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DO LEONIS: A NEW ECLIPSING CATACLYSMIC VARIABLE

T. M. C. ABBOTT, A. W. SHAFTER*, J. H. WOOD†, A. B. TOMANEY, AND C. A. HASWELL
McDonald Observatory and Department of Astronomy, University of Texas, Austin, Texas 78712

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ABSTRACT

Photometric and spectroscopic observations of DO Leo have been obtained using the McDonald Observatory high-speed CCD photometer and a conventional two-channel photoelectric photometer. The data reveal eclipses that are approximately $1\overset{m}{.}5$ deep. A total of nine eclipses were observed in February and March 1988 and in April 1989. These data were used to establish an orbital period of $0\overset{d}{.}2345147(2)$. A low-resolution optical spectrum reveals significant He II $\lambda4686$ emission (EW = 6 Å) in addition to the characteristic Balmer and He I emission lines. Although the orbital period is in excess of 5 hr, spectral features from the secondary star were not apparent in our data. Overall the spectrum is more characteristic of a novalike variable than of a dwarf nova.

Key words: eclipsing binary–novalike variable

1. Introduction

Cataclysmic variables are short-period binary stars. They include novae, recurrent novae, dwarf novae, and the novalike variables. General introductions to these systems can be found in Robinson (1976), Warner (1976), Cordova and Mason (1983), and Wade and Ward (1985). These systems are all semidetached binaries with mass transfer from a late-type, near-main-sequence star (the secondary) onto a white dwarf (the primary). Unless the white dwarf is strongly magnetic the transferred material forms an accretion disk before finally impacting the surface of the white dwarf. Normally, viscous heating causes the accretion disk to be the dominant source of radiation at optical and near-ultraviolet wavelengths and produces the characteristic strong, broad emission lines. The spectrum of the white dwarf is rarely observed and the secondary star is usually visible only in the near-infrared.

The compact nature of cataclysmic variables, together with the presence of an accretion disk, permits eclipses to occur at orbital inclinations as small as 65°. Eclipsing systems offer the best opportunities for determining the fundamental properties of cataclysmic variables. The orbital inclinations can be constrained, allowing more reliable mass estimates than would otherwise be possible. Also, the structure of the accretion disk may be studied through deconvolution of the eclipse light curve (Horne 1985; Zhang, Robinson, and Nather 1986).

DO Leonis (= PG 1038+155) was originally identified in a search for faint blue stars at high galactic latitude (Green, Schmidt, and Liebert 1986). Subsequent low-dispersion spectroscopy by Green *et al.* (1982) revealed the object to be a $V \sim 16$ mag cataclysmic variable. As part of a program of studying high galactic latitude cataclysmic variables at McDonald Observatory, we have obtained extensive high-speed photometry of several selected systems. In this paper we report the discovery of eclipses in the light curve of DO Leo.

2. Photometry

2.1 *Background*

One of the primary motivations for obtaining high-speed photometry of the high-galactic-latitude cataclysmic variables is to determine their orbital periods. Most of these stars are too faint for radial-velocity studies to be feasible using moderate-size telescopes. Fortunately, it is possible, in a surprisingly large number of instances, to determine orbital periods photometrically. The orbital period can reveal itself in several ways: through eclipses, through ellipsoidal variations of the tidally distorted secondary star, through reflection or heating effects caused by the disk radiation illuminating the secondary star, or by orbital modulations caused by the varying aspect of the bright spot.

If the system is eclipsing, a determination of the orbital period using conventional high-speed photometric techniques is straightforward. Historically, the principal problem with determining the orbital periods of non-eclipsing systems has been that the amplitude of the orbital modulation can be, and quite often is, quite low. Such low-amplitude, low-frequency modulations are very difficult to detect against the small extinction and/or sky-brightness variations which typically plague long-duration, high-speed photometry runs. Recent investigations

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*Current address: Department of Astronomy, San Diego State University, San Diego, CA 92182.

†Current address: Institute of Astronomy, Cambridge University, Cambridge CB3 0HA, England.

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of the use of two-dimensional detectors (CCDs) have demonstrated the ability of these devices to obtain useful time-series data under these less-than-ideal conditions. High-speed CCD photometers are described by Howell and Jacoby (1986), by Stover and Allen (1986), and, most recently, by Abbott and Opal (1988).

