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ULTRAVIOLET, OPTICAL, INFRARED, AND MICROWAVE OBSERVATIONS OF HR 5110

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ABSTRACT

HR 5110 is a close binary system ($P = 2^{d}.6$) which is viewed nearly pole-on ($i = 13°$). A comparison of the characteristics of Algol and RS CVn systems to those of HR 5110 shows that HR 5110 can also be considered an Algol system. Because the primary star is relatively cool (F2 IV) and there is no apparent emission from an accretion disk, we are able to detect in *IUE* spectra the emission of an active chromosphere and transition region of the cooler (K0 IV) secondary. HR 5110 is important because it is the only known Algol system for which the properties of the secondary star can be studied in detail. Velocity shifts of the ultraviolet emission lines relative to the absorption lines formed in the F2 IV star photosphere, which are measured in a short-wavelength high-dispersion spectrum obtained near quadrature, show unambiguously that the active chromosphere and transition region are located on the K0 IV star and not the F2 IV or an accretion disk around the F2 IV star. The surface fluxes of the UV emission lines of the K star are similar to those of active RS CVn binaries (HR 1099, UX Ari). The line fluxes appear to vary with orbital phase and are interpreted as emission from an active region on the K star moving across the line of sight. Two large radio flares were detected, but coordinated observations of the second flare in the UV and at the Ca II and Hα lines showed no detectable effect of the flare in these spectral regions 26 hr after the flare onset, during a time of continuing activity at radio wavelengths. VLBI observations during one of these flares indicated that half the emission came from a region more than 4 times the binary separation. The visual and near-infrared broad-band colors of HR 5110 are best matched with an F2 IV primary and a spotted K0 IV secondary.

Subject headings: stars: binaries — stars: individual — stars: radio radiation — ultraviolet: spectra

I. INTRODUCTION

The short-period spectroscopic binary HR 5110 (HD 118216 = BH CVn) presents a unique opportunity to study the similarities and differences between Algol and RS CVn variable stars. RS CVn binaries are detached systems having orbital and rotational periods generally less than 20 days and mass ratios close to unity (Hall 1981). They were first recognized as a (separate) class of objects distinct from Algols and other close binaries by Hall (1976) and are noted for unusually strong Ca II H and K emission, which arises in the active chromosphere of the cooler component. This intense activity is also observed in UV spectra taken with the *International Ultraviolet Explorer* (*IUE*) satellite in strong emission lines of ions from Mg II through N V; these lines are diagnostic of chromospheric and transition region (TR) plasmas ranging in temperature from about 10^4 K to 2×10^5 K. This enhanced activity is thought to be due to the rapid rotation of the cooler component (Ayres and Linsky 1980; Dupree 1981). Evidence for dark starspots on RS CVn stars is found in the wavelike distortion of their optical light curves (Eaton and Hall 1979; Rodonó 1983). They are also strong coronal X-ray emitters (Walter and Bowyer 1981) and undergo large radio and UV flares (Feldman *et al.* 1978).

Algol binaries, on the other hand, are semidetached systems whose mass ratios average about 0.2. Their more

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evolved but less massive member fills its Roche lobe. The general properties of 101 eclipsing Algol systems are summarized by Giuricin, Mardirossian, and Mezzetti (1983). Over 50% of the primary spectra are early A but do range from B through K. Relatively little is known about the secondaries except that the spectral classes in over two-thirds of the systems range from late G to early K. Spectra of the secondaries can be obtained during primary eclipse but emission from accretion disks or gas streams often dominates the stellar flux (Plavec 1983; Plavec, Weiland, and Koch 1982). These eclipse spectra show strong emission lines of C IV, N V, C II, Si IV–II, Al II–III, and Fe III and are qualitatively similar to spectra of RS CVn stars (except for the lack of He II emission). This emission has been attributed to accretion disks around the hotter stars based primarily on the decreasing strengths of the emission lines as the system proceeds toward totality during primary eclipse (Plavec 1983; Plavec, Weiland, and Koch 1982). Plavec argues that the absence of observed He II emission in Algol systems is consistent with a recombination spectrum formed at 10^5 K. In the case of AW Peg, Hα emission from the cooler K component has been attributed to an extended chromosphere (Plavec and Polidan 1976). Algols are soft X-ray sources with the emission appearing to come from a corona around the cooler component, but at flux levels 3 times lower (for a given rotation period) than RS CVn systems (White and Marshall 1983). Algols show sporadic radio outbursts (Hjellming, Webster, and Balick 1972) with characteristics similar to RS CVn binaries. The radio emission is probably associated with the secondary (Gibson 1980; Feldman and Kwok 1979). VLBI observations by Mutel *et al.* (1985) when HR 5110 was quite active indicated a source with angular diameter 0".0010 (FWHM), which is about twice the inferred angular diameter of the secondary (see below).

The most relevant characteristics of Algols and RS CVn systems are summarized in Table 1. The principal distinction between the two systems appears to be that the secondaries of Algols fill their Roche lobe whereas the RS CVn secondaries are detached. Many of the other differences may be outgrowths of this: in Algols, mass flow through the inner Lagrangian point produces the observed gas streams and accretion disks around the primary; eventually mass transfer to the less evolved component makes it the more massive member of the system (by a factor of 5 on the average) and produces undermassive K subgiant secondaries. As Popper and Ulrich (1977) pointed out, RS CVn stars appear to evolve from ordinary nonemission close binaries that develop their characteristics when the more massive star enters the Hertzsprung gap. With time, this primary swells and may fill its Roche lobe as it evolves across the H-R diagram. The second major distinction between Algol and RS CVn binaries is the fact that in RS CVn systems we are able to observe chromospheric and TR emission produced by the rapidly rotating, cooler, larger component. Spin-orbit synchronization does not allow these stars to dissipate their rotational angular momentum as they cross the Hertzsprung gap for the first time as is seen in single stars (Simon 1984).

The secondaries of short-period Algol systems are also in synchronous orbits and should, like RS CVn binaries, exhibit enhanced chromospheric and TR emission. This emission is best studied in the UV with *IUE*. However, in Algols, the UV spectrum is usually dominated by either the hot primary, an accretion source, or hot gas streams. Only when the primary is relatively cool and has a faint accretion disk, will we be able to study UV emission from an Algol secondary. This is the situation we observe for the nearby HR 5110 system but for no other known bright Algol system. According to Conti's (1967) analysis HR 5110 consists of an F2 IV primary and an evolved late-type secondary in a nearly pole-on ($i = 13°$) circular orbit (Lucy and Sweeney 1971) with a period of 2.61 days, a mean separation of 0.05 AU (about 10 $R_\odot$), and a mass ratio of 0.28. If we assume a mass of 1.5 $M_\odot$ for the F2 IV star, then the mass of the secondary is 0.43 $M_\odot$. Based on the separation of the components and the estimated spectral and luminosity class of the secondary (as long as it is not a dwarf), the secondary fills its Roche lobe of 2.6 $R_\odot$. Hence mass loss or transfer is the likely reason for making the current secondary the less massive component. From the statistics of Algol systems we find that F star primaries have early K secondaries with a mass in the range 0.2–0.4 $M_\odot$ as is found for HR 5110. This system was included by Hall (1976) in his list of RS CVn binaries based on the fact that strong Ca II emission is associated with the K secondary (Conti 1967), but it can also be described as an Algol system as a comparison of the characteristics of Table 1 show. Hence HR 5110 gives us the unusual opportunity of studying an Algol system in a nearby pole-on configuration. (Many noneclipsing Algols should exist, but they are difficult to detect.) HR 5110 does show a slight periodic photometric variation of 0.01 mag but no pronounced photometric wave

