IUE OBSERVATIONS OF LONG PERIOD ECLIPSING BINARIES: A STUDY OF ACCRETION ONTO NON-DEGENERATE STARS

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ABSTRACT

It has long been thought that β Lyrae is a unique system, by virtue of its UV spectrum and its nature. I will argue that a whole class of interacting long-period binaries exists, similar to β Lyrae. According to IUE observations made in 1978-79 by myself and R. H. Koch, this group comprises: RX Cas, SX Cas, V 367 Cyg, W Cru, β Lyr, and W Ser. AR Pav is a transition case linking them with the symbiotics. I also suggest that HD 218393 (KX And), HD 72754, and HD 51480 are their non-eclipsing counterparts. I will call the whole group the W Serpentis stars.

These systems are mass-transfering binaries (case B) in which the mass transfer rate is relatively high, probably on the order 10^{-6} to 10^{-4} $M_{\odot}$/year. They display an ultraviolet continuum with a color temperature definitely higher than the one observed in the optical region. Even more characteristical is the presence of strong emission lines of N V, C IV, Si IV, Fe III, Al III, and lower ions of C and Si. I will attempt to discuss these phenomena on the assumption that they are due to accretion onto non-degenerate stars.

INTRODUCTION

We seem to understand reasonably well how a star reacts to mass loss. Evolutionary sequences describing the evolution of the losers in mass-transfering binary systems were calculated already more than ten years ago. We understand very poorly how the on-flowing mass is accreted by the gainer. Several authors (to name only some: Flannery and Ulrich, 1977; Packet and de Grève, 1979) argue that the gainer will swell up rapidly soon after the onset of mass transfer and will also fill its critical Roche lobe. With less certainty, these authors suggest that rapid mass loss from the system will ensue, causing the system to shrink and thereby aggravate its instability against mass loss. One is tempted to wonder how all the observed Algols could have survived this ordeal!

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This paper is a preliminary report on a systematic effort aimed at studying accretion observationally. Every Algol system offers us some information, and not all of it has been extracted yet. For example, the chemical composition and atmospheric structure of the gainers have been almost neglected, although they should provide important clues on the problem mass transfer vs. mass loss from the system. This is why J. Dobias and myself at UCLA have embarked on a program studying not only the composition of the losers (a controversial topic, see Plavec and Polidan, 1976), but also of the gainers. Spectrograms to be used in spectrum synthesis are being supplemented by scanner data on the energy distribution in the continuum, and by IUE observations in the far UV. The IUE spectra I have obtained (U CrB, RZ Sct, TX UMa, even the more anomalous AU Mon and V356 Sgr), and those obtained by Koch (U Cep, TT Hya, RW Per) appear normal and agree with the spectral classification in the optical region. This is not surprising, since the rate of mass transfer in ordinary Algols is probably quite low. The Algols are simply ladies with a most interesting past, but are (contrary to what is fashionable nowadays) extremely uncommunicative about that past.

DISCOVERY OF THE W SERPENTIS CLASS OF BINARIES

In order to study cases with higher rates of mass transfer, I began to study certain Algol-like systems of longer period, such as W Ser, V 367 Cyg, W Cru, and of course β Lyr. Fortunately, R. H. Koch had other similar stars on his (originally Sobieski's) program: SX Cas, RX Cas, and AR Pav (which can probably be classified both as an Algol and a symbiotic star). These systems have one important feature in common (apart from a relatively long period, 13 - 605 days): They display emission lines (H, He I, Fe II as the case may be) which, if the energy supply is radiative, imply the presence of a much hotter source in the system than the observed optical spectra indicate. For example, at Lick, Plavec, Polidan and Peters discovered emission lines of He I in W Ser (Fig. 1), whose optical spectrum is usually classified as F5 II, and which certainly shows no traces of anything hotter than early A. Because of these emission lines, the UV spectra promised important answers. What we found is exciting, in both senses of this word, but poses more problems than answers (for a preliminary report, see Plavec and Koch, 1978).

