

PART III

EVOLUTIONARY PROCESSES IN CLOSE BINARY SYSTEMS

EVOLUTION OF CLOSE BINARY STARS: OBSERVATIONAL ASPECTS

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ABSTRACT

Detached close binary systems define the main sequence band satisfactorily, but very little is known about the masses of giants and supergiants. High-dispersion IUE observations promise an improvement, since blue companions are now frequently found to late-type supergiants. The interesting cases of μ Sagittarii and in particular of ϵ Aurigae are discussed in more detail. The barium star abundance anomaly appears now to be due to mass transfer in interacting systems. The symbiotic stars are another type of binary systems containing late-type giants; several possible models for the hotter star and for the type of interaction are discussed. The W Serpentis stars appear to be Algols in the rapid phase of mass transfer, but a possible link relating them to the symbiotics is also indicated. Evidence of hot circumstellar plasmas has now been found in several ordinary Algols; there may exist a smooth transition between very quiescent Algols and the W Serpentis stars. β Lyrae is discussed in the light of new spectrophotometric results.

INTRODUCTION

By its format and title, this Colloquium closely resembles the Colloquium On the Evolution of Double Stars held at Uccle 15 years ago, in September 1966 (Dommanget, 1967). That was a memorable colloquium, since the evolution in binary stars was, for the first time, the topic of a whole meeting. Since then, our field has expanded tremendously. We held two large-scale Symposia discussing the evolution of close binaries only (Eggleton, Mitton and Whelan, 1976; Plavec, Popper and Ulrich, 1980), in addition to several other meetings on a slightly lower scale. After the most recent Symposium, held in Toronto in 1979, I concluded that in the future it would no longer be possible to cover adequately, in one full Symposium, the whole field of close binaries. Thus the goals set for this Colloquium are in no way small. By coincidence, I have been entrusted with the same type of introductory talk at this Col-

loquium as I gave fifteen years ago, and this gives me a good opportunity to compare.

The topic of my Uccle talk, as well as the topic of the subsequent extremely important contributions by Paczyński and by Kippenhahn and Weigert, was practically entirely the evolution leading from two binary components on the Main Sequence to a semi-detached Algol system. I think only Paczynski went beyond this framework and suggested that the Wolf-Rayet stars may be products of a similar process of mass transfer between the components. Thanks to Kippenhahn and Weigert and to Paczynski, we heard for the first time about actual model sequences describing this process; naturally, those calculations were based on the "conservative" assumptions, namely that both the total mass of the system and its orbital angular momentum remain preserved. Nevertheless, I remember vividly the remark made in the discussion by Kruszewski, who declared in a rather prophetic and (therefore?) tragic voice: "... The question of rate of mass loss looks hopeless from both the theoretical and the observational points of view... A question of first importance ... is the ratio of the matter lost from the system to the matter transferred to the opposite component... The accuracy of magnitude estimate that we can get from spectroscopic observations tells us nothing about this ratio." (Dommanget, 1967, p. 124). After fifteen years, this dilemma is still plaguing us, and a good part of my talk will be devoted to the problem whether the spectroscopic observations can tell us something or no thing at all.

Concerning the scope of the topics discussed at Uccle, it would be wrong to assume that at that time in the past, the field of close binary star evolution was really so narrow as to include only the incipient concepts of the formation of the Algol systems. Very little was said at Uccle about two extremely important types of binary stars the investigation of which was at that time just about to start the fantastic explosion of activity and knowledge that transformed binary star astronomy from "arcane art", to use the term coined by R. P. Kraft, into one of the forefront fields in astrophysics: I mean the X-ray binaries and the cataclysmic variables.

Accretion as the mechanism powering the galactic compact X-ray sources emerged at about that time, perhaps symbolically introduced to the wider astronomical community by the famous remark by Ginzburg at a Radio Astronomy Symposium (van Woerden, 1967, p. 411) to the effect that "We have such a large amount of gravitational energy available in such a binary source: we must use it! of course!". Soon after, Trimble and Thorne (1969) opened the search for black holes in binary systems; although this venture has so far been much less fruitful than it was originally hoped for, their paper is still a landmark. The evidence that binary nature is essential for the existence of novae and dwarf novae developed gradually, but by the time of the Uccle Colloquium it was already firmly established by the work of Kraft (1963) and others. There is no doubt that the X-ray binaries, cataclysmic variables, and other binary systems remain in the forefront of interest today. And I think

we can add to them another important class of binary stars, namely the RS Canum Venaticorum systems. Their unusual photometric properties, their X-ray and radio emission, and their obvious relation to chromospheric activity of G-K type stars attracted many astrophysicists who were never before interested in binary stars. It is really impossible to cover these three important groups in one talk, and it would make no sense to attempt it. There have been so many good reviews, talks, and conferences on them in the recent few years that I have nothing of value to add. I want to concentrate on binary systems in the earlier stages of evolution of both components. They may not generate such excitement and so conspicuous phenomena, but they represent stages of evolution through which all of the exciting objects had to pass; and since we are here to trace stellar evolution in all its twists and turns, they deserve proper attention.

You will have noticed that there exists a subtle difference between the title of the whole Colloquium, Binaries as Tracers of Stellar Evolution, and the title of my talk, Evolution of Close Binaries. It is true that close binary stars, in particular their eclipsing variety, are the most important tracers of stellar evolution, since they can provide the most complete set of parameters characterizing the evolutionary state of each component, if circumstances are favorable. However, quite often they mark a detour from the proper track of the normal stellar evolution: they lead us along a track which they themselves laid differently. Since a large fraction of stars are actually members of close binary systems, it is naturally quite justified to study their evolution as an important alternative to the single star evolution. Nevertheless, it is quite proper to say first a few words on how close binary stars contribute to the knowledge of single star evolution.

DETACHED BINARY SYSTEMS AS TRACERS OF STELLAR EVOLUTION

Tracing stellar evolution means plotting the evolutionary tracks point by point. A star of a given mass is described by a number of parameters, such as effective temperature, luminosity, radius, chemical composition, rotation, atmospheric structure, possibly also stellar wind and/or a circumstellar envelope. Combined photometry, spectrophotometry, and radial velocity studies can give us practically all this information if the star is member of an eclipsing system and circumstances are favorable.

We often hear it said that eclipses are a real miracle, a royal road to knowledge. This all is true, but purely physically, the eclipses are a simple consequence of the fact that the orbital planes of close binary stars are oriented at random. What should be considered as a truly remarkable fact, one that is not a priori obvious and easy to anticipate, is that binary stars tend to come as pairs of stars of nearly equal masses. Statistical studies, whether they find bi-modal or unimodal distributions of mass ratios, agree that there exists a strong

trend towards mass ratios close to one (see, e.g., Trimble, 1974). Close binary stars have become the most important tracers of stellar evolution mainly because of this property. Otherwise, the strong positive dependence of radius, effective temperature and in particular of luminosity on stellar mass would make eclipses shallow and secondary spectra undetectable at any wavelength. This is in particular true about the main sequence band.

