SYMBIOTIC STARS AND RELATED PECULIAR OBJECTS

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I. INTRODUCTION

Stellar classification in spectral types and absolute luminosities is based on the absolute or relative intensities of the absorption or emission lines of one or several atoms or molecules. The absorption or emission intensities, or more generally the profiles, result from the combined effects of absorption and emission in the stellar atmosphere. Certain geometrical, physical, kinematical, and dynamical factors may affect the intensities of emission or absorption of certain lines, rendering them anomalous in the sense that they differ from those of most stars having otherwise similar general characteristics. Since these factors may thus upset the spectral classification or even render it precarious or erroneous, it is important to gain a general understanding of them. Such a study will help in realizing the full meaning of normal intensities, hence of the normal classification. Actually one may wonder whether any star may be regarded as entirely free of peculiarities, or at least of a predisposition to develop them, either from time to time, or at certain evolutionary stages.

The factors introducing spectral anomalies are best studied in the case of conspicuously peculiar stars. In such cases, the mechanisms producing ionization, dissociation, and excitation must be examined individually. The present report is essentially devoted to the objects which received from Paul W. Merrill the name of "symbiotic stars"; in these objects high excitation emission lines are superposed on a low-temperature absorption spectrum, usually of type M. The symbiotic stars yield "combination spectra." In biology the word "symbiosis" indicates an actual dependence or interdependence of dissimilar organisms. This biological expression seems thus well adapted to the group of peculiar stars which we shall consider, since these stars are indeed characterized by a similar spectroscopic behavior of apparently inconsistent features. The symbiotic stars are extreme pathological cases.

In order to gain some understanding of the symbiotic stars (abbreviation: SS) I shall consider a wide range of other peculiar objects whose behavior will help in explaining various aspects of the SS. Obviously I shall not be able to describe in detail all the spectral and physical characteristics of the various peculiar classes, and so I shall confine myself to these characteristics which may help in explaining the phenomena observed in the SS. Occasionally priority will also be granted to phenomena observed at the McDonald Observatory, in the large program carried out under the leadership of Otto Struve. The emphasis will also be placed on individual objects, as our understanding of the nature and evolution of the astronomical bodies has been and still is conditioned to a considerable extent by the progress of individual spectroscopic investigations. Indeed we would have progressed neither far nor deeply in our physical knowledge of the stars and of their origin and evolution without the detailed spectroscopic investigations of the type carried out by Struve. To promote further progress, two factors which Struve stressed on numerous occasions remain as essential now as they were in 1939 when the 82-inch Otto Struve Memorial reflector became operational: widen the covered spectral range as well as the geometrical and the spectral resolution; accelerate the securing of observational material, especially by increasing the sensitivity of the receivers and adapting the newly discovered optical, photographic, or electronic equipment.

My task has been rendered easier by the fact that Miss Anne B. Underhill prepared the preceding chapter on the formation of lines in extended atmospheres, and was generous in letting me read her original text before mine was typed. I wish to acknowledge her help and courtesy. Her detailed discussions enable me to shorten several of my own.

In all peculiar stars, including the Wolf-Rayet, Of-, P Cygni-, Be-type and shell stars, and the novae and planetary nebulae, the observed spectra are superpositions of features that are formed in different regions of the atmosphere. In particular the effects of the geometrical and physical dilution factors[1] may be different for various absorption or emission lines. Many selectivities affecting the relative intensities of transitions in the same atom or ion disappear when the dilution decreases.

The prototype of the SS is Z And which we shall discuss in some detail, beyond the discussion in the paper "The Evolution of a Peculiar Shell Spectrum: Z Andromedae" (Swings and Struve 1941) reproduced in this volume. The brightness of this star fluctuates semi-regularly; the fluctuations are generally rather small, but at times they may amount to 3 magnitudes, the rises in brightness being steeper than the declines.

Most SS have been listed in Bidelman's "Catalogue and Bibliography of Emission Line Stars of Types later than B" (1954) and in Mrs. Gaposchkin's book *The Galactic Novae* (1957). A few recently discovered objects may be added. We shall consider here:

Z And (the prototype);
AG Peg, AX Per, CI Cyg, BF Cyg, RW Hya, Nova (T) CrB, R Aqr, Nova (RS) Oph, FR Sct, MWC 603.
The southern SS's WY Vel and AR Pav have been studied by Sahade (1952).

For comparison, the following objects which are related to the SS will also be considered:

17 Lep, AX Mon, RX Pup, MWC 17, RY Sct, CD $-27°$ 11944, MHα 328–116 MWC 349, B 1985, B 5481, WY Gem, W Cep, VV Cep, the companion of α Sco, W Ser, α Her, α Sco A, M1–2, and HD 45677.

Many of these objects are definitely binaries, others may be single.

In 1939 the spectroscopic group at the Yerkes and McDonald Observatories, under the leadership of Otto Struve, engaged in a large program of spectroscopic observations of all types of outer envelopes which are not accounted for by the usual theories of normal stellar atmospheres. We knew that the long and exceptionally successful period of development carried by the use of thermodynamic equilibrium was gradually being replaced by a new period in which emphasis was being placed upon departures from equilibrium conditions. On the other hand it was clear that our understanding of the physical, dynamical, and geometrical conditions prevailing in the SS would eventually be based on the spectroscopic variations in these stars which are actually all variable to some extent. The time was ripe, since a great deal of progress had been made in laboratory atomic spectroscopy. The Yerkes astronomers had at their disposal the new 82-inch reflector, equipped with an efficient Cassegrain prism-spectrograph, enabling observations in the near ultraviolet as well as in the usual region. The ultraviolet region of the peculiar stars had been very little explored. Soon

[1] The geometrical dilution factor at a point P is the ratio of the solid angle subtended by the photosphere at P to 4π:

$$W(r) = \tfrac{1}{2}\left[1 - \sqrt{1 - \left(\frac{r_*}{r}\right)^2}\right]$$

where r = radius of the "shell," and r_* = radius of the underlying star. For $r/r_* > 2$, the approximation $\frac{1}{4}(r_*/r)^2$ suffices.

To this geometrical factor, a physical factor should be added, expressing the influence of absorption or emission features of the underlying radiation at the active wave length, taking into account the relative radial velocities.

it became also possible to do some work in the photographic red and infrared region. I had the great privilege to be a member of that spectroscopic group. On my very first night of observation, the ultraviolet spectrograms obtained revealed emission features which had never before been observed. So began an excitingly fruitful period of collaboration with Otto Struve, continuing my previous short periods of joint work with him in 1931 and 1936.

II. IMPORTANCE OF FURTHER EXPERIMENTAL AND ASTRONOMICAL SPECTROSCOPIC INVESTIGATIONS

Laboratory spectroscopy has lost some of the glamour that it used to have. Yet much experimental work of astrophysical importance remains to be done. The present report provides me with an opportunity to express a plea in favor of spectroscopy, experimental and theoretical as well as astronomical. We know that, even in a strategically located star, like the Sun, at least 30 percent of the absorption lines listed in the Revised Rowland Table are still unaccounted for, and, actually, this Table is still rather incomplete. Hundreds of lines remain unidentified in all kinds of astronomical objects. A few laboratory spectroscopists continue to render outstanding services to the astronomers. Among the latest examples, we should mention the long-awaited analysis of the Fe IV spectrum[2] which Edlén completed in March 1966. Progress is being made also in the field of transition probabilities.

At the invitation of the Joint Commission for Spectroscopy I published (Swings 1951) a general discussion "Spectroscopic Problems of Astronomical Interest"; another report "Problems of Astronomical Spectroscopy" was published ten years later (Swings 1960). In these compilations—which are outdated and should be repeated[3]—many unidentified absorption or emission lines and bands were listed. Of course several of these lines have now been assigned satisfactorily. But many puzzling cases remain, in practically all spectral types, including peculiar objects (Wolf-Rayet, Of-, P Cygni-type and symbiotic stars, and novae) especially in the red and near-infrared region. There remain hundreds of unassigned lines in the rare-earth stars, but good progress is being made in the analysis of the laboratory spectra of the neutral, singly ionized and doubly ionized rare earths: this problem should be re-examined, especially in α^2 CVn. There are also many unassigned absorptions in the spectra of hydrogen-poor stars, such as υ Sgr; of R CrB stars, of phosphorus stars, etc. We must prepare ourselves for the moment which appears near when, thanks to orbiting astronomical observatories and to balloon-carried telescopes, we shall obtain spectra of many astronomical objects in the ultraviolet ($\lambda < 3000$), the X-region and the infrared.[4] A considerable amount of laboratory work is still lacking in the ultraviolet and the infrared.

[2] The Fe^{+++}-ion remained the last ionization stage of iron which had not been satisfactorily analyzed until 1966. The permitted Fe IV lines will probably be observed in the absorption spectra of hot stars (especially in the far ultra-violet). Certain forbidden [Fe IV] lines seem to be present is RR Tel (1953–54). The metastable levels of the $3d^5$ and $3d^44s$ configurations which give rise to [Fe IV] transitions in the region $\lambda > 3000$ are rather high (EP > 6.1 ev). Hence [Fe IV] will probably not play as important a role as [Fe II, III, V, VI, VII].

[3] The author began work on such a revision in 1968.

[4] The importance of the infrared will become more and more apparent. Very cool stars have been and will be discovered, including, probably, unknown cool companions of peculiar stars, which are presently supposed to be single. New forbidden lines will be found, including coronal and other forbidden lines. Even the near photographic infrared deserves scrutiny. For example, the observation of the auroral transition of [O II], λ7319–λ7330 (EP = 5.0 ev) which has a much higher probability than the nebular transition λ3726–λ3729 (EP = 3.31 ev), but a higher excitation potential would help in understanding peculiar stars. The other following forbidden lines in the photographic infrared are also interesting: [S II], $^4S^o$–$^2D^o$ (λ6717–λ6731) which have low transition probabilities ($\approx$ 0.001 sec^{-1}) and low excitation potentials (1.8 ev); [Ar III], ^3P–$^1D_2$ (λ7136–λ7751) which have a high transition probability (0.32 and 0.085 sec^{-1}) and a low excitation potential (1.73 ev).

The extension of the covered spectral range into the ordinary ultraviolet proved most fruitful in the hands of the McDonald astronomers as soon as the 82-inch reflector became operational. I shall never forget the excitement which prevailed in our group when the ultraviolet region revealed to us the forbidden lines of Ne V and Fe VII and many other features: new forbidden lines of [Fe II], [Ni II], [Cr II], [V II], . . . The tremendous extension in spectral range which will be attained thanks to space vehicles will open entirely new possibilities for the study of the astronomical objects. In the SS, a wide range of ionization occurs; thus many lines may appear in the ultraviolet, as should also be the case in the richest planetaries, such as NGC 7027. Of course there will always remain obstructions, such as the region[5] from 912 Å down to the X-rays near 20 Å which is absorbed by the interstellar H, He, and He^+.

There is still a great need for accurate measurements and the analyses of numerous atomic spectra, and for various transition probabilities. Garstang's computed probabilities for many astronomically important atoms and ions are of tremendous interest. Indeed, the data on [Fe II, III, V] recently computed by Garstang make imperative a revision of many old discussions of spectra of peculiar stars (including novae, long-period variables, etc. . . .). This revision is at present under way in Liège.

III. EXAMPLE OF ASTRONOMICAL APPLICATIONS OF A SINGLE ANALYZED SPECTRUM: Fe III

In 1937 Edlén and I (1942) took the decision to analyze the Fe III spectrum, the original limited aim being to locate the metastable levels. At that time we had a vague hope that the forbidden lines of Fe III might possibly explain the coronal lines. Eventually we classified 1500 lines and established 320 energy levels. At the time we started, Bowen had only identified 3 multiplets of Fe III; later Green discovered 3 additional multiplets which we had independently found. Our spectrograms covered the region from approximately 500 Å to 6500 Å, with a dispersion of about 4 Å/mm shortward of 2000 Å.

The deepest electron configuration of Fe III is $3d^6$, the next higher is $3d^5\,4s$; the lowest odd configuration is $3d^5\,4p$. About 450 combinations belong to $3d^5\,4p \rightarrow 3d^6$ (region 679 Å to 1143 Å); about 1000 connect $3d^5\,4s$ and $3d^5\,4p$ (region 1700–4000 Å); strong quintets and septets connect $3d^5\,4p$, $3d^5\,4d$, $3d^5\,4f$, $3d^5\,5p$ and $3d^5\,5s$. The analysis took us two years of steady work. It has now been extended by S. Glad (1956).

Two types of strong permitted Fe III lines appear in the astronomical region. In the first group the lower levels are metastable or quasi-metastable even terms of the configuration $3d^5\,4s$. In the second group the lower levels are the high terms associated with $4p$, $4d$, $4f$, $5s$ and $5p$ which are *not* metastable. In an extended atmosphere, excited by diluted radiation, the first group becomes considerably enhanced relative to the second. The enhancement gives an estimate of the dilution factor; in various early-type shells this is actually the easiest way to ascertain the presence of dilution. For example λ4165 and λ4372 (second group) are much stronger than λ4419 (first group) in ordinary absorption B stars, whereas the opposite is true in P Cyg, γ Cas, and ζ Tau.

The forbidden ^5D–^3F and ^5D–^3P transitions are very strong in many objects. Their strongest transitions are respectively those of J-values 4–4, λ4658 and 3–2, λ5270.

The transition probabilities of [Fe III] have been computed by Garstang (1957); λ4658 ($^5D_4$–$^3F_4$, EP = 2.66 ev) is intrinsically stronger than λ5270 ($^5D_3$–$^3P_2$, EP = 2.41 ev) and is observed as such when the star is not heavily reddened. Our analysis of the Fe III spectrum led to results which had nothing to do with the solar corona. Yet we were well rewarded for our labor.

Many unidentified absorption lines in B stars (example: γ Peg) turned out to be due to Fe III, as was shown as early as 1938–1939. The latest paper is one by B. Warner (1966), who used the Fe III lines to determine the abundance of iron in early-type stars. The region $\lambda < 3300$ of P Cyg contains one line of He I, four of Si III and nineteen of Fe III (lower metastable levels); certain multiplets, such as a^5D–z^5P^0 (λ5127–λ5156) which are weak in the laboratory are strong in P Cyg as a result of the dilution effect. γ Cas at the time of its sharp-line stage of 1939 was very rich in strong Fe III shell lines; except for H and He I, the Fe III lines constituted the most conspicuous features of the entire spectrum of γ Cas; the sharp Fe III lines remained very intense until late in 1940[6]; the multiplet a^5D–z^5P^0 was very characteristic in the visual region.

The [Fe III] lines are strong in MHα 328–116, BF Cyg, RY Sct, MWC 17, etc. They are found in many novae of the slow as well as the fast type. Of course they are more easily detected in the slow novae which, after the η Car stage ([Fe II] strong, [Fe III] absent), pass through stages showing [Fe III], the relative intensities of [Fe II] and [Fe III] giving an indication of the ionization conditions. Typical stellar comparison spectra are: η Car ([Fe II] only), MWC 17 ([Fe II] and [Fe III] present simultaneously), Nova (DO) Aql (1925) in 1931 ([Fe III] stronger than in MWC 17), Nova (RT) Ser (1909) in 1931 ([Fe III] strong), BF Cyg (very strong [Fe III] at certain phases), MHα 328–116 (extremely strong [Fe III], weaker [Fe II]) and RY Sct ([Fe III] only). [Fe III] is present in many gaseous nebulae, for example in the Orion Nebula.

In BF Cyg, a relatively unreddened star, λ4658 is stronger than λ5270, but in MWC 349, which is located in a dark region of the Milky Way and is reddened to a considerable extent, λ5270 is much stronger than λ4658.

