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THE LOW STATE OF AM HERCULIS: OBSERVATIONS FROM 0.12 TO 10 MICRONS

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ABSTRACT

Observations of AM Her during a low state over a wavelength range from 0.12 to 10 μm are reported. These include *IUE* ultraviolet spectra, light curves at U, B, V, R, J, H, K, and magnitudes at L, M, and N. The UV observations reveal a nearly Rayleigh-Jeans continuum spectral distribution and broad Lyα-absorption from a hot ($T_{\rm eff} \approx 50{,}000$ K) white dwarf. Of the strong emission lines present in the high state, only weak C IV (1550 Å) and Mg II (2800 Å) features remain. The optical light curves are markedly different from the high state, while the infrared light curves are similar in appearance to the high state. The infrared variations cannot be explained solely by the ellipsoidal variations of a secondary star which is heated by an accretion column. The 10 μm flux is less than the high state, but it is not possible to tell if the excess noted during the high state is still present. We use the large available wavelength range to constrain the relative contributions of the white dwarf, the red dwarf, and the accretion columns.

Subject headings: stars: individual — stars: white dwarfs — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

The AM Her system is a close binary X-ray source with a 3.1 hr orbital period and a strong magnetic field (Hearn and Richardson 1977; Tapia 1977). It has been extensively studied in its bright state ($V \approx 12.5$) at X-ray, ultraviolet, visual, and infrared wavelengths (reviews in Kruszewski 1978; Chiappetti, Tanzi, and Treves 1980). The high state observations revealed that the luminosity of the system is dominated by the emission from one or two accretion columns which are formed by the transfer of material from a late main-sequence star to a magnetic white dwarf. Using observed Na I absorption lines and the lack of observed TiO band heads Young and Schneider (1979) determined the secondary to be an M4–M5V star with $V \approx 17.5$.

When AM Her began an extended low state ($V \approx 15.2$) in 1980 May (Mattei 1980), it became possible to investigate the stellar components of the system when the accretion luminosity of the column was presumably low. Optical data obtained by several groups showed features that were very different from the high state. Spectroscopic observations revealed Zeeman split Balmer lines, implying that the magnetic field strength of the white dwarf is 10–20 Mgauss (Schmidt, Stockman, and Margon 1981; Latham, Liebert, and Steiner, 1981; Hutchings, Crampton, and Cowley, 1981; Young, Schneider, and Shectman 1981). Sharp emission lines, presumably arising from a heated secondary star, were present, and the Balmer decrement was consistent with recombination values. Strong TiO bands in the red spectra confirmed the presence of an M4–M5V secondary in the system. Photometry at 4400 and 6100 Å covering almost an orbital cycle was reported (Patterson and Price 1981). They suggested that the blue light originates from a hot spot near the pole of the white dwarf and the red light from a secondary star which is heated by the accretion column.

Since the emission from the components in the system is expected to peak in the UV (for the white dwarf) and the IR (for the secondary) with a major contribution to the optical from the accretion column, we have attempted to put together a data set over this large wavelength range. We report observations obtained from 1980 June to 1980 September, which include ultraviolet *IUE* spectra (0.12 to 0.30 μm) covering four orbital

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cycles, optical broad band light curves (0.36 to 0.81 μm) covering several cycles, IR (1.25 to 2.2 μm) light curves covering one cycle, and single measurements at 3.5, 5, and 10 μm. These observations are compared with those at the high state and attempts to sort out the contribution from the white dwarf, secondary, and accretion columns are made by using the total flux distribution from UV through IR and by calculating the expected variations from a Roche-lobe filling secondary star.

II. OBSERVATIONS

a) *Ultraviolet*

IUE spectra at low dispersion with the large aperture were obtained on 1980 June 22, June 30, and September 28. The visual magnitude obtained from the measurements with the Fine Error Sensor was between 15.0 and 15.5 during these observations. On June 22, one short wavelength exposure of 90 minutes was followed by a long wavelength exposure of 120 minutes. These spectra were calibrated with the 1980 May (Bohlin and Holm 1980) calibration and are shown in Figure 1. The only emission lines present are weak C IV 1550 Å and Mg II 2800 Å. The other notable feature is a broad absorption trough about Lyα.

