Time-Resolved Spectroscopy of Accretion Disks in Algols

Ronald H. Kaitchuck
Department of Astronomy
The Ohio State University
174 W. 18th Ave.
Columbus, Ohio 43210
U.S.A.

(Received 20 October, 1988)

ABSTRACT. Time-resolved spectroscopy during the eclipse of short-period Algol systems, has shown their accretion disks to be small, turbulent structures with non-Keplerian velocity fields and asymmetries between the leading and trailing sides of the disk. These transient disks are produced by the impact of the gas stream on the mass-gaining star, and occur in systems where the star is just large enough to ensure the stream collision is complete. These emission line disks and the excess continuum emission do not always occur together. The permanent accretion disks in at least a few of the long-period Algol systems have features in common with the transient disks including non-Keplerian velocity fields.

1. Introduction

In 1934 Arthur Wyse (1934) discovered Doppler-shifted emission lines on a spectrogram taken four minutes after mideclipse of the Algol system RW Tau. The importance of this observation did not become apparent until further observations were made by A. H. Joy (1942). This short-period Algol system has a very deep total eclipse. The emission lines can be seen only when most of the competing light of the primary star has been diminished by the eclipse. Joy found redshifted emission lines near second contact which faded and were replaced by blueshifted emission at third contact. He postulated that the primary star is surrounded by a rotating gaseous ring.

In the 1940's Struve and coworkers studied the rings in Algol systems (Struve 1948, 1949; Struve and Huang 1957). They found that the rings could be divided into two general groups. Those found in long-period systems (P > 5 days) show bright emission lines that are visible in the full light of the uneclipsed stars and appear to be permanent features, while those in short-period systems, like RW Tau, are only visible during primary eclipse and are transient features. Because the inner radii are probably equal to the radii of the stars they surround, these rings are now more commonly referred to as disks. They are the product of mass accretion from the secondary star. Wyse's 1934 observations mark the first detection of the astrophysically important structures

Space Science Reviews **50** (1989), 51–61.
© 1989 *by Kluwer Academic Publishers. Printed in Belgium.*

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

now known as accretion disks. (See Batten 1988 for a review of the historical development of this field.)

In the modern theoretical picture (e.g. Pringle 1981; Verbunt 1982), an accretion disk is formed by Roche lobe overflow of the secondary star. The gas leaving the L_1 point has too much angular momentum to fall directly onto the mass gaining star. Instead, the gas stream spirals around the star's trailing hemisphere and eventually circles it. Viscous processes lead to the spreading of the gas into a flat disk, the outward transport of angular momentum and the inward mass accretion. The disk is pictured as rotating in a nearly Keplerian fashion, in hydrostatic equilibrium in the direction perpendicular to the plane of the disk. This disk formation process can occur provided that the mass gaining star is small compared to the separation of the stars. This is the case for cataclysmic and long-period Algol binaries. However, for the short-period Algols the gas stream will impact the trailing hemisphere of the star (Lubow and Shu 1975). This may, in fact, be the origin of the differences between the disks in long and short-period Algols noted by Struve. The transient disks in the short-period Algols are somehow produced by the star/stream collision. Algol systems provide a laboratory for the study of different kinds of accretion disks: those formed in a conventional manner, which presumably result in stable Keplerian disks, and those in short-period systems which are formed by a star/stream impact. It is perhaps a bit ironic that the first detected accretion disk, that of RW Tau, is of the latter type and does not fit our modern conception of a normal accretion disk.

2. Time-Resolved Spectroscopy

If the mass-gaining star undergoes an eclipse, so too must the accretion disk surrounding it. The spectrum of this disk will obviously change as portions of the disk with different physical conditions and rotational velocities are occulted and others uncovered. By obtaining many closely timed spectra during eclipse, a spatial mapping of the accretion disk structure is possible. Early attempts at photographic time-resolved spectroscopy failed (Wyse 1934). Modern detectors and fast computer acquisition devices are required to deal with the simultaneous constraints of time resolution sufficient to resolve spatial structure and spectral resolution sufficient to resolve the Doppler shifts.