The seven systems enumerated above show two prominent features in the far ultraviolet: (1) A continuum with a color temperature higher than the one inferred from the optical spectrum, but apparently not hot enough to excite He I (about 12,000 K). (2) A very rich and prominent emission line spectrum with the N V doublet at 1240 A, C IV doublet at 1550 A, and lines of Si II, Si III, Si IV, C II, Fe III, Al III, etc. These are mostly zero-volt lines, that is transitions to the ground state level of the ion, and are no doubt excited collisionally. The source of energy maintaining the relatively high level of ionization is not so clear. If C IV and N V are ionized collisionally under conditions similar to the transition zone between the chromosphere and the corona in the Sun, then they require electron temperatures up to and above 200,000 K. The He II recombination lines, such as λ 1640 A, are absent (except in AR Pav)

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Figure 2 shows the UV spectrum of SX Cas with its numerous strong emissions and deep absorptions, as well as its optical spectrum observed with the Lick scanner. The Figure shows that the whole energy distribution cannot be fitted by the Kurucz model atmosphere for a giant with T_{eff} = 8,500 K, which appears quite appropriate for the optical spectrum. Figure 3 shows the UV spectrum of W Serpentis and demonstrates that at primary mid-eclipse, which is partial, the continuum flux is diminished but the emission lines are almost unafffected. Observations of a total eclipse of SX Cas in February 1979 (Fig. 4) give an even more definite picture: When the optical spectrum of the gainer, usually classified as A6 III, disappears, the hotter UV continuum disappears as well, but the emissions stay and are not markedly weakened. A more complete discussion of our observations will be published elsewhere, jointly with R. H. Koch. Here I would like to present my own thoughts on them.

ACCRETION ON NON-DEGENERATE STARS

Obviously, both the optical continua (A6 III in SX Cas, F5 II in W Ser) and the hotter (perhaps B8) UV continua are associated with the gainers; therefore the gainers cannot be ordinary stars, and must have a more complex structure. Perhaps a more complete run through the total eclipse of SX Cas will reveal a phase shift in the eclipses of the two continua. On the other hand, the emission lines cannot originate anywhere near the gainer, since they are not eclipsed together with it. The emission lines are not too different from those typically observed in giants like Capella. In view of the close similarity between Capella and the G5 III loser in SX Cas, it is tempting to explain the emissions as the loser's chromosphere-corona signature. However, there are serious objections: (1) The energy radiated in these lines in SX Cas and other W Ser stars is several orders of magnitude greater than in Capella or even the RS CVn stars. (2) The N V line competes in strength with C IV, or is stronger, while in giant chromospheres and in all regions of the Sun, N V is always considerably weaker (Doschek et al., 1978). (3) In SX Cas and RX Cas a suitable G-type giant is available, but there is none in β Lyr (where the loser is B8 II). (4) In β Lyr, most of the emissions do not participate in the orbital motion of either component, and those few that do indicate trend to move with the gainer (Hack et al. 1976, 1977; Plavec and Dobias, 1979).

I believe that both the hot continua and the very hot plasmas whose presence has been detected by means of the IUE spectra, are related to a large rate of mass transfer in the W Ser stars. β Lyr, W Ser, SX Cas, RX Cas, and V 367 Cyg are known to display unusually large period variations; the two long-period systems, W Cru and AR Pav, are of course less well observed. All are case B systems, where a higher mass transfer rate must be anticipated at all times except at the very end of the process. Large and often erratic fluctuations of light are known to exist in all of them. The optical absorption spectra of the gainers in SX Cas, RX Cas, V 367 Cyg, and W Ser are shell spectra, indicating a dense circumstellar envelope, which is also manifested by the presence of emission lines even in the optical spectra.

