THE SYMBIOTICS AS BINARY STARS

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ABSTRACT

Symbiotic stars have become an important testing ground of various theories of binary star evolution. Several physically different models can explain them, but in each case certain fairly restrictive conditions must be met, so if we manage to identify a definite object with a model, it will tell us a lot about the structure and evolutionary stage of the stars involved. I envisage at least three models that can give us a symbiotic object: I have called them, respectively, the PN symbiotic, the Algol symbiotic, and the novalike symbiotic. Their properties are briefly discussed. The most promising model is one of a binary system in the second stage of mass transfer, actually at the beginning of it: The cool component is a red giant ascending the asymptotic branch, expanding but not yet filling its critical lobe. The hot star is a subdwarf located in the same region of the Hertzsprung-Russell diagram as the central stars of planetary nebulae. It may be closely related to them, or it may be a helium star, actually a remnant of an Algol primary which underwent the first stage of mass transfer. In these cases, accretion on this star may not play a significant role (PN symbiotic). Perhaps more often, the subdwarf is a "rejuvenated" degenerate dwarf whose nuclear burning shells were ignited and are maintained by accretion of material coming from the red giant in the form of a stellar wind. Eruptions are often inevitable: this is the novalike symbiotic. A third alternative is a system in the first stage of mass transfer, where the photons needed for ionization of the nebula come from an accretion disk surrounding a main sequence star: an Algol symbiotic.

In spite of considerable observational effort, the symbiotics are known so poorly that it is hard to decide between the models, or even decide if all three can actually exist. The theorists seem to be ahead of the observers. Every effort should be made to obtain better information on the components stars of any of the symbiotic systems.

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1. INTRODUCTION: LET'S ACCEPT THE HETEROGENEITY OF THE SYMBIOTICS

We hear frequent complaints that the symbiotic stars are a very inhomogeneous group of objects. The first prize in this respect goes to Roberto Viotti, who last year in Trieste (discussion following Plavec, 1981, p. 455) came forward with the statement that symbiotics do not exist, while this year he has organized an excellent three-day colloquium on them with a rather crowded program. His argument, of course, was that the symbiotics do not exist as a homogeneous class of objects. I do not understand why anything like this should be held against them; in fact, heterogeneity makes them much more important, since they can tell us a lot about the evolution of binary stars. I do not want to claim that single-star models are excluded; the heterogeneity may easily go that far. My task is to talk about binary models for the symbiotics, and I believe that any binary system that contains a red giant and at the same time displays evidence of the presence of a much hotter object in the system is worth looking at, whether it satisfies any formal criteria or not.

According to Merrill's original definition, symbiotic stars have combination spectra, in which the high-excitation emission lines regularly found in planetary nebulae are superposed on a low-temperature absorption spectrum. We usually are a little more specific and postulate the co-existence of a He II emission with the TiO absorption bands. By this specification we have selected the most extreme cases from a much more general phenomenon, namely the existence, in a binary system spectrum, of emission lines requiring a hotter radiation source than the one suggested by the underlying stellar continuum. An M star spectrum with superposed emission lines of He II and [O III] is a puzzle; but it is only an extreme case of the puzzle presented by the existence of Balmer emission lines in, for example, the eclipsing binary SX Cassiopeae, whose components have been classified as A6 III + G6 III. This potential relationship of the symbiotics to a much larger group of stars with emission lines should be kept in mind.

In order to construct a symbiotic object, we need a) a source of a late-type continuum, b) a source of circumstellar gas, c) a source of ionizing photons. The two former requirements are satisfied simultaneously if we postulate the presence of a late-type giant or supergiant. Observations of single stars of high luminosity have provided ample evidence of stellar winds from late-type giants or supergiants. The rate of mass outflow generally increases with increasing luminosity and decreasing effective temperature. This makes the M giants prime candidates for membership in the symbiotics, and this is what we actually observe. Only M supergiants produce an even higher mass outflow, and indeed in related stars like VV Cephei, red supergiants are present. There must be some reason why giants predominate in the symbiotics.

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2. A SUMMARY OF OBSERVED PROPERTIES.

We agree that most, if not all, symbiotics are binary systems. But coming to the properties of the stellar components of these presumed binaries, how many hard facts about them do we know? Very few indeed, and that must be kept in mind whenever we are tempted to generalize.

For several systems, we know orbital periods. The eclipsing systems are most reliable: AR Pavonis has P = 605 days, CI Cygni has 855 days. Then there are well-observed spectroscopic orbits: AG Pegasi with P ≅ 820 days, T Coronae borealis with 227 days. For other systems the radial-velocity data are less reliable, but in general, periods between 1 year and perhaps 20 years or more are indicated.

Concerning masses, we are even worse off. For AG Peg, Hutchings, Cowley, and Redman (1975) assumed the cool star mass to be 3-4 M_o, and obtained about 1 M_o for the hot star. For AR Pav, again from the radial velocity curve of only the cool component, Thackeray and Hutchings (1974) suggest $M_c \cong 2.5\ M_o$, $M_h \cong 1.2\ M_o$. In the recurrent nova T CrB, both radial velocity curves were determined by Kraft (1958), and the rediscussion by Paczynski (1965) indicates $M_c > 2.2\ M_o$, $M_h > 1.6\ M_o$.

Actually, no object has been analyzed succesfully enough to make it possible for us to present it here as a model case. Since we need to have a model before our eyes, I will describe AG Pegasi. It is questionable if it is a representative symbiotic object, or if a representative symbiotic object exists at all. At least, AG Pegasi may have a representative orbital period, 2.25 years. From a number of discussions of AG Peg, I will attempt a synthesis. If we assume $M_h = 1\ M_o$, $M_c = 3\ M_o$, then their separation is probably $A \cong 600\ R_o = 2.7$ AU. The radius of the critical Roche lobe around the red giant is then about $A \cong 280\ R_o$. The temperature of the cool star appears to correspond to about a spectral type M2, and this in turn permits us to express its radius and luminosity as functions of the distance D (in kpc): $R_c = 108$ D, $L_c = 1.7 \times 10^3\ D^2$, $MBOL_c = -3.3 - 5 \log D$. The cool component's luminosity class apears to be III. Then, using the calibration of Lee (1970), $MBOL_c = -1.9m$, $R = 56\ R_o$, $D = 0.5$ kpc. If, however, the luminosity class is II, $MBOL_c = -3.8m$, $R_c = 134\ R_o$, and $D = 1.24$ kpc, putting the star 0.6 kpc below the galactic plane. Note that even in this case the star remains substantially smaller than its critical Roche lobe (Keyes and Plavec, 1980).

