Mon. Not. R. astr. Soc. (1971) **154**, 415–427.

ON THE NATURE OF ETA CARINAE

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(Communicated by the Director of Princeton University Observatory)

(Received 1971 June 28)

SUMMARY

Various details of the spectrum of η Carinae are found to be consistent with a model in which a compact H II region is photoionized by radiation from a very massive star whose surface temperature is about 30 000° K. The infra-red spectrum is presumed to be thermal re-emission from dust surrounding the ionized region.

1. INTRODUCTION

The discovery of a prodigious infra-red luminosity, in conjunction with a visual emission-line spectrum and remarkable behaviour during the past two centuries, has inspired renewed speculation about η Carinae in recent years. Gratton (1963) has summarized the apparent-visual history of this object: probably of second to fourth magnitude just prior to 1837, it then brightened to first or zeroth magnitude and remained bright until, from 20 to 30 years later, a progressive seven-magnitude fading occurred. The present visual appearance is of sixth magnitude, consisting of a small nucleus surrounded by a halo with a few condensations several seconds away; the condensations are moving apart and may have originated in the nucleus near the times of observed light maxima (Gaviola 1950; Thackeray 1953; Ringuelet 1958). The visual spectrum includes numerous emission lines (notably the Balmer series and [Fe II] lines) superimposed upon a continuum, while most of the observed energy flux is in the far infra-red (Aller & Dunham 1966; Rodgers & Searle 1967; Neugebauer & Westphal 1968; Westphal & Neugebauer 1969). Various distance estimates place η Carinae between 1·5 and 3 kpc away (Gratton 1963; Feinstein 1963), implying a total luminosity of the order of 10^{40} erg s^{-1} = $2{\cdot}5 \times 10^6 \mathscr{L}_\odot$. Only a few other galactic objects produce comparable luminosities for significant lengths of time.

Several alternative views have been expressed regarding the nature of η Carinae: (i) it may be a very young, massive star approaching the main sequence (see for example Gratton 1963); or (ii) it may be a very massive star which has reached and perhaps evolved away from the main sequence and which may be pulsationally unstable (Burbidge 1962; Talbot 1971); or (iii) it may be a non-thermal or non-stellar object such as the remnant of a recent massive supernova (Ostriker & Gunn 1971; Zwicky 1965). The infra-red flux may be thermal re-radiation by circumstellar dust in the first two models, and in the third might be non-thermal.

The purpose of the following discussion is to support picture (ii) (or conceivably (i)), by demonstrating that the observed emission lines can probably be produced in a dense, compact H II region, which may be identified with either the 'nucleus' or the 'halo', and which is photoionized by the continuous spectrum of a very massive star whose effective temperature is about 30 000 °K. This is largely in accord with the discussions by Pagel (1969a, b) and Viotti (1969), in which the continuous visual spectrum is corrected for reddening through consideration of certain relative emission-line intensities; Pagel in particular noted that the corrected continuum would resemble that of an early-type star whose total luminosity matches the observed infra-red luminosity. Rodgers & Searle (1967) suggested that some of the line-emitting gas is hotter than would result from photoionization-heating; but a process which can modify their conclusions will be described in Section 3 below.

2. PHOTOIONIZATION AND THE CENTRAL OBJECT

By comparing the observed intensities of different forbidden or permitted lines originating from each level of Fe^+, it is possible to estimate the reddening of η Carinae due to intervening dust. Pagel (1969a), Viotti (1969), Lambert (1969), and Ade & Pagel (1969) have discussed this, and the resulting colour excess E_{B-V} seems to be about $1^{m}\cdot 1$ or $1^{m}\cdot 2$. When this correction is applied, the relative [Fe II] intensities indicate that at least the lower levels of Fe^+ are populated in a Boltzmann distribution at a temperature of the order of 7500 °K.

At such a temperature, the Balmer lines cannot be excited by thermal collisions—so presumably a flux of fast particles or ionizing photons must be invoked to explain the excitation of hydrogen and probably the heating of the gas to 7500 °K as well. Unfortunately, the observed emission lines do not provide any clear distinction between suprathermal particle collisions and photoionization as the mechanism for heating the gas. If the heating is due to fast particles or X-ray photons, then the gas resembles the interstellar medium (see Field, Goldsmith & Habing 1969; Spitzer & Scott 1969; Silk 1970; Bergeron & Souffrin 1971) and the temperature indicates that hydrogen is 10 to 30 per cent ionized, while heavier ions would be more completely ionized. If the gas is photoionized by ultra-violet photons just above the Lyman limit, the situation resembles a galactic H II region and the first stage of ionization is more complete for most elements. In either case there may be some difficulty in explaining why Fe^+ is not further ionized to Fe^{++}.

In order to seek the most conventional possible model, and to avoid the problems of the production and motions of fast particles, the following discussion will suppose that the emission lines originate in an envelope of gas which is photoionized by the continuous spectrum of a central starlike object. If most of the dust lies outside the ionized region, so the visual continuum from the starlike object experiences about the same extinction as the emission lines, it will be possible to estimate the ultra-violet spectrum of the central object from the emission lines.

