51 — SYMBIOSIS IN ASTRONOMY: INTRODUCTORY REPORT

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The biological term *symbiosis* was first applied to astronomical objects, I believe, in a paper I presented before the American Astronomical Society at Yerkes Observatory in 1941. The beginning of the subject, however, lay in the detailed examination of the spectrum of Z Andromedae by H. H. Plaskett.

This star, HD 221650, had long been known at Harvard as an irregular variable with a peculiar spectrum. A note in the Henry Draper Catalogue reads: «The spectrum is very peculiar. On a photograph taken October 17, 1900, the lines Hβ, Hγ, Hδ, Hε, and 4686 are bright.» Plaskett obtained 16 slit spectrograms at the Dominion Astrophysical Observatory, Canada, between 1923 and 1926, and in 1928 he published (1) a comprehensive account of his extensive investigations under the title «The Composite Stellar and Nebular Spectrum of Z Andromedae». He noted the presence of certain emission lines regularly found in planetary nebulae. These require high excitation; but his careful photometric measurements of the energy-curve of the continuous spectrum of Z Andromedae from 3900 to 5100 A yielded the surprisingly low temperature of 5200° K $\pm$ 900°. In 1932 I noticed absorption bands of TiO in the illustrations accompanying Plaskett's paper, and F. S. Hogg (2) confirmed the identification from the original spectrograms. Thus Z Andromedae has become the prototype for those anomalous «symbiotic» stars in which high-excitation emission lines are superposed on a low-temperature absorption spectrum, usually of type M.

In referring to spectra of stars of this kind I have at times used the word *combination* instead of *symbiotic* and have been asked which word I prefer. The usage I prefer is indicated by the statement, «Symbiotic stars yield combination spectra». The word *composite* might conveniently be limited to spectra formed by the addition of light from two nearly normal separate stars which have little if any effect on each other's spectra. This I believe was the original usage by Miss Cannon at Harvard.

Five groups of stars whose spectra show high-excitation emission lines superposed on a low-temperature absorption spectrum are listed, with typical examples, in Table 1. The following discussion relates chiefly to stars in the first group. It might be expedient to reserve the terms *symbiotic* and *combination* for these objects.

Twenty-three stars called «Stars with Combination Spectra» have been listed, with many references, in a valuable catalogue of emission-line objects by W. P. Bidelman ([3]). These appear to correspond to group I of Table 1. Bidelman's descriptive remarks are as follows : «Stars with combination spectra are those whose spectra show simultaneously very high-excitation lines and low-temperature absorption features, but which cannot be considered certain binaries. Some or all may however, be so. A number of these stars show nova-like light-variations». Two fairly bright stars, HD 4174 and RY Scuti, should probably be added to Bidelman's list, and a number of fainter objects have been found by R. Minkowski in his survey for planetary nebulae at Mount Wilson. Because of Bidelman's convenient bibliography, only a few references, most of them recent, are mentioned in the present paper.

TABLE 1

Objects with Late-Type Spectra plus Emission Lines

1. *Symbiotic Stars.* M type + bright H, He I, He II, [O III], [Ne III]

Z And = prototype	T CrB, nova	
AX Per, CI Cyg	HD 4174; var bright H, weak He I, [ ]	Changes not large; stable at times
BF Cyg, RW Hya		
AG Peg = BD + 11°4673	AG Dra = BD + 67°922; G-type + bright H, He I, He II, No [ ]	

II. *M type + Bep*

a) AX Mon = HD 45910; 17 Lep = HD 41511
b) VV Cep = Boss 5650 = HD 208816; [Fe II]

III. *Typical long-period variables*

M, S, (N) types + bright H, metals, [Fe II], AlH.
R Leo M8e; χ Cyg Mpe; R Cyg Se; U Cyg Ne

IV. *Long-period variables with peculiar companions*

o Cet Me } + Bep
R Aqr Me } + Bep; } + Nebular lines
UV Aur Ne } + Nebular lines

V. *Dwarfs; subject to flares*

a) M type + bright H, Ca II. UV Cet dM6e
b) G, K types
  1. Bright H, metals; T Tau dG5e
  2. Wide bright H, Ca II; SS Cyg dG5e
c) G types + corona; sun dG2.

