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A census of the Carina Nebula – I. Cumulative energy input from massive stars

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ABSTRACT

The Carina Nebula (NGC 3372) is our richest nearby laboratory in which to study feedback through ultraviolet radiation and stellar winds from very massive stars during the formation of an OB association, at an early phase in the evolution of the surrounding proto-superbubble before supernova explosions have influenced the environment. This feedback is triggering successive generations of new star formation around the periphery of the nebula, while simultaneously evaporating the gas and dust reservoirs out of which young stars are trying to accrete material. This paper takes inventory of the combined effect from all the known massive stars that power the Carina Nebula through their total ionizing flux and integrated mechanical energy from their stellar winds. Carina is close enough and accessible enough that spectral types for individual stars are available, and many close binary and multiple systems have recently been spatially resolved, so that one can simply add them. Adopting values from the literature for corresponding spectral types, the present-day total ionizing photon luminosity produced by the 65 O stars and three WNL stars in Carina is $Q_{\rm H} \simeq 10^{51}$ s^{-1}, the total bolometric luminosity of all stars earlier than B2 is 2.5×10^7 L$_\odot$, and the total mechanical luminosity of stellar winds is $L_{\rm SW} \simeq 10^5$ L$_\odot$. The total $Q_{\rm H}$ was about 25 per cent higher when η Carinae was on the main sequence, before it and its companion were surrounded by its obscuring dust shell; for the first 3 Myr, the net ionizing flux of the 70 O stars in Carina was about 150 times greater than in the Orion Nebula. About 400–500 M$_\odot$ has been contributed to the H II region by stellar wind mass-loss during the past 3 Myr. Values for $Q_{\rm H}$ and $L_{\rm SW}$ are also given for the individual clusters Tr14, 15 and 16, and Bo10 and 11, which are more relevant on smaller spatial scales than the total values for the whole nebula.

Key words: stars: early-type – stars: formation – stars: winds, outflows – ISM: bubbles – H II regions – ISM: individual: NGC 3372.

1 INTRODUCTION

Feedback from young massive stars may play an integral role in star and planet formation. Most stars are born in the vicinity of the hottest and most massive stars spawned only from giant molecular clouds, and the effects of feedback from these massive stars cannot be studied in nearby quiescent regions of star formation. Even the nearest H II region, the Orion Nebula, may not be representative of the extreme environments where most stars are born, since it is dominated by just a single O6 dwarf.

A much more extreme collection of stars can be found in the Carina Nebula (NGC 3372). Its star clusters are almost as spectacular as those of 30 Dor in the LMC (Massey & Hunter 1998), or objects in our own Galaxy like the Arches cluster near the Galactic Centre (Figer et al. 1999, 2002; Najarro et al. 2004) and NGC 3603 (Moffat et al. 2002). However, these other regions are too distant for detailed studies of small-scale phenomena like irradiated protoplanetary discs and jets, and their study is hampered by considerably more extinction. The low extinction towards Carina combined with its proximity and rich nebular content provide a worthwhile trade-off for its less concentrated star clusters. While this may be a liability for investigating the upper end of the initial mass function, the fact that Carina's stars are more of a loose aggregate may be an advantage for studying feedback and triggered star formation. Carina provides a snapshot of an OB association in the making, which may be more representative of the environments in which most stars form than are bound superstar clusters. It may also provide an early analogue of the local Galactic environment that evolved into Gould's Belt.

Recent studies suggest that at the present epoch there exists an upper mass limit to the most massive stars of ∼150 M$_\odot$

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(Weidner & Kroupa 2004; Figer 2005; Kroupa & Weidner in press; Oey & Clarke 2005). While the star clusters that power Carina may not be as dense as the Arches cluster or NGC 3603, Carina does contain several examples of stars that probably began their lives with 100–150 $M_{\odot}$. Among these are η Carinae, the prototypical O2 supergiant HD 93129A, three late-type hydrogen-rich Wolf–Rayet stars (WNL stars), and the remaining original members of the O3 spectral class for which this spectral type was first introduced (Walborn 1973; although see Walborn et al. 2002). For these colossal stars, lifetimes of ~3 Myr before they explode as supernovae (SNe) are shorter than the time it takes to clear away their natal molecular material. Consequently, we already have a situation in Carina where the most massive members like η Car are approaching their imminent demise while new stars are being born from dense molecular gas only 5–20 pc away. In the next 1–2 Myr, there will be several very energetic SNe in the Carina Nebula, which will carve out an even larger cavity in the interstellar medium and form a giant superbubble in the Galactic plane, and may pollute protoplanetary discs with nuclear-processed ejecta. In the mean time, studying this rich region provides a snapshot of a young proto-superbubble (Smith et al. 2000) energized only by ultraviolet (UV) radiation and stellar winds, immediately before the disruptive SN-dominated phase.

In just the past decade, the Carina Nebula has been recognized as a hotbed of ongoing active star formation. It provides a laboratory to study several star formation phenomena in great detail, all of which have recently been identified in this region: (1) evaporating protoplanetary discs (the so-called 'proplyds'), small cometary clouds or globules (Cox & Bronfman 1995; Brooks et al. 2000; Smith 2002b; Smith, Bally & Morse 2003a; Brooks et al. in press), (2) the erosion of large dust pillars and the triggering of a second generation of embedded star formation within them (Megeath et al. 1996; Smith et al. 2000; Rathborne et al. 2004; Smith, Stassun & Bally 2005), (3) irradiated Herbig–Haro (HH) jets that are a signpost of active accretion (Smith, Bally & Brooks 2004), (4) photodissociation regions (PDRs) on the surfaces of molecular clouds across the region (Brooks, Whiteoak & Storey 1998; Smith et al. 2000; Rathborne et al. 2002; Brooks et al. 2003; Mizutani, Onaka & Shibai 2004; Brooks et al. in press), and on the largest scales, (5) the early formation of a fledgeling superbubble (Smith et al. 2000). These phenomena trace a second generation of stars, perhaps triggered by feedback from the first generation clusters. Carina is near enough that an upcoming program with the *Hubble Space Telescope* will undertake the same types of detailed studies of feedback that have been done in Orion at visual and near-infrared wavelengths, but sampling a more extreme environment.