The lower solid curves in Fig. 1 show the observed continuum according to Rodgers & Searle (1967), including the nucleus and most of the halo and with no correction for extinction. Let A_λ represent the extinction (in stellar magnitudes) at wavelength λ. According to Pagel (1969a) and Viotti (1969),

$$E_{B-V} = A_B - A_V \approx 1^{m}\cdot 1.$$

Comparing the observed Brackett-γ line (Westphal & Neugebauer 1969) with Hβ (Aller & Dunham 1966; Rodgers & Searle 1967), recombination theory (Seaton 1959) provides another reddening estimate, $A_\lambda(4861 \text{ Å}) - A_\lambda(2\cdot 2\mu) \approx 3^{m}\cdot 7$. Similarly, the Paschen/Balmer ratios observed by Rodgers and Searle lead to

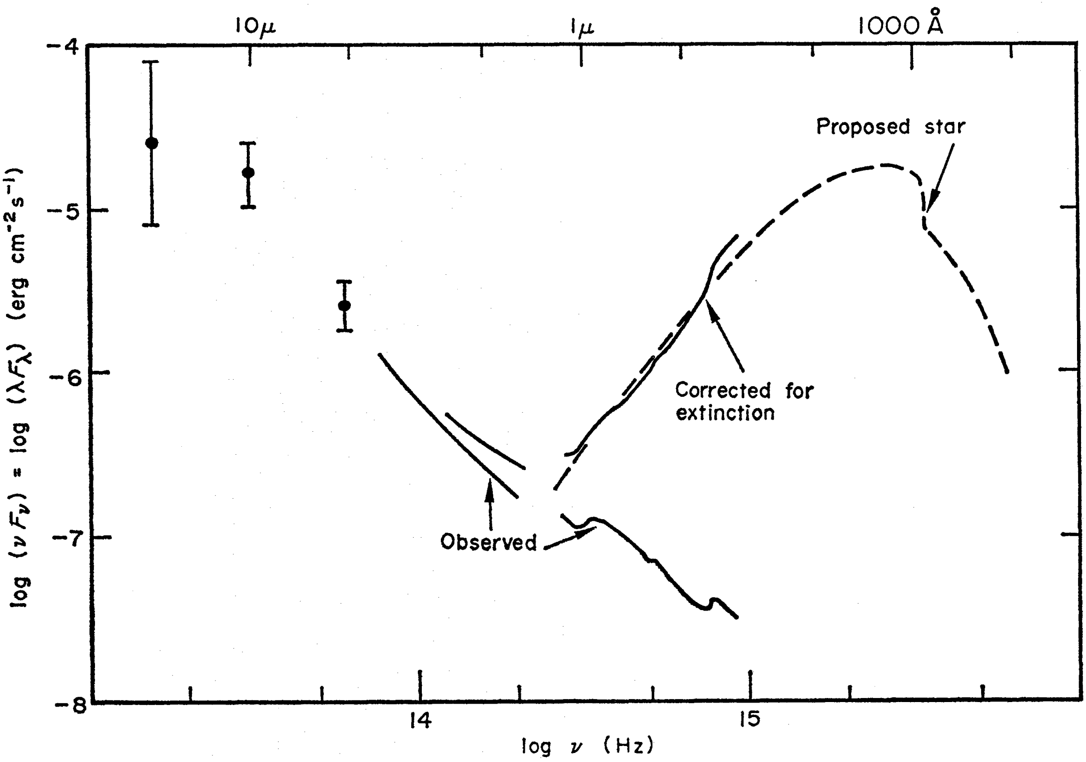

Fig. 1. *The continuous spectrum of η Carinae, according to observations by Rodgers & Searle* (1967), *Neugebauer & Westphal* (1968), *and Westphal & Neugebauer* (1969), *and proposed stellar continuum.*

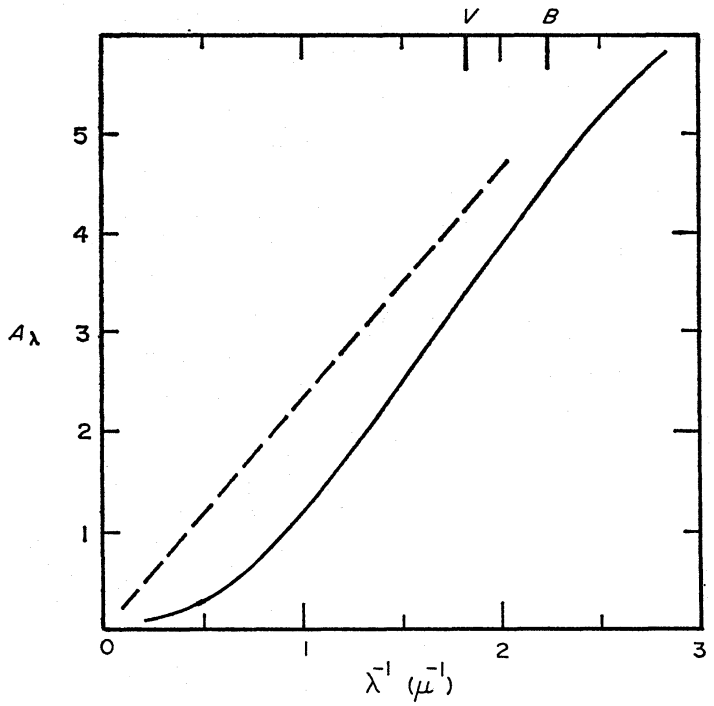

Fig. 2. *Total correction for extinction* (*see text*).

