EINSTEIN OBSERVATIONS OF EXTENDED GALACTIC X-RAY SOURCES

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I. INTRODUCTION

With the X-ray optics of the Einstein Observatory, it is now possible, for the first time, to "see" X-ray sources. Previously known extended sources have been resolved: sometimes into several sources, sometimes into clouds of diffuse emission with perhaps knots and filaments. Spatial resolution of the X-ray pictures is comparable to that of radio and optical observations, and we can now compare the X-ray morphology of a source with that observed at other wavelengths.

This paper presents some early results. Since analysis of these data has just started, this is not a formal presentation of scientific conclusions, but rather a discussion of the basic features of the X-ray pictures.

Let us first consider supernova remnants. A supernova is caused by the explosion of a massive star. The central regions of the star collapse, releasing an enormous amount of gravitational energy. The explosion ejects the outer layers of the star at high velocity and much of the energy goes into kinetic energy of the moving debris. This material plows into the interstellar medium, at first expanding freely, then after hundreds of years accumulating an appreciable mass of interstellar material and slowing down. The kinetic energy of the expanding debris is turned into thermal energy and will eventually appear as a shock wave moving outward through the interstellar medium. This blast wave is the same phenomenon as that produced by a large explosion in the atmosphere.

A supernova remnant consists of the expanding debris, the blast wave, and the remains of the imploded stellar core (probably a neutron star). Supernova remnants are studied to learn about the supernova explosion itself. It should be possible to derive the initial energy release, the mass of the pre-supernova star, and the composition of the material produced in the explosion. Observation of the expanding shell and the blast wave also yields information concerning the interaction of this material with the interstellar medium and the interstellar medium itself.

Each supernova remnant has its own personality. It is obvious that some are very young and some ancient. However, it is somewhat difficult to arrange the various observations to illustrate an evolutionary sequence. Often emission from one feature is so strong that fainter features of interest are obscured. Nevertheless, we present here five supernova remnants arranged approximately in order of increasing age.

Recall that the Einstein Observatory carries two imaging detectors, the Imaging Proportional Counter (IPC) having a resolution of 1 arc min and a field of view approximately 1 degree in diameter, and the High Resolution Imager (HRI) with spatial resolution of 3 arc sec and a field of view 25 arc min in diameter (Giacconi, et al. 1979). The energy range covered by both instruments is 200 eV - 3 keV. The IPC is capable of determining the photon energy, and it is possible to obtain IPC pictures in three broad X-ray energy ranges.

II. CAS A

The youngest supernova remnant observed is Cassiopeia A. Although the optical event was not witnessed, the motion of the expanding material can be followed backwards in time to the point of origin. The date of the explosion has been estimated by van den Bergh and Dodd (1970), with an accuracy of a few years, as 1667. The Einstein observation of Cas A has been described by Murray, et al. (1979), and Figure 1 shows the HRI picture. The diameter of this remnant is 4 arc min. The brightest parts are probably regions containing the actual debris from the stellar explosion. Optical pictures of Cas A show many faint fast moving knots of material (van den Bergh, et al. 1973). Optical spectra of these knots show very strong emission from oxygen and sulphur indicating that the material has been enriched in heavier elements.

Figure 2 compares X-ray, optical, and radio maps of Cas A taken from Dickel and Greisen (1979). The spatial regions containing fast moving knots are identical with the brightest regions in the X-ray picture. The X-rays must come from a plasma at a temperature of approximately 10^7 degrees. This material has been heated either by the original supernova explosion or by friction with the interstellar medium. There is a faint X-ray halo just outside of the bright regions. This faint outer shell is real and is interpreted as a shock wave moving just ahead of the expanding debris.

The X-ray spectrum shows at least two thermal components with many emission lines. The generally accepted picture is that the blast wave is hotter than the debris. The solid state spectrometer on the Einstein Observatory shows strong emission lines from silicon, sulphur, argon, calcium, and iron proving beyond doubt that most of the X-rays are from a thermal source and strongly indicating that the material has been enriched in heavy elements (Holt, et al. 1979).

The radio picture of Cas A (which is an extremely strong radio source) shows a shell virtually identical in size and shape to the X-ray shell. Some knots of emission appear in both radio and X-ray pictures, but in general the regions of strongest X-ray emission are not prominent in the radio picture.

There is no sign of a pulsar in the central regions of the supernova remnant. The X-ray picture shows nothing obvious which might correspond to the remnant of the core of the imploded star.

III. TYCHO

The supernova was observed by Tycho Brahe in 1572. The light curve was typical of Type I supernovae. Various estimates have been given for the distance, and we have used 3 kpc in our calculations.

Figure 3 shows the HRI picture of this remnant. This was a 10-hr exposure requiring approximately 1 day of Observatory time. The appearance of the remnant is an almost circular shell with diameter 8 arc min. It shows limb brightening varying from a maximum in the northwest to a minimum in the southeast. The center is filled with emission which the HRI resolves into patches or knots.

Figure 4 shows a 6 cm Westerbork radio map taken from Duin and Strom (1975). Radio and X-ray emission come from shells of equal diameter. The correlation is remarkably good in places, particularly in the eastern part of the shell where there is a projection or discontinuity with two knots of emission. There is also a knot of emission to the north of this feature in radio and X-rays. The radio bright region on the northeast limb is identical with the X-ray bright region, but the brightest part of the X-ray picture, the northwestern limb, is not a strong radio source.

