1982ApJ...254L..47D

THE ASTROPHYSICAL JOURNAL, **254**:L47–L51, 1982 March 15

THE REMARKABLE SPECTRUM OF SOME MATERIAL EJECTED BY ETA CARINAE

KRIS DAVIDSON[1]
University of Minnesota
NOLAN R. WALBORN
Cerro Tololo Inter-American Observatory
AND
THEODORE R. GULL
NASA Goddard Space Flight Center

Received 1981 November 9; accepted 1981 December 1

ABSTRACT

Outlying condensations of ejecta from η Carinae have nebular emission-line spectra, which are easier to analyze than the spectrum of the central object. Here we report some ground-based and *IUE* observations of the brightest outer condensation. It appears to be nitrogen rich; five ionization states of nitrogen but none of carbon or oxygen are observed. This is perhaps the most definite known clue to the evolutionary status of this very massive star.

Subject headings: stars: circumstellar shells — stars: massive — stars: winds

I. INTRODUCTION

Eta Carinae is a very massive star, one of the most luminous known, whose appearance during the past 200 years has been "fitfully variable to an astonishing extent" (Herschel 1847) as several episodes of mass ejection have occurred (see Walborn and Liller 1977 and references therein). This object is located in a region noted for its massive stars, probably about 2800 pc distant (Walborn 1973; Feinstein, Marraco, and Muzzio 1973). Eta Carinae now has the following structure (see, e.g., Thackeray 1949, 1950; Gaviola 1950; Gehrz and Ney 1972; Walborn 1976*a*; Walborn, Blanco, and Thackeray 1978; Hyland *et al.* 1979): (1) The central star, probably with a dense wind, is surrounded by (2) a dusty halo whose size is of the order of 2″ or 10^{17} cm. (3) Around the compact halo is the "homunculus," 10″ across, an irregular shell of condensations ejected from the central star during the nineteenth century[2] and moving outward at about 500 km s^{-1}. (4) Outside the homunculus are some fainter condensations, mostly ejected earlier. The outward movements of these condensations are easy to see by comparing photographs taken years apart.

The precise nature of the central object is uncertain. Its luminosity is about $10^7 L_\odot$, corresponding to $M_{\rm bol} \approx -12.5$. Two independent arguments (neither definitive by itself, but plausible when taken together) suggest that *something* about η Car has an effective temperature close to 30,000 K (Davidson 1971; Humphreys and Davidson 1979). This may be the star itself (in which case it is far from the main sequence), or else a thick circumstellar wind or envelope, or even an accretion disk (Bath 1979). Thus it is possible to imagine η Car alternatively as a pre–main-sequence object, or as a main-sequence star with a very strong wind, or as a more evolved object—conceivably binary in any case. We must reduce this uncertainty in order to understand the evolution of very massive stars in general.

Spectra of the central object, halo, or homunculus are very complicated because of high densities in gas around the central star (see Rodgers and Searle 1967; Cassatella, Giangrande, and Viotti 1979; and earlier references cited by Walborn, Blanco, and Thackeray 1978). This complexity unfortunately precludes analysis much beyond that done by Pagel (1969).

In this *Letter* we note that some of the *outer condensations* have simpler emission-line spectra which convey remarkable clues to the nature of the star from whence they were ejected. We describe ground-based spectrograms as well as ultraviolet *IUE* data on the brightest such condensation. Since our purpose is mainly to draw attention to the outer condensations, and our present data are unsuitable for full quantitative analyses, the following discussion is necessarily tentative; but even so, the results are striking.

---

[1] Visiting Astronomer, CTIO, operated by AURA, Inc., under contract with NSF. Guest Investigator, *IUE* satellite, sponsored and operated by NASA, the Space Research Council of the United Kingdom, and the European Space Agency.

[2] Dates mentioned in this *Letter* are of course *apparent* dates, not corrected for light-travel times.