Notes

Double: o Cet, VV Cep	Shell spectra at times
Double ?: R Aqr, AX Mon, T CrB	Z And, BF Cyg, T CrB

(For references to individual stars, see W. P. Bidelman, *Ap. J. Supplement*, **1**, 175, 1954).

Various members of this odd group of stars are by no means identical, individual peculiarities being numerous and sometimes striking; but at the same time the group is bound together by a remarkably similar general pattern of spectroscopic behavior. Hence these intimate associations of features that appear physically inconsistent are probably something more than chance juxtapositions of separate bodies. The comparison with symbiosis, which in biology indicates not casual association but actual dependence or interdependence of dissimilar organisms, while of course general and metaphoric, is nevertheless reasonably valid.

These bizarre objects present challenging problems. In addition to their intrinsic interest as peculiar individuals, there is another reason for studying them. The apparently anomalous phenomena which are so conspicuous and so easily open to study in these stars may perhaps be exaggerated or pathological examples of features which, scarcely noticed, occur in a minor degree in many other stars. Symbiotic stars may thus be strategic objects in which to study phenomena actually of fairly common occurrence. For example it is possible that studies of symbiotic stars may eventually extend our comprehension of phenomena in normal dwarf stars of type G, e.g., the sun with its mysterious corona.

Looking in another direction we may enquire into the relationship between symbiotic stars and planetary nebulae. Planetary nebulae are believed to be relatively impermanent structures; the lifetimes of their visible forms are probably measured in thousands or tens of thousands of years rather than in millions or billions as for stars. W. Liller and L. H. Aller of the University of Michigan have recently discovered that in the small, unusually dense planetary nebula IC 4997 the line 4363 of [O III] has faded noticeably since 1916. Other nebulae should be checked occasionally for possible changes in intensities of their bright lines. Possibly a few objects listed as planetary nebulae are actually symbiotic stars in which the M-type spectrum is relatively inconspicuous. Spectra of nuclei of planetaries should be re-examined for traces of TiO bands.

Features overlooked when presumption is against them can sometimes be detected in a special search.

Is it possible that more extensive observations will tend to fill the gap between symbiotic stars and typical planetary nebulae? May planetary nebulae be regarded as huge stabilized symbiotic stars in which the spectrum is completely dominated by forbidden emission lines and a high-temperature continuous spectrum? Can an object change, in the course of time, from one form to the other? These are questions for the future.

The physical interpretation of symbiotic stars is incomplete. One reason for this is that present observations lack continuity, and the complicated spectral changes have not been recorded in sufficient detail. We do not know with certainty whether the stars are actually binaries. Martin Johnson ([4]) has published a brief survey of the binary hypothesis and the physical problems involved, and has made an interesting suggestion, namely, that in a binary star surrounded by a gaseous ring, instability may arise if a prominence from one star erupts into the ring.

Several astronomers have suggested that in symbiotic objects a hot central star is surrounded by a distant shell which under certain circumstances may produce an M-type absorption spectrum ([5]). P. Swings ([6]) has suggested that symbiotic stars may represent a turning point in the evolution of red giants at which the nucleus contracts and becomes hotter and tends to separate from the relatively cool atmosphere which instead of contracting begins gradually to dissipate into space.

Dr. F. J. M. Stratton, I believe, once made a somewhat similar suggestion concerning R Aquarii except that here the hot star was placed outside. Thus instead of an ordinary binary with a hot star and a cool one side by side, perhaps one star is inside the other.

If we consider the solar corona, these suggestions do not seem too facetious. This possible analogy with the sun and its corona has, in fact, been stressed by at least two writers. L. H. Aller ([7]), thinks that possibly the M-type star «is surrounded by an extended envelope in which the bright lines are excited by the dissipation of shock-wave energy, much as the bright coronal lines are excited in the theory of Schwarzschild.» J. Gauzit (8) «proposes to explain the observations by admitting an M star surrounded by a corona, similar to that of the sun, but a hundred or a thousand times denser and where the physical conditions are often varying, chiefly upon the influence of strong protuberances.»