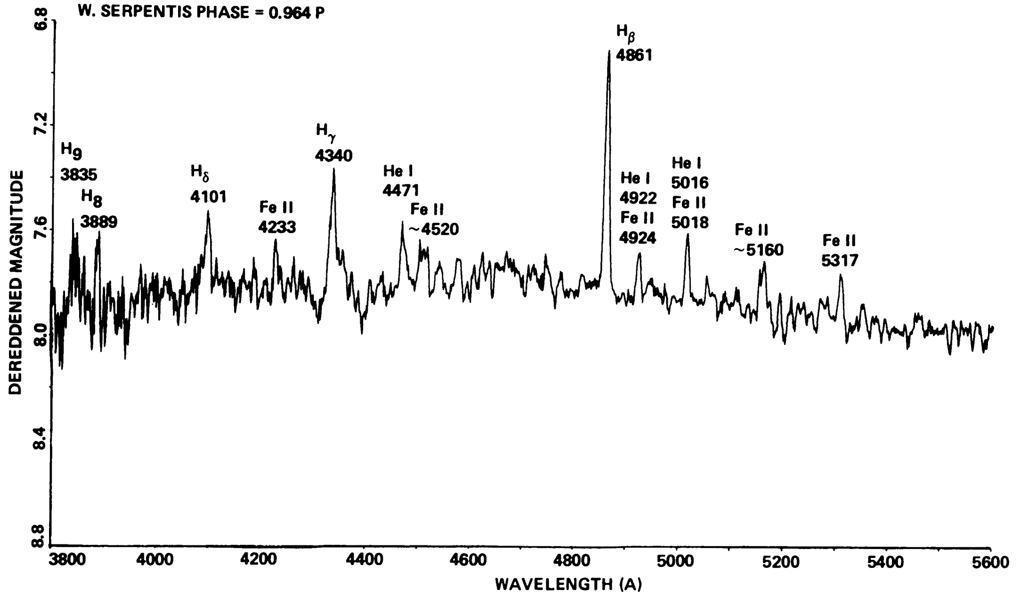

Fig. 1: Optical spectrum of W Serpentis at primary eclipse.

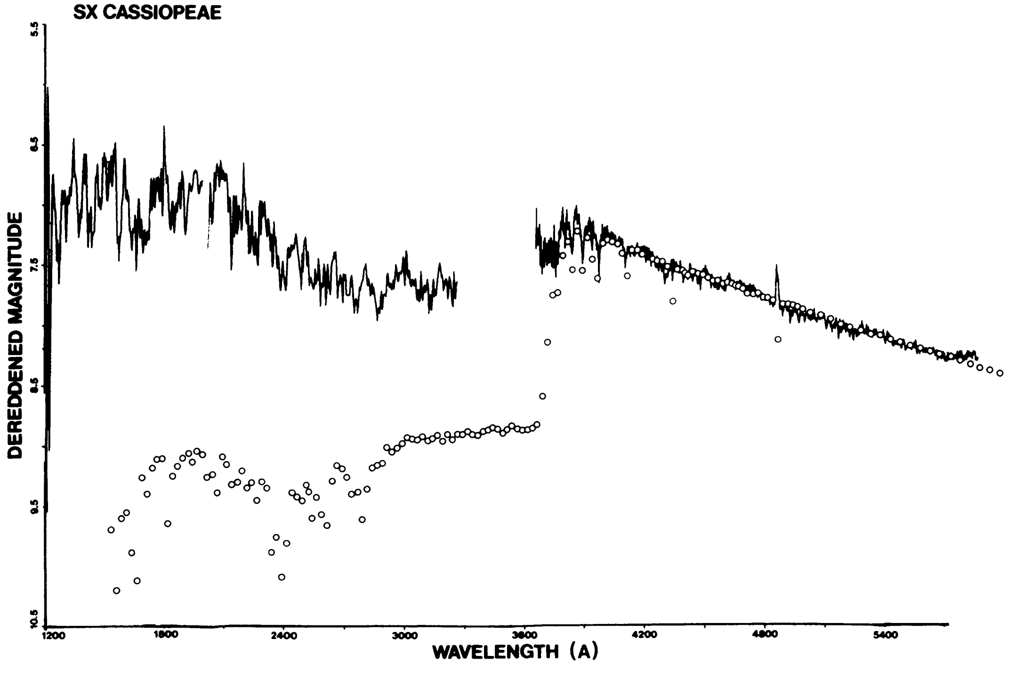

Fig.2: SX Cassiopeae: Energy distribution outside eclipse.