My collaborator, Kent Honeycutt, and I are indebted to Alan Batten, who in his book Binary and Multiple Systems of Stars (Batten 1973), called this interesting observational problem to our attention. We have successfully obtained time-resolved spectroscopy of Algol systems with the 0.91 m telescope and SIT Vidicon spectrograph of Indiana University, the 2.1 m telescope and the intensified-image-dissector spectrograph (IDS) of KPNO and The Ohio State University IDS on the 1.8 m Perkins reflector at Flagstaff Arizona. In all cases, short integration times, typically 120-300 seconds are used with a "dead time" of 30 seconds or less between integrations for data storage. The IDS observations were usually made in the Hβ - Hγ region with 2.5 - 2.7

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

Å resolution.

2.1 AN OBSERVATIONAL DESCRIPTION OF TRANSIENT DISKS

Current knowledge of transient disk structure in short-period Algol binaries is based on just six systems: RW Tau, U Cep, SW Cyg, TZ Eri, RW Mon, and RR Dra. This reflects the facts that transient disks are difficult to detect and that transient disk systems are uncommon. All these systems have shown rapid variability of their disk structure. For example, the disk in RW Tau (Kaitchuck and Honeycutt, 1982a) has been seen to appear and disappear in one orbital period or less. A representative data set is presented in Figure 1 which shows the flux, width and radial velocity for the Hβ emission line during one eclipse of SW Cyg. The filled and open symbols indicate the red and blue Doppler components respectively. The vertical dashed lines indicate the limits of totality. The line flux data in the bottom panel shows that the disk eclipse was partial, but this can change from eclipse to eclipse. The middle panel shows that the line widths remain essentially constant during totality and the upper panel shows the radial velocity of each Doppler component.

We have now sampled enough eclipses that some general properties have emerged. For instance, asymmetries between the leading and trailing sides of the disk have been seen at every eclipse. The trailing side is usually (but not always) brighter than the leading side, and they often have different rotational velocities, line widths, and radii.

2.1.1 *Disk Radii.* When the system parameters are known, the times of appearance and disappearance of the Doppler emission components can be used to measure the disk radii directly. Previous estimates for RW Tau (e.g. Plavec 1968) were 2 - 3 times the radius of the central star, and were dependent on the assumption of Keplerian motion in the disk. Our estimates of disk radii, from 14 eclipses where emission was present, range from 1.1 to 1.7, but rarely exceed 1.5. Similar results were found for the other systems. The disks are often non-circular, with the radius of the trailing and leading sides being unequal.

2.1.2 *Rotational Velocity Field and Emission Line Broadening.* It became clear from our earliest observations of RW Tau that the rotational velocity in the disk is non-Keplerian. This can be seen in a number of ways. The disk radius and outer rotational velocity can be determined directly from the observations. This shows the velocity to be sub-Keplerian for the adopted mass of the primary. Even allowing for an error in the primary's mass, other problems remain. For instance, the slopes of the velocity data in plots such as Figure 1 are usually much steeper than expected from a Keplerian disk, and sometimes the velocity field on the leading side is reversed. Figure 2 shows another eclipse of SW Cyg where the slope of the blueshifted component is reversed (compare it to Figure 1). This means that as more of the disk on the leading side emerges from eclipse, the mean velocity decreases (in an absolute sense). In other words, the highest rotational velocity is found at the *outer* edge of the disk. This

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

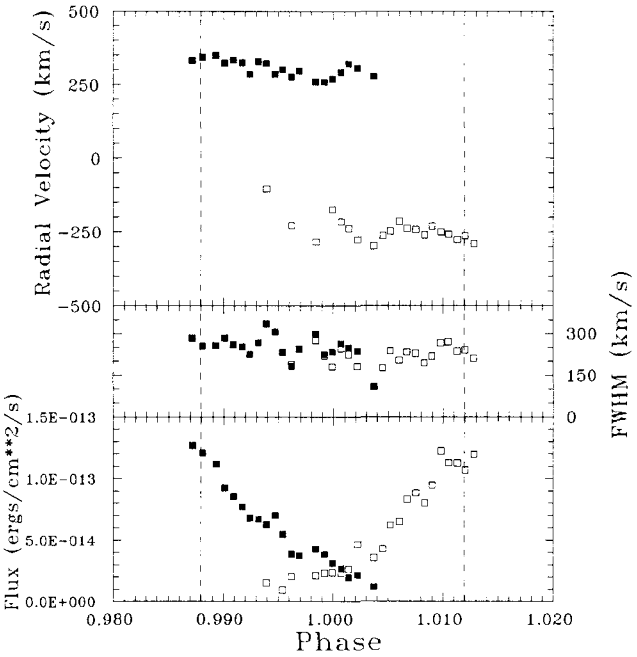

Figure 1. Hβ emission line flux, width and velocity during the July 28, 1982 eclipse of SW Cyg. The filled and open symbols refer to the redshifted and blueshifted Doppler components respectively. The vertical lines mark the limits of totality.

