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SPECTROSCOPIC AND PHOTOMETRIC OBSERVATIONS OF TRANSIENT ACCRETION DISKS IN U CEPHEI

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ABSTRACT

We present combined spectroscopic and photometric observations of the Algol-type system U Cep during six eclipses in a 3 month interval. U Cep is known for its accretion disk surrounding the primary star which gives rise during eclipse to excess continuum light and Doppler-shifted emission lines. Intuitively, one would expect these two types of disk emission to be closely related because they are both products of the impact of the stream and the primary star. These observations showed the radius of the continuum-producing disk to be remarkably constant at 1.2, while the emission region varied from 1.2 to 1.6 times the radius of the primary star. There is only a weak correlation between the presence of the continuum excess and line emission. This suggests these two regions are not as closely related physically as expected. We confirm the findings of Crawford, namely that the gas in the emission-line region does not rotate in a circular Keplerian fashion and that the emission lines are much broader than that expected from a solely rotationally broadened line. During one eclipse, a third emission line was visible through most of totality which may indicate mass loss from the system.

Subject headings: stars: accretion — stars: eclipsing binaries — stars: individual (U Cep)

I. INTRODUCTION

U Cep is a binary of the Algol-type with deep total eclipses every 2.5 days. This system has been the subject of numerous studies, and it has played an important role in our understanding of the mass transfer and accretion processes in binary stars (see Batten 1974 for a review of the early work). U Cep is well known for its distorted light curves and for emission lines which are sometimes visible in eclipse. These effects are products of the mass transfer process. The secondary star appears to experience occasional large transient increases in mass transfer. Olson has observed U Cep photometrically for over a decade (Olson 1978, 1980*a*, *b*, 1982). When the mass transfer is high he finds evidence for a stream, for a disk, and for cool spots on the surface of the mass-gaining B star.

The evidence for the disk derives from excess continuum light seen during eclipse. The colors of this light are best matched by a stellar photosphere with a temperature somewhat less than that of the primary star. In short-period Algol-type systems, such as U Cep, the primary is rather large relative to the stellar separation, and the accretion stream from the secondary will impact the trailing hemisphere of the primary star (Lubow and Shu 1975). In Olson's model the disk is actually an equatorial bulge produced by deposition of energy into the star by the gas stream. These elevated regions of the atmosphere are seen during totality beyond the limb of the occulting secondary star and produce a continuum excess, which is especially apparent in the ultraviolet bandpass. At phases outside of eclipse the cooler bulge seen in front of the primary star produces light deficits.

Spectroscopic observations of the mass transfer process in U Cep have been somewhat limited. Filling in of absorption lines by emission had long been suspected (see, e.g., Struve 1944). The first definite observation of line emission was made in 1969 of Hα (Batten 1974). In 1974 mass transfer in U Cep became very active and highly variable Hα emission was seen in totality by Plavec and Polidan (1975). In this same time period, Batten *et al.* (1975) found strong emission in all of the Balmer lines from Hβ to H18. Crawford (1981) obtained 24 spectrograms at Hα during this outburst. Hα emission varied during eclipse in the same manner as the emission lines found in the Algol system RW Tau by Wyse (1934), namely redshifted emission near the start of totality and blueshifted emission near the end of totality. Joy (1942) interpreted this behavior as an eclipse of a rotating gaseous ring surrounding the primary star. Crawford (1981) found that the ring or disk in U Cep did not rotate in a Keplerian fashion and that the line widths were much broader than could be accounted for by broadening in a rotating disk. Independently, Kaitchuck and Honeycutt (1982*b*) had found the same phenomena in RW Tau and suggested, as did Crawford, the possibility of supersonic turbulence. Shock fronts and high-excitation emission lines are expected from supersonic turbulence. Such lines have indeed been found in U Cep (Kondo, McCluskey, and Stencel 1979; Kondo, McCluskey, and Harvel 1981; Plavec 1983) and RW Tau (Plavec and Dobias 1983).

It is necessary to make a distinction between the disks seen in continuum photometry and those seen spectroscopically via the presence of emission lines. The continuum disks are apparently the product of a bulging equatorial region of the accreting primary star produced by the stream penetration. Olson's photometry has shown the continuum disks to be highly variable and transient, sometimes disappearing in about one orbital period. The properties of emission-line disks have been defined by observations of short-period Algols in eclipse (Kaitchuck and Honeycutt 1982*a*; Kaitchuck, Honeycutt, and Schlegel 1985; Kaitchuck and Honeycutt 1982*b*; Crawford

1981; Kaitchuck and Park 1988). These studies have shown the emission-line disks to be regions above the stellar photosphere, usually rotating at a different speed than the primary star, and with low optical depth in the continuum. There are often large differences between the leading (blueshifted) and trailing (redshifted) side of the disk in terms of line strengths, rotational velocity, and radial extent above the central star. The emission lines vary considerably in strength from eclipse to eclipse, sometimes appearing and disappearing in one orbital period or less. This indicates that the disks in short-period Algol systems are transient structures which come and go with fluctuations in the mass transfer rate.

To distinguish between the two types of disks, in the remainder of this paper we will use the terms continuum transient disks (CTD) and emission-line transient disks (LTD). Intuitively, one might expect these two type of disks to be very closely related, perhaps even two aspects of the same basic structure. For example, the emission-line region may just be a chromosphere-like region above the equatorial bulge. This close relationship is especially appealing because the radii of both the LTD and the CTD are small and both appear to be variable and transient. Yet, the observational confirmation of our intuition is still lacking. The observations presented in this paper are an attempt to learn more about the nature of the LTD in U Cep and its physical relationship to the CTD. To the best of our knowledge, this is the first time that these two types of disks have been studied during the same eclipse by combining simultaneous photometry and spectroscopy.

II. OBSERVATIONS

U Cep was observed on the nights of 1982 September 17, October 2, 17, and November 16, 22, and 27 (UT) with the 0.91 m telescope of Goethe Link Observatory of Indiana University equipped with a Meinel slit-spectrograph and a SIT Vidicon detector. The observations were made with a 500 Å bandpass centered on Hα with 2.5–3.5 Å resolution. Integration times were short (300 s) in order to preserve good time resolution during the total phase of eclipse, which is required for spatial mapping of the accretion disk surrounding the occulted star. Wavelength comparison spectra were observed at frequent intervals to ensure accurate wavelength calibrations. With the exception of 1982 October 2, simultaneous differential *UBV* photometry was obtained with the 0.4 m telescope at the Morgan-Monroe station of the Goethe Link Observatory. The comparison star (HD 6006) was the same one used by Olson (1980*b*) to define the undisturbed light curve. Therefore, Olson's Strömgren *y* filter curve should correspond closely to our *V* filter data. We also expect a close correspondence between Olson's *u* filter curve and our *U* observations because during the low-activity interval of these observations the spectrum of U Cep during totality was dominated by the secondary star with its weak Balmer discontinuity. There may be small differences between the effective wavelengths of the two photometer systems.

The spectroscopic observations, of six eclipses in a 3 month interval, showed a remarkable range of behavior of the LTD in U Cep. The spectroscopic observations for each night will be discussed in turn and are displayed in Figures 1, 3, 4, 6, 8, and 10. In these figures the equivalent width of the line emission in the partial phases were corrected for the continuum variations of the primary by reference to the simultaneous photometry or to the undisturbed light curve of Olson (1980*b*). A correction for the underlying absorption line from the partially eclipsed primary star was not made because this profile is asymmetric and changes rapidly with time. This means that the emission-line width and strength will be underestimated and the radial velocity will be overestimated (because the emission line is Doppler-shifted into the wing of the absorption line). In totality, the underlying absorption profile becomes a much weaker Hα line from the G-type secondary star, making the effects on the emission-line measurements far less severe. This absorption line was removed from the totality observations of October 2 by subtracting the spectrum of the secondary star obtained near phase zero during another eclipse when the emission lines were absent. This procedure introduces noise due to slight misregistration between the two spectra. Therefore, this subtraction was not done on the other nights where the emission was much weaker.

All radial velocity measurements were referred to absorption lines in the secondary star. This is equivalent to the center of mass of the system because the motion of the secondary star is nearly perpendicular to the line of sight during eclipse. The line widths were corrected for the instrumental broadening by reference to the wavelength comparison spectra. The orbital phases were calculated from JD 2,438,291.4858 + 2.2930683E (E. C. Olson 1982, private communication). The simultaneous photometry provided new times of minimum light (Faulkner and Kaitchuck 1983), and all phases were then corrected by adding 0.033 to those calculated from this ephemeris.

a) *1982 September 17*

There was good phase coverage all through totality of this eclipse. Yet line emission was only seen near third contact. This is the first time this kind of behavior has been seen in U Cep or any other transient disk binary. However, this behavior cannot be a rare event for U Cep since it was seen again 2 months later. The usual situation is for emission to be visible at both internal contacts or at second contact only. Figure 1 shows the equivalent width, the full width at half-maximum (FWHM), and the radial velocity. In this, and all the following figures, the vertical dashed lines mark second and third contact (±0.019 phase; Olson 1980*b*). The emission was so weak on this night that it was necessary to co-add the spectra in overlapping groups of three for measurement. The effective phase resolution in Figure 1 is therefore somewhat coarser than the actual data spacing. (This is not true of the remaining figures.)

