THE ASTROPHYSICAL JOURNAL, 247:960–968, 1981 August 1

A QUEST FOR THE RED COMPANION IN SIX CATACLYSMIC BINARIES

PETER YOUNG AND DONALD P. SCHNEIDER
Palomar Observatory, California Institute of Technology
Received 1980 October 3; accepted 1981 February 19

ABSTRACT

Near-infrared CCD spectra of six cataclysmic binaries have been obtained in an attempt to detect their red dwarf components. Similar observations of M dwarfs yield a classification scheme, based on the TiO bands, which allows one to describe the red dwarfs in cataclysmic binaries despite their dilution by light from an accretion disk of unknown character. Observations of AM Her while in its low state found a red dwarf of type $M4^+$ V and a distance of 80 pc, confirming our previous work. The red dwarf in DQ Her was detected in an observation centered on mid-eclipse, although it remained invisible in observations out of eclipse. The red star in DQ Her has a spectral type of $M3^+$ V, a mass $\mathfrak{M}_R = 0.32\ \mathfrak{M}_\odot$, and a radius $r_R = 0.45\ R_\odot$. It does not lie on the main sequence; although its temperature is correct for its mass, the radius is 25% too large. We obtain a spectroscopic distance estimate of 400 pc to the DQ Her binary system, compared with previous estimates of 300 pc. In four additional systems, the red dwarf defied detection, and we give lower limits to their distances.

Subject headings: stars: binaries — stars: dwarf novae — stars: novae — stars: U Geminorum

I. INTRODUCTION

It is notoriously difficult to find the absorption lines of the red dwarf in cataclysmic binary systems whose periods are less than 6 hours (Robinson 1976). In isolated cases, determined observation has managed to prise out the red dwarf. Such cases are U Gem (Wade 1979), AM Her (Young and Schneider 1979, hereafter YS), MV Lyr (Schneider, Young, and Shectman 1981), and probably VV Pup (Liebert *et al.* 1978; Greenstein and Zimmerman 1978).

With the advent of CCD spectrographs, it has become possible to make very high signal-to-noise ratio observations in the near-infrared. The extremely red spectra and huge band structures of late-type stars make observations in the region from 7000 Å to 9000 Å a sensitive probe for the presence of an M dwarf. We searched for an M dwarf in the spectra of six cataclysmic binaries and found the dwarf in two of them. For these two, we obtain spectroscopic distance estimates; for the other four, we give lower limits to the distance, assuming various spectral types for the red dwarfs.

II. OBSERVATIONS

The 200 inch (5.08 m) reflector was equipped with the prime focus CCD camera/spectrograph (PFUEI). For each binary system, we obtained direct broad-band photometry in the *griz* system (Thuan and Gunn 1976; Wade *et al.* 1979). In addition, we obtained an infrared spectrum by inserting a 400 line grating to give a spectral dispersion of 440 Å mm^{-1} and a slit of 0″.5 by 180″ to give a resolution of 12 Å over the range from 6800 Å to 9200 Å. The seeing varied between 1″ and 1″.5, so that the narrow slit collected only 25% of the light; the high quantum efficiency of the CCD more than compensates, however. In addition, a number of M dwarf stars were observed in order to calibrate the appearance of their bands and lines with spectral type.

Stars of very early spectral type were observed to calibrate the atmospheric absorption features; such features were removed by dividing spectra by these suitably scaled O stars. Flux standards were observed to remove the detector response. Helium, neon, and argon gas bulbs were used to obtain an accurate wavelength scale.

III. M DWARF OBSERVATIONS

a) Objects Observed

The M dwarfs were observed on the dates listed in Table 1. The spectral types given are from the system of Boeshaar (1976); four of the stars were classified by Boeshaar. We have classified the three others on the basis of their color (continuum slope) after demonstration of the good correlation of this parameter with Boeshaar type by Greenstein (1981, private communication). For the three spectral features of interest, we give values in Table 1:

1. The equivalent width in Å of the Na I λλ8183–8194 feature. The total equivalent width of the feature present was measured without regard to whether it is pure Na I (note that the H_2O atmospheric bands were removed by dividing the spectra by those of O stars).

2. The fractional depth D of the TiO bands as measured at 7150 Å and 7700 Å.

Also given is the flux f_ν relative to the flux at 9000 Å in the continuum for the seven stars in Table 1.

b) Mean Properties

It is useful to have the mean properties of the M dwarf sequence which we have derived in Table 2. Given are:

