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RADIAL VELOCITY STUDIES OF CATACLYSMIC BINARIES. II. THE ULTRASHORT PERIOD DWARF NOVA T LEONIS

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ABSTRACT

We present spectroscopic and photometric observations of T Leo which reveal the object to be an ultrashort period dwarf nova. In particular, our analysis indicates that T Leo has an orbital period of 84.69936 (± 0.00068) minutes, which is the third shortest orbital period of any known cataclysmic variable and the shortest known for any U Gem type dwarf nova. Our observations enable us to place upper limits of 0.19 and 0.4 $M_\odot$ on the mass of the red dwarf and white dwarf, respectively. The overall energy distribution is relatively flat ($f_\lambda \sim$ constant) which is consistent with a low mass accretion rate. The models of Williams and Ferguson suggest that $\dot{M} \sim 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. A narrow peak component of Hα is observed, the phasing of which cannot be explained by the canonical hot spot model. Possible explanations for its origin are presented and discussed. We predict that future observations of T Leo may reveal the object to be a SU UMa type dwarf nova.

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

I. INTRODUCTION

The dwarf nova T Leo is one of the brightest cataclysmic variables when in outburst ($V \approx 10$), and at quiescence ($V \approx 15.5$) it has one of the strongest Balmer emission spectra of any known cataclysmic. However, until now, few details concerning the nature of this object were known. T Leo was discovered by Peters (1865), who observed the star to brighten to $V \approx 10$ on two separate occasions. The first time was in 1862 April. It was then seen to brighten for a second time on 1865 April 24. During the following century no confirmed outbursts of the star were reported. As a consequence, the specific nature of the star remained uncertain, although it was generally believed to be either a dwarf nova or an unusual old nova. It was primarily based on a spectrum obtained by Kraft (1962) during quiescence which eventually resulted in T Leo being classified as a dwarf nova. He argued that the strong lines of H and He I were more characteristic of the U Gem variables than of typical old novae.

Since Kraft published his spectrum over 20 years ago, not a single observation of this star has appeared in the literature, except for its inclusion in the spectroscopic surveys of Oke and Wade (1982) and Williams (1983). Fortunately, amateur astronomers have not neglected T Leo during the last decade, and for a large fraction of that time members of the American Association of Variable Star Observers (AAVSO) have monitored its visual brightness (J. Mattei 1982, private communication). Their observations have established conclusively that T Leo is a dwarf nova and that it has a mean outburst period of ~ 2 yr. It is possible that the mean outburst period is somewhat less than 2 yr, because normal outbursts typically last for only ~ 1 day, and several could have been missed by the AAVSO observers.

With the above considerations in mind we decided to undertake a comprehensive photometric and spectroscopic study of T Leo in an attempt to determine the fundamental physical properties of the system. In particular our objective was to determine the orbital period, study the overall energy distribution in the context of other cataclysmics, and hopefully constrain the masses of the component stars. We begin by describing the observations in § II. We then discuss the spectroscopic and photometric characteristics of T Leo in §§ III and IV. In § V we present the radial velocity study and, finally, in § VI we derive possible masses for the system. Our conclusions are summarized in § VII.

II. OBSERVATIONS

a) Optical Spectroscopy

The spectroscopic observations were obtained with the Robinson-Wampler Image Dissector Scanner (Robinson and Wampler 1972) at the Cassegrain focus of the Mount Lemmon 1.52 m reflector. The observing program consisted of obtaining a low-dispersion spectrum in order to study the general spectral characteristics, and a series of higher dispersion observations, spanning several nights, to be used in a radial velocity study. Both the high- and low-dispersion observations have been divided by the spectrum of a tungsten lamp in order to remove channel-to-channel irregularities.

The low-dispersion observations were obtained 1982 February 2 and represent a total integration time of 32 minutes. The observations have a resolution of ~ 11 Å (FWHM) and cover a wavelength range of 3800–6800 Å.

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The resulting spectrum has been reduced to an absolute flux scale by calibration with standard stars observed by Stone (1977).

The high-dispersion observations used in the radial velocity study were obtained during seven nights in 1982 January, February, and April. These observations have a time resolution of 8 minutes, a spectral resolution of ~4 Å (FWHM), and span a 1300 Å region centered near Hα. The seven nights of observation resulted in a total of 121 individual 8 minute spectra. For a complete description of the observing technique used for the radial velocity observations see Shafter (1983, hereafter Paper I).

b) *UV Spectroscopy*

The UV spectra were obtained with the *IUE* satellite on 1982 November 22/23 using the large aperture in the low-resolution mode. One SWP exposure of 115 minutes, and one LWR exposure of 80 minutes were obtained. The FES magnitude (comparable to V) at this time was 14.9, which was about one-half magnitude above the normal quiescent value.

c) *Optical and Infrared Photometry*

All photometric observations were obtained with the Kitt Peak 1.3 m telescope. The optical photometry was obtained 1982 February 28 and March 1, using a three channel photometer which measures the U, B, and V colors simultaneously. The integration time with each filter was 10 s, which resulted in statistical uncertainties of less than 0.03 mag. More than one cycle was obtained each night, with mean magnitudes and colors of $V = 15.51$, $B-V = 0.15$, and $U-B = -1.10$ on the first night, and $V = 15.49$, $B-V = 0.15$, and $U-B = -1.16$ on the second night.

Infrared photometry was obtained 1982 March 4, 5, and 7 using the InSb system Otto cycled between J, H, and K filters. The total integration time for one cycle was 0.5 hr, resulting in a signal-to-noise ratio of 5–10 for each of the three measurements. The cycle was repeated seven times during the three nights of observation, resulting in mean magnitudes of $J = 14.07 \pm 0.05$, $H = 13.67 \pm 0.05$, and $K = 13.42 \pm 0.05$.

The details of the spectroscopic and photometric observations can be found in the journal of observations which is presented in Table 1.

III. THE SPECTRUM

a) *Ultraviolet*

Our *IUE* spectrum of T Leo is presented in Figure 1. The emission line spectrum, with strong lines of C IV, N V, Si IV, and Mg II, is characteristic of dwarf novae at quiescence. In particular, the line strengths are similar to SU UMa and YZ Cnc (see Szkody 1981), with the exception of the Mg II line, which is approximately a factor of 3 larger in T Leo. Unlike the higher excitation lines, the Mg II line is probably produced in the optically thin outer regions of the accretion disk. It therefore appears that the accretion disk in T Leo probably has a more extensive optically thin region than do the disks in SU UMa or YZ Cnc.

