SECTION III

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THE SPECTRA OF WOLF-RAYET STARS AT HIGH DISPERSION

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1. Introduction

The Wolf-Rayet stars have perhaps the most spectacular spectra among the various celestial species that have been examined with the aid of the spectrograph. The wide emission lines that provide a striking display continue to be the enigma they have been for decades. Progress, however, in evaluating the contributions to the spectrum by different ions has been fairly complete, thanks to the splendid efforts in the laboratory by Edlen and his collaborators. Many lists of wavelengths of individual features exist from the studies of Plaskett, Beals, Cecilia Payne and Swings. Efforts at identification have been such as to provide a list of likely contributors, that by wavelength position and plausible intensity could be present in the emission band at a specified wavelength. The large width of the lines form the principal limitation. For, one can have a wide limit of coincidence in wavelength with resultant emission features that are complexes covering well over a hundred ångstrőms. The wide nature of these complexes have perhaps encouraged in the past the use of low spectral resolution only, for the many studies that have been carried out. Seldom has one used the resolutions and dispersions that have been usefully employed for the study of the more common relatively narrow absorption lined objects. This situation pertaining to the Wolf-Rayet stars is happily undergoing a change in recent years when coudé spectra with the larger telescopes are becoming increasingly available. The southern hemisphere has been particularly rich in these objects both in variety of behaviour and in having many bright ones, and one can, therefore, justifiably hope that our information on these objects will progress henceforth with remarkable rapidity.

One might well ask the question whether such objects that are characterized by enormously wide emission features could really reveal any additional information when subjected to scrutiny with high dispersion. My answer to this is in the affirmative. The study of microphotometer tracings of high to moderate dispersion spectra does indeed show up details that are often lost in efforts with lower dispersions. I hope, in what follows, to be able to convince you of some of the advantages of higher dispersion spectroscopy of Wolf-Rayet stars.

The first efforts at comprehensive identifications have been of Payne (1933) and Edlen (1933). Later in 1956, Edlen (1956) was able, using new laboratory data for C II, C III, and predicted transitions between high quantum states in C IV, to reach at an almost complete identification of the emission features in the stars of the carbon sequence. The observations that were used for this purpose were principally those

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made by Swings (1942) and in the near infrared region by Swings and Jose (1950). Later efforts by Bappu (1957), Bappu and Ganesh (1968), Underhill (1959, 1962, 1967), Smith and Kuhi (1970) and Smith and Aller (1971) have only added details of contributing wavelengths, profiles and line intensities to the Edlen study.

We have heard this morning a detailed discourse on the dichotomy of spectral display and the basis of the categorization into the WC and WN classes. We are certain today that He I, He II, C II, C III, C IV, O III, O IV, are present in a typical WC8 (Lindsey Smith's classification) star like HD 192103. Probably present in this star are lines of H, N III, N IV, N V, O V, O VI and Si IV. In the case of a WN6 star, HD 192163, we are definite of the presence of He I, He II, N III, N IV, N V and Si IV. Many including myself would add to this list C IV, first identified independently in the WN sequence by Swings (1942) and Aller (1943). Probably present are H and O V. The dichotomy of spectral behaviour is an accepted characteristic that needs quantitative theoretical interpretation. The dominant role of nitrogen ions and carbon ions in their respective classes is seen so obviously. The question of interest has been whether a pure carbon sequence free of nitrogen exists. I believe that the moderate to high dispersion spectra obtained give evidence that nitrogen exists in the carbon sequence. Independent support for this statement comes also from the rocket ultraviolet data of Gamma Velorum wherein N V absorption lines and possibly N IV emission lines can be seen. The observed effects are nevertheless marginal and might find interpretation only from the standpoint of stellar evolution.

Our ultimate aim of observation of the spectra of these objects is to build up a physical picture from a theoretical analysis of intensities, profiles, etc. It may not be long before we can compute synthetic spectra that will match in every detail the fluctuations in a line contour caused by the kinematics of the situation or by a contributing blend. To do so, the base necessarily has to be the availability of a minimum set of data of good quality and completeness of information. It is possible to achieve this only by high dispersion studies of selected objects that are amenable to such analyses. My aim in recounting the current status of such information is to give you a picture of the problems we encounter by virtue of the heavy blending of wide lines to form emission complexes. We would have indeed, preferred to have instead of these complexes, single emission features that are likely to be more easily amenable to theoretical analysis!

2. Line Identifications in WC and WN Stars

Let us examine first of all the general problem of identification as applied to a typical star of the carbon sequence and another of the nitrogen sequence. I have chosen for this purpose the direct intensity tracings of HD 192103 and HD 192163 from amongst a collection of such tracings that Mr. Scaria and I have in print in the Kodaikanal Observatory Bulletins. We have used for this purpose coudé spectra that I had obtained some years ago on the Mount Wilson 100-inch at 10 Å/mm in the blue and 20 Å/mm in the red. We have chosen these two objects essentially because they have the narrowest lines amongst the spectra that we have of both sequences. The illustrations of HD 192103 also contain in the lower half the equivalent region in HD 184738, or Campbell's hydrogen envelope star. This tracing is from a blue plate of 10 Å/mm and of 8 hr exposure, obtained by Olin Wilson. The red plate was also obtained by him at 20 Å/mm in order to provide completeness to the study.

The identifications in WC spectra are marked in Figures 1 to 9. It is possible to make an almost complete identification for Campbell's star because (a) the lines are narrow and provide little cause for ambiguity, (b) laboratory wavelength data are

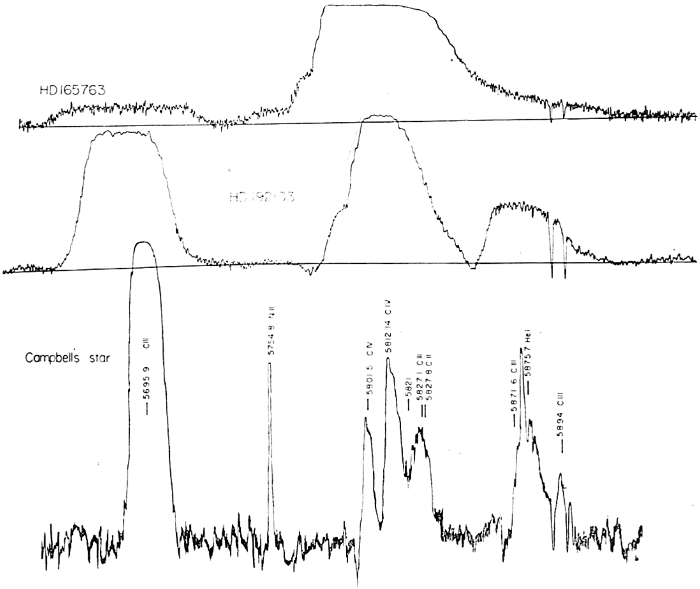

Fig. 1. The 5800 Å region in WC stars. Note the violet absorption edges of C IV 5801, 5812, the flat-topped nature of the C III 5696 profile, and the blends at 5876 Å.

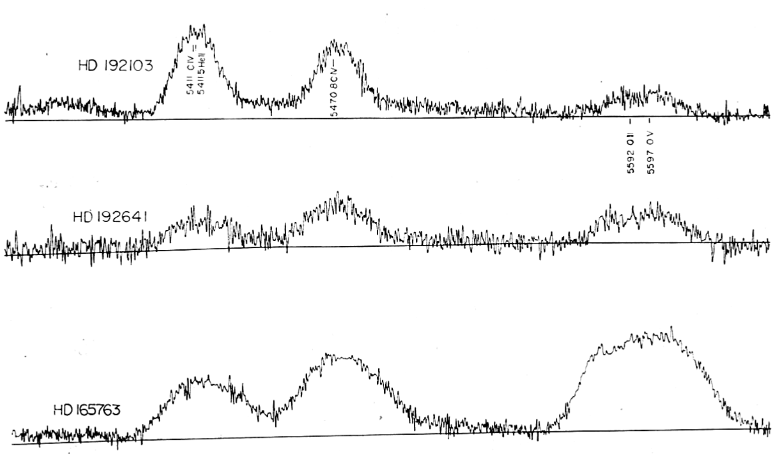

Fig. 2. The 5500 Å region in WC stars.

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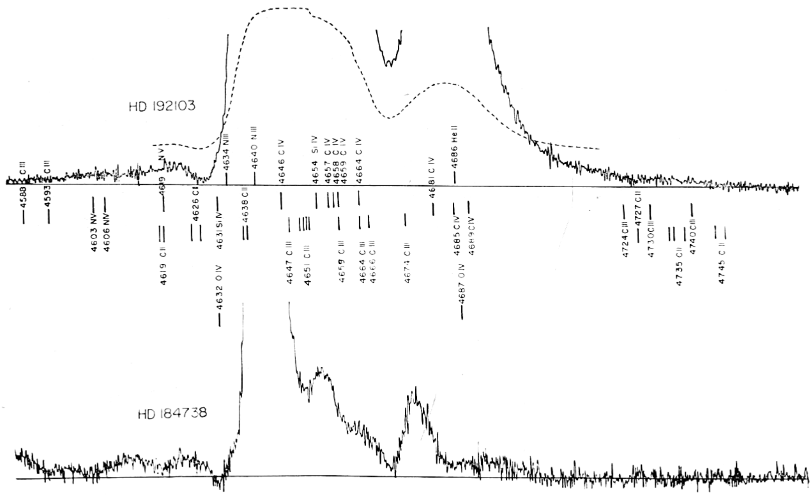

Fig. 3. The 4600 Å region in HD 192103 and HD 184738.

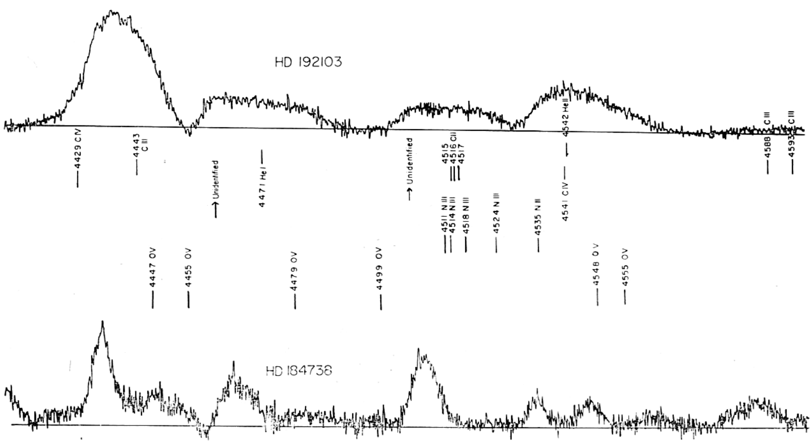

Fig. 4. Region 4429–4590 Å in HD 192103 and HD 184738.

comprehensive. Allowing for excitation differences between the WC8 and the equivalent of a WC9 star, the identifications in Campbell's star aid in our effort to determine the blending in HD 192103. The details are as follows:

He II *5-n series*: One can see with certainty on the original tracings not reproduced here, the He II lines at 6234 Å (5–17), 6171 Å (5–18) and 6118 Å (5–19). One can follow this series upto the transition (5–21).

***5876 Å*: He I is the principal contributor. C III exists at 5872 Å, 5894 Å while C II is at 5889 Å and 5892 Å. C II contribution is possible at 5907 Å and 5915 Å also, while C IV 5866 Å (8–13) can be of appreciable intensity.**

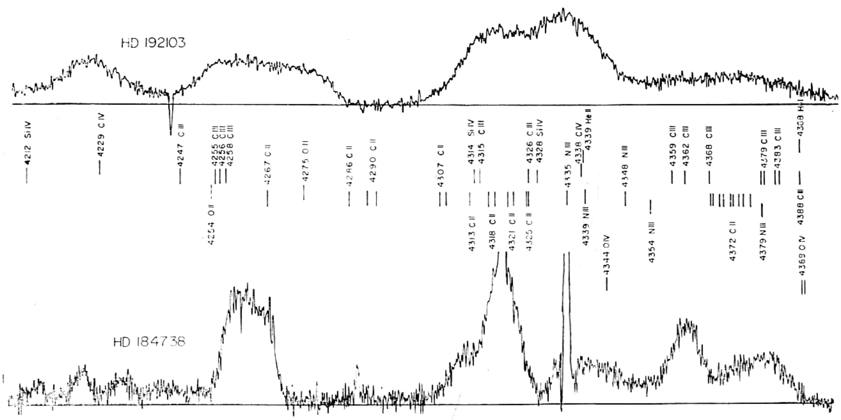

Fig. 5. The region 4210–4390 Å in WC stars.

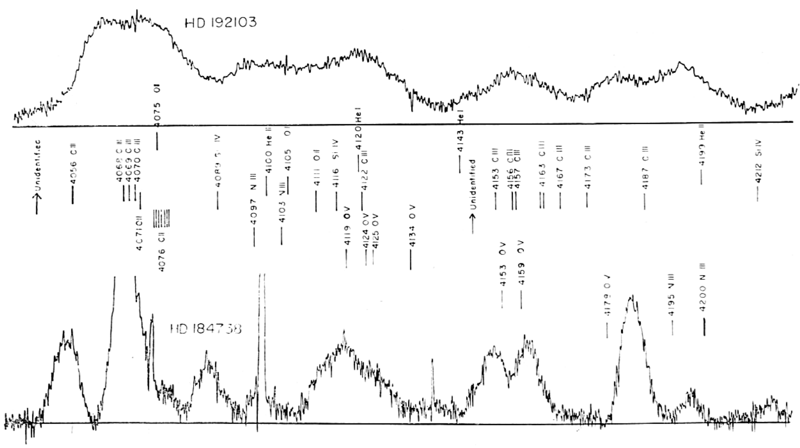

Fig. 6. The 4100 Å region in WC stars.

