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X-RAYS FROM ETA CARINAE AND THE SURROUNDING NEBULA

F. D. SEWARD, W. R. FORMAN, R. GIACCONI, R. E. GRIFFITHS, F. R. HARNDEN, JR., C. JONES, J. P. PYE[1]
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, Massachusetts 02138
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ABSTRACT

Two X-ray pictures have been obtained of the η Car nebula using the imaging detectors of the *Einstein* Observatory. One covers a field 1° square with a resolution of 1′; the second covers a field 25′ in diameter with resolution of a few arcsec. These show a region of diffuse X-ray emission with luminosity $\sim 10^{35}$ ergs s^{-1}. The sources have been positively identified as the peculiar object η Car, a Wolf-Rayet star, a cluster of O stars, and five individual O stars. The η Car X-ray source is extended and coincides with the outer shell of the diffuse object η Car itself. One X-ray bright spot may be emission from a central object within η Car.

Subject headings: nebulae: individual — stars: coronae — stars: early-type — stars: Wolf-Rayet — X-rays: sources

I. INTRODUCTION

X-rays from the η Car region were first detected in 1970 using a rocket-borne detector (Hill *et al.* 1972). Subsequently, the *Copernicus* X-ray telescope viewed η Car through a 12′ aperture and reported no X-rays with an upper limit significantly below the rocket detection (Griffiths, Peacock, and Pagel 1974). There followed definite detections using the *Ariel 5* (Seward *et al.* 1976), *OSO 8* (Becker *et al.* 1976; Bunner 1978), and *Uhuru* (Forman *et al.* 1978) satellites. Agreement was unanimous over the presence of a 2–10 keV X-ray source. There was confusion over the existence of a moderately strong source emitting photons with energy below 1 keV. It was particularly difficult to reconcile the *Copernicus* upper limit with other reported observations of soft X-rays.

This difficulty is now resolved by the *Einstein* X-ray Observatory (*HEAO 2*) images: the region is in fact a source of X-rays, but they come from many sources embedded in a large area of diffuse emission. The object η Car is indeed an X-ray source, but emits only 1/20 of the soft X-rays observed from the entire region.

Eta Carinae is a unique object. While it is now a sixth-magnitude, almost stellar object, in 1843 there was a spectacular outburst during which η Car brightened briefly to magnitude −1. It remained bright for about 20 years, then declined to approximately its present level, as can be seen in the light curve given by Walborn and Liller (1977).

Eta Carinae forms the central part of an optical nebula, the homunculus, of dimension 10″ × 15″ (Gehrz and Ney 1972), which contains several knots of luminosity and which is expanding with a velocity of $\sim$600 km s^{-1}. This material was probably generated during the great outburst. The homunculus is surrounded by a faint outer shell of dimensions 21″ × 29″ (Walborn 1976).

Eta Carinae itself is now the brightest extrasolar infrared source at a wavelength of 20 μm. At a distance of 2600 pc, the bolometric luminosity is $\sim 2 \times 10^6 L_{\odot}$ (Westphal and Neugebauer 1969). The infrared emission comes from a shell of dust with dimensions approximately that of the homunculus (Aitken and Jones 1975), and it is generally accepted that the energy source is a massive central object (or objects) obscured by the dust.

The homunculus is embedded in a large emission nebula, NGC 3372, of dimension $\sim$2°, which contains many luminous early stars (Walborn 1973). There is general agreement that the energy to support optical emission from the nebula comes from the early stars embedded in it and that the nebula is massive and expanding, and contains shells of moving gas (Faulkner and Aller 1965; Dickel 1974).

II. OBSERVATIONS

The instrumentation is described by Giacconi *et al.* (1979). Observations were made both with the high-resolution imager (HRI) during 1978 December 14 and 15 and with the imaging proportional counter (IPC) on 1978 December 22; and were centered on η Car itself. The total observing times amounted to 8000 and 13,000 s, and the data are shown in Figures 1 and 3*a* (Plates L16 and L18) for the IPC andHRI, respectively.

The X-rays observed come from discrete sources and an apparently diffuse emission permeating the entire region. The general appearance of the IPC X-ray picture is quite similar to that of an optical photograph of the region. The discrete sources detected, all of which are early stars, with the exception of η Car itself, are listed in Table 1. Magnitudes and spectral types have been taken from Walborn (1973).