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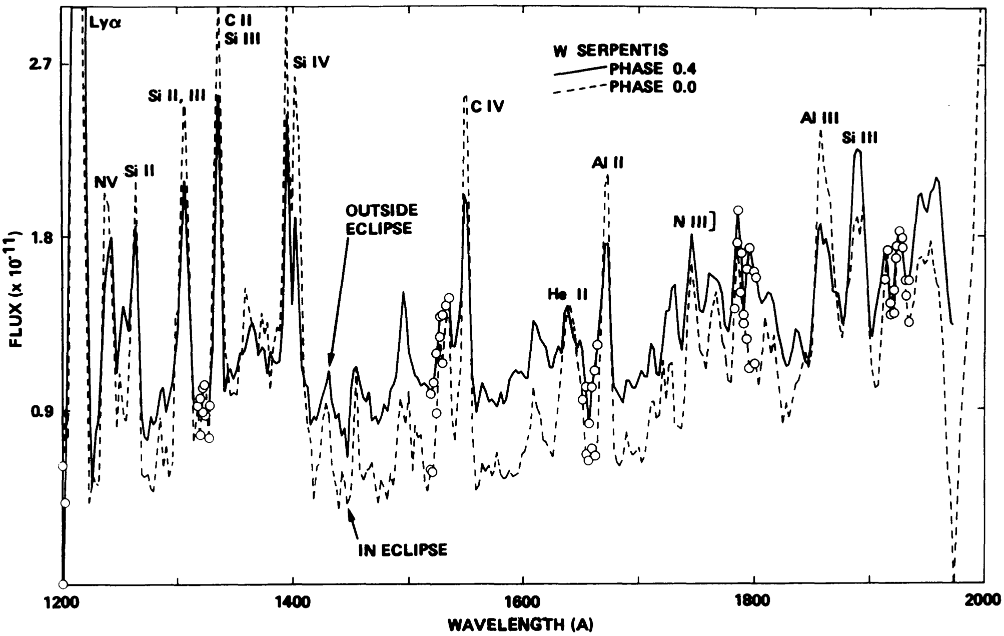

Fig. 3: Ultraviolet spectra of W Serpentis.

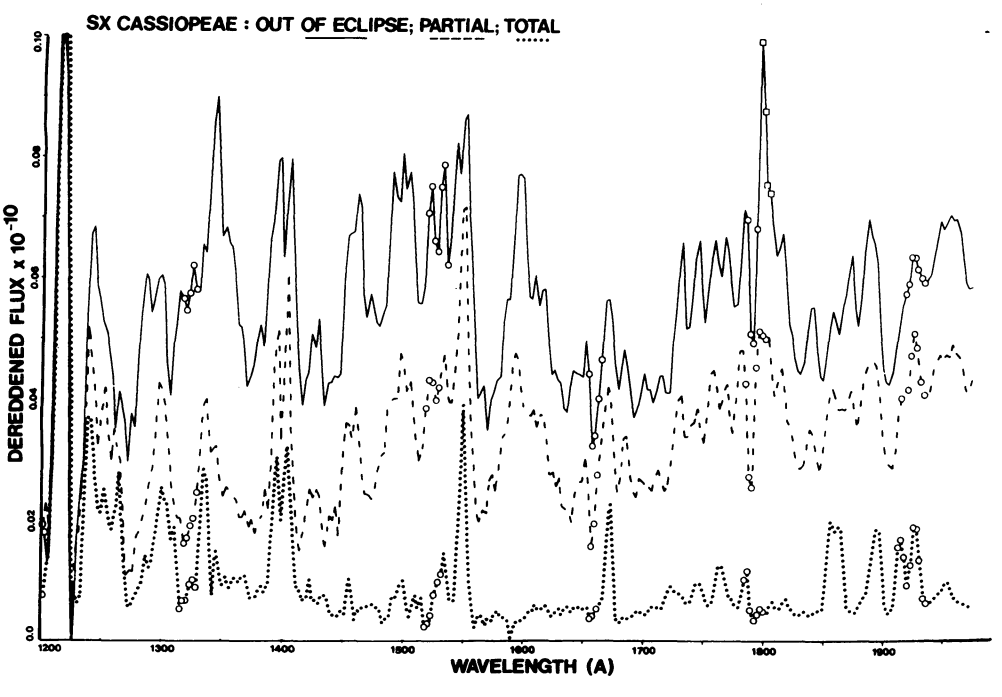

Fig. 4: Ultraviolet spectra of SX Cassiopeae.