From this picture, we can measure characteristics of the X-ray emitting shell. The measured features are real, the detector resolution is better than the observed thickness of the shell. The sharpness of the edge of the shell is not limited by the detector resolution. The shell thickness is on the average 0.3 of the radius. It is 0.1 of the radius where the emission is maximum in the northwest. There is no indication of a shell at all in the southeast.

One might interpret this spherical shell as a blast wave. However, the knots of emission and the discontinuity in the western part of the shell are inconsistent with this hypothesis. We are probably seeing the ejected material. It may be immersed in a blast wave or producing local shock waves closely associated in space with the material itself. Again, the SSS spectrum of Tycho's remnant shows very strong emission lines, proving thermal emission from hot gas and being highly suggestive that the emitting gas has been enriched in heavy elements.

We can derive the density of the emitting gas from the observed surface brightness of the material. The average electron density in the northwest part of the shell where the limb is brightest is about 6 electrons/cm^3; the density in a bright knot is about 15 electrons/cm^3. The thermal energy in the hot gas is approximately 10^{50} ergs, the kinetic energy of the expanding shell is approximately 3×10^{51} ergs, and the total mass of the shell is approximately 6 $M_{\odot}$. The nonuniformity of the shell indicates spatial asymmetry in the ejected material or density variations in the interstellar medium.

Once more, there is no sign of a pulsar or other X-ray emitting remnant of the imploded core.

IV. THE SUPERNOVA OF 1006

In the year 1006, a very bright supernova was seen in the constellation Lupus. Figure 5 shows the IPC picture of the remnant. It is 30 arc minutes in diameter, almost exactly the apparent size of the full moon. Optically, very little is seen at the position of this remnant. The radio map (Milne 1971) looks quite similar to the X-ray picture showing an approximately spherical shell with brightest emission from two opposing faces in the east and southwest. This remnant looks more like the expected blast wave. There are no resolved bright knots indicating regions of high density of material. The expanding debris has probably picked up an appreciable amount of interstellar material, more of the kinetic energy has been thermalized, and the hot gas appears as a shock wave moving outward. Once again, no pulsar is seen.

V. THE CRAB NEBULA

The Crab Nebula is the remnant of a supernova explosion of 1054 AD. Although about the same age as the remnant of SN 1006, the Crab is radically different in appearance. Figure 6 shows an optical picture of the 5 × 7 ft Nebula. The entire shell is laced with red filaments emitting mostly line radiation from hydrogen atoms. The central regions are filled with an amorphous diffuse continuum which appears blue in contrast to the red filaments. Figure 6 shows the continuum radiation clearly whereas the filaments appear only faintly.

The southwest member of the double star seen in the center of the nebula is a pulsar. This neutron star, spinning at 30 rps, is the most rapid pulsar known and is visible clearly at all frequencies: radio, optical, X-ray and gamma-ray. Figure 7 shows the Einstein HRI picture of the Crab Nebula. The pulsar is seen as a point source surrounded by a patch of diffuse X-ray emission approximately 2 arc min in extent. The strongest diffuse emission comes from a region located northwest of the pulsar, corresponding closely with the region of maximum optical emission.

The diffuse emission, both X-ray and optical, is caused by extremely high energy electrons moving in a weak magnetic field. These electrons are probably created at the pulsar and accelerated in the strong electric and magnetic fields of the rotating pulsar. The apparent X-ray point source at the pulsar location is due to pulsed X-rays. These X-rays are created very close to the pulsar analogously with the pulsed optical and radio emission observed from this object. The reason for the asymmetrical location of the diffuse synchrotron source with respect to the pulsar is not understood.

The Crab Nebula as an X-ray source is completely dominated by the pulsar. If there is any thermal radiation from the expanding envelope or from a blast wave, it is completely swamped by the powerful synchrotron source in the center of the Crab. The Crab could be surrounded with a weak envelope identical to that of the supernova remnant of 1006, and it would be extremely difficult to see with our detectors. We are presently searching the data very carefully for this effect.

VI. NEUTRON STARS

The Crab Pulsar is the brightest neutron star seen in the X-ray data. Strong pulsed radiation is seen from the pulsar itself which appears as a point source to the Einstein detectors. The diffuse synchrotron source associated with the pulsar is a second manifestation of the neutron star in the X-ray data.

A third source of X-rays from pulsars might be blackbody radiation associated with high surface temperature. Theoretically, pulsars are born with high temperatures and cool as they age. Even though only 10 km in radius, if the surface temperature were 10^7 degrees, blackbody radiation from the surface would peak at soft X-ray frequencies and the neutron star would appear very bright to the Einstein telescope. The fact that no pulsars are seen in the vicinity of several SNR allow us to set upper limits on the surface temperatures. An upper limit of 2×10^6 degrees can be set on possible neutron stars associated with Cas A and Tycho's remnant, and a limit of 1×10^6 degrees can be set on any neutron star in the vicinity of the remnant of SN1006. We expect these limits to constrain models of the internal composition of neutron stars, perhaps requiring the existence of pions in the core to explain the apparent rapid cooling observed (Helfand, et al. 1979).

