1981ApJ...251..611R

THE ASTROPHYSICAL JOURNAL, 251:611–619, 1981 December 15

MV LYRAE: SPECTROPHOTOMETRIC PROPERTIES OF MINIMUM LIGHT; OR ON MV LYRAE OFF

EDWARD L. ROBINSON[1], EDWIN S. BARKER, A. L. COCHRAN, W. D. COCHRAN, AND R. E. NATHER
Department of Astronomy and McDonald Observatory, University of Texas at Austin
Received 1981 April 29; accepted 1981 June 18

ABSTRACT

The nova-like variable MV Lyr is normally at maximum light near $B \sim 12.5$, but it occasionally fades to minimum light near $B \sim 17.3$. We have obtained photometric and spectrophotometric observations of MV Lyr at maximum light in 1969 and at minimum light in 1980. We show that minimum light is caused by a total cessation of mass transfer from the late-type star to the white dwarf in the system. The distribution of orbital periods of the cataclysmic variables has a gap at orbital periods between 2 hr and 3 hr, and MV Lyr is at the long-period edge of the gap. We argue that the cataclysmic variables do evolve through the gap, but that they cease mass transfer while in the gap, becoming very difficult to detect. MV Lyr is an example of a cataclysmic variable about to enter the gap.

Subject headings: stars: binaries — stars: dwarf novae — stars: individual

I. INTRODUCTION

The photographic magnitude of the cataclysmic variable MV Lyrae normally varies irregularly between 12.0 and 14.0, making it one of the brightest members of its class (see Robinson 1976 and Warner 1976 for reviews of the cataclysmic variables). The long-term behavior of its light curve also makes it one of the most unusual of the cataclysmic variables: MV Lyr occasionally fades by 5 magnitudes or more, to magnitude 18.0, remaining faint for as long as a year and a half. Three such minima have been observed, one from 1956 to the summer of 1957, one in the summer of 1976, and one which began in 1979 August and has persisted—with a few temporary increases in brightness—at least through 1980 December (Mattei 1980; Romano and Rosino 1980; Wenzel 1980). Relatively little was known about MV Lyr until it became conspicuous by its absence during the 1979 to 1980 minimum, at which time several groups, including ourselves, began to collect observations of the star. Most notably, Schneider, Young, and Shectman (1981, hereafter SYS) observed MV Lyr spectroscopically and found its orbital period to be 0.1336±0.0017 days. They also detected the spectrum of the late-type star between 7000 Å and 9000 Å, and from its spectral type, M5 V, deduced a distance of 320 pc to the system.

Our observations of MV Lyr consist of spectrophotometry and high speed photometry obtained in 1980 and of high speed photometry obtained in 1969 when MV Lyr was at maximum light. Using our data, we show in this paper that the 1979–1980 minimum was caused by a reduction in mass transfer from the M5 V star to its white dwarf companion, with a consequent fading of the accretion disk around the white dwarf, and that the mass transfer terminated altogether during part of 1980 July. We further show that the behavior of MV Lyr provides the solution to the long-standing problem of why no cataclysmic variables have been found with orbital periods between 2 and 3 hr.

II. OBSERVATIONS

a) Photometry

The photometric data were acquired at McDonald Observatory, using equipment described by Nather (1973) and consist of two successive nights of high speed photometry in August of 1969 and five nights of high speed photometry over a six night interval in July of 1980. The observations were all made in unfiltered light with blue-sensitive photomultiplier tubes, an RCA 1P21 in 1969 and an RCA 8850 in 1980. Other details concerning the observations can be found in Table 1.

MV Lyr was near maximum light throughout 1969; on the two nights we observed it in August 1969 the star was at $B \sim 12.9$. Figure 1 shows a portion of the light curve of MV Lyr on the night of 1969 August 13. The light curve displayed large-amplitude, rapid flickering with a peak-to-peak range of 0.3 mag and with time scales as short as 15 s. The flickering was also present on 1969 August 14 and appears to be typical of MV Lyr at maximum light as it was observed by Walker (1954) on five nights in July and August of 1953 when MV Lyr

---

[1] Alfred P. Sloan Foundation Fellow and 1980–1981 Visiting Fellow, Joint Institute for Laboratory Astrophysics, National Bureau of Standards and University of Colorado.

TABLE 1

HIGH-SPEED PHOTOMETRY OF MV LYRAE

Day	Start Time (UT)	Length	Integration Time (s)	Telescope (m)
1969 Aug 13 ...	3:12	3^h39^m	5	0.9
1969 Aug 14 ...	4:13	1^h55^m	5	0.9
1980 Jul 8	10:09	0^h25^m	5	2.1
1980 Jul 9	6:19	2^h2^m	5	2.1
1980 Jul 10	9:05	0^h25^m	5	2.1
1980 Jul 12	5:46	3^h4^m	5	2.1
1980 Jul 13	5:15	1^h21^m	5	2.1

was between $B=12.7$ and 14.0. We find no evidence of any modulation in the light curve at the 3^h12^m orbital period.

