# CIRCUMSTELLAR MATTER IN ALGOLS AND SERPENTIDS

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ABSTRACT. A systematic search is reported for phenomena associated with circumstellar matter in interacting binary systems of the Algol and W Serpentis type. Ultraviolet emission lines have been detected by the author in 10 Algols and 6 Serpentids. No conspicuous difference exists between systems with disk accretion and those with direct stream impact. Evidence is indicated that the lines are formed predominantly by scattering in an induced stellar wind. Relative intensity of Fe II and Fe III emissions appears to be correlated with the spectral type of the gainer. It is suggested that in the Serpentids we see a thick disk nearly edge–on, but that the emission lines indicate the nature of the gainer inside.

I wish to report on my studies of circumstellar matter in interacting binary systems with non–degenerate components. In this progress report, I will concentrate on the "superionized" emission lines observed in the ultraviolet part of the spectrum, as observed with the *IUE* satellite. I will use the following terminology: The mass–losing star, which is the secondary, less massive, and cooler star in Algols, will be called the *loser*; the other component will be the *gainer*. When not otherwise qualified, by "the star" I will mean the gainer; and the circumstellar matter will often be simply called *plasma*. I will also distinguish between the "ordinary", or "genuine", or "classical", or "simple" *Algols*, and the *W Serpentis stars*. The latter are binary systems in which I was able to see the ultraviolet emission lines at all orbital phases, which most likely signals a higher rate of mass transfer than in the Algols (although the size of the volume avaliable for emission certainly also plays a role), and may mean more profound structural differences. The following interacting binary stars are considered to be of the W Serpentis type in this article: RX Cassiopeiae, SX Cassiopeiae, W Crucis, V367 Cygni, $\beta$ Lyrae, and W Serpentis. In the Algols, the ultraviolet emission lines are visible only during the deepest parts of the total eclipse of the hotter component. It is no easy matter to accumulate such observations.

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## Lessons from non-detection

Five Algol systems were found to have only partial eclipses, or there may be a total eclipse of very short duration which I missed: U CrB, S Equ, RX Gem, AW Peg, and RW Per. The lack of a total eclipse is particularly painful in U CrB and in AU Mon (observed by others): These are relatively early-type Algol systems, about B6. Such Algol systems are rare. In classical Algols, the lack of a total eclipse of the primary component eliminates our chances of detecting the UV emission lines, or at best we can see the emissions only as tiny peaks above the star's continuum, peaks that cannot be reliably evaluated. The strongest emissions I have seen in an Algol are N V and Si IV in RY Persei, and their tips still lie 2.5 magnitudes below the local continuum level.

No emission lines were detected in three other systems: W Del, BM Cas, and RZ Eri. Only W Del was observed in eclipse, with good timing (at $\phi = 0.0037$ and exposure time 45 min), and showed nothing - no light from the primary and no emission lines either. W Del has been classified as B9.5 V (Hill *et al.*, 1975), and Struve (1946) saw weak emission components to Balmer lines in eclipse. Our out-of-eclipse scan taken on 1982 August 6 shows deep strong absorptions at all Balmer lines including H$\alpha$. The system may display variable emission line intensities like RW Tauri (see below), but evidence is lacking. In BM Cas and RZ Eri, I relied on the fact that the spectral types of the primary components are so late (A5 and F0, respectively) that the emissions should show at any phase. They did not. These two systems may not be sufficiently interacting; but I consider them as the second suggestion that the process by which the emission lines radiate may be simply scattering of stellar radiation by abundant ions. While we do not see the primary component during the total eclipse, the circumstellar material continues to see it, and abundant ions scatter enough photons toward us. The first indication of such a process came from $\beta$ Lyrae, whose P Cygni profiles seem to be formed in a strong stellar wind and can be modeled as expansion combined with rotation (Mazzali 1986). The third supporting argument comes from the appearance of the UV spectrum of S Velorum, traditionally classified as A7, but reclassified by Dobias (to be published) as A2.5 V. The gainer's flux falls off rather abruptly near 1600 Å, and so does the flux and emission line strengths observed in eclipse, so that the emission lines of C IV, Si IV, Si II, and C II are extremely weak, while longward of 1600 Å both fluxes are higher and emission lines of Al III, Fe II, and in particular Mg II are conspicous. In other systems, such as RY Gem and TT Hya, the general flux distribution in the spectrum of the circumstellar plasma, as seen at totality, also resembles that of the primary star.