5816 Å: C IV 5801.3 Å, 5812.0 Å and C III 5826 are certain. There are also the two violet edges corresponding to 5801 Å and 5812 Å. Also, O V 5836 Å seems to be a contributor.

Weak emission between 5696 Å and 5806 Å: From wavelength coincidences alone the likely contributors are N II 5747 Å, 5767 Å and weak C III at 5772 Å. The emission is a definite feature; its identification is not satisfactory.

5696 Å: This is principally due to C III 5696 Å. Possible N II contamination could exist from the strong transitions at 5667 Å, 5676 Å, 5680 Å, 5686 Å and 5711 Å. The identification of N II is very uncertain because the infrared transitions of N II do not appear in the star spectrum.

5592 Å: This is a double humped feature. The humps consist of O V 5572 Å, 5580 Å and 5583 Å as well as 5598 Å. O III 5592 Å also contributes. A possible contributor is 5602 Å of O VI.

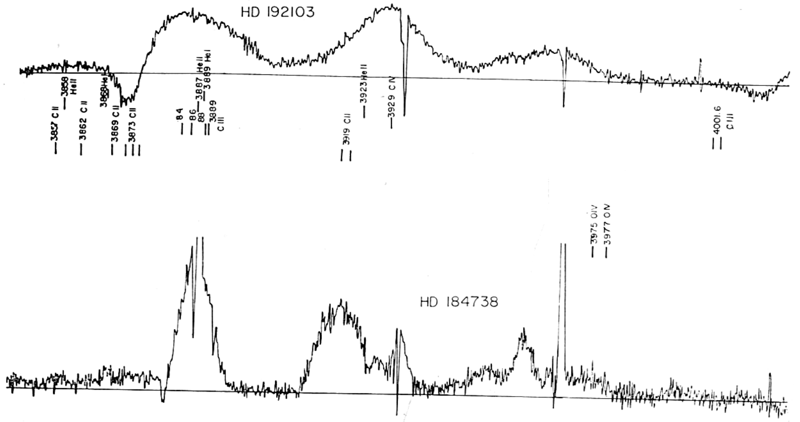

Fig. 7. Region 3860–4000 Å in HD 192103 and HD 184738.

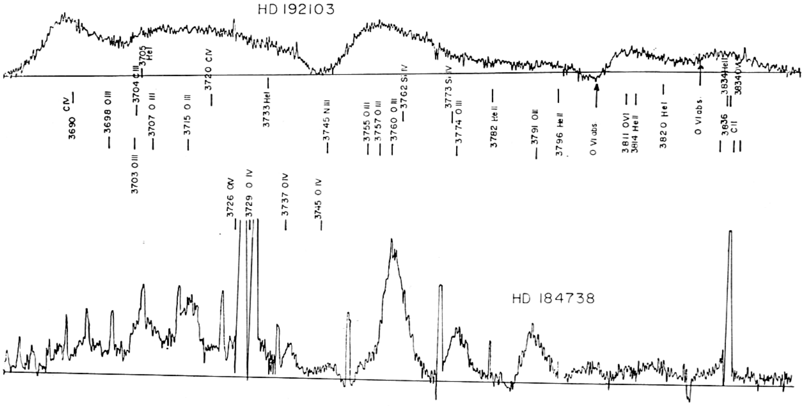

Fig. 8. The spectral region 3690 Å–3840 Å in WC stars.

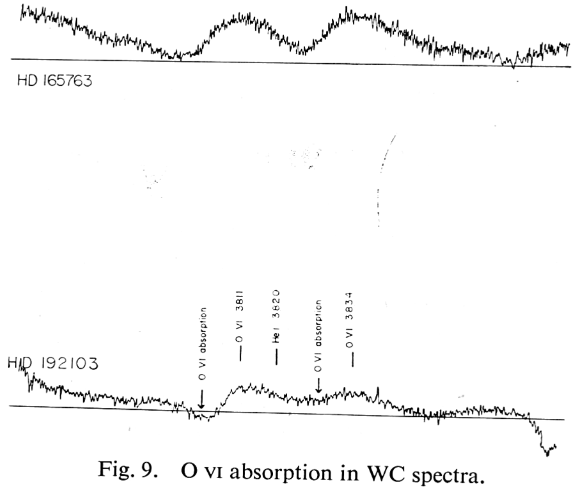

Fig. 9. O VI absorption in WC spectra.

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5469 Å: The most dominant ion is C IV 5070.8 Å (7–10). On the longward side some weak blending which is noticeable on the profile can be ascribed to 5479 Å and 5486 Å of C II. Farther away in the red wing, a slight hump above the continuum can be ascribed to 5508 Å O III. Weak emission caused by C II 5535 Å and 5538 Å can be seen at 5536 Å. This line is another of those rare unblended lines that could be used for derivation of reliable physical parameters of the star.

5411 Å: He II is the principal contributor. C IV 5411 (8–14) has an appreciable share of the intensity considering that C IV 5093 Å (8–15) has about 8% intensity of 5411 Å. Figure 2 illustrates tracings of this region.

Red wing of 4686 Å: C II lines fall at 4745 Å, 4735 Å and 4727 Å. The strongest among these is 4745 Å. C II is unlikely to be dominant. The C III lines at 4739 Å, 4730 Å and 4724 Å probably contribute more than C II even though they are weak.

4686 Å: The principal contributor is He II. The (7–11) transition of C IV at 4689 must be a contributor. The intensity of C IV will be substantial because the next line in the (7-n) series earlier to it is 5470 Å which is quite intense. Other contributors of C IV are 4685 Å (6–8) and 4681 Å (8–17). The transition (6–8) will also be substantial since (6–9) at 3689 Å is quite intense and (6–7) 7726 Å is very noticeable despite its location in the vicinity of the oxygen 'A' band.

4652 Å: Principal contributors range from C III 4674 Å to 4647 Å, with the most intense ones being 4647 Å, 4650 Å and 4651 Å. The profile of the line indicates that its maximum intensity is between 4647 Å and 4653 Å in accordance with the C III dominance. C IV also falls in this region with appreciable intensity at 4646 Å (5d–6f), 4658 Å (5gf–6hg) and 4664 Å (5f–6d). C II has lines in this range from 4638 Å to 4618 Å with the most intense ones at 4618 Å. One has to explain the contribution of intensity over a range 4630–4647 Å before the violet edge comes in at 4627. It is here that one must depend entirely on N III at 4634 Å and 4640 Å to play a role, in the absence of any other contributor. Si IV 4631 Å and 4654 Å also exist and have a share in the intensity profile.

The strongest lines of N III, other than 4634 Å and 4641 Å, are at 4097 Å and 4103 Å. When we look at the spectrum of HD 192163 and compare 4200 Å with 4100 Å, it is obvious that the complex at 4100 Å is many times more intense than what is expected from He II alone. This is caused by a principal additive contributor to the blend by N III and in a minor way by Si IV. In the case of HD 192103, the complex at 4100 Å on the long wavelength side has much added to it by C III 4122 Å and the O V lines. The peak intensity of 4100 Å is higher than in the case of 4200 Å. Hence we conclude that N III 4097 Å and 4103 Å are present and definitely distort the He II intensity and profile. But we do not notice such contribution to the extent that we observe at this wavelength in a WN6 star.

Another line of evidence of the presence of N III in the spectrum of HD 192103 is the following. The large complex from 3748 Å to 3792 Å contains many contributors, amongst which O III is a good contributor. Shortward of 3748 Å and until 3725 Å, the primary effects are of O IV. Amongst the lines of O III, 3774 Å and 3791 Å are usually of equal intensity. The profile near 3774 Å picks up in intensity because of N III 3771 Å.

Also while the maximum intensity at 3757 Å in the complex can be due to O III 3755 Å, 3757 Å and 3760 Å, its overall increase above 3774 Å and 3791 Å calls for an additional reinforcement from N III 3754 Å. Also N III 3745 Å falls on O IV 3745 Å which is of sufficient intensity to record its existence. The fact that instead of an increase in this position, the contour sweeps down to the continuum level can be explained only by virtue of a violet edge to the O III complex 3755 Å, 3757 Å, 3761 Å. A mild depression in the contour at 3768 Å may represent the violet edge of O III 3774 Å. Both these violet edges are seen in HD 184738. Hence we need to recognize the contribution of N III to this complex also, thus reinforcing our conjecture that the N III ion can be seen in the spectrum of HD 192103.

Complex shortward of the C III *violet edge at 4627 Å*: The possibility exists that this could be the extended wing of the principal line near 4634 Å, and that what seems to be a complex of lines is actually the violet wing of 4634 Å into which the violet edge has made a deep cut. One can consider in addition that N V contribution at 4603 Å, 4619 Å is present. But 4603 Å by itself may not be very bright and 4619 Å will contribute less. Another possibility is N IV 4606 Å. But judging from possible N IV 4058 Å, the contribution of which, if present, is very small, the role of 4606 Å towards the blend is unlikely. Weak contributors may be C III 4593 Å and 4588 Å.

4542 Å: The intensity of this band is shared principally by He II followed by C IV 4541.3 Å (8–18) and two O V lines at 4548 Å and 4553 Å. C IV 4541 Å must necessarily be fainter than 5093 Å (8–15). Hence C IV 4541 Å, while detectable, must be having a small contribution. Two humps on the longward side of the profile portray well the contribution of O V and make the identification beyond doubt. The gap between 4542 Å and the emission band at 4516 Å can be identified as due to a violet edge of 4542 Å of the Pickering series. A similar violet edge is seen in HD 192163 as well as HD 184738.

4516 Å: The appearance of the band indicates its composite nature. C III 4515 Å, 4516 Å and 4517 Å are present. By itself the shortward extension seen can be formed only with the aid of another contributor. Two N III lines at 4514 Å and 4511 Å form this possibility. O V 4498 Å can be seen as a weak emission on the shortward side, even though it seems much weaker than its counterpart 4479 Å, which seems to dominate in the emission band about 4471 Å.

Emission at 4471 Å: He I 4471 Å occurs at the centre of this band with a steep violet absorption edge. O V 4479 Å contributes on the longward side. An unidentified feature at 4465 Å makes a significant contribution.

4441 Å: The principal constituents are C IV 4441 Å and 4429 Å with the former as the dominant contributor. A hump on the longward side agrees with O V 4447 Å. Another O V line at 4455 Å of intensity comparable to 4447 Å falls in the midst of the He I violet absorption edge, and hence is invisible.

4355 Å–4400 Å complex: C III contributors are at 4359 Å, 4362 Å, 4368 Å, 4380 Å, 4383 Å and 4388 Å. C II exists at 4372 Å, 4374 Å, 4375 Å and 4376 Å with fair intensity. O IV 4389 is a likely contributor, but is weak. There needs to be a feature at 4395 Å to give rise to the weak hump in the profile, and this could be O II 4396 Å. He I 4388 Å and N III 4354 contribute weakly.

4339 Å: The principal contribution is of He II. A slight hump on the longward side is caused by O IV 4344 Å. C IV 4338 Å (8–20) must be present, but cannot be separated from He II. On the shortward side the line blends with C III 4326 Å and 4317 Å. In particular, C III 4313 Å, 4317 and 4318 Å merge to form a conspicuous feature at 4316 Å. The central hump can be ascribed to 4326 Å. At this position C II 4325 is also present. Appreciable contribution to the overall band also comes from Si IV 4314 Å and 4328 Å.

4267 Å: C II at 4267 is undoubtedly the principal contributor. Weak contribution at 4247 Å, 4255 Å, 4256 Å and 4258 Å comes from C III. But these do not by themselves explain the peculiar profile. O II at 4254 Å and 4275 Å contributes.

4229 Å: The entire profile is mostly due to C IV 4229 Å (7–12) and is one of the few unblended lines in the entire spectrum. Its longward wing at the very extreme merges with C III 4247 Å. On the shortward side the wing blends with Si IV 4212 Å. The hump is so clear cut that it definitely establishes the presence of Si IV. N III 4216 Å may contribute weakly.

4200 Å: This band is mostly due to He II. N III 4196 Å and 4200 Å may contribute weakly. On the shortward side C III 4186 Å is most definite and this along with O V 4178 form the principal hump on the shortward side.

4157 Å: The emission band consists principally of C III 4153 Å, 4157 Å and 4163 Å. In addition there must be O V 4159 Å and O II 4153 Å. An unidentified contributor at 4149 Å has an appreciable effect.

The 4100 Å–4122 Å complex: Contributors are O V 4134 Å, 4124 Å, O II 4133 Å, 4120 Å, C III 4122 Å, Si IV 4116 Å and O II 4111 Å. He II 4100 Å is the principal contributor to the complex. This is flanked by N III 4097 Å and 4103 Å appreciably. While the net intensity indicates the reality of the N III overlap, its contribution is not consistent with the intensity it should have relative to 4634 Å and 4640 Å. Si IV 4089 Å is also present. O II 4092 Å, 4097 Å and 4105 Å have detectable effects.