Figures 2 and 3 show portions of the light curve of MV Lyr on the nights of 1980 July 10 and 1980 July 12 when MV Lyr was at minimum light. We obtained *UBV* photometry of MV Lyr on these two nights just prior to the beginning of the high speed observations and found $B=17.3$ on both nights. The colors on the individual nights are given in Table 2, and average to $B-V\sim-0.35$ and $U-B\sim-1.25$. At maximum light, the colors are somewhat redder, with $B-V\sim-0.1$ and $U-B\sim-1.0$ (Walker 1954), but MV Lyr is always exceptionally blue, becoming one of the bluest objects in the sky at minimum light. The light curve of MV Lyr on 1980 July 12, shown in Figure 3, is typical of the light curve on four of our five nights of observations: There were no detectable variations, the upper limit to any random variations being a few percent. We also calculated the power spectrum of this light curve to search for periodic variations, and we found no periodic signals between 10 s and 500 s with amplitudes greater than 5×10^{-4} mag. On the exceptional night, 1980 July 10, shown in Figure 2, MV Lyr displayed rapid flickering. The light curve is too short to allow a definitive comparison of the flickering at minimum light to the flickering at maximum light, but to first order the properties of the flickering in both states are identical. In contrast to the flickering at maximum light, however, the flickering at minimum light was transient, as the long high speed light curves obtained 1 day before and 2 days after the 1980 July 10 light curve showed no trace of rapid variations.

b) *Spectroscopy*

The spectroscopic observations were made at McDonald Observatory with an intensified dissector scanner similar to the one described by Robinson and Wampler (1972) attached to the UVITS spectrograph on the 2.7 m telescope. We obtained spectrograms of MV Lyr on two nights in July of 1980 and two nights in September of 1980, one spectrogram per night, at the times and with the exposure lengths given in Table 3. The spectrograms cover a useful wavelength range of 3400 Å to 6200 Å at a FWHM resolution of 8 Å for the July data and 11 Å for the September data. The data were calibrated using Stone's (1977) standard stars, and as the seeing was good and the observations were made with wide slits (2″ or 4″), the relative flux calibrations are reliable. The absolute flux calibrations are also reliable except for the 1980 September 15 data when clouds may have been present. There were no measurable differences between the two July spectra, so we have averaged them together. Figure 4 shows this average spectrum of MV Lyr in July. The two spectra in September were also identical except for a multiplicative factor presumably due to the clouds on 1980 September 15. Therefore, for all quantities involving relative fluxes we have used the average of the two spectra, but for absolute fluxes we have used only the 1980 September 16 data. The spectrum of MV Lyr on 1980 September 16 is shown in Figure 5.

The continuum of the September spectrum is more or less uniformly brighter than the continuum of the July spectrum by about 0.8 mag at 5000 Å, but the continuum slopes are nearly identical. This can be seen more clearly in Figure 6 where the continuum distributions have been replotted after being normalized to unity at 5000 Å. The continuum slope is perhaps slightly flatter in September than in July but the flattening is small and within the measurement errors. From 4000 Å to 6000 Å the continuum distribution can be fit equally well either by $F_\lambda\propto\lambda^{-2.33}$, corresponding to an optically

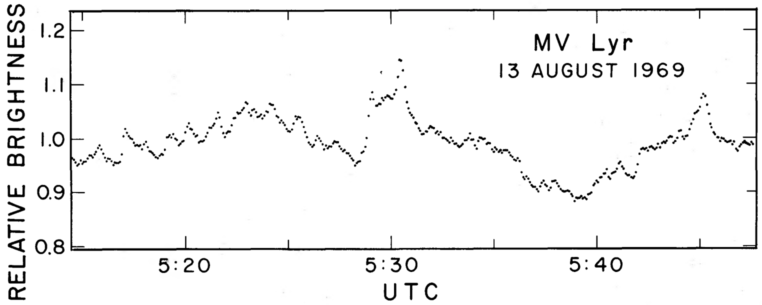

FIG. 1.—A portion of the light curve of MV Lyr on 1969 August 13, when MV Lyr was at $B\sim12.9$. Each data point is a 5 s integration in unfiltered light.

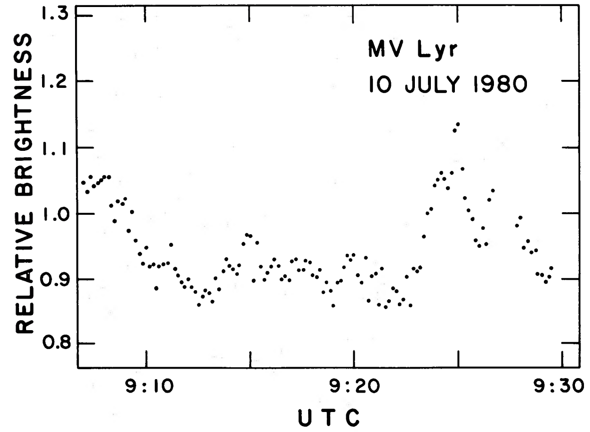

FIG. 2.—A portion of the light curve of MV Lyr on 1980 July 10, when MV Lyr was at $B\sim17.3$. Each data point is a 10 s integration in unfiltered light.

TABLE 2

UBV PHOTOMETRY OF MV LYRAE AT MINIMUM LIGHT

Day	B	$B-V$	$U-B$
1980 Jul 10 ...	17.33 ±0.03	−0.30 ±0.2	−1.30 ±0.07
1980 Jul 12 ...	17.32 ±0.03	−0.40 ±0.2	−1.20 ±0.05
Average.......	17.33	−0.35 ±0.15	−1.25 ±0.05

