FUNDAMENTAL PARAMETERS OF THE W SERPENTIS STARS

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(Received 20 October, 1988)

ABSTRACT. Application of digital cross-correlation spectroscopy to the spectra of the W Serpentis binaries SX Cas and RX Cas has allowed an accurate determination of the orbits and rotations of the (mass-losing) K-subgiant secondary components. The distortion of the primary radial-velocity curves due to the influence of the prominent accretion disks in these systems has been modelled to first order. This enables us to estimate K_1, and thereby the mass ratio $q \approx 0.30$, to within ~±20%. The absolute radii of the secondaries are derived independently from the observed rotations and periods, assuming synchronous rotation. They show that the stars fill their Roche lobes, or at least very nearly so. Rough fits to the available photometry shows both primaries to be unevolved mid-B stars; that in RX Cas appears completely obscured by the disk. Preliminary spectroscopic data for W Ser and W Cru show some promise for similar analyses of these systems.

1. INTRODUCTION

The W Serpentis group of binaries was defined by Plavec (1980); it comprises the Algol-like eclipsing systems RX Cas, SX Cas, V367 Cyg, W Cru, β Lyr, and W Ser itself, and possibly some related objects. Plavec showed that they are mass-transferring binaries in which the mass-transfer rate is relatively high. This is manifest in the large period changes observed, in the prominent accretion disks surrounding and in some cases completely obscuring the mass-gaining components, and in the rich far-UV emission-line spectra which persist through the eclipses and show much higher ionization levels than can be produced by the stellar components themselves. The W Serpentis stars offer important observational clues to the understanding of the accretion processes in mass-exchange binaries, in particular the fundamental question of the amount of mass and angular momentum lost *from* these systems during the mass-transfer process. Hence, they are significant in understanding the evolutionary history of the whole class of Algol binaries, to which they are generally considered closely related, and considerable attention has been given to them at this Colloquium from a number of viewpoints.

Space Science Reviews **50** (1989), 179–189.

With the authors' background in observational programmes designed to provide fundamental data - masses, radii, and luminosities - useful in the study of the evolution of *single* stars, it appeared of interest to attempt to provide improved data of this type also for some W Ser stars. Certainly, the present masses, radii, and luminosities of the components are some of the most basic observational constraints on any theoretical models of the evolution of these systems, even if they cannot be determined to the sub-percent level of accuracy which is possible in systems without photometric and spectroscopic complications.

One of the key questions to be addressed in this connection is whether the basic configuration of the W Ser systems really *is* similar to that of the "normal" Algol binaries. The latter were defined by Alan Batten at this Colloquium as binaries in which the less massive component fills its Roche lobe and the more massive star is not degenerate. Models of W Ser binaries have generally assumed that this is indeed the case, i.e. that they are semi-detached. However, studies of some individual systems have variously concluded that they appeared to be detached (SX Cas: Koch, 1972; Andersen, 1973a,b) or in contact (RX Cas: Strupat, 1987). Clarification of this fundamental point is obviously needed, and we have attempted to provide some relevant observational data.

The prominent accretion disks in the W Ser stars partially or completely obscure the spectra of the *primary* (mass-gaining) components from direct observation and introduce major distortions and irregular variability into the light curves. While some theoretical modelling of these effects is possible and has been done, we have concentrated on the information which can be obtained by studying the spectrum of the comparatively uncomplicated *secondary* (mass-losing) components. Observational difficulties arise from filling-in and blending by the primary spectrum. These can be alleviated by performing cross-correlation spectroscopy on photoelectrically recorded spectra of relatively high resolution. By controlling the S/N ratio and averaging over many lines, the net blending effects in even a faint secondary spectrum are minimized, and the secondary radial-velocity curve and rotational velocity can be determined to considerable precision. These new data provide quite strong constraints on the system geometry, as will be shown below.

In the following, we shall summarize our results for SX Cas and RX Cas, the details of which are now in press (Andersen et al., 1988a,b; Papers I and II), and briefly mention work in progress on W Ser itself and on W Cru. Our conclusion, that all the observational data are now consistent with a semi-detached model for these systems, did not meet with quite the expected general approval at the oral presentation of the paper. In this written version, we have therefore elaborated somewhat on the geometrical constraints imposed by the data (Sect. 3).