To illustrate the basis for the identifications, Table 1 lists measured X-ray source positions and those of the stars. The HRI identifications are obvious since the measured positions are all within 4″ of bright early stars. In contrast to this, the IPC locations have an accuracy of about 1′. Once the HRI identifications had been made it seemed clear that the IPC sources should

[1] Also Physics Department, University of Leicester, Leicester, LEI 7RH, England.

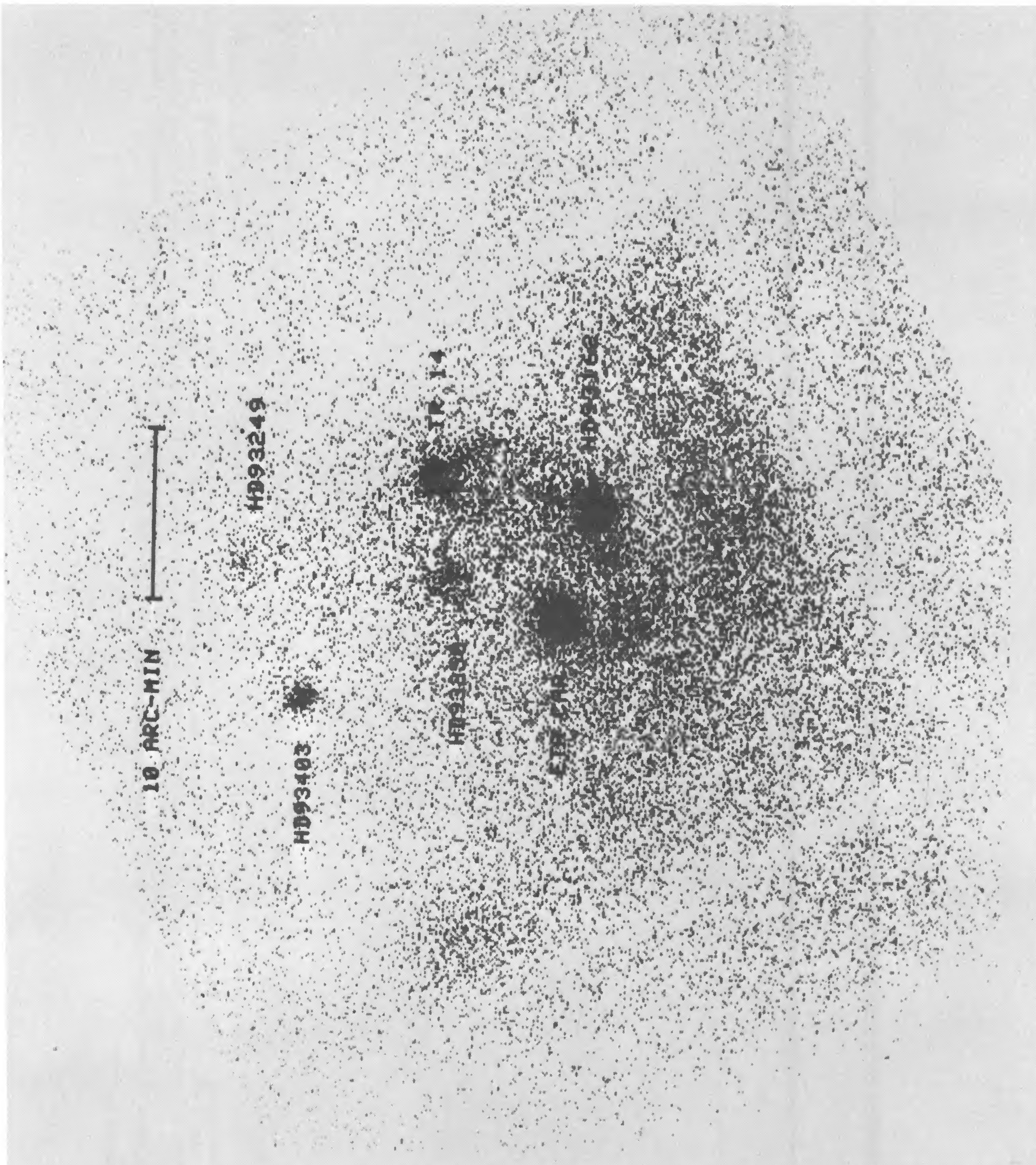

FIG. 1.—Picture of the η Carinae region taken with the IPC. The window support structure shadows part of the field of view (cf. Fig. 3). The central unocculted region is 38′ on a side.