1. Absolute magnitude M_V from the relation

$$M_V = 8.88 + 0.24S + 0.16S^2\ , \qquad (1)$$

TABLE 1

THE SEVEN DWARFS

Star	Gliese Number	Spectral Type[a]	Date (UT) 1980	Na I 8183–8194 W(Å)	TiO λ7700 D	TiO λ7150 D	$\mathcal{F}_\nu$(8190 Å)	$\mathcal{F}_\nu$(7700 Å)	$\mathcal{F}_\nu$(7150 Å)
HD 209290	846	M0.5 V	Jun 13.43	2.2	0.09	0.22	0.92	0.77	0.55
BD +1°4774	908	M1.5 V	Aug 22.39	2.8	0.13	0.27	0.87	0.80	0.58
BD +68°946	687	M3 V	Aug 23.24	2.9	0.25	0.40	0.89	0.77	0.51
BD +4°4048	752A	M3 V	Jun 13.41	4.1	0.21	0.41	0.88	0.69	0.42
G3 −33	83.1	M4.5 Ve	Aug 22.41	5.3	0.34	0.52	0.74	0.59	0.30
G208 −44	...	M5+ Ve	Aug 21.30	8.9	0.47	0.59	0.81	0.60	0.28
G208 −45	...	M5.5 V	Aug 21.30	8.3	0.50	0.65	0.75	0.53	0.24

[a] In the system of Boeshaar (1976).

given by Boeshaar (1976) for spectral type MS V.

2. The bolometric correction (BC) was obtained from the stars listed in Table 3 of Boeshaar (1976). A smooth curve was fitted to a plot of S versus BC and the mean values in Table 2 extracted.

3. The $(V-K)$, $(V-I)$, and $(V-R)$ color indices were found from Johnson (1965). We interpolated our value of BC in his table and extracted his corresponding color indices. (This bypasses the need to relate the various systems by which S is measured).

4. The equivalent width W of Na I $\lambda\lambda$8183–8194 was found by fitting a smooth curve to a plot of log W versus S containing our seven M dwarfs.

5. The TiO band depths were obtained from plots of D versus S for dwarf standards.

6. The luminosity in the continuum at 9000 Å. In order to compute this, we synthesized magnitudes through the I filter, normalizing the observed energy distributions to give the correct absolute magnitude M_I. Units of L_ν are ergs^{-1} Hz^{-1}.

7. The luminosity deficit L in the Na I $\lambda\lambda$8183–8194 line in ergs^{-1}. This was obtained by plotting a smooth curve through the points defined by the seven standards in Table 1.

8. The luminosity deficit ΔL_ν (ergs^{-1} Hz^{-1}) in the TiO band dips at 7700 Å and 7150 Å. Again the points are a smooth curve fitted through the standards.

9. The mass $\mathfrak{M}$ in $\mathfrak{M}_\odot$ from the relation

$$M_{\rm bol} = -5.5 \log_{10} (\mathfrak{M}/\mathfrak{M}_\odot) + 6.5 , \quad (2)$$

given by Veeder (1974).

We express the strength of the spectral features in terms of L and ΔL_ν in order to facilitate determination of distances to M dwarfs seen in cataclysmic binaries. A flux deficit Δf_ν (ergs^{-1} cm^{-2} Hz^{-1}) observed in a TiO band yields a distance

$$D = [\Delta L_\nu(S)/4\pi\Delta f_\nu]^{1/2} \quad (3)$$

when a spectral type S has been decided upon.

In order to check the relations in Table 2, we took 15 red dwarf stars that were classified by Boeshaar (1976) which were also observed with the 200″ multichannel spectrophotometer (MCSP) (Greenstein 1981; private communication). The quantity L_ν (9000 Å) was deduced from the observed AB$_\nu$ magnitudes and parallaxes. The mean relation from Table 2 agreed well with the observations, enabling us to have confidence in our absolute flux calibration within the Boeshaar classification system. Individual stars exhibited a scatter about the mean relation of $\Delta \log_{10} L_\nu$ (9000 Å) = 0.2, presumably because of errors in the classifications of up to half a subtype and intrinsic scatter in the stellar properties.

The Na I line and TiO band properties could not be deduced for these 15 stars from the MCSP data because of the low resolution compared with PFUEI. The results given in Table 2 for these quantities are based on the seven dwarfs in Table 1 and must be regarded as preliminary, to be refined with further observations of M dwarfs using PFUEI. Nevertheless, the observed properties of the Na I lines and TiO bands vary so drastically with spectral type that these seven stars should serve quite well to delineate the relevant relations.

IV. THE CATACLYSMIC BINARIES

a) Observations

In Table 3 we show the broad-band *griz* photometry of the six cataclysmic binary stars observed. The stars RW Tri, WW Cet, DQ Her, and WZ Sge have flat spectra, AM Her has a red spectrum, and 2A 0311−227 has a red spectrum peaking in the i band (8300 Å) and turning over by the z band. This photometry was used to flux calibrate the PFUEI spectra taken immediately afterwards. Short time-scale flickering in these systems means our fluxes will not be secure to better than 10%.

In two of the binaries (AM Her and DQ Her), the red star is clearly visible. At the time of observation, AM Her was in its low state, and the appearance of the red dwarf is consistent with the predictions of YS. For DQ Her, the red dwarf was not readily visible outside eclipse. However, a 900-second exposure centered on mid-eclipse shows the dwarf quite clearly. None of the other systems showed a red dwarf; typical flux limits being 4% of the total light in the i band. In Table 4 we quantify the observations of and limits on the red star in the various systems. We give (a) the equivalent width W of the Na I $\lambda\lambda$8183–8194 line; (b) the depth D of the TiO bands as a fraction of the continuum; (c) the energy deficit j (ergs cm^{-2} s^{-1}) in the Na I $\lambda\lambda$8183–8194 line; (d) the flux depression Δf_ν (ergs cm^{-2} s^{-1} Hz^{-1}) in the TiO bands.