1982ApJ...254L..47D

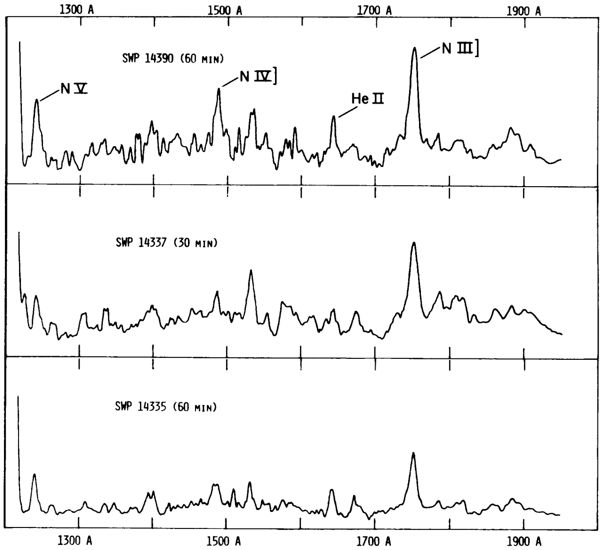

FIG. 4.—Tracings of the *IUE* spectra of the S condensation shown in Fig. 3, slightly smoothed. The vertical ordinate is F_λ; the upper border represents $F_\lambda = 2.5 \times 10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1} for SWP 14390, and 5×10^{-13} ergs cm^{-2} s^{-1} Å^{-1} for the other two spectra.

II. SOME OBSERVATIONAL DATA

Figure 1 (Plate L5) includes the sketch map used by Walborn (1976*a*) and Walborn, Blanco, and Thackeray (1978). Most of our discussion will be about the prominent "S condensation," about 10″ WSW of the central object. The observed motion of this condensation suggests that it was ejected between the years 1770 and 1850—perhaps at the start of the great outbursts seen around 1840.

Figure 2 (Plate L6) shows two spectrograms of the S condensation, obtained by N. R. W. with the 1 m telescope and image-tube spectrograph at the Cerro Tololo Inter-American Observatory. Also shown is a spectrogram of the central object. The former spectra show three types of emission lines: (1) narrow, tall lines (i.e., extending the full length of the slit), especially [O III] λλ4959, 5007, due to the surrounding Carina Nebula NGC 3372; (2) broader, shorter lines matching the continuum in height, due to scattered light from the central object (the widths are due to a large velocity dispersion—see as examples the Fe II and [Fe II] features on each side of [N I] λ5199); and (3) nearly circular spots which are images of the S condensation, most prominently the [N I], [N II], and [S II] features. *There is no sign of* [*O I*] *λ6300*, [*O II*] *λ3727*, *or* [*O III*] *λ5007 emission from the condensation*. This naturally led us to suspect an unusually large nitrogen/oxygen abundance ratio there.

Enlarged spectrograms of the Hα and [N II] λλ6548, 6583 lines in several condensations, obtained by A. D. Thackeray with the CTIO 4 m telescope and image-tube spectrograph, are shown in Figure 1. In each case the narrow Hα emission from the Carina Nebula is present, with corresponding [N II] λ6583 in some cases; these provide convenient wavelength references against which to compare the Doppler-shifted lines from the condensations. Hα is brighter than [N II] λ6583 in the nebula and also in the homunculus (cf. the upper spectrum in Fig. 2); but in each condensation, Hα is fainter than the *weaker* [N II] line, λ6548.

Inspired by these spectrograms, in 1981 June and July we obtained ultraviolet spectra of the S condensation, using the *IUE*'s short-wavelength camera and large entrance aperture (a 10″ × 20″ oval). In each case the long dimension of the entrance aperture was oriented roughly N–S and the condensation was placed near the aperture's NE edge; the principal observational difficulty lay in avoiding the edge of the homunculus, which is far brighter than the condensation. Three observations, *IUE* exposure numbers SWP 14335, SWP 14337, and SWP 14390, were made; the integration time was 30 minutes for SWP 14337 and 60 minutes for each of the others. Resulting spectral images are shown in Figure 3 (Plate L7), along with two short-exposure spectra (one trailed) of the homunculus. Each spectrum of the condensation is contaminated by light from the edge of the homunculus, appearing largely as a continuum; but displaced emission lines, obviously due to the condensation rather than the homunculus, are also visible. The ultraviolet spectrum of the condensation is quite different from an ordinary nebular spectrum and includes the following emission features: N V λ1240; Si IV (?) λ1397; N IV] λ1486; Si II (?) λ1531 (cf. Böhm, Böhm-Vitense, and Brugel 1981); He II λ1640; Al II (??) λ1673; N III] λ1749; and several uncertain features between 1750 Å and 1920 Å, where contamination by homunculus light is worst. These features can be seen in tracings of the spectra, as shown in Figure 4. *C III*] *λ1908 and C IV λ1549, which in ordinary nebular spectra are far stronger than the nitrogen lines, are too weak to detect with certainty in our data.*

We attempted to obtain *IUE* data on the S condensation in the 2000–3000 Å wavelength range, but were frustrated by light from the homunculus. The condensation is brighter relative to the homunculus at shorter ultraviolet wavelengths, mainly because the homunculus is dusty and therefore has considerable internal extinction.