When we first detected the hot continuum in the far ultraviolet spectrum of AG Peg with the IUE, we were very happy to be able to fit it by an atmospheric model with $T_{eff} \cong 30{,}000$ K. However, the Zanstra temperature derived from the He II lines is considerably higher, close to 10^5 K, and this probably is the actual temperature of the hot star in AG Peg; what we observe with the IUE must therefore be the Rayleigh-Jeans tail of the energy distribution. From the observed flux we conclude that the luminosity of the hot star is $L_h = 6.9 \times 10^3\ D^2\ (L_o)$, $MBOL_h = -4.8 - 5 \log D$, and its radius $R_h = 0.28$ D (R_o). As we will explain in more detail elsewhere (Plavec and Keyes, in preparation), we prefer D =

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0.6 kpc, in which case we have the following parameters of the system: $R_h = 0.16\ R_o$, $MBOL_h = -3.7m$, $R_c = 65\ R_o$, $MBOL_c = -4.4m$.

While we do not know how representative these stellar parameters are for the whole family of the symbiotics, we can at least be more definite about the spectral types of the components. The most homogeneous compilation of atmospheric model fitting to the optical and UV continua of the symbiotics was made by Slovak (1980). In five out of nine objects, he finds that the far ultraviolet continuum can be fitted by a B0 V star. This means that the hot components in these objects are rather similar to AG Peg as described above: while the observed slope of the continuum can be formally fitted by a Kurucz model atmosphere continuum for an effective temperature not far from 30,000 K, the presence of the He II emissions indicates that this continuum is most likely only the Rayleigh-Jeans tail of a much hotter object, whose actual effective temperature probably lies between 6×10^4 and 1.5×10^5 K. In three of the remaining four objects surveyed by Slovak, the continuum in the ultraviolet can be formally fitted by a stellar continuum corresponding to about spectral type A0 V. I think this fit only means that the UV continuum is essentially flat, without any definite trace of the hot component. But such a hot component must be present, since the observed emission lines are pretty much the same as in the previous five cases. The interpretation, already suggested by Slovak, is that the hot star is surrounded by a disk or an envelope which is sufficiently optically thick to produce its own continuum and to obscure the hot star inside. The last of the nine cases, AG Dra, is best fitted in the UV by a B5 V star, and this continuum may well be a superposition of a hot stellar continuum and a disk or envelope.

As to the cool components, Slovak's survey finds an M giant in seven out of nine cases, while in the remaining two symbiotics the cool component is K4. It is worth noticing that all nine cool giants are classified as of luminosity class III --a fact that is not easy to reconcile with evolutionary considerations, as we will see in Section 3. On the whole, we see that AG Peg is reasonably representative. In this object, too, there is an additional near-ultraviolet continuum due to circumstellar hydrogen. There probably exists a continuous transition between systems displaying the hot star continuum clearly, and those in which the circumstellar continuum dominates entirely. The observed range in the sources of the cool continuum is much narrower. Thus it is easier for us to start an attempt at modeling and evolutionary interpretation by a discussion of binaries that can harbor a cool giant.

3. BINARIES WITH A LATE-TYPE GIANT COMPONENT.

An old Latin proverb, applied to the birth of a baby, says: "Mater semper certa, sed pater incertus." We have a similar case in the symbiotics: one of the "parents" is known: the cool component in each symbiotic binary system is a late-type giant of spectral type M, K, or occasionally G. Therefore these components are located on either of the

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two giant branches of the stellar evolutionary tracks in the H-R diagram, and have deep convective envelopes. Moreover, the observed mass outflow from these stars (necessary to maintain the circumstellar/ circumbinary nebula, and even possibly to generate or stimulate the production of ionizing photons) probably demands that the cool giant either fill its critical Roche lobe, or be at least not very far from it (say its radius should be at least 50% of the critical Roche radius).

What kind of binary systems can contain a star satisfying these conditions? Consider first systems either in the phase of the first mass transfer, or approaching it (depending on whether the late giant fills its critical lobe or not). In the notation I used at the Trieste Colloquium No. 59 on mass loss from stars (Plavec, 1981), these binaries are of type Bc (hydrogen shell burning, contracting He core, deep convective envelope) with the cool star on the first giant branch, or of type Cc (He and H shell burning, CO core, deep convective envelope), with the cool star on the asymptotic branch. In both cases the cool star must be the more massive component.

In order to be more quantitative, assume now that the mass ratio is 3:1 (many binaries have mass ratios closer to 1:1; our choice has little effect on the numbers that follow). Assume that the mass of the primary component is $M_1 = 5\ M_o$. Then the primary star will reach its critical Roche surface on the first giant branch if the system's period is $30 < P < 55$ days, and on the asymptotic branch if $55\ d < P < 3$ years. On the first giant branch, before the mass loss starts, the star will be a G8 -K3 III giant. On the asymptotic branch, it will be late K to M star, with a luminosity class changing from II to Ib.

If the primary is, instead, a 3 M_o star, the critical periods for the first giant branch will be $7d < P < 25$ d, and for the asymptotic branch $25\ d < P < 16$ years. On the first giant branch, the star is again a G8-K3 III giant. In its long ascent to the point where it ignites carbon --and this point is identical with that for the 5 M_o star! (Paczynski 1971a) --it changes all the way from K3 III to something like M5 II-Ib.