2.2 *Observations*

We used the McDonald Observatory high-speed CCD photometer (with a thinned TI 800 × 800 pixel CCD operating in frame transfer mode (Abbott and Opal 1988)) at the Cassegrain focus of the 0.76-m telescope to search for the orbital period of DO Leo. The light curves resulting from observations on 1988 February 21, 22, and 23 are shown in Figure 1. In addition to background subtraction, these data have been divided by the flux from a nearby comparison star in order to correct for minor transparency variations. We have, therefore, plotted the light curves on relative intensity scales, separated by an arbitrary constant.

Initially we optimized our observations for the detection of ellipsoidal variations from the secondary star. Since the secondary stars typically have temperatures between 3000 K and 5000 K and are significantly cooler than the accretion disks, their relative contribution to the total flux reaches a maximum in the very near-infrared. Consequently, we decided to define our bandpass using an *I*-band filter. The photon flux through this filter was quite modest making integration times of 3 min necessary to achieve an adequate signal-to-noise ratio. Approximately 3 hr into our initial run we noticed a sharp drop in the count rate from DO Leo signaling the onset of an unexpected eclipse.

DO Leo was observed again on the next two nights to secure the additional eclipses necessary to establish the orbital perod. To better resolve the eclipse without compromising the signal-to-noise ratio, and since we no longer required particular sensitivity to ellipsoidal variations, we shortened the integration time to one minute and removed the filter. The bandpass of the filterless data was set by the spectral response of the TI CCD. The increased depth of the eclipse over that in the *I* band may be explained by the greater sensitivity to the relatively blue light from the eclipsed disk.