## How strong is the circumstellar radiation?

Figure 1 gives an idea about the total amount of ultraviolet radiation emitted by the circumstellar plasma in the sufficiently well observed systems, and compares it with the radiation of the primary star, i.e. the gainer, as measured outside eclipse.

Among the Algols, the strongest circumstellar radiation has been recorded for RY Per, with RS Cep being a distant second. Both stars are very distant objects, near 0.9 kpc from us, and consequently the distance may be affected by a fairly large error; but this cannot affect the result qualitatively. The faintest plasma radiation was found in U Sge and S Cnc. This is not surprising, since both systems are known to be nearly dormant; In S Cnc this is quite understandable, as the loser has only 0.18 solar masses and can hardly lose much more. U Cephei falls close to them if we take the mid-totality spectrum; but I have found (Plavec 1983) that by mid-totality, a large portion of the radiating plasma is eclipsed by the loser. The amount of radiation seen at the beginning of totality is five times larger, and places U Cephei on nearly equal footing with RY Gem or RS Cep. In the outburst, an additional increase can be expected, although the actually observed enhacement of the strongest far UV emission lines increased the total *SWP* flux by only 18% compared to the quiescent flux observed at $\phi = 0.981$. How much the fluxes from other systems fluctuate for the same two causes (eclipses and outbursts) is unknown, although in other systems the eclipse effects seem to be smaller than in U Cep.

Perhaps more informative are the ratios of UV fluxes plasma vs. star shown in Fig. 1, where they are plotted logarithmically. The advantage of these ratios is that they eliminate the uncertainties of interstellar reddening and of distance determination. I find it obvious that the amount of radiating material plays an important role, making S Cnc and U Sge very faint in eclipse and SX Cas relatively very bright. In U Sge, RW Tau, and S Cnc, we get, in total eclipse, less than 1% of radiation observed outside eclipse, while in RS Cep, it is 12%, and in the Serpentids SX Cas and $\beta$ Lyrae, it is 20% and 34%, respectively. Both numbers are actually lower limits, since the emission lines are visible at all phases and their contribution is almost impossible to subtract completely from the "continuum". There is little doubt that the rate of mass transfer, and no doubt also the volume available to the circumstellar material, plays an important role in these differences between the systems.

However, Fig. 1 tells me that in general, the amount of radiation emitted by the plasma is probably also proportional to the UV radiation of the star; and in that I see my suspicion confirmed that the main process behind the plasma radiation output is scattering of the light of the gainer.

## Accretion disk or direct impact?

The first surprise came when I separated the systems in which a canonical accretion disk is anticipated from those where the mass-transfering stream hits the gainer directly. Intuitively, I expected that high-ionization lines will occur mainly in systems with disks, while Peters and Polidan (1984) concluded, albeit on the basis of very limited statistics, that on the contrary, only the "direct impact" systems generate these lines. Actually, superionized lines are observed in both types of systems (Fig. 2), and if they differ, then the differences are rather subtle.