4070 Å: The centre of the band is made up of C III 4070 Å, 4069 Å and 4068 Å with sizeable contributions from C III 4056 Å on the shortward wing and from C II 4076 Å on the longward side. O II 4071 Å and 4076 Å are the most prominent of the O II lines whose presence is denoted by distortions at these wavelengths. N IV 4058 Å may be present. However, we find no trace in the spectrum of its counterpart at 3483 Å. A feature at 4051 Å remains unidentified.

4026 Å: He I 4026 is undoubtedly the principal contributor with a conspicuous violet absorption edge. C II 4017 is present weakly in the violet wing. He II is also present.

3965 Å: He II is dominant. O III 3962 Å and He I 3965 Å are present. C II 3972 Å, 3974 Å, 3977 Å, 3980 Å and O IV 3957 Å, 3975 Å add up to the intensity.

3929 Å: C IV 3929 Å is undoubtedly the dominant contributor. In the shortward wing, C II at 3919 Å and 3921 Å and He II 3923 Å produce the observed asymmetry.

3889 Å: The most conspicuous contributor is He I. C III 3884 Å, 3886 Å, 3889 Å, C II 3876 Å, He II 3887 Å and O II 3882 Å are present. The profile is not flat topped as is seen in the WN stars. Presumably the presence of C III distorts the profile from flatness. An unidentified feature may exist at 3893 Å unless one assumes that He I is flat topped from 3882 Å to 3894 Å on which lies superposed the C III contribution.

3858 Å: He II is present with additional weak contribution from C II 3857 Å, 3862 Å and 3869 Å.

O VI *at 3811 Å and 3834 Å*: Two features with mean wavelengths 3814 Å and 3834 Å exist in the spectrum. He II 3814 Å and 3834 Å can contribute to these, but considering the intensity of the next earlier line in the Pickering series 3858 Å, such contribution to these positions is apt to be small. These are identified as due to O VI. He I 3820 exists with appreciable intensity .A weak contribution from C II 3831 Å and 3836 Å is possible. An interesting feature is the absorption seen off the violet edge of 3811 Å. A weak dip can be seen corresponding to a likely absorption edge of O VI 3834 Å. A remarkable coincidence produces the ambiguity. He I 3820 Å (2^3P^0–3^3D) is a member of the series ($2^3P^0-n^3D$). Others in this series like 4471 Å and 4026 Å all have violet absorption edges. The next line in the series falls at 3705 Å with a violet absorption edge that multilates the peak of C IV 3689 Å, which is otherwise intense. A suggestion of a weak violet absorption edge exists at 3622 Å caused by He I 3634 ($2^3P^0-8^3D$). Hence we must conclude that the major share in the violet absorption edge at 3804 Å is that of He I 3820 Å.

This does not rule out the detection of displaced absorption by the O VI doublet. We infer its presence from the spectrum of HD 165763 (WC5) in Figure 9 where the absorption does not reach the continuum level. However, the shapes of the violet wings of 3811 Å and 3834 Å are such as to show the existence of the displaced absorption. Assuming the depression at 3745 Å seen in Figure 8 as due to O III displaced absorption one finds that the wavelength interval seen in HD 165763 between the displaced absorptions of O VI and O III at 3804 Å and 3745 Å respectively is retained in the case of HD 192103. The spectrum of HD 115473 reproduced in Lindsey Smith's paper shows the violet edges for the O VI doublet; a higher dispersion spectrum should settle the issue.

Emission complex 3745 Å–3795 Å: This complex has been described earlier to justify the identification of N III. The interesting feature is the shallowness of the displaced absorption edge caused by O III 3755 Å, 3757 Å and 3760 Å.

The complex 3680 Å–3745 Å: O IV 3726 Å, 3727 Å and 3739 Å undoubtedly exist on the longward side and individual humps can be seen at these locations. Definite identifications can be made of C IV 3720 Å (7–14) and C IV 3690 (6–9). There are numerous O III lines at 3698 Å, 3703 Å, 3707 Å and 3715 Å which contribute to the profile. There is also He I 3705 Å, the displaced violet edge of which affects the peak intensity of C IV 3690 Å.

3609 Å: The main contribution arises from C III 3609 Å, with some additional intensity caused by He I 3614 Å and O VI 3622 Å. The profile is typical of one that has several contributing constituents.

A similar detailed examination of intensity tracings of blue and red spectra of the WN6 star HD 192163 cause the following comments:

6678 Å: He I 6678 Å and He II 6683 Å, contribute predominantly.

6563 Å: The most intense contributor is He II. He II 6527 Å (5–14) falls on the violet wing. Possible O V contribution at 6460 Å, 6466 Å and 6500 Å exist.

6406 Å: A broad band at 6406 Å is the combined effect of 6406 Å He II (5–15) and 6380.7 N IV. The He II line is quite intense and N IV is sufficiently well resolved.

6234 Å: He II 6234 Å (5–*n*) is seen. The (5-*n*) series can be followed to $n=21$.

5875 Å: He I 5875 Å principally is a lone contributor with a striking violet edge. The profile is almost flat-topped.

5806 Å: Principally due to C IV with likely violet edges at 5781 Å and 5792 Å as seen in Figure 10. The profile looks as though it has contamination at 5836 Å and this could be due to O V. But this is not certain since stronger O V lines are not seen.

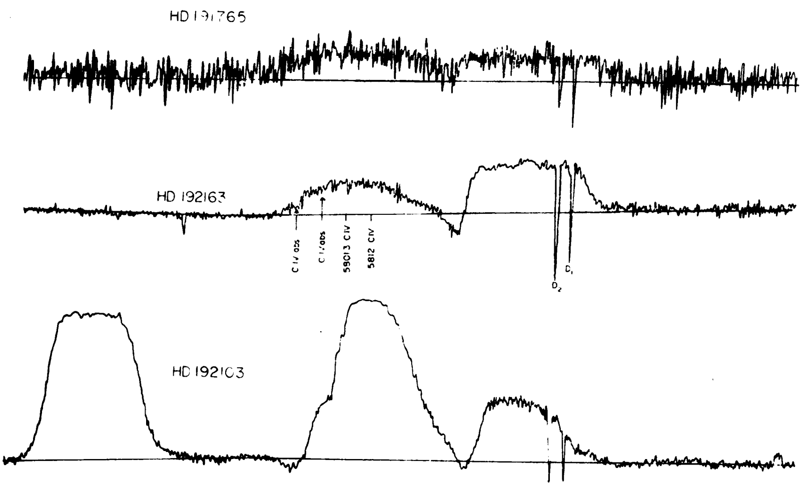

Fig. 10. The 5800 Å region in WN stars. A tracing of the WC star HD 192103 is included to establish the identification of C IV, 5801 Å, 5812 Å.

5411 Å: He II is the principle contributor. The profile of the line indicates contamination on the longward side. In particular a redward wing extension going upto 5528 Å is seen. One can identify O III 5508 Å. But the more intense line 5592 Å exists only weakly. In this group one may also include a weak contribution from O V. A large number of N II lines fall in this region and they could all be possible contributors. But here again stronger contributors between 5666 Å and 5710 Å do not exist. C IV 5470 Å could be assigned on the basis of wavelength coincidence.

4860 Å: He II is the principal contributor. The line has N III contamination and at least 10% is due to N III. The profile on the longward side indicates additional contamination which is unidentified. Very much like 5411 Å, there is an extended red wing going upto about 4965 Å. N V 4944 Å is certain in this extended feature, and the same applies to O V 4930 Å.

4686 Å: The contributions of 4713 Å He I can be inferred from the extension of the redward wing of 4686 Å. 4686 Å is predominantly caused by He II with a weak con-

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tribution, if any, of the C IV hydrogenic transitions 4680 Å (8–17), 4685 Å (6–8) and 4689 Å (7–11). The strongest of these three is likely to be 4685 Å, (6–8), in which case, one could see C IV (6–9) 3689 Å. This is not seen. Hence, it is unlikely that the hydrogenic transitions of C IV are generally seen in this star. This does not rule out the possibility of the (5d–6f) 4646 Å, (5gf–5hg) 4658 Å and (5f–6d) 4664 Å transitions being present.

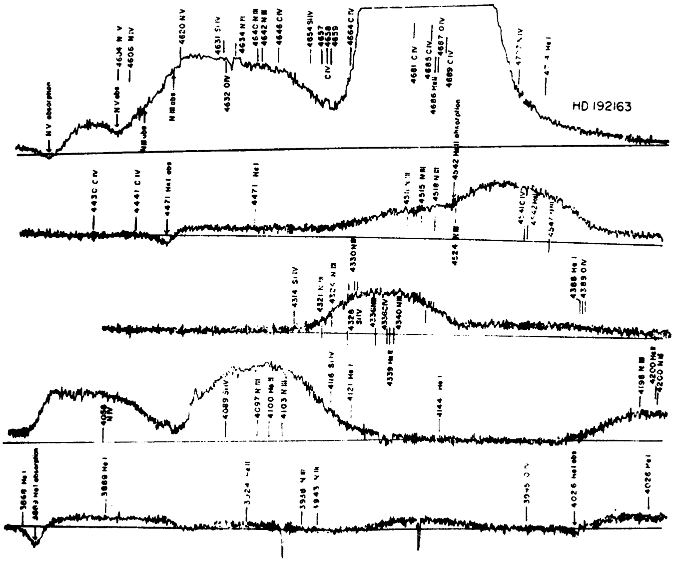

Fig. 11. The blue spectrum of HD 192163.

4640 Å complex: The principal contributors are N III 4634.2 Å, 4640.6 Å, 4641.1 Å and N V 4619.98 Å and 4603.7 Å. From the shape of the profile, Si IV 4654 Å is present and hence 4631.4 Å should also be existent. C IV 4646 Å is present and hence C IV 4657 Å, 4658 Å, and 4664 Å are likely contributors. Depressions in the contour at 4615 Å and 4621 Å can be tied up with N III violet absorption edges. These are not as striking as those of N V that are at 4590 Å and 4602 Å as can be seen in Figure 11.

4542 Å: He II 4542 Å is undoubtedly the principal contributor. In the violet wing there is considerable contribution by N III, going down from 4534 Å to 4511 Å. The violet wing merges with He I 4471 Å. A violet edge for 4542 Å is seen at 4525 Å. There is also unidentified emission at 4504 Å.

4471 Å: This is a perfect example of a flat-topped profile. There seems to be no contamination. A striking violet edge is seen.

Emission at 4379 Å: In the longward wing He I 4387.9 Å can be seen to be present. Most of the band is taken up by N III 4379 Å. The profile of this is remarkably flat.

4340 Å: The principal contribution is from He II. The line is contaminated appreciably by N III both on the longward and shortward sides. The contamination is greater on the longward side as can be seen from the distension on the longward side by more intense N III 4348 Å. On the shortward side Si IV at 4328 Å and 4314 Å are definite contributors and can be noticed. At least 20% of the line intensity comes from contributors other than He II.

4200 Å: While He II is the principal contributor there is appreciable contamination from N III 4196 Å, 4200 Å and 4216 Å. Also contribution from Si IV 4212 Å can be significant. This is not a pure He II line.

4144 Å: Weak He I can be seen at this wavelength.

4100 Å: He II 4100 Å is dominant. Si IV 4116 Å, 4089 Å are substantial contributors. N III 4097 Å and 4103 Å also contribute well. In the longward wing there seems to be some contamination from emission at 4134 Å.

4058 Å: One associates this entire feature with N IV 4058 Å. The profile, however, has little relationship to that of N IV 3483 Å. Contamination may exist though abnormal excitation causing a patchy surface distribution on the star with different kinematical characteristics, is a possibility.

4026 Å: Contributors here are He I 4026 Å and He II 4025.6 Å. The line has a violet edge.

3965 Å: He II. No other contributor is apparent.

3940 Å: Weak N III at 3938 Å and 3934 Å is present.

3923 Å He II: No other contributor is apparent.

3888 Å: He I. There is weak He II contamination at 3887.4 and this must be about 10%, as judged from the weakness of the next line in the Pickering series. The most striking feature is the violet absorption edge.

3858 Å: He II very weakly present.

3834 Å: He II weakly present.

Complex at 3762 Å: N III is principal contributor.

3483 Å: This is due entirely to N IV. However, there must be something on the redward side which is contributing. This could be O IV and He I. But the identification is not certain. 3483 Å has a violet edge.

It is impossible to be certain about the presence of N II in the blue. The closest is a slight contamination in the violet side of the 4058 Å N IV line. The presence of this ion has to be established in the red.

