SECTION IV

CHAIRMAN: D. C. MORTON

O AND Of STARS

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1. Introduction

My intention here is to discuss the 'high temperature' portion of this symposium and call attention to those stars that are called Of. There are some similarities in spectral appearance to WR stars, e.g. emission lines. I should first like to define what I think are the essential differences among four groups of hot stars;

O stars: Stars that have *only* absorption lines in the visible spectrum. Type O is distinguished from type B by the presence of He II 4541 at MK dispersion. It may be that some (supergiants) O stars will have emission lines in the rocket UV region but this description will be primarily concerned with ground based observations.

Of stars: These are O type stars that also have λλ 4634,40 N III in emission above the continuum. In addition to normal O star absorption lines and N III emission, they may also have other lines in emission. I will discuss this further below.

Oe stars: These are O type stars that have emission in the hydrogen lines (or at least at Hα), but with no emission in N III or in other lines. I personally think that this small class of objects is related to the Be stars in their evolutionary status and in their emission mechanism.

WR stars: These stars are primarily characterized by emission lines. The *only* absorption lines seen are *violet shifted* (P Cyg type). Although in some cases emission lines appear which are similar to those found in some Of stars, the latter types *always* have some *unshifted* absorption lines present. Several Of stars have P Cyg profiles in some lines.

I think these definitions will clearly differentiate between Of and WR type stars. My personal belief is that the evolutionary status of Of and WR stars is completely different, although for some lines the emission mechanisms may be similar.

Some of the work I will describe today will be published soon in the *Astrophysical Journal* (Conti and Alschuler, 1971) but other material concerning these spectra is newly presented here. I will first briefly review the results described there and then go on to more recent work.

2. Relation Between O and Of Stars

Conti and Alschuler (1971) discussed 16 Å/mm blue spectra of 130 O type stars, obtained at the Lick Observatory 120″ coudé. About fifty of these stars had absolute

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[*] Visiting Fellow, 1971–72.

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magnitudes which were obtainable from memberships in clusters and associations with 'well established distances.' From direct intensity tracings made of these spectra, it was possible to measure equivalent widths of certain lines normally used in spectral classification. The spectral classification adopted was entirely based on the measured ratio $\lambda\lambda$ 4471 He I/4541 He II.

This relatively high dispersion and availability of direct intensity tracings also enabled us to make a careful decision as to whether or not a star was 'Of' using the definition above. Perhaps the most important result from that paper is shown in Figure 1, where the O and Of stars are plotted with separate symbols. There is a relatively clean separation between the O and Of stars in that the latter are more luminous and hotter than normal O stars. Earlier than O6, *all* O stars are Of; for later types all the brighter O stars are Of, up to O8.5. The O9 and O9.5 supergiants do not show N III in emission, but as we will discuss below do show λ 5696 C III in emission.

Also shown in Figure 1 is an evolutionary track of 30 solar masses, adapted from Simpson (1971), using the temperature scale and bolometric corrections of Morton (1969). This figure shows there is nothing anomalous about an Of star, it is merely a more massive O star that is hot enough and/or luminous enough, to have N III in emission. There can be age-zero Of stars, and evolved Of stars, just as for normal O stars. The dividing line for O and Of stars is not very sharp but is near 30 solar masses.

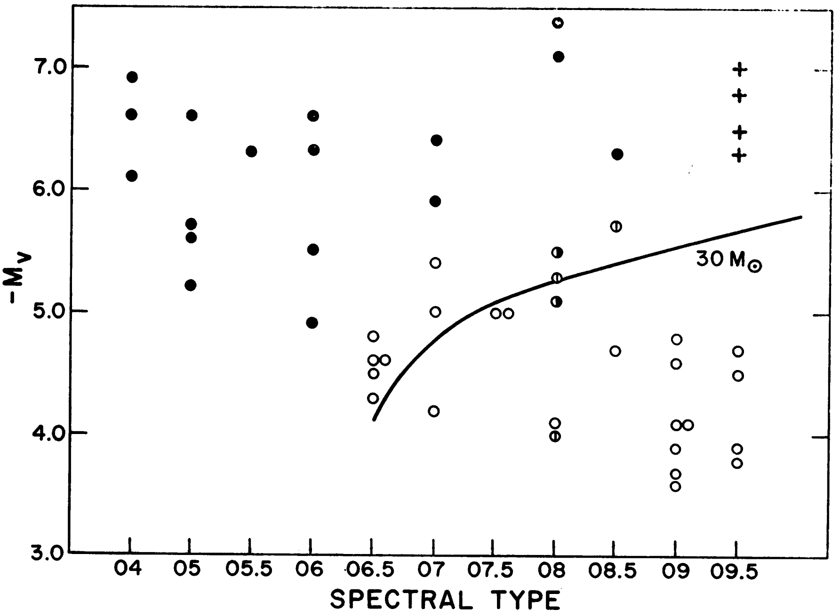

Fig. 1. HR diagram of the O stars of Conti and Alschuler (1971). The O stars are *open circles*, the Of stars, *filled* or *half filled circles*. *Circles with vertical lines* are luminosity Type III and *crosses* are O9 supergiants. Also shown is an evolutionary track of 30 $M_\odot$ from Simpson (1971). The Of stars are concentrated in the brightest and hottest part of the HR diagram.

The fact that Of stars are generally brighter than O stars can be used as a luminosity indicator. Conti and Alschuler (1971) also discussed an absorption line luminosity indicator, namely 4089 Si IV/4143 He I. Using the same O stars with known distances, they were able to calibrate this ratio and demonstrate that for stars of type O6.5 and later, an estimate of M_v could be made. In earlier type O stars these lines disappear but for such hot stars there is not too much of a spread in M_v. Almost invariably, those O stars with a large ratio for Si IV/He I also had N III in emission, and conversely.

