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DIFFUSE *EINSTEIN* X-RAY EMISSION FROM THE REGION OF RCW 49, A BRIGHT SOUTHERN EMISSION NEBULA

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ABSTRACT

An X-ray exploration of a region of the Galactic plane in Carina near $l = 284°$ with the *Einstein Observatory* is presented, consisting of two IPC and one HRI fields. Three new X-ray sources are seen, of which one is clearly extended and can be associated with RCW 49, an H II region/emission nebula, containing a cluster of young stars. The X-ray data could be consistent with a central source of diffuse emission; however, the X-ray flux appears significantly greater than that expected for an object like RCW 49.

Subject headings: nebulae: H II regions — nebulae: individual (RCW 49) — X-rays: sources

I. INTRODUCTION

The region of the Galactic plane around $l = 284°$ $b = 0°$ was explored in soft X-rays (0.2–4.5 KeV) with the Imaging Proportional Counter (IPC) of the *Einstein Observatory* (Giacconi *et al.* 1979) to search for X-ray counterparts of the *COS B* gamma-ray source 2CG 284–00 (Bignami and Hermsen 1983; Caraveo 1983). The error circle ($\sim 1°$ radius) of the gamma-ray source was covered with four IPC fields (an image of which has already been reported in Fig. 7 of Caraveo 1983), and three X-ray sources were discovered in one of them. Table 1 lists the source numbers as used in this paper together with their *Einstein Observatory* names and other characteristics.

Follow-up observations were carried out both with the IPC and with the High Resolution Imager (HRI) of *Einstein* 1 yr later, and some brief results on the sources found were reported by Hertz (1983) and by Hertz and Grindlay (1984), who included them in their *Einstein* galactic plane survey catalog. The faintest one (source 1) has an X-ray–to–optical flux ratio compatible with the hypothesis of a coronal origin for its X-ray emission, while the two other (sources 2 and 3), preliminarly associated by Hertz with faint emission-line stars of early spectral types, have $f_x/f_o > 10^{-2}$, well above the value observed in "normal" early-type stars (e.g., Vaiana *et al.* 1981; Pallavicini *et al.* 1981). As to the nature of these two sources, the X-ray data contain two important clues: source 3 appears clearly extended, while source 2 is variable on a time scale of a year. In the following we shall concentrate on the extended source, the point like, variable one will be discussed elsewhere.

The diffuse source is clearly correlated with the H II region RCW 49 (Rodgers, Campbell, and Whiteoak 1960; Westerlund 1960) and its ionizing O star cluster (van den Bergh and Hagen 1975). This bright emission nebula, about 6 kpc distant, is a thermal radio source, known as G284.3–0.3 (Kesteven 1969; Shaver and Goss 1970). It was included in the catalog of the H109 recombination line sources of Wilson *et al.* (1970) and in the more recent 5 GHz catalog of the southern H II regions of Haynes *et al.* (1979). Moreover RCW 49 is seen as an extended feature in the *IRAS* data.

The strong correlation found with RCW 49 suggests that it may represent the sixth known case of an X-ray bubble powered by the stellar wind of the O stars, e.g., resembling those observed in the Carina nebula (Seward and Chlebowski 1982) and in S155 (Fabian and Stewart 1983). This interpretation, however, is not fully satisfactory, and the possibility of a supernova remnant buried in an H II region will also be considered.

II. OBSERVATIONS AND DATA ANALYSIS

Our soft X-ray data (0.2–4.5 KeV) were collected during two IPC observations performed on 1979 July 13 (sequence number I3341) and on 1980 July 8 (I7715), for a total exposure time of 11,500 s (1700 s and 9800 s, respectively), and an HRI observation of 7000 s exposure time, performed on 1980 July 10. All the pointing directions were at about R.A. = 10^h22^m, decl. = $-57°30'$, but in the HRI image only one of the three IPC sources was marginally detected.

In Figure 1 (Plate 1) we present the IPC field with the longer exposure time (I7715). Three X-ray sources are well visible.

