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ANOMALIES IN THE EARLIEST SPECTRAL TYPES *

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Summary. — *Suggestions for further work on the classification of Wolf-Rayet stars are made, especially in relation with the anomalies presented by certain nuclei of planetary nebulae.*

In the Of-stars, in which the spectra are superpositions of typical absorption O-stars and shell lines, remarkable differences occur in the relative intensities of various shell lines. The relations between X-and Of- stars are discussed.

The peculiar intensities presented by certain transitions of various atoms in anomalous stars of early type are examined. The physical factors (dilution, fluorescence, departure from black body distribution, chemical composition) affecting the relative intensities of various transitions within one atom, and of various atoms relative to each other, are discussed.

General considerations

The spectral classification in types and 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 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 the same 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 realising 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 from time to time.

The factors introducing spectral anomalies are best studied in the case of conspicuously peculiar stars, in which striking departures from thermodynamic equilibrium are observed. In such cases the mechanisms producing ionization and excitation must be examined individually. " By investigating objects in which the peculiar effects are very prominent, we may throw light upon the less conspicuous effects in otherwise normal stars " [1].

My purpose here is to discuss some of the mechanisms affecting the spectral

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classification in the early type stars. However my report could easily be extended to cover the late type objects as well, since similar physical factors are at play in all stellar atmospheres. In the spectroscopic observations of novae — which are not discussed here — essentially identical physical phenomena are also observed.

There will be no discussion of the peculiar A type stars [2], such as the « Silicon Stars », the « Strontium Stars », the « Manganese Stars », the stars with abnormally weak or abnormally strong Ca II, and the spectrum variables especially those rich in rare earths (α^2 Canum Venaticorum) [3]. At least in the case of stars similar to α^2 Canum Venaticorum, anomalies in the abundances or ionization departures from thermodynamic equilibrium do not suffice to explain the observations [4]. An influence of the stellar magnetic field is probable in such cases, but the full implications of the magnetic field can not yet be discussed. Neither shall I discuss the B or A stars which are poor in hydrogen (such as those found recently by Popper and by Bidelman), nor stars such as υ Sagittarii or R Coronae Borealis.

All the objects considered in this report possess extended shells. There is a wide variety of such stellar shells, corresponding to great ranges in conditions of temperature and density, hence of ionization. In many shells, the underlying stars belong to the main sequence ; yet the pressures and thicknesses of the shells suggest structures similar to normal supergiant atmospheres. The understanding of the factors in the shells will thus help in understanding the physics of supergiants.

This report will not be concerned with the relation between the stellar peculiarities and the location of the object (f. ex. in dark clouds). It will not discuss any detail on eclipsing binaries as long as such a detail is not purely spectroscopic.

The Wolf-Rayet Stars

Beals' outstanding contributions to the knowledge of these stars gave rise to the classification in WC and WN stars, officially adopted by the I.A.U. at the 1938 meeting. Recent investigations [5] make it desirable to re-examine this classification. It has been shown recently that C IV [6] is present in early WN-stars, reaching its maximum in WN6, but being still present in WN7. On the other hand, no nitrogen line has been found so far in typical WC stars which are not nuclei of planetary nebulae. Special difficulties arise in the classification of these nuclei for the following reasons :

(*a*) many reveal lines of C, N and O simultaneoulsy, with similar intensities (Ex : nuclei of NGC 6 543, IC 4 997, IC 418) ;

(*b*) the lines are often relatively sharp ;

(*c*) it is often difficult to separate the nuclear and nebular contributions in the H, HeI, HeII and other lines.

The problem of the W.R. stars appears especially important in relation with the sources of energy and evolution. Yet the determinations of relative abundances are extremely uncertain. It seems that the W.R. atmospheres are essentially composed of helium [7] with varying admixtures of other elements. Roughly (ALLER) these admixtures would be of the following order :

in WC stars, He : O = 50 ; He : C = 15 ;
in WN stars, He : N = 20 ; He : C = 300.

For observational as well as theoretical reasons the notion of excitation temperature has also considerable limitation. In fact the figures obtained for the excitation temperature depend on the ionization potential, in the sense that the higher the ionization potential, the higher the excitation temperature. It seems inescapable to admit considerable stratification effects. Moreover the ionization by lines may be important enough to vitiate completely the determinations of Zanstra temperatures.

The electron densities are of the order of 10^{11}-10^{12} per cm^3, i.e. much higher than in envelopes of novae. The background spectrum is sufficiently intense to blot out any possible forbidden line.

The ejection hypothesis has recently been criticized, yet should probably still be retained, although other dynamical factors, such as turbulence and electron scattering accompany probably the ejection.

When a nebula is excited by a nucleus of W. R. type, the ionization in the nebula is due to the far ultraviolet lines as well as to the continuum of the nucleus ; the ionization is also affected by the overlapping regions of photoelectric absorption. The ionization of C^{++} and N^{++} may thus be considerably favored relative to O^{++}. This would explain the strength of C III and N III and the absence of O III in the nebula NGC 6543 [8].

Whenever the visual region of a planetary nebula has been observed, the [N II] lines have been found, even when the nucleus is a WC star (Ex. : BD 30° 3 639, NGC 40, HD 167 362). If the nucleus contains carbon and nitrogen [9], the nebula reveals also [N II]. The association of a WC nucleus and a [N II] nebula may possibly be due to a phenomenon related to the " nitrogen flaring stages " of novae [10].

The classification suggested by BEALS and adopted by the I.A.U. is based on the following criteria of excitation :

(*a*) in the WN stars : N III /He II ; N V /He II and He I /He II ;

(*b*) in the WC stars : C III /C IV ; C III/O V ; C III /He II ; He I /He II and band widths.

It should be noted that, since different relative abundances of C and N have been observed, it is not certain that the relative abundances of C and He, or of N and He, or of C and O are constant for all W.R. stars.

For these reasons, the following suggestions are tentatively made :

1. Continue to use the WN and WC notations whenever the predominance of N or C is definitely ascertained ; in case of simultaneous presence of N and C with similar intensities, simply use the notation W.

2. Devise criteria not involving He I and He II lines for the planetary nuclei, in a way agreeing quantitatively with the presently adopted criteria.

