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PHYSICAL CONDITIONS IN WOLF-RAYET ATMOSPHERES*

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Abstract

A critical discussion of present-day knowledge regarding the Wolf-Rayet atmosphere is presented. It is shown that the large widths usually ascribed to the emission lines are formed by heavy blending, and that the individual components are in many cases seen distinctly on high dispersion coude spectra. Arguments are given to show that the single stars alone do not yield observational information of the exact dynamical conditions in the atmosphere.

The results obtained from the binary systems V444 Cygni and CQ Cephei are discussed. The widening of the He II 4686 profiles is ascribed to the 'stream motion' around the stars as well as electron scattering. The results of monochromatic light curves of CQ Cephei are shown to be explained satisfactorily by a 'common envelope' model.

The suggestion by Johnson (1954), that a large scale operation of the Giovanelli mechanism of solar flares is responsible for Wolf-Rayet emission, is critically examined. Self-reversal effects should be conspicuous in such a picture, and these are rare in Wolf-Rayet stars.

The existence of the WC and WN sequences is discussed on the basis of anomalous abundances. These may have originated as a result of nuclear reactions coupled with good mixing. It is suggested that any satisfactory theory of the formation of WN and WC sequences will have to explain the negligible amount of oxygen found in the WN stars.

Numerous investigations carried out during the last decade have added materially to our knowledge concerning the Wolf-Rayet atmosphere. We have at our disposal many independent facts of observation that suggest the classical Beals' model to be over-simplified in its approach to what actually constitutes a Wolf-Rayet star. The stage is set, wherein we can evaluate concisely our methods of analysis and choose the best possible avenues of approach, as we see today, which might successfully elucidate the problem.

In 1938 the I.A.U. adopted Beals' classification of Wolf-Rayet stars into two sequences, a pure nitrogen sequence and a carbon sequence having no traces of nitrogen. In 1942 Swings and independently Aller showed that the line at 5805A in nitrogen stars must be attributed to the $3s^2S$–$3p^2P^\circ$ transition of C IV. Other doublets of C IV that possess a much higher excitation potential and higher n-values are $5g^2G^\circ$–$6h^2H$ at 4658·64A and $5f^2F^\circ-6g^2G^\circ$ at 4656·5A. In nitrogen stars these lines fall in between the emission lines of He II 4686 and N III 4640, making their detection difficult. Plaskett measured two maxima in the broad band near 4640A, one at 4631A and the other at 4652A. This observation remained doubtful because of the difficulty involved in the measurements. However, using low dispersion spectra obtained with the Harvard 61 inch reflector, I have measured (Bappu, 1951*b*) in HD 190918 a line at 4658·32A which can probably be identified with the $5g^2G^\circ$–$6h^2H$ transition of C IV. The 4058A line attributed by Beals to N IV was found to be split into three components at 4044A, 4057A and 4066A. The 4066A line arises from the $4C^3F^\circ$–5^3G transition of C III. A puzzling feature is the complete absence in nitrogen stars observed in the northern hemisphere of the line 5696A ($3p^1P^\circ$–$3d^1D$) which is exceedingly strong in the WC stars. Numerous other lines having the same excitation potential as 5696A can be seen. Miss Underhill (1955) has discovered recently that the line is prone to appear in emission in several Of stars. Its absence from the WN sequence becomes all the

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* The observational data discussed in this paper were obtained at the Mount Wilson and Palomar Observatories.

more conspicuous. In carbon stars the C III 5696A line in HD 192641 is found to be flanked on the short wave-length side at 5681A by an emission line identified as the $3s^3P^\circ$–$3P^3D$ transition of N II. The splitting of 5696A can be seen very clearly on coude spectra taken with the 100 and 200 inch telescopes of the Mount Wilson and Palomar Observatories. These high dispersion spectra, taken with the highest resolution available for the study of stellar spectra, reveal the 5015A line of He I to be blended with 5010A of N II. The other transitions of N II cannot be easily detected consequent to the heavy blending in those wave-length regions where they occur.

A search for oxygen lines in HD 192163 revealed the presence of a weak line at 5470A which presumably is the $3p^3P$-$3p^3D^\circ$ transition of O V seen in the WC stars.

The detection of weak N II in the carbon stars and of oxygen in the nitrogen stars proves the non-existence of a completely pure carbon sequence, although it is obvious that the intensities of the observed lines of carbon, nitrogen and oxygen in both sequences do not suggest that the relative abundances of the elements in these stellar atmospheres are similar to that observed in normal stars. We shall treat this problem later.