Beside the strong ^5D–^3F and ^5D–^3P transitions, the line $^5D_4$–$^3H_4$ (λ4881.14) is found in certain nebulae.[7] The a^5D–a^3D and a^5D–a^7S multiplets (3200–3400 Å) did not appear on strongly exposed McDonald spectrograms of the Orion Nebula, taken for this purpose;[8] however traces of these multiplets have been found on strongly exposed spectra of BF Cyg taken at McDonald in 1947, 1949, and 1950) (Swings and Swensson 1953), and on Mt Wilson coudé spectrograms of planetary nebulae (Kaler, Aller, and Bowen 1965). No trace has been found of ^5D–^3G (EP = 3.8 ev) except a very weak line observed in NGC 7027 at 4008 Å ($^5D_4$–$^3G_4$). This is due to the lower probability of this transition (0.019 sec^{-1}), and possibly also to the higher excitation potential.[9]

The reason for reporting these astronomical applications of the analysis of an atomic spectrum is to encourage young astronomers to tackle research problems,

[5] As a result, many important lines will be forever unobservable, such as the lines shortward of 912 Å which play a role in fluorescence mechanisms (He II, O III, N III). For the physics of the atmospheres of hot stars the region $\lambda < 912$ plays a major role; but this may be predicted on the basis of the observations $\lambda > 912$. For example, in high excitation nebulae, the Lα quanta of He II will provide an important source of electron kinetic energy by ionization of H. Such electron energy may excite resonance lines, such as λ1551–λ1548 of C IV. Actually the planetaries will not reveal many forbidden lines in the vacuum ultraviolet (for example [S III], [O II, III], [Ne III, IV, V], [Ar IV, V]), but many permitted lines—which may be excited by collision—will be found, including many resonance and nonresonance lines (atoms of C, N, O, Mg, Al, Si, Fe, S, Ar, . . . at various stages of ionization).

[6] In January 1941, the Fe III lines had disappeared; γ Cas had resumed its broad lined B-spectrum.

[7] The presence of $^5D_4$–$^3H_4$ has been interpreted by I. S. Bowen (1960).

[8] The weakness of a^5D–a^3D (EP = 3.81 ev) cannot be explained by low transition probabilities, the values for ^5D–^3D (0.23 sec^{-1}) being of the same order as for ^5D–^3F (0.44 sec^{-1}). Probably the weakness is due to the higher excitation potential.

[9] Several wavelengths of [Fe III] have been measured accurately on coudé spectrograms of planetary nebulae and of the Orion Nebula (Bowen 1960, Flather and Osterbrock 1960). Example: 4658.10 ± 0.05 Å.

especially the analysis of atomic spectra of astronomical interest, which may take a long time, patience, and precision. There are still quite a number of such problems.

It is gratifying to see that there is a real renewal of interest among young physicists in atomic and molecular spectra of astronomical importance. New excitation techniques such as the beam foil method are providing important new data. Convincing evidence of this renewed attention is provided by the great number of interesting contributions and discussions at the Symposium on Beam Foil Spectroscopy, organized by Professor Stanley Bashkin at the University of Arizona in November 1967 (Bashkin 1968).

IV. BEHAVIOR OF CERTAIN EMISSION LINES IN PECULIAR STARS

I shall place myself mainly at the point of view of the astrospectroscopist. The dilution effects[10] have been discussed theoretically in Miss Underhill's chapter. Generally we adopt as excitation mechanisms: the recombination of ions and electrons, the impacts by particles, the fluorescence excitation (either by discrete emissions or by continua) or the molecular processes. But other processes have also been occasionally considered, such as collisions of clouds in the atmosphere (conversion of kinetic energy of turbulence into excitation), ejections of subphotospheric layers (conversion of thermal energy) and shock waves.[11] I shall only consider spectroscopic effects given little or no discussion by Miss Underhill.

The selectivity effects observed among the atomic lines in Of stars (i.e., O-type stars with shells) have been studied by Miss Underhill (Liège 1957). The presence of the $\lambda 5696$ C III line ($2s\,3p\,^1P_1^0$–$2s\,3d\,^1D_2$) in emission while the other C III lines are found in absorption has been attributed to the formation of a C^{++} ion in the $2s\,3d\,^1D_2$ level after ejection of a $2s$-electron from a C^+ ion by absorption of a $\lambda 304$ He II quantum. The energy match between $\lambda 304$ and the energy difference between $C^+\ 3d\ ^2D$ and $C^{++}\ 2s\,3d\ ^3D$ is not so close as in the case of $C^{++}\ 2s\,3d\ ^1D$. Another interpretation has been suggested by J. Gauzit (1966), on the basis of the coincidence between $\lambda 322.575$ C III (transition between the ground state and $2p\,3s\ ^1P_1^0$) and $\lambda 322.570$ N IV (transition $2s\,2p\ ^3P_1^0$–$2s\,3s\ ^3S_1$). The absorption of the N IV photon leads first to an unobservable emission $\lambda 2982.2$ C III, then to $\lambda 5696$. The observation of Of stars from space vehicles will possibly give us a convincing interpretation, although the region $\lambda < 912$ will not be reached. The observation of the photographic infrared, especially of $\lambda 8499.7$ C III ($3s\ ^1S$–$3p\ ^1P^0$) would be of interest.

As for the emission of $\lambda 4634$–4640 N III while the other N III lines are present in absorption, it was first thought by Struve and myself that it could not be due to the usual fluorescence effect described by I. S. Bowen (Lα of He II absorbed by O III, then absorption of resonance O III quantum by N III), since no O III line was observed in emission. However this point of view is not convincing. Indeed two of my collaborators, J. Humblet and G. Mannino (Liège 1957), stressed the point that the selectivity may indeed be due to Bowen's fluorescence mechanism. The absence of emission in the observed lines of O III does not imply that the resonance line $\lambda 374$ O III cannot be an emission line able to bring the ions N^{++} to the excited state $3d\ ^2D$.

[10] The dilution effects in the far ultraviolet would be profitably studied theoretically, in preparation for space observations.

[11] There may even be more "exotic" excitation mechanisms, of the type suggested by P. Swings and Y. Öhman (1939). Amorphous metals produced by condensation at low temperature seem to have a critical temperature at which the solid undergoes a transition from the amorphous into the crystalline state. Such a transition would be accompanied by a sudden emission around 200 or 300 Å. One may wonder if this mechanism could not explain emissions in regions of the sky where none of the usual energy sources seem to exist.

The Fe II spectrum behaves in a typical fashion in P Cygni-type stars. The a^6S–z^6P^0 multiplet (λλ4923.92, 5018.43, 5169.03) differs strongly from the b^4P–$z\ ^4D^0$ (λλ4233.7, 4351.76, 4385.38) although the equivalent widths are very similar in the solar spectrum (sextet: 167, 210 and 154 mÅ; quartet: 139, 133 blended, 81 mÅ). In BD + 47°3487, HD 160529, 17 Lep, Z CMa, CD–27° 11944, RS Oph (at 1938 outburst), Nova Her 1963, the sextet is strong, while the quartet is very weak. Generally the $a\ ^6S$–$z\ ^6P^0$ transition consists of emission lines with shortward absorptions; the radial velocities differ appreciably. In Z CMa, the effect is striking. The multiplets with lower level b^4 P, $b\ ^4F$, $a\ ^4G$ are pure sharp emissions, without absorption component. On the contrary the $a\ ^6S$–$z\ ^6P^0$ transition has strong, violet-displaced absorption components. Yet the excitation potentials are very similar,[12] but $a\ ^6S$ has the same multiplicity as the ground level of Fe II. Actually the behavior of Fe II in P Cygni stars resembles those of Si III, N II, N III, N IV and C III in shells of higher excitation. In supergiants, some "multiplicity effect" is present, although all lines are present in absorption; at this point of view 3 Pup is closer to the P Cygni stars than to α Cyg.

The very different behavior of the O I triplets (λ8446) and quintets (λ7772) in peculiar stars is very striking. λ8446 sometimes appears in emission, while λ7772 is in absorption. It is generally assumed that Lβ may bring the oxygen atoms to the ^3D level, and thus give rise to emission in the triplets. But this is not necessarily required. B. Pagel (1960) has shown that oxygen atoms placed in a field of diluted radiation become overpopulated on level ^5S relative to ^3S. As a result λ7772 acquires a high opacity and appears in absorption. Moreover the ^5S level can be de-excited by collisions only, while the triplets may be de-excited by radiation; hence at very low densities, ^5S is less de-excited. More generally it should be clear that apparently abnormal relative intensities among emission lines may sometimes be simply due to the fact that certain emissions are more re-absorbed than others.

The behavior of the emission lines of He I is interesting. While the triplets are much stronger than the singlets in planetary nebulae, the opposite is true in certain peculiar stars. This important point will be discussed in detail later on.

Many peculiar stars show either Fe II or [Fe II] emissions or both. Actually the relative intensities of these emissions depend not only on the electron densities n_e, but also on the electron temperatures T_e. The observations indicate that the Fe^+ ions are excited by collisions to higher levels, with subsequent cascading to lower ones. The lower levels of the observed permitted Fe II transitions are metastable, and the forbidden [Fe II] lines correspond to jumps downward to the deepest electronic levels. If T_e is sufficiently high the permitted lines will be much stronger. A low T_e and a large extent of the radiating layers enhance [Fe II].

Certain lines vary rapidly in intensity with time. This is, for example, the case of [O III], [Fe III] and [Ne III] in BF Cyg. While [O III] may be the strongest transition at times, it may have become extremely weak a few days later. Such variations require a rather high n_e, say of the order of 10^6 cm^{-3} in the shell responsible for [Fe III]. We shall consider this point in relation to the "relaxation time" later on. Actually the minimum electron density 10^6 is more comparable with the densities found in nova shells than with the densities found in planetary nebulae.

Although the continuum of symbiotic stars is uncomfortably intense in the red and photographic infrared, the observation of emission lines in this region is helpful. The lines of H (Paschen series), He I, O I, N I, Ca II, C III, [S I], [Ar III], etc . . . may be strong (as in BF Cyg) and furnish useful information; for example the relative intensities of λ7772 (quintets) and λ8446 (triplets) of O I may vary considerably in a few

[12] The effect of the excitation potential on the bright Fe II lines is marked, the low-excitation lines being enhanced. For example: λ3938.29 (lab. int. 2; $a\ ^4P - z\ ^6D^0$, EP = 4.80 ev) is present in Be stars, while λ3938.97 (lab. int. 4; $d\ ^2D - x\ ^2F^0$, EP = 9.02 ev) is always absent.

days. Incidentally, many emissions of the peculiar stars in the red region are still unassigned. No [Fe I] has been observed;[13] the presumably strongest [Fe I] line is $^5D_3$–$^3P_2$, 5565.68 Å (EP = 2.27 ev).

Strong [Fe II] lines have been found in planetary and diffuse nebulae, in novae (slow and fast), and in a variety of stars, especially in systems composed of M- and B-type stars, such as VV Cep, B 5481, B 1985, WY Gem, the B-type companion of α Sco. Such observations are suggestive: possibly the association is necessary for the production of strong [Fe II] lines. It is true that HD 45677 shows strong [Fe II], whereas there is no evidence of a cool companion: but one may be found eventually (perhaps by infrared spectroscopic observations?).

The peculiar star η Car is especially rich in [Fe II]. Merrill identified in it the following transitions:

$a\,^6D$–$a\,^6S$, $b\,^4P$, $b\,^4F$;
$a\,^4F$–$b\,^4F$, $a\,^4G$, $b\,^4P$, $a\,^4H$.

Investigations of B 1985, WY Gem, W Cep, B 5481, HD 45677, etc. increased the number of observed [Fe II] transitions, some of them rather strong in the ultraviolet[14] and infrared:

$a\,^6D$–$b\,^4D$;
$a\,^4F$–$b\,^4D$, $a\,^2G$;
$a\,^4D$–$b\,^2D$.

B1985 and WY Gem are richest in [Fe II] in the ultraviolet.

The first ultraviolet spectrograms of B 1985, WY Gem, and HD 45677 revealed strong emission lines in addition to Fe II, [Fe II] and Cr II; they were later on assigned to [Ni II]: $a\,^2D$–$a\,^2P$, $a\,^2G$. Other transitions were found in the violet ($a\,^2D$–$b\,^2D$, $a\,^4P$) and in the infrared regions ($a\,^2D$–$a\,^2F$). The $a\,^2D$–$a\,^2F$ multiplet (λλ6667, 7378, 7412, 8302) has a low excitation (1.92 ev) and is very strong in η Car.

In addition to the forbidden lines of singly ionized iron and nickel, only weak lines of a few other metallic ions have been observed (Swings 1951):

[Cr II]: $a\,^6S$–$a\,^4P$, $a\,^6D$ (found in η Car);
[Mn II]: $a\,^5D$–$a\,^5F$ (in B 1985, WY Gem, HD 45677);
[V II]: $a\,^5D_4$–$c\,^3F_4$ (λ3334.66 in HD 45677).

Thackeray has also considered [Cu II] and [P II] in η Car, but these assignments are not convincing. Among the forbidden lines of neutral metals one should mention:

[Mg I]: 4562.48 Å (a magnetic quadrupole transition observed in nebulae, but not yet in peculiar stars, not even in η Car); the permitted line Mg I λ4571 is often found in peculiar stars.

[13] One may hope to find [Fe I] in a peculiar star of low excitation or in a nova at a low-excitation stage.

[14] The identification of an infrared [Fe II] line of low excitation potential is permissible even when none of the usual violet [Fe II] lines are observed. As a general rule, any element will have stronger forbidden lines in the infrared than in the violet, because, in a statistical way, the infrared lines correspond to excitation energies lower than those of the violet lines. A [Fe II] $a\,^6D$–$a\,^4D$ multiplet near 12,000 Å may be expected to be very intense in all [Fe II] stars since the excitation potential of $a\,^4D$ is only about 1 ev. The $a\,^4F$–$a\,^2G$ transition in the infrared has been observed in η Car and other [Fe II] stars; it is present in υ Sgr while the violet [Fe II] lines are not found in that star.

In addition to [Fe III], the other doubly ionized metals do not play a major role. Some uncertain coincidences have been found (Swensson 1953):

[Mn III]: $a\,^4G$–$a\,^4F$, possible in Z And (1948), planetary nebulae;
[Co III]: doubtful: in Orion Nebula, η Car, WY Vel, planetary nebulae;
[Ni III]: rather convincing: $a\,^3F$–$a\,^3P$, λ6001 in Orion Nebula, Z And in 1949, Nova Ser 1948, novae;
[Cr III]: not excluded in RY Sct: $a\,^5D_3$–$a\,^3P_2$, λ5714.6;
[Ti III]: doubtful: ^3F–^1S, ^1G.

In many cases the predicted wavelengths are not accurate enough for convincing assignments. The forbidden lines of more highly ionized iron play an extremely important role in peculiar stars, planetary nebulae, novae, etc. Actually [Fe V, VI, VII] provide valuable information; the recently analyzed [Fe IV] may possibly be of help too.

[Fe V] had not been identified convincingly until 1942, despite Wyse's endeavors in nebulae. The first good observation was made in AX Per in January 1942, as a result of a systematic monitoring of the variable spectrum of this symbiotic object. The excitation in AX Per varies considerably. The McDonald observations during the period 1939–1941 always revealed [Fe VII, VI]. A phase of lower ionization produced [Fe V] in January 1942. Later the [Fe V] spectrum has been repeatedly found in AX Per, CI Cyg, Z And, etc., and on old spectrograms of Nova (RR) Pictoris and Nova (RT) Ser. Bowen's observations in planetary nebulae have provided accurate wavelengths: 3891.28 ± 0.08; 3895.52 ± 0.05; 4227.49 ± 0.11 Å. The strongest [Fe V] lines are $a\,^5D_4$–$a\,^3F_4$ (λ 3891.3) and $a\,^5D_3$–$a\,^3P_2$ (λ 3895.5); they fall near H8 + He I (λ3889) and hence are not easily separable in novae with broad Balmer emissions.

[Fe VI] has a characteristic line λ3664, $^4F_{7/2}$–$^2D_{5/2}$ in a relatively clear region. The other transitions ^4F–^2G, ^2P, appear in the visual region and are not so easily observed in symbiotic objects on account of the presence of the late-type companion. [Fe VI] is found in many novae.

[Fe VII] has three characteristic transitions ^3F–^3P, ^1D, ^1G; the spectrum is observed in AX Per, CI Cyg, Z And, RX Pup, Nova (RR) Pic, Nova (RT) Ser, Nova (RS) Oph, and many other novae.

A new and systematic discussion of the behavior of the [Fe VII] lines in different objects would probably be fruitful. Certain "intensity anomalies" may have been caused by instrumental effects, for example to the "green dip" of the photographic emulsions. Image tube cathodes avoid this difficulty. A general study of the [Fe VII] lines is at present under way in Liège.

Thus forbidden lines of iron have been observed in many stages of ionization: II, III, IV, V, VI, VII, X, XI, XII, XIII, XIV, XV; many permitted lines have also been observed for Fe I, II, III, and higher stages (in the solar corona).

