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THE STELLAR CONTENT OF THE CARINA NEBULA

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RESUMEN

Se discuten los cúmulos de tipo O3 ionizantes de la Nebulosa de Carina. Luego de un resumen de la literatura reciente, se consideran los temas de sus distancias y edades relativas. La interpretación preferida es que Trumpler 14 y 16 constituyen una asociación con una distancia común, pero que el primero es significativamente más joven que el segundo. Varios obstáculos observacionales que pueden confundir estos temas son señalados; algunas investigaciones en curso presentadas en esta conferencia podrían contribuir a resolverlos.

ABSTRACT

The O3-type clusters which ionize the Carina Nebula are discussed. Following a summary of recent literature, the issues of their relative distances and ages are addressed. The preferred interpretation is that Trumpler 14 and 16 constitute an association at a common distance, but that the former cluster is significantly younger than the latter. Several observational obstacles which may confuse these issues are pointed out; some current work presented at this meeting may contribute to their resolution.

Key words: **OPEN CLUSTERS AND ASSOCIATIONS: INDIVIDUAL: TRUMPLER 14/16 — STARS: DISTANCES — STARS: EARLY-TYPE**

1. INTRODUCTION

The Carina Nebula (NGC 3372) is one of the most spectacular features of the Milky Way. Not surprisingly, the stellar content which energizes the H II region is correspondingly extraordinary: in addition to η Carinae —the most extreme Luminous Blue Variable— and three high-luminosity WN-A objects, it includes the initial six members of the O3 spectral class (Walborn 1971, 1973a), which comprises the hottest and presumably most massive Population I stars. The spectroscopic classification criteria, current census, and physical parameters of the O3 class were recently reviewed by Walborn (1994): it now contains 70 definite and possible members, but 59 of them are in the Magellanic Clouds while the few additional Galactic members are distributed among several different regions. Hence, the Carina Nebula stellar content provides the most accessible laboratory for investigation of the evolution of the most massive stars.

The apparent groupings of stars within the Carina Nebula have been designated with several cluster names, principally Trumpler (Tr) 14, 15, and 16 and Collinder (Cr) 228 and 232. They are identified in Figure 1 (Plate 2); charts showing their locations are also provided by Turner & Moffat (1980). However, not all of these distinctions are physically significant or related to the Nebula. Tr 15 is a compact object probably in the background of the northern part of the Nebula; its brightest member (HD 93249) is of type O9 III, a relatively minor source of ionization, and this cluster will not be further considered here. Tr 14 is also a very compact object to the north but containing three of the O3 stars; its spatial and temporal relationships to the other stellar content are highly relevant to the interpretation of the region, as will be extensively discussed. Tr 16 comprises η Car and most of the remaining early-type stars distributed throughout the northern part of the Nebula. Cr 232 is not a physical entity; the three brightest components of this wedge-shaped asterism east of Tr 14 and north of η Car include an O3 member of Tr 16 (HD 93250), a fainter O5 star (HDE 303311) which is either in the background or associated with Tr 14, and an A-type foreground star (HD 93268). Finally, Cr 228 is the designation given to the principal stellar content of the southern part of the Nebula; however, this apparent division is due to a large, V-shaped dust lane in front of the H II. Cr 228 contains no O3 stars but does include one of the WN-A objects (HD 93131); its characteristics are consistent with those of Tr 16 and it will be subsumed within the latter designation here. (There is a possibility that Cr 228 could be a somewhat older region, especially if HD 93131 originated in Tr 16. It is curious that the WN-A stars HD 92740 and 93131 are equidistant from η Car on the sky at about $25' \approx 20$ pc, near the western and southern edges of the bright nebulosity, respectively. They could have traveled that distance in 2 million years with velocities of only 10 km s^{-1}. The third WN-A star, HD 93162, is projected much nearer to η Car.) To summarize, the stellar content of the Carina Nebula is here defined as the clusters Tr 14 and 16 (the latter including Cr 228), and the relationships between them will be the focus of the discussion. There are also numerous individual early-type foreground and background stars in the field, especially in the southern part of the Nebula, as will also be further discussed; it should be kept in mind that the line of sight in this direction is along a galactic spiral arm.

