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Ultraviolet Photometry of Eta Carinae and Its Interpretation

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Summary. Measurements of Eta Carinae in the ultraviolet are reported. They are used to determine the extinction. It is concluded that the foreground material will produce the observed extinction, and there is no need to introduce anomalous extra extinction as has been argued by earlier authors. The consequences of this for the infrared radiation is discussed. The intrinsic properties of Eta Carinae are also discussed.

Key words: interstellar matter — extinction — ultraviolet observations — infrared radiation

I. Introduction

Eta Carinae is a star whose spectrum and history is poorly understood. It was probably of second to fourth visual magnitude just prior to 1837, then it brightened to first magnitude and remained bright for about 20 years, after which a slow fading to about seventh magnitude occurred (Gratton, 1963). Its present visual magnitude is about 6.3 and varies somewhat. Its spectrum consists in the visual of a continuum upon which are superimposed numerous emission lines (Balmer series Fe II, [Fe II], [S II], [N II] among others), somewhat reminescent of a nebular spectrum.

Rodgers and Searle (1967) have estimated that in the visual about 70% of the light observed comes from the continuum emission and the remainder from the line emission. The temperature of the star is very uncertain, the value $T=30000$ °K has been suggested by Davidson (1971). The star is apparently very luminous. Much of the luminosity is produced in the far infrared (Neugebauer and Westphal, 1968; Westphal and Neugebauer, 1964).

We have observed the star in the far ultraviolet, between 1500 and 3300 Å in five bands. The purpose originally was to be able to better specify the temperature and luminosity of the star. We shall discuss this aspect in the present paper. Our discussion will emphasize, however, another aspect: the extinction in the direction of Eta Carinae. This is an important problem for the following reason:

Because of the peculiar spectrum of the star, there is no standard to refer it to in determining the extinction. In such a case the extinction can be determined by knowing the expected intensities of a series of lines at different wavelengths and comparing them with observation. The Balmer series is often used in nebulae to determine the extinction.

In Eta Carinae the Balmer series cannot be used because the lines are formed in a high density region (probably greater than $10^6\,\mathrm{cm}^{-3}$) where the usual theory may not be applicable, and the optical depths in the lines may be high. We shall go more into detail on this point presently. Pagel (1969) and Lambert (1969) have suggested using the lines of [Fe II] to determine the extinction. They obtained very high values: $E_{B-V}=1^{\mathrm{m}}.2$ (Pagel) and $1^{\mathrm{m}}.9$ (Lambert). The extinction found for the neighboring stars is substantially lower: the recent careful discussion of Feinstein *et al.* (1973) gives a value of $E_{B-V}=0^{\mathrm{m}}.5$ for the stars within 3′ of Eta Carinae, and similar values for the members of the cluster Trumpler 16 (in which η Car is located) and the nearby cluster Trumpler 14. This difference has been taken seriously in recent literature and interpreted as a large amount of dust in the immediate vicinity of Eta Carinae. This dust is then considered to be the source of the observed infrared radiation.

A primary purpose of this paper is to demonstrate that the ultraviolet measurements can be used to make an accurate determination of the extinction, and that the extinction is approximately $E_{B-V}=0^{\mathrm{m}}.50\pm0.06$, in agreement with the extinction in the direction of neighboring stars. No anomalous extinction due to Eta Carinae itself is present and we discuss why this erroneous conclusion was earlier reached.

II. Observations

The observations were made on 14 January 1975, between U.T. $18^{\mathrm{h}}10^{\mathrm{m}}$ and $18^{\mathrm{h}}15^{\mathrm{m}}$, with the ultraviolet experiment aboard the Astronomical Netherlands Satellite (ANS). The instrument consists of a 22 cm diameter telescope followed by a five channel photometer. The

Table 1. Measurements of Eta Carinae

Wavelength	ANS counts	Total observed flux	Flux corrected for field star
Å	s^{-1}	10^{-11} erg cm^{-2} s^{-1} $Å^{-1}$	
3300	370±3	2.41	1.95
2500	329±2	3.45	2.90
2200	239±2	1.25	0.93
1800	431±3	3.04	2.0
1550 wide band	519±6	3.08	1.7
1550 narrow band	172±3		

wavelengths measured are summarized in Table 1. We have converted the ANS counts to energy units as discussed by van Duinen *et al.* (1975) except for the 2200 Å channel where a somewhat better calibration has been used.