TABLE 3

SPECTROSCOPIC OBSERVATIONS OF MV LYR

Day	Mid-Exposure (UT)	Exposure Length (min)
1980 Jul 15	8:25	34
1980 Jul 18	6:05	48
1980 Sep 15 ...	4:43	63
1980 Sep 16 ...	5:55	54

thick accretion disk (Mayo, Wickramasinghe, and Whelan 1980), or by a blackbody distribution with $T=13{,}000$ K. Shortwards of 4000 Å, the continuum steepens radically, and between 3500 Å and 4000 Å becomes steeper than a blackbody of infinite temperature. It is exactly this steep continuum slope which gives MV Lyr its exceedingly blue $U-B$ color. Part of the steepening must be caused by Balmer continuum emission, but inspection of Figures 4 and 5 demonstrates that the Balmer jump is not large and cannot alone account for all of the steepening. A high temperature blackbody source is still required. Szkody (1981*a*) observed the ultraviolet spectrum of MV Lyr on 1980 December 8, when MV Lyr was at $V\sim15.7$, using the *IUE* satellite. At that time the spectrum was proportional to λ^{-4} from 1200 Å to 3000 Å and required a blackbody source with a temperature greater than 35,000 K. The sharp rise we see below 4000 Å would appear to be the beginning of the λ^{-4} distribution observed by Szkody. The continuum of MV Lyr is thus made up of three components. From 1200 Å to 4000 Å, the continuum has a blackbody distribution with $T>35{,}000$ K; from 4000 Å to 6000 Å, the distribution can be produced either by an optically thick accretion disk or by a blackbody with $T=13{,}000$ K; and from 7000 Å to 9000 Å, SYS found that the distribution matches that of an M5 V star partly veiled by the disk or blackbody sources seen at shorter wavelengths.

The fluxes of the identifiable emission lines in the spectrum of MV Lyr are given in Table 4. In contrast to the continuum distribution, the emission line spectrum changed considerably between July and September: With the possible exception of the Ca II λ3933 line, all of the emission lines were three to four times stronger in September than in July; the He II λ4686 line was present in September but absent in July; and the Balmer decrement was much shallower in September than in July. There was a concomitant change in the emission line profiles. The emission lines were very narrow in July—too narrow to be resolved in our spectrograms. When measured by SYS on spectrograms obtained two weeks after ours, the lines had a FWHM of only 150

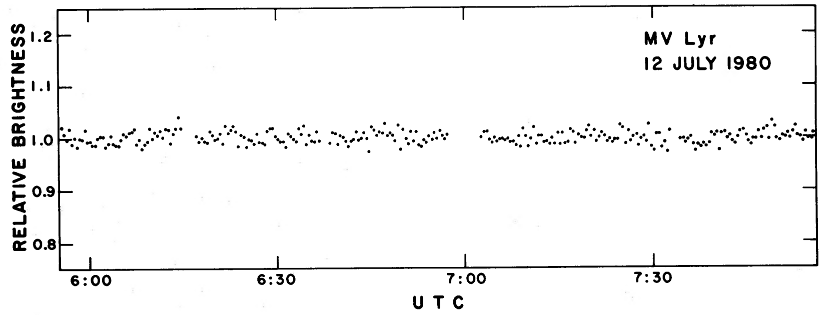

FIG. 3.—A portion of the light curve of MV Lyr on 1980 July 12, when MV Lyr was at $B\sim17.3$. Each data point is a 25 s integration in unfiltered light.

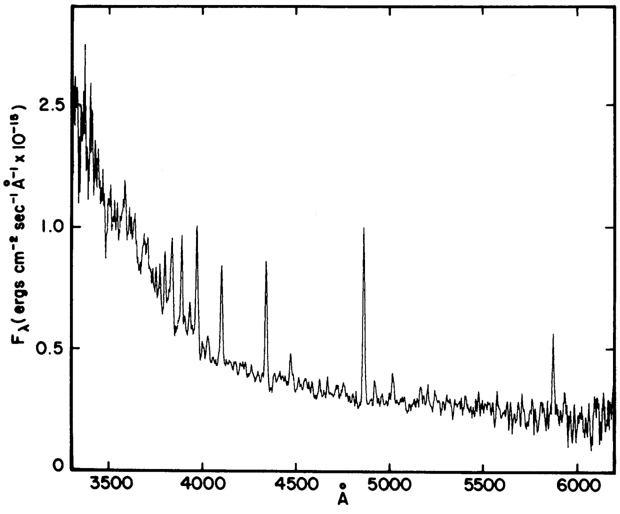

FIG. 4.—The average of the spectra of MV Lyr on 1980 July 15 and 1980 July 18 when MV Lyr was at minimum light.

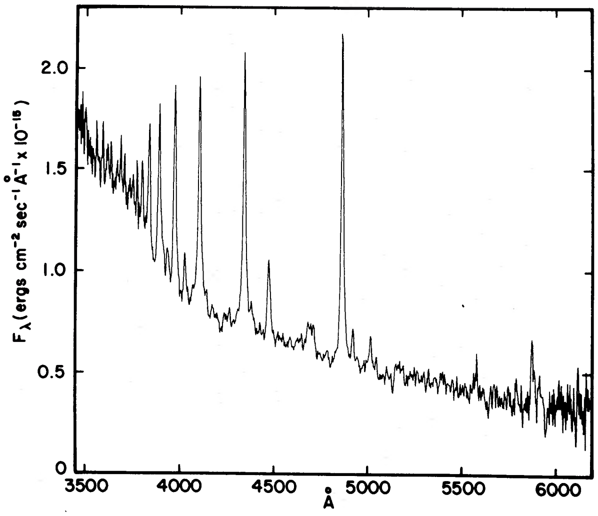

FIG. 5.—The spectrum of MV Lyr on 1980 September 16, when MV Lyr was about 0.8 mag brighter than minimum light.

km s^{-1}, or about 2.5 Å at Hβ. The line profiles were much broader in September, having a FWHM of about 15 Å and a full width at the base of about 75 Å at Hβ. These line widths are two to three times greater than the line widths observed near maximum light by Greenstein (1954) and Voikhanskaya (1980).