The above considerations clearly point out that considerable 'fine structure' exists in most of the emission lines found in Wolf-Rayet spectra. High dispersion with good resolving power should in most cases unravel the blending. Neglect of the individual contributions by the different components will give spurious values of width for the entire emission band. Since the dynamical parameters of Wolf-Rayet atmospheres are usually inferred from the widths of the emission lines, considerable care has to be exercised in assigning a width to a line resulting from any particular transition. The profiles of N IV 4058A in HD 191765 and C III 5696A in HD 192641 as seen in Fig. 1 demonstrate the validity of this precaution.

The correlation between band width and ionization potential found by Beals, and used so far as proof that the excitation originates by the operation of the Zanstra-Menzel mechanism, should therefore be reconsidered on the basis of new measurements of band widths where the blended components have been separated. I have hopes that the investigation of high dispersion coude spectra, now in progress at Naini Tal, should clarify the matter greatly.

A necessary consequence of the simple expanding shell is the occurrence of flat-topped profiles for the emission lines. The 5696A and 4058A lines in certain carbon and nitrogen stars have been found to possess such profiles and on this basis the success of the theoretical model seemed assured. On high dispersion plates no exact flat-topped structure for these bands can be seen; on the other hand it shows clearly that the final shape of the band is the result of the blending of the individual components.

Wilson (1942) was the first to question the validity of Beals' expanding shell hypothesis since the 'transit-time effect' that he predicted on the basis of this model for eclipsing binaries could not be detected in the binary system V444 Cygni.

The absence of the 'transit-time effect' and of a flat-topped structure for the emission lines cannot be taken, however, as definite proof of failure of the expanding shell model. If a range in ejection velocities exists, the extent of the flat tops will be defined by the lower limit of the velocities (Bappu and Menzel, 1954). If this value is sufficiently low, we can hardly observe it.

We are at an impasse in our efforts to unravel the actual dynamical conditions prevalent in the Wolf-Rayet atmosphere from the detailed studies of a single star. An alternative approach has to be found if we are to make headway. The binaries, at present, seem to offer the best means for such an approach.

The non-dependence of form of light curve on wave-length found in the eclipsing Wolf-Rayet system V444 Cygni is typically characteristic of electron scattering, as shown by Kopal and Mrs. Shapley (1946). Additional evidence of the correctness of this approach has come from the study by Munch, of the change in the profiles