Furthermore the small corrections due to the change in sensitivity of the detectors in the 1550 and 1800 Å channels are taken into account in Table 1. Combination of the narrow and wide band measurements, at 1550 Å has been made, which indicates that there is an absorption line at 1550 Å. The equivalent width is 6.0±0.4 Å. This correction has been made in the values given in Columns 3 and 4 of Table 1.

The ANS photometer has a 2ʹ.5 square entrance aperture. This has the consequence that in a cluster such as Trumpler 16, other stars may in advertently also contribute to the measured flux. We have checked the maps of Feinstein *et al.* in this region and find that the star HD 303 308 (O 3 V), which is located 1ʹ.1 away, probably is contributing to the observed light, and it is probably the only star which can make an important contribution. We have estimated the contribution of this star by measuring the ultraviolet flux from the neighboring star HD 83250. This star has the same spectral type (03) and about the same E_{B-V}(=$0^m.49$ compared to $0^m.44$ for HD 303 308). The flux of 93250 was reduced in the ratio of its visual magnitude (7.37 compared to 8.17 for 303 308). The resultant values of the Eta Carinae flux are given in the last column of Table 1. Since the O 3 V star was at the edge of the field of view, it may have wandered in and out, so that the correction may have been overestimated.

III. Determination of the Extinction

We have determined the extinction in the following manner. The preliminary average extinction curve, (extinction as a function of wavelength) in the ANS photometric system has been determined by van Duinen and Kester (internal report ROG 75–41). This extinction curve, given in Column 2 of Table 2 is very similar to that obtained from the OAO A-2 data (Savage, 1975) and from the TD 1 data (Nandy *et al.*, 1975). All these investigations show that, at least in the solar neighborhood and on the long wavelength side of 2000 Å, the curve does not significantly change from one object to another and the concept of an average curve is a good one. More scatter is found in this relation below 1900 Å. We have corrected our measurements for these average extinction values assuming various values of E_{B-V}. The results are plotted in Fig. 1. If we require that the points form a smooth curve, without peak or dip at 2200 Å, it is clear from the figure that we can specify the extinction within narrow limits:

$$E_{B-V}=0.50\pm0.06\,.$$

Two points require further discussions:
1) the assumption that the actual spectrum is smooth, i.e. it does not have a dip or peak at 2200 Å;
2) the assumption that the average extinction curve used is a good approximation for restoring the original intensities in this case.

Relevant to point 1) is Rodgers and Searle's (1967) estimate that in the visible part of the spectrum 70% is contributed by the continuum and the rest by emission lines. The contribution of the emission lines may increase toward the ultraviolet, but this is not certain. No extremely bright lines are expected. Many lines of Fe II are expected but, judging from their intensity in the visual spectrum, they will not be very strong, and, in addition, they will be found both in the 2500 Å and in the 2200 Å channel. For these reasons we estimate the chance that there is an excess emission of greater than 20% in the 2200 Å band above that in other bands, to be small.

With regard to point 2), the question arises: since Eta Carinae is such a peculiar star, might not the dust associated with it have entirely different properties. While this might be true, it is probably not relevant for the following reason. Eta Carinae is probably associated with the open cluster Trumpler 16 (e.g. Feinstein *et al.*, 1973). The stars in this cluster all are reddened by a similar amount (mostly E_{B-V} between $0^m.4$ and $0^m.55$). The material causing this reddening, must also cause extinction in Eta Carinae; it is clearly sufficient to cause

Table 2. Reddening correction (magnitudes)

λ	$(A_\lambda-A_{3300})/E_{B-V}$
1550	2.63
1800	2.51
2200	4.64
2500	2.12
3300	0
4300 (*B*)	−1.04
5500 (*V*)	—2.04