Six spectra of 1 hour duration each, alternating between long and short wavelengths, were obtained on June 30. Unfortunately, some of these spectra were obtained when the object was near the edge of the aperture, so the 20% variability seen between exposures could not be ascribed to orbital variation. Four 40-minute exposures in September (3 SWP and 1 LWR) were consistent (to within the error bars) with the June 22 data. Again, there was some problem with the object sliding out of the aperture. Taking into account the aperture effect and the error bars of the shorter time exposures, it appears that the spectrum is constant, even during the phase corresponding to the eclipse of the high state Rayleigh-Jeans component (see § III). The discontinuity between the long and short exposures is seen on the other exposures and is probably due to the lower sensitivity of the LWR camera at 1900 Å and to the edge of the aperture problem. The absorption and emission seen shortward of C IV are not permanent features on the other spectra and are probably a result of a radiation hit and a reseau in the background at those wavelengths.

b) *Optical*

Optical photometry with standard *UBV* filters and an *R*2 ($\lambda_{eff} = 0.81$ μm) filter was obtained on 1980 August 16 and 19 at Manastash Ridge Observatory (MRO) with the University of Washington 76 cm telescope. Integrations of 20 s were used, giving uncertainties of $< \pm 0.02$ mag at each wavelength. The data, which covered an orbital cycle on each night, are shown in Figure 2.

c) *Infrared*

The *JHK* light curves were obtained at Kitt Peak National Observatory with the InSb system Otto on the 1.3 m telescope on 1980 June 3. A signal-to-noise ratio of 20/1 was obtained in about 2 minutes of integration time for each filter, and the filters were cycled sequentially. One 15 minute integration at filter *L* was done with a signal-to-noise ratio of 3. The data are shown in Figure 3 along with the *JHKL* light curves obtained with the same equipment when AM Her was in a high state (1978 July 5).

Longer wavelength IR data were obtained at the 3 m NASA Infrared Telescope Facility (IRTF) at Mauna Kea. A 3 σ upper limit giving $N = 8.4$ was made on 1980 June 8, and an upper limit on $M = 10.5$ was obtained on 1980 June 9. Both measurements entailed 3 hr integrations so that no orbital phase resolution was possible.

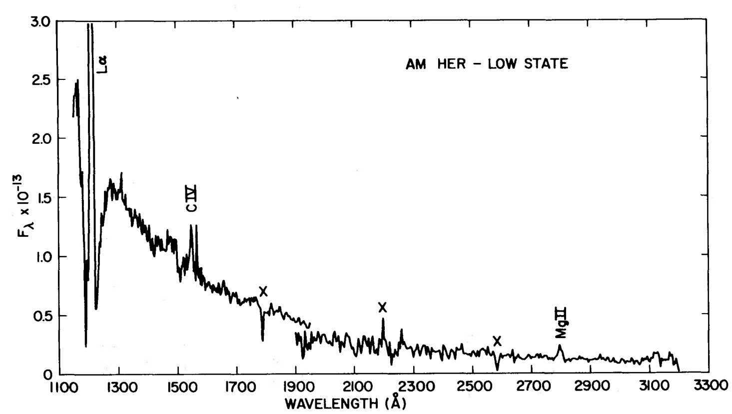

FIG. 1.—The short and long wavelength *IUE* spectra obtained on 1980 June 22. The X's mark bad pixels or regions of reseaux.