The faintest source at north (source 1, number 88 of Hertz) centered at R.A. (1950) = $10^h21^m32^s.25$, decl. (1950) = $-57° 20'26''.1$ has an observed flux of 4×10^{-13} ergs cm^{-2} s^{-1}. A search on the red and IIIa-J plates of the ESO Southern Sky Survey does not show any bright or peculiar star inside the IPC error circle (1′ radius) which, however, contains several stars with $m_v > 14$. The X-ray–to–optical (V band) flux ratio lower limit (of about 5×10^{-2}) does not exclude that the source could be produced by coronal emission from a late spectral type star. No spectral or timing analysis was performed on its X-ray emission due to the low count statistics available.

The strong source on the eastern side of the field (source 2, number 90 of Hertz) is the only one detected also with the HRI. Its HRI position is R.A. (1950) = $10^h24^m4^s.35$, decl. (1950) = $-57°33'22''.7$ with an associated error of 8″, greater than the typical HRI error box ($\sim 4''$) because of its off-axis position. On the basis of the IPC position, the source was associated by Hertz with an emission-line early-type star of $m_v = 12.8$ (Wack 2134 or TH 3542) cataloged by Wackerling (1969). The HRI position reduces the offset between the X-ray centroid and the

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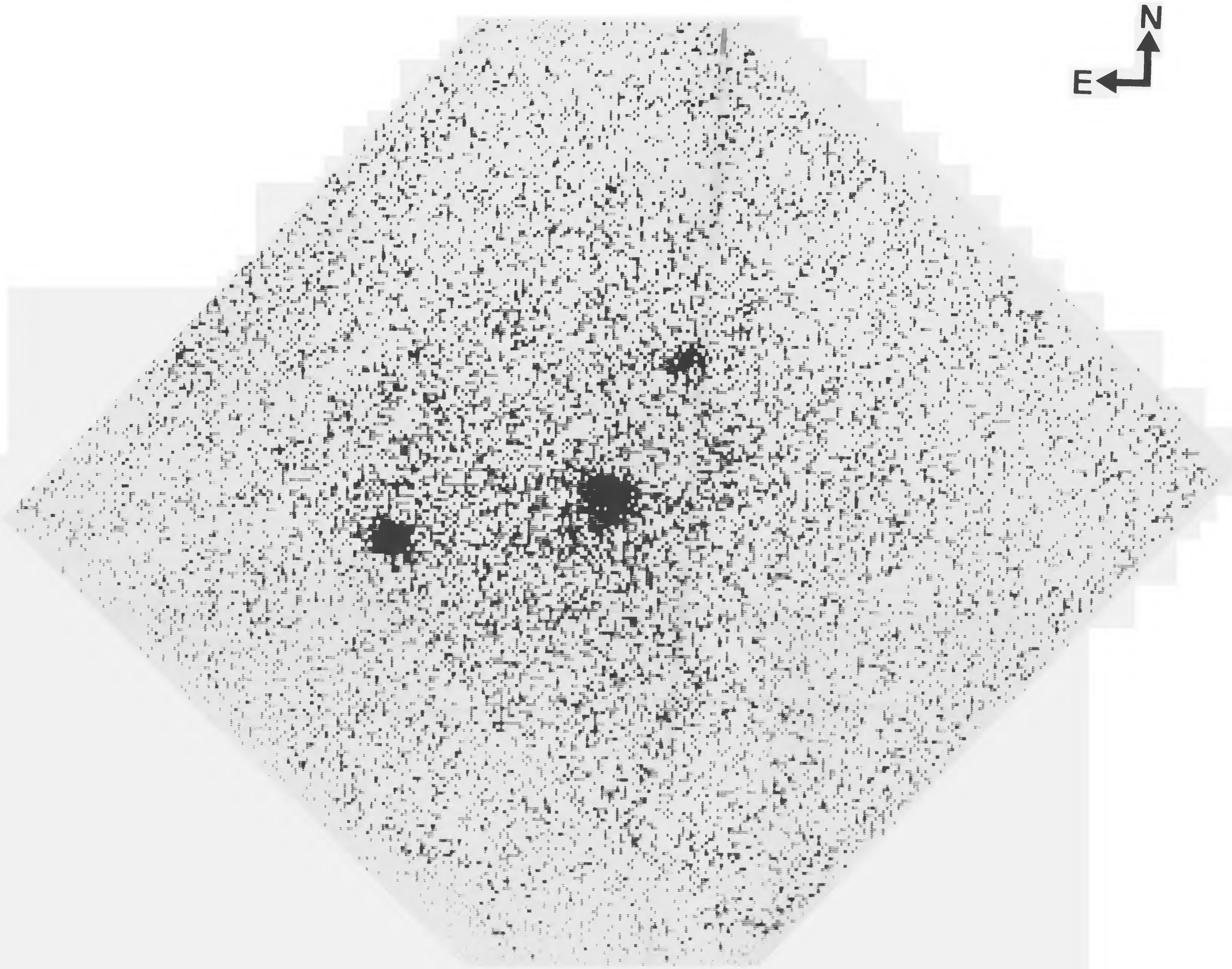