Conti and Alschuler (1971) also discussed the appearance of λ 4686 He II. In most O stars the line is strongly present in absorption. In some Of stars this line appears in emission or is not present, and in some Of stars the line is strongly present in absorption. There does not seem to be any certain relation between the absolute magnitude of an O star and the strength of He II. The tendency to emission of λ 4686 does not appear to be related in a simple manner to T_e or L. It is likely that this line is excited by a 'selective' mechanism via emission at Lα and a ground state line of He II.

3. Emission Lines in Of Stars

Figure 2 is a schematic version of Figure 1. The O and Of stars are all found within the region of the HR diagram enclosed by the outside solid lines; the O and Of stars are separately found above and below a line near the 30 solar mass evolutionary track. The hotter, brighter regime is where N III 4634,40 is found in emission. Mihalas (1971)

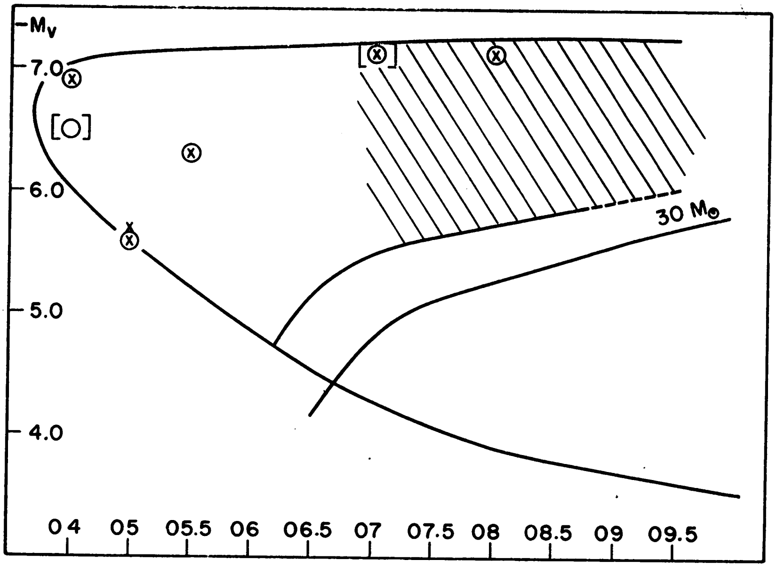

Fig. 2. Schematic version of Figure 1. The lower line is a 'ZAMS' for O stars, the upper boundary the bright M_v limit. The line, partly dotted, near the 30 $M_\odot$ track is the rough dividing line for Of and O stars. The cross hatched area is where all stars showing λ 5696 C III are found; also the regime for the lines λ 4485, 4503. The X denotes stars with C III λ 4647, 50 in emission, *open circles*, Si IV λ 4089, 4116 is emission. The two stars with brackets have M_v estimated from their spectral types only.

has suggested that N III emission is due to a recombination from an autoionizing level just above the N III continuum. The absence of N III in O9 and later type supergiants may indicate that there is not yet enough N IV population. There must be also another ingredient besides sufficient N IV population necessary for the formation of N III emission else *all* O stars hotter than O9 would show these lines in emission. It is tempting to suggest that this other condition is an extended atmosphere, but other physical conditions might be imagined.

Singlet C III 5696 appears in emission in those stars inside the cross hatched portion of Figure 2. I am not yet certain that all stars in this region have this C III emission (and conversely) since I do not yet have complete spectral data but it looks as if it will be so. The C III emission extends into the region of O9 and O9.5 supergiants, which do not show N III emission. C III emission lines are not found earlier than about type O7. A C III λ 5696 emission mechanism has been discussed by Castor and Nussbaumer (1972) for WC stars. It may be the same mechanism for these Of stars but this is not yet certain.

There are two emission lines at λ 4485 and 4503 in some O stars which have long defied identification (Wolff, 1963). These two lines are roughly of equal strength and do not show any absorption components, nor do any absorption lines appear at these wavelengths in other stars. It was a surprise to me to find that the appearance of these lines correlates very nicely with the appearance of emission at λ 5696 C III. As far as my data go, and they are nearly complete, when the former lines are present, the latter are, and conversely. This strongly suggests that *these unidentified lines are* C III. An interpretation in which the lines behave similarily to C III without the ion being C III is not completely ruled out but appears less likely. It is important to note that the $\lambda\lambda$ 4485, 4503 lines are found in O9 and later supergiants and are not found earlier than about O7 If. This behavior is rather dissimilar to that of N III emission suggesting that that ion is unlikely to be the source of these lines.

The remainder of the emission lines I will discuss here are only found in a few Of stars; apparently the mechanism of emission needs a rather unusual stellar atmosphere and/or a very extended envelope.

Triplet C III 4647,50 are found in those stars shown in Figure 2 with the ‘X’ sign. Four Of stars with these lines in emission are considerably hotter than any Of stars showing the C III singlet in emission, but two later type Of stars show both. These latter stars have P Cyg profiles in hydrogen lines and some other lines and are probably an extreme example of the Of phenomenon.

Si IV 4089,4116 are found in those stars with the open circles in Figure 2. In the two later type Of stars these lines show P Cyg structure. Generally when a star shows these lines in emission it also shows the C III triplet, but there is one counter example for each emission feature. Unfortunately, there is no obvious luminosity effect for either of these emission features as two Of stars on the age-zero main sequence show both ions in emission. The emission mechanisms for S IV and C III (triplet) are not well understood.