It is of fundamental interest to know how the excess continuum light relates to the strength of emission lines. It is hoped that this can reveal the spatial relationship between the CTD and LTD. For instance, a simple timing of the disappearance of emission lines after second contact and their reappearance before third contact can reveal if the line-emitting region is more or less extended than the continuum producing region. Figure 2*a* shows the *U*-band light curve for this night. Unfortunately, there is considerable scatter because the sky conditions were less than optimal. The solid line in the figure is the undisturbed light curve defined by Olson (1980*b*). Figure 2*b* shows the excess *U* flux, found by subtracting the undisturbed curve from the observations, normalized to the *y* flux of the secondary star (see equation on p. 499 of Olson 1980*a*). There is a very small amount of excess light at second contact, approximately 0.1 of the visual flux of the secondary star. Olson (1980*b*) has seen this quantity reach values exceeding 2 during strong episodes of mass transfer. Figures 1 and 2*b* indicate that the presence of line emission and continuum emission are not correlated. There was continuum emission at second

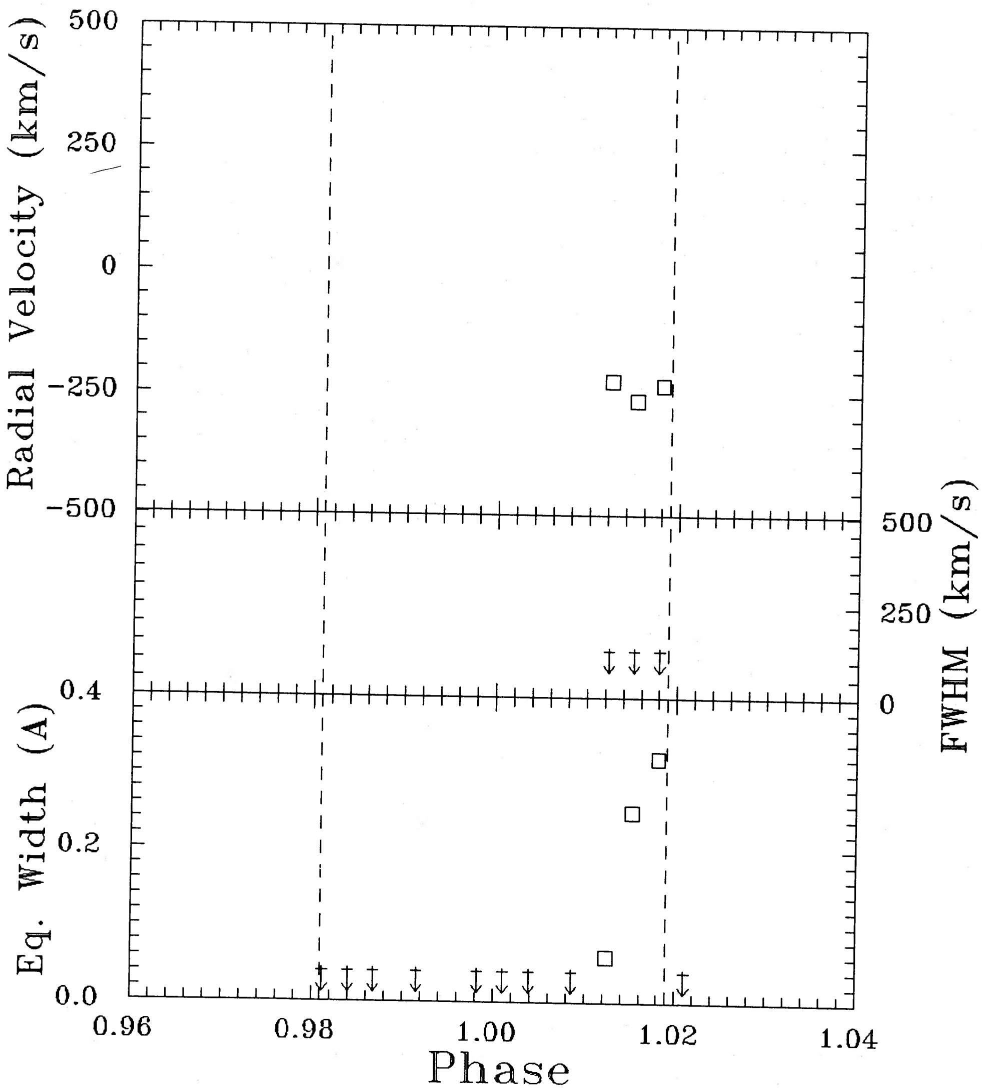

FIG. 1.—The equivalent width, full width at half-maximum (FWHM), and radial velocity of the Hα emission line 1982 September 17. In this and all following figures the vertical dashed lines mark the limits of totality. Open symbols refer to the blueshifted component and the arrows indicate detection limits.

contact but no line emission was detected. There was a definite detection of line emission at third contact but there was no apparent continuum emission.

b) *1982 October 2*

This eclipse had the strongest line emission (EW = 3 Å) of this study, but still weaker than the 1974–1975 outburst (EW = 5 Å; Crawford 1981). Unfortunately, there was no photometry available for this night. The subtraction of the secondary star spectrum resulted in a third emission component located between the two Doppler disk components. An undersubtraction can produce a spurious emission line at the location of an absorption line. This does not appear to be the case for the following reasons. First, this third emission component is not centered on the absorption line, as would be expected; rather it is shifted redward of the absorption line by ~ 100 km s^{-1}. Second, the Hα absorption line in the unsubtracted spectra look filled in. This does not appear to be the case for the other absorption lines. Finally, the third component disappears briefly near mid-eclipse. If it were a product of the subtraction process it would be present through all of totality.

Figure 3 shows the equivalent width, full width at half-maximum (FWHM), and the radial velocity of all three Hα components during eclipse as determined by Gaussian profile fits. The solid and open symbols represent the redshifted and blueshifted Doppler components, respectively. The pluses indicate the third emission component.

The scatter in the equivalent width data is such that it is difficult to say a great deal about the surface brightness distribution on the two sides of the disk. The disk eclipse is total because both disk components disappeared near mid-eclipse. So does the third component, although it disappears slightly later than the redshifted disk component. The disk component and the third component reappeared together after mid-eclipse.

Before continuing, it is worthwhile to consider the expected behavior of the radial velocity and the width of rotationally broadened emission lines in eclipse. Consider the trailing side of the disk as seen at second contact. The line profile is determined by summing the contributions at each wavelength from the corresponding locations in the disk with the proper Doppler shifts, weighted by the surface brightness distribution.