TABLE 1

COMPARISON OF RS CANIS VENATICORUM BINARIES, ALGOL SYSTEMS, AND HR 5110

Parameter	RS CVn	Algol	HR 5110
Mass ratio (secondary/primary)	≈ 1.0	≈ 0.2	0.28
Secondary fills Roche lobe	No	Yes	Yes
Typical inclination of orbit (degrees)	~ 60	~ 90	13
Evidence for mass streams	No	Yes	Maybe
Evidence for accretion disks	No	Yes	No
Evidence for active regions	Yes	No	Yes
Photometric wave	Yes	No	No
Typical spectral type of secondary stars	K0 IV	Early K	K0 IV
Typical mass of secondary ($M_\odot$)	~ 1	0.2–0.4	0.42
Typical spectral type of primary stars	G V	Early A	F2 IV
Flaring	Yes	Yes	Yes
Radio, X-ray emission	Yes	Yes	Yes
Ca II H + K emission	Yes	No	Yes
UV surface fluxes	High	High	High

(Hall *et al.* 1978). Since the decrease in magnitude coincides with conjunction at phase 0.0 (cooler star in front), Dorren and Guinan (1980) interpreted the variability as a reflection effect rather than rotational modulation due to dark starspots.

The ultraviolet spectrum (1200–2000 Å) of HR 5110 observed with *IUE* shows the strong emission lines typical of RS CVn binaries (interpreted as coming from chromospheres and TR around the cooler secondary) (Simon, Linsky, and Schiffer 1980*a*, *b*); but the spectrum also resembles spectra observed during the primary eclipse of Algol (W Serpentis) systems (interpreted as coming from accretion disks around the hotter primary) (Plavec 1983; Plavec, Weiland, and Koch 1982). Hence it is essential to pinpoint the location of the UV emission of HR 5110 in order to interpret the system correctly. HR 5110 is also a soft X-ray source with an X-ray luminosity of 1.3×10^{31} ergs cm^{-2} s^{-1} (Walter and Bowyer 1981), which is more typical of the higher X-ray luminosity of RS CVn stars rather than Algols (White and Marshall 1983). HR 5110 has also been detected as a flaring and nonflaring radio source. A recent reanalysis of the orbit (Bonsack and Simon 1983; Lyons, Bolton, and Fraquelli 1984) indicates a slight period change and/or a phase shift of about 0.1 phase relative to the previous analysis of Conti (1967). We found a similar shift in analyzing Ca II K line region from CCD spectral data kindly made available to us by F. Walter.

II. INFRARED OBSERVATIONS

An interpretation of HR 5110 depends critically on knowing the spectral type and luminosity class of the two stars in the system. Line surface fluxes (to be compared to RS CVn binaries) can be calculated if the sizes of the components (as estimated from the spectral information) are known. The primary was classified as F2 IV by Slettebak (1955) and F5 III by Cowley (1976). From the visual colors of the system, Conti (1967) estimated that the secondary is an evolved K star and that the difference in V magnitude between the components is 2.5 mag. Dickens and Penny (1971) determined $\theta(=5040/T) = 0.76$ and $\log g = 3.8$ from fitting model atmospheres to the continuum energy distribution of HR 5110. Their surface gravity would be more in line with a luminosity classification of IV or III–IV rather than Cowley's luminosity classification.

To estimate the spectral type and luminosity class of the secondary we obtained near-infrared *JHKLM* photometry of HR 5110 on the 1.3 m telescope of the Kitt Peak National Observatory in 1980 February and June and also 1981 May. HR 5110 was measured with respect to the standard stars used by Castor and Simon (1983), on magnitude scales whose zero points were defined by the primary standard α Lyrae. There was no clear evidence, even at the longest wavelength, for any photometric wave above observational uncertainties (e.g., ± 0.03 mag at M). An infrared photometric wave has been observed by M. Zeilik (private communication). We have derived a best fit of the combined colors for different types of primaries (F2 V, F2 IV, F5 IV, F5 III, G0 V) and secondaries (G5 IV, G8 IV, K0 IV, K1 IV) to the observed colors of HR 5110. Our photometry is listed in Table 2A.

Line doubling is present at Li I 6707 Å (M. Tripicco and F. Fekel, private communication), so the model derived from fitting the colors should give a reasonable small V magnitude difference for the primary and secondary components, i.e., $V_s - V_p \lesssim 2.5$ mag. Following Conti (1967, eq. [2]) we calculate the flux f (normalized to V) of the system at any wavelength according to $f = \alpha f_p + (1 - \alpha) f_s$, where $f_{p,s}$ is the normalized flux of the primary and secondary, respectively. The factor α is given by $\alpha = r(r+1)^{-1}$, where r is the ratio of the brightness in the V band of the primary to the secondary. The value of α, or equivalently r, is not known *a priori* but is calculated from spectral fitting. The value of α is obtained from a least-squares fit to the observed flux f of HR 5110, starting from the assumed colors and hence normalized fluxes f_p and f_s at each wavelength. That is, we take

$$\alpha = \frac{\sum_i (f - f_s)_i (f_p - f_s)_i}{\sum_i (f_p - f_s)_i^2} ,$$

where the sum is carried out over filter bands other than V. In practice we usually summed over (1) R and I, or (2) J, H, K, and L in order to derive a best fit to these particular wavelength regions. Tables 2A and 2B summarize the derived colors for HR 5110, for several primaries and secondaries, and for the most relevant models. For each model we list the value of α (and the filters used for its derivation), the standard deviation σ of the fit, and the V magnitude difference between the secondary and primary, $V_s - V_p$.

Our final models were calculated with σ Boo (F2 V) as primary. Its IR photometry is better established than that of the standard F2 IV star of Johnson *et al.* (1966) and the fit to the IR region is most critical for determining the characteristics of the secondary. As can be seen (Table 2A), σ Boo is photometrically similar to an F2 IV star. The best fit to the photometry of HR 5110 is obtained for an F2 IV (σ Boo) + K0 IV model. Fitting the R and I colors gives an IR excess of ~0.2 mag at both L and M'. On the other hand, fitting the $J-L$ colors produces a deficit of ~0.05–0.1 mag at I, which seems large considering the small statistical errors of the photometry. Figure 1 shows the residuals $(O-C)$ of these models as open circles (to fit R and I) and as triangles (to fit $J-L$). The range of residuals produced by combining different secondaries (G5 IV, G8 IV, K1 IV, as listed in Table 2B) with σ Boo as primary is indicated by the hatched areas. The $J-L$ colors cannot be fitted with a G5 IV secondary. Using an F5 IV or F5 III primary gave the same general trends except that the residuals were larger. The result of our spectral synthesis is in agreement with the statistics found for Algol systems by Guiricin, Mardirossian, and Mezzetti (1983): every F primary has a K secondary.