Another area that must be investigated, however, is the assumption that the neutron star surface is a blackbody. Because of extremely high magnetic fields at the surface, all states are not possible to electrons. For a given temperature, the radiation emitted may be considerably less than that predicted under the assumption that the surface is black.

VII. VELA X

This is a very old remnant (age approximately 10^4 years) in the constellation Vela at a distance of approximately 400 pc. The blast wave has cooled and left an array of filaments quite visible in the optical band (Miller 1973). The remnant has a diameter of 5.5 degrees and is a source of strong radio and X-ray radiation. We are mapping this region with the IPC. It takes 27 pointings to complete this mapping and only 6 have been accomplished. Figure 8 shows the results of three pointings. These are IPC pictures covering fields 1-degree square. The detector is shadowed by window support ribs which form a tic-tac-toe pattern obscuring some of the diffuse X-rays.

X-ray emission from Vela X is patchy. The inside of the remnant contains wisps and blobs of hot gas which show strongly in the X-ray pictures. The Vela remnant also contains a pulsar which is an X-ray source. In contrast to the Crab, the X-ray picture of the Vela remnant is dominated by thermal radiation. These X-rays are very soft and most of the energy appears as photons with energies of a few hundred eV. Pulse height spectra from the IPC are shown on the right hand side of Figure 8 to illustrate this. The upper spectrum shows the soft diffuse X-rays from one of the bright patches of emission, the lower spectrum is that of the pulsar. By restricting the picture to only high energies, the pulsar appears more clearly as is also shown in Figure 8.

Figure 9 shows an HRI picture centered on the pulsar. The pulsar appears as a point source surrounded by a weak diffuse nebula of diameter 1 arc min. In comparison with the Crab pulsar, this diffuse radiation is much, much weaker and the apparent point source is not pulsed. This apparent point source is either a small diffuse region surrounding the pulsar and too small to be resolved by the Einstein telescope, or it is radiation from the surface of the pulsar. If this is the "blackbody" radiation, the surface temperature implied is 1.5×10^6 degrees.

VIII. THE ETA CARINAE NEBULA

Now let us consider a region where new stars are forming. The Eta Carinae Nebula is a bright emission nebula approximately 2 degrees in extent. It contains many bright early stars and the region is permeated with gas clouds having densities approximately 10^3 atoms/cm^3. A prominent V-shaped dust lane traverses the lower part of the nebula. Eta Carinae itself is a unique object. It is now a 6th magnitude, almost stellar object, but in 1843 there was an outburst during which it brightened briefly to magnitude -1. It remained bright for 20 years and then declined to approximately its present level.

Eta Carinae forms the central part of an optical nebula, the homunculus, of dimension 10 × 15 in. which contains several knots of luminosity and is expanding with a velocity of approximately 600 km/sec. This material was probably generated during the great outburst. The homunculus is surrounded by a faint outer shell of dimension 20 × 30 in. (Walborn 1976).

Eta Carinae itself is now the brightest extrasolar infrared source at a wavelength of 20 μ. At a distance of 2600 pc, the bolometric luminosity is approximately 2×10^6 solar luminosities. The infrared emission comes from a shell of dust with dimension approximately that of the homunculus, and it is generally accepted that the energy source is a massive central object(s) obscured by the dust.

We obtained two X-ray pictures, both centered on Eta Carinae, both 3 hour exposures (Seward, et al. 1979). Figure 10 shows the IPC X-ray picture and Figure 11 shows contours of constant X-ray emission overlaid on a near UV photograph of this region. The X-ray picture is remarkably similar to the optical. Several bright sources are imbedded in diffuse emission. The western dust lane is seen in absorption. The brightest apparent point sources are Eta Carinae, a Wolf-Rayet star, and a cluster of O stars, Tr 14. The other sources have all been identified with O stars.

Eighty percent of the emission from this region is diffuse, coming mostly from the optically bright region, but not completely. This diffuse X-ray emission probably comes from hot gas. The region is 40 pc in extent and the temperature is about 5 million degrees. The total X-ray luminosity is approximately 10^{35} erg/sec. The derived gas properties are: density approximately 0.4 electrons/cm^3, lifetime approximately 10^7 years, total thermal energy approximately 10^{50} ergs. The western dust lane is seen clearly in the X-ray data and has a width of approximately 5 pc. The assumption of a comparable depth and a density of material the same as that of the optical emission nebula gives sufficient path length of cold material to absorb the X-rays.

This diffuse hot gas is probably the result of past supernova explosions or strong stellar winds. The O stars in this region are known to have strong winds, and these winds interacting with the surrounding dense material might give rise to X-ray emitting gas. Alternately, since the lifetime of O stars is short, a region such as this is expected to generate a supernova explosion approximately every million years. The diffuse emission might be part of an ancient supernova remnant or remnants, so old that it has lost its original characteristic shell-like structure.