2. SURVEY OF RECENT LITERATURE

As might be expected, this exceptional region attracts considerable observational attention. A brief summary of studies since 1981 addressing the stellar content follows. Spectral classifications have been discussed by Levato & Malaroda (1981, 1982), Walborn (1982a,b), Morrell, García, & Levato (1988), and Massey & Johnson (1993). Radial velocities and spectroscopic binaries were investigated by Levato et al. (1990, 1991a,b) and Penny et al. (1993). Photometric analyses are presented by Feinstein (1982, 1983), Thé & Groot (1983), and Massey & Johnson (1993). Infrared observations were discussed by Smith (1987) and Tapia et al. (1988). A proper-motion study was conducted by Cudworth, Martin, & DeGioia-Eastwood (1993), while astrophysical parameters of several O3 stars were derived by Kudritzki et al. (1992).

3. RELATIVE DISTANCES AND AGES OF TR 14/16

3.1. Distance Moduli

Despite extensive research, these basic structural issues remain controversial, and substantial discrepancies occur among the results of even the recent investigations cited above. One reason for this continuing uncertainty is the ambiguity between the two quantities, since a fainter upper main sequence may correspond to either a larger distance or a smaller age. As discussed by Walborn (1973a) and Morrell et al. (1988), the O-type stars at a given spectral type in Tr 14 are fainter than their counterparts in Tr 16. Using a common absolute-magnitude calibration, Walborn (1973a) derived true distance moduli of 12.72 and 12.13 for the two groups, respectively, which were interpreted in terms of a distance difference, although the alternative possibility of an age difference was also discussed and subsequently preferred by Walborn (1982a,b), with a common modulus of 12.26 ± 0.12 ($n = 20$). Recently, Massey & Johnson (1993) have completed an extensive digital spectroscopic and photometric study of Tr 14 and 16. They derive moduli of 12.79 ± 0.18 ($n = 8$) and 12.49 ± 0.09 ($n = 37$), respectively, but consider these values to be indistinguishable within the errors and adopt a common modulus of 12.55 ± 0.08, discounting any discernible age difference as well. However, it should be noted that their result for Tr 14 separately is nearly identical to that of Walborn (1973a). Furthermore, a very important contribution of the Massey & Johnson work is the addition of numerous B-type main-sequence members of Tr 16 observed spectroscopically for the first time. If these objects are systematically nearer to the ZAMS than the typical calibrators, as might be expected in an O3-type cluster, then they will artificially raise the Tr 16 modulus. Indeed, the data of Massey & Johnson support that possibility: taking their O V and B V stars separately, one obtains moduli of 12.38 ± 0.11 ($n = 21$) and 12.70 ± 0.11 ($n = 26$), respectively, indicating that the latter may be systematically fainter relative to the calibration.

It should be noted that the modulus determinations by Walborn were made with the assumption of a ratio of total-to-selective extinction $R = 3.0$, while Massey & Johnson used $R = 3.2$. The photometric and IR studies cited above, and earlier references therein, reach conflicting conclusions regarding the value of R in the Carina Nebula, ranging from normal to uniformly high, or anomalous and variable from star to star. Also, the results of Walborn (1973a) were based on the spectroscopic absolute-magnitude calibration of Walborn (1972), while later work incorporated the calibration revisions of Walborn (1973b, 1982a). For consistent reference, all Tr 14/16 O-type members classified by the author are listed in Table 1, with alternative distance moduli corresponding to $R = 3$, 4, and 5 based on the 1973b/1982a calibration. Average moduli and corresponding Tr 16 distances in parsecs are also given. For comparative purposes, the Tr 14 moduli in Table 1 are computed with the standard calibration, leading to larger values than for Tr 16, but both clusters are now believed to

