SESSION 4.

OTHER LUMINOUS STARS WITH EMISSION LINES.

Chairman : V. NIEMELA.

1. N.R.WALBORN: Optical and UV Spectral Morphology of Luminous OB Stars in the Galaxy and the Magellanic Clouds.

2. P.S.CONTI: Parameters of Wolf-Rayet Stars.

3. P.MASSEY: Wolf-Rayet Stars in Nearby Galaxies.

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OPTICAL AND ULTRAVIOLET SPECTRAL MORPHOLOGY OF LUMINOUS OB STARS IN THE GALAXY AND THE MAGELLANIC CLOUDS

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ABSTRACT

Three areas of current progress relevant to the theme of this Symposium will be discussed. (1) New spectroscopic observations of the 30 Doradus central cluster, obtained independently by the author and by J. Melnick, confirm the presence of numerous very early O-type members, including several of type O3. In combination with sophisticated new direct imagery of the luminous central object R136 by A. Walker and by G. Weigelt, these results have evident implications for understanding the ionization of the supergiant H II region, as well as for the interpretation of R136 itself and of the apparently similar regions seen in more distant galaxies. In particular, no evidence remains for a supermassive object in 30 Doradus, but its central cluster is revealed as a spectacular grouping of very massive hot stars. (2) A further member of the Ofpe/WN9 category in the LMC has been identified, bringing their number to seven, with no exact spectroscopic counterparts yet known in the Galaxy. One of these objects is currently in a state of outburst and has been interpreted by O. Stahl et al. as the hottest known Hubble-Sandage variable. (3) An extensive survey of IUE high-resolution data has revealed a strong correlation between the ultraviolet stellar wind features and the optical spectral classifications for the majority of normal O stars. These results are relevant to future studies with the High Resolution Spectrograph on the Hubble Space Telescope, which may observe restricted UV wavelength ranges in faint extragalactic OB stars lacking optical data of comparable quality.

I. THE STELLAR CONTENT OF 30 DORADUS

There has been substantial progress toward an understanding of the 30 Doradus cluster and its luminous central object R136 since this

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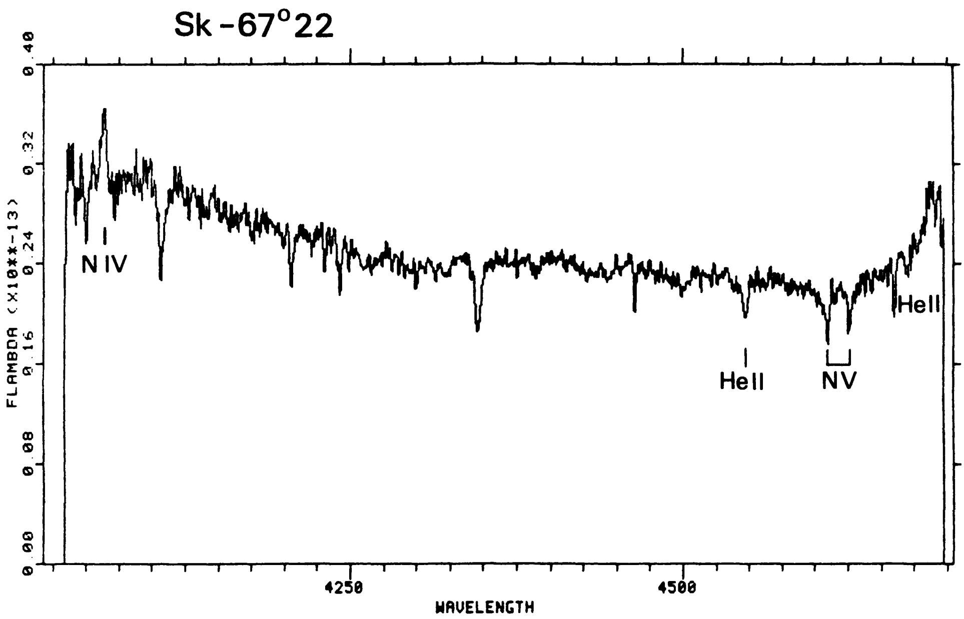
subject was reviewed at IAU Symposium 108 (Walborn 1984). Indeed, it is not too strong to say that the situation has developed from one of predominantly indirect, hypothetical, and plausibility arguments at that time, to one dominated by direct evidence now. This evidence shows conclusively that R136 is a complex multiple system, which constitutes the core of a spectacular cluster rich in the most massive hot stars. Important new data have been contributed by Chu, Cassinelli, and Wolfire (1984), Chu and Daod (1984), and Moffat, Seggewiss, and Shara (1985). Qualitatively new information has been provided by two other approaches: sophisticated direct imagery of R136 itself by Walker and O'Donoghue (1984) and by Weigelt and Baier (1985); and detailed spectroscopy of the cluster stars surrounding R136 by Melnick (1985) and by this author (to be presented here).