3. Avoid comparisons between intensities of lines belonging to different elements and concentrate as much as possible on different stages of ionization of one element.

The application of these suggestions requires of course further photometric work.

The correlation of band width of certain lines and spectral type, especially in the carbon sequence, has often been emphasized. But here again great caution should be exercised in applying this excitation criterion, which holds only statistically. In some stars intermediate between Wolf-Rayet and Of stars, such as the nucleus of IC 418, which has strong emission lines of N III, C III, and He II, the lines have only a width of 155 km /sec, corresponding to an ejection velocity of the order of 80 km /sec. In W stars of very early type, such as the nucleus of NGC 6 543, the two carbon lines λ 5 801.5 and λ 5 812.1 are very well separated on our spectrograms, whereas the average band width of class WC6 is 70 Å. The nucleus of IC 4 997 has also fairly sharp lines.

Except in rare cases the spectra of planetary nuclei have not exactly the typical W. R. type corresponding to their excitation. R. Minkowski has found a very high ejection velocity in the nucleus of NGC 6 571, but this appears to be an exception. Here are some general indications concerning the best-known nuclei :

IC 418	nucleus intermediate between W and Of, contains N and C
NGC 2 392	nucleus of type Of
NGC 6 543	nucleus containing C and N ; nuclear lines unusually sharp for observed excitation
NGC 6 572	nucleus containing C and N ; lines λλ 4 634, 4 641, 4 650, 4 685 well separated ; width of λ 4 686 only 15 Å
BD + 30° 3 639	lines rather sharp (Pl. VII, a)
NGC 6 826	nucleus containing C and N ; width of λ 4 686 only about 8 Å
IC 4 997	nucleus containing C and N ; lines rather sharp
NGC 40	normal WC8 (Pl. VII, b)
HD 167 362	lines very sharp (Pl. VII, c and d)

On the whole, the planetary nuclei with emission lines seem to have lower ejection velocities than the W objects similar of excitation. Many nuclei have also a pure continuous spectrum.

For the time being it seems desirable to regard the planetary nuclei and the typical W. R. stars as somewhat different types of objects (in size, luminosity and possibly chemical composition).

THE OF-STARS [11]

The spectra of these stars are superpositions of typical spectra of absorption O-stars and of shell lines of high excitation, principally N III, C III and He II ; sometimes also of H, He I, N IV, N V and Si IV. All varieties are observed between pure absorption O-stars and pure WR-stars. A good example of Of-star with strong emission is the nucleus of IC 418 ; a good example of WR-star with strong absorption lines (of He I, C III and C IV) is the WC8 object, HD 164 270. The Of-shells are in general variable ; f. ex. striking variations are observed in HD 108 [12].

There is a wide variety in the relative intensities of the nitrogen and carbon lines. One observes :

(1) Of-shells showing nitrogen lines, but no trace of carbon (Ex. : BD + 35° 3930 N, nucleus of NGC 2 392, HD 152 386) ;

(2) Of-shells showing nitrogen lines and weaker carbon (Ex.: 9 Sagittae, HD 108 in 1941) ;

(3) Of-shells showing N III 4 641 and C III 5 686 of approximately the same intensity (Ex. : HD 151 804, HD 152 408, possibly the nucleus of IC 418) ;

(4) Of-shells in which C III λ 5 686 is much stronger than N III λ 4 641 (Ex.: HD 192 639).

A very striking selection is found among the emission and absorption shell lines observed in Of-stars. The emission lines observed are listed in table 1.

TABLE 1

Emission lines observed in the shell of Of-stars.

ELEMENT	WAVE LENGTHS	NOTATIONS	TERM VALUES (IN VOLTS)
N III	4 634.2-4 640.6	$3p^2P^0$-$3d^2D$	30.3-33.0
N IV	4 057.8	$3p^1P^0$-$3d^1D$	49.9-53.0
N V	4 603-4 619	$3s^2S$-$3p^2P^0$	56.3-59.0
C III	5 696	$3p^1P^0$-$3d^1D$	32.0-34.1
Si IV	4 089-4 116	$4s^2S$-$4p^2P^0$	24.0-27.0
Hα, Hβ	6 563-4 861	$2p^2P^0$-$3,4d^2D$	10.2-12.0 (12.7)
He I	5 876	$2p^3P^0$-$3d^3D$	20.9-23.0
He II	4 686	$3d^2D$-$4f^2F^0$	48.2-50.8

The observed selection has no connection either with the metastability of certain spectral terms or with the excitation potential. This selection decreases when the emission and absorption in the shell increase (f. ex. the selection has almost disappeared in HD 15 2 408 which is closer to the W.R. stars than are HD 151 804, 9 Sagittae,...). The selection has actually disappeared in W.R. atmospheres. As will be seen in a later section the most likely explanation of this phenomenon is a fluorescence excitation.

We may try to determine the ionization in the Of-shells. The electron density is smaller than $N_2 = 1{,}5 \times 10^{13}$ /cm³ which is the figure obtained for the underlying star in 9 Sagittae and HD 152 408 by application of the formula of INGLIS and TELLER to the quantum number n = 22 where the Pickering series of He II terminates. We may adopt $T \simeq 40{,}000^{\circ}$. The geometrical dilution is not very pronounced in Of- or W-stars ; we may try $W = 0.2$. The ionization computed on this basis would be such that recombinations of ions and electrons should be the main source of excitation for the N III and C III emission lines ; in such a case the observed selection could not be explained. It is probable that the ionization is much lower than computed in the assumption of a geometrically diluted black body exciting radiation. The ionization of N^{++} requires $\lambda < 261$ which is not far to the He^{+} ionization limit λ 228. Moreover since the absorption lines of N III are very strong in the underlying star, we may expect that the continuous stellar spectrum is appreciably reduced beyond the ionization limit of N^{++} at λ 261. In other words, the underlying radiation must be depleted between λ 261 and λ 228, and still more beyond λ 228, thus reducing the ionization of N^{++}. Similar considerations may be applied also to C^{++} (ionization limit λ 259) and still more to O^{++} (ionisation limit λ 226, very close to that of He^{+}).