V. DESCRIPTION OF TYPICAL SYMBIOTIC STARS

1. *Z Andromedae* (*HD 221650*)

In these descriptions of typical symbiotic stars and closely related objects, the emphasis is placed on the spectroscopic observations which may help by intercomparisons to understand the physical, geometrical, dynamical, and evolutionary characteristics.

The article by Struve reproduced here[15] had been preceded by only one detailed spectroscopic description of Z And, by H. H. Plaskett (1928). Quite a number of papers followed. Z And is really a prototype of the family of symbiotic stars; for this reason it will be described and discussed in some detail. The history of Z And until 1941, as well as our geometrical, dynamical, and physical views up to that date have been given in the reproduced article, and will thus not be repeated here.

As will be discussed later on, the possible connections between symbiotic stars and somewhat similar objects (such as planetary nebulae, W-R stars, shell stars, novae, etc.) have been stressed repeatedly in recent years. Actually our present ideas of stellar evolution are still rather vague in the region of the H-R diagram between the red giant and the white-dwarf phases. It has often been suggested that planetary nebulae and (or) symbiotic objects may provide missing links. In 1940, Struve and I could of course not have guessed that there might be evolutionary connections between symbiotic stars and planetary nebulae. But we had been impressed by various spectroscopic similarities between the spectrum of Z And at certain phases and that of planetary nebulae, especially those having a fairly high electron density, such as IC 4997. It is for this reason that we had combined our spectroscopic descriptions of Z And and IC 4997 in a single paper; actually the spectroscopic similarities are very great indeed, although IC 4997 has a lower ionization ([Ne V] is absent). The "nebular spectrum" of Z And resembles that of a high-excitation planetary nebula with lines of [Ne III, V], [O III], etc. The chief spectroscopic differences lie in the intensity of [Fe V, VI, VII] and the high intensity of λ4363. On the basis of these differences, a higher density of the order of 10^6 ions cm^{-3} may be assigned to the nebular shell surrounding Z And, as against 10^3 or 10^4 ions cm^{-3} in the gaseous nebulae. The region λλ4632–4658 of Z And, just as the nucleus of IC 4997, contains characteristic emissions of N III, C III and C IV, but they are sharper in Z And than in Wolf-Rayet stars. They were designated as the "nuclear lines," but they may possibly be produced in the innermost layer of the nebular shell.

Many light curves of Z And (Pickering, Shapley, Mrs. Greenstein, Parenago, Prager, Mrs. Gaposchkin, Whitney) have been published. There are small amplitude variations with a period of approximately 694 days, plus occasional sharp outbursts. The nova-like outburst of 1939 and the spectroscopic behavior during the period 1939–1942 were described by Struve and associates.[16] During the period August 1940–January 1941, $N_{1,2}$ increased in intensity relative to λ4363; the P Cyg absorptions disappeared; a Balmer continuum appeared in emission. In January 1941 (star at minimum) the spectrum of Z And was of the postnova type. The P Cyg absorptions had disappeared; the intensities of $N_{1,2}$ relative to λ4363 had increased. In 1941 there was a new maximum, but less pronounced than in 1939: [O III], [Ne III] and [Ne V] decreased in intensity; λ4363 increased relative to $N_{1,2}$; a new shell appeared, but no appreciable dilution was apparent. There was no variation in the structure of the "nuclear features" λλ4632–4658, but these had weakened relative to the Fe II emission. Indeed there were increases in the following intensity ratios: Fe II/N III, C III, C IV; O III fluor./[Ne V]; He I/[Ne III]; Fe II/He I; Fe II/[O III]; Si II/continuum; Mg II/continuum.

[15] In Table I of Struve's paper, λλ3277.0, 3281.1, and 3323.6 should be assigned to Fe II. In Section VI "The Spectrum of the P Cygni Type of Z Andromedae," a comparison is made with BD + 11°4673 (AG Peg), with the restriction that "the comparison with a P Cygni type star which is single may be quite artificial, etc. . . ." Actually it turned out later on that AG Peg is a symbiotic object too!

[16] Struve and his associates were very fortunate during their work on symbiotic stars: a major outburst in Z And, followed by minor outbursts; important spectroscopic changes in AX Per, RW Hya, AG Peg. The fact that the near-ultraviolet region could be covered was also of great help.

Six months after this minor outburst the star had returned to its appearance nine months following the major outburst of 1939; the [Fe VII] lines were strong again. In 1942 a considerable increase of [Ne V] was observed in comparison with 1941. There were also very striking changes in the intensity of the fluorescent line λ3444 O III (excited by λ 303 He II). Indeed the intensity ratio of λ3444 and λ3426 [Ne V] appears to be very sensitive to changes in excitation, density gradient and velocity distribution in the shell. During the second half of 1942 [Fe VII] became very intense again: actually this was the first time in the history of Z And that such a high intensity of [Fe VII] was observed, making Z And similar to AX Per. [Fe V] was present, but weaker than [Fe VII]. There seems to have been a peak in excitation during the summer of 1942. Relative to 1941, there were strong variations in the relative intensities of the triplets and singlets of He I (λλ4471/4388; 4026/4009; 4026/4144), indicating that the relative contributions of the recombination and fluorescence mechanisms had varied. During the period November 1943–October 1944, the excitation increased; [Fe VII] and [Ne V] became very strong, while Fe II weakened (but [Fe II] increased in intensity). Late in 1946, when the star was again bright, Merrill observed a shell spectrum, resembling Pleione; the only previous observation of a shell in Z And had been made by Struve and collaborators in 1939. Merrill succeeded in obtaining high-dispersion coudé spectrograms (10.3 and 20.6 Å/mm). More than 200 shell absorption lines of early type were present; 60 emission lines were also observed; there were only traces of TiO bands. The Balmer series extended to H37 in absorption and was followed by a strong absorption continuum; emission was seen to Hη. In other words a steep decrement was present in emission, while the decrement was very slow in absorption. Struve and collaborators had found in the shell of 1939 that the continuous absorption shortward of λ3613 was all due to the Balmer continuum, and that the ultraviolet continuum was absorbed by the overlying He I-atoms (absorption at λλ3634, 3587, 3554). The high-dispersion spectrograms showed that the bright lines were diffuse; the widths of the lines of different elements did not decrease with increasing atomic weights: the structure of the lines was thus not due to kinetic motion. Merrill (Liège 1957) suggested that the structure probably arises either (*i*) in gross motions of portions of the star's extended atmosphere (prominences?) or (*ii*) in motions of streams of gas coursing about in a system containing more than one star. Late in 1947, the shell had again disappeared; only emission was present in the Balmer series; there was no progression in radial velocity within the Balmer lines. The radial velocity of the He I triplets exceeded that of the singlets by +16 km/sec. The radial velocity fluctuations in the mean curve for [O III] and [Ne III] follow those for permitted lines (H and He I) by about 200 days. This time lag is probably a relaxation phenomenon of the type described by Grotrian for Nova (DQ) Her and applied in the accompanying paper by Struve. Z And increased in brightness in June 1959, then again in May 1961. During the period 1946–1959 a few spectroscopic observations had been made by Miss M. Bloch and Tcheng Mao Lin (in 1956 and 1957). In 1956–57 the spectrum was of the "minimum type": in addition to emissions of low excitation, nebular lines of high excitation including [Fe III–V–VII]; [Ca VII] and TiO absorption bands are observed.

Spectrograms taken in August 1960 by Bloch did not reveal appreciable changes since October 1959. They extended to λ3050, and revealed the ultraviolet emissions of O III (fluor.), He II 3203, [Ne V], [Fe VII], [Ne III] 3343; the Balmer continuum appeared in emission.

Coudé spectrograms were taken at Mt. Wilson by Swings in September and October 1959 in the ultraviolet and the blue region. This high-dispersion material (10 and 20 Å/mm) is similar in quality to that obtained in 1946 by Merrill. It has been described in detail by F. Dossin (1964 and *Thesis*, unpublished). Many lines which previously had been observed as blends are resolved on these spectrograms; hence better identifications have been made possible. The H emissions are strong and broad, and have important wings, easily observable to H8; the Balmer series extends to H31 and the continuum is seen to λ3390. The lines are asymmetrical, widened on the shortward side, with a sharper drop on the longward side; the profiles agree qualitatively with the occultation hypothesis. As previously observed, the He I singlets and triplets have different radial velocities (−15 and −10 km/sec respectively). Only the fluorescent O III and N III lines are present, with no trace of the recombination spectrum of O III. [O II] ($\lambda\lambda$3726, 3729) is absent as usual (the density is too high). On the whole the spectra of 1959 resembled greatly those of 1942, a few months after an outburst, at the beginning of the decline. It would be most valuable to obtain accurate profiles on the basis of spectrograms of still higher dispersion; 2 Å/mm is technically possible.

Prager in 1939 suggested a period of 630 days for the variation in brightness; according to Merrill the radial velocities indicate a period of recurrence of approximately 680 days. The interstellar K line is weak, indicating that Z And is not very distant; its luminosity is considerably lower than that of an average star of class B0.

The general relation between the light curve and the spectroscopic behavior of Z And is as follows:

(*i*) When the object is near minimum brightness, emission lines of low and high excitation, generally including forbidden [Ne V] and [Fe VII], are present, together with an M-type absorption spectrum. The "stellar" emissions belong to H, He I, Fe II, Mg II, Ca II, Ti II, Cr II, C II, Si II, . . . The "nebular" lines are due to He II, C III, N III, O III, [O III], [Ne III, V], [Fe III, VII], [S II], [Ca VII], . . .

(*ii*) When the brightness increases the high excitation emissions weaken progressively; the other emissions (H) show intensity fluctuations. The TiO bands become less conspicuous.

(*iii*) Near maximum brightness a B-type shell develops, sometimes of P Cygni type. The remaining emissions are due to H, He I, Ca II, [O III], [Fe II]. The high members of the Balmer series are in absorption. The TiO bands have disappeared.

(*iv*) In the phase of brightness decline the metallic absorption lines disappear. The high members of the Balmer series and continuum appear in emission again. The TiO bands reappear progressively.

(*v*) Near minimum the nebular lines and the TiO bands are present again. There are considerable fluctuations in intensity ratios: for example $N_{1,2}/\lambda4363$; Fe II/[Fe II]; emission lines/continuum; [Ne III]/[Ne V].

L. H. Aller estimated the "Zanstra temperature" on the basis of the He II-emission (during the nebular stage) and found approximately $T_Z = 90{,}000°$. The electron temperature based on the intensity ratio $\lambda4363/N_{1,2}$ is estimated to be between 8500° and 10,500° near minimum brightness. At the time of an outburst the electron density in the expanding shell is so high that forbidden lines cannot appear. The "nebular" stage begins when the probability of the forbidden transition becomes approximately equal to the probability of collisional deexcitation.

2. *AG Pegasi* (= *BD* + 11°4673 = *HD 207757*)

AG Peg is a remarkable, bright, symbiotic object which possesses a variable magnetic field. The slow transformation of its Be-type spectrum into a combination spectrum has been observed; it takes a few decades, whereas Z And goes through the same evolution in a few months. The spectrum of AG Peg has been studied at various phases by Merrill (first description in 1929), Struve and associates, Aller, G. and M. Burbidge, B. Pagel, Miss Bloch, Dossin. The radial velocity has changed from −13 km/sec in 1915 to −200 km/sec in recent years, while the symbiotic character was

becoming more apparent. This seems to indicate that a strong outflow of gas from a central region is involved in symbiotic phenomena (Merrill). The profiles and radial velocities of λ4363 and of $N_{1,2}$ differ considerably: λ4363 is rather narrow, while $N_{1,2}$ are broader and have much flatter profiles; the radial velocity of λ4363 varies with a range of 65 km/sec and a period of 800 days, whereas $N_{1,2}$ are nearly stationary. These behaviors give some idea of the geometry and kinematics of the system: λ4363 comes predominantly from an inner zone, while $N_{1,2}$ come probably from a shell so extended that motions in all directions radial from the center can be observed (although streams of the types considered by Struve, as for β Lyr, are not excluded).

The first descriptions based on McDonald spectrograms (1939) differed considerably from those of the Mt. Wilson plates (1929). N III was strong in 1939, absent in 1929. We found that the emission lines of P Cygni type showed the same selectivities as the typical stars of that type. For example, the Si II transitions $4p\ ^2P^o$–$4d\ ^2D$ ($\lambda\lambda$5055, . . .) and $4p\ ^2P^o$–$5s\ ^2S$ (λ5958, . . .) are present, while $3d\ ^2D$–$4f\ ^2F^o$ ($\lambda\lambda$4128, 4131) is absent. Silicon in present in four stages, Si I, II, III, IV, probably indicating an effect of stratification. N II and N III are strong, while C II and C III are very weak or absent. AG Peg is thus related to the nitrogen sequence, rather than to the carbon sequence of Wolf-Rayet stars.

The trend toward higher excitation and more marked symbiotic character continued. By 1941, λ3905 Si I disappeared, Ca II and Fe II decreased in intensity, He II, N III and Si IV increased appreciably.

In 1960 Miss Bloch observed intense N IV ($\lambda\lambda$3479–3485). Dossin examined the near infrared region, which is characterized by a strong emission λ8446 O I, whereas λ7772 O I is very weak.

The mechanism of excitation of the Balmer emissions has been discussed theoretically by G. R. and E. M. Burbidge (1953, 1954, 1955) and by B. Pagel (Liège 1957) in order to estimate the sizes of the emitting shells.

3. *AX Persei and CI Cygni*

These two typical symbiotic objects are treated together, because they both exhibit sharp emission lines of high excitation and very characteristic M-type spectra (AX Per: gM3e; CI Cyg: gM4e). There is however an appreciable difference: the spectrum of AX Per varies much more rapidly than CI Cyg.[17] Both stars were first studied by Merrill (1931–1932); later on they have been investigated by Merrill, Swings and Struve (1939–1943), Aller, J. Gauzit, Bloch, Dossin. The best measurements of CI Cyg, based on coudé spectrograms, have been published by Merrill (1950).

When Struve and his associates started their work on these two objects in 1939 it was immediately noticed that AX Per had changed greatly since 1931–32 (from Merrill's description) in the sense of an increased excitation, while the emission lines of CI Cyg had not changed appreciably. Actually there were even noticeable spectroscopic changes in AX Per between September 1939 and February 1940, while there was no appreciable variation of the emission lines of CI Cyg from 1931 to 1942. A few characteristics of both stars at the end of 1939 were:

[O II] λ3727 extremely weak, and [O III] λ4363 very strong (much stronger than $N_{1,2}$) as in the "stellar planetary" IC 4997.

O III fluor. and N III fluor. strong; [N II] fairly strong.

[Ne III, V] strong.

Fe II fairly strong, but [Fe II] uncertain; [Fe III] 4658 very weak.

[17] There seems to have been a photometric outburst of CI Cyg in 1911 (from m = 12.1 to 10.7, then back to 12.1 in 200 days).

[Fe V, VI] present (the first fairly convincing identification of [Fe V]).

[Fe VII] prominent (the only identification of [Fe VII] prior to 1939 was that of Bowen and Edlén in Nova (RR) Pic; [Fe VII] was very weak in 1931).

[Fe X] (coronal line) probable.

Si I λ3905 and Mg I λ4571 (characteristic of long period variables) present; a few other weak forbidden lines of ionized metals.

The spectrograms of AX Per taken during the period January–March 1941 exhibit very marked changes in one year; indeed the spectrum had resumed its aspect of 1931–32: [Fe VI, VII] had almost completely disappeared; there was a considerable increase in intensity of $N_{1,2}$ relative to λ4363 and of [Ne III] relative to H. New changes took place during the period Jan. 15 to May 30, 1941: [Fe VII] was absent, although [Ne V] was still present, as well as fluorescent O III; [O II] was absent. Then again the excitation increased, so that in August 1941 [Fe VII] and [Ne V] had recovered their intensities of 1939. The intensity ratios of the singlets and triplets of He I vary considerably. The spectra taken in January–February 1942 revealed striking new changes, compared to those of August 1941. [O II] had become stronger (lower densities in O^+-regions?), λ4363 had declined relative to $N_{1,2}$; [Fe VII] λ3587 had increased relative to fluorescent O III λ3444; [S II] was present for the first time. The ratio singlets/triplets of He I was intermediate between those in nebulae and in low-excitation objects like RW Hya (see section 5, below).