Walker and O'Donoghue (1984) have analyzed CCD images of R136 by maximum entropy methods, achieving a resolution of 0".4 and isolating 22 components with V magnitudes between 11.4 and 15.7 within 4".6 of R136a_1, including the 0".5 component of a as well as b and c. Their outermost faint components are visible in the best direct photographs, such as Figure 3 below. Weigelt and Baier (1985), using the remarkable technique of holographic speckle interferometry, have determined the structure within R136a at a resolution of 0".09, discovering 8 components within 0".70. Two of these components are only 0.3 mag fainter than a_1 in the red (note that Weigelt and Baier have reversed the definition of a_2 and a_3 with respect to usage in the previous literature), three are 2 mag fainter, and two more are 2-3 mag fainter. On the assumptions that the visual magnitude differences are the same, that V = 10.8 for all of R136a (Schmidt-Kaler and Feitzinger 1981), that A_V = 1.2 mag (Panagia, Tanzi, and Tarenghi 1983; Savage *et al.* 1983; Fitzpatrick and Savage 1984), and that $V_o - M_V = 18.6$, it follows that $M_V = -7.7$ for R136a_1, -7.4 for a_2 and a_3, -5.7 for a_4-a_6, and -5.2 for a_7-a_8. R136b has $M_V = -5.2$ and c has -5.7. It will be shown below that the same range of values is found for stars in the surrounding cluster. Thus we now have 28 resolved components in R136 within a radius of 4".6, all of which are included in the IUE large aperture as well as in the original optical photometry which was interpreted as due to a single object.

Melnick (1985) has performed an extensive investigation of the spectral types of the 30 Doradus cluster stars surrounding R136. Independently, I have observed about 40 of them with the CTIO 4-meter SIT vidicon system at 1.5 Å resolution, during four nights in Dec. 1984/Jan. 1985. These studies have revealed the most spectacular clustering of massive hot stars for which such detailed information is available. As already indicated by the preliminary results of Melnick (1983), it contains several examples of what may be considered a new class of hot stars, whose spectra show the strong absorption lines of He II and N V and the narrow N IV λ4058 emission characteristic of type O3 If*, along with the broad He II λ4686 emission typical of WN-A spectra. I have classified such spectra as intermediate O3 If*/WN-A. The first example to be described was Sanduleak -67°22, also in



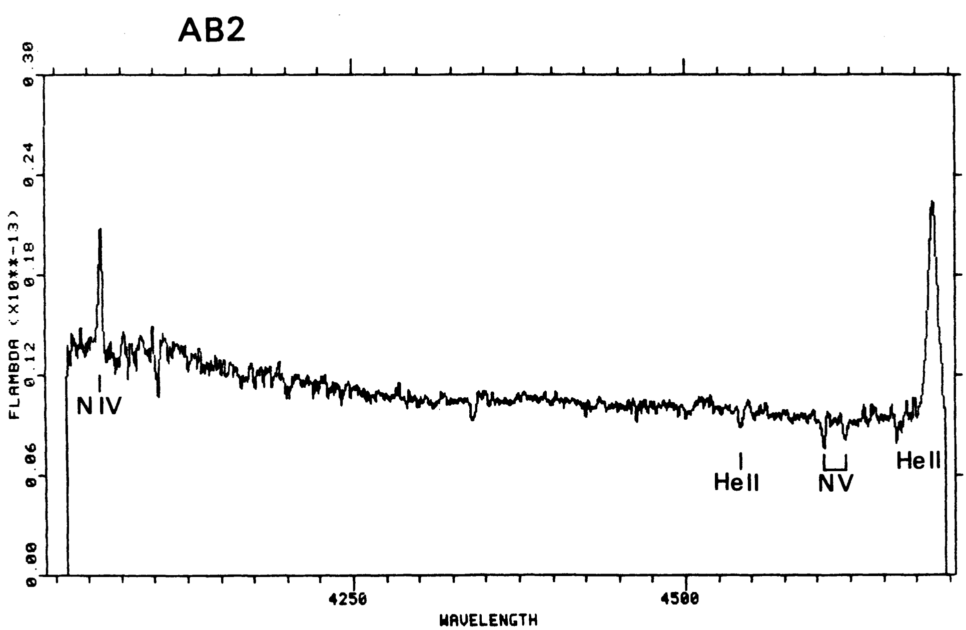


Fig. 1 - Vidicon spectrograms of the O3If*/WN6-A stars Sk-67°22 (M_V = -5.4) in the LMC and AB2 (M_V = -5.2) in the SMC. The flux scales are correct as given. The spectral features identified are N IV λ4058 emission, He II λ4541 and N V λλ4604-4620 absorption, and He II λ4686 emission.