FIG. 1.—Image of IPC field (I7715) centered at R.A. (1950) = $10^h22^m14^s$, decl. (1950) = $-57°30'36''$. About 9800 s exposure time.

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TABLE 1

X-Ray Sources Detected in the 7715 IPC Observation

Source Number	Name	IPC Count Rate (10^{-2} counts s^{-1})	Source Characteristics	Proposed Identification	F_x/F_v
1......	1E 1021.5 − 5720	0.18	weak	...	5×10^{-2}
2......	1E 1024.0 − 5732	5.9	variable	Wack 2134	5×10^{-2}
3......	1E 1022.2 − 5730	{ 5.0	pointlike (?)	Wack 2121 (?)	9×10^{-2}
		{ 3.2	diffuse	RCW 49	

star coordinates to 8″.8. The flux measured at the time of the second IPC observation is 1.4×10^{-12} ergs cm^{-2} s^{-1}, so the ratio f_x/f_v must be $\sim 5 \times 10^{-2}$. The source appears variable on long time scales: the X-ray flux observed in the last IPC observation is about 70% higher than that measured in the first one.

The third source (source 3, number 89 of Hertz) lies in a region of strong radio, infrared, and optical diffuse emission, and, although in the center of the field (where the narrowest point spread function [PSF] is expected), appears extended in the east and south-east directions, or at least permeated by a faint diffuse emission. Such X-ray morphology is clearly shown by the contours of costant X-ray intensity overlaid in Figure 2 (Plate 2) on a red ESO Sky Survey plate of the region, characterized by an optical diffuse emission dominated by the bright emission nebula RCW 49 (at the center of the plate of Fig. 2) and by an arc-shaped nebula at east, linked, perhaps, to RCW 49. The X-ray isophotes are obtained from the sum of the two IPC images (taking photons with energies between 0.3 and 4.5 keV to reduce the background), convolved with a Gaussian smoothing function of 56″ width (FWHM) and are at levels of 4 σ, 8 σ, 16 σ, 36 σ, and 64 σ (corresponding at intensities of 0.23, 0.33, 0.56, 1.12, and 1.91 counts $pixel^{-1}$ with 1 pixel = 64 $arcsec^2$) over the local background.

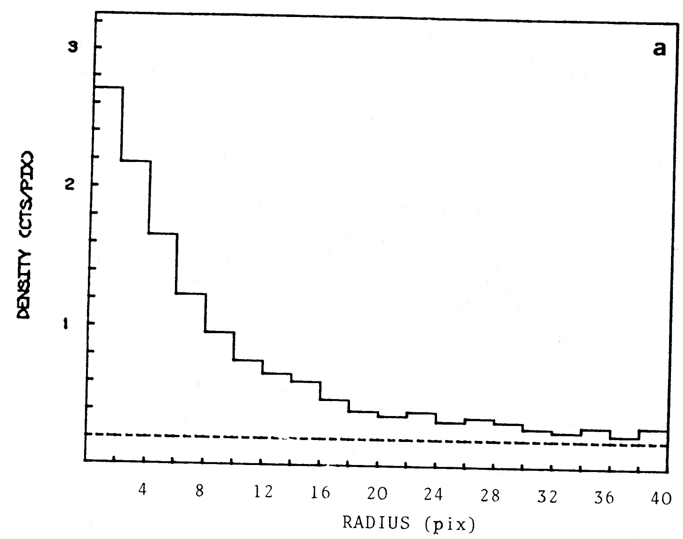
To further check the extended nature of the source, Figure 3 shows two differential radial distributions of the source photons (count density in half-annuli vs. radius): one using only the eastern side (Fig. 3*a*) of the source, and the other selecting the western side (Fig. 3*b*). While the latter may be compatible with the IPC PSF (FWHM ≈ 17 pixels or 2′.3), the former clearly shows presence of emission not ascribable to the background (*dashed line*) even up to a distance of about 4′ (~30 pixels).