TABLE 2

MEAN M DWARF PROPERTIES

Spectral Type[a]	M_v	BC	$V-K$	$V-I$	$V-R$	Na I $\lambda\lambda$8183–8194 W(Å)	TiO λ7700 D	TiO λ7150 D	$\log_{10}L_\nu$ (9000 Å)	$\log_{10}L$ (Na I $\lambda\lambda$8183–8194)	$\log_{10}\Delta L_\nu$ (TiO λ7700)	$\log_{10}\Delta L_\nu$ (TiO λ7150)	$m/\mathfrak{M}_\odot$
M0 V	8.88	−1.30	+3.71	+2.28	+1.32	2.1	0.07	0.21	17.81	28.81	16.64	16.91	0.64
M1 V	9.28	−1.46	+3.92	+2.43	+1.39	2.3	0.11	0.24	17.71	28.65	16.56	16.78	0.58
M2 V	10.00	−1.65	+4.14	+2.60	+1.46	2.6	0.16	0.30	17.49	28.48	16.45	16.60	0.46
M3 V	11.04	−1.91	+4.44	+2.83	+1.56	3.3	0.21	0.39	17.16	28.31	16.32	16.41	0.33
M4 V	12.40	−2.42	+4.98	+3.29	+1.74	4.6	0.30	0.49	16.80	28.09	16.10	16.05	0.23
M5 V	14.08	−3.28	+5.88	+3.98	+2.06	6.9	0.42	0.58	16.41	27.81	15.78	15.58	0.17
M6 V	16.08	−4.27	+6.82	+4.76	+2.54	10.9	0.55	0.67	15.92	27.50	15.40	15.12	0.11

[a] In the system of Boeshaar (1976).

1981ApJ...247..960Y

TABLE 3

PHOTOMETRY OF SIX CATACLYSMIC BINARIES

Star	Date (UT) 1980	Phase ϕ	$g-r$	r	$r-i$	$i-z$
WW Cet	Aug 23.283	...	+0.03	13.60	+0.18	−0.01
			13.66	13.39	13.11	13.13
AM Her	Aug 22.201	0.98[a]	+0.62	14.72	+0.72	+0.43
			15.36	14.51	13.69	13.26
DQ Her	Aug 21.194	0.63[b]	−0.05	14.57	−0.04	+0.00
			14.55	14.36	14.31	14.31
WZ Sge	Aug 22.322	0.44[b]	−0.32	15.11	−0.26	+0.03
			14.80	14.90	15.06	15.04
RW Tri	Aug 23.356	0.46[b]	−0.07	13.31	−0.06	0.00
			13.26	13.10	13.06	13.07
2A 0311−227	Aug 23.417	0.40[a]	+0.69	14.32	+0.72	−0.30
			15.03	14.11	13.29	13.60

[a] $\phi = 0$ for linear polarization pulse.
[b] $\phi = 0$ for photometric mid-eclipse.
NOTE.—The first line for each star gives the magnitude and colors in the *griz* system. The second line gives AB magnitudes at 5000(g), 6500(r), 8300(i), and 10,000(z) Å respectively. The g and r measurements are enhanced by line emission.

b) *AM Herculis*

In Figure 1 we show the low-state spectrum of AM Her together with that of BD +1°4774 (M1.5 V) and G3−33 (M4.5 Ve). In YS a spectral type of M4.5 V for the red dwarf in AM Her was deduced from the Na I λλ8183–8194 lines only. The star AM Her was in the high state in YS with AB (8300 Å) = 12.35. The Na I lines had $W = 0.63$ Å in YS; since the continuum has dropped 1.35 mag, we would expect to observe $W = 2.2$ Å. This compares well with the value $W = 2.6$ Å given in Table 4.

The level of the flux in AM Her in the g and r bands suggests 20% of the flux in the i band does not arise from the red dwarf (if that flux is flat). The energy distribution of AM Her suggests the presence of an M4.5 V dwarf as was predicted in YS, and the TiO band strengths are in agreement with this. However, inspection of Figure 1 shows the Na I λλ8183–8194 line to be too weak for this spectral type in AM Her; its strength suggests the red dwarf is M3$^+$ V. This discrepancy may be due to the lower surface gravity on or heating of the Roche cusp, particularly as we observed AM Her with the red dwarf near superior conjunction (this occurs at phase $\phi = 0.15$). The TiO bands are probably a more reliable indicator of surface temperature, and we shall use a spectral type of M4$^+$ V for distance determination. It would be interesting to observe the strength of Na I with orbital phase. The slightly weaker than normal Na I lines caused us to underestimate slightly the contribution of red dwarf light to AM Her in its high state (in YS).