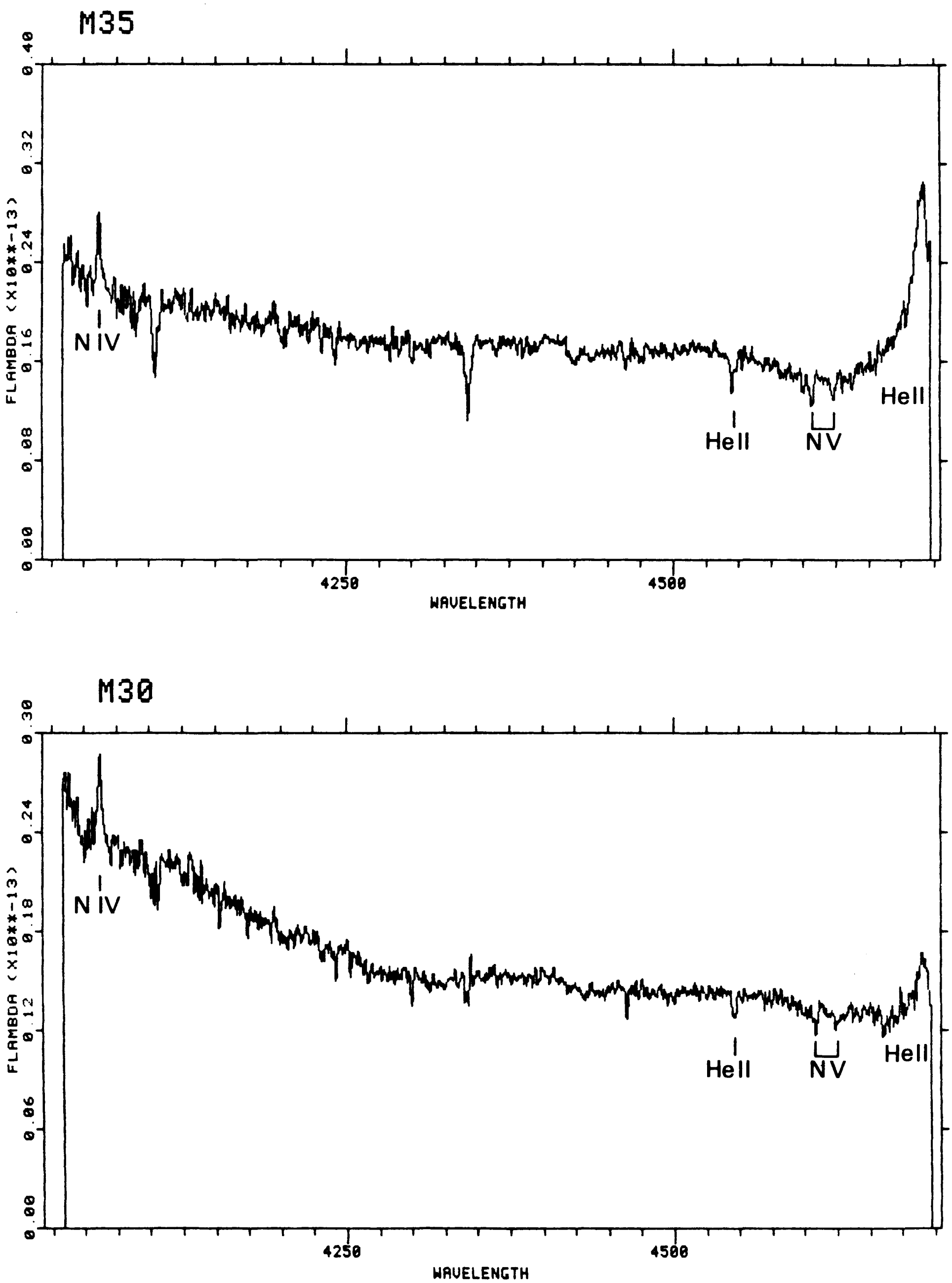


Fig. 2 - Vidicon spectrograms of the O3If*/WN6-A stars Melnick 30 and 35 in 30 Doradus. The flux scale for M30 should be brighter by a factor of 1.9 at 4330 Å and that for M35 by 1.45. The spectral features identified are as in Figure 1.

the LMC (Walborn 1982a); recently another has been found in the SMC, namely AB2 (Azzopardi and Breysacher 1979a; Garmany and Massey 1984). The vidicon spectrograms of these two stars are shown in Figure 1, and those of the similar stars Melnick 30 and 35 in 30 Doradus are shown in Figure 2.