According to our first solution (col. [2] of Table 2B), HR 5110 has an IR excess which could be due to intrasystem material. To interpret the IR excess, we assume an absolute flux calibration and plot this excess against λ. The excess from J to M' is fairly well matched with a blackbody curve of 3100 K and therefore is too hot to be produced by dust and has the wrong wavelength dependence to be produced by free-free emission. We believe the IR excess can be explained if the colors of the secondary itself are composite because it is heavily spotted. Assuming a weighting factor A for the spot coverage on the secondary, and a temperature of about 3100 K for the spots (Vogt 1983), we recalculated the combined flux f of the system for an F2 IV primary and spotted K0 IV secondary from $f = \alpha f_p + (1-\alpha)[(1-A) f_{sq} + A f_{ss}]$, where $f_{sq,ss}$ is the normalized flux of the quiet photosphere and the spotted area of the secondary, respectively. For f_{sq} we used the colors corresponding to K0 IV and for f_{ss} we used the average of the colors of the M3 III and M5 V standard stars (Johnson *et al.* 1966). However, the colors of the M filter are not very reliable. The best fit to the observed flux for $\alpha = 0.85$ is produced with

TABLE 2A

SPECTRAL SYNTHESIS FOR HR 5110

Color	HR 5110 Observed	F2 IV Standard	σ Boo F2 V	48 Gem F5 IV	β Com G0 V	μ Her A G5 IV	β Aql G8 IV	η Ser K0 IV	κ CrB K1 IV
$U-V$	0.45[a]	0.39[a]	0.29[b]	0.45[a]	0.66[a]	1.14[a]	1.35[a]	1.59[a]	1.87[a]
$B-V$	0.41[b]	0.29[a]	0.36[b]	0.36[a]	0.58[b]	0.74[b]	0.86[a]	0.94[a]	1.00[a]
V	4.96[b]	0.00	4.48[b]	5.85[a]	4.25[b]	3.42[b]	3.71[a]	3.25[a]	4.82[a]
$V-R$	0.41[b]	0.35[a]	0.34[b]	0.43[a]	0.45[b]	0.55[b]	0.66[a]	0.70[a]	0.76[a]
$V-I$	0.69[b]	0.55[a]	0.57[b]	0.68[a]	0.76[b]	0.90[b]	1.15[a]	1.20[a]	1.25[a]
$V-J$	1.03	0.68[a]	0.76	0.77	1.09	1.28	1.53	1.68	1.75
$V-H$	1.35	0.83[c]	0.95	0.94	1.36	1.60	1.99	2.17	2.24
$V-K$	1.43	0.93[a]	0.98	1.00	1.40	1.67	2.07	2.25	2.33
$V-L$	1.49	1.07[a]	1.00	1.02	1.44	1.66	2.06	2.29	2.38
$V-M'$	1.52	0.93?[a]	1.05	1.12	1.43	1.61	1.99	2.19	2.27

NOTE.—Colors from this paper unless otherwise indicated; units are mag throughout.
[a] Johnson *et al.* 1966; Johnson 1966.
[b] Moffett and Barnes 1979.
[c] Calibration for H taken from Koorneef 1983.

TABLE 2B

SPECTRAL SYNTHESIS FOR HR 5110

Parameter (1)	σ Boo + η Ser (F2 V + K0 IV) (2)	σ Boo + η Ser (F2 V + K0 IV) (3)	48 Gem + η Ser (F5 IV + K0 IV) (4)	48 Gem + β Com (F5 IV + G0 V) (5)	σ Boo + η Ser + spot (F2 V + K0 IV + spot) (6)
$U-V$	0.41	0.47	0.63	0.48	0.41
$B-V$	0.43	0.46	0.47	0.39	0.43
V	0.00	0.00	0.00	0.00	0.00
$V-R$	0.40	0.43	0.50	0.43	0.41
$V-I$	0.69	0.75	0.82	0.70	0.74
$V-J$	0.96	1.04	1.06	0.84	1.03
$V-H$	1.25	1.36	1.37	1.02	...
$V-K$	1.29	1.41	1.44	1.08	1.42
$V-L$	1.32	1.44	1.47	1.11	1.49
$V-M'$	1.32	1.42	1.48	1.17	1.44
α	0.84	0.78	0.77	0.83	0.85
Filters[a]	*R, I*	*J, H, K, L*	*J, H, K, L, M*	*B, I*	*R, I*
σ	0.11	0.05	0.09	0.24	0.04
$V_s - V_p$ (mag).....	1.80	1.37	1.31	1.67	1.88
a_s	...	..	...	...	0.35–0.40

[a] The value of α is derived by fitting the predicted and observed fluxes of the listed filter bands.

$A = 0.025$ (see Fig. 1 and Table 2B), but there remains a flux deficit at I of ~0.05 mag. The weighting factor A of 0.025 corresponds to a spot filling factor a_s of 0.35–0.40 for an estimated flux contrast ratio c_s between spot and quiet photosphere of 20–25. The contrast ratio is estimated from the assumed spot and photospheric temperatures; then $a_s = Ac_s(1 - A + Ac_s)^{-1}$.

It is important to match the absolute magnitudes (M_v) deduced for the components with what is expected from evolutionary considerations. We derived M_v's for two assumed values of the parallax π considered by Conti (1967), 0".019 and 0".027. The π of 0".027 forces the primary onto the post–main-sequence evolutionary track for a 1.5 $M_\odot$ star, while a π of 0".019 places HR 5110 closer to the 2 $M_\odot$ track. The locus of possible secondaries is close to the 1.0 $M_\odot$ track for $\pi = 0''.027$. Thus if $M_s = 0.4\ M_\odot$, the secondary is overluminous for its mass.

Shore and Adleman (1984) have suggested that the components of HR 5110 are F5 IV + G0 V, based on a comparison with the composite spectral energy distribution between 4000 Å and 11000 Å of β Com (G0 V) and 48 Gem (F5 IV). We disagree with their conclusion. First, their model is incompatible with the observed near-IR infrared colors of the system (Table 2B). A least-squares fit to the B, V, R, and I data gives an IR excess of ~0.4 mag at L and M' and a V magnitude difference of 1.67. This is less than the V magnitude difference between a G0 V and a F5 IV star of 2.1 star cited by Allen (1981). Second, if we assume a mass of 1.1 $M_\odot$ for their G0 V secondary, then the known mass ratio would imply a mass of ~4 $M_\odot$ for their F5 IV primary, which is larger by a factor of ~2 than expected for a typical F5 IV star. In conclusion, an F2 IV + K0 IV system is a better match to the observed broadband colors of HR 5110 than Shore's and Adelman's choice of F5 IV + G0 V. In fact, except for the U and B colors, the colors of β Com itself match those of HR 5110 quite well, but no combination of a G0 V secondary with any F primary matches HR 5110 over the entire spectral range. The observed line doubling near 6700 Å eliminates any dwarf cooler than G2 as a candidate for the secondary of HR 5110.