Essentially, from the spectroscopic point of view, the physical conditions in the nebular region had become such that [Fe V] and [Fe VI] could appear with considerable intensity, making AX Per the first striking example of a [Fe V, VI] object. A strong [Fe VI] feature at λ3664 ($^4F_{7/2}$–$^2D_{5/2}$) accompanied strong [Fe V] lines:[18]

$$^5D_4–^3F_4\ (\lambda3892),\ ^5D_3–^3F_3\ (\lambda3839);$$
$$^5D_3–^3P_2\ (\lambda3896),\ ^5D_2–^3P_1\ (\lambda4071).^{19}$$

Between February and November 1942 AX Per showed decreases in the intensity ratios [Ne V]/O III (fluor.) and [Fe VII]/[Ne III], indicating a decrease in excitation; [Fe V] was still present at the end of 1942. The last spectrograms taken by Struve and his associates in January 1943 revealed again differences, compared with the spectra of February and July 1942, in the sense of an increase in excitation: [Fe V]/[Fe VII] weaker, [Ne III] much weaker, [Ne V]/O III increased, He I singlets stronger.

In recent years AX Per has been placed on the observing program of Miss Bloch, who has found intensity variations similar to those observed by Struve and associates.

In a general way one could conclude that, between September 1939 and May 1941 the excitation had decreased (the disappearance of [Fe VII] may be due to a decrease in temperature of the exciting nucleus). T_e had not changed greatly, but n_e had decreased (by a factor 10?). Of course it is necessary to be careful in considering excitation criteria in an object such as AX Per, in which effects of stratification and asymmetry may be important: for example the emissions of [Fe VII] and of H or He I are presumably localized in different regions.[20] Moreover a change in the temperature of the exciting nucleus will influence the ionization of distant layers only after a certain lag which evidently varies with the distance from the nucleus, the density and the

[18] Fe III and Fe V have complementary electronic configurations $3d^6$ and $3d^4$ with regard to the half-closed shell $3d^5$. Hence similar forbidden transitions are found in both cases.

[19] This line, located between the two [S II] lines, had often been mistaken for [S II] in previous descriptions of nova spectra.

[20] In the case of a planetary nebula the "stratification effects" may be observed directly by taking slitless spectrograms or direct photographs with filters, or by scanning techniques, but this is not possible in the symbiotic stars!

physical characteristics of the different atoms. [Fe VII] is probably excited in the region closest to the nucleus and would be first to react to a nuclear variation. It is known that a post-nova nucleus fluctuates in brightness; such fluctuations affect the surrounding nebulosity after certain relaxation times which are functions of the nebular density and of other geometrical and spectroscopic characteristics (see the case of Z And in the accompanying article by Struve). A striking example of behavior of [Fe VII] in a postnova is given by Nova (RR) Pic. [Fe VII] attained its maximum intensity in 1932, then decreased in the following years. The "lag" may be short (a few days in BF Cyg, see next section) or may amount to months or years. The time lag in symbiotic stars has been studied by M. Johnson (1952).

The line emission of AX Per behaves in a way similar to that of the postnovae in their nebular stages, but the ejection process in AX Per is slower than in novae. In a nova shell the density decreases and, generally speaking, the excitation increases, but the fluctuations of the nova produce nebular variations, and in certain cases (as in symbiotic stars) the phenomena are recurrent.

The simultaneous presence of [Fe II] to [Fe VII] in AX Per and CI Cyg indicates a nebulous envelope exhibiting a wide range of excitations, akin perhaps to the planetary NGC 7027.

As for the radial velocities, whose complicated pattern has been studied in greatest detail by Merrill, the main results are: the displacement of the He I singlets differ greatly from the He I triplets (emissions in different regions of the radiating shell); [O III] and [Ne III] show the same displacements, indicating an origin in the same shell; H, He II, Fe II, O III and N III all show different shifts, as though the radiation of each ion tended to be concentrated in a different layer.

The He II and fluorescent N III lines are not closely correlated in intensity, but this is not strange on account of differences in ionization behavior.

4. *BF Cygni*

This object has been studied by Merrill, Struve and associates, Aller, Bloch, Dossin. Until 1965 BF Cyg was the object which showed the strongest known [Fe III] emission; recently another star, MHα 328–116, showing occasionally extremely strong [Fe III] has been described by Miss Bloch and by O'Dell; we shall consider this later on.

The apparition of very strong [Fe III] does not coincide with a maximum of [O III]. The underlying gM4 absorption spectrum is not always observable; most of the time it is masked by the continuous emission of the hot source. This contrasts with the case of AX Per and CI Cyg whose M-spectra always are prominent. BF Cyg has not reached a high excitation phase: the highest observed ionization is that of Ne III and O III.

The radial velocities deduced from Fe II, [Fe II], [Fe III], H, He I and the nebular lines differ considerably, indicating that they originate in different regions. The He I singlet/triplet ratio is much stronger than in planetary nebulae, as it is in most other symbiotic objects. The relative intensities of Fe II and [Fe II] vary in a complex manner, depending certainly upon T_e and probably on other factors. The excited Fe II and [Fe II] levels are presumably excited by collisions: a relative enhancement of [Fe II] relative to Fe II results from a decrease in T_e and (or) n_e. Aller's estimates are $T_e = 7500°$ to $15{,}000°$; $n_e \approx 10^6\ cm^{-3}$. We are tempted to believe that T_e is even lower than 7500°. The enhancement of the Fe II lines of low excitation potential is such that identifications must proceed very cautiously. Sometimes a weak laboratory line, or even a predicted one of low excitation potential may play a greater role than a very strong laboratory line of higher excitation potential.

Extremely rapid changes in the intensities and velocities of [O III] and [Ne III] have been observed to take place in the course of one day. Additional theoretical work on the time lags in the case of BF Cyg is desirable.

Dossin has observed the photographic infrared region of BF Cyg. Certain intensity ratios, especially λ7772/λ8446 of O I vary strongly in an interval of two days. The identified infrared emissions are those of H, He I, Ca II, O I, NI, C III, [Ar III], but there remain several strong unassigned emissions which are not present in η Car.

In addition to the complex rapid variations of the intensities and displacements of the emission lines, BF Cyg shows slow variations. In recent years these have been followed by Miss Bloch. In the spring of 1955 the lines of [O III], [Ne III], [Fe III] were absent, whereas they were strong in October 1952 and in 1956.

5. *RW Hydrae*

This SS was first studied by Merrill in 1933, and later by Struve and associates in 1939–1943. It shows a "nebular" part having an excitation definitely lower than in AX Per and CI Cyg (no trace of [Ne V]); the excitation resembles that of R Aqr. The observed emission lines are those of H, He I, He II, [O III] (strong λ4363, very weak N_1), very weak [O II] and relatively strong O III. Actually RW Hya is a unique case in which a strong, almost pure recombination spectrum of O III is present: no planetary nebula has been found showing such an intense and complete recombination spectrum of O III (see however sec. X). Fourteen lines of O III have been identified between λ3265 and λ3962. Bowen's fluorescence mechanism is not present to any appreciable extent: the lines of the singlet, triplet and quintet systems have the normal intensities of a recombination spectrum. The relative intensities of the O III lines are the same as in Campbell's object BD + 30°3639, but the latter belongs to the WC sequence, while RW Hya contains nitrogen and no carbon. New observations with higher dispersion are very desirable. One cannot exclude the possibility that the O III lines belong to a Wolf-Rayet nucleus of type WN with abnormally sharp lines. The WC nucleus of the stellar planetary HD 167362 (Swings and Struve 1940) has also relatively sharp lines, but the lines in RW Hya are still sharper. The estimated classifications of the late-type spectrum range from K5 to M0.

Further observational work is desirable because the spectrum of RW Hya varies slowly. Between 1939 and 1941 there was a slow gain in excitation, indicated by the ratios He II/He I and O III λ4363/He I λ4388. As in Z And, BF Cyg and RS Oph, the He I singlets are strong as indicated by the ratio of $2\,^1P^o–5\,^1D$ (λ4388) and $2\,^3P^o–5\,^3D$ (λ4026). In AX Per, CI Cyg, RX Pup and the planetary nebulae λ4026 is much stronger than λ4388. On general grounds one should expect that the singlets are favored by very low pressures. λ4686 He II is present in RW Hya, suggesting that a recombination mechanism leading to the He I emission is also possible, but stratification effects must be present.

6. *Nova (T) Coronae Borealis*

The recurrent nova T CrB of small range, associated with a gM3-type star, may be a transition between the SS and the novae proper. Moreover T CrB is definitely a binary. In 1949 Sanford found that the M3 III component had a variable velocity with a period of about 230 days and a semi-amplitude of 21 km/sec. In 1958 Kraft demonstrated completely the binary character, the velocity of the hot component being obtained from the bright Hβ line (period $227^d.6$): Kraft concluded that the M3 giant of $M_v = -0.5$ and mass $\geq 3.7\,\odot$ probably fills its lobe of the first critical equipotential surface in the restricted three-body problem. There may be transfer of matter from the M3-component toward the blue subdwarf companion, of $M_v = +4.4$ and mass $\geq 2.6\,\odot$, through the Lagrange point L_1.

The most extraordinary spectroscopic event of T CrB was the appearance of the coronal [Fe X] and [Fe XIV] lines during the decline after the outburst in 1946 (Liège 1957, CNRS 1963). Similar observations of coronal lines have been made also in the composite object Nova (RS) Oph and in the probably-not-composite[21] object Nova (T) Pyx.

The spectrum of T CrB has been described by several observers, especially Struve and associates, R. Minkowski and Miss Bloch (CNRS 1963). After the 1936 outburst the excitation in the emission layers increased, and the intensity of the P Cygni-type absorption fringes of Hβ and Hα decreased as compared to the bright components. In 1940 the fluorescent lines of O III and N III were very conspicuous. The red companion appeared strongly in 1941, λ4686 He II and the fluorescent lines of O III, N III were strong, so that T CrB was approaching the appearance of RW Hya. However, in 1942 bright Fe II lines were present, and T CrB became somewhat similar to Z And, except that [Ne V] was absent from T CrB.[22] During the interval 1942–1943, considerable changes took place in the spectrum of the blue component. The H, He I, Ca II, Si I and Si II lines acquired a complex structure. Beside the previously observed He II λ4686, [O II], [O III], O III fluor., N III fluor., [Ne III] and Fe II, the spectrum showed a trace of [Ne V] λ3426, of [Fe VII] λ3586 and of the [S II] doublet. These changes are reminiscent of the analogous case of Z And.

The observations made by Miss Bloch and Tcheng Mao Lin (Liège 1957) in 1950 showed the presence of H, Ca II, He II, N III and [Ne III] in emission and of strong TiO and Ca I λ4226 in absorption. In 1955–1956, only the Balmer lines appeared in emission. Lawrence, Ostriker and Hesser (1967) have discovered very rapid oscillations (period from 98 to 112 seconds) similar to those found by Walker in Nova (DQ) Her (period 71 sec.).

7. *R Aquarii*

R Aqr is a complex assemblage of a hot source, a long period variable and an extended variable nebulosity. Here we shall not concern ourselves with the outer lenticular nebulosity. As for the long period variable its character seems quite regular.

This object has been studied by a number of observers, especially Merrill. When the McDonald group observed it in 1939, [O II] was strong while λ4363 was weak. This is an unusual behavior: [O II] must be produced in a nebular region of very low density. R Aqr deserves further scrutiny, especially more quantitative spectrophotometry. In 1939 there seemed to be a possible effect of occultation by the TiO bands: N_2, which falls close to a head of TiO seemed too weak relative to N_1. Old observations by W. H. Wright seemed to indicate that [Ne III] λ3968 was absent (perhaps absorbed by Ca II?) while [Ne III] λ3869 was present. A careful photometric study of the intensity ratio N_1/N_2 should be made, but this is a rather difficult investigation. Thus far the published results do not appear convincing.

[Fe III] has been prominent at times; this was the case in 1941, whereas [Fe III] was absent in 1931. At other times [Fe II] has been strong.

The most recent spectroscopic observations of R Aqr near minimum light are those by Herbig (1965) and by Ilovaisky and Spinrad (1966). The comparison of R Aqr near minimum with the Mira variable R Leo is very instructive. On Herbig's spectrograms, strong nebular emission lines appear due to the nebulosity extremely near the star. The Ilovaisky and Spinrad plates of 1966 (compared to those of Merrill obtained

[21] An infrared search for a possible cool component of T Pyxidis is desirable.

[22] A comparison between T CrB (1942) and Z And is especially interesting in the region $\lambda < 3400$. Like Z And, T CrB shows O III λ3344 (fluor.), Fe II λ3323, O III λ3133 (fluor.), Fe II λ3277, but there is no trace of [Ne V].

in 1919–1949) did not reveal any trace of the so-called "blue companion spectrum." Emissions of [Fe II], [S II], [O II], Mg I, Mn I, Fe I, Si I, Fe II, Sr II, and Balmer lines to H15 were present. The spectrum of R Aqr was rather similar to that of R Leo in October 1964. The intensity ratio in the [O II] doublet corresponded to $n_e \approx 10^3$ cm^{-3}. The "nebular component" had decreased considerably in intensity: [O III] λ4363 and [Ne III] were present.[23]

8. *Nova (RS) Ophiuchi*

Four major outbursts have been observed: the first in 1898, a second in 1933 which was well-studied spectrographically, a third in 1958 also well investigated (CNRS 1963), and another in 1967 (Code 1968). In addition there have been minor outbursts. The astronomers around 1983 may have a chance to observe a spectacular new display! Since they will be able to cover the far ultraviolet ($\lambda > 912$ Å) and the X- and γ-ray regions from orbiting telescopes, we may imagine the exciting discussions which will take place. Actually it would be very interesting to have the far-ultraviolet spectrum of this object now, during minimum.

Nova (RS) Oph was the first instance in which the coronal lines were observed in a nova, soon after the outburst of Aug. 12, 1933. Although RS Oph had the characteristics of a fast nova, comparatively sharp nebular lines appeared soon: λ4363 on Aug. 18; $N_{1,2}$, λ4640 N III and λ 4686 He II on August 29. The [Fe X] line λ6374 was probably present as early as September 7, enhancing the strength of λ6371 Si II. At the end of October, λ5303 [Fe XIV] had approximately the intensity of Hβ and λ6374 was twice as strong as D_3 (He I). At the end of the observing season (Nov 13, 1933) the coronal lines were strong. By the beginning of the next season (March 1934) the coronal lines had completely disappeared.

The excitation in the [Fe X, XIV] regions of RS Oph is definitely lower than in most regions of the solar corona. RS Oph reveals several stages of ionization of Fe and other atoms, lower than X: the presence of [Fe VII] in RS Oph, and its absence in the corona may be explained by the transition probabilities (Bowen and Swings 1947):

[Fe VII]: 0.49 and 0.37 sec^{-1};
[Fe X]: 69 sec^{-1};
[Fe XIV]: 60 sec^{-1};
[Ar X]: 106 sec^{-1}.

The identifications of the post-maximum lines were discussed by A. H. Joy and P. Swings (1945).

A minor outburst may have taken place on April 25, 1942. The red coronal line λ6374 [Fe X] was observed on July 19, 1942, whereas there was no trace of the green line λ5303 [Fe XIV].

The outburst of July 14, 1958 was the object of considerable attention (CNRS 1963); the parallelism with the 1933 outburst is extraordinarily close. As in 1933 coronal lines appeared in September 1958, especially [Fe X, XI, XIV], [Ar X, XI], [Ni XII, XV]. Very strong variations have been observed in the intensity ratios of the singlets and triplets of He I, of the auroral and nebular transitions of O III, of the λ8446 triplet and the λ7772 quintet of O I. The relative behavior of the quartets and sextets of Fe II was similar to that in the P Cygni stars. [O II] was absent (on account of the too high electron density: $n_e \gg 10^7$ cm^{-3}, probably $> 10^9$). An estimation of the mass of the gas cloud given off in the outburst is of the order of 10^{-6} ⊙.

[23] Sanford (1949) discovered that the long-period variable UV Aur also shows emission lines of H, [O III], and [Ne III].

As in 1933 the color temperature was low and the Balmer decrement rapid. The red color was not necessarily due exclusively to the interstellar scattering, although the interstellar absorption bands were strong; there may also be a reddening by the Kosirev-Chandrasekhar effect.