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also be identified with early stars in the error boxes. This procedure is different from the usual technique of X-ray astronomy in which arcmin error boxes in the galactic plane contain many objects, and a study of optical characteristics of all objects in the error boxes is usually necessary to make an identification. In the η Car region, inspection of the X-ray photograph revealed that the pattern of X-ray sources was the same as the pattern of early stars, and there is high confidence that these are the X-ray sources.

The IPC gives X-ray spectra in addition to locations. It is obvious by inspection of the pulse-height spectra that these sources are at a distance of several kpc: there are no low-energy photons in the data. It is also obvious that the spectra of all sources are not the same. We have fitted the pulse-height spectra with model thermal spectra (exponential) and have derived numbers for the column density of interstellar material and for the source temperature with uncertainties of about a factor of 2.

Table 2 gives the results for individual sources. In some cases, this procedure yielded a very high column density and a very low temperature. This is because the slope of the spectrum is greater than the response function of the detector; this determination of column density and temperature is not unique. In these cases, we have fixed the column density, and the listed temperature is that calculated for this column density. The X-ray luminosities were derived using these temperatures.

Savage *et al.* (1977) measured the UV absorption of hydrogen in the direction of the star HD 92740, which is close to and at the same distance as the η Car nebula, and obtained a value of 1.8×10^{21} atoms cm^{-2}. Using the average extinction measured by Feinstein, Marraco, and Muzzio (1973) and the average relation between X-ray and optical absorption derived by Gorenstein (1975) and by Ryter, Cesarsky, and Audouze (1975), we obtain 3×10^{21} atoms cm^{-2}. Confirming this, the computer fits to the two strongest X-ray sources in Tr 16, η Car and HD 93162, give $N_{\rm H} \approx 2$ and 3×10^{21},

TABLE 1

LOCATION, MAGNITUDE, AND SPECTRAL TYPE OF DISCRETE X-RAY SOURCES IN THE η CARINAE NEBULA

IPC X-Ray Location R.A.(10^h)	IPC X-Ray Location decl. (−59°−)	Difference between IPC Location and Star Position	HRI X-Ray Location R.A.(10^h)	HRI X-Ray Location decl. (−59°−)	Star Position R.A.(10^h)	Star Position decl. (−59°−)	Identification	m_v	Spectral Type
							Tr 14		
41^{m}58^s.1	17′47″	(47″)	...	...	42^m 0^s.9	17′ 5″	HD 93128	8.8	O3 V((f))
							HD 93129A	7.3	O3 If
							HD 93129B	8.9	O3 V((f))
42 12.0	27 44	(26″)	42^{m}14^s.3	27′21″	42 14.2	27 24	HD 93162	8.1	WN6
...	...	...	42 37.3	28 25	42 37.4	28 28	HD 93205	7.7	O3 V
...	...	...	42 45.6	31 4	42 45.5	31 8	CPD−59°2600	8.6	O6 V((f))
42 39.0	5 48	(59″)	...	...	42 46.8	5 37	HD 93249	8.4	O9 III
42 45.7	18 39	(37″)	42 48.0	18 6	42 48.3	18 7	HD 93250	7.4	O3 V(f)
43 3.0	25 35	(35″)	43 6.7	25 14	43 6.9	25 15	η Car		pec
43 44.4	9 26	(50″)	...	...	43 46.7	8 39	HD 93403	7.3	05 III(f)

TABLE 2

RESULTS FOR INDIVIDUAL SOURCES

Identification	Distance (pc)	IPC Rate (cts s^{-1})[a]	HRI Rate (cts s^{-1})	Spectrum: $N_{\rm H}$ ($\times 10^{21}$ atoms cm^{-2})[b]	Spectrum: kT (keV)	Flux[a] (ergs cm^{-2} s^{-1})	Luminosity[a,c] (ergs s^{-1})
Tr 14	3500	0.078	...	8	>5	1.5 (−12)	4.7 (33)
HD 93162	2600	0.14	0.014	3	5	2.8 (−12)	3.3 (33)
HD 93205	2600	0.024	0.003	[2]	0.6	5.7 (−13)	8.3 (32)
CPD −59° 2600	2600	...	0.001	...	...	...	...
HD 93249	3700	0.011	...	[2]	0.5	2.2 (−13)	6.6 (32)
HD 93250	2600	0.044	0.004	[2]	1	1.0 (−12)	1.2 (33)
η Car	2600	0.16	0.05	2	>8	3.1 (−12)	3.3 (33)
HD 93403	2600	0.034	...	[2]	3	7.3 (−13)	8.0 (32)
All NGC 3372	2600	2.47	...	[2]	0.8	6.1 (−11)	8.2 (34)
Only diffuse nebula	2600	2.0	...	[2]	[0.5]	3.9 (−11)	6.1 (34)

[a] 0.5–3.0 keV.
[b] Square brackets indicate assumed value.
[c] Corrected for interstellar absorption.

respectively. Therefore, we have used $N_{\rm H} = 2 \times 10^{21}$ for the weak sources observed in this region.