Table 1 gives spectral classifications for 56 stars in the 30 Doradus cluster exclusive of R136, from either my results (W) or Melnick's (M); there is excellent agreement in detail between the two studies. Many of my classifications are preliminary, because the intended tailored nebular emission-line subtractions have not yet been accomplished; in these cases I have given spectral-type ranges which are unlikely to be exceeded. The table contains 15 definite or potential O3 stars, whereas only 12 members of this class were previously known (the 10 discussed by Walborn 1982a plus R136a and AB2). None of the spectral types earlier than O6 was known before these investigations, confirming the suggestion of Melnick (1983) and Walborn (1984) that the principal sources of ionization in 30 Doradus other than R136 had not yet been identified. Table 1 also lists blue magnitudes derived from the vidicon fluxes; these have had to be corrected, with reference to the photographic photometry of Westerlund (private communication), for an improper positioning of a guide probe into the telescope beam affecting three of the four nights, and they are accurate to a few tenths of a magnitude. Accurate photometry of the 30 Doradus cluster is in preparation by Melnick and by Chu and Seitzer. The absolute visual magnitudes in Table 1 are approximate

Table 1. The Stellar Content of 30 Doradus (Exclusive of R136)

Melnick/ Radcliffe	Spectral Type	Source	m_B	M_V	Remarks
30	O3 If*/WN6-A	W	13.3	-6.6	
35	O3 If*/WN6-A	W	13.4	-6.5	
39	O3 If*/WN6-A	W	12.6	-7.3	
42	O3 If*/WN6-A	W	12.6	-7.3	
51	O3 If*/WN7-A	W	14.0	-5.9	Moffat, Seggewiss, and Shara (1985)
13	O3-4	W	13.9	-6.0	
23	O3-4 (f?)	W	14.3	-5.6	
24	O3-4 V	W	14.0	-5.9	
25	O3-4 V	W	12.9	-7.0	
26	O3-4 V	W	13.8	-6.1	
36	O3-4 V	W	14.2	-5.7	
10	O3-6 V	W	14.2	-5.7	
14	O3-6 V	W	14.5	-5.4	
15S	O3-6 V	W	14.3	-5.6	
55	O3-6 V	W	14.5	-5.4	

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Table 1. The Stellar Content of 30 Doradus (continued)

Melnick/ Radcliffe	Spectral Type	Source	m_B	M_V	Remarks
28	O4 V	M			
47	O4-6 (f)	W	13.9	-6.0	
4	O5-6 V:	W	14.4	-5.5	
8	O5-6	W	14.5	-5.4	
35S	O5-6 V	W	13.8	-6.1	
35N	O5-7:	W	14.0	-5.9	
48	O5-7	W	14.4	-5.5	
R139	O6-7 Iaf	W	12.1	-7.8	
7	O(7) V	M			
15	O7 V	W	13.5	-6.4	
21	O7 V	M	14.2	-5.7	
R133	O7-8 II	W	12.6	-7.3	
32	O8 II	W	13.1	-6.8	
6	O8-9	W	14.6	-5.3	
58	O8-9	W	13.9	-6.0	
59	O8-9	W	14.4	-5.5	
1S	O9-9.5	W	14.7	-5.2	90" south of Melnick 1
38	O9.7 Iab	W	13.6	-6.3	Could be OC
14N	O V	M			
22AB	O	M	13.8	-6.1	
33	WC5+O4	M			
R140N	WC5+WN4	M			
34	WN4.5	M			
37	WN7-A	W	12.7	-7.2	Strong, symmetrical Hγ absorption
49	WN7	M			
53	WN8	M			Azzopardi and Breysacher (1979b)
R134	WN7	M			
R135	WN6	M			
R140S	WN4.5	M			
R145	WN6	M			
27	B0 I	W	13.5	-6.4	
50	B0: I:	W	14.3	-5.6	
11	B0-0.5 Ia	W	13.2	-6.7	
12	B0-0.5 Ia	W	12.4	-7.5	
54	B0.5 Ia	W	13.0	-6.9	
R141	B0.5 I	W	12.4	-7.5	
R142	B0.5-0.7 I	W	11.8	-8.1	
R137	B0.7-1.5 I	W	12.0	-7.9	
52	B1 Ia	W	13.8	-6.1	
5	B2: Ip?	W	14.3	-5.6	Hγ P Cyg profiles?
R138	A0 I	W			

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and have been derived with the assumptions of B - V = 0.1, A_V = 1.2, and $V_o - M_V$ = 18.6 for all stars. The absolute magnitudes of Melnick 39 and 42 are essentially the same as those of R136a_1-a_3.

The distribution of the (abbreviated) spectral types is shown on photographs of the 30 Doradus cluster in Figure 3 for types O3-O6 and WR, and in Figure 4 for the later types. Note that four of the O3 If*/WN-A objects immediately surround R136. On the other hand, the later-type stars show rather less of a concentration toward R136. Whether the several late O and early B supergiants present belong to the 30 Dor cluster or are related to the general field in which the nebula is situated will have to be determined by comparably detailed spectroscopy of the latter.

The brightest unresolved component in R136, namely a_1, is about 1 mag brighter in M_V than HD 93129A; following the discussion of Walborn (1984), the upper limit to its mass is therefore 250 $M_\odot$. The entire 30 Doradus cluster, including R136, may contain 15-20 stars with masses of 100-200 $M_\odot$, and there is no evidence for the presence of substantially greater masses than these. The nebular ionization balance has been recalculated with the new spectral types by Melnick (1985), with the result that R136a contributes about one-third of the ionization and the other cluster stars provide the remainder.