Figure 12 shows the HRI picture. The diffuse feature in the northwest corner is an instrumental effect, not a real X-ray feature in the sky. Several point sources are seen: The Wolf-Rayet star, HD 93162, and three O stars. Eta Carinae itself is seen to be an extended source. There is a small bright horseshoe with weak emission extending to the southeast. Figure 13 shows Eta Carinae expanded. The contours of constant X-ray emission have been overlaid on an optical picture. The Homunculus (the IR source) forms the overexposed central part of this region and, in this photograph, has blended with emission features attributed to the outer shell. Most X-ray emission is associated with this outer shell, and there appears to be a point source at the center of the Homunculus coincident with the brightest part of the nebula. If we assume that this X-ray emitting shell is a blast wave from an explosion, we can use the observed X-ray luminosity (3×10^{33} ergs/sec) and size (0.2 pc) to estimate the initial energy of the outburst, and the gas density. These are $E_o = 10^{46}$ ergs and $N_o = 20/cm^3$. These numbers are not compatible with the hypothesis that the 1843 outburst was a slow supernova. The energy released and the amount of material in the expanding shell are orders of magnitude too small to be the result of a supernova outburst.

The point source in the middle of the nebula is exciting. Perhaps this is the underlying massive object which supplies energy for the infrared source. This has been postulated by Davidson (1971) to be a star with mass approximately 100 solar masses. Such a star is expected to rapidly consume the nuclear fuel in its core and to end its brief extravagant life as a supernova.

Now we come again to Cassiopeia A, the remnant of a supernova which was unusual in that the optical event was not seen. One explanation given is that the exploding star was surrounded with a dense cloud of material and the optical radiation was attenuated to the point where it was not bright enough to be noticed by 17th century astronomers. Eta Carinae gives every sign of being an extremely massive star surrounded by a dense shell. Perhaps in the not too distant future (astronomically speaking) it too will explode as a supernova and leave a remnant similar to Cas A.

You should appreciate that the entire Eta Carinae region is only a weak X-ray source having an intensity of 3 Uhuru flux units. The Einstein pictures resolve this weak source into the peculiar object, Eta Carinae, at least seven stars, and diffuse emission. We are also observing the structure of Eta Carinae itself.

To those of us who a few years ago were doing X-ray observations with small rocket borne detectors, progress has been amazing. We are now seeing things undreamed of before the launch of the Einstein Observatory.

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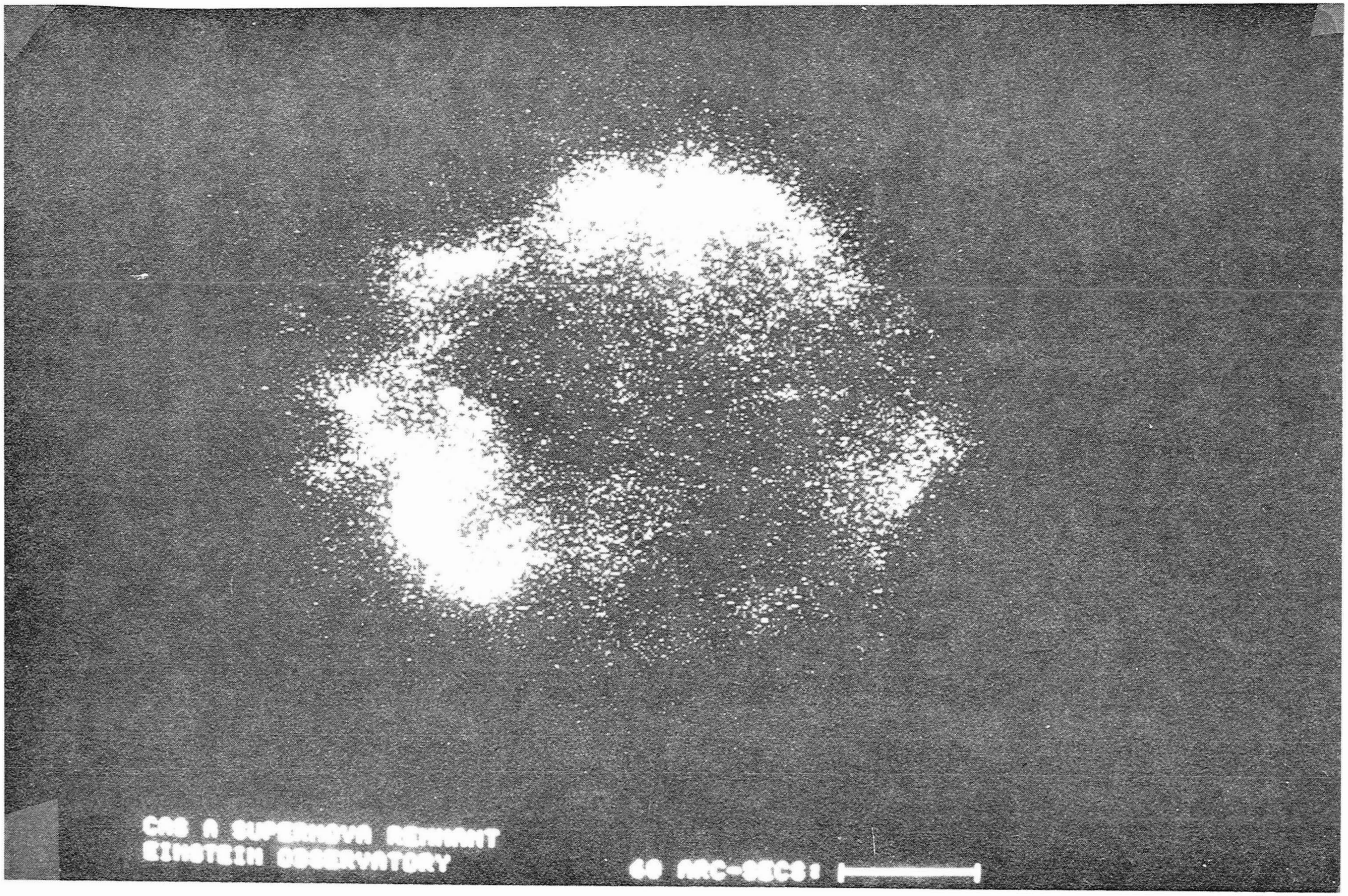