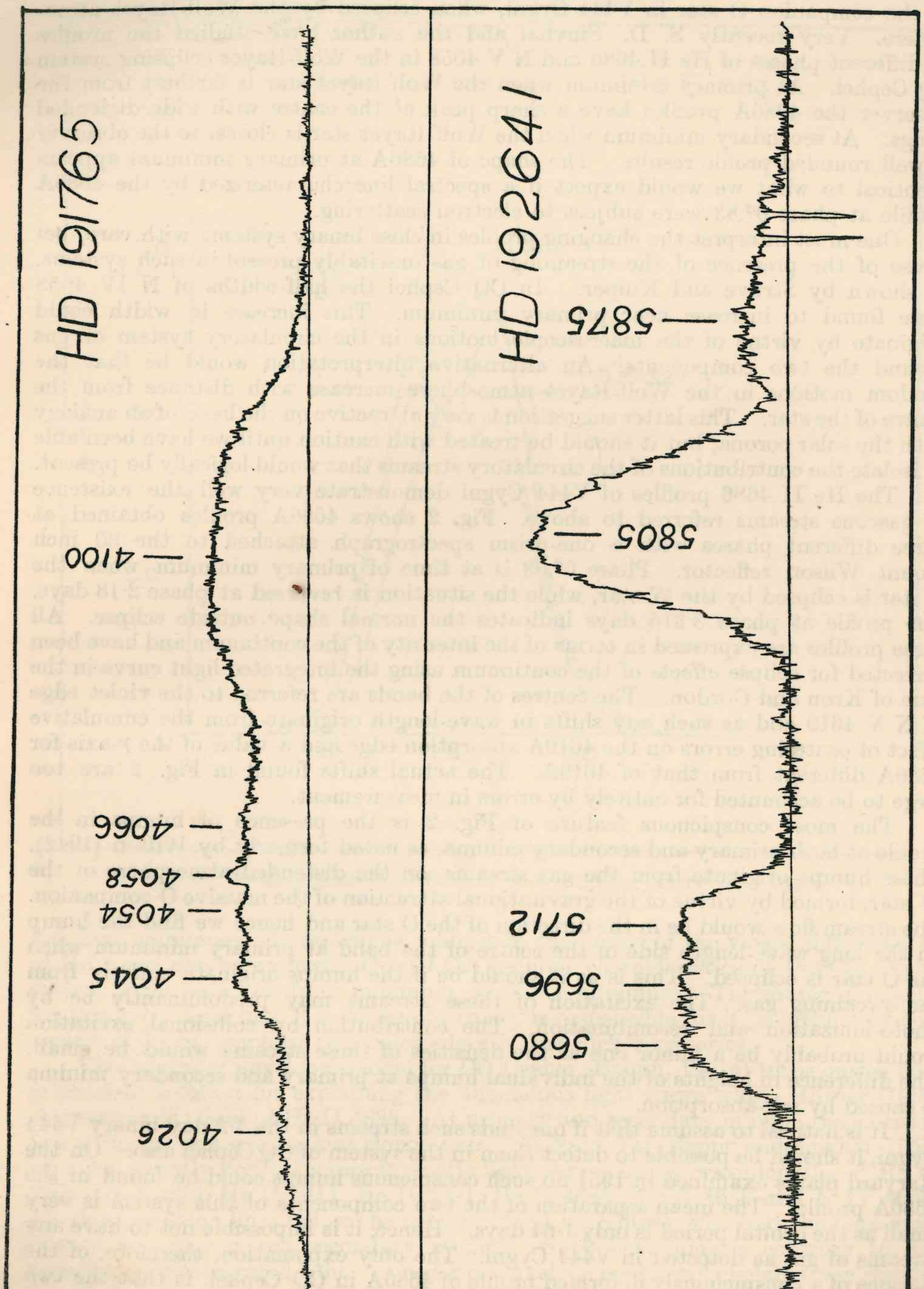

FIG. 1. Microphotometer tracings of the 4058A and 5696A regions in the spectra of HD 191765 and HD 192641.

of the companion O star in V444 Cygni, when eclipsed by the Wolf-Rayet atmosphere. Very recently S. D. Sinvhal and the author have studied the profiles at different phases of He II 4686 and N V 4058 in the Wolf-Rayet eclipsing system CQ Cephei. At primary minimum when the Wolf-Rayet star is farthest from the observer the 4686A profiles have a sharp peak at the centre with wide distended wings. At secondary minimum when the Wolf-Rayet star is closest to the observer a well rounded profile results. The shape of 4686A at primary minimum appears identical to what we would expect if a spectral line characterized by the 4686A profile at phase $0^d.83$ were subject to electron scattering.

One must interpret the changing profiles in close binary systems with care, because of the presence of the streaming of gas inevitably present in such systems, as shown by Struve and Kuiper. In CQ Cephei the half-widths of N IV 4058 were found to increase near primary minimum. This increase in width could originate by virtue of the macroscopic motions in the circulatory system of gas around the two components. An alternative interpretation would be that the random motions in the Wolf-Rayet atmosphere increase with distance from the centre of the star. This latter suggestion is very attractive on the basis of an analogy with the solar corona, but it should be treated with caution until we have been able to isolate the contributions of the circulatory streams that would logically be present.

The He II 4686 profiles of V444 Cygni demonstrate very well the existence of gaseous streams referred to above. Fig. 2 shows 4686A profiles obtained at three different phases with a one-prism spectrograph attached to the 60 inch Mount Wilson reflector. Phase $0^d.03$ is at time of primary minimum when the O star is eclipsed by the W star, while the situation is reversed at phase 2·18 days. The profile at phase 3·315 days indicates the normal shape outside eclipse. All three profiles are expressed in terms of the intensity of the continuum and have been corrected for eclipse effects of the continuum using the integrated light curve in the blue of Kron and Gordon. The centres of the bands are referred to the violet edge of N V 4619 and as such any shifts in wave-length originate from the cumulative effect of centering errors on the 4619A absorption edge and a value of the γ-axis for 4686A different from that of 4619A. The actual shifts found in Fig. 2 are too large to be accounted for entirely by errors in measurement.