An accretion disk can form around the gainer only if the stream leaving the $L_1$ point has a sufficient excess of specific angular momentum to miss the gainer at the point of nearest approach. Lubow and Shu (1975) tabulated the condition quantitatively. The stream will leave $L_1$ with an excess angular momentum if the loser is the less massive star, and it will miss the gainer more likely if the fractional radius of the gainer is small. The first condition is fulfilled in all Algols, but we do not know

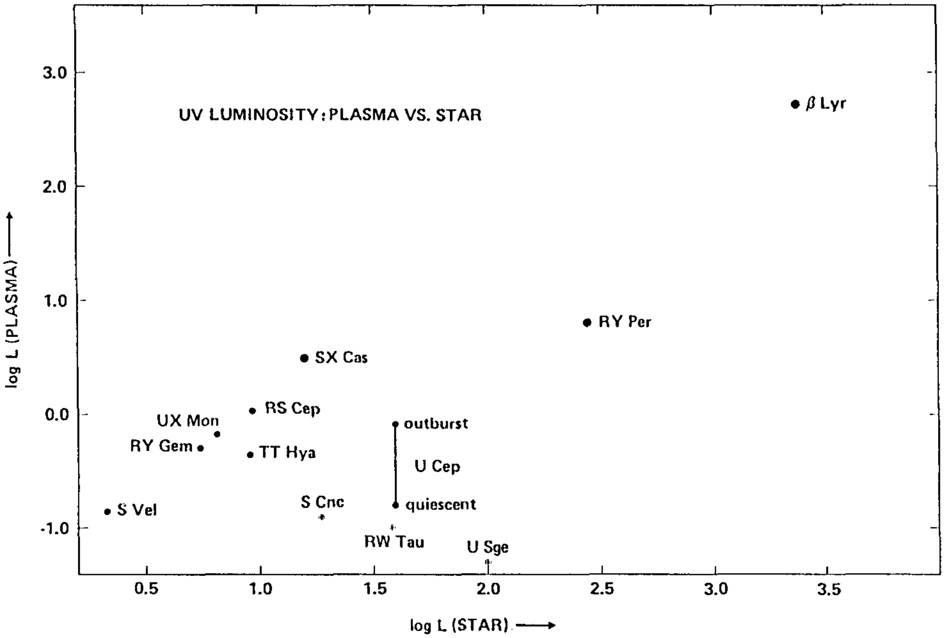


Fig. 1. - Plasma luminosity vs. gainer's luminosity (in solar units).

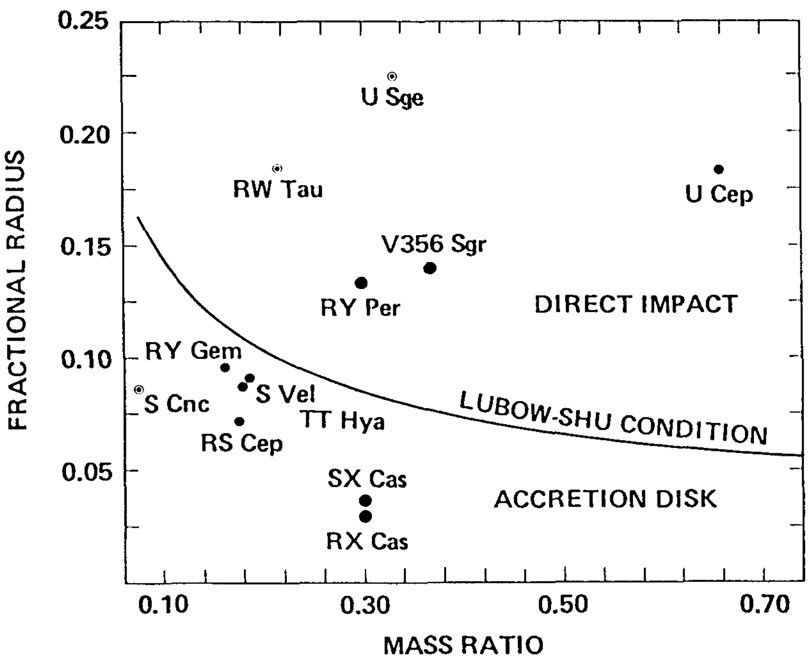


Fig. 2. - Fractional radius of gainer vs. mass ratio (loser/gainer).