Thanks to favorable mass ratios, a large part of the main sequence is now well described empirically by means of the components of eclipsing binaries. Popper (1980) whose criteria are unusually severe, lists 36 reliable systems which cover satisfactorily the range of spectral types between B6 and G2. Then there is a gap between G2 and the two well-determined pairs of early M type stars, YY Gem and CM Dra. This gap is unlikely to be filled. Eclipsing binaries in this region tend to be either of the contact (W UMa) type, or of the probably mildly evolved type (RS CVn).

Popper noticed a somewhat similar difficulty with eclipsing stars earlier than about B6. The difficulty seems to be primarily technical. Proximity effects distort the light curves and shallow and blended spectral lines adversely affect the radial velocity work. As a consequence, it is difficult to distinguish between the detached, semidetached, and contact systems among the early-type binaries. I encountered this difficulty when I attempted to introduce two-dimensional classification of eclipsing binaries (Plavec, 1964). Hot and luminous early-type stars have extensive and dynamical outer atmospheres; thus it may well be that the difficulty is not merely technical but represents an inherent property.

DETACHED SYSTEMS WITH GIANT AND SUPERGIANT COMPONENTS: A NEW ERA BEGINS

As soon as the more massive star of the pair leaves the main sequence, differential evolution will quickly create a large gap in the H-R diagram between the two components, even if their masses are very similar. Now the less massive star, still sitting on the main sequence, will be associated with a late-type giant or supergiant. For stars more massive than about $4 M_{\odot}$, i.e. practically for all B stars, the evolutionary track in the H-R diagram is practically horizontal all the way from the main sequence to the red giant tip. The luminosity does not change markedly, while the peak in the spectral energy distribution shifts to longer wavelengths. The giant or supergiant now, as a rule, dominates the visual region of the spectrum. But the other star, although somewhat less massive and therefore also less luminous, will make a strong showing in the ultraviolet. Until recently, the knowledge of this fact was of little comfort to astronomers, and eclipsing binaries with one component away from the main sequence were no good tracers of stellar evolution. Visual binary stars were no better in this respect, although for a different reason: giants and supergiants are rare anim-

als in solar vicinity. As a consequence of this conspiracy, the masses of giants and supergiants are still very poorly known, and many important studies of the various peculiar and exciting objects suffer from this lack of knowledge.

Among the systems consisting of a giant or supergiant and a main sequence star, the eclipsing binaries 31 Cyg, 32 Cyg, ζ Aur, and VV Cep became famous, but for a different reason. They exhibit atmospheric eclipses when the hotter, much smaller star traverses behind the very extended atmosphere of the cool supergiant (a K supergiant in the first three cases, an M supergiant in VV Cep). The systems are essentially detached because of the large separations between the components, as indicated by their long periods, between 3 and 20 years. Therefore, they are important tracers of single star evolution, and should enable us to obtain the mass and other parameters of the supergiant component. Complete orbital parameters and hence also masses were derived from radial velocities obtained from the optical spectra, although with difficulties, since the lines of the blue star are as a rule severely blended. From the published orbits, as reviewed e.g. by Wilson (1960) and more recently by Wright (1970), it transpires that in ζ Aur, 31 Cyg, and 32 Cyg the supergiant is about twice as massive than its blue mate, so it agrees with single star evolution that the blue components are probably still on the main sequence. In VV Cep, the M supergiant appears to have a mass only equal to its blue companion, or even slightly smaller. Small discrepancy in this direction can perhaps be explained in terms of mass loss from the supergiant. It should be remembered that in spite of truly heroic efforts, in particular by Wright (1977), the orbital parameters and hence the masses in VV Cephei are poorly known. No absorption feature can be safely attributed to the hotter component alone, and the orbit of the hotter star is based on a detailed reconstruction of a complex emission profile of $H\alpha$, of which one component is supposed to be associated with the hotter star; however, it is not clear if its radial velocities are identical with those of the photosphere of the hot star, even if it could be safely identified, isolated, and measured.

A new epoch came with the advent of the IUE satellite. When the high-dispersion mode of the spectrograph can be used, we have the opportunity to measure radial velocities of the hot component; and both the low-dispersion and high-dispersion modes enable us to study the spectral energy distribution and the line profiles. As in the optical region, a careful study is needed in each individual case in order to isolate clean lines of the hotter star. This may not be possible at all in certain cases. Thus it seems, according to Stencel *et al.* (1980), that in 32 Cyg the B star is moving rather deep inside the stellar wind structure of the K4 supergiant, and that a hot turbulent region surrounds the B star. Yet I am convinced that clean lines can be found, if not in this system, then in others. So far, everyone has been excited about eclipse studies and about winds and interactions. I would like to point out the importance of the "old-fashioned" approach. If our good luck lasts and the IUE satellite remains operative for a few more years, there is good hope for improving orbital data.

Nor is it necessary to attach our hopes only to the ζ Aurigae stars. A number of supergiants are now known or strongly suspected to be accompanied by blue components. Independently of the far ultraviolet observations, multicolor photometric studies indicated a large incidence of blue companions in the Cepheids. From an extensive photometry in the Walraven five-color system, Pel (1978) concluded that among the southern Cepheids he studied, at least 25% are members of close binary systems. Madore and Fernie (1980) use the differential color effect a potential blue component will have on the minimum phase of the light and color curves of Cepheids, and conclude that $(35 \pm 5)\%$ of them have blue companions. Parsons (1981b) examined 50 supergiants of spectral types F and G, and concluded that at least 17 among them are double, and at least 10 of these have hot companions. All these numbers agree well with the statistical conclusions by Abt and Levy (1978) on the incidence of binary stars among B type stars. Since binary star components tend to have similar masses, and since the giants and supergiants examined have evolved from main-sequence B stars, Abt and Levy's statistics have a direct bearing on the supergiant surveys.

An extension of the supergiant survey to supergiants of an earlier spectral type than A will certainly reveal additional binaries. Observationally, the task becomes more and more difficult as the supergiant will also dominate the ultraviolet. A good example is the discovery of a hot companion to the luminous B8Ia supergiant μ Sagittarii. The hotter star, of spectral type near B0 V, does not contribute significantly to the total flux of the system except at wavelengths shorter than about 150 nm; and its character can actually be established with some degree of confidence only thanks to the eclipses. That an eclipse occurs in spectroscopic binary system of μ Sgr has been known since 1938. But this must be the shallower eclipse, since it occurs at the conjunction with the B8 star behind. When R. Polidan discovered lines of P V in the Copernicus spectrum of the star, obtained in our joint project, it was clear that another and deeper eclipse must occur when the hotter component is eclipsed by the B8 supergiant. I predicted this primary eclipse for September 1979 (Plavec, 1979), and combined observations by several people (Guinan and Dorren, Kondo, Plavec and Polidan) confirmed the prediction. The duration of the eclipse is probably several weeks, but far from safely determined. The system is not easy to study since its period, 180 days, is not only long but is fairly close to half a year. Only one primary eclipse can be observed per year, in August-September; the other occurs at a time when the sun is too close to the star in the sky. By subtracting the IUE spectra, we were able to obtain the spectral energy distribution of the hotter component (Plavec, 1981a; Plavec and Weiland, 1980), which clearly suggests a spectral type near B0; but the effective temperature remains uncertain within wide limits, probably mainly because of the quasi-periodic fluctuations of the light of the B8 supergiant, discovered by Dorren, Guinan, and Sion (1981). Our estimates vary between 18,000 - 40,000 K, but we are reasonably sure that the correct value will be nearer the lower limit of this interval. The radial velocity curve of the B8 supergiant is well determined and gives a