Si III 4552,4567 is found in emission in only one Of star, HD 108, which is also shown in Figure 2 as the star at spectral type O7 If with C III and Si IV in emission. N IV 4057 is seen in emission in the two hottest stars in Figure 2, both of which also show Si IV emission. In both of these stars, and only these stars, N V absorption at λ 4603,4618 is also seen. This is also the case for two other very early Of stars discussed by Walborn (1971). These data may suggest a relation between emission at λ 4057 and N V 4603,4618 being present.

4. Emission Lines and Classification in Early Of Stars

As I have pointed out, all early O stars are Of. Figure 3 shows a montage of spectra of six early type Of stars. The absorption line widths are not very dissimilar for Hγ, He I and λ 4541 He II, and are similar to the emission line widths in N III. The spectral classification is given by the ratio 4471/4541. Although HD 46223 has been called O4 by Abt *et al.* (1968), the observed ratio of these lines is more nearly O5 by comparison with other stars classified by Morgan and his associates. However, there are stars which have decidedly weaker λ 4471 He I and these stars I have classified O4 by analogy with Abt *et al.* (1968).

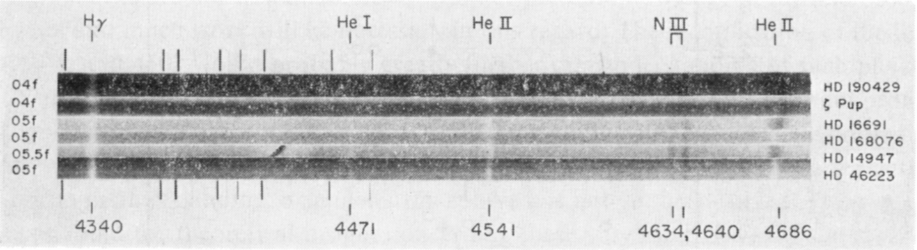

Fig. 3. Montage of six early Of stars. Spectral types are given by the ratio 4471 He I/4541 He II. Although the emission strengths at N III are not too dissimilar, the He II line at λ 4686 differs drastically from star to star. The emission line widths are similar to the absorption line widths, except for the two O4f stars in which λ 4686 is broader.

We see in Figure 3 that the strengths and breadths of N III emission are a little different from star to star but not markedly so. There is a drastic difference in appearance in λ 4686 He II among these stars. It changes from a strong absorption line in HD 46223 to a strong emission line in HD 190429. This behaviour does not depend strongly on either T_e or L as all these stars have similar values for these parameters. It presumably does give us some useful information as Auer and Mihalas (1972) have suggested this line can be strongly in emission *only* in the presence of an extended envelope.

5. Relation Between N III and He II 4686 Emission

Figure 4 shows the measured line strengths of λλ 4634, 40 N III and λ 4686 He II for the Of stars. We are unable to measure with confidence equivalent widths of He II smaller than about 100 mÅ so that the ordinate scale is 'squeezed up' in this region.

The open circles are Of stars of type O6.5 and later; the filled circles are earlier types. We note immediately that there is no difference in behavior of these lines between these classes.

For λ 4686 He II in absorption, but of various strengths, there is little correlation with the strength of emission of N III. Auer and Mihalas (1972) suggest this behavior of He II can be understood in terms of non-LTE and plane parallel atmospheres alone. For λ 4686 filled in, or strongly in emission, they suggest an extended envelope must be present. N III emission is also generally stronger in these stars. There does not seem to be a predictable relation between the strength of N III emission and He II emission except in these most general terms. This suggests the emission mechanisms are dissimilar although both may require certain atmospheric conditions, e.g., an extended atmosphere. Roughly half of the Of stars have λ 4686 absorption, and half have this line in emission.

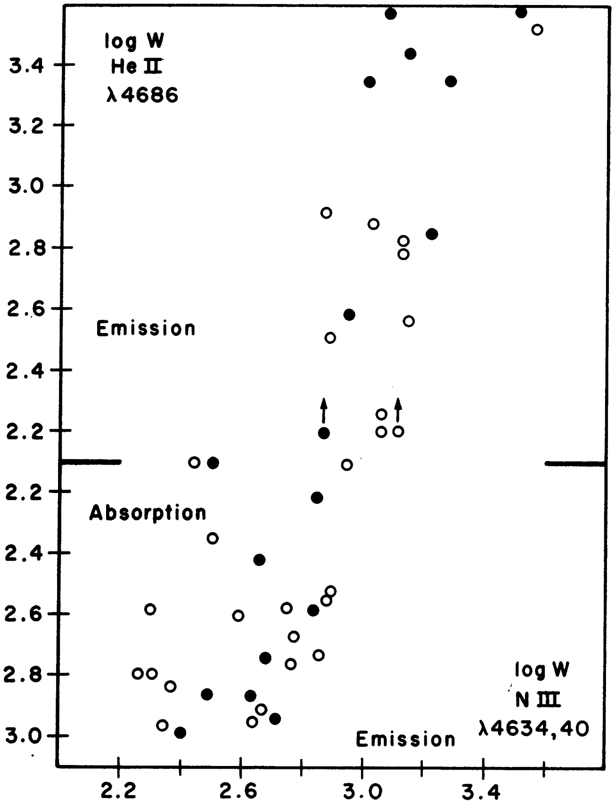

Fig. 4. Measured line strength (log W) of N III 4634, 40 and He II 4686 in Of stars. *Filled circles*, stars O6 and earlier, *open circles*, type O6.5 and later. There is little correlation between these lines except when He II is in emission.