The equivalent widths and intensities of the prominent lines are presented in Table 2. The absence of a significant 2200 Å feature implies that T Leo is not appreciably reddened. We have adopted $E(B-V) = 0$.

b) *Optical*

The low-dispersion Mount Lemmon spectrum of T Leo is presented in Figure 2. The spectrum is dominated by very strong and broad emission lines of hydrogen and neutral

TABLE 1

JOURNAL OF OBSERVATIONS

Julian Date 2,440,000+ (start of observations)	Integration Time (min)	Duration (hr)	Spectral Coverage	Resolution (FWHM)
		Spectroscopy		
4973.956 (Jan 4)	8	2.6	λλ5800–7000	4
4993.925 (Jan 24)	8	2.5	λλ5800–7000	4
4994.902 (Jan 25)	8	3.4	λλ5800–7000	4
4995.839 (Jan 26)	8	5.3	λλ6100–7300	4
4996.946 (Jan 27)	8	0.4	λλ6100–7300	4
5000.940 (Jan 31)	8	1.1	λλ6100–7300	4
5002.944 (Feb 2)	32	0.53	λλ3800–6800	11
5089.654 (Apr 30)	8	5.6	λλ6000–7200	4
		Photometry		
5028.921 (Feb 28)	0.17	2	U, B, V	...
5029.882 (Mar 1)	0.17	3	U, B, V	...
5032 (Mar 4)	10	2	J, H, K	...
5033 (Mar 5)	10	1	J, H, K	...
5035 (Mar 7)	10	0.5	J, H, K	...
		IUE		
5296 (Nov 23)	{SWP = 115, LWR = 80}	3.3	λλ1150–3150	~6

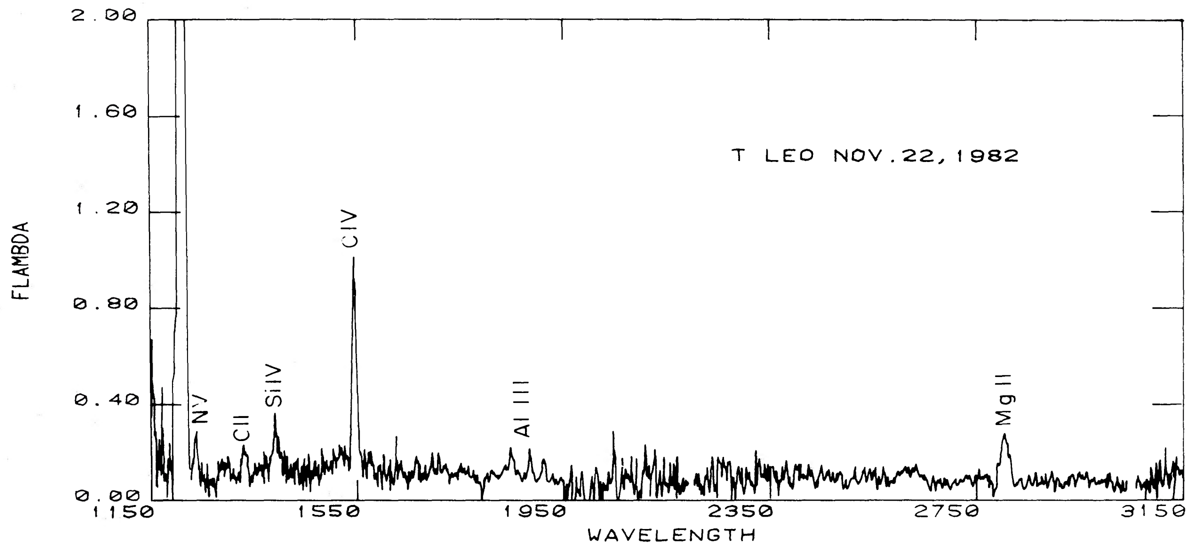

FIG. 1.—The *IUE* short and long wavelength spectra of T Leo. The absolute flux ($\times 10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1}) is plotted as a function of wavelength.

helium. The equivalent widths and fluxes of the major optical emission lines are presented in Table 2. The Balmer lines are particularly strong, Hα having an equivalent width of ~100 Å. Such strong lines are characteristic of emission from an accretion disk with an extensive optically thin outer region. This is consistent with a relatively low mass accretion rate which we argue in favor of in the next section. Referring to Figure 2, there is evidence for a broad absorption trough centered at Hβ. There are two likely explanations for the origin of this absorption. One possibility is that it arises in the inner, optically thick regions of the accretion disk (e.g., see Herter *et al.* 1979 and Mayo, Wickramasinghe, and Whelan 1980). The other possibility is that it arises in the photosphere of the white dwarf. Because we expect the mass accretion rate in the system to be relatively low, it seems unlikely that the accretion disk would have a sufficiently extensive optically thick region to produce the observed absorption. On the other hand, based on the UV spectrum, particularly the lack of Lyα absorption, it appears unlikely that we are seeing the photosphere of the white dwarf. Consequently, at the present time, the origin of the broad absorption at Hβ remains a mystery.

TABLE 2

LINE FLUXES AND EQUIVALENT WIDTHS OF PRINCIPAL UV AND OPTICAL EMISSION LINES

Species	Line Flux ($\times 10^{-13}$ ergs cm^{-2} s^{-1})	EW(Å)
N V λ1240	2.01	29
C II λ1336	1.52	16
Si IV λ1394, 1403	2.71	23
C IV λ1550	9.25	62
Mg II λ2800	3.84	54
Hδ	0.94	35
Hγ	0.97	37
He I λ4471	0.19	8
Hβ	1.30	62
He I λ5876	0.39	20
Hα	1.52	87
He I λ6678	0.16	8

c) *Infrared*

With the flux ratio method described in Berriman and Szkody (1983) we can obtain a limit to the magnitude of a late-type secondary. The flux ratios are $F_\nu(K)/F_\nu(H) = 0.76$ and $F_\nu(R)/F_\nu(H) = 1.02$, which means the secondary spectral type could be anywhere from K0 to M6. However, for a period of 84.7 minutes, the mass of the secondary should be near that of a late M star ($M_2 \leq 0.19\ M_\odot$ as we will see in § VI). For a M6 star, the maximum contribution of the star to the H flux would be 50% for the observed colors, so that H would be greater than 14.4 and K would be greater than 14.2. Using the distance method of Bailey (1981), we conclude that the distance of T Leo is greater than 136 pc.

There does not appear to be a major component present at long wavelength UV and optical regimes that could be identified with a ~10,000 K hot spot as seen in U Gem (Wu and Panek 1982), EM Cyg, AH Her, etc. (Szkody 1981). Thus, the flickering source evident in the optical with amplitudes of ~0.5 mag in U, ~0.4 mag in B, and ~0.3 mag in V could be associated with an inner disk reprocessing as in TT Ari (Jensen *et al.* 1983).

d) *Overall Energy Distribution*

The overall energy distribution is presented in Figure 3. The distribution is put together from *IUE* continuum points in 100 Å wide bins (excepting areas of line emission) combined with the mean *UBV* fluxes from 1982 March and a red filter flux obtained 1982 February 28 (filter center 0.81 μm) and mean *JHK* fluxes. The open circle represents the FES magnitude which is brighter than the optical points. To within the uncertainties of matching the nonsimultaneous points, the flux distribution is fairly well represented by a Williams and Ferguson (1982) model with $\dot{M} = 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$. Although (1) the steady state condition used by Williams and Ferguson probably is not a valid representation of the quiescent state disk, and (2) the mass accretion rate probably varies throughout the disk (Falkner, Lin, and Papaloizou 1983), we claim that the flat flux distribution is an indication of a lack of UV flux compared to other dwarf novae (Szkody 1981).