additional, fairly consistent information about A_λ. Fig. 2 shows two possible extinction curves which agree with these considerations. The upper (dashed) line is proportional to λ^{-1} and may be an upper limit. The lower (continuous) curve,

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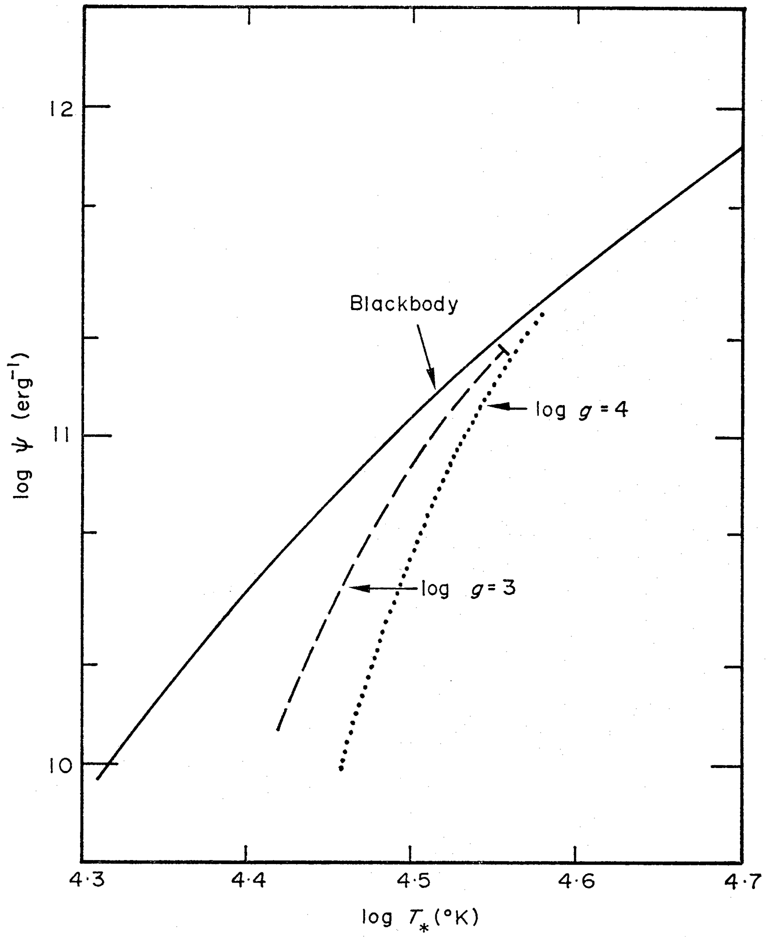

FIG. 3. *The function $\psi(T_*, g)$ defined by equation* (3), *for various stellar atmospheres.*

which will be adopted below, has the same shape as an interstellar extinction curve with a rather low value of $A_V/E_{B-V} = 3$ (see Johnson 1968; Wickramasinghe 1967; and references therein).

Allowing for such extinction, the corrected continuum is represented by the upper continuous curves in Fig. 1. Using the photoionization hypothesis, one may extrapolate into the ultra-violet by a Zanstra-like method, as follows: Let L_ν denote the continuous luminosity-spectrum of the supposed central source (in erg Hz^{-1} s^{-1}) and denote the total rate of production of ionizing photons by

$$S_\mathrm{i} = \int_{\nu_\mathrm{H}}^{\infty} \frac{L_\nu \, d\nu}{h\nu}, \tag{1}$$

—where $h\nu_\mathrm{H} = 13{\cdot}6$ eV. Suppose (as for an ordinary ionization-limited H II region) that nearly all of these photons are absorbed in maintaining the hydrogen ionization equilibrium in the line-emitting gas. Since the hydrogen lines are due to recombination, S_i then determines the total Hβ-luminosity:

$$\mathscr{L}_{\mathrm{H}\beta} \approx (4{\cdot}6 \times 10^{-13}\ \mathrm{erg})\, S_\mathrm{i}. \tag{2}$$

Here the coefficient is appropriate to radiative recombination 'Case B' near 7500 °K, and is only slightly temperature-dependent (Seaton 1959). It is convenient to compare $\mathscr{L}_{\mathrm{H}\beta}$ with the nearby continuum L_ν (λ 4861). Define for the continuous spectrum of the ionizing source a quantity

$$\psi = \frac{S_\mathrm{i}}{(\nu L_\nu)_{\lambda 4861}} = \frac{S_\mathrm{i}}{(\lambda L_\lambda)_{\lambda 4861}}. \tag{3}$$

According to (2), this may be observed in the form

$$\psi \approx (2{\cdot}2 \times 10^{12}\,\mathrm{erg}^{-1})\,\frac{\mathscr{L}_{\mathrm{H}\beta}}{(\lambda L_\lambda)_{\lambda 4861}}, \tag{4}$$

which is just proportional to the equivalent width of Hβ in emission. Rodgers & Searle (1967) give an equivalent width such that $\psi \approx 5 \times 10^{10}\,\mathrm{erg}^{-1}$.