Unfortunately, this source is not visible in the HRI image, although it has an IPC count rate similar to the more off-axis source 2. So we cannot distinguish if it is a discrete source embedded in a diffuse emission or a diffuse source with a strong unresolved peak of emission.

The failure to detect a signal from source 3 in the HRI data may be in favor of the latter hypothesis. A diffuse nature of the source, together with the strong interstellar absorption present, would make it difficult to separate source from background photons in the HRI image. Another possibility would be that of a variable source, on a time scale of less then few days. Clearly the constancy of the flux in the two IPC observations, albeit taken 1 yr apart, gives no support to this possibility.

When the standard point-spread function of the IPC instrument is used to fit the peak emission, the source position obtained (R.A. [1950] = $10^h22^m11^s.1$, decl. [1950] = −57°30′ 7″.4) coincides with the compact (~1′.5) cluster of OB stars, exciting the H II region RCW 49. This positional coincidence is depicted in Figure 4 (Plate 3), where the IPC error circle is drawn on an enlarged IIIa-J ESO plate. The cluster contains also the Wackerling line emission star (Wack 2121, TH 3536) previously associated with this X-ray source by Hertz. This star, of $m_v = 13.2$ and unknown spectral type, is 8″ distant from the X-ray centroid.

As to the spectrum of source 3, the substantial absorption effect, folded with the instrument energy range and sensitivity, leaves few energy channels for the spectral fitting, making the whole procedure rather uncertain. Nevertheless, the source



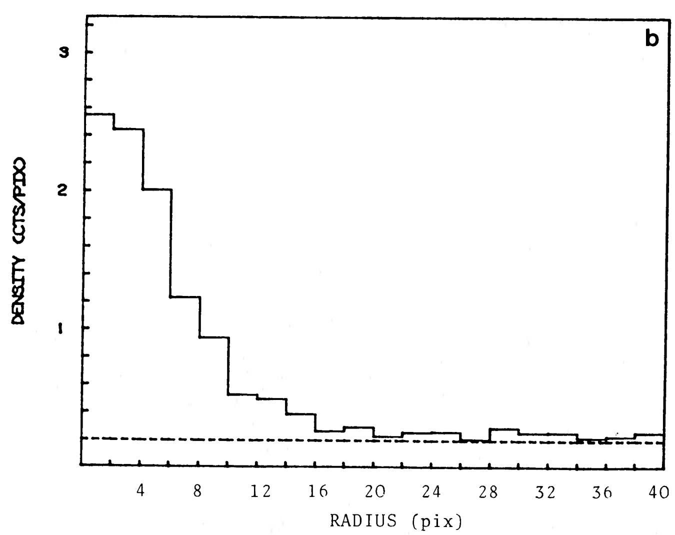


FIG. 3.—Differential radial count distributions for the eastern side (*a*) and for the western side (*b*) of source 3. Density of counts (per pixel) in half annuli is given vs. radius (in steps of 2 pixels or 16″). The broken line indicates the background density.