Figure 1. HRI picture of Cas A. Exposure approximately 3×10^4 sec.

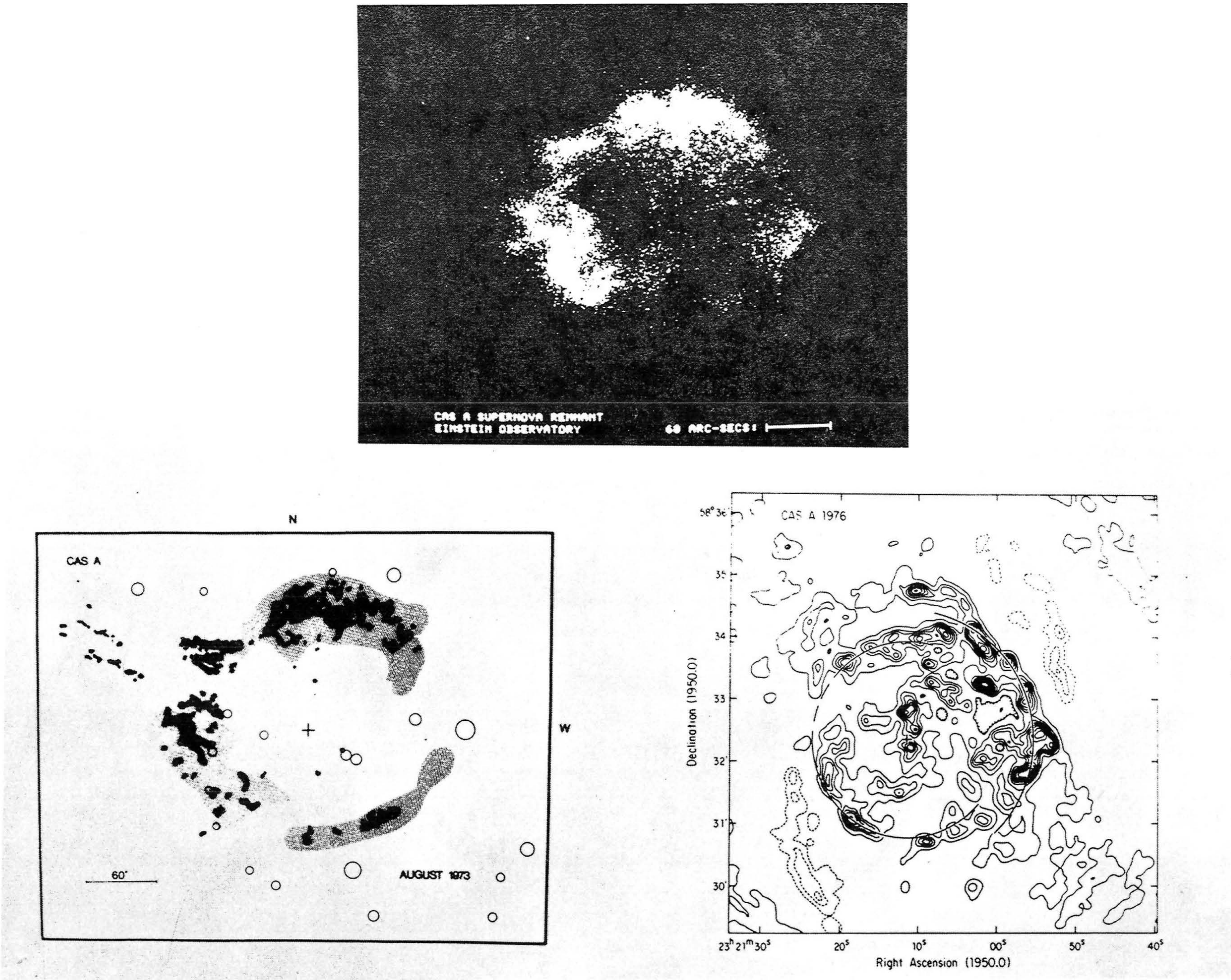

Figure 2. Cas A: X-ray picture, schematic of optical features from Kamper and van den Bergh (1976), and 6 cm radio map from Dickel and Greisen (1979).