large mass function, $f(m) = 2.67$. If the mass of the supergiant lies between 10 and 20 solar masses, as is reasonable to suppose, then the hotter component must have 8-13 solar masses. Since it is about 2.5^m fainter in V than the B8 supergiant, it is probably a main-sequence star, and the two components have evolved essentially independently: the system is still detached. But there exists interaction between the two components in the form of a strong stellar wind blowing from the luminous supergiant. Additional absorption lines in the spectrum have been found both by Polidan in the Copernicus spectra, and by us in the high-dispersion IUE spectra. They are due mostly to Fe II and have the character of shell lines. Thus we may observe a kind of an atmospheric eclipse preceding the bodily eclipse of the hotter star. The system promises to yield valuable information on the structure of the stellar wind from a supergiant that is much hotter than those in which atmospheric eclipses were studied in the past: thus I believe that this has been a significant discovery.

Similar direct discoveries of hotter companions are becoming more and more frequent. Mariska, Doschek and Feldman (1980) report the discovery of components of spectral types not far from AO V in the two classical Cepheids η Aql and T Mon. Parsons (1981a) announced that V810 Cen (HR 4511 = HD 101947), which is probably another classical Cepheid but with quite a large period of 125 days, is associated with a hot B star (actually seen already by Bohm-Vitense and Dettman, 1980); the hot star seems to have a stellar wind indicating a supergiant, while its continuum flux suggests a less luminous star, perhaps luminosity class III.

ϵ AURIGAE: ENIGMA OF THE QUARTER CENTURY (OR OF 27 YEARS)

Before I leave the realm of the supergiants, I would like to talk about one of the most mysterious eclipsing binaries, namely ϵ Aurigae. Since the term "Enigma of the Century" has already been requisitioned for SS 433, I must call ϵ Aur only an enigma of a quarter century. In fact, the enigma always comes only every 27 years, when we get an eclipse of the star, and outside eclipse we have very little hope to make a real breakthrough into its mystery (observationally, I mean; bright ideas can come any time). Unlike the ζ Aur supergiant eclipsing systems, the primary eclipse -- the only one observed -- comes when the supergiant is eclipsed by -- well, by something. The eclipsing object is the enigma. It causes a long eclipse about 0.75^m deep over a wide range of wavelengths, and the eclipse is reasonably flat, as if it were total. But it cannot be total since the spectrum of the FOIa supergiant remains visible without profound changes, and no other spectrum emerges, although judging from the depth of the eclipse, the other component should be certainly sufficiently bright to be seen.

Numerous clever schemes were invented to explain these paradoxes, among them the idea that the eclipsing body is essentially a disk; and, of course, as one alternative for the central object of the disk, a

black hole was suggested. In connection with recent ultraviolet observations, an alternative idea advanced by Hack (1962) becomes very important: The nearly neutral opacity of the disk is explained in terms of electron scattering, and the necessary source for the photons that must ionize hydrogen over a very large volume is sought in a Be star. And indeed, low-dispersion IUE spectra do show a flux excess over that of the F supergiant in the far ultraviolet; the excess flux is detectable at wavelengths shorter than about 150 nm with certainty, and a little beyond this wavelength if the flux of the supergiant can be properly subtracted. After an approximate subtraction, Hack and Selvelli (1979) concluded that the source of the excess flux is most likely a B star, with an effective temperature of about 15,000 K, and with an absolute visual magnitude of about -1^m . The supergiant is much brighter in the visual region, $M_v = -6.7^m$ according to van de Kamp (1978), who also finds that the distance to the system is 580 pc from a combination of astrometric and spectrographic observations. A companion of the above temperature and luminosity would be probably a main-sequence star. What puzzles me is the problem how such a modest star of a rather late B spectral type can ionize such a vast volume, whose radius must be about 850 solar radii in order to perform the eclipsing duties properly. I observed the system with the IUE, too, and did find the extra flux in the far UV. From the very short spectral segment observable, it is very hard to conclude anything about the nature of the hotter source; if I fit it by a Kurucz atmosphere model for $T_{\text{eff}} = 15,000$ K, I find that the object is a subdwarf rather than a main-sequence star. Its light may be variable; or it may be largely obscured by a disk at whose center it may reside.

Dynamical considerations only augment the puzzle. The radial velocity curve of the F0 supergiant appears to be simple and reliable. It yields a mass function $f(m) = 3.12$. The orbital inclination cannot be too far from 90° because of the long quasi-total eclipse, so adopting $\sin i = 1$ does not introduce a serious error. We also know that the orbit of the supergiant with respect to the center of gravity of the system is $A_F \approx 2.8 \times 10^3 R_\odot$. One more assumption then gives us an idea about the masses. We can argue that the evolutionary tracks of massive stars in the H-R diagram are almost horizontal, i.e. their luminosity remains nearly constant. Then the absolute visual magnitude $M_v = -6.7^m$ determined by van de Kamp (1978) suggests $M_F \approx 13.5 M_\odot$ and the mass function then gives for the unknown star $M_U \approx 13 M_\odot$, and for the separation $A \approx 5.8 \times 10^3 R_\odot$. A completely invisible object has the same mass as the luminous F0 supergiant!

This is such an outrageous result that one is tempted to abandon the value of $13.5 M_\odot$ for the F0 star (although it appears reasonably justified), and to attempt to vary the mass ratio in order to see if anything plausible emerges. It won't! Going to a mass ratio 2:1 in favor of the F0 supergiant quickly increases the masses of both stars above $20 M_\odot$ and deepens the puzzle of the large secondary mass. If we want to reduce the secondary mass, we must go to an inverse mass ratio, i.e. make the invisible star more massive! For $M_U/M_F = 2$ we get $M_U = 7$

M_{\odot} , $M_F = 3.5 M_{\odot}$: now we must explain why 3.5 solar masses give us a luminous supergiant, while twice that mass remains invisible. One may recall the case of β Lyrae, in which a similar situation obtains. But in β Lyrae the more massive component is not really invisible, we only do not observe any absorption lines from it; it emits enough continuous radiation to make the secondary eclipse quite perceptible.