All of these phenomena respond to the cumulative UV radiation and/or stellar winds from star clusters that power the H II region, and a census of this energy input is essential in order to understand the relationship between them. Estimating the total stellar energy input in Carina is a more difficult problem than in smaller H II regions like Orion, where a single star dominates the photoevaporation of proplyds and the irradiation of HH jets. Instead, Carina has dozens of massive O stars over many parsecs. Although the remarkable stellar content of the Carina Nebula has been discussed many times in the literature (e.g. Massey & Johnson 1993; Feinstein 1995; Walborn 1995, 2002, 2005), there is no complete and up-to-date census of the massive stars, and especially there has been no estimate of their *collective* UV radiation and mechanical (wind) luminosity that powers the region. This is the main purpose of the present investigation. A second paper in this series will compare the total energy input from stars with the apparent energy budget inferred from observations of the surrounding Carina Nebula.

2 ADOPTED PARAMETERS

The basic strategy in this paper will be to use the observed spectral type of each massive star (spectral types as late as B2 will be considered, although their influence is minimal) to assign a corresponding value for the hydrogen-ionizing photon luminosity Q_{H}, as well as the mass-loss rate $\dot{M}$ and terminal wind speed V_{∞}, and hence, the wind mechanical luminosity $L_{\mathrm{SW}} = (1/2)\dot{M}V_{\infty}^2$. Table 1 lists the values that will be adopted for stars later than O3. In Table 1, values of log L and Q_{H} for each spectral type are taken from the 'observed' temperature-scale models of Martins, Schaerer & Hillier (2005). Values for $\dot{M}$ are taken from Repolust, Puls & Herrero (2004), and terminal velocities for each spectral type are taken by a rough fit to the average values listed by Prinja, Barlow & Howarth (1990).[1]

The stellar content of the Carina Nebula is truly remarkable and accessible, and several of the more spectacular stars have received enough attention that the desired parameters have been derived individually for them. In some cases, when noted below, individual studies may supersede the average values adopted in Table 1. Many of these stars are, in fact, benchmarks for their spectral types in the three papers just mentioned. In addition, the three WNL stars in Carina are of particular interest, as are HD 93129A and η Car (when it was on the main sequence), since these are the most luminous sources that have the most influence. The specific stellar content of the nebula is described in more detail in the following section.

3 STELLAR CONTENT

Tables 2–6 compile the stellar content powering the Carina Nebula. References for the stellar content of each cluster are noted in each table. Several reviews exist in the literature (especially Feinstein 1995; Walborn 1995, 2005); these were invaluable in compiling the tables. Every effort has been made to provide the most recent information with regard to binarity/multiplicity through spectral types or high spatial resolution techniques, especially for Tr14 and 16. This, of course, does not preclude the possibility that additional companions may be identified, and their influence should be considered by readers in that case.

Following Walborn (1995) and Tapia et al. (1988), it is assumed that all these clusters share a common distance to the Carina Nebula, taken here to be 2.3 ± 0.1 kpc (Allen & Hillier 1993; Walborn 1995; Smith 2002a). The distance of 2.3 kpc determined for η Carinae itself is very reliable, having been derived from proper motions and Doppler velocities of the expanding Homunculus (Allen & Hillier 1993; Smith 2002a). Furthermore, η Car is known to be at the same distance as the Keyhole nebula, since its reflected spectrum is seen across the Keyhole (Walborn & Liller 1977; Lopez & Meaburn 1986). Differences in photometric distance moduli given in the literature are probably due to anomalous or varying reddening laws, patchy extinction, small-age differences or other factors. For example, photometric distances as high as 3.7 kpc have been given for Tr15 (Walborn 1973), requiring that Tr15 be several hundred parsecs *behind* the rest of the Carina nebula. This seems implausible, although not impossible, for several reasons, including the fact that

[1] Given the spread in terminal velocities listed by Prinja et al. (1990), we adopted the same velocities for all three luminosity classes in Table 1. This is a reasonable approximation for the earliest spectral types that dominate the energy budget.

Table 1. Adopted parameters for each spectral type.

Spectral type	Luminosity class	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ ($10^{-6}\,M_\odot\,yr^{-1}$)	V_∞ ($km\,s^{-1}$)	L_{SW} ($L_\odot$)
O3	V	5.84	49.64	3.1	3160	2450
O3.5	V	5.76	49.54	2.5	3080	1870
O4	V	5.67	49.44	2.0	2990	1410
O4.5	V	5.58	49.33	1.6	2870	1040
O5	V	5.49	49.22	1.3	2760	780
O5.5	V	5.41	49.10	1.0	2650	550
O6	V	5.32	48.99	0.8	2560	410
O6.5	V	5.23	48.88	0.6	2460	290
O7	V	5.14	48.75	0.4	2320	170
O7.5	V	5.05	48.61	0.35	2210	135
O8	V	4.96	48.44	0.26	2100	91
O8.5	V	4.86	48.27	0.22	1960	67
O9	V	4.77	48.06	0.18	1820	47
O9.5	V	4.68	47.88	0.15	1660	33
B0	V	4.57	47.70	0.12	1510	22
B0.5	V	4.47	47.50	0.10	1460	17
B1	V	4.37	47.28	0.08	1180	8.8
B1.5	V	4.28	47.05	0.06	960	4.4
B2	V	4.19	46.80	0.05	750	2.2
O3	III	5.96	49.77	6.5	3160	5130
O3.5	III	5.91	49.71	5.5	3080	4120
O4	III	5.85	49.64	4.7	2990	3320
O4.5	III	5.79	49.56	4.0	2870	2600
O5	III	5.73	49.48	3.4	2760	2050
O5.5	III	5.67	49.40	2.7	2650	1500
O6	III	5.61	49.32	2.2	2560	1140
O6.5	III	5.54	49.23	1.8	2460	860
O7	III	5.48	49.13	1.5	2320	640
O7.5	III	5.42	49.01	1.2	2210	460
O8	III	5.35	48.88	0.8	2100	280
O8.5	III	5.28	48.75	0.7	1960	210
O9	III	5.21	48.65	0.5	1820	130
O9.5	III	5.15	48.42	0.4	1660	87
B0	III	5.08	48.28	0.3	1510	54
B0.5	III	5.00	48.10	0.25	1460	42
B1	III	4.93	47.90	0.20	1180	22
B1.5	III	4.86	47.68	0.15	960	11
B2	III	4.78	47.44	0.11	750	4.9
O3	I	5.99	49.78	13.0	3160	10300
O3.5	I	5.96	49.74	11.3	3080	8470
O4	I	5.93	49.70	10.0	2990	7060
O4.5	I	5.90	49.66	8.9	2870	5790
O5	I	5.87	49.62	8.0	2760	4810
O5.5	I	5.84	49.58	7.1	2650	3940
O6	I	5.81	49.52	6.4	2560	3310
O6.5	I	5.78	49.46	5.7	2460	2730
O7	I	5.75	49.41	5.0	2320	2130
O7.5	I	7.72	49.31	4.3	2210	1660
O8	I	5.68	49.25	3.6	1960	1090
O8.5	I	5.65	49.19	3.0	1820	790
O9	I	5.61	49.11	2.5	1660	540
O9.5	I	5.57	49.00	1.9	1510	340