It is known (see, e.g., Webbink, 1979) that the probability for a given star to have a less massive companion revolving about it in a period P is approximately 0.14 per decade of the period. Imagine 100 binaries with a 5 M_o primary and with periods less than 3 years. Out of this sample, we can expect that 40 will have periods corresponding to case Cc, 8 to case Bc, and 42 to Br (Roche lobe overflow from a radiative envelope, when the primary crosses the Hertzsprung gap). For systems with a 3 M_o primary, the odds shift even more in favor of convective mass transfer: out of 100 systems with periods shorter than 11 years, 61 can be expected to start the mass transfer on the asymptotic branch, 15 on the first giant branch, and 24 in the Hertzsprung gap.

However, this does not mean that we will observe such binary systems with primary components located along their evolutionary tracks according to the above probability distribution. The lifetimes at the various phases will affect the observed distribution, and will heavily favor the inconspicous and uninteresting configuration in which the two

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stars form a wide detached main-sequence system. The odds are only 1 in 4 for the 5 M_0 primary (1 in 3 for the 3 M_0 primary) that it will be seen outside the Main Sequence band; and 1 in 19 (or 1 in 12, repectively) that it will be caught in one of the phases of rapid expansion. All the evolutionary phases outside the main sequence, particularly the giant phases are relatively very short, except for the core He-burning phase lying between the two giant branches. The question is,though, if we can have a symbiotic object with the primary in the core helium burning phase. A star of 5 M_0 makes a loop in the H-R diagram all the way to spectral type about A4 III, where its radius is only 21 R_0. Such a star will not generate a sufficiently strong stellar wind to maintain the circumstellar/circumbinary nebula needed for a symbiotic object, even if we were willing to stretch out the criterion and accept the A giant as the late-type component in a symbiotic. However, stars of 3 M_0 or less do not make this blue loop, and remain in the red giant region, although their radius does shrink temporarily when they start core helium burning. I think they remain candidates for symbiotics even at the phase of core helium burning, thereby increasing the probability of catching a binary system with a < 3 M_0 primary at the red giant stage.

It is better to intercompare the probabilities for the phases of a rapid expansion only. The chances that a system will be seen with the primary in the Hertzsprung gap are about the same as that we will see the primary on the second giant branch (better in favor of the latter for less massive stars). Compared to them, the odds of catching the primary on the first giant branch are 6 to 20 times lower.

In think that this is a most interesting result. It suggests that most of the observed symbiotics should be on the asymptotic branch, and indeed the observed orbital periods very strongly support this conclusion. Actually, no symbiotic is known to have an orbital period of the order of a few months, as it would be appropriate for the first giant branch. Where are the short-period symbiotics? My guess is that they do not look like symbiotics. I think that the dimensions indicated in AG Peg, namely of the order of several AU, are essential, since only this size of the nebulosity enables us to see the prominent forbidden lines so typical for the symbiotics. Also the rate of mass outflow by stellar wind will be considerably higher for the more luminous giant on the asymptotic branch. It is quite possible that the short-period relatives of the symbiotics are the W Serpentis stars, to be discussed later on; if it is so, then we must take this potential relationship into consideration when we discuss the models for both kinds of objects.

However, there is a puzzle here. The stars on the asymptotic branch have luminosities of class II if not Ib, whereas observationally, the symbiotic giants appear to be of lower luminosity class, namely III. The difference is about 2 magnitudes in the absolute visual magnitudes, not negligible! Assuming class III, we get reasonable distances from us as well as reasonable z-distances of the symbiotics from the galactic plane. If we postulate class II for example in T CrB, we get an improbable value of $z = 2.2$ kpc. On the other hand, we must admit that we seldom have a direct evidence from the spectrum, since the criteria

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distinguishing classes II and III in M stars lie in the infrared and are rarely accessible to most observers. It may be that Iben's evolutionary tracks I have been using for this discussion are not suitable, since they assume conservation of mass; quite possibly the observed symbiotic giants have already suffered such a large mass loss that they are now evolving along different tracks, and the usual correlation between luminosity and surface gravity is broken. In the models we calculated some time ago for an initially 7 $M_{\odot}$ mass-losing giant (Plavec, Ulrich and Polidan, 1973), the star indeed deviated from the "conservative" track": its effective temperature decreased so that its spectral type changed from K to M, and its luminosity strongly depended on the instantaneous rate of mass loss. It is worrisome to realize that our estimates of distances, and therefore also of the luminosities of the hot components, which are based on a luminosity classification of the red giant, may not be fully reliable since the spectrum might actually reflect the surface gravity rather than luminosity, and be affected by the rate of mass outflow from the giant.

Incidentally, the above evolutionary calculations, and those by Harmanec (1974) suggest that, following a short phase of truly devastating mass loss, a red giant on the first giant branch will embark on a relatively long phase of quiet evolution during which the mass loss from its atmosphere is still fairly high to begin with (10^{-4} $M_{\odot}$ per year) but declines quickly, to be replaced by a phase of no mass loss through the Roche lobe overflow (stellar wind was not considered, but must of course be present), when the star is burning helium in the core. The common thing for these two stages is that the star remains in the red giant region, but is now the less massive component! Such binaries do indeed exist: the peculiar binary shell stars AX Monocerotis and 17 Leporis have the required properties. They are not symbiotics, however, although they show mass transfer and interaction between the components. The hotter components are obviously not hot enough to ionize and excite the nebulosity. But one cannot exclude the existence of symbiotics of this type.

The common property of all these systems discussed so far, i.e. of systems before or at the first phase of mass transfer, is that the other component is less advanced in its evolution, i.e. in all probability it is a Main Sequence star, and definitely not a degenerate star. Such a star cannot have sufficiently high effective temperature to ionize the surrounding nebulosity. Therefore the only type of a symbiotic object that can form in the first phase of mass transfer is the one advocated by Bath (1977), namely what I will later call the Algol symbiotic: a non-degenerate star surrounded by an accretion disk which is hot enough in its central regions to simulate a hot star and to produce the required number of ionizing and exciting photons.