3. Some Features of Bright Wolf-Rayet Stars Seen at High Dispersion

The effects of a companion, when such a star is comparable in intensity to the Wolf-Rayet star, are easily noticeable on spectra of good resolution. Illustrated here in Figure 12 are the 3800 Å regions of three stars HD 193576 (WN5+06); HD 193077 (WN5+OB) and HD 192641 (WC7+Be). Notice the appreciable intensity of the Balmer series of the companion in each case even though continuum and emission features of the Wolf-Rayet star tend to mask them. A more striking case is the detection of the companion's presence at 6560 Å in the case of HD 192641 (Bappu, 1957). Miss Underhill later independently found this feature (1962) and ascribed it to a Be shell companion. Figure 13 depicts the companion's presence at 6560 Å, 4860 Å and in the near ultraviolet. At my request Olin Wilson had examined in 1957, five other

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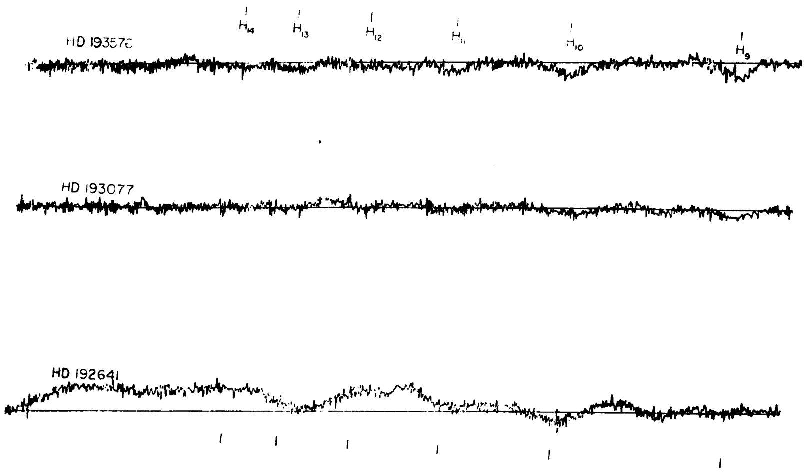

Fig. 12. Effects of a companion. The tracing of HD 193576 shows the higher members of the Balmer series originating from the O-type companion in a well-established Wolf-Rayet binary system. Note the presence of the Balmer series members in the spectra of HD 193077 and HD 192641. No velocity shifts are measurable in these spectra but the presence of a companion can be inferred.

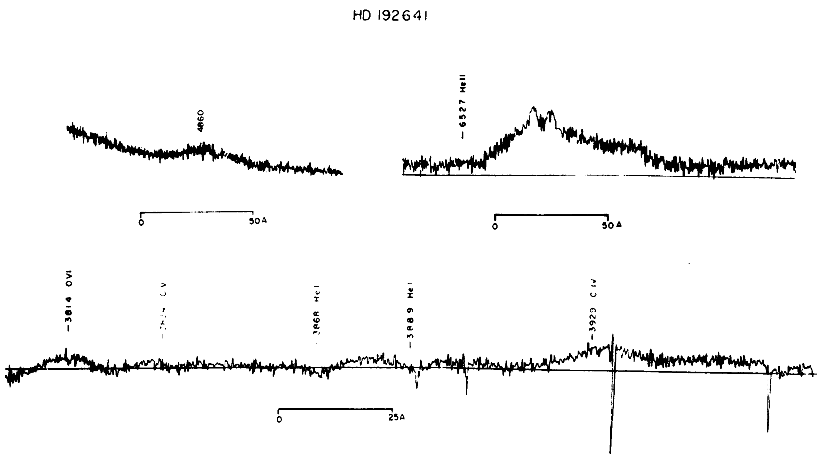

Fig. 13. Effects of a companion in HD 192641. Note the reversals, ascribed to the companion, at 6560 Å, 4861 Å and in the near ultra-violet.

coudé spectra in his possession of this star, and measured the narrow reversal for velocity shifts. None was seen.

An interesting feature of studies similar to those made by Smith and Aller for HD 184738 and by us for the brighter Wolf-Rayet stars is the finding that violet absorption edges are more common than we had assumed initially. Smith and Aller give a sizable list of these features for a variety of ions that include transitions from metastable levels or ones connected to these to normal levels of the abundant ions. These violet edges are easily seen in the later stages of the Wolf-Rayet temperature sequence. Apart from the fact that the lower temperature enhances these features and brings out many that do not exist in the earlier types, the relatively narrower emission lines enhance the possibility of measurable detection. Table I gives my measures of violet displacement for the different ions in different stars. This table includes the Smith-Aller values for HD 164270.

The presence of violet absorption edges to some of the emission lines has been known since Beal's studies. We have been unaware of the selection which enables some lines to display the phenomenon. Underhill (1968) finds two classes of lines giving rise to the absorption edges. There are those which arise from levels over-populated by dilution effects, like the He I triplets, C III 4647 Å, 4650 Å, 4651 Å and N IV 3478 Å, 3482 Å and 3484 Å, where the lower level is either metastable or connected to one such by a strong transition. There are violet edges seen also on lines arising from relatively low-lying normal levels of ions of the abundant species like C IV 5801 Å, 5812 Å and N V 4603 Å, 4620 Å. In HD 151932 Struve has reported that the violet absorption edge of 4542 Å of He II varies.

Smith and Aller find no violet edge in HD 184738 for the common ion C II which has low lying levels while others like O III 3755 Å, C IV 5801.12 Å, He II 4542 Å that are not low lying, display them. They derive from their observations the following criterion.

A line of a given ion has a violet absorption edge if and only if the excitation potential of the lower level of the line is less than some critical value, which depends on the ion but is always greater than or equal to the ionization potential of the previous level of ionization.

The strength of the foregoing depends on the finding that no isolated line which satisfies it fails to show a violet edge.

A feature of the tabulation of the violet absorption edges is that the largest displacements are usually for He I, while the heavier ions which also have a higher excitation potential display a smaller absorption shift. The expanding shell is thus non-uniform in its kinematical characteristic. The suggestion is reasonable since an ion can exist when there is enough energy to ionize the previous state of ionization. This energy also suffices to maintain a reasonable population in any level for which the excitation potential is less than the ionization potential of the previous ion. Hence Smith and Aller rightly conclude that the violet absorption edge may be formed in regions of the atmosphere that do not have the energy required to form the corresponding emission lines.

The Smith-Aller postulate is not violated by lines observed to have violet edges. However, there are numerous anomalies. There are some ions that have violet edges despite the fact that the E.P. of the lower level is much greater than the ionization potential of the previous ion while other ions having E.P. of lower levels closer to the I.P. still do not possess violet absorption edges. Notable is the difference between He I (I.P. = 0.0; E.P. = 21 eV) and C II (I.P. = 11.2eV and E.P. = 14eV). Smith and Aller point out that since He is more abundant and also has only two levels of ionization, any line of He is formed over a much greater depth in the atmosphere than are other

TABLE I

Measures of violet displacement for the different ions in different stars. (The Smith-Aller values for HD 164270 are also included.)

Atom/Ion	Violet displacement								
	HD 165763 WC5	HD 193793 WC + O5	HD 192641 WC7 + Be	HD 192103 WC8 + OB?	HD 184738 Plan. neb. nucleus	HD 164270 WC9	HD 192163 WN6	HD 191765 WN6	HD 50896 WN5
				Km/s					
He I 3705				−1125					
He I 3820				−1154					
He I 3889	−1889	−2552	−1041	−1195	−510	−800	−1380	−1611	
He I 4026				−1124	−458	−740	−1296		
He I 4471	−1946		−1154	−1127	−444	−670	−1402	−1537	
He I 5876		−2342	−1332	−1148	−490	−840	−1378	−1546	−1431
He II 4542				− 759	−370	−560	−1188	−1214	
C III 4647		−2664	−1638	−1213	−400	−880			
C IV 5801	−1660	−1664	−1204	− 997	−415	−670	−1035	−1015	
C IV 5812	−1620	−1578	−1161	− 892		−575	−1104	− 979	− 815
O III 3755	−1404			− 750	−393				
O VI 3811	−1015			− 551					
O VI 3834	− 962								
N III 4634							−1300	−1294	
N III 4640							−1288	−1238	
N V 4603							− 958	−1243	
N V 4619							− 849	−1194	

lines and presumably this accounts for the difference in behaviour. For He II lines they have seen absorption edges only on two of the Pickering series (4542 and 5411). This needs confirmation.

Before going on to a discussion of line profiles in these objects, I would like to briefly discuss the near infrared spectra of the Wolf-Rayet stars of the two sequences. My comments are based on low dispersion spectra of 75 Å/mm, 111 Å/mm and 250 Å//mm and serve to give a qualitative idea of the appearance of the spectrum in the photographic infrared. The C IV spectrum is dominant in HD 165763. In the nitrogen stars the N IV, N V spectrum is striking in HD 50896 and HD 192163, while N V is almost absent in the two southern stars HD 92740 and HD 93131. A feature of much interest is the apparent continuum of HD 151932 which shows even in this wavelength region a much greater infrared excess than the others do. This star needs a photoelectric scan study of the continuum urgently. The excess may be intrinsic or may be caused by a red companion.

Work in the infrared accessible to the S1 photosensitive surface has been essentially the splendid coverage by Kuhi (1966). With a 10 Å resolution he has been able to extend identification into the infrared till 1.1μ. One hopes that information in this spectral region will be available on many southern stars in the near future.

Line profiles: Most profiles in WR stars have rounded tops and steep sides. A few selected lines have flat tops like 5696 Å in the carbon sequence. And 3889 Å has in the nitrogen sequence a flat topped profile together with a violet absorption edge that falls in perfectly with the classical model of Beals. Most of the prominent lines can be fitted with a function given by exp $[-\Delta\lambda^2/\sigma^2]$. The values of σ thus obtained describe the degree of random motion inherent in the atmosphere that contributes to the width of the profile, if it is free of all blends. Such a fitting procedure must, therefore, be adopted only where one can be reasonably sure of freedom from blends. In HD 192103, the only lines that are almost free of blends are the C IV lines 5470 Å, 4229 Å, He II 5411. C IV 3933 Å and 3567 Å fall closely to the standards prescribed. In table II we have σ in km/s derived from the observed profiles. Notice the remarkable uniformity in the values derived. The superposed profiles for four lines are shown in Figure 14. Consider the alternative case of the Pickering series in HD 192163. Our identifications made earlier lead us to believe that only a few lines in the spectrum, like 5411 Å, are free of blends that distort the profile. The values for the Pickering series demonstrate this without doubt. In particular σ for 4100 Å, is as expected, unusually high. Only He II 5411 and N IV 3483 Å share a common value which we can consider as depicting the real kinematic state of the emitting atmosphere.

Coming to the flat topped profiles, we find that only a few lines display these and in many cases blending distorts the profile. C III 5696 Å sustains its flat topped nature throughout the list of stars for which we have been able to possess high dispersion spectra. The relative fluctuations of intensity over the flat top can have a two-fold origin. Either superposed blends produce them or they originate from the non-uniformity in spatial intensity distribution of a expanding shell. Such non-uniformity can be present in lines where selective processes of excitation prevail as in C III 5696 Å and

TABLE II

σ in km/s derived from the observed profiles.

HD 192103

Ion	λ	σ (km/s)
He II	5411	798
C IV (7–10)	5470	793
C IV (7–12)	4229	781
C IV (7–13)	3933	863
C IV (7–15)	3567	776

HD 192163

Ion	λ	σ (km/s)
He II	6560	1474
He II	5411	1274
He II	4860	1334
He II	4340	1461
He II	4200	1396
He II	4100	1882
Ni IV	3483	1236

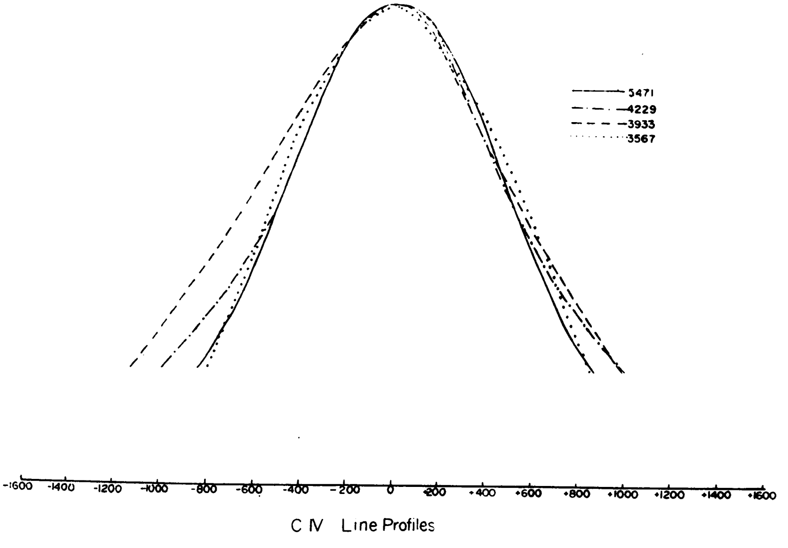

Fig. 14. Normalized profiles of four lines of C IV. These are the hydrogenic transitions that are relatively free of blends.

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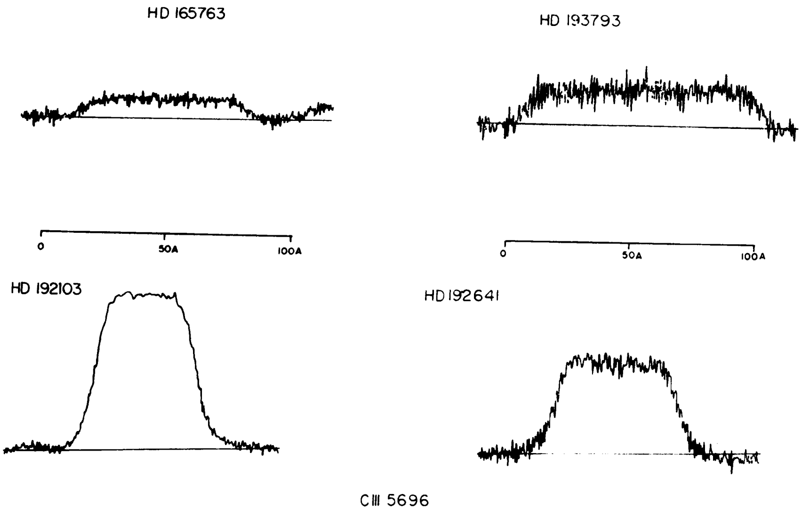

Fig. 15. The flat-topped nature of C III 5696 Å.