Over the range of mass ratios considered, the separation of the components remains of the same order of magnitude, $A \cong 5 \times 10^3 R_{\odot} \cong 23$ AU. Thus the F0 supergiant, whose radius we can estimate from its absolute magnitude and temperature to be $R_F \cong 200 R_{\odot}$, is far too small to fill its critical Roche lobe. If the secondary is star inside a disk (an idea which is rather plausible because of the shape of the eclipse light curve, see e.g. Wilson, 1971), why is it surrounded by a disk? This can hardly be accretion from the supergiant!

My IUE observations confirm Hack and Selvelli's finding that there is one and just one emission line visible in the ultraviolet, namely O I(2) λ 1302 Å. I know of only one other spectrum which shows just this one emission line, and that is the symbiotic star CH Cygni, which consists of a semiregularly variable M6 III giant and a hot object which, according to Luud (1981) should be white dwarf, while according to Wing and Carpenter (1981) most likely is an O or early B star close to the main sequence. The latter observations, based on recent IUE spectra, are probably more reliable, yet in either case there is most likely no connection with ϵ Aurigae here, only the similarity of the underlying physical process (for a discussion, see Hack and Selvelli, 1979).

It appears that the number of puzzles surrounding ϵ Aurigae is endless. Fortunately for us, the next eclipse is just around the corner. The partial phase is supposed to start in June/July 1982, the famous "totality" should last from January/February 1983 through the end of December 1983 or early January 1984, and the partial phase should then end in June/August 1984. The dates of the contacts are somewhat uncertain and the actual duration of the eclipse appears to be variable, which is not surprising if at least one of the components is actually a disk rather than a star. For the first time, we will be able to observe the eclipse in the infrared and in the ultraviolet. Some traditionally accepted concepts, like the greyness of the eclipse, may disappear just because of the broad wavelength range covered this time. If nothing else shows up, the least we will get in the ultraviolet is a better look at the mysterious additional light: if the light of the F0 star is dimmed by about 0.75^m, then a wider segment of the FUV spectrum of the hotter source should be seen. I will not be surprised, though, if this hotter source is eclipsed, too! We have seen this combination of a \sim B8 source with another, F-type continuum in one and the same component in W Serpentis: I interpreted it as a B star embedded in an optically thick disk. If the F0 spectrum were due to a flat disk, the flat shape of the eclipse light curve would be easy to understand. But it is hard to explain the observed high luminosity and large size of the eclipsed star by this idea. What is not hard to explain in ϵ Aurigae? Let's wait, watch and see!

SYMBIOTIC STARS AS BINARIES: WHAT IS THE DEGREE OF INTERACTION?

The so-called symbiotic objects have long existed at the outskirts of stellar astrophysics as a small group of mysterious objects. By the classical definition of P. W. Merrill, a symbiotic object displays a combination spectrum: emission lines indicating a hot source are superimposed upon a late-type stellar continuum. In typical cases (if such a thing exists for the symbiotics), we observe TiO absorption bands together with the emission lines of He II and [O III]. However, the underlying continuum can also be of spectral type K or G, and a certain variety in the presence of the emission lines must also be accepted even by purists.

It has long been believed that most if not all symbiotics are binary systems, but hard evidence was slow to come. In a few systems, radial velocity variations suggested Keplerian motion with long periods, between 1 and 20 years. Thus large dimensions of the systems are indicated, and obviously the nebulosity radiating the emission lines will be of the same order of size, otherwise the typical forbidden lines of [O III], [Ne III], and occasionally of [Fe VII] would not show up. But there existed hardly any direct evidence of the presence of a hot component in the system. In fact, the veiling of the late-type absorption lines, often considered as the evidence for a hot blue continuum, is more likely due to a continuous radiation of circumstellar hydrogen.

The advent of the International Ultraviolet Explorer satellite opened a new epoch in the investigation of the symbiotics. We can now directly observe the continuum due to a hotter object in AG Pegasi, AG Draconis, Z Andromedae, and other objects. But it is still not easy to recognize the nature of the hot components. The slope of the continuum in several objects resembles that of a B0 star, but the presence of the emission lines of He II λ 164 nm, C IV λ 155 nm, and N V λ 124 nm demands a hotter source of ionizing photons: the Zanstra temperatures are near 10^5 K. Thus the FUV continuum we observe with the IUE is probably only the Rayleigh-Jeans tail of the actual stellar continuum. And it is often contaminated by continuous hydrogen radiation, in particular longward of λ 200 nm. In some symbiotics, we observe only an essentially flat, probably circumstellar continuum (AR Pav, CI Cyg, CH Cyg, AX Per). Yet the hot star must be there, since the high-ionization emission lines are strong. It appears that the hot source must be a small star if it can be hidden in some sort of a disk or envelope; after all, in spite of its high emissivity, its contribution to optical fluxes is negligible compared to the red giant.

The cool components appear to be normal K-M type giants, but some are semiregular variables (CH Cygni), others are Miras (R Aquarii). Compared to them, the hot components must have very much smaller effective radiating areas. They appear to be subdwarfs, with radii of the order of 0.1 to $1 R_{\odot}$, and with masses not very different from $1 M_{\odot}$ (but our statistics, in particular of masses, are woefully incomplete!). A central star of a planetary nebula has just the right temperature, size, and lu-

minosity. Moreover, spatial distribution of the symbiotics strongly resembles that of the planetary nebulae (Boyarchuk, 1975). Thus it would be easiest to assume that the hot components of the symbiotics are close relatives of the central stars of the planetaries, and the red component is present in the system only to provide (all or most of) the material for the nebulosity, which is ionized by the photons generated by nuclear burning of the subdwarf. The cool giant would be losing mass by stellar wind, as is usual for late-type luminous stars, although we may have to postulate an "enhanced" wind mass loss on order of 10^{-5} to $10^{-6} M_{\odot}/\text{year}$ (perhaps enhanced by the relative proximity of the photosphere of the red giant to its Roche critical lobe). This would be the simplest, "pure natural" model of a symbiotic object, and I called it a PN symbiotic or a subdwarf symbiotic (Plavec, 1982). The difficulty with this scheme is that the subdwarfs are, according to theoretical calculations (Paczynski, 1971), extremely short-lived objects, in particular with masses even a little above $1 M_{\odot}$. These subdwarfs have degenerate carbon-oxygen cores and produce energy in nuclear-burning shells of hydrogen and helium, located in a fairly thin envelope, which is quickly consumed because of this shell burning. A slight modification of the same model would be a helium star as the hot component, formed from a moderately massive Algol subgiant which at the end of its mass loss stage ignited helium in its core. But we encounter another difficulty with the "natural" model: it appears that flares and slow nova-like eruptions are typical in the symbiotics, and these are hard to explain by the above model, which implies little or no interaction between the components. Perhaps the so-called BQ[] stars (Ciatti, D'Odorico and Mammano, 1974) are built on this model.

