1985ApJ...290..707S

THE ASTROPHYSICAL JOURNAL, 290:707–720, 1985 March 15
© 1985. The American Astronomical Society. All rights reserved. Printed in U.S.A.

TT ARIETIS: THE LOW STATE

ALLEN W. SHAFTER
McDonald Observatory, University of Texas, Austin; and Department of Astronomy, University of California, Los Angeles

PAULA SZKODY[1,2]
Department of Astronomy, University of Washington

JAMES LIEBERT[3] AND WILLIAM R. PENNING[3]
Department of Astronomy, University of Arizona

HOWARD E. BOND[2]
Department of Physics and Astronomy, Louisiana State University; and Space Telescope Science Institute

AND

ALBERT D. GRAUER[2]
Department of Physics and Astronomy, University of Arkansas, Little Rock
Received 1984 June 29; accepted 1984 October 4

ABSTRACT

We present photometric and spectroscopic observations extending from the ultraviolet through the infrared of the novalike variable TT Ari, which were obtained during its recent (1982) low state ($V \approx 16.5$). Our observations indicate that mass transfer did not cease completely, but appeared to be occurring sporadically during the low state. Our spectroscopic observations reveal strong, narrow (~ 150 km s^{-1} FWHM) Balmer and He I emission superposed on a blue continuum when mass transfer is diminished. In addition to the narrow emission lines, we have detected broad Balmer absorptions at Hβ, Hγ, Hδ, and He II λ4686 which are most likely produced in the photosphere of the white dwarf with $T_{\rm eff} \gtrsim 50{,}000$ K, as also indicated from the *IUE* spectrum. Limits on Balmer line shifts constrain any surface magnetic field to $B \lesssim 4 \times 10^6$ G. The radial velocity variations of the low-state emission lines are 180° out of phase with the high-state ephemeris recently established by Thorstensen, Smak, and Hessman. The most plausible interpretation of this phasing is that the low-state emission arises in the chromosphere of the secondary star. We also consider the possibility that the emission lines arise from a residual accretion disk in the system.

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

I. INTRODUCTION

TT Ari (= BD +14°341) is one of the brightest cataclysmic variables at maximum light ($V \approx 10.2$); yet, considering the numerous interpretations of its long-term photometric behavior, this system appears to be one of the least well understood. After the discovery of its cataclysmic nature (Smak and Stepien 1969), it was classified as a novalike variable by Cowley *et al.* (1975). This interpretation seemed satisfactory, and despite the relative brightness of the system and the fact that its orbital period was not firmly established, TT Ari slipped into relative obscurity until the summer of 1980. At that time TT Ari made an unprecedented descent (based on the photometric records of this system) to a faint ($V \approx 14$) state where it remained for several months (several previous minima of about 12th magnitude have recently been discovered on archival plates by Hudec, Huth, and Fuhrmann 1984). This event stirred a renewed interest in TT Ari and sparked a series of papers beginning with one by Krautter *et al.* (1981*b*). These authors argued, based on the spectral character during the faint state, that TT Ari was in fact a Z Cam–type dwarf nova and that prior to 1980 it had been in an extended standstill. More recently, Jameson *et al.* (1982) have argued that TT Ari is a nonsynchronous magnetic rotator, similar to the DQ Her systems (Warner 1982). These authors were led to their model by the apparent discrepancy between the photometric and spectroscopic periodicities exhibited by the object. Smak and Stepien's original photometry revealed a modulation with a period of $0^{\rm d}1329$. Later spectroscopic studies by Cowley *et al.* (1975) indicated a period of approximately $0^{\rm d}13755$. Accepting the differences between these two periods as real, Jameson *et al.* proposed that the shorter period, i.e., the photometric one, actually reflects the rotation of the white dwarf and that the radial velocity variations observed by Cowley *et al.* reflect the orbital period of the system. The viability of this model obviously rests on the assumption that the photometric and spectroscopic periods are indeed different. Recently, Thorstensen, Smak, and Hessman (1984) have presented observations which have enabled them to refine the spectroscopic period. Their period, which is essentially identical to the Cowley *et al.* period, definitely excludes the published photometric period (Smak and Stepien 1969, 1975).

In 1982 July, TT Ari was again discovered to be in a low state, this time reaching $V = 16.5$. In this paper we report photometric and spectroscopic observations during this recent deep minimum (see also Shafter *et al.* 1982, 1984). These observations indicate that the mass transfer in TT Ari has become very erratic and may cease completely for brief intervals. The spectrum at times is reminiscent of the low state of MV Lyr, displaying extremely narrow emission lines and a relatively steep Balmer decrement. In general we conclude that

[1] Guest Observer, *International Ultraviolet Explorer* satellite.
[2] Visiting Astronomer, KPNO, NOAO, operated by AURA, Inc., under contract with the NSF.
[3] Research performed, in part, with the MMT, operated jointly by the Harvard-Smithsonian Center for Astrophysics and the University of Arizona.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

TT Ari and MV Lyr are remarkably similar systems, although we do not *necessarily* ascribe the narrow emission to the chromosphere of the red dwarf, as did Robinson *et al.* (1981) and Schneider, Young and Shectman (1981) in the case of MV Lyr.

II. OBSERVATIONS

a) Photometry

High-speed photometric observations of TT Ari were obtained during 1979, 1980, and 1982 using a variety of telescopes and photometers. The 1979 and 1980 observations were obtained with the Louisiana State University (LSU) 0.9 m reflector equipped with the two-star photometer described by Grauer and Bond (1981). In each case, a comparison star 35″ west and 5′44″ north of TT Ari was monitored simultaneously with the variable, and division by these measurements was used to remove effects of variations in atmospheric extinction and transparency. A single *UBV* measurement of the comparison star at KPNO yielded $V = 10.99$, $B-V = 0.69$, $U-B = 0.23$. The 1979 and 1980 high-speed photometry of TT Ari was obtained with an unfiltered EMI 9840 photomultiplier, giving a broad-band blue response (from the atmospheric cutoff up to 6000 Å). The measurements were converted to blue magnitudes by assuming the comparison star to have $m_b = 11.68$.

TT Ari was at its "normal" brightness, about 10th magnitude, on 1979 November 16. The 1980 November 29 observations were obtained during the first deep minimum when TT Ari faded to a visual magnitude of ~14. During the latest and deepest minimum, several observations were obtained at KPNO using both the 0.9 m and the 1.3 m reflectors. The observations made with the 0.9 m were obtained on 1982 September 21 and 25 by using the two-star photometer and the observing procedure previously described. The 1.3 m observations were obtained on October 11 by using the Mk II photometer, and consisted of 5 s integrations in the *U*, *B*, and *V* bandpasses cycled for ~2.5 hr. The mean of the resulting 471 points yielded the following magnitudes for TT Ari in the low state: $U = 15.12 \pm 0.04$, $B = 16.32 \pm 0.04$, and $V = 16.45 \pm 0.04$ (the error bars designate the standard deviation from the mean of all points). In addition to the optical observations made with the 1.3 m, we have obtained infrared magnitudes of TT Ari using the InSb system Otto. We found that $J = 14.1 \pm 0.1$, $H = 13.5 \pm 0.1$, and $K = 13.3 \pm 0.1$.

b) Spectroscopy

Spectroscopic observations of TT Ari were made during the low state by using a Wampler scanner (Robinson and Wampler 1972) at the Cassegrain focus of the Mount Lemmon 1.5 m reflector, an intensified photon-counting Reticon system at the Cassegrain focus of the Steward Observatory 2.3 m, and the Multiple Mirror Telescope (MMT) echelle spectrograph.

The Mount Lemmon observations consist of both high- and low-dispersion spectra. The high-dispersion data were obtained with a 1200 lines mm^{-1} grating in first order which resulted in about 1000 Å of useful data at a resolution of ~4 Å FWHM. These observations were centered on Hα and were primarily obtained for use in a radial velocity study. We have restricted our radial velocity observations to Hα primarily because the high-dispersion grating is blazed at 6800 Å. For a complete description of the observing technique used in acquiring the radial velocity data, see Shafter (1983*a*). The low-dispersion data were obtained with a 600 lines mm^{-1} grating in first order. Two grating settings were employed, each yielding ~2500 Å of spectral coverage. The resulting spectrum covers 3800–8600 Å at a resolution of ~11 Å FWHM.

The Steward observations were obtained by using a 600 lines mm^{-1} grating in first order. This configuration yields a useful spectral coverage of 3600–6000 Å at a resolution of ~7 Å FWHM.

Our MMT echelle data were obtained on two nights, 1984 January 17 and 19 (UT). We obtained a total of 18 spectra (eight on the first night and ten on the second). The observations on the first night covered roughly half of the spectroscopic period. The observations on the second night were timed to cover the remainder of the orbit. Our integrations were 10 minutes in length, with a comparison lamp observation taken after each. The spectra covered a range of about 66 Å centered on Hα. The MMT spectrograph image stacking

TABLE 1

SUMMARY OF OBSERVATIONS

JD (2,440,000+)	Observer	Telescope	Mean *V* Mag	Integration Time (minutes)	Duration (hr)	Spectral Coverage (λ)	Resolution (Å)
			Spectroscopy				
5286 (1982 Nov 13)	A. W. S.	Mount Lemmon	16.5	8	3.3	3800–6800	11
5288 (1982 Nov 15)	A. W. S.	Mount Lemmon	16.5	32	...	3800–6800	11
5288 (1982 Nov 15)	A. W. S.	Mount Lemmon	16.5	72	...	6300–8600	11
5288 (1982 Nov 15)	J. L.	Steward	16.5	48	...	3600–6100	7
5325 (1982 Dec 22)	P. S.	*IUE* (SWP)	16.5	240	...	1150–1950	6
5325 (1982 Dec 22)	P. S.	*IUE* (LWR)	16.5	148	...	1950–3150	6
5717 (1984 Jan 17)	J. L./W. R. P.	MMT	16.5	10	1.5	6530–6600	0.1
5719 (1984 Jan 19)	J. L./W. R. P.	MMT	16.5	10	2.0	6530–660	0.1
			High Speed Photometry				
4193 (1979 Nov 16)	H. E. B.	LSU 0.9	~11.2	...	3	blue	...
4572 (1980 Nov 29)	H. E. B.	LSU 0.9 m	~14	...	3	blue	...
5233 (1982 Sep 21)	H. E. B./A. D. G.	KPNO 0.9 m	~15.5	...	2	blue	...
5237 (1982 Sep 25)	H. E. B./A. D. G.	KPNO 0.9 m	~15.5	...	2.5	blue	...
5239 (1982 Sep 27)	P. S.	KPNO 1.3 m	~16	...	0.5	*J, H, K*	...
5253 (1982 Oct 11)	P. S.	KPNO 1.3 m	16.5	...	2.5	*U, B, V*	...