Approximately one month later, on 1988 March 16 and

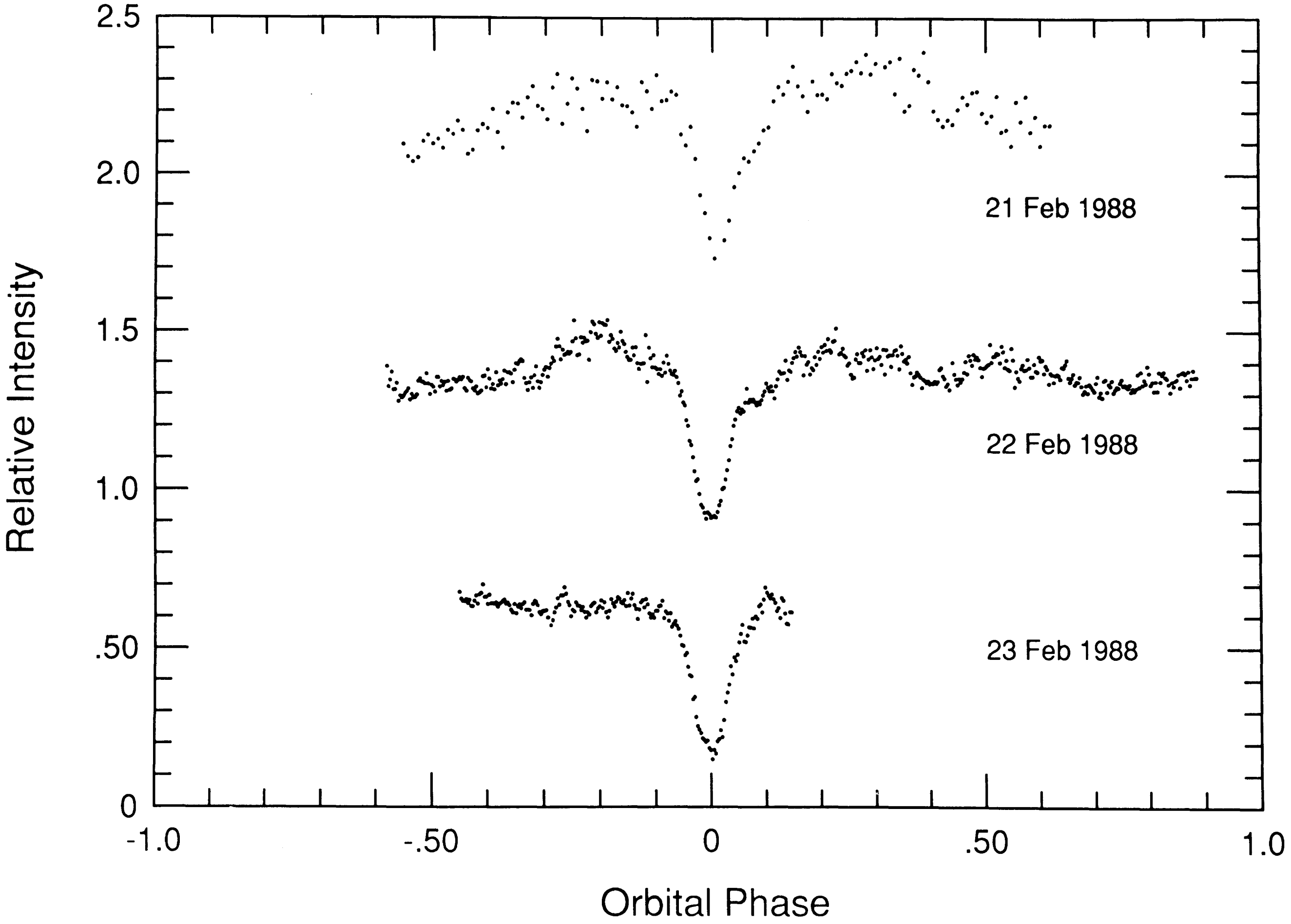

FIG. 1–The high-speed CCD light curves of DO Leo from February 1988. The time resolution is 1 min per point. The curves are offset by 0.75 intensity unit.

18, two additional eclipses were observed with a standard two-star photometer on the McDonald Observatory 0.91-m telescope. To maximize the count rate no filter was used and the bandpass of the data is set by the response of the RCA 8850 photomultiplier. The response of this tube results in an effective wavelength similar to the Johnson *B* filter but with a wider bandpass. The observations were interrupted briefly every 15 min or so (outside eclipse) in order to monitor the sky brightness. The observations were originally made with a 5-s integration time but have been binned to one minute in Figure 2 for comparison with the CCD data. A polynomial fit to the sky data points was used to subtract the sky background and the data were then corrected for atmospheric extinction using an extinction coefficient of 0.3 mag per air mass. Since the sky background was a considerable fraction of the total signal, accurate sky subtraction was difficult to achieve. Consequently, although these data are useful for eclipse timing purposes, the eclipse depths are not reliable.

To improve the precision of the orbital period we obtained four additional eclipses on 1989 April 4, 6, 7, and 8. These data were taken using the high-speed CCD photometer, this time in conjunction with a *BVR* filter having an effective bandpass of roughly 4000 Å–7000 Å. The data were reduced in an identical manner to the February 1988 observations and the resulting light curves are displayed in Figure 3. The count rate for these data was down by roughly a factor of five as compared with the February 1988 data. Comparison with the flux from the nearby comparison star reveals that the *BVR* filter was responsible only for approximately a factor of 2 loss in throughput as compared with the previous year. Thus, DO Leo was apparently a magnitude fainter during our April 1989 observations.

In general, the observed eclipses are approximately $1^{\mathrm{m}}.5$ deep and have a full width at half-intensity of ~ 0.05 *P* = ~ 17 min; they are "V"-shaped and show little evidence of structure from different ingress and egress times of white dwarf and disk hot spot. The time resolution and signal-to-noise ratio of our present data are insufficient to warrant a detailed analysis of the eclipse profile at this time. We have also noted the presence of a low-level, signal-dependent noise source in our CCD data, which we cannot properly characterize. Therefore, we cannot

