THE Hα EMITTING REGIONS OF THE ACCRETION DISKS IN ALGOLS

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(Received 20 October, 1988 – accepted 7 February, 1989)

ABSTRACT. The circumstellar plasma that produces Hα emission in Algol binaries has been investigated using phase-resolved, high dispersion data acquired from CCD and image tube detectors. Results are summarized in this paper, including discussions of the disk geometry and size, asymmetry in the distribution of material, long-term or non-phase dependent variability, mass outflow, the mean electron density, and how the latter properties vary with the system's period or location in the r - q diagram. Five systems which display permanent emission with periods ranging from 4.5 to 261 days (SW Cyg, UX Mon, TT Hya, AD Her, and RZ Oph) are intercompared. If P < 4.5 days, no permanent disks are observed, while if P > 6 days, stable disks with only slight long-term variations in their Hα brightness are seen. The most variable systems appear to be those in the 5 - 6 day range, but the star's position in the r - q diagram has the largest influence on its behavior. The *trailing* side of the accretion disk, where the gas stream impacts the inner disk, is usually brighter, and the *leading* side is often times more extended. The disk extends out to at least 95% of the Roche surface of the primary and is highly flattened ($\leq R_p$). Mass outflow near phase 0.5 is commonplace.

1. INTRODUCTION

Balmer emission lines were first discovered in an Algol-type binary in November of 1933 when A. B. Wyse (1934) observed the short period system RW Tau during totality. Joy (1942) later confirmed the presence of these features and interpreted his observations as evidence for a rotating, extended gaseous ring positioned about the equator of the primary. Joy's ring geometry was eventually replaced with a disk-like model and the concept of an accretion disk began to emerge. Throughout his career, O. Struve subsequently discovered Balmer emission lines in several additional Algol systems and appears to have been the first one to recognize that the accretion disks in the systems with shorter periods are less visible and more transient than those in the longer-period systems.

Space Science Reviews **50** (1989), 9–22.

New detectors, such as CCD's and image tubes, used with coudé spectrographs have allowed us to extend Joy's and Struve's pioneering work on accretion disks. Currently, we are able to obtain spectroscopic data of higher dispersion, higher signal/noise, and especially data on Hα, the strongest Balmer line, which can reveal the presence of even a small amount of circumstellar material. In this paper, I discuss some recent progress that I have made in determining the geometry, degree of variability, and physical conditions in the Hα-emitting regions about the primaries in Algol systems and how these vary with systemic parameters. These regions could be described as *luke-warm* ($8,000 \leq T \leq 50,000$ K) and they do not necessarily include those that produce the emission and absorption lines from the highly ionized species (e.g. N V, C IV, Si III-IV, etc.) observed in the UV. Since the portion of the accretion disk that can primarily be seen in Hα is generally of low density ($N_e \approx 10^9$-10^{11} cm^{-3}), Hα observations alone probably cannot be used to obtain information on the dense, inner region of the disk which merges with the stellar photosphere.

The Hα observations reported here were obtained with the 0.9-m Coudé Feed Telescope at Kitt Peak National Observatory during two periods. The most recent data were secured in 1985-1988 using the TI3 CCD detector with Camera No. 5. These spectra have a resolution of 0.2 Å/pixel and the signal/noise is typically 100-200. An earlier data base was acquired with the Carnegie-type (S-20) image tube during 1979-1981 and consists of calibrated spectrograms taken on Kodak IIIa-J plates (dispersion 15 Å mm^{-1}, widened to 0.7-1 mm). Over 400 spectrograms were acquired of nearly 50 Algol systems during the earlier program while about 130 CCD images have been obtained of about 20 systems in the newer study.

2. CIRCUMSTELLAR MATTER AND THE r-q DIAGRAM

Whether or not a permanent accretion disk can be formed in a system depends upon the size of the primary relative to the size of the orbit. If the cross section presented by the gainer is large, the gas stream particles will simply impact the star's photosphere and no permanent accretion disk can be formed. Generally speaking, the systems with shorter periods fall into this category and this qualitatively explains the existence of the two classes of systems. The borderline period is about 5 - 6 days (Struve 1948,1949; Peters 1980).