In the absence of a reliable concept of the constitution of symbiotic stars, what hypotheses or partial deductions can be drawn from observations now on record?

These objects seem to consist of one or two stars immersed in a small, variable planetary nebula. Surprisingly, the system often shows a normal or nearly normal absorption spectrum of type M. Moreover the general rule seems to be that when the object is variable, as most of them are, the fainter the total light the more clearly is the M-type spectrum displayed. When the object is unusually bright, an early-type shell spectrum may become dominant. A very brief descriptive analysis of the three chief phases of combination spectra is offered in Table 2.

TABLE 2

Phases of Combination Spectra

1. M-type absorption spectrum
   Prominent when star is faint
2. A-type absorption shell spectrum
   Prominent when star is bright
3. High-excitation emission lines of variable intensity.
   Superposed on (1); partially quenched by (2).

These circumstances appear to indicate the presence of an M-type star that remains nearly constant while something else varies. The key question then arises: are the conspicuous bright lines which are superposed on the M-type spectrum due to another much hotter companion star or to some unusual physical circumstance arising in the M-type star itself? The answer is uncertain. Martin Johnson ([4]) has generalized the question and has briefly discussed several possible types of interaction between two stars.

Is a fairly normal M-type star immersed in a small, variable planetary nebula? If so, what is the origin of the high excitation required for the bright hydrogen, helium, and nebular lines? Before concluding that a hot companion star is necessary, we should think of the solar corona. Moreover we should recall that long-period variables at certain phases exhibit intense bright lines of hydrogen, and the evidence is strong that these lines are excited

TABLE 3

Periods of Symbiotic Stars

Star	Period			Lag.	Approx. Range In Rad. Vel.	
	Light Days	Rad. Vel. Days	Forb. Days	Forb. — Perm. Fraction of Per.	Perm. km/sec	Forb. km/sec
					Emission	
Z And	714	725±	200	0.28	60	30
AX Per	600-650	880	160	.18	23	40
CI Cyg	—	800-900	200	.2	25	40
RW Hya	370	376?	—	—	40	45
BF Cyg	754	700-800	120	.16	30	60
AG Peg	—	800	120	0.15	40*, 10†	65‡, 10 §
					Absorption	
RW Hya	370	376?	—	—	(12)	—
AG Peg	—	800	—	—	small	—
T CrB	—	230	—	—	42	—
AX Mon	—	232	—	—	104	—

* H
† Fe II
‡ λ 4363
§ λ 5007

internally. A significant difference, however, is that the forbidden lines of combination spectra probably arise in a large volume of gas at a density even lower than that of the tenuous atmospheres of Me variables. Is R Aquarii an intermediate object?

Light-curves of most symbiotic stars are more or less irregular, e.g. Z Andromedae and AX Persei ([9]), but nevertheless some of them exhibit changes in light and also in spectrum which at times appear definitely periodic. Examples derived from the all-too-meager data are collected in Table 3.

Variations in magnitude and in radial velocity frequently appear to have the same periods, but the relationships are not simple or uniform and many more observations are needed. The periods thus far derived for various stars lie between 200 and 900 days, values which might possibly correspond to volume pulsations in large spheres of extremely low density. The large ranges of velocities in some objects, however, would seem unfavorable to this hypothesis. As an alternative working hypothesis we could consider a mechanism involving rotation of an unsymmetrical body or more probably orbital revolution of two bodies. Unfortunately the observational data are too meager to make the kinematic system obvious.

Effects of variations in density (either spatial or with time) are clearly present in the spectra of symbiotic stars and deserve careful attention. The emphasis on this feature by J. Gauzit in his work on AX Persei ([8]) was wholly justified, for studies like his constitute one of our most promising lines of attack. This is true even if certain correlations do not immediately find a simple interpretation. An example is furnished by Gauzit's unexpected conclusion that in AX Persei «the intensity of the lines excited by fluorescence increases when the density decreases, but generally at the same time the ionization goes down.» We must remember that densities and emission intensities of more than one zone are probably involved.