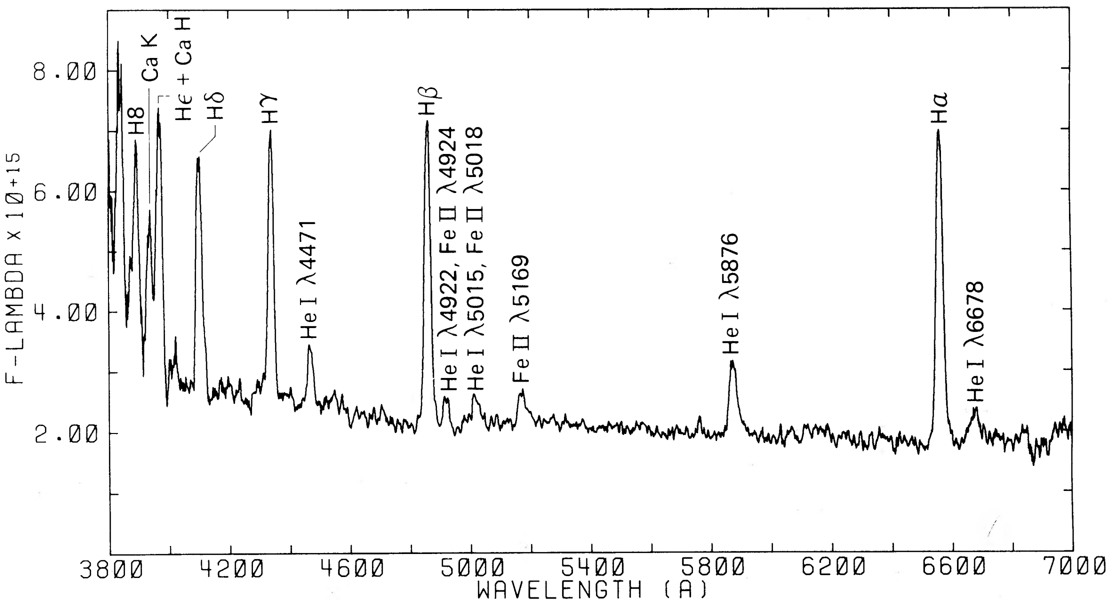

FIG. 2.—The low-dispersion Mount Lemmon spectrum of T Leo. The absolute flux (ergs cm^{-2} s^{-1} $Å^{-1}$) is plotted as a function of wavelength. The spectrum is typical of the ultrashort period dwarf novae which usually have relatively flat continua and strong Balmer emissions. Note the shallow absorption trough at Hβ.

This is consistent with a lower temperature, a lower mass white dwarf, and a lower accretion rate compared to other observed dwarf novae.

IV. PHOTOMETRY

Figures 4 and 5 show our three color (*UBV*) photometry of T Leo obtained 1982 February 28 (2 hr) and March 1 (3 hr). There is nothing unusual about either of the light curves, with the possible exception of the strong flicker which occurred during March 1 observations. The observations from both nights span time intervals longer than the orbital period of the system. The system does not eclipse and, in addition, there does not appear to be any significant orbital modulation in the light curve. Although the strong flicker seen in the March 1 light curve appears at a phase normally associated with viewing the hot spot ($\phi = 0.74$), it does not repeat on

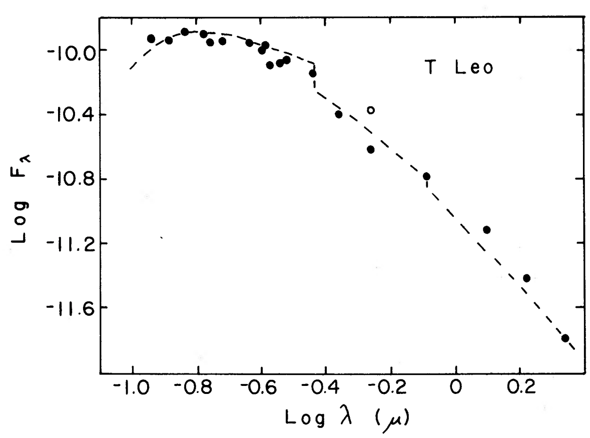

FIG. 3

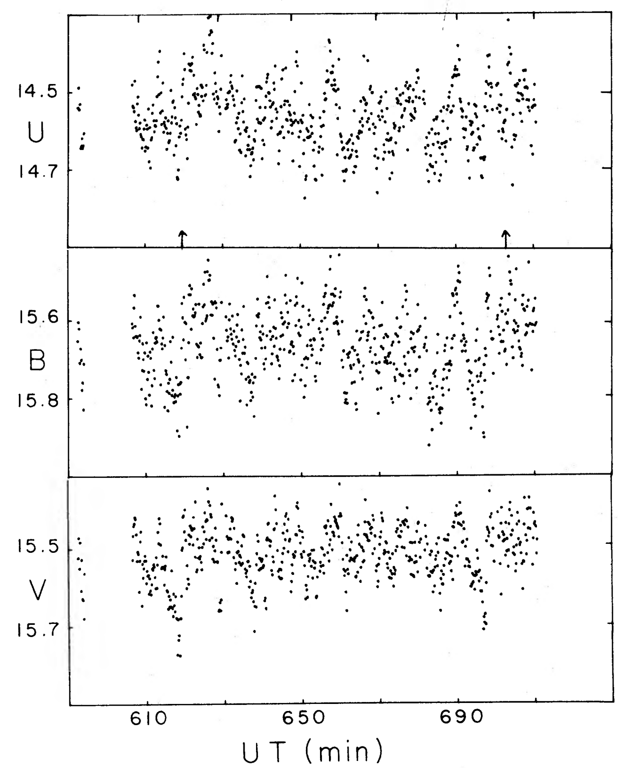

FIG. 4

FIG. 3.—The overall energy distribution of T Leo. The UV points have been derived from the *IUE* spectrum using 100 Å wide bandpasses. The remaining points represent the *U*, *B*, *V*, *R*, *J*, *H*, and *K* magnitudes from the Kitt Peak photometry. The open circle represents the FES magnitude from the *IUE* observations. The dashed line represents the Williams and Ferguson model with $\dot{M} = 10^{-10}\ M_\odot\ yr^{-1}$.

FIG. 4.—The Kitt Peak *UBV* photometry of T Leo obtained on February 28. The random flickering of 0.2–0.5 mag is typical of most cataclysmic variables. The two arrows mark the orbital phase where a large-amplitude flicker was observed on March 1 (see Fig. 5).