At this stage a short comparison between the ejection velocities of Wolf-Rayet, Of-and P Cygni stars may be interesting. It is often assumed that the lines in P Cygni stars are narrower than in novae and in Wolf-Rayet stars, but there are many cases in which this assumption does not hold. For comparison, here are a few approximate values of the ejection velocities :

P CYGNI STARS

	Km/Sec.
P Cygni	~ 120
BD + 11° 4 673	~ 125
BD + 47° 3 487	~ 180
CD — 27° 11 944	~ 350
ZCMa	~ 350

WOLF-RAYET STARS

BD 30° 3 639	~ 300 (He II)
HD 167 362	~ 185 (C III)

OF-STARS

9 Sagittae	~ 250
BD + 35° 3930 N	~ 300

NOVAE

Very low velocities in Z And, T CBr, RS Oph

The process of ejection of matter if essentially the same in Wolf-Rayet objects, P Cygni stars, Of-Stars, and novae. In all four cases there is a wide range in the velocity of ejection. An Of-star differs from a Wolf-Rayet object in that the ejected layer is optically thin, so that the spectrum of the underlying star itself appears, although encountering continuous and line absorption in the shell ; but for the essential properties (similar excitations, absence of forbidden lines) this thin layer is similar to a Wolf-Rayet envelope. The P Cygni stars have simply a lower excitation. The P Cygni shells may have widely different opacities, so that the underlying star may not be observed (as in P Cygni, CD — 27° 11 944, and many novae) or may partly shine through (as in BD + 47° 3 487,17 Leporis, HD 19 0073, and novae at certain stages) [13]. The P Cygni shells have a wider variety of dilution than the Wolf-Rayet stars ; consequenly, the dilution effects may be more pronounced in the P Cygni stars [14], and some of them present forbidden lines (e.g., BD + 11°4 673, ZCMa, RY Scuti, etc. and novae, e.g. in the η Carinae or RY Scuti stages).

ANOMALOUS INTENSITIES WITHIN THE SPECTRA OF INDIVIDUAL ATOMS ; ANOMALOUS RELATIVE INTENSITIES OF LINES OF DIFFERENT ATOMS

Before discussing systematically the various geometrical, dynamical and physical factors which play an important role in peculiar early type stars, it is of interest to list a few striking anomalies. Whenever their explanation appears reasonably clear, it will be mentioned as a preparation to the later sections. The atoms are listed in the order of their atomic numbers.

Helium II. — λ 4686 ($3d^2D$-$4f^2F^0$) is often present in emission (shell) while λ3 203 ($3d^2D$-$5f^2F^0$) is a strong absorption line (underlying star). There is a possible excitation of He^+ from $n = 2$ to $n = 4$ by Ly_α (λ 1 215.66) which almost coincides with the He II transition λ 1 125.13 ; the $2s^2S$ level of He II is metastable. From $n = 4$ the only observable downward transition would be λ 4686.

Carbon II. — λ 4 267 C II ($3d^2D$-$4f^2F^0$) is very weak in P Cygni and similar stars, while λ 6 578.0-λ 6 582.8 ($3s^2S$-$3p^2P^0$) is quite conspicuous. In normal B stars (absorption) and in late WC stars (emission), λ 4 267 is a very intense line. To determine whether the red emission is abnormally strong relative to λ 4 267 would require photometric measurements. The red doublet is also very intense in absorption in Rigel ; thus the fact that λ 4 267 is usually considered the characteristic stellar line of C II may simply be due to its location in the violet region.

Carbon III. — The $3p^1P^0$-$3d^1D$ line at λ 5 695.8 appears in emission (sometimes, plus absorption, f. ex. in P Cygni) while the $3s^3S$-$3p^3P^0$ group, λλ 4 561, 4 650, 4 647 which is stronger in the laboratory and in WC stars is absent (or in extremely weak absorption). The ground level of C III is a singlet ($2s^1S$), and no intercombination has been found in the laboratory between singlets and triplets (except a doubtful faint one). The line λ 5 696 may thus be excited by absorption of stellar radiation from the ground level of the C^{++} atoms. The excitation of C III 4647 would have to go through the triplet levels.

Nitrogen II. — There is some selection among the N II lines observed in P Cygni or similar stars ; no metastable level is involved ; but the general picture is not quite clear. It seems that the low levels are privileged in shells.

Nitrogen III. — The presence of strong emission at λ 4 634-λ 4 641 ($3p^2P^0$-$3d^2D$) in the shell, while the $3s^2S$-$3p^2P^0$ doublet λ 4 097-λ 4 103 is only present in stellar absorption has already been mentioned.

It seems extremely probable that such a behavior is caused by fluorescence excitation. The absorption of the stellar radiations at λ 374.44 and λ 374.20 by the N^{++} atoms of the shell will bring these to the level $3d^2D$ in one absorption process. According to the general theory of cyclical transitions in a field of diluted radiation [15], there will be a number of downward transitions of longer wavelengths at the expense of λ 374. Especially λ 4 634 and λ 4 640 will be emitted and will lead to the $3p^2P^0$ level. From here a large number of possible upward and downward transitions arise that will reduce the intensity of $3s^2S$-$3p^2P^0$ (λ 4 097 and λ 4 103) relative to λ 4 634 and λ 4 640. On the other hand the odd level $3p^2P^0$ cannot be reached directly by one permitted transition from the ground level $2p^2P^0$. The total emission at λ 4 097 and λ 4 103 may thus be too weak to fill up the absorption lines of the underlying star. Moreover, the lower level $3s^2S$ may itself be populated by absorption of stellar radiations of wavelengths λ 451.87 and λ 452.23.

Since the absorption lines of N III are strong in the spectrum of the underlying star, we may ask whether enough stellar radiation of wavelength λ 374 will reach and excite the N^{++} atoms of the shell, since the lines λ 374.44 and λ 374.20 should be expected to be strong in absorption in the stellar spectrum. But the effect of these absorption lines must be quite minor because of the radial velocities of the ejected atoms of the shell, relative to the stellar reversing layer. Actually, since no fluorescence of BOWENS's type is excited in the O^{++} atoms by the resonance line of He II, we may assume that the differences of radial velocity existing between the different layers of the envelope are sufficient to shift the lines, which would otherwise coincide in wavelengths.