References: L, Q_H: Martins et al. (2005); V_∞: Prinja et al. (1990); $\dot{M}$: Repolust et al. (2004). L and Q_H for B stars were extrapolated from Martins et al. (2005) following Crowther (in press).

Tr15 is seen along the same line of sight as dense gas and dust structures, some of which are dust pillars that point towards Tr16. Yet, stars in Tr15 have an average $E(B-V)=0.5$ (Feinstein, Fitzgerald & Moffat 1980) – roughly the same as Tr14 and 16 (Feinstein, Marraco & Muzzio 1973; Walborn 1995) – which could not be the case if Tr15 were far behind the rest of the nebula and obscured. Similarly, relatively large distances to Tr14 (Vázquez et al. 1996) are implausible. Even though Tr14 must be somewhat more distant

Table 2. Stellar Content of Trumpler 16 and Collinder 228.

Name	Spectral type	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	V_∞ (km s^{-1})	L_{SW} ($L_\odot$)
η Car-now	LBV	6.67	...	1000	600	28700
η Car-MS	O2 If (?)	6.57	50.36	8.32	3200	6780
η Car-B	O5 V (?)	5.49	49.2	1.3	2760	780
HD 93162	WN6ha	6.22	50.0	10.5	2480	5140
HD 93131	WN6ha	5.94	49.7	13.8	2160	5130
HD 92740A	WN7ha	6.01	49.8	14.5	1785	3680
HD 92740B	O8-9 V	4.86	48.27	0.22	1960	67
HD 93205A	O3.5 V((f))	5.76	49.54	2.5	3080	1870
HD 93205B	O8 V	4.96	48.44	0.26	2100	91
HD 93250	O3.5 V((f))	5.76	49.54	2.5	3080	1870
HDE 303308	O4 V((f))	5.67	49.44	2.0	2990	1410
HD 93204	O5 V((f))	5.49	49.22	1.3	2760	780
Tr16-244	O4 If	5.93	49.70	10.0	2990	7060
CPD-59 2600	O6 V((f))	5.32	48.99	0.8	2560	410
CPD-59 2603A	O7 V((f))	5.14	48.75	0.4	2320	170
CPD-59 2603B	O9.5 V	4.68	47.88	0.15	1660	33
CPD-59 2603C	B0.2 V	4.57	47.70	0.12	1510	22
CPD-59 2628A	O9.5 V	4.68	47.88	0.15	1660	33
CPD-59 2628B	B0.3 V	4.57	47.70	0.12	1510	22
CPD-59 2635A	O8 V	4.96	48.44	0.26	2100	91
CPD-59 2635B	O9.5 V	4.68	47.88	0.15	1660	33
CPD-59 2636A	O7 V	5.14	48.75	0.4	2320	170
CPD-59 2636B	O8 V	4.96	48.44	0.26	2100	91
CPD-59 2636C	O9 V	4.77	48.06	0.18	1820	47
CPD-59 2641	O5 V	5.49	49.22	1.3	2760	780
HDE 303311	O5 V	5.49	49.22	1.3	2760	780
HDE 305536	O9 V	4.77	48.06	0.18	1820	47
HD 93027	O9.5 V	4.68	47.88	0.15	1660	33
HD 93028	O9 V	4.77	48.06	0.18	1820	47
HD 93130	O6 III(f)	5.61	49.32	2.2	2560	1140
HD 93146	O6.5 V((f))	5.23	48.88	0.6	2460	290
HD 93160	O6 III((f))	5.61	49.32	2.2	2560	1140
HD 93161Aa	O8 V	4.96	48.44	0.26	2100	91
HD 93161Ab	O9 V	4.77	48.06	0.18	1820	47
HD 93161B	O6.5 V((f))	5.23	48.88	0.6	2460	290
HD 93206A	O9.7 Ib:(n)	5.57	49.00	1.9	1510	340
HD 93206B	O9 III	5.21	48.65	0.5	1820	130
HD 93222	O7 III(f)	5.48	49.13	1.5	2320	640
HD 93343	O7 V(n)	5.14	48.75	0.4	2320	170
HD 93403A	O5 III(f)var	5.73	49.48	3.4	2760	2050
HD 93403B	O7 V	5.14	48.75	0.4	2320	170
Tr16-2	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-3	O8.5 V	4.86	48.27	0.22	1960	67
Tr16-4	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-5	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-8	B0.5 V	4.47	47.50	0.10	1460	17
Tr16-9	O9.5 V	4.68	47.88	0.15	1660	33
Tr16-10	B0 V	4.57	47.70	0.12	1510	22
Tr16-11	B1.5 V	4.28	47.05	0.06	960	4.4
Tr16-12	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-13	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-14	B0.5 V	4.47	47.50	0.10	1460	17
Tr16-16	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-17	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-19	O9.5 V	4.68	47.88	0.15	1660	33
Tr16-20	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-21	O8 V	4.96	48.44	0.26	2100	91
Tr16-22	O8.5 V	4.86	48.27	0.22	1960	67
Tr16-23	O7 V	5.14	48.75	0.4	2320	170
Tr16-24	B2 V	4.19	46.80	0.05	750	2.2
Tr16-27	B1 V ?	4.37	47.28	0.08	1180	8.8
Tr16-28	B2 V	4.19	46.80	0.05	750	2.2