Table 1. Distance Moduli of Tr 14/16

HD/HDE/CPD	Spectral Type	E_{B-V}	M_V	$V_0 - M_V$ $R = 3$	$R = 4$	$R = 5$
Tr 14						
93128	O3 V((f))	0.56	(−5.5)	12.59	12.03	11.47
93129A	O3 If*	0.54	−6.4	12.1	11.5	11.0
93129B	O3 V((f))	0.54	(−5.5)	12.8	12.2	11.7
−58°2611	O6 V((f))	0.60	(−5.3)	13.13	12.53	11.93
−58°2620	O6.5 V((f))	0.50	(−5.3)	13.07	12.57	12.07
Average	...	0.55	...	(12.90)	(12.33)	(11.79)
				±0.13	±0.13	±0.13
Tr 16/Cr 228						
93027	O9.5 V	0.30	−4.1	11.92	11.62	11.32
93028	O9 V	0.25	−4.3	11.91	11.66	11.41
93130	O6 III(f)	0.54	−5.6	12.04	11.50	10.96
93146	O6.5 V((f))	0.34	−5.3	12.72	12.38	12.04
93160	O6 III(f)	0.49	−5.6	11.94	11.45	10.96
93161AB	O6.5 V((f))	0.54	−6.05	12.27	11.73	11.19
93204	O5 V((f))	0.42	−5.5	12.66	12.24	11.82
93205	O3 V	0.37	−5.5	12.14	11.77	11.40
93222	O7 III((f))	0.37	−5.6	12.60	12.23	11.86
93250	O3 V((f))	0.47	−5.5	11.47	11.00	10.53
93343	O7 V(n)	0.61	−4.8	12.44	11.83	11.22
93403	O5 III(f) var	0.53	−6.4	12.09	11.56	11.03
303308	O3 V((f))	0.45	−5.5	12.32	11.87	11.42
305536	O9 V	0.36	−4.3	12.16	11.80	11.44
−59°2600	O6 V((f))	0.53	−5.3	12.32	11.79	11.26
−59°2603	O7 V((f))	0.46	−4.8	12.19	11.73	11.27
−59°2635	O7 Vnn	0.55	−4.8	12.46	11.91	11.36
−59°2636	O8 V	0.62	−4.4	11.85	11.23	10.61
−59°2641	O5 V	0.64	−5.5	12.87	12.23	11.59
Average	...	0.47	...	12.23	11.76	11.30
				±0.08	±0.08	±0.09
Distance [pc]				2800	2250	1800

have a common distance, with the lower luminosities of the O-type members of Tr 14 being due to a smaller age. (HD 93129A is excluded from the mean moduli since its M_V depends on the assumption of the Tr 16 distance —Walborn 1982a). Allen & Hillier (1993) have recently derived a distance to η Car of 2.2 ± 0.2 kpc from the expansion of its ejected nebulosity, lending some indirect support for a value of $R = 4$. As shown by Table 1, if R(Tr 14) = R(Tr 16) + 1, there would be no need for either a distance or age difference between the two clusters.

3.2. Further Evidence for a Younger Tr 14

In addition to its fainter upper main sequence, several other characteristics support the interpretation that Tr 14 is younger than Tr 16. (i) Tr 14 is a remarkably compact, high-density object, possibly indicative of relatively recent formation. (ii) As well as their fainter absolute magnitudes, the early and mid-O dwarfs in Tr 14 display a possible spectroscopic diagnostic of lower luminosity, namely larger He II $\lambda\lambda$4686/4541 absorption-line ratios than the classification standards and their Tr 16 counterparts. The weakening of λ4686 absorption and its transition to emission are a well-established luminosity criterion in O-type spectra (Walborn 1973b). The inverse effect relative to typical main-sequence spectra may well correspond to lower luminosities; a number of examples have recently been found in very young regions (Parker et al. 1992; Walborn & Parker

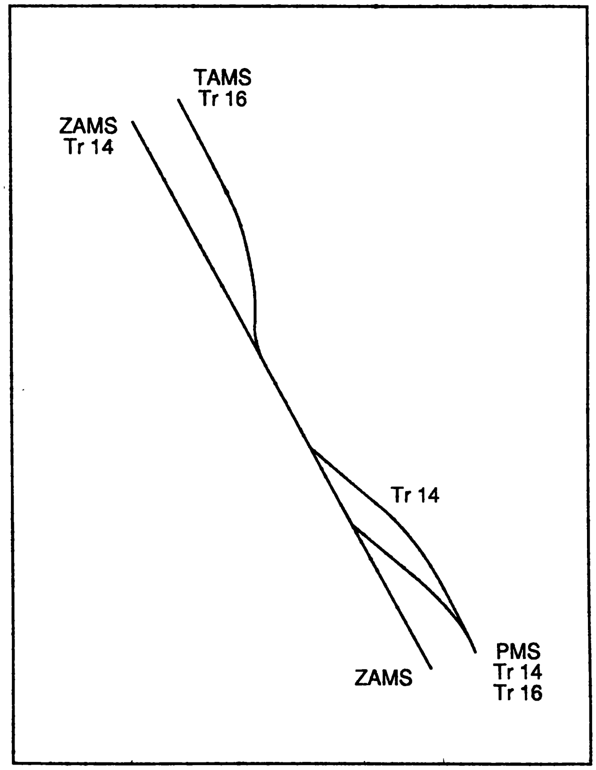

Fig. 2. Schematic color-magnitude sequences of Tr 14/16. See the text for discussion.