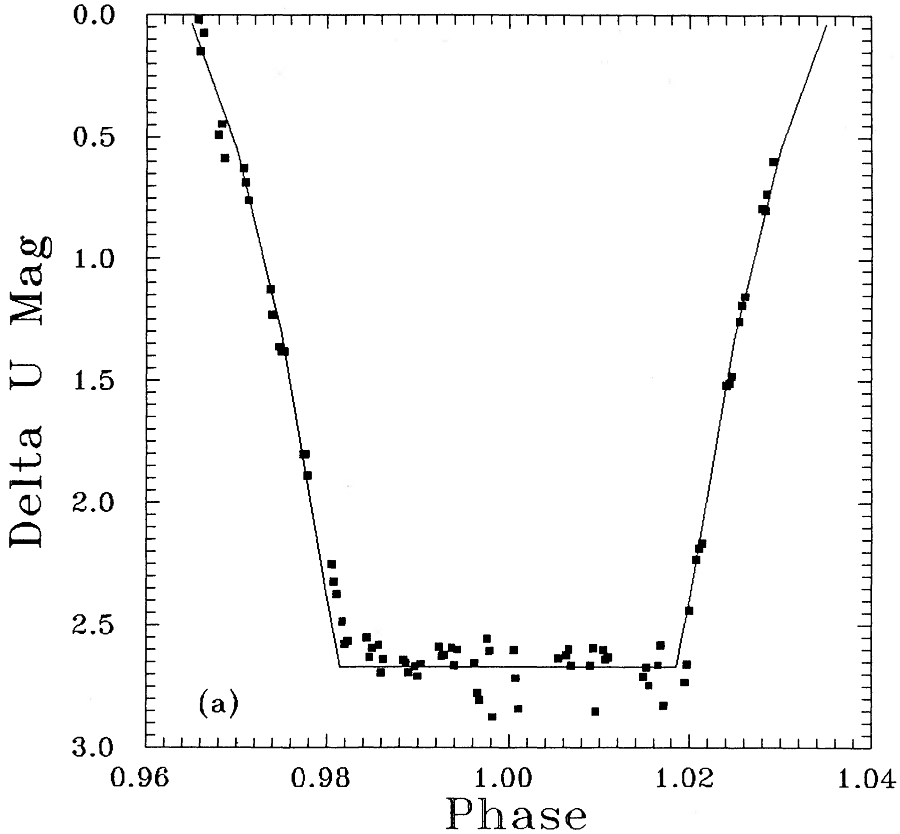

FIG. 2*a*

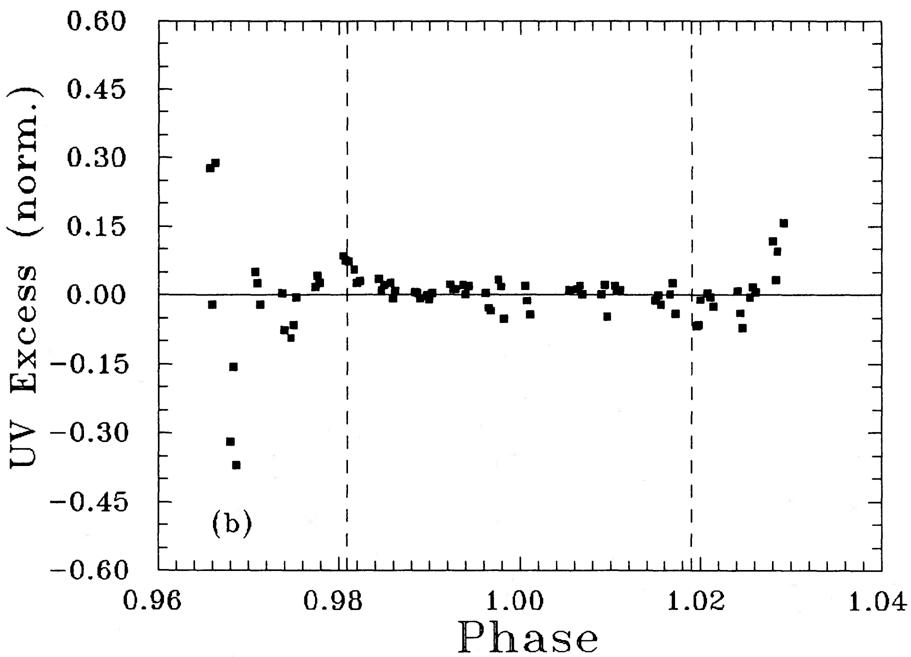

FIG. 2*b*

FIG. 2.—(*a*) The *U* bandpass light curve of U Cep on 1982 September 17. The solid line is the undisturbed light curve. (*b*) The ultraviolet excess obtained by subtracting the reference curve from the data and normalizing to the *y* bandpass flux of the secondary star.

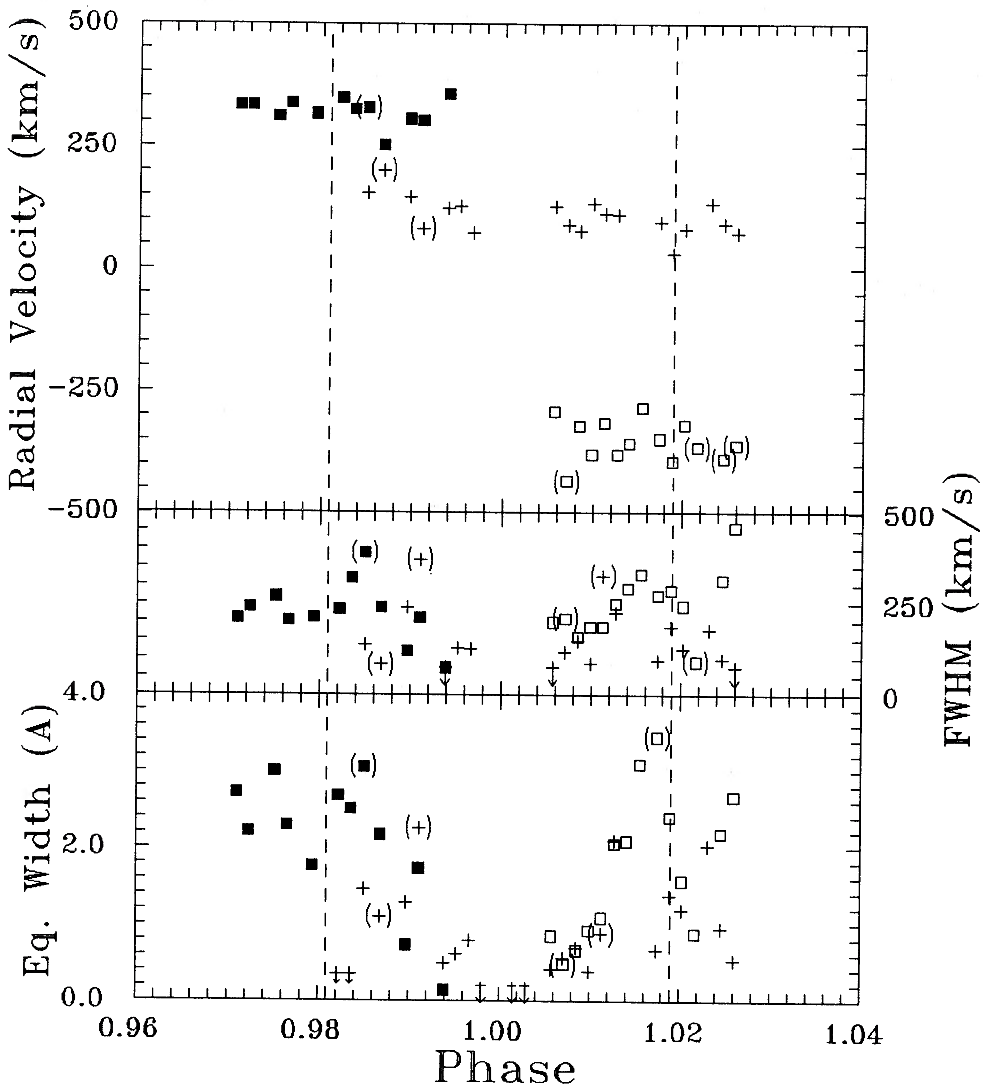

FIG. 3.—The equivalent width, FWHM, and radial velocity of the emission components observed during the 1982 October 2 eclipse. The filled and open symbols refer to the redshifted and blueshifted components, respectively, the pulses refer to the third emission component, and the arrows indicate detection limits. Symbols enclosed in parentheses are uncertain.

As the eclipse of the trailing side progresses, the high-velocity regions closest to the central star and the low-velocity regions moving most nearly perpendicular to the line of sight are covered first. Therefore an emission line will narrow rapidly with increasing phase. For a circular Keplerian disk with a uniform surface brightness, the mean velocity of the line actually rises as the inner disk is covered (Crawford 1981) because the low-velocity regions in the "foreground" portion of the disk have a larger projected surface area than the high-velocity regions closest to the central star. This is a small increase which is not easily detected at our spectral resolution. So it is possible for the emission lines to show little or no radial velocity change during eclipse. For the case where the disk is significantly brighter in the center, the radial velocities fall as the inner disk is occulted. So in general, we expect the line width of the redshifted component to decrease as the eclipse progresses, while the radial velocity either remains nearly constant or decreases. Likewise, because the leading side of the disk emerges from eclipse with time, we expect the line width and the magnitude of the velocity of the blueshifted component to follow the redshifted component in reverse chronological order.

Contrary to these expectations, the emission line widths during the eclipse of transient disks often show little variation (see, e.g., Kaitchuck and Honeycutt 1982*b*). However, the middle panel of Figure 3 shows that during this eclipse of U Cep, both Doppler components varied considerably in a way qualitatively consistent with the expected behavior. However, it will be shown later that these variations are not compatible with a circular Keplerian disk.

The upper panel of Figure 3 shows little variation in the radial velocity of the disk components during eclipse. As discussed above, this can be understood within the framework of a Keplerian disk. But, in fact, it will be shown that the magnitude of the rotational velocity is too small for a disk of the measured radius. The third emission component shows an almost constant radial velocity of about $+100$ km s^{-1}.

c) 1982 October 17

There were equipment problems on this night, so the phase coverage shown in Figure 4 was somewhat incomplete. The redshifted emission is strongest prior to second contact and disappears quickly thereafter. Blueshifted emission was weakly visible at third contact. These observations followed those of October 2 by six orbital periods.