In order to calibrate the spectral type of the red dwarf using the TiO bands, we define the quantity

$$B = \log_{10}\,[\Delta L_\nu(\text{TiO }\lambda7150)/\Delta L_\nu(\text{TiO }\lambda7700)]\,, \quad (4)$$

which one may measure with Δf_ν for the cataclysmic binaries. In Figure 2 we show how B varies among the M standards in Table 1 along with our adopted mean relation. As can be seen, this is a good indicator of spectral type; it will be necessary in the future to observe many more M dwarfs to determine their scatter in this diagram.

The ratio B for AM Her is shown as a horizontal line and intersects the mean relation for a spectral type $S = 4.25$. The spectral type M4$^+$ V yields a distance estimate, using equation (3), of

$$D = 71 \pm 18 \text{ pc}\,. \quad (5)$$

TABLE 4

RED STAR PARAMETERS IN CATACLYSMIC BINARIES

Star	Date (UT) 1980	Phase ϕ	Na I λλ8183–8194 (WÅ)	TiO λ7700 D	TiO λ7150 D	$\log_{10} j$ (Na I λλ8183–8194)	$\log_{10}\Delta f_\nu$ (TiO λ7700)	$\log_{10}\Delta f_\nu$ (TiO λ7150)
WW Cet	Aug 23.317	...	<1.0	<0.03	<0.03	<−14.03	<−26.21	<−26.20
AM Her	Aug 22.239	0.29[a]	2.6	0.21	0.24	−13.85	−25.74	−25.84
DQ Her	Aug 21.265	0.00[b]	<2.5	0.08	0.13	<−14.69	−26.88	−26.79
WZ Sge	Aug 22.362	...[c]	<0.5	<0.03	<0.03	<−15.11	<−26.98	<−27.00
RW Tri	Aug 23.385	0.60[b]	<0.25	<0.02	<0.02	<−14.62	<−26.36	<−26.36
2A 0311−227	Aug 23.463	0.28[a]	<0.3	<0.02	<0.02	<−14.63	<−26.45	<−26.41

[a] $\phi = 0$ for linear polarization pulse.
[b] $\phi = 0$ for photometric mid-eclipse.
[c] Averaged over an orbit.