1992; Parker 1993). Currently, N. Morrell, R. Méndez, and the author are investigating this hypothesis through the determination of physical parameters from high-resolution observations of an appropriate sample, including several members of Tr 14 and 16. (iii) The brightest member of Tr 14 is HD 93129A, of type O3 If*, which may be a pre-WN object (Walborn 1971, 1973a, 1974). Penny et al. (1993) derive ages of less than a million years for it and HD 93128, an O3 V member of Tr 14. On the other hand, Tr 16 has associated with it three WN-A objects, which are generally regarded as corresponding to evolutionary ages greater than two million years. (iv) Smith (1987) found three objects with large IR excesses very near Tr 14 and cited other evidence that it is interacting more strongly with the surrounding interstellar material and is hence possibly younger than Tr 16. The discovery of a small IR cluster announced by P. Cox at this meeting indicates ongoing star formation within the Carina Nebula and indirectly supports the possibility of an age difference between Tr 14 and 16.

3.3. Observational Obstacles

Given the considerable evidence discussed above, why has an age difference between Tr 14 and 16 been so difficult to establish, and why are the results of different studies so often contradictory on this issue? A number of reasons can be suggested. (i) If an age difference of the order indicated above exists between Tr 14 and 16, their cluster sequences are expected to bear the relationships shown schematically in Figure 2. At the upper end, Tr 14 members will lie on the zero-age main sequence (ZAMS), while those of Tr 16 are approaching the terminal-age main sequence (TAMS) and will be brighter. Progressing downward, members of both clusters will coincide on the ZAMS, beginning at a point corresponding to about 20 $M_{\odot}$ or slightly less according to the formulation of Maeder & Meynet (1988). (Note also that their high-mass tracks inflect back toward the ZAMS on significant timescales, predicting overlap between the upper sequences.) Below the common ZAMS region, Tr 14 members will diverge toward the pre-main sequence (PMS) before those of Tr 16, inverting the relative luminosities of the two sequences with respect to the upper region. Finally, Tr 14 and 16 members may again coincide on a PMS at the lower end. Combined with other difficulties discussed below, these crossing and overlapping sequences may generate substantial confusion in efforts to discern an age difference between them. (ii) There will be projected spatial overlap between the two clusters, which becomes more severe at larger radii from the compact core of Tr 14. An extreme case in point is the bright triple system HD 93160/93161AB, which is here associated with Tr 16 but has been included in the Tr 14 sequence by some authors due to their angular proximity. (iii) The very crowded core of Tr 14 further aggravates the foregoing problem. Slit spectroscopic programs will be dominated by the bright members of the core, while some photometric programs and in particular the astrometric study of Cudworth et al. (1993), which found no distinctions between the Tr 14 and 16 sequences, have been forced to avoid it entirely. (iv) There are a considerable number of early-type foreground and background stars in the field, especially in the southern part of the Nebula, which may not always be easy to eliminate in purely photometric studies, due to ambiguity between reddening and luminosity effects. Well-known foreground objects are the B stars HD 92741 and 93695, and the A star HD 93268 mentioned before. More problematic are the background objects, which may be expected to increase in numbers at fainter magnitude levels. Known examples in the southern part of the Nebula are HDE 305520, 305523, 305532 and 305539; Feinstein 12 and 97; and probably HD 93632, of type O5 III(f) var, the brightest member of the small cluster Bochum 11 which may be the principal ionization source for the apparent southeastern "lobe" of the Nebula. An interesting, relatively recently discovered example in the northern part of the Nebula is the heavily reddened O4 If object Thé 149 = Feinstein 244 = Massey 257. (v) To the foregoing difficulties, one must add the standard uncertainties arising from composite members, peculiar reddening laws, and photometric errors. It may be hoped that several of the studies described at this meeting, especially those involving careful analysis of higher precision photometry for larger numbers of stars with CCD techniques, will provide substantial improvements in the observational situation of Tr 14 and 16.