A strong emission line at λ6827 has been observed on numerous occasions in RS Oph and in Nova (RT) Ser. A tentative assignment to [Kr III] remains somewhat doubtful. The recent outbursts (March–April 1965 and October–December 1967) seem not to have been studied in detail. However, in January 1968 (three months after the maximum of 1967 October 26) Rosino and Mammano (1968) observed that the nova had reached a stage of extremely high excitation. Many coronal and nebular lines were present, including [Fe X], [Fe XIV], [Ar X], [O III], [Ni XII], He II, N III; there were also many Fe II lines.

9. *FR Scuti*

This object, first mentioned by W. P. Bidelman and C. B. Stephenson (1956), is definitely of symbiotic character with strong TiO bands. It has been described by Miss Bloch and Tcheng Mao Lin (Liège 1957). It is characterized by the emissions of H, Fe II, [Fe II, III], [O III].

10. *MWC 603*

This remarkable variable SS has been described by W. G. Tifft and J. L. Greenstein (Liège 1957) on the basis of 18 Å/mm spectrograms. Two hundred emission lines are listed: [O III], [Ne III], [Fe V], [Fe II], H, He I, Mg I, Si I, Si II, Fe II, He II, C III, O II, O III, N III, C III and probably [Ne IV] and [Fe VI]. He I shows variations in the singlet-triplet ratio. There is a strong dependence of line sharpness on excitation, and presumably on location in the nebulous envelope. Most diffuse of all are the forbidden lines of high excitation ([Fe V]).

VI. SPECTROSCOPIC DESCRIPTION OF PECULIAR BINARIES OR SUSPECTED BINARIES RELATED TO SYMBIOTIC OBJECTS

1. *17 Leporis and AX Monocerotis*

These objects are related to the SS, but differ greatly from typical objects such as AX Per or Z And. 17 Lep and AX Mon display emission lines of low excitation; they have combination spectra (late- and early-types) and they suffer outbursts which are not strictly periodic (Cowley 1964, 1967).

17 Lep shows the TiO band at λ7054 (Slettebak); it combines a gM1 and an early-type (B9) companion; the orbital period is 260 days. The most probable masses are 1.4 and 4.6 ⊙, respectively. The B9 primary has a shell, but various broad features (He I λ4471, Mg II λ4481, Si II λλ4128, 4130) belonging to the underlying star are observable. 17 Lep displays similarities to T CrB. As for AX Mon, it combines a gM- or a gK-star with a rapidly rotating B3nn component. The period according to Mrs. Cowley is 232 days.

2. *RX Puppis*

Besides strong bright lines of H, He I, and He II, RX Pup shows lines of [O III], [Fe VII] (very strong), [Ne V], [Fe VI], [Ca VII] and C IV, which make it similar to CI Cyg as far as emissions are concerned. But the evidence for a late-type component is not quite definite. The low-dispersion spectra which have been obtained in the red region reveal certain absorption features which are similar to those of MWC 17 (see next paragraph), but no spectral type could be assigned to the possible red component. Spectra of higher dispersion in the red and near infrared would be most valuable, not only to confirm or deny the symbiotic character, but also to check on the possible presence of [Fe X] (close to λ6363 [O I]) and of the auroral transition λ7319–λ7330 of [O II]. λ4363 is very strong, yet the ratio $\lambda 4363/N_{1,2}$ is smaller than in CI Cyg or AX Per. Nebular [O II] λλ3726–29 is absent (density too high), but nebular [N II] is present. Nebular [O I] is present, but not the auroral transition: [O I] is excited on the outskirts. This star, unfortunately rather far south, deserves further observational attention.

3. *MWC 17*

The spectrum of this object is intermediate between RY Sct ([Fe III] only) and η Car (an [Fe II] star) as [Fe III] and [Fe II] appear with similar intensities. Beside the ^5D–^3F and ^5D–^3P multiplets of [Fe III] and the usual [Fe II] transitions, MWC 17 shows H, He I, Si II, [O I], [N II] and [S II], whereas [O III], [Ne III], [O II] and the permitted Fe III lines are absent. There is some suspicion of a red component, but better spectra should be obtained in the red. MWC 17 is possibly a SS of lower excitation (absences of O^{++}, Ne^{++}, Fe^{+++}, but presence of Fe^{++}, N^+ and S^+). As in RX Pup, the nebular [O I] lines must be emitted in regions where the ionization and the electron density are lowest. On the other hand the absence of nebular [O II] indicates that the electron density prevailing in the regions where oxygen is ionized is too high. λ5270 ($^5D_3$–$^3P_2$) and λ4658 ($^5D_4$–$^3F_4$) of [Fe III] have about the same intensity (an effect of reddening). The Si II lines show the same selectivity as in Z And, AG Peg and P Cyg.

4. *RY Scuti*

The early-type "component" of this binary occupies a special place among the P Cygni stars. Its spectrum has been described by Merrill and later by Struve and associates. Emissions of H, He I, [N II] (nebular and auroral) and [Fe III] are present. RY Sct represents a definite stage in the evolution of certain novae, which follows the η Car stage ([Fe II]). There is no trace of Fe II, Fe III or [Fe II]. λ5270 is approximately of the same intensity as λ4658. There remain several unidentified emissions in the visual region. There is a late-type component.

5. *CD − 27°11944*

This peculiar star of P Cygni type (with weak [Fe II]) may have a late component, possibly of R-type but not of M-type (no TiO bands). It should be observed in the red region with a higher resolution. The P Cygni emission features are unusually broad; they may extend over 600 or 700 km/sec. They are indeed broader than the emissions of some Wolf-Rayet stars (BD + 30°3639 [Campbell's object], HD 167362, the nucleus of IC 4997) and of slow novae. Ca II and Na I are present in emission.

CD–27°11944 belongs to the group of P Cygni stars in which the expanding shell is observed but not the exciting star, while other P Cygni- or Of-objects show the spectrum of the stellar reversing layer.

6. *V1016 Cyg = MHα 328-116*

This object, which rose abruptly in brightness from $m_{pg} = 15.3$ in 1963 to 11.9 in 1964, has been studied by Miss Bloch (1966), by Fitzgerald, Houk and McCuskey (1966), and by O'Dell (1967). The pre-outburst type was late M. On October 5, 7, and

13, 1965, strong emission lines of H, He I–II, C II–III–IV, N II–III, [N II], O I, [O I, III], [S II, III], [Ne III], [Ar III], Fe II, [Fe II, III] were present. H was represented by the Paschen series to P23 and the Balmer series to H24. O I λ8446 was strong, while λ7772 was weak. The red doublet of [O I] was intense, but the green line weak. The [O II] lines λ7320–λ7330 were intense, but λλ3726–29 faint. The [O III] lines $N_{1,2}$ and λ4363 were among the strongest emissions, together with [S II] λλ4068, 6730 and [Ne III]. The lines [S III] λλ3721, 6312 and [Ar III] λλ7136, 7751 were also present. About sixty [Fe II] lines were observed, as well as several of [Ni II]. [Fe III] was very well marked; indeed it seems that V1016 Cyg is the richest object in [Fe III] thus far observed. The relative line strengths of [O III] were found to vary as well as the Balmer lines, whose decrement indicated that the envelope was optically thick in those lines.

The symbiotic character of V1016 Cyg, which was doubtful for a time, is now well established.

7. *MWC 349*

This star which bears a striking spectral analogy to MWC 17 has been observed by Merrill in 1932, then by Struve and associates in 1941. [Fe III] was strong in 1932, as well as in 1941. λ5270 ($^5D_3$–$^3P_2$) is much stronger than λ4658 ($^5D_4$–$^3F_4$). This is certainly due to interstellar reddening. No late-type absorption features appear clearly, but better spectrograms should be obtained in the red.

8. *Boss 1985 = HD 60414-5 and Boss 5481 = HD 203338-9*

B 1985 consists of a M2 I*ab* and an early B-type star (B2V, or perhaps a hot subdwarf). It is characterized by strong [Fe II] and [Ni II]. Mrs. Cowley (1964) has obtained the period (about 27 years). In all probability the late-type component fills its lobe of the first critical equipotential surface. Certain emission features ([Fe II], [Ni II]) may arise in a very extensive nebulosity enveloping the system.

While no spectacular change has been observed during the period 1939–1947 except a slow intensity increase of the H emission from 1942 to 1946, very striking changes have been observed in the ultraviolet region beginning October 18, 1947. While previous spectrograms had mostly revealed emission lines of H, Fe II, Cr II, [Fe II] and [Ni II], the autumn 1947 McDonald material (Swings 1950) showed intense absorption lines of the shell type, similar to those at an outburst of Z And or an eclipse of VV Cep. Similar observations have been made by R. F. Sanford and by D. B. McLaughlin. The [Ni II] emission remained strong. The Balmer continuum appeared in absorption. Compared with the shell of Pleione or with the supergiant 3 Puppis, B 1985 exhibited stronger Sc II and Ti II absorptions (of low excitation), and much weaker Cr II and Fe II. The Balmer lines had the appearance of reversed P Cygni lines, similar to the lines of the eclipsing binary VV Cep. McDonald coudé spectrograms obtained during 1963–64 revealed the red [O I] emission λ6300, but not the auroral green line. Additional observations are needed. It would be interesting to measure the ultraviolet magnitude regularly.

In the triple system B 5481, the spectroscopic behavior of the primary (M1 I + B2 V) resembles that of B 1985, including the temporary production of a shell.

9. *WY Geminorum and W Cephei*

Both of these binaries consist of M- and Be-type components, and are rich in [Fe II], especially WY Gem which strongly resembles B 1985. Several ultraviolet emission lines are still unassigned. The ultraviolet spectrum of WY Gem is entirely free of the late-type component.

10. *VV Cephei*

This is an eclipsing binary consisting of an M supergiant (radius $\approx 1200\ \odot$) and a Be-type main-sequence star. It has bright lines of H, Fe II, Ca II, [Fe II], [Ni II]. Struve and associates have described the early-type spectrum for $\lambda > 3100$ Å. The low-excitation transitions of Fe II are considerably enhanced. These Fe II lines do not share in the orbital motion of either of the components. The Fe II and [Fe II] emission originates most probably in an extended envelope surrounding the whole system, while the H emission must be closely associated with the Be star.

Investigations covering more than one orbital cycle of 20.4 years have been recently carried out in the blue region by Peery (1966) and in the photographic infrared by Glebocki and Keenan (1967). In the blue, a few unexplained peculiarities and discordances remain. The region 7000–8000 Å is particularly interesting. The transient appearance of the O I blends at $\lambda\lambda 7772$, 8446 which in 1944 had been found to last for less than 55 days, was again observed in 1964. No strong streaming motions are evident in the O I surrounding the early-type component; this absorption spectrum appears when the material is projected upon the M-type star. In the region occupied by the O atoms there probably is no appreciable Lβ flux, because the $\lambda 8446$ absorption line is relatively deep.

It would be interesting to examine the photographic infrared spectra of other similar systems, such as 31 and 32 Cyg and ζ Aur, at the times of their secondary minima.

11. *The Companion of α Scorpii*

α Sco B is of mag. 5.2, at a distance 3″ from the M0 supergiant. Struve and associates have tried to determine the extension of the [Fe II] lines in the nebulosity surrounding the Be-type companion. The observation is rather difficult, but deserves being repeated with a longer focal length, a higher dispersion and perfect seeing. The radius of this nebulosity is approximately 2″ or 2″.5 (≈ 200 astronomical units).

The Be star itself has a [Fe II]-rich spectrum resembling MWC 17 and η Car. There is no trace of Fe I, [Fe I], Fe II, [Fe III]. If the H lines are bright, they are certainly weaker than [Fe II]. The absence of Fe II indicates that T_e is low. The abundance of H may also be abnormally low.

12. *W Serpentis, α Herculis, and α Scorpii*

The eclipsing variable W Ser has been the object of many spectroscopic investigations (C. A. Bauer (1945), Struve, J. Sahade, M. Hack, A. Beer, A. Fresa, etc . . . Liége 1957). While certain emission lines, for example [Fe II], are seen at all phases, other broad emissions appear only during eclipses and border the shell lines. The [Fe II] emissions must be produced in the outermost layers of the envelope surrounding the system.

Herzberg observed Fe II emissions (EP up to 5.6 ev) in the region $\lambda < 3300$ Å in the supergiants α Her and α Sco. These could not be due to the hotter companions. Herzberg assigns the emission lines to a "corona-like nebulosity."

13. *M1 − 2 = VV 8*

This object was originally found by Minkowski (1946), and identified by him as a stellar planetary nebula. Attention was called specifically to it by Razmadze (1960). It has been studied by O'Dell (1966) who detected the absorption spectrum of a G2 supergiant. The object is either a G supergiant plus a hot companion, or a single hot star surrounded by a very extensive outer shell that is ionized only in the innermost region.

14. *CH Cygni*

The type M6 semiregular variable CH Cyg had an outburst in June 1967. The emission lines in the ultraviolet (3140–3500 Å) have been described by Swings and Swings (1967), and compared with those in VV Cep, B 1985, BF Cyg and η Car. These lines are mainly due to Ti II, Mn II, Cr II, and Fe II; lines of [Fe II] and [Ni II] are very weak or absent.

The 3680–5050 Å region has been described by Faraggiana (1968), and compared to the same region in 30 Her and VV Cep. She found sharp emission lines of Fe II, [Fe II], [S II], broad He I emissions, P Cygni-like structure at the Balmer lines and the H, K lines of Ca II. She lists the radial velocities from absorption lines, from the P Cygni structure, and from the emission lines of different elements.

15. *HD 45677 (= MWC 142)*

This star, which is one of the richest objects in [Fe II], is not known to be a binary. Yet the intensity of [Fe II], [Ni II] and other emissions, and also the spectroscopic variability of HD 45677 lead one to believe that a cool companion may be found.

At the time of the first McDonald observations (1939), the spectrum seemed to be identical to that described by Merrill (1923–1927). There were bright lines of H, [O I], Fe II, Cr II, [Fe II], [Ni II], and exceedingly sharp absorption cores in the Balmer lines to H29 or H30. The radial velocities from the lines of the shell agreed well with those from the reversing layer. The McDonald spectrograms revealed new [Fe II] transitions (EP up to 4.72 ev, by parallel studies of B 1985 and WY Gem), and led to the discovery of [Ni II] and [Cr II]. There remain some still unassigned emissions.

The spectrum changed appreciably during the period 1939–1943. Ca II $\lambda 3968$ (H) acquired a complex profile, similar to that in HD 190073. On the other hand the sharp emissions of Fe II, [Fe II] and [Ni II] remained the same. The profiles of the permitted and forbidden lines differ considerably.

This star is at present being investigated at Liège.

VII. Comparison with Spectroscopic Observations of Novae

The SS display a bewildering variety of spectroscopic phenomena. In order to acquire general views regarding the physical characteristics of these objects it seems instructive to compare the behavior of the typical SS, not only with individual peculiar stars as we have done in the preceding section, but also to related classes of objects: novae, planetary nebulae (including their nuclei), Wolf-Rayet, Of and P Cygni stars. Obviously, in all these classes, we have retained and summarized only the spectroscopic phenomena which may help directly in understanding the SS.

In all the peculiar objects the continuum—on the assumption of elementary models—arises at depths which depend primarily on the wavelength and which differ completely from the layers giving rise to the discrete emissions. A light curve has a physical meaning only if it concerns a stated wavelength, hence a defined region of the star. The maximum of a light curve in the ultraviolet does not necessarily occur at the same time as the maximum in the visual or the infrared regions. In an expanding atmosphere the effective photospheric surface is a purely optical notion. In other words, at any given wavelength λ the luminosity (if due to a continuum) is determined by the diameter D and the temperature T of the non-static photosphere corresponding to this λ. The maximum of λ results from the combined effects of D and T. On the other hand the emitted energy may originate essentially in discrete lines and not in a continuum: this would be the case of coronae in the far ultraviolet. These considerations are especially applicable to novae and SS at the time of outbursts.

Actually what we need most in the photometric field is a set of monochromatic light curves, such as in $H\alpha$, in the pure late-type spectral region, in specific forbidden lines such as $\lambda 4363$, $N_{1,2}$, [Ne V], [Fe VII], and in the pure continuum of the hot component.[24] The establishment of a program of this kind for SS, novae and representative peculiar stars is imperative. It should include specially interesting phases of the nova evolution: apparition and evolution of the coronal lines, nitrogen outbursts, phases with molecular absorption. Once orbiting telescopes become operational it will become of great interest to record light curves in $L\alpha$ and other characteristic ultraviolet emissions.