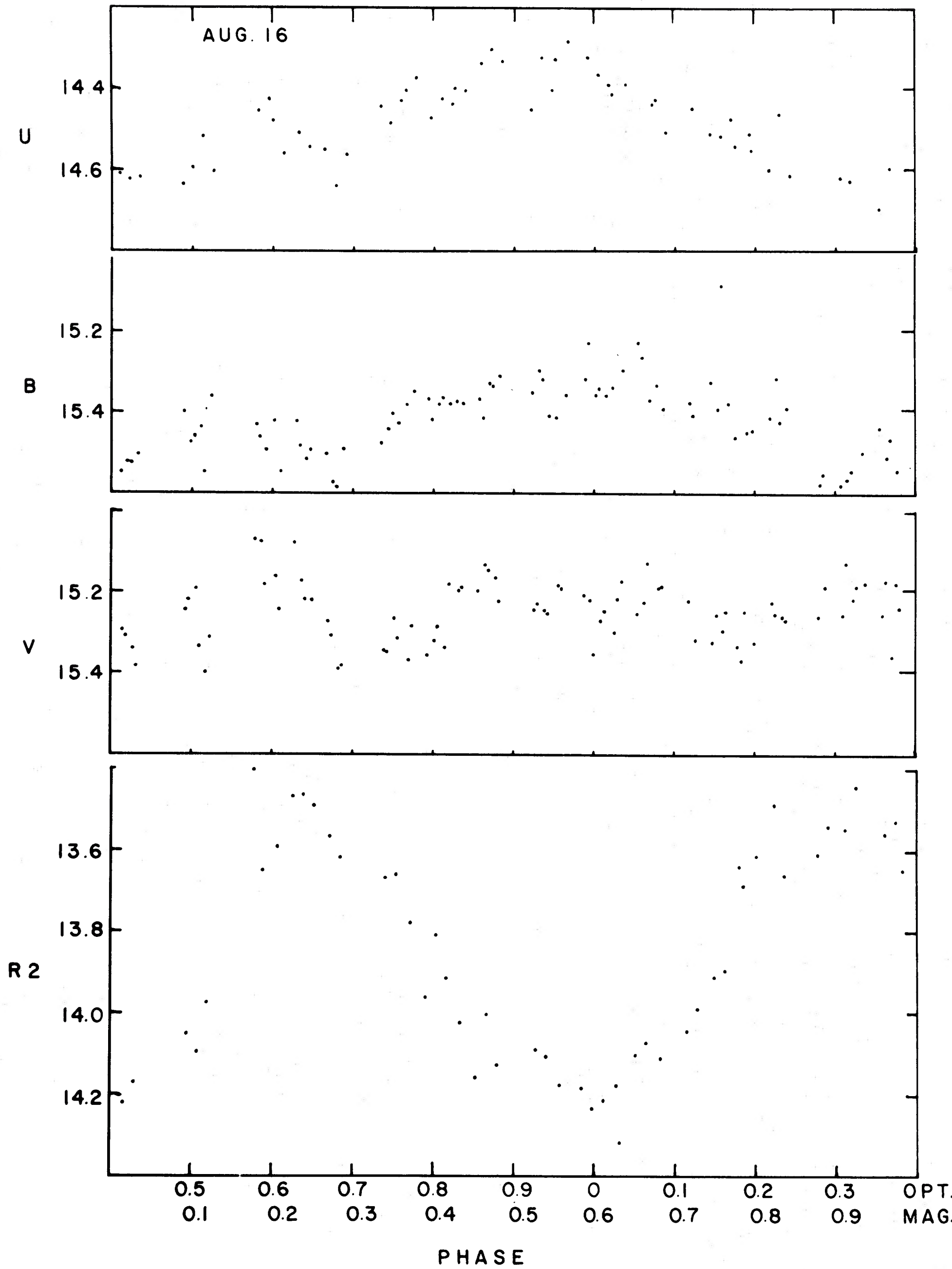

FIG. 2*a*

FIG. 2.—The optical light curves obtained on 1980 Aug. 16 (Fig. 2*a*) and 1980 Aug. 19 (Fig. 2*b*). Each point represents a 20 s integration with uncertainties of <0.02 mag.

d) *Phasing*

All phases used throughout this paper are computed according to the following:

$$\phi_{\rm opt} = 2443014.712660\ \mathrm{HJD} + 0.12892774E\,,$$

$$\phi_{\rm mag} = 2443014.765\ \mathrm{HJD} + 0.12892774E\,.$$

The optical phasing is from Szkody and Brownlee (1977) and refers to phase 0 at the primary optical minimum at V during the high state. The magnetic phasing is from Tapia (1977) and refers to phase 0 at the time of the linear polarization spike. The period in each case is from Young and Schneider (1979).