Broad, shallow absorption features are also occasionally visible in the spectrum of MV Lyr. In the data obtained by SYS on 1980 August 2 the absorption features are relatively strong, and can be seen as a pure absorption line at He II λ4686 and as absorption wings at Hβ, Hγ, and Hδ. The absorption features are significantly weaker in our data. In July the He II λ4686 absorption line is absent, and only Hβ has absorption wings; and in September there is no absorption whatsoever. Similar absorption lines are sometimes visible when MV Lyr is at maximum light (MacRae 1952; Voikhanskaya 1980), but they are not present when MV Lyr is at intermediate brightness.

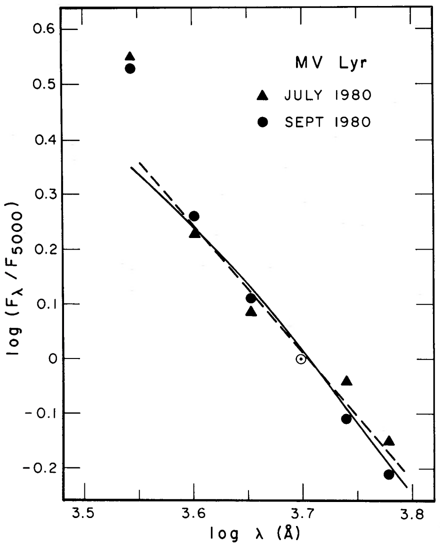

FIG. 6.—The triangles are the relative continuum fluxes of MV Lyr at selected wavelength regions in 1980 July, and the circles are the fluxes in 1980 September. Both fluxes have been normalized so that $F_{5000}=1.0$. The solid line is a blackbody distribution with $T=13{,}000$ K, and the dashed line is the $\lambda^{-2.33}$ distribution of an optically thick accretion disk.

III. THE CESSATION AND REESTABLISHMENT OF MASS TRANSFER

We show in this section that the dramatic drop in the brightness of MV Lyr was caused by a modulation in the rate of mass transfer from the M5 V star to the white dwarf. The mass transfer was proceeding vigorously during our observations in 1969, ceased completely during much of 1980 July, and then reestablished itself at a relatively low rate during our observations in 1980 September. We divide our discussion of the changing rate of mass transfer into separate sections concerning its effects on the photometric properties of MV Lyr, its effects on the spectral continuum, and its effects on the emission line spectrum.

a) *Photometric Effects*

As the rapid flickering in cataclysmic variables is caused, without exception, by the mass transfer and accretion process (Robinson 1976; Warner 1976), the rapid flickering displayed by MV Lyr in 1969 indicates that mass transfer was taking place at that time. The *UBV* colors of MV Lyr at maximum light are within the range of colors of other cataclysmic variables in which

1981ApJ...251..611R

TABLE 4

MV LYRAE EMISSION LINE FLUXES (ergs cm^{-2} s^{-1})

LINE	$I(\times 10^{15})$ 1980 Jul	$I(\times 10^{15})$ 1980 Sep 16	LINE	$I(\times 10^{15})$ 1980 Jul	$I(\times 10^{15})$ 1980 Sep 16
H 4861	7.3	24.6	He I 5876	3.0	5.2[b]
H 4340	4.6	21.6	He I 5016	1.2	2.6
H 4101	3.6	17.8	He I 4922	0.9	2.9
H 3970[a] ...	4.6	14.9	He I 4471	1.1	7.1
H 3889[a] ...	3.7	11.1	He I 4026	0.9	2.4
H 3835	4.5	9.3	He II 4686[a]	...	4.9
H 3797	1.9	4.4	Ca II 3933	1.6	1.4
H 3770	1.2	...			

[a] Strongly blended lines.

[b] The He I λ5876 line was severely distorted in September by a defect in the response of the IDS.

mass transfer is known to be taking place—for example, VY Scl with $B-V=-0.10$ and $U-B=-1.00$ (Burrel and Mould 1973)—supporting our inference of normal mass transfer in MV Lyr at maximum light. Likewise, the absence of rapid flickering in 1980 July indicates that no mass was then being transferred. The *UBV* colors of MV Lyr at that time again support this inference. The colors are bluer at minimum light than those of any other cataclysmic variable (Warner 1976), but they are essentially identical to the colors of Feige 24 which has $B-V=-0.23$ and $U-B=-1.25$. Feige 24 is a binary system consisting of an M1 Ve star and a hot white dwarf, but because the orbital period of Feige 24 is 4.2319 days, the M1 Ve star underfills its Roche lobe and is not transferring any significant amount of mass (Thorstensen *et al.* 1978).

As the flickering is typical of MV Lyr at maximum light and nonflickering was typical of MV Lyr at minimum light in 1980 July, we conclude that maximum light corresponds in general to times of vigorous mass transfer and minimum light corresponds in general to times of no mass transfer. There are some exceptions, however. The rapid flickering on 1980 July 10 shows that there was still some low level mass transfer taking place even at minimum light, but the transfer occurred in short bursts separated by longer intervals of quiescence. This nonzero rate of mass transfer is important, because it is necessary to invoke a residual disk in MV Lyr even in 1980 July.

b) *The Continuum Distribution*

Based on its slope alone, the continuum between 4000 Å and 6000 Å could be produced either by an optically thick accretion disk, as suggested by SYS, or by a white dwarf with a temperature of about 13,000 K as suggested by Voikhanskaya (1980). On other grounds, however, we can eliminate the white dwarf as the source of the continuum. First, a star with a temperature of 13,000 K at a distance of 320 pc would require a radius of $(1.5\text{–}2.0)\times 10^9$ cm, depending on interstellar extinction, in order to produce the flux of 3×10^{-16} ergs cm^{-2} s^{-1} Å^{-1} at 5000 Å observed in July. This radius is three to four times too large for a white dwarf, but it is quite reasonable for a residual accretion disk. The discrepancy between the required radius and a white dwarf radius is even worse in September when the observed flux was two times larger but the blackbody temperature remained the same. Second, the He II λ4686 absorption line cannot be produced by a 13,000 K white dwarf, but it could very well come from an optically thick accretion disk because of the disk's large range of temperatures. Finally, if the 13,000 K continuum comes from the white dwarf, we are left without a reasonable source for the ultraviolet continuum with $T>35{,}000$ K. We note in passing that an optically thick accretion disk has no difficulty in producing broad, shallow absorption lines of the kind observed in MV Lyr (Herter *et al.* 1979). Indeed, the absorption lines observed when MV Lyr is at maximum light must come from the disk rather than the white dwarf because the increased mass transfer at maximum light makes the accretion disk so bright that it dominates the luminosity of MV Lyr and totally masks the white dwarf.