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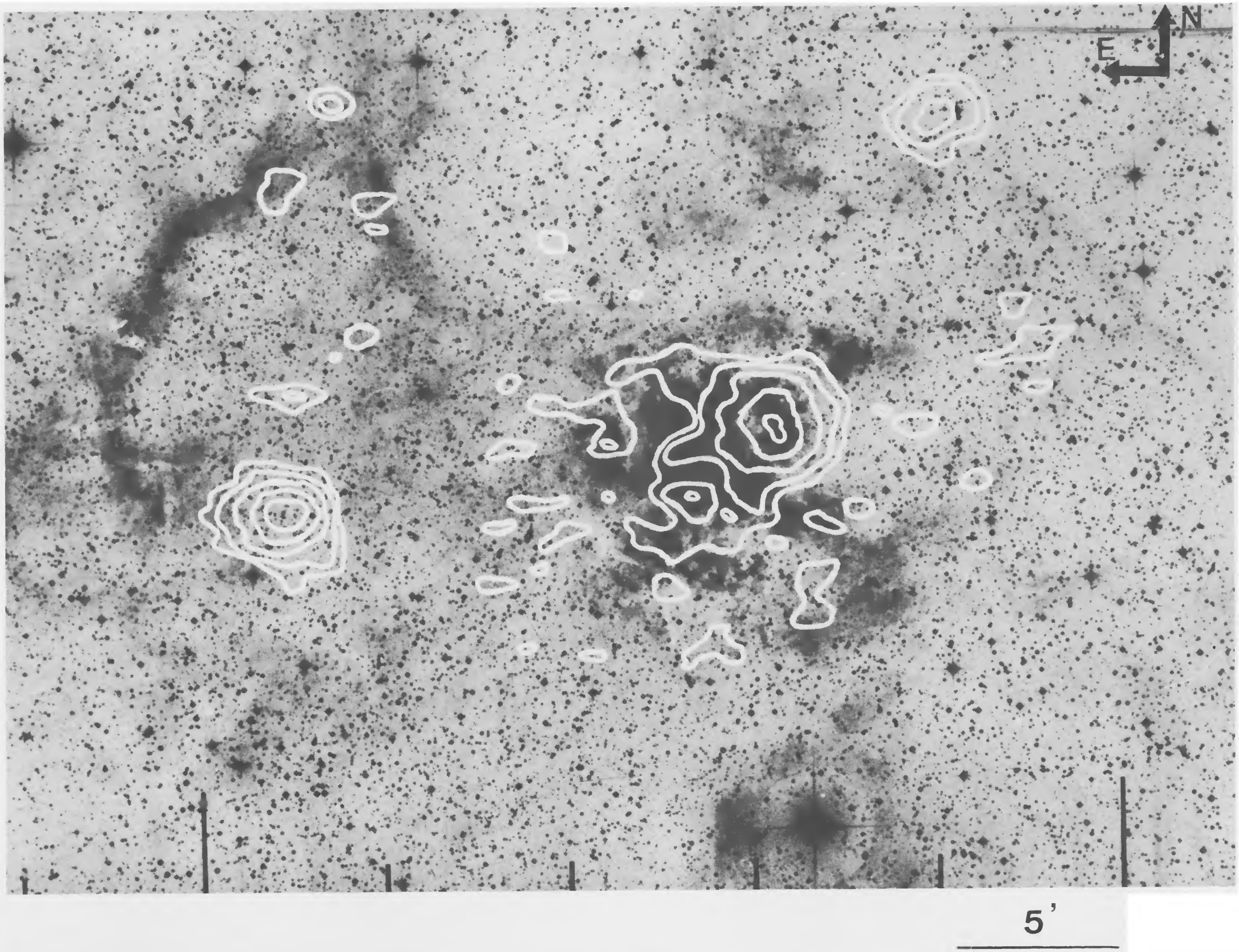

FIG. 2.—Contours of constant X-ray intensity overlaid on a red ESO sky survey plate. The isophotes are obtained from the sum of the two IPC images (I3341 and I7715) convolved with a Gaussian smoothing function of 56″ width (FWHM). The contour levels are at 0.23, 0.33, 0.56, 1.12, 1.91 counts pixel^{-1} (1 pixel = 64 arcsec^2) corresponding to 4 σ, 8 σ, 16 σ, 36 σ, 64 σ, over the local background