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yet if it is always fulfilled in the Serpentids. Certainly during the rapid phase of mass transfer, when the loser is still the more massive star, this condition is not fulfilled. In reasonable model cases of rapid mass transfer, the stream will hit the gainer directly, and there should be no canonical accretion disk. The interaction of the stream with the gainer thus represents an important theoretical problem. Many observations suggest that a "splash disk" is formed, not terribly different from an ordinary disk, except perhaps by its short–term duration. As to an observational study, we do not have yet a certain case of a system caught at the rapid phase. The best substitute would be a fairly strongly interacting Algol in which the gainer has a large relative radius; this is for example U Cep, RY Per, and V356 Sgr. These systems, then, should possess no canonical accretion disk; yet they display moderate (U Cep, V356 Sgr) to strong (RY Per) emission lines. Two other Algols also should not have an accretion disk: RW Tau and U Sge. These display very weak plasma radiation, although in RW Tauri it may be strongly variable.

The strongest cases for fairly large accretion disks are the two systems with fairly long periods, SX Cas (Plavec, Weiland and Koch 1982; Andersen *et al.*1988, preprint) and RX Cas (Andersen and Pavlovski, 1988, preprint). In both, the gainer is small compared to the size of the system. The margin by which the stream should miss the surface of the gainer is smaller in RS Cep, S Cnc, TT Hya, S Vel, and RY Gem, in this order, but in all five systems the condition for an accretion disk is satisfied.

It surprises me very much that the strength of the emission lines does not seem to depend on whether the system can or cannot have a canonical accretion disk. In both categories there are all degrees of strength of the emission lines. Good examples of pairs of systems located at the opposite side of the Lubow-Shu borderline, yet having comparable line strengths, are S Cnc and U Sge with very weak emission, and RY Per and SX Cas with very strong emission.

In RW Tau and U Cep, evidence has been found for considerable variations of emission line intensities both in the UV as well as in the optical spectrum. When I looked at RW Tau for the first time, on 1982 August 29, the *SWP* spectrum taken at $\phi = 0.011$ (with 30 min. exposure on each side of this phase, equivalent to $\Delta\phi = \pm 0.0075$) was already dominated by the re-emerging B8 gainer, but the Si IV, C IV, and Al III emissions were still detectable. My second attempt, on 1984 August 26, was more accurately timed ($\phi = 0.9974 \pm 0.0075$), indeed showed no UV stellar flux, but also virtually no emission lines. The transient character of the optical circumstellar features in RW Tau is well documented, most recently by Kaitchuck and Honeycutt (1982). It would be interesting to see if the behavior in the optical and in the ultraviolet is parallel.

A definite evidence of parallel behavior was documented in a 1986 outburst of U Cep (McCluskey, Kondo, and Olson 1988, preprint). There exists some uncertainty about the phase of their totality spectrum, *SWP 28503*. One part of the uncertainty always is, at least for U Cep, the variability of the period. If I adopt the 1985 ephemeris used in their article, then the uncertainty lies in the timing. The time given by the authors is 1986:167, 20:26 UT, and leads to $\phi = 0.9812$; however, from the official catalog of the *IUE* spectra, this time seems to be the beginning of a 20–min exposure; and if I take the mid–exposure as 20:36 UT, then the phase is 0.9840. In each case, the phase interval covered is $\pm 0.0025$. I have shown (Plavec 1983) that the overall intensity of the non–stellar spectrum still varies with phase even during the totality, and reaches a minimum at mid–totality. Fortunately, I took, in 1982, a spectrum at phase 0.9816. Next, we must hope that there was no secular change in the line intensities at quiescent states between 1982 and 1986 (none was indicated over 13 months between 1981 and 1982). The "continuum" has nearly identical flux level in the 0.9816 (quiescent) and the outburst spectrum. This may still indicate an increase in the flux level in outburst, since my *LWR* quiescent spectrum, taken at phase 0.9853, *i.e.* closer to the phase of the *SWP* outburst spectrum, would match *SWP* fluxes about half of those at phase 0.9816. Thus we may crudely estimate that if a flux increase was present at all, it was no more than by a factor of about 2, and this is plausible, since the apparent "continuum" is probably formed by a forest of faint emission lines, and strong emission lines show a definite enhacement during the outburst.