As a footnote to this discussion, I would like to mention the interesting VLA study of the optically obscured, galactic supergiant H II region W49 by Dreher et al. (1984). They have discovered a very luminous, multiple stellar system therein, which may well represent an earlier evolutionary state of those in 30 Doradus and NGC 3603 (Walborn 1973), since it is associated with masers and compact H II regions.

II. A NEW Ofpe/WN9 STAR IN THE LMC

A large number of OB supergiants with P-Cygni and other emission-line characteristics have been known in the LMC since the pioneering work of Henize (1956) and Feast, Thackeray, and Wesselink (1960). Recently a considerable wealth of information about them at both optical and ultraviolet wavelengths has become available through the work of Shore and Sanduleak (1984) and Stahl et al. (1985 and references therein; see also the review by B. Wolf in this volume). I have been interested in the hottest subgroup of these objects, which display peculiar Of-like spectra (Walborn 1977, 1982b). They may be further subdivided into three categories: (1) HDE 269858 and Sk-67°266, which have exceptionally narrow Si IV λ4089, N III λ4097 absorption lines and expanding nebular shells; (2) HDE 269227, HDE 269927C, and Bohannan-Epps 381, which appear most strongly related to the narrow-line WN-A sequence; and (3) HDE 269445, a unique superluminous object with a nearly pure emission-line spectrum in the blue-violet. HDE 269858 (=R127) is currently in a remarkable state of

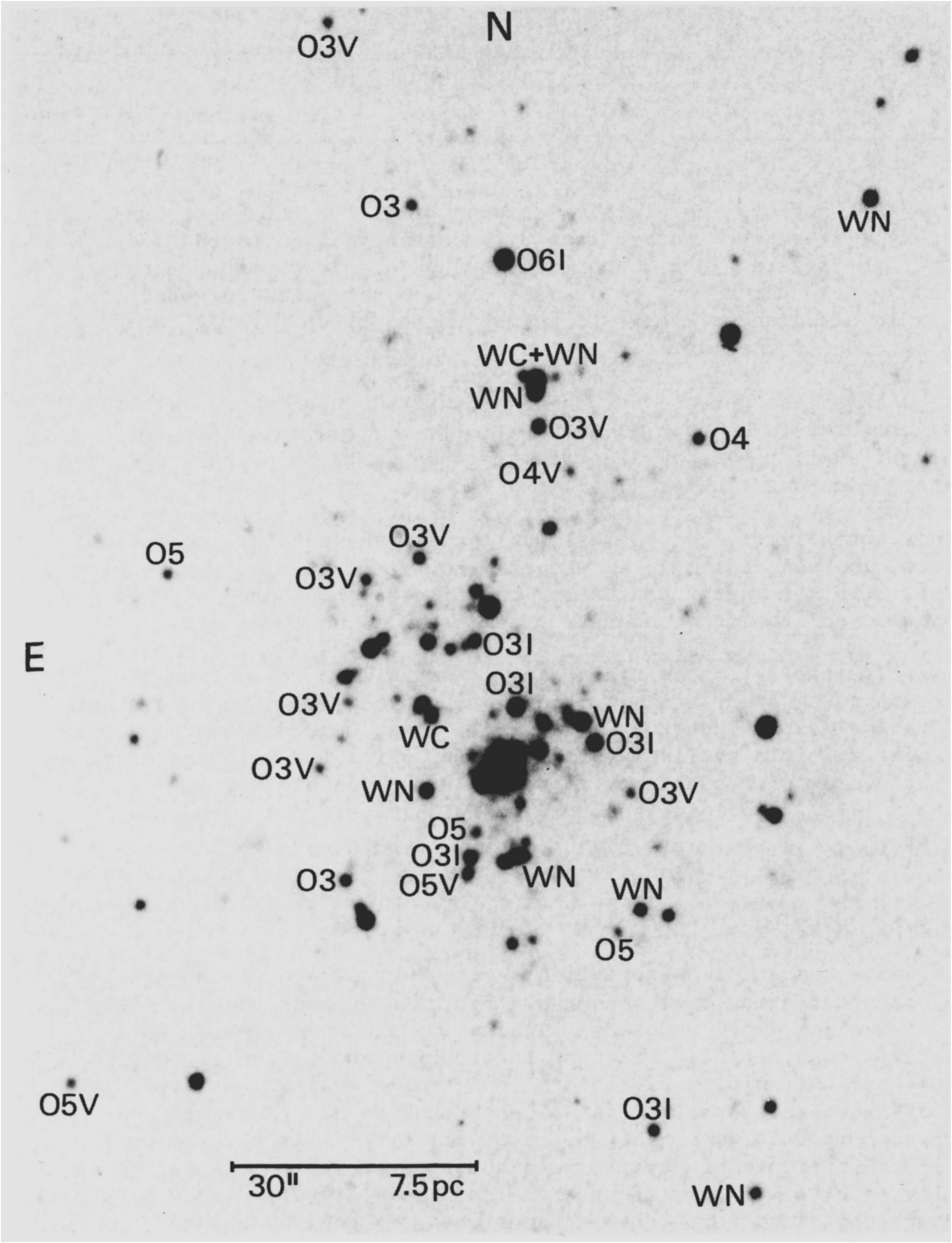

Fig. 3 - The distribution of the O3-O6 and WR stars (exclusive of R136) in the 30 Doradus cluster. This excellent photograph was obtained by Dr. Y.-H. Chu through a blue-continuum (λ4765) interference filter at the CTIO 4-meter prime focus.