6. Discussion

I would like to stress what I think is an essential difference between Of stars and WR stars; the former have a more or less 'normal' O star photosphere plus a few emission lines; the latter have a completely different atmospheric structure in that a 'normal' photosphere and its associated absorption lines are not present. There is also an apparent composition difference since Of stars have definite evidence of the presence of hydrogen in their atmospheres, but as far as I am aware, this element has *not* been demonstrated to be present in WR atmospheres. My feeling is that all Of stars have extended atmospheres. For some Of stars we have direct evidence of this, e.g. P Cygni profiles in the rocket UV region, or the visible region. Extended atmospheres probably come about because these stars are hot enough, and/or luminous enough so that radiation pressure in resonance lines (or continuum?) is sufficient to drive out the atmosphere.

It appears that the microscopic mechanism causing the emission lines of several ions, e.g. N III 4634, 40, C III 5696, can be understood as peculiarities in the term structure of the ions. Probably these mechanisms are the same in both Of and WR stars. Other emission lines are not well understood with our present knowledge of the microscopic physics and much work will be necessary in this regard. The identification of the lines at 4485, and 4503 would probably greatly further our understanding of such physics.

An important question is the mass loss rate for Of stars, given the P Cygni profiles we observe in some of them. It seems that this rate is not significant on an evolutionary time scale. I am not certain this is beyond all doubt as the non-LTE line formation problem in an expanding, extended atmosphere has not yet been solved. There is still lots of room for theoretical insight concerning these very interesting Of stars.

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DISCUSSION

Alcaino: How many O stars are found as members of very young open clusters such as those analyzed by Walker?

Conti: NGC 2264 has one O star, 15 Mon; and NGC 2244 has five O stars. 15 Mon is one of these stars in the first diagram that I classify as an O III star that has emission lines; NGC 6530 has two O stars, 9 Sgr being one of them. I did not include NGC 6611 because I did not have a good distance, which is unfortunate, for there are four O stars in it. It has moduli given in the literature ranging from

12.6 to 11.2 depending on who did it. I think you could get the distance from the B stars, but people have not yet tried this.

Underhill: I know, I tried to reach it from Victoria, but it was too far south and the stars were too faint.

Paczyński: Some of those stars do show P Cygni type profiles for some lines. What is the typical velocity shift? What is the expansion velocity?

Conti: Up to about a few hundred kilometers per second in the visible. Hutchings has made some measures for two stars in the upper part of the HR diagram, one of them HD 152408, and I really cannot improve on those numbers. Velocities measured in the rocket UV come out about 1–2 thousand km s^{-1}.

Sahade: From your description of the Of spectra it was not clear to me whether you found any lines with Wolf-Rayet like characteristics similar to those that Robert Wilson found?

Conti: I want to look into that, but I have not had a chance to do so. I am not convinced of the presence or absence of really extended wings. There are a few stars that have rather broad lines; ζ Puppis is a good example. But I do not think that is what Wilson was talking about. I think the emission lines in ζ Puppis are rather broad but other Of stars also have lines this broad.

Sahade: What is your opinion?

Conti: I am going to go and look very hard, but there is nothing obvious to me. I think my spectra are at least as good as Wilson's, but he may have been looking harder.

Morton: To see the Wilson effect one really wants to make the measurement with a photoelectric scanner in order to get a better signal-to-noise ratio than possible with the photographic plate.

Underhill: I did not believe in it at first, but I found that I had to put it in. The continua are just not flat in the 4600 Å region but rise up by 3 to 5 %. It is very hard to draw the continuum in this region because of the changing photographic sensitivity.

Conti: I have used the same plates to measure interstellar λ 4430, which is a somewhat similar measurement. At least down to the 5 % level I was getting the same as the photoelectric measures Wampler reported, so if these emission lines are less than 5 % over the continuum they may still be there and I have not seen them yet. I have generally only one plate per star. (*Added 21 September, 1971*): I looked 'real hard' at my tracings of 9 Sge and there is *no* extended emission near λ 4640.

Underhill: If it is less than 5 %, you have to average several plates to see it.

Bappu: I remember that Henry Smith looked at ζ Puppis both in the infrared and in the blue violet and seemed to suspect that there was a Wolf-Rayet companion to ζ Puppis. In other words, he did find certain spectral details that were not purely Of and this led him to suggest a possible Wolf-Rayet companion.

Conti: All I can say is that the width of the emission lines that I have shown you in ζ Puppis is a little wide for a 'normal' Of. But then HD 190429 needs some attention too; it has absorption lines of the same width as the N III emission and the He II is much broader. The point is that if ζ Puppis is a Wolf-Rayet plus O one expects velocity variations. So far as I know there are none. That is an interesting question. I will confess that the emission width in ζ Puppis is a little large; however, you do see absorption lines which are also very wide.

Morton: The measurements of ζ Puppis with the Narrabi intensity interferometer indicate that any companion must be considerably fainter by at least 1 mag. and probably by as much as 3 mag.

Bappu: If it is two magnitudes fainter, you would not see it in the spectra either.

Wood: Would you comment about the energy budget of these stars? Yesterday, at lunch, you and Lindsey Smith said you thought radiation pressure was sufficient to support an extended atmosphere and get a Wolf-Rayet-type spectrum, but now you point out that in the instability part of the HR diagram, the mechanical energy flux may be important.