Most definitely, we can have symbiotics near the second stage of mass transfer, by which term we mean the situation when the initially less massive star has become the more massive one, and is now ascending one of the giant branches. Perhaps due to some sort of cosmic justice, it is now about to return some of the acquired matter back to its mate.

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But is the other component ready to accept it? There exists a rather bewildering variety of possible evolutionary tracks leading to quite different configurations for this second phase of mass transfer; some almost unexplored alternatives still obtain, too. I would like to ask the interested reader to study the excellent review by Webbink (1979). Here I will concentrate on the much narrower problem of potential symbiotic systems.

Mass transfer occuring, in the first phase of mass transfer, by Roche lobe overflow when the primary component was crossing the Hertzsprung gap produces the semidetached systems of the well-known Algol type. The mass transfer ends when either helium is ignited in the loser and it detaches itself from the Roche lobe, or when the hydrogen-rich envelope is nearly completely exhausted and the remnant collapses on the helium-rich degenerate core. The latter case occurs for stars initially less massive than about 3.6 M_o, and directly leads to helium white dwarfs with masses below 0.46 M_o. Stars initially more massive than ≅ 3.6 M_o will convert into helium-burning stars. As already mentioned above, helium-burning stars can also be obtained in case Bc. In both cases, hydrogen-rich envelope of a non-negligible mass still exists around the helium-burning core, so the star is not a pure helium star yet. Most unfortunately, practically no evolutionary calculations are available for this phase, so important for us. Paczynski (1971b) computed evolutionary models for pure helium stars, starting with equilibrium configurations on the zero-age helium main sequence. One interesting result is that pure helium models with masses in the range (about) $1\ M_o < M < 2.6\ M_o$ evolve into the red giant region again when helium burning is shifted into a shell. Thus they may initiate a second phase of mass transfer from the same star, with the other star being practically anywhere along its own evolutionary track -- on the Main Sequence or beyond. In any case, the companion is non-degenerate, so if a symbiotic system is to result, we will again have the formerly discussed Algol symbiotic type, nothing new.

Eventually, all the helium stars less massive than 2.6 M_o should become carbon-oxygen white dwarfs with masses below the Chandrasekhar limit. In view of the fact that probably the masses of the hot components in the symbiotics are not higher than, say, 2 M_o at most, it is not necessary to discuss more massive helium stars. Thus the final stage appears to be always a white dwarf, and in view of the longevity of the white dwarfs, models of symbiotics involving them must certainly be of importance. The white dwarf itself, although often quite hot, is of too low luminosity to produce the necessary quantity of ionizing photons; therefore it must be "rejuvenated" by accretion to such an extent that hydrogen and helium burning shells are ignited and maintained by fresh supply of hydrogen-rich material from the red giant. This is in essence the model proposed first by Tutukov and Yungelson (1976) and further developed by Paczynski and Rudak (1980). This model works on the same principal basis as the conventional model for nova outbursts. At first I thought that it could be called a cataclysmic symbiotic. However, this term may be misleading, since among the cataclysmic vari-

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ables we include the dwarf novae, where the outbursts are caused by accretion disks, not by a sudden ignition of a nuclear fuel. Therefore, the proper term for these white dwarf symbiotics is novalike symbiotics.

But the helium remnants of Algol binaries should not be forgotten in our discussion. For a certain time, they exist on their own nuclear fuel, and are quite luminous; in fact, Paczynski's models for helium stars with masses of no more than about 2 M_o yield just the right order of luminosities postulated by observations. A critical question is the lifetime of these objects. Paczynski's pure helium models have lifetimes longer than those of red giants.

The relation between the binary orbital period and the relative expectation of finding the other star on the giant branches remains the same for the second phase of mass transfer, since it depends only on the masses. In general, the first phase of mass transfer lengthens the orbital period, so the chances are greater that indeed the other star will be approaching its Roche limit when on one of the giant branches -- more likely again on the asymptotic branch.

Finally, some of the observed symbiotics seem to have periods so long that a Roche lobe overflow is unlikely to occur at all. Then the initially more massive components, provided they are stars of lower to moderate mass, will lose most of their mass by stellar wind and then by a planetary nebula ejection. Such a wide system will be ready to become a symbiotic when the other star reaches its giant stage. The hot component is then a central star of a planetary nebula. It contains a highly degenerate carbon-oxygen core surrounded by an envelope with a helium and a hydrogen burning shells. Mass flows into the core as it burns in the shells, and the envelope is rapidly consumed (Paczynski, 1971c), especially for relatively large core masses (above 1 M_o). Soon the shells die out and the object cools off to the white dwarf stage, unless a steady supply of accreting matter keeps the shells alive. So, while again here is another track possibly leading to the white dwarf, novalike symbiotics, there exists a phase when the hot component is a subdwarf, intrinsically much more luminous than a white dwarf because of its own energy sources, independent of accretion.

4. POSSIBLE MODELS FOR THE SYMBIOTICS

The abvove discussion of the possible symbiotic models was based entirely on their combination spectra. However, actual theoretical models of the symbiotics have been developed with an additional postulate, namely to explain their photometric activity (flares and eruptions). This postulate is probably justified, since eruptive activity on a moderate scale appears to be endemic in the symbiotics. The question is only if the photometric activity is really an inevitable aspect of all symbiotics, or if we are misled by observational selection and overemphasize this characteristic. There exist the so-called BQ[] stars (Ciatti, D'Odorico, and Mammano, 1974), which may be quite similar to the symbiotics, yet do not display any conspicuous eruptive activity. I

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believe that systems with combination spectra need not be eruptive.