Not only the intensities of various lines but also the observed motions seem to bear some relation to the probable density of the emitting gas. A remarkable feature apparently characteristic of symbiotic stars is the lag of about 0.2 period of the velocity-curve derived from forbidden lines with respect to that from permitted lines. See Table 3. Moreover, ionized metals seem usually to exhibit much smaller fluctuations in velocity than do the gases H, He, N, O, and Ne. Singlet lines of He I, which are favored by low density, may yield velocity-curves which differ appreciably from those based on triplet lines of He I. Forbidden lines of O and Ne yield velocity-curves with amplitudes which are usually greater than those derived from hydrogen lines. In addition the λ5007 line of [O III] may behave differently from λ4363 also of [O III]. It is well known that, because of its lower transition probability, λ5007 requires a lower density (greater mean free time) for its efficient production than does λ4363. These phenomena point strongly to a marked localization of the effective zones of emission of various lines, with density playing an important role.

In AG Pegasi, formerly known as BD + 11°4673, we have in a few decades witnessed the transformation of a Be spectrum into a combination spectrum. Although extraordinary, this performance is not entirely unique; on one occasion Z Andromedae did somewhat the same thing in a few months. Because spectroscopic observations of AG Pegasi are now more extensive than those of any other symbiotic star, it will be interesting to ascertain from future observations whether it can be considered truly typical of the group. Present data seem favorable to this assumption.

Data for AG Pegasi are too extensive and too diverse to be summarized here, but a few significant items may be noted. Dr. H. W. Babcock has kindly permitted me to include in the discussion nearly 20 high-dispersion spectrograms taken by him at Mount Wilson and Palomar since 1950. Data obtained by G. R. and E. M. Burbidge ([10]) from two spectrograms taken in 1953 at the McDonald Observatory agree closely with results from Babcock's plates.

Since 1915, velocities from high-excitation B-type absorption lines have gradually changed from —13 km/sec, a value probably close to the velocity of the system as a whole, to about —200 km/sec. As the negative velocity increased, the symbiotic characteristics became more pronounced. This certainly suggests that a strong outflow of gas from a central region is involved in symbiotic phenomena.

The intense bright hydrogen lines oscillate through a velocity range of about 40 km/sec in a period of 800 days. Occasionally an unsymmetrical line yields an algebraically small velocity as if a component from a jet directed toward the observer were superposed on a broader line in its normal position. This behavior suggests prominence-like action on the side of the star toward the observer. Careful examination with high dispersion of profiles of the stronger emission lines is a promising line of attack.

In recent years the velocity from λ4363 of [O III], a fairly narrow bright line, has varied about 65 km/sec in a well-marked period of 800 days. The lines λ4957 and λ5007 also of [O III] are wider with much flatter profiles and are nearly stationary. Their widths are in fact approximately equal to the width of λ4363 plus its velocity range. Because these lines of [O III] are intrinsically narrow, their observed profiles must be due to the velocity range of the emitting gases. It is therefore a plausible hypothesis that in λ5007 we observe on one spectrogram the whole range of motion in the system, while in λ4363 a certain fraction of the range is decidedly emphasized either because motions in directions with a different projection on the line of sight did not exist when the plate was taken or were blocked off from our view. It is now an easy step to the conclusion that (1) emitting oxygen atoms are moving outward from a small volume relatively near the center of the system; (2) λ4363 comes predominately from an inner zone, while λ5007 comes from a toroidal or spherical shell so extended and so transparent that motions in all directions radial from the center can be observed on a single spectrogram — a type of integration clearly present in spectroscopic observations of novae and of certain planetary nebulae.

We may still have two alternative models to explain how this differentiation of the lines λ4363 and λ5007 can occur.