III. DISCUSSION

a) Early Stars

This observation shows that at least six O-stars and one Wolf-Rayet star in this region are X-ray sources of moderate strength. The X-ray luminosity of each is $\sim 10^{33}$ ergs s^{-1}. There are several mechanisms by which these X-rays might be generated: they could be from a stellar corona; they might be caused by interaction of a strong stellar wind with the surrounding medium; or these stars might have compact binary companions (similar to Cen X-3, powered by accretion from a stellar wind, but at an earlier stage in their evolution when the wind is not as strong).

In this field, we see almost every bright O star listed by Walborn (1973), and the X-ray flux above the atmosphere is proportional to the visual flux (within a factor of 2). Either those O stars which are not seen as X-ray sources are shadowed by an IPC rib, are close to and possibly confused with a brighter source, or the X-ray luminosity predicted from the optical brightness is below the local background.

Walborn lists three W-R stars in the field of our IPC observations. Two sixth-magnitude WN stars are close to the edge of the field (where the detector sensitivity is reduced but still appreciable) and are not detected. Since the eighth-magnitude WN star HD 93162 appears as a strong source, we conclude that the X-ray emission from these stars, unlike that from the O stars, is not simply correlated with the optical luminosity.

Because O stars have been detected as X-ray sources in other regions (see Harnden *et al.* 1979), we defer further discussion of this topic to a subsequent paper treating a greater number of stars. Also, source mechanisms are subject to observational tests which might be accomplished in the near future.

b) The Diffuse Nebula

A low-frequency radio observation was interpreted as showing the existence of a small supernova remnant, probably located a few arcmin east of the star η Car (Jones 1973). A subsequent detection of a 7 keV X-ray line was interpreted as arising from the ionized iron in this remnant (Becker *et al.* 1976). Elliott (1979) has proposed a ring of optical filament 3′ in diameter and close to η Car as the SNR. Our X-ray data, however, show no sign of a conventional SNR in this area. Such a remnant would be a strong source of soft X-rays having the appearance of a patchy, approximately spherical shell. The diffuse X-rays from the η Car nebula may indeed be the result of past supernovae, but there is not a single dominant remnant in this area.

The diffuse emission is most probably from hot gas. For a typical bright spot in the diffuse emission, the size is ~ 2.5 pc diameter (3′) and $L_x \sim 1 \times 10^{33}$ ergs s^{-1}. The derived gas properties are: density ~ 0.4 electrons per cm^3, lifetime $\sim 1 \times 10^7$ years, total thermal energy $\sim 10^{50}$ ergs.

This hot gas must be in front, or on the near side, of the colder luminous gas in most of the bright nebula. There is also hot gas in regions not seen optically, particularly in an arm extending to the northeast. This gas does not permeate the western dust lane and is therefore probably behind it. Figure 2 (Plate L17) compares X-ray and optical emission.

The western dust lane, so prominent in optical photographs, is seen clearly in the X-ray data and has a width of ~ 5 pc. The assumption of a comparable depth and a density of 700 atoms cm^{-3} of cold material gives a column density of 10^{22} atoms cm^{-2}. This is sufficient to absorb all X-rays below 1 keV and is the same density as that required to explain optical emission from the bright nebula (Faulkner and Aller 1965). Because inner-shell electrons are still bound in the bright nebula, X-ray absorption is expected to be the same as in the dust lane, and the observed emission cannot originate from behind the nebula.

A possible origin for the hot gas is in stellar winds. Castor, McCray, and Weaver (1975) have explored the possibility that a stellar wind would produce a bubble of hot-gas surrounding the star. The diffuse X-ray emission from the η Car nebula shows no obvious large structures associated with the individual stars which are the X-ray sources; but in view of the complexity of this region, the morphology observed is not inconsistent with a stellar wind origin for the hot gas.