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All these facts suggest that we should study accretion processes in these stars, and apply the concepts developed for cataclysmic variables to accretion onto non-degenerate stars. We do not have a fully convincing evidence that the gainers in the W Ser systems are (or, better, initially were) main-sequence stars, but the systems appear to be a natural continuation of the Algols to longer periods. For simplicity, I will assume that the gainers are MS stars of moderate mass. My estimate of 3.6 $M_\odot$ for the gainer in SX Cas may be typical, or may be a bit below average). For some order-of-magnitude estimates it is useful to assume that the radii of the MS stars scale approximately as $R \sim M^{0.7}$ and intrinsic luminosities as $L \sim M^{3.5}$.

If mass is transferred ultimately to the surface of the gainer, the total accretion energy available is $L_a = 3.1\times10^7 \dot{M} M/R$, in solar luminosities. (I will consistently express M, R, L in solar units, and the mass transfer rate $\dot{M}$ in solar masses per year). Comparing the accretion luminosity L_a with the star's intrinsic luminosity L_* , we find for MS stars

$$L_a/L_* \simeq 3.1\times10^7 \dot{M} M^{-3.2} . \quad (1)$$

For low- and moderate mass stars, it is fairly easy to produce more energy by accretion than by nuclear generation. If we assume a 3.6 $M_\odot$ main-sequence gainer in SX Cas, both luminosities will be equal for $\dot{M} = 2\times10^{-6}$ $M_\odot$/year, which may very well be the correct value for SX Cas. β Lyrae, with its much more massive gainer ($\sim$ 15 $M_\odot$) requires 2×10^{-4} $M_\odot$ per year for $L_a = L_*$, but this value, too, is quite possible. Thus we must realize that in some case B systems, the true nature of the accreting star may be greatly obscured by the accretion process.

An upper limit to $\dot{M}$ for the gainer is set by the Eddington luminosity, which (for electron-scattering opacity) is $L_c = 3.2\times10^4$ M, and is reached for $\dot{M}_c = 1.1\times10^{-3}$ R. For most W Ser systems, where we can anticipate $\dot{M} \sim 10^{-5}$ $M_\odot$/year, we are comfortably in the subcritical domain. However, even for MS gainers supercritical accretion is not ruled out, and certain observations of the emission lines in βLyr suggest that that system may not be far from critical accretion.

With MS gainers, it may happen that the characteristic accretion temperature will fall below 10^5 K, in which case photoionization tends to become more important than electron scattering. Buff and McCray (1974) showed that for photoionization as the main opacity source, the Eddington limit may fall below the above-given value by a factor of 10 if not 100. The effect is difficult to evaluate, since Buff and McCray assumed a simple continuous spectrum with a cutoff, while actually the EUV spectrum at these temperature is dominated by individual emission lines (Stern et al., 1978).

On the other hand, the peak rate of mass outflow from losers with radiative envelopes is $\dot{M} = 3.2\times10^{-8}$ R L / M , where all the values (in solar units) refer to the loser at the onset of mass transfer (Paczynski, 1971). For a 7 $M_\odot$ starting to lose mass just beyond the Main Sequence, this value is $\dot{M} = 10^{-4}$. Supercritical rate of mass loss will induce an optically thick wind blowing the material away from the gainer.

This effect should probably be taken into account when we discuss if and how the gainer survives the peak rate of mass transfer. Apparently, mass outflow from deep convective envelopes may easily lead to super-critical conditions, and may be responsible for the outbursts of the recurrent giant nova T CrB (Plavec, Ulrich, and Polidan, 1974; Webbink, 1976).