The available data are not sufficient to uniquely determine the rate of mass transfer in MV Lyr in either state, but we may make a rough estimate of the transfer rates by using the theoretical models of accretion disks calculated by Mayo, Wickramasinghe, and Whelan (1980). The orbital inclination of MV Lyr is less than 14° according to SYS, and with a distance of 320 pc, MV Lyr has an absolute magnitude $M_v \sim 10.2$ at minimum light and $M_v \sim 5.2$ at maximum light. With these parameters the models yield $\dot{M} \lesssim 6\times 10^{15}$ gm s^{-1} ($\lesssim 10^{-10}\ M_\odot$ yr^{-1}) at minimum light and $\dot{M} \sim 6\times 10^{17}$ gm s^{-1} ($\approx 10^{-8}\ M_\odot$ yr^{-1}) at maximum light.

It has been suggested that MV Lyr has a strong magnetic field and should be classified as an AM Her

1981ApJ...251..611R

star (Voikhanskaya *et al.* 1978). If this were true, our foregoing discussion could not be correct because the magnetic field would disrupt the residual disk, but for the following reasons we do not agree that MV Lyr is an AM Her star. The magnetic fields of AM Her stars have given unequivocal evidence of their presence in three entirely different ways. First, at minimum light AM Her has Zeeman-split hydrogen absorption lines produced by the photosphere of its white dwarf (Latham, Liebert, and Steiner 1981). If we picture a strong enough magnetic field in MV Lyr to disrupt the disk, the hydrogen absorption lines in MV Lyr also would have to be produced in the white dwarf photosphere and would also be subject to Zeeman splitting. The absorption lines in MV Lyr are never split, either at maximum or minimum light, so this picture cannot be correct. Second, at intermediate brightness VV Pup displays absorption features due to cyclotron high harmonics (Visvanathan and Wickramasinghe 1979). Although observed at intermediate brightness by both us and by Greenstein (1954), MV Lyr shows no sign of these cyclotron absorption features. Voikhanskaya and Mitrofanov (1980) interpret an emission feature they observed in MV Lyr at maximum light as cyclotron emission, but as no such emission feature has been observed in the AM Her stars, their interpretation is not convincing. Third, and most importantly, the AM Her stars display large and variable circular polarization. Voikhanskaya *et al.* (1978) claim to have detected variable circular polarization in MV Lyr, but in actual fact the polarization they found was always small, usually less than one standard deviation from zero, and never more than three standard deviations from zero (see their Fig. 1). We consider this a textbook example of a null result. Tapia (1981) has measured the circular polarization of MV Lyr on several occasions, finding the polarization to be always less than 0.13% and always within two standard deviations of zero. We conclude, therefore, that MV Lyr is not an AM Her star.

The source of the high temperature blackbody spectrum in the ultraviolet may now be identified as the white dwarf without introducing any inconsistency. If the white dwarf has a radius of 5.4×10^8 cm, corresponding to a 1 $M_\odot$ white dwarf (Hamada and Salpeter 1961), and if it has a temperature of 3.5×10^4 K and a distance of 320 pc, the expected flux at the earth at 3500 Å is 1.8×10^{-15} ergs cm^{-2} s^{-1} Å^{-1}. Inclusion of a small amount of interstellar extinction would lower this flux enough to give excellent agreement with the observed flux.

c) The Emission Line Spectrum

We have already noted the similarity between Feige 24 and MV Lyr at minimum light. The emission lines from Feige 24 are known to come from the chromosphere of the late-type star because their radial velocity curve is in phase with the radial velocity curve of the absorption lines of the late-type star (Thorstensen *et al.* 1978). In the case of MV Lyr the emission lines in the July spectrum—but *not* the September spectrum—also come predominantly from the chromosphere of the late-type star. The evidence is twofold. First, in July the lines had a width of only 150 km s^{-1}, and thus were far too narrow to come from the accretion disk, or indeed to come from anywhere in the neighborhood of the white dwarf. Second, the Balmer decrement in July was a typical chromospheric decrement. The decrement is shown in Figure 7. The H7 and H8 lines have been excluded from the figure because they are heavily contaminated by the Ca II λ3968 line and the He I λ3888 line respectively, and, in addition, the H9 line at λ3835 has been excluded for reasons we will discuss separately. The dashed line in Figure 7 is the observed Balmer decrement of the solar chromosphere as seen just after second contact of the 1962 solar eclipse (Dunn *et al.* 1968). The agreement is good. There is an equally good agreement with the observed Balmer decrement of the dMe flare star AD Leo at quiescence, whose emission is presumed to be chromospheric in origin (Gershberg 1970). We conclude that the accretion disk in MV Lyr during 1980 July was a negligible contributor to the emission line spectrum, allowing the faint chromosphere of the M5 V star to be observed.