Nitrogen IV. — The line λ 4 057 ($3p^1P^0$-$3d^1D$) appears in emission in 05f shells, whereas λλ 3 479, 3 483 and 3 485 ($3s^3S$-$3p^3P^0$), which are stronger in the laboratory and in ordinary reversing layers, appear only in stellar absorption.

The ground level of N IV is a singlet ($2s^1S_0$) and no intercombination between singlets and triplets is known. A fluorescence excitation similar to that of C III is probably responsible for the observed selection.

Strictly speaking, the populations in the lowest triplet, $2p^3P^0$, of C III and N IV (6.5v. for C III ; 8.3v. for N IV) are quite comparable to the populations in the ground singlet level. Some factor must therefore exist which reduces the excitation to higher triplets, compared with the singlets. There may be more stellar radiation available to ionize the C^{++} or N^{+++} atoms from $2p^3P^0$ level, so that the transitions from $2p^3P^0$ to the ionization continuum may not be neglected.

Oxygen I. — λ 8446 is often observed in emission while λ 7773 is in absorption [16]. This has been explained by BOWEN [17] as a fluorescence effect, the exciting radiation being Ly_β which coincides with an absorption line of O I.

Oxygen III. — As in well known very striking selections are observed in the O III emission when BOWEN's fluorescence mechanism (excitation by λ 303.78 of He II) is operating. In certain shells this mechanism is not present, presumably on acccount of radial velocity effects. For example in the shell of RW Hydrae, the complete O III emission spectrum is observed. The lowest singlet $2p^1D$ of O III is only 2.5 v. higher than the ground term, $2p^3P$. The radiations required to ionize O^{++} from $2p^1D$ are depleted by an amount comparable to $2p^3P$. Moreover, there are strong intercombinations between the singlets and triplets. Hence the fluorescence spectrum excited by the underlying star should be similar to the complete recombination spectrum. For example, it is difficult to ascertain whether the complete spectrum of O III observed in RW Hya is produced by fluorescence or recombination. From the fact that He I is to a considerable extent excited by fluorescence in RW Hya (strong singlets) we may at first sight expect that the O III spectrum is also produced by fluorescence. But this is not necessarily the case. The excitation of the observable O III lines by absorption from the three lowest levels, $2p^3P$, $2p^1S$, and $2p^1D$, requires wavelengths between λ 300 and λ 345 Å [18]. It does not seem plausible to attribute the absence of bright lines of O III in 9 Sagittae to a depletion of the stellar spectrum in the region λλ 300-345. The nearest ionization limit to the red is that of O^+ at λ 353, but the O II absorption lines are very weak in 9 Sagittae. Hence the absence of bright O III lines in 9 Sagittae results probably from the conditions of this particular cycle. As a consequence, it would seem more logical to attribute the O III spectrum of RW Hya to a recombination process.

Mg II. — The absorption line λ 4481 is usually reduced in shells, relative to Fe II, Ni II,... The lower level of λ 4481 is not metastable, while many Fe II and Ni II lines have a lower metastable state. Geometrical dilution enhances these Fe II or Ni II lines relative to that of Mg II.

Ca II. — In many peculiar stars of early type, the $3d^2D$-$4p^2P^0$ triplet (λλ 8498, 8542, 8662) appears in emission [19] while the $4s^2S$-$4p^2P^0$ transition (H and K, λ 3934-λ 3968) is in absorption. A.B. Wyse [20] has tried to attribute this belavior to the fact that 3 d^2D may be depopulated by absorption toward the continuum in preference to absorption toward $4p^2P^0$, hence disturbing the balance. This is due to the fact that L_α (82,257 cm^{-1}) is only slightly superior to the ionization energy from $^2D_{1\frac{1}{2}}$ (82,098 cm^{-1}) and $^2D_{2\frac{1}{2}}$ (82,037 cm^{-1}).

Silicon II. — Striking selections are observed in P Cygni stars. Si II has a very typical behavior in P Cygni stars [21]. The lines arising from the level $4d^2D$ (which can be reached directly from the ground level) are present in the spectrum :

$4p^2P^0 - 4d^2D$: λ 5041 (1 E), λ 5056 (1 E) ;
$4s^2S - 4p^2P^0$: λ 6347 (3 E,OA), λ 6371 (2 E,OA),

while the — usually stronger — doublet λ 4128, λ 4131 ($3d^2D$-$4f^2F^0$) is absent. Such behavior cannot be explained on the basis of the recombination mechanism and must undoubtedly be due to a fluorescence process. In order to excite the $3d^2D$-$4f^2F^0$ lines by absorption of radiation from the ground state $3p^2P^0$, the level $5d^2D$ (nearest to $4f^2F^0$, connected to $3p^2P^0$ and $4f^2F^0$) must be reached. The excitation potential of $5d^2D$ is 13.87 v., which is only slightly more than the ionization potential of hydrogen (13.54 v.). The absence of Si II 4128, 4131 in P Cygni shells would thus indicate that the underlying radiation is appreciably depleted on the short-wavelength side of the Lyman limit. The photospheric temperature obtained for P Cyg by applying ZANSTRA's theory to the H lines is quite satisfactory [22]. This suggests that the hydrogen emission lines are mainly due to the recombination mechanism and that the stellar radiation is appreciably depleted beyond λ 912.

An other feature of Si II is the presence of the group λλ 3853.7-3856.0-3862.6 ($3s\,3p^2\,{}^2D$-$3s^2\,4p^2P^0$) even when λ 4128 and λ 4130 ($3s^2\,3d\,{}^2D$-$3s^2\,4f\,{}^2F^0$) are absent. It should be noticed that the electron configuration of the ${}^2D$ level is $3s\,3p^2$, whereas all the other terms giving strong lines are due to the addition of one excited electron to the closed subshell $3s^2$. The lower level $3s\,3p^2\,{}^2D$, although not really metastable, is connected with the ground level $3s^2 3p\,{}^2P^0$ by a weak transition (weak lines at λ 1817 and λ 1808) ; dilution effects may thus possibly affect the λλ 3853.7-3856.0-3862.6 group.