The most conspicuous feature of Fig. 2 is the presence of humps in the profile at both primary and secondary minima, as noted formerly by Wilson (1942). These humps originate from the gas streams, on the distended atmosphere of the W star, formed by virtue of the gravitational attraction of the massive O companion. The stream flow would be in the direction of the O star and hence we find the hump on the long wave-length side of the centre of the band at primary minimum when the O star is eclipsed. This is as it should be if the humps originate entirely from the streaming gas. The excitation of these streams may predominantly be by photo-ionization and recombination. The contribution by collisional excitation would probably be a minor one as the densities of these streams would be small. The difference in heights of the individual humps at primary and secondary minima is caused by self-absorption.

It is natural to assume that if one finds such streams in the 4·2 day binary V444 Cygni, it should be possible to detect them in the system of CQ Cephei also. On the Harvard plates examined in 1951 no such conspicuous humps could be found in the 4686A profile. The mean separation of the two components of this system is very small as the orbital period is only 1·64 days. Hence, it is impossible not to have any streams of gas as detected in V444 Cygni. The only explanation, therefore, of the absence of a conspicuously deformed profile of 4686A in CQ Cephei, is that the two components are so close to each other that the stream motion now assumes the form of a common envelope which surrounds the system.

The helium lines of the Pickering series develop violet edges near eclipse and these persist all along that portion of the light curve which corresponds to a

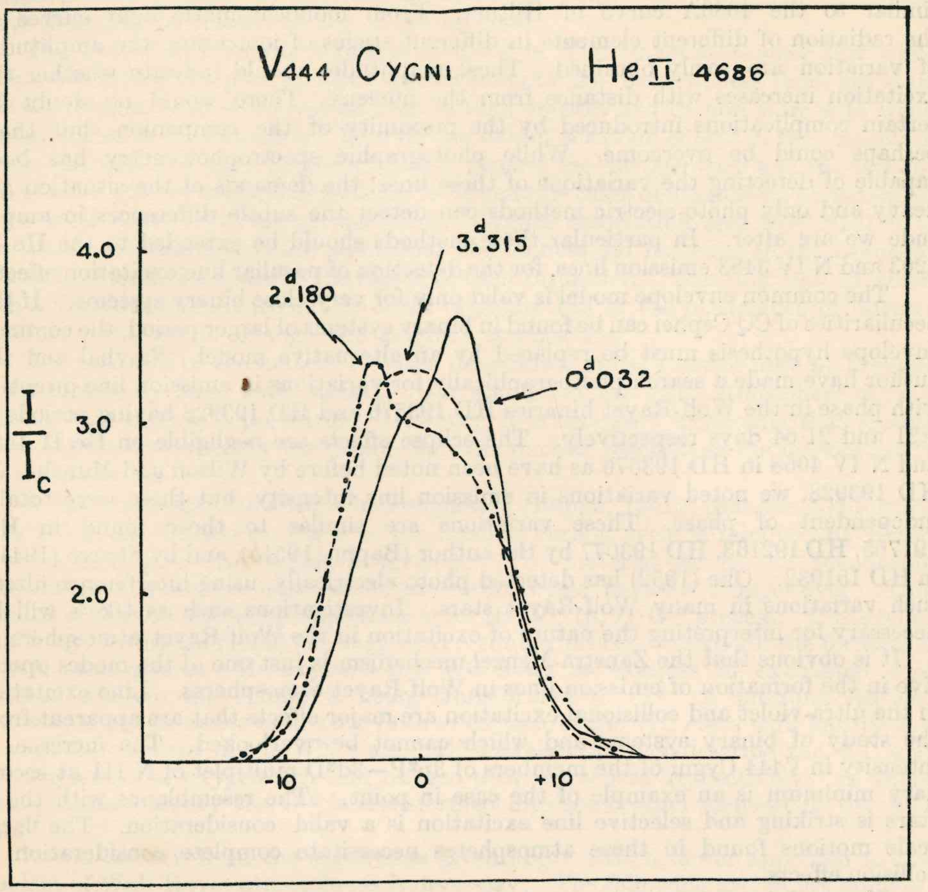

FIG. 2. Profiles of He II 4686 in the W-R eclipsing binary V444 Cygni.

rise from minimum. Conspicuous changes in the profile of the violet edge of 4471A of He I can also be noticed. One of the peculiar characteristics of the CQ Cephei system is the slow rise from minimum, at either minimum. The source of opacity for this extra light loss, if a source of opacity is responsible for it, is intimately connected with the origin of the violet edges of the Pickering series.