A very promising model was developed by Tutukov and Yungelson (1976) and by Paczynski and Rudak (1980). Again, the hot component is a subdwarf as described above, but its lifetime is artificially prolonged by the material which is continually transferred from the red giant, is accreted in the atmosphere, and then consumed in the nuclear burning shells. In fact, a degenerate white dwarf can be "rejuvenated" in this way, its nuclear-burning shells ignited, and then maintained by this influx. The theorists often speak of this component as of a degenerate dwarf: however, because of the formation of the non-degenerate envelope of substantial thickness, it is really a subdwarf by its size, effective temperature, as well as luminosity. Paczynski and Rudak (1980), Rudak (1982) and Tutukov and Yungelson (1982) have shown that this model is very sensitive to the rate of mass transfer, and can produce either quasi-periodic flares or slow nova-like eruptions. Perhaps the term novalike symbiotics may be appropriate for them. We see that in the symbiotics built on this model, the red component not only maintains the nebulosity but also stimulates and maintains the production of the ionizing photons -- at the surface of the other star! Fairly low rates of accretion are sufficient, in fact needed, of the order of $10^{-7} M_{\odot}/\text{year}$, so again mass loss from the red giant via a stellar wind is all that is needed.

A third model for the symbiotics postulates accretion not as a stimulant of nuclear burning, but rather as the direct generator of the ionizing photons. Since we need temperatures only of the order of 10^5 K and the symbiotics are not known to be X-ray emitters (with one or two exceptions), the surfaces of degenerate dwarfs represent too deep potential wells for accretion in this type, and the model postulates accretion on main-sequence stars or on subdwarfs. The required temperature of 10^5 K is then generated in the innermost parts of an accretion disk surrounding the star, and in particular in the transition zone between the disk and the star itself. This transition zone is thin and therefore has a small effective radiating area, even if the accreting star is fairly large. Thus in this model, the small size of the hot source postulated by its low emission in the optical region, does not necessarily mean that the companion to the red star is a star below the main sequence. Bath (1977, 1981) developed this model as an analogy to his model of optically thick envelopes of novae outbursts (1978). The model requires very high rates of mass transfer between the components of a symbiotic, $10^{-4} M_{\odot}/\text{year}$ or higher, and these can be reached only if the red giant fills its critical lobe and loses mass by Roche lobe overflow. The model is again concerned primarily with the eruptive activity observed in many symbiotics, and strongly depends on another theory by Bath (1972), according to which the red giant components of binary stars become temporarily unstable and eject large amounts of gas in spurts. Since the basic mode of mass transfer in this model is the same as in the Algols, and since the gainer is believed to be most likely a main-sequence star as in Algols, I think that the name Algol symbiotics is appropriate.

The cool components of the symbiotics are most likely giants on the second (asymptotic) giant branch of the stellar track through the H-R diagram. This conclusion is less based on a direct determination of the luminosity class of the giant, and more on the fact that the known orbital periods of the symbiotics are of the order of years. The giant should either fill or temporarily fill its critical lobe (as in the case of the Algol symbiotics), or at least it should not be an order of magnitude smaller than the critical lobe (otherwise its wind would probably be too weak). This reasoning suggests that the cool components must be large stars, and therefore lie on the asymptotic branch; the Mira nature of some of them confirms this conclusion. But then, why don't we observe symbiotics with the cool components on the first giant branch? Their orbital periods would be of the order of months. Perhaps the size of the system would not permit the existence of a nebulosity extended enough to display the typical emission lines of the symbiotics. Possibly, the W Serpentis stars (Plavec, 1980) -- or rather some of them, such as RX Cas or SX Cas -- are the relatives of the symbiotics with the cool components on the first giant branch.

At this time, we are unable to decide with certainty which of the above models is the most appropriate for the symbiotics, or if all three apply, each one to different cases. A whole Colloquium, IAU No. 70 has

been devoted to them (Viotti and Friedjung, 1982), and the reader will find many answers and even more questions in that publication.

BARIUM STARS: NO SUCH THING OUTSIDE A BINARY SYSTEM?

Remember the many discussions whether abundance anomalies are intrinsic, or due to mass transfer in binary stars? Well, a new twist to the story is here. McClure, Fletcher, and Nemeč (1980) found that all stars exhibiting the strong Ba II anomaly vary in radial velocity, and may well all be binaries; in two cases they could go beyond this statement and concluded that the mass functions indicated the presence of a component with a mass between 1 and 2 solar masses. These low masses, low luminosities one must expect for the hypothetical companions, and small radial velocity ranges of the Ba II giants, all suggest that the systems are rather wide and that the companions will probably be degenerate stars. Now Bohm-Vitense (1980) reports that the Ba II class 2 star ζ Cap, G5 II, indeed has such a component, since the far ultraviolet spectrum shows an increase of the flux shortward of λ 150 nm. From the observed flux distribution, the star must have an effective temperature of about 22,000 K, while its mass is near $1 M_{\odot}$: the object is rather similar to Sirius B. These observations strongly suggest that the barium anomaly may be due to mass transfer rather than to an internal mixing process intrinsic to the star.

THE ALGOLS: A BETTER LOOK AT THE COMPONENT STARS IS NOW POSSIBLE

The semidetached binaries of the Algol type, believed to be products of the first phase of mass transfer observed near the end of the mass transfer phase, are easy to detect and study photometrically, but much harder to study spectroscopically. The cooler and fainter subgiant secondary components are as a rule suppressed in the combined spectrum over the spectral range ordinarily explored. As a result, our knowledge of their masses and other characteristics was for years about as crude as were theoretical evolutionary sequences explaining Algols. Recently, however, the situation on the observational front improved substantially with the introduction of red-sensitive image tubes. Popper (1980) lists already 17 reasonably well determined systems; and to them, we should add U Cep (Tomkin, 1981) and U CrB (Batten and Tomkin, 1981).

Although this sample is still insufficient for truly reliable statistical studies, some conclusions can be drawn with more confidence than was possible in the past. I will only mention here an interesting observation about the masses of the subgiants. The masses of the subgiants that accompany the B-type primaries, U Cep, U CrB, and U Sge, are actually not small, not far from $2 M_{\odot}$, and reasonably appropriate for G stars above the main sequence. Truly small masses of the subgiants, and hence fairly large overluminosities, are encountered mainly in systems whose primaries are A stars (S Cnc, RY Gem, AS Eri, AW Peg). But there are exceptions among B stars, like RY Per and Algol itself, with rather low-mass secondaries ($\sim 0.8 M_{\odot}$).

Studies based on the improved determinations of the masses of the Algol systems (De Greve and Vanbeveren, 1980; De Greve, preprint, 1981) confirm the suspicion voiced earlier (Kopal, 1971; Plavec, 1973) that the present configurations of the Algols demand considerable mass loss from these systems at the earlier stages of mass transfer. This would not be so surprising if the principal mode of mass loss from the losers (the initially more massive components) were an isotropic stellar wind. But the losers typically have too low luminosities for a normal stellar wind to be efficient (unless it is tremendously enhanced by the proximity to the Roche lobe). Evolutionary calculations postulate Roche lobe overflow with an ensuing gas stream directed into the vicinity of the other component (the gainer). So why should the transferred gas leave the system in large quantities, instead of being accreted? Why, when, and how does it happen? In particular: can we identify the systems that are currently in the rapid phase of mass transfer, when this escape from the system must occur?