Now, assume the continuum to be stellar. A stellar atmosphere with effective temperature T_* and surface gravity g produces a definite value of $\psi = \psi(T_*, g)$, as illustrated in Fig. 3. Here the upper (continuous) curve represents a blackbody at temperature T_* while the lowest (dotted) curve represents atmosphere models with line-blanketing and $g = 10^4\,\mathrm{cm\,s^{-2}}$ (Morton & Bradley 1969; Morton 1969). The intermediate (dashed) curve represents very simplified calculations with $g = 10^3\,\mathrm{cm\,s^{-2}}$ and with opacity due only to electron scattering plus the Lyman continuum. (Note that very high surface temperatures are impossible if $g \sim 10^3\,\mathrm{cm\,s^{-2}}$, because of radiation pressure.) As will be clear below, the curve for $g = 10^3\,\mathrm{cm\,s^{-2}}$ is most appropriate; and so $T_* \approx 30\,000\,°\mathrm{K}$ is found to give the value of ψ quoted above.

The dashed curve in Fig. 1 shows a simplified continuum for $T_* = 29\,300\,°\mathrm{K}$ and $g = 10^3\,\mathrm{cm\,s^{-2}}$, approximated below the Lyman limit by a blackbody at 30 300 °K and normalized to match the corrected visual observations. Pagel (1969b), considering only the total luminosity, proposed a somewhat cooler stellar continuum, but preferred a hydrogen two-photon spectrum because no Balmer-absorption discontinuity is observed. However, in the model proposed here, even the Lyman discontinuity is not extreme and so Balmer absorption should be rather modest. (The Balmer continuum in emission, from the photoionized region, is visible in the observed spectrum.) If D is the distance of η Carinae, the suggested parameters for the central star are approximately

Effective temperature: $T_* = 29\,300\,°\mathrm{K}$

Radius: $R_* = (4{\cdot}4 \times 10^{12}\,\mathrm{cm})\left(\dfrac{D}{2\,\mathrm{kpc}}\right)$

Luminosity: $\mathscr{L}_* = (10^{40}\,\mathrm{erg\,s^{-1}})\left(\dfrac{D}{2\,\mathrm{kpc}}\right)^2$

Ionizing photons: $S_\mathrm{i} = (4 \times 10^{49}\,\mathrm{s^{-1}})\left(\dfrac{D}{2\,\mathrm{kpc}}\right)^2.$

The luminosity of a very massive star is insensitive to surface temperature; hence it is possible to estimate a mass–luminosity relation from the work of Stothers (1966), and thus obtain the mass:

$$\frac{M_*}{M_\odot} \approx 115\left(\frac{D}{2\,\mathrm{kpc}}\right)^{1{\cdot}5}.$$

The surface gravity is

$$g \approx (800 \text{ cm s}^{-2}) \left(\frac{D}{2 \text{ kpc}}\right)^{-0.5}.$$

This is reasonably close to the value assumed above, and low enough for radiation pressure to be very important, i.e. the stability of the atmosphere is perhaps questionable.

It is necessary to remark that if some of the ionizing photons are absorbed by dust grains, then the 'observed' value of ψ is an underestimate; therefore it is possible that the surface temperature and luminosity have been slightly underestimated above. The calculated atmosphere is in any case very crude and approximate.

If the emission lines originate in a compact photoionized region as hypothesized above, they must be consistent with the equilibrium of heating and cooling in the gas. The ionization equilibrium primarily involves absorption by hydrogen of S_i ionizing photons/sec, with average frequency $\langle\nu\rangle_\text{i}$. If $\epsilon = h\langle\nu\rangle_\text{i} - 13.6$ eV, then the total supply of energy to the free electrons is about $S_\text{i}\epsilon$. Cooling of the free electron gas is mostly due to collisionally-excited emission lines and radiative recombination. Since ionization is balanced by recombination, the total recombination cooling rate is roughly $S_\text{i}kT$ (where T = electron temperature). Denoting the total luminosity of the collisionally-excited lines by $\mathscr{L}_\text{coll}$, thermal balance requires

$$\mathscr{L}_\text{coll} + S_\text{i}kT \approx S_\text{i}\epsilon. \tag{5}$$

Introducing the Hβ-intensity through (2), this becomes

$$\frac{\mathscr{L}_\text{coll}}{\mathscr{L}_{\text{H}\beta}} \approx \frac{\epsilon - kT}{(0.29 \text{ eV})}. \tag{6}$$