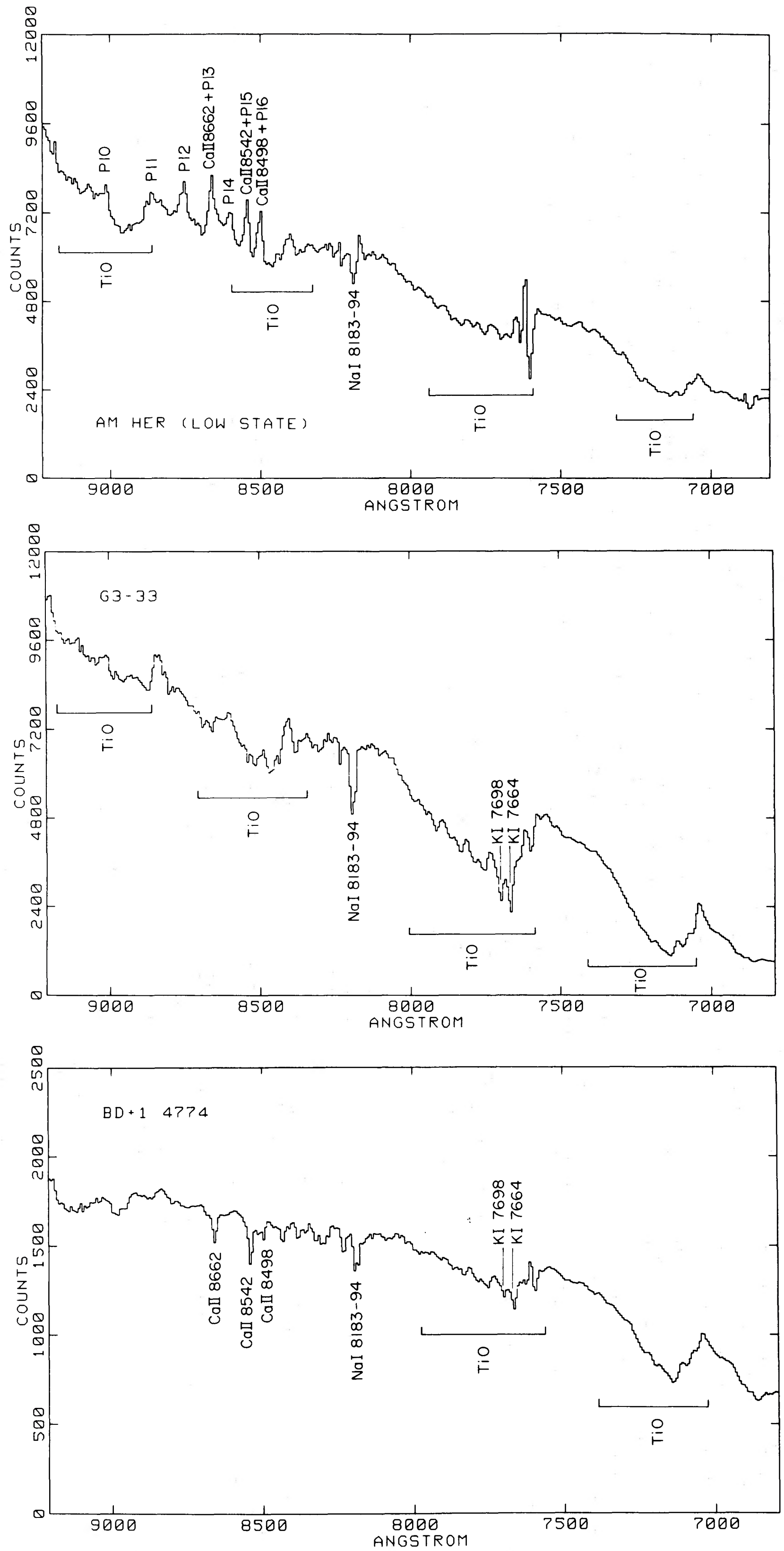

FIG. 1.—Spectrum of (*a*) AM Her in the low state. Each pixel is 6.5 Å and the resolution is 12 Å. The data are on a linearized flux scale with 1 count representing $AB_v = 23.2$. The atmospheric A band (λ 7600) did not divide out well and leaves spurious rugosities there. The magnetic phase $\phi = 0.29$. Spectrum of (*b*) G3−33. an M4.5 Ve star; and (*c*) BD +1°4774, an M1.5 V star.

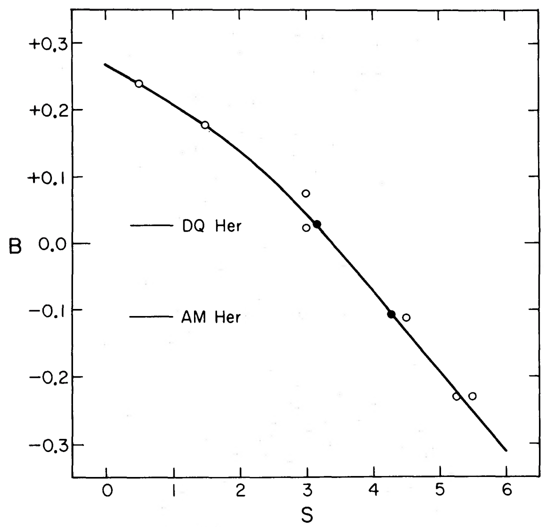

FIG. 2.—The TiO band ratio B as a function of spectral subclass S along the M dwarf sequence. The open circles represent observations from our seven standards, and the curve is the adopted mean relation. The band ratios for DQ Her and AM Her are shown as horizontal lines which intersect the mean curve at the filled circles. This diagram is used to find the spectral subclass of the M dwarfs in those binaries.

(the error arises from the intrinsic scatter in the luminosities of M dwarfs). It should be noted that the red dwarf must obey the main-sequence mass-radius relationship (YS) but may be too cool for its mass (Wade 1980). In that case, its surface area is larger than that of a main-sequence star of the same *temperature*. The distance estimate (eq. [5]) should probably be regarded as a lower limit. If the star lies above the zero-age main sequence (see YS), then $m_R < 0.44\ \mathfrak{M}_\odot$ and $r_R < 0.38\ R_\odot$. Since a main-sequence star of spectral type M4$^+$ V in AM Her would have $m_R = 0.22\ \mathfrak{M}_\odot$ and $r_R = 0.29\ R_\odot$ (see Fig. 8 in YS), the distance cannot be increased by more than the ratio of the two radii $0.38\ R_\odot/0.29\ R_\odot$. An upper limit of 93 pc for the distance results.

c) DQ Herculis

In Figure 3 we show spectra of DQ Her in and out of eclipse together with the red dwarf BD +68°946 (M3 V). The spectra of DQ Her out of eclipse show He I λλ7065, 7281 and Paschen emission lines as well as strong O I λλ7772–7775 absorption. This strong absorption was also seen in Stepanyan's star which seems to be similar to DQ Her (Young, Schneider, and Shectman 1981). These lines hold no further interest in the present study; we note that no sign of the red dwarf is visible out of eclipse. The spectrum DQ Her in eclipse was of 900 seconds duration and has a continuum depressed by 1.6 mag at 8300 Å. As may be discovered by scrutinizing Figure 3, the red dwarf is easily visible. The TiO bands have appeared at quite respectable strength. The red dwarf is not nearly so prominent as the one in AM Her; considerable dilution of the red dwarf in DQ Her is still occurring at mid-eclipse. The eclipse depth at 8300 Å is 2 mag (Schneider and Greenstein 1979), so that our observation cannot be improved significantly with a shorter exposure centered on mid-eclipse.