On the basis of the preceding discussion, it appears that we can have three physically distinct physical models for the symbiotics:

(1) A red giant combined with a main sequence star. The ionizing photons are produced in an accretion disk surrounding the main-sequence star. This is the model proposed and developed by Bath (1977), which I called the Algol symbiotic. Mass transfer between the components and accretion on a main-sequence star is the main characteristic of the semidetached binaries briefly called Algols. It is true that in typical Algols, the accretion rate is too low to generate a substantial disk of high central temperature, and that the luminosity generated by accretion is negligible compared to the intrinsic luminosity of the gainer. But all these "typical" Algols must have passed through a stage when the mass transfer was much more significant. We will eventually find some binaries in this rapid phase of mass transfer; indeed, we may already have identified them: β Lyrae is a very likely candidate, and others may be hiding under the label of the W Serpentis stars (Plavec, 1980).

Bath's primary concern were actually the nova-like eruptions. He modeled his type of symbiotics very much alike his model of novae: If the accretion rate becomes supercritical, the disk is disrupted, an induced stellar wind will create an optically thick stellar envelope which expands and gradually thins out. Thus, if the supercritical rates can indeed be accomplished in nature, we will have a "cataclysmic Algol". An important feature of Bath's model is an instability of the red giant component.

(2) A red giant combined with a white dwarf. The ionizing photons are available from the white dwarf since the hydrogen and helium nuclear burning shells have been re-ignited and are maintained by accretion of material coming from the red star. The difference from the previous case is not solely in the different nature of the gainer. In the above case, accretion must occur at a very high rate since it directly generates all the required "hot star" luminosity; in the present case, much lower rate of mass accretion is needed, since it only stimulates the nuclear energy production. As I explained before, these symbiotics may be called the novalike symbiotics.

(3) Finally, the possibility must be considered seriously that the companion to the red giant in a binary system is intrinsically hot and luminous enough, so that no accretion is needed. This would be the simplest, "natural" type of a symbiotic, in which the mass loss from the cool star is needed only for maintaining the nebulosity which is to be ionized by the hot star (and it is not excluded that here, as in the preceding two cases, the hot object may itself contribute to the formation of the nebula). This model would simply require a subdwarf, similar to the nuclei of planetary nebulae. Thus perhaps this type of a symbiotic object (if it indeed exists) should be called a subdwarf symbiotic or a PN symbiotic.

I would now like to discuss these three models in turn.

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5. ALGOL SYMBIOTICS: MODELS WITH AN ACCRETING MAIN-SEQUENCE STAR

In an Algol symbiotic, the necessary flux of ionizing photons is produced by an accretion disk, more precisely it originates in the interior part of the accretion disk and predominantly in a hot transition zone in which the gas particles leave the Keplerian orbits and pass through a series of shocks, eventually landing on the surface of the accreting star. Pringle (1977) derived a formula for the temperature of the transition zone, which in solar units reads

$$T = 2.3 \times 10^6 \dot{M}^{6/19} M^{8/19} R^{-18/19} \quad (K) \qquad (1)$$

where the mass M and radius R of the accreting star are in solar units, and the accretion rate is in solar masses per year. The radiation has an approximately blackbody distribution. Now let us assume that the accreting star is a main-sequence object. This specification is sufficient for the crude estimate we need, since there exists a close correlation between M and R for main sequence stars. In other words, this assumption transforms equation (1) into a relation between T and $\dot{M}$ only, while the remaining terms on the right-hand side can be lumped together into a constant. Thus, for main-sequence accreting stars, equation (1) can be approximated by the relation

$$\dot{M} = 3 \times 10^{-20} \quad T^{19/6} \qquad (2)$$

For T = 10^5 K postulated by the equivalent width of He II λ 164 nm in AG Pegasi and most other well-studied symbiotics, we find from equation (2) that the mass accretion rate must be on the order of 2 x 10^{-4} M_o/ year. For the Roche lobe overflow, we may equate the accretion rate on the gainer to the mass transfer rate from the loser. But if we assume mass loss from the loser via stellar wind rather than Roche lobe overflow, then we must postulate initial mass outflow rates from the loser to be at least by a factor of 10^2 higher, i.e. about 2 x 10^{-2} M_o/year. It is obvious that the Algol model of the symbiotics demands mass transfer from the cool star to its mate by means of a directed stream emanating from the first Lagrangian point and due to Roche lobe overflow (in analogy to Algols, which is another reason why I think that the term I am using is not bad).

Many binary systems must be of the type which makes an Algol symbiotic phase possible. We also know that once a giant star with a deep convective envelope reaches the Roche critical surface by its photosphere, an almost catastrophic mass transfer ensues. (Paczynski and Sienkiewicz, 1972; Plavec, Ulrich and Polidan, 1973). Tremendous amounts of gas will be transferred to the other star on a nearly dynamical time scale of the giant. This event will not create a quiescent symbiotic; perhaps it can explain outbursts often observed in symbiotics. Possibly the high mass transfer rates occur in spurts if Bath's model of the envelope instabilities in red giants is correct (Bath, 1972), the gainer

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forms an optically thick envelope like in Bath's models of novae outbursts (Bath, 1978), and this envelope takes a fairly long time to disperse entirely. Thus the slow-nova outburst of AG Peg could be explained. The small effective radiating area of the hot component in AG Peg (expressed implicitly in the finding that the radius of the hot star is only about 0.16 R_o) is in this model translated into the statement that the hot transition region of the disk is naturally small. The difficulty with the rather small mass of the hot object need not be serious: the mass is actually quite uncertain and can easily be 2 M_o if the giant is ~ 6 M_o; or we can assume that the gainer is a star on the lower part of the Main Sequence, which is almost a necessary postulate, since its intrinsic spectrum does not show. But a very serious objection is that the high photon flux must be maintained, i.e. the high rate of mass transfer must exist now --and there is no evidence of it.

It is most unlikely that this model can explain all symbiotics. If the symbiotics were interacting systems like the Algols, their galactic distribution would be similar, i.e. they would be young disk objects. But observational evidence shows that the distribution of the symbiotics is very much like that of the planetary nebulae, so that most of them must be old disk population objects --in other words, evolved systems probably in the second phase of mass transfer. However, even a single observed Algol symbiotic, positively identified, would be very interesting. Recently, Bath (1981) and Kenyon et al. (1981) suggested that the repetitive outbursts in CI Cygni are accretion-powered, although the nature of the central star is not clear. Another potential candidate for an Algol symbiotic is T CrB, which deserves a more detailed discussion.