Two symbiotic objects, T CrB and RS Oph have had genuine recurrent nova outbursts. Indeed all SS suffer, at certain phases, variations of an explosive character. Z And has shown nova-like outbursts. All SS exhibit light variations, sometimes of small amplitude, always resembling certain phases of novae. In all cases the envelopes of SS as well as of novae depart from local thermodynamic equilibrium. There are of course differences in ejection velocities; the dilution effects may be quantitatively different. But essentially the mechanisms have close similarities. At the time of an outburst of either an SS or a nova, the expanding, probably asymmetric circumstellar shell has an electron density which is too high for forbidden lines. The latter appear when the density in certain regions of the expanding shell decreases to an extent such that the collisional de-excitation of the excited metastable levels is less efficient than the radiative de-excitation by emission of the forbidden lines. Each forbidden transition of each atom or ion has its specific requirements for appearance. Consideration of the required "time lags" is also essential. As for T_e, it is kept at a specific value, fairly constant on account of the thermostatic effect of the forbidden lines.

The similarity of the spectroscopic history of the SS with typical large scale nova outbursts is striking, but there is as yet no evidence that the physical causes of the outbursts are similar. Merely descriptive similarities of behavior may be deceptive. The total mass of a nova shell is of the order of 10^{-4} ⊙, while that of an SS shell is definitely smaller.

The presence of molecular bands at certain phases of novae is probably not due to the same mechanisms as the presence of a cool component in the SS. It is known that the CN and C_2 bands have been observed in several novae, especially in Nova (DQ) Her 1934. The molecules may be much more abundant in a nova layer than in thermodynamic equilibrium at the "photospheric" temperature (whatever this may mean) as the radiation reaching the molecular layers may have been previously depleted in the spectral regions required to photodissociate the molecules. Indeed the departures from equilibrium may even be such that absorption bands of ionized molecules, such as CH^+ or CO^+ may someday appear in a nova!

The SS seem to possess abnormal abundances, and so do the novae. [Fe VII] seemed abnormally strong in Nova (RR) Pic (1925), [Ne III] in Nova (GK) Per (1901) and Nova (RT) Ser (1909), [Fe III] in Nova Ser and Nova (DO) Aql (1925). Nova Ser is rich in N III and poor in C III. But such anomalies may be purely apparent, in the novae as well as the SS, since the spectra integrate over a wide range of layers.

The observations of changing radial velocities of specific lines are similar in SS and novae. There is actually no need to envisage phenomena of acceleration or deceleration while the atoms are in flight. There is presumably an original spread in the velocity of ejection. "At different epochs, the material moving with one velocity may be more readily observed than that moving with another velocity, owing to the changing

[24] C. R. O'Dell has in progress at the McDonald observatory a program devoted to systematic observations of a number of SS. Certain emission-line ratios and the flux distribution in the continua are measured with a spectrum scanner. Large changes in these quantities have already been observed.

density and excitation which produce or destroy measurable spectral features" (A. B. Underhill).

Most SS appear to have an individuality. So do the novae. The differences in spectroscopic appearance result from the wide possible varieties of density and velocity. Actually there are certain SS which look spectroscopically very similar, more in fact than novae: this is the case of AX Per and CI Cyg at certain phases.

We have seen that strong coronal lines have been observed in two symbiotic novae: RS Oph and T CrB; coronal lines have been found in other novae, such as T Pyx, and very probably [Fe X] was present in two SS, AX Per and CI Cyg at certain phases. The behavior of the coronal lines is in accord with the properties of the ions concerned. The apparent anomalies are actually caused by the operation of the primary mechanisms of ionization and excitation, attention being paid to the transition probabilities, the electron densities, the departures from equilibrium and the fact that the ionizing underlying radiation may differ considerably from a black body.

The Zanstra mechanism has been applied to SS as well as to novae and planetary nebulae. However it is clear that the usually adopted hypothesis of ultraviolet ionizing radiation of the black body type is only a very crude approximation. In fact atoms which have approximately the same ionization potential compete for the ultraviolet quanta (continuum, modified by discrete emission and absorption features) (Swings 1942). For example the ionization of O^{++} may be reduced by the fact that the ionization potentials of He^+ and O^{++} are nearly equal (this explains observations in NGC 6543). The ionization of C^{++} and N^{++} may be favored by the presence of emission lines of He II superimposed on the continuum. Indeed the far ultraviolet continuum—if there is any—differs considerably from a black body. If the underlying radiation is absorbed by He II for $\lambda < 228$ there will result a higher abundance of C^{+++}, N^{+++}, O^{++}, Ne^{++} and Ar^{+++} in the higher layers. Similarly a strong continuous Lyman absorption increases the population of Si^+, Fe^+, N, and Ar, and the He I absorption continuum affects the ionization of C^+, N^+, O^+, Ar^+ and Si^{++}. All those phenomena will become clearer once we obtain ultraviolet spectra ($\lambda > 912$ and $\lambda < 20$ Å) with orbiting telescopes (CNRS 1963).

VIII. SPECTROSCOPIC REMARKS ON INDIVIDUAL NOVAE

Certain post-novae reveal spectroscopic information which are of interest in relation to the SS.

Nova (DQ) Her which was studied extensively at the time of its outburst in 1934 is a typical representative of the slowly developing type, hence may be a source of instructive comparison with SS. It has been re-observed at McDonald on numerous occasions since 1940. At that time the N III spectrum was strong in emission; it was not excited only by Bowen's mechanism because $\lambda 4379$ was present. On the other hand the strong O III emission lines may have been mainly excited by fluorescence. [O I], [O II], [O III], [N II], etc. . . were present. $\lambda 4363$ was fairly strong. In July 1942 the relative intensities differed greatly from 1940; [O II] was stronger, while the ratio $\lambda 4363/N_{1,2}$ had not decreased significantly. The range and variations in expansion and in radial velocity are rather complex, or even appear almost contradictory. The spectra taken in 1947 and 1949 reveal striking changes in the spectrum of the nebulosity since 1942. The apparently contradictory spectroscopic changes may be understood if we assume that the far-ultraviolet exciting radiation of the nucleus differs considerably from a black body. This departure could bring about an irregular distribution among the stages of ionization. It is also possible that fluorescent excitation by the underlying radiation plays an important role in the emission. Such a mechanism would be affected considerably by the far-ultraviolet absorption or emission features of the exciting nuclear spectrum. On the other hand the evolution of regions where different physical conditions prevail must also differ and the geometry of the system is certainly far from spherical symmetry.

Observations made in 1950 showed that the striking spectroscopic changes observed between 1942 and 1949 continue while the mean velocity of expansion remains practically the same as in previous years. The nebular spectrum progresses toward a stage characterized by very strong [O II], strong He II, N III, H; the other usual emissions [O III], [Ne III], [Ne V] and [Fe VII] have practically disappeared in 1950.

Following Merle Walker's discovery that Nova (DQ) Her is an eclipsing binary of period 4^h39^m, various attempts have been made to determine a radial velocity curve. The most complete results based on wonderful prime-focus spectrograms taken at the 200-inch reflector have been described jointly by J. L. Greenstein and R. P. Kraft (1959), and by R. P. Kraft alone (1959). These two remarkable investigations deserve a detailed review. Outside eclipse the spectrum is qualitatively the same as it was in 1950 (strong [O II] and [S II], very weak [O III]). Complex phenomena which differ for different emissions take place in the course of a period. Greenstein and Kraft suggest that He II and the higher members of the Balmer series are produced in a rotating disk of gaseous material that follows the motion of the nova in its orbit; the material undergoes eclipse along with the star. However, Hβ together with the forbidden emission lines is produced mostly in the expanding nebular envelope seen on direct photographs. In 1956–1958 DQ Her consisted probably of a hot, rather bright, white dwarf of approximate mass 0.25$\odot$ coupled with a "dark star", possibly dM3.

It is desirable that DQ Her continue to be investigated spectroscopically and photometrically from time to time; Greenstein's study of 1959 is a model for such work.

Nova (RT) Ser had an outburst in 1909 and has developed abnormally slowly. Its spectrum was taken by A. H. Joy 22 years after the outburst: [Fe III] was very strong. Spectra taken at McDonald in May 1940 revealed the following: [Fe III] had become very weak, while [Fe VI], [Ne III, V] were strong. Beside Hα the strongest line was [Ne III] λ3868, as in Nova Per 1901 and Nova Sgr 1936 at certain phases. The N III emission was strong, while O III was absent. In July 1942 [Fe V] and [Fe VI] had developed more completely than in 1940. Actually RT Ser was an ideal object for [Fe VI] in 1942. The McDonald spectrograms obtained in May 1950 revealed tremendous changes since 1942: [Fe VII] and [Ne V] had become very intense, while [Fe V, VI] and [Ne III] had become weak. λ4363 was still much stronger than $N_{1,2}$, 41 years after the outburst: the density in the nebular envelope was still high, compared with most planetary nebulae including IC 4997, but resembled that in AX Per and CI Cyg. Since the ionization has been increasing steadily during the period 1909–1950 it would not be surprising if RT Ser would acquire coronal lines in the not-too-distant future.[25] The spectrum of this object should be observed periodically. Herbig has discovered late-type absorption features in the red; thus RT Ser is a symbiotic nova.

The fourth outburst of the recurrent nova T Pyx in 1945 revealed spectroscopic phenomena similar to those in Nova (RS) Oph, including the appearance of coronal lines. However the ionization in T Pyx was higher than in RS Oph, while the density was lower in the layers which emit [Fe VII]. In fact [Fe VII] is stronger relative to [Fe X] and [Fe XIV] in T Pyx than in RS Oph. It would be interesting to search for a possible red component.

Another excellent representative of [Fe VII] emission, beside T Pyx and RT Ser, was Nova (RR) Pic (1925). [Fe VII] attained its maximum intensity relative to

[25] Two spectrograms obtained by G. H. Herbig in 1963 and 1964 do not yet reveal convincing evidence of [Fe X] or [Fe XIV].

λ4686 and Hα in 1932, and then decreased in the following years. The behavior of RR Pic showed similarities to that of AX Per. Actually RR Pic is an important example of the slow nova type. It was described in considerable detail by H. Spencer Jones during the period 1931–1934, but many identifications, especially those of [Fe III, V, VI, VII] could be made only several years later: [Fe VI, VII] by Bowen and Edlén (in 1939), [Fe III] by Edlén and Swings (in 1939) and [Fe V] by Edlén (in 1939) and by Swings and Struve (in 1942). The broad [Fe V] emissions in RR Pic could be discussed only after [Fe V] had been clearly observed as sharp lines in AX Per. The successive appearance of [Fe II], [Fe III] in 1925, [Fe V] in 1926, [Fe VI, VII] in 1934 resembles that in RT Ser and in various SS and other peculiar stars. Actually a similar succession has also been observed in Nova (RR) Tel, in which Edlén has moreover made tentative identifications of [Fe IV].

Among recently observed novae, Novae Her 1960 and 1963 showed spectroscopic phenomena which resemble those in SS: appearance of coronal lines; variations in the intensity ratios λ8446/λ7772 of O I; sextets/quartets of Fe II; λ5812/λ4658 of C IV. In both novae the usual Wolf-Rayet emissions in the infrared are present: He I, He II, C II and C IV, but the usually strong C III infrared transitions which are prominent in WC stars are absent in the novae (CNRS 1963).

IX. GENERAL COMPARATIVE REMARKS ON THE EXCITATION MECHANISMS AND THE PHYSICAL PHENOMENA

We have mentioned earlier that coronal lines have been observed in several novae and probably in SS; all these emissions are actually forbidden transitions. In the far ultraviolet and in the soft X-region the permitted lines of the highly ionized atoms must be prominent at the phases when the coronal lines of the usual spectral region are intense. Actually high excitation permitted lines may also appear in the ordinary region (CNRS 1963). The high ionization is probably due to inelastic collisions with electrons; so may arise the forbidden and permitted lines of the highly ionized atoms. This would indicate that there may be "coronal regions" in nova envelopes where $T_e > 500{,}000°$ as in the solar corona. The ionization and excitation in the "coronal regions" of novae would thus differ radically from those in planetary nebulae. Actually it has generally been assumed that the excitation and ionization in the SS, novae, Wolf-Rayet and other peculiar objects of early type are due to electromagnetic radiation. But electrons of high energy may also play a major role. Magneto-hydrodynamic methods must be applied.

The typical novae which show strong coronal lines are recurrent objects; in the case of RS Oph and T CrB a cool companion exists, and it definitely seems that recurrent novae and the U Geminorum stars have companions (CNRS 1963). According to Kraft the period of recurrence would be the time required by an unstable component to accrete enough matter coming from the other star; the critical instability would give rise to an outburst. From the spectacular photometric and spectrographic studies of Nova (DQ) Her and other post-novae one may indeed wonder if all post-novae, not only the recurrent of fairly short period, are not close binaries.

What causes the occasional ejections in the evolution of SS and at certain phases of novae? Should the radiation pressure be considered? In the course of the evolution of a shell a slight change in density or velocity distribution or in the "quality" of the exciting radiation may appear, which enhances the fluorescence excitation. As a consequence, the selective radiation pressure in the resonance lines will increase, and a more or less sudden ejective outburst may result owing to the fact that the increased velocity of the shell, relative to the reversing layer, displaces the shell absorption lines outside the depleted regions of the stellar spectrum. This explains the more or less sudden appearance of bright lines excited by fluorescence.

Turbulence and axial rotation may play a role in the fluorescence excitation. Axial rotation should be considered not only as a dynamical agent in the formation of a shell, but also a mechanism influencing the fluorescence excitation and the expansion which might result from the corresponding radiation pressure.

An extreme case may be the "nitrogen flaring stage" of novae, such as was described by W. H. Wright for Nova Gem (1912). When an adequate variation of the velocity gradient or stratification in the nova shells or of the quality of the underlying radiation appears, Bowen's fluorescence mechanism of He II, O III and N III may become prominent. The selective radiation pressure due to the accumulating quanta in N III λ452 may expel suddenly the N^{++} atoms (Bowen 1935), thus giving rise to very broad N III and N IV bands. Since this abnormal ejection destroys the conditions required for Bowen's fluorescence mechanism, the outburst is only temporary. Its spectroscopic effects depend on the location of the atoms considered. The variation in the exciting nucleus reacts on the intensities and profiles of the nebular lines arising in the outer nebulosity. The resulting line modifications depend on the distribution of matter and physical conditions in the nebulosity and on the various relaxation times.

The continuous absorption of the flaring shell may affect considerably the lines arising in the deepest layers: a He II emission line arising in the inner layers may even be replaced by an He II absorption line arising in the outskirts of the "nucleus."

Eventually this mechanism may possibly help in explaining the formation of peculiar associations, such as have been observed in BD + 30°3639, NGC 40, and other planetaries in which a pure carbon nucleus WC is surrounded by a nebulosity rich in N (characterized by strong [N II] lines). Other planetary nuclei containing both C and N are also surrounded by a nebulosity showing strong [N II] (*e.g.*, IC 418, IC 4997, NGC 6572, NGC 6210).

The general analogy of the N-flaring stages of novae with the less spectacular variations observed in the Of, P Cyg or Be stars is obvious.

In the early stages of a nova or SS outburst there is only a minor influence of dilution, as the "shell" is not very distant yet from the region emitting the continuum. Later dilution effects appear, and give a possibility to estimate the distances of the shells from the photosphere. We refer to Miss Underhill's chapter for a thorough critical review of these dilution effects, including their influence on the spectral classification criteria. This chapter contains also a study of the effects of the strong emission lines, such as Lα of H (λ1215) and He II (λ304).

The paper by Struve on Z And stresses the importance of time lag in the sense considered by W. Grotrian. A change in the temperature of the exciting radiation will influence the ionization of distant layers only after a certain delay, which evidently varies with the distance to the nucleus, with the density, and with the atomic properties. [Fe VII] is probably excited in a region close to the nucleus and would be first to react to a nuclear variation. It is well known that a post-nova nucleus fluctuates in brightness, and in case of a surrounding nebulosity this will obviously give rise to a variation of the excited nebular spectrum after certain relaxation times. These may be short (of the order of a few days in BF Cyg) or long (months in other SS or novae). Since the fast particles reach greater distances the corresponding lag may be longer. The time lag has been reconsidered recently by J. S. Pecker (CNRS 1963), who suggested a theoretical treatment which is more complete than that of Grotrian.

X. COMPARISON WITH SPECTROSCOPIC OBSERVATIONS OF PLANETARY NEBULAE AND THEIR NUCLEI

The spectroscopic characteristic of planetary nebulae is the presence of strong forbidden lines; this is true also for the SS.