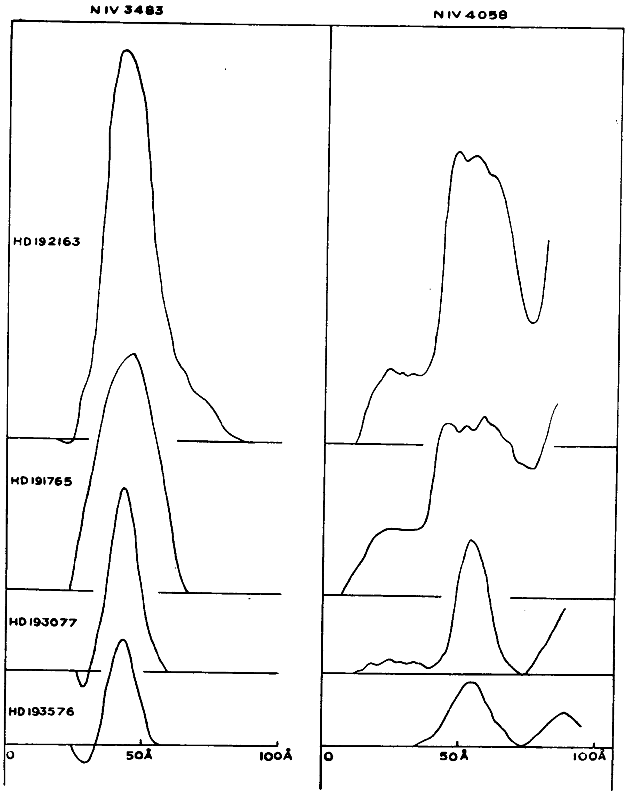

Fig. 16. Profiles of N IV 3483 Å and 4058 Å in a few WN stars.

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N IV 4058 Å. The profiles of 4058 Å in HD 192163 and HD 191765 bear no resemblance whatsoever to the corresponding one of N IV 3483. The same prevails for 5696 Å. The He I lines 3889 Å, 4471 Å, 5876 Å, usually are flat topped as in HD 192163. Kuhi (1968) has scanned the 10830 Å region in four stars with a 4A exit slit. All the stars show a violet displaced edge. HD 192163 shows the classical flat topped nature, HD 192103 has a profile similar to that of non-metastable lines and the other

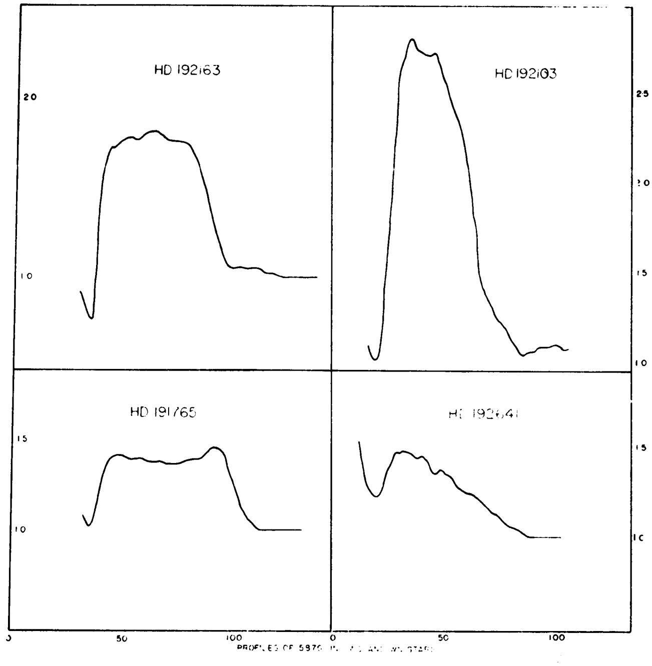

Fig. 17. Profiles of He I 5876 Å in WC stars and WN.

two, HD 192641 and HD 193077, have profiles in between with fine structure at the top. In the carbon sequence the He I lines have usually closeby emission lines that distort the essentially flat character of the profile. The association of the flat topped profile with violet displaced absorption in the neutral helium lines justify our concept of an expanding shell over and above the atmosphere that gives rise to the normal emission lines.

Besides random motions and the expanding shell, as broadening agencies, electron scattering plays a substantial role. Munch (1950) first invoked this mechanism to explain line broadening. The effect of electron scattering in widening the absorption lines of the O star when viewed through the extended atmosphere of the Wolf-Rayet star amply demonstrates the possibility. Recently Castor, Smith and Van Blerkom (1970) have satisfactorily explained the broad emission wings of 3483 Å in HD 192163 by non-coherent scattering of electrons.

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Smith and Aller (1971) have measured the total width at half intensity for both HD 184738 and HD 164270 for several of the ions. They have then determined a mean value of line width for each ion and plotted it as a function of ionization potential. A correlation between line width and ionization potential is clearly seen. They claim that an improvement over the past has been possible because they have taken into account that an ion will dominate the spectrum of a given element over a wide range of available excitation energies. Vertical bars in their diagram extend from the energy

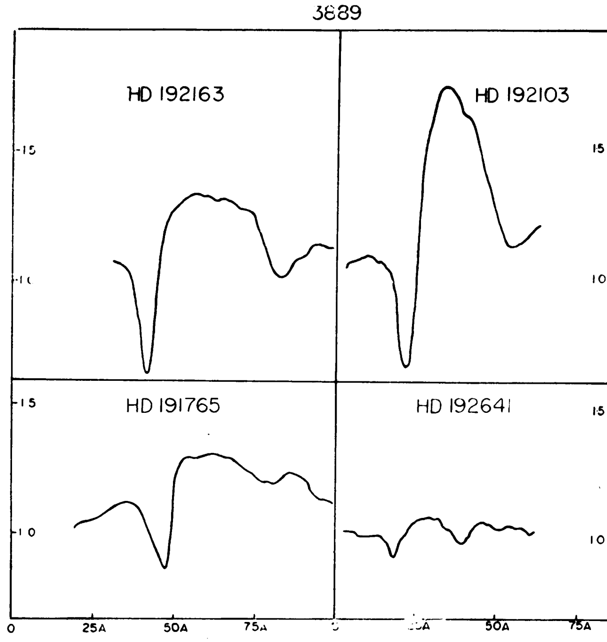
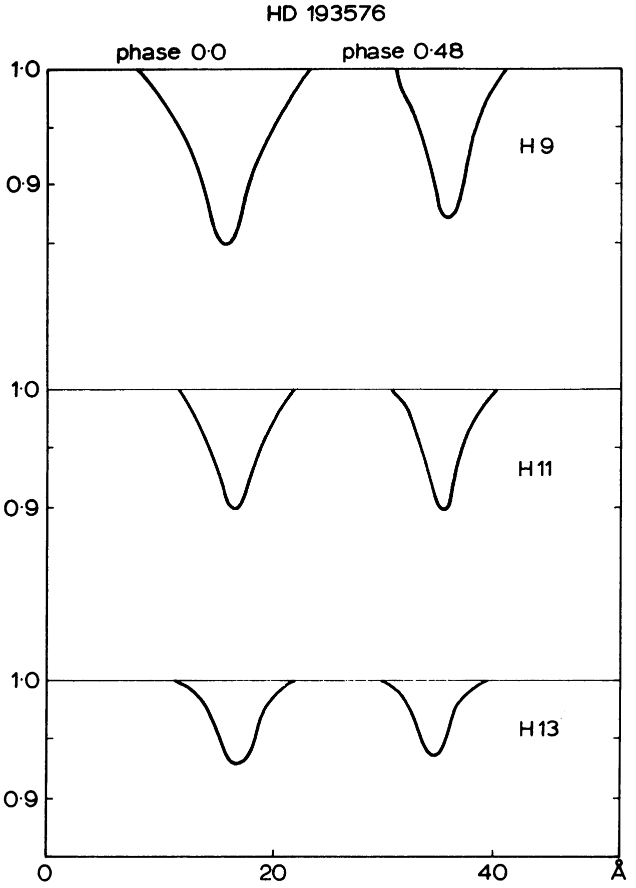


Fig. 18. Profiles of He I 3889 Å in WC and WN stars.

required to ionize the ion, to the energy needed to ionize the next stage of the atom. The good correlation observed eliminates the last outpost of opposition to Beal's model of a radially expanding symmetric atmosphere. Other objections to the model have been 'knocked out' systematically. The transit time effect is too small to be seen according to Castor (1970a) and optically thick shells in a radially expanding atmosphere can produce line shapes that simulate those caused by turbulence (Castor, 1970b; Castor and Van Blerkom, 1970). Smith and Aller favour the model where both velocity of expansion and the amount of energy available for excitation of the atoms in the atmosphere are monotonic functions of the radius. The spectrum of a given ion thus originates from a shell defined by the radius limits at which the available energy is in the range of the vertical bars in their Figure 7, and the widths of the emission lines reflects the radial velocity and range thereof in that region of the atmosphere.

Smith and Aller prefer material to leave the stellar surface at zero speeds and accelerate outwards. While deceleration is plausible they consider that accelerated motion is more likely. Hence, the correlation of ionization potential with line width facilitates the inference that the ionization decreases outward. The mechanism of acceleration is assumed to be radiation pressure. Many Wolf-Rayet stars are near the limit for



Profiles of H_9, H_{11} and H_{13} in the spectrum of HD 193576 at primary and secondary minimum.

Fig. 19. Electron scattering effects on the higher members of the Balmer series in HD 193576 (From Ganesh, K. S.; Bappu, M. K. V.; and Natarajan, V., 1967, *Kodaikanal Obs. Bull. No.* 184).

stability to radiation pressure. For a pure He atmosphere Rose (1969) states the condition for instability, due to radiation pressure on the electrons as $L/M \geqslant (L_\odot/M_\odot) \times \times 60000$. For $M = 10M_\odot$ the limit is $L = 600000\ L_\odot$ or $M_{bol} = -10$ mag. For a temperature of 40000 K the bolometric correction = 4 mag. Hence $M_V = -6$ mag., a value not inconsistent with Smith's range of values of M_V for the W's.

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Line intensities: There have been several efforts made in the past to provide line intensities for the various emission features. Several limitations prevail in utilizing these values effectively for physical interpretation. If a line is not freed of blends its intensity value is hardly representative of the observed transition. Work in the future will need to be very specific on this point and use only those lines for astrophyscal calculations wherein we can be sure of no contamination. Once this criterion

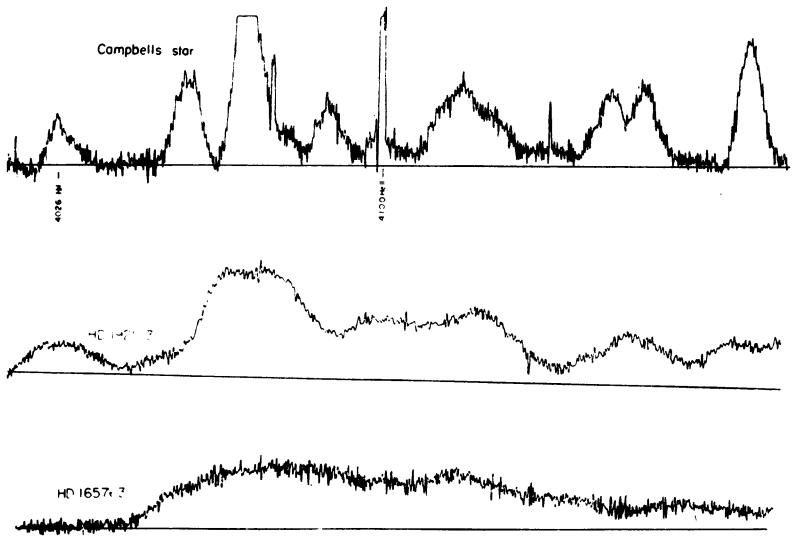

Fig. 20. Blending effects in Wolf-Rayet spectra.

is accepted there are few lines that cater to such measurement and one can be methoddical and precise in deriving the intensity. Practical difficulties in intensity estimation are enormous for several reasons. Firstly the latitude of the emulsion restricts the chances of accurate estimates of the peaks of the very strong lines. Here obviously the photo-cell has the last say in accuracy. The photo-cell coupled with good resolution can really provide a good line profile. The problem of a continuum exists and specially that of drawing in the wings of the line. Some of the C IV lines in the carbon sequence and particularly in the narrow lined objects are quite amenable to all these procedures of care. They also have by virtue of their similarity to hydrogen fewer limitations imposed from theory. They are, therefore, ideal for use in acquiring information on the WC sequence. The WN sequence in the domain 3400–6700 Å has only 5411 Å and N IV 3483 Å that come close to these criteria. An extension into the infrared may be helpful.