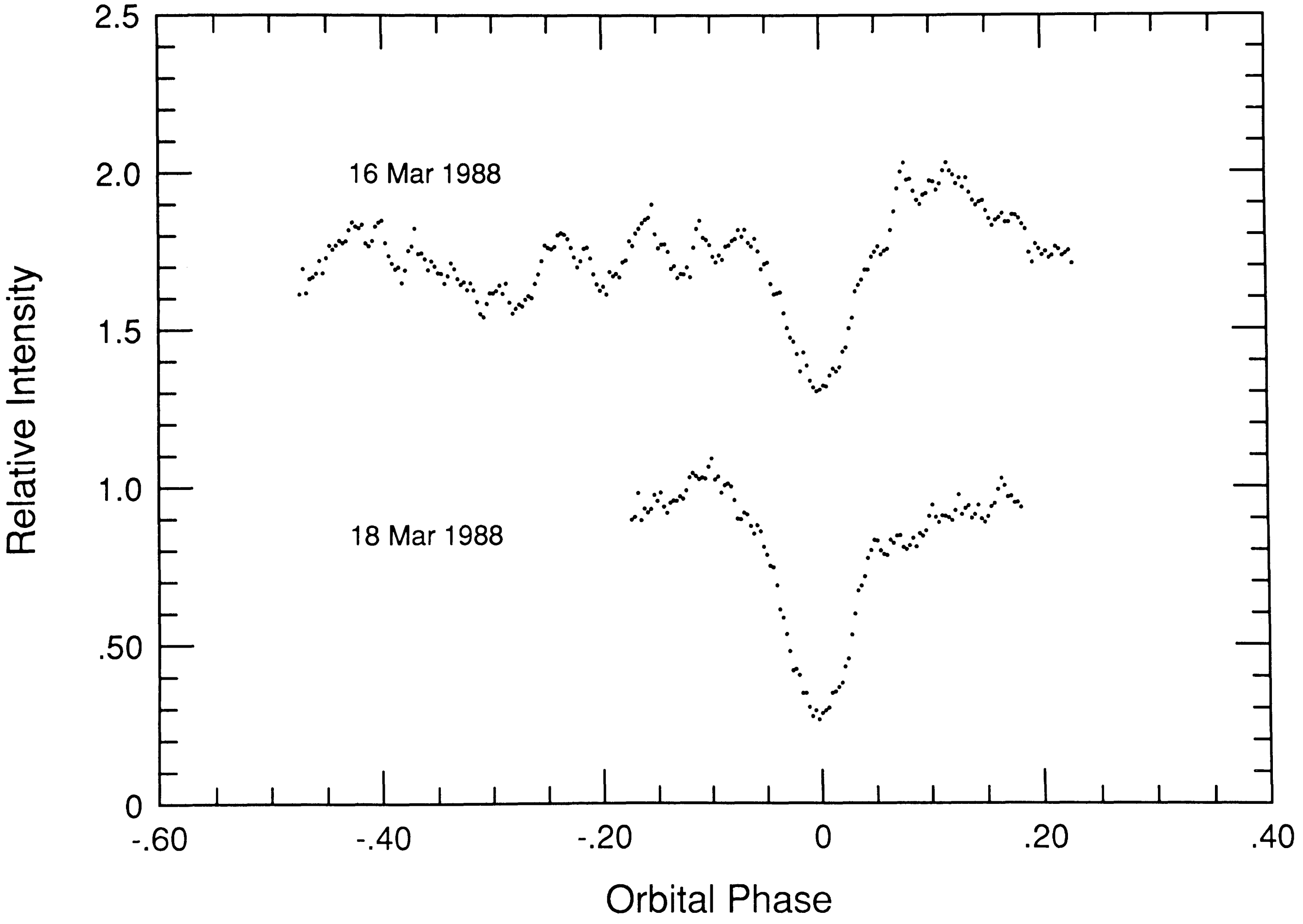

FIG. 2–The high-speed photoelectric light curves from March 1988. The time resolution has been degraded to 1 min for plotting purposes. The curves are offset by 0.75 intensity unit.