THE W SERPENTIS SYSTEMS: A LINK BETWEEN THE ALGOLS AND THE SYMBIOTICS?

I believe that we do observe interacting systems in the rapid phase, and that they are probably of the W Serpentis type (Plavec, 1980), and we do observe direct evidence of mass outflow from them in the profiles of the far ultraviolet emission lines. Generally, the presence of any emission lines is a good indicator of the existence of a fairly large volume around one component or around the whole system, filled with fairly dense circumstellar material. But the emission lines of the Balmer series, observed in many Algols particularly at the time of the eclipses, were always believed to come from rings encircling the gainer; only recently did Crawford (1981) show that this picture may be oversimplified. The emission lines discovered in the FUV by R.H. Koch and me (Plavec and Koch, 1978; Plavec, Weiland and Koch, 1982) tell a different story. When they can be observed at high dispersion (like β Lyrae and KX Andromedae), then all their emission lines display distinct P Cygni profiles. The lines in question are mostly resonance lines of C II, C IV, N V, Si II, Si III, Si IV, Al II, Al III, and some low-level transitions of Fe III. Thus we observe a stellar wind, and there exists a certain degree of analogy with hot luminous early-type stars. In those, too, mass outflow was long suspected, but only the lines of the abundant elements observed in the FUV clearly demonstrated the existence of the winds. But the wind observed in the Serpentids is different from the "classical" wind observed in luminous hot supergiants. The terminal velocity in β Lyrae is no more than 500 km/s, the profile is asymmetrical with the emission part stronger than the absorption component. Probably collisional excitation of the upper levels of the transitions plays a more important role in the Serpentids. The luminosity and temperature of the central star (the gainer) are too low to provide the necessary driving force. More likely, the energy is ultimately derived from the gravitational potential energy released in the process of accretion.

The nature of the components of the W Serpentis stars is not easy to establish because the spectra and photometric light curves are complicated by the circumstellar matter, which, in addition to the emission lines also produces deep shell absorption lines and a hydrogen continuum. In SX Cas, we now believe that the correct spectral types are B7 III + K3 III, plus a fairly strong optically thin hydrogen continuum (Plavec, Weiland and Koch, 1982). In RX Cas, we detected only the late-type component, K1 III, and the hydrogen continuum (Plavec, Weiland, Dobias, and Koch, 1981); the primary component appears to be lost in the hydrogen continuum, and may be either a main-sequence star fainter than A0, or a star below the main sequence. In W Serpentis, we seem to observe only one object, the one that is partially eclipsed at primary eclipse, but two continua appear to be associated with this object: a hotter one, about B8, seen in the FUV, and a cooler one, about F5, dominating in the optical region. Two possible models come to mind: either the primary component is an F5 star, surrounded by an accretion disk, whose innermost part radiates as a smaller B8 object. Or the primary component is actually a B8 star, to a large degree obscured by a thick disk, whose edge radiates as another photosphere simulating a star of spectral type F5. We are now inclined to prefer the latter explanation (Plavec and Sakimoto, 1978; Plavec *et al.*, 1981). But a third explanation, unknown to us at the moment, may be the right one.

It is rather natural to assume that the W Serpentis stars are a natural continuation of Algols toward longer periods. The analysis of SX Cas seems to support this idea, and RX Cas does not contradict it. But it is interesting to realize that their periods are longer than one month, and that the cool components are giants probably on the first giant branch. The flat spectrum of RX Cas obtained when the K1 III giant is subtracted is quite similar to that of the symbiotic star AR Pavonis. The emission line spectra are not identical: AR Pavonis displays He II emissions and intercombination lines indicative of a moderate electron density ($10^6 - 10^9 \text{ cm}^{-3}$), while RX Cas displays only weak He I emissions, and almost no intercombination lines; the density in its circumstellar envelope must be much higher (10^{12} cm^{-3}). But these density differences in the nebulosity may be simply consequences of the different dimensions of the two systems, obvious already from the very different orbital periods (32 days in RX Cas as against 605 days in AR Pav). Otherwise the nature of the objects need not be drastically different. Don't we have here an indication of a possible similarity?

THE ALGOLS REVISITED: OBJECTS NOT SO DORMANT AS WE THOUGHT

The "classical" Algol systems have periods of only a few days, and have long been considered disappointingly quiescent, "old ladies with an interesting but remote past". Some Algols are probably indeed rather clean of circumstellar matter now (see Fig. 1 for U Sge), but others are more active than we have thought.

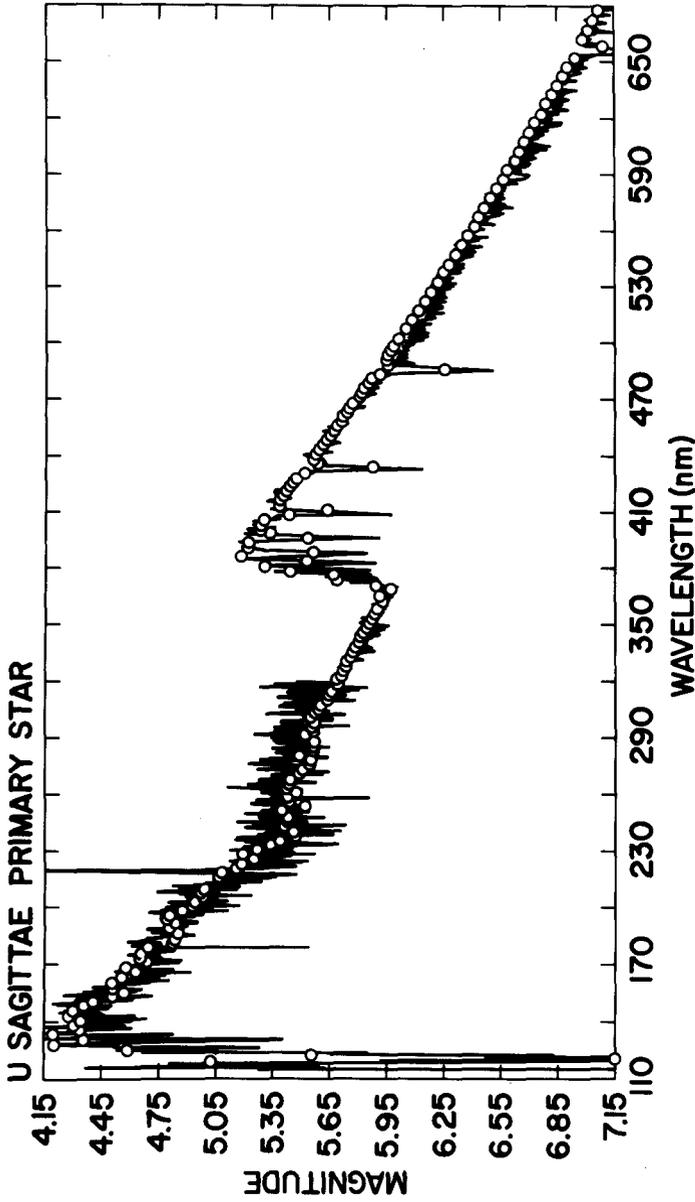


Fig. 1.: The primary component of the Algol system U Sagittae displays an uncomplicated spectrum, which can be well matched by an interpolated Kurucz model atmosphere for $T_{\text{eff}} = 12,250$ K, $\log g = 3.85$.

