THE STELLAR CONTENT OF 30 DORADUS

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ABSTRACT

The supergiant H II region 30 Doradus is placed in context as the optically most spectacular component in a much larger region of recent and current star formation in the Large Magellanic Cloud, as shown by deep Hα photographs and the new IRAS results. The current state of knowledge concerning the concentrated central cluster in 30 Dor is summarized. Spectroscopic information exists for only 24 of the brightest members, most of which are WR stars; however, photometry shows over 100 probable members earlier than B0. The spectral classification of these stars is a difficult observational problem currently being addressed; in the meantime their hypothetical ionizing luminosity is calculated from the photometry and compared with that suggested for the superluminous central object R136a alone, and with the H II region luminosity. With reference to related regions in the Galaxy, the likelihood that many of the brightest objects in 30 Dor are multiple systems is emphasized. An interpretation of R136a as a system containing a few very massive stars (as opposed to a single supermassive object) is in good accord with the observations, including the visual micrometer results. The study of 30 Dor and its central cluster is vital for an understanding of the numerous apparently similar regions now being discovered in more distant galaxies.

I. INTRODUCTION: THE 30 DORADUS REGION

The 30 Doradus (Tarantula) Nebula, with a diameter of 200 pc and nearly 10^6 $M_\odot$ of ionized hydrogen, might properly be categorized as a supergiant H II region, with the Great Carina Nebula, smaller by a factor of five in diameter and by two orders of magnitude in mass, relegated by comparison to mere giant status. Yet despite its spectacular attributes, in another sense the Tarantula is only a hot spot, the optically most prominent component of a much larger region of

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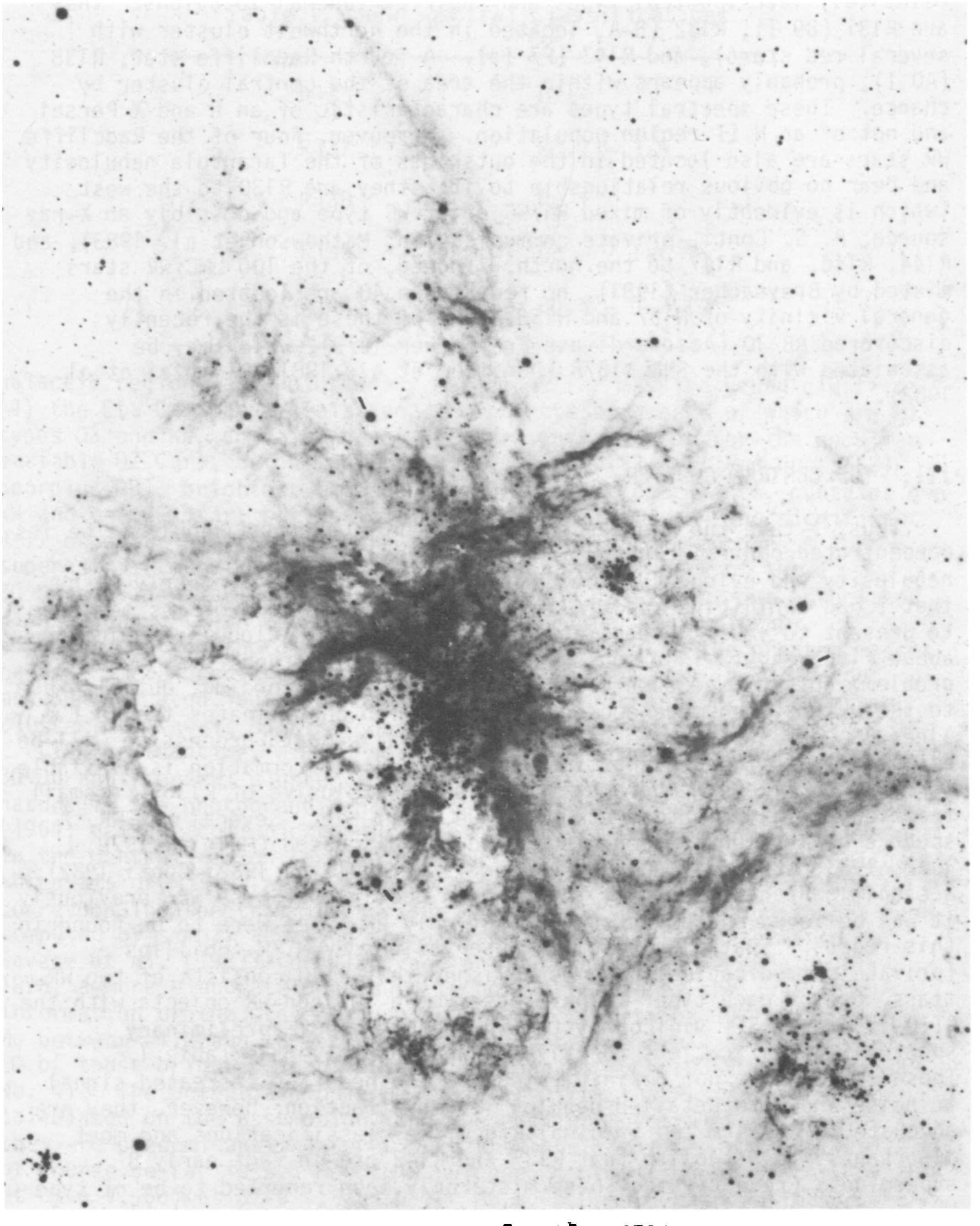
recent and current star formation in the Large Magellanic Cloud. This aspect of the 30 Doradus region is well shown by the beautiful Hα photographs from the UK Schmidt (Elliott et al. 1977; Meaburn 1979), which reveal apparently related filamentary structure on a scale of 2 kpc. To the south are the fascinating N158/N159/N160 complexes (Henize 1956), which contain LMC X-1 (Hutchings and Crampton 1983), a young SNR (Mathewson et al. 1980), a molecular maser (Scalise and Braz 1981; Caswell and Haynes 1981), an infrared protostar (Gatley et al. 1981), and other strange objects (Heydari-Malayeri and Testor 1982). There is also strong CO emission from this area (Israel et al. 1982). Indeed, some of the first observations with the IRAS satellite have evidently discovered a hotbed of current star formation in this area south of the Tarantula (Sky and Telescope 1983).