Another possible origin for the hot gas could be supernovae. In a region such as this containing many O stars, the supernova rate is expected to be high. The diffuse emission could be thermal radiation resulting from a supernova or supernovae which occurred $\sim 10^6$–10^7 years ago. The lifetime of the hot gas is long enough, and there are no other data which exclude this from consideration.

SNRs in regions containing a high density of gas and dust have not been previously observed. If the diffuse X-ray emission comes from a SNR, the geometrical appearance is quite different from other old remnants such as the Cygnus loop and Vela X, which are strong, diffuse, soft X-ray sources. There is the interesting possibility that supernova remnants in dense regions have a different appearance from those already observed in less dense regions of the galaxy.

c) η Carinae

The HRI contour map of η Car is overlaid on an Hα image from Walborn (1976) in Figure 3*a* (Plate L18). For a better representation of the optical features, the reader is referred to the paper of Walborn (1976), which delineates them.

The overall morphology of the X-ray image is that of a bright horseshoe, together with a faint region which extends to the southeast and envelops the eastern condensations. There is also an X-ray bright feature coincident with the bright optical emission from the center of the homunculus, one that is perhaps associated with a single central massive star (see Figure 3*b* [Plate L19]).

Apart from the X-rays which might be associated with a central star, this emission may be interpreted as thermal radiation from a shock front caused by material expanding outward from the outburst of ~ 1843 (Davidson and Ostriker 1972). The outer condensations

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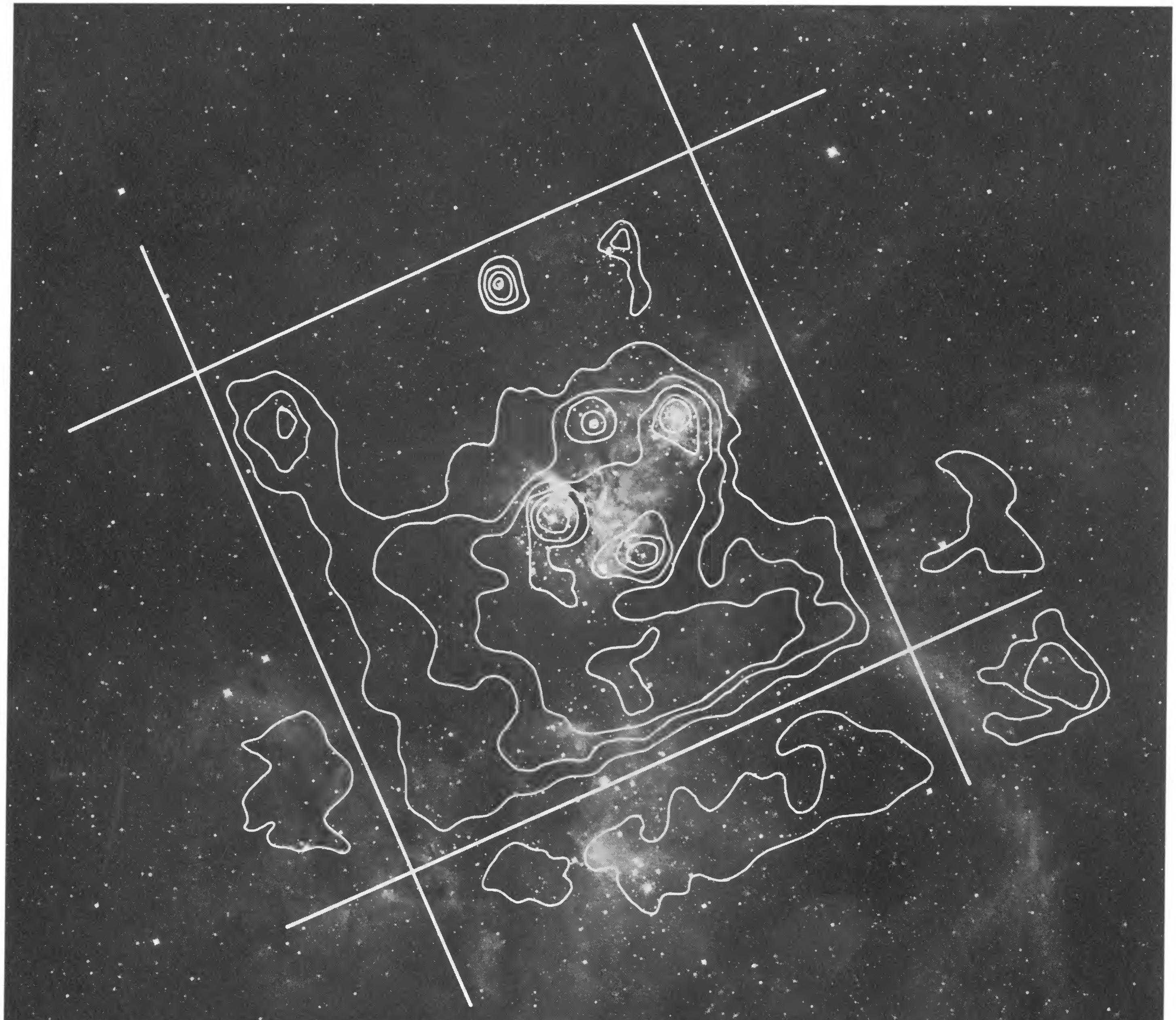