The ionizing spectrum proposed above has $\epsilon = 2.9$ eV while $kT = 0.65$ eV if $T = 7500°$ K (as implied by the [Fe II] lines); hence $\mathscr{L}_\text{coll}/\mathscr{L}_{\text{H}\beta}$ should be about 8. Table I gives the total intensity of the collisionally-excited lines (i.e. all except the hydrogen and helium lines) in the visual region, according to Aller & Dunham (1966) and corrected for extinction according to the lower curve in Fig. 2. The resulting contribution to $\mathscr{L}_\text{coll}$ is about 7.7 $\mathscr{L}_{\text{H}\beta}$. Inclusion of ultra-violet and

TABLE I

Intensities of collisionally-excited lines measured by Aller & Dunham (1966), *relative to Hβ*

Wavelength interval (Å)	Extinction factor	Relative intensities Observed	Relative intensities Corrected
3587–3700	180	0·22	40
3700–3900	150	0·37	56
3900–4100	115	0·22	25
4100–4400	83	1·14	95
4400–4700	57	1·04	59
4700–5020	41	1·01	41
		Total =	316
Hβ λ 4861:	41	1·00	41
		Ratio =	7·7

infra-red lines must increase this somewhat beyond the predicted value, indicating perhaps that the adopted stellar effective temperature T_* may be too low as mentioned above.

3. DENSITY AND ABUNDANCES IN THE CIRCUMSTELLAR GAS

From the relative intensities of several [N II] and [S II] emission lines, Rodgers & Searle (1967) derived a density $n_e \sim 3 \times 10^6\,\mathrm{cm}^{-3}$ and temperature $T \sim 20\,000\,^\circ\mathrm{K}$ for part of the emitting region. This section will demonstrate that if a certain type of indirect photoexcitation is considered in addition to collisional excitation, the temperature may be lower—simplifying the model by placing all of the N^+, S^+, and Fe^+ in the photoionized gas near 7500 °K. Table II lists the relative intensities of some emission lines measured by Rodgers and Searle, after correction for reddening. The resulting line ratios differ from those discussed by Rodgers and Searle, who assumed much less reddening. According to Rodgers (1971), the smaller amount of extinction may in fact be appropriate for the [S II] lines and possibly the [N II] lines; this will be considered below.

TABLE II

Relative line intensities, corrected for reddening (Adapted from Rodgers & Searle (1967), *with revised reddening)*

Line		Intensity	Line		Intensity
Hα	λ 6562	2·75	[N II]	λ 6584	0·026
Hβ	4861	1·00	[N II]	6548	0·0062
Hγ	4340	0·56	[N II]	5755	0·093
[S II]	6730	0·0039	He I	4471	0·052
[S II]	6716	0·00087	[Ne III]	3868	0·033
[S II]	4076	0·018	[O III]	5007	<0·002
[S II]	4068	0·093	[O II]	3727	<0·001

$\mathscr{L}_{\mathrm{H}\beta} = 2 \times 10^{37}\,\mathrm{erg\,s^{-1}}$ if $D = 2$ kpc.

Transition probabilities for the [S II] lines have been given by Czyzak & Krueger (1963) while Czyzak *et al.* (1970) have estimated the collision strengths for excitation. If the electron density exceeds $10^5\,\mathrm{cm}^{-3}$, collisions cause the excited levels producing the λ 6716 and λ 6730 lines to be populated almost according to a Boltzmann distribution, relative to the ground level—but the higher levels which produce the λ 4068 and λ 4076 lines have faster radiative decay rates which are not so easily dominated by collisional de-excitation. If $n_e \gtrsim 10^5\,\mathrm{cm}^{-3}$, it is found that

$$\frac{I(\lambda\,4068+\lambda\,4076)}{I(\lambda\,6716+\lambda\,6730)} \approx \frac{267\,e^{-1\cdot395/t}}{\left(1+5\cdot4\times10^6\,\dfrac{\sqrt{t}}{n_e}\right)}$$

$$\approx \frac{41\cdot6}{\left[1+\left(\dfrac{4\cdot7\times10^6}{n_e}\right)\right]} \quad \text{for } t = 0\cdot75, \tag{7}$$

where $t = T/(10^4\,^\circ\mathrm{K})$. According to Table II, the value of the ratio (7) is about 23, indicating $n_e \approx 6 \times 10^6\,\mathrm{cm}^{-3}$ if $T = 7500\,^\circ\mathrm{K}$. Reducing the reddening correction according to the suggestion by Rodgers (1971) would lead to a lower density, $n_e \approx 6\times 10^5$ cm^{-3}; in this case the S$^+$ must lie outside some of the circumstellar dust which causes part of the extinction shown in Fig. 2. Saraph & Seaton (1970) have proposed a revision of the [S II] collision strengths, which would reduce the derived electron densities by a factor of 1·8.