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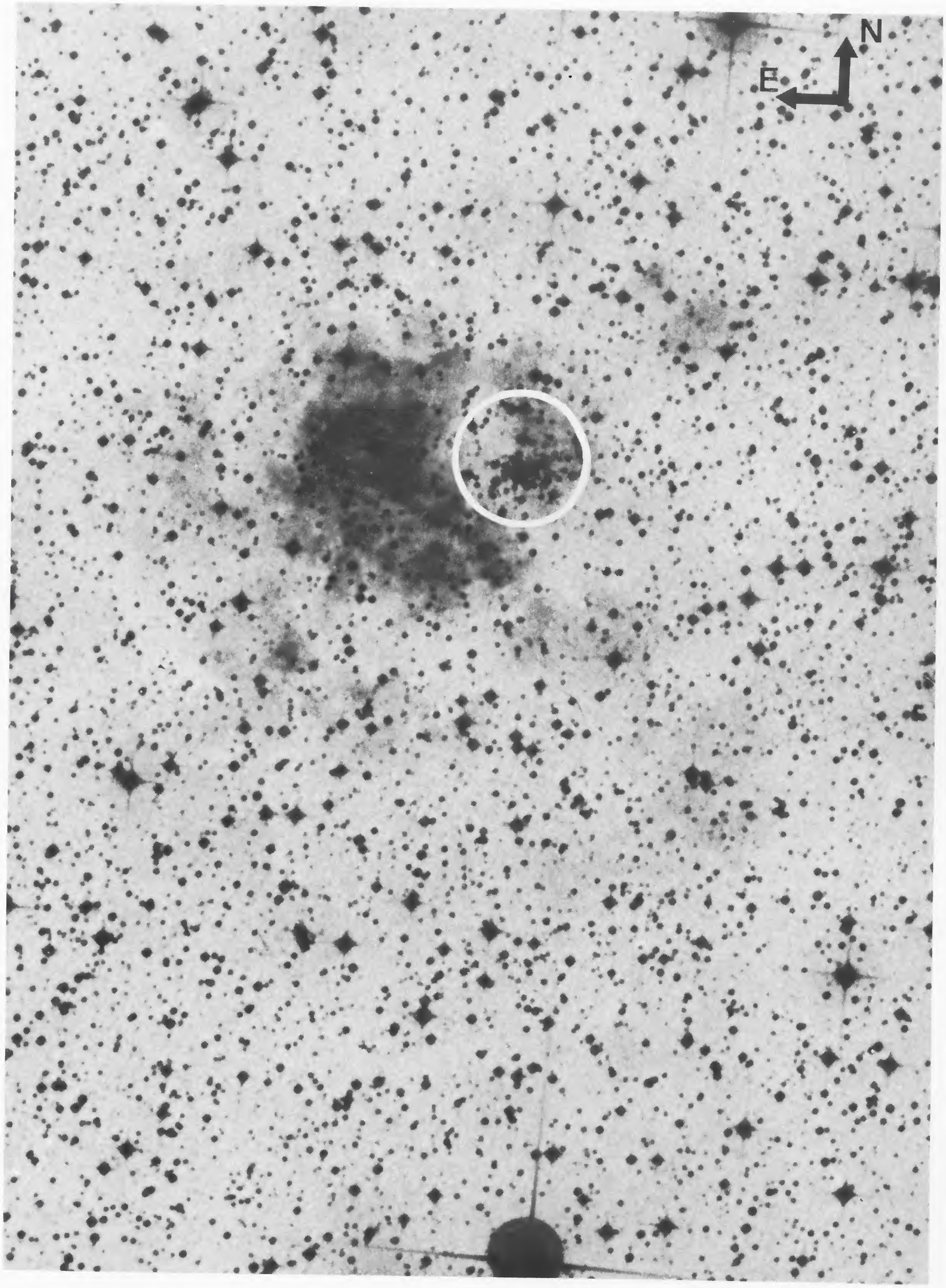

FIG. 4.—An enlarged IIIa-J ESO plate showing the star cluster embedded in the H II region RCW 49. The IPC error circle (1′ radius) of source 3 is also shown.

counts (300 within a radius of 15 pixels and with energy between 0.3 and 5.0 keV) have been fitted using power-law and bremsstrahlung models. As expected, acceptable χ^2 values are obtained for steep, very absorbed spectra. The power-law fitting describes well the data only for photon indexes greater than 4 and number of atoms on the line of sight (N_H) values greater than 2×10^{22} cm^{-2}, while a bremsstrahlung spectrum with kT between 0.3 and 0.9 KeV, and N_H greater than 2×10^{22} cm^{-2} gives acceptable χ^2 values. The latter spectral parameters, albeit intrinsically uncertain, have been used to evaluate the flux of the pointlike "peak" which turns out to be $(1.3 \pm 0.2) \times 10^{-12}$ ergs cm^{-2} s^{-1} in the energy range 0.5–3.5 Kev and shows no variation between the 1979 and 1980 observations.