Fig. 2.—Contours of constant X-ray counting rate showing discrete sources and diffuse emission have been overlaid on a UV photograph. Strengths of contours in arbitrary units are approximately 3, 5, 7, 12, 18, and 30. The shadowing window supports are indicated as straight lines and have a length of 60′. These contours were taken directly from the data shown in Figure 1. The picture was taken by W. Liller with the CTIO Curtis Schmidt and a filter which passed the band 3300–3900 Å.

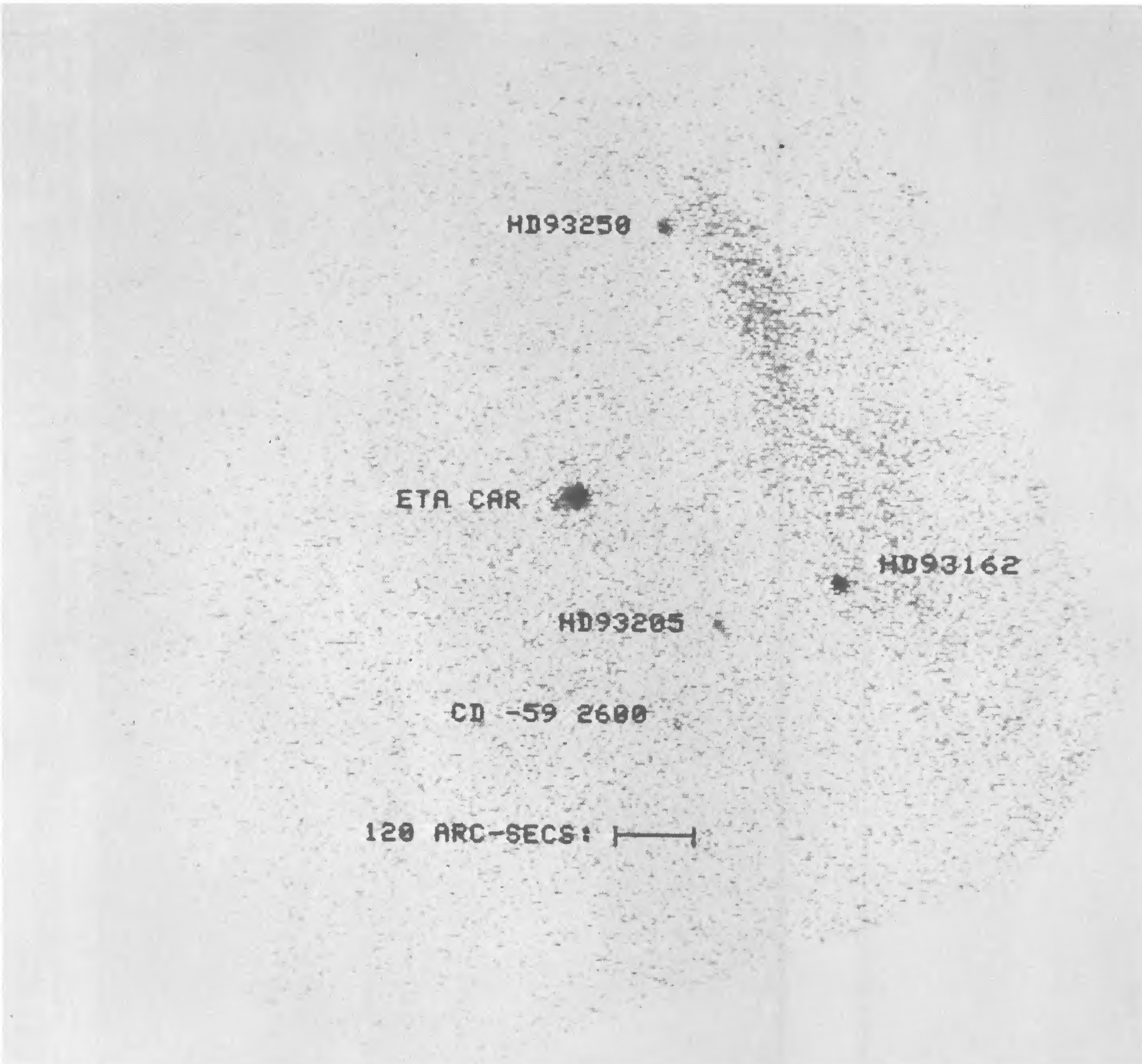

FIG. 3*a*.—An HRI picture centered on η Car showing that η Car itself is an extended source. Four stars are also seen. The diffuse feature in the northwest is an instrumental effect (in the HRI only).

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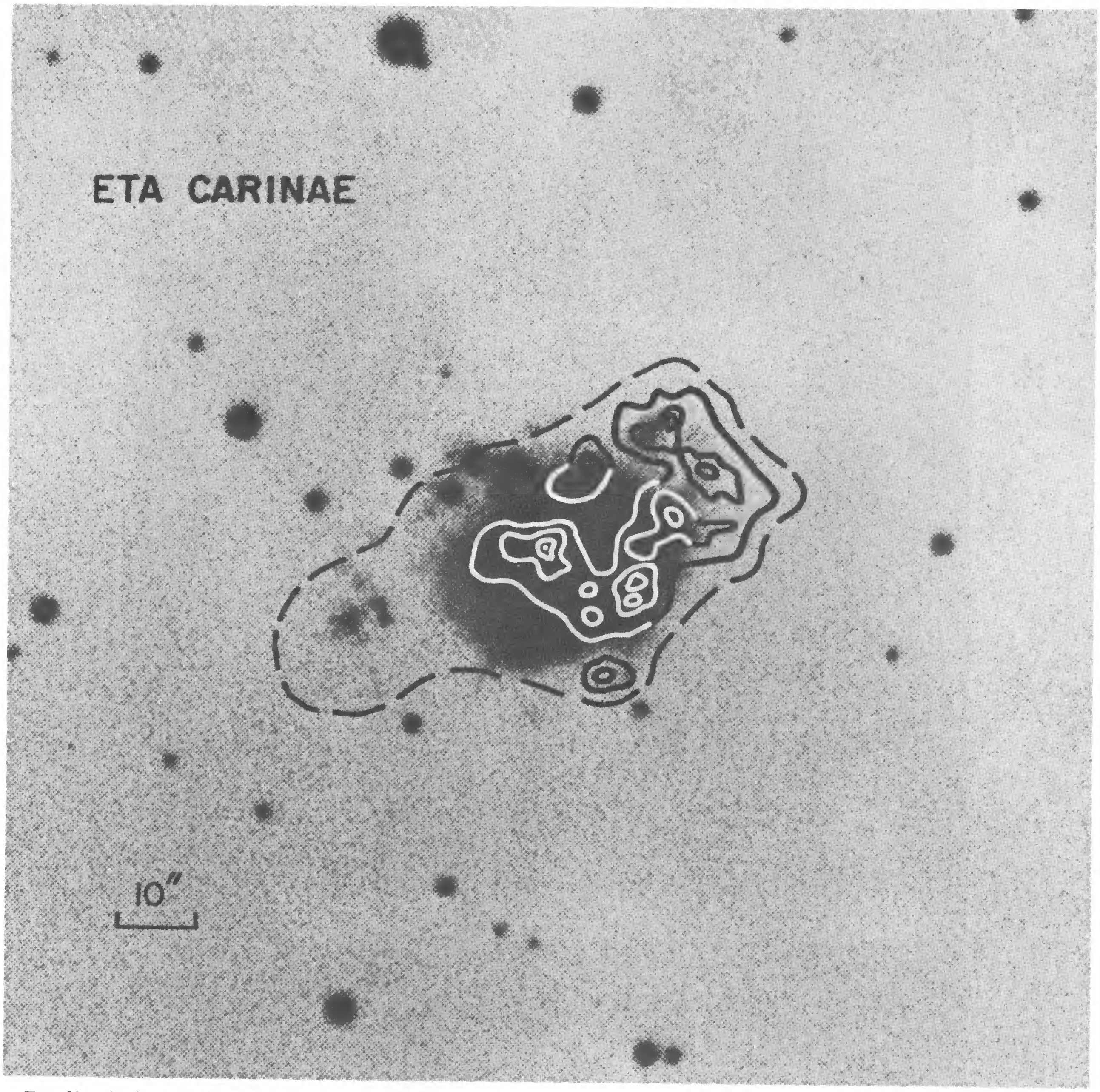