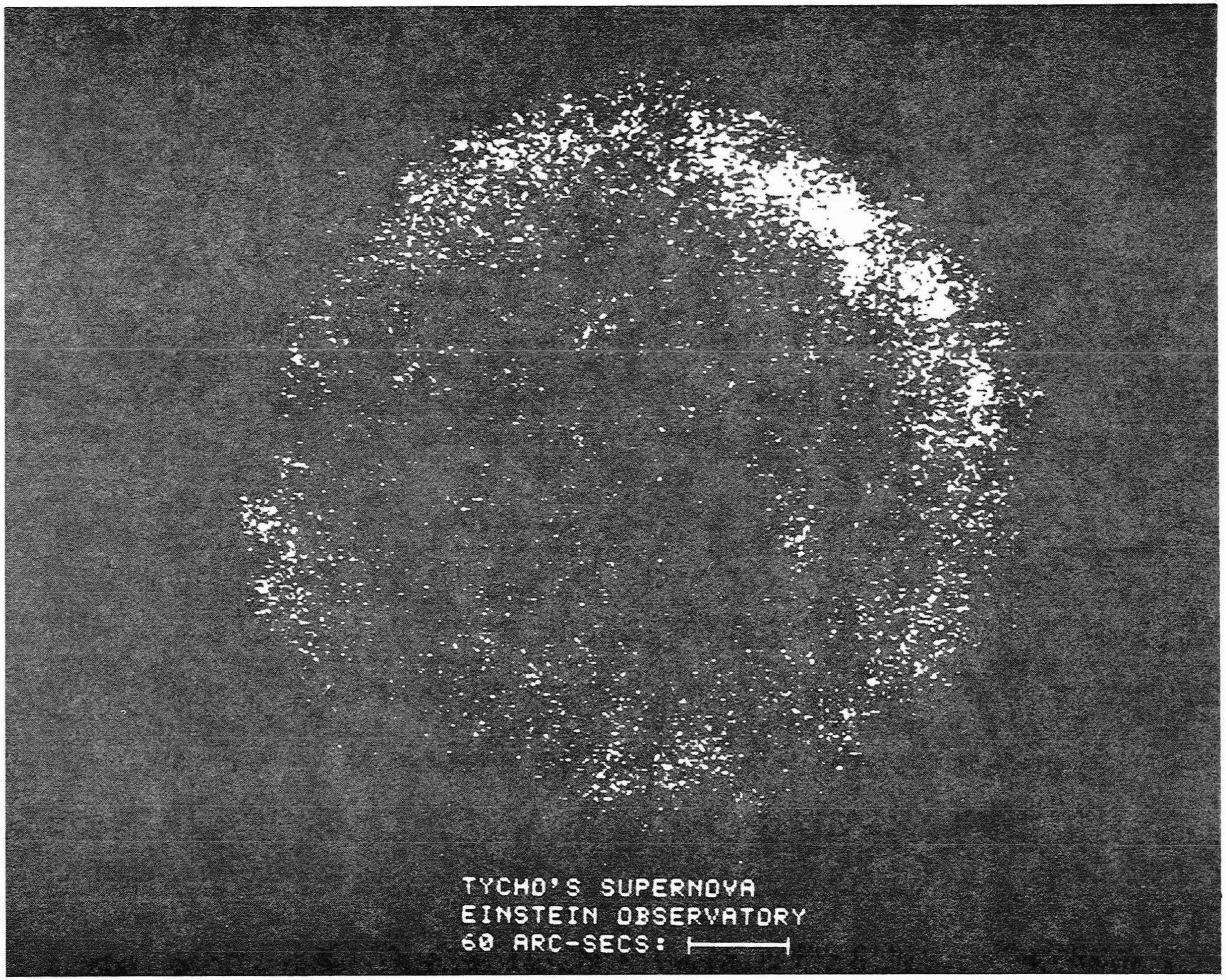

Figure 3. HRI picture of Tycho SNR. Exposure approximately 4×10^4 sec.