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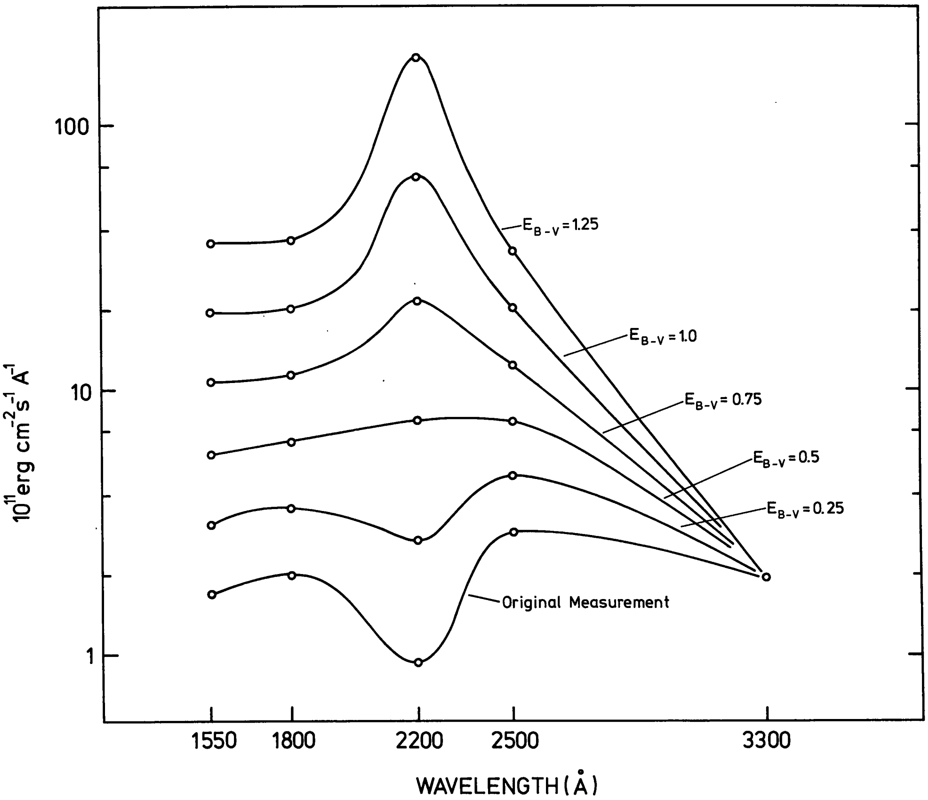

Fig. 1. The points in the lowest curve represent the observed flux from Eta Carinae. Each curve above this gives the flux after correction for extinction as explained in the text

all the extinction observed in the direction of Eta-Carinae.

IV. Other Determinations of Extinction

A) Hydrogen Line Ratio in the Emission Line Spectrum of Eta Carinae

If one uses the observed hydrogen line intensities and compares them with what theoretically is expected from a low density gas (Seaton, 1959), one can obtain a value of relative extinction between two wavelengths. If we use a reddening curve we can express each ratio in terms of E_{B-V}. We shall express the ratios relative to Hβ as is usually done.

Using the emission line spectrum of Eta Carinae we obtains strange results. For example using the data of Rodgers and Searle for Paschen γ we find $E_{B-V}=1\overset{\mathrm{m}}{.}30$ and from Hδ, which originates from the same level, we find $E_{B-V}=0\overset{\mathrm{m}}{.}66$. This difference can only be explained by either the use of the wrong extinction curve (we used that given by Code *et al.*, which in this spectral range is based on the work of Whitford) or by the fact that self-absorption is important. This last is almost certainly the case, not only because it is very probable from the physical situation, but because Rodgers and Searle report that the Balmer line profiles show evidence of self-absorption. It is clear that no information about the extinction can be derived from these measurements.

B) Hydrogen Line Ratio near Eta Carinae

To circumvent the self absorption problem, Rodgers and Searle measured four Balmer lines with a diaphragm 17″ diameter placed 20″ from Eta Carinae. We find an average value of $E_{B-V}=0\overset{\mathrm{m}}{.}48$ using these measurements and the method described above. The Hα and Hγ determinations are equal and lower ($0\overset{\mathrm{m}}{.}37$) and the H$\delta$ is higher ($0\overset{\mathrm{m}}{.}70$) which we ascribe to substantial observational uncertainty. We further note that Rodgers and Searle, using the same measurements, conclude that $E_{B-V}=0\overset{\mathrm{m}}{.}69$. They do not give sufficient information for us to see why their result differs from ours ($0\overset{\mathrm{m}}{.}48$). We conclude that these measurements agree well with our determination of the extinction.