Table 2 – *continued*

Name	Spectral type	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ ($10^{-6}\,M_\odot\,yr^{-1}$)	V_∞ ($km\,s^{-1}$)	L_{SW} ($L_\odot$)
Tr16-29	B2 V	4.19	46.80	0.05	750	2.2
Tr16-31	B0.5 V	4.47	47.50	0.10	1460	17
Tr16-37	B1 V ?	4.37	47.28	0.08	1180	8.8
Tr16-74	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-76	B2 V	4.19	46.80	0.05	750	2.2
Tr16-94	B1.5 V	4.28	47.05	0.06	960	4.4
Tr16-115	O8.5 V	4.86	48.27	0.22	1960	67
Tr16-122	B1.5 V	4.28	47.05	0.06	960	4.4
Tr16-124	B1 V	4.37	47.28	0.08	1180	8.8
Tr16-126	O9 V	4.77	48.06	0.18	1820	47
Tr16-127	O9 V	4.77	48.06	0.18	1820	47
Tr16-245	B0 V	4.57	47.70	0.12	1510	22

Note: η Car's hypothetical value for Q_H on the main sequence is taken by adopting the same Q_H/L_{Bol} ratio as for HD 93129Aa. References: Nelan et al. (2004); Massey & Johnson (1993); Walborn (1973, 1995, 2002, 2005); Penny et al. (1993); Repolust et al. (2004); Nazé et al. (2005; for HD 93161); Smith, Shara & Moffat (1996); Crowther et al. (1995, 2002; although Q_H and $\dot{M}$ values for the WNL stars are from Crowther 2005, private communication, modified to include clumping in the wind).

Table 3. Stellar content of Trumpler 14.

Name	Spectral type	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ ($10^{-6}\,M_\odot\,yr^{-1}$)	V_∞ ($km\,s^{-1}$)	L_{SW} ($L_\odot$)
HD 93129Aa	O2 If*	6.17	49.96	8.32	3200	6780
HD 93129Ab	O3.5 V	5.76	49.54	2.5	3080	1870
HD 93129B	O3.5 V((f+))	5.76	49.54	2.5	3080	1870
HD 93128	O3.5 V((f+))	5.76	49.54	2.5	3080	1870
CPD-58 2611	O6 V((f))	5.32	48.99	0.8	2560	410
CPD-58 2620	O6.5 V((f))	5.23	48.88	0.6	2460	290
Tr14-3	B0.5 IV-V	4.50	47.70	0.15	1460	26
Tr14-4	B0 V	4.57	47.70	0.12	1510	22
Tr14-5	O9 V	4.77	48.06	0.18	1820	47
Tr14-6	B1 V	4.37	47.28	0.08	1180	8.8
Tr14-9	O8 V	4.96	48.44	0.26	2100	91
Tr14-18	B0 V	4.57	47.70	0.12	1510	22
Tr14-21	O9 V	4.77	48.06	0.18	1820	47
Tr14-27	O9 V	4.77	48.06	0.18	1820	47
Tr14-30	B0 III-IV	4.90	48.10	0.25	1510	45

References: Nelan et al. (2004); Massey & Johnson (1993); Walborn (1973, 1995, 2005); Penny et al. (1993); Repolust et al. (2004).

than Tr16 (perhaps as much as 20 pc) because silhouette objects projected in front of it point towards Tr16 (Smith et al. 2003a), it cannot be several hundred parsecs farther away. The outermost filaments of the Carina region span a distance of ~120 pc (Smith et al. 2000), yet Tr14 and 16 are projected only about 5 pc from each other on the sky, and even the Keyhole Nebula near Tr16 shows signs of ionization from the northwest (i.e. from Tr14).

Additional clusters that are sometimes associated with Carina, such as NGC 3324 and 3293, are ignored in the present analysis. They do not appear to lie within the nebular structures that define the outermost boundaries of the Carina Nebula, and the stars of NGC 3324 are associated with their own separate circular H II region.

3.1 Trumpler 16

Energy input in Carina is dominated by the massive cluster Tr16, of which the infamous massive star η Car is the most luminous member. This is clear even before a detailed look at its stellar content, since optical images of Carina show numerous sculpted dust pillars and other elongated structures located across several degrees of the sky, and nearly all of them point back towards η Car and the centre of Tr16 (Smith et al. 2000; Walborn 2002; Smith et al. 2003a, 2004, 2005).

As noted by Walborn (1995) and others, Cr 228 and 232 are probably part of Tr16, where their apparent separation on the sky is an artefact caused by dust lanes on the near side of the nebula. Thus, Table 2 includes Cr 228 and 232 as members of a larger Tr16 cluster. Table 2 also includes the O5 V star HDE 303311, which is part of Cr 232, as a member of Tr16, even though its membership is somewhat uncertain (Walborn 1995). In this and other cases, whether this star is considered part of Tr16 or Tr14 has no net effect on the global energetics of the region, but it may inflate the relative importance of Tr16.

Also included within Tr16 in Table 2 are the three WNL stars in the region. HD 93162 is almost certainly a member of Tr16. The two other WNL stars, HD 92740 and 93131, are quite a bit farther

Table 4. Stellar content of Trumpler 15.