A useful representation for understanding the behavior of accretion disks in Algol systems is shown in Figure 1, the so-called r-q diagram. The mass ratio of the system, $q = M_{loser}/M_{gainer}$, is plotted versus the fractional radius of the gainer (R_p/a) and compared with the theoretical computations of gas stream hydrodynamics of Lubow and Shu (1975). The upper curve, ω_d, delineates the radius of the dense accretion disk relative to the semi-major axis for the system for binaries of different mass ratio. The lower curve, ω_{min}, shows the minimum distance that a stream particle will approach the center of the gainer. If the system falls above the upper curve, then one expects any emission to be

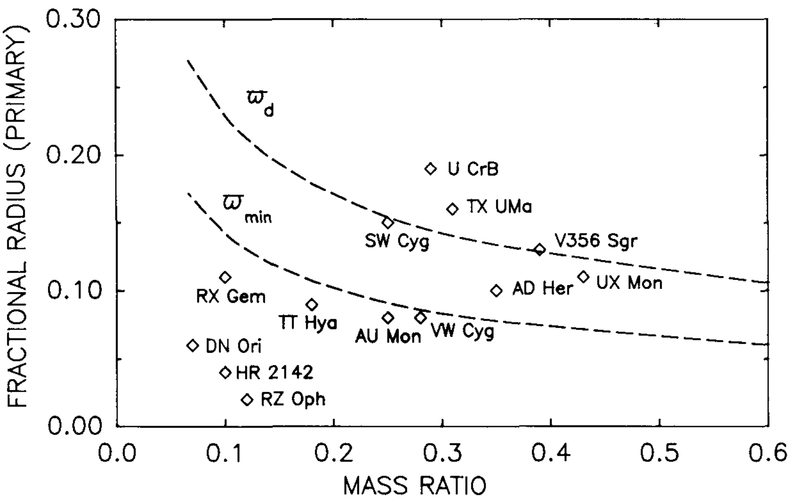

Figure 1. The location of selected Algol primaries in the r-q diagram. The dashed curves labeled ω_d and ω_{min}, from Lubow and Shu (1975), show the radial extent of the dense disk and the minimum distance of approach between a stream particle and the center of the primary. The significance of a star's location in this diagram is explained in the text. The position for HR 2142 is representative for mass transfer binary Be stars.

transient as the gas stream will strike the photosphere of the primary. Alternatively, if the system falls below the lower curve, then one should see a permanent disk which emits strongly in Hα. The most variable disks should be the ones in systems which fall *between* the two curves, as the wide gas stream will graze the photosphere with the inner portion striking the primary and the outer part of the stream forming an accretion disk. The present study indeed confirms the above predictions. Selected systems considered in the present study are plotted in Figure 1, and details on SW Cyg, UX Mon, TT Hya, AD Her, and RZ Oph will be given below.

3. RESULTS

The profile of Hα as a function of phase contains a wealth of information on the size of the accretion disk, its geometry, and extent of mass outflow from the system. The phase at which the accretion disk begins to be eclipsed or emerges from eclipse reveals the radial extent of the disk, while the relative strength of the two lobes of the Hα emission feature provides data on any asymmetries that might exist in the distribution of material. The strengthening of the Hα core and its velocity reveal density enhancements or localized streaming along the line of sight. Five systems, all of which display Hα emission but different periods and locations in the r-q diagram, will now be considered in detail.

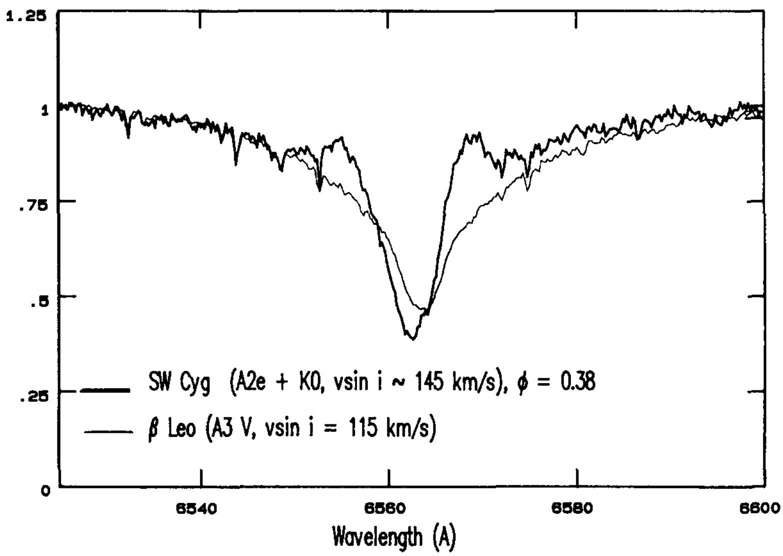

Figure 2. The Hα emission in SW Cyg observed on 1988 May 25 (the light contributed by the secondary has been subtracted) can be clearly discerned when the feature is compared with that observed in a suitable standard. Both observations were made with a TI CCD detector.