We often say that systems like β Lyr or SX Cas are in the rapid phase of mass transfer, but actually they are already in its slower, advanced stage, since in both of them, the masses are already reversed in favor of the gainer. It would be most exciting to catch a system at a peak mass transfer rate, even in the radiative case B.

Typically, in the W Ser systems, the size of the gainer is so small compared to the dimensions of the system that accretion occurs via an accretion disk. It is possible to scale up the disk models used for dwarf novae. If we do so, we find that a truly extended, optically thick disk is unlikely to form unless the mass transfer rate is quite high. Consider again SX Cas, which is a better determined case than the rest: It is totally eclipsing, has a reasonably good photometric solution (Shao, 1967; Koch, 1972), and Andersen (1973) published a fairly reliable radial velocity amplitude for the G5 III loser. Assuming that the giant fills its critical Roche lobe, the mass ratio is found to be ~ 8 in favor of the gainer, the separation of the components is $A \simeq 75\ R_\odot$, and the radius of the gainer's Roche lobe is $\sim 0.56\ A \simeq 42\ R_\odot$. The radius of the gainer itself is only $\sim 0.08\ A \simeq 6\ R_\odot$, i.e. the star appears to be located somewhat above the Main Sequence if its mass is really $3.6\ M_\odot$. A fully developed accretion disk could probably extend as far as some $30\ R_\odot$. Perhaps the double-peaked Balmer emission lines found by Struve (1944) indicate an edge of the disk, with their circular velocities of ~ 150 km/s. But for moderate rates of mass transfer (10^{-6} to $10^{-5}\ M_\odot$/year), the temperatures of the scaled-up disks may fall below 10^4 K. In the disk models (e.g. Shakura and Sunyaev, 1973), the peak disk temperature comes at $r = 1.36\ R \sim 8\ R_\odot$, and is for our model of SX Cas $T_{max} = 10^5\ \dot{M}^{1/4}$. At such low temperatures, the gas opacity is low, and a truly optically thick disk will probably not develop. Eclipse observations do not signal any presence of a very extended, optically thick disk. However, even an optically thick disk would be geometrically thin perpendicularly to the orbital plane, with a maximum thickness of perhaps 1/10 of the star's radius in SX Cas, and seen edge-on, it would hardly cause more than a slight perturbation in the eclipse light curve.

If an extended, optically thick disk existed in SX Cas, we would expect to see a hot spot where the on-flowing gas stream hits the disk. Because the potential well of the outer edge of the disk is quite shallow, the hot spot would emit a small fraction of the total accretion energy. The ratio L_{hs}/L_a scales approximately as $R/R_d \sim 0.2$ in SX Cas. A weak hot spot may exist in W Ser, where it is suggested by observations, but not in SX Cas, where there is no evidence for it. Part of the released accretion energy is radiated in the emission lines from a thin disk. An optically thick (but geometrically rather thin) disk may exist in SX Cas much closer to the surface of the gainer.

Most of the accretion energy is probably released at the interface between the disk and the accreting star. In the scaled-up disk model, accretion occurs along a narrow equatorial belt of the gainer. Adopting the expressions derived by Pringle (1977), the boundary layer temperature can be estimated to be no higher than

$$T = 2.3\times10^{6} \ \dot{M}^{\alpha} \ M^{\beta} \ R^{-\gamma} \ , \tag{2}$$

where $\alpha = 6/19$, $\beta = 8/19$, and $\gamma = 18/19$. The color temperature of the "hot" UV continuum observed by IUE in SX Cas and W Ser is near 12,500 K, which indicates a mass transfer rate $\dot{M} \simeq 2\times10^{-6} \ M_{\odot}$/year, a very plausible result. When the corrected IUE 1978 spectra become available, it will be possible to be more definite about the relative luminosities of the transition zone and the underlying star, and estimate the thickness of the accretion belt; from my preliminary results, the semithickness is $H/R \simeq 0.06$.

A tentative picture that emerges is that in SX Cas, the UV continuum is due to accretion in the boundary layer, while the optical region is dominated by the radiation of the star itself. It should be stressed, however, that the observed absorption spectrum of the gainer is a shell spectrum, so that some kind of gaseous envelope -- optically thick at least in the absorption lines of Fe II, Ti II, etc. -- surrounds most of the gainer, not only a thin equatorial belt.