How much the strong emission lines were enhanced during the 1986 outburst is not easy to tell, firstly for the inherent uncertainties of phase shifts and secular changes, and secondly because in the outburst spectrum, the strongest lines are saturated: C IV and Al III badly, Si IV and C II less so. For the unsaturated lines, the enhancement factor (taken simply as the intensity ratio at phases 0.9840 and 0.9816) is as follows: Al II, 2.7; Fe III (34), 1.2; Si II (2), 2.1; N V, 2.1. Ignoring the overexposure, we find the following additional enhacement factors: Al III, 1.9; C II, 3.4; C IV, 2.5; and Si IV, 2.5. There is no clear answer to my main question, namely if the outburst implies a rise in the plasma temperature, or merely an increase in the amount of the radiating plasma; this latter explanation seems to be more likely.

I wish to emphasize here that observing such outbursts like those in RW Tau and U Cep is of considerable importance for broader problems. It is well known that a battle has been raging for years concerning the mechanism that triggers the outbursts of cataclysmic variables. One school of thought claims that the trigger is the instability of the loser, which leads to an increased rate of mass transfer; the other school maintains that the ultimate cause is the instability in the accretion disk. In the case of U Cep and RW Tau, there should be no regular accretion disk; therefore an increased rate of mass transfer seems to be the cause, although we do not have direct evidence yet.

The gainer in U Cep is known to rotate very rapidly, and the velocity of rotation is probably even higher in the two direct-impact gainers, RY Per (Van Hamme and Wilson 1986) and V356 Sgr (Polidan 1988, preprint). This high rotational speed has no doubt been caused by the oblique impact of a strong mass-transfering stream. In turn, the rapid rotation quite possibly generates the "magnetically assisted, accretion driven" stellar wind proposed by Shu (1987, preprint), as has already been suggested by Polidan (1988, preprint).

## Systems with a strong Fe II emitting region

In five spectra, we notice elevated flux levels in the region roughly between 2300 and 2630 Å, and an abrupt drop near 2640 Å. I believe that this enhanced flux is due to superposition of numerous emission lines of Fe II and several other singly-ionized metals like Cr II, Ni II, and Mn II. This explanation is justified as follows. In full light, the star TT Hydrae has been observed with high dispersion, and the spectrum shows very deep and very broad blends in the region mentioned above; then near 2645 Å, there is a region of higher flux, that is lower extinction, extending between 2634 and 2661 Å, after which deeper absorptions gradually set in again. Degraded in the low dispersion, this brighter region produces a spurious and rather striking "emission line" at 2647 Å (see Plavec 1988), while on either side the flux is much depressed by the absorption blends. A comparison with a star of the same spectral type shows that the deep absorptions are shell lines, formed outside the photosphere. In eclipse, a reversal occurs similar to that in the solar chromospheric spectrum at total solar eclipse, and the circumstellar material is seen in emission (Fig. 3).

The blends are so broad that it is impossible to separate any individual line that would represent the strength of the Fe II emission. My attempts to isolate the strong Fe II (1) line at 2599 Å failed. Fortunately, the depth of the abrupt drop near 2640 Å seems to be a useful measure of the contribution of Fe II to the emission, since its bottom seems to lie at about the same level as the "continuum" near 1600 Å. Another good indicator is the strength of the broad emission blend at 2750 Å, consisting of Fe II multiplets 62 and 63.