FIG. 3*b*.—A photograph of η Car taken from Walborn (1976) with contours of constant X-ray emission superposed. The homunculus is blended with the outer shell which shows strongly to the southwest and only as faint condensations to the northwest and east. The dashed contour contains very faint emission and is not well determined.

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are observed to be expanding at a velocity of 750–1000 km s^{-1} (Walborn 1976). If the X-rays originate from an outgoing shock, the predicted temperature of the X-ray emitting plasma is $T \sim 10^7$ K, an order of magnitude lower than the estimated $T > 9 \times 10^7$ K (Table 2), but the higher energy X-rays may come from only part of this region—perhaps from only the central object. Using the Sedov solution (Culhane 1977) from the observed X-ray luminosity (3×10^{33} ergs s^{-1}) and size (0.2 pc) we may estimate the initial energy of the outburst, $E_0 \sim 10^{46}$ ergs, and the initial gas density, $n_0 \sim 20$ cm^{-3}. The mass in the emitting gas is only $\sim 10^{-2}$ $M_{\odot}$. This energy and density seem reasonable, and the symmetry of the X-ray emission with respect to the central nebula is further support of a shockwave interpretation. The hypothesis that the η Car outburst was a supernova is not supported. X-ray emission from other SNR always indicates much greater energy release and mass of hot gas.

The emission observed at the center of the homunculus might be from a single central object, perhaps the corona of a massive star. The characteristics of η Car do not exclude the existence of a single central star, and Davidson (1971) has calculated its properties. The surrounding dust, which radiates so strongly in the infrared, obscures the star at optical wavelengths. We would expect the object to appear much stronger at higher energies, and perhaps (rather than the diffuse nebula source) to account for some of the 5–10 keV emission.

d) Comparison with Previous Results

The present observation does not account for all soft X-rays detected in previous observations (Bunner 1978). The most likely source of this emission is the southern part of the nebula, as shown by Figures 1 and 2, in which emission extends out of the field of view to the south.

Past experiments have also detected higher energy 2–10 keV X-rays (Becker *et al.* 1976). The *Einstein* telescope has little efficiency above 4 keV and cannot see this high-energy component. One possibility is that the high-energy photons originate in the diffuse part of the NGC 3372 nebula which accounts for 80% of the soft X-rays seen in our observation.

A second possibility is that the hard X-rays come from the central object of η Car. The η Car emission then would come from the blast wave, which should have a temperature of $\sim$1 keV, and from the central source attenuated by $\sim 10^{23}$ atoms cm^{-2} of material in the dust cloud. The image of the central source seen in Figure 3b would be caused only by photons of energy >2 keV. Eta Carinae is the hardest source in the field and is entirely contained in one resolution element of the IPC, and so we cannot separate spectra from its different regions. If the higher energies come from a central source, it would have $T \sim 5 \times 10^7$ K and $L_x \sim 3 \times 10^{34}$ ergs s^{-1} (after a very uncertain correction for attenuation in the dust cloud).

IV. SUMMARY

The η Car region is not a strong X-ray source. The total emission amounts to only $\sim$3 *Uhuru* counts per s. It was a surprise to see diffuse emission and many weak sources rather than the one moderately strong source previously expected. The X-ray luminosity of the early stars is only about 10^{-4} of the total luminosity of each star and is probably from hot gas in an extended atmosphere of the star. The diffuse emission also is probably from hot gas representing only a small fraction of the material contained in, and a small fraction of the energy radiated by, the η Car nebula (NGC 3372).

X-rays generated in the outer shell of η Car are consistent with a blast wave from the outburst in the early 1840s and account for only 10^{-7} of the energy radiated by η Car. This X-ray emission is completely incompatible with the interpretation of the η Car outburst as a supernova. The data favor the present energy source of η Car as being a single massive object. The weak X-ray source seen coinciding with the center is perhaps the massive star itself shining through the surrounding dust cloud, which is the source of the infrared radiation.

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