Silicon III. — Si III reveals very striking selectivities in P Cygni stars. The transitions $4p^1P^0$-$5s^1S$, $4p^1P^0$-$4d^1D$, $4p^3P^0$-$4d^3D$, whose lower levels are $4p^1P^0$ and $4p^3P^0$, appear in emission ; whereas the transitions $4s^1S$-$4p^1P^0$, $4s^3S$-$4p^3P^0$, $3d^3D$-$4p^3P^0$, whose higher levels are $4p^1P^0$ and $4p^3P^0$, are present in absorption only. Such behavior is so similar to that of N III in Of shells that it is plausible to consider it also as a result of cycles. The Si III spectrum presents also a striking similarity to He I. If we refer to Plate XVIII of the paper on P Cygni by STRUVE and ROACH [23], we notice that, whereas the triplet line $4p^3P^0$-$4d^3D$, λ 3806, is strong in absorption in τ Sco and 55 Cyg, the singlet line $4p^1P^0$-$4d^1D$, λ 3590, is extremely weak. The opposite is true for the emission in P Cyg, in which the singlet line λ 3590 is much stronger than the triplet line λ 3806. This is quite similar to the enhancement of the singlet lines relative to the triplets in the case of He I (see a later section, p. 16).

Scandium II, titanium II, vanadium II, chromium II. — These ionized metals react differently to conditions in shells. The dilution effects are probably not of the geometrical type alone. The SAHA and BOLTZMANN formulae, adapted for geometrical dilution, are unable to explain the observations statisfactorily. Examples in which the absorption lines of these ions have been studied are Pleione [24] and 14 Comae [25].

Iron II and nickel II. — In Z Canis Majoris, CD-27°11 944, 17 Leporis, HD 160 529 and other shell stars, the Fe II lines which have the lower level a^6S possess strong absorption components, whereas those which have the lower levels b^4P, b^4F or a^4G are present in emission only. Yet the excitation potentials are very similar, and so are the intensities in the sun or in α Cygni. The Nf-values are also very similar ; according to C. W. ALLEN [26] λ 4 924 and λ 4 352 have the solar equivalent widths 0.131 and 0.124 A and the Log Nf-values 3.14 and 3.13, respectively. The level a^6S has the same multiplicity as the ground level a^6D. The different behavior of the multiplets $a^6S z^6P^0$, z^6F^0, compared with b^4P-z^4D^0, z^4F^0, b^4F-z^4D^0, z^4F^0, and a^4G-z^4F^0, is perhaps a phenomenon similar to the selectivities observed among the lines of Si III, N III, N IV, C III, etc..., in shells of higher excitation. In some of the P Cygni type stars the velocities obtained from the different Fe II multiplets are quite different.

In AX Monocerotis (HD 45 910) STRUVE [27] found that, at one stage of the development of the star, the sharp α Cygni lines are represented (in addition to H) only by Ca II and by a set of strong ultraviolet Ni II-lines. " This prominence of Ni II is unusual and is not duplicated by a similar stage within the sequences of supergiants or main sequence-stars. The Ni II stage of AX Mon may, however, be related to certain stages in the development of the shells of Pleione and 48 Librae ".

There may be a relation between the enhancement of the Fe II-sextets and of the Ni II-lines ; actually, as is shown by the simultaneous appearance of forbidden lines of Fe II and Ni II, these two metallic ions play parallel roles in peculiar stars [28]. The metastability of the lower terms of the observed Ni II lines may possibly resemble the metastability of the Fe II sextet a^6S, more closely than that of the Fe II quartets. The persistence of the Ni II absorption lines in shells would be similar to the presence of absorption lines for the Fe II sextets when the Fe II atoms are in the proper conditions of dilution. In either case a field of dilute radiation would create abnormal overpopulations in the lower levels of the lines considered, as a result of the type of metastability and of the general distribution of the levels.

Iron III. — The Fe III-spectrum shows the dilution effect conspicuously. While the absorption lines of Fe III in normal stars like γ Pegasi show relative intensities similar to those observed in the laboratory, shell stars such as P Cygni , γ Cassiopeae (in 1940) or ζ Tauri show a striking enhancement of the lines whose lower level is one of the metastable terms of the $3d^54s$ configuration. The enhancement of these latter lines gives an estimate of the dilution factor ; in various early-type shells this is in fact the easiest way to ascertain the presence of dilution. For example, λ 4 165 and λ 4 372 (non metastable) are much stronger than λ 4 419 (metastable) in ordinary absorption B stars, whereas the opposite is true in P Cygni or γ Cassiopeae.

GEOMETRICAL, DYNAMICAL AND PHYSICAL FACTORS AFFECTING THE ABSOLUTE AND RELATIVE INTENSITIES OF THE ATOMIC LINES

In the course of the description of the selectivities, in the preceding section, a number of factors have been mentioned. These factors will now be listed together, then discussed individually.

The essential geometrical factor is the geometrical dilution ; the stratification effects will rather be grouped with the physical factors.

Stellar rotation and turbulence are probably closely related to the formation and evolution of shells, but this aspect of the problem ot the peculiar stars will not be considered here. Moreover the dynamical factors play an important role in the fluorescence excitation, on account of the wavelength coincidences which may appear or disappear as a result of radial velocity shifts. Indeed axial rotation should be considered not only as a dynamical agent in the formation of a shell, but also as a mechanism influencing the fluorescence excitation and the expansion which might possibly result from the corresponding radiation pressure [29]. I shall not discuss here the circulation effects of the types observed in β Lyrae and other similar stars [30].

The simple case of purely geometrical dilution is an exception. Usually the exciting radiation will depart from black body radiation, mostly because of the presence of absorption lines or continua, sometimes also on account of the presence of emission lines or continua. I shall designate this departure as " physical dilution ". Fluorescence will often play a significant role. The ionizations will be affected by the intensity distribution within the exciting star. There will also be effects due to stratification in the shells. The excitation potentials will affect the intensities of the emission lines.

The veiling by the shell will have to be considered. The spectral distribution of the continuous opacity in the shell and in the underlying star plays a role also [31].

In the case of binaries in which shell features are observed the nebulous envelope excited by the hot component may influence the cool star.

It is only as a last resort that variations in the relative abundances of the elements should be considered.

When a variation in one or several of these factors occurs the relaxation time has to be considered. In very dilute atmospheres such a relaxation time may be very long, of the order of days or weeks [32].