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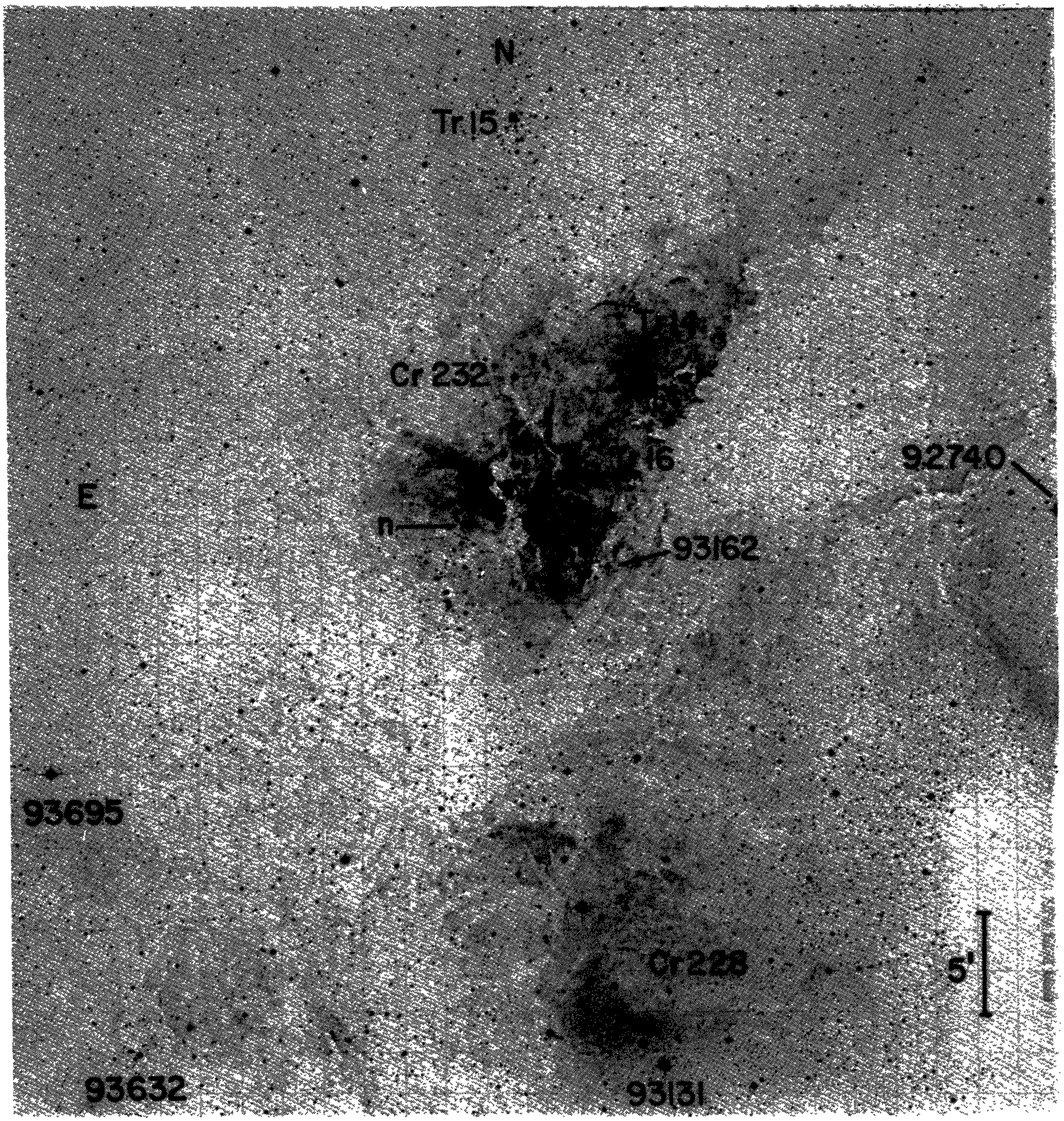

Fig. 1. The Carina Nebula field, with the stellar clusters, η Car, and the HD numbers of several stars discussed in the text marked. (The bright WN-A star HD 92740 is partially outside the field to the west.) The photograph is an unsharp-mask copy of a 15 min, IIa-O+GG385 plate from the prime focus of the Anglo-Australian Telescope, obtained by and courtesy of D. Malin.

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