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

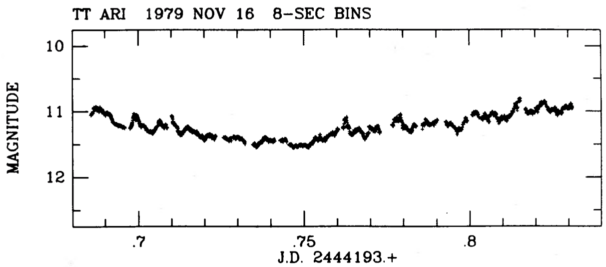

FIG. 1

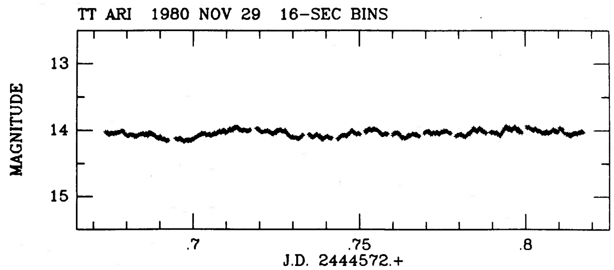

FIG. 2

FIG. 1.—Broad-band "blue" light curve of TT Ari obtained in 1979 when system was in the high state. Note modulation at the orbital period. Intervals between tick marks are $0^{d}.01$ = 14.4 minutes. Blue magnitudes plotted against heliocentric Julian date, and original integrations summed into 8 s bins.

FIG. 2.—Broad-band "blue" light curve of TT Ari obtained in 1980 when system was in an intermediate state. Note low amplitude of flickering and disappearance of orbital modulation. Integrations summed into 16 s bins.

system, which corrects for the different beam angles from the various primary mirrors, improved the resolution of our observations to 0.1 Å.

The UV spectra were obtained with the *IUE* satellite on 1982 December 22 by using the large aperture in the low-resolution mode. One SWP (1150–1950 Å) exposure of 240 minutes, and an LWR (1950–3200 Å) exposure of 148 minutes were obtained. The FES magnitude limit was 16.5, indicating that TT Ari was still in the low state.

A summary, giving the details of the photometric and spectroscopic observations, is presented in Table 1.

III. HIGH-SPEED PHOTOMETRY

The broad-band "blue" light curves obtained with the two-star photometer are shown in Figures 1, 2, 3, and 4. The light curves for the 1979 and 1980 runs cover approximately one orbital period. The 1979 "high-state" light curve shows an overall modulation at (or near) the orbital period of the system. This is the modulation that was initially observed by Smak and Stepien (1969). The usual small-amplitude, rapid flickering can be seen superposed on the sinusoidal "orbital" variation. In the canonical model for cataclysmic systems, the orbital modulation is believed to be the consequence of the changing aspect of the hot spot with orbital phase. The rapid flickering in some systems (e.g., U Gem) is also ascribed to the hot spot (Warner and Nather 1971). Additional photometric observations of the high state may be found in Mardirossian *et al.* (1980).

Jameson *et al.* (1982) have argued that the hot spot cannot be the source of the orbital modulation seen in TT Ari. These authors have observed that the flux distribution of the modulation is flat (in frequency units) in the range 1265–5500 Å. Because of the large amplitude of the variation (1.53 mag) in the UV, Jameson *et al.* conclude that a relatively cool hot spot at the edge of the disk cannot be responsible for the observed modulation. As an alternative, they have proposed that TT Ari is an oblique magnetic rotator similar to the DQ Her stars. Within the framework of this model, Jameson *et al.* ascribe the observed photometric orbital modulation to the changing aspect of the accretion spot on the surface of the magnetic white dwarf component. This model provides a natural explanation for the apparent discrepancy between the orbital period (as determined spectroscopically) and the photometric period. If reprocessing of hard radiation from the accretion spot by material at rest in the corotating frame of the binary is occurring as in H2252−035 (Patterson and Price 1981; Hassall *et al.* 1981), then, as pointed out by Jameson *et al.*, a detection of this reprocessed radiation would be a crucial test for the magnetic rotator hypothesis. A modulation of any reprocessed radiation would occur at the best period between the spectroscopic and photometric periods. The beat period should be quite long (∼4 days), based on the current values for the photometric and spectroscopic periods. Detection of such a long period modulation would obviously be difficult. It is our feeling, therefore, that accurate determinations of both the photometric and spectroscopic periods be made before a search for the best period is undertaken.

The light curve which was obtained in the intermediate state ($V \approx 14.5$) does not display any modulation near the orbital period (see Fig. 2). In addition, the amplitude of flickering seems to be somewhat diminished. Spectroscopic observations by Williams (1982) during the intermediate state reveal moderately strong (EW ≈ 23 Å) and moderately broad (∼600 km

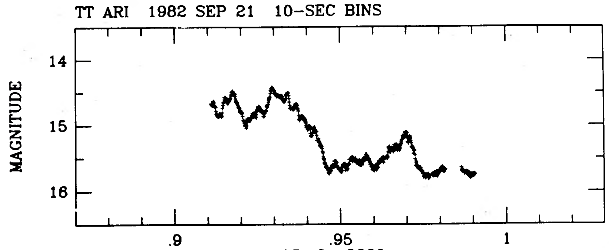

FIG. 3

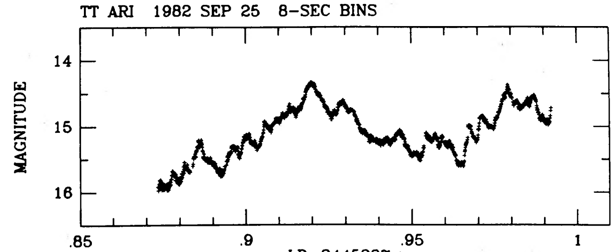

FIG. 4

FIG. 3.—Broad-band "blue" light curve of TT Ari obtained in 1982 September when system was slightly above minimum light. Note very conspicuous flickering (although in absolute units the flickering in the high state is considerably more energetic). Integrations summed into 10 s bins.

FIG. 4.—Broad-band "blue" light curve for 1982 September 25. See caption for Fig. 3, except that the integrations have been summed into 8 s bins.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

s^{-1} FWHM) Balmer emission, characteristic of dwarf novae at quiescence. It appears that the ~ 3 mag drop from the high state to the intermediate state can be explained simply in terms of a decrease in the mass transfer rate by a factor of 20 or so, assuming steady state disk theory where $L \propto \dot{M}$. The resulting decrease in the hot spot (or accretion spot) luminosity may provide an explanation for the lack of any obvious modulation at or near the orbital period in the intermediate-state light curve.

Finally we come to the light curves which were obtained near and during the recent low state of TT Ari. The data shown in Figures 3 and 4 were obtained on 1982 September 21 and 25 when TT Ari had a visual magnitude between 15 and 16. This is slightly brighter than the lowest state which was observed on 1982 October 11. Our October photometry, shown in Figure 5, indicates that TT Ari was near $V \approx 16.5$. Although the data shown in Figure 5 are quite noisy, it is apparent that TT Ari was still flickering even at minimum light. In sharp contrast to the high- and intermediate-state light curves, the flickering during the low state is much more conspicuous (although in absolute units the flickering in the high state is considerably more energetic). Unfortunately, our individual light curves from the low state do not quite cover a full orbit.

It is tempting to compare the long-term photometric behavior of TT Ari with that of the novalike variable MV Lyr. The latter system was discovered to be in an unusually faint state in 1979 August (Romano and Rosino 1980; Wenzel 1980). Subsequent photometric and spectroscopic studies of MV Lyr by Robinson *et al.* (1981) at minimum light established that the mass transfer had apparently ceased completely at times. In particular, Robinson *et al.* presented high-speed photometry which revealed a quiescent light curve (i.e., an absence of flickering) during one night in 1980 July. These authors also noted that on one night (1980 July 10) while at minimum light, MV Lyr displayed strong flickering (cf. their Fig. 2). The flickering observed by Robinson *et al.* at minimum light is

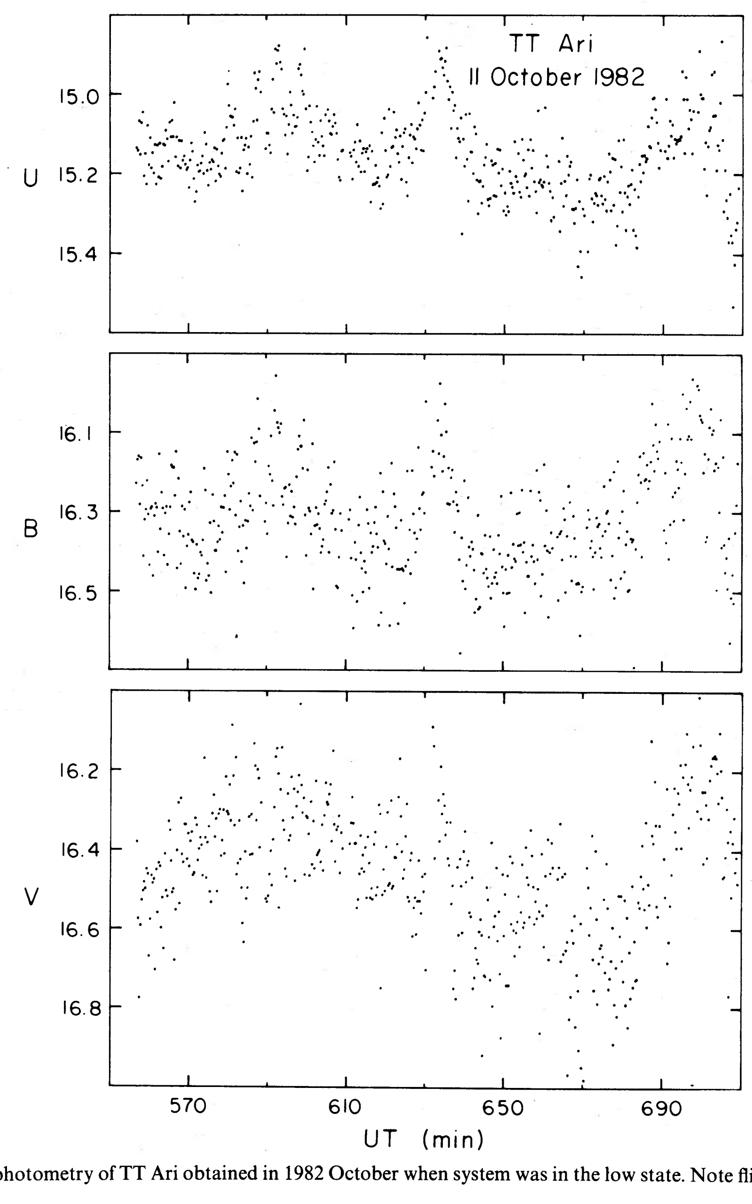

FIG. 5.—High-speed *UBV* photometry of TT Ari obtained in 1982 October when system was in the low state. Note flickering present even at $V \approx 16.5$.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