In the accompanying paper, Struve and I described the spectrum of IC 4997 on account of its resemblance to Z And at a certain phase (see the section on Z And).

Like the SS, the planetary nebulae are impermanent structures. Indeed L. H. Aller and W. Liller (in 1957) found an intensity variation of λ4363 in IC 4997 in the course of the last 40 years. One may wonder if spectroscopic variations have not occurred also in IC 3568 (Swings and Fehrenbach 1958). Spectrograms taken in 1958 at the Haute Provence Observatory reveal a strong He II line which was not mentioned by W. H. Wright in 1918. Aller's description of IC 3568 does not mention [Ar IV] which is present on the Haute Provence spectrograms.[26] The very great variety of planetary nebulae is of course due partly to evolutionary effects. Slight differences of central star (including its age), T_e, n_e, and relative abundances, geometry and velocities give rise to very different spectra of the planetaries. Photographs and slitless spectrograms of planetary nebulae reveal their complex geometry, including stratification and a filamentary structure; different regions produce different spectra; in particular different filaments may have different T_e and n_e. Unfortunately in the peculiar stars we do not have such direct evidence of stratification effects although stratification is certainly present, and we have to use integrated intensity ratios of different emissions, essentially the intensity ratios of the nebular, auroral, and transauroral transitions of various ions and the [O II] ratios λ3726/λ3729. There are planetaries of low excitation (H, strong [O II], weak [O III]); of higher excitation (strong [O III], weak [O II], strong [Ne III]); of highest excitation (strong He II and [Ne V], strong fluorescence of O III and N III). We have encountered similar stages in the SS.

The recent spectroscopic descriptions of planetary nebulae based especially on Mt. Wilson, Lick and Haute Provence coudé spectrograms have brought a wealth of information which has been and will be in the future of great help in interpreting the SS spectra. For example, nebulae reveal λ4562 [Mg I] and the $^5D_4$–$^3H_4$ transition of [Fe III] (λ4881.14) and of [Fe V] (λ4227.49).

The intensity ratio λ3726/λ3729 of [O II], $^4S_{3/2}$–$^2D_{5/2,3/2}$ depends on T_e and n_e in a theoretically well-established way and constitutes a valuable criterion of electron density in certain ranges of n_e (of the order of 10^3 cm^{-3}) and T_e. The transauroral doublet of [S II], λ4068–λ4076 is also valuable for assessing density fluctuations.

The Orion Nebula which is the brightest and one of the nearest of the H II regions (Kaler, Aller, Bowen 1965) has been observed spectrophotometrically with high dispersion (16 and 20 Å/mm); we thus have reliable intensities for [Fe III] and many permitted lines (He I, C II, N II-III, O II, Ne II, Si II, S III).

The richest nebular spectrum is that of NGC 7027 which has been studied in detail recently (Aller, Bowen, Wilson 1963). Many recombination lines (O II-IV, C II-III-IV, Ne II, Mg II, etc . . .) are observed together with many forbidden lines, revealing a great range in excitation (from Mg I and Fe II to recombination lines of O IV, N IV, N V and forbidden [Fe VII] among the filaments and other condensations. Among the observed emissions the following are of special interest: [Na IV-V], [Cl III], [N I], [Fe III-V-VII], [K IV-V], [Mg I].

L. H. Aller and W. Liller have prepared (1968) a new detailed report on planetary nebulae, with main emphasis on the physical mechanisms. Important theoretical contributions, especially by Seaton's group (Seaton 1963–1966), have recently interpreted many observational data on planetaries, and deduced the radii and masses of the nuclei, and the masses and luminosities of the nebulosities; many considerations may sometimes be applied readily to the SS.

As in the case of the SS, planetaries may present Bowen's fluorescence mechanism, or it may be absent. For example, Bowen's mechanism is absent in NGC 6543 (no trace of He II and O III emission in the nebula) and the strong lines of C II, C III and N III are due to a recombination process. On the other hand the SS RW Hya has a

[26] The [N II] doublet near Hα is absent. As in NGC 6543, IC 4997, and NGC 6826 the nucleus of IC 3568 contains lines of carbon and nitrogen.

very complete O III spectrum, excited by a recombination process, while N III is very weak or uncertain.

The great range in excitation observed in nebulae such as NGC 7027 is found also in SS, for example AX Per and CI Cyg.

The chemical composition of a planetary nebula (or of the nebulosity of a SS) is that of the outer skin of the star from which it originated. There seem to be real differences in chemical composition of the nebulae; these must be due to the nuclear processes and the amount of mixing in the pre-planetary object. We shall return to this point later on.

The photoionization processes (Zanstra mechanism) are, in principle, similar in SS and in planetary nebulae. In particular the effects of the overlapping regions of photoelectric absorption and of the far-ultraviolet emission or absorption features are of importance, as we have stated previously; the case of NGC 6543 is especially convincing (Swings 1940). The discrete far-ultraviolet features play an essential role. It is possible (but dangerous!) to draw synthetic far ultraviolet spectra of the nuclei, then to deduce the most active features (Swings 1942). In high excitation nebulae, H is ionized to an appreciable extent by strong emission lines of the exciting radiation, especially Lα of He II (λ 304). The photoelectrons are thus provided with a high kinetic energy and are able to excite various permitted lines of high excitation. The same consideration applies to the SS: many lines, including far ultraviolet lines, may be excited by collisions. It will be extremely interesting to obtain far ultraviolet spectra of SS stars by telescopes on space vehicles.

There is a considerable range in the spectra of the nuclei of planetary nebulae (Liège 1957), and resemblances to parts of the spectra of SS are common. We are only at the beginning of the construction of theoretical models for the atmospheres of nuclei (Böhm and Deinzer 1966); the adopted effective temperatures vary from 45,000 to 150,000°K. The central stars must have masses of the order of 0.6 $\odot$, *i.e.*, of the same order as the white dwarfs.[27] The masses of the ejected nebulosities are a few tenths of the solar mass.[28] The central stars of NGC 1514 and 2392 "flicker" like old novae (Lawrence, Ostriker, and Hesser 1967).

XI. COMPARISON WITH SPECTROSCOPIC OBSERVATIONS OF WOLF-RAYET STARS

At least half of the W-R stars are binaries, and various astronomers have suggested that the W-R stars are all binary systems. Different orientations of the orbital planes would explain why not all W-R stars show velocity variations. However there is no truly convincing evidence that all W-R stars are double. The close binary V444 Cyg (WN5 + O6) has been the object of numerous photoelectric and spectrographic observations and theoretical discussions, involving, as is necessary in most close binaries, the *problème restreint* and the Lagrangian points.

The spectral classification of the W-R stars has been re-examined recently (Hiltner and Schild 1966). Two parallel sequences within the WN group are recognized. They differ principally in emission band width and strength of the continuum. The sequence with the relatively weak narrow lines contains many binaries. In addition to the well-recognized carbon sequence that shows a regular increase of band width with excitation, a group of WC stars with relatively stronger emission (relative to the continuum) has been observed; two of them are central stars of planetaries. Their identity as a physical group is uncertain. A W-R star with only emission bands of He and Hα has been found. A class WC5 should be added to Beals' classification (very strong C IV, weaker lines of C III, O V, Hα).

[27] This was recognized first by Menzel in 1926.
[28] One of the queerest nuclei is an Of star with a strong O VI emission at $\lambda\lambda$3810–3835.

Actually C IV is found in the hottest WN stars, and it has been suggested that N lines are present in WC stars. Among the planetary nuclei there are Wolf-Rayet stars containing both N and C. There are also pure WC nuclei surrounded by a nitrogen-rich nebulosity. The subdivision into a WN- and a WC-sequence has generally been assigned to a difference in the relative abundances of N and C. However A. B. Underhill has suggested that the subdivision may be due to different physical conditions (different temperatures and departures from black-body radiation in the vacuum ultraviolet) rather than to different chemical abundances. There are strong arguments in favor of this view.

The spectra of the W-R stars which appear to be single have not changed appreciably over a few decades. We have to deal with atmospheres in a stationary state, although the motions are similar to those observed in novae. The shells of W-R stars are small (order of a few solar radii), much smaller indeed than those of novae.

The W-R stars do not show forbidden lines; reasonable values for n_e are of the order of 10^{12}–10^{13} cm^{-3}. Some are nebulous (Smith 1967). Further effort should be made to discover extended shells with the observational techniques developed to detect very weak nebulosities, such as that of G. Courtès who uses a focal reducer and a narrow interference filter at Hα.

The production of the broad, rounded W-R emission bands has been assigned either to ejection (by C. S. Beals, as in novae), or to electron scattering (by G. Münch), or to turbulent motion (by R. N. Thomas). As for the excitation itself, it is usually attributed to recombination,[29] but collisions of turbulent clouds, ejection of "sub-photospheric" hot bubbles and shock waves have also been considered by E. R. Mustel (Liège 1957).

Great care has to be exercised in the interpretation of the Zanstra temperatures obtained for the W-R stars because of stratification effects and of the photoionization by emission lines, as was also the case for novae and SS. Lines from levels of high excitation (for example, the 4-n series of He II) are formed in deeper layers where the temperatures and pressures are higher than in the outer regions where lines of lower excitation (the Balmer lines) are formed.

XII. COMPARISON WITH SPECTROSCOPIC OBSERVATIONS OF Of STARS

The spectra of Of stars are superpositions of spectra of typical absorption O-stars and of shell emission lines of high excitation, principally N III and He II; sometimes H, He I, C III, N IV, N V and Si IV are also present. There is a wide range in intensity of these lines. All varieties are observed between pure absorption-O stars and pure W-R stars. There is also a wide variety in the relative intensities of the N III and C III lines, going from Of shells with strong N III and no C III, to Of shells with strong C III and weak N III. There remain several fairly strong unidentified emissions (for example, $\lambda\lambda$4485, 4503 in 9 Sge); a detailed study of high-dispersion spectrograms might reveal more weak emission lines.

We have described earlier the selectivities observed among the lines of N III, C III, etc. These effects decrease when the intensity of the emission increases, and actually disappear in the W-R spectra.

No forbidden lines are observed; actually the electron density in the shell is of the order of 10^{13} cm^{-3}. The shell is rather close to the star, and the dilution factor is only of the order of 0.1. No dilution effects are observed, but it should be noticed that the usual dilution effects, such as those in He I, are theoretically much weaker around 50,000° than they are at 15,000° or 20,000° for the same geometrical dilution factor of the order of 0.1.

[29] The intensities of the stronger lines such as He II $\lambda\lambda$3203, 4686 may be affected by self-absorption.

The absorption He I triplets are much stronger than the He I singlets as in normal B-type stars. Contrary to the case of emission He I in many SS, λ4686 He II is a weak emission in 9 Sge while λ3203 He II is a very strong absorption line. This is probably due to a fluorescence effect excited in He II by Lβ.[30]

A complete understanding of the Of stars and of the possible intensity variation of their emission lines will require accurate photometric data, and ultraviolet spectrograms taken from space vehicles.

XIII. COMPARISON WITH SPECTROSCOPIC OBSERVATIONS OF STARS OF THE P CYGNI TYPE

As described earlier, SS occasionally go through a P Cygni-like phase; Z And provides an excellent example, described in the paper by Struve. The prototype P Cyg has changed in brightness in a nova-like manner and is related to the extremely slow novae such as η Car and RR Tel. The spectrum of P Cyg continues to vary definitely, although only very slowly; most other stars of P Cygni type such as HD 45910 and HD 218393 do likewise (CNRS 1963), imitating the recurrent novae on a much smaller scale. According to Pagel, the electron density in the shells of P Cygni stars is some 10^7 to 10^8 times higher than in planetary nebulae (Liège 1957).

The dilution effects observed in P Cyg (and in Z And), especially of Fe III, Si II, Si III and He I are very conspicuous (Swings 1944), but dilution alone does not seem able to explain all the striking selectivities observed.[31] P Cyg showed an interesting demonstration of the help gained by extending the covered spectral range. The infrared transition of C II, $3p\ ^2P^o$–$3d\ ^2D$ (λλ7231, λ7236) connecting the upper level of λλ6578, 6583 (in emission) and the lower level of λ4267 (in absorption) is intermediate (weak emission and absorption) between the two usual transitions of C II. The O I quintet (λ7772) is much stronger in absorption than the triplet λ8446. The ultraviolet region λ3000–λ3300 revealed one strong line of He I, 4 lines of Si III and 19 lines of Fe III, all with metastable lower level. All the observed transitions of Si III for which the term $4p\ ^{1,3}P^o$ is the upper level are present in absorption, whereas those transitions for which this term $4p\ ^{1,3}P^o$ is the lower level are in emission. These selectivities are not yet clearly understood.

The other P Cygni stars exhibit a similar behavior. An example is Z CMa, investigated by Merrill in 1927 and by Struve and associates in 1942. All the spectrograms revealed the striking behavior of Fe II stressed in a preceding section: the Fe II multiplets with lower level a^6S have very strong, violet-displaced absorption components, whereas the multiplets with lower level b^4P, b^4F and a^4G (of EP similar to a^6S) appear in pure emission. Many P Cygni stars behave likewise (17 Lep, HD 160529, CD−27°11944, BD+47°3487, etc.); a similar, but weaker effect is found in supergiants such as 3 Puppis (which however is related to P Cyg, as it shows bright Hα and [O I]).

Recombination, collisional excitation and fluorescence are all active for all elements, but their relative importance varies widely. In P Cyg, the emission lines of O I are produced by recombination, complicated by dilution effects. An ion of higher ionization potential such as Fe^{++} may be excited mainly by fluorescence. In shells of

[30] This cycle phenomenon renders the use of λ4686 as a classification criterion rather dangerous. A valid classification must be based on features which originate approximately in the same regions of the atmosphere. This is not the case for the He I and He II lines.

[31] The selectivity in Si II observed in P Cyg, Z And, AG Peg, etc. . . is striking: the group $3s\,3p^2\ ^2D$–$3s\,4p\ ^2P^o$ (λλ3854, 3856, 3863) is present while $3s^2\,3d\ ^2D$–$3s^2\,4f\ ^2F$ (λλ4128, 4130), strong in normal B8 to B5 stars, is absent. This may be due to the fact that the lower level $3s\,3p^2\ ^2D$, although not really metastable, is connected with the ground level of different electron configuration $3s^2\,3p\ ^2P^o$ by a weak transition (λλ1817, 1808). Moreover the only way to reach $4f\ ^2F^o$ by absorption from the ground state is through $5d\ ^2D$, and the radiation thus required, of energy 13.87 ev, is only slightly higher than the ionization potential of H (13.54 ev).

lower excitation the predominance of low-level Fe II lines is very pronounced, which is probably a result of the collisional excitation at low T_e. These considerations serve to illustrate again the great caution that one should use when trying to estimate abundances of elements in peculiar stars, on the basis of either emission or absorption lines. Apparent anomalies may be due to the effects of dilution, fluorescence, or mechanical agents.

XIV. ADDITIONAL CONSIDERATIONS ON IONIZATION AND EXCITATION IN SYMBIOTIC STARS AND RELATED PECULIAR OBJECTS

All the essential mechanisms are discussed in the chapter by Miss Underhill. Only a few minor comments need to be added here.

The three usual excitation mechanisms—recombination, collisions and fluorescence—account satisfactorily for the spectra of the planetary nebulae. The situation is somewhat different in stellar envelopes of much smaller extension such as novae, Of, P Cygni and Be-type shells, and consequently in the SS at similar phases. At other phases, the SS should rather be related to planetary nebulae. The selectivities observed in He I, N II-III-IV, C III, Si II-III, Fe II, etc. may probably be assigned to recombination and fluorescence, coupled with the effects of the geometrical and physical dilution, the stratification or more complex geometry of the layers, the velocity and density distributions within the atmosphere. The details of these selectivities are not all clearly understood yet, nevertheless they are of great help in classifying the types of shells during the evolution of the SS, novae and other peculiar objects. A more satisfactory interpretation of the selectivities will require a detailed treatment along the lines of Rosseland cycles. The dilution effects may be quite different from the classical cases in which only the geometrical dilution of a continuous black-body radiation is considered. The fluorescence mechanism may become active when the mean interval of time between two collisions becomes longer than the average lifetime of an atom in the excited state. The density and temperature conditions are favorable in both the shells and nebulae.