The spectral type of the red dwarf is obtained by measuring the flux defects in the TiO bands. This, when plotted in Figure 2, yields a spectral type $S = 3.25$. We obtain a distance estimate for a spectral type M3$^+$ V of

$$D = 327 \pm 84 \text{ pc} \tag{6}$$

for a normal main-sequence object. In Young and Schneider (1980), a dynamical analysis yielded

$$m_R = 0.32 \pm 0.03\ \mathfrak{M}_\odot$$
$$r_R = 0.45 \pm 0.01\ R_\odot\ . \tag{7}$$

(the errors in $\mathfrak{M}_R$ and r_R are correlated to make the density $\mathfrak{M}_R/r_R{}^3$ invariant), whereas a normal main-sequence star of type M3$^+$ V has

$$m_R = 0.31\ \mathfrak{M}_\odot\ ,$$
$$r_R = 0.37\ \mathfrak{M}_\odot\ , \tag{8}$$

so that DQ Her B is 25% larger than a main-sequence star of the same mass. Plotting a mass-radius diagram for DQ Her (like Figure 8 in YS) shows this result to be independent of any errors in the mass, provided $0.1\ \mathfrak{M}_\odot < m_R < 0.35\ \mathfrak{M}_\odot$. Within the errors, however, its spectral type (and thus temperature) is normal for its mass. Smak (1980) independently arrived at nearly identical masses using photometric/spectroscopic data. Since DQ Her B is somewhat larger than a main-sequence star of M3$^+$ V, we should revise the distance estimate up to $D = 400 \pm 103$ pc. This is to be compared with previous estimates ranging from 230 pc (Baade 1940) to 370 pc (Kraft 1959). This result differs slightly from the M4 dwarf postulated in Schneider and Greenstein (1979); this arises because of the increase in distance.

The current values for the red dwarf in DQ Her indicate a spectral type similar to that of a main-sequence star of the same mass but a radius 25% larger than the main-sequence star. The most important measurement required now is the radial velocity of the red dwarf to sharpen up its mass determination.

d) Distance Limits

Figure 4 displays spectra of three of the four systems for which no M dwarf was detected. All show the usual He I and Paschen emission. None seems promising ground for detection of the red dwarf until they slide into a low state.

2A 0311−227: A member of the AM Her class of variables, it has a period of 81 minutes. The Paschen emission is quite weak. The shape of the continuum is strange, rising strongly from 4000 Å to a peak at 7800 Å, then a downturn occurring at longer wavelengths. Galactic reddening should not be a factor ($b = -57°.7$).

RW Tri: An eclipsing system with a 5.6 hour period. Using scans during eclipse (λλ 4000–10000), Borne (1977) detected an M0 V red companion, the spectroscopic parallax being 200 pc. The CCD data rules out a normal M0 dwarf at this distance.