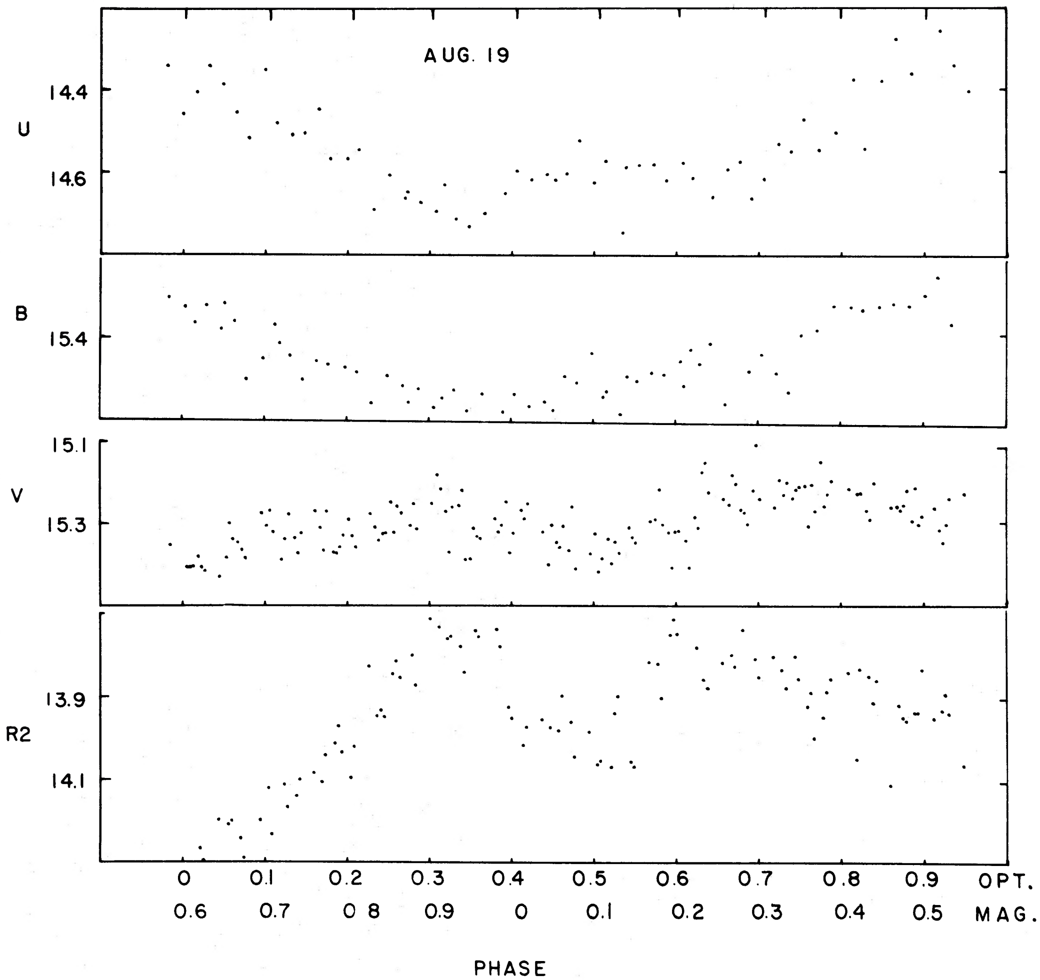

FIG. 2b

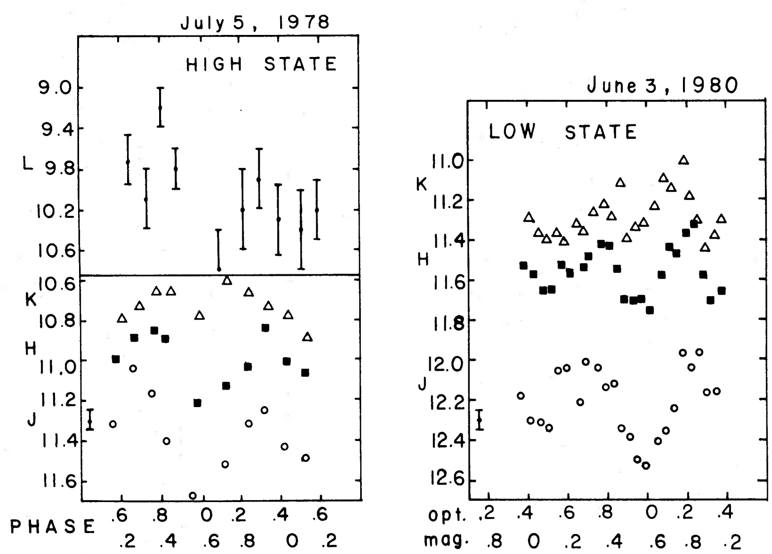

FIG. 3.—The infrared light curves at 1.25 μm (○), 1.65 μm (■), and 2.2 μm (△) obtained during high and low states

TABLE 1

DIFFERENCES BETWEEN HIGH AND LOW STATES

Filter	Magnitude Difference
1500 Å	1.0
U	2.5
B	2.4
V	2.5
R2	1.9
J	0.9
H	0.6
K	0.6
L	>1.2
M	>2.0
N	>2.3

III. DISCUSSION

a) *Differences between High and Low States*

Table 1 summarizes the decrease in magnitudes at the various wavelengths under study. The following section describes the individual changes and model implications at different wavelengths.

i) *Ultraviolet*

During the high state, *IUE* spectra show a continuum which is the sum of two power-law components: an $F_\nu \propto \nu^{-1}$ component which is always present, and an $F_\nu \propto \nu^2$ component which disappears during the X-ray eclipse (Raymond *et al.* 1979). The ν^{-1} component is identified with the accretion column, and the ν^2 component as the tail of a ~30 eV blackbody which produces the soft X-ray emission. Strong emission lines of N V, Si IV, C IV, and He II are present.

The low state observations are dramatically different in three ways:

1. The ν^{-1} component has disappeared and the spectrum is basically ν^2 (Rayleigh-Jeans) with a decrease in flux level at 1500 Å by a factor ~2.5 from the blackbody flux component at the high state (Raymond *et al.* 1979).