The H9 line presents an interesting exception to our discussion of the Balmer decrement because, with I_9/I_4 ~0.62, it fails utterly to fit not only a chromospheric decrement, but any Balmer decrement ever observed or calculated. The anomalous strength of the H9 line is not due to blending as there are no known emission lines strong enough to contaminate it significantly. Therefore,

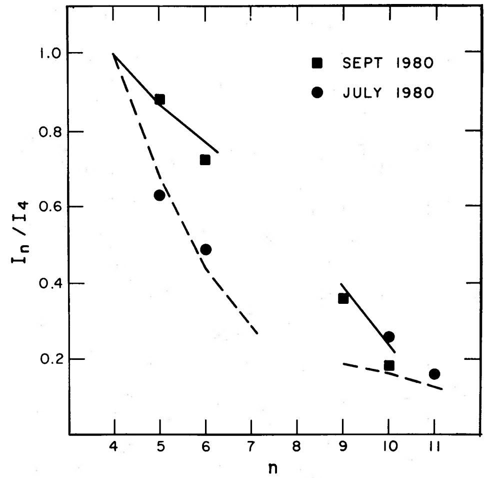

FIG. 7.—The circles are the Balmer decrement of MV Lyr in July 1980 when MV Lyr was at minimum light, where I_4 is the flux in Hβ. The squares are the Balmer decrement in 1980 September when MV Lyr was about 0.8 mag brighter than in July. The solid line is the observed Balmer decrement of the dwarf nova SS Cyg, and the dashed line is the observed Balmer decrement of the flash spectrum of the solar chromosphere.

discounting the possibility that the H9 line strength is simply bad data, we attribute the anomalously large line strength to fluorescence. The 9 level of hydrogen can be pumped from the ground state of hydrogen by photons with a wavelength of 923.15 Å. A candidate source of the photons is the N IV λ923.2 line, which is a permitted transition out of the metastable ground state of N IV triplet system. As the 923 Å region of the spectra of cataclysmic variables has never been observed, we cannot know for certain if the N IV line is present, but there are reasons to believe that it should be. A N IV line at λ1719 has been identified in TT Ari (Krautter *et al.* 1981), and N V λ1240 is very strong in most cataclysmic variables at minimum light (Szkody 1981*b*). The Sun is one of the very few objects whose spectrum near 923 Å has been measured with high accuracy. In the spectrum of a solar active region the N IV line is not only present in emission, but it is stronger than the corresponding Lyman line (Dupree *et al.* 1973). Therefore, fluorescence is a viable mechanism for enhancing the λ3835 line of hydrogen. As the conditions necessary for this fluorescence mechanism to significantly alter the Balmer decrement are quite unusual, we expect that the mechanism will be important only in rare cases. One such case might be flare stars while they are flaring.

The emission line spectrum of MV Lyr changed radically between July and September, turning into a typical accretion disk spectrum rather than a chromospheric spectrum. The lines became Doppler broadened to half widths at the base of more than 2000 km s^{-1} due to orbital or turbulent motion in the disk; the high excitation line He II λ4686, which is often strong in normally accreting cataclysmic variables but not in chromospheres, appeared in September; and the Balmer decrement changed to the typical shallow Balmer decrement of cataclysmic variables. The Balmer decrement of MV Lyr in 1980 September is shown in Figure 7 along with the Balmer decrement of the dwarf nova SS Cygni, whose emission lines are known to be produced by an accretion disk (Stover *et al.* 1980). The two decrements are the same to within measurement errors.

As the emission lines had three to four times more flux in September than in July, and the continuum at 5000 Å had twice as much flux in September as in July, the accretion disk in September was much brighter than the residual disk we observed in July. Mass transfer had clearly been reestablished, albeit at a low rate, sometime between our two observations.

IV. THE EVOLUTION OF CATACLYSMIC VARIABLES FROM ORBITAL PERIODS OF 3 HOURS TO 2 HOURS

The typical cataclysmic variable has an orbital period between 80 minutes and 16 hr, but the distribution of periods within this range is far from uniform. The most striking of the nonuniformities is the total absence of cataclysmic variables (or of *any* binary stars) with orbital periods between 2 hr and 3 hr. In the list of cataclysmic variables and related systems with known orbital periods given by Whyte and Eggleton (1980), the gap in the distribution of periods shows quite clearly: For 1.3 hr$<P<$2.0 hr, there are eleven systems; for 2.0$<P<$3.0 hr, there are no systems; and for 3.0 hr$<P<$4.0 hr, there are eight systems. The existence of the period gap poses two problems for the theory of the evolution of cataclysmic variables:

1. Either no cataclysmic variables are formed initially in the gap, or if they are formed in the gap, they remain undetectable until they evolve out of the gap. This problem has been partly solved by Webbink (1979) who has been able to suggest a set of plausible mechanisms for preventing binaries from ever forming in the gap.
2. Cataclysmic variables outside the gap either do not evolve into the gap, or if they do, they become undetectable while in the gap. This second problem is particularly severe because according to our present theories of the evolution of cataclysmic variables, most systems with orbital periods between 3 and 4 hr are inevitably driven into the gap by the effects of gravitational radiation (Rappaport, Joss, and Webbink 1981; Paczynski and Sienkiewicz 1981).

The properties of MV Lyr suggest the solution to the second problem: Cataclysmic variables do evolve into the period gap, but cease mass transfer while in the gap, and thus become essentially undetectable. Outside the period gap cataclysmic variables have high rates of mass transfer ($\gtrsim 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$) and look similar to MV Lyr at maximum light. They attract attention both by their brightness and their variability, and are easily found. For example, MV Lyr itself appears to have been found twice, first by Parenago (1946) because of its variability, and then later and independently by MacRae (1952) because of its unusual colors and spectrum. Within the gap, cataclysmic variables have little or no mass transfer and look similar to MV Lyr at minimum light: They are 5 magnitudes fainter and thus 100 times more difficult to detect. Although this factor of 100 provides a strong enough selection effect to be sufficient alone to account completely for the missing stars in the gap, there is yet another selection effect acting against the detection of stars in the gap: Without mass transfer a system cannot have nova or dwarf nova eruptions and will not be detected because of its variability. Thus, we may safely claim that the binary nature of MV Lyr would have remained unknown and unsuspected if it were a nonvariable binary star at $V=17.7$.