1981ApJ...247..960Y

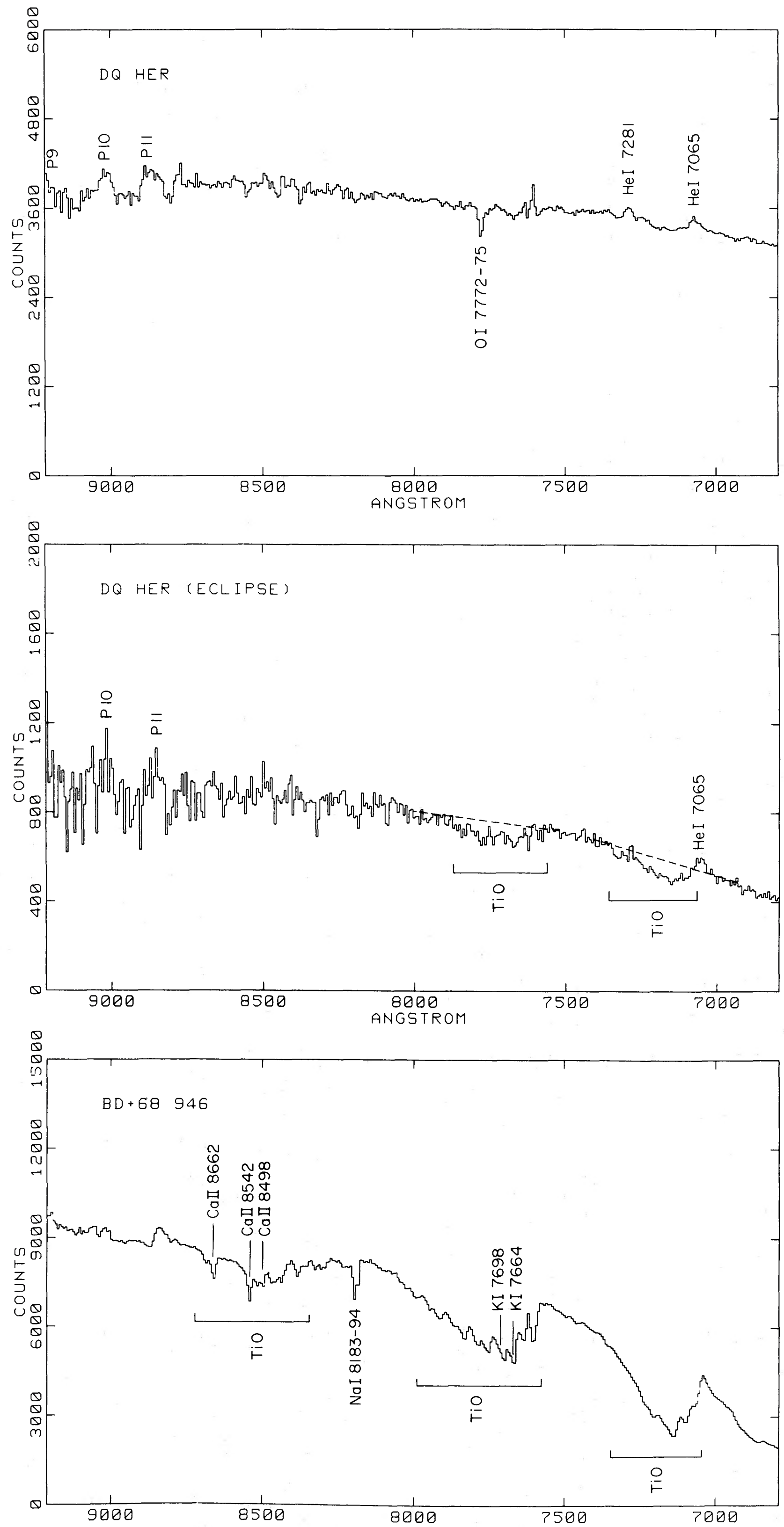

FIG. 3.—(*a*) Spectrum of DQ Her out of eclipse (phase $\phi = 0.90$). Each pixel is 6.5 Å and the resolution is 12 Å. The data are on a linearized flux scale with 1 count as $AB_\nu = 23.3$. The emission at λ 7600 is the result of a poorly divided A band. (*b*) Spectrum of DQ Her at mid-eclipse ($\phi = 0.00$). One count represents $AB_\nu = 23.3$. (*c*) Spectrum of BD $+68°946$, an M3 V star.