Name	Spectral type	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	V_∞ ($km\,s^{-1}$)	L_{SW} ($L_\odot$)
HDE 303304	O8 V	4.96	48.44	0.26	2100	91
HD 93249	O8 II/O9 III	5.28	48.75	0.7	1960	210
HD 93342	O9 III	5.21	48.65	0.5	1820	130
Tr15-18	O9 I-II	5.61	49.11	2.5	1660	540
Tr15-2	O9 III	5.21	48.65	0.5	1820	130
Tr15-19	O9 V	4.77	48.06	0.18	1820	47
HD 93190	B0 IV	4.83	48.00	0.21	1510	38
Tr15-3	B2 V	4.19	46.80	0.05	750	2.2
Tr15-4	B1 V	4.37	47.28	0.08	1180	8.8
Tr15-7	B2 V	4.19	46.80	0.05	750	2.2
Tr15-9	B1 V	4.37	47.28	0.08	1180	8.8
Tr15-10	B2 V	4.19	46.80	0.05	750	2.2
Tr15-13	B1 V	4.37	47.28	0.08	1180	8.8
Tr15-14	B2 V	4.19	46.80	0.05	750	2.2
Tr15-15	B0.5 IV-V	4.47	47.50	0.10	1460	17
Tr15-20	B1 V ?	4.37	47.28	0.08	1180	8.8
Tr15-21	B0 III	5.08	48.28	0.3	1510	54
Tr15-23	B0 V	4.57	47.70	0.12	1510	22
Tr15-26	B0.5 V	4.47	47.50	0.10	1460	17

References: Feinstein et al. (1980); Morrell et al. (1988).

Table 5. Stellar content of Bochum 10.

Name	Spectral type	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	V_∞ ($km\,s^{-1}$)	L_{SW} ($L_\odot$)
HD 92809	WC6	5.32	49.20	16	2280	6620
HD 92725	O9.5 III	5.15	48.42	0.4	1660	87
HD 92964	B2 Ia	5.30	48.35	0.5	750	22
HD 92759	B0 III	5.08	48.28	0.3	1510	54
HD 92894	B0 IV	4.83	48.00	0.21	1510	38
HD 93002	B0 IV	4.83	48.00	0.21	1510	38
HDE 302989	B2 V	4.19	46.80	0.05	750	2.2
HDE 303190	B1 V	4.37	47.28	0.08	1180	8.8
HDE 303296	B1 V	4.37	47.28	0.08	1180	8.8
HDE 303297	B1 V	4.37	47.28	0.08	1180	8.8
Bo10-2	B0.5 IV	4.74	47.80	0.18	1460	30
Bo10-7	B2 IV	4.49	47.12	0.08	750	3.5
Bo10-15	B1 V	4.37	47.28	0.08	1180	8.8

References: Feinstein (1981); Fitzgerald & Mehta (1987); Prinja et al. (1990); Smartt et al. (2001).

Table 6. Stellar content of Bochum 11.

Name	Spectral type	log L ($L_\odot$)	log Q_H (s^{-1})	$\dot{M}$ (10^{-6} $M_\odot$ yr^{-1})	V_∞ ($km\,s^{-1}$)	L_{SW} ($L_\odot$)
HD 93632	O4-5 III(f)	5.79	49.56	4.0	2870	2600
Bo11-2	O9 V	4.77	48.06	0.18	1820	47
Bo11-3	B2 V	4.19	46.80	0.05	750	2.2
Bo11-4	B0.5 V	4.47	47.50	0.10	1460	17
Bo11-5	O9 V	4.77	48.06	0.18	1820	47
Bo11-9	O9 IV	4.99	48.36	0.34	1820	89
Bo11-10	O9 IV	4.99	48.36	0.34	1820	89

References: Fitzgerald & Mehta (1987); Walborn (1973).

away from η Car on the sky. Walborn (1995) notes that they are both roughly equidistant (∼20 pc) from η Car, and that they could easily have travelled this far in 2 Myr with a kick of $\sim 10\,km\,s^{-1}$. Previously, on the main sequence, they presumably had O2 spectral types like HD 93129A, and somewhat different Q_H values. In order to account for this stellar evolution, the cumulative 'main-sequence' values in Table 7 (see Section 4) were calculated using Q_H values lowered by 0.1 dex for each WNL star. This is roughly correct if

Table 7. Total stellar energy input.

Cluster	Number of O stars	log L ($L_\odot$)	log $Q_{\rm H}$ (s^{-1})	log L(FUV) ($L_\odot$)	$\dot{M}$ ($10^{-6}\,M_\odot\,yr^{-1}$)	$L_{\rm SW}$ ($L_\odot$)
Tr16 (MS)	47	7.215	50.91	6.91	91	45400
Tr16 (LBV)	43	7.240	50.78	7.05	1083	67000
Tr16 (now)	42	7.240	50.77	6.79	1083	67000
Tr14	10	6.61	50.34	6.31	18.7	13500
Tr15	6	6.18	49.56	5.88	5.9	1300
Bo10	1	6.00	49.42	5.69	18.3	7120
Bo11	5	6.00	49.64	5.70	5.2	2900
CPD-59 2661	1	4.68	47.88	4.38	0.15	33
Total (MS)	70	7.38	51.06	7.08	139	70200
Total (LBV)	66	7.40	50.97	7.18	1131	91800
Total (now)	65	7.40	50.96	7.00	1131	91800

they were ~0.1 dex less luminous on the main sequence (Maeder & Meynet 2000), with the same $Q_{\rm H}/L_{\rm Bol}$ ratio as HD 93129A.

The age of Tr16 is probably about 2–3 Myr. This comes from the fact that it contains H-rich WNL stars but no He-rich WR stars, and that η Car has a likely zero-age main-sequence mass $>100\,M_\odot$ and has already evolved off the main sequence – as well as the fact that there is no clear evidence for an SN having exploded yet.