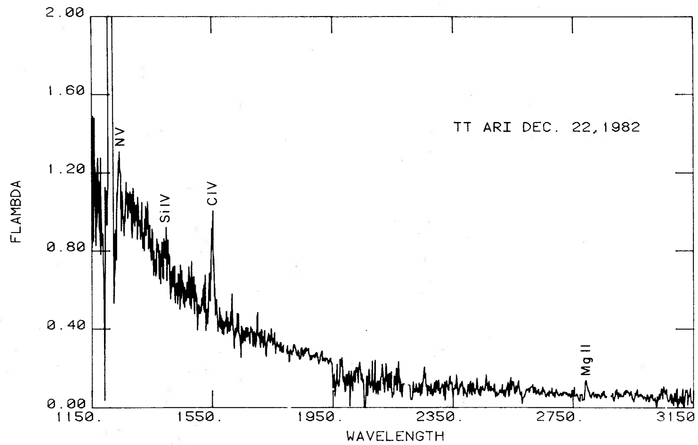

FIG. 6.—*IUE* spectrum of TT Ari obtained on 1982 December 22 while system was at minimum light (FES magnitude ~ 16.5). Note rapid rise in flux shortward of ~ 2000 Å indicating presence of a hot white dwarf.

similar to the flickering we have observed during the low state of TT Ari, as a comparison of Figure 2 of Robinson *et al.* with our Figures 3, 4, and 5 illustrates. It appears that either the mass transfer never completely ceased during the low state of TT Ari, or we unfortunately missed observing the system at the appropriate time. Nevertheless, whether TT Ari completely ceased mass transfer or not, it is clear that the long-term photometric behavior of the system is quite similar to that of MV Lyr and that a drastic reduction in the mass transfer rate occurred in both systems. Spectroscopically, TT Ari and MV Lyr also appear similar at the low state, with both objects displaying extremely narrow Balmer and He I emission (Schneider, Young, and Shectman 1981; Robinson *et al.* 1981).

Before turning to a detailed discussion of our optical spectroscopic data on TT Ari, we first present UV and IR data obtained during the low state which clearly indicate that, although a residual accretion disk may still exist in the TT Ari system, it is no longer the dominant source of light.

IV. UV AND IR OBSERVATIONS AND THE OVERALL ENERGY DISTRIBUTION

Figure 6 shows our *IUE* Spectrum taken on 1982 December 22. The FES magnitude limit was 16.5, indicating that TT Ari was still in the low state. In Table 2 we compare our *IUE* observations of TT Ari in the low state with previous *IUE* observations obtained during the intermediate and high states. The most interesting difference between the low and the intermediate or high states is the drastic change in the shape of the spectrum.

Unlike previous *IUE* data, the continuum of TT Ari at $V \approx 16.5$ has a slope $F_\lambda \propto \lambda^{-4}$, consistent with a hot ($T \gtrsim$ 50,000 K) white dwarf. In Figure 7, the *IUE* points in 50 Å bins that are uncontaminated by emission lines are plotted along with optical *UBV* and infrared *JHL* fluxes obtained at the low state. The dashed line through the UV is a 50,000 K Wesemael *et al.* (1980) model. This temperature is also consistent with the Lyα absorption width (~ 19 Å from the line center), although this is somewhat difficult to determine due to the presence of N V in emisson. Temperatures up to 70,000 K are also permitted with this line width, while the continuum fit cannot distinguish between higher temperature models since there is little change in the slope plus the possibility of slight reddening. This high temperature could also represent the accretion spot on the white dwarf in the model of Jameson *et al.* (1982). The optical absorption features discussed in the next section are consistent with a temperature in this range.

As seen in Figure 7, the observed optical fluxes fall slightly above those for a hot white dwarf or hot blackbody, while the IR fluxes imply the presence of a cool secondary. The IR colors alone ($V-J = 2.4$, $V-K = 3.2$) imply a K7 star, but the V magnitude has some contribution from the hot component and possibly from a third component as well. If we make the assumption that the secondary is a Roche lobe filling main-sequence star, then for an orbital period of 3.2 hr, we estimate that $M_2 \approx 0.35\ M_\odot$, consistent with an M3 star (a K7 star would overfill its Roche lobe by a factor of 2). Under the assumption that all of the 2.2 μm light is contributed by the secondary (an M2–M3 star), we can estimate the distance and

TABLE 2

IUE SPECTROSCOPY OF TT ARI

Date	FES Magnitude	α[a]	F_λ(1500 Å) (ergs cm^{-2} s^{-1} Å^{-1})	Peak C IV Flux (ergs cm^{-2} s^{-1} Å^{-1})	Lines	Reference
1979 Jul 12	11.7	2.29	1.2×10^{-12}	...	absorption	1
1980 Sep 14	12.5	2.3	0.6×10^{-12}	1.0×10^{-12}	C IV emission others absorption	2
1980 Nov 17, 23	14.5	2.22	0.07×10^{-12}	0.1×10^{-12}	emission	3
1982 Jan 9	11.9–12.4	2 comp	0.9×10^{-12}	1.0×10^{-12}	C IV, Mg II emission others absorption	4
1982 Dec 22	16.5	4	0.06×10^{-12}	0.1×10^{-12}	emission	5

[a] Parameter α is defined as $F_\lambda \propto \lambda^{-\alpha}$.

REFERENCES.—(1) Krautter *et al.* 1981*a*. (2) Jameson, King, and Sherington 1982. (3) Krautter *et al.* 1981b. (4) Jameson *et al.* 1982. (5) This work.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

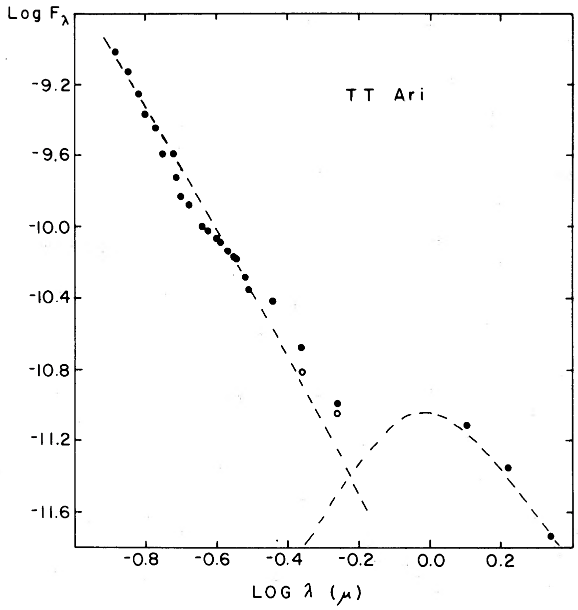

FIG. 7.—Overall energy distribution of TT Ari in the low state. UV points derived from *IUE* spectrum using 50 Å wide bandpasses uncontaminated by emission. Remaining points are based on *UBV* optical and *JHK* infrared fluxes. Dashed line through UV is a 50,000 K Wesemael *et al.* (1980) model. Dashed line in the red represents estimate of red dwarf contribution. Open circles represent sum of white dwarf and secondary.

contribution of this component. Jameson, King, and Sherrington (1982) estimated $K = 11.75$ for the secondary, leading to a distance of 100 pc for the system. This is clearly an underestimate. Using our value of $K = 13.3$ and the same method (Bailey 1981) gives a distance of 214 pc. The distance will be somewhat larger if there is another component contribution at 2 μm.

A further distance estimate (consistency check) is available by comparing the inferred primary star V magnitude (~ 17.0) with the absolute magnitude expected for a normal-radius white dwarf with $T_{\rm eff} \gtrsim 50{,}000$ K. Because the V band is well down the Rayleigh-Jeans tail of the flux distribution, $M_v \approx +9.0 \pm 0.3$ for $50{,}000 \lesssim T_{\rm eff} \lesssim 80{,}000$ K stars. We thus estimate $V - M_v \approx +8$, $D \approx 400$ (± 100) pc. This is a factor of 2 larger than that estimated from the assumed secondary K magnitude, at the 2 σ level.

Since the photosphere may have a very nonuniform temperature, and the radiation may essentially be emitted from a region smaller than the full white dwarf surface, this method may overestimate the distance. It certainly suggests that any magnetic "spot" responsible for this radiation should have $\gtrsim 10^{-1} R_{\rm wd}$. It might seem logical to use the *IUE* fluxes rather than the inferred V magnitude for this exercise, since the primary component clearly dominates the energy distribution at the ultraviolet wavelengths. However, the expected ultraviolet fluxes are very sensitive to the assumed surface $T_{\rm eff}$, which may be uncertain by a factor approaching 2.

The rough energy distribution of the secondary is sketched in Figure 7, using the colors of an M2–M3 main-sequence star (i.e. $V-J \approx 3.5$, $V-K \approx 4.4$). With these two components (white dwarf + secondary), the secondary contributes 32% of the V light and 7% of the B. The white dwarf contributes 56% at V and 65% at B. The open circles in Figure 7 are the sum of the white dwarf and secondary. This leaves $\sim 12\%$ and $\sim 28\%$ of the V and B fluxes for a third component, possibly a residual disk which may cause the activity which we have observed in the optical light curves at the low state.