SW Cyg (P=$4^{d}.57$, A2e + K0) is the shortest-period system considered in this program for which permanent, though variable Hα emission is observed. Using the results of the photometric study by Hall and Garrison (1972), the light from the secondary at Hα was subtracted and the resultant profile was compared (Figure 2) with that of a standard star (β Leo) of comparable spectral type and vsin *i*. Emission with a n equivalent width (E.W.) of 3.2 Å can clearly be seen outside of eclipse. Although the emission is weak, the observations reveal that it is initially eclipsed at a phase of about 0.80, which implies that the circumstellar material extends out to at least 95% of the Roche surface of the primary ($\mathfrak{R}_p$). The core in Hα is enhanced near phase 0.5, as one typically observes in the longer-period systems.

UX Mon (P=$5^{d}.90$, A5e + G2) definitely qualifies as the most variable of the systems investigated. Perhaps this should not be surprising because the system nearly falls on the dividing line in the r-q diagram where the gas stream just begins to fully impact the gainer's photosphere. Both the CCD images and the plate data show striking phase and time dependent variations in Hα. Two sequences from the earlier data base are shown in Figure 3. The strong emission peak seen in the observation of 1979 December 2 (ϕ=0.849) arises from the *trailing* portion of the circumstellar disk. Note the prominent absorption core, which reveals the presence of mass outflow of

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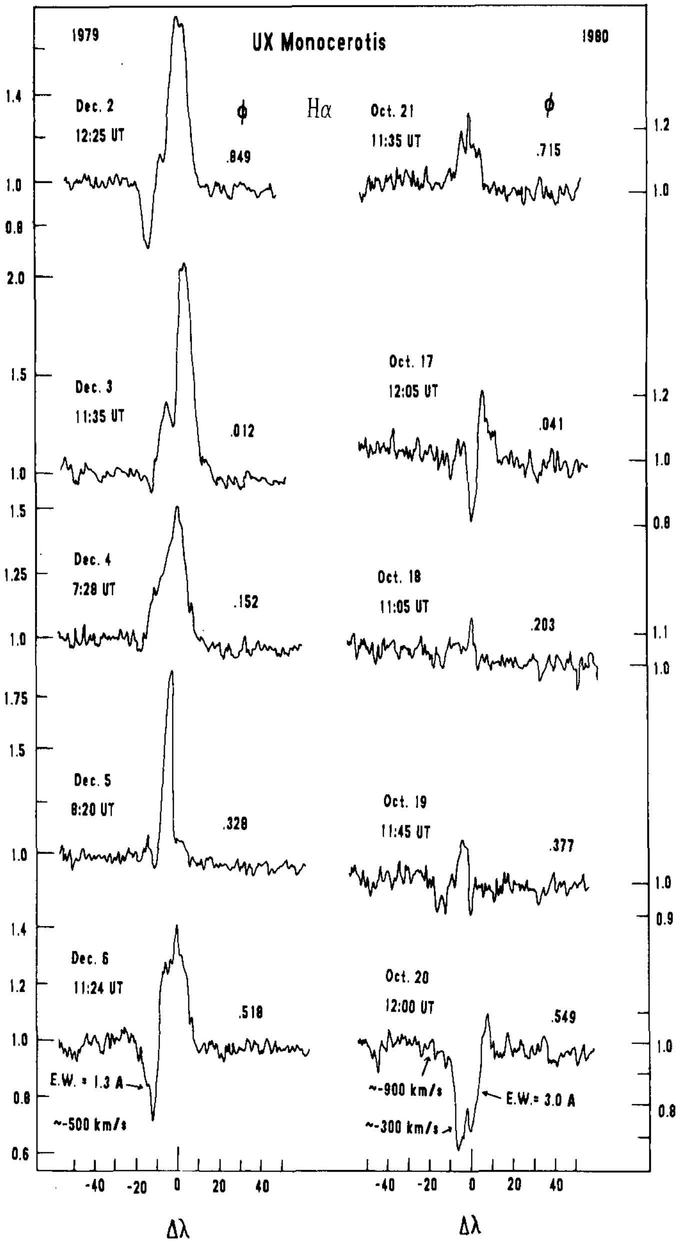

Figure 3. Hα observations of UX Mon (from image tube spectrograms) during two different epochs. Note the striking phase and time dependent variations and the conspicuous mass loss in this system. The intensity relative to the continuum for each profile can be found along the vertical axis nearest to it.

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approximately -500 km s^{-1}. The profile observed on the following night, near mid-eclipse, confirms that most of the material in this system indeed resides on the side of the accretion disk that is fed by the gas stream. Such an effect was reported for RW Tau by Kaitchuck and Honeycutt (1982). The conspicuous change that was observed between December 4 and 5 apparently was due to the fact that the *bright spot* in the disk came into view on the approaching limb during this time interval. Systemic mass loss was again observed at phase 0.5. The corresponding sequence of observations displayed on the right hand side of Figure 3, show that the basic phase dependent behavior prevailed even though the total amount of emission in the system had waned. Although the emission measure had declined, the mass outflow seen near ϕ=0.5 had increased ($\dot{M}\approx 2\times 10^{-9}$ $M_{\odot}$ yr^{-1}). A series of CCD observations in 1987 April-May confirmed that overall variations in the emission can occur in just three orbital cycles. Further observations are needed to determine whether these changes are due to a change in the ionization or in the rate of mass transfer.