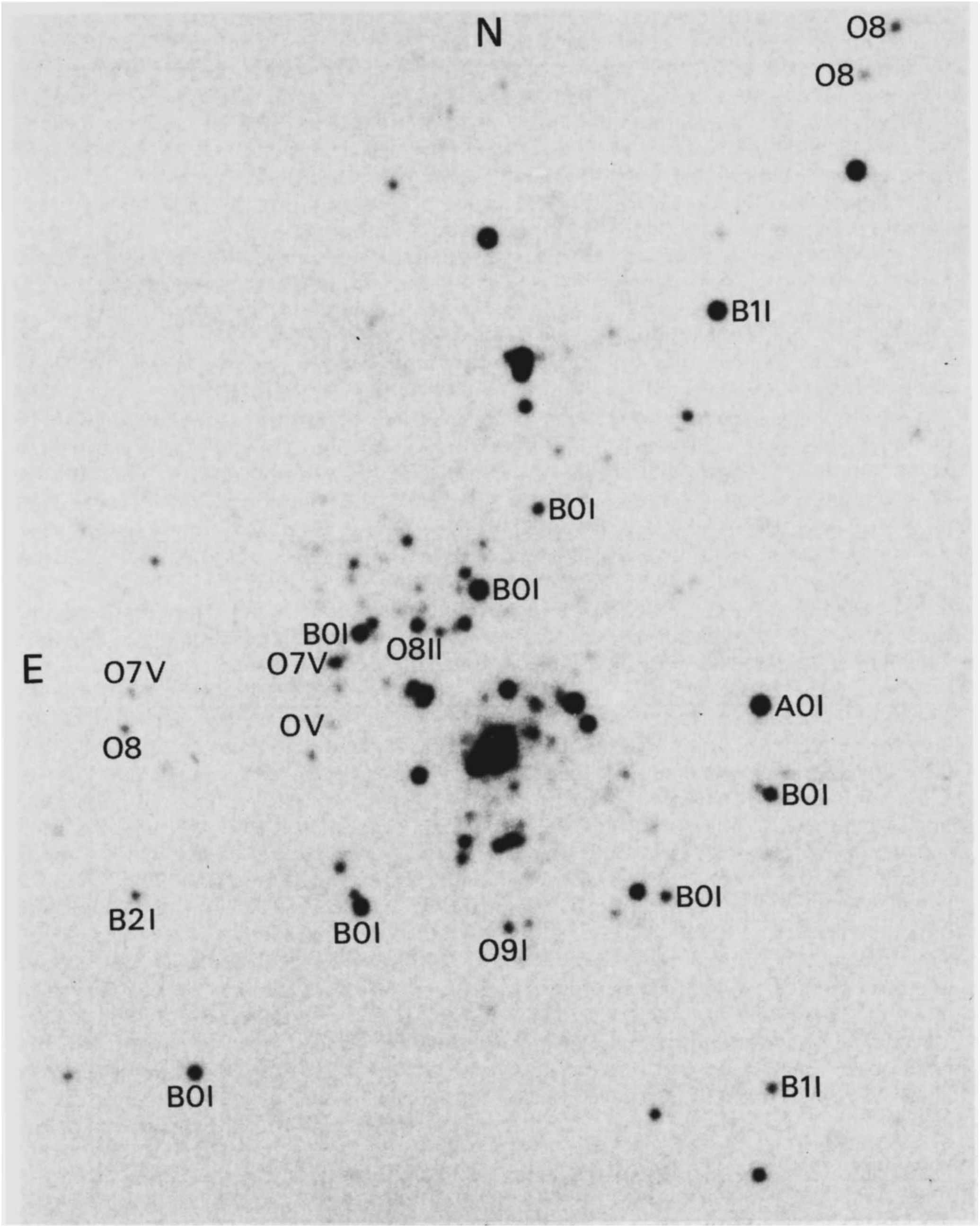

Fig. 4 - The distribution of the later-type stars on an He II λ4686 interference-filter photograph of 30 Doradus (which enhances the WR images), also obtained by Dr. Chu at the CTIO 4-meter.