The exciting radiation reaching an atom A at a specific location in a shell differs always from the black-body radiation at the effective temperature T_e reduced by a geometrical dilution factor independent of λ. Even if the photospheric radiation is that of a black body at T_e, the radiation reaching A will normally be depleted by discrete or continuous absorption features or will be enhanced by emission features. Whenever the stellar exciting radiation possesses absorption or emission features the resulting fluorescence should be considered as a superposition of monochromatically excited patterns, each of these having a specific intensity.[32]

The absorption coefficient for the fluorescence excited by the underlying radiation is much greater than the coefficient of photoelectric absorption. But since the photoionization is produced by a wide range of wavelengths beyond the ionization limit, the recombination mechanism will usually be more efficient than fluorescence, unless the ultraviolet ionizing radiation of the underlying layers is depleted.

The case of the emission lines of He I is especially interesting. On account of the high EP's in He I, collisional excitation is unlikely in objects of relatively low excitation such as T CrB, RW Hya, AG Peg, P Cyg, etc. If the He atoms are mostly neutral, electron captures are not frequent. The absorption of the underlying radiation enhances the singlet system relative to the triplets since the ground level is $1s^2\ ^1S_0$, because the lowest triplet $1s\ 2s\ ^3S$ corresponds to a high excitation potential (19.74 ev), and since there is no intercombination between singlets and triplets. The exciting wavelength range is essentially λ500–λ580; this region may contain absorption or

[32] The peculiar structure of the molecular bands in comets has been explained in this manner by taking into account the influence of the Fraunhofer lines of the exciting solar radiation.

emission features. Moreover the excitation depends on radial velocity effects. In objects of high excitation (CI Cyg, AX Per, RX Pup, nebulae) most He is in the He^+ or He^{++} state; the He I singlets are much fainter than the triplets. A convenient comparison may be based on $2p\ ^1P^o$–$nd\ ^1D$ ($n = 5$, λ4388) and $2p\ ^3P^o$–$nd\ ^3D$ ($n = 5$, λ4026). But one should keep in mind that stratification occurs and that neutral He may be expected on the outskirts of certain high-excitation shells.

The lowest singlet term of O III, $2p^2\ ^1D$, is only 2.5 ev higher than the ground term $2p^2\ ^3P$, and there are strong intercombinations between singlets and triplets. Hence the fluorescence of O III excited by the underlying star may contain triplets as well as singlets; this fluorescence may in fact be similar to a complete recombination spectrum if the exciting radiation does not contain strong discrete features coinciding with the wavelengths of the O III absorption from low levels. In RW Hya the He I singlets are much stronger than the triplets, and are to a considerable extent excited by fluorescence. But this does not mean necessarily that the O III spectrum is also excited by fluorescence, on account of stratification effects.

In P Cyg, the Si III transitions behave in a way similar to N III in Of stars. The absence of $3d\ ^2D$–$4f\ ^2F^o$ of Si II has been considered previously.

In the shells of lowest excitation, the Balmer emission lines themselves may be excited by fluorescence. The efficiency of this mechanism depends on the velocity and density distributions of the H atoms of the shell and on the profiles of the absorption lines of the exciting radiation. Any variation in these factors will give rise to changes in intensity and profile of the Balmer emission lines. If the underlying star has strong deep Lyman absorption lines and if the shell is stationary or expanding or contracting slowly, only a small proportion of the H atoms in the shell will be raised to the levels $n = 3, 4, \ldots$. If the shell is expanding or contracting rapidly, the Lyman absorption lines of the atoms in the shell may be shifted by the Doppler effect outside the deep parts of the Lyman absorption lines of the star, and fluorescence may operate. In such a case emission lines must be expected.

Why does Bowen's mechanism not affect O III in the Wolf-Rayet stars? This is due to the velocities of the O^{++} ions relative to the layer in which $L\alpha$ of He II is emitted. The O^{++} ions located at a specific place in the W-R shell are able to absorb only a small fraction of the resonance radiation of the ejected He^+ ions on account of the relative radial velocities. There is no selectivity in O III in the planetary nebula BD + 30°3639 or in RW Hya (O III λ3444, 3760 are not enhanced). In other SS (T CrB, AX Per, CI Cyg, RX Pup) the incomplete multiplets of O III and N III are prominent: in all cases the relative velocities are small and the situation resembles that in planetaries. In novae the role of the O III, N III fluorescence varies considerably with the phase.

Merrill has mentioned the possibility that the emission line Mg II λ3848 which is anomalously strong in Z And may be excited by $L\beta$.

Since most of the atoms in the inner parts of the shells are either H or He^+, the stellar radiation will generally be strongly depleted for $\lambda < 912$ and $\lambda < 228$. As a result any ion whose ionization limit falls just shortward of λ912 or λ228 will not be further ionized as rapidly as ions whose limits fall on the longward sides. The absorption below λ912 should cause an increase in the abundance of O I, Si II, Fe II; similarly the absorption shortward of λ228 will enrich C IV, N IV, O III, Ne III, Fe IV. One should therefore expect low excitation potential lines of these ions (either forbidden or permitted) to be abnormally strong. In particular the lines of Fe II must be stronger than those of Ca II. High-excitation potential lines (usually permitted) are normally produced by recombination of the ion with an electron. This type of line should therefore appear with enhanced intensity for the next lower stage of ionization in each atom. This effect will be still further enhanced by the presence of strong emission lines of H and He II in the spectral regions just longward of λ912 and λ228. For example the population of Fe IV should be increased with respect to Fe III. This may explain why RS Oph is rich in [Fe II] and [Fe VII] and poor in [Fe III] and [Fe V]. Ca^+ may be ionized from the metastable $3d\ ^2D$ level by absorption of $L\alpha$.

The third ionization potentials of C and N are almost identical (47.64 or 260 Å and 47.20 ev), while the corresponding value for O is higher (54.62 ev), approximately the same as the ionization potential of He^+ (54.14 ev or 228 Å). C^{+++} and N^{+++} are probably abundant in the same regions of high-excitation atmospheres; the same is true for O^{+++} and He. The recombination spectra of C III and N III should appear simultaneously, while those of O III and He II may be absent. Not only is the continuum stronger near λ260 than shortward of λ228; there may also be a crowding of strong bright emission lines of He II (λλ256, 243, . . .), O IV, N IV and N V appearing between λ260 and λ228; the region $\lambda < 228$ is poorer in such emissions. The simultaneous appearance of [Ne III] (IP of $Ne^{++} = 40.9$ ev) and [Ar IV] (IP of $Ar^{+++} = 40.7$ ev) is readily understandable.

The same tendency to favor certain ions has been evident to varying degree in the spectra of AX Per, CI Cyg, RX Pup which show a wide range of stages of ionization. The fact that [Fe II] and [Fe VII] are both strong at the same time, in comparison to the intervening stages, has long been a puzzle of these objects. The interpretation has often been sought in the binary character or in stratification phenomena. The above interpretation may be correct; it should however be treated in greater detail on the basis of the transition probabilities of Fe II to VII which are now known. This work is at present under way in Liège.

We refer to Miss Underhill's chapter for other considerations and details on all these departures from the usual equilibria and on the excitation mechanisms.

XV. GENERAL CONSIDERATIONS AND CONCLUSIONS

A number of ordinary light curves of SS have been published but, as mentioned before, a great effort should be made to obtain more monochromatic and more accurate curves. We shall mention here only the light curves of Z And (visual and photographic) and AX Per (photographic only) discussed by Mrs. C. H. Payne Gaposchkin (1946). She has tried to separate two sources of light, variable in brightness, but constant in color (color index = 1.3 mag. for the M component, 0.0 mag. for the blue component). In Z And both "components" vary together with the 690-day cycle: the blue "component" has an observed range of approximately 6 mag., while the red "component" varies by 2.5 mag. at most. At the highest maxima of the blue "component" of Z And the spectrum is that of a minor nova outburst, which is succeeded as the star declines by the typical spectral development of a very slow nova. AX Per behaves in a similar way. Such photometric studies do not furnish an entirely convincing argument for or against the binary character.

Several SS have been found by H. W. Babcock (1958) to have magnetic fields; this is the case for AG Peg, WY Gem, HD 4174, VV Cep. Merrill (Liège 1957) has suggested that this magnetic field may give rise to driving forces by interaction of the charged particles with the field.

Before attempting to discuss the nature of the SS, let us collect a few last geometric, energetic or kinematical data. The theoretical intensity ratio of $N_{1,2}$ is known to be very nearly 3. If N_2 appears much weaker than it should relative to N_1, one might be tempted to assign the anomalous intensity ratio to a different absorption of N_1 and N_2 by TiO, since N_2 is nearer the strong TiO band head λ4954 (degraded to the red) than is N_1. We have mentioned such a possible observation in the case of R Aquarii; a similar indication exists also for AX Per. However this is a very delicate type of photometric measurement which should be repeated with higher resolution and more accurate photometry (CNRS 1963).

As far as the range of variation is concerned we may distinguish the SS which are real recurrent novae (RS Oph, T CrB) and those which have more moderate and slightly more frequent outbursts (Z And, AX Per).

We have mentioned that the radial velocities of different elements, or even of different lines of the same element may differ appreciably in SS. In particular, the radial velocities of the He I singlets may differ greatly from the triplets: the latter show systematically greater displacements than do the singlet lines. [O III] $\lambda 4363$ yields a velocity curve which differs appreciably from that of N_1. Similarly, Fe II and [Fe II] behave differently. The variations in brightness and in velocities appear to have the same periods (from $P = 200$ to 900 days). What do these variations mean? A volume pulsation in a large mass of gas (Merrill)? Or are they due to orbital motion? Or to the rotation of an unsymmetrical body? Or to a revolving stream or jet which discharges continuously into an outer zone? The observed velocity curves point strongly to specific localizations of the zones of emission of various lines. Remarkable time lags have been observed.

The first and essential question that arises is: are the SS queer associations of two very different stars, or exceedingly peculiar single stars? The next question is: why do outbursts occur, and where does the energy required to give rise to the high excitation features come from? The observational study of a wide variety of close binaries, combined with numerous theoretical investigations—beginning especially with Kuiper's dynamical theory of 1941—leaves little doubt that binary nature may stimulate the process of formation of shells or layers or streams, giving rise to line emission in the integrated spectra. These shells or layers may very well be stratified and unsymmetrical in nature. There is observational evidence in support of the hypothesis that the matter which forms the shells, layers, streams or rings comes from the secondary component through the Lagrangian point L_1. Matter may also leave the system through the external Lagrangian points (Sahade 1963, 1965). Prominence action may be the mechanism of loss of mass in the vicinity of L_1. Struve has described eight possible configurations; four relatively wide pairs and four close pairs (Liège 1957).

The close binaries present an enormous range of bright-line phenomena. One or both components may be near the main sequence; others may belong to the subgiant, giant or supergiant classes. Typical early-type binaries are the Wolf-Rayet binaries and the post-novae. Examples are found in practically all spectral types. On the other hand there are many close binaries which show no tendency toward emission.

Let us first consider the single star hypothesis. The first suggestion was given by D. H. Menzel in 1946: a hot star could be covered only partially, either toward the poles or at the equator, by a cool, M-type atmosphere; an outer envelope would be excited by the radiation from the stellar region. Sobolev in 1960 also suggested a hot nucleus surrounded by a very large envelope.[33] Aller in 1954 took the opposite point of view: a late-type star would be surrounded by a corona in which emission lines are excited by the dissipation of shock waves, much like the solar coronal lines in Schwarzschild's theory. A somewhat similar view had been expressed by F. J. M. Stratton for R Aqr. The "coronal" hypothesis was also adopted and extended by J. Gauzit (1955): the stellar corona surrounding the M star would be a hundred or a thousand times denser than the solar corona; the physical conditions of the SS would vary chiefly through the influence of strong prominences. In the period 1956–1957 various astronomers: A. J. Deutsch (1956), Aller (1959) and Swings (1959), independently envisaged that the SS may represent the turning-point in the evolution of the red giants. At this stage the nucleus contracts, becomes hotter, and tends to separate from the relatively cool atmosphere characterized by TiO bands. This

[33] H. L. Johnson (1967) has found that several known shell stars (ϕ Per, κ Dra, P Cyg) are abnormally red in K − L. This he interprets as due to infrared emission by circumstellar shells.

M-type atmosphere instead of contracting begins gradually to dissipate into space; the emission lines would originate below it. An SS would thus be a transition between a red giant and a blue predegenerate phase.

The hypothesis of a binary system is the oldest and simplest. It was proposed by F. Hogg (in 1934) who described Z And as a normal, possibly somewhat variable M giant, and a variable, very hot dwarf which excites a nebular envelope. In the binary hypothesis the nebular shell may arise by ejection of matter in the nova-like outbursts of the hot star. This hypothesis was considered by L. Berman (in 1932), Merrill (in 1935–40–57), C. H. Payne-Gaposchkin (in 1938–46–57), Struve and Swings (in 1939–1945), G. P. Kuiper (in 1941), Aller (in 1954) and defended especially by J. Sahade (1965). According to this hypothesis, a SS would be a binary consisting of a giant or supergiant red star and of a hot subdwarf; the red component would fill its lobe of the first critical equipotential surface. One or the two stars would be immersed in a small variable planetary nebula. Our current ideas on stellar evolution do not exclude the association of a giant late-type star and a hot companion; such a combination may produce a highly peculiar, explosive binary system. Kraft in 1958 showed that T CrB is a double-lined binary formed by a giant M3 and an underluminous, blue, emission-line companion. The red component of T CrB probably fills its lobe of the inner contact surface. Matter thus escaping from the M component is accreted by the blue companion.

Let us remember that certain ordinary novae, such as Nova (DQ) Her, are binary systems. Other binaries which have more frequent but less spectacular (no forbidden line!) outbursts are the U Gem stars; in the latter case the primary is a cool dwarf or subdwarf.

A solution intermediate between a single or a binary star has been suggested by Mrs. C. H. Payne-Gaposchkin (Liège 1957). In the course of its evolution a binary may become an essentially binucleate star. If the common pattern is developed, the more massive nucleus may outrun the other. "Perhaps such a developing binary . . . might show the characteristic spectrum and behavior of a *symbiotic variable*. Whether such an object would be a single or a binary star at this time is almost an academic question. . . . The greater the disparity of rate of development between the two components, the greater would be the range of excitation displayed."

Where are the SS located in the H-R diagram? Our ideas on stellar evolution are extremely uncertain after the red giant phase. There is a great temptation to consider the planetary nebulae as intermediate links, somewhere between the red giants and the white dwarfs, although we have no proof that all stars possessing a mass in the proper range pass through the stage of planetary nebula. But what are the immediate parents and descendants of the planetaries? Deeming (1965), among others, considers that "infrared supergiants" may be the predecessors of the planetary nebulae, and the predecessors of these infrared supergiants might be either the long period variables or the SS. What the evolutionary sequence really is we do not know. At any rate, there are many points in common between the planetary nebulae and the SS. Indeed, about ten years ago, Merrill (Liège 1957), Sobolev and others suggested that the SS may be the parents of the planetaries. Deeming separates them by the "infrared supergiants." Considering our very poor knowledge of the region between the horizontal branch and the white dwarfs, a greater effort in the study of the planetary nebulae and the SS is well worth while. The central stars of the planetaries are evolving toward the white dwarfs; the SS are somewhere in the same region, but their evolutionary track is most uncertain.

There is no doubt that, as Merrill stated: "Persistent observations, both spectroscopic and photometric, . . . of the brighter symbiotic stars would surely help us understand their mysterious behavior and might develop ideas of considerable general interest." Such investigations would certainly lead to a better understanding of evolutionary trends in stars. In particular the cataclysmic phenomena in stars would become clearer.

I hope that a few young astronomers who have access to a fairly large instrument, such as the Otto Struve Memorial Telescope, will endeavor to continue the investigations which Otto Struve and Paul W. Merrill conducted so brilliantly and which are now rather neglected. What should such a program on SS comprise? We would stress essentially the following points:

(i) light curves in specific wavelengths, either by slitless spectrograms or preferably by narrow-band interference filters or a scanning spectrograph and photoelectric receivers;
(ii) high resolution spectrograms, in order to obtain more accurate profiles, radial velocities and identifications;
(iii) attempts to determine abundances, especially the ratio He/H;
(iv) theoretical and observational study of time lags;
(v) attempt to measure accurately the intensity ratio of $N_{1,2}$;
(vi) make a more detailed observational and theoretical study of the line selectivities.

I do hope that we shall in a few years have a few doctoral theses in this field.

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