I. A large sphere of gas alternately expands and contracts about an opaque star at its center. The origin of λ4363 lies so near the star that we see only that half on the side of the star toward us, and hence at any one time a spectrogram registers only half the complete range of motion. The λ5007 line, however, comes from a sphere so large that only an insignificant portion is blocked off by the opaque star, and we see virtually the whole range of radial motion as in the expanding shell of a nova. A simple volume pulsation is unsatisfactory, however, in several respects. It does not account for the observed differences of phase in the velocity-curves from various lines (see Table 3). Secondly, at times of maximum and minimum volume, the whole sphere would be momentarily stationary and all lines narrow; this has not been observed in AG Pegasi. Moreover, unless the nucleus is very massive, it is hard to understand how a huge sphere of tenuous gas could pulsate with velocity changes as large as those observed.

It is possible that this first model could be modified in such a way as to be more acceptable. For example, there might be running waves in the extended atmosphere with differences in phase between different zones and with a considerable range in radial velocity always observable. Or possibly the bright lines originate not in a uniformly pulsating sphere but in fixed or nearly fixed zones through which the observed atoms move alternately outward and inward. This type of motion clearly prevails at high atmospheric levels in shell stars like 48 Librae ([11]), and HD 33232 ([12]) where velocity ranges comparable to those in symbiotic stars occur in periods measured in years. A nearly fixed outer shell, possibly quite extensive, through which gases are moving outward is observed also in giant and supergiant red stars, for example, α Herculis, R Andromedae, α Orionis, and RW Cephei.

II. Another model to be considered is that of a revolving directed stream or jet which discharges continuously, but in ever changing direction, into a nearly circular outer zone. The picture I have in mind resembles that devised by O. Struve ([13]) for the peculiar emission-line variable β Lyrae. If the motions are confined largely to one plane, presumably that of orbital revolution, the observed phenomena would depend on the angle between the plane and the line of sight. If this angle were about 90°, changes in the projected motions would be minor and the objects might appear nearly stable (e.g. HD 4174 and AG Dra = BD + 67°922), although changes in intensity of various features of the spectrum might be caused by irregularities in eruptive action due possibly to varying distance between two bodies in eccentric orbits. In BF Cygni, however, certain very quick changes of intensity of the nebular lines, in intervals of a day or two, where presumably due to changes in the exciting radiation ([14]). From the time required for the disappearance of the [O III] lines, i.e., the time of relaxation, L. H. Aller ([15]) has estimated the lower limit of electron density in the nebular shell to be about 10^6 electrons per cm^3. This is considerably higher than densities in planetary or diffuse nebulae and is more comparable with the densities found in newly formed shells of novae; it may be near the upper limit for intense emission of the observed forbidden lines of oxygen and neon. Lines of [O II] at 3727A are seldom observed in combination spectra; this also indicates a density higher than in most planetary nebulae.

Studies of Zeeman effects in spectra of symbiotic stars may in the future yield important information. H. W. Babcock ([16]) has already found two stars, AG Pegasi and HD 4174, to have variable magnetic fields.

To solve the challenging questions raised by these symbiotic objects, we need series of spectroscopic observations much more extensive and more nearly continuous than any made as yet. To record numerous small details and to measure precise displacements of various groups of lines, higher dispersion, say 10 A/mm, is desirable. But the general spectroscopic behavior and the relative intensities of many key features could be studied satisfactorily with smaller dispersion such as that used effectively by Tcheng Mao-Lin and M. Bloch (17).

L. H. Aller has made a suggestion which I heartily endorse, namely, that important information could be obtained from systematic series of measurements of *absolute* intensities of certain spectral features. This is not easy in observations through a slit, but with normal photometric precautions useful accuracy could doubtless be achieved on slitless spectrograms. Accurate photometric measures of integrated brightness and color also would be highly useful and could easily be made with small telescopes.

Persistent observations, both spectroscopic and photometric, for 5 or 10 years of the brighter symbiotic stars would surely help us understand their mysterious behaviour and might develop ideas of considerable general interest.

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