In contrast, the 30 Doradus Nebula itself appears to be a well evolved H II region. No compact far IR sources were found there by Werner et al. (1978), and only some weak CO emission was detected by Israel et al. (1982). On the other hand, it harbors large internal motions seen in both the nebular emission lines (Smith and Weedman 1972; Cantó et al. 1980; Meaburn 1981; Cox and Deharveng 1983) and the interstellar absorption lines (Blades 1980; Walborn 1980; Blades and Meaburn 1980; de Boer, Koornneef, and Savage 1980), as well as an extended X-ray source (No. 72) discovered by the Einstein Observatory (Long, Helfand, and Grabelsky 1981). The latter was originally classed as an SNR, but it may well represent instead the effects of the energetic stellar winds within the Nebula, as also observed in the Carina Nebula (Seward et al. 1979; Seward and Chlebowski 1982; Walborn 1982a; Walborn and Hesser 1982).

II. FIELD STARS

All of this impressive radiative and dynamical activity in the 30 Doradus Nebula is of course ultimately due to the massive stars it contains, so it is appropriate to focus our attention on what is currently known about them. I shall begin by specifying some objects which probably do not belong to the stellar content of 30 Doradus; in this connection the status of the Nebula as a component within a larger young region containing a range of evolutionary states is relevant. From interesting near-IR surveys, Hyland, Thomas, and Robinson (1978) and McGregor and Hyland (1981) discovered 13 M supergiants in the field of the Tarantula, and they suggested a causal relationship to the younger exciting stars of the Nebula in terms of successive star formation events. However, as they also pointed out, the late-type supergiants likely belong to the population of the larger region which contains 30 Doradus. Seven of the M stars are associated with two small clusters 3' northwest and 8' southeast of R136, which appear unrelated to the Nebula, and only one (No. 18) is near the central exciting cluster. In fact, three of the original Radcliffe stars (Feast, Thackeray, and Wesselink 1960) are probably related to the M supergiants and not to the Nebula, on the basis of both their



The 30 Doradus Nebula in the light of [S II] λλ6716,6731; 30 min. exposure at the CTIO 4m prime focus, through a 100Å interference filter on 098-04 emulsion. North is at the top and east to the left. Tick marks identify the peripheral stars R130 to the west, R144 to the north, and R143 to the south. The latter two are separated by 6!1 in declination, corresponding to 93 pc in projection. N157B is at the SW corner.