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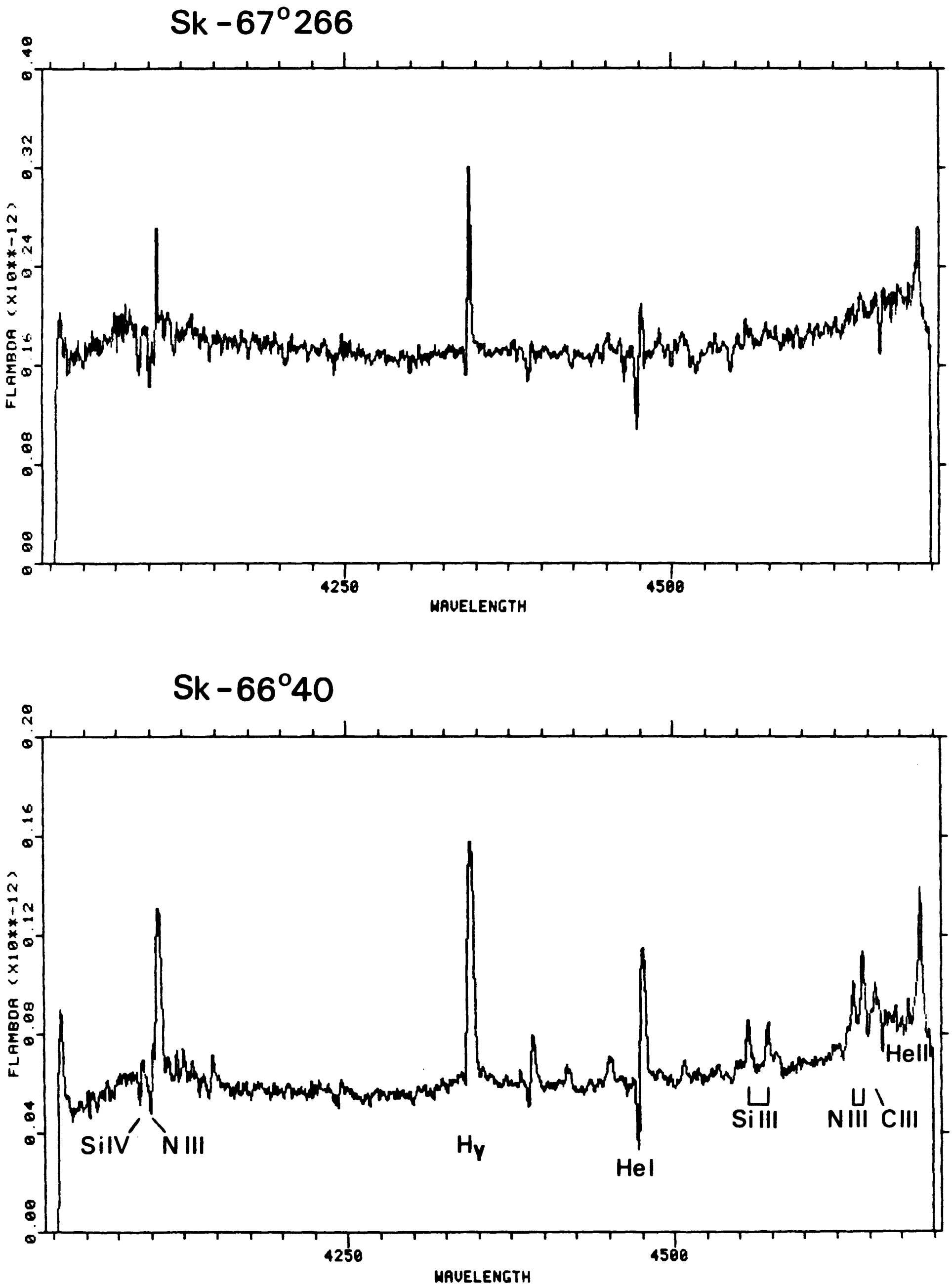

Fig. 5 - Vidicon spectrograms of the Ofpe stars Sk-66°40 and -67°266 in the LMC. Both flux scales should be fainter by a factor of 1.7 at 4330 Å. The spectral features identified are Si IV λ4089 and N III λ4097 absorptions, Hγ emission, He I λ4471 P Cygni profile, and Si III $\lambda\lambda$4552-4568, N III $\lambda\lambda$4634-4641, C III λ4650, and HeII λ4686 emissions.

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outburst and has been shown to be the hottest known Hubble-Sandage variable by Stahl et al. (1983) and Stahl and Wolf (1985); also its nebular shell has apparently been directly resolved by Stahl (1985). The purpose of this note is to establish that the star Sk-66°40 is a further member of the HDE 269858/Sk-67°266 subclass. A SIT vidicon observation of its spectrum is shown along with one of -67°266 in Figure 5. The narrow Si IV and N III absorptions are easily seen; the strength of the Si III and C III emission lines in -66°40 is also noteworthy. Thus the Ofpe/WN9 category in the LMC now contains seven members, while no spectroscopically identical counterparts have yet been identified in the Galaxy.