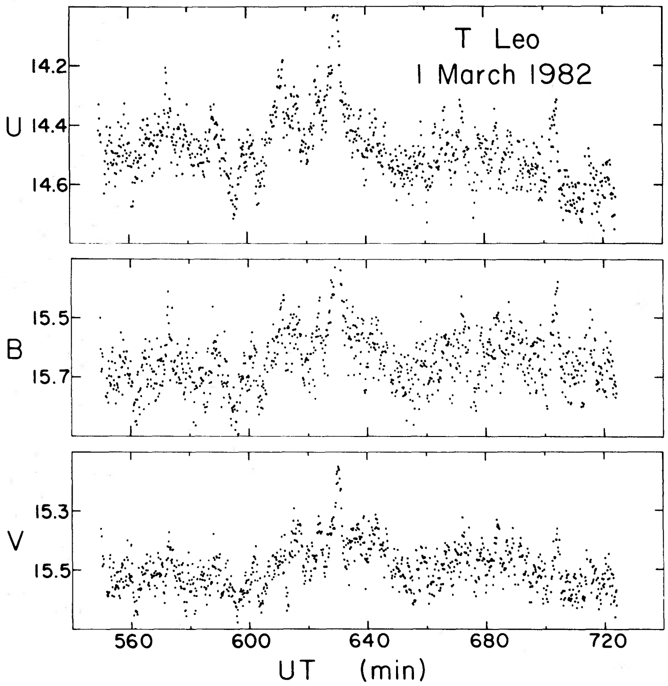

FIG. 5.—The *UBV* photometry from March 1. The large-amplitude flicker seen near the middle of the observations apparently is not orbital phase-dependent as it does not repeat on this night or on February 28 (see Fig. 4).

the same night, nor does it appear in the light curve of the preceding night (the two arrows on the February 28 light curve mark the same orbital phase, where the March 1 flicker occurred). The photometric behavior described above allows us to place a conservative upper limit of $\sim 65°$ on the orbital inclination.

V. THE RADIAL VELOCITY CURVE

Following the analysis presented in Paper I, we have chosen to determine the radial velocities by measuring the wings of the Hα emission line. The wings presumably originate in the rapidly rotating material close to the surface of the white dwarf and therefore should represent its motion with the highest reliability. The radial velocities have been extracted from the line wings using the method employed in Paper I. This method, originally outlined by Schneider and Young (1980), consists of convolving each spectrum with a pair of Gaussian bandpasses. The width and separation of the two Gaussians can be adjusted to suit the characteristics of the spectra (i.e., emission line width and signal-to-noise ratio of the data). If a is the half separation of two Gaussian band-passes with standard deviation σ, then the wavelength λ of an emission line in a spectrum $S(\Lambda)$ can be obtained by solving the equation

$$\int_{-\infty}^{\infty} S(\Lambda)K(\lambda - \Lambda)d\Lambda = 0 , \qquad (1)$$

where $K(x) = \exp[-(x-a)^2/2\sigma^2] - \exp[-(x+a)^2/2\sigma^2]$.

After measuring velocities for all 121 spectra of T Leo, we searched for the true orbital period using Deeming's method (see Bopp, Evans, and Laing 1970). The result of the period search is presented in Figure 6. The minima of the discriminant function, R (defined in Bopp *et al.*), correspond to possible orbital periods, with the period having the smallest value of R being the most probable period. Referring to Figure 6, we argue that the true orbital period of T Leo is $0^{\mathrm{d}}.05882$ and that the two minima at $0^{\mathrm{d}}.0555$ and $0^{\mathrm{d}}.0625$ correspond to ± 1 cycle per day aliases of this period.

In order to compute the remaining orbital elements, we have made a least squares fit of the velocity points to a circular orbit of the form

$$V(t) = \gamma + K_1 \sin[2\pi(t - t_0)/P] . \qquad (2)$$

The best fit values of the systemic velocity (γ), the time of superior conjunction of the white dwarf (t_0), and the orbital period (P) are presented in Table 3A, and the resulting radial velocity curve is shown in Figure 7. As we pointed out in Paper I, the value of the semiamplitude (K_1) can be a function of the choice of the parameter a in equation (1). We argued further that the best estimate of the true semiamplitude of the white dwarf is obtained by adopting the largest value of a which can be effectively employed. If a is too large, then the resulting velocity measurements will be overly contaminated by noise in the continuum.

In order to increase the signal-to-noise ratio of the individual spectra (particularly in the extensive line wings), and thereby improve the reliability of the velocity measurements for large values of a, we have phased the individual spectra with the orbital period and then co-added the spectra into 10 separate phase bins. We have excluded the April observations from the co-adding because the equivalent width of the Hα emission line was ~ 130 Å in April, as opposed to ~ 90 Å in January and February. Next, we have remeasured the velocities using a wide range of values for a followed by a redetermination of $K_1(a)$ from equation (2). The best estimate

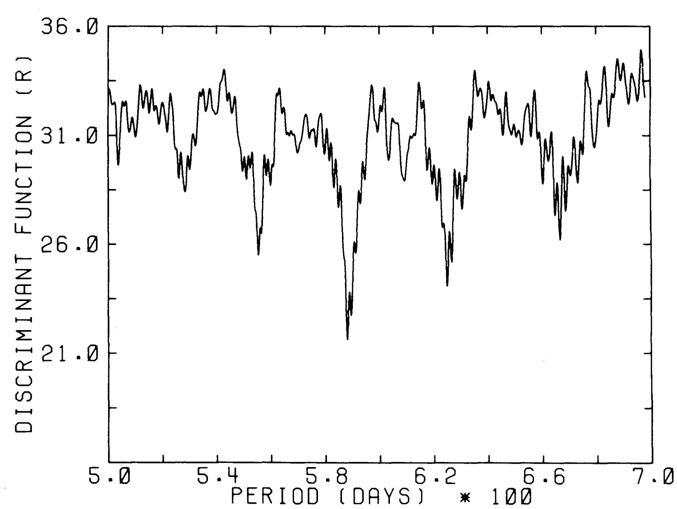

FIG. 6.—The results of a search for possible periodicities in the radial velocity data. The discriminant function (R) is defined in the appendix of Bopp *et al.* (1970). The minima of this function indicate possible periodicities in the data. The most probable orbital period is $0^{\mathrm{d}}.058819$. The two periods of $0^{\mathrm{d}}.0555$ and $0^{\mathrm{d}}.0625$ correspond to ± 1 cycle per day aliases of the true period.