The above discussion of the [S II] lines differs from that of Rodgers and Searle mainly in the assumption that $T \approx 7500$ °K rather than 20 000 °K. They were led to the higher temperature estimate through consideration of the [N II] lines. The levels which produce these lines are qualitatively in the same situation described above for [S II]; so using transition rates and collision strengths as listed by Garstang (1968) and by Czyzak *et al.* (1968), the relation analogous to (7), valid for $n_e \gtrsim 10^5$ cm^{-3}, is

$$\frac{I(\lambda\,5755)}{I(\lambda\,6583+\lambda\,6548)} \approx \frac{61\,e^{-2\cdot503/t}}{\left[1+1{\cdot}7\times10^{7}\,\dfrac{\sqrt{t}}{n_e}\right]}$$

$$\approx \frac{2{\cdot}2}{\left[1+\left(\dfrac{1{\cdot}5\times10^{7}}{n_e}\right)\right]} \qquad \text{for } t = 0{\cdot}75. \tag{8}$$

The observed ratio (Table II) is about 2·9, which cannot be matched by relation (8) with $T \approx 7500$ °K, especially if $n_e < 10^7$ cm^{-3}. Thus Rodgers and Searle concluded that a higher electron temperature is necessary.

However, another solution is possible, involving an indirect photo-excitation process of the type described by Burgess (1967): in which a photon of the stellar continuum is absorbed by a N$^+$ ion in the lowest forbidden-line (singlet) level, causing excitation to a higher singlet level, followed by cascade to the level which produces λ 5755. Fig. 4 shows the most important levels: $2p^2\,{}^3P_{0,1,2}$ (the ground term), $2p^2\,{}^1D_2$, $2p^2\,{}^1S_0$, and $2s2p^3\,{}^1P_1^0$, labelled for convenience *0*, *1*, *2*, and *3*. The λ 6583 and λ 6548 lines result from *1* → *0* transitions while λ 5755 is due to *2* → *1*. Allowed transitions are possible between *3* and either *1* or *2*; so given an incident continuum flux near 660 Å, photoexcitation *1* → *3* may occur. Decay

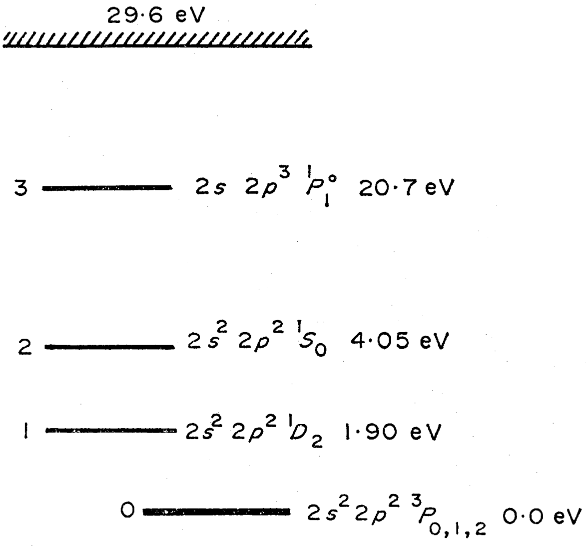

FIG. 4. *Some levels of N$^+$.*

$3 \rightarrow 2$ may then populate level 2. Neglecting ordinary collisional excitation (which is represented in (8) above), the line ratio would be

$$\frac{I(\lambda\,5755)}{I(\lambda\,6583+\lambda\,6548)} \approx \left(\frac{6560}{5755}\right) C(n_e) \left(\frac{A_{21}}{A_{21}+A_{20}}\right)\left(\frac{A_{32}}{A_{32}+A_{31}}\right)\left(\frac{A_{13}'}{A_{10}}\right), \qquad (9)$$

—where $C(n_e) = [1+(n_e/1\cdot5\times10^7)]^{-1}$ is a collisional de-excitation factor for $T \approx 7500\,°\mathrm{K}$. The A_{ji} are spontaneous transition rates (listed by Wiese, Smith & Glennon 1967) except that A_{13}' is the rate for photoexcitation $1 \rightarrow 3$. If $F_\nu(\nu_{13})$ is the incident continuum flux in the gas at frequency $\nu_{13} = 4\cdot54\times10^{15}$ Hz ($\lambda = 660$ Å), then $A_{13}' \approx (9\times10^8\ \mathrm{cm^2\ Hz\ erg^{-1}})\ F_\nu(\nu_{13})$. Using these parameters, (9) becomes

$$\frac{I(\lambda\,5755)}{I(\lambda\,6583+\lambda\,6548)} \approx \frac{C(n_e)F_\nu(\nu_{13})}{(2\cdot4\times10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}})}. \qquad (9')$$

The observed line ratio would result from an average flux in the gas of the order of $F_\nu(\nu_{13}) \approx 7\times10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}}$. If the stellar continuum is as proposed in Section 2 above, this implies a mean distance of the gas from the star of the order of $\langle r\rangle \approx (2\times10^{16}\ \mathrm{cm})\ (D/2\ \mathrm{kpc})$. The apparent size of the ionized region would be about 2″ (evidently representing the observed ‘ nucleus ’ rather than the ‘ halo ’). A process like that described here for [N II] may also affect the [S II] lines to some extent.