From Table 2, it is apparent that an $F_\lambda \propto \lambda^{-2.3}$ component (an optically thick disk?) remains until at least $V \approx 14.5$ (Krautter *et al.* 1981*b*), although Jameson *et al.* (1982) break this down into a two-component model. Between the 14.5 and 16.5 states there is little change at 1500 Å and in the emission lines, but the flux at 3000 Å is a factor of 5 less at the lower state. This is all consistent with the "third component" decreasing in importance at the low state, so that the hot component (white dwarf or spot) and secondary are revealed. However, this component does not disappear completely, resulting in some observed activity even at the low state. This is very similar to the behavior of MV Lyr (Robinson *et al.* 1981; Szkody and Downes 1982) and AM Her (Szkody, Raymond, and Capps 1982), where the disk and accretion column, respectively, remain detectable at the low state.

V. THE WHITE DWARF REVEALED

Our low-dispersion, low-state spectra of TT Ari are presented in Figures 8 and 9. The equivalent widths and line fluxes for the major emission features are given in Table 3. The broad Balmer absorption and narrow emission is similar to that observed in MV Lyr (Schneider, Young, and Shectman 1981; Robinson *et al.* 1981). The observed Balmer emission (see Fig. 8) appears to be produced by two separate regions—one with a relatively flat decrement and another with a much steeper one. The flat decrement can be ascribed to the cool (~ 6000 K) outer regions of an accretion disk in LTE (Williams 1980). On the other hand, the steeper decrement could be produced by emission from a lower density region such as a corona surrounding the secondary star or the entire binary or both.

The broad absorptions seen predominantely at Hβ and Hγ are particularly conspicuous in the Steward data (see Fig. 9*b*). As we discussed in the previous section, the *IUE* data suggest that the mass-transfer rate has decreased sufficiently in the low state so that the white dwarf is revealed. The *IUE* observations, in conjunction with the difficulty in imagining how such a low mass-accretion rate could sustain an optically thick disk, led us to conclude that the Balmer absorptions arise in the photosphere of the white dwarf itself and not in the accretion disk. Proceeding under this assumption, we have attempted to estimate crudely the temperature of the white dwarf by fitting

TABLE 3

LINE FLUXES AND EQUIVALENT WIDTHS OF PRINCIPAL OPTICAL LINES

Emission Line	Flux (10^{-14} ergs cm^{-2} s^{-1} Å^{-1})	Equivalent Width (Å)
He I λ7065	0.31	6
He I λ6678	0.43	9
Hα	7.1	119
He I λ5876	0.85	13
He I λ5016	0.25	3
He I λ4922	0.32	4
Hβ	3.2	39
He I λ4471	0.43	4
Hγ	2.1	19
Hδ	1.7	11
He I λ4026	0.95	6
Hε + Ca II H	2.6	15
Ca II K	1.6	9

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

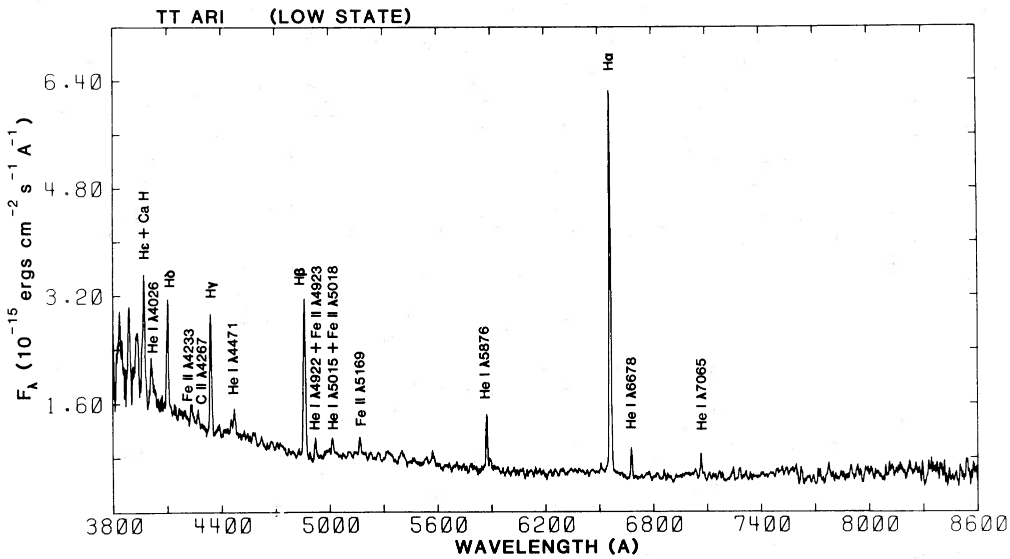

FIG. 8.—Low-state ($V \approx 16.5$) spectrum of TT Ari obtained with Mount Lemmon IDS. Emission lines unresolved at spectral resolution of ~11 Å FWHM. Spectrum is a combination of two individual spectra spliced together. Red segment, covering ~6300 Å to 8600 Å, divided by spectrum of an O subdwarf (BD +28°4211) to remove any atmospheric absorption bands. Broad absorption near 7600 Å could be evidence for TiO but is probably result of incomplete removal of atmospheric A band.

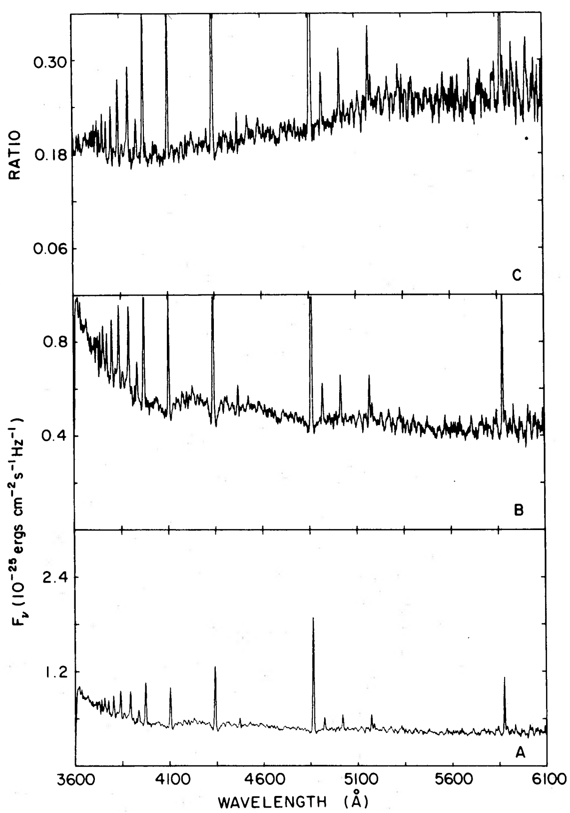

FIG. 9.—(*a*) Low-state spectrum of TT Ari obtained with intensified Reticon spectrometer on Steward 90 in. Higher spectral resolution than displayed in Fig. 8. Broad Balmer absorption troughs at Hβ, Hγ, and Hδ. (*b*) Steward spectrum expanded to better illustrate broad Balmer absorptions. (*c*) Spectrum in (*a*) divided by spectrum of hot white dwarf G191-B2B. Note complete removal of Balmer absorption lines, indicating close resemblance between Balmer line strengths and widths of TT Ari and G191-B2B.

the Balmer absorption profiles with various white dwarf spectra. Figure 9*c* shows the Steward spectrum of TT Ari divided by the spectrum of the 6×10^4 K white dwarf G191-B2B (Shipman 1979). Notice that the Balmer absorption wings cancel nicely in the divided spectrum. The temperature (implied by comparison to G191-B28) of this hot white dwarf is also in good agreement with the *IUE* data which indicate the presence of a hot component with $T \gtrsim 5 \times 10^4$ K in the TT Ari system.

It is interesting to note that the Steward spectrum (Fig. 9*b*) also displays weak He II λ4686 absorption. This is very unusual since, in most isolated DA white dwarfs, the helium sinks out of the atmosphere due to the high gravity. However, if the white dwarf is the accreting component in a close-binary system such as a cataclysmic variable, then a fresh supply of helium is continually added to the equatorial regions of the white dwarf's photosphere. The absence of strong He II absorption and the observed strength of the Balmer absorption suggest an upper limit of $\sim 8 \times 10^4$ K for the white dwarf.

The spectrum attributed to the white dwarf primary shows Hδ, Hγ, and Hβ absorptions unshifted from the emission lines to the accuracy (± 15 Å) allowed by the resolution and signal-to-noise ratio. We can thus constrain the magnetic field of the primary to $\lesssim 4 \times 10^6$ G; this is nearly an order of magnitude less than those known for the AM Her systems. Such a lower value would hardly be unexpected for a rapidly rotating DQ Her model (cf. Lamb and Patterson 1983), however, the assumption of slow asynchronous rotation leads to the expectation of an AM Her–like field $\gtrsim 10^7$ G for TT Ari (Chanmugam and Ray 1984).

The nearly vertical Hγ absorption wings suggest that the primary star has not been spun up to a very large ($\gtrsim 1000$ km s^{-1}) rotational velocity. Due to the modest spectral resolution, we do not attempt detailed fits to Balmer line profiles. An attempt to restudy the star again at higher resolution in 1983 November was unsuccessful, since the system had brightened to $V \approx 15$ and the absorptions were no longer present

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

(presumably due to a much brighter disk component which exhibited broad emission lines).

This is one of several clear instances of the exposure of a white dwarf primary star during a low state of a cataclysmic variable. In other similar cases, for example MV Lyr (Szkody and Downes 1982), U Gem (Panek and Holm 1984), and AM Her (Szkody *et al.* 1980), *IUE* Spectra have also indicated that these primary stars are quite hot. It is now generally thought that the mass transfer must be rapid enough to substantially inhibit or stop the cooling of the white dwarfs in cataclysmic binaries. The normal cooling "age" of a 50,000 K white dwarf is only $\sim 10^6$–10^7 yr, while cataclysmics are believed to have lifetimes of order 10^9 yr or greater; thus less than 1% would have primaries at $T_{\rm eff} \gtrsim 50{,}000$ K if the latter were allowed to cool normally.

Our distance estimate for TT Ari permits us to test the above argument by deriving a minimum accretion rate necessary to maintain the white dwarf at 50,000 K. For a normal radius (*and* the assumption that most of the photosphere is near 50,000 K), the white dwarf radiates about 1 $L_\odot$. If about half of the total accretion (gravitational) energy is radiated away at the white dwarf surface, then

$$L_{\rm wd} \sim 0.5GM\dot{M}/R \sim 4 \times 10^{33}\ {\rm ergs\ s^{-1}}\ .$$

Using $M \sim 1\ M_\odot$, $R \sim 10^{-2}\ R_\odot$, we require $\dot{M} \approx 10^{-9}\ M_\odot$ yr^{-1}. This happens to be the order of magnitude most compatible with disk models showing optically thick disks (cf. Williams 1980; Patterson 1984, Fig. 7); note that the normal high-state spectrum of TT Ari is quite consistent with this interpretation. At a distance of ~ 200 pc, the high-state absolute visual magnitude of TT Ari is (using $V \approx 10.2$)$M_v \approx +4$, again a value in line with various estimates for dwarf novae in outburst. Of course if the primary $T_{\rm eff} \approx 80{,}000$ K, the values of $\dot{M}$ and L must be scaled upward by a factor of ~ 6.