In determination of continua of these stars one has few guide lines which could be applied rigorously. Obviously the narrower lined objects are the most helpful in this regard. What appears as continuum at a specific wavelength for one spectral class range does not often serve the same purpose in another. The problem is severe in the blue. There are often stretches of continuum in the red which can be utilized with ease. This limitation applies not only for measurement of line intensities but more so for flux determination and magnitude estimates through narrow band photometry.

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DISCUSSION

Johnson: Did I hear you say that you thought there could be a red companion to HD 151932?

Bappu: The redness, of the companion I visualize, comes from the appearance of the slope of the energy curve in the near infra-red. I have no other basis. In fact when you take a spectrum you really have to overexpose the 8000 Å region in order to pick up features at 7000 Å and that I thought was rather anomalous considering some of the other Wolf-Rayet stars. It is not necessary that we should have a red companion for this purpose, but I have been biased for many years towards the possibilities of Wolf-Rayet stars looking red in one aspect and Wolf-Rayet-like in other. This has influenced my statement.

Kuhi: Could you give us some more details on your line identification procedure; for example, were you able to use more or less one value of ionization and excitation potential as a criterion?

Bappu: Yes, I have adopted procedures in line identification that follow earlier work. And I believe that these have been possible because of the very thorough work which has come out of the laboratory in Sweden of Edlen. It then reduces to identifying the right bumps with the correct wavelength assignments and intensity values and see if these fall in place. And most of them do. But I think it is really the laboratory analyses that furnish the key to the entire problem.

Kuhi: Could you not also say that the atmosphere is terribly complicated, that there are stratification effects?

Underhill: Not necessarily. The laboratory people excite these in hot plasmas. And they would get very different intensities for the multiplets in different ionization stages. You cannot take their relative intensities and expect to find the same. But within one multiplet the intensity ratios can be duplicated. I do think your study of the O VI lines is particularly beautiful. I have struggled with that region but could not satisfy myself whether it was there or not there.

Kuhi: As regards the O VI absorption, could you indicate how you establish its presence; I am not quite convinced about it.

Bappu: It is to some extent inferred indirectly. There is no clear cut indication as you see in the case of C IV or N V. The argument runs as follows. To add to the difficulty we have superposed on the same region a violet edge of the He I 3820 line originating from the transition ^3P–n^3D. So we establish first the presence of the O III violet edge a hundred angstroms or so earlier and measure the spacing of the O VI violet edges with respect to this in HD 192103. The same spacing is maintained in HD 165763 also, which is hotter and has less of the harmful effects of the He I violet edge. Hence the violet edges must exist in HD 192103 for O VI. Also you would have seen that I proved that the O VI lines were free of contamination by He II which falls in this position, since earlier members of the He II series were quite weak. Hence the emission features are uncontaminated. And when such a situation prevails you can only explain the steep slopes on the violet side as due to the violet edges only, since there can be no other obvious causes for the asymmetry in the profiles.

Underhill: You showed very clearly that C III 5696 is flat topped and no other C III emission lines are so flat topped. This, I think, is good evidence that the line is excited in emission in some particular way. Recently Nussbaumer has rediscussed the subject and although I have not studied this paper seriously yet, I believe that the tenure of his conclusions was that there was nothing particularly unexpected with λ 5696. If you were going to get a C III emission line, you ought to get λ 5696. I think the fact that this line has a distinctive shape in WC stars is evidence that something unusual is going on.

Bappu: I believe that in the four thousand five hundred angstroms of spectral region I have covered the aspects shown by λ 5696 are not shown by the other C III lines.

Smith: So, the absence of λ 5696 from the spectrum of HD 50896 does not surprise you?

Bappu: No. What bothers me is that when you have C IV established in the visual region and in the ultra-violet and then you have a comparable excitation of C III ions, where does λ 5696 vanish to?

Underhill: If there is no C III 5696 you do not see C III in any WN star; you do see weak C IV. I rather suspect that this can be accounted for by restrictions on the electron temperature. I shall expand this idea later when I give my talk.

Kuhi: The behaviour of C III 5696 is not definitely unique in WC stars since other C III lines tend to show the same effect. However, as Bappu has pointed out very clearly, it is almost impossible to get such lines free of blends, and, hence, the C III 5696 line (which is free of blends) remans the outstanding example of a flat-topped profile. The C III line at λ9710 also shows a somewhat similar behaviour, becoming flat topped at an earlier spectral class than C III 5696.

Westerlund: You started your paper saying that 19 Å mm^{-1} is a suitable dispersion for studying line identifications and line profiles in Wolf-Rayet stars, but towards the end of it you said that for defining the continuum you would need as high a dispersion as possible. Could you possibly specify for all of us here your thoughts on what dispersions should be useful for various types of problems particularly the one dealing with violet absorption edges. We have coude spectrographs available in more places now than before and that is why it interests us.

Bappu: I am happy that the Southern Hemisphere is getting so many coude spectrographs in operation. It is particularly gratifying that opportunities for looking at some of these very exotic objects are becoming increasingly available. I have a feeling that the large widths of these lines have tended to catch the investigators off their guard and tended to make them not so strict in the procedures that they need to adopt regarding the kind of dispersions, the slit widths required and so forth. The main idea has been to just get a spectrum, and when you have a broadlined object, it was supposed that opening the slit a trifle and admitting more light into the spectrograph would cause little harm to the information yielded. Hence, apart from the most striking details, faint features have been overlooked because of the lack of adequate resolution. My feeling is that dispersions comparable to say 20 to 10 Å mm^{-1} are the figures that one would require to see these undulations and so forth on the contours and to establish the identifications with some degree of confidence. It is not possible with dispersions of the order of 60 to 70 Å mm^{-1} to do anything better than just say that here is a large complex and the contributing ions are the following. As far as the continuum is concerned it is better to be able to get as much of the spectrum as possible with some resolution, before one undertakes to examine which region of the spectrum is really free of the emission lines. And, I think, it is particularly important to do so specially when one is going to use the scanner on these objects. One tends to do this in the case of the absorption line spectra where blanketing corrections for the absorption lines are made in the spectrum admitted by the scanner onto the photomultiplier. I do not believe it is going to be as simple as all that when you have the emission features coming through and, therefore, I would suggest that you really look for those few gaps between complexes and change the investigation accordingly to suit these continuum regions rather than decide *a priori* the wavelengths you would like to work at and then make appropriate corrections. When it comes to a question of intensities my feeling is that it is not as simple as it looks. First of all let us assume that you have the best of photometric procedures. Even then we must be prepared to admit the possibility of a large error coming in because of the well known fact known to every investigator of the WR stars that it is not easy to draw the continuum, and to extend the wings of these emission features to intersect the continuum. It is here that you can have errors of the order of 5 to 10 %, easily coming in, no matter what the photometry initially was to start with. I suppose you could overcome this problem by drawing in the wings many times and taking a straight mean by improving on your continuum many times and again taking a mean value, and thus reducing the overall scatter of your final measurements considerably. But this is a feature you should be well aware of before utilizing the intensities subsequently for hair-splitting theoretical conjectures. That is in the nature of things and I am sure that is something we are all going to have to live with and it is better that we realize it soon enough and be aware of the dangers that lie ahead. For line contours and general purpose photometry, wavelength identifications, I would settle for a dispersion in the neighbourhood of 10 to 15 Å mm^{-1}. Anything higher than that is probably welcome if you can afford it, and I do not think that you can really afford it for many objects besides γ_2 Velorum. So that is probably the limitation I should think you would have. On the other hand, using a 250 Å mm^{-1} spectrum and trying to go through what we did yesterday on the 10 Å mm^{-1} plates is probably something that you should not easily accept.

Johnson: When you observe absorption lines, do you always detect motions? Are you sure the absorption lines never belong to the Wolf-Rayet stars?

Bappu: I can be more specific in this matter, as regards HD 192641. When on the high dispersion spectra I first saw these absorption features, I had no access to plates other than what I had, which were just about three or four. And, therefore, I requested Olin Wilson to go through his collection of plates on HD 192641 and make measurements of these absorption features. And I think he had about 6 to 7 plates on which he made his measurements and he found absolutely no changes in the velocities as given by these lines. So presumably we are seeing the system face on.

Johnson: Do you know for sure that the absorption lines do not belong to a single star, namely, the Wolf-Rayet star itself.

Bappu: We have indirect means of saying that it possibly may not. Let us go back to the case of V444 Cygni where you have a definite case of an O companion and you have the superposed Wolf-Rayet star spectrum. You see the hydrogen lines shifting with respect to the emission lines. Now supposing the hydrogen lines did not shift with respect to the emission lines as they would if the orbit were face on, then I think another aspect that we must consider is the relative lack of contrast between the emission features and the continuum. You can easily determine the spectral type of the Wolf-Rayet star and when you have such a spectral type you assign mentally a certain intensity pattern for the emission lines. And when it gets washed out considerably, because of the presence of the other continuum which would be necessary to show up your absorption lines, then I believe the inference becomes simpler that you are really running into a situation of having the spectrum of another object rather than of having absorption lines intrinsic to the same star itself. The argument is that we pick out cases where we know we have O plus W or B plus W and then extrapolate to this situation wherein you have no relative movement and yet you have a duplication of the same features. The only thing lacking now is the relative velocities and, therefore, the arguments that lead to such a conclusion should be right.

Seggewiss: You mentioned that HD 151932 perhaps has a red companion which is not to be seen in the spectrum. Could it be possible to detect orbital motion from the emission lines of the Wolf-Rayet star?

Bappu: You should be able to detect orbital motion if the geometry of the system is favourable.

Seggewiss: I have taken a lot of spectra of this star at 12 Å mm^{-1} at La Silla.

Bappu: Such spectra on this narrow-lined object would be most useful. I do feel it is worth looking into as far as binary characteristics are concerned. I would say that you have some chance of success in this matter essentially because of the fact that I remember Struve considering the possibility of a 3.4 day period in spectral variations. Not only did he suspect periodicity, but he did find violent changes in intensity patterns of λ4542 and others which are typical of happenings under orbital motion and, therefore, you have every chance of bagging a good binary in this case.

Underhill: You may know that I have been assigned the job of summarizing the problems of Wolf-Rayet stars and their nature. Problems I have found in abundance and I have been getting a few more ideas about the nature. I thought it might be helpful if I put a short summary of yesterday's discussions and in particular some of the things that Bappu said at the end, with the hope that we might be able to sort one or two of these things out so that my list of problems of Wolf-Rayet stars and their nature might fit into one hour on the last day of the Symposium. We started with an abstract when Thomas discussed several problems of extended atmospheres. This comes down to the question of what regimes we should divide the atmosphere into in order to obtain a theoretical insight. Next I have to put down a very brief summary of a paper which we have not taken up yet and which will be expanded upon by Van Blerkom. These first attempts at theory by Van Blerkom and Castor in 1970 are important because this is the first paper that departs from the truly classical ways of handling a Wolf-Rayet atmosphere, yet the authors, by the difficulty of the subject, are forced to make quite restrictive assumptions. I mention this because I think you ought to know what these are. Castor and Van Blerkom are trying to interpret the He II lines plus or minus hydrogen in the case of a Wolf-Rayet atmosphere. You have a spherical expanding atmosphere of uniform characteristics, the model comes out with a photosphere of 13 $R_{\odot}$, the outside edge at 70 $R_{\odot}$ and they take a representative point at about 40 $R_{\odot}$. This gives you the dimensions. They assume an 'on the spot approximation', that is, anything that happens to the radiation is only concerned with the local temperature, pressure and so on. They use a thirty-level atom as the first way of dealing with non-LTE transfer effects, uniform expansion and the escape probability method, to take into account the effects of motion.

The results are only for WN6 stars, that hydrogen relative to He is 0.2 by number, N_e is about 10^{11}, T_e is about 10^5. This is the electron temperature. Here are some remarks which occur to me as points worthy of discussion; something about these has been implicity assumed in some of the things we are saying. Are we right or are we wrong? Castor and Van Blerkom showed that the He II lines with $n \geqslant 14$ were optically thin. They assumed the same to be true for Hε and then derived the relative H to He abundance. Under these conditions with $N_{\mathrm{H}}/N_{\mathrm{He}} = x$, is the optical depth, small in H and in He, at $N_e = 10^{11}$ and $T_e = 10^5$? I know the arguments but I do not recall that Castor and Van Blerkom actually calculated an optical depth, or a pathlength. Now do you assume on the above model that your real pathlength is something like 40 $R_{\odot}$ or is it a short distance and all the rest of the atmosphere does not count because it has the wrong velocity? How thin is that layer? The other thing I worry about is, given N_e and T_e, what is the free-free emission? Free-free emission gets very strong in the optical wavelengths at high temperatures. You have got a certain number of hydrogen atoms present, depending on the value of x which is 10, or considerably less. You also get free-free emission from He III and you get electron scattering. These last two are not really affected by the velocity field because they cover wide ranges. I am very much worried about not having calculated the optical depths of the hydrogen lines and for the free-free emission. However, that is our first theoretical attempt and it is quite good, offering considerable new insight. The next paper we had was that of Lindsey Smith. I will just pick out of this the assertions made here. They are not yet published, I believe, so I cannot give you a reference. Here a study of the evolutionary state of WN spectra was presented. Very interesting remarks that I extracted from Lindsey Smith's presentation are the suggestion that WN stars are pure helium stars at a helium-burning stage, the masses are from 6 to about 15 solar masses, the stars are Population I, there are ring nebulae around some WN but not WC stars, and the bolometric absolute magnitude is about -8.0 to -9.2 Following this we had further discussion by Hugh Johnson about the properties of some of the ring nebulae. We saw the uneveness of the intensity distribution in the nebula and considered the question of the radio radiation and what it told about the effective temperature. According to Morton we get effective temperatures running from 50000°–25000°. One remark that occurred to me on reflection and which, perhaps, you might discuss further or clarify now, is how do you get X equals 0, Y presumably greater than 0.99, Z an order of 0.01, for a pure helium, helium burning star. This I take to be the meaning of pure helium. One starts with the original Population I composition, which is X of the order of 0.7, Y of the order of 0.27, and Z around 0.03. Kippenhahn and colleagues have calculated evolutionary tracks for masses of 3 to 15 solar masses, but I do not remember them ending up with a pure helium core of the mass required for a Wolf-Rayet star.