When considering the cumulative effect of the massive stars in Tr16, we must bear in mind the peculiar present state of its most luminous member, η Car. As we observe it today, η Car is a pitiful source of UV photons for the larger region. Whatever ionizing radiation is able to escape its very dense optically thick stellar wind[2] (Hillier et al. 2001; Smith et al. 2003b) is eventually absorbed by dust in the surrounding Homunculus nebula and converted into infrared radiation (Cox et al. 1995; Smith et al. 2003c). However, more than 10^4 yr ago, before it entered its presently observed luminous blue variable (LBV) phase and was on the main sequence – or even more than 160 yr ago before the Homunculus existed – η Car was a *much* stronger source of UV radiation. Indeed, it probably contributed ~20 per cent of the total ionizing photons for the entire region (see below). By the same token, its main-sequence stellar wind was weaker than its presently observed LBV wind. Its spectral type prior to the LBV phase is of course unknown, but given its extreme luminosity, it is reasonable to assume that it was an O2 supergiant like HD 93129A while on the main sequence. From stellar evolution tracks for very massive stars (e.g. Maeder & Meynet 2000; Young 2005), it is likely that η Car was ~0.1 dex less luminous at that time. The value for $Q_{\rm H}$ at that time is then calculated assuming this lower $L_{\rm Bol}$, and assuming the same ratio of $Q_{\rm H}/L_{\rm Bol}$ as for HD 93129A.

It is also likely that η Car has a close companion star in a 5.5 yr eccentric orbit (Duncan et al. 1995; Damineli et al. 2000; Corcoran 2005). While its UV radiation does not escape the Homunculus at the present time, it did contribute to the ionization of the larger region throughout the 2–3 Myr lifetime of Tr16. The nature of η Car's companion star is highly uncertain and a matter of current debate (Davidson 1999; Duncan et al. 1995; Ishibashi et al. 1999; Pittard & Corcoran 2002); a tentative spectral type of O5 V is adopted in Table 2. The bolometric luminosity of η Car (the primary star) in Table 2 has the contribution of its companion subtracted.

[2] The mass-loss rate for η Car listed in Table 2 is from Hillier et al. (2001), and includes the effects of clumping in the wind.

3.2 Trumpler 14

Trumpler 14 is a smaller, much more compact, and perhaps somewhat younger cluster than Tr16. Some members of Tr16, like HD 93161, 93160 and 93250, are projected nearby on the sky (Walborn 1973) and are often mistaken as members of Tr14. As noted above, it is likely that Tr14 is perhaps 10–20 pc more distant than Tr16, since silhouette objects seen in front of it point towards Tr16 (Smith et al. 2003a), but it is still part of the central engine that powers the Carina Nebula. Its most conspicuous member is the prototypical O2 If* supergiant HD 93129A.

Because of its compact size, its relatively faint upper main sequence, and certain spectral diagnostics, Tr14 may be 1–2 Myr younger than Tr16 (Walborn 1995). Penny et al. (1993) estimate ages younger than 1 Myr for HD 93129A and 93128, while Vázquez et al. (1996) find a cluster age of ~1.5 Myr. In addition, Tr14 remains closer to its natal molecular cloud than Tr16 (e.g. Brooks et al. 2003).

The stellar content summarized in Table 3 is compiled from several references listed at the end of the table, with particular attention to recent results on the binarity and multiplicity of stars in the cluster (see Nelan et al. 2004; Walborn 2005), including a new companion to HD 93129A (Nelan et al. 2004). The greatest source of uncertainty in the net output of this cluster is in the parameters for HD 93129A itself. The value of log $L_{\rm Bol} = 6.17$ is adopted from Repolust et al. (2004), and the value for $Q_{\rm H}$ was calculated from the luminosity using the revised $T_{\rm eff}$ calibration scale of Martins et al. (2005).

3.3 Trumpler 15

Tr15 is an open cluster located about 20 arcmin north of Tr16 on the sky. It is thought to be at the same distance and has roughly the same reddening as Tr16, but it is somewhat older, with a likely age of 6 ± 3 Myr (Feinstein et al. 1980; Morrell, Garcia & Levato 1988). It is seen near a very bright red star on the sky – the M2 Ia supergiant RT Car, which is probably not a member of the cluster. Table 4 adopts the cluster members listed by Feinstein et al. (1980) and Morrell et al. (1988), including the O8 V star HD 303304 which was listed as a possible non-member by Feinstein et al. (1980), as well the O9 giant HD 93342 and the highly reddened O9 I-II star Tr15-18, which were listed as possible members. Table 4 does not include the non-member O5 III star HD 93403, which is taken to be a member of Tr16.

3.4 Bochum 10

Bo10 is a relatively meagre cluster located roughly 40 arcmin north-west of Tr16, with a handful of OB stars and a probable age of ~7 Myr (Feinstein 1981; Fitzgerald & Mehta 1987). Thus, it may be significantly older than Tr14 and 16, but perhaps not much older than Tr15. Feinstein (1981) found a large distance of 3.6 pc, but a later analysis by Fitzgerald & Mehta (1987) favoured a closer distance of 2.5 kpc, placing it inside the Carina complex associated with some nearby nebulosity. Because of its larger age of ~7 Myr, it is likely that the nearby WR star HD 92809 may be associated with Bo10, or at least with the larger Carina complex. Therefore, HD 92809 is included in Table 5 along with the other members of Bo10. For the total far-ultraviolet (FUV) luminosity of HD 92809 in Table 7 (see Section 4), we adopt $L_{\rm FUV}/L_{\rm Bol} = 0.39$ (for 912–3650 Å) following the study of Smartt et al. (2001).

3.5 Bochum 11

Bo11 is a loose open cluster in the southeastern Carina Nebula. Fitzgerald & Mehta (1987) find an age for Bo11 of less than 3 Myr. They also find that the cluster includes several pre-main-sequence stars, consistent with an age as young as 0.3 Myr. This very young age is interesting in light of the fact that Bo11 is located amid what is currently the most active region of star formation in Carina – the so-called South Pillars (Smith et al. 2000; Rathborne et al. 2004). The age and stellar content is similar to the nearby embedded cluster known as the Treasure Chest (Hägele et al. 2004; Smith et al. 2005).[3] There is considerable discrepancy as to the spectral type of the most luminous star in Bo11, which is HD 93632 or Bo11-1. Fitzgerald & Mehta (1987) list this star as O8 Iap, whereas Walborn (1973) classifies it as O4-5 III(f). Walborn (1973) noted that the spectral type was somewhat variable, while Fitzgerald & Mehta (1987) noted a few problems with their photometric classification of stars in Bo11. A spectral type of O4-5 III(f) is adopted in Table 6.