THE EMISSION LINES

The high-ionization emission UV lines in SX Cas radiate a total power of several solar luminosities. All the emission spectra of the "W Serpentis stars" are very similar to each other. Similarity with β Lyrae is very important, since for that system it was possible to obtain high-dispersion spectra. All the emission lines in β Lyr have P Cygni profiles indicating an outflow at a velocity of about 150 km/s. Moreover, high dispersion spectra permit to decide with confidence that among the expected intercombination lines, only Si III] λ 1892 A is present. Its comparison with the permitted Si III line at 1298 A, as calibrated by Nicolas (1978), and the absence of the other intercombination lines indicate that the electron density is surprisingly high, $N_e \simeq 3\times10^{12}$ cm^{-3}. If the chromospheric model is applied, the resulting emission measures indicate that the lines are formed in a very thin slab. This is hard to reconcile with the P Cyg character. The emission lines do not participate in the orbital motion of either component, with a very few exceptions (C III λ 1175 A seems to be emitted by a region close to the gainer, and is moving with it and expanding at the same time: Hack *et al.*, 1977). Moreover, the strength of the emission lines does not appear affected by the eclipses.

It can be concluded that most probably the line-emitting plasma surrounds the whole system. Quantitatively, this leads to a very high rate of mass outflow from β Lyr, if we interpret the observed outflow velocity as the local escape velocity, and at the same time accept the high value of electron density mentioned above. The separation of the components in β Lyrae is $\sim 50\ R_\odot$, and the radius of the emitting region should be several times as large. Adopting for it $D = 200\ R_\odot$, we get $\dot{M} \sim 3\times10^{-3}\ M_\odot$/year or more, i.e. we are essentially in the domain of the critical accretion. The required kinetic energy itself is close to $10^4\ L_\odot$. Often there exists an approximate equipartition between the energy radiated and the energy locked in mass motions. It is therefore puzzling that the UV continuum of SX Cas is rather similar to that of β Lyr. It is true that the accretion disk in β Lyr is certainly optically thick, since it behaves like a star; thus a much higher $\dot{M}$ is to be anticipated for β Lyrae. My estimates based on the rate of the period variation (Hack et al., 1975) gave for it only $5\times10^{-5}\ M_\odot$/year. Perhaps we should think in terms of a very anisotropic distribution of both the mass motions and the radiation.

It appears that the origin of the emission lines remains a puzzle. They are no doubt also connected with the accretion process, and fed from the accretion energy.

CONCLUDING REMARKS

It is very fortunate that we have a whole group of systems with similar properties. Each of the systems is so complicated that it is hardly possible to extract all the necessary information from it. It is hoped that a "group treatment" will be more succesful. β Lyrae is of course the brightest and best known member of the group. It may not be the simplest case, however, because the gainer is at all wavelengths accessible to us now fainter than the loser (B8 II). The most complex behavior we have observed is that of W Ser during primary eclipses. This may be due to the fact that -- unless our model is quite wrong -- the loser in W Ser acts more or less like a dark screen, thereby permitting us to see all the complexities of the structure of the gainer. It is because of this promise that I think the systems should be labeled the W Serpentis stars.

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REFERENCES

Andersen, J.: 1973, Publ. Astron. Soc. Pacific 85, 191.
Buff, J. and McCray, R.: 1974, Astrophys. J. 189, 147.
Doschek, G.A., Feldman, U., Mariska, J.T., and Linsky, J.L.: 1978, Astrophys. J. Lett. 226, L 35.
Flannery, B.F. and Ulrich, R.K.: 1977, Astrophys. J. 212,533.
Hack, M., Hutchings, J.B., Kondo, Y., McCluskey, G.E., Plavec, M., and Polidan, R.S.: 1975, Astrophys. J. 198, 453.
Hack, M., Hutchings, J.B., Kondo, Y., and McCluskey, G.E. : 1977, Astrophys. J. Suppl. 34, 565.
Koch, R.H.: 1972, Astron. J. 77, 500.