To search for periodicities up to 0.03 s we have performed a fast Fourier analysis on the photon arrival times, corrected to the solar system baricenter. No significant powers ($>2\sigma$) were seen for the frequencies tested. Moreover, the folding analysis, performed from 1 s to 1000 s, has not given positive results.

As mentioned earlier, and shown by the isophotes of Figure 2, there is also evidence for X-ray diffuse emission, of about 8′ diameter, covering a large part of the optical nebulosity of RCW 49.

We have estimated the total X-ray flux from the region enclosed by the 4 σ isophote of Figure 2 (roughly 10′ × 8′), subtracting the local background and applying the appropriate corrections (dead time, vignetting, scattering). To determine the contribution of the diffuse and of the pointlike source, we have assumed the discrete source to be embedded in a uniform diffuse emission with intensity equal to the mean intensity measured at 15 pixels ($\sim$2′) from the source center ($\sim$0.3 counts pixel^{-1}). To convert the IPC count rates to the energy flux the same spectral parameters, as previously derived, have been used. The total observed flux is $(2.2 \pm 0.2) \times 10^{-12}$ ergs cm^{-2} s^{-1} of which about $\frac{3}{5}$ can be attributed to the unresolved peak and the rest to diffuse emission with a mean brightness of 1.1×10^{-14} ergs cm^{-2} s^{-1} arcmin^{-2}.

The weakness of the diffuse emission prevents any search for spectral variations over the emitting region.

III. DISCUSSION AND CONCLUSIONS

Three, new, probably independent, X-ray sources have been observed in a 1 deg^2 region around $l = 284°$, $b = 0°$. The faintest one, source 1, although unidentified, can be explained as coronal emission of a late-type star.

Source 2, on the other hand, is a relatively strong and variable source of soft X-rays tentatively identified with an early-type star. If this association is correct, its origin cannot be coronal.

The case for source 3 is more complex. We have shown that this source is related, on the basis of its position as well as its extended morphology, to the emission nebula RCW 49 and to the small star cluster near its center. This bright optical and radio nebula is a classical H II region of $\sim 5' \times 7'$ at a distance of 6 ± 1.2 kpc (Wilson *et al.* 1970; Westerlund 1960). From radio data taken in the H109 line a dimension of 14 pc, an electron density of 220 cm^{-3}, and a total mass of 7×10^3, $M_\odot$ were inferred, assuming a spherical uniform model (Wilson *et al.* 1970).

Using this distance value we have estimated on the source side of absorption, a total X-ray luminosity in the range (2×10^{35})–(5×10^{35}) ergs s^{-1}, where the uncertainty is mainly due to the uncertainty in the high value of interstellar absorption required to fit the data. Of this, about $\frac{3}{5}$ may be due to a pointlike source coinciding with the O star cluster and the rest to diffuse emission covering the brightest region of the nebula.

If this interpretation is correct, it would be the sixth extended X-ray source associated with an H II region. The five previously known, observed in the Orion Nebula (Ku and Chanan 1979), in the Carina nebula (Seward *et al.* 1979; Seward and Chlebowski 1982), in S155 (Fabian and Stewart 1983), in the Rosette nebula (Leahy 1985), and in the Cygnus superbubble (Abbott, Bieging, and Churchwell 1981; Bochkarev and Sitnik 1985), are explained as "bubbles" of hot gas ($T \approx 10^6$–10^7 K, $n_e \approx 10^{-2}$ to 1 cm^{-3}) filled and powered by the strong stellar wind of the O stars embedded in the H II regions. The bubble X-ray luminosities are in the range 10^{32}–10^{36} ergs s^{-1}.