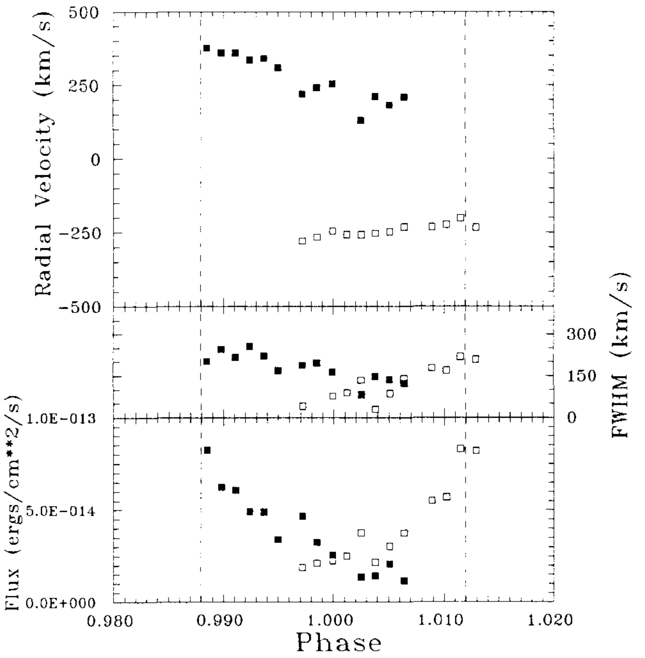

Figure 2. Hβ emission line flux, width and velocity during the October 17, 1987 eclipse of SW Cyg. The filled and open symbols refer to the redshifted and blueshifted Doppler components respectively. The vertical lines mark the limits of totality.

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

behavior has also been seen to occur in RW Tau (Kaitchuck and Honeycutt 1982a), and TZ Eri (Kaitchuck and Park, 1988).

As already noted in Figure 1, the widths sometimes remain constant in totality. (This is not always true, see Figure 2.) For a line which is broadened by rotation in a disk, the observed line width and velocity will vary in a correlated way during eclipse. As inner regions of the disk are occulted on the trailing side, both the line width and velocity of the redshifted component will decrease, as 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. As the leading side emerges from eclipse, the width and velocity of the blueshifted component will increase. Therefore, a plot of line width versus radial velocity during eclipse should produce a smooth curve for a rotationally broadened line. In fact, when this plot is made for transient disk systems, the result is usually a scatter diagram. Figure 3 shows such a plot for U Cep (Kaitchuck, Honeycutt and Faulkner 1988). The curve in the upper left is the expected relationship for a Keplerian disk of the measured radius. Note that not only does the data fail to define a curve, but it also displays a much larger range of velocity and greater line widths than that expected from a Keplerian disk. This problem of line broadening and non-Keplerian rotation was discovered independently by Crawford (1981) for U Cep.

The fact that the ratio of line widths to rest wavelength is the same for Hβ and Hγ suggests Doppler broadening by turbulence. To account for the observed line widths this turbulence would have to be highly supersonic (Mach 10-20), which in turn should produce strong shock fronts and high-ionization emission lines. Such lines have been detected with the IUE in U Cep (Plavec 1983) and in RW Tau (Plavec and Dobias 1983). Plavec's (1983) observations of U Cep show high excitation emission lines in both emission and absorption whose widths suggest supersonic turbulence (100 km s^{-1}). Evidence for supersonic turbulence has also been found in UV absorption lines of several other Algol systems (Peters and Polidan 1984). These authors find a hot (10^5 - 10^6 K) turbulent accretion region (HTAR) preferentially located on the trailing hemisphere of the mass-gaining star. The physical and spatial relationship between the HTAR, the optical emission line regions of the transient disks, and the continuum disks (to be discussed below) is still not clear.