6. T CORONAE BOREALIS: A CATACLYSMIC ALGOL-TYPE SYMBIOTIC?

T Coronae borealis is a well known recurrent nova, which erupted in 1866 and in 1946 in two apparently similar, extremely fast outbursts. Unlike typical novae, it is not a short-period binary system consisting of two dwarfs. Its orbital period is 227 days, and the late-type component is an M3 III giant. To further stress the difference from ordinary novae, the mass of the hotter star appears to be definitely above the Chandrasekhar limit. The spectroscopic observations by Kraft (1958) were rediscussed by Paczynski (1965) who obtained $M_h > 1.6\ M_o$, $M_c > 2.2\ M_o$.

According to our recent observations at Lick Observatory, this object probably does not now fully qualify as a symbiotic object, if we apply Merrill's criteria. The late-type continuum is there all right, but the optical emission lines are weak (except for Hα); in fact, there may be no He II or O III emissions present at all. At the time of Kraft's observations, i.e. 1956/57, He II λ 468.6 nm and O III λ 376.0 nm were "very feeble", and most likely weakened since then. But in the far UV, we do see the typical emission lines of the symbiotics, He II λ 164 nm and the various intercombination lines which are strong e.g. in

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AG Peg and AR Pav. More importantly, the object definitely met Merrill's criteria between 1921 and its most recent outburst in 1946 (see, e.g., Swings and Struve, 1943).

T CrB attracted our attention when we studied the case of Roche lobe overflow in late-type giants (Plavec, 1973). Paczynski and Sienkiewicz (1972) found that Roche lobe overflow from a deep convective envelope leads to an extremely rapid mass loss on a timescale approaching the dynamical timescale. Subsequently, we studied the process in more detail (Plavec, Ulrich and Polidan, 1973), on a giant originally of 7 M_o. When the expanding giant reaches the Roche limit, a rapid adiabatic phase of mass loss sets in and the mass loss rate grows exponentially until it reaches rather unbelievable values, such as 0.1 solar masses per year. When the mass ratio in the system is reversed, the rate slows down considerably to $\dot{M} \sim 10^{-4}$ M_o/year. This phase is then followed by a stage of a still slower mass loss (by another 3 or 4 orders of magnitude), during which the devastated giant still adheres to the Roche lobe but only its outermost atmospheric layers exceed it. Only this phase may be relatively long: it is terminated when the core of the giant ignites helium and the star shrinks, and this occurs quite independently of the amount of mass previously lost from the envelope. Thus, if the giant reaches the Roche lobe near the bottom of the giant branch, the slow phase of mass loss will be as long as a single-star ascent to the red giant tip.

Our calculations were primarily intended to explain the system AX Monocerotis, where a K2 II giant supports a variable circumstellar shell around a B2 IV main-sequence star (Cowley, 1963). The period of the system is 232.5 days, and the mass ratio is $M_c/M_h \approx 0.4$. Thus if the system ever followed anything like our scenario, it must be in the slow mass loss phase now. Searching for a counterpart in the rapid phase, we found T CrB where the late-type giant is not dissimilar to AX Mon, and the orbital period is identical, 227 days. The mass ratio in T CrB is in favor of the cool star, $M_c/M_h \approx 1.4$, which must be so for the rapid phase. The two observed outbursts of course suggest rather intermittent mass transfer, perhaps triggered by an instability of the red giant as suggested by Bath (1972). Perhaps, as suggested by Webbink (1978), the system happens to be just in the very short evolutionary phase immediately preceding the onset of the catastrophic mass transfer.

Webbink (1976) studied the outbursts in considerable detail and concluded that the light curve almost demands an explanation in terms of accretion on a main-sequence star. Our recent optical scans, combined with IUE spectra, should enable us to check on these ideas. The IUE spectra show, in addition to a number of moderately strong emissions (C IV, N III], O III], N IV], Si III]), a continuum which would be rather flat if it were not for numerous very deep absorptions. The continuum can be formally fitted reasonably well by a Kurucz model atmosphere with Teff = 11,000 K and log g = 2. It is reasonable to assume that the cool component is a luminosity III giant. With an apparent visual magnitude of 10.15^m and $E(B-V) = 0.08^m$, the distance to the system is $D \approx 1.35$ kpc. Again, we use Kurucz model atmospheres (Kurucz, 1979). The Kurucz model fit for the hotter component then fixes its radius by

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means of the relation R/D = 0.91, which for the adopted distance yields $R_c = 1.2\ R_o$, a little too small for a B9 star, but not by a large margin. But we cannot boost its radius by assuming a larger distance. If we assume that the red giant is of luminosity class II, that places it at a distance of 3.2 kpc; but with the high galactic latitude of the object, $\beta = 47^o$, this would place it 2.2 kpc above the galactic plane. Yet the main arguments against the main-sequence interpretation of the FUV continuum are elsewhere. Firstly, we do not observe any Balmer jump which would increase the total light from the system longward of λ 365 nm; our Lick scans show only the light of the M star. Secondly, T_{eff} = 11,000 K is totally inadequate to explain the presence of the emission line λ 164 nm of He II which is definitely present, although considerably fainter than in AG Peg. The reasonably good fit of the FUV continuum by a 11,000 K atmosphere only means that the continuum is to a large degree flat. Most likely, this continuous radiation comes from a disk surrounding a much hotter but also much smaller object.

We can learn something about the nature of the object by using the He II line to determine its Zanstra temperature. The total flux in the line is $f \sim 5.5 \times 10^{-13}$ erg s^{-1} cm^{-2}, which translates to a total power emmitted in the line of 0.03 solar lumniosities. In AG Peg, the power is 9 L_o. Assuming $T_{eff} = 10^5$ K as in AG Peg, we find that in T CrB the hot object should have a radius of only 0.01 R_o as against the 0.16 R_o in AG Peg. Most likely the hot object is cooler than in AG Peg, but we cannot go below about 80,000 K, otherwise there would be no He II line. Taking all the uncertainties, it is possible to adopt a radius several times larger, but it will still remain in the domain of extremely small subdwarfs. It is therefore not surprising that we see no direct evidence of its light: what we observe in the far ultraviolet is only the light of a surrounding disk.