Conti: Lucy and Solomon calculated for two O-type supergiants, that the radiation pressure in resonance lines is sufficient to provide an expanding envelope. As you proceed hotter it is going to still be sufficient to remain extended. These supergiant stars have been calculated to have mass loss. I am not sure mechanical instability has anything to do with extended atmospheres in these stars. I would like to point out the possibility of radiation pressure in the continuum to form an extended atmosphere. The calculations of Lucy and Solomon, by the way, have not treated in detail the line formation problem, which is not a trivial calculation.

Morton: I think in fairness to Lucy and Solomon, they did more, the full details are not there, but they did go one extra step. They tried to put the transfer effects in photons being absorbed in lines, transferring momentum. It is not all quite there, but at least they have gone quite a bit further than these back-of-the-envelope arguments.

Thomas: They did treat the aerodynamic interaction of this material with the rest of the atmosphere?

Morton: No.

Paczyński: They were unable to construct static models above a certain line on the HR diagram, because of the radiation pressure in resonance lines.

Thomas: Did they solve the differential flow problem?

Paczyński: They found that the mean free path is sufficiently small to produce the hydrodynamic flow. Recently Lucy wrote me that the mean free path of the heavy ions with respect to hydrogen is small but not negligible. This results in the heating of the medium, because the ions of carbon or nitrogen are accelerated significantly before they lose their energy by means of collisions. This may be a heating agent for the expanding envelope. Still the mean free path is sufficiently small to justify hydrodynamic description.

Thomas: Once you justify the hydrodynamic description, then you have to solve the hydrodynamic flow problem.

Paczyński: They have done it. This is in a recent letter I received from Lucy. In the paper which is published they obtained a steady flow in the expanding envelope. If you cannot find a static solution then the next simple assumption you may make is that you have a stationary outflow, like in the solar wind. You may get a critical point of the flow, and you may calculate the rate of mass loss.

Thomas: What about the stability of the solution? If one introduces mechanical heating, then that is the critical thing so far as asking what efficiency of conversion do I have. I have then a mass flow, a momentum flow and an energy flow, and I want to ask, is this assumed steady flow pattern really stable against breakup?

Paczyński: This has not been done. However, the results obtained for the steady flow have been compared with the observations, and the agreement was quite reasonable. We can compare line profiles and equivalent widths, and the agreement is fairly good.

Conti: In the rocket UV lines.

Morton: There I think I disagree. For example, the calculations predict that only one strong line should appear, say N V, whereas the rocket observations show that at the same time, C IV, O VI, and Si IV are also strong. Moreover, the predicted profiles do not have zero intensity over a large part of the line as suggested by some of the observations.

Paczyński: Another small question to discuss is where are the Oe stars to be placed on the diagram.

Conti: There is one star in NGC 2244, with M_v near the main sequence.

Paczyński: If I understand you properly you find Of stars all the way down to the main sequence. Of supergiants have been found to loose mass rapidly according to the observations in the ultraviolet. If we exptrapolate this finding to all the Of stars, then this phenomenon should operate on the main sequence too. So, there is no disagreement between Lucy and Solomon and the observations at this point.

Conti and Morton: They predicted mass loss for B-type main sequence stars.

Conti: By the way, there are three very luminous Of stars that show strong P Cygni profiles in the visible. None of them have been looked into in the rocket UV region, presumably the P Cygni profiles will be stronger there.

Sahade: At the beginning of your talk, Conti, you said that you were going to explain the difference in widths of certain lines in Of stars.

Conti: What I said and I thought it was important, was that the widths of the emission lines were not the same for N III and for He II. There were cases where He II was considerably broader than N III. There were cases, for example ζ Puppis, where the widths were both very large. There were cases where these lines were of about the same width. That suggests to me that at least the region of the stellar atmospheres in which these lines are formed is not the same. The only additional comment that I can also make is that when one looks at the very broad emission line profiles, in some stars they are Gaussian while in other stars, as in ζ Puppis, they look suspiciously like scattering profiles.

Thomas: You mean you are dealing with flat-topped profiles?

Conti: No, they are not flat-topped like Kuhi's description of λ 5696 in WC stars. In some cases the profile is narrow, in others it gets very broad.

Underhill: You cannot exclude that ζ Puppis, with its double line spectra, could be double, because you could have a Wolf-Rayet with a continuum two magnitudes fainter and the strong lines, such as λ 4686, would still stand out against the combined two continua.

Conti: It is possible, but I do not believe that ζ Puppis has a WN companion.

Underhill: I would like to make one other remark. I find it fascinating that the Hα emission is so weak in Of stars. There is no suggestion ever made that O stars are short in hydrogen. They have almost all their hydrogen ionized in the outer atmosphere and the result is very little emission. This is a point that I wanted to make about the apparent absence of hydrogen lines in Wolf-Rayet stars. We can have hydrogen present and fully ionized and yet not see the Balmer lines strong in the emission.

Morton: Do you ever see the O VI lines in absorption in any of the Of stars?

Conti: None of these O stars have shown it. Lots of them show O III in absorption and probably a few of them show O IV, but I have not really played around with O VI. I have not observed O VI.

Walborn: Since this is the day for quasi-Wolf-Rayet phenomena, I would like to start out with some slides of certain OB stars, and work my way back through some remarks about Of stars and comments on Conti's beautiful results, and then end up with a couple of comments about a Wolf-Rayet star. (For illustrations see *Astrophys. J. Letters* **161**, L149; **164**, L67; **167**, L31; *Astrophys. J. Suppl.* **23**, 257.)