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relatively late spectral types and their peripheral locations: they are R131 (B9 I), R132 (B-A, located in the northwest cluster with several red stars), and R143 (F7 Ia). A fourth Radcliffe star, R138 (A0 I), probably appears within the area of the central cluster by chance. These spectral types are characteristic of an h and χ Persei and not of an H II region population. Moreover, four of the Radcliffe WR stars are also located in the outskirts of the Tarantula nebulosity and bear no obvious relationship to it: they are R130 to the west (which is evidently of mixed WN/WC or of WC type and possibly an X-ray source; P. S. Conti, private communication; Mathewson et al. 1983); and R144, R146, and R147 to the north. Indeed, of the 100 LMC WR stars listed by Breysacher (1981), no fewer than 40 are located in the general vicinity of N157 and N158. One of these is the recently discovered AB 10 (Azzopardi and Breysacher 1979), which may be associated with the SNR N157B (Danziger et al. 1981; Gilmozzi et al. 1983).

III. THE CENTRAL CLUSTER

Thus, I take the stellar content of the 30 Doradus Nebula to be its concentrated central cluster, which clearly interacts with the nebulosity and evidently provides its energy source. I dearly wish that I had definitive spectral classifications for all of its members to present to you - perhaps at the next Magellanic Cloud symposium in about five years! They constitute a very difficult observational problem, not only because of their faintness and crowding, but also due to the bright, inhomogeneous nebulosity which contaminates the He I lines. A sky-subtracting detector and detailed data processing will be essential. At the present time, spectroscopic information is available for only 23 likely members of this cluster exclusive of R136 - a small fraction of its brightest stars, as we shall see. Several new WR spectra have recently been discovered and discussed (Melnick 1978, 1982, 1983; Azzopardi and Breysacher 1979; Phillips 1982; Conti 1982). A significant new result is that two of them are of type WC; previously it was believed and often stated that only WN types were to be found in this region. Spatially resolved observations by M. M. Phillips (private communication) have established that R140 consists of two WR stars, one of each type. I have observed a few non-WR objects with the CTIO 1.5-meter SIT vidicon system in December 1982; preliminary spectral classifications for five of them are given in Table 1. These results are not definitive due to the need for increased signal to noise and more detailed nebular line subtraction; however, they are adequate to confirm the original Radcliffe classifications and most importantly to establish that R137 and R142 are in fact early B supergiants (recently they have mistakenly been reported to be of type WN). Three additional stars of the central cluster are probably early B supergiants as well. The presence of these and the WC types raises a basic question about the 30 Doradus stellar population. It seems unlikely that all of them could be chance alignments on the central cluster. I often refer to the following three distinctly different

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Table 1. New Spectral Classifications

R133	07:
R137	B0.7 - 1.5
R138	A0 I
R139	06 - 7 Iaf
R142	B0.5 - 0.7 I

galactic regions as evolutionary paradigms for massive young clusters: (1) the Eta Carinae Association, the brightest members of which are of types 03 and WN, containing no OB supergiants (except for the peculiar variable QZ Car), but associated with substantial H II and dust; (2) Scorpius OB1, brightest members late O-early B supergiants, contains one WN and one WC star, but no late B/AF/M supergiants, and no significant H II or dust; and (3) h/χ Persei, visually brightest members A supergiants, many M supergiants. Hence, at least part of the 30 Doradus population corresponds to the Sco OB1 stage, but associated with strong H II and dust as in Eta Car. Either evolutionary differences from the galactic regions (due, e.g., to the greater masses or lower metal content), or a mixture of stellar ages in 30 Doradus, may be indicated, but a conclusive interpretation of this interesting cluster must await spectroscopy of its abundant fainter members.

In the meantime, a data set which includes most members of the 30 Doradus central cluster and can provide an indication of its possible nature is the photographic narrow-band photometry by B. E. Westerlund (1964; private communication). The numbers of early-type stars present in the central region (exclusive of R136) are listed by half-magnitude intervals of M_V in Table 2, together with the possible alternative corresponding spectral types. The absolute visual magnitudes have been computed by simply adopting for all stars $A_V = 1\overset{m}{.}2$ as determined by Savage et al. (1983) for R136, and an LMC true distance modulus of $18\overset{m}{.}6$; a more elaborate procedure is not warranted by the available information or the present purpose. Table 2 contains 109 stars with M_V between -4.0 and -8.3; spectroscopic data are available only for 20 of those brighter than -6.0 and for one at -5.4 (03 V, Melnick 1983 No. 4). The potential ionizing radiation from these stars has been calculated on the assumption that the earlier spectral types apply; if they are predominantly later-type giants the ionizing luminosity will of course be far less. For this purpose, incompleteness factors of 20% at 03-6 V, 50% at 07-9 V, and 0 for $M_V \leq -6.0$ have been estimated from Westerlund's charts and lists; this estimate adds 25 stars with M_V between -4.0 and -6.0, and it is conservative in view of the probable incidence of unresolved multiple systems and spectroscopic binaries. Two new WN stars from Melnick (1983) have also been added, giving a total of 136 stars. The ionizing luminosities given by