2. NEW OBSERVATIONAL RESULTS ON SX CAS AND RX CAS

2.1. Radial-velocity curves of the secondary components

Based on the rationale outlined above, we began observing SX Cas and RX Cas with the photoelectric scanner CORAVEL (Mayor, 1985), attached to the 1-m Swiss telescope at Observatoire de Haute-Provence, France, in October, 1981. CORAVEL basically performs a hardware cross-correlation between the stellar spectrum and a template based on the spectrum of Arcturus (K2 III), which includes some 1500 spectral lines in the region λλ 3600-5200. An approximate value for the heliocentric radial velocity is provided on-line at the end of each observation. Hence, it was immediately confirmed that we could indeed detect and measure the secondary spectrum in both systems. It also became clear that the early photographic velocities for SX Cas by Andersen (1973a) were fairly reasonable and that the secondary orbits for both systems were very similar, thus ruling out Struve's (1944b) puzzling orbit for the secondary of RX Cas. Observations of both systems were therefore continued; 24 CORAVEL observations of RX Cas had accumulated by January, 1983, and 43 of SX Cas by June, 1986, enough to define the secondary orbits of both stars to quite adequate precision (Figs. 1 and 2).

However, the scatter of the CORAVEL velocities of RX Cas around a preliminary circular orbit was rather higher than expected (~4 km s^{-1}). This could be due to the shallow and broad lines of this rather fast-rotating star, or it could be due to pulsations as suggested by Kalv (1979). RX Cas was therefore reobserved in 1986-87 with the CfA echelle system (Latham, 1985) on the 1.5-m Tillinghast reflector of the Fred L.

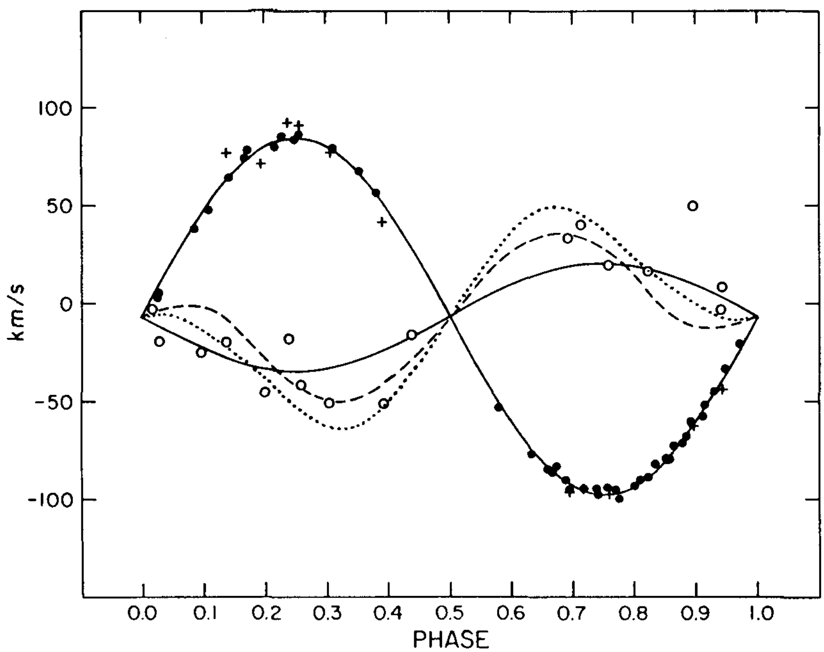

Fig. 1. Radial-velocity curves of SX Cas. *Dots:* CORAVEL observations; *crosses:* secondary and *circles:* primary (shell) velocities from Andersen (1973a). *Full lines:* adopted orbits and *short-dashed:* computed shell velocity curve for q = 0.30; *dotted line:* shell curve assuming q = 0.40.

https://doi.org/10.1017/S0252921100087777 Published online by Cambridge University Press

Whipple Observatory at Mt. Hopkins, Arizona. A total of 45 observations covering a 50-Å spectral range centered on λ 5187 was obtained; radial velocities were determined by numerical cross-correlation with a K1 III template spectrum, corresponding to the spectral type of the secondary star as observed by Weiland and Plavec (1983).