The systems with a conspicous Fe II emission are S Vel ($\Delta m = 2.60$ mag), RY Gem (1.37 mag), UX Mon (1.23 mag), RS Cep (0.96 mag), and TT Hya (0.93 mag). In the parantheses, I give the magnitude difference of fluxes at 2630Å and 2648Å, respectively, that is, I am measuring the height of the "$\lambda$2640 discontinuity". The revised spectral types of these gainers are: S Vel, A2.5 V; RY Gem, A0 V; RS Cep, B9.7 V; TT Hya, B9.5 V (see Dobias and Plavec 1988, this meeting). The correlation is very nice. Now UX Monocerotis is a rather puzzling system, the hotter component of which has been classified as as late as A7, but is clearly variable. My UV spectra indicate a spectral type variable between B9 and A0. The $\lambda$2640 Å jump in the totality spectrum classifies it as very close to A0 V.

## Systems with a strong Fe III emitting region

Four other spectra, namely those of $\beta$ Lyrae, RY Persei, RX Cassiopeiae (Fig. 4), and W Crucis have a dominating region centered at about $\lambda$1900 Å. Three prominent emission lines of Fe III, multiplet 34, are located there (at 1985, 1914, and 1927 Å). These lines by themselves can hardly explain the enormous enhacement of that region seen in $\beta$ Lyrae, and for a long time I have suspected the presence of an underlying elevated continuum. The source of such a continuum is hard to find; thus it seems that Viotti (1976) was right in attributing this bulge to numerous weaker Fe III lines overlapping in emission; I can only add that Ni II and Ni III also seem to contribute. The Fe III emission reaches up to about 2200Å in $\beta$ Lyrae and RY Per, but beyond

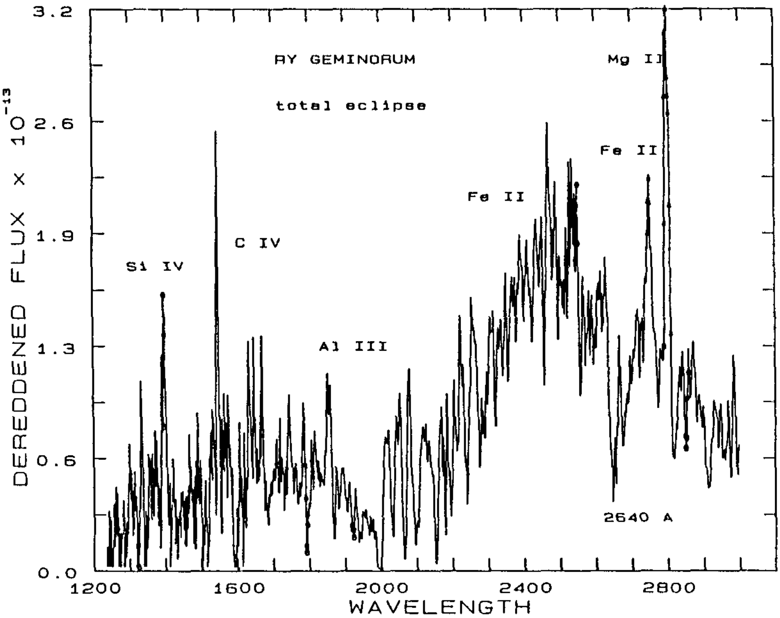


Fig. 3. - Plasma radiation seen in RY Geminorum (A0 V) at totality.