TT Hya (P=6$^{d}_{.}$95, B9.5 Ve + G9-K1 III) has recently been studied by Etzel (1988) and Plavec (1988). This system displays remarkably constant Hα emission and predictable phase dependent behavior, which one might expect given its new location in the r-q diagram where permanent

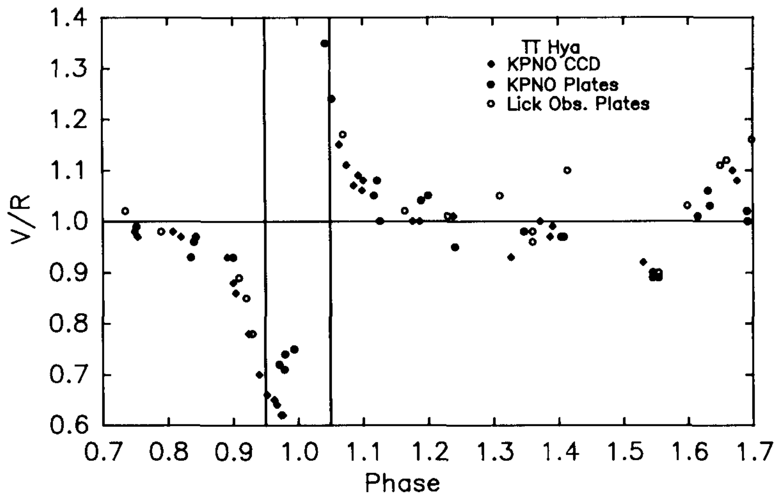

Figure 4. The relative intensity between the violet and redshifted emission components in TT Hya versus phase. V and R are measured relative to the continuum (I_V/I_C, I_R/I_C). Observations include the newer KPNO data as well as image tube spectrograms obtained at Lick Observatory from 1973-1976. Note the remarkable repetitive behavior over a period of 15 years! The vertical bars show the interval of the stellar eclipse. Disk eclipse is evident from 0.84 < ϕ < 1.15, consistent with the disk extending out to 95% of the primary's Roche surface. The dip near phase 0.5 results from mass outflow.

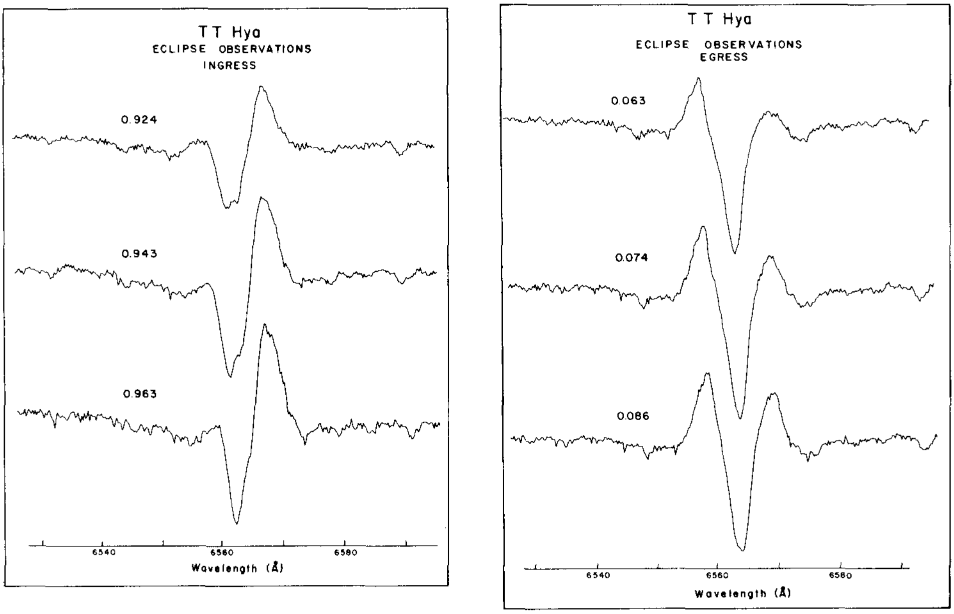

Figure 5. Selected CCD observations of Hα in TT Hya throughout the eclipse of the disk. The peak emission intensity was 1.2 - 1.4 I_c.