Presumably because the somewhat lower resolution of the CfA spectra is better matched to the broad spectral lines in RX Cas, the precision of the CfA radial velocities is considerably higher (~1.3 km s^{-1}) and rule out the presence of any significant pulsational motion in the secondary. Moreover, they allow a very convincing empirical check of the velocity corrections for tidal deformation and gravity darkening of the star, and for reflection, as computed by the Wilson and Sofia (1976) method (Paper II). After these corrections have been applied, the CORAVEL and CfA orbits are in excellent agreement (Fig. 2).

The spectroscopic orbits of the secondaries of both SX Cas and RX Cas are clearly circular, as expected from their light curves. The orbital elements are very similar: γ = -6.5±0.5 km s^{-1} and K_2 = 91.1±0.5 km s^{-1} for SX Cas, γ = -5.65±0.17 and K_2 = 99.20±0.24 km s^{-1} for RX Cas. This precision is quite ample for all practical purposes; apart from the orbital periods, γ and K_2 are now the best-known observational parameters for both systems. Note that the precise value of γ is of more than usual interest in these systems, because it fixes one of the two orbital elements to be derived from the velocity measurements of the (shell around the) primary component, leaving only K_1 to be adjusted.

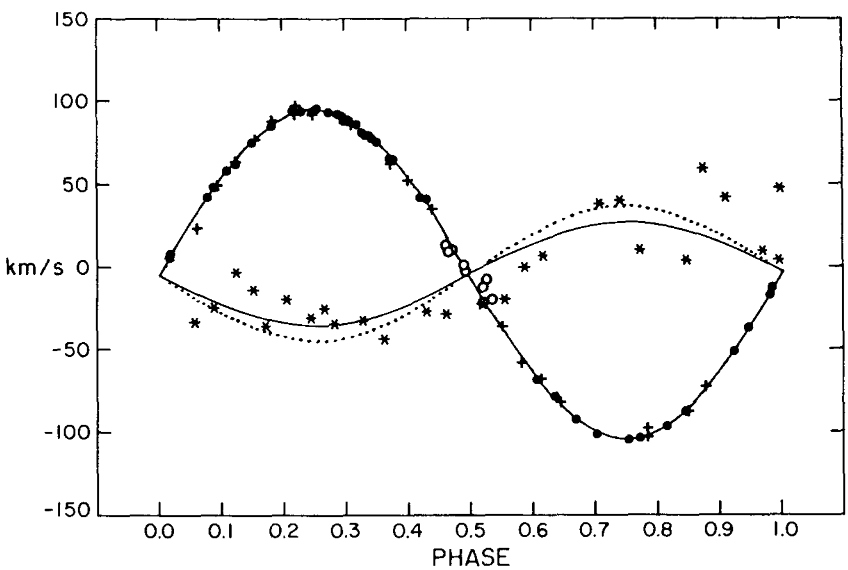

Fig. 2. Radial-velocity curves of RX Cas. *Dots:* CfA and *crosses:* CORAVEL secondary velocities; *asterisks:* Struve's (1944b) primary (shell) Ca II K velocities. *Full lines:* adopted orbits (q = 0.30); *dotted line:* primary orbit assuming q = 0.40.

https://doi.org/10.1017/S0252921100087777 Published online by Cambridge University Press

In addition to γ and K_2, the radial velocities provide a zero-phase epoch - effectively a predicted time of minimum - which is precise to $\pm 0^d.015$ (20 min or $0^P.0005$) in the case of the CfA observations of RX Cas. Here again, observing the unobscured secondary component enables us to determine an equivalent time of minimum more precisely than is possible by photometry due to the long duration of the eclipses and the irregular light variations. Our results confirm and improve earlier determinations of the period changes in the two stars. In RX Cas the period increases, as expected in the case of conservative mass transfer from the less massive to the more massive component. In SX Cas the period *decreases*, however, a possible indication of non-conservative mass-transfer.