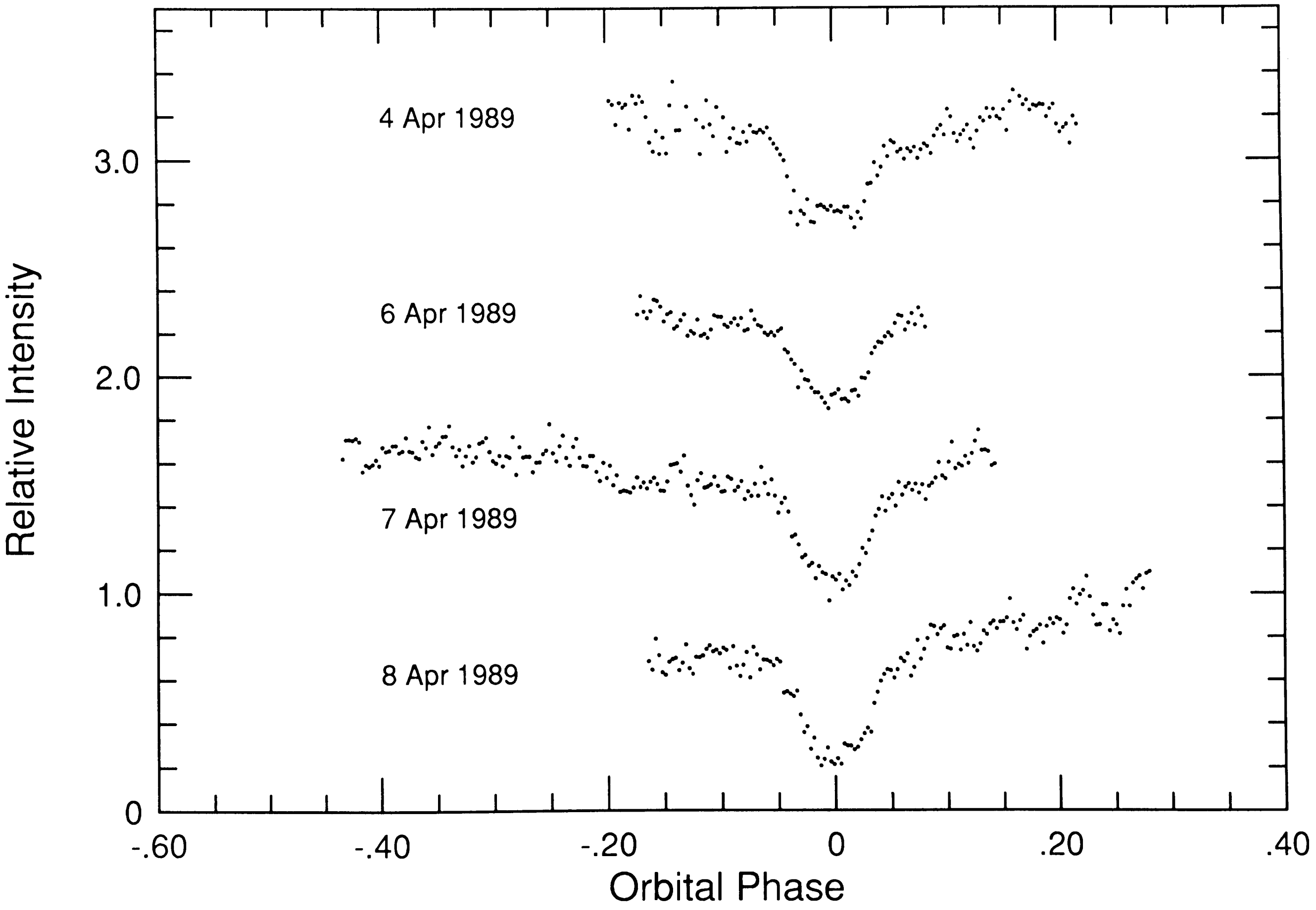

FIG. 3–The high-speed CCD light curves from April 1989. The *S/N* of these data is lower than that for the February 1988 data because we used a *BVR* filter and DO Leo was approximately one magnitude fainter during our 1988 observations. The time resolution is again 1 min and the curves are offset by 0.75 intensity unit.

make any firm statement concerning the finer structure of these light curves, although we are confident that there is flickering in evidence outside of eclipse. A summary of our photometric observations is presented in Table 1.

2.3 *The Orbital Period*

The long run of 1988 February 22 rules out a period shorter than about $0^{d}.2$ and provides an unambiguous cycle count for the 1988 data which can be extended into the 1989 data without error. The times of mideclipse were determined by parabolic fits to sections of the data centered near eclipse. The resultant timings, which are listed in Table 2, were then fit with a linear least-squares routine to yield the following ephemeris for the times of mideclipse:

$$T_{\text{mideclipse}} = \mathrm{JD}_{\odot}\underset{\pm 17}{2447225.75578} + \underset{\pm 2}{0.2345147}\,E \quad . \qquad (1)$$

The differences between the observed and calculated times of mideclipse are given in Table 2 and plotted as a function of cycle number in Figure 4. The observed scatter corresponds to timing discrepancies of less than one minute. This is consistent with expected measurement errors.