These are 63 Å mm^{-1} classification spectrograms 1.2 mm wide, taken at Kitt Peak National and Cerro Tololo Inter-American Observatories, in connection with a program to attempt refinement of the MK spectroscopic parallax system for OB stars. The classification O9.7 is an interpolation between the previous types O9.5 and B0; the primary criterion is comparable strengths in the two lines He II 4541 and Si III λ 4552. In O9.5 supergiant standards the He II line is much stronger than the Si III line; conversely, in the B0 supergiant standards the Si line is by far the stronger. This top star is a very luminous star, HD 195592 O9.7Ia. I say that because not only is the Si IV, which is a primary luminosity criterion, extremely strong at λλ 4089 and 4116, but also there is no feature at λ 4686 of He II. The negative luminosity effect at λ 4686 is one of the primary, well-established luminosity criteria at late O and B0, that is, it is very strong in the dwarfs, it declines smoothly with increasing luminosity, and it is completely absent in the most luminous stars at O9–B0. You will note also in HD 195592 the N III blends at λλ 4634–40–42, which are the ones that come into emission in Of stars. We see absorption there in this very luminous star, which is very interesting because at O9.5, these lines are not present or they may be very weakly in emission in the most luminous stars. The second star, HD 191781 (ON9.7 Iab), is of similar spectral type although slightly less luminous, and I think you can see the very striking behaviour in the region of λλ 4640–50, in which the N III blends are quite strong and the C III blend is almost absent. This is very unusual, of course, and this is the reason that I have introduced the classification 'ON' for such spectra. For contrast here is HD 194280 (OC9.7 Iab) with the same spectral type and luminosity class and yet the N III line λ 4097, which is very strong in the other two stars, comparable almost with λ 4089, is extremely weak, although it is there. Also, the C III blends at λ 4070 and 4650 are stronger even than in the more luminous star.

Considering next some B2 supergiant classification standards, the expected behaviour of N II λ 3995 is greater strength than λ 4009 of He I in the Ia star and about equal strengths in the Ib. At B2 Ia the maximum of the N II spectrum occurs within the two-dimensional MK reference frame. Then we have the star HD 14443 (BC2 Ib) which has an interesting, very peculiar spectrum; if you just looked at it out of context, you would say it is not peculiar as are other spectra that show strange configurations, which are however, partly accidental results of the normal two-dimensional variation in the criteria. This star is peculiar because there is a very strong contradiction between the behaviour of the helium and silicon lines, which are the primary basis of my classification with this higher dispersion, and the carbon and nitrogen lines. (The classification is explained in detail in *Astrophys. J. Suppl.*, No. 198). The star cannot be earlier than B2, it cannot be B1.5, because of the absence of Si IV. It cannot be B2.5 because of the weakness of Si II relative to He I, so it has to be B2, on the basis of the criteria. But, for a B2 spectrum, the CNO line intensities are completely abnormal; λ 3995, which should be about equal to λ 4009, is just barely visible. I classified it B2 Ib, by the way, and there is no deficiency of silicon, because Si III λ 4552 is normal in intensity relative to He I, for the luminosity class. The normal behaviour in a B2 supergiant in the region of λ 4630–50 is, comparable to intensities in N II λ 4631 and the oxygen blends at λ 4639–42 and 4649–51. In HD 14443, however, λ 4650 is stronger than λ 4640, indicating a contribution from C III at the former wavelength, and λ 4631 is essentially invisible. Finally, consider HDE 235679 (BN2.5 Ib:); oxygen appears to be completely absent and the very unusual green region of the spectrum is dominated by the N II lines at 4601, 4607, 4614, 4621, 4631, and 4643 Å. This star also has abnormally large He/H line intensity ratios, which is the reason for the noted uncertainty in the luminosity classification. Next consider the spectrum of HD 201345 (ON9 V), which is the prototype of the nitrogen-enhanced, late-O dwarfs. All helium-silicon criteria indicate that it is in fact a dwarf, but the N III lines are comparable in strength to those in a supergiant. Moreover, the great strength of N III λλ 4634–40–42 (greater than that of C III λ 4650) also provides evidence that the star is a dwarf, since these lines are never seen in absorption in high-luminosity stars at spectral type O9 (e.g., HD 210809, O9 Ib), although they may be present weakly in normal dwarfs (e.g., 10 Lac, O9 V), but with less intensity than C III λ 4650.

The fact that these particular N III lines have a selective negative luminosity effect at O9–B0, as does He II 4686, suggests that the selective emission effects in these same lines in the O stars may be a related phenomenon, and that the latter may, therefore, also be a luminosity indicator. These effects have formed the primary basis of a proposed luminosity classification for the earlier O stars. The following extension of the f designation is introduced: ((f)), strong λ 4686 absorption and weak N III emission; (f), λ 4686 absorption filled in or 'neutralized' and N III emission; f, λ 4686 and N III emission. Main sequence stars are those with strong λ 4686 absorption (e.g., HD 46149, O8.5 V; 15 Mon, O7 V((f)); HD 46223, O4 V((f))), intermediates have weaker absorption or no feature at λ 4686 (λ Ori, O8 III((f)); HD 225160, O8 Ib(f); HD 15558, O5 III(f)), and the most luminous stars are those classified Of (HD 151804, O8 Iaf; λ Cep, O6 If; HD 15570, O4 If). When the present two-dimensional classifications are compared with published equivalent widths of Hγ in O stars, a remarkably tight correlation is found to exist as early as O4, in the sense that the Hγ strength decrease with increasing luminosity.