Table 2. Content of the 30 Doradus Central Cluster

M_V Range	No. of Stars	Possible Spectral Types	
-4.0/-4.4	20	08-9 V	B1 III
-4.5/-4.9	14	07 V	B0 III
-5.0/-5.4	26	06 V	09.5 III
-5.5/-5.9	15	03-5 V	06-9 III, II
-6.0/-6.4	13	03-5 III, 03 I	Ib
-6.5/-6.9	10	WR	
-7.0/-7.4	4	and/or	Ia
-7.5/-7.9	6	Multiple	
-8.0/-8.4	1	systems	Ia^+

Note: Stars with photometry by Westerlund, excluding R136.

Cruz-González et al. (1974) have been adopted, but scaled to the absolute visual magnitude calibration of Walborn (1973a). The value for type 09 I has been used for all WR stars. These results are presented in Table 3, where they are also compared with the ionizing luminosity of R136a implied by the spectral mix matched to its UV flux by Savage et al. (1983), and with the H II region luminosity within a diameter of 140 pc determined at 6 cm by Mills, Turtle, and Watkinson (1978). The ionizing luminosity of the 22 spectroscopically classified stars is consistent with that found by Feitzinger et al. (1980), but the potential contribution from the remaining cluster stars is seen to be much greater, and altogether comparable to that from R136a alone. The total ionizing radiation from the cluster is in good agreement with the H II region luminosity, considering the uncertainties involved in the stellar computations. The parallel discussion by Melnick (1983) leads to essentially the same conclusions reached here.

IV. R136

With reference to some related galactic regions, I would now like to emphasize further the high probability that many of the brightest stellar images in the 30 Doradus cluster correspond to multiple systems. In the Carina Nebula, for instance, the systems HD 93128/93129AB, 93160/93161AB, and 93204/93205AB, each containing at least three massive stars, have projected dimensions of about 0.25 pc, corresponding to 1" at the LMC. There one also finds the double spectroscopic binary HD 93206 (QZ Carinae; Leung, Moffat, and Seggewiss 1979; Morrison and Conti 1980) - four massive stars along the same line of sight at a distance of only 2.8 kpc. Even more germane is the spectacular HD 97950 system at the center of the galactic supergiant H II region NGC 3603 (Walborn 1973b; Moffat and Seggewiss 1983), which

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Table 3. Ionizing Luminosities in 30 Doradus

Spectral Types	No. of Stars	$L_H(10^{49}s^{-1})$	Total $L_H(s^{-1})$
Photometrically observed stars			
O3 V	6	36	
O4 V	6	25	
O5 V	6	19	
O6 V	31	47	
O7 V	21	13	
O8 V	15	5	
O9 V	15	3	1.5×10^{51}
O3 III, I	4	51	
O4-5 III	10	74	1.2×10^{51}
Spectroscopically observed stars (excluding R136)			
WN	12[a]	} 21	
WC	2[b]		
O6-7 I	3[c]	9	
B I	5[d]	---	0.3×10^{51}
Total			3×10^{51}
R136a (Savage et al. 1983)			
O3 III	15	193	
WN3	15	22	2×10^{51}
H II luminosity (Mills et al. 1978)			8.7×10^{51}

[a]R134, 135, 140, 145; Melnick A, C, G = 42, H = 39, J, 30, 35N; Azzopardi-Breysacher 11
[b]R140, Melnick E
[c]R133, 139; Westerlund 6
[d]R137, 141, 142; Westerlund 10, 29

I submit as a closeup view of R136! Here a volume of diameter 0.25 pc contains HD 97950ABCDEF, each of which may be at least double from the appearance of the stellar images. From published photometry of nearby stars (Moffat 1974, 1983; van den Bergh 1978) and my plates, I have estimated V ~ 9.6 for the 0"6 double AB, which with a distance of 7.5 kpc and $A_V = 3^m_.9$ implies $M_V = -7.9$ for each component. Moreover, through a 20" aperture (0.75 pc) V = 9.2, so that AB contributes 0.7 of the visual light from that volume. The integrated spectral type of HD 97950 is O5-6(n) + WN6-A(B) (Walborn 1982b).