Adopting a spotted K0 IV star for the secondary, we obtain from the Barnes-Evans relationship (Barnes and Evans 1976) between color, visual magnitude, and angular diameter, an angular diameter of 0.47 mag if $V-R = 0.70$ (see Table 2A) and $V_s = 7.1$, corresponding to $V_s - V_p = 1.88$. This diameter yields a radius of 1.9–2.7 $R_\odot$ for a parallax of $0''.027 \gtrsim \pi \gtrsim 0''.019$. Hence, we conclude that the secondary fills its Roche

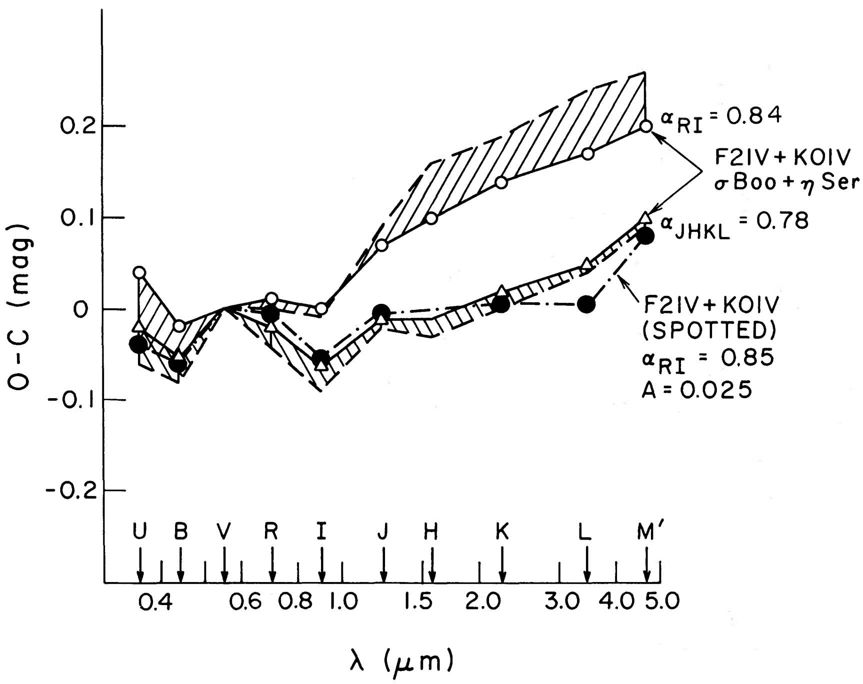

FIG. 1.—The residuals (observed − computed colors) of HR 5110 as compared to an F2 IV + K0 IV system. Open circles show the fit if the *R* and *I* colors are matched; triangles show the fit to *J*, *H*, *K*, and *L* colors, and filled circles show the fit for an F2 IV + spotted K0 IV secondary with a filling factor $\alpha_s = 0.25$. The hatched areas indicate the range in residuals for F2 IV + (G5 IV or G8 IV or K IV secondary).

lobe radius of 2.6 $R_\odot$ calculated from the mass ratio and the separation of the stars, as originally suggested by Conti (1967).

III. RADIO OBSERVATIONS

HR 5110 was detected during two major radio flaring events, and also detected by VLBI techniques. The first major flare was observed from the Algonquin Observatory (Feldman 1979) on 1979 May 29 (8:26 UT) with a measured flux at 10.46 GHz of 425 mJy. Flaring continued over the next 2 days at the 200–350 mJy level. The second flare (Feldman 1981) was similar to the first. On 1981 April 4 the system was observed at a flux level of 240 mJy. A larger outburst at the 350–410 mJy level occurred on 1981 April 5 starting at 6:30 UT and lasted for about 4 hr. Flaring continued at the 150–200 mJy level for the next several days (Feldman 1983). These radio outbursts are probably due to gyrosynchrotron emission from mildly relativistic electrons (Owen, Jones, and Gibson 1976; Lestrade *et al.* 1984). Figure 2 shows the radio light curve for the second flare together with the times of coordinated VLBI, *IUE*, Ca II, and Hα observations. While these other observations were made 1–2 days after the major outburst, radio activity continued at the time of these observations.

On 1981 April 6 we observed HR 5110 at 5.0 GHz (6 cm) in left-hand circular polarization using the Mark III VLBI System with 56 MHz bandwidth. The stations used were the OVRO 130 foot (40 m) and the NRAO 140 foot (43 m) telescopes. At 03:50 UT we obtained a 10 minute correlated scan for HR 5110, followed by a 3 minute scan on the unresolved (D. Shaffer, private communication) VLBI calibration source 0552+398. Reductions of this one-baseline VLBI "snapshot" indicate that the fringe-visibility amplitude was 0.53 ± 0.05 at fringe spacing of 3.7 mas. This implies that during the later (plateau) phase of the outburst about half of the radio emission arose from a region greater than 3.7 mas in size ($= 2.7 \times 10^{12}$ cm $= 0.17$ AU $= 40\ R_\odot$ for an assumed distance of 45 pc) which was characterized by a brightness temperature $T_B > 3 \times 10^8$ K. This source region is at least 4 times the separation of the components and accordingly, at this stage in the evolution of the flare, gyrosynchrotron emission comes from a region which is not limited to the confines of either stellar component or to the binary as a whole. During a smaller flare (1982 December 19) Lestrade *et al.* (1984) detected a source of maximum size 1.4 mas using a four-element Mark III VLBI network at 8.4 GHz, and during another smaller flare (1983 July 26/27) Mutel *et al.* (1985) detected a source of size 1.0 mas using a six-element Mark III VLBI network at 5.0 GHz. In these cases the flare region was comparable to or smaller than the size of the binary system and $T_B \approx 2 \times 10^{10}$ K. These VLBI observations of three flares on HR 5110 are consistent with the hypothesis that the flux tubes responsible for the flare emission expand and the electrons lose energy with time.

IV. Ca II AND Hα EMISSION

After being notified by P. Feldman of the occurrence of the 1981 April flare, we obtained 6.5 Å mm^{-1} (taken at DAO) and 8 Å mm^{-1} (taken at DDO) spectra of the Ca II region starting about 21 hr and 47 hr, respectively, after the onset of the major radio burst and continuing for the next two weeks at DDO. The Ca II emission at this later (plateau) stage of the flare does not show any evidence of flare induced activity. The intensity of the Ca II emission at other times is known to vary by a factor of 3–4 (Conti 1967) and was confirmed by visual inspection of other spectra kindly loaned to us by P. Conti. Whether or not these variations are accompanied by other (unobserved) radio flares is unknown. Hα spectra obtained at DDO at 16 Å mm^{-1}, starting at about 5 UT on April 7 and continuing for the next two weeks, also showed normal, variable, weak emission in the Hα profile. The Hα emission is variable in both