The unexpected flaring up of the $H\alpha$ emission in U Cephei (Batten *et al.*, 1975; Plavec and Polidan, 1975) called attention to this object, and systematic observations, mainly by Olson (1980) and Crawford (1981), revealed a complex and variable structure of the circumstellar material surrounding the gainer. One could still argue that U Cephei is a uniquely active Algol; but the truth is rather that other Algols have not been studied carefully enough. Olson (1981a) reported a similar phenomena in RW Tauri, and Kaitchuck and Honeycutt (1981) fully confirm his findings. Theirs and Crawford's studies reveal various puzzles. The relative size of the gainer in such short-period systems like U Cep and RW Tau are too large, and the stream from the loser should impact on them directly, rather than form a disk normally expected in longer-period systems (Lubow and Shu, 1975). Yet some sort of transient disks apparently exist in U Cep and RW Tau. Moreover, the emission lines are broadened much more than a Keplerian motion of a simple disk would do. The optical emission lines are not the only evidence of circumstellar activity. Olson (1981b) noticed a near-ultraviolet excess in two Algols of very different period: RS Cephei ($P = 12$ days) and AI Draconis ($P = 1.2$ days). In the W Serpentis stars, the near-ultraviolet excess was found to be due to a circumstellar hydrogen continuum with the Balmer jump in emission, but in some systems it can also be the long-wavelength tail of a "hot" far-ultraviolet continuum (originating in a star or in the transition layer between the gainer and the surrounding disk). It would seem that the small system of AI Draconis must be rather similar in its structure.

Another indication that the Algols are far from dormant came with the discovery of the high-ionization emission lines (C IV, N V, Si IV) in the FUV totality spectra of V356 Sagittarii (Plavec and Dobias, 1980) and of U Cephei (Plavec, Dobias and Weiland, 1982). A chromospheric origin of these lines is unlikely: in U Cephei, it would give unusually large surface fluxes, in V356 Sgr we have no star that would be expected to have a chromosphere. Thus, the two stars are probably related to the W Serpentis stars. This means that we must assume the existence of hot circumstellar plasmas even in relatively short-period Algols. Further evidence for the existence of such plasmas comes from the studies of the absorption spectra of the Algols. Kondo, McCluskey, and Harvel (1981) discovered strong absorption lines of Si IV and C IV in U Cephei. Polidan and Peters (private communication) made similar observations in other Algols, such as CX Dra, AU Mon, or U CrB. Our high-dispersion spectra (Plavec, Dobias, and Weiland, 1982) also confirm the presence of absorption lines in a number of Algols of ions of a much higher level of ionization than would be appropriate for the spectral type of the stellar components. Apparently, regions of highly heated plasmas exist in many (if not all) accreting systems, and the transition between the short-period Algols and the W Serpentis stars is only a matter of degree.

BETA LYRAE: ALWAYS DESERVES A SPECIAL CHAPTER

We have observed β Lyrae at both eclipses and at several intermediate phases, both with the IUE satellite and with the Lick Observatory ITS scanners. By subtracting the eclipse scans from those taken at full light, we obtained energy distributions for each component separately (Plavec, Weiland and Dobias, 1982). No better procedure is available since the eclipses are not total. But a degree of uncertainty enters since the light outside the eclipses is not constant. An improvement will be possible when a better phase coverage is obtained and the observations are tied in with photometric light curve solutions. Nevertheless, even the preliminary results are quite interesting.

The component whose spectral lines are observed at all phases is usually classified as B8 II. It is surprising to see (Fig. 2) that the corresponding Kurucz atmosphere providing the best fit ($T_{\text{eff}} = 11,000$ K, $\log g = 2$) matches the observed flux distribution reasonably well just only over a part of the optical region (370 -560 nm). There appears to be a flux deficiency shortward of λ 160 nm; this may be the consequence of an incomplete inclusion of line blanketing in Kurucz's models of hotter supergiants. Everywhere else, the observed flux exceeds the model flux. An infrared excess has been known to exist for some time. Now we see that there exists at least as strong (probably stronger) ultraviolet excess as well. Both can be probably explained by the same hydrogen circumstellar cloud. Unfortunately, the important spectral segment in the vicinity of the Balmer jump has not yet been adequately covered by our Lick scans.

We have obtained a similar flux distribution for the secondary component, a truly mysterious object: Although it is more massive than the primary, it contributes less but still significantly to the continuous radiation, but shows no detectable absorption lines. In the optical region, the secondary's continuum parallel closely that of the B8 II star, i.e. the two objects have nearly the same color temperature there. In the far UV, beginning at about λ 160 nm, the secondary component is brighter, i.e. its color temperature is higher (See Fig. 3). The secondary eclipses are deeper in the FUV than the primary ones. This variation of the color temperature across the spectrum is explained in principle if we assume that the secondary object radiates as a disk. Contamination by circumstellar hydrogen continuum is even stronger than for the primary component. It is impossible to decide if the secondary star itself is visible in certain regions of the spectrum. On the whole, the thick disk model advocated by Wilson (1974) is supported by our observations.

A curious thing happens in the spectral region between λ 180 - 220 nm: There are practically no eclipses observed in β Lyrae in that spectral region! Obviously, the circumstellar material surrounding both stars, or the whole system, extends to such large distances that eclipses of its parts do not significantly reduce its light; and in the