Our preliminary conclusion seems to be in favor of a subdwarf in T CrB, rather than a main-sequence star, as the gainer.

7. THE NOVALIKE SYMBIOTICS: BINARIES WITH REJUVENATED DEGENERATE DWARFS

This appears to be the most popular model nowadays, and you will hear very detailed accounts from Rudak and from Tutukov and Yungelson. I will make only a small remark. The theoreticians often talk about the hot component being a white dwarf in this model. This stirs a number of objections since the surface of a "naked" white dwarf lies in a deep potential well, and this in turn leads to very high temperatures for the accretion disks. Using formula (1) with $M_h = 0.6\ M_o$ and $R_h = 0.0158\ R_o$, we find peak disk temperatures on the order of 10^6 K, and therefore we must expect X-rays coming from this gainer, as they indeed do in cataclysmic variables. But actually what the theoreticians are talking about are subdwarfs, namely objects with degenerate carbon-oxygen cores like genuine white dwarfs, but surrounded by a non-negligible hydrogen-rich envelope, which is large and dense enough to stop any infalling material high above the degenerate core, and make the star larger. For example

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Tutukov and Yungelson (1976, p. 347) consider a "dwarf star" with a radius about 10^{10} cm, which is 0.14 R_o. This of course is no white dwarf! Thus it is important to realize that when, for example in this volume, the observers consistently talk about subdwarfs and the theoreticians equally consistently talk about white dwarfs, they actually mean the same thing: and the thing should properly be called a subdwarf. Consider a subdwarf with the dimensions we found above for AG Peg: $M_h = 1$ M_o, $R_h = 0.16$ R_o. If the accretion rate is $\dot{M} = 10^{-7}$ M_o/year as is often assumed for these objects, then the temperature in the inner parts of an accretion disk may be as high as 8×10^4 K, and the disk's luminosity about 20 L_o. While the disk temperature is not too different from the intrinsic temperature of the gainer, the luminosity of the disk is negligible compared to the gainer's intrinsic luminosity.

As explained by Paczynski and Rudak (1980 and this volume) and by Tutukov and Yungelson (1976 and this volume), the induced nuclear luminosity and photometric behavior of the model is a very sensitive function of the mass accretion rate. High mass influx will convert the hot star into a core of a supergiant; in a narrow range we get a fairly stable hot subdwarf in which eruptions must be due to a variable mass outflow rate of the giant (symbiotics of type I in the notation by Paczynski and Rudak); and for still smaller mass accretion rates, we get hydrogen flashes leading to slow nova outbursts (type II).

8. PN SYMBIOTICS, OR SUBDWARFS UNPOWERED BY ACCRETION: DO THEY EXIST?

But what if the accretion rate is negligibly small? I think such a case is also possible. The mass outflow rate due to stellar wind from late-type giants can be calculated e.g. by means of a formula by Reimers (1975):

$$\dot{M}_c = 4 \times 10^{-13} \ L/ \ g \ R \qquad (3)$$

where all the quantities, including the surface gravity g , are in solar units, or by a similar formula given by Mullan (1978):

$$\dot{M}c = 1.6 \times 10^{-9} \ M \ R^{1/2}. \qquad (4)$$

Inserting the values for AG Peg again, $M_c = 1$ M_o, $R_c = 65$ R_o, $L_c = 600$ L_o, we obtain $\dot{M}c = 1.6 \times 10^{-8}$, respective 1.3×10^{-8} M_o/year. Of this amount, the hot star accretes only 0.7%, so that $\dot{M}_{acc} \cong 10^{-10}$ M_o/year. This is too low to power the subdwarf in either way. One can argue that all our values for AG Peg are too low, but there certainly is no evidence for an accretion disk in it. Possibly also, the proximity to the Roche critical surface enhances the stellar wind blowing from the symbiotic giants, and the above formulae must be modified for binaries. On the other hand, there are indications that the orbital periods in some symbiotics are as long as 20 years. In such a case the fraction of the stellar wind accreted by the subdwarf is less than 10^{-3}, and even a fairly strong stellar wind will not be able to power the subdwarf.

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Yet if such long-period symbiotics with undersize giants do exist, we will have to conclude that the subdwarf is intrinsically sufficiently hot and luminous to provide enough ionizing photons. After all, central stars of planetary nebulae do the job without accretion. And the spacial distribution of the symbiotics is surprisingly similar to that of planetary nebulae (Boyarchuk 1975, Wallerstein 1980). The hot component of AG Peg has the characteristics of a Wolf-Rayet nucleus of a planetary nebula (Keyes and Plavec, 1980). Or the hot component may be a core helium burning star, a remnant of an Algol subgiant. In any case, it is worth looking for these "natural" symbiotics. Their eruptions would not be easy to explain, but do we have to postulate eruptions in all cases? *May be the BQ[] stars are of this type*.

9. RELATED BINARY SYSTEMS THAT ARE NOT SYMBIOTICS

We can learn somethin about the symbiotics also if we study binary systems that have some similar properties, yet are not symbiotics. I already mentioned AX Monocerotis, in which a less massive K giant is combined with a B1-3 IV star. There is evidence of gas streaming due to Roche lobe overflow in spite of a long period of 232 days. An absorption shell spectrum signals the presence of circumstellar material around the hotter star, and an outflow from that region is evident from P Cygni profiles of the Balmer lines, but otherwise there are no emission lines. Why? Apparently the hotter component is not hot enough, and the mass transfer rate is not high enough for an Algol symbiotic. A related object is the shell star 17 Leporis, which has an appropriate period (260 days) and appropriate giant (M1 III) for a symbiotic, does indeed show the presence of a circumstellar envelope around the accreting star, and some mass outflow from its vicinity is indicated by their violet displacements, but no emission is seen except in one or two Balmer lines. The hotter star, an A6 III giant (Plavec *et al*., 1981) is again not hot enough, and accretion is insufficient.