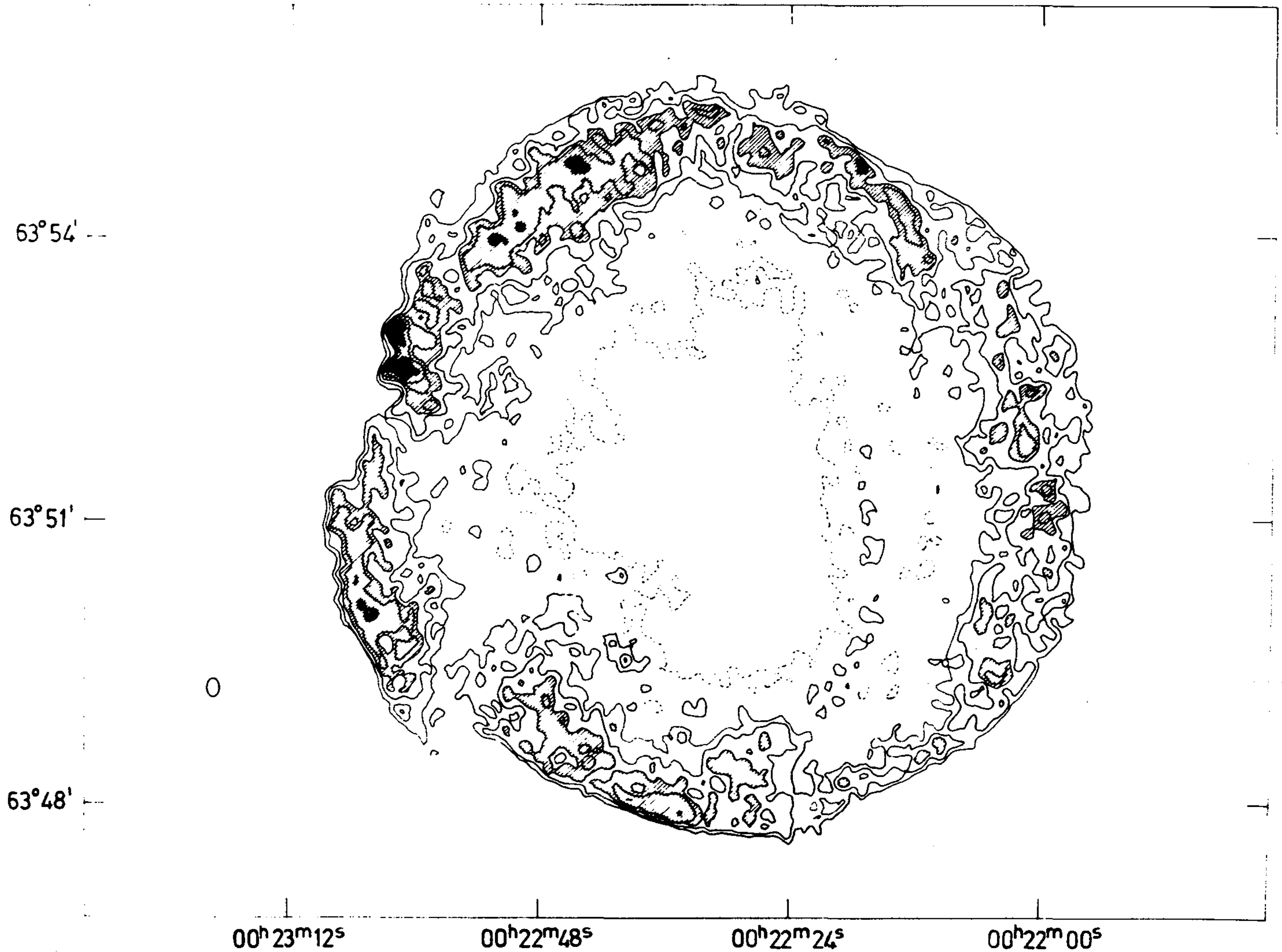

Figure 4. Tycho SNR: 6 cm radio map from Duin and Strom (1975).