2.1.3 *Structural Differences Between the Two sides of the Disk.* For each eclipse we have observed, differences between the leading and trailing sides of the disk have been apparent. Unfortunately, these differences are difficult to model, except for those eclipses where the emission lines are quite strong so that reliable line strengths and line ratios can be obtained. During one particularly favorable eclipse of RW Tau (Kaitchuck and Honeycutt 1982a) the trailing side of the disk was nearly isothermal with a density of ~ 10^{11} cm^{-3}. On the leading side the outer regions were at a much lower density, with line ratios consistent with Menzel case B. Closer to the star the densities increased to match those of the trailing side. This was taken as

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

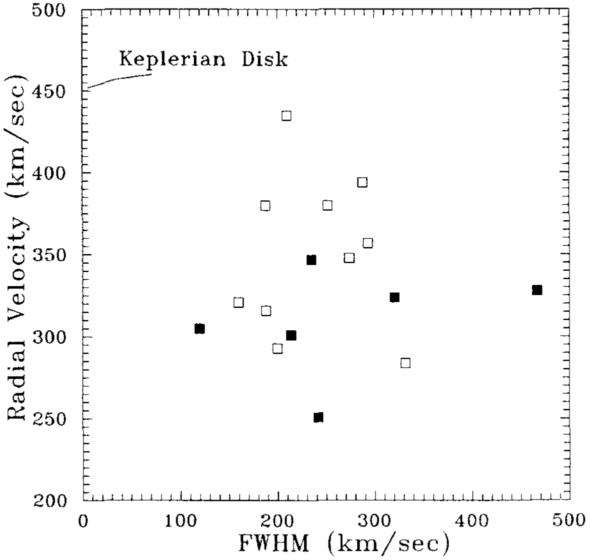

Figure 3. The emission line radial velocity versus line width during a eclipse of U Cep. The filled and open symbols refer to the redshifted and blueshifted components respectively. The curve in the upper left shows the expected relationship for a Keplerian disk of the measured radius surrounding a star of the mass of the U Cep primary.

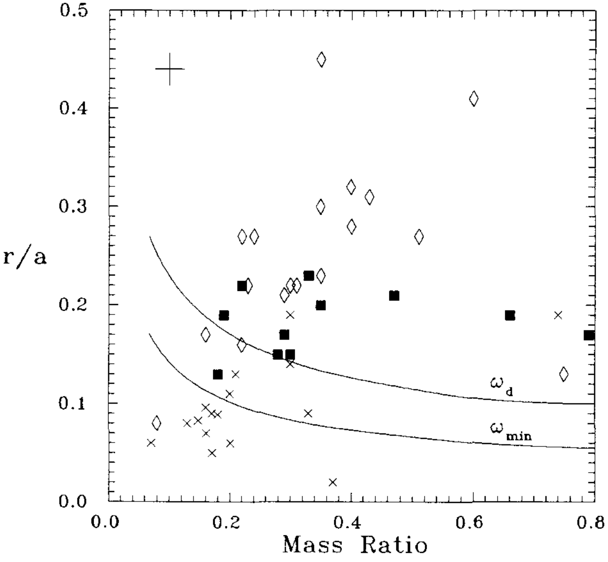

Figure 4. A plot of the size of the accreting primary star relative to the orbital separation versus mass ratio (loser/gainer) for Algol-type binaries. The diamonds represent systems for which no line emission was detected in eclipse. The filled squares mark the transient disk systems, and the crosses the permanent disk systems. The upper curve indicates the expected radius for a disk with no viscosity, while the lower curve is the distance of closest approach of the center of the stream to the mass-gaining star.

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

evidence for infall toward the central star. The velocity field was reversed on the leading side, with the lower density gas at the outer edge rotating the fastest. There was also indirect evidence for a collapse of the gas toward the disk plane. A difference in the brightness distribution between the two sides was seen during this eclipse of RW Tau and also in later eclipses of TZ Eri and SW Cyg. The line flux for the redshifted component declines steadily from second contact. However, the blueshifted component often shows a plateau or an abrupt change in slope between mideclipse and third contact. The latter is visible in both Figures 1 and 2. This may indicate a bifurcation or a two-component structure of the gas on the leading side.

2.1.4 *Relationship to Continuum Disks*. Olson has observed U Cep photometrically for over a decade (Olson 1978, 1980a, 1980b, 1982). When the mass transfer is high he finds evidence for a transient continuum emitting disk, revealed by 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 Olson's model the continuum 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 star and produce a continuum excess. Intuitively, one might expect the continuum and emission line disks to be very closely related. 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 continuum disk and the emission line disk are small and both appear to be variable and transient.