The bright star δ Sagittae (Reimers and Kudritzki, 1980) is interesting in this context, because the authors find evidence of an accretion disk surrounding a late B star, whose companion is a luminous M2 II giant, and the system is unusually large, the period being 10 years.

Perhaps most interesting is the fact that the rather flat ultraviolet energy distribution in the eclipsing symbiotic AR Pavonis is very similar to what we see in the eclipsing system RX Cassiopeae (Plavec, Weiland, Dobias, and Koch, 1981). In the optical region, late-type giants dominate: M3 III in AR Pav, K1 III in RX Cas. The hot component is hidden is a disk or envelope, but must be there, since we observe high-ionization emission lines in the ultraviolet. The hot star may be cooler in RX Cas since we do not see He II, only He I in emission. But this may primarily be a density effect. The system of RX Cas, with its period of 32 days, is much more compact, and the absence of most intercombination indicates much higher density ($N_e \cong 10^{12}$ cm^{-3}) than in AR Pav. RX Cas is in turn similar to other members of the W Serpentis

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group (Plavec 1980), for example to SX Cas, which contains a K3 III giant. Are these objects transition cases between the symbiotics and the "ordinary" Algols? Are they perhaps quasi-symbiotics with the giants on the first giant branch?

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DISCUSSION ON BINARITY

Kwok: I am not sure we should place too much emphasis on wind accretion. Observations of single-star mass loss show that M-giant winds are always accompained by dust emission. The implication is that S-type symbiotics have no significant cool-star wind. This is consistent with the correlation of radio emission with D-type infrared excess.
If there are weak cool-star winds in S-type symbiotics, they could have been detected in the radio.

Plavec: I agree that the source of the material might be the hot star. But if it is a general rule, then: (1) why is always an M giant present? (2) Why don't we observe P Cygni emission profiles in a typical symbiotic star? I know only of AG Peg as a case that shows mass outflow from the hot star.

Andrillat: My question concerns the hot component. There exists a very small number of WR stars which are members of symbiotic stars and they are of the WN type. In my opinion it is possible to find also WC types, because among the nuclei of Planetary Nebulae we have both WN and WC types.

Plavec: I thought that the central stars of the PN, if they are of the WR type, tend to belong to the WC subclass. On the contrary, in AG Peg the hot component is WN. Since this is the only surely found WR star among the hot components of the symbiotics, I don't dare to predict what the rule is.

Kafatos: In all fairness to the accretion model of symbiotics by Bath, the high accretion rates that you mentioned ($\dot{M} \gtrsim 10^{-5} M_{\odot} yr^{-1}$) are only needed to provide the outbursting mechnism, not all the time.

Plavek: Yes. How long will then an object remain a symbiotic?
In AG Peg, 120 years has elapsed since the outburst. This time is comparable to the dispersion time of the nebula as estimated by Tutukov and Yungelson.

Rudak: (1) Prof. Plavek mentioned among the arguments against Roche lobe outflow, that orbital periods would be in that case below 100 days. I should propose to cancel it, as in Case C evolution of binaries, Roche lobe outflow can take place.
I would rather emphasize the importance of a possible mass ratio greater than one, favouring the cool component, as in that case one would expect

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very rapid mass transfer on an almost dynamical time scale for the giant's envelope.

(2) Let me make some comments on "Algol-type" symbiotic model, which have been developed by G. T. Bath. One should be very careful considering the qualitative picture of instabilities in mass transfer arising in the outer layers of giant's envelope filling its Roche lobe. As was indicated by Wood in 1977, the way in which mass transfer takes place strongly depends on surface conditions accepted on the Roche lobe. What Wood got, was a constant mass outflow in contradiction to Bath's episodic mass transfer with a periodicity of several hundred days.
The influence of the deep convective zone is also of great importance, as Osaki's work indicates.

Viotti: Concerning the binary as opposed to single star models, I would like to recall that there are some generally accepted criteria which may give direct evidence of binarity. They are:
(1) the simultaneous presence of two absorption "photospheric" spectra;
(2) the presence of a "photospheric" absorption spectrum with a periodically variable radial velocity; (3) a light curve characteristic of an eclipsing binary, with minima separated by constant time intervals;
(4) astrometric observations of the apparent orbit of the visible component. Only a few number of symbiotic objects satisfy one or two of these criteria (e.g. CI Cyg, AR Pav), while for other objects we have only indirect evidence for binarity, that in many cases is open to criticism.

Hack: Your binary model explains in a very natural way many symbiotic features. However, I think that at least in some cases a symbiotic spectrum can equally well be explained by a single star model.
An M giant in the transition stage to a planetary nebula can have an instability phase, possibly correlated with the occurrence of the Helium-flash, and the star can emit a shell sufficiently thick to produce a blue-UV continuum. This shell moving in the circumstellar envelope produced by slow wind of an M star will excite the gas by collision, thus producing low excitation features and permitted emission lines.

Cassatella: Is it a general trend for what you called Algol type symbiotics to show the presence (e.g. from line profiles) of an accretion disk?

Plavec: I think that the evidence for a large disk in the Algol symbiotics should indeed be rather obvious - and since I don't see much of it, this only corroborates my doubts about the broad applicability of the Algol concept to the symbiotic stars.

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Slovak: The IUE spectra of symbiotic stars do not show absorption lines, with the exception of TX CVn. Thus there is no direct evidence in the UV for a main sequence companion, but argues for a hot subdwarf or a main sequence star obscured in an accretion disk.

Plavec: I agree, although I know now that absorption lines may also form in or outside a hydrogen circumstellar disk or envelope, or in front of a disk. So even if I do see the absorptions of say spectral type A, it still does not necessarily imply that a main-sequence (or any other) A star is indeed present.

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