Figure 5*a* shows the light curve for this night. Excess emission is clearly seen in the partial phases and into a portion of totality. Figure 5*b* shows the normalized *U* excess. The presence of line emission and the continuum excess emission are correlated on this night.

d) 1982 October 22

There was no line emission detected this night (EW < 0.6 Å). Figure 6 shows the phases of the spectroscopic observations, which followed the previous ones by just two orbits. Figure 7*a* shows the light curve, which clearly shows a continuum excess, especially during ingress. Figure 7*b* confirms this impression. The spectroscopic observations did not begin until after the ingress continuum excess was gone. However, there were spectroscopic observations at third contact which failed to detect line emission even though continuum emission was present.

e) 1982 October 27

The observations followed the previous ones by two orbital periods. This appears to be almost a repeat of the observations of October 17. In Figure 8 the redshifted emission was fairly strong during ingress but disappeared shortly after second contact. There was some blueshifted emission, but curiously, it disappeared by third contact. Photometry (Figs. 9*a* and 9*b*) extended only to shortly after second contact when clouds moved in at that site. These data show continuum excess which disappeared at about the same phase as the line emission.

f) 1982 November 16

Figure 10 shows that this night looked very similar to September 17 when emission was visible only at third contact.

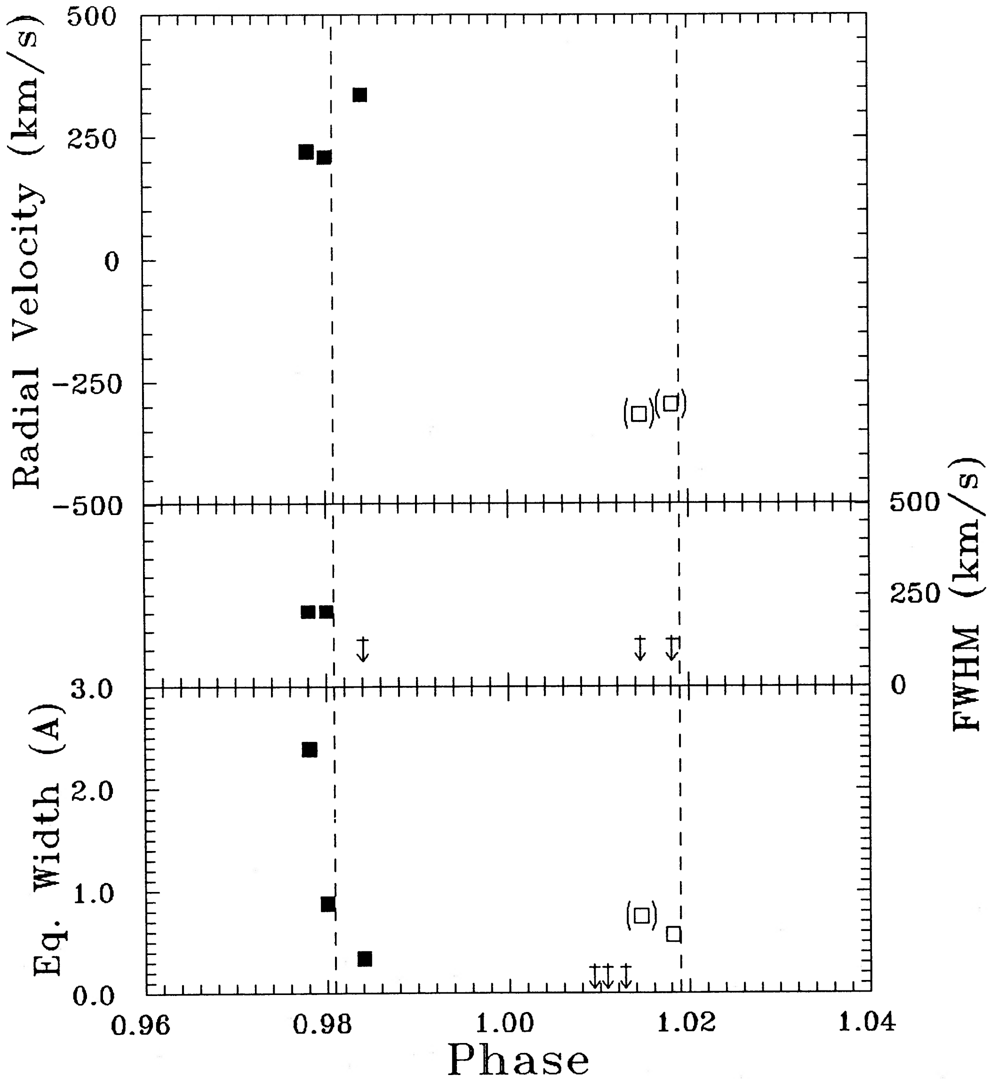

FIG. 4.—The equivalent width, FWHM, and radial velocity of the emission components observed during the 1982 October 17 eclipse. The filled and open symbols refer to the redshifted and blueshifted components, respectively, and the arrows indicate detection limits. Symbols enclosed in parentheses are uncertain.

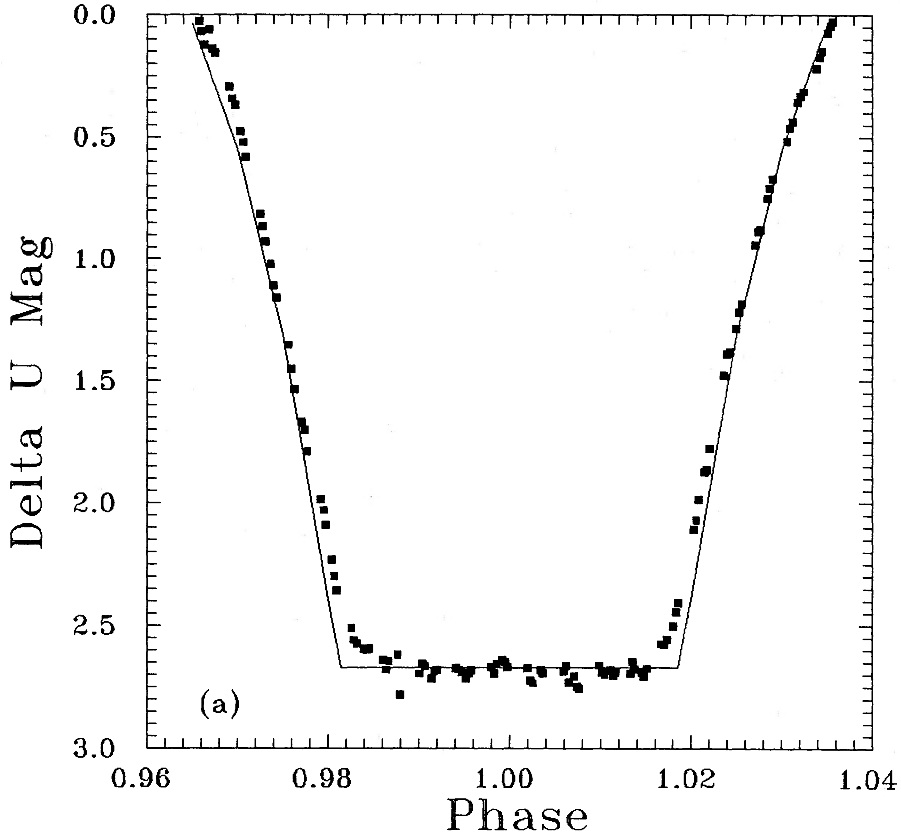

FIG. 5*a*

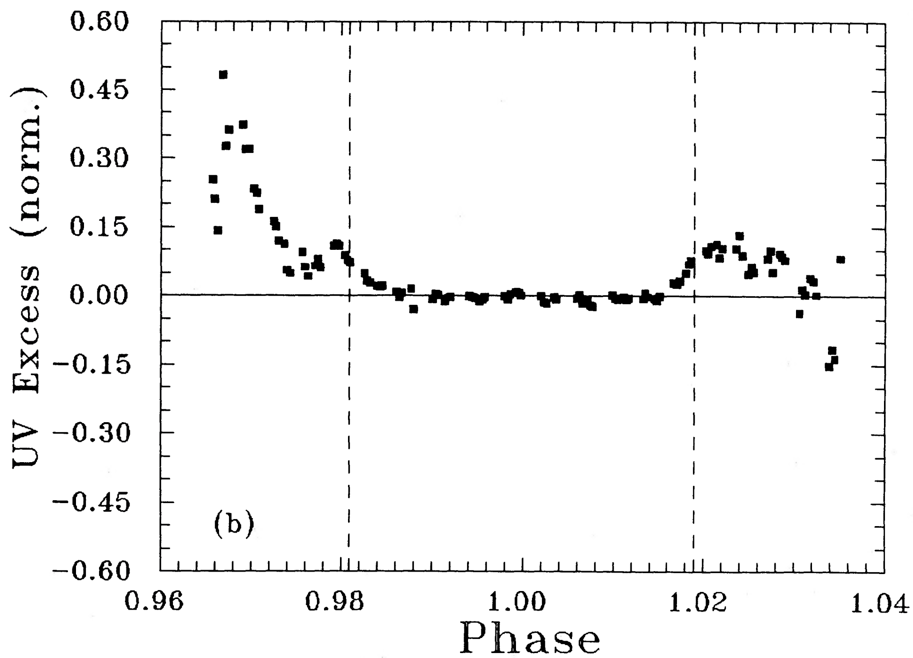

FIG. 5*b*

FIG. 5.—(*a*) The *U* bandpass light curve of U Cep on 1982 October 17. The solid line is the undisturbed light curve. (*b*) The ultraviolet excess obtained by subtracting the reference curve from the data and normalizing to the *y* bandpass flux of the secondary star.