TABLE 1

Summary of Photometric Observations

HJD (Beginning of obs.) (2,440,000+)	Telescope (m)	Int. Time (s)	Duration (hr)	Filters
7212.7241 (1988 Feb. 21)	.76	60	6.65	I
7213.6589 (1988 Feb. 22)	.76	60	8.27	-
7214.8623 (1988 Feb. 23)	.76	60	3.37	-
7236.6667 (1988 Mar. 16)	.92	5	4.07	-
7238.6117 (1988 Mar. 18)	.92	5	2.09	-
7620.6335 (1989 April 4)	.76	30	2.34	BVR
7622.7478 (1989 April 6)	.76	30	1.46	BVR
7623.6359 (1989 April 7)	.76	30	3.26	BVR
7624.6264 (1989 April 8)	.76	30	2.50	BVR

3. Spectroscopy

Because the orbital period of DO Leo is in excess of

TABLE 2

Eclipse Timings of DO Leo

HJD (mid-eclipse) (2,440,000+)	Cycle Number (N)	O-C (cycles)
7212.8581	-878	0.0026
7213.7953	-874	-0.0011
7214.9681	-869	-0.0001
7236.7788	-776	0.0000
7238.6538	-768	-0.0014
7620.6796	861	0.0034
7622.7891	870	-0.0014
7623.7277	874	0.0009
7624.6649	878	-0.0028

5 hr, we considered the possibility that the secondary star may be visible in the optical or near-infrared. If so, DO Leo would become one of a handful of double-lined eclipsing cataclysmic binaries which provide the cornerstones for determining masses and dimensions of these stars. The first indication that the secondary star may be visible was provided by the initial spectroscopic survey of Green *et al.* (1982) who described the spectrum as consisting of strong and broad (FWZI = 5500 km s^{-1}) Balmer emission superimposed on a "red" flux distribution. Specifically, they noted a continuum excess to the red of 5000 Å. Assuming the secondary star is near the main sequence, an orbital period of 5.6 hr suggests that the secondary may have a late-K spectral type. If so, the Mg I b triplet ($\lambda \sim 5175$ Å) should be one of the stronger spectral features.

To search for spectral features from the secondary, we obtained a low-resolution spectrum of DO Leo using the CCD spectrograph at the Cassegrain focus of the McDonald Observatory 2.7-m reflector. The spectrum, shown in Figure 5, covers 4300 Å to 6800 Å at a resolution of ~ 11 Å FWHM. The data were obtained with a 3-arc-sec slit and