With parameters as mentioned above, the photoionized gas should be stratified into two or three zones, each characterized by a particular ionization level and opaque to ionizing photons beyond a particular threshold frequency (see Hummer & Seaton 1964; Flower 1969). The ions mentioned above, N^+, S^+, and Fe^+, are found in the least-excited ionized zone, with H^+ and He^0. A different zone, containing H^+ and He^+, would produce the [Ne III] and He I lines included in Table II. He I λ 4471 is a recombination line, whose intensity depends upon the number of helium-ionizing photons ($h\nu > 25\cdot6$ eV) rather than the helium abundance. Denote the supply of such photons by S_i' while S_i represents the supply of hydrogen-ionizing photons. If most of the former are absorbed by helium and most of the latter by hydrogen, then the observed ratio $I(\mathrm{He\,I}\ \lambda\,4471)/I(\mathrm{H}\beta)$ implies $S_i'/S_i \approx 0\cdot1$. This value is of the same order of magnitude as expected for the proposed stellar spectrum, but may be somewhat too large for a surface temperature of 29 300 °K—suggesting again that T_* may in fact be slightly higher than this value.

The abundances of a few ions may be estimated. If the electron density is n_e and the distance of η Carinae is $D = 2$ kpc, then the Hβ-luminosity gives the total number of ionized hydrogen nuclei: $\mathrm{N(H^+)} \approx (1\cdot3\times10^{56})\ (10^6\ \mathrm{cm^{-3}}/n_e)$. Assuming $T = 7500\,°\mathrm{K}$, the [Fe II] and [Fe III] intensities given by Aller & Dunham (1966), corrected for extinction and using transition probabilities listed by Garstang (1968), lead to $\mathrm{N(Fe^+)}$ and $\mathrm{N(Fe^{++})}$ as given in Table III. Similar estimates for N^+, O^+, and S^+ follow from the intensities in Table II. In Table III, the values of $N(Z^z)$ depend only slightly upon density but the abundances relative to hydrogen are proportional to n_e, which for convenience is assumed to be $4\times10^6\ \mathrm{cm^{-3}}$. At this density the mass of the line-emitting region would be $0\cdot03 M_\odot$. Since the nitrogen and iron abundances are then quite reasonable, such a density is perhaps not far from the truth. However, oxygen is surprisingly scarce, and as noted by Rodgers and Searle, the absence of the [O III] λ 5007 line adds to this problem.

Table III

Abundances of several ion species, if $n_e = 4 \times 10^6\ \mathrm{cm}^{-3}$

Z^z	$10^{-50}N(Z^z)$	$10^5NZ^z)/N(H^+)$
N^+	18·0	6·0
O^+	<40·0	<13·0
S^+	2·6	0·8
Fe^+	6·5	2·0
Fe^{++}	0·3:	0·1:

Sulphur also seems underabundant; and if Rodgers (1971) is correct in suggesting a reduced extinction correction for the [S II] lines, then $N(S^+)/N(H^+)$ must be even smaller.

There may be some difficulty in explaining the small Fe^{++}/Fe^+ ratio under the photoionization hypothesis, since the ionization potential of Fe^+ is only slightly higher than that of hydrogen. Let σ denote an average cross-section for photoionization of Fe^+, and α the corresponding recombination coefficient. The supply of Fe^+-ionizing photons ($h\nu > 16{\cdot}2$ eV) is S_i'', while most of the gas has electron density n_e at distance r from the central star. Then the ionization equilibrium is approximately

$$\frac{N(\mathrm{Fe}^{++})}{N(\mathrm{Fe}^{+})} = \frac{\sigma S_i''}{4\pi\alpha n_e r^2}. \tag{10}$$

Bahcall & Kozlovsky (1969) have suggested $\sigma \approx 2\times10^{-19}\ \mathrm{cm}^2$. If $D = 2$ kpc, Fig. 1 gives $S_i'' \approx 2\times10^{49}$ photons s^{-1}. Then, if $r \approx 2\times10^{16}$ cm and $n_e \approx 4\times10^6\ \mathrm{cm}^{-3}$, the observed ionization ratio would require $\alpha \approx 4\times10^{-9}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$. This greatly exceeds the quasi-hydrogenic radiative recombination coefficient, but may conceivably be due to dielectronic recombination or recombination through autoionizing states.

4. THE CIRCUMSTELLAR DUST

Confirming the surmise of Pagel (1969b), the stellar continuum estimated in Section 2 above contains about the same energy flux as the far infra-red spectrum measured by Westphal & Neugebauer (1969). It is natural to conclude that the infra-red represents thermal re-radiation by circumstellar dust which absorbs most of the visual and ultra-violet luminosity. Such dust is known to be present, for the reddening $E_{B-V} \approx 1^{\mathrm{m}}{\cdot}1$ exceeds the interstellar value $E_{B-V} \approx 0^{\mathrm{m}}{\cdot}44$ observed for the stars near η Carinae (Feinstein 1963, 1969).