2. The strong line emission has disappeared, and only weak lines of C IV and Mg II emission are left. The C IV flux from the low state exposures ranges from 2 to 5×10^{-13} ergs cm^{-2} s^{-1}, which is only 1–2% of the high state flux in this line. The flux in Mg II is 0.7–1.6×10^{-13} ergs cm^{-2} s^{-1}.

3. A broad Lyα absorption feature has appeared. An unexplained plateau between 1250 and 1270 Å is apparent in the June data but has disappeared in the September data.

These apparent changes in the UV are all consistent with the view that the UV flux in the low state arises from the white dwarf, while in the high state, the accretion column dominates the UV luminosity.

The continuum flux throughout the UV can be compared to Wesemael *et al.* (1980) white dwarf models to estimate the temperature of the white dwarf. The best fit slope to the observed *IUE* fluxes from 1275 to 3050 Å is $\lambda^{-3.4}$ which corresponds to a model at $T = 60{,}000$ K. However, models from 40,000 to 70,000 K are within the observed error bars.

The absorption profile of Lyα can also be used to estimate the temperature of the white dwarf. Figure 4 shows the flux with respect to the continuum in the average spectrum of the June 30 data. The data from September are in excellent agreement with this profile except that the plateau at 1250 Å is absent. There are no points at the line center because of geocoronal Lyα emission and a reseau near 1193 Å. The figure also shows Lyα model profiles from Wesemael *et al.* (1980). The models shown are 30,000 and 50,000 K models of $\log g = 8.0$ pure hydrogen white dwarfs. While the lower temperature model fits the data quite well, it does not include Zeeman splitting. The optical spectra of Schmidt, Stockman, and Margon (1981) and Latham, Liebert, and Steiner (1981) indicate that the magnetic field of the white dwarf is 1.3 to 2×10^7 gauss. The calculations of Smith *et al.* (1972) then imply that Lyα components lie 10 to 15 Å away from the line center. Detailed models are needed to derive a firm conclusion of the white dwarf effective temperature, but it appears that a 50,000 K model with Zeeman splitting would account for the observations.

The lack of He II 1640 emission yields another temperature estimate. Fabbiano *et al.* (1981) show that the narrow component of the He II emission seen in the bright state can be attributed to recombination at the surface of the M dwarf following photoionization by

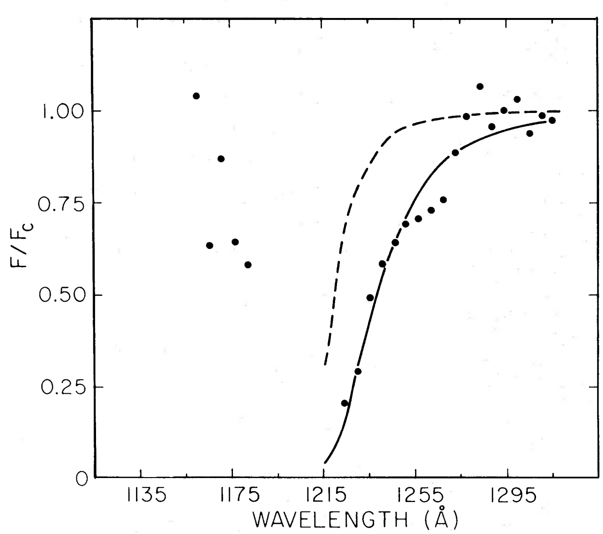

FIG. 4.—The absorption profile of Lyα with respect to the continuum flux for the 1980 June 30 *IUE* data. The dots are observations, while the solid and dashed lines are 30,000 and 50,000 K, $\log g = 8$ models, respectively (Wesemael *et al.* 1980).

XUV photons. We find that the 1640 line flux is at least 100 times below the narrow component observed in the high state (Raymond *et al.* 1979). If T_{BB} was previously ~ 28 eV and the emitting area has remained the same, the upper limit on He II 1640 implies an upper limit on the low-state blackbody temperature of 11,000 K. The presence of 4686 (Patterson and Price 1980; Latham, Liebert, and Steiner 1981) indicates that the temperature is still above 30,000 K. The assumption that the Hα flux of 8×10^{-14} ergs cm^{-2} s^{-1} observed by J. Patterson and C. Price (1980, private communication) represents recombination following capture of 2.5% of the blackbody photons below 912 Å by the M star (see Fabbiano *et al.* 1981) leads to a Zanstra temperature of $\sim 45,000$ K.