GEOMETRICAL DILUTION

The general result of the geometrical dilution is the relative enhancement of lines with lower metastable level ; roughly speaking enhancement is understood with the theory of cycles whenever this theory can be applied numerically.

The effect of dilution of the exciting radiation depends not only on the metastability or lifetime of the level considered, but also on many other levels and transitions, including the ionization continuum. The effect may, for example, be entirely different when transitions to or from the ionization continuum are possible (see section on physical dilution).

The atoms which are most characteristic in the case of dilution are He I and Fe III, for which the lines having a lower metastable level may become considerably enhanced [33]. It may even happen that the only strong sharp shell line in the spectrum is λ3 889 He I ($2s^3S$-$3p^3P^0$) ; ex. : HD 172 692 and HD 155 851.

PHYSICAL DILUTION AND RELATED PHENOMENA

The dilution effects considered in the preceding paragraph may be considerably modified by the presence of absorption or emission features in the underlying exciting radiation. In fact, the emission and absorption lines of peculiar early type stars reveal departures from the laboratory intensities which suggest that the various levels are populated by highly selective mechanisms, and not by a process (such as recombination or thermal excitation) permitting the use of a (possibly modified) BOLTZMANN formula.

In one of the preceding sections, the observed selectivities in He I, N III, Si III, etc... have been discussed ; they seem to indicate that the excitation of the anomalous lines is essentially due to a fluorescence mechanism, account being taken of the general properties of the radiation and of the shell : spectral distribution of the exciting radiation, stratification of the layers, velocity and density distribution within the shell. In principle, fluorescence mechanisms may be treated theoretically by the theory of cyclical transitions of ROSSELAND [34] ; however the numerical calculations can seldom be made.

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 states considered. In many shells we can determine the maximum value of the electron density by applying the formula of INGLIS and TELLER on the termination of spectral series ; the maximum densities obtained in this way for nebulae, Of, P Cygni, or Be shells are of the order of 10^{12}-10^{13} electrons per cm^3 [35]. On the other hand, at an electron temperature of 25,000° the critical electron density for which the mean interval between two electron impacts on an atom becomes equal to 10^{-7} seconds, is about 10^{15} electrons per cm^3. Consequently, the densities in Of or P Cygni shells are favorable to fluorescence excitation.

It should be pointed out that the exciting radiation reaching an atom A at a specific location in the shell is usually different from the black-body radiation at the effective stellar temperature T_e, reduced by a geometrical dilution factor W independent of λ. Even if the photospheric radiation is that of a black body at a temperature T_e, the radiation reaching A will usually be depleted by discrete or continuous absorption features or will be enhanced by emission features. For example, strong Lyman absorption lines in an underlying star should strongly affect the intensities of the Balmer lines excited by fluorescence in an outer stationary shell. In HD 190 073, Struve [36] finds intense metallic emission combined with weak shell lines of H : the straightforward explanation is found in the presence of Lyman absorption, discrete and continuous, in the underlying star.

A comparison with the classical laboratory experiments on atomic and molecular fluorescence is useful. The fluorescence of any atomic or molecular vapor excited in the laboratory by continuous " white light " is totally different from that excited monochromatically. 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 [37]. Similar considerations should be applied to atomic ionization and molecular dissociation.

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

The relative efficiency of the recombination and fluorescence mechanisms may be stated as follows: As a first approximation, the probability of the capture of an electron by an ion A^+ (recombination mechanism) is proportonal to $p(A^+) \times p_e$, if p designates the density. If collisions of the second kind are absent, the probability of the fluorescence excitation of a specific line is proportional to $p(A)I$, if I is the amount of exciting radiation in the appropriate wavelengths required for the excitation of the line. For example, in the case of the bright lines of He I, the relative efficiency of the recombination and fluorescence mechanisms is proportional to

$$\frac{p(\mathrm{He}^+) \times p_e}{p(\mathrm{He})} \times \frac{1}{I}.$$

For a given density, $p(\mathrm{He}^+)/p(\mathrm{He})$ and p_e depend upon the amounts of radiation available beyond the ionization limit of He I and beyond the Lyman limit, respectively. I depends in a complicated manner on the spectral distribution of the exciting radiation, account being taken of the relative velccities of the excited atoms with respect to the regions emitting the exciting radiation.

One of the most intriguing problems in relation with fluorescence is that of He I. In the laboratory or in normal stellar absorption, the triplets are always much stronger than the singlets, which is simply a question of statistical weights. Geometrical dilution still tends to increase the populations of the triplet levels at the expense of the populations of the singlet levels. However in many peculiar bright line stars, such as RW Hydrae, T Coronae Borealis, AX Persei, AG Pegasi, Z Andromedae and P Cygni, the He I singlets are definitely stronger than the triplets, This appears especially when comparing the $2p^1P^0$-nd^1D and $2p^3P^0$-$nd\ ^3D$ series, f. ex. λ 4 388 ($2p^1P^0$-$5d^1D$) and λ 4 026 ($2p^3P^0$-$5d^3D$). In variable objects such as AX Per or Z And, the intensity ratio singlets/triplets varies considerably.

Fluorescence excitation of He I will have a tendency to enhance the singlet system relative to the triplet system [38], since the ground level of He I is $1s^1S$, since the lowest triplet level $2s^3S$ corresponds to a high-excitation potential (19.74 v.), since there are no intercombinations between singlets and triplets, and since collisions are negligible. The exciting wavelength range is approximately λ 500-λ580. The observation of strong singlets still requires that the ionization of He I is considerably reduced [39].

Generally speaking, the relative emission intensities of the singlets and triplets of He I will give us some indication concerning the relative importance of excitation by electron captures or by absorption of underlying radiation. In objects of high excitation, like nebulae, Cl Cygni, RX Puppis, etc., the He I singlets are much fainter than the triplets. In these objects most of the He atoms are in the He^+ and He^{++} states, so that the recombination mechanism may be important. Conversely, objects of relatively low excitation, such as TCBr, RW Hya, AG Peg, P Cyg and the stars AX Per, RS Oph and Z And at low excitation stages, will be rich in neutral helium; the fluorescence excitation of these He I atoms will enhance the singlets relative to the triplets. Variations in the intensity ratio singlets/triplets are directly correlated with changes in the relative contributions of the recombination and fluorescence mechanisms.