Bappu gave us a beautiful summary of some detailed and careful work on the identifications in Wolf-Rayet spectra. O V is present in WN stars. The presence of O VI in WC stars but not in WN stars indicates that some part of a WC atmosphere must be hotter than any part of a WN atmosphere, although on the whole one gains the impression that the electron temperature is higher in WN atmospheres than in WC atmospheres. One wonders if a model containing 'cool' condensations moving in a 'hot' medium (cf. spicules and the interspicule medium of the Sun) is relevant for understanding Wolf-Rayet spectra.

Thomas: Those T_{eff} for the WC stars range enormously. Do you mean all WN stars have T_{eff} greater than all WC stars.

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Underhill: There is a wide range in nominal effective temperature but you have to have something more than just that, to explain the observed spectra.

Thomas: If I adopt what people put on the board, specially in Morton's table, I see a range from 22000° to 55000°.

Underhill: That has little to do for an understanding of the line spectra. I would start from the ground rule that the effective temperature has nothing to do with the spectrum. From the spectrum we find out the energy in the electrons. Then we know what energy has to be put into the atmosphere. Then we can go back and ask whether we can get this energy from the radiation field. If we cannot, we have to get it from elsewhere.

Thomas: Let me be specific about what you are talking about. What you have is an effective temperature that means something somewhere, but you are not sure what. And then you have a rise in temperature or may be a fall in temperature somewhere in the outer atmosphere, and the effective temperature is about the same for all WC stars and about the same for all the WN stars and it may differ between these two classes. Is that a good caricature of what you say?

Underhill: Your model is much simpler than any model I dare to make.

Thomas: So you are talking about T_e of about 10^5 for the line-forming medium which in some way increases from the $3\text{–}5 \times 10^4$ of the visual continuum. If I understand well the effective temperatures essentially refer to the flux, total bolometric magnitude.

Underhill: It refers to a total radiation flux.

Morton: It is essentially a color temperature – a ratio of short wavelength to long wavelength flux – with sufficient separation to give a useful comparison between the models and the observations.

Thomas: So in a very caricatured way again what Anne Underhill is saying, is that I have an effective continuum flux in the star and then, above that, I have a layer which does not contribute much to the continuum and it has an electron temperature much exceeding that corresponding to the continuum.

Underhill: That is the sort of model I am playing with in this discussion.

Thomas: If I ask Castor and Van Blerkom, what they would say is that really the effective temperature by itself fixes conditions in the stellar atmosphere. If I take what other people are talking about now, the electron temperature is fixed by something else, most likely a mechanical energy flux.

Van Blerkom: No. In the case of the WN6 stars we analyzed, the electron temperature in the envelope was higher than the effective temperature we assumed, implying that mechanical effects determine the electron temperature.

Thomas: From what Castor told me before I left, if you judge from the evolution of his thinking, his current position is the opposite of this.

Van Blerkom: His current position is based on an analysis of γ_2 Velorum, where he found that he did not require a higher envelope temperature than the core temperature, as it was necessary in the previous case.

Thomas: I think you need one general picture of Wolf-Rayet stars. I do not believe that in one case we can have mechanical heating and in another case no mechanical heating. Whatever we do it is going to have to apply to the class of stars as a whole. I think that is what we would like to agree on this week, to try to get some overall physical picture even if we cannot get the details.

Van Blerkom: That is what our simple model can accomplish.

Thomas: A simple model had better come out with correct general physical details. Otherwise it is not going to be simple.

Underhill: Let us wait till we have had the general presentation of theory before we go further into these details. I prefer Thomas' arguments that a model, however simple must be able to embrace the major number of things you have got here. I am trying to isolate what appears to me as significant factors of all that is given to embrace.

Thomas: That is basically what you are doing when you tell me that the effective temperature of the star is one thing whose meaning you do not know, and the electron temperature in the envelope in another thing. You are really focussing on what is the basic point. Does the effective temperature control the electron temperature or is it a perturbation, or is it the whole works. That overall picture is what one wants to get into in some detail.

Underhill: That is the great worry. For I am not sure. I have chosen one type of analysis, the paper by Castor and Van Blerkom which attempted for the first time to give us an electron temperature from the observations. It is a simplification which is literally necessary in order to make any type of progress. We have given you the answer. Now we are looking at some of the observations. I cannot help having intuitive feelings about physics and exhibit them on occasions like this. I have used these ideas to suggest that you might want to consider a model of the type used for the Sun. Now, you are a solar physicist, Thomas, and models for the Sun and all the things that are in them are familiar to you. I have associated with solar physicists over the last eight years and I have got used to hearing their words and to understanding them. Before that I could not care less about the Sun. It was a lot of words that I did not understand and the models meant nothing. I see that most of these people deal with stars and I assume that they are not familiar with solar terminology and detail.

Thomas: Now, remember one thing. For every solar physicist, there is another solar model and the situation is just as bad as for Wolf-Rayet stars. It does not look as though there is a consensus of opinion.

Niemela: I have a spectrum of one Wolf-Rayet star, HD 104994, a WN 3 star, with O VI emission lines.

Smith: Presence of O VI lines in high excitation WN and WC spectra was demonstrated at the last Conference, e.g. see Kuhi's review.

Paczyński: I was going to present some of the best established results of the theory of stellar evolution next Friday. However, the discussion we have heard here today convinced me that it may be worthwhile to spare about 10 or 15 minutes now for such a presentation. Let us consider a star with a typical Population I composition: the initial hydrogen content of 0.7, and metal content of 0.03. The evolution is not changed very much if the abundances are varied to some extent. The pre-main-sequence contraction is not likely to be relevant for the Wolf-Rayet stars. Let us consider the main sequence first. From the theoretical point of view this is the sequence of stars of various masses that burn hydrogen in their cores. The sequence has a width of about one magnitude in stellar luminosity. This phase of stellar evolution is terminated by hydrogen exhaustion in the core. It is followed by a brief phase of hydrogen burning in a thick shell, while the models remain close to the main sequence. They have no hydrogen left within their isothermal helium cores. As soon as the helium core mass exceeds about 10 % of the total stellar mass (the so called Schonberg-Chandrasekhar limit) theoretical models depart from the main sequence and cross the Hertzsprung gap on a thermal (i.e. Kelvin-Helmholtz) time scale.

Subsequent evolution depends on the total mass of a star. If this is below 2.5 $M_\odot$ then the contracting helium core becomes degenerate, and the star becomes a red giant with the hydrogen burning shell as the main energy source. As soon as the helium core mass grows to about 0.4 $M_\odot$ the helium flash takes place. If the total stellar mass exceeds 2.5 $M_\odot$ the contracting helium core does not become degenerate and helium is ignited soon after the departure from the main sequence. In all these cases the star enters the evolutionary phase of helium burning in the core and hydrogen burning in the shell. Helium ignition takes places while the star is a red supergiant. It is so atleast with those stars that have masses below 15 $M_\odot$. The situation with the more massive objects is uncertain. These massive stars have semiconvective regions in their interiors, and then nobody knows to what extent matter is mixed in such regions. Theoretical models of massive stars ignite helium either as blue or as red supergiants, depending on the assumptions applied to the semiconvection.

Stellar models evolve along complicated loops on the H-R diagram during the phase of core helium burning. Unfortunately, the size of those loops depends very strongly on the input physics and the details of the numerical technique used for the model computations. However, all the computations indicate that stars enter the red giant or supergiant region as soon as helium is exhausted in their cores. At that time we have a carbon-oxygen core surrounded by the helium burning shell source, the hydrogen burning shell source, and finally, the extremely extended hydrogen rich envelope. The carbon-oxygen core becomes degenerate in the stars with a total mass below 8 $M_\odot$. In a more massive object carbon is ignited soon after helium exhaustion, and the core never becomes degenerate. It is very unlikely that such a star may lose enough mass to become a white dwarf. It is more likely to explode as a super-nova at the end of its nuclear evolution. A star below 8 $M_\odot$ may ignite carbon explosively if the degenerate carbon-oxygen core will increase in mass to 1.37 $M_\odot$. However, if enough mass will get lost from the red supergiant envelope of such a star the core may never reach the 1.37 $M_\odot$ limit, the carbon will never get ignited, and the core will become a white dwarf.

Massive stars that are relevant for the Population I Wolf-Rayet stars spend 90 % of their lifetime on the main sequence. If we believe that Wolf-Rayet stars are post-main-sequence objects, and if we think that two different subgroups of W-R stars have different ages then it means that they originate from main sequence stars of different mass or different chemical compositions, and that these two subgroups do not make an evolutionary sequence. This statement applies to the single and binary stars as well. I think this statement is correct as I believe we cannot notice a 10 % difference in age by studying the distribution of stars. This 10 % is the age difference between a star that has just exhausted hydrogen in the core, and a star that explodes as a supernova, provided the two stars had the same mass on the main sequence.

Westerlund: Would you comment on the question of where the evolution of massive stars would end up according to your ideas?

Paczyński: It depends on what you assume about the evolutionary status of a Wolf-Rayet star. I hope to show convincingly in my talk later that if you have a Wolf-Rayet star in a binary, that Wolf-Rayet star must be essentially a helium star. There may be a small hydrogen envelope left on top of the helium core. The luminosity of such a star is about the same as the initial luminosity of the hydrogen star from which our helium star has been formed. The temperature of the star depends on its radius, and the radius depends on the amount of hydrogen you have in the envelope, and also on the possible instabilities. You cannot meaningfully compare the radii of theoretical models, which are assumed to be in hydrostatic equilibrium, with the radii of Wolf-Rayet stars which are not in hydrostatic equilibrium: we do see a rapid mass outflow from these stars. However, you may meaningfully compare bolometric magnitudes. It is very important to have reliable bolometric magnitudes for Wolf-Rayet stars. One magnitude is sufficient for a meaningful comparison.

Thomas: You say there is no hydrostatic equilibrium in Wolf-Rayet stars. I say that is the real problem; it is not obvious where the departure from it sets in. The reason is that, in some of your interior calculations that you are talking about, you do not have hydrostatic equilibrium either.

Paczyński: If you do not have hydrostatic equilibrium in the centre, it is likely that the whole star will be blown out or it will collapse on a dynamical time scale, i.e. one hour or so. But we know that Wolf-Rayet stars live for at least 100 yrs!

Thomas: It seems that there are three points here which are getting mixed up very successfully. One point is what the bolometric magnitude of the star is; another point is whether I do have or I do not have any hydrogen in the shell; and the third one is simply defining a Wolf-Rayet star. After all, definition is based on the spectrum, and has nothing to do with the absolute luminosity, nothing to do with the size of the star. It is just a very characteristic spectrum. If you take that last point very seriously, then you must remember that we have Wolf-Rayet spectra characterizing these so-called massive stars which should be derived from some other consideration; we have Wolf-Rayet spectra characterizing the central stars of the planetary nebulae, which have their own mass; and you do have Mrs. Gaposchkin's characterization of the solar rocket UV spectrum. Now I think this is a very difficult point, because, if they talk about the absolute luminosities and bolometric magnitude of the stars, that is just something characterizing the mass of the star. And if from this I come up to the effective temperature of the star, again, that is something characterizing the internal structure of the star. Then if I say I want to decide whether or not this star has hydrogen in the envelope, the fact that the star may be evolved or whether I have a pure helium core is almost irrelevant because I do not see how you get rid of the hydrogen in the envelope, unless some real catastrophe leads you down to that point where you have only He burning. It is these three considerations we must place in perspective. If I say I must have a He star *because of these internal characteristics*, that has nothing to do with the spectrum which you observe. It may or it may not have any hydrogen in the envelope. If you embroider to make the star with no hydrogen in that part of the atmosphere producing the observed spectrum, that requires too some real catastrophe. So now we have to say what are the kinds of catastrophes that get rid of all the hydrogen of the envelope. Then I have to answer the question, and I have to reckon always the fact that there are three types of stars. Those, according to some people's analysis, which have no hydrogen. Those, like the central stars of the planetary nebulae, for which nobody claims I do not have a lot of hydrogen. And thirdly, the solar atmosphere where there is no attempt to say there is no hydrogen. I would be awfully suspicious if I am going to say the Wolf-Rayet spectrum primarily reflects lack of hydrogen. If you are going to say there are stars which have a Wolf-Rayet spectrum, which do not have any hydrogen at all, that simply means that the Wolf-Rayet spectrum is a phase phenomenon, and it really covers a wider area of objects.