An obvious and hardly unexpected implication is that the temperature of the primary star in a cataclysmic binary may decrease with $\dot{M}$ in the system. This may imply that the white dwarfs slowly cool as the systems evolve toward shorter periods and generally smaller mean accretion rates (cf. Patterson 1984). Of course the occurrence of thermonuclear (nova) explosions during the secular evolution of the cataclysmic may inject still more energy into the white dwarf's reservoir.

VI. EVIDENCE FOR A COOL COMPONENT

Referring to Figure 9*c*, we notice that there is a "red excess" when we divide the spectrum of TT Ari by the spectrum of G191-B2B. If this excess were due to a substantially lower photospheric temperature for the TT Ari primary (say, 40,000 K) relative to G191-B28, the hydrogen absorption wings would not divide out cleanly in Figure 9*c*, He II could not appear strongly, and the *IUE* slope would be too steep. Consequently, the energy distribution of TT Ari is inconsistent with the hypothesis that the continuum is all coming from a hot white dwarf over the wavelength range covered. We propose that the excess flux is either due to radiation from the heated face of the red dwarf star or from a residual accretion ring in the system.

We have extended the wavelength coverage of the Mount Lemmon data into the near-infrared with the hope of detecting spectral features (such as TiO bands) from the secondary, which must be an M dwarf in order to fit within its critical Roche surface.

There is a serious problem with detecting TiO bands, however. Two of the stronger TiO bands are located near strong atmospheric water vapor and O_2 bands at 7150 Å and 7700 Å (the atmospheric A band). The spectrum shown in Figure 8 is actually a composite consisting of a "blue" (3800–6800 Å) and a "red" (6300–8600 Å) spectrum. The red segment has been divided by the spectrum of an O subdwarf (BD +28°4211) prior to flux calibration in an attempt to remove the atmospheric bands. Referring to figure 8, we see that there appears to be broad absorption at 7700 Å and at 8400 Å (the latter feature may be the Paschen jump in emission). Unfortunately, both of these features are very weak and could easily be a consequence of our inability to completely remove the atmospheric bands. Thus we cannot confidently claim a detection of any spectral features from the secondary in TT Ari. We do not expect the white dwarf to dominate the spectrum redward of 7000 Å, but it is hard to estimate the contribution of a residual disk component.

It is interesting to note that the photometry at $V = 16.5$ (Fig. 5) shows a hint of a sinusoidal modulation in the V filter. The best-fit solution is a double sinusoid at half the orbital period with an amplitude of 0.12 mag from a mean of $V = 16.46$. The phasing (see § VII and Table 4) of maxima of the sine waves (at 606 and 705 UT = phase 0.7 and 0.2) implies an origin consistent with an ellipsoidal variation from the secondary, although the amplitude is large for a low-inclination system with 30% contribution from the secondary. Further red photometry over the whole orbit during the low state is needed to confirm this effect.

TABLE 4

ORBITAL ELEMENTS[a]

Parameter	Peak Value	Broad-Base Value	Narrow-Base Value
MMT Observations			
Time of conjunction, T_0[b]	5717.653(3)	5717.659(1)	5717.659(3)
Semiamplitude, K (km s^{-1})	21 ± 3	93 ± 6	210 ± 28
Systemic velocity, γ (km s^{-1})	17 ± 2	11 ± 4	39 ± 23
Mount Lemmon Observations			
Time of conjunction, T_0[b]	5286.709(2)	5286.712(1)	...
Semiamplitude, K (km s^{-1})	40 ± 3	80 ± 3	...
Systemic velocity, γ (km s^{-1})	−3 ± 3	−5 ± 2	...

[a] Eccentricity e and longitude of periastron ω assumed as 0; $P = 0^{\rm d}1375512$ (Thorstensen, Smak, and Hessman 1984).

[b] Inferior conjunction of low-state emission line source; HJD 2,440,000+.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

VII. THE LOW-STATE RADIAL VELOCITIES

We have already commented briefly on the similarity of the strong and narrow Balmer and He I emission lines observed in TT Ari to those observed by Schneider, Young, and Shectman (1981) and Robinson *et al.* (1981) in MV Lyr. In the case of the latter system, both groups of authors concluded that the emission lines were produced in the chromosphere of the red dwarf when MV Lyr was at minimum light. In particular, Robinson *et al.* argued that the lines were too narrow and the Balmer decrement too steep to have been produced in a residual accretion disk. However, they were similar to the lines observed in the spectrum of Feige 24, a close (but detached binary system consisting of a white dwarf and a late-type main-sequence star.

In view of the similarities between the spectra of MV Lyr and TT Ari in their low states, it seems worthwhile to attempt to explain the origin of the narrow emission observed in TT Ari. In the case of TT Ari, we have one very crucial observational advantage which was unavailable to observers of MV Lyr. Namely, a reasonably well established spectroscopic ephemeris for TT Ari has recently become available (Thorstensen, Smak, and Hessman 1984). These authors have determined the orbital period very accurately by compiling high-state radial velocity observations of TT Ari which span

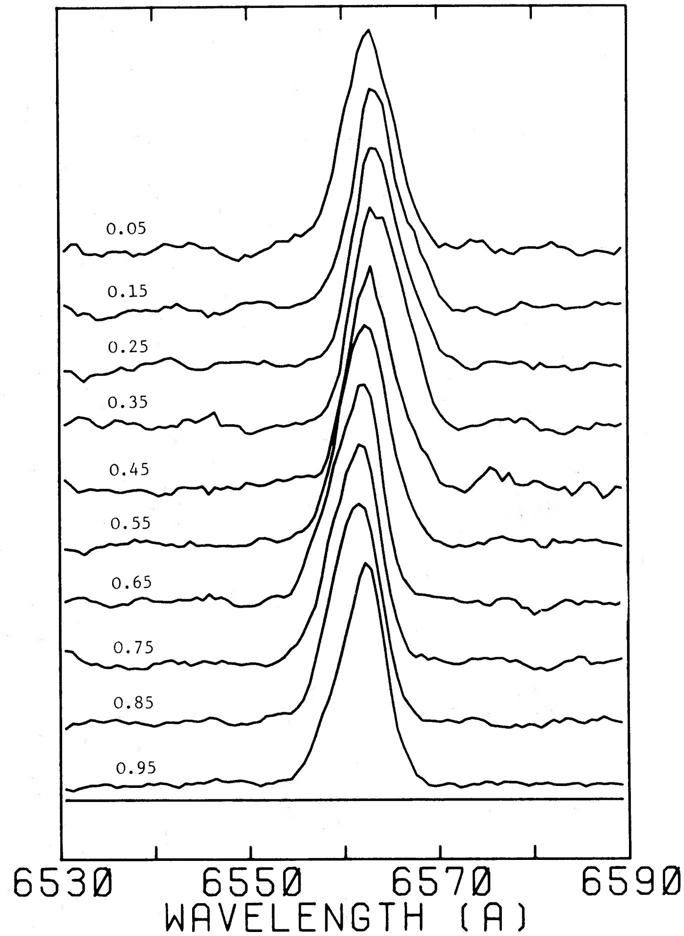

FIG. 11.—Hα line profiles from Mount Lemmon data plotted as function of orbital phase. Because of lower resolution, the two emission components not resolved as in the MMT data (see Fig. 10). Nevertheless, orbital phase-dependent line profile indicates presence of at least two components.

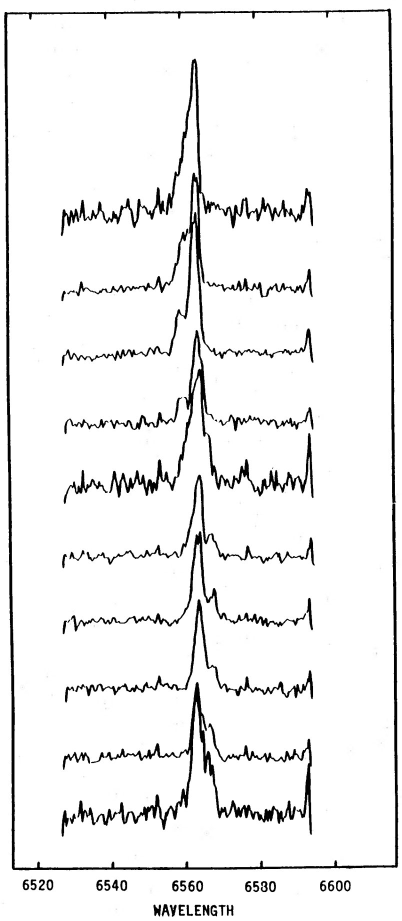

FIG. 10.—Hα line profiles from MMT data obtained 1984 January 19 plotted in chronological order. Top spectrum, HJD 2,445,719.683; bottom spectrum, HJD 2,445,719.762. Note two distinct components. Stronger "peak" component is relatively stationary, but weaker "base" component exhibits significant radial velocity variations.

~10 yr. If a 180° phase shift were found between the high and low states, it would provide strong (although, as we will see later, not conclusive) evidence that the low-state emission lines are produced in the chromosphere of the secondary star. With this goal in mind, we have obtained several high-dispersion spectra of TT Ari using the Mount Lemmon IDS and the MMT echelle spectrograph. The integration times of each spectrum (8 min for the IDS and 10 min for the MMT observations) were chosen to be ~5% of the orbital period in order to avoid serious phase smearing. These high-resolution observations, particularly the MMT data, suggest that the Hα line is actually composed of at least two distinct components. These two components can easily be identified in Figure 10, where we have plotted our MMT data from 1984 January 19 in a time sequence. The time interval between successive spectra is approximately 13 minutes. In Figure 11 we have folded the Mount Lemmon data with the orbital period of Thorstensen, Smak, and Hessman (1984) and plotted the Hα line profile as a function of orbital phase. The components are not resolved in these data; nevertheless it is obvious that two components are present. Henceforth we will refer to the stronger component as the "peak" component and the weaker component as the "base" component.