In applying these considerations, care must be taken not to overlook the stratification effects, somewhat along the line of Strömgren's hydrogen zones. Around a hot star there may be a small zone where He is doubly ionized, followed by one in which He is singly ionized, while He remains neutral on the outskirts where the incident radiation has practically no energy beyond λ 504. In the He^{++} region recombination will give the He II spectrum. In the He^+ region we may have the fluorescence emission of λ4 686 He II and the recombination spectrum of He I (with triplets stronger than singlets). In the He region, fluorescence would predominate. The extensions of these regions depend on the spectral distribution of the exciting radiation. The relative intensities of He II, λ4 686, He I triplets and He I singlets will depend on the relative efficiencies of the different mechanisms.

Since fluorescence excitation depends on wavelength coincidences it depends on the velocity distribution within the shell. This has already been illustrated in the case of N III in the descriptive section on anomalous intensities. The absence of Bowen's fluorescence mechanism on O III in W.R. stars is also probably a result of velocity effects.

The absorption coefficient of an atom for radiation coinciding with one of its transitions leading to the ground level is very much larger than the photoelectric absorption coefficient for radiation having a wavelength shorter than the ionization limit. For this reason Bowen's fluorescence mechanism-excitation of O III by the resonance line He II 304 and subsequent excitation of N III by the resonance line O III 374-plays a very important role in nebulae and other similar objects. Yet this type of excitation is not observed in ordinary Wolf-Rayet envelopes, which do not reveal an appreciable enhancement of the incomplete multiplets excited by He II. Actually, O III is always very weak or absent in the WN stars ; it is strong in WC stars but does not show any selectivity, so that there is no reason to make a difference between the excitation of O III and that of O II or O IV. The absence of Bowen's fluorescence is due to the velocities of the radially ejected atoms. The O^{++} atoms located at a specific place in the Wolf-Rayet shell are able to absorb the resonance radiation of only a small fraction of ejected He^{+} atoms, since these must have a definite radial velocity with respect to the O^{++} atoms condidered. In various objects, bright He II lines are observed, whereas the fluorescence multiplets of O III and N III are not enhanced. In the WC nucleus of BD + 30°3 639, He II 4 686 is present, yet λ 3 444 and λ 3 760 of O III are not enhanced ; the same is true for the similar object HD 167 362. No Bowen fluorescence is observed in RW Hya or in the deep layers of Wolf-Rayet type of Z And. In the nebula NGC 6 543, N III is not excited by Bowen's mechanism. In other objects, like T CBr, AX Per [40], CI Cyg, RX Pup, the incomplete multiplets of O III and N III are prominent : in all these cases the ejection velocity is extremely small, and the situation is very similar to the planetaries.

Since the fluorescence excitation in the shell depends on the velocities of the atoms, different shell lines of a specified atom (also lines belonging to different atoms) may give different profiles and radial velocities, both of the absorption and of the emission components. Actually the physical interpretation of the profiles and of the measured line displacements in peculiar stars is a matter of extreme complexity. For example, the radial velocities of the He I triplets may differ from those of the singlets.

In a previous section the anomalies observed in Ca II have been related to a possible depopulation of the lower level by excessive ionization, such a mechanism stimulating the emission of a line. We may also envisage that depopulation of the upper level by cyclical processes sustained by coincidences may result in the production of a stronger absorption line. This should be kept in mind when trying to interpret abnormally strong absorption lines.

Stratification effects seem an inescapable conclusion in a number of observations : line widths and intensities (hence excitation temperatures) in W.R. stars ; systematic differences in radial velocity in P Cygni stars ; differences in dilution effect ; different line widths in rotating shells ; different intensity ratios of emission and absorption components, etc... However care should be exercised, and the stratification effects should not be invoked generally ! The simultaneous appearance of strong [Fe II] and [Fe VII] lines in Z And, AX Per or CI Cyg, while intermediate stages of ionization are absent or weak, has often been interpreted as meaning that [Fe II] and [Fe VII] are excited in entirely different regions of the objects. This is not necessarily required, since such an intensity distribution among the different ionization stages of iron may also result from the spectral characteristics of the exciting radiation combined with the transition probabilities of the lines considered [41].

The intensities of the permitted emission lines observed in Be-stars vary with excitation potential in a manner corresponding to a fairly low excitation temperature [42], say of the order of 5 000°. This appears strikingly in the case of the emission lines of Fe II which decrease in intensity much more steeply than the corresponding absorption lines in α Cygni or than the laboratory lines. It is far from certain that a true Boltzmann distribution is present.

The continuous absorption of shells in the visual region differs widely in different objects. The opacity of the shell may be very low as in α Cygni or β Orionis, or very high (underlying star invisible) as in P Cygni or in CD-27°11 944.

Peculiar spectral distributions of the continuous opacity would give rise to anomalous line intensities. However such distributions are not known in early type stars. The opposite is true in the case of late type stars [43].

In binaries consisting of a hot and a cold components in which a gaseous envelope is observed, the envelope is excited by the hot companion. In turn the envelope affects the ionization and the excitation of atoms in the cool star's atmosphere. If H_α is strong in the shell, Ly_α must also be strong (excited by the hot component, even if the latter is invisible). This point of view has recently been emphasized by J.L. GREENSTEIN and W.S. ADAMS [44] in the case of υ Sagittarii (however the presence of a hot companion in this case is still hypothetical). It may happen that the star which we observe is surrounded by a source of ultraviolet radiation corresponding to a high temperature, which governs the excitation and ionization of the high temperature elements of the cool star.

ABUNDANCES OF THE ELEMENTS

Differences in relative abundances of the elements should be considered only as a last resort. In fact, great caution is required when trying to estimate the abundances of elements in peculiar stars, including novae. This is especially true for the emission lines of C, N and O, which in recent years have often been considered in relation with the energy generation. We have seen that even in the case of absorption lines, anomalies may be produced by physical agents such as fluorescence or dilution, combined with mechanical agents such as ejection, rotation or turbulence.