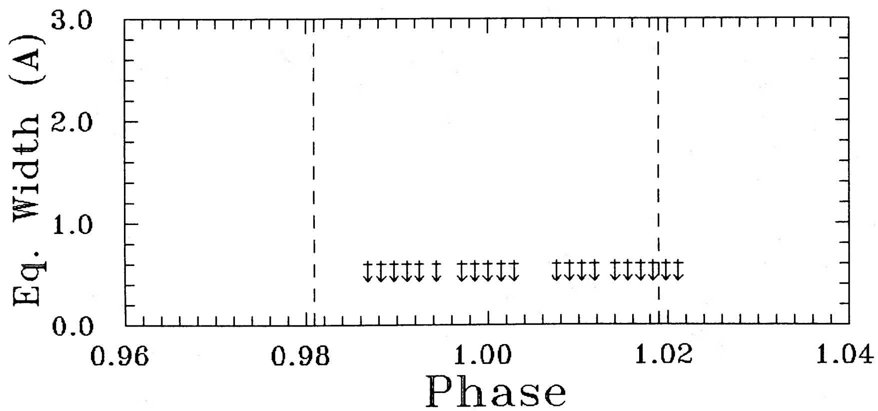

FIG. 6.—Spectroscopic observations of 1982 October 22. No line emission was detected. The arrows indicate the time of each observation and the upper limit to the Hα emission equivalent width.

However, the observations did not begin until shortly after second contact. The photometry on this night was of poor quality due to sky conditions.

III. DISCUSSION

The radius of the disk surrounding the primary star can be computed from the times of disappearance of emission after second contact and reappearance before third contact. This will give a separate radius estimate for the trailing and leading side of the disk. This calculation can be done for both the Hα and the continuum excess, to give a radius for the LTD and the CTD. A comparison of these numbers can give some indication of the spatial relationship of these two regions.

For a disk which has a very small projected thickness, the disk radius can be calculated by

$$\frac{R_d}{R_p} = \frac{\sqrt{(R_s/a)^2 - \cos^2 i} - \sin(2\pi\,\Delta t)}{R_p/a},$$

where R_d, R_p, and R_s are the radius of the disk, primary, and secondary star, respectively, a is the stellar separation, i is the orbital inclination, and Δt is the magnitude of the phase difference between mid-eclipse and the appearance or disappearance of the emission.

There is much evidence that the CTD in U Cep are not thin, but rather have an apparent thickness comparable to that of the central primary star (Olson 1980*a*). An extreme case would be a disk with a circular apparent cross section. The radius of such a disk would be given by

$$\frac{R_d}{R_p} = \frac{R_s/a - \sqrt{\sin^2(2\pi\,\Delta t) + \cos^2 i}}{R_p/a}.$$

These two equations can be used to establish the upper and lower limits of the disk radii, respectively. The value of Δt can be estimated directly from the previous figures. The system parameters are taken from Olson (1984*b*), i.e., $R_p/a = 0.183 \pm 0.004$, $R_s/a = 0.324 \pm 0.002$, and $i = 85.8 \pm 0.3$. Table 1 lists the results of these calculations. The disk radii are all rather small, as was found in other transient disk systems. The radius of the CTD was remarkably constant at $1.2R_p$. The radius of the LTD was more variable, ranging from 1.2 to $1.6R_p$ (0.53–$0.70R_{\rm Roche}$). This suggests that, on average, the LTD may be slightly larger than the CTD. The LTD and the CTD did not always occur together, but when they did they had the same radius to within the error of a single pair of measurements. The disks are generally circular except for October 27 where the leading side appears to be larger. However, this difference could also be due to different thicknesses on the two sides of the disk.

The lack of correlation between the presence of the CTD and the LTD can be seen in another way. Olson has seen the continuum excess exceed those presented here by more than a factor of 20. Yet the line emission has never been seen to exceed that reported here by more than a factor of 2. Even the well-studied outburst of 1974–1975 produced equivalent widths of Hα only 5 Å (Crawford 1981) in totality.

It is not clear why on two occasions blueshifted emission was seen from the leading limb of the primary star with no redshifted emission at the trailing limb. The disks in transient disk systems like U Cep are not the expected circular Keplerian disks and they are quite unstable. When mass transfer stops there is undoubtedly a rapid collapse of the disk onto the star. Perhaps the mass transfer had temporarily stopped and the last gas to be accreted was that which had circulated to

TABLE 1

DISK RADII[a]

Date (UT)	Trailing Side LTD	Trailing Side CTD	Leading Side LTD	Leading Side CTD
1982 Sep 17:				
Thin	NE[b]	1.25 ± 0.08	1.36 ± 0.07	NE[b]
Thick	...	1.15 ± 0.06	1.23 ± 0.06	
1982 Oct 02:				
Thin	1.54 ± 0.04	NO[c]	1.58 ± 0.06	NO[c]
Thick	1.33 ± 0.04		1.34 ± 0.04	
1982 Oct 17:				
Thin	~1.18	1.25 ± 0.06	1.26 ± 0.04	1.21 ± 0.05
Thick	~1.09	1.15 ± 0.04	1.15 ± 0.04	1.12 ± 0.04
1982 Oct 22:				
Thin	NO[c]	1.25 ± 0.06	NE[b]	1.16 ± 0.04
Thick	...	1.15 ± 0.04	...	1.08 ± 0.04
1982 Oct 27:				
Thin	1.28 ± 0.04	1.25 ± 0.06	1.47 ± 0.04	NO[c]
Thick	1.17 ± 0.04	1.15 ± 0.04	1.30 ± 0.04	
1982 Nov 16:				
Thin	NO[c]	NO[c]	1.27 ± 0.06	NO[c]
Thick	...	...	1.16 ± 0.05	

[a] ($R_{\rm pri} = 1.0$).
[b] No emission detected.
[c] No observations.