The peak component seems to be relatively stationary com-

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

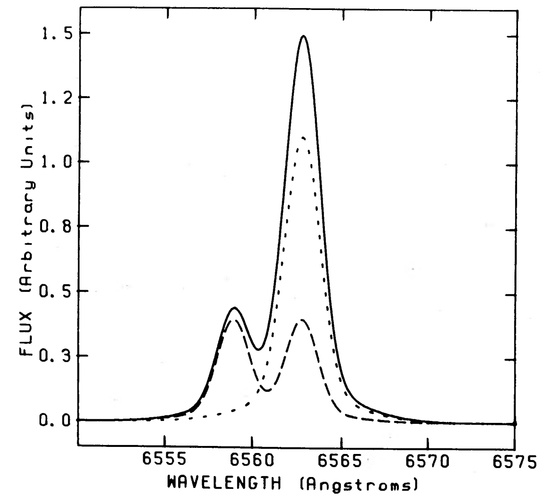

FIG. 12.—Schematic diagram showing how superposition of a narrow peak and a broad base component can reproduce observed low-state line profile observed at quadrature. Solid curve sums the dashed curves. The advantage of such a configuration is that overall line profile would appear relatively broad at conjunction, while allowing the base component to appear narrow at quadrature.

pared with the velocity variations of the base component. At first glance it appears that the base component is quite narrow, becoming almost completely separated from the stronger peak component near quadrature (see Fig. 10). There is, however, another possibility. If the base component is produced in an accretion ring surrounding the white dwarf, then it may actually be double-humped. Such a component could appear narrow and single-humped, as observed, if one of the two humps (the choice would depend on the orbital phase) is always blended with the relatively stationary peak component. This effect is demonstrated schematically in Figure 12.

In order to measure the true velocity variations of the base component, it is obviously important to know whether it is single- or double-humped. For example, the velocity semi-amplitude of a single-humped component would be significantly larger than it would be for the broader, double-humped case. Because of the present uncertainty concerning the structure of the base component, we have decided to measure its velocity by using two different methods. The first method assumes that the base component is narrow and single-humped. This method consists of simply measuring the centroid of the "observed" base component when it is possible (i.e., near quadrature). We will refer to this measurement as the "narrow-base" measurement. The second method consists of measuring the center of the entire emission line (peak + base components) just above the continuum level. We will refer to this as the "broad-base" measurement because it should reflect the velocity semiamplitude of a broad (and presumably double-humped) base component. We note that because of blending with the peak component, the second method may yield an underestimate of the actual semiamplitude of a broad-base component unless the base component is sufficiently broad to render lending with the peak component unimportant. Because of the lower resolution of the Mount Lemmon data we have not been able to resolve the base component, even at quadrature. Consequently, we have only made a broad-base measurement for these observations. In order to measure the velocity of the stronger peak component, we have simply measured the centroid of the upper ~20% of the emission line for both the Mount Lemmon and MMT observations.

After measuring the velocities of the emission line components as described above, we made nonlinear least squares fits of the resulting values to circular orbits of the form:

$$V(t) = \gamma + K \sin [2\pi(t - T_0)/P] .$$

The best-fit values for the parameters γ, K, and T_0 for both the narrow- and broad-base component measurements and the peak component measurement are presented in Table 4. The radial velocity curves for the MMT and Mount Lemmon data are shown in Figures 13 and 14, respectively.

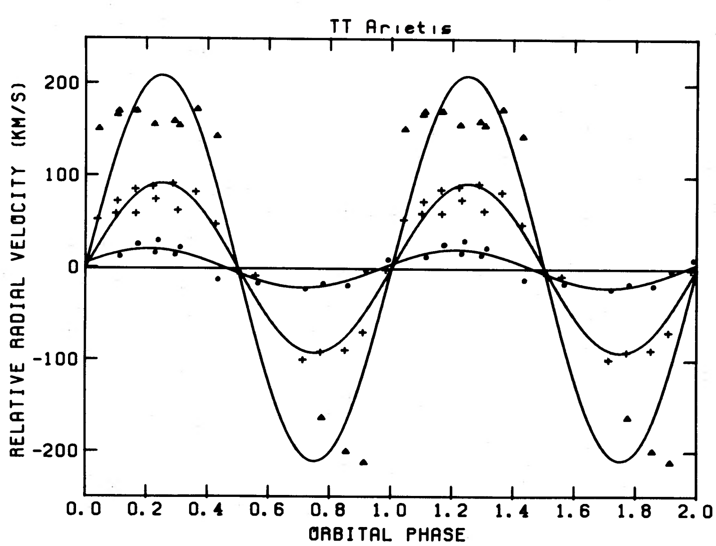

FIG. 13.—Radial velocities of MMT data folded with orbital period and plotted as function of orbital phase. Radial velocity curves are shown for "peak" component (*dots*), "broad base" component (*crosses*), and "narrow base" component measurements (*triangles*). Semiamplitudes for best-fitting sinusoids are 20 km s^{-1}, 92 km s^{-1}, and 210 km s^{-1} respectively. Peak component leads base components by ~0.04 in phase. Note particularly rapid transition through conjunction for narrow base component.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

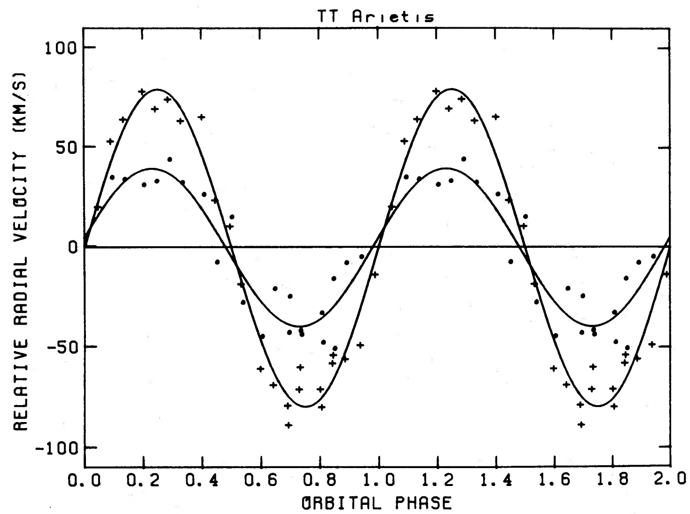

FIG. 14.—Radial velocities of Mount Lemmon data folded with orbital period and plotted as function of orbital phase. Radial velocity curves are shown for "peak" (*dots*) and "broad" (*crosses*) component measurements. Narrow-base measurements not possible for these data because of insufficient spectral resolution. Semiamplitudes of best-fitting sinusoids are 40 km s^{-1} and 80 km s^{-1} respectively. As in MMT data, peak component slightly leads the base component, by ~0.02 in phase. Note semiamplitude of broad-base component agrees well with that derived from the higher resolution MMT data. Semiamplitude of peak component is a factor of 2 larger than for the MMT data because of blending with base component.

VIII. THE ORIGIN AND PHASING OF THE HIGH- AND LOW-STATE EMISSION LINES

One significant result of the radial-velocity study just presented is that *the peak and base components are essentially in phase* (the base component lags the peak component by ~0.04 in phase). It is interesting that for the MMT data, the velocity semiamplitude of the peak component is a factor of ~5 smaller than that for a broad-base component. The difference is only a factor of 2 for the Mount Lemmon data, which have a much lower resolution. It appears that the velocity measurements of the peak component are being contaminated by the relatively large amplitude velocity variations of the base component. This is certainly the case for the Mount Lemmon data, and it appears likely to be the case for the MMT observations as well.

We have conducted line profile simulations which suggest that velocity variations of order 20 km s^{-1} can be introduced to a *stationary* emission component (FWHM ≈ 150 km s^{-1}) by the addition of a weaker (relative intensity = 0.3) component of approximately the same width but having a semiamplitude of order 150 km s^{-1} (a broad, double-humped base component could produce a similar modulation in the peak component with a somewhat smaller amplitude). We wish to stress that our simulations do not enable us to use the observed modulation of the peak component to reliably estimate the amplitude of the base component. This is primarily a result of our ignorance concerning the true profiles of the individual components.

Of course, this artificially induced velocity modulation would be in phase with the variation of the perturbing component. Consequently, we feel that the simplest explanation of the peak component is that it is due to emission from material which is essentially at rest in the system, the small velocity amplitude which we have measured being a result of blending with the base component. The peak component could arise near the center of mass of the binary (near the inner Lagrangian point if the mass ratio is near unity), or, more likely, it may arise in a circumbinary shell which could be the result of mass loss from the system during the high state. Consistent with this, *IUE* observations of TT Ari in the high state show strong evidence for mass outflow (Krautter *et al.* 1981*a*).

Another intriguing explanation for the origin of the peak component is that it arises in a circumbinary ring. Such a ring might be the result of mass loss through the outer Lagrangian point. This model was suggested by Gilliland and Kemper (1980) to explain the narrow, and relatively stationary, emission observed during the 1978 outburst of WZ Sge. If we assume that emission from the external ring is powered by photoionizing radiation from the hot white dwarf, then a segment of this ring will always be shadowed by the secondary. As the binary resolves, this shadowed segment will migrate around the ring. One attractive feature of this idea is that the orbital phase–dependent shadowing could potentially explain the small velocity modulation of the peak component without requiring the blending effect described earlier.

a) The Chromospheric-Emission Model for the Origin of the Base Component

A comparison of the ephemeris of Thorstensen, Smak, and Hessman (1984) with the results presented in Table 4 immediately reveals that *the low-state radial velocities are 180° out of phase with the high-state radial velocities.* The most plausible interpretation of this phase shift is that the base component observed in the low state arises in the chromosphere of the secondary and that the lines seen in the high state arise in the accretion disk. There are several strong arguments in favor of this interpretation. (1) The traditional explanation of the origin of the high-state emission lines is that they are produced in the accretion disk. Cowley *et al.* (1975) argued that the high Balmer lines (which yielded the highest K velocity) were most likely produced in the accretion disk because of their relatively constant intensity (flat decrement). (2) The small width (full width at the continuum ≈ 400 km s^{-1}) of the low-state emission components makes it difficult (although not impossible, as we will see later) to imagine how these lines could be produced in the vicinity of the white dwarf. If we invoke a low value for the orbital inclination in order to explain the narrow lines, then we have trouble explaining the relatively high velocity semiamplitude of the base component, unless we constrain the mass of the white dwarf to be quite small. (3) Finally, we note that the observed semiamplitude of the base component is easy

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

to explain in a model where this line originates in the chromosphere of the secondary star. In particular, the orbital parameters favored by Cowley *et al.* (1975) ($q = 0.4$, $i = 30°–40°$, $K_1 = 60$ km s^{-1}) predict that the secondary should have a velocity semiamplitude near 150 km s^{-1}. This value is in good agreement with our estimate of the semiamplitude of the base component.