Comparison of the observed flux at 1300 Å with two other hot white dwarfs of similar temperature, HZ 43 and HZ 21 (Greenstein and Oke 1979) implies that the distance to AM Her must be greater than 100 pc or the size of the white dwarf is smaller in AM Her. Studies of the polarization and Zeeman components around the orbit (Schmidt, Stockman, and Margon 1981; Latham, Liebert, and Steiner 1981) have pointed out that the white dwarf in AM Her may not have a uniform temperature and hot spot areas may be present. Thus, comparison with normal white dwarfs may not be reasonable.

ii) *Optical*

During the high state, the V light curve typically shows a primary minimum of 0.7 mag depth at phase $\phi_{opt} = 0$ and an intermittent 0.4 mag secondary minimum near phase $\phi_{opt} = 0.5$. The U and B light curves show only one minimum of about 0.3 mag depth centered near $\phi_{opt} = 0.1$. Red light curves show increasing depth of both primary ($\phi_{opt} = 0$) and secondary ($\phi_{opt} = 0.5$) minima with increasing wavelength (Priedhorsky and Krzeminski 1978; Szkody 1978).

In contrast to the high state, the V light curve during the low state shows relatively little change over the orbital cycle, while U and B have a single pronounced minima of about 0.4 mag depth at optical phase 0.5 and maxima occurs at optical phase 0. The red light curve ($R2$) is similar to the high state.

The differences in the light curves at different wavelengths at both high and low states argue for a separate origin for blue versus red light. Of course, since the U filter spans the Balmer jump and the B and V filters contain Balmer and/or helium emission lines, these filters are effectively measuring some contribution from the line emission areas as well as the continuum.

In the high state, the blue light could originate from the stream (to account for the 0.1 phase offset of the minimum from the red light) and the red light from the accretion column. At the low state, the red light could originate from the secondary star and the blue light either from the white dwarf accretion area or the heated secondary. The U and B minima could originate from the heated secondary only for those models that have inferior conjunction of the red star at $\phi_{opt} = 0.5$ (Hutchings, Crampton, and Cowley 1980). However, most models argue that inferior conjunction occurs at $\phi_{opt} = 0$ which is $\phi_{mag} = 0.6$ (Latham, Liebert, and Steiner 1980; Schmidt, Stockman, and Margon 1980; Young and Schneider 1980). This implies an origin for the blue light from the white dwarf accretion area. A secondary dominated by heating (Patterson and Price 1980) cannot explain the two distinct minima seen in the $R2$ light curve, since a single minimum would be expected at inferior conjunction of the red star (the Patterson and Price data set lacks phase coverage of the second minimum).

iii) *Infrared*

The minima of the J, H, K light curves in both states occur at the same phases, but the amplitudes at the low state are less by 0.1–0.2 mag. Since the IR light is probably a combination of emission from the secondary and the accretion area, this effect could be due to the increased dominance of the secondary over the accretion column.

Table 2 compares the IR colors of AM Her at the high and low states with those of M4–M5 V stars. The colors at the low state are consistent with those of an M4–M5 secondary star. In order to determine if the secondary alone can account for the IR light curves, we have calculated the ellipsoidal and heating effects of an M4 secondary star heated by a point source accretion column located at the white dwarf position with luminosity of the column between 10^{31}–10^{33} ergs s^{-1}. A program described by Mochnacki and Doughty (1972) with modifications described by Berriman *et al.* (1981) was used. The basic input parameters which represent the range of inclinations given by Young and Schneider (1979) are listed in Table 3.

The inclination has the greatest effect among the listed parameters. The gravity and limb darkening are very small in stars with convective envelopes (using solar limb darkening only changes the amplitude of variation by 3%), and using an M5 star rather than an M4 changes the absolute values of the flux, but not the amplitude of variation. Increasing the albedo could increase the amplitude but the value of 0.5 is typical for late type stars (Rucinski 1969). From Drake and Ulrich (1980) the ratio of the Brackett lines to HB (at $T \sim 10^4$,

TABLE 2

IR COLORS AT HIGH AND LOW STATES

State	$J-H$	$H-K$	$K-L$
High	0.37	0.26	0.63
Low	0.65	0.27	0–0.3
M4 star[a] ...	0.59	0.26	0.2
M5 star[a] ...	0.56	0.28	0.33

[a] Mould and Hyland 1976.