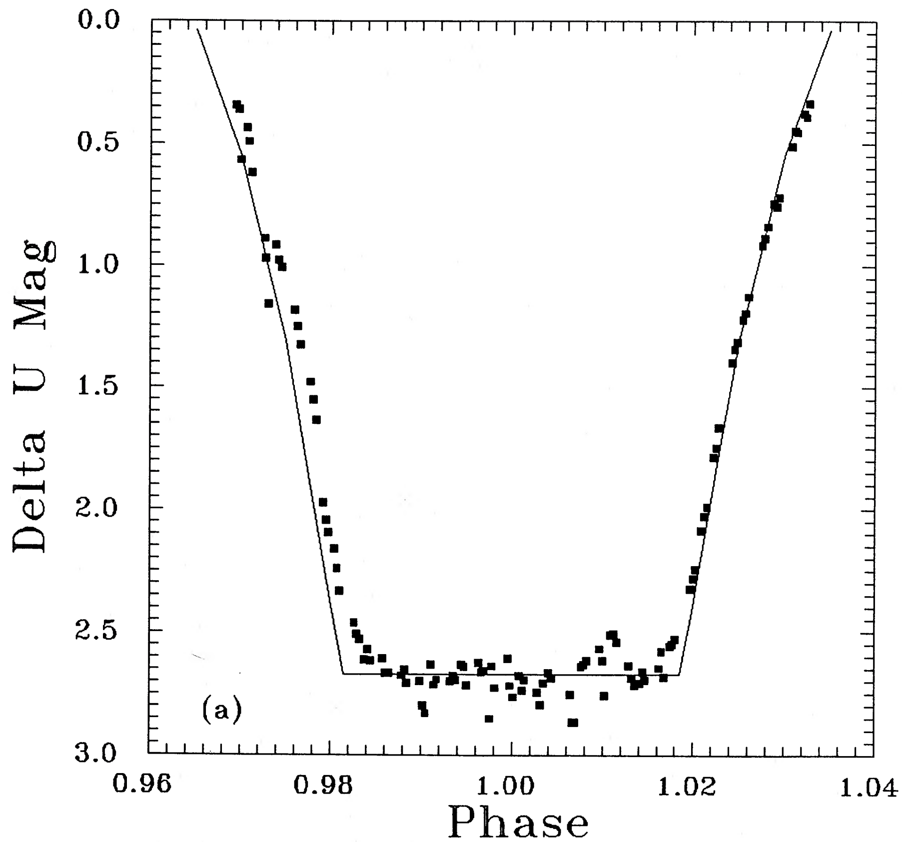

FIG. 7*a*

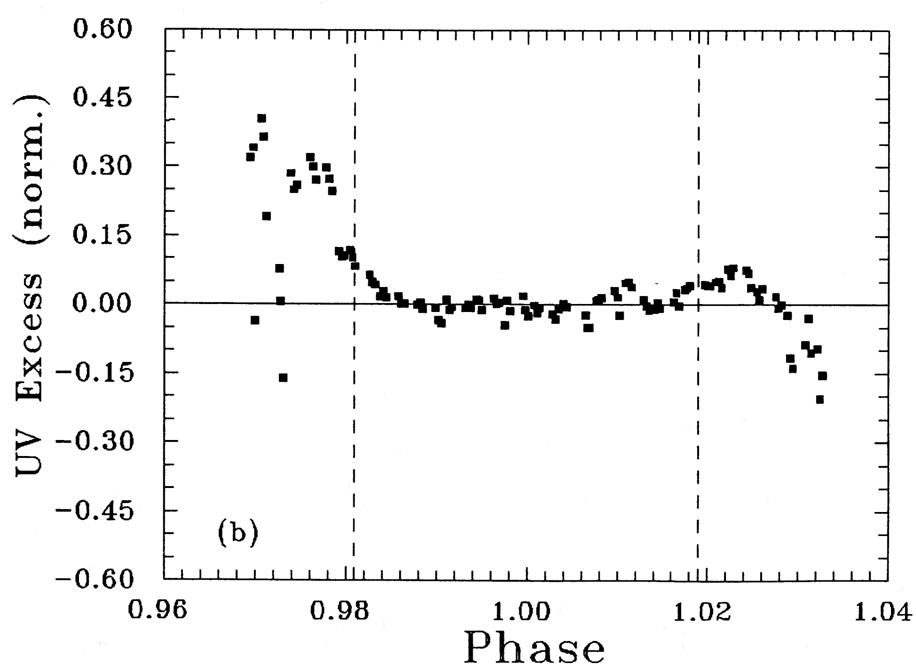

FIG. 7*b*

FIG. 7.—(*a*) The *U* bandpass light curve of U Cep on 1982 October 22. The solid line is the undisturbed light curve. (*b*) The ultraviolet excess obtained by subtracting the reference curve from the data and normalizing to the *y* bandpass flux of the secondary star.

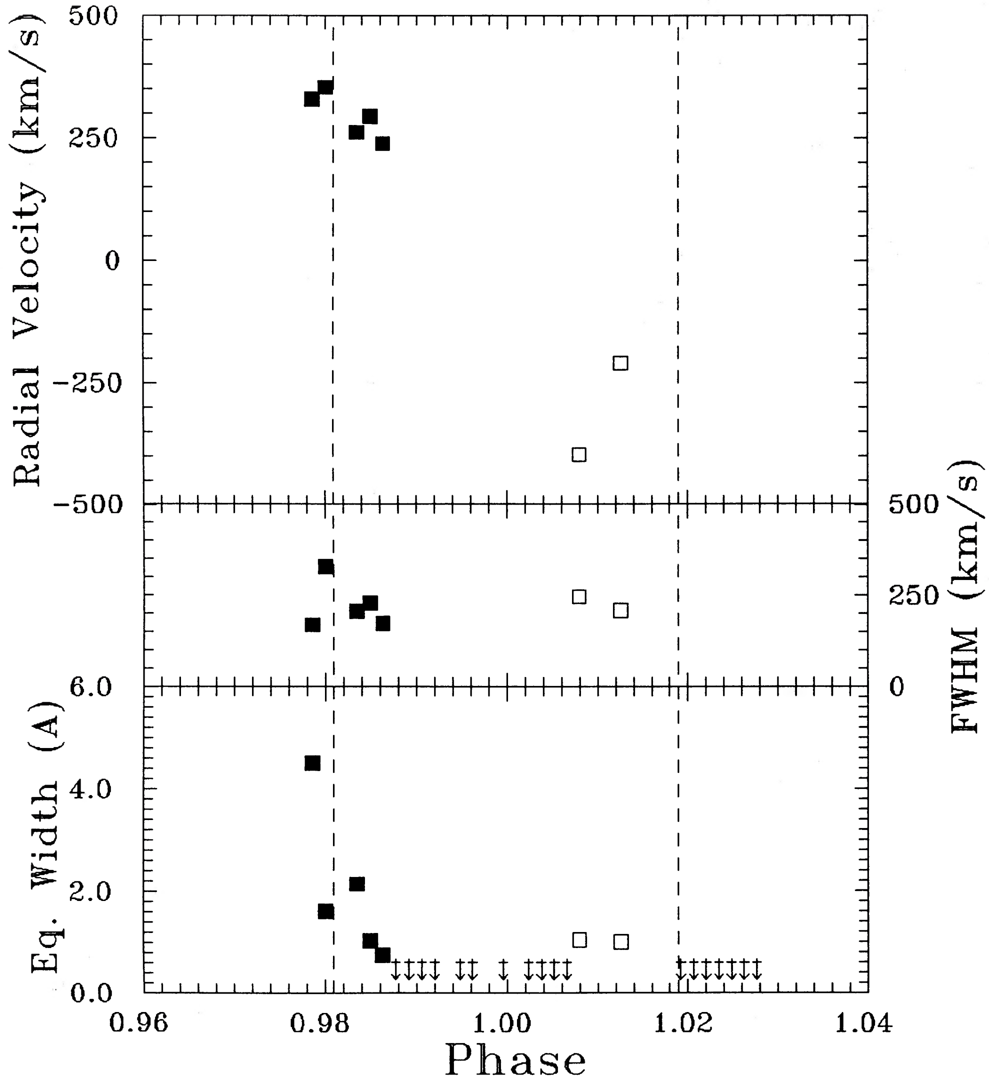

FIG. 8.—The equivalent width, FWHM, and radial velocity of the emission components observed during the 1982 October 27 eclipse. The filled and open symbols refer to the redshifted and blueshifted components, respectively, and the arrows indicate detection limits.

the leading side. This would explain that lack of emission prior to second contact because the stream impact would be absent.

The third emission component seen during the October 2 eclipse is especially interesting. The redshifted radial velocity could be explained by a flow from the secondary star to the primary. The disappearance near mid-eclipse implies a projected radius of the emitting region which is nearly the same as the disk. This suggests a close association of the third component with the disk and the primary star, rather than with the expected narrow mass stream from the secondary star. Perhaps this emission arises from gas which is leaving the system near the L_3 point. Evidence for mass loss from U Cep has been reported from *IUE* observations (Kondo, McCluskey, and Harvel 1981; McCluskey, Kondo, and Olson 1988) in the form of blueshifted absorption features. It is not clear how this might relate to the redshifted emission reported here. However, it should be kept in mind that none of the *IUE* observations was obtained in primary eclipse. So it is not certain how much of these differences are due to an aspect effect.

Olson *et al.* (1985) reported that U Cep underwent a period change 2–3 months prior to the observations reported here. They report undisturbed photometric behavior before and after the time of the period change, and they point out a general lack of evidence that abrupt period changes are correlated with disturbed light curves. The weak photometric disturbances and rather weak line emission reported in this paper represent the more common situation in U Cep as opposed to the large outbursts of 1984–1975 and 1986 (Olson 1986; McCluskey, Kondo, and Olson 1988). Because the continuum excess and line emission do not always occur together, is it possible that mass transfer through the LTD is responsible for the period change? And what is the relative contribution to the mass accretion from the gas in the LTD and from the gas in the direct stream penetration of the star? To answer these questions, we first want a rough estimate of the mass accretion rate from just the LTD. The first step is to estimate the gas density in the LTD. We will follow the approach of Crawford (1981). For the optically thin case,