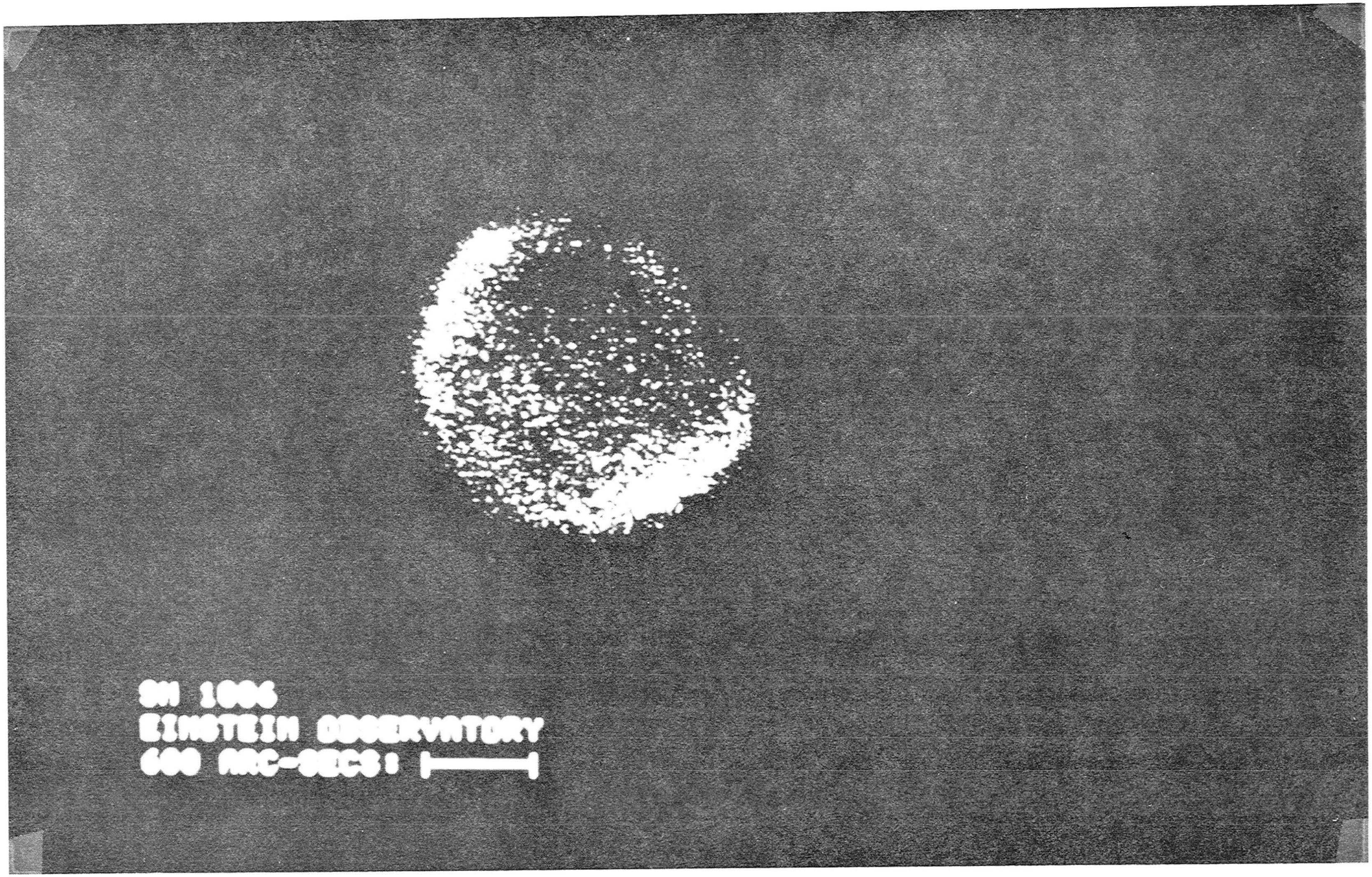

Figure 5. IPC picture of SNR 1006. Exposure approximately 3000 sec.

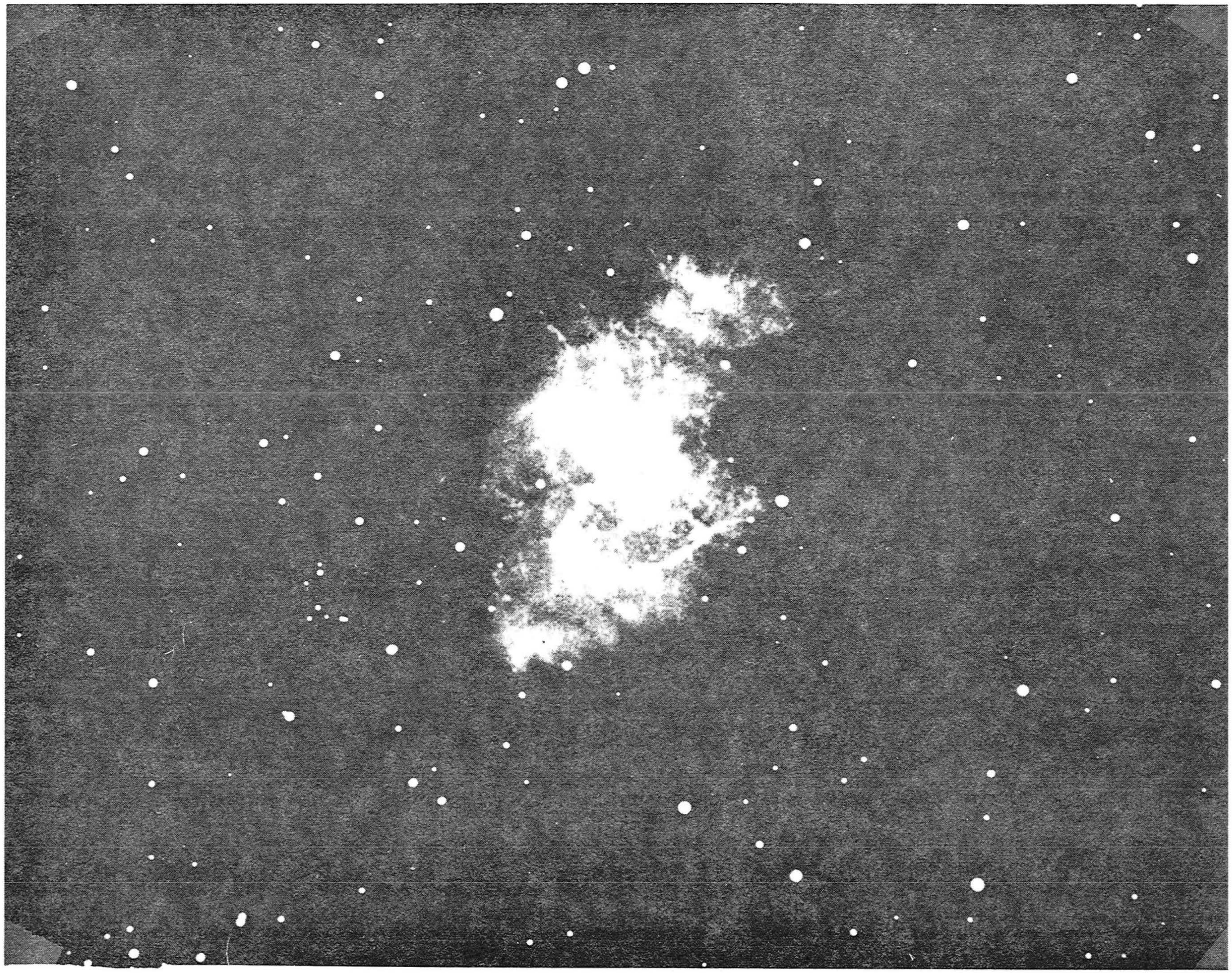

Figure 6. The Crab Nebula (from a color Hale Observatory photo).

Figure 7. HRI picture of the Crab Nebula. Exposure approximately 5×10^4 sec.