TABLE 3

PARAMETERS[a] FOR THEORETICAL FITTING

Inclination	Luminosity of Accretion Col. (ergs s^{-1})	$\phi_{mag} = 0.6$ Depth of Min at Inf. Conj. J(mag)	K(mag)	$\phi_{mag} = 0.1$ Depth of Min at Opposition J(mag)	K(mag)
40° [b]	10^{31}	0.12	0.11	0.11	0.10
	10^{32}	0.15	0.12	0.06	0.07
71° [c]	10^{31}	0.22	0.16	0.18	0.15
	10^{32}	0.22	0.16	0.10	0.10
Observed values ...	...	0.5	0.2–0.3	0.3	0.2–0.3

[a] M4 star; $T = 3000$ K; reflection albedo = 0.5; gravity darkening index = 0.08; no limb darkening.
[b] $K1 + K2 = 293$ km s^{-1}; $m_{wd}/m_{rd} = 3$ (Young and Schneider 1979).
[c] $K1 + K2 = 315$ km s^{-1}; $m_{wd}/m_{rd} = 1.25$ (Young and Schneider 1979).

$Ne \sim 10^{14}$ cm^{-3}) $\leq 3\%$ so that the line contribution to the broad-band J, H, K fluxes should be negligible.

The calculated light curves show the sinusoidal variation with minima at inferior conjunction and opposition due to the ellipsoidal variation. As the accretion luminosity increases, the depth of minimum at inferior conjunction increases, while the minimum at opposition decreases. At a luminosity of 10^{33} ergs s^{-1}, the light curves are completely dominated by the heating effect and there is a single minimum at inferior conjunction.

As evident from Table 3, the observed amplitudes of variation are about double the calculated values, even with the inclination up to its maximum plausible value of 71°. Thus, the column must be producing a significant amount of emission in the IR to account for the observations. The similarity of the IR light curves at the high and low states also argues for this interpretation.

We may place a limit to the accretion column luminosity at the low state of less than 10^{32} ergs s^{-1} from a comparison of the amplitude of the calculated and observed light curves.

b) The Flux Distribution

We have plotted the observed flux distribution from UV to IR in Figure 5. Continuum points were chosen approximately every 100 Å throughout the UV (1150–3050 Å), while mean values of the *UBVR2* and *JHK* fluxes over the orbit were used. Summing the observed fluxes from 0.12 to 2 microns gives a luminosity of 10^{32} ergs s^{-1} (for $d = 100$ pc) which is about a factor of 10 below the high state luminosity (Stockman *et al.* 1977).

In order to derive a flux distribution for the accretion area at the low state, we have used available knowledge about the white dwarf and the secondary to subtract out these stellar components.

As discussed above, the effective temperature of the white dwarf appears to be about 50,000 K. We have plotted a $T = 50{,}000$ K, $\log g = 8$ model (Wesemael *et al.* 1980) as (+) in Figure 5. This model is consistent with the observed data for wavelengths less than 2700 Å, while at longer wavelengths, there is increased observed flux over that expected from the white dwarf. Subtracting the white dwarf flux from the observed UV to filter B fluxes leaves the component marked (c) in Figure 5.

From the strength of TiO bands at the low state, Hutchings, Crampton, and Cowley (1980) and Patterson and Price (1980) derive a secondary star contribution of 20% in the V filter, which leads to $V_{sec} = 16.6$ and a distance to the system of 38–72 pc. A secondary with this V magnitude contributes 50% of the light at J, which leaves enough column flux to explain the large amplitudes in the IR light curves as due to self-absorption or self-eclipse effects of the column throughout the orbit. This secondary is marked as (s) in Figure 5, and the subtraction of the secondary star from the V to L fluxes leaves the resulting column radiation marked (c).

This resulting column distribution after subtraction of the white dwarf and the secondary from the observed fluxes does not appear to follow any simple power-law distribution.

During the high state, the accretion column has a distribution $F_\nu \propto \nu^{-1}$ ($F_\lambda \propto \lambda^{-1}$) in the optical and $F_\nu \propto \nu^2$ ($F_\lambda \propto \lambda^{-4}$) in the IR (Stockman *et al.* 1977). In recent calculations of the emission of magnetic accretion columns (Meggitt and Wickramasinghe 1981; Chanmugam and Dulk 1981), this distribution may be explained by a critical frequency for the cyclotron emission in the optical region. At lower frequencies, the cyclotron source is optically thick and above the critical frequency, the source is thin and therefore, does not contribute much to the blue and UV. The optical region is the flat transition zone.