III. THE ULTRAVIOLET SPECTRA OF THE O STARS

Recently an extensive survey of the 1200-1900 Å region of O-type spectra has been completed, based upon the unprecedented sample of homogeneous, high-resolution data contained in the International Ultraviolet Explorer archives. The primary result of this survey, comprising about 120 different objects, is conclusive evidence for a high degree of detailed correlation between the UV spectra and the optical spectral classifications, as well as between the photospheric and stellar-wind features, for the great majority of the O stars. The pronounced luminosity dependence of the Si IV stellar-wind effect, the main-sequence phenomena, and the ON/OC spectra have been discussed by Walborn and Panek (1984a, b; 1985), respectively. The Of supergiant and WN-A sequences provide further striking examples of detailed correspondences between stellar-wind features and the optical spectral types. For instance, the λλ1300-1600 Å region provides a unique signature of an O3 If* spectrum, with a strong O V λ1371 wind profile, no Si IV λλ1394-1403, and very strong C IV λλ1548-1551. Similarly, the O4 If spectra, with no O V, intermediate Si IV, and strong C IV can be readily discriminated from both earlier and later types. Such effects assume considerable significance in the context of future programs with the Hubble Space Telescope High Resolution Spectrograph, since they provide a framework relative to which one can interpret observations of restricted UV wavelength ranges in faint extragalactic OB spectra lacking high-quality optical data. Unfortunately, space does not permit these spectral sequences to be reproduced here, but an extensive atlas displaying montages of the 1200-1900 Å range in about 100 objects is currently in press at NASA for wide distribution (Walborn, Heckathorn, and Panek 1985).

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Discussion : WALBORN.

STALIO :

Regarding your statement that there exists no individuality among OB stars when you look at the UV lines formed in the stellar wind, I would like to point out the following :

1. That your sample does not include that rather large fraction of OB stars with emission lines : Oe stars and more importantly Be stars. This is a limitation because these stars have the same parameters (T_{eff}, gravity) as the stars you have studied and there is no reason to invoke high rotation to explain these differences because this is not true (see Polidan, Stalio, Peters, 1985 and references there for a discussion on these points).

2. Costero and I (A.A. Suppl. 58, 95, 1984) found similar morphological results as yours from a smaller sample (40 stars) of non-Oe, non-Be stars. However we found measurable differences in edge velocities among stars of the same spectral class. In some cases these differences were quite noticeable. Did you find the same? If yes, how do you explain these differences in terms of current modeling of the stellar wind?

3. I would like to call your attention to a paper by Morton (MNRAS, 189,57, 1979) showing Copernicus OVI profiles of two BOV stars : Tau Sco and upsilon Ori which are absolutely different. IUE unfortunately does not have OVI, but in our poster paper (Polidan and Stalio) we report evidences of changes in OVI in Tau Ori from Voyager data.

4. You didn't mention the occurrences of narrow components in some of these profiles.

WALBORN :

I did not state that no individuality exists. I stated that the UV spectra of 80-90% of the O stars, including their stellar wind features, display strong systematic trends and a high degree of correlation with their optical spectral types and luminosity classes. They thus provide an empirical reference frame relative to which the 10-20% of peculiar individuals and categories can be recognized and described.

1. The Of stars have emission lines and are included. There are only a handful of known Oe stars. My work does not refer to the B stars. An excellent discussion of the UV spectra of Be relative to 2. The morphological trends in the wind profiles I have discussed are independent of even large differences in terminal velocity, for the few cases in which the latter occur. For instance, the ON supergiant HD 105056 has an anomalously low terminal velocity, yet displays a supergiant SiIV profile. I have suggested that this star may be less massive than normal stars of the same spectral type (Ap.J. 291, 806,

1985). Your paper concluded that the UV spectra of the O stars on the whole are dominated by individuality, which is incorrect.

3. Tau Sco has highly peculiar, enhanced wind features, which I have discussed in Ap.J. 296, 718 (1984).

4. I did in fact point out narrow absorption components in the CIV profile of 15 Mon, and they are reported in a large sample of main sequence spectra in the above references. The variations found in these components and in profile shapes by numerous investigators are small relative to the systematic morphological trends with spectral type and luminosity class.

DE JAGER :

One of the arguments initially put forward by those, suggesting that R136a should be a supermassive object, was based on the degree of ionization of the HII region surrounding the stellar complex. This would need an object with a temperature of 60000 to 70000 K. This high temperature yields a large bolometric correction, and that was the only reason for making the luminosity as large as 10^8 solar values. The high temperature and luminosity demands the presence of a large number of O3 objects. Does the observed HII ionization and consequent T and L values, agree with the number of O3 objects now identified in that region?

WALBORN :

Yes. I discussed this question on the basis of photometry in my review at IAU Symposium 108. Melnick (1985, in press) has redone the exercise with the new spectral types; R136 provides one third of the ionization and the other cluster stars provide two thirds.