TABLE 3

T LEONIS: SYSTEM PARAMETERS

Parameter	Value
A. Orbital Elements[a]	
Period, P (days)	0.0588190 ± 0.0000005
Time of conjunction, T_0 (HJD)[b]	4974.0099 ± 0.0005
Semiamplitude, K_1 (km s^{-1})	135 ± 8
Systemic velocity, γ (km s^{-1})	44 ± 20:
B. Derived System Parameters	
Primary mass, M_1 ($M_\odot$)	$\lesssim 0.4$
Secondary mass, M_2 ($M_\odot$)	$\lesssim 0.19$
Orbital inclination, i (deg)	$28 < i < 65$
Distance, D (pc)	>136

[a] $e = w = 0$ (assumed).

[b] Superior conjunction of primary; 2,440,000+.

of K_1 may then be found by plotting K_1 and the fractional 1 σ error in K_1 (σ_{K_1}/K_1) as functions of a. We define the best estimate of the true semiamplitude of the white dwarf as the value just prior to the point where the fractional error in K_1 begins to increase sharply. In the case of T Leo, this point occurs at the maximum value of K_1. Figure 8 shows K_1 and σ_{K_1}/K_1 for 11 different values of a ranging from 12 Å to 26 Å. Referring to this figure we see that a value of 135 km s^{-1} is the best estimate of the semiamplitude of the white dwarf.

Figure 9 shows the Hα line profile from each of the 10 phased spectra. The presence of a narrow peak component which is out of phase with the broad base component is clearly evident. This figure clearly illustrates the importance of measuring the extreme wings of the line profile when determining the velocity curve for the white dwarf. Figure 10 shows the radial velocity curves for the broad base and the narrow peak components measured from the 10 phased spectra. The broad base component has been measured using equation (1) with $\sigma = 1$ Å and $a = 21$ Å. The velocity of the narrow peak component has been measured by hand, using an interactive computer console.

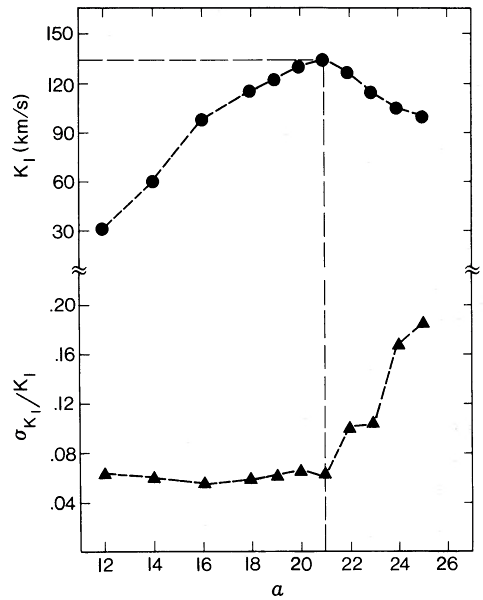

FIG. 8.—The semiamplitude of the primary (●), and its fractional 1 σ error (▲) are shown as a function of the parameter a. The best estimate of K_1 is indicated by the dashed line.

The phasing of the narrow component, which lags the base component by ~230°, makes it extremely difficult to ascribe its origin to the hot spot in the system. Since the hot spot is expected to be on the trailing side of the accretion disk (with reference to the binary motion), we expect that the radial velocity of any emission arising from it should lag the motion of the white dwarf by less than 180°. In the case of T Leo, if we ascribe the peak component to the hot spot, then we are forced to place the spot on the leading side of the accretion disk. Smak (1970) has shown that the true time of conjunction can be spuriously delayed due to distortion of the

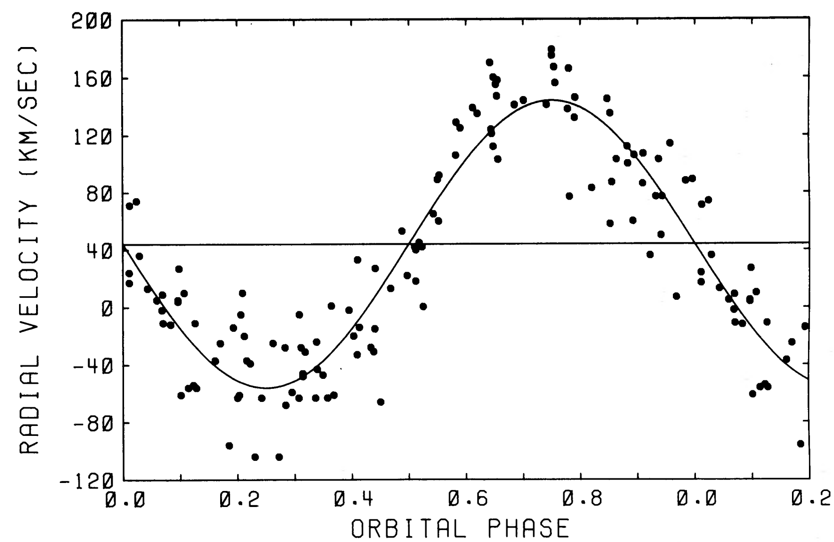

FIG. 7.—The radial velocities of the Hα emission line from all 121 high-resolution spectra, plotted as a function of orbital phase

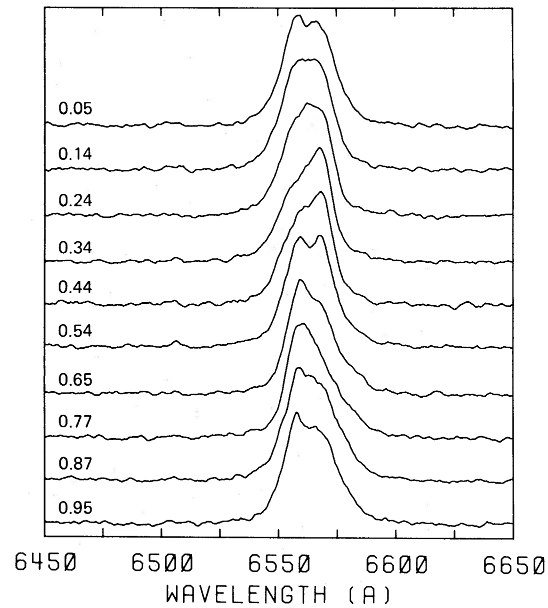

FIG. 9.—All 121 of the individual 8 minute spectra folded with the orbital period and co-added into 10 phase bins. Note the presence of a narrow peak component which is ~230° out of phase with the broad base component. An orbital phase of 0 corresponds to superior conjunction of the white dwarf (i.e., the broad base component).