Since the observed infra-red spectrum (Fig. 1) extends through a rather wide frequency range, the temperatures of the dust grains must range from about 200 °K (or less) to about 1500 °K. Various grain materials, having different infra-red emission efficiencies, may have such temperatures. Small grains of graphite (see Wickramasinghe 1967) would approach a temperature of 1500 °K at a distance of about 10^{16} cm from the central star while higher temperatures are precluded by evaporation. The cooler grains might be silicates, which radiate efficiently near 10 μ and 20 μ (Gaustad 1963); but even these should be 10^{17} cm or more from the central star in order to be sufficiently cool. Therefore both the 'nucleus' and 'halo' of η Carinae contain dust, with the halo radiating preferentially at longer wavelengths.

The visual halo may be considered as a compact reflection nebula. The polarization measured by Visvanathan (1967) is qualitatively consistent with scattering by grains; but since this polarization is almost wavelength-independent throughout the visual region, the required grain sizes are likely to be quite small (see Hanner 1971).

If the gas density is of the order of 4×10^6 cm^{-3} at $r \sim 2 \times 10^{16}$ cm as suggested in Section 3, and distributed in a configuration resembling a shell or sphere, then the column density of the gas is comparable to that found in a distance of at least several kiloparsecs in the galactic plane; thus it is clear that a rather modest dust/gas ratio would suffice to produce two or three magnitudes of visual extinction. Since the circumstellar material is expanding at several hundred kilometres per second (Ringuelet 1958; Thackeray 1961), and also since radiation pressure is exerted on the grains, the innermost grains cannot have been present for as long as 100 yr. Therefore it seems that the grains are somehow forming within the expanding gas, possibly in neutral condensations surrounded by ionized material. Geisel (1971) has listed a number of other objects which (although various in detail) resemble η Carinae in having low-excitation emission lines and infra-red spectra, and where grains may be forming under non-LTE conditions in circumstellar envelopes.

5. DISCUSSION

η Carinae has been portrayed above as a very massive star surrounded by an expanding envelope of gas and dust. With a surface temperature of the order of 30 000 °K, it appears to be well above the main sequence. Perhaps a very young star, approaching the main sequence, could present such an appearance—in which case the halo may be a stellar ' cocoon ' formed by the outer layers of the original proto-star, being pushed away from the star by radiation pressure acting on the dust (Davidson & Harwit 1967; Davidson 1970). However, such a model is less likely than the alternatives mentioned below, because of difficulties with the time scale.

The star may instead be evolving away from the main sequence. Stars with masses of the order of $100 M_\odot$ have been discussed by Simon & Stothers (1970), Appenzeller (1970), Ziebarth (1970), Talbot (1971), and others. While on the main sequence, such objects are subject to pulsational instability—which may lead to mass ejection but probably not to catastrophic destruction. As hydrogen is depleted at the centre of the star, the instability may cease. However, as the surface temperature decreases while the evolving star expands, radiation pressure is likely to cause some mass ejection. This might be invoked to explain the outbursts and circumstellar envelope of η Carinae—especially since with $T_* \approx 30\,000$ °K, the Lyman-continuum opacity is almost as important near the surface as electron-scattering. If the temperature were slightly reduced, the surface opacity would rise, causing radiation pressure to overwhelm gravity.

Appenzeller (1970) has described another plausible situation, in which a very massive star on the main sequence may seem to be above the main sequence. In this model, the star pulsates and continuously ejects material, which forms an opaque envelope—so the apparent radius and temperature refer to the envelope rather than the star. If this is actually the case, then the atmosphere calculations used in Section 2 above are invalid in detail; but the derived effective temperature is probably not far wrong.

Finally, it is necessary to mention the outburst of η Carinae during the 1840's. The visual appearance was then six or seven magnitudes brighter than at present but the luminosity need not have been correspondingly higher, for the bolometric correction and extinction by dust may have changed since that time. The object is visually of sixth magnitude now; the *circumstellar* extinction is probably about two magnitudes, and the bolometric correction is about $2^{\mathrm{m}}\cdot 8$. If, therefore the expanding envelope of gas and dust were removed, and if the stellar surface expanded until the effective temperature were only 6000 °K and the bolometric correction zero, then η Carinae would appear as a first-magnitude star without much change in luminosity. One may imagine a hypothetical sequence of events as seen during the past 150 yr, as follows: Initially, the star was about the same as it is now, but since there was no circumstellar dust, it was seen at fourth magnitude rather than sixth. Then, some instability caused the sudden ejection of material. This formed a shell rather similar in behaviour to the type described by Ostriker & Gunn (1971); and when the shell had expanded to the point where most of its radiation was at visual wavelengths, it was observed as a bright star. Later, it seemed to fade as it became yet cooler and as dust grains began to form. When the expanding envelope became optically thin for electron scattering but visually opaque because of the dust, η Carinae assumed its present appearance.

ACKNOWLEDGMENTS

I am grateful to Drs J. Ostriker and G. Bath for various discussions. This work was supported by NASA grant NGL-31-001-007, and used computer facilities supported by NSF grants GJ-34 and GU-3157.

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