2.2. Rotational velocities of the secondary components

In cross-correlation spectroscopy, the width of the cross-correlation peak is a function of the average spectral line width and thereby of the rotation of the star. The high resolution and stable instrumental profile of CORAVEL make this instrument well suited for measuring rotational velocities to a precision of ~1 km s^{-1}, as shown by the calibrations of Benz and Mayor (1981, 1984). From the CORAVEL observations and these calibrations, we determine rotational velocities (mean over the orbital cycle) of $v\sin i$ = 31±1 km s^{-1} for SX Cas and 34±1 km s^{-1} for RX Cas.

These results are of decisive importance in the case of the W Ser binaries: The secondary components must be assumed to have synchronous rotation, so $v\sin i$ multiplied by the orbital period immediately establishes their absolute radii. This determination is quite independent of *both* spectroscopic *and* photometric orbital elements, except for the projection factor $\sin i$, which is close to unity in the eclipsing systems. From the measured rotations, we find $R_2 \sin i$ = 22.4±0.7 $R_\odot$ for SX Cas, $R_2 \sin i$ = 21.7±0.7 $R_\odot$ for RX Cas. The constraints on the system geometry imposed by these results are further explored in Sect. 3.

2.3. Spectroscopic orbits of the primary components

As noted above, our knowledge of the (circular) shape of the orbits and their γ-velocities leaves only the primary radial-velocity amplitudes, K_1, or equivalently q, the mass ratio, to be determined in order for the masses of both components to be completely known. The difficulty in determining K_1 is that the spectrum of the primary component itself is not directly observable, only that of the accretion disk surrounding it (cf. Struve, 1944a,b; Andersen, 1973b). The relationship between the motions of the star and of the disk is not *a priori* clear, and even the study of the disk spectrum itself is frustrated by its complex line profiles and large cycle-to-cycle fluctuations, added to the faintness of the systems. Spectroscopic observations of good phase and wavelength coverage combined with high spectral resolution and S/N ratio are needed for significant progress in understanding the structure and dynamics of the accretion disks. Such data do not yet exist and are neither easily nor quickly obtainable.

In the absence of definitive spectroscopic data, we have rediscussed the previous spectrographic observations by Andersen (1973a; SX Cas) and Struve (1944b; RX Cas), attempting to assess whether the effects of motions in the shell are likely to lead to major systematic over- or underestimates of K_1. In Paper I, a first-order model of particle trajectories in the disk of SX Cas for various assumed mass ratios led to an estimate of the shape of the observed (distorted) radial-velocity curve as illustrated by the short-dashed curve in Fig. 1. Although cycle-to-cycle variations produce large scatter in the shell velocities measured by Andersen (1973a), the computed curve is seen to reasonably represent the data for a K_1 of 27 km s^{-1} - which is exactly the result found by Struve (1944a). It is also seen that a brute-force sinusoidal fit to a reasonably balanced distribution of points would not lead to grossly incorrect results.

We do not have similarly "modern" spectroscopy for RX Cas. However, the Ca II K shell line should suffer relatively little blending with the broad and deep Ca absorption lines of the secondary spectrum. Encouragingly, the γ-velocity of a circular orbit determined from Struve's (1944b) measurements of the Ca II K shell line is very close to the true value, and the general trend of the deviations from a sine curve (Fig. 2) is not unlike that computed for SX Cas. We have therefore force-fitted a sine curve through Struve's K-line velocities and find K_1 = 30 km s^{-1}. Varying K_1 in the range of values for which the curves do not obviously misrepresent the data, we assign an uncertainty of ~20% to K_1. In summary, we find $q = m_2/m_1 = 0.30 \pm 0.06$ for both systems, or $K_1 = 27 \pm 5$ km s^{-1} for SX Cas, $K_1 = 30 \pm 6$ km s^{-1} for RX Cas (see also Sect. 3).