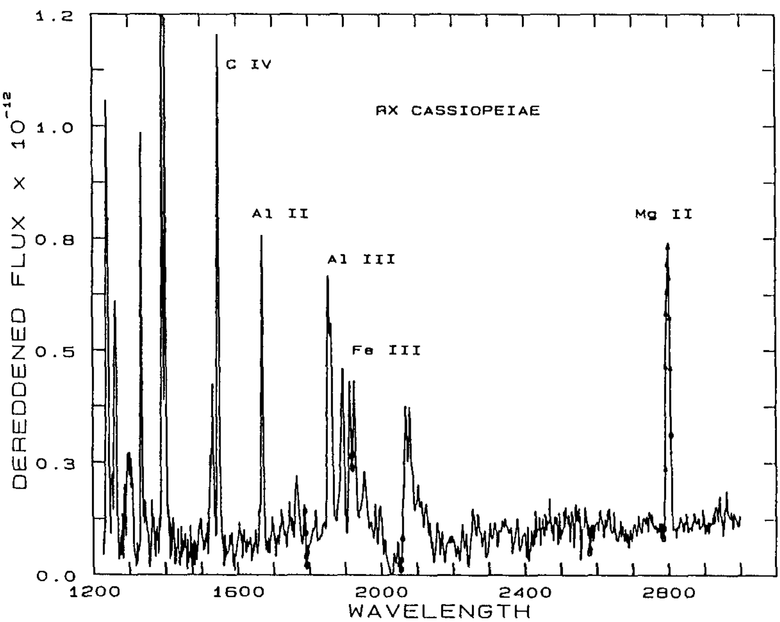


Fig. 4. - Plasma radiation seen in RX Cassiopeiae (B5-B6 ?; Serpentid).

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that, where the emission should be dominated by Fe II, the flux level is significantly lower and flat. Also Mg II, whose emissivity (in the purely collisional case) peaks at an electron temperature $T_e$ = 16,000 K, is weak in $\beta$ Lyrae and RY Per. All this suggests that the plasma is generally hotter when it surrounds hotter gainers. In RY Per, the gainer is no later than B5 from optical observations (Popper 1980 and private communication), although, rather mysteriously, its ultraviolet spectrum is no earlier than B9. The problem of the representative temperature for the gainer of $\beta$ Lyrae is well-known; either the embedded star or the inner parts of the disk are certainly hotter than B6.

Now the ultraviolet spectrum of RX Cassiopeiae is rather similar to that of these two stars; thus it is tempting to classify the gainer of RX Cas as an approximately B5-B6 star. However, no such star is seen, and the same ultraviolet spectrum with very strong emission lines and very low (if any) continuum is seen at all phases. In the optical region, we observe two spectra, neither of which is earlier than F (Plavec *et al.* 1981; Plavec and Weiland, in preparation). The best explanation appears to be that in the optical region, we observe the edge of an optically thick accretion disk, at the center of which is a B5-B6 star. This interpretation would agree with the work of Andersen and Pavlovski (1988, preprint).

And then the very mysterious system of W Crucis could be explained in a similar way. Optically, a spectrum usually classified as G1 Ib is observed, although there are several puzzles, in the first place the presence of emission components at the Balmer lines (Woolf 1962). In the ultraviolet, we see – again at all orbital phases – a spectrum rather resembling $\beta$ Lyrae. It seems possible that the low surface gravity optical spectrum comes from the edge of an optically thick accretion disk rather than from a genuine G supergiant.

As a rough estimate of the relative contributions of the Fe III and Fe II lines, I measured the total flux in the regions (1875 – 1940 Å) and (2505 – 2570 Å), respectively, and derived the magnitude difference. It is 0.90 mag for $\beta$ Lyrae, 0.72 mag for RY Per, 0.86 mag for RX Cas, and 0.84 mag for W Cru. Thus the two mysterious W Serpentis systems do indeed resemble $\beta$ Lyrae.

## Intermediate cases

Finally, there are three binary systems which seem to lie halfway between the two types described above, that is, both the Fe II and Fe III regions are mildly prominent. One of them is U Cephei, but this aspect of its plasma spectrum is perceptible actually only in the spectra taken at the edges of totality, rather than at mid-eclipse. We have classified U Cep as B8.3 V (Dobias and Plavec 1985). More pronounced are the two flux bulges in two more bizarre binaries. These are SX Cassiopeiae and W Serpentis. SX Cas was, I hope, sufficiently and correctly demystified by Plavec, Weiland, and Koch (1982) and the source of the ultraviolet flux identified with a star about B7, partly obscured by an optically thick disk. The model was corroborated as well as significantly improved by Andersen *et al.* (1988, preprint). The gainer is totally eclipsed, and during totality the plasma spectrum seems to fall between the two distinct groups discussed above, so that an intermediate spectral type, near B7, is again indicated.