In the next section we shall make some quantitative remarks; but even qualitatively, the ultraviolet-to-red spectrum of the S condensation is remarkable. It shows prominent emission lines of *five* successive ionization stages of nitrogen, but no perceptible lines of carbon or oxygen.

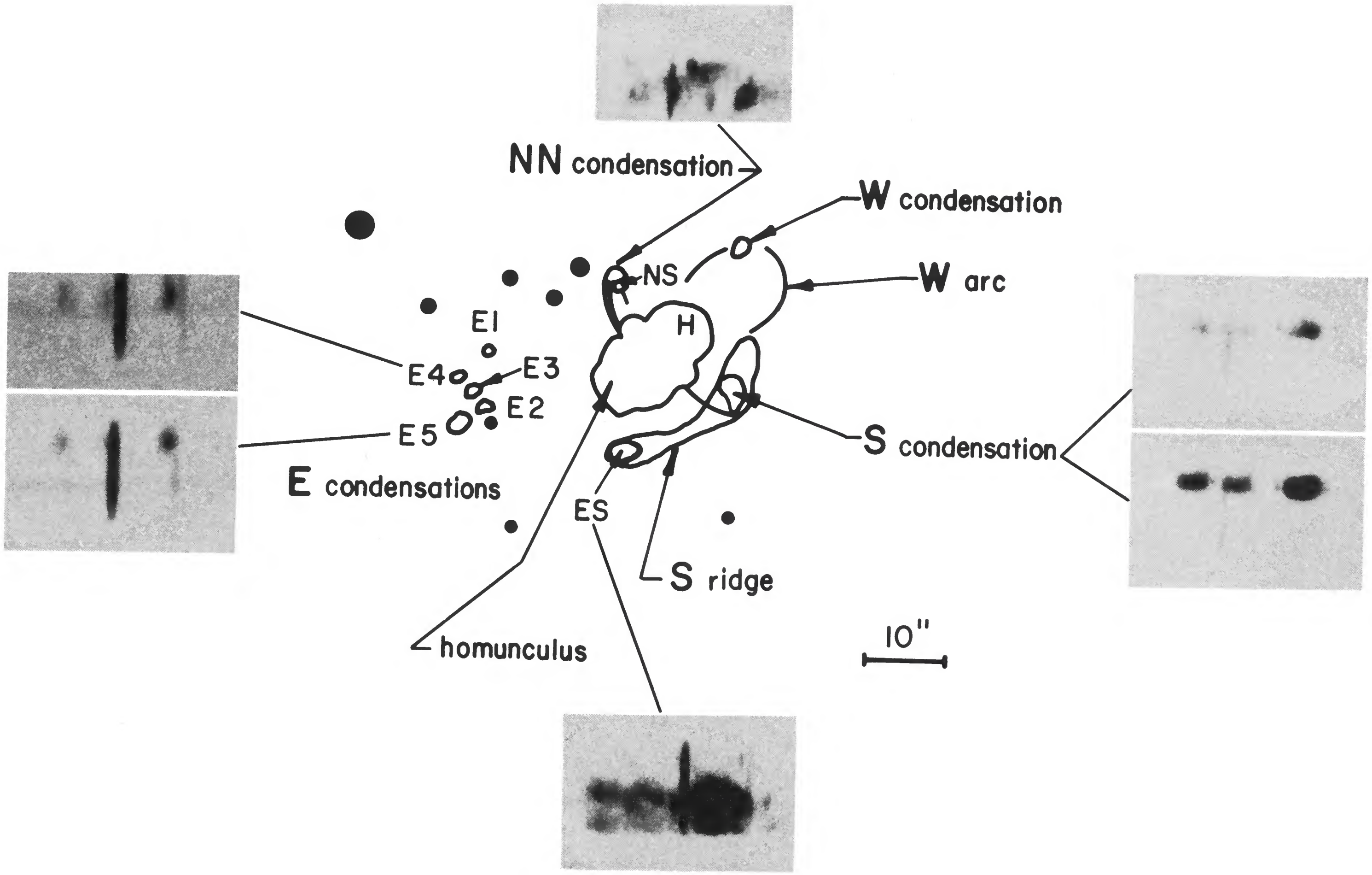

FIG. 1.—Untrailed Hα + [N II] $\lambda\lambda$6548, 6583 spectrograms of outer condensations around η Car, obtained by A. D. Thackeray in 1976 with the CTIO 4 m telescope and image-tube spectrograph, original dispersion 26 Å mm^{-1}. In the sketch map, north is up and east is to the left. The slit position angle was 90° for the S, ES, and N spectrograms (east is up) and 45° for E2–4 and E5 (northeast is up); the scale of the spectrograms perpendicular to the dispersion is 0.4 times that of the map. Exposure times ranged from 20 s for the shorter one of the S condensation to 600 s for E2–5. The prominent narrow features are Hα and [N II] λ6583 from NGC 3372. Radial velocity information about the condensations (clockwise from the right) and other remarks follow: (1) Two different exposures on the S