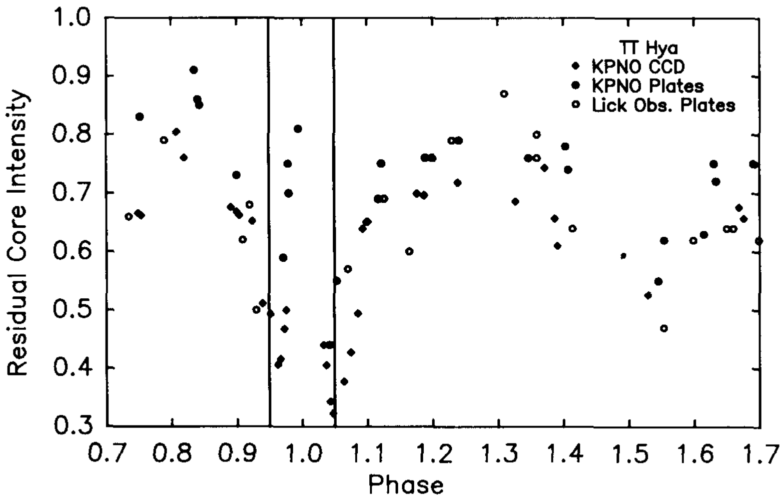

Figure 6. The intensity of the core in Hα in TT Hya versus phase. Note the increase in strength just before and after the stellar eclipse (interval shown by vertical bars) and from $0.4 < \phi < 0.6$.

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disks prevail. The emission from its *leading* hemisphere (the "V" lobe) begins to be occulted at a phase of 0.84 (Figure 4) and its counterpart from the *trailing* side (the "R" lobe) fully emerges from its eclipse by phase 0.15. This implies that the disk is fairly symmetrical and extends out to 0.95 $\mathcal{R}_p$. Some representative line profiles seen during the disk eclipse are given in Figure 5. The separation of the peaks of the emission feature near totality (≈400 km s^{-1}) supports the earlier conclusion that the disk extends out to at least 90% of the Roche surface of the primary, if the particles are in stable Keplerian orbits (Peters 1980). Since the observations show that nearly all portions of the disk appear to be occulted at sometime during the eclipse sequence, the disk must be highly flattened ($\leq R_p$), or less than 20% of its overall radial extent.

In this system, as well as in several others, the Hα core displays an increase in depth just prior to and after eclipse, which can be seen in the data displayed in Figure 6. This additional absorption is probably from the dense inner region of the accretion disk. The core of Hα steadily becomes stronger beginning at phase 0.4, reaches an r_ν=0.5 at phase 0.5, then returns to its previous value by phase 0.6 (Figure 6). This core shows a velocity of about -50 km s^{-1} relative to the photosphere and implies a mass loss of $\approx 10^{-11}$ $M_\odot yr^{-1}$ in this domain.

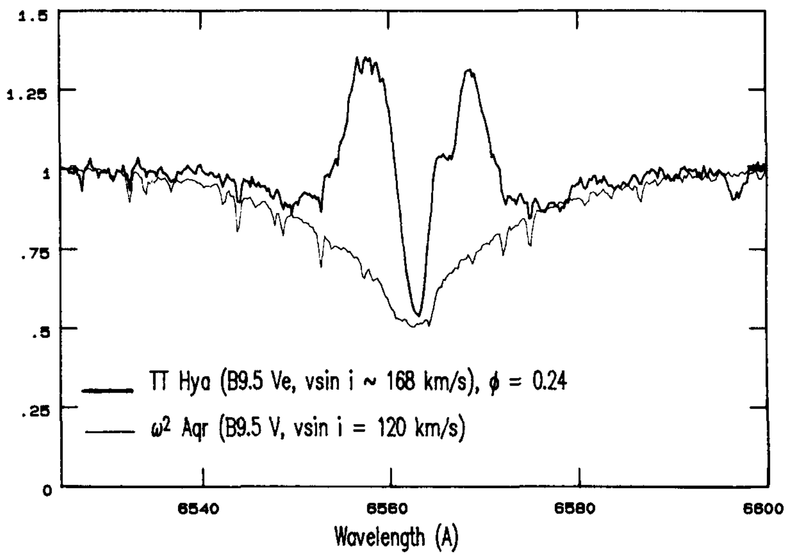

Figure 7. A CCD observation of Hα in TT Hya at quadrature compared with that observed in a standard star of comparable spectral type and vsin *i*. The light from the secondary has been subtracted using the photometric solution of Etzel (1988).