2.4. Photometric elements

The light curves of both systems are strongly affected by proximity effects, by asymmetries and distortions caused by the accretion disks, and - especially in RX Cas - by large intrinsic variability. As the following discussion will show, both systems are semi-detached or very nearly so, and the code used in the light-curve analysis must include an appropriate (Roche) geometry; Russell-Merrill or similar methods cannot be expected to give trustworthy results. Even then, application of standard differential-correction techniques is clearly fraught with dangers and cannot be recommended. Our approach has been to see if an acceptable approximation to the observed light curves could be obtained by assuming the systems to be semi-detached with the mass ratios given above and secondary temperatures as indicated by the spectral types, varying the other orbital parameters to improve the fit.

For SX Cas (Paper I), we have studied the light curves by Shao (1967), using the Wilson-Devinney (1971) program with the (unproved) assumption of near-critical rotation for the primary component, but without explicit allowance for the disk. For RX Cas, Paper II provides new *UBVRI* photometry by V. Piirola, analyzed with the method by Pavlovski and Kříž (1985), which includes Roche geometry, critical rotation of the primary, and a simple disk model. The detailed results are given in Papers I and II and will not be repeated here. Suffice it to say that without a disk model, a plausible, but not good fit to the light curves of SX Cas can be obtained. With a disk model, a quite respectable fit to the light curves of RX Cas can be found, but at the expense of three

https://doi.org/10.1017/S0252921100087777 Published online by Cambridge University Press

additional free parameters (disk temperature, thickness, and radius).

The salient results of these light curve fits can be summarized as follows: First, the fractional radii of the two secondaries are, of course, the same, $r_2 \approx 0.28$, as imposed by the specified mass ratio and semi-detached condition. Second, both inclinations are near 80°. Third, also the radii of the primaries are very similar, $r_1 \approx 0.03$, although in RX Cas this is only an upper limit as the disk is found to have a thickness of 3% of the orbital radius and to completely obscure the primary star itself from view. Fourth, also in RX Cas, the disk radius is found to be $r_d/a \approx 0.16$, and the disk temperature $T_d \approx$ 5500-6000 K, in agreement with the observation (Plavec, priv. comm.) that no continuum hotter than this is visible in the IUE spectra of RX Cas. The disk is evidently a more dominant feature in RX Cas than in SX Cas.

2.5. Physical parameters of the components

Combining the various spectroscopic and photometric parameters described above, we arrive at the masses, radii, and other parameters of the two systems as given in Table I below. The following points should be noted: First, the secondary stars fill their Roche lobes, by design. Second, assuming synchronous rotation for these stars leads to predicted *vsini*'s in excellent agreement with the observations; these relationships are further explored in Sect. 3. Third, the mass-gaining primaries are found to be mid-B stars, as indicated for SX Cas by the IUE spectra of Plavec et al. (1982), and are unevolved as one would expect for stars which have been refueled recently. Fourth, a disk of dimensions as found in RX Cas easily fits inside the Roche lobe of the primary, but any actual understanding of its structure requires far better spectroscopic data than those presently available.

We conclude that it is indeed possible to construct semi-detached models for both stars which are consistent with all modern observational data. As shown below, the actual properties of the components cannot be much different from those given in Table I. We suggest that they supersede earlier results until more definitive studies of the accretion disks have been completed.

Table I. Physical parameters of the components of SX Cas and RX Cas.

	Primary		Secondary	
	SX Cas	RX Cas	SX Cas	RX Cas
Mass ($M_\odot$)	5.1±0.4	5.8±0.5	1.5±0.4	1.8±0.4
Radius ($R_\odot$)	3.0±0.4	2.5::	23.5±1.3	23.5±1.2
log g (cgs)	4.2±0.1	4.4::	1.9±0.1	1.9±0.1
$vsini_{sync}$ (km s^{-1})	-	-	32±1	36±2
T_e (K)	8500 (disk)	?	4000±300	4400±300
M_v	0.7±0.4	?	0.1±0.4	-0.5±0.3
Distance (pc)	530±75	500±100		