Paczyński: Let me make one thing perfectly clear. We should make a distinction between the interior structure of stars and their spectral characteristics. If we accept observational evidence according to which Population I Wolf-Rayet star have bolometric magnitudes of -8 or -9, and masses close to $10\ M_{\odot}$, then we put rather strong restrictions on the possible interior structure of those stars. In fact we may get such luminosity and mass combination for a helium star only. I mean there must be predominantly helium in the stellar interior. If you want to add (or to leave) some hydrogen at the top of the star, that is all right with me. As long as the mass of the hydrogen rich layer is small, it is not going to affect the mass-luminosity relation for those objects. In fact, Kippenhahn's models with mass exchange have some hydrogen left at the surface. If you consider Wolf-Rayet nuclei of planetary nebulae you find that their masses are believed to be close to 1 $M_{\odot}$, and their luminosities are of the order of 10^4 $L_{\odot}$. Unless the present day theory of stellar interiors is entirely wrong, such objects must be in a helium shell burning phase of evolution, and they must have degenerate carbon-oxygen cores. I believe that the available information about masses and luminosities of Wolf-Rayet stars is sufficient to establish with a fair degree of certainty the interior structure of those stars. The reliability of the available information is a different thing. We have to realize that the interior models have very little to do with the appearance of stellar spectra. In particular they cannot explain what is the mechanism for the observed mass loss, estimated to be in the range of 10^{-6}–10^{-4} solar masses per year. I think this mass loss is the most critical phenomenon one has to understand in order to explain the observed spectra. There is no theory known that could predict this kind of mass loss. This must be a different phenomenon from that discovered in early type supergiants by Morton, as there is a 2 or 3 order of magnitude difference in the estimated rate of mass loss. The Morton-type mass loss may be understood in terms of radiation pressure in resonance lines being the driving force, as demonstrated by Lucy and Solomon. This mechanism is not efficient enough to operate at the mass loss rate increased by a factor of 100 or 1000. This is a difficult problem and you cannot expect that simple interior models may solve it. These models may account just for the observed masses and luminosities. These are two different things.

Thomas: That is precisely the point I am trying to reach. Separate things carefully. What you mean when you talk about a Wolf-Rayet star, and when you talk about a Wolf-Rayet phenomenon. It is the Wolf-Rayet atmosphere spectral phenomenon which embraces a wide variety of stars. Then, separately, you can talk about a class of objects which have a helium core if you like, a class of objects which have a carbon core, a class of objects like the Sun; all of them betray in some sense a Wolf-Rayet spectrum. But do not confuse the two concepts. I think we are saying the same thing

Paczyński: We agree on that statement.

Underhill: That is the clearest thing we have heard this week!

Conti: That was a very good argument about Population I Wolf-Rayet stars. It is predominantly helium in the interior; hydrogen is not seen in these objects. Two independent arguments say the star is mostly helium.

Thomas: But neither of them implies the other.

Conti: No, neither of them implies the other, but I want to emphasize that there is no observational evidence for the presence of hydrogen in Wolf-Rayet stars.

Thomas: I disagree with your second point. Agreed we may have a central structure which does not have any hydrogen in it; but it has hydrogen in the outer layer, unless some way the star succeeds in blowing it off. So you have to reconcile the two sets of observations.

Conti: We have Population II Wolf-Rayet stars, which are nuclei of planetary nebulae. Now we believe that one solar mass stars can very often get to the state where they loose all their hydrogen envelope and you are left with a helium core. The interior evidence says it is a helium-burning star. And you look at them spectroscopically and it looks like a Wolf-Rayet star. Again you do not see any hydrogen.

Underhill: You do not see some hydrogen in some of the stars.

Conti: It appears to me that if you take this star and you peel off most of the hydrogen, for reasons which are perhaps mechanical or something else, either a large mass or a low mass star looks like a Wolf-Rayet star.

Thomas: I disagree with this and I say you should better consider what I quoted about the Sun.

Conti: The Sun may look like a Wolf-Rayet star in the UV spectral regions, but in the rest of the spectrum you see lots of absorption lines which you never see in Wolf-Rayet stars.

Thomas: Because I am looking in a different part of the atmosphere. You see, this is my argument. If there is a kind of an atmosphere region where I produce what looks like a Wolf-Rayet star, then I should better understand how I produce that kind of atmospheric region.

Conti: I agree about the phenomenological argument you are making. The Wolf-Rayet phenomenon in a sense means a certain spectral region or atmosphere that gives you emission lines. But there are lots of stars that have their entire atmosphere in this way.

Thomas: There are stars whose internal characteristics or whose blast characteristics produce an interior configuration, and associated with that interior configuration, an atmospheric configuration which comes we do not know how yet, which has a Wolf-Rayet spectrum.

Niemela: I want to make a comment on a possible mechanism to have interior models that could produce Wolf-Rayet stars. If we have complete mixing in a star, then, when it enters the main sequence it has high abundance of C and O. Then, if it burns H through the CNO cycle the luminosity of the star rises and when it leaves the main sequence it has high abundances of N. May be we can explain in this way the two sequences and the overluminosity, because in complete mixing the luminosity is proportional to the mean molecular weight. This may also explain why WC stars are less luminous than the WN sequence stars.

Morton: I think that the references to the solar UV spectrum really confuse the issue. The solar UV spectrum does not look very much like the UV spectra we have of Wolf-Rayet stars.

Thomas: Not really, if you are naive enough.

Underhill: There is a fourth type of objects with a very Wolf-Rayet-like optical spectrum. There are two of them known, namely, Sco X-1 and WX Centauri, both of which are X-ray sources. There may be a third object belonging to this group.

Paczyński: I object against calling the Sun a Wolf-Rayet star. For me the main characteristic of a Wolf-Rayet star is the tremendous rate of mass loss. This is the common feature of all the WR stars. This phenomenon produces high density expanding envelopes, and within those envelopes the prominent emission lines are produced.

Thomas: Let us be very clear now. Never have I called the Sun a Wolf-Rayet star. I only say it looks like a WR spectrum in the UV. Mrs. Gaposchkin, an old time spectral classification person, says, at the immediate first appearance, the rocket UV solar spectrum is like a WC6 spectrum. Let us be very specific. First, there is a Wolf-Rayet object, as which you classify some stars. Then there is what you may call a Wolf-Rayet phenomenon which may be exhibited by an atmosphere in producing a spectrum which looks like this spectrum, or some of whose spectral characteristics resemble those spectral characteristics of WR stars. Be very careful. I am pushing you, Morton, because to me the WR spectrum is characterized by an atmosphere with a high rate of energy input and momentum input. A Wolf-Rayet star has such an atmosphere. So may something else. May be it is mass input that causes this, may be something else. That is why I tried to make these three categories of transfer effects: energy, momentum, and mass.

Morton: Are you not putting too much weight on Mrs. Gaposchkin's comment? Because really, what particular feature in the UV spectrum of the Sun reminds you of a WC6 star?

Thomas: The lack of nitrogen compared to carbon, the presence of high excitation phenomena. Go back fifteen years ago, when we were talking about what were the features of the solar chromosphere and corona and things like this, before you had a UV spectrum. Then we got one, and it displays those excitational ionization effects that one had in only one class of stellar spectra: the WR. Remember we discuss a conceptual evolution in understanding how to produce spectra. What is the big characteristic of the outer solar atmosphere? Twenty years ago one said the solar corona began at 50000 km outside the surface. Now we say it begins at 1500 km, a high density region, where we have lots of things happening we would not have thought of before. We are trying to understand the mechanism of production of that solar structure.

Walborn: Do you know the equivalent widths of these emission lines in the Sun and the wavelength region roughly? Because for WC6 one of the criteria is that the lines are extremely broad and I wonder if $\Delta\lambda/\lambda$ is compatible with that kind of classification for the Sun.

Thomas: You know, one of the most difficult things in the solar spectrum is how do you get the observed widths for ordinary things like Ca II and Mg II. You cannot do it with thermal motions only, you have to have some kind, of motion other than local thermal motions; the broadening mechanism for spectral lines profiles is one of our major problems. There is obviously a big difference in degree between these and WR problems, but that is what we are trying to understand; what is the physical mechanism and what size does it take in various situations?

Walborn: Yes, but I think it is important that a criterion for calling something WC6 is the line width.

Thomas: No, Mrs. Gaposchkin emphasized that *presence* of ions, not how wide the lines are, is the major point. The whole phenomenon of macroscopic motions, macroscopic turbulence in stellar atmospheres, is not understood at all.

Walborn: Morphologically, I object to placing something in a category if it does not satisfy an important criterion defining that category.

Thomas: Well, criteria either characterize something or they do not.

Kuhi: If Mrs. Gaposchkin were given the spectrum of γ_2 Velorum now, taken in the rocket UV, and were to compare it with the spectrum of the Sun, I am sure she would say that there is no resemblance.

Thomas: Remember, caricatures are what I am talking about. Let me return again to these non-classical effects which I assert are necessary to produce a stellar spectrum: population and transfer effects. They take you from the deepest atmospheric layer to the interstellar medium. Think back on what was the point of spectral classification when people first set it up. They thought that if they gave you all the characteristics of a stellar spectrum, that any two stars whose spectra were identical, were exactly the same object. Probably that is true; the only trick lies in specifying all the spectral features you need to know and what you mean by 'identical objects'. Some theoreticians in the field of stellar atmospheres, of which I am *not* that kind at least, assert that if you give somebody the effective temperature and the gravity, they will tell you all about the stellar atmosphere. I deny this possibility. I myself do not know yet what information you need to know in order to predict the spectrum of everything from photosphere to the interstellar medium. I do not know either, in terms of what observation I have, enough to be able to infer atmospheric structure. I think the Wolf-Rayet spectrum is a good example. In spectral classification, one first talked about an O star, a B star, a Wolf-Rayet star. Then one started to talk about a B star with five luminosity classes. Now we start to talk about a B star with five luminosity classes, an infrared excess, a UV excess, and with certain characteristics of a velocity field, interstellar wind, etc. *If* we really know all these characteristics, we can distinguish whether two objects may be identical. But in the Wolf-Rayet situation, there is a *Wolf-Rayet spectrum* but not a unique one. We talk about different kinds of Wolf-Rayet spectra; the central star of a planetary nebula almost looks like an ordinary Wolf-Rayet star which we think has 10 solar masses because some other star, with a similar looking spectrum was measured as a component in a binary. So I have a Wolf-Rayet spectrum. For some stars we talk about Population I, Population II, and something else. All these stars have Wolf-Rayet spectra, they also have certain mass characteristics. I had a big lecture from Lindsey Smith to the effect that we should not confuse these things by saying the Sun belongs to them because anybody knows the Sun does not resemble much in any way a 10 solar mass Wolf-Rayet star and that is true. But the Sun certainly resembles a one solar mass central star in a planetary nebulae in mass characteristics, may be only in mass characteristics. It may be it has no other resemblance to a planetary central star which has possibly a He core burning, the Sun not being that at all. So you have to define what it is with respect to which you say two things are similar. If it is our aim to be able to look at a star and say two stars, with the same set of observational parameters must be identical, then I assert that we do not yet know what are those sets of observational parameters with respect to which they must be identical. Until we know that, if there are some features of the stars which are similar, then I say those stars are similar with respect to the conditions fixing those features. When I talk about the effective temperature, then I can be talking about the model in which the star is built: the effective temperature for a given radius. When I talk about the observations in a particular region of the star where I produce O VI, C IV, whatever the lines are, then I assert that is a very interesting spectral region, atmospheric region, and what we want to do is to ask how do you produce that? If you make the assertion that if you tell me what the effective temperature is, and the gravity, then you will make a star, then remember we have four kinds of non-classical effects in the atmosphere that disprove this assertion: population effects, and three kinds of transfer effects, energy, momentum and mass transfers. Now if I look at the current stage of evolution so far as model atmosphere calculation go, then, all of these non-classical things at one time were thought to be irrelevant; today one accepts population effects, that is, non-LTE effects, still preserving radiative equilibrium, hydrostatic equilibrium and the like. That is the basis on which Auer and Mihalas computed their B star and O star models. But they are models. If in these models I introduce a mechanical energy transfer, I introduce another effect. If I introduce a momentum transfer, it is another effect. What do we need to introduce the WR model? Kuhi asserts that the main characteristic is a mass transfer or mass loss. That may be the main characteristic of several classes of those objects defining Wolf-Rayet spectra. May be it is true for only the purest kind of Wolf-Rayet spectra. May be in those I only need this mass input. Do I need in addition a mass flow through the star? Is that sufficient? Or must I also produce a momentum flow through the star? Must I also produce an energy flow through the star? Or is it sufficient, from the assertion that Castor makes with respect to one star, that I need only to have a radiative energy input? I am trying not to be dogmatic in saying this. I am only saying be very clear what you say semantically; be very clear what you are saying by implication when you say a spectral class implies a particular stellar model.

Underhill: You are being semantic. All these things were not considered to be irrelevant in the early studies. First, the physical problem was reasonably well analysed by Milne and by Eddington in 1928, but the problem was not susceptible to analytical analysis. So the decision was made to leave out much detail and to do the simplest case.

Thomas: Oh, yes, I agree. Eddington, if you read all he wrote, was aware of all these things in there. But people have offered models which they claim to represent stars, that ignored all these effects. But now we have better data and better knowledge of non-equilibrium physics. So now we can begin to handle them. But we are nowhere near other than scratching the surface. Let us just be honest and admit it. Either you believe your simplified models represent reality or you are doing computing exercises.