The present conclusions concerning the O stars are in substantial agreement with those of Conti. It will be noted that his definition of 'Of' includes all three categories used here, so that some 'contradictory' statement are only apparently so. The principal disagreement concerns the luminosity effect in λ 4686 (and hence the luminosity classification earlier than O6.5); Conti concluded that it was not a reliable indicator. However, a star-by-star consideration of his figure shows that the number of stars in serious disaccord is actually rather small and includes two peculiar objects (weak P Cyg profiles at λ 4686), as well as a few (in the region of the Perseus Arm) for which there may be some uncertainty in the absolute magnitudes assumed. Further investigation of these particular cases is needed. Finally, I would like to drawn your attention to the remarkable high-excitation spectrum of HD 93129, which is so far unique and in several respects appears intermediate between those of a very early Of star (e.g., HD 190429, O4 If) and certain Wolf-Rayet stars. This star is one of four in the region of η Carinae classified O3 because they are earlier than the earliest MK standards. HD 93129 is additionally unusual in that it has N IV λ 4058 emission of greater intensity than that at N III λλ 4634–40–42, and N V absorption at λλ 4604 and λ 4620 of intensity comparable with that of He II λ 4541. These characteristics are also possessed by the Wolf-Rayet stars HD 92740 (WN7-A) and 93131 (WN6-A) of the same region, but in addition they show other N III lines in emission; P Cyg profiles at hydrogen, helium, and N V lines; and much broader and stronger λ 4686 emission. I would like to suggest that further study of HD 93129 may contribute to an understanding of the late-type WN stars of the narrow-line sequence (Hiltner and Schild, *Astrophys. J.* **143**, 770). Also, it is of considerable importance to determine directly whether HD 92740 and 93131, which show high Balmer lines in absorption, are in fact spectroscopic binaries or not.

Niemela: I have some spectrograms of HD 93131 in which absorption lines of the Balmer series upto H 11 are visible; it looks very much like a WN 7 + O spectrum. I have also measured radial velocities of some lines and they are variable.

Walborn: I might mention that among the old Harvard observations of HD 93129 variable P Cygni emission at the hydrogen lines is reported, so it is an extremely interesting star. I have never seen another one like it, with N IV emission stronger than N III.

De Groot: I would like to point out that in HDE 235679 there is a series of N II lines, that you find also in P Cygni.

Walborn: I should mention that the N II lines between λ 4601 and λ 4643 are there also in χ^2 Orionis, the normal B2 Ia standard; you can see them, but they are much weaker relative to the carbon and oxygen feature, than is the case in HDE 235679.

De Groot: P Cygni is believed to be a star of quite normal composition. There may be a little over abundance of hydrogen.

Underhill: The N II lines in the middle B supergiants are queer lines in the sense that they get very, very strong. If you compute a middle B supergiant model atmosphere with $\log g = 2$, which you can do, you can compute from that the wings of the Hγ line following Strom and Peterson using LTE, and fit the model to the star satisfactorily. Then compute the N II lines using LTE as the only available method – a sort of zero order approximation – and you get lines very much too weak. This is one more indication that the lines of the second and third spectra of the metals in supergiants and stars with extended atmosphere are very sensitive to local conditions. The minute you get to an atmosphere with an electron density between 10^{11} and 10^{12}, if the model of the hydrogen lines means anything, then your simple line theory is well off and you have got to do the theory properly.

I just wonder what the empirically assigned small difference in luminosity class and spectral type mean. Have you really got the correct empirically selected type lines to be sure that all your stars have the same basic flux coming through them, that is, effective temperature? You then ask, if I did the solution for the hydrogen spectrum correctly, will the rest give me something that I can relate to luminosity? Is it just a difference in the extent of the atmosphere? The part that bothers me – and I am curious – is that when you assign these various letters (and empirically you have probably got a very consistent system) with those luminosity classes, have you any outside confirmation of difference of luminosity classes that are significant?

Walborn: Yes, this brings up a very basic point about the MK approach to the problem of spectral classification. What Miss Underhill says is right, the MK approach is empirical and is essentially hypothetical at first. It is an empirical arrangement of the spectra according to certain arbitrarily defined criteria which are a function of what is available in the spectrum and which also may be a function of the resolution and of other things. Of course these are not blind hypotheses; there was earlier work and there are physical reasons behind the choices of criteria, but the question of the validity and the usefulness of this kind of approach can only be answered in terms of the calibration in terms of physical parameters. One must derive the absolute magnitudes and I can state that for some number like 90% of the OB stars, the calibration work that I have done indicates a smooth relationship between the two-dimensional classification and the physical parameters. Of course we are primarily concerned with getting spectroscopic parallaxes in order to do galactic structure and the relevance of this work to stellar evolution is incidental. The sort of thing I have been showing is a by-product and not illustrative of the main purpose of this work. I think it illustrates, however, that the MK system provides a very useful method for discovering and describing unusual objects with respect to a very tightly defined two-dimensional reference frame.

Underhill: I am still wondering about the meaning of this redefinition.

Walborn: I have in my paper a comparison with previous MK classifications and one can see no systematic differences. In the case of the O stars my experience indicates, in comparison with the Morgan and Hiltner lists, essentially no disagreement greater than one tenth of a spectral class.

Conti: Walborn may be right about this business of the classification, but I would like to add a few cautions. He is using a luminosity classification based on He II. I personally feel that the luminosity dependence of He II has not been well established in the early O stars independently of the absolute magnitude. Now, what he did show was a very nice correlation between Hγ equivalent width and the He II 4686 equivalent width. If a star had λ4686 in emission he called it a Type I, if it had strong absorption he called it a Type V, and anything intermediate as Type III. If λ4686 was in emission the Hγ equivalent width was weak and conversely. That may or may not be related to absolute magnitude. It may be related, as I said, to some non-LTE population effect.