3. VALIDITY OF A SEMI-DETACHED MODEL

In Sect. 2 we have shown that our observational data are *consistent with* the view that both SX Cas and RX Cas are semi-detached with a mass ratio of 0.30±0.06; we have not yet discussed how large deviations from this configuration can be permitted by the data. In order to do this, we take our new values of K_2 and $v\sin i$ for both systems to be valid and further assume that the rotation of the late-type secondaries is synchronized with the orbit; for convective stars of such large relative radii, this should be a quite safe assumption. The observed rotations then lead to mean radii R_2 for the two stars of 23.7±0.7 $R_\odot$ for SX Cas, 22.8±0.7 $R_\odot$ for RX Cas (the projection factor $\sin i^{-1}$ has been applied, but cancels out in the $v\sin i$ and radius ratios computed below).

The two quantities of interest in the following are the mass ratio $q = m_2/m_1$ (or equivalently, K_1), and the ratio between the actual mean radius R_2 of the secondary star and the corresponding mean (volume) radius of its Roche lobe, $R_{\rm Roche}$. For a number of assumed mass ratios, Table II gives the fractional mean radius $r_{\rm Roche}$ of the secondary Roche lobe, then, for each system, K_1, M_1, and $R_{\rm Roche}$, and the mean synchronous rotational velocity ($v\sin i$) for a hypothetical lobe-filling secondary star, and finally $R_2/R_{\rm Roche}$, which turns out to be the same for both systems for given q. The corresponding values of M_2 are calculated trivially from q and M_1.

Table II clearly shows that, on the minimum assumption that the secondaries rotate synchronously and do not *over*fill their Roche lobes, the observed $v\sin i$ rule out mass ratios less than about 0.25, i.e. the range favored by most earlier photometric solutions. We also see that if we assume q = 0.40, i.e. 2 σ above our adopted mean value, the secondary *could* underfill its Roche lobe by 15-20% while retaining the observed

Table II. Primary radial velocity amplitudes, masses, relative and absolute secondary Roche lobe dimensions, and Roche lobe rotations for specified mass ratios in SX Cas and RX Cas, and actual secondary radius in units of the Roche lobe radius.

		SX Cas				RX Cas				
q	$r_{\rm Roche}$	K_1 km/s	M_1 $M_\odot$	$R_{\rm Roche}$ $R_\odot$	$v\sin i$ km/s	K_1 km/s	M_1 $M_\odot$	$R_{\rm Roche}$ $R_\odot$	$v\sin i$ km/s	$R_2/R_{\rm Roche}$
0.10	0.21	9.1	3.7	15.1	21	9.9	4.1	14.5	22	1.57
0.15	0.23	13.7	4.0	17.6	24	14.9	4.5	16.9	26	1.35
0.20	0.25	18.2	4.4	20.0	27	19.8	4.9	19.2	30	1.19
0.25	0.27	22.8	4.8	22.4	30	24.8	5.4	21.6	32	1.06
0.30	0.28	27.3	5.1	23.5	32	29.8	5.8	23.5	36	1.01
0.35	0.29	31.9	5.5	26.4	36	34.7	6.3	25.3	39	0.90
0.40	0.30	36.4	6.0	28.4	38	39.7	6.7	27.2	42	0.83
Observed					31±1				34±1	

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vsini. However, this requires accepting a 1/3 increase of K_1 for both systems. The corresponding (shell and stellar) velocity curves are shown in Figs. 1 and 2 as dotted lines, which we do not consider to reasonably represent the observed shell velocities.

We conclude that our quoted errors are in fact fairly realistic estimates of the actual uncertainty of the results. It follows that both systems, and presumably the W Ser stars as a group, do indeed conform quite closely to Alan Batten's definition of Algol binaries. Current mass transfer would then appear to involve Roche-lobe overflow, although we cannot exclude the possibility that the secondaries *might* underfill their Roche lobes by perhaps 10% or so.