At the low state, the cyclotron emission must still be present since the circular polarization is 11% and the orbital dependence is similar to that seen during the high state (Latham, Liebert, and Steiner 1981). The

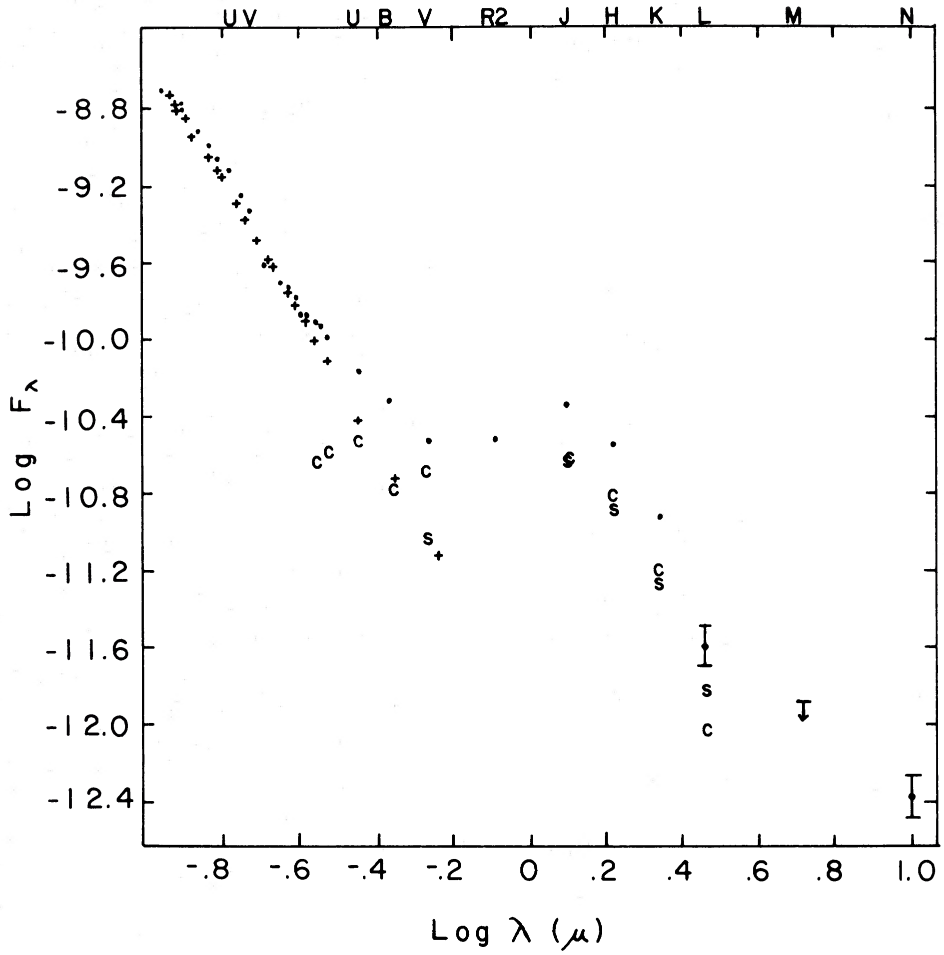

FIG. 5.—The total flux distribution from ultraviolet through infrared wavelengths. The dots are observations, the (+) are a Wesemael *et al.* 1980 white dwarf model with $T = 50{,}000$ K, $\log g = 8$, the (s) are an M4–M5V star (Mould and Hyland 1976) with $V = 16.6$. The (c) are the subtraction of the white dwarf and secondary from the observed points which are taken to be the column flux.

discrepancies between the observed and calculated column distributions at the low state may be due to one or both of the following reasons. First, the observations are *not* simultaneous and they are orbit *averages*, so that the observed column distribution may not be reasonable. Second, the calculations correspond to an idealized case of a homogeneous plasma with constant magnetic field, which may not be a reasonable representation of the column at the low state.

At 10 μm, the observed 3 σ detection is essentially an upper limit to the flux. The decrease in flux in the low state as compared to the high state is at least as large as the decrease in the optical flux, which tends to favor some association with the optical column emission. Due to the low flux level, it is not possible to determine if the 10 μm excess seen at the high state (Szkody and Capps 1980) is still present.

IV. CONCLUSIONS

Our multiwavelength observations at the low state have revealed:

1. A UV flux distribution consistent with emission from a hot ($T \approx 50{,}000$ K) white dwarf.
2. Orbital variability in the optical which exhibits phase and amplitude changes from the high state and which argues for separate origins for the blue versus red light.
3. Mean IR colors and fluxes consistent with an M4–M5 star contributing 50% of the light at J (1.25 μm) and IR light curves whose amplitude of variability argues for a significant amount of column emission.
4. A 10 μm flux which scales down from the high state at least as much as the optical magnitudes decrease.

5. A flux distribution for the remaining light (after subtraction of the white dwarf and secondary) which does not follow the $F_\nu \propto \nu^{-1}$ distribution seen in AM Her at the high state.

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