The 'common envelope' model for CQ Cephei (Bappu, 1951*a*) turns out to be a convenient solution for explaining the anomalous light curve which Hiltner (1950) obtained in the light of He II 4686. At primary and secondary minima the emission was strongest and was weak at elongations. At Naini Tal (Bappu and Sinvhal, 1955) we have recently derived monochromatic light curves in the wave-lengths of He II 6560, He I 5875, He II 5411, He II 4861, He II 4686, N III 4630 and N IV 4058. All these emission lines follow the pattern found by Hiltner, viz. that they are most intense at primary and secondary minima. Such behaviour is contrary to our experiences in integrated light. A common envelope model will explain these results, for, if the emission arose in the common shell, a larger portion of it would be occulted during elongations than during conjunctions.

Let us assume tentatively that the 'common envelope' hypothesis represents the working of the CQ Cephei system. The methods of photographic spectrophotometry have demonstrated that all the emission lines studied vary in intensity similar to the 4686A curve of Hiltner. From monochromatic light curves of the radiation of different elements in different stages of ionization, the amplitudes of variation are easily obtained. These amplitudes should indicate whether the excitation increases with distance from the nucleus. There would no doubt be certain complications introduced by the proximity of the companion, but these perhaps could be overcome. While photographic spectrophotometry has been capable of detecting the variations of these lines, the demands of the situation are heavy and only photo-electric methods can detect the subtle differences in amplitude we are after. In particular these methods should be extended to the He II 3203 and N IV 3483 emission lines, for the detection of peculiar line-excitation effects.

The common envelope model is valid only for very close binary systems. If the peculiarities of CQ Cephei can be found in binary systems of larger period, the common envelope hypothesis must be replaced by an alternative model. Sinvhal and the author have made a search photographically for variations in emission line intensity with phase in the Wolf-Rayet binaries HD 193576 and HD 193928 having periods of 4·21 and 21·64 days respectively. The eclipse effects are negligible on He II 4686 and N IV 4058 in HD 193576 as have been noted before by Wilson and Munch. In HD 193928, we noted variations in emission line intensity, but these were totally independent of phase. These variations are similar to those found in HD 191765, HD 192163, HD 193077 by the author (Bappu, 1951*b*), and by Struve (1944*b*) in HD 151932. Oke (1952) has detected photo-electrically, using interference filters, such variations in many Wolf-Rayet stars. Investigations such as Oke's will be necessary for interpreting the nature of excitation in the Wolf-Rayet atmosphere.

It is obvious that the Zanstra-Menzel mechanism is just one of the modes operative in the formation of emission lines in Wolf-Rayet atmospheres. Line excitation in the ultra-violet and collisional excitation are major effects that are apparent from the study of binary systems and which cannot be overlooked. The increase in intensity in V444 Cygni of the members of $3p^2P-3d^2D$ multiplet of N III at secondary minimum is an example of the case in point. The resemblance with the O stars is striking and selective line excitation is a valid consideration. The large scale motions found in these atmospheres necessitate complete consideration of collision effects.

Martin Johnson (1954) has made the very interesting suggestion that the emission lines in Wolf-Rayet stars originate in a way similar to Giovanelli's theory of solar flare formation (Giovanelli, 1948). The Wolf-Rayet atmosphere is considered to be a seat of multiple high current discharges, with Stark broadening yielding the observed widths of the lines. The suggestion is an attractive one and merits further theoretical investigation and experimentation in the physical laboratory. Johnson postulates the emission to originate at very low levels above the star's photosphere, in a region of high density. The monochromatic light curves of CQ Cephei indicate the emission to extend to large heights in the atmosphere. The correspondingly large densities required at these higher levels would prove to be a major obstacle in the Johnson hypothesis. The flare mechanism probably exists in a certain way as is seen in the short-lived variations of intensity and form of the emission lines. The rapid changes found certainly originate from such excitation mechanisms.

If the emission originates in the lower layers of the atmosphere self-absorption and self-reversal effects would be existent. The latter in particular would be present conspicuously. Actually self-reversals are found only rarely in the emission lines. The helium lines in HD 152270 have absorption cores in the centre but these have been found to originate from the other component of the binary system though Struve (1944*a*) suspects that there is an intrinsic self-reversal effect in the atmosphere of the W component. A self-reversal was found in the 4686A line of HD 191765 on the 1950 Harvard spectra. Coude spectra of HD 192641 show central reversal effects in 6563A and 4861A. According to Wilson (*private communication*) a

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