We have obtained time-resolved spectroscopy and UBV photometry of U Cep during 6 eclipses in a 3 month interval (Kaitchuck, Honeycutt and Faulkner, 1988). On four nights the photometry and spectroscopy were simultaneous. The radius of the continuum disk (when present) was remarkably constant at 1.2 R_{pri}, while the emission line disk varied from 1.2 to 1.6 R_{pri}. This suggests that the emission line disk is larger on average than the continuum disk. There were times when line emission was seen at an inner contact point without any continuum excess. At other times the reverse was true or both were present. This suggests that these two regions are not as closely related physically as our intuition would have led us to believe. These observations sampled a time period when neither the line emission nor the continuum emission were particularly strong.

2.2 SURVEY FOR TRANSIENT DISKS

To obtain some basic statistics on transient disks, we undertook a spectroscopic survey of short-period Algol systems (Kaitchuck and Honeycutt 1982b; Kaitchuck, Honeycutt and Schlegel 1985). There have been few modern surveys of the accretion disks in Algol systems (Plavec and Polidan 1976; Peters 1980). Unlike previous surveys all of our observations were conducted with time-resolved spectroscopy during

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

primary eclipse in order to enhance the probability of detection.

We have observed over 52 systems and 104 eclipses. For the systems with periods under 5 days, emission was found in 6 out of 47 systems. It should be noted that in short-period Algol systems a null detection at a single epoch does not prove the lack of a transient disk. However, had line emission been visible in all systems as frequently as it was seen in U Cep and RW Tau (~ 50 % of the time) there should have been ~ 23 systems with detected emission. In addition to RW Tau and U Cep, emission was detected in 4 systems: SW Cyg, RW Mon, RR Dra and TZ Eri. SW Cyg has long been suspected of having a disk based on photometric distortions of its light curve, and emission lines seen by Hall et al. (1979). TZ Eri, RR Dra and RW Mon were new discoveries; no disk had been previously reported in these systems.

Most short-period Algol systems are probably still undergoing some mass transfer, because period changes are common and Olson's survey (Olson 1982) found photometric disturbances to be common. Then why do so few of them show emission lines in eclipse? The answer may lie in the mechanics of the disk formation. Figure 4 shows a plot of the radius of the primary star (in units of the stellar separation) versus mass ratio M_{sec}/M_{pri}. Systems without disks are plotted as diamonds. Only systems which have been surveyed in eclipse are plotted since this is a strong null detection. The filled squares are the transient disk systems found in our survey as well as those reported by others in the literature. The third group, plotted as crosses, are the permanent disk systems. These are the long-period systems which always show emission lines characteristic of disks. The two curves in the figure are taken from Lubow and Shu (1975). The upper curve represents the expected radii of inviscid Keplerian disks. The lower curve is the minimum distance between the center of the mass-gaining star and center of the stream. For systems which fall well below this lower curve, a stable, Keplerian disk is expected to form. For systems which fall slightly above or below the lower curve only a portion of the stream strikes the star, due to the finite width of the stream. For systems high in the diagram the stream collision with the mass-gaining star is complete. The three disk types tend to occupy distinct regions of the plot. The transient disk systems appear to be those for which the mass-gaining star is just large enough to insure a collision with the entire stream. One possible explanation for Figure 4 is the following. For systems high in the diagram, the stream strikes the star near the center of the stellar disk and the stream may simply penetrate the star as suggested by Olson (1980a) for U Cep. For systems lower in the diagram, the stream will make a more grazing impact with the primary star near its limb, resulting in more "splashed" material producing a transient disk. For systems somewhat lower in the diagram the stream collision is partial, and enough material misses the star to produce a highly visible "permanent" disk. But the disturbance of the star/stream interaction may prevent this from being a classical Keplerian disk (see the next section). Finally, for systems below the lower curve, the stream completely misses the mass-gaining star and a classical accretion disk structure is formed. In order to test these ideas it is important to extend these observations to other objects

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

falling in various locations of this diagram, especially to systems which appear to have permanent disks, yet which should have partial stream collisions.

2.3 PERMANENT DISK SYSTEMS

The Keplerian nature of the permanent disks has rarely been tested observationally (e.g., Baldwin 1978; Smak 1981). Obviously this test is important for our ideas about disks and disk formation. To date we have examined only three such systems: RY Gem, RY Per, and RW Per.