Nicolas, K.R.: 1977, PhD thesis, University of Maryland
Paczynski, B.:1971, Ann. Rev. Astron. Astrophys. 9, 183.
Packet, W. and De Grève, J.P.: 1979, Astron. Astrophys. 75, 255.
Plavec, M. and Polidan, R.S.: 1976, in "Structure and Evolution of Close Binary Stars" (ed. P. Eggleton, S. Mitton, and J. Whelan: Reidel) p. 289.
Plavec, M. and Koch, R.H.: 1978, Inf. Bull. Var. Stars No. 1482.
Plavec, M., Ulrich, R.K., and Polidan, R.S.: 1974, Publ. Astron. Soc. Pacific 85, 769.
Pringle, J.E.: 1977, Mon. Not. R.A.S. 178, 195.
Shakura, N.I. and Sunyaev, R.A.: 1973, Astron. Astrophys. 24, 337.
Shao, C.Y.: 1967, Astron. J. 72, 480.
Stern, R., Wang, E., and Bowyer, S.: 1978, Astrophys. J. Suppl. 37, 195.
Struve, O.: 1944, Astrophys. J. 99, 89.
Webbink, R.F.: 1976, Nature Phys. Sci. 262, 271.

DISCUSSION FOLLOWING PLAVEC

Andersen: A few years ago, I spent quite some time measuring Alan Batten's plates of SX Cas (PASP 85, 191, 1973), and it left me with the conviction -- very much in agreement with your model -- that I had never seen the spectrum of the gainer itself, only the shell. The radial velocities of the gainer also show very large scatter, as you know, while the few measurements of the loser seemed more reasonable. Now, in your model, the loser fills its Roche lobe. Don't you think that the mass ratio implied by this assumption is extreme?

Plavec: You are quite right. In view of the probably large rate of mass transfer, I am ready to accept it. If we assume mass loss from the loser via stellar wind only, we may reduce the mass ratio to about 3, but hardly below this value, since otherwise both masses will become unrealistic. It would be necessary, however, to explain why the G5 III star, i.e. a star of relatively low luminosity, should have such a strong stellar wind.

Leung: From my preliminary analysis of the light curves of V 367 Cygni, I found that this system is extremely close. It has either a semidetached or contact configuration. I welcome your suggestion that the temperature of the gainer should be higher. The previously published spectral type leads to unacceptable underluminosity of this star.

Plavec: The gainer is probably a complex structure. The system is rather similar to β Lyrae, and may possess a thick accretion disk simulating a contact component.

Friedjung: A similar situation seems to exist for the symbiotic star Z Andromedae about which I shall talk on Friday. The high ionization emission lines and the hot continuum observed by IUE do not seem to come from the same region.

Plavec: R.H. Koch and myself found that the star AR Pavonis can be classified both as a symbiotic object and as a member of our W Ser class. There indeed seems to exist a profound similarity.

Collins: A definitive consequence of your model is that the observations of the hot star's equatorial region should reveal a very large polarization (of the order of 10%) in the far ultraviolet. Thus polarization observations in the UV should provide significant observational check on mass transfer models where high temperatures are anticipated.

Plavec: I would also recommend attempts to detect flickering, in particular in W Ser.

Scarfe: Would you include RZ Ophiuchi among your W Serpentis-type binaries?

Plavec: Yes, I believe so. Other suspects are RS Cep and RX Gem. Douglas Hall suggested some ten years ago that these two latter stars have accretion disks.

Wilson: What is the prospect for finding the rotational velocities of the higher mass components in any of your systems?

Plavec: The observed optical spectrum of SX Cas is a shell spectrum. Typically in shell stars, we observe an underlying photospheric spectrum due to a fairly rapidly rotating central star. The same may be the case in SX Cas, but so far I have not been able to detect the broadened lines. I read the abstract of your and Twigg's talk on rotationally unstable gainers (to use my terminology), and I think that your ideas should be seriously pursued. We know that U Cephei rotates fast, no doubt because of accretion. That star is of course not shielded by a large disk, since it is itself large relatively to the size of the system.