Walborn: That is right The illustration does not say that there is an absolute magnitude effect in Hγ for the O stars. All it shows is a relationship between two spectroscopic features. However, if the proposed luminosity classification is correct, it follows that there is a luminosity effect in Hγ.

Conti: The second point I wanted to talk about is the MK classification which I have also redone. My spectral classification actually agrees well with Walborn's. An interesting sidelight is θ Orionis; I called this star class O7, the MK class was O6. Peimbert has studied the Orion Nebula and he has very good reasons to believe from the size of the nebula that it is excited by a 38000° star which is exactly the temperature of an O7 star.

Walborn: There is nebular emission in the helium lines in the spectrum of θ Orionis.

Conti: I want to emphasize again that the N IV emission is seen in the two stars you showed with N V in absorption and I want to call people's attention to the fact that of the four or five stars that have N IV emission, all have N V absorption and this may be telling something about how the lines are formed in emission. I also want to say by my definitions that I noted earlier that HD 93131 would be called an Of because it has absorption and it would be very important to see if it is one star or two stars.

Walborn: I think the absorptions are blue shifted.

Conti: The N V are also blue shifted?

Underhill: They are definitely blue shifted. The emissions on tracings made of a Radcliffe plate are always broad. You get the idea of a drowned Wolf-Rayet. The N V lines are sharp.

Conti: You do not see N V absorption in any Wolf-Rayet star.

Underhill: N V absorption does come in many Wolf-Rayet WN stars. It is very strong.

Smith: Anne Underhill is correct. Violet absorption edges on the N V lines 4603, 4620 are usual in

WN spectra. However, in the spectrum of HD 9974 (WN3), N IV 4057 is absent and there is no absorption on the N V lines. So the correlation noted by Conti appears to apply to WR stars as well.

Paczyński: What is the fraction of binaries among the Of type stars?

Conti: I know of three Of binaries and I am now working on their spectra. Two of these systems are double-lined and have been studied in the past. One of them is HD 228766 which was called a WR star but is now called on Of, and the other is BD + 40°4220. Both these are of considerable interest because their mass ratios derived 15 to 20 yrs ago show that the Of star has a mass lower than the O star. I personally do not believe that result. If it were correct it would suggest that the Of star is going to become a Wolf-Rayet star.

Underhill: And there is one other case. Sally Heap showed me a tracing of an O sub-dwarf with a WN8-like spectrum. It is like that picture of HD 93131. I showed her my tracings of a Radcliffe plate of this star; almost identical in all respects.

Paczyński: Does it mean that out of 130 Of stars only two are members of binaries?

Conti: Two Of's out of about 50 Of stars are known double line binaries. There are a number of O-type binaries.

Morton: For how many of these O stars have you measured radial velocities to see whether they are variable?

Conti: There are only two that are known Of binaries with double lines. There may be some more. I think, I may have found double helium lines in another Of star.

Morton: For how many of these stars do you have more than one plate?

Conti: Mostly I only have one spectrogram. I would say that two thirds of the stars are listed in the radial velocity catalogue. It may be possible to detect velocity variations by measuring my plates and comparing to the catalogue value. I am working on this now. I think my statistics are premature at present.

Smith: We seem to be having a little session here of putting odd things on record. There is one I would like to contribute which I have noticed amongst the WN spectra; it concerns the absorption components of the helium Pickering lines. You can see from Table 4 of my review paper that absorption edges are definitely observed on the Pickering lines in 3 of the WN stars studied, the WN4, WN7 and WN8 stars. Let me describe first the WN7 star, HD 151932 (it is a member of Scorpius OBI). The derived H^+/He^{++} ratio is 1.0, i.e. there is hydrogen present, and its contribution to the strength of the emission lines is equal to that of helium. However, a plot of the strength of the absorption lines is smooth, apparently indicating that hydrogen does not contribute to the absorption at all. That strikes me as exceedingly odd. I would also note that it rules out the possibility that the lines arise in the spectrum of a companion star, since I believe that in O absorption spectra the hydrogen always makes some contribution to the absorption.

An even more extreme situation occurs in the WN4 spectrum of HD 187282: The derived H^+/He^{++} ratio is 0.4, so again hydrogen is contributing to the emission lines. The odd-*n* lines show an absorption component, narrow, double and violet shifted; the even-*n* lines, to which hydrogen contributes, show no absorption components. Similarly the spectrum of the WN8 star, MR 119, shows strong violet shifted absorption lines on the odd-*n* Pickering lines, but not on the even-*n* lines. Apparently the hydrogen somehow masks or fills in the helium absorption; this strikes me as even more peculiar than the previous case. I note again that it is obvious that such absorption cannot be due to a companion.

Underhill: In the very early O type stars, where you run down the equivalent widths of Hβ, 4542, Hγ, etc, the contribution due to hydrogen absorption is quite small.

Smith: Is that correct? Is that corroborated?

Walborn: Hβ measurements have been done and compared with Mihalas models and the hydrogen lines hardly decline in intensity at all, to the earliest types, a non-LTE effect. If you look at the grating Atlas, in which the sequence goes all the way to O4, you can see that the hydrogen lines seem to have almost constant intensities all the way from O8 to O4.

Conti: If you can see what you are calling Balmer lines down to H16, then you are sure it is hydrogen.

Underhill: We still have to solve that problem. If you get a very hot plasma you are going to ionize all the hydrogen, and there will be very little chance of recombination with the consequent emission of the Balmer lines. In the Of stars Hα emission is very weak. You know there is plenty of hydrogen in these stars yet you would never say that the emission is strong. We cannot determine the abundance of hydrogen from the emission-line strength without setting up and doing the calculations for a hot extended plasma.