It is obvious that spectral peculiarities are not necessarily due to true differences of abundances. In the preceding section the work of Greenstein and Adams on υ Sagittarii has been mentioned in this connection : the observed anomalies among line intensities may possibly be due to the excitation by the surrounding nebulous envelope, instead of being caused by abnormal abundances.

Yet, all factors considered, there does not seem a possibility of escape to the conclusion that the abundance ratio C/N is different in various W-or O-stars ; also that the abundance ot hydrogen may vary within wide limits. However, so many factors may be at play, including stratification, radiation pressure, magnetic field, etc..., that there is no certainty of a relation of the observation of differences in abundances with the nuclear transformations.

Most of the results discussed in this report have been obtained in collaboration with O. Struve.

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[1] O. Struve, *Ap. J.*, **95**, 134 (1942).

[2] O. Struve and P. Swings, *Observatory*, **64**, 291 (1942).

[3] O. Struve and P. Swings, *Ap. J.*, **98**, 361 (1943).

[4] P. Swings, *Ap. J.*, **100**, 73 (1944).

[5] C. S. Beals, *J. R. A. S.* Canada, **34**, 169 (1940) ; *Observatory*, **64**, 42 (1941) ;
O. C. Wilson, *Ap. J.*, **91**, 379 and 394 (1940) ;
P. Swings, *Ap. J.*, **95**, 112 (1942) ;
L. H. Aller, *Ap. J.*, **97**, 135 (1943).

[6] C. IV doublet $3s^2S$ — $3p^2P^0$, at λ 5 801.5 — λ 5 812.1 ; excitation potential of $3p^2P^0$, 39.5 v.

[7] The lack of hydrogen sets these stars apart from all other stars, except the supernovae ; in certain W. R. stars, hydrogen and helium seem to be equally abundant.

[8] P. Swings, *Ap. J.*, **92**, 289 (1940) and **95**, 133 (1942).

[9] To my knowledge, no planetary nucleus of WR type can at present be attributed to the nitrogen sequence. The only exception may be the nucleus of NGC 2 392, in which Wright observed bright N III lines and in which Swings and Struve found also weak N V. But this star is essentially an Of-star and the emission is not the essential feature.

[10] For a discussion, see Swings and Struve, *Ap. J.*, **97**, 225 (1943).

[11] The suffix ***f*** used by the Victoria observers refers to the emission at λλ 4 634, 4 640 and 4 686.

[12] P. Swings and O. Struve, *Pub. A. S. P.*, **53**, 35 (1941) ; *Ap. J.*, **96**, 259 (1942).

[13] All the dilution effects observed at certain stages of novae have their equivalent among the P Cygni, Of, or Wolf-Rayet stars.

[14] As was mentioned before, the dilution effects on absorption lines are greater for lower temperatures.

[15] The dilution factor is of the order of 0.1 in the Of shells.

[16] W. A. Hiltner, *Ap. J.*, **105**, 212 (1947) ; the presence of the O I lines in absorption (high excitation) in the late type spectrum of VV Cephei has been discussed by Keenan and Hynek (*Ap. J.*, **101**, 270 (1945) ; **105**, 500 (1947).

[17] I. S. Bowen, *Pub. A. S. P.*, **59**, 196 (1947).

[18] See the Grotrian diagram of the O III spectrum in Edlén's thesis, pp. 122 and 123, Upsala (1934).

[19] See, f. ex., W. A. Hiltner, *Ap. J.*, **105**, 212 (1947). The first observation of this kind was made by Merrill in long period variables. The infrared triplet was found in emission in υ Sagittarii by Weaver.

[20] *Pub. A. S. P.*, **53**, 184 (1941).

[21] C. S. Beals, *M. N.*, **95**, 581 (1935) ; P. W. Merrill, *Ap. J.* **95**, 386 (1942) (AG Peg).

[22] C. S. Beals, *M. N.*, **92**, 677 (1932).

[23] *Ap. J.*, **90**, 727 (1939) (plate facing, p. 751).

[24] O. Struve and P. Swings, *Ap. J.*, **93**, 446 (1941).

[25] P. Swings and O. Struve, *Ap. J.*, **94**, 291 (1941).

[26] *Mem. Commonwealth Solar Obs.*, Canberra, **5**, Part II, 91 (1934).

[27] *Ap. J.*, **98**, 212 (1943).

[28] As do the higher ionization stages in the solar corona.

[29] P. Swings and O. Struve, *Ap. J.*, **97**, 223 (1943).

[30] When expanding motions exist, their sources may be located at a low level (O. Struve, *Ap. J.*, **98**, 212 (1943)). In HD 45 910 the doubling of the H absorption lines was accompanied by a similar doubling of the sharp Ca II and Ni II lines, and of the rotationally broadened He I- lines. The surges of outflowing gas embrace all layers of the shell, from the one where He I is produced to the one where H originates.

[31] Evidently the interstellar reddening will also affect the relative intensities of different emission lines of the same atom. For example, the intensity ratio of the two [Fe III] lines, λ 5 270 and λ 4 658, may be affected by the interstellar reddening to a considerable extent.

[32] As an example, see the case of Z Andromedae (P. Swings and O. Struve, *Ap. J.*, **93**, 356 (1941).

[33] The effect depends on the temperature as well as on the dilution factor.

[34] *Ap. J.*, **63**, 218 (1926).

[35] See sec. I ; Also, *Ap. J.*, **95**, 124 (1942).

[36] *Pub. A. S. P.*, **54** (1942).

[37] 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 (Swings, *Lick Obs. Bull.*, **19**, 131 (1941)).

[38] For a detailed discussion, see : P. Swings and O. Struve, *Ap. J.*, **96**, 262 (1942).

[39] O. Struve, *Rev. Mod. Phys.*, **16**, 286 (1944).

[40] In AX Per the intensity of O III 3 444 (fluor) is highly variable (See Sec. I).

[41] I. S. Bowen and P. Swings, *Ap. J.*, **105**, 92 (1947).

[42] P. Swings and O. Struve, *Ap. J.*, **97**, 206 (1943).

[43] See the explanation of the intensity of the red CN bands in carbon stars, relative to the blue bands (A. S. King and P. Swings, *Ap. J.*, **101**, 1 (1945).

[44] *Ap. J.*, **106**, 339 (1947).

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