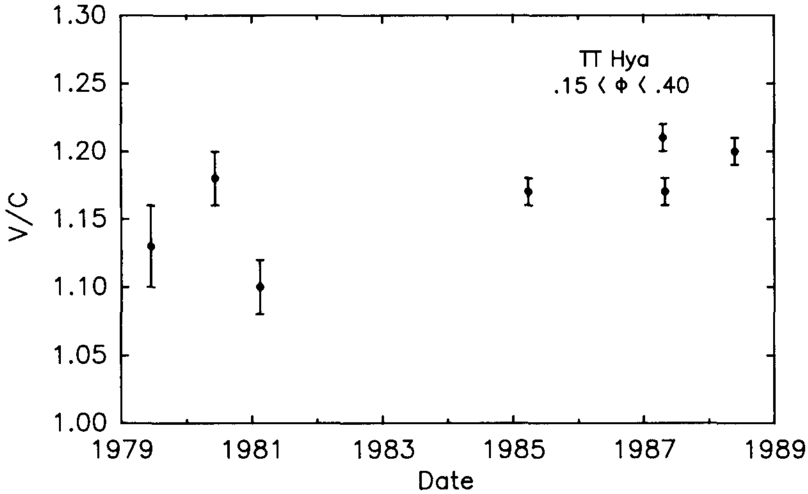

Figure 8. The intensity of the V emission lobe in TT Hya observed near quadrature over a time span of 9 years.

The profile of Hα observed at quadrature is shown in Figure 7. Etzel's photometric solution has been employed to subtract the light contributed by the secondary and the resultant feature is compared with a suitable standard. Note that emission is observed nearly 30 Å from the line center and reveals the presence of non-Doppler line broadening (perhaps electron scattering or turbulence). The volume emission measure typically observed in TT Hya implies a mean electron density of 10^{10} cm^{-3} in the disk. Although the disk in TT Hya is quite stable, there does appear to be some fluctuation in the overall strength of Hα. In Figure 8, the mean intensity of the V lobe observed in the *quiet* phase interval 0.15 - 0.4 is shown. A 5% variation can occur on a time scale as short as two weeks, or two orbital periods.

AD Her ($P=9^{d}.77$, A4e + K2), investigated by Batten and Fletcher (1978) displays permanent Hα emission with a phase-dependent behavior similar to that seen in TT Hya. There are a few subtle differences, however. The profile seen at $\phi=0.25$ (Figure 9) shows R to be slightly stronger. This and the fact that at phase 0.5, V > R implies that there is a slight asymmetry in the disk with more material on the *trailing* side. However, since at $\phi=0.0$ the two lobes of the Hα emission feature are of equal strength, this density enhancement must reside close to the primary, or the spot where the gas stream strikes the photosphere tangentially. In Figure 9, the Hα profile is compared with a fairly close standard, β Leo. The light from the secondary (about 25%) was subtracted with the aid of two CCD observations acquired at mid-totality. As in the case of TT Hya, emission is observed at 30 Å from line center, but there appears to be *enhanced* emission on the red wing. This is tentatively identified as emission from the C II doublet

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at λλ6578, 6583, which is frequently seen in Be stars during periods of increased activity.

In AD Her, the accretion disk begins to be eclipsed at phase 0.86 and again this suggests a size comparable with the gainer's Roche surface and a vertical dimension of $\leq R_p$. There is evidence in this system that the rim of the accretion disk is brighter than its central region, since substantial occultation of its *leading* edge is observed within 4 hours at phase 0.90. The separation of the peaks during mid-eclipse, about 400 km s^{-1} implies a line formation region of 0.85 $\mathfrak{R}_p$ and the presence of Keplerian velocities in the outer portion of the disk. The volume emission measure, VN_e^2, combined with the above information on the size and geometry of the disk suggest a mean electron density of 5 x 10^{10} cm^{-3}. CCD observations at mid-eclipse reveal a low velocity (-30 km s^{-1}) mass outflow, perhaps from the Lagrangian point behind the secondary. This is about the same value observed at phase 0.5. The present data base also shows evidence for temporal variability in the Hα emission intensity, of the same magnitude and time scale as in TT Hya.

RZ Oph (P=261$^{d}_{.}$93, F5e + K-M) was most recently analyzed by Knee, *et al*. (1986). The Hα emission in this system is strong, about 4.5 times the continuum intensity. Although the disk in this system is quite massive, it displays many of the same properties seen in systems of shorter period. In particular, the disk appears to be asymmetric with a slightly higher density on its *trailing* side as is evident from the Hα observations at mid-eclipse and phase 0.5 shown in Figure 10. Eclipse