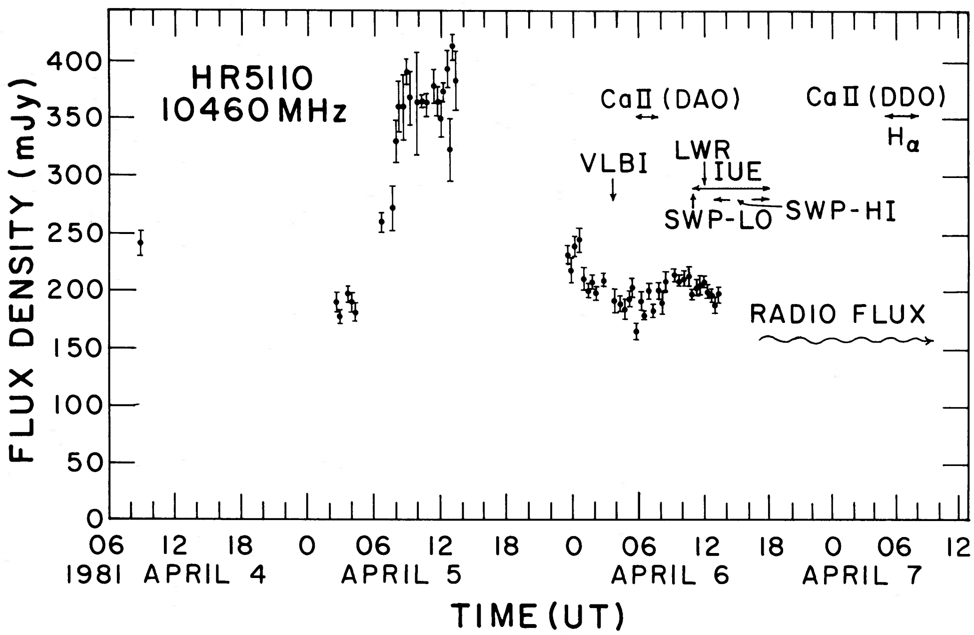

FIG. 2.—The radio light curve of HR 5110 during and immediately following the 1981 April 5 flare (Feldman 1983). The time line of spectroscopy of the Ca II region at DAO and DDO, of the Hα region at DDO, of the UV region with *IUE*, and the time of the VLBI observation are indicated during the later "plateau" phase of the flare.

mean wavelength and intensity but does not appear to be well correlated in velocity with either binary component or to show any effect from flaring. The emission may be due to permanent intrasystem material (Fraquelli 1981; Bopp 1983), but the large mass motions deduced from Hα observations in Algol-type systems are not evident in HR 5110.

In conclusion, we find no increase in emission in Hα, Ca II H and K, and the UV (see § V) from enhanced chromospheric and TR activity about 20 hr after the onset of a major radio outburst, although the radio emission was still greatly enhanced.

V. *IUE* OBSERVATIONS

We obtained *IUE* spectra during the latter (plateau) phases of both radio outbursts, roughly 56 hr after the first major event and 26 hr after the second. We also observed HR 5110 in 1980 February and in 1983 August. An analysis of the data associated with the first flare was reported by Simon, Linsky, and Schiffer (1980*b*). A search through the *IUE* archives yielded two additional spectra presumably taken when the system was quiescent. The observational data for the four SWP low-dispersion spectrum (1200–2000 Å at ~6 Å resolution), the five LWR high-dispersion spectra (2000–3200 Å at ~0.2 Å resolution) and one SWP high-dispersion spectrum (1200–2000 Å at ~0.2 Å resolution) are summarized in Table 3. The phases were calculated from an ephemeris having an epoch of JD 2,445,079.478 and period of 2.61328 days, obtained from the reanalysis of the orbit by Lyons, Bolton and Fraquelli (1984); we have adjusted the epoch so that an orbital phase of 0.0 corresponds to conjunction (K0 star in front) rather than to quadrature (with the secondary at maximum velocity of approach) as in their analysis.

The spectra were calibrated in absolute flux units at Earth using standard *IUE* calibration factors. The latest Intensity

TABLE 3
IUE OBSERVATIONAL DATA FOR HR 5110

Image Number	Dispersion	Date	Time (UT) (hr/minutes/s)	Orbital Phase[a] ϕ	Exposure Time (minutes)	Comment[b]
SWP 5415	Low	1979 May 31	15:56:21	0.56	30	1
LWR 4652	High	1979 May 31	17:47:25	0.58	10	1
LWR 6333	High	1979 Dec 7	17:17:32	0.67	15	
SWP 7344	Low	1979 Dec 7	17:49:40	0.68	35	
LWR 6838	High	1980 Feb 1	5:31:01	0.52	10	
SWP 7834	Low	1980 Feb 1	5:53:48	0.53	25	
LWR 10297	High	1981 Apr 6	11:40:31	0.17	10	2
SWP 13668	Low	1981 Apr 6	11:06:07	0.16	25	2
SWP 13669	High	1981 Apr 6	17:53:33	0.27	378	2
LWP 16548	High	1983 Aug 8	8:36:00	0.91	10	

[a] Based on ephemeris JD = 2,445,079.478 + 2.61328 ϕ, where ϕ = 0.0 corresponds to conjunction with the K0 IV star in front.
[b] COMMENTS.—(1) Flare: 1979 May 29, 8:26 UT. (2) Flare: 1981 Apr 5, 6:30 UT.

TABLE 4

INTEGRATED EMISSION-LINE FLUX FOR HR 5110 AT EARTH ($\times 10^{-12}$ ergs cm^{-2} s^{-1})

Image Number	Phase	N V λ1240	O I λ1305	C II λ1335	Si IV λ1400	C IV λ1549	He II λ1640	Continuum[a] 1560–1630 Å	Mg II *k* λ2796	Comments
SWP 13668	0.16	0.32	0.69	0.87	0.79	1.87	0.57	0.19	...	Flare
LWR 10297.........	0.17	...	...	...	...	...	...	...	13.0	Flare
LWR 6838..........	0.52	...	...	...	...	...	...	...	17.1	
SWP 7834	0.53	0.75	1.75	1.67	1.23	2.63	1.30	0.20	...	
SWP 5415	0.56	0.35	1.61	1.53	1.15	2.56	1.17	0.25	...	Flare
LWR 4652..........	0.58	...	...	...	...	...	...	...	15.3	Flare
LWR 6333..........	0.67	...	...	...	...	...	...	...	13.7	
SWP 7344	0.68	0.30	0.81	0.83	0.61	1.23	0.66	0.19	...	
LWR 16548.........	0.91	...	...	...	...	...	...	...	12.4	
SWP 7834 / SWP 13668	0.53 / 0.16	2.3	2.5	1.9	1.6	1.4	2.3	1.09	...	To show flux variation at different phases
LWR 6838 / LWR 10297	0.52 / 0.17	...	...	...	...	...	...	...	1.3	

[a] Average continuum flux level in units of 10^{-12} ergs cm^{-2} s^{-1} Å^{-1}.

Transfer Function was applied to SWP 5415 with computer programs at the *IUE* Regional Data Analysis Facility at the University of Colorado. The SWP spectra are saturated longward of 1700 Å due to the rapidly rising photospheric continuum of the F2 IV primary. We measured the integrated flux at Earth of the emission lines of N V, C IV, Si IV, He II, C II, and O I in the low-dispersion spectra. The integrated flux of the Mg II lines was also measured in the LWR high-dispersion spectra. No other emission lines could be identified in the LWR spectra. The Fe II (multiplet UV1) lines near 2600 Å as well as Si II (1804 Å), Si I (1903 Å), and C III (1909 Å) appear in absorption, indicating that the F primary dominates the spectrum in these regions. We also measured the mean continuum level of the primary between 1560 Å and 1620 Å. These fluxes are summarized in Table 4 and are plotted as a function of time in Figure 3.

The fluxes vary by about a factor of 2 in unison during this time interval, but maximum flux in the lines does not uniquely correspond to the times of flares unless an unobserved flare also occurred on 1980 February 1. Although the continuum was brighter after the first flare than at other times, the continuum was not enhanced after the second flare, when the *IUE* observations were made a day closer to the peak of the radio outburst.