Although the case presented above appears to be quite strong, there are a few potential (though not serious) problems with this interpretation which should be discussed. For example, our photometric observations (see Fig. 5) reveal flickering taking place in the low state. If this flickering is taken as evidence of mass transfer, then it would be reasonable to expect the formation of an accretion ring surrounding the white dwarf. As indicated earlier, we have detected a component in the overall energy distribution which implies the presence of such a ring. Assuming the ring exists, it would be exposed to a strong UV flux from the hot white dwarf. It therefore seems reasonable to expect it to be a line as well as a continuum source. Yet there is no evidence for any emission 180° out of phase with the base component (which we have argued has an origin in the chromosphere of the secondary star).

Robinson *et al.* (1981), in their study of the low state of a similar system, MV Lyr, also observed strong flickering when the system was slightly above minimum light. In addition, these authors noticed a slight increase in the emission line width when MV Lyr was flickering. A plausible interpretation of this behavior is that the flickering signaled mass transfer which then led to the formation of an accretion ring surrounding the white dwarf. Emission from this ring would then naturally explain the slight broadening of the emission lines seen by Robinson *et al.*

There are a few other minor problems with the chromospheric emission model which concern the behavior of the emission lines during spectroscopic conjunction. To begin with, although our high-resolution observations are not spectrophotometric, the Hα line appears to become weaker at superior conjunction of the emission line source. This behavior does not appear consistent with an origin in the heated face of the secondary which would be facing the Earth at superior conjunction. Furthermore, the total emission line profile does not appear to become narrower at conjunction, as we would expect if the base component were as narrow as it appears near quadrature. As described earlier, one interpretation of this behavior is that the base component is double-humped and is actually broader than the peak component.

The radial velocity curves for the base component seem to imply that it may be double-humped as well. The observed hump of the base component seems to pass through conjunction very rapidly, going from maximum blueshift to maximum redshift in only 15% of the orbital period (see Fig. 13). If the base component is double-humped, such a rapid transition could be explained as the result of measuring the velocity of the red hump of the base component near phase 0.25, and that of the blue hump near phase 0.75.

b) The Accretion Ring Model for the Origin of the Base Component

The arguments presented above, which seem to indicate that the base component may be double-humped, along with the difficulty in understanding the apparent lack of line emission from the vicinity of the white dwarf, have led us to reconsider the possibility that the base component may actually be produced in an accretion ring. As we have already indicated, in this case the observed width and velocity semiamplitude of the base component put strong constraints on the mass of the white dwarf (M_1) and the orbital inclination (i) of the system. However, one can imagine values for M_1 and i which are consistent with the observed emission-line characteristics and which are not terribly implausible. For example, if we adopt $i = 30°$, $M_1 = 0.25\ M_\odot$, and $K = 90$ km s^{-1} (broad-base measurement), and assume that the secondary is a Roche lobe–filling main-sequence star, we find that the observed emission line width (~ 200 km s^{-1}) is consistent with emission from an accretion ring with an inner radius $R_{\rm in} \approx 2.0 \times 10^{10}$ cm. This is approximately 20 times the radius of a 0.25 $M_\odot$ white dwarf (Hamada and Salpeter 1961). Consequently, the orbiting material can best be described as an accretion "ring" rather than a disk. Such a ring would fit comfortably inside the Roche lobe of the 0.25 $M_\odot$ white dwarf of our example, which has a mean radius of 2.3×10^{10} cm. Incidentally, it is worth pointing out that the specific angular momentum in the accretion ring, $j_r \approx 4 \times 10^{17}$ cm^2 s^{-1}, is in good agreement with the specific angular momentum of the material spilling over from the inner Lagrangian point, $j_{L1} \approx 5 \times 10^{17}$ cm^2 s^{-1}. Thus a ring of radius $R \approx 2.0 \times 10^{10}$ cm would naturally be expected to form in the system described above, assuming conservation of angular momentum.

A serious drawback of this interpretation is that it implies a very low mass for the white dwarf. The only way to accommodate a more massive white dwarf in this picture would be to allow the accretion ring to rotate more slowly than the Keplerian velocity appropriate for its radius. It is unclear whether this is physically possible.

An obvious consequence for the accretion ring interpretation is that the weak emission lines seen in the high state of TT Ari (which were used in the determination of the spectroscopic ephemeris of Thorstensen, Smak, and Hessman 1984) must arise in the chromosphere of the secondary star or at some other location which has an orbital motion 180° out of phase with the white dwarf (possibly near the inner Lagrangian point). While at first this suggestion appears to be implausible, it may have precedent. The spectrum of the dwarf nova SS Cyg in eruption strongly resembles that of TT Ari in the high state. Both systems show broad, shallow Balmer absorption with central emission cores. In a recent study of SS Cyg, Hessman (1984) has found an $\sim 180°$ phase shift between the radial velocity solution derived from the broad Balmer emission observed at quiescence, and that derived from a component of the emission-line core seen in outburst. Since the broad Balmer emission in SS Cyg during quiescence is known to originate in the accretion disk, it appears that a component of the emission-line cores observed during outburst arises in the heated face of the secondary star. This is consistent with the expectation that the secondary star is exposed to a larger amount of hard radiation during an outburst than it is during quiescence. The effect may even be stronger during the high state of TT Ari because in this system the orbital period is shorter and hence the stellar separation is smaller than in SS Cyg. Furthermore, TT Ari is known to be a hard X-ray source while in the high state (Jensen *et al.* 1983), as well as being particularly luminous in the ultraviolet (Wargau *et al.* 1982).

Although it appears plausible, even likely, that a component of the high-state emission lines in TT Ari is produced in the chromosphere of the secondary star, it is still unclear whether

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

this component would dominate the phasing of the emission lines during the high state. However, we feel that the real stumbling block for the low-state accretion ring model is not only the fact that it requires the high-state phasing to be dominated by the secondary star, but also the strict constraint that it places on the mass of the white dwarf. On the other hand, despite a few unanswered questions, there appear to be no comparable drawbacks with the interpretation that the low-state emission arises in the chromosphere of the secondary star. We therefore consider this to be the most likely interpretation of the 180° phase shift between the high and low states of TT Ari.

IX. RELATIONSHIP OF TT ARI TO THE VY SCL SYSTEMS

The VY Scl objects are a subclass of the novalike variables which was originally pointed out by Bond (1980). These cataclysmics have a long-term photometric behavior which is somewhat similar to those of R CrB stars or, alternatively, opposite to that of normal dwarf novae. They remain in what could be described as an outburst state for a long period of time (typically several years) and then occasionally fade by 3–5 mag or more for relatively short periods of time before returning to their normal bright state. Spectroscopically, the high and low states are similar to the corresponding states for typical dwarf novae. A more detailed description of the VY Scl phenomenon, along with minor variations on its exact definition, can be found in Robinson *et al.* (1981), Webbink (1982), and Shafter (1983*b*).

There are now a number of systems known to display the photometric behavior described above: KR Aur, V425 Cas, AM Her, MV Lyr, VV Pup, LX Ser, VY Scl itself, VZ Scl, AN UMa, and, as a result of its recent deep minimum, TT Ari. With the exception of the ultra-short period AM Her systems VV Pup and AN UMa, all the systems listed above have orbital periods between 3–4 hr (although the orbital period of VY Scl is still uncertain, recent observations by Hutchings and Cowley (1984) indicate that the period is most likely near 4 hr). It is difficult to evaluate the significance of this apparent period grouping because the overall orbital period distribution of cataclysmics is subject to various selection effects (see, e.g., Robinson 1983; Patterson 1984). Nevertheless, it is hard to imagine how removal of possible selection effects could increase the total number of cataclysmics in the 3–4 hr range so dramatically that it would make the VY Scl grouping insignificant. We wish to point out, however, that it is unclear whether in evaluating the significance of the grouping we should compare the distribution of VY Scl periods with the period distribution of cataclysmic variables as a whole or just with the distribution of novalike variables. Shafter (1983*b*) has shown that if we compare the VY Scl period distribution with that of all cataclysmics with $P \leq 10$ hr, then the probability that the VY Scl grouping would occur by chance is $\sim 2 \times 10^{-4}$. If, on the other hand, we were to compare the distribution of VY Scl systems with the distribution of novalike variables alone, then the observed grouping would not be surprising.

Robinson *et al.* (1981), in a paper on the low state of MV Lyr, were the first to note the tendency of objects which show deep minima to have orbital periods near the 2–3 hr period gap. These authors speculated that as a result of structural change within the core of the secondary star (conversion from a radiative to a convective core), stars evolving through the 2–3 hr period gap may become detached systems, thereby becoming virtually unobservable. This scenario assumes, quite obviously, that systems do indeed evolve through the gap. As pointed out by Paczyński and Sienkiewicz (1983) and Patterson (1984), this may not be the case. Nevertheless, assuming systems evolve through the gap, the Robinson *et al.* hypothesis qualitatively explains not only the existence of the period gap but also the VY Scl stars as systems which are attempting to cease (or reinitiate) mass transfer as they prepare to evolve into (or out of) the period gap.

It is interesting that eight of the 10 VY Scl systems have orbital periods on the long-period side of the gap, while only two, the AM Her systems VV Pup and AN UMa, are found on the short-period side. One possible explanation for this imbalance is that the process of shutting down mass transfer may be a much slower one than reinitiating it. In any case, if Robinson *et al.* are right, then this process must be quite prolonged, or we would hardly expect to witness so many systems in the actual process of shutting down their mass transfer.

X. CONCLUSIONS

We have made a comprehensive photometric and spectroscopic study of the low state ($V \approx 16.5$) of the novalike variable TT Ari, with observations spanning the UV to IR spectral regions. Our principal conclusions are summarized below:

1. The ~ 5 mag drop in the system's luminosity from the high state indicates that the mass-transfer rate decreased by more than two orders of magnitude. Nevertheless, our rather limited high-speed photometry indicates that some mass transfer was still occurring even during the low state.