condensation, centroid shift +270 km s^{-1}, range 650 km s^{-1}. (2) ES, shift −570 km s^{-1}, range 900 km s^{-1}. (3) E5, shift −120 km s^{-1}; continuum from the star 14″ southwest is visible. (4) E2–4, shift −200 km s^{-1}; slightly trailed, so that images of E2, E3, and E4 are merged; continuum from star just southwest of E2 is visible. (5) NN–NS condensations are so disturbed that interpretation is difficult, but both bright spots longward of the NGC 3372 Hα seem to be [N II] λ6583, with shifts of −620 km s^{-1} and +90 km s^{-1} and a total range of 1360 km s^{-1}. These radial velocities are consistent with tangential velocities measured by Walborn, Blanco, and Thackeray (1978).

DAVIDSON *et al.* (*see* page L48)

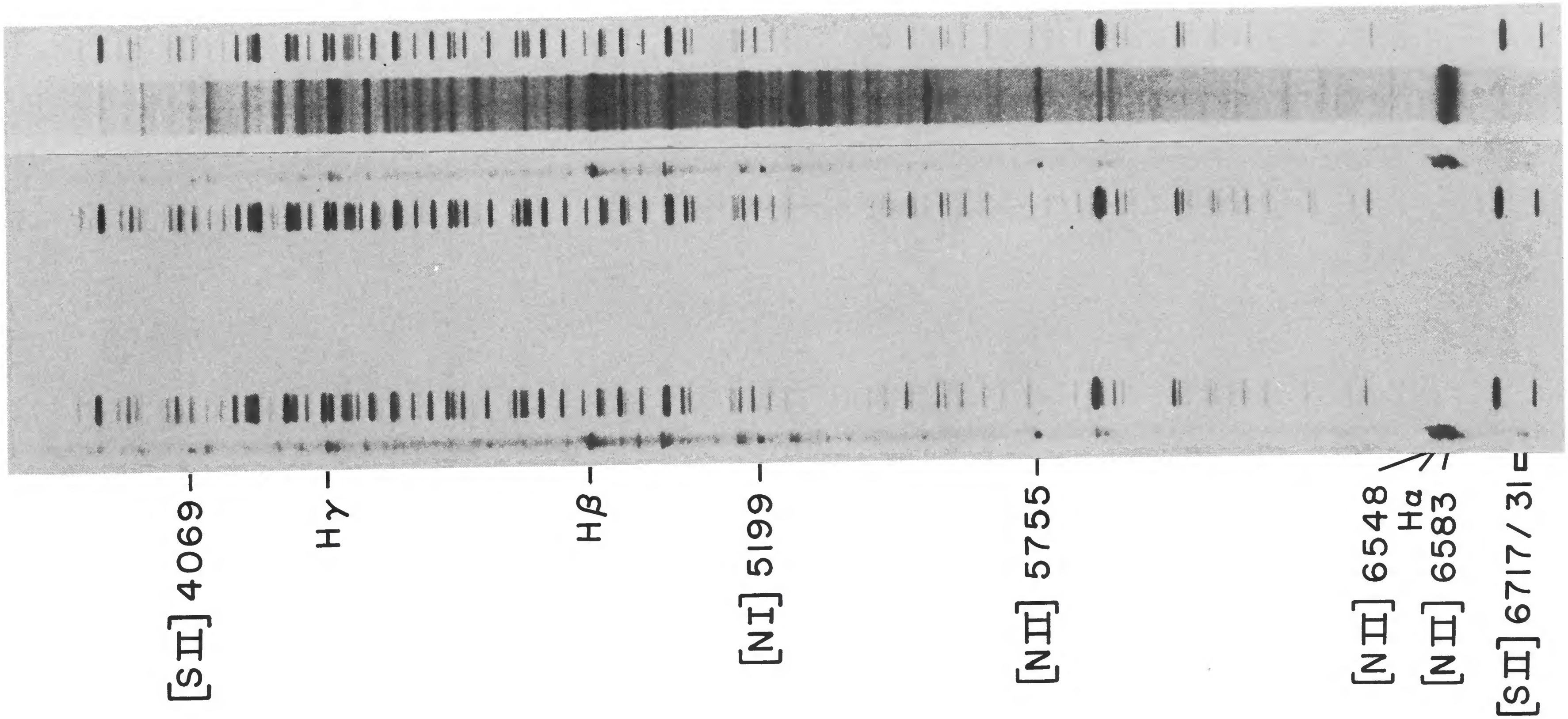

FIG. 2.—Trailed spectrogram of the η Car central object (*top*) and two untrailed spectrograms of the S condensation, obtained by N. R. W. in 1976 with the CTIO 1 m telescope and image-tube spectrograph, original dispersion 122 Å mm^{-1}. Exposure times on the condensation were 1 minute and 3 minutes, slit position angle 127°. The comparison spectrum is helium-argon.