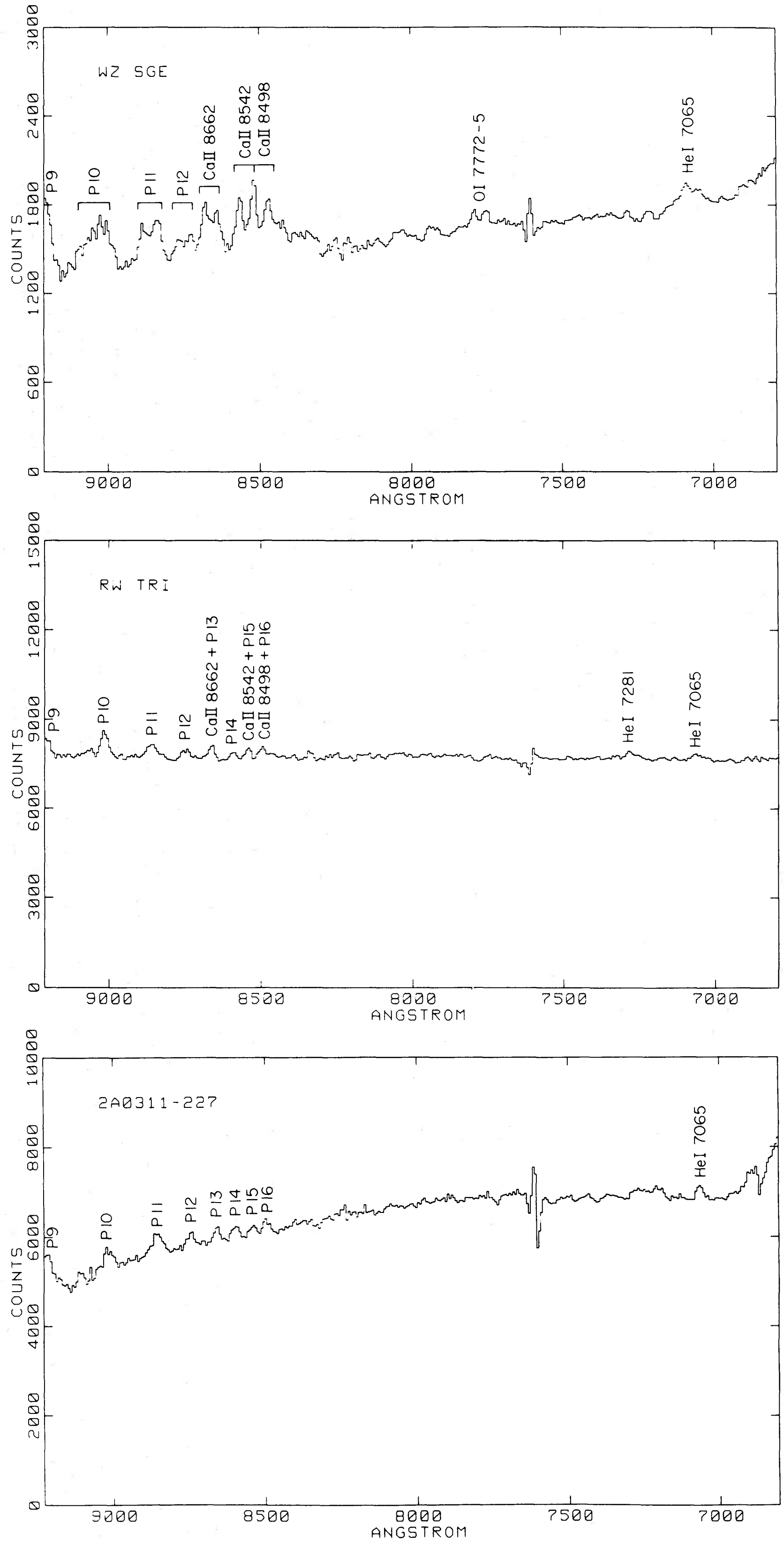

FIG. 4.—(*a*) Spectrum of WZ Sge averaged over an orbit. Each pixel is 6.5 Å and the spectral resolution is 12 Å. The data are on a linearized flux scale with 1 count as $AB_\nu = 23.1$. (*b*) Spectrum of RW Tri at orbital phase $\phi = 0.60$ One count has $AB_\nu = 22.8$. (*c*) Spectrum of 2A 0311−227 at magnetic phase $\phi = 0.28$ One count has $AB_\nu = 22.8$.

TABLE 5

LOWER DISTANCE LIMITS FOR CATACLYSMIC BINARIES

Star	D_{min}(M1 V) (pc)	D_{min}(M3 V) (pc)	D_{min}(M4 V) (pc)	D_{min}(M5 V) (pc)
WW Cet	289	187	135	90
WZ Sge	...	...	328	219
RW Tri	347	224	161	107
2A 0311−227.........	...	...	178	119

WZ Sge: Another eclipsing system, but very bizarre. The emission lines are 90° out of phase with the eclipse, and a mass ratio of 20 has been proposed (Krzeminski and Kraft 1964). In the near-infrared, it has strong He I, O I, Ca II, and Paschen emission.

WW Cet: Little is known about this system. Kraft (1964) found radial velocity variations with a period of 3^h50^m, and Liller (1962) detected strong H I emission. At 8000 Å the continuum is flat with weak emission.

Distance limits, obtained from equation (3) are given in Table 5 for various spectral types for the red dwarf. They are obtained using the more stringent of the TiO bands for M1 V to M5 V red dwarfs. The star WZ Sge seems to be particularly remote from the Earth. Some of the limit entries are blank because a main-sequence red dwarf of the specified type would not fit into the Roche lobe of the cataclysmic binary.

We are very grateful to Jesse Greenstein for numerous discussions and for allowing us to use several of his multichannel observations. We thank James Westphal and Jim Gunn for the use of the PFUEI CCD camera/spectrograph and for the use of the Space Telescope VAX 11/780 computer, and Richard Wade for the M dwarf finding charts. We thank Juan Carrasco for his excellent assistance with the Hale reflector. This work was partially supported by the National Science Foundation grant AST80-03398.

REFERENCES

Baade, W. 1940, *Pub. A.S.P.*, **52**, 386.
Boeshaar, P. 1976, Ph.D. thesis, Ohio State University.
Borne, K. D. 1977, *Bull. AAS*, **9**, 556.
Greenstein, J. L., and Zimmerman, B. A. 1978, *IAU Circ.*, No. 3197.
Johnson, H. L. 1965, *Ap. J.*, **141**, 170.
Kraft, R. P. 1959, *Ap. J.*, **130**, 110.
———. 1964, in *First Conference on Faint Blue Stars*, ed. W. Luyten (Minneapolis: University of Minnesota), p. 77.
Krezeminski, W., and Kraft, R. P. 1964, *Ap. J.*, **140**, 921.
Liebert, J. H., Stockman, H. S., Angel, J. R. P., Woolf, N. J., Hege, K., and Margon, B. 1978, *Ap. J.*, **225**, 201.
Liller, M. H. 1962, Harvard Coll. Obs. Announcement Card 1576.
Robinson, E. L. 1976, *Ann. Rev. Astr. Ap.*, **14**, 119.
Schneider, D. P., and Greenstein, J. L. 1979, *Ap. J.*, **233**, 935.
Schneider, D. P., Young, P. J., and Shectman, S. A. 1981, *Ap. J.*, **245**, 644.
Smak, J. 1980, *Acta. Astr.*, **30**, 267.
Thuan, T. X., and Gunn, J. E. 1976, *Pub. A.S.P.*, **88**, 543.
Veeder, G. J. 1974, *A.J.*, **79**, 1056.
Wade, R. A. 1979, *A.J.*, **84**, 562.
———. 1980, Ph.D. thesis, California Institute of Technology.
Wade, R. A., Hoessel, J. G., Elias, J. H., and Huchra, J. P. 1979, *Pub. A.S.P.*, **91**, 35.
Young, P. J., and Schneider, D. P. 1979, *Ap. J.*, **230**, 502 (YS).
———. 1980, *Ap. J.*, **238**, 955.
Young, P. J., Schneider, D. P., and Shectman, S. A. 1981, *Ap. J.*, **244**, 259.

DONALD P. SCHNEIDER and PETER YOUNG: Robinson Laboratory of Astrophysics 105-24, California Institute of Technology, Pasadena, CA 91125.