Figure 4 compares the two SWP spectra taken after these two flares. The increase in brightness of the continuum in SWP 5415 is clearly evident. Since the continuum arises from the F star, it is likely that this new emission also arises from the primary. It is unclear why excess emission is visible after the first flare but not after the second. Since the two spectra were taken at different phases, the excess may be unrelated to the flare mechanism. We conclude that the radio flares produced no discernible effect on the intensity of the lines and that the changes we observe are normal variations in the activity of the system. A similar conclusion was reached by Simon, Linsky, and Schiffer (1980*b*) from their earlier analysis of the data associated with the first flare.

By contrast, *IUE* spectra of a flare on UX Ari also taken 26 hr after the initial detection of radio flaring showed a factor of 5.5 enhancement of the UV line strengths (Simon, Linsky, and Schiffer 1980*a*). Simon, Linsky, and Schiffer suggested that the mechanism for producing flares in these two systems might be quite different. Magnetic field annihilation of interacting coronal loops may be the energy source for the UX Ari flare, whereas the flare on HR 5110 may be produced by mass trans-

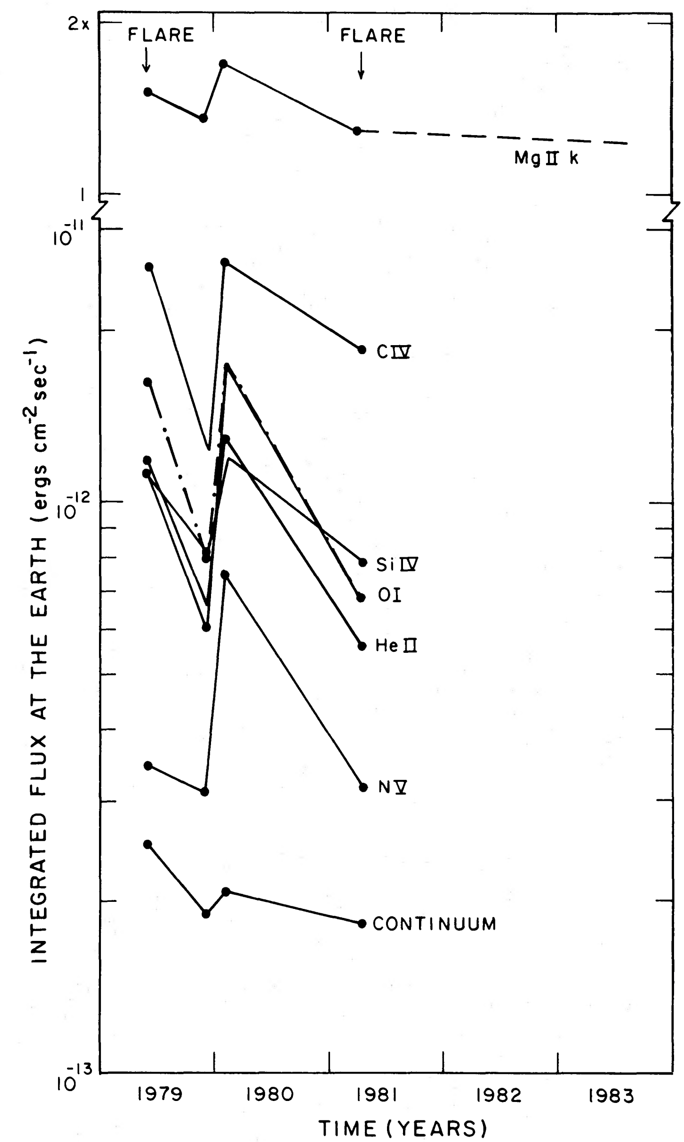

FIG. 3.—The integrated UV emission line flux received at Earth from HR 5110 as a function of time. The occurrences of the two radio flares are indicated with arrows. The continuum flux is the average flux measured in the region 1560–1620 Å.

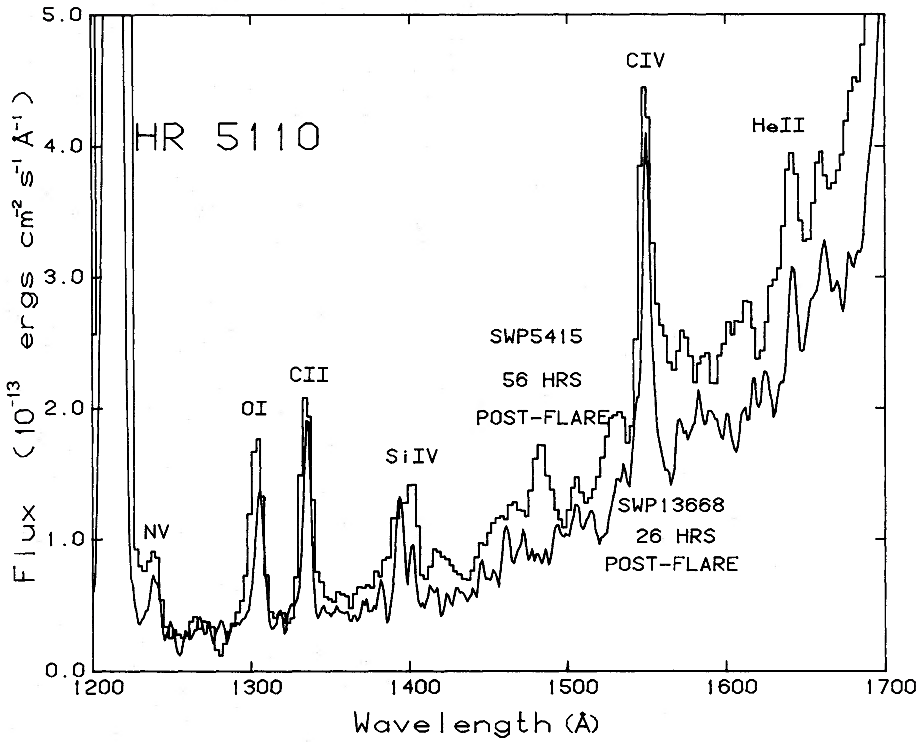

FIG. 4.—A comparison of short-wavelength, low-dispersion spectra of HR 5110 taken within 56 hr after the 1979 flare (SWP 5415 plotted as a histogram) and within 26 hr after the 1981 flare (SWP 13668). The much higher level of the continuum after the 1979 flare is clearly visible.

fer from the secondary to the primary star through the inner Lagrangian point. The expected asymmetry of the ultraviolet lines due to mass motions was not observed in HR 5110 during the second flare, but this flare occurred near quadrature when mass flow through the inner Lagrangian point would be primarily across our line of sight.

VI. DISCUSSION

a) *Modulation of the UV Emission*

Unless an unobserved flare occurred in 1981 February, our *IUE* data do appear to show correlations with phase (Fig. 5) with maximum flux occurring near phase of 0.5, i.e., when we observed the side of the secondary star that faces the F star in this nearly pole-on system. This result is very tentative as it is based on four sets of spectra taken over a time period of 4 yr. The fluxes in all the lines vary in unison by roughly a factor of 2 except for the Mg II *k* lines which varies by a factor of about 1.3.