DAVIDSON *et al.* (*see* page L48)

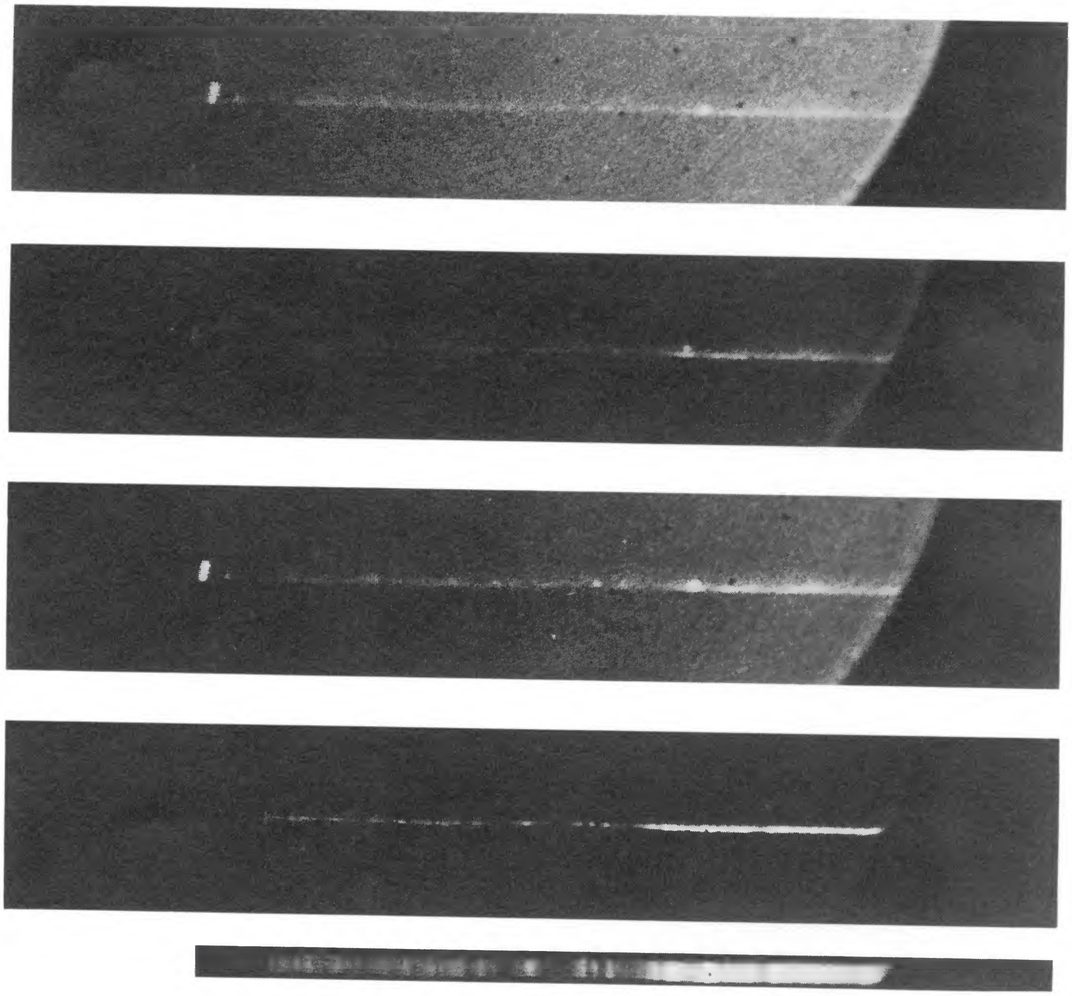

FIG. 3.—*IUE* spectral images from 1200 Å (*left*) to 1950 Å (*right*). The top three exposures (SWP 14390, 14337, and 14335, top to bottom) are spectrograms of the S condensation, with some contamination from the edge of the homunculus. The bottom two exposures (SWP 14336 and 14389) are short-exposure spectra of the homunculus and central object; SWP 14389 is trailed. The oval spots on the left ends of the long-exposure spectra are due to geocoronal Lyα emission.