C) [Fe II] *Emission Line Ratios*

Pagel (1969) has suggested using the measured intensity ratios of the [Fe II] emission lines to determine the extinction. The lines are weak (Aller and Dunham, 1966), thus the intensities are uncertain. Furthermore, the measurements are in a limited wavelength region. The lines originate from many energy levels, and, in order to make use of all the lines, the relative population of these levels must be known to begin with. Pagel assumes that they are populated according to a Boltzmann distribution with $T=8500$ °K. Since the lines originate in a region of reasonably low density (of the order of 10^6

Table 3. Flux from Eta Carinae corrected for extinction

	Flux (10^{-11} erg cm^{-2} s^{-1} Å^{-1})
1550 Å	77
1800	86
2200	103
2500	103
3300	26
4000	7.0
6000 Å	3.6
1 μ	2.04
2.2	1.76
4.8	6.8
10	16
19.5	11.3
34 μ	4.7

electrons cm^{-3}) it is very doubtful whether collisional processes so dominate over other processes populating the levels as to justify a Boltzmann distribution. This question has been discussed in more detail by Lambert (1969) who also concludes that such a distribution is unlikely to be realized in fact, and the reddening derived, $E_{B-V} \simeq 1^{\mathrm{m}}.2$, is likely to be in error.

Lambert suggests deriving the reddening from those [Fe II] lines which originate from a single level. In principle, this is a correct procedure. In practice its shortcoming is that there are a very limited number of lines available which originate from a single level. This limits the wavelength range available for defining the extinction curve to at most 400 Å. Furthermore the scattering in the derived populations (which involves not only uncertainties in the intensities, but uncertainties in the theoretically calculated transition probabilities as well) is at least a factor of two, judging from multiplets originating from single lines very close together in wavelength. For this reason we conclude that this method is likely to give a wrong result.

Lambert derived a reddening in this way of $E_{B-V} = 1^{\mathrm{m}}.8$. With such a reddening, coupled with the ultraviolet extinction curve, it would have been impossible for us to measure any emission at 2200 Å at all. We must therefore conclude that this value is strongly overestimated, probably because the line intensities and atomic parameters are not sufficiently well known to apply it.

V. Intrinsic Properties of η Car

The flux from η Car as a function of wavelength is given in Table 3, where measurements are listed from 1550 Å through 20 μ. These values have been corrected for extinction using the extinction curve of Whitford (1958) in the visual and the ANS curve (van Duinen and Kester, 1975) in the ultraviolet together with the value $E_{B-V} = 0^{\mathrm{m}}.5$. It has been assumed that there is no extinction at 20 μ.

Table 4. Comparison of ultraviolet photometry of early type stars with η Car

	F_λ/F_{1800}			
Type	1550	2200	2500	3300
O 7	1.28	0.70	0.41	0.15
B 4	1.24	0.71	0.51	0.26
A 0	0.85	0.87	0.67	0.59
η Car	0.90	1.20	1.20	0.30

In the visual part of the spectrum only the continuum radiation is given in the table, so that the total radiation from 4000 Å to 1 μ is about 30% higher. This will not affect our calculations in a substantial way.

A. Luminosity

As can be seen from the table, the radiation does not at all resemble a black body: there are peaks of radiation both in the far infrared and in the ultraviolet. The total luminosity between 1500 Å and 34 μ is

$$2 \times 10^{40}\ \mathrm{erg\ s^{-1}} \simeq 10^7 L_{\odot}$$

assuming that η Car is at the same distance as the stars in the cluster Trumpler 16 in which it is embedded. The distance used was 3000 pc (Feinstein *et al.*, 1973). This is a minimum luminosity since some radiation will be found outside these wavelength limits, and furthermore there may still be some extinction at 20 μ. Most of the energy (90%) is emitted in the far infrared. Only 10% is emitted between 1500 and 3300 Å. Very little of the energy is emitted in the visual region.

B. Temperature and Radius

A double peaked function cannot be approximated by a Planck curve. There is a suggestion that each of the peaks represents a separate physical phenomenon: the ultraviolet is formed by a hot star and the infrared by a medium (some authors speak of radiation by "dust") much further out. In that sense we may consider the ultraviolet radiation and ask what temperature and radius a star must have to produce this spectrum. We may compare the ultraviolet photometry after the extinction correction has been applied with that of normal unreddened early type stars measured with the same instrument. (Wu, 1975) (internal report ROG 75–36). There is no good agreement as is demonstrated in Table 4. If one still wishes to characterize the radiation by a parameter, one might suggest $T = 15000$ °K. This is somewhat higher than the temperature expected from a black body that peaks at 22–2500 Å, but this is compensated by the very sharp rise from 3300 Å and the rather slow fall off at the shorter wavelength. A black body of this temperature, if it is to produce the observed ultraviolet radiation, must have a radius of $100 R_{\odot}$, or somewhat more.