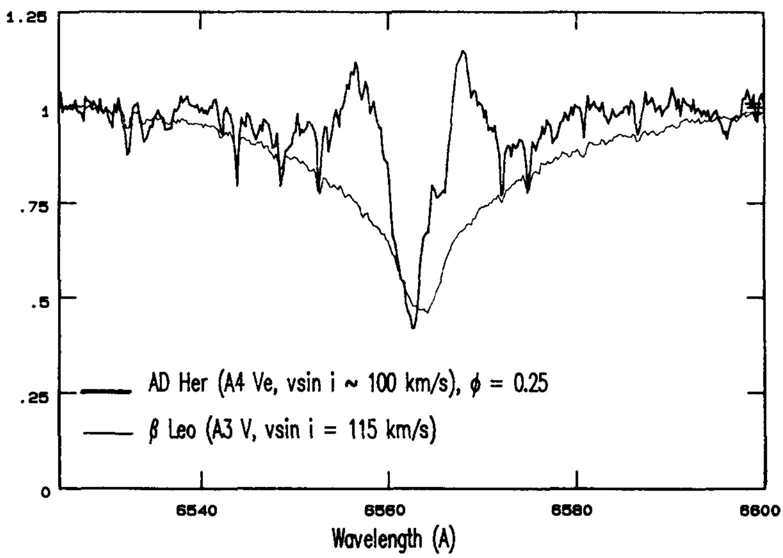

Figure 9. Hα observed in AD Her at quadrature with the TI3 CCD detector. The light from the secondary has been subtracted and the resultant profile is compared with the standard β Leo.

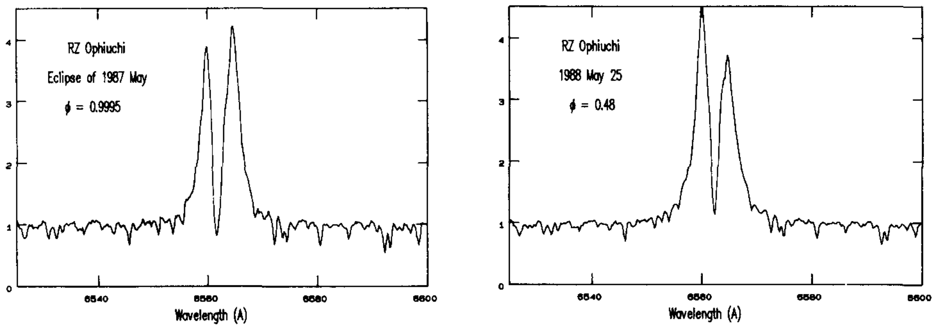

Figure 10. CCD observations of Hα in RZ Oph at mid-eclipse and near phase 0.5 provide clear evidence that the accretion disk is brighter on the *trailing* side, as V < R in the former and V > R in the latter. Note that during primary eclipse part of this apparent density enhancement on the *trailing* side is occulted, and therefore it must be located closer to the gainer than to the periphery of the disk.

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of the disk is first observed at phase 0.85 and implies a radial size of about 0.90 $\mathcal{R}_p$. At mid-eclipse the peaks of the Hα emission are separated by 215 km s^{-1}. This suggests sub-Keplerian particle velocities in the disk for a wide range of assumptions concerning the size of the secondary (even if it fills its critical Roche lobe) and the radial distribution of brightness in the disk.

4. CONCLUSIONS

Some of the characteristics of the disks in selected Algol disks implied by this investigation are enumerated in Table 1. For each system, its period, phases at which disk occultation begin/ends (ϕ_V, ϕ_R), the estimated radial extent of the disk relative to the size of the primary's Roche surface ($R_d/\mathcal{R}_p$), and comments on whether any asymmetry in brightness has been observed are given.

The conclusions from this study can be summarized as follows:

1. The presence and stability of an Hα emitting accretion disk appear to depend on the location of the system in the r-q diagram (Fig. 1). Since the fractional radius of the primary scales as $P^{-2/3}$, the shorter period systems tend to be located in the upper third of the diagram and the longer period systems in the lower third. Thus one can now understand why, as mentioned in §1, the visibility of Balmer emission in Algols has historically been linked to the period of the system. Based upon the data used for this study, we have the following empirical results:

a. If the period of the system is less than about 4.5 days, permanent Hα emission is rarely observed. One noteworthy exception is TZ Eri (P=2.6 days), which displays weak Hα emission outside of eclipse.