4 CUMULATIVE EFFECTS

Table 7 lists the total luminosity, ionizing flux, total FUV (Balmer continuum) luminosity, mass-loss and mechanical luminosity for each cluster, as well as the cumulative total of all clusters for each parameter. For the FUV luminosity (in all cases except where noted above), $L_{\rm FUV} \simeq 0.5 L_{\rm Bol}$ is assumed, which is adequate considering the inherent uncertainty in the bolometric luminosity as a function of spectral type. Brooks et al. (2003) found a similar result for the FUV luminosity of Tr14 alone. More detailed stellar atmosphere models typically have $L_{\rm FUV}/L_{\rm Bol}$ values of 0.39–0.85 for 912–3650 Å (e.g. Smartt et al. 2001; Crowther et al. 2002; Crowther in press, private communication). Three cases are given for Tr16 and for the total of all clusters.

The first case corresponds to the history of Carina up until recent times, when η Car and its companion were not surrounded by a dust shell and did not have a dense LBV wind choking off the Lyman continuum flux, and when the WNL stars in Tr16 were O2 stars. For this first case, there was a total of 70 O-type stars in Carina, producing $Q_{\rm H} = 1.15 \times 10^{51}\ {\rm s}^{-1}$. This would be the appropriate number to adopt when considering the history and formation of the nebula, the lifetimes of evaporating proplyds, globules and dust pillars, triggered star formation by radiative driven implosion, and the growth of the cavity that will blow out of the Galactic plane as a bipolar superbubble.

The second case is the LBV phase of η Car during the last $\sim 10^4$ yr, when η Car had a dense wind that reprocessed most of the Lyman continuum radiation into the Balmer continuum (FUV). During this phase, η Car was not surrounded by a dense dust shell, allowing its FUV luminosity to escape. Since the UV radiation of its companion could also escape, and since the WNL stars were no longer on the main sequence, the total number of O stars is listed as 66 in Table 7. This brief phase may be important in understanding the recent photoevaporation of neutral globules and PDRs throughout the nebula, since η Car was such an incredibly luminous FUV source.

The third case represents the currently observed state of the Carina Nebula, when η Car and its companion are surrounded by an obscuring dust shell, blocking all their contribution to the total ionizing flux and FUV luminosity. With η Car's companion blocked by the Homunculus, the effective number of O stars is reduced to 65. For this third case, the cumulative ionization source is $Q_{\rm H} = 9 \times 10^{50}\ {\rm s}^{-1}$. This would be the appropriate number to adopt when considering the current UV flux incident upon evaporating proplyds, globules and irradiated jets over most of the nebula.

For most of its lifetime, gas and dust in the Carina Nebula has been exposed to an ionizing luminosity about 150 times stronger than that of the Orion nebula. This changed 160 yr ago when η Car ejected a thick dust shell that cut off essentially all of its UV output, and the total $Q_{\rm H}$ of the Carina Nebula dropped by about 20 per cent due to the loss of ionization from the most luminous member of the region.[4]

This change illustrates the dominant role of the most luminous star in any region, and highlights a truly unique property of the Carina Nebula – it offers a laboratory where we can address variability in $Q_{\rm H}$ over short time-scales. This behaviour has not been witnessed anywhere else in our Galaxy to a similar degree. We can observe some of the effects of this variable UV output – for example, neutral cometary globules and dust pillars that point at η Car are seen only in silhouette today, but their shape suggests that they were formed by a strong UV flux from η Car in the past (Smith et al. 2003a). It is interesting to note that the outer edges of the Carina Nebula, beyond a radius of 160 light-year or 50 pc (1.5×10^{20} cm) from η Car, have not yet seen the Great Eruption of η Car, and still see its pre-eruption UV output. Also, if the complex nested circumstellar ejecta around η Car are a fair indication, this type of UV cut-off has probably happened multiple times in the past due to previous outbursts, and may yet happen again.

The main uncertainty in deriving the pre-eruption UV output of Carina is in the spectral type and ionizing luminosity of η Car itself, which has a likely uncertainty of perhaps ±15 per cent (roughly 3 per cent of the total for the region) if the models at lower luminosity and later spectral types are correct. In terms of the cumulative effect of the entire stellar population, then, dwarf stars later than O9 can be safely ignored, since their collective contribution is less than the uncertainty in the value for $Q_{\rm H}$ from the most luminous members. For the other luminous members, in case 1 (when η Car was on the main sequence), about 8 per cent of the total $Q_{\rm H}$ came from the O2

[3] Although it is not discussed in detail here, the O9.5 V star CPD-59 2661 in the Treasure Chest cluster is included in Table 7.

[4] Actually, the change might not have been so sudden, since much of the Lyman continuum flux from η Car may have already dropped when it developed a thick stellar wind upon entering the LBV evolutionary phase in the last 10^4 yr. During this time, the majority of η Car's radiation escaped as FUV photons.

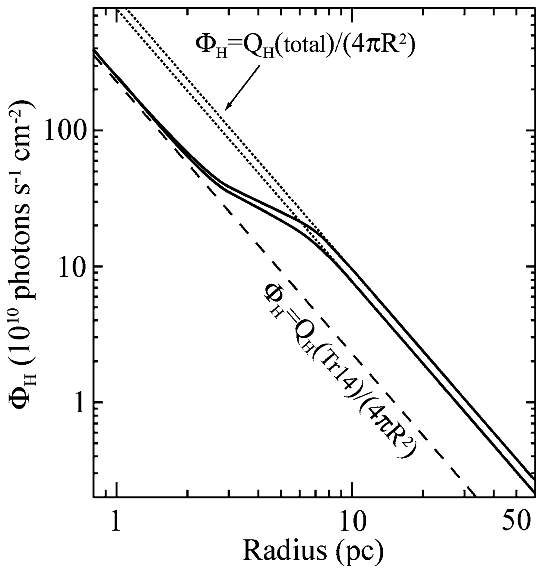

Figure 1. Ionizing photon flux Φ as a function of radius. The two solid curves are for cases 1 and 3 (i.e. η Car on the main sequence and at the present time).