DAVIDSON *et al.* (*see* page L48)

TABLE 1

ESTIMATED LINE INTENSITIES FROM THE S CONDENSATION
(as seen above the Earth's atmosphere, in units of 10^{-12} ergs cm^{-2} s^{-1})

Line	Apparent	Intrinsic[a]
N v λ1240	1.4	120
Si iv ? λ1397	0.9	40
N iv] λ1486	1.1	50
Si ii ? λ1531	0.9	35
C iv λ1549	($<$ 0.6)	($<$ 30)
He ii λ1640	0.9	30
(?) λ1673	0.6	20
N iii] λ1749	2.8	100
C iii] λ1908	($<$ 0.6)	($<$ 20)
[O iii] λ5007	($<$ 4?)	($<$ 20?)
Hα λ6563	10(?)	30(?)
[N ii] λλ6548, 6583	100(?)	300(?)

[a] Corrected for interstellar extinction, $E_{B-V} = 0.5$ (see text).

III. SOME QUANTITATIVE ESTIMATES

The spectrograms shown in Figures 1 and 2 are unsuitable for quantitative measurements (because the bright lines are saturated, and for other reasons), while the spectra shown in Figure 4 do not all have the same line intensities (probably because of pointing errors as well as noise). Nevertheless, we shall make what estimates we can; uncertainties can be judged partly by referring to Figure 4.

Table 1 is a list of line intensities from the S condensation, consistent with our spectra and with other data mentioned below. *Relative* ultraviolet intensities here are rough averages of the three *IUE* spectra; but the absolute values are adjusted so that the N iii] λ1749 flux matches that measured in spectrum SWP 14337, the largest value among the three spectra. The smallest N iii] flux, in SWP 14335, was only slightly more than half as large. We adopted the largest value because some light from the condensation was probably lost at the edge of the entrance aperture, depending on pointing errors (as suggested by previous *IUE* experience). The visual-wavelength values in Table 1 were estimated with the aid of some SIT vidicon direct images through interference filters, obtained by K. D. with the CTIO 1.5 m telescope in 1981 February. Using one of these images, comparing the flux from the S condensation with that from the star CPD $-59°2628$ on the same image, and using data on that star obtained by Feinstein, Marraco, and Muzzio (1973) and by R. P. Stone (private communication), we estimated the apparent Hα plus [N ii] λλ6548, 6583 flux from the condensation. Furthermore, we know theoretically that the λ6583 line is about 3 times as bright as the λ6548 line; so by inspection of Figure 1 we *guess* that the [N ii]/Hα intensity ratio in the condensation is roughly 10. This leads to the Hα and [N ii] values in Table 1. Our upper limit to the important [O iii] λ5007 line is based on the assumptions that (1) the spectrograms would have shown [O iii] emission from the condensation if it were much brighter than the corresponding Hβ emission, and (2) the intrinsic Hβ/Hα intensity ratio in the condensation is equal to or smaller than the standard recombination value, as expected if the Balmer lines are due to recombination plus a "normal" form of collisional excitation. Regarding corrections for interstellar extinction, both E_{B-V} and the wavelength dependence are quite uncertain; we have assumed $E_{B-V} = 0.5$ mag (rather like the value for stars around η Car and for NGC 3372, but much less than the value for the central object within the homunculus; see Feinstein, Marraco, and Muzzio 1973; Pagel 1969). We have used the typical extinction curve given by Savage and Mathis (1979), thus obtaining the last column in Table 1.

We do not yet understand the excitation of the S condensation. Photoionization by ultraviolet starlight seems unlikely, because neither η Car itself nor the associated early-type stars can supply enough local radiation density, and also because so many ionization stages of nitrogen are seen. Excitation by X-rays is likewise inadequate, even though the condensation coincides with a feature in the X-ray map shown by Seward *et al.* (1979); the total energy flux in the emission lines listed in Table 1 is of the order of 300 times larger than the 0.5–3 keV X-radiation estimated for *all* of η Car by Seward *et al.* Probably the excitation is due, directly or indirectly, to one or more shock fronts. Gas temperatures relevant to the observed emission lines are therefore probably between 10^4 K and 10^5 K. If we assume that most of the Hα emission is due to recombination at a temperature of 20,000 K (recombination is only moderately temperature-sensitive), we can make some useful order of magnitude estimates regarding the gas density and mass in the S condensation. Let n_e = electron density, $M_{\rm H}$ = mass of ionized hydrogen, and ε = a volume-filling factor ($\varepsilon \lesssim 1$). We assume that the distance is 2800 pc. From photographs and from the vidicon images mentioned above, we estimate that the condensation has a projected area of about 10^{34} cm^2, so we may take the volume to be roughly 10^{51} cm^3. Then, the estimated Hα luminosity of 3×10^{34} ergs s^{-1} implies that $n_e \approx (10^4 \text{ cm}^{-3})\ \varepsilon^{-1/2}$, which is consistent with the observed [S II] λ6731/λ6717 intensity ratio, and $M_{\rm H} \approx (0.01\ M_\odot)\ \varepsilon^{1/2}$. The condensation is therefore comparable to a planetary nebula in density and mass. The total emission-line luminosity implied by Table 1 is of the order of 10^{36} ergs s^{-1}.