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TABLE I
Disk Characteristics

System	Period (days)	q	ϕ_V	ϕ_R	$R_d/\mathcal{R}_p$	Br. Asymmetry?
SW Cyg	4.57	0.25	0.80	....	>0.95	Yes
UX Mon	5.90	0.43:	<0.90	....	....	Yes
TT Hya	6.95	0.18	0.84	0.15	0.95	Yes
V393 Sco	7.71	0.3::	0.75	0.14	....	No
VW Cyg	8.43	0.28	0.80	0.10	>0.95	Slight
RY Gem	9.30	0.16	0.80	0.20	>0.95	Yes
AD Her	9.77	0.35	0.86	0.10	0.95	Yes
AW Peg	10.62	0.15:	0.82	0.09	0.95	Yes
AU Mon	11.11	0.20	0.90	0.11	>0.65	No
RX Gem	12.21	0.10	0.80	0.13	>0.95	Slight
DN Ori	12.97	0.07	0.82	>0.10	0.95	No
RZ Oph	261.93	0.12	0.85	0.10	0.90	Yes

b. If the period is in the range 5-6 days, highly variable emission and extensive mass loss from the system are seen.

c. If the period is greater than 6 days, permanent Hα disks, which show only slight long term variations in brightness, are observed. There are some exceptions such as S Cnc in which we believe that mass transfer has ceased.

2. The Hα emitting region is *asymmetric* in both distribution of flux and linear dimension. The *trailing* side, where the gas stream adds to the disk is brighter. Most systems show their *leading* edge to be more extended.

3. The *leading* edge of the disk appears to extend out to at least 95% of the Roche surface of the primary.

4. The disk typically has a diameter that is larger than the diameter of the secondary star, as double Hα emission can frequently be observed at mid-eclipse, and it appears to be highly flattened (the vertical dimension is <20% of the radial extent).

5. There is usually enhanced shell absorption near phase 0.5. Sometimes there is evidence for mass loss from the system near this portion of the orbit. Systems seen at smaller inclinations are more likely to show mass loss.

6. Frequently increased shell absorption, which may arise in a density enhancement in the inner accretion disk between the two stars, is seen

before and *after* eclipse. Such a build-up of material could result from an interaction between the gas stream and disk.

Observational errors in R_p and q and varying stream widths are possible reasons why the disks observed in some systems may differ from what is predicted. An unexpected Hα profile might be a clue that the systemic parameters are in need of improvement. For systems that fall in the middle of the r-q diagram, between the curves for ω_d and ω_{min}, the behavior of the disk probably depends critically on the width of the gas stream relative to the primary ($\propto T^{1/2}P$). Systems with wider, less focused gas streams should display more variable Hα emitting regions. Differences in stream width and possible errors in systemic parameters may explain why the disks in SW Cyg and AD Her are less variable than the one in UX Mon, even though all three systems occupy the middle domain in the r-q diagram.

Phase-resolved, high dispersion spectroscopic observations with new detectors have produced a wealth of information on the geometry of the Hα emitting regions of accretion disks in Algol binaries and the distribution of material within them. A number of properties of the disks have now been well established. Future observations with even higher time and spectral resolution analyzed with the technique of "Doppler imaging" have an even greater potential of producing impressive images of these accretion disks. It is now time to undertake theoretical modelling of the disks, especially the region of gas stream-disk interaction and the domains of material outflow such as the ubiquitous one at phase 0.5. In addition, an attempt should be made to establish the relationship, if any, between the Hα emitting portion of the disk and the high temperature plasma observed in the ultraviolet.

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https://doi.org/10.1017/S0252921100087637 Published online by Cambridge University Press

DISCUSSION

Rucinski commented on the desirability of expressing emission-line strengths in absolute flux units and also enquired if there was comparable information available from any other Balmer line, since knowledge of the Balmer decrement would be physically significant. Peters replied that she intended eventually to convert to absolute flux units, but she was often handicapped by the uncertainties in our knowledge of the distances of the stars. She had not yet had sufficient observing time to study these systems in any line other than Hα. Smak emphasized the need for caution in the interpretation of emission-line profiles in terms of a purely emitting disk when strong absorption lines (as in the spectrum of TT Hya) can also be seen in the spectrum. He also suggested that effects observed near phase $0^{p}.5$ in TT Hya and other systems might be due to absorption by the stream. In response, Peters distinguished between absorption by the disk and occultation - both could affect line profiles. She thought that the main gas stream in most systems could not be responsible for effects observed near phase $0^{p}.5$, but it was possible that some mass could flow around the primary towards the Lagrangian point and produce the observed effects. Olson commented that his five-colour photometry of UX Mon had shown, in January and February of 1988, an anomalous dip in the light-curve, $0^{m}.7$ deep, that could not be explained by absorption in a circumstellar stream. A similar dip had been observed in the light-curve of U Cep during its active bursts. In response to Bolton, who asked what evidence there is that disks are thin, Peters replied that both trailing and leading sides are completely occulted just before and after the actual eclipse. If a system is seen exactly edge on, this would permit a maximum disk thickness of about twice the primary star's diameter. Since we usually observe systems from a few degrees outside the orbital plane, we can usually be sure that the true thickness is less than twice that diameter.

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