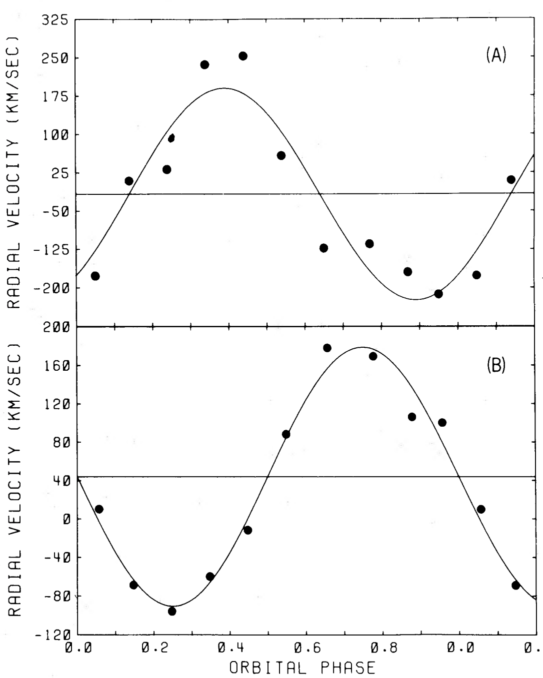

FIG. 10.—The radial velocities derived from the Hα emission line of the 10 co-added spectra plotted as a function of the mean orbital phase of each bin. (*a*) The velocities of the narrow peak component. The solid line is the best fitting sinusoid with a semiamplitude of 207 km s^{-1}. The RMS error of the velocity points with respect to the sine curve is 69 km s^{-1}. (*b*) The velocities of the broad base component. The solid line is the best fitting sinusoid with a semiamplitude of 135 km s^{-1}. The RMS error of the velocity points with respect to the sine curve is 18 km s^{-1}.

radial velocity curves caused by emission from the hot spot. Unfortunately, this effect cannot offer us an explanation for the unusual phasing observed for T Leo. If we assume that the hot spot in the system has spuriously delayed the true time of conjunction and then ask the question: "What will be the effect on the phase difference between the base and peak components if we advance the phase of the base component?," the answer is that it will *increase*, rather than decrease, the phase lag between the narrow and base components. Consequently, the effect described by Smak can only push the point of origin of the narrow component farther around on the leading side of the accretion disk, rather than bringing it back around on the trailing side, where the hot spot is expected to be located.

After spending a considerable amount of time trying to understand the origin of the peak component, we became aware that Young, Schneider, and Shectman (1981) observed an identical effect in their time-resolved spectroscopy of the dwarf nova HT Cas. These authors made no attempt to explain the origin of the narrow component in that system. Below we consider a few possible phenomenological explanations for the origin of the peak component observed in T Leo and HT Cas and discuss the plausibility of each.

Consider the possibility that T Leo contains a magnetized white dwarf whose rotation is synchronized with the orbital period. By analogy with the AM Herculis systems, the accretion geometry of such a system could explain the observed phasing of the base and peak components by an appropriate choice for the orientation of the magnetic axis (i.e., the accretion column) of the white dwarf. The fact that observations of T Leo have failed to reveal optical polarization (J. Liebert 1983, private communication) may, at first, appear to pose a serious problem for this model. However, recent calculations by Lamb *et al.* (1983) imply that magnetic field strengths on the order of a megagauss may be sufficient to phase lock the white dwarf in an ultrashort period cataclysmic binary. These authors attribute the synchronous rotation of the white dwarfs in AM Herculis systems to the magnetohydrodynamic (MHD) torques, which result from currents flowing between the stars.

It seems reasonable to expect that the white dwarf will eventually be forced into synchronous rotation if the MHD torque dominates the accretion torque which results from mass transfer in the binary. If $N_{\rm MHD}$ is the MHD torque and $N_{\rm acc}$ the accretion torque, then using equation (1) from Lamb *et al.* we can derive an expression for the critical magnetic field strength necessary to achieve the condition $N_{\rm MHD} = f N_{\rm acc}$. We find

$$B_c \approx \frac{P}{8\pi^2}\left[\frac{f\dot{M}(1+q)}{\alpha\gamma}\right]^{1/2}\left(\frac{G^3 M_1{}^3}{R_1{}^{11}}\right)^{1/4}\left(\frac{R_2}{d}\right)^{-1}, \qquad (3)$$

where α is the fractional area of the secondary threaded by magnetic flux, γ is the pitch of the magnetic field linking the two stars, P is the orbital period, $\dot{M}$ is the mass accretion rate, M_1 and R_1 are the mass and radius of the white dwarf, q $(=M_2/M_1)$ is the mass ratio of the system, and (R_2/d) is the radius of the secondary in units of the binary separation d, and is given by the following approximations (Plavec and Kratochvil 1964):

$$R_2/d = \begin{cases} 0.38 + 0.2 \log q\,, & 0.5 < q < 20 \\ 0.462[q/(1+q)]^{1/3}\,, & 0 < q < 0.5\,. \end{cases} \qquad (4)$$

Assuming that the broad component of the emission lines originates in the accretion column, then the velocity amplitude ($K_1 = 135$ km s^{-1}) does not represent the motion of the primary, and the mass of $\sim 0.4\ M_\odot$ which we derive for the white dwarf in the next section is not valid. Consequently, for the purposes of estimating B_c, we will be conservative and adopt $M_1 = 1\ M_\odot = 2 \times 10^{33}$ g, $R_1 = 6.1 \times 10^8$ cm (Hamada and Salpeter 1961), and $q = 0.2$. In addition, the value of $\dot{M}$ derived earlier is not appropriate for this model because it assumes that the bulk of the luminosity is produced in an accretion disk. In order to estimate the mass transfer rate for T Leo without relying on accretion disk models, we can appeal to an empirical relation between the mass transfer rate and the orbital period of the system. From Patterson (1984) we have

$$\dot{M} \approx 6 \times 10^{-12}(P/1\ \mathrm{hr})^{3.3 \pm 0.3}\ M_\odot\ \mathrm{yr}^{-1}\ . \quad (5)$$

For an orbital period of 1.41 hr (this paper) we estimate that $\dot{M} \sim 2 \times 10^{-11}\ M_\odot$ yr^{-1}. Plugging the above values into equation (3), noting that $\gamma \sim 1$ (see Lamb *et al.* 1983), and, as a conservative estimate, taking $f\ (= N_{\mathrm{MHD}}/N_{\mathrm{acc}}) = 10$, we find that B_c must be greater than $\sim 8.5 \times 10^5$ gauss to assure eventual synchronism. This field strength is almost an order of magnitude smaller than the minimum field strength necessary to produce observable optical polarization (J. Liebert 1983, private communication). Even if the accretion rate were $\sim 10^{-10}\ M_\odot$ yr^{-1}, the magnetic field strength required to achieve synchronism could still be small enough to avoid producing observable optical polarization. Consequently, the lack of observed polarization does not pose any problem for the model of T Leo described above.