2. The drastic reduction in the luminosity of the accretion disk between the high and low states has enabled us, for the first time, to observe directly the white dwarf component in this system. The broad absorption profiles at Hβ, Hγ, Hδ, He II λ4686, and Lyα and the ultraviolet energy distribution are best fitted by a hot ($\gtrsim$50,000 K) white dwarf. The relatively high temperature is probably a result of accretion heating caused by a high $\dot{M}$ in the recent past.

3. Using the method described by Bailey (1981), we have derived a lower limit of 200 pc for the distance to TT Ari. This distance is based on the observed K magnitude (13.3) and the assumption that the secondary is a main-sequence dwarf. There is some evidence for detection of the ellipsoidal variations of the secondary in the V filter, which is in need of confirmation.

4. We have compared the behavior of TT Ari with another novalike variable, MV Lyr. In their low states, the two systems appear to be quite similar spectroscopically. Upon closer inspection the emission lines in TT Ari appear to be composed of two distinct components. We attribute the stronger "peak" component to emission from material essentially at rest in the system. This material is most likely located either near the center of mass of the binary or in a circumbinary shell or ring. The "base" component, which has a velocity semiamplitude of ~ 150 km s^{-1} and is 180° out of phase with the high-state ephemeris of Thorstensen, Smak, and Hessman (1984), is most likely produced in the chromosphere of the secondary star. As an alternative, we have suggested that the base component could actually be produced in a residual accretion ring if the white dwarf mass is quite low ($\sim 0.25\ M_{\odot}$). Although this model is quite speculative, it cannot be ruled out by existing observations.

In addition, MV Lyr and TT Ari are remarkably similar photometrically. Both systems have recently experienced a drastic reduction in mass transfer rate. MV Lyr faded ~ 5 mag

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1985ApJ...290..707S

from its normal brightness at $V \approx 12.5$ to $V \approx 17.5$ in 1979, while TT Ari faded by roughly the same amount from $M_v \approx 11$ to $M_v \approx 16.5$ in 1982. Since the orbital periods of the two systems are very similar [P(MV Lyr) = 3.1 hr; P(TT Ari) = 3.2 hr], the luminosities of the secondary stars in the two systems should be similar. If we assume that the white dwarfs in the two systems have roughly the same luminosities, then the intrinsic brightnesses of the two systems should be similar. Consequently, the distance to the MV Lyr system should be a factor of ~1.6 greater than that to TT Ari. The distance of 320 pc for MV Lyr derived by Schneider, Young, and Shectman (1981) is in reasonable agreement with this expectation.

5. The long-term photometric behavior of TT Ari makes it a typical member of the VY Scl subclass of the novalike variables. The VY Scl stars are systems which are normally in a "high" state but have a tendency to fade occasionally by 3–5 mag or more to a deep minimum for a relatively brief period of time. The objects which exhibit this behavior (ten in all) have orbital periods near the 2–3 hr gap. It is unclear whether the VY Scl behavior is a common property of all cataclysmics with orbital periods near the gap and hence a possible evolutionary effect, or whether it is simply a property of the class of novalike variables which are strongly clumped in the 3–4 hr period region.

As a final note, we encourage observers, especially high-speed photometrists, to monitor TT Ari in order to determine if the mass transfer stops completely. Such a situation would provide a rare opportunity to use spectroscopic observations to establish conclusively whether the base component originates in the chromosphere of the secondary or whether it is formed in a residual accretion ring. Likewise, more extensive high-resolution spectroscopic observations of the primary's absorption features could determine unambiguously the phasing of this component.

We would like to thank Joe Patterson, Rob Robinson, Greg Shields, and John Thorstensen for valuable discussions. Rick Hessman deserves special thanks for many enlightening discussions and for a thorough reading of a preliminary version of the manuscript. We wish to thank Ed Nather for pointing out that a circumbinary ring may explain the origin of the peak component of the low-state emission lines. A. W. S. acknowledges expert observing assistance provided by R. Nolthenius, the use of the spectroscopic binary orbit program kindly provided by P. Etzel, and financial support provided by Roger K. Ulrich through NSF grant AST 78-20236. H. E. B.'s portion of the work was done during a sabbatical leave at Lick Observatory; he acknowledges R. P. Kraft's hospitality. P. S. acknowledges partial support by grants from NASA (NSG 5395) and NSF (AST 82-04488); J. L. acknowledges support through NSF grant AST 82-18624.

REFERENCES

Bailey, J. 1981, *M.N.R.A.S.*, **197**, 31.
Bond, H. E. 1980, paper presented at the 5th Annual Workshop on Cataclysmic Variables and Related Objects, University of Texas, Austin.
Chanmugam, G., and Ray, A. 1984, *Ap. J.*, **285**, 252.
Cowley, A. P., Crampton, D., Hutchings, J. B., and Marlborough, J. M. 1975, *Ap. J.*, **195**, 413.
Gilliland, R. L., and Kemper, E. 1980, *Ap. J.*, **236**, 854.
Grauer, A. D., and Bond, H. E. 1981, *Pub. A.S.P.*, **93**, 388.
Hamada, T., and Salpeter, E. E. 1961, *Ap. J.*, **134**, 683.
Hassall, B. J. M., *et al.* 1981, *M.N.R.A.S.*, **197**, 275.
Hessman, F. V. 1984, *Pub. A.S.P.*, submitted.
Hudec, R., Huth, H., and Fuhrmann, B. 1984, *Observatory*, **104**, 1.
Hutchings, J., and Cowley, A. P. 1984, *Pub. A.S.P.*, **96**, 559.
Jameson, R. F., King, A. R., and Sherrington, M. R. 1982, *M.N.R.A.S.*, **200**, 455.
Jameson, R. F., Sherrington, M. R., King, A. R., and Frank, J. 1982, *Nature*, **300**, 152.
Jensen, K. A., Cordova, F. A., Middleditch, J., Mason, K. O., Grauer, A. D., Horne, K., and Gomer, R. 1983, *Ap. J.*, **270**, 211.
Krautter, J., Klare, G., Wolf, G., Duerbeck, J., Rahe, J., Vogt, N., and Wargau, W. 1981*a*, *Astr. Ap.*, **102**, 337.
Krautter, J., Klare, G., Wolf, G., Wargau, W., Drechsel, H., Rahe, J., and Vogt, N. 1981*b*, *Astr. Ap.*, **98**, 27.
Lamb, D. Q., and Patterson, J. 1983, in *IAU Colloquium 72, Cataclysmic Variables and Related Objects*, ed. M. Livio and G. Shaviv (Dordrecht: Reidel), p. 229.
Mardirossian, F., Mezzetti, M., Pucillo, M., Santin, P., Sedmak, G., and Giuricin, G. 1980, *Astr. Ap.*, **85**, 29.
Paczyński, B., and Sienkiewicz, R. 1983, *Ap. J.*, **268**, 825.
Panek, R. J., and Holm, A. V. 1984, *Ap. J.*, **277**, 700.
Patterson, J. 1984, *Ap. J. Suppl.*, **54**, 443.
Patterson, J., and Price, C. M. 1981, *Ap. J. (Letters)*, **243**, L83.
Robinson, E. L. 1983, in *IAU Colloquium 72, Cataclysmic Variables and Related Objects*, ed. M. Livio and G. Shaviv (Dordrecht: Reidel), p. 1.
Robinson, E. L., Barker, E. S., Cochran, A. L., Cochran, W. D., and Nather, R. E. 1981, *Ap. J.*, **251**, 611.
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, p. 1.
Schneider, D. P., Young, P., and Shectman, S. A. 1981, *Ap. J.*, **245**, 644.
Shafter, A. W. 1983*a*, *Ap. J.*, **267**, 222.
———. 1983*b*, Ph.D. thesis, UCLA.
Shafter, A. W., Nolthenius, R. A., Patterson, J., Bond, H. E., Grauer, A. D., Szkody, P., and Kemper, E. 1982, *IAU Circ.*, No. 3748.
Shafter, A. W., Szkody, P., Liebert, J., and Bond, H. E. 1984, *Bull. AAS* **16:1**, 407.
Shipman, H. L. 1979, *Ap. J.*, **228**, 240.
Smak, J., and Stepien, K. 1969, in *Non-Periodic Phenomena in Variable Stars*, ed. L. Detre (Budapest: Academic Press), p. 355.
———. 1975, *Acta Astr.*, **25**, 379.
Szkody, P., Córdova, F. A., Tuohy, I. R., Stockman, H. S., Angel, J. R. P., and Wisneiwski, W. 1980, *Ap. J.*, **241**, 1070.
Szkody, P., and Downes, R. A. 1982, *Pub. A.S.P.*, **94**, 328.
Szkody, P., Raymond, J. C., and Capps, R. W. 1982, *Ap. J.*, **257**, 686.
Thorstensen, J. R., Smak, J., and Hessman, F. V. 1984, *Pub. A.S.P.*, in press.
Wargau, W., Drechsel, H., Rahe, J., and Vogt, N. 1982, *Astr. Ap.*, **110**, 281.
Warner, B. 1982, in *IAU Colloquium 72, Cataclysmic Variables and Related Objects*, ed. M. Livio and G. Shaviv (Dordrecht: Reidel), p. 155.
Warner, B., and Nather, R. E. 1971, *M.N.R.A.S.*, **152**, 219.
Webbink, R. F. 1982, invited review presented at Pulsations in Classical and Cataclysmic Variables Workshop, Joint Institute for Laboratory Astrophysics, Boulder, Colorado.
Wenzel, W. 1980, *Inf. Bull. Var. Stars*, No. 1810.
Wesemael, F., Aver, L. H., Van Horn, H. M., Savedoff, M. P. 1980, *Ap. J. Suppl.*, **43**, 159.
Williams, G. 1982, Ph.D. thesis, University of Michigan.
Williams, R. 1980, *Ap. J.*, **235**, 939.

HOWARD E. BOND: Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218

ALBERT D. GRAUER: Department of Physics and Astronomy, University of Arkansas, 33rd St. & University, Little Rock, AR 72204

JAMES LIEBERT and WILLIAM R. PENNING: Steward Observatory, University of Arizona, Tucson, AZ 85721

ALLEN W. SHAFTER: Department of Astronomy, University of Texas, Austin, TX 78712

PAULA SZKODY: Department of Astronomy, University of Washington, Seattle, WA 98195

© American Astronomical Society • Provided by the NASA Astrophysics Data System