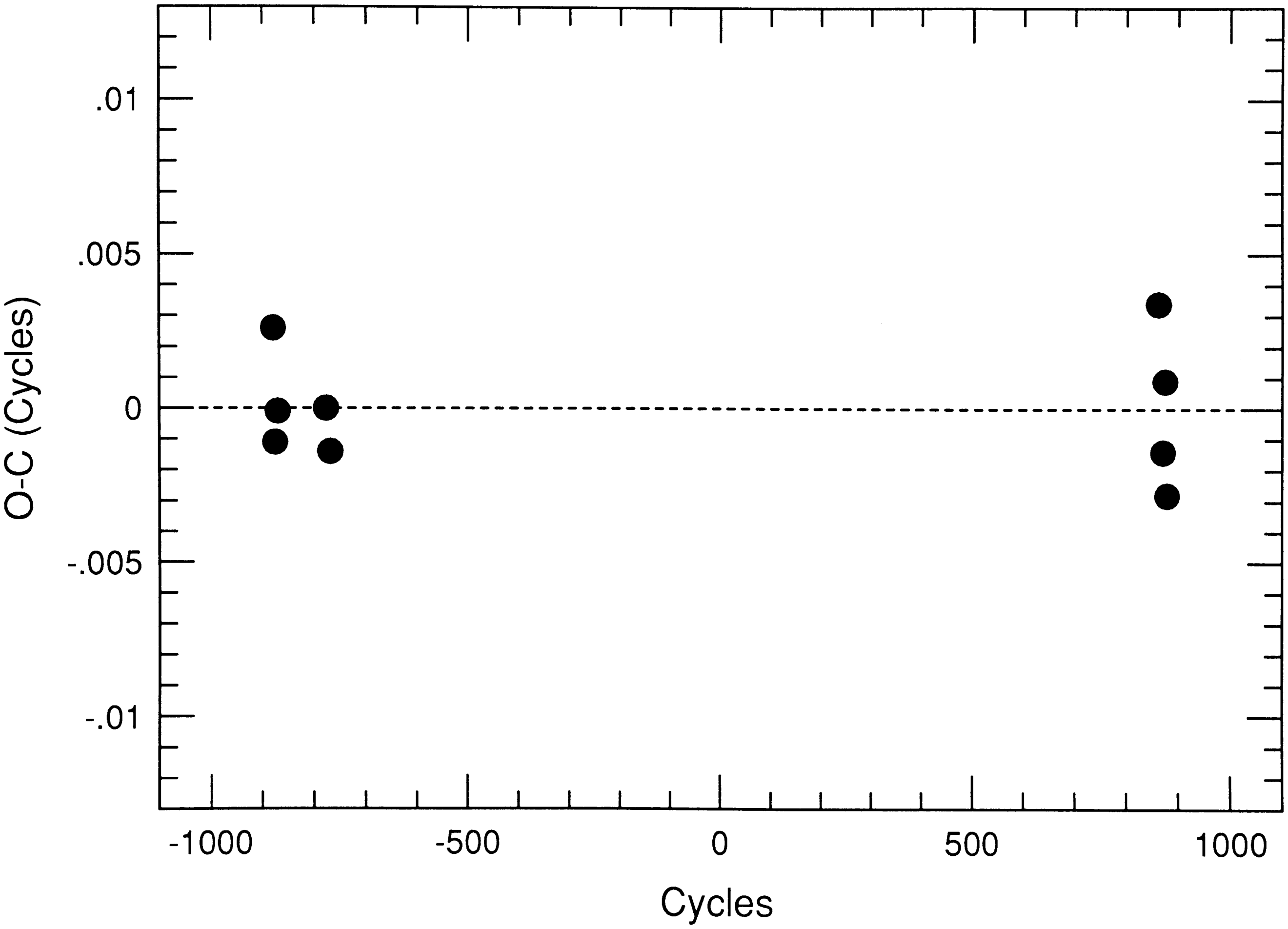

FIG. 4–The $O-C$ diagram for the orbital period of DO Leo. The observed scatter corresponds to less than ~1 min and is consistent with measurement error.

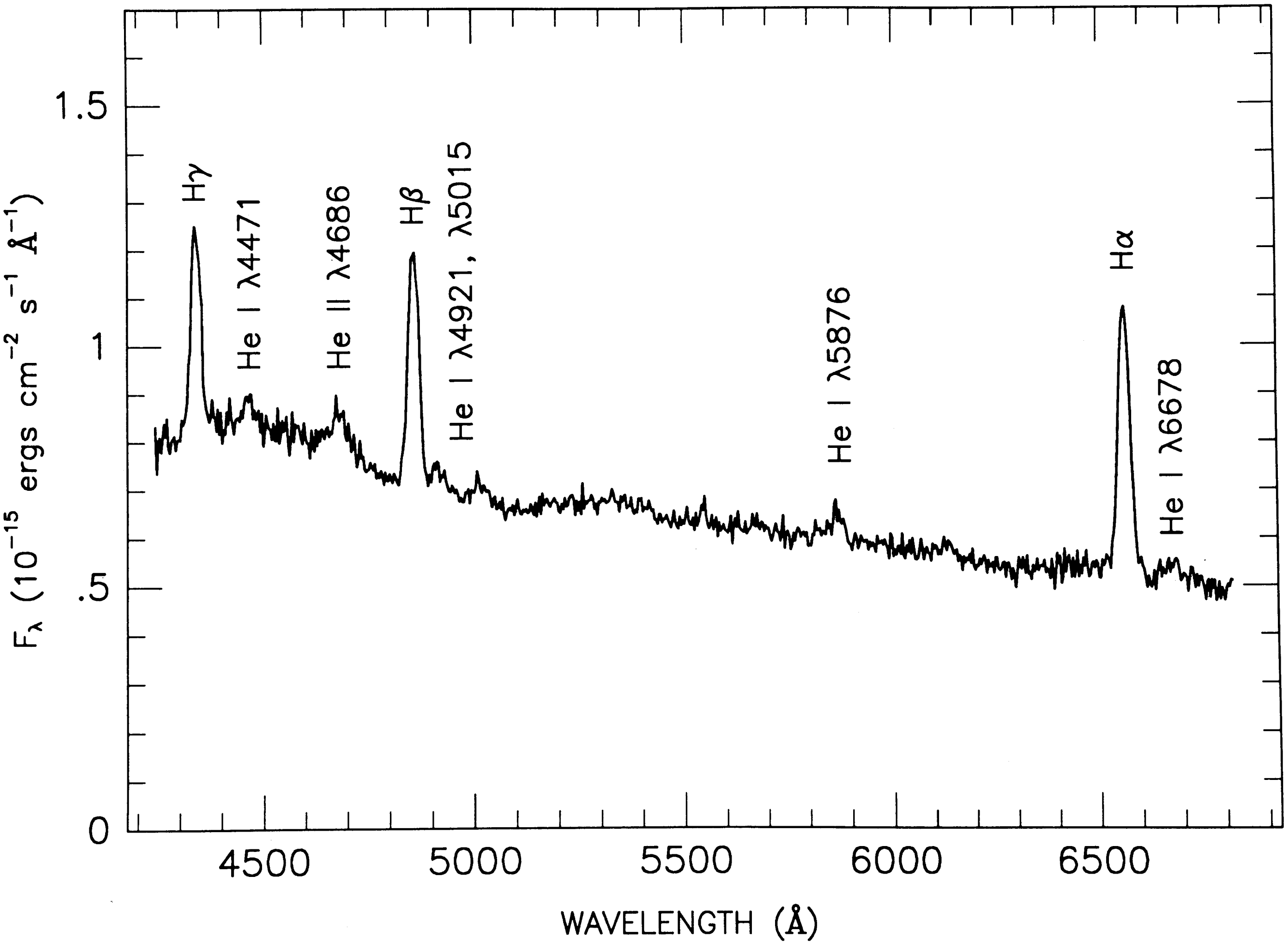

FIG. 5–The spectrum of DO Leo. Note the presence of He II λ4686. The strength of the Balmer and He I emission features relative to the continuum is typical of the novalike variables. There are no obvious spectral features from the secondary star.

we expect the absolute flux to be accurate to better than ~ 10%. The equivalent widths and line fluxes for the principal optical emission lines are given in Table 3. Overall, the spectrum is similar to that of a novalike variable. In particular, the He II λ4686 emission is rarely seen in the spectrum of a dwarf nova but is quite common in the spectra of novalike variables.

There are no obvious spectral features from the secondary star in our spectrum. There may be a broad absorption feature near 5080 Å, but its wavelength is almost 100 Å shorter than the expected wavelength of the Mg I b absorption band. Unfortunately, our spectrum does not extend far enough into the blue to determine whether the downturn in flux blueward of Hγ is due to the G band. If DO Leo is in fact a novalike variable having a relatively high-mass-accretion rate (as compared with dwarf novae), it is not surprising that the spectral features from the secondary are not obvious in our spectrum.

4. Conclusions

We have established that DO Leo is an eclipsing cata-

TABLE 3

Equivalent Widths and Line Fluxes of Principal Optical Emission Lines

Line	Equivalent Width (Å)	Flux (10^{-15} ergs cm^{-2} s^{-1})
Hγ	13	10.7
He I λ4471	3	2.2
He II λ4686	6	4.9
Hβ	21	14.9
He I λ4921	2	1.2
He I λ5015	2	1.5
He I λ5876	5	2.8
Hα	38	19.9
He I λ6678	4	4.2

(Indicated line fluxes are accurate to approximately 10%)

clysmic variable with a period of 5.6 hr. The eclipses have a "V" shape and have a full width at the half-flux level of ~5% of the orbital period. The observed eclipse depth of $1^{\mathrm{m}}_{\cdot}5$ implies that the system is seen almost edge-on. We also observed an apparent 1-magnitude drop in continuum brightness from the February 1988 to the April 1989 data.

The relatively high excitation spectrum is, in general, more typical of a novalike variable than of a dwarf nova. In particular, the presence of significant He II λ4686 emission is common in the spectra of novalike variables. The spectra of dwarf novae, on the other hand, are characterized by strong emission in the lower-excitation Balmer and He I lines. Although we cannot claim a detection of the secondary star based on our single spectrum, it seems possible that future observations, in particular near-infrared observations, may reveal spectral features from the secondary. A detection of the spectrum of the secondary star in either the optical or near-infrared would establish DO Leo as a double-lined eclipsing system. Because such systems are so vital in determining the fundamental properties of cataclysmic variable stars, further spectroscopic observations are to be strongly encouraged.

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