There are other observational properties of this system which are more difficult to explain within the framework of the model described above. For example, the lack of any clear orbital modulation in the light curve seems hard to reconcile with the changing aspect of an accretion funnel. In addition, the high temperatures associated with the accreted funnel should result in the production of high excitation emission lines, for example He II λ4686. No high-excitation emission lines are observed in the spectra of T Leo. Another problem for this model is that the Alfvén radius for a 1 $M_\odot$ magnetic white dwarf with $B = 8.5 \times 10^5$ gauss which is accreting material at a rate of $2 \times 10^{-11}\ M_\odot$ yr^{-1} is $\sim 2.3 \times 10^{10}$ cm. An accretion disk is unlikely to form in such a system, although an outer ring may form as in the DQ Herculis stars (Patterson 1979; Lamb and Patterson 1983; Warner 1983). Since an accretion disk is known to exist in HT Cas (Young, Schneider, and Shectman 1981) and this system shows the same relative phasing of the peak component, it seems unlikely that T Leo is without a disk. Finally, if the magnetic white dwarf model is correct, and we assume that it applies to both T Leo and HT Cas, then we are forced to require an identical accretion geometry for both systems. Based on the above arguments we conclude that it is extremely unlikely that the phasing of the peak component is the result of a magnetic white dwarf lurking in the T Leo system.

As an alternative to the magnetic white dwarf model described above, consider the possibility that the secondary star in T Leo, in addition to transferring mass to the accretion disk via L_1, also loses a significant amount of mass in the form of a stellar wind. Assuming such a wind exists, we envision it as originating primarily from the side of the secondary which faces the white dwarf. This anisotropy in the wind is a result of the fact that the surface gravity is lower and the temperature higher (due to heating from irradiation by high energy photons from the white dwarf and inner disk) on this hemisphere of the secondary.

In our attempt to understand the origin of the peak component, we are interested in the interaction of the hypothetical wind with the accretion disk (or its magnetosphere). We expect that this interaction will form a shock front and presumably result in enhanced emission. A quantitative analysis of the detailed flow pattern of the wind is beyond the scope of this paper. However, from a qualitative standpoint, we can estimate the luminosity of the shock front and the position in the disk where the maximum luminosity would be located. The accretion luminosity can be approximated as

$$L_{\mathrm{acc}} \sim \rho(d) A V_r^3\ , \quad (6)$$

where $\rho(d)$ is the mass density of the wind at a distance d from the secondary (d is the distance between the centers of the two stars), A is the area of the disk (or its magnetosphere) which intercepts the wind, and V_r is the relative velocity of impact between the wind and disk. The maximum luminosity is expected to be located in the region of the disk where the combined effects of orbital motion and disk rotation result in the highest relative velocity with the wind. Thus, we expect that the accretion shock will be located in the quadrant of the disk which is on the leading side and facing the secondary (i.e., between 0° and 90° from the line of centers of the component stars in the direction opposite to the disk rotation). This is precisely the region of the disk where the observed peak component apparently originates.

The next step is to determine if the luminosity generated in the shock region is sufficient to account for the observed strength of the peak component in T Leo. We can approximate the wind density $\rho(d)$ by assuming a steady flow from one hemisphere of the secondary. Neglecting the orbital motion and gravitational attraction of the white dwarf we can write:

$$\rho(d) = \frac{\dot{M}_w}{2\pi d^2 V_w}\ , \quad (7)$$

where $\dot{M}_w$ is the mass loss rate from the secondary due to the wind with velocity V_w. Because the orbital velocity of the secondary will effectively lower the wind velocity in its wake, equation (7) will almost certainly yield a lower limit to the wind density in the region of interest. Substituting equation (7) into equation (6), we obtain:

$$L_{\mathrm{acc}} \sim \frac{\dot{M}_w A V_r^3}{2\pi d^2 V_w}\ . \quad (8)$$

As trial values we adopt $\dot{M}_w \sim 10^{-11}\ M_\odot$ yr^{-1}, $A \sim 10^{19}$ cm^2, $d \sim 3 \times 10^{10}$ cm, and $V_w \sim 10^7$ cm s^{-1}. If d_1 is the distance from the center of mass to the center of the primary and r_d is the radius of the outer rim of the disk, then we estimate that $V_r \sim \{[(2\pi d_1)/P] + (GM_1/r_d)^{1/2}\} \sim 5 \times 10^7$ cm s^{-1}. We wish to emphasize that all of these values are highly uncertain. Our purpose is merely to obtain a crude estimate of L_{acc} which can be compared with the observed luminosity of the peak component. Plugging these values into equation (8) we estimate

$L_{acc} \sim 10^{28}$ ergs s^{-1} from the shock front. The observed luminosity of the narrow Hα emission component is $\sim 5 \times 10^{27}$ ergs s^{-1} assuming a distance of 150 pc for T Leo. Consequently, it appears that the accretion luminosity is just barely able to account for the observed peak component, even if essentially all the energy is radiated in Hα. Nevertheless, given the large uncertainty associated with our estimate of L_{acc} we conclude that it is conceivable that a wind could account for the peak component observed in the T Leo system.

Before the wind model can be taken seriously, there are a few points which must be addressed. To begin with, we have *inferred* the existence of the wind as a possible explanation for observed phasing of the peak component of Hα. We have not demonstrated quantitatively that such a wind should be *expected* to exist. Furthermore, if the hypothetical wind exists, the hydrodynamics of the flow between the two stars should be computed in order to establish a detailed model for the shock front. Such a model should describe the radiated spectrum in sufficient detail to be compared with observations. An additional point which requires an explanation is why the mass transfer stream emanating from the inner Lagrangian point does not produce a "normal" hot spot. Considering that the mass transfer through the inner Lagrangian point is presumably greater than the amount of wind material swept up by the disk, it seems reasonable to expect that a hot spot should be produced on the trailing side of the disk as a result of the impact of the accretion stream if the interaction of the disk with the relatively low density wind can produce the observed peak component. Perhaps the mass transfer stream impacts the disk almost tangentially so that the shock temperature is relatively low. If the hot spot is optically thick and the radiation is completely thermalized, the resulting temperature may not be high enough to produce appreciable Hα emission.

Finally, we come to the simplest, and perhaps the most obvious, explanation for the observed phasing of the peak component. If we allow the secondary star to rotate nonsynchronously, then it may be possible to alter the angular momentum (with respect to the white dwarf) of the material flowing through L_1. In this case, the mass transfer stream could either swing around the disk impacting on the leading side (secondary rotating slower than synchronous), or be flung backward eventually impacting the leading side of the disk (secondary rotating faster than synchronous). Unfortunately, this model appears unlikely because of the severe departures from synchronism which would presumably be required to have an appreciable impact on the trajectory of the mass transfer stream.

In view of the problems associated with the three speculative explanations presented above, it is safe to say that the origin of the peak component in HT Cas and T Leo has yet to be determined. Clearly, all three models will need to be explored in considerably more detail from a theoretical aspect before they can be satisfactorily evaluated.