Now let us consider relative abundances. We suppose, from the ionization potentials, that O^{+2}, N^{+2}, and C^{+2} coexist, as do N^{+3} and C^{+3}. Then, assuming various temperatures between 10^4 K and 10^5 K, and supposing that the [O III] lines are not severely collisionally deexcited, we can use Table 1 to derive upper limits to the O/N and C/N abundance ratios. For this purpose we adopt collision strengths quoted by Jackson (1973), Seaton (1975), and Osterbrock and Wallace (1977). The results are as follows: (1) If the temperature is as high as 10^5 K, then the maximum allowed O/N ratio is 0.5. (2) But for temperatures below 30,000 K, the O/N limit is 0.15 or less. (3) The C III] and N III] lines suggest an upper limit of about 0.05 for the C/N ratio, regardless of temperature. (4) C IV and N IV] give a less stringent C/N limit: 0.15. These results are subject to modification if the ionization ratios have unexpected values, but, on the other hand, the O/N limit is probably conservative, because the [O III] intensity is probably well below the limit given in Table 1. "Normal" Population I abundances are roughly C/N/O ≈ 4/1/7; so nitrogen must be quite overabundant, relative to carbon and oxygen, in the S condensation.

These results apply to gaseous material. Carbon might conceivably be depleted by grain formation, but oxygen cannot be seriously depleted unless there is a relative overabundance of heavier elements with which oxygen can combine.

The uncertainties in our results stem mostly from deficiencies in our data (which should not be difficult to rectify by improved observations) and from a lack of calculations of temperatures and ionization ratios in the situation of interest here. In principle, a spectrum like that of the S condensation, being basically nebular and not involving high densities, can be analyzed with fewer pitfalls than the spectrum of, say, a stellar wind. With improved data, it should be possible to estimate helium and nitrogen, and possibly oxygen and carbon abundances relative to hydrogen. Meanwhile, we can safely say that *C/N/O abundance ratios, in the material that η Car has lately been ejecting, have been modified by nuclear processing.*

IV. DISCUSSION

Our observations show that η Car is not a pre–main-sequence object. Its excess nitrogen presumably results from the C/N/O cycle (Caughlan and Fowler 1962; Caughlan 1965), implying that the star is at least moderately evolved. Moreover, nitrogen-rich material must have been brought to the surface of the star and then ejected.

We think that this situation is related to conditions observed in various other objects. There is reason to suspect that many O- and B-type supergiants have atmospheric nitrogen enhancements (Walborn 1976*b*), and of course this is also true of some Wolf-Rayet stars (e.g., see Willis and Wilson 1979 and references therein). But abundances derived from the spectra of complicated stellar atmospheres and winds might conceivably be erroneous; so it is desirable to seek less dense stellar ejecta with nebular spectra, like the condensation discussed in this *Letter*. One example is NGC 6888, according to Parker (1978) and Kwitter (1981); while some very extended nebular envelopes around *Of*-like stars in the Large Magellanic Cloud also appear to be nitrogen-rich (Walborn 1982). As remarked by Walborn (1976*a*), the supernova remnant Cas A is also relevant, because its "quasi-stationary flocculi" are nitrogen-rich (Peimbert and van den Bergh 1971; Chevalier and Kirshner 1978). These condensations are thought to have been ejected from the massive pre-supernova star (see Lamb 1978—although our present discussion suggests that the stellar surface may have been nitrogen-rich somewhat earlier than in her scenario). Another supernova remnant, Pup A, may also contain nitrogen-rich material (Dopita, Mathewson, and Ford 1977).

These facts seem consistent with recent discussions by Maeder (1980, 1981), who suggests that turbulent mixing, combined with mass loss, causes a very massive star like η Car to evolve quasi-homogeneously—so the surface composition follows the internal nuclear reactions.

Further details need not be discussed here; we await more data on the outer condensations of η Car, particularly regarding their abundances of He, C, N, and O, relative to H.

