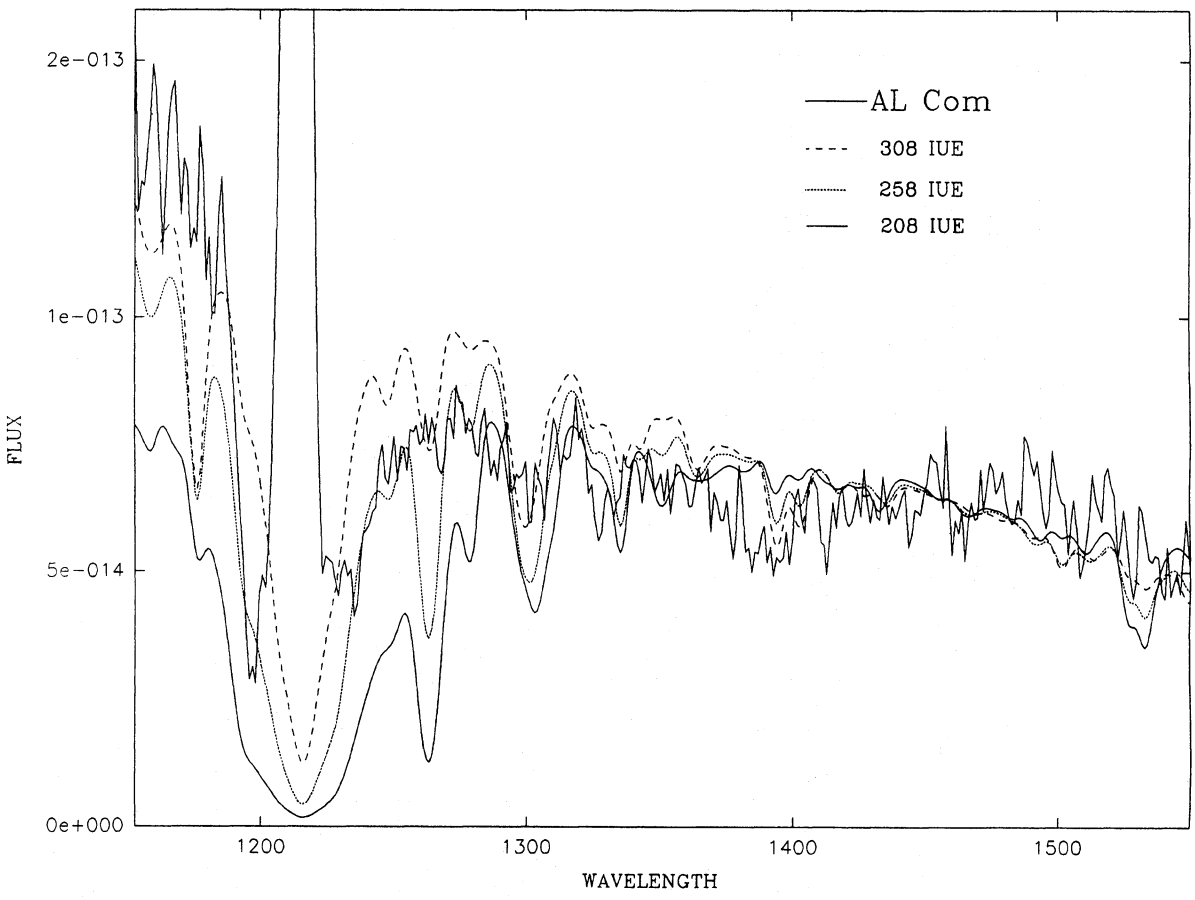

FIG. 3. The fits of the Hubeny models with log g=8 and T of 30,000 K (308), 25,000 K (258), and 20,000 K (208) to SWP 54505.

quiescence contributes about half the V flux, it would have a V mag of about 20.7 (M_v of 14.7) and would have to cool from 25,000 to 9000 K to account for this difference, or undergo a temperature change from 25,000 to 15,000 K (the white dwarf temperature of WZ Sge at quiescence) with an accompanying radius decrease of the hot zone by about 30%. These are all reasonable numbers for the temperatures of white dwarfs in cataclysmic variables (Sion 1991).

Since Lyα can also be produced by the accretion disk, we also made a preliminary comparison between the same *IUE* spectrum and a synthetic spectrum of a steady-state accretion disk with a mass transfer rate of 3×10^{-9} $M_\odot$ yr^{-1}, a white dwarf mass of 0.6 $M_\odot$, and a disk inclination of 60°. This fit produced poor agreement with the *IUE* data primarily because the disk Lyα profile was too narrow, the continuum shortward of 1550 Å was too steep (compared with the much flatter observed continuum between 1550 Å and the Lyα turnover), and the absorption features of the metals were too broad to satisfactorily match the observed spectrum. Since an accretion disk model is dependent on many parameters, including how to treat viscosity, irradiation, opacities, etc. (Hubeny 1991), this poor fit does not rule out the possibility of some type of accretion disk producing the UV spectrum, however it would mean that the disk in AL Com is different than in other outbursting dwarf novae like Z Cam or novalikes like IX Vel which do give reasonable fits with models of this type (Long *et al.* 1991, 1994b). Thus, the lack of Lyα absorption in the first *IUE* spectrum (SWP 54446), when the accretion disk should also be present, and the better fit with the white dwarf model leads us to favor the interpretation that the Lyα region at 19 days past outburst is dominated by a hot white dwarf, and the inner part of the accretion disk is thinning out by accreting or being evaporated (Liu *et al.* 1995).

5. CONCLUSIONS

Optical and *IUE* spectra of AL Com obtained during the first 3 weeks following a long outburst show only weak absorption lines, in comparison to the emission and P Cygni profiles apparent in WZ Sge following its long outburst. By the 19th day past outburst, a strong Lyα feature was apparent. Fitting this spectrum with white dwarf and disk models results in a better fit for a 25,000 K white dwarf, although there is disagreement between the observed and theoretical strengths of Si II and Si IV absorption lines. The narrowness of the metallic absorption strongly suggests formation in the accreted atmosphere of the white dwarf in the system. Further observations of the UV flux decline can be used to determine the type of accretion occurring at outburst, as was done for WZ Sge following its long outburst (Sparks *et al.* 1993). Confirmation of the temperature and contribution of the underlying white dwarf can be provided by UV observations with a more sensitive satellite than *IUE* when AL Com is far from outburst.

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