The structure and the evolution of such bubbles, created by the interaction of strong stellar winds with the ambient material of H II regions or molecular clouds, can be described as follows (Avedisova 1972; Falle 1975; Castor, McCray, and Weaver 1975; Weaver *et al.* 1977; Dyson 1977; Shull 1980). The wind-driven circumstellar shell passes most of its lifetime in the snowplow phase, in which the system is composed of three different zones. An innermost region of freely expanding stellar wind terminates in a strong shock through which the stellar wind passes into a thick, near-isobaric region of hot gas. This region pushes ambient material outward, and so it is surrounded by a thin, dense, cold shell of the swept-up H II region matter. About 80% of the kinetic energy of the stellar wind goes into thermal energy of the hot ($T \gtrsim 10^6$ K) region of shocked stellar wind, which could be observable at X-ray frequencies.

The region of diffuse emission which we have observed in the direction of RCW 49 has a size of 8′ ($\sim$7 pc), and for a mean temperature above 3×10^6 K it must have a particle density $\gtrsim 0.2$ cm^{-3} in order to produce a luminosity of 2×10^{35} ergs s^{-1}. Thus the total thermal energy of this bubble is $\lesssim 10^{49}$ ergs and its lifetime against thermal radiation $\sim 10^6$ yr.

Although the stellar types of the stars in the cluster are not known, the absolute magnitudes reported by Westerlund (1960), with a mean bolometric correction of -4 (Humphreys 1978), imply bolometric luminosities greater than 10^{39} ergs s^{-1} for at least five stars of the cluster. Using the empirical relations between L_b and the stellar wind mass-loss rate (Abott, Bieging, and Churchwell 1981; Garmany *et al.* 1981) and assuming the terminal stellar wind velocity to be 2000 km s^{-1}, the kinetic power of the stellar wind must be 5×10^{35}–10^{36} ergs s^{-1}. Therefore, just five such O stars can fill and power our observed X-ray bubble in $\sim 10^5$ yr. More detailed predictions (e.g., like those made by Abbott, Bieging and Churchwell 1981 for Cygnus X) on the properties of the bubble, require precise estimates of the ambient interstellar density and of the age of the cluster, currently not available.

Although the general properties of the source are similar to those of the other X-ray bubbles associated with H II regions and in particular of that found in the Carina nebula (Seward and Chlebowsky 1982), this simple thermal model fails to account for the strong peak (or pointlike source) present inside the diffuse emission. The theory predicts that X-ray emission come from the near-isobaric shell of hot shocked gas which, having a flat density distribution, cannot produce the strong emission gradient toward the cluster as observed in RCW 49. Inhomogeneities in the ambient material can produce gradients (Dyson 1977), but they probably would appear as distributed clumps of emission (Fabian and Stewart 1983) rather than as a single peak.

On the other hand, such a peak cannot be due to pointlike "coronal" emission of the O stars of the cluster, because, even after subtraction of the diffuse contribution, the ratio L_x/L_b would be at least 100 times higher than the typical value observed for all normal O stars (Pallavicini *et al.* 1981; Vaiana *et al.* 1981; Cassinelli 1981; Seward and Chlebowski 1982).

Another obvious scenario to be considered for the understanding of source 3 is that of a SNR with a central source. Several authors have suggested that H II regions and their embedded OB associations may be the sites of a large fraction of the type II supernova (Maza and van den Bergh 1976; Ritchter and Rosa 1984). A young ($\sim 10^3$–10^4 yr) Crab-like SNR (a plerion rather than a shell-like one) powered by the stellar remnant of a Type II supernova could account for this centrally peaked diffuse emission of few 10^{35} ergs s^{-1}. While the energetics could be easily satisfied and a central pulsar could naturally account for the central peak, the observed X-ray spectrum does not seem to match the expected non-thermal shape. Moreover, no hint for the presence of a SNR can be found even in the most recent radio data (A. Turtle and R. F. Haynes, private communication) of the region. Deeper spectroscopic observations of the star cluster and of the diffuse emission at optical frequencies would be useful to unveil the nature of this diffuse X-ray source.

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