All this gives me some encouragement with the difficult case of W Serpentis. In the optical, the spectrum has usually been classified as F5 II from the absorption lines; and indeed, our optical scans show that the continuum could be classified similarly. This still does not mean that we are dealing with a real star. It is possible that the ultraviolet "continuum" is some sort of a real continuum. It is also possible, however, that it is only a forest of strong emission lines; and since both Fe III and Fe II regions are about equally pronounced, it is possible to guess that we see an accretion disk edge-on, and that the embedded star is again B7, or that the central parts of the disk radiate like such a star.

## Conclusions: One step closer to understanding the Serpentids?

Work is continuing on a quantitative analysis of the emission line spectra. From the qualitative discussion presented here, one important fact emerges: It seems to me that the emission lines can tell us a lot about the nature of the object embedded in the optically thick disk and invisible to us. If true, this means a great leap forward in unraveling the secrets of the W Serpentis stars.

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DISCUSSION

Eaton asked if, in Plavec' model, even the strong Mg II line is also produced by scattered radiation from the unseen central parts of a disk. If so, it would (as in the $\zeta$ Aur binaries) provide a measure of the monochromatic luminosity of that source. He also asked if the strength of scattered Fe II radiation is dependent on spectral type (of the gainer) simply because of the temperature dependence of $f_\lambda$ in the ultraviolet. Plavec' answer to the first question was cautious: he believed that scattering is an important component of the plasma radiation, but he was aware that Ivan Hubeny (p.117) would shortly put forward an opposing view. To the second question, he answered yes; even if collisional excitation of the plasma is important, photoionization by the gainer should not be ignored.

Guinan asked what estimate Plavec would make of the spectral type of the loser in W Ser, given his guess that the gainer was likely to be an ~ B7 V star embedded in an ~ F6 II disk. Plavec replied that the loser must be much later than F5.

Polidan stated that a group at LPL had been working on line-formation mechanisms in V356 Sgr and they agreed with Plavec that resonance scattering is the only possible mechanism. In this system, the line-formation region has an ionization temperature of $10^5$ K, but the electron temperature may be much lower. There is a continuum excess (over and above the B-type and A-type continua) in the spectrum of V356 Sgr that they find to be a true continuum - it is not resolved into separate lines at higher resolutions. In $\beta$ Lyr, on the other hand, *Voyager* observations show a very hot plasma (T > 30,000 K), which rules out a B5 star as the hotter member of the system - even a B0 star could hardly explain the observations. The data also show that the far UV continuum of the "B6/B8" star corresponds to 12,000 K. Since it is an He-rich and H-poor star, he felt that spectral types and Kurucz model atmospheres should be used with caution in defining the characteristics of the loser. Plavec agreed that V356 Sgr displayed a genuine A-type stellar continuum, and suggested that in this respect it is similar to V367 Cyg. With regard to the loser in $\beta$ Lyr, Polidan confirmed the opinion that he (Plavec) had already expressed at the 1987 European regional I.A.U. meeting (*Publ. Astr. Inst. Csl.* No. **70**, 193, 1987 ed. P. Harmanec). Plavec thought there is still much uncertainty about the gainer and disk; Polidan's *Voyager* data are undoubtedly important.

Wilson questioned the validity of the correlation displayed in Plavec' Figure 1, since it depended heavily on the point representing $\beta$ Lyr - which might not belong in the Algol group. Plavec conceded that the correlation is weak. Smak asked if Plavec had examined any correlation between the properties of the high-excitation lines and the velocity of the stream at the impact point which, he felt, was more fundamental than the luminosity of the central star or the mass-transfer rate. Plavec replied that the gainer's luminosity increases as its mass, as does also the amount of accretion energy per gram of matter released by the impact. Which dependence dominated, could not be decided until the circumstellar-radiation field had been modelled.