The permanent disk system RY Gem is located slightly below the lower curve of Figure 4 ($q = 0.16$, $r_1 = 0.096$; Plavec and Dobias 1987) in a region where just the inner surface of the stream should collide with the mass-gaining star. Yet this system contains a disk which is in many ways similar to a transient disk (Kaitchuck 1988). There is a 50 km s^{-1} difference in the rotational velocity between the leading and trailing side, and the rotational velocity on the trailing side is a steeper function of distance from the star than it is on the leading side. The rotational velocities on the leading side appear to be sub-Keplerian. As in the transient disk systems, the plot of velocity versus line width shows no smooth curve, indicating that the lines are not rotationally broadened. The lines on the trailing side are broader than expected from a Keplerian disk. This again indicates the presence of turbulence. Indeed, Plavec and Dobias (1987) have found high excitation emission lines in RY Gem. These data suggest that a partial stream collision can produce a turbulent, non-Keplerian disk.

RY Per is a permanent disk system, yet if we adopt the recent system parameters of Van Hamme and Wilson (1986) we find that the stream should impact the star completely ($q = 0.30$, $r_1 = 0.14$). Analysis of two eclipses is still underway. However, in neither eclipse was a blue Doppler component seen, only a red component which was visible until the end of totality.

On the other hand, RW Per is a system for which the stream should completely miss the mass-gaining star ($q = 0.15$, $r_1 = 0.08$; Wilson and Plavec 1988). We have only one set of data, but there appears to be a velocity difference between the two sides of the disk of about 100 km s^{-1}. Clearly this is not the signature of a Keplerian disk.

3. **Summary**

The picture of accretion disks in Algol systems which has emerged is more complete than Joy's gaseous rings, and much more complex. The emission line disks in short-period Algol systems are small, with variable asymmetries between the leading and trailing sides. The velocity fields are non-Keplerian and there appears to be supersonic turbulence. The relationship between the continuum and the emission line disks is still unclear. The latter is probably slightly more extended. They need not be present together. Transient disk systems appear to be those in which the mass-gaining star is just large enough to stop the entire stream. Much work remains to be done in order to understand the spatial and physical relationships between the optical

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

continuum producing region, the HTAR and the optical emission line producing region. Our initial observations of permanent disk systems do not give support for the presence of Keplerian disks in long-period Algol systems. The results for RY Gem suggest that if one accounts for partial stream collisions, then the *majority* of the Algol systems may contain non-Keplerian disks.

References

Baldwin, B. W. 1978, *Ap.J.*, **226**, 937.
Batten, A. H., 1973, *Binary and Multiple Systems of Stars* (New York: Pergamon).
__________., 1988, *Pub.A.S.P.* **100**, 160.
Crawford, R. C. 1981, Ph.D. Dissertation, University of California, Los Angeles.
Hall, D. S., Quarles, T., Roberts, J., Whelan, J. A. J. 1979, *Acta Astr.* **29**, 653.
Joy, A. H. 1942, *Pub.A.S.P.* **54**, 35.
Kaitchuck, R. H. 1988, *Pub.A.S.P.* **100**, 594.
Kaitchuck, R. H., and Honeycutt, R. K. 1982a, *Ap. J.* **258**, 224.
__________. 1982b, *Pub.A.S.P.* **94**, 532.
Kaitchuck. R. H., Honeycutt, R. K., and Faulkner, D. R. 1988, *Ap.J.*, in press.
Kaitchuck, R. H., and Park, E. A. 1988, *Ap.J.* **325**, 225.
Kaitchuck, R. H., Honeycutt, R. K., and Schlegel, E. M. 1985, *Pub.A.S.P.* **97**, 1178.
Lubow, S. H., and Shu, F. H. 1975, *Ap. J.* **198**, 383.
Olson, E. C. 1978, *Ap. J.* **220**, 251.
__________. 1980a, *Ap. J.* **237**, 496.
__________. 1980b, *Ap. J.* **241**, 257.
__________. 1982, *Ap. J.* **259**, 702.
Peters. G. J. 1980 in *Close Binary Stars: Observations and Interpretation, I.A.U. Symposium No. 88*, M. J. Plavec, D. M. Popper, and R. K. Ulrich, eds. (Dordrecht: Reidel), p. 287.
Peters, G. J., and Polidan, R. S. 1984, *Ap. J.* **282**, 745.
Plavec, M. J. 1968, *Bull. Astr. Inst. Czechoslovakia*, **19**, 11.
Plavec, M. J. 1983, *Ap.J.*, **275**, 251.
Plavec, M. J., and Dobias, J. J. 1983, *Ap. J.* **272**, 206.
__________________. 1987, *A.J.* **92**, 440.
Plavec, M. J., and Polidan, R. S. 1976, in *Structure and Evolution of Close Binary Systems, I.A.U. Symposium No. 73*, M. J. Plavec, D. M. Popper, and R. K. Ulrich, eds. (Dordrecht:Reidel), p. 289.
Pringle, J. E. 1981, *Ann. Rev. Astron. Astrophy.*, **19**, 137.
Smak, J. 1981, *Acta Astron.*, **31**, 25.
Struve, O. 1948, *Pub.A.S.P.* **60**, 160.
__________. 1949, *M.N.R.A.S.* **109**, 487.
Struve, O., and Huang, S.-S. 1957, *O.N.R.A.S.*, **3**, 161 (No. 19).
Verbunt, F. 1982, *Sp. Sci. Rev.*, **32**, 379.
Van Hamme, W., and Wilson, R. E. 1986, *A.J.*, **92**, 1168.
Wilson, R. E., and Plavec, M. J. 1988, *A.J.*, **95**, 1828.
Wyse, A. B. 1934, *Lick Obs. Bull.* No. 464, **17**, 37.