$$\mathrm{EW} = \frac{A_{32}\, h\nu n_3\, V}{4\pi L_*},$$

where EW is the Hα equivalent width, n_3 is the mean number

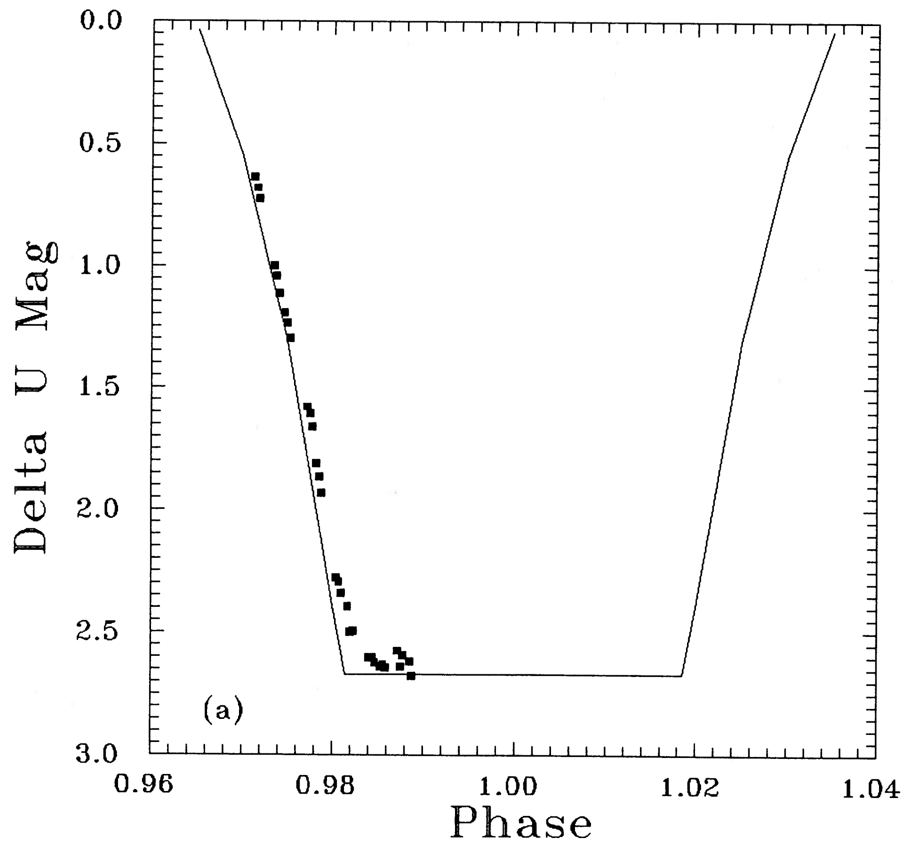

FIG. 9*a*

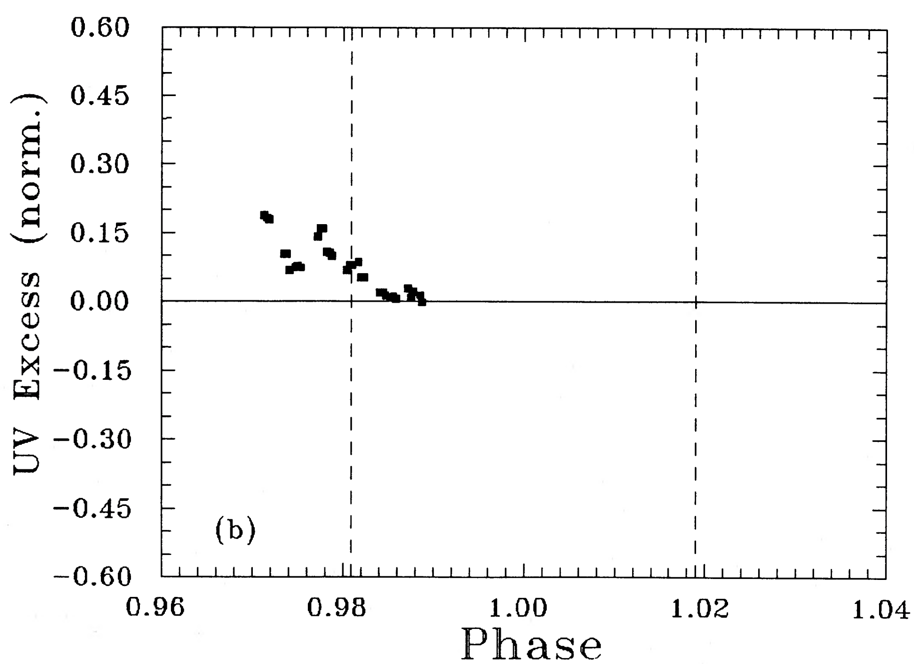

FIG. 9*b*

FIG. 9.—(*a*) The *U* bandpass light curve of U Cep on 1982 October 27. The solid line is the undisturbed light curve. (*b*) The ultraviolet excess obtained by subtracting the reference curve from the data and normalizing to the *y* bandpass flux of the secondary star.

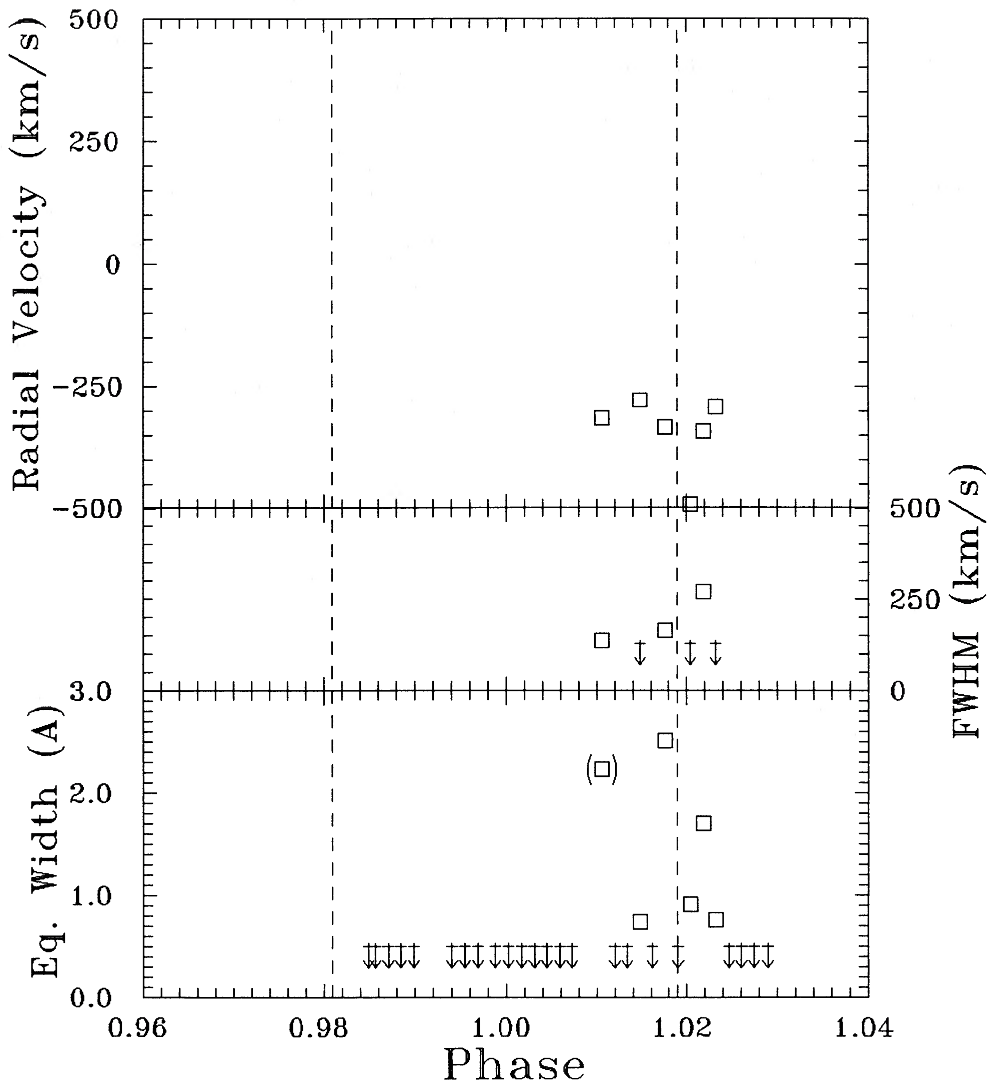

FIG. 10.—The equivalent width, FWHM, and radial velocity of the emission components observed during the 1982 November 16 eclipse. The filled symbols refer to the blueshifted component, and the arrows indicate detection limits. Symbols enclosed in parentheses are uncertain.

density of hydrogen atoms in the $n = 3$ state, A_{32} is the Einstein emission coefficient, V is the emitting volume, and L_* is the luminosity of the secondary star at Hα. Using the observed equivalent width and the flux of the G star from a model atmosphere grid, the mean value of n_3 was found to be ~ 20 cm^{-3}. With the assumptions of LTE, complete ionization, and the use of the Saha equation, the electron number density can be calculated from

$$\frac{n_e^2}{n_3} = 2.7 \times 10^{14} T^{3/2} \exp\left(\frac{-1.7 \times 10^4}{T}\right) .$$

For an assumed temperature of $\sim 10^4$ K this equation yields $n_e \sim 3 \times 10^{10}$ cm^{-3}. This is nearly the same density found by Crawford for U Cep (as expected) and close to the value found for the LDT of RW Tau by a very different method (Kaitchuck and Honeycutt 1982*b*). The above calculation is subject to numerous uncertainties but even an error of a few orders of magnitude will not change the basic conclusions to follow.

Olson *et al.* (1985) give the period change as $\Delta p/p = 1.9 \times 10^{-5}$. Using Olson's equation (1980*a*), this corresponds to $\Delta M = 2.5 \times 10^{-4}\ M_\odot$. The mass accretion rate can then be estimated by

$$\dot{M} = 4\pi R_p^2 n v_{\rm ff} m_{\rm H} ,$$

where n ($\sim n_e$) is the number density of hydrogen, $m_{\rm H}$ is the mass of a hydrogen atom, and $v_{\rm ff}$ is the mean free-fall velocity to the star from the disk. The free-fall assumption was used in order to get an upper limit to the accretion rate. The result is that $\dot{M} < 2 \times 10^{-16}\ M_\odot$ s^{-1}. At this rate the observed period change would require more than 4×10^4 yr instead of the observed less than 100 days. Clearly, the gas seen in the emission-line disks has very little to do with observed period changes. Because the stream penetration is thought to be responsible for the CTD, this still leaves open the question of the apparent lack of correlation of the abrupt period changes and photometric distortions. Perhaps these changes are brought about by extremely brief and strong bursts of mass transfer which to date have been missed.