4. W SERPENTIS AND W CRUCIS

Encouraged by our results on SX Cas and RX Cas, we have proceeded to explore the possibilities of applying the same methods to two other members of the W Ser group, W Ser itself and W Cru. These systems appear to be more difficult than SX Cas and RX Cas, W Ser because the accretion disk appears to be even more dominant in both spectrum and light curve than in RX Cas, and W Cru because of its long period (198^d). However, it appears worthwhile to examine their spectra for signatures of late-type secondaries which might provide improved data on the masses and radii of the components. We have therefore started exploratory observations of W Ser with the CfA echelle systems, and of W Cru with CORAVEL II on the Danish 1.5-m telescope at ESO, La Silla.

Our results on both stars still cannot be considered definitive detections, but present indications are that cool secondaries are in fact present in both stars. In W Ser, the mass ratio may be considerably smaller than in SX Cas and RX Cas; observations are being continued. In W Cru, the secondary correlation peak is so broadened by rotation that it may be impossible to get meaningful measurements with CORAVEL. However, an improved primary radial-velocity curve should be quite easy to obtain, and we would then hope to determine the mass ratio from CCD spectra in the red, obtained near the quadratures; with a half-year orbital period, this is obviously a several-year project.

5. CONCLUSIONS

We have shown that digital cross-correlation spectroscopy applied to the spectra of the cool secondary components in W Ser (and potentially other Algol) binaries is a powerful tool in improving the data on the masses and radii of the components. As a result, the basic physical parameters of both SX Cas and RX Cas have been determined much more reliably than before, and a semi-detached model with $q = 0.30$ (±20%) has been shown to be acceptable for both systems. The observed rotations show that q cannot be significantly *smaller* than this result, but without more accurate data on the motion of the primaries we cannot exclude the possibility that q might be a bit larger, with the secondary underfilling its Roche lobe by perhaps 10%. Even larger values of q would appear to be incompatible with the observed velocity variations of the accretion disks.

Our results on SX Cas and RX Cas, and their implications for the W Ser binaries as a group, should be of interest in future studies, both of the structure of the accretion disks and the details of the mass-transfer process, and of the evolutionary history of these systems. Perhaps it will become possible to shed light on the question whether mass loss from the originally more massive star and/or mass transfer to its companion has proceeded mainly according to the conventional picture of Roche-lobe overflow, or whether stellar winds and magnetic braking play a major role as proposed by Eggleton and Tout (this Colloquium).

Acknowledgements. We thank our collaborators on Papers I and II, especially M. Mayor, and several of our CfA colleagues, for their contributions to this study. Financial support from the Carlsberg Foundation and the Danish Natural Science Research Council for this research, and from the IAU for our participation in this Colloquium, are gratefully acknowledged.

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DISCUSSION

In response to Hall, Andersen stated that he believed neither star in RX Cas to be responsible for the long-period variation between high and low states. The variation appears to be in the disk, which may be hotter and thicker in the "high" state. Wilson emphasized that the fitting of light-curves of systems that have disks should be done with models that have disks built in; otherwise erroneous values may be obtained for the radii of the stars. Andersen emphasized the importance of the spectroscopic information now available for SX Cas and RX Cas and that he used the light-curves only to supply estimates of the orbital inclination and the radius of the secondary. Rucinski commented that both stars exhibit strong changes in polarization and these could be used to provide additional information about the sizes of the disks. Leung drew attention to the new light-curves of SX Cas obtained in Korea and on display in the poster room.

Guinan recalled that the effective wavelengths of the bandpasses of the UBV filters are dependent on spectral type. During the eclipse of an Algol-type system, therefore, the effective wavelength of each filter could change by as much as 200Å (20nm) and if care is not taken in the reduction of observations, serious errors may be introduced into the interpretation of light-curves. He recommended use of the Strömgren ubvy system, whenever practicable. In reply, Andersen claimed never to have been guilty of observing any astronomical object in our own Galaxy in the UBV system!

Peters asked if mass-loss from SX Cas had been studied. As do other Algols, this system seemed to show spectroscopic evidence near phase $0\overset{p}{.}5$ for increased mass outflow (the Hα core is stronger the ratio of V/R emission is smaller). Andersen replied that their chief interest had been in the properties of the stars. He pointed out that the evidence from period changes is ambiguous.

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