To understand and model the variations in the emission correctly we must determine which star has the activity associated with it. Conti (1967) showed that the radial velocity variations of the Ca II emission are out of phase with those of the F star. This emission therefore defines the orbit of the secondary star. To establish from which star the *upper* chromospheric and TR emission originate, we analyzed a high-dispersion short-wavelength spectrum SWP 13669 taken near quadrature centered on phase 0.27. Although this spectrum is underexposed shortward of 1600 Å, it does show the He II, C IV, C II lines and, very weakly, the O I and Si IV lines in emission. Since the absolute wavelength calibration of the spectrum is uncertain owing to possible thermal flexing of the spectrograph (Leckrone 1980; Turnrose, Thompson and Bohlin 1982) and no platinum lamp spectrum was taken for wavelength calibration at the time, we determined the shift in wavelength of the emission lines relative to the photospheric absorption lines of the F star by aligning the absorption lines of HR 5110 with those of Procyon (F5 IV–V). The two photospheric spectra match very well. Measuring next the wavelengths of the emission lines of HR 5110 relative to those of Procyon as a template, we determined an average velocity difference of $+40 \pm 10$ km s^{-1}. At phase 0.27 the difference in radial velocity between the secondary and primary in HR 5110 is about $+45$ km s^{-1}, in agreement with the velocity of the emission lines. We therefore conclude that the TR and chromospheric plasmas observed in the UV are located on the secondary star. The measured absolute velocity shifts of the emission lines, corrected for orbital motion of Earth and the spacecraft gave similar results. Hence this analysis shows unambiguously that the active chromosphere and TR phenomena in HR 5110 are located on the cooler K0 IV star and are not associated with the F star or with an accretion disk around the F star as in Algol systems. No emission lines are at the velocity of the F star.

Ayres, Marstad, and Linsky (1981) estimated the difference in the flux in the UV emission lines between a "moderately active" Sun and a quiet Sun to be about a factor of 2. We interpret the variation in intensity of the lines of HR 5110 as being due to the rotation of a near equatorial ($< \pm 13°$) magnetic active region (plage) into and out of our line of sight. The latest Mg II spectrum (LWP 16548 obtained at phase 0.91) gives a flux slightly lower than that observed three years earlier at phase 0.67. This point would not add significantly to Figure 5 and has not been included. Complete phase coverage during one or more cycles would be needed to develop a definitive model of the active longitude and latitude. The reflection effect

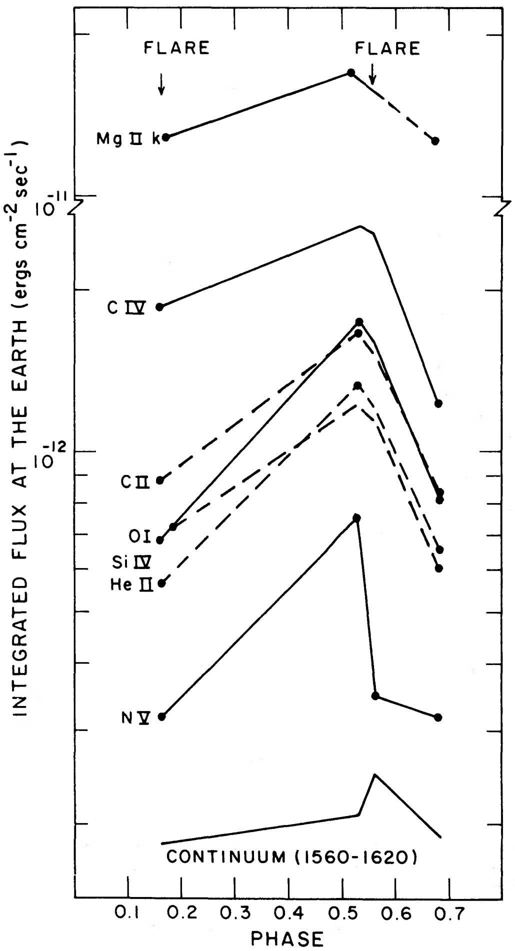

FIG. 5.—The integrated emission-line fluxes of various lines received at Earth from HR 5110 as a function of phase. All lines (except Mg II) vary in unison by roughly the same factor with maximum emission occurring at phase 0.52.

(Hall *et al.* 1978) increases the photospheric temperature on the side of the K star that is facing the F star but should not increase the amount of flux emitted by the chromospheric and TR lines.

The variation of the UV continuum presents an enigma. It shows a 40% increase at phase 0.56 after the first flare relative to phase 0.17 or 0.67, but no increase after the second flare. Only a moderate increase of about 15% was observed at phase 0.52 when the emission lines reached peak brightness. Thus more data are needed in order to disentangle possible phase- from flare-related variations of the continuum.

The behavior of the Mg II *h* and *k* emission lines is more difficult to interpret. Figure 6 shows the Mg II *h* and *k* emission line profiles arranged in order of increasing phase. The shape of both Mg II lines changes dramatically with phase from emission primarily on the red side (red asymmetry) at phase 0.17 to emission primarily on the blue side (blue asymmetry) at phases 0.66 and 0.67. We interpret this as the effect of the relative motion of the stellar Mg II emission line across a stationary interstellar absorption line. Similar changes have been seen in the Mg II profiles of Capella (Ayres, Schiffer, and Linsky 1983). The velocities of the HR 5110 emission peaks relative to the interstellar feature are roughly in agreement with an orbital velocity variation of 50 km s^{-1} expected for the secondary between phase 0.17 and 0.67 (the velocity variation predicted from Conti's orbit is about 70 km s^{-1}). Therefore, like the Ca II lines, the Mg II emission appears to be formed on the secondary star. The Mg II flux varies by a factor of 1.3 between phases close to quadrature and conjunction. On the other hand, the velocity variation of the center of emission (the midpoint at FWHM) relative to the interstellar line is only about 15 ± 10 km s^{-1}, i.e., about one-third of the variation of the emission peak, but in the same sense as the peak variations. We interpret this as an interaction of three phenomena: (*a*) the orbital variation of about 70 km s^{-1} of a relatively narrow Mg II emission peak arising from the secondary star, (*b*) the orbital variation of about 18 km s^{-1} of a broader Mg II emission peak arising

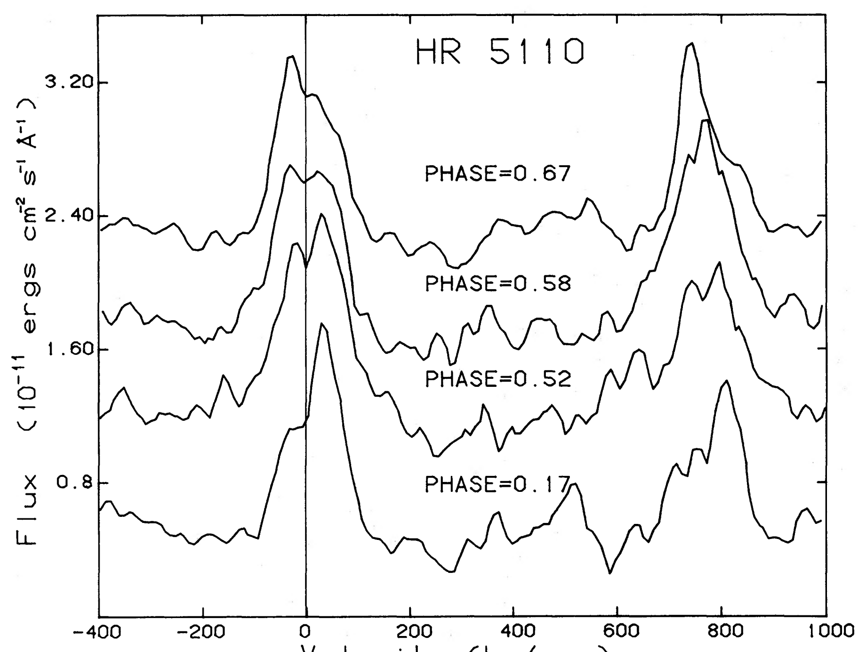

FIG. 6.—The Mg II *h* and *k* profiles at different phases. The profiles have been aligned on the interstellar absorption feature of Mg II *k*. Each profile except for phase 0.17 has been shifted vertically by 6×10^{-12} flux units.