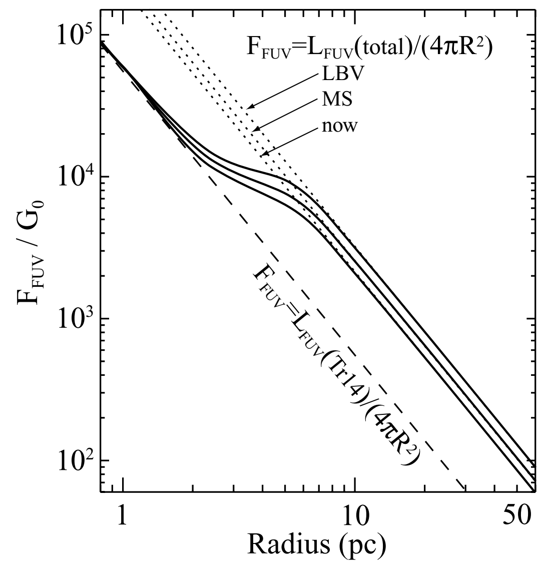

Figure 2. Same as Fig. 1, but for FUV radiation, plotted in units of the Habing flux, $G_0 = 1.6 \times 10^{-3}$ erg s $^{-1}$ cm^{-2}. The three cases from Table 7 are shown.

supergiant HD 93129Aa alone, 15 per cent came from the 3 WNL stars, and 15 per cent from the remaining five O3.5 V stars. For case 3, corresponding to the present state of affairs, these contribution have changed to about 10 per cent of the total from HD 93129Aa alone, 23 per cent from the three WNL stars and 19 per cent from the remaining five O3.5V stars.

Fig. 1 shows the ionizing photon flux Φ_H as a function of radius. The two solid curves are for cases 1 and 3 (i.e. η Car on the main sequence and at the present time). Beyond a radius of roughly 10 pc from the centre of the nebula, the ionizing source can be treated roughly as a point source, so that the photon flux drops as r^{-2}. Within a few parsecs of any cluster, however, the local radiation from that cluster becomes more important than the diminished collective effects from all clusters. This is due to the fact that the stellar population in Carina is a loose aggregate, rather than a single dense cluster. The specific case of Tr14 is shown in Fig. 1, but within a few parsecs of any individual cluster, its own ionization will dominate, while the influence of more distant clusters diminishes.

Fig. 2 shows the radial dependence of the FUV radiation field in the Carina Nebula, compared to the Habing flux, $G_0 = 1.6 \times 10^{-3}$ erg s $^{-1}$ cm^{-2} (Habing 1968). The three curves correspond to η Car on the main sequence, in the LBV phase, and in its present state obscured by its own dust shell. The strongest FUV fluxes in the region arise when the LBV phase of η Car is considered, when most of its bolometric luminosity escaped in the Balmer continuum. Throughout the Carina Nebula, this resulted in a local FUV flux that was roughly 75 per cent higher than the present state when η Car is surrounded by dust. Thus, for extremely massive stars, their changing UV output in various evolutionary states can profoundly effect the radiation field of their environments, and consequently, the evaporation of protoplanetary discs and the erosion of dust pillars. Again, however, individual clusters dominate over the collective radiation field within a few parsecs of any cluster core.

The present total mechanical luminosity from stellar winds is just under 10^5 L$_\odot$ or 7×10^4 L$_\odot$ during the main-sequence phase, having contributed a total energy of about 2.6×10^{52} erg so far during the 3 Myr lifetime of the region. This is higher than a previous estimate of several times 10^{51} erg (Walborn 1982) because it includes the influence of many more stars. The estimated kinetic energy of the expanding proto-superbubble (Smith et al. 2000; Walborn 1982) is only 5–30 per cent of this mechanical energy from stellar winds, suggesting that most of the energy injected by stellar winds is radiated away, even in the early phases of the growth of a bubble. The total energy radiated by early-type stars during the same time was over 350 times more than the mechanical energy. This situation will change dramatically when the most massive stars begin to explode as SNe in the next few 10^5–10^6 yr, each injecting an additional 10^{51}–10^{52} erg in a very short time.

With a total mass-loss rate of $\dot{M} \approx 1.4 \times 10^{-4}$ M$_\odot$ yr^{-1}, the mass ejected by stellar winds over the past 3 Myr is about 420 M$_\odot$. This is only about 10 per cent of the mass of ionized gas estimated to be filling the interior of the H II region (e.g. Walborn 2005). Thus, the majority of ionized gas inside the H II region cavity probably comes from photoevaporative flows (e.g. Bertoldi 1989) off the surfaces of molecular clouds and evaporating globules embedded within the region. Note that the present value of $\dot{M}$ for η Car's brief LBV wind phase is much greater than the cumulative mass-loss of rest of the stars in Carina combined.

5 COMPARISON WITH OTHER MASSIVE CLUSTERS

Finally, it is interesting to see how the stellar energy input in Carina stacks up to other young massive star clusters. As noted earlier, in general, Carina's overall stellar content is similar to the most well-studied massive clusters like NGC 3603, Arches and 30 Dor, except that these clusters are more compact than Carina. For example, Crowther & Dessart (1998) list $\log Q_{\rm H} = 51.19$ and $L_{\rm SW} = 1.5 \times 10^5$ L$_\odot$ for NGC 3603. The total energy input in Carina is essentially the same as these values, because Crowther & Dessart used an older $T_{\rm eff}$ scale, leading to higher $Q_{\rm H}$ values for O stars, and did not account for wind clumping in their analysis; if those same assumption were made here for Carina, the results would be identical to NGC 3603 within the uncertainties. Carina has about 25–30 per cent of the total ionizing flux of the more massive Arches cluster in the Galactic Centre (Figer et al. 2002), and roughly

25 per cent of both the total Q_{H} and L_{SW} of R136 in 30 Doradus given by Crowther & Dessart (1998). Given the similar cumulative energy input and stellar content, it is interesting that Carina's clusters are less tightly bound than the others, especially if this gives rise to different effects on the nearby star forming environment. A future paper will investigate how the cumulative stellar energy input assessed directly from the observed massive stars in Carina compares with more indirect tracers of the energy budget of the larger Carina Nebula.

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