Only a few cataclysmic variables have deep minima of the kind displayed by MV Lyr, but of them, six have known orbital periods: VV Pup, AM Her, TT Ari, AN UMa, Stepanyan's star, and MV Lyr itself. In AM Her, as in MV Lyr, minimum light is caused by longer intervals of negligible mass transfer punctuated by short bursts of accretion, whereas in VV Pup, TT Ari, and probably AN UMa, minimum light is caused by a reduction without total cessation of mass transfer (Latham, Liebert, and Steiner 1981; Liebert *et al.* 1978; Szkody *et al.* 1981; Krautter *et al.* 1981). No minima of Stepanyan's star have occurred recently, so their cause is unknown, but in the absence of evidence to the contrary we will assume its minima are also caused by a reduction or cessation of mass transfer (Horne 1980; Liller 1980). VV Pup lies well below the period gap, but AM Her, MV Lyr, and TT Ari, with periods of 3.09 hr, 3.21 hr, and 3.30 hr respectively, are exactly the three cataclysmic variables closest to the upper edge of the period gap, and Stepanyan's star, with a period of 3.80 hr, is not far from the upper edge (Walker 1965; Young and Schneider 1979; SYS; Cowley *et al.* 1975; Horne 1980). The variable AN UMa, with an orbital period of 1.91 hr, is the cataclysmic variable closest to the lower edge of the gap. We believe that this clustering at the upper and lower edges of the gap of stars which behave like MV Lyr is not just a remarkable coincidence. We are seeing in the stars at the upper edge four cataclysmic variables making their first abortive attempts to terminate mass transfer and disappear into the period gap, and in AN UMa at the lower edge a cataclysmic variable attempting to reinitiate mass transfer and reappear out of the gap.

In order to terminate mass transfer the late-type star must contract to a radius less than the radius of its Roche lobe and remain at the smaller radius until gravitational radiation reduces the original period from 3 hr to 2 hr. If the masses of a binary star remain constant, and if R is the radius of the Roche lobe and A is the separation of the stars then $R^3 \propto A^3 \propto P^2$. Therefore, the late-type stars in cataclysmic variables would need to shrink by about 25% at the upper edge of the gap in order to remain out of contact until reaching the lower edge of the gap. We have no convincing explanation for why the late-type star should shrink in this way, but we do note the following coincidence. According to Grossman, Hays, and Graboske (1974), main-sequence stars with masses greater than 0.3 $M_\odot$ have radiative cores, while those with masses less than 0.3 $M_\odot$ have convective cores. A 0.3 $M_\odot$ zero-age, main-sequence star in a binary system with a solar mass white dwarf just fills its Roche lobe at an orbital period of about 2.2 hr, or if the star is somewhat evolved, at an orbital period of perhaps 3 hr (Faulkner 1971; Whyte and Eggleton 1980). Thus, the period gap corresponds precisely to the boundary between main-sequence stars with radiative and convective cores. The responses of radiative and convective stars to mass loss are quite different, a radiative star contracting but a convective star expanding during mass loss, so the structure of the late-type star can affect the transfer rate (Faulkner 1976). Therefore, we suggest that the shrinking of the lobe-filling star necessary to terminate mass transfer is caused by the switchover from radiative to convective energy transport at orbital periods between 2 and 3 hr.

There is some evidence against our suggestion, of which the most telling is (1) calculations by Faulkner (1976) indicate that the envelope of the late-type star is more important than its core in determining the response of the star to mass transfer, and (2) stars with deep convective envelopes tend to expand, not contract, in response to mass transfer. Our suggestion must, therefore, be considered to be primarily a plausibility argument: We require the late-type stars of cataclysmic variables in the period gap to behave in a unique way, and we have identified one property of their structure which does, indeed, make them unique—the change in the structure of their cores while they are in the gap. It is quite possible that some other mechanism is responsible for the termination of mass transfer, but theoretical calculations will be necessary to decide just what the actual mechanism is. Unfortunately, theoretical calculations made to date give no information about the evolution of cataclysmic variables with orbital periods between 2 hr and 4 hr. Neither Taam, Flannery, and Faulkner (1980) nor Chau and Lautherborn (1977) evolved their models to orbital periods as short as 4 hr. Rappaport, Joss, and Webbink (1981) and Paczynski and Sienkiewicz (1981) began their calculations at periods of 3 to 4 hr and evolved their models through the period gap, but in both sets of calculations the late-type star was forced to be fully convective at all times. Their results are not realistic until the orbital periods decrease to 2 hr or less, and they are unreliable for systems lying in the period gap.

We conclude that there are observational reasons for believing that cataclysmic variables cease mass transfer while their orbital periods are between 2 hr and 3 hr. Theoretical models do not preclude and may even lend support to our conclusion. We predict that a detailed, physically realistic calculation of the evolution of cataclysmic variables beginning at orbital periods of 4 to 5 hr will reveal the termination of the mass transfer in the period gap.

We are grateful to P. Szkody, S. Tapia, and P. Young for communicating their observations of MV Lyr to us prior to publication, and we thank S. O. Kepler for assistance with the data reductions. We have benefited from enlightening conversations with J. Cox, C. Hansen, H. Van Horn, and R. Webbink. This research was supported in part by NSF grant AST79-06340.