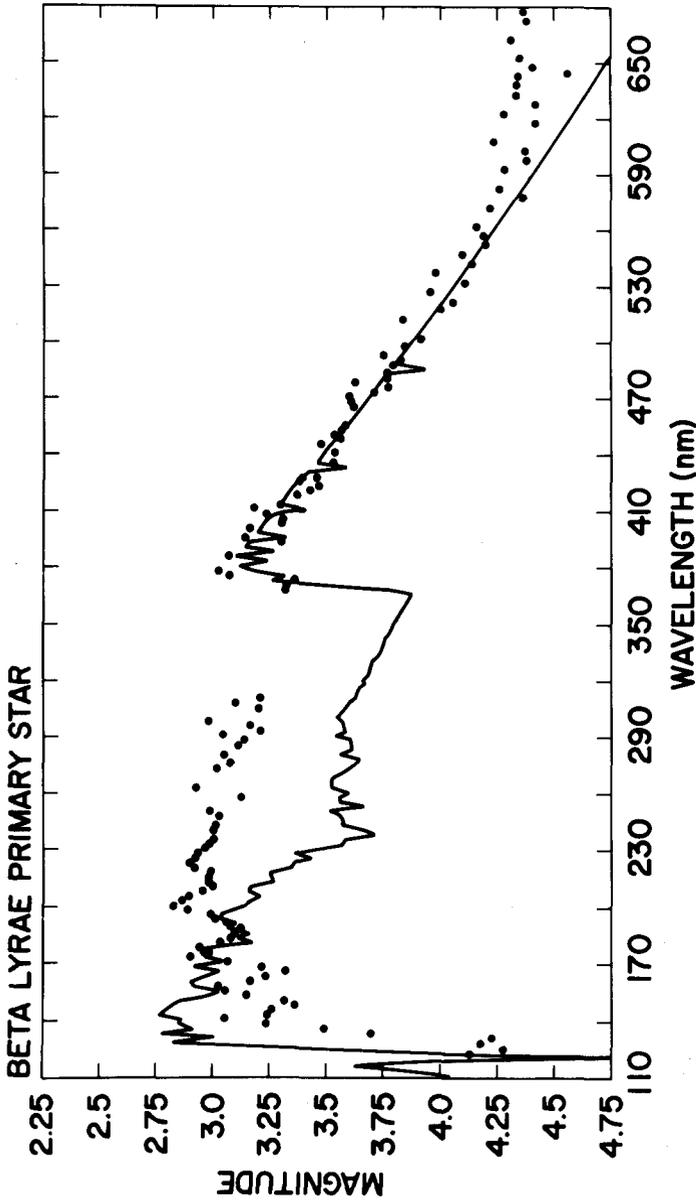


Fig. 2.: The primary (B8 II) component of β Lyrae is well matched by a Kurucz model atmosphere only in the optical spectral region. Over most of the spectrum, the observed fluxes (dots) lie above the model fluxes (full line).

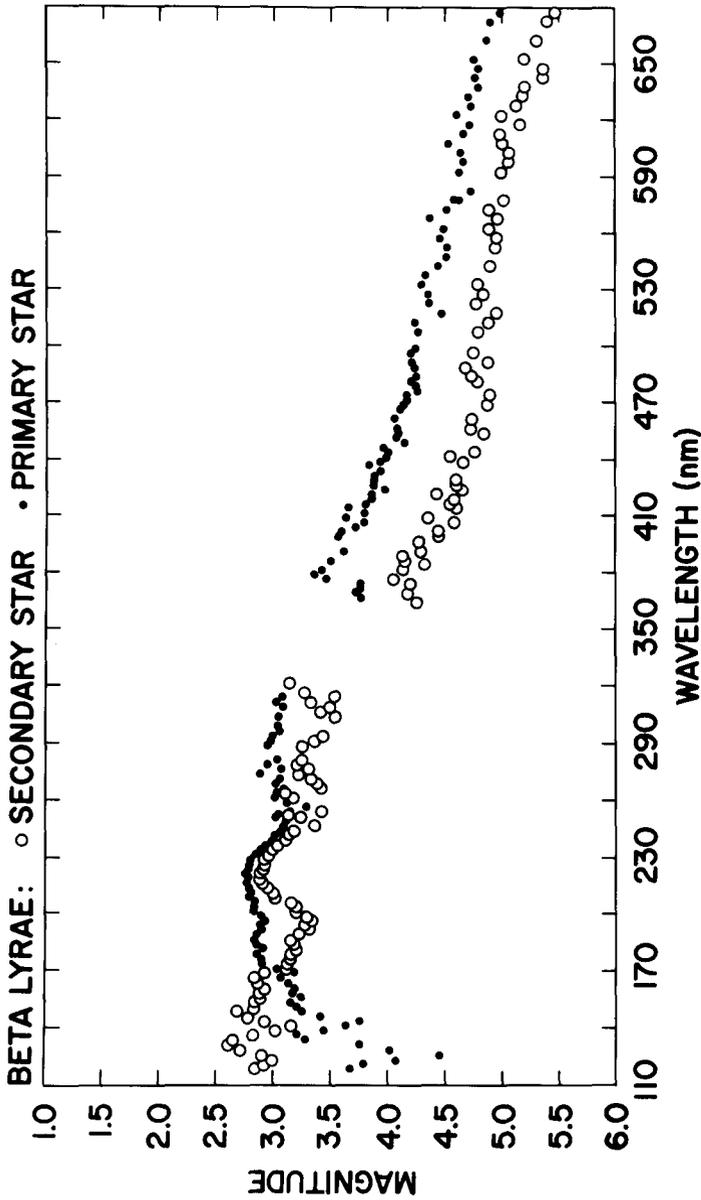


Fig. 3.: The relative energy distributions of the two components of β Lyrae are compared. The secondary star is the brighter one in the far ultraviolet.

spectral region mentioned, the circumstellar material emits more flux than the two stellar components. This excess flux, or the " λ 200 nm bulge" is visible in the combined spectrum at all phases, and was known already from the Copernicus observations. It was explained as a superposition of numerous weak emission lines of Fe III, for example by Viotti (1976). Indeed, a number of prominent isolated Fe III emission lines are visible in the IUE spectrum of β Lyrae, and multiplet tables show that very many lines of Fe III cluster just in the above spectral region. Nevertheless, I do not believe that this explanation is complete, in fact it may not even represent the dominant cause of the bulge. Each of the individually observed emission lines of Fe III has a distinct P Cygni profile, and a quasi-continuum consisting of a number of such lines should show traces of this structure, although degraded by superposition. But the continuum is smooth. I would like to suggest that the bulge is due primarily to continuous radiation of hydrogen, with a non-negligible optical thickness at the Balmer limit, and corresponding to an electron temperature near 15,000 K. A comprehensive computer code developed by Drake and Ulrich (1980) at UCLA shows that with a suitable choice of parameters, one can get a local maximum of flux at the observed wavelength. Our observations have revealed the presence of similar bulges in the spectra of all the Serpentids; in some, such as W Crucis, the λ 200 nm bulge is very prominent. The Serpentids do not help us to decide between the two above explanations, since Fe III emissions are always present in their spectra. But the symbiotics do not show Fe III emissions, yet the bulge is observed in some of them. Moreover, and this is decisive, it is seen displaced to shorter wavelengths, such as λ 160 nm, which is easily possible if we assume an electron temperature of the hydrogen cloud to be closer to 20,000 K, but is impossible to explain by an accumulation of Fe III emissions there.

A FINAL REMARK

I will not attempt to summarize the various topics I mentioned in this paper. There appears to exist a bewildering variety even among the objects most of which we would simply describe as binary systems in the first phase of mass transfer. Yet we also notice surprising links that connect many of them, unexpected similarities: are they Rosetta stones or red herrings?

We could look at the same problem from a different point of view. At times some of the objects: ϵ Aurigae, β Lyrae, and above all SS 433 appear completely unique. Yet I cannot believe that it is so: I think that much more likely these bizarre systems are just rather extreme cases to which one or more links lead, and for which certain, hopefully simpler, relatives exist. If we manage to identify them, we may be much closer to a better understanding of the greatest puzzles.

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