from the primary, and (*c*) the interstellar absorption feature with which these two emission peaks are blended. The width of the Mg II emission from the primary star must be roughly 3 times the width of the secondary's line in order not to produce an asymmetry in the base of the blended line profile near quadrature. The analysis of the Mg II lines is further complicated by the fact that the widths of the lines (defined as the full width at three-fourths maximum flux) vary from 1.4 Å at quadrature to 2.0 Å near conjunction. This cannot be due to the orbital velocity variation, since that would produce the greatest width at quadrature. A possible interpretation is that this larger width is caused by streaming of material from the secondary to the primary star through the inner Lagrangian point. At quadrature this flow would be primarily across our line of sight and hence would produce no additional broadening, whereas near conjunction the motion is partly along the line of sight. The minimum velocity along the line of sight inferred from the increase in width is about 65 km s^{-1}, which corresponds to a stream velocity of 300 km s^{-1} (assuming $i = 13°$). The lines even near conjunction are fairly symmetric implying that the stream has a relatively large angular size.

b) *Activity Levels*

Table 5 lists the average surface line fluxes for the quiet Sun, HR 5110, UX Ari, and HR 1099 on the assumption that all the flux in the binaries originates on their cooler components. UX Ari ($P = 6^{d}.4$; K0 IV + G5 V) and HR 1099 ($P = 2^{d}.8$; K0 IV + G5 IV) are both known as very active RS CVn binaries for which several major radio and UV flares have been observed. The surface fluxes for HR 5110 and the two RS CVn stars are comparable and are about 100 times larger than the corresponding fluxes for the quiet Sun, except chromospheric Mg II which is enhanced by only a factor of ~ 10. It seems plausible to attribute the large surface fluxes for the secondary star in the HR 5110 system, like those for UX Ari and HR 1099, to rapid rotation. From the data presented by Vilhu and Rucinski (1983, their Table 3), we estimate that for stars with rotation periods of ~ 3 days the difference in UV line flux between an F8 star (θ Dra) and a K star (HR 1099) is about a factor of 10. This difference at a given rotational velocity in the strength of chromospheric and TR emission must be related to another parameter, e.g., the shallower depth of the convection zone in the F stars, and hence it is not surprising that in HR 5110 we find no evidence of emission from an active TR associated with the F2 IV primary (at the 10%–20% level). This is despite the fact that the radii of both components are nearly the same so that their rotational velocities are nearly identical given synchronous rotation.

Our observations of HR 5110 has given us the unique opportunity of studying the chromosphere and TR of the secondary of an Algol system. We have shown that the behavior we observe is similar to that of rapidly rotating spotted RS CVn systems and hence must be determined primarily by the large rotational velocity of the K0 star and dynamo action rather than being related to an accretion disk. Whether other secondaries of Algol systems have magnetic active regions is not yet known, since the UV spectra of the few systems that have been observed during primary eclipse (cooler star in front) appear to be dominated by an accretion disk around the primary.

We have analyzed the SWP 17707 spectrum of one other Algol system, AS Eri, which has a period (2.67 days), secondary (K0), and mass ratio (0.11) similar to those of HR 5110. The radiation of the hot A3 primary dominates the 1200–2000 Å region, making the detection of any chromospheric emission from the secondary of AS Eri impossible. The absence of a strong C IV absorption line in this spectrum may indicate that AS Eri lacks a high temperature accretion region (Peters and Polidan 1984). Unfortunately, this system undergoes only a partial eclipse, and it would be difficult to distinguish the effects of an active chromosphere from mass transfer processes. A search through the Giuricin, Mardirossian, and Mezzetti (1983) list of Algol systems revealed only three additional short-period Algol systems composed of an F primary and K secondary, QY Aql, AL Gem, and RT UMi. All three are too faint to be studied with *IUE*. Until more bright Algol systems like HR 5110 are discovered, it appears to be the only one to which this type of analysis can be applied and for which we are able to establish the probable presence of active regions and active chromospheres and TRs on the secondary.

VII. SUMMARY

The broad-band colors of HR 5110 are best matched with an F2 IV primary and a spotted K0 IV secondary. This system is important because it is a nearly pole-on close binary in which the less massive but more evolved K secondary fills its Roche lobe, and the system can be observed in the ultraviolet. HR 5110 can be classified as an Algol system since it shows many of the common characteristics with Algols as Table 1 illustrates. Many systems like this should exist, but they are easily detected only when $i \approx 90°$ through eclipse observations. Through precisely measured wavelength shifts of the UV emission lines of HR 5110 relative to the photospheric absorption lines on a high-dispersion short-wavelength *IUE* spectrum, we can uniquely assign the active chromosphere and TR to the cooler component. This emission is most likely associated with

TABLE 5

INTEGRATED LINE SURFACE FLUXES OF THE SECONDARY COMPONENTS OF HR 5110 AND TWO RS CANIS VENATICORUM STARS ($\times 10^5$ ergs cm^{-2} s^{-1})

Star/State	Phase	$F(\Delta\lambda)^a / f(\Delta\lambda)$ ($\times 10^{+17}$)	N V λ1240	O I λ1305	C II λ1335	Si IV λ1400	C IV λ1549	He II λ1640	Mg II *k* λ2796
HR 5110/	0.68–0.52	7.85	1.2–3.1	3.4–7.3	3.5–6.9	2.5–5.1	5.1–10.9	2.7–5.4	52–71
HR 1099[b]/quiescent	0.73	3.2	2.1	...	6.1	3.0	9.7	...	110
UX Ari[b]/quiescent	0.61	4.6	1.9	4.4[c]	4.4	2.5	6.5	3.5	68[c]
Sun[d]/quiet	...	...	0.0086	0.04	0.046	0.025	0.058	0.031	6.8

[a] $F(\Delta\lambda) = [(4.125 \times 10^8)/\phi]^2 f(\Delta\lambda)$, where ϕ is the stellar angular diameter in mas.
[b] Simon and Linsky 1980.
[c] Simon, Linsky, and Schiffer 1980*b*.
[d] Quiet Sun surface fluxes from Ayres and Linsky 1980.

a plage facing the primary star. This system also flares at radio wavelengths, but any effects produced in other parts of the spectrum are short-lived, since within 21 hr after a flare no effects were detected either in the UV or optical region. As in other Algol systems, mass transfer from the primary to the secondary through the inner Lagrangian point may be occurring as indicated by the increased width of the Mg II lines near phase 0.5. Large amounts of intrasystem material do not appear to be present, however, as only very weak Hα emission is observed and the infrared excess is too hot to be dust.

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