REFERENCES

Burrel, J. F., and Mould, J. R. 1973, *Pub. A.S.P.*, **85**, 627.
Chau, W. Y., and Lauterborn, D. 1977, *Ap. J.*, **214**, 540.
Cowley, A. P., Crampton, D., Hutchings, J. B., and Marlborough, J. M. 1975, *Ap. J.*, **195**, 413.
Dunn, R. B., Evans, J. W., Jefferies, J. T., Orall, F. Q., White, O. R., and Zirker, J. B. 1968, *Ap. J. Suppl.*, **15**, 275.
Dupree, A. K., Huber, M. C. E., Noyes, R. W., Parkinson, W. H., Reeves, E. M., and Withbroe, G. L. 1973, *Ap. J.*, **182**, 321.

Faulkner, J. 1971, *Ap. J. (Letters)*, **170**, L99.

______. 1976, in *IAU Symposium 73, Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Milton, and J. Whelan (Dordrecht: Reidel), p. 193.

Gershberg, R. E. 1970, *Astrofizika*, **6**, 191.

Greenstein, J. L. 1954, *Pub. A.S.P.*, **66**, 79.

Grossman, A. S., Hays, D., and Graboske, H. C. 1974, *Astr. Ap.*, **30**, 95.

Hamada, T., and Salpeter, E. E. 1961, *Ap. J.*, **134**, 683.

Herter, T., Lacasse, M. G., Wesemael, F., and Winget, D. E. 1979, *Ap. J. Suppl.*, **39**, 513.

Horne, K. 1980, *Ap. J. (Letters)*, **242**, L167.

Krautter, J., Klare, G., Wolff, B., Wargau, W., Drechsel, H., Rahe, J., and Vogt, N. 1981, *Astr. Ap.*, in press.

Latham, D. W., Liebert, J., and Steiner, J. E. 1981, *Ap. J.*, **246**, 919.

Liebert, J., Stockman, H. S., Angel, J. R. P., Woolf, J., Hege, E. K., and Margon, B. 1978, *Ap. J.*, **225**, 201.

Liller, M. H. 1980, *Inf. Bull. Var. Stars*, No. 1743.

MacRae, D. A. 1952, *Ap. J.*, **116**, 592.

Mattei, J. 1980, *AAVSO Circ.*

Mayo, S. K., Wickramasinghe, D. T., and Whelan, J. A. J. 1980, *M.N.R.A.S.*, **193**, 793.

Nather, R. E. 1973, *Vistas in Astronomy*, **15**, 91.

Paczynski, B., and Sienkiewicz, R. 1981, *Ap. J. (Letters)*, **248**, L27.

Parenago, P. 1946, *Perem. Zvezdy*, **6**, 26.

Rappaport, S., Joss, P. C., and Webbink, R. 1981, *Ap. J.*, in press.

Robinson, E. L. 1976, *Ann. Rev. Astr. Ap.*, **14**, 119.

Robinson, L. B., and Wampler, E. J. 1972, *Pub. A.S.P.*, **84**, 161.

Romano, G. and Rosino, L. 1980, *Inf. Bull. Var. Stars*, No. 1776.

Schneider, D. P., Young, P., and Shectman, S. A. 1981, *Ap. J.*, **245**, 644 (SYS).

Stone, R. P. S. 1977, *Ap. J.*, **218**, 767.

Stover, R. J., Robinson, E. L., Nather, R. E., and Montemayor, T. J. 1980, *Ap. J.*, **240**, 597.

Szkody, P. 1981*a*, private communication.

______. 1981*b*, *Ap. J.*, in press.

Szkody, P., Schmidt, E., Crosa, L., and Schommer, R. 1981, *Ap. J.*, **246**, 223.

Taam, R. E., Flannery, B. P., and Faulkner, J. 1980, *Ap. J.*, **239**, 1017.

Tapia, S. 1981, private communication.

Thorstensen, J. R., Charles, P. A., Margon, B., and Bowyer, S. 1978, *Ap. J.*, **223**, 260.

Visvanathan, N. and Wickramasinghe, D. J. 1979, *Nature*, **281**, 47.

Voikhanskaya, N. F. 1980, *Soviet Astr.—AJ*, **24**, 300.

Voikhanskaya, N. F., Gnedin, Yu. N., Efimov, Yu. S., Mitrofanov, I. G., and Shakhovskoi, N. M. 1978, *Pis'ma Astron. Zh.*, **4**, 272.

Voikhanskaya, N. F., and Mitrofanov, I. G. 1980, *Pis'ma Astron. Zh.*, **6**, 159.

Walker, M. F. 1954, *Pub. A.S.P.*, **66**, 71.

______. 1965, *Mitt. Sternw. Budapest*, No. 57.

Warner, B. 1976, in *IAU Symposium 73, Structure and Evolution of Close Binary Systems* (Dordrecht: Reidel), p. 85, ed. P. Eggleton, S. Mitton, and J. Whelan.

Webbink, R. 1979, in *IAU Colloquium 53, White Dwarfs and Variable Degenerate Stars*, ed. H. M. Van Horn and V. Weidemann (Rochester: University of Rochester Press), p. 426.

Wenzel, W. 1980, *Inf. Bull. Var. Stars*, No. 1810.

Whyte, C. A., and Eggleton, P. P. 1980, *M.N.R.A.S.*, **190**, 801.

Young, P., and Schneider, D. P. 1979, *Ap. J.*, **230**, 502.

EDWIN S. BARKER, A. L. COCHRAN, W. D. COCHRAN, R. E. NATHER, and EDWARD L. ROBINSON: Department of Astronomy, University of Texas at Austin, Austin, TX 78712