VI. MASSES

a) The Secondary Star

The spectrum of the secondary star has not been detected in the T Leo system. This is not surprising considering that short orbital period. Nevertheless, we may estimate the mass of the secondary star assuming that (1) the secondary fills its critical Roche surface and (2) that it obeys the mass radius relation for the lower main sequence, in particular that $R_2/R_\odot = \beta M_2/M_\odot$. The first assumption seems justified considering that mass transfer is taking place in the system. The second assumption is more dubious, but has been found to be generally valid for systems whose secondaries have been detected and have orbital periods less than ~10 hr. Theoretical models which follow the evolution of the secondary star in the ultrashort period systems show that the secondaries gradually become degenerate as a result of mass loss (e.g., see Paczyński and Sienkiewicz 1981). Consequently, for T Leo, we will compute the mass of the secondary assuming it to be a main-sequence star and regard the resulting value as an upper limit. Following Falkner (1971) to a first approximation we may write:

$$M_2 \approx 0.11\beta^{3/2}P , \quad (9)$$

where P is the orbital period in hours. The value of β probably lies within the range 0.87–1.0 for the lower main sequence (Falkner 1971; Robinson 1976; Warner 1976). Consequently, for the T Leo system we estimate $M_2 \lesssim 0.19$ $M_\odot$ subject to the assumptions made above.

b) The White Dwarf

The relatively large value of K_1 for a system with such a short orbital period immediately suggests a low mass for the white dwarf. In particular, with an upper limit of 0.19 $M_\odot$ on M_2, the mass function for the system places an upper limit on the mass of the white dwarf of 0.5 $M_\odot$, even if $i = 90°$! As we argued in § IV, we can safely assume that $i \lesssim 65°$, in which case we find that $M_1 \lesssim 0.40$ $M_\odot$. In addition to this upper limit, we may obtain a lower limit on the mass of the white dwarf by requiring that the maximum velocity of the extreme line wings not exceed the Keplerian velocity at the surface of the white dwarf. In the case of T Leo, we require that:

$$(GM_1/R_1)^{1/2} \sin i \geq 1900 \text{ km s}^{-1} . \quad (10)$$

Employing the models of Hamada and Salpeter (1961) for the mass-radius relation for white dwarfs, and assuming $i \lesssim 65°$, we find that $M_1 \gtrsim 0.35$ $M_\odot$. We wish to emphasize that this lower limit is more uncertain than the upper limit, because other line broadening mechanisms may be contributing to the velocity of the extreme line wings, in addition to Doppler broadening. A summary of our mass estimates is presented in Table 3B and illustrated in Figure 11. The mass of the white dwarf most likely lies in the range 0.35–0.4 $M_\odot$. We note that for all possible values of M_1 (i.e., $M_1 > 0$) we require that $i > 28°$.

VII. CONCLUSION

Our major conclusions concerning T Leo can be summarized as follows:

1. The system has an orbital period of 84.69936 (±0.00068) minutes, making it the third shortest orbital period of any known cataclysmic variable. Only the unusual SU UMa type dwarf nova WZ Sge ($P = 81.6$ minutes) and the AM Herculis star EF Eri ($P = 81.0$ minutes) have shorter orbital periods.

2. We have been able to place upper limits of 0.19 and

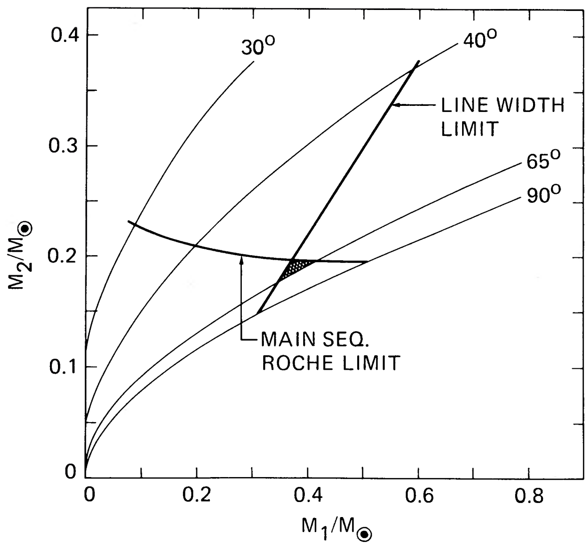

FIG. 11.—The possible masses for the T Leo system. The curves have been generated using the value of K_1 and P from Table 3. The shaded area indicates the most probable location of the T Leo system.

0.4 $M_\odot$ on the mass of the red dwarf and the white dwarf. The upper limit on the mass of the primary is particularly significant because it makes T Leo one of the few cataclysmic variables which is known to contain a low mass white dwarf.

3. The mass accretion rate is probably quite low, resulting in an accretion disk with an extensive optically thin region which gives rise to the strong Balmer emission lines. We estimate that $\dot{M} \sim 10^{-10}$ $M_\odot$ yr^{-1} based on a comparison of the observed energy distribution with the models of Williams and Ferguson (1982).

At the present time, T Leo is classified as a U Gem type dwarf nova, making it, along with HT Cas, the only two such systems below the period gap. However, based on the fact that all the remaining known ultrashort period ($P \leq 2$ hr) dwarf novae are all SU UMa stars, there is good reason to expect that HT Cas and T Leo will eventually be revealed to belong to the SU UMa subclass as well.

The SU UMa stars, in addition to displaying frequent, very short eruptions of the U Gem type, also exhibit occasional, energetic eruptions which can last for several weeks. These eruptions are usually referred to as "supermaxima." During supermaxima, the SU UMa stars show strong periodic modulations or "superhumps" in their light curves recurring with a period which is typically a few percent longer than the orbital period of the system (for a review of the SU UMa systems see Vogt 1980).

Because SU UMa stars generally exhibit many normal or U Gem type eruptions for every one supermaximum, it is sometimes difficult to distinguish SU UMa systems from U Gem systems. This is particularly true for systems such as T Leo and HT Cas which are relatively faint at quiescence, and probably have long outburst periods. The long-term light curves of such systems are poorly determined as they are very difficult for amateur astronomers to monitor. Consequently, many outbursts (including supermaxima) of these systems undoubtedly go unrecorded. J. Mattei (1983, private communication) has informed us that T Leo exhibited an outburst in 1982 June which resembled a supermaximum (it lasted for at least 7 days as opposed to its normal outbursts which last for $\sim$ 1 day). Unfortunately, no high-speed photometry was obtained to search for superhumps.

There is clearly a need for additional work on T Leo, both observational and theoretical. Needless to say, from the observational standpoint, high-speed photometry during future eruptions is urgently required in order to establish T Leo as a bona fide member of the SU UMa subclass. On the theoretical side, the origin of the peak component still awaits a detailed explanation. In view of the fact that a similar peak component was observed in HT Cas, it would not be surprising if such a component turns out to be a common property of the ultrashort period dwarf novae. This possibility suggests that time-resolved spectroscopy of the SU UMa systems should be obtained and phased with the orbital period in order to search for the presence of a peak component similar to the ones observed in HT Cas and T Leo. A detailed explanation of the origin of this unusual component promises to make an important contribution to our understanding of the mass transfer process in the ultrashort period dwarf novae.

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