VI. Discussion

The infrared radiation is presumably produced by a much lower temperature medium which therefore must extend much further possibly to 0.1 pc from the star. It has often been argued that this radiation is produced by "dust" since this material exists in many places in the interstellar medium, probably has a low temperature, and presumably is capable of producing a continuous spectrum. Interstellar dust, as we know it, has an extinction coefficient which increases through the infrared toward the shorter wavelengths, reaching a peak somewhere in the ultraviolet. To produce the observed infrared radiation with a low temperature material (we shall use $T=150$ °K in our calculations, but the value is not critical for the conclusion), this material must have a radius of at least 2×10^{17} cm, if it is optically thick at 20 μ. But if it is normal "dust" with an optical depth of 1 at 20 μ, it will have approximately an optical depth of 200 at 2200 Å.

The value 200 is poorly known. Caroff *et al.* (1973) indicate a value of 150. The uncertainty has no significant effect on the argument in the text. This is clearly in contradiction to the observation, where, as we have shown, no extra absorption above that produced in the general neighbourhood, is observed. If we therefore turn the argument around and say that the maximum optical depth at 2200 Å is 0.5, then that at 20 μ must be of the order of 2×10^{-3}. To produce the observed radiation we must then have a radiation producing volume with a radius of at least 6×10^{18} cm. At a distance of 3000 pc this is 2′, which is substantially larger than that measured by Westphal and Neugebauer, who report that all the infrared radiation originates within 15″ of η Car. (Gehrz *et al.*, 1973, conclude that it is emitted within a diameter of 6″). The above argument applies only to a spherically symmetric nebula or to a geometry in which the infrared emitting material is in the line-of-sight to η Car.

Finally we should mention the possibility that we do not see the effects of the "dust" simply because it scatters the ultraviolet radiation, and since our diaphragm includes the entire nebula, all the radiation scattered by the nebula is measured, at the same frequency as it was emitted. This requires that the scattering be total, i.e. the albedo is greater than 0.99. Measurements of the albedo at 2200 Å from interstellar dust (Witt and Lillie, 1973) indicate an albedo of about 0.15 at 2200 Å, which makes this effect impossible. Code (1973) has discussed the effect in detail and has shown that because the albedo is probably smaller at 2200 Å than at neighboring wavelengths, the effect will actually produce a stronger absorption band at 2200 Å.

We can only conclude that the source of the infrared radiation from η Car cannot be understood on the basis of it being produced by a medium with the same properties of interstellar "dust" as long as we require the ultraviolet radiation to be produced at the center of this region. It is possible that some geometrical effect (e.g. a hole in the "dust") may negate this conclusion. It seems to us, however, that one must seriously consider that the infrared radiation is produced by a material other than "interstellar dust", in the sense that this material does not produce an absorption band at 2200 Å.

VII. Summary

We report measurements of the ultraviolet flux of η Car. The extinction can be derived from the measurements and the assumption that a normal extinction curve is applicable. The extinction is found to be $E_{B-V}=0\overset{\mathrm{m}}{.}5\pm0.06$. This is in good agreement with the extinction found for neighboring stars, especially the cluster Trumpler 16. This is an additional piece of evidence for the association of η Car with this cluster.

It is furthermore clear that earlier reports of much higher reddening in η Car are not substantiated and are probably wrong because the observations on which they were based were overinterpreted. There appears to be no additional extinction in η Car above that of the surroundings, which has important consequences in the interpretation of the infrared radiation.

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Note added in proof: see p. 448.

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Note added in proof: The researchers working with the ANS data have decided to use a "standard" extinction curve in correcting all their data. The arguments leading to this curve will be published soon. Thus our Table 2 is somewhat changed: the first four entries in column 2 of this Table should be 2.99, 2.76, 4.52, 2.15. This has the effect that the derived value of $E_{B-V}=0.53\pm0.06$ instead of 0.50 ± 0.06. This difference has no effect on the further discussion, and at the same time points out that the result is not sensitive to the precise reddening curve.

The corrected flux, especially at λ1550 and 1800 is also increased somewhat by this change. The increase, however, is substantially less than the uncertainty caused by the presence or absence of the field star.