Anyone interested in η Car is indebted to the late A. D. Thackeray for his many years of attention to this object; here we have used some of his last, unpublished spectrograms. We thank the staff of the *IUE* observatory for their help, and P. Conti, R. M. Humphreys, and M. Shull for relevant discussions; it should be noted that the *IUE* observations were made in indirect connection with a project of Humphreys. We are grateful to R. P. Stone for special measurements of a calibration star. K. D. wishes to thank the Kitt Peak National Observatory and especially Cerro Tololo Inter-American Observatory for hospitality during visits there, where much of this *Letter* was written. K. D.'s work is partly supported by NSF grant AST-7916247.

REFERENCES

Bath, G. T. 1979, *Nature*, **282**, 274.

Böhm, K. H., Böhm-Vitense, E., and Brugel, E. W. 1981, *Ap. J.* (*Letters*), **245**, L113.

Cassatella, A., Giangrande, A., and Viotti, R. 1979, *Astr. Ap.*, **71**, L9.

Caughlan, G. R. 1965, *Ap. J.*, **141**, 688.

Caughlan, G. R., and Fowler, W. A. 1962, *Ap. J.*, **136**, 453.

Chevalier, R., and Kirshner, R. P. 1978, *Ap. J.*, **219**, 931.

Davidson, K. 1971, *M.N.R.A.S.*, **154**, 415.

Dopita, M. A., Mathewson, D. S., and Ford, V. L. 1977, *Ap. J.*, **214**, 179.

Feinstein, A., Marraco, H. G., and Muzzio, J. C. 1973, *Astr. Ap. Suppl.*, **12**, 331.

Gaviola, E. 1950, *Ap. J.*, **111**, 408.

Gehrz, R. D., and Ney, E. P. 1972, *Sky and Tel.*, **44**, 4.

Herschel, J. F. W. 1847, *Results of Astronomical Observations... at the Cape of Good Hope* (London: Smith, Elder, and Co.), pp. 32–40.

Humphreys, R. M., and Davidson, K. 1979, *Ap. J.*, **232**, 409.

Hyland, A. R., Robinson, G., Mitchell, R. M., Thomas, J. A., and Becklin, E. E. 1979, *Ap. J.*, **233**, 145.

Jackson, A. R. G. 1973, *M.N.R.A.S.*, **165**, 53.

Kwitter, K. B. 1981, *Ap. J.*, **245**, 154.

Lamb, S. A. 1978, *Ap. J.*, **220**, 186.

Maeder, A. 1980, *Astr. Ap.*, **92**, 101.

______. 1981, preprint.

Osterbrock, D. E., and Wallace, R. K. 1977, *Ap. Letters*, **19**, 11.

Pagel, B. E. J. 1969, *Nature*, **282**, 274.

Parker, R. A. R. 1978, *Ap. J.*, **224**, 873.

Peimbert, M., and van den Bergh, S. 1971, *Ap. J.*, **167**, 223.

Rodgers, A. W., and Searle, L. 1967, *M.N.R.A.S.*, **135**, 99.

Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.

Seaton, M. J. 1975, *M.N.R.A.S.*, **170**, 475.

Seward, F. D., Forman, W. R., Giacconi, R., Griffiths, R. E., Harnden, F. R., Jones, C., and Pye, J. P. 1979, *Ap. J.* (*Letters*), **234**, L55.

Thackeray, A. D. 1949, *Observatory*, **69**, 31.

______. 1950, *M.N.R.A.S.*, **110**, 524.

Walborn, N. R. 1973, *Ap. J.*, **179**, 517.

______. 1976*a*, *Ap. J.* (*Letters*), **204**, L17.

______. 1976*b*, *Ap. J.*, **205**, 419.

______. 1982, *Ap. J.*, **255**, in press.

Walborn, N. R., Blanco, B. M., and Thackeray, A. D. 1978, *Ap. J.*, **219**, 498.

Walborn, N. R., and Liller, M. H. 1977, *Ap. J.*, **211**, 181.

Willis, A. J., and Wilson, R. 1979, in *IAU Symposium 83, Mass Loss and Evolution of O-Type Stars*, ed. P. S. Conti and C. W. H. de Loore (Dordrecht: Reidel), p. 461.

KRIS DAVIDSON: School of Physics and Astronomy, University of Minnesota, 116 Church Street, S.E., Minneapolis, MN 55455

THEODORE R. GULL and NOLAN R. WALBORN: Laboratory for Astronomy and Solar Physics, Goddard Space Flight Center, Code 683.0, Greenbelt, MD 20771