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Well, what about R136? Feitzinger et al. (1980) isolated the relatively faint components b and c at about 2" and 3".5, respectively, to the southeast of a, while Schmidt-Kaler and Feitzinger (1981) derived V = 10.77 for the latter. I wish to emphasize that there are now four independent and concordant observations of the R136a_1-a_2 structure with a separation of 0".48, position angle 220°, and magnitude difference ~1^m: visual micrometer measurements by Innes (1927) and Worley (1983), photography by Chu and Wolfire (1983), and speckle interferometry by G. Weigelt (quoted by Moffat and Seggewiss 1983). Moreover, Weigelt has reportedly now observed an a_3 component at 0".1 and $\Delta m \sim 1^m$, and fainter components a_4 - a_5. With $A_V = 1^m.2$ from Savage et al. (1983), these numbers imply M_V = -8.3, -7.7, and -7.3 for R136a_1,a_2, and a_3, respectively. Furthermore, through a 3" aperture (0.75 pc) V ~ 10.1 (Y.-H. Chu, private communication), so that R136a contributes 0.5 of the visual light from that volume. The integrated spectral type of R136 (HD 38268) is OB(n) + WN5-A(B) (Walborn 1977). Hence, the virtually identical structures of R136 and HD 97950 should be clear, in agreement with the more detailed discussion of Moffat and Seggewiss (1983).

Both UV (Savage et al. 1983) and near-IR (Vreux, Dennefeld, and Andrillat 1982) spectroscopic observations show that one or more components of R136 emit on O3-type spectrum. If one assumes that these are the visually brightest components, they can be compared directly to HD 93129A in the Carina Nebula, which has M_V = -6.6 and ~100 $M_\odot$ (Walborn 1982c and references therein). R136a_1 is $1^m.7$ brighter, which with a linear mass-luminosity relation leads to 480 $M_\odot$. The mass-luminosity relations of Maeder (1983) would reduce this value to 220 or 280 $M_\odot$. This is a weak upper limit for the most massive object in R136, because of the likely possibilities that R136a_1 is itself multiple, and that the visually brightest components are not the hottest.

Recent high signal-to-noise spectroscopic observations of supergiant H II regions in more distant galaxies have frequently revealed the presence of WR emission bands in their central regions; more than two dozen cases are now known (D'Odorico and Rosa 1982; Rosa 1983; Massey and Hutchings 1983). It is evident that the LMC will play its canonical role as stepping-stone to the galaxies in the context of this problem: an understanding of R136 and the 30 Doradus central cluster will be essential to the interpretation of the more distant objects.

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DISCUSSION

Appenzeller: Is it possible to derive an age for the stars in the 30 Doradus region from the fact that we seem to see so many evolved massive stars (WR stars, supergiants, ...)?
Walborn: The age of the Eta Carinae association has been estimated at 3 million years, and Scorpius OB1 would appear to be 5 to 7 million years old by interpolation between the former and h/χ Persei. The HII and O3 stars in 30 Dor indicate an Eta Carinae stage, while the B supergiants and WC stars correspond to Sco OB1. This mixture could indicate either evolutionary differences from the galactic regions, or a range of ages, in the 30 Dor central region.
Humphreys: Is anything known about circumstellar dust shells around any of the hot stars in the 30 Dor region or in NGC3603? We know that evolved very massive stars (60 to 100 $M_\odot$) such as η Car often eject processed material. Have any stars in these two very massive star complexes evolved to that stage?
Walborn: McGregor and Hyland (1981) found near-IR excesses in several of the brightest hot stars in 30 Dor, which they interpreted in terms of free-free emission and mass-loss rates. No η Car like objects are known in 30 Dor or NGC3603.
Geyer: Concerning the age of the 30 Dor association it might perhaps be of interest that the young globular cluster NGC2100, which is boardering on the east side of the complex, has an age of about 8-10 million years.
Walborn: 30 Doradus is located within a larger young region containing both earlier and more advanced evolutionary states.