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press

DISCUSSION

In answer to Linnell, Kaitchuck stated that the uncertainty of velocity measurements was about the size of the symbols (± 20 km s^{-1}). Linnell also asked if the observed velocity distributions did not imply that matter accumulated somewhere in the system. Kaitchuck replied that probably much of the matter fell onto the star before reaching the leading edge of the disk. The leading edge sometimes appeared to be of lower density than the trailing edge. Budding questioned the use of the term "Keplerian" which could be strictly applied only in a two-body system. The presence of a second star implies that velocities in the stream can be only approximately Keplerian. Kaitchuck replied that the observed velocities were sometimes a factor of two smaller than the expected Keplerian velocity for a system consisting of star-plus-stream-element. The presence of a second star could not account for this.

Richards said that Hα work on Algol (M.T. Richards, S.W. Mochnacki and C.T. Bolton Astr. J. **96**, 326, 1988) showed a transient disk around the primary. The gas stream strikes the primary, but at a point above the photosphere (if the mass-loss rate is less than about 10^{-10} $m_\odot$ yr^{-1}). Algol falls on the upper line in Figure 4 of Kaitchuck's paper. Bolton confirmed that indications of circumstellar matter (but not necessarily of a disk) were almost always present in Algol and supposed that Kaitchuck's spectra were obtained with too low a signal-to-noise ratio to detect much of the activity. Livio cautioned against using as exact values the radii derived, for different mass-ratios, by S.H. Lubow and F.H. Shu (Astrophys. J.**198**, 383, 1975) and exhibited in Figure 4. The radii of disks in cataclysmic variables are usually larger than those obtained in the calculations of Lubow and Shu. Kaitchuck replied that he had observed Algol twice but was hampered by the partial eclipse and the brightness of the continuum. Quite possibly Bolton and Richards could detect lower levels of activity than could he. He agreed entirely with Livio and felt that the lower curve in Figure 4, which represents the minimum distance between the centre of the stream and that of the mass-gaining star, to be the more important.

Rucinski inquired about optical-depth effects in the Balmer lines. Kaitchuck replied that sometimes the Hγ/Hβ ratio corresponds to Menzel's case B (optically thin) but usually the ratio is close to unity, which implies an appreciable optical thickness. Neither the observed line-widths nor the radial-velocities are easily explained, however. Even if simple radiative transfer is assumed (which would be questionable because of the velocity gradient along the line-of-sight) the lines should be narrower, not broader as is observed. The last spectrum seen before totality and the first after are of the outer edges of the disk, no matter what the optical thickness. They give velocities that are sub-Keplerian. (Note: in a later discussion session, Plavec objected to the term sub-Keplerian, but no alternative was suggested. The term implies that the orbits in which stream particles are travelling will intersect the surface of the star.)

https://doi.org/10.1017/S0252921100087662 Published online by Cambridge University Press