The line emisssion is seldom a lot stronger than that reported in this paper. This implies that the vast majority of the transfered gas must be accreted by direct stream penetration of the star. The fraction of the matter which penetrates was estimated by considering the interaction of the star and the stream. Olson (1980*b*) calculated the penetration depth by equating the ram pressure in the stream to the local atmospheric pressure. We have done a similar calculation, but for a stream with a Gaussian density cross section (Lubow and Shu 1975). Because of this density gradient, the outer regions of the stream have a lower ram pressure and will not penetrate as deeply as the central stream. It was assumed that it is these outer stream layers that find their way into the LTD. Unfortunately, we do not know the critical penetration depth, beyond which the gas can no longer escape to the LTD. This critical depth was used as a parameter in the calculation and specified as an optical depth. The central stream density for U Cep as calculated from the Lubow and Shu (1973) model is given by

$$\rho_0 = 4.27 \times 10^{-28} \dot{M} \text{ g cm}^{-3} .$$

The location in the stream where the ram pressure equals the atmospheric pressure was calculated from

$$P_{\text{atm}}(\tau_{\text{crit}}) = 4.27 \times 10^{-28} v^2 \dot{M} \exp\left[-\frac{1}{2}\left(\frac{z}{\sigma}\right)^2\right],$$

where $P_{\text{atm}}(\tau_{\text{crit}})$ is the atmospheric pressure at the critical depth (dynes cm^2) taken from a model atmosphere grid, v is the impact velocity (cm s^{-1}), $\dot{M}$ is the accretion rate (g s^{-1}), z is the displacement from the stream center, and σ is the dispersion of the stream. Once the pressure was specified, the value of (z/σ) was calculated and the fraction of the stream, f, within $\pm(z/\sigma)$ was found.

This calculation was done for τ_{crit} from 0.001 to 10 and showed two interesting effects. First, except at the lowest accretion rates ($<10^{-9}\ M_\odot\ \text{yr}^{-1}$), the fraction of the stream that penetrated the star was always in excess of 99%. Second, as the mass accretion rate increases, the fraction of the mass going into the LTD, given by $\dot{M}(1-f)$, slowly decreases, making the gas accreted into the LTD a weak function of $\dot{M}$. This happens because increases in $\dot{M}$ are nearly compensated by decreases in $(1-f)$. For example, for a critical depth of $\tau = 10$, changing the accretion rate from 10^{-9} to $10^{-5}\ M_\odot\ \text{yr}^{-1}$ only changes the accretion rate into the LTD from 1.8×10^{-11} to $1.0 \times 10^{-11}\ M_\odot\ \text{yr}^{-1}$. This calculation does show a way to understand the observed weak correlation between the CTD and LTD. However, considering the simplistic nature of this calculation, and the expected complexity of the star/stream interaction, neither the predicted anticorrelation of the CTD and the LTD, nor the accretion rates into the LTD, should be taken too seriously.

The mass of the primary star is known and the disk radii have been measured directly, so it is possible to compare the Doppler velocity for a circular Keplerian disk with the observed velocities. The expected Keplerian velocity should be in excess of 450 km s^{-1} all through totality. Yet the observed velocities are typically below 350 km s^{-1}. As explained earlier, for an emission line which is rotationally broadened, there will

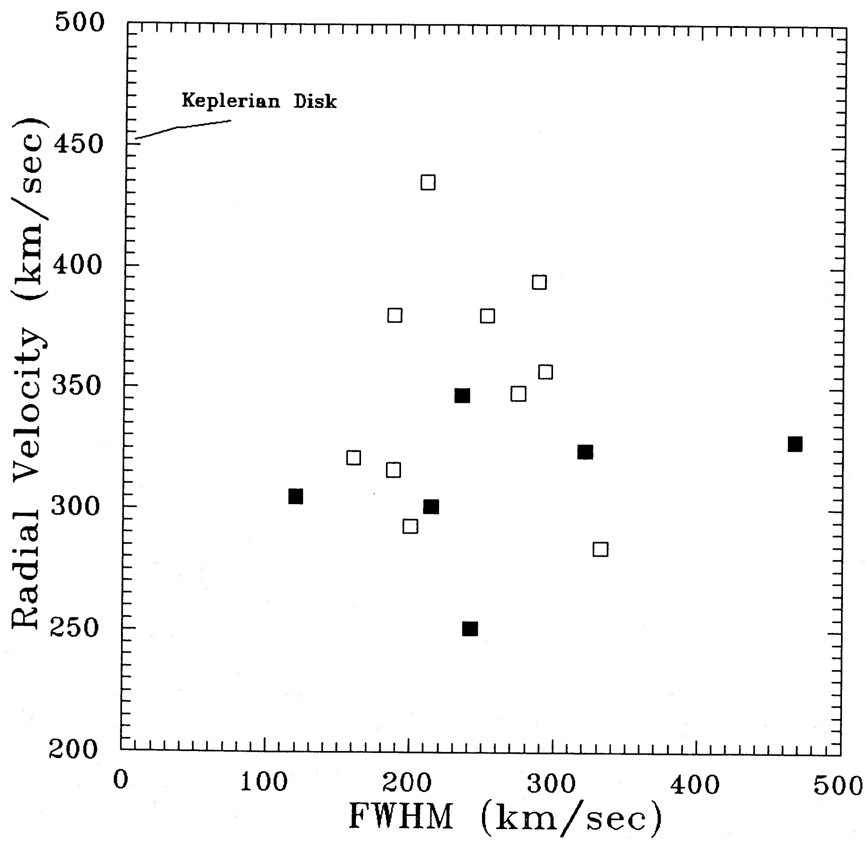

FIG. 11.—Emission-line radial velocity vs. line width during the U Cep eclipse of 1982 October 2. The filled and open symbols refer to the redshifted and blueshifted component, respectively. The curve shows the expected relationship for a circular Keplerian disk of the measured radius surrounding a star of the mass of the U Cep primary.

be a relationship between velocity and line width as the disk undergoes eclipse. Figure 11 shows the velocity versus line width for the Hα emission during the eclipse of October 2. In the upper left-hand corner is the expected curve for an optically thin circular Keplerian disk, adopting a disk radius of $1.5R_p$ and $M_p = 4.4\ M_\odot$ (Plavec 1983). (The differences in this curve between the optically thin and thick case are quite small.) The obvious conclusion is that velocities are lower and the lines are much broader than the Keplerian case. This confirms the findings of Crawford (1981) from the 1974–1975 outburst. Furthermore, Figure 11 gives little support to the notion that the lines are rotationally broadened because these data appear to form a scatter diagram. A similar scatter diagram was found for TZ Eri (Kaitchuck and Park 1988) and RY Gem (Kaitchuck 1988), and the same conclusions were reached for RW Tau (Kaitchuck and Honeycutt 1982*b*). There can be little doubt that U Cep belongs to the class of LTD binary systems.

IV. SUMMARY

One of the more interesting aspects of the data presented here is the time scale and extent of the changes in the structure of the circumstellar matter in the U Cep system. On September 17 the LTD was only on the leading side of the primary star while the CTD was only on the trailing side. After six orbital periods, on October 2, there was a well-developed LTD fully surrounding the central star. Six orbital periods later, there was a much smaller LTD and CTD of nearly the same radii. Within two orbital periods all line emission was gone but a CTD of approximately the same size was still present. After two more orbital periods, the LTD and CTD were both present again. In eight more orbital periods the structure had changed again so the LTD was only found on the leading side of the primary star. Clearly, the mass transfer process can produce a variety of rapidly changing accretion structures.

We fully confirm the findings of Crawford (1981) that in U Cep the velocity field is not that of a circular Keplerian disk and the emission lines are much broader than that expected for such a disk. Some other broadening mechanism, such as turbulence, must be operative. Both the CTD and the LTD have small radii. During this set of observations the radius of the CTD was remarkably constant at $1.2R_p$, while the LTD varied from 1.2 to $1.6R_p$ (0.53–$0.79R_{\rm Roche}$). This suggests that the LTD is larger on average than the CTD.

These observations show that, at best, there is a weak correlation between the presence of the CTD and the LTD. (However, these observations were made when both types of emission were weak and a stronger correlation might exist when the mass transfer rate is higher.) While both types of disk are the product of mass transfer, they may be produced in different ways. The photometric distortions are largely the product of the stream penetrating and depositing energy into the stellar interior, producing an elevated and cooler equatorial atmosphere. The origin of the rotating transient disk is unclear. Perhaps this is merely material from the less dense outer layers of the stream, which is "splashed" off the stellar surface by the stream impact, or perhaps it is elevated off the star by a turbulent atmosphere which results from the deposition of the stream energy in the star. Any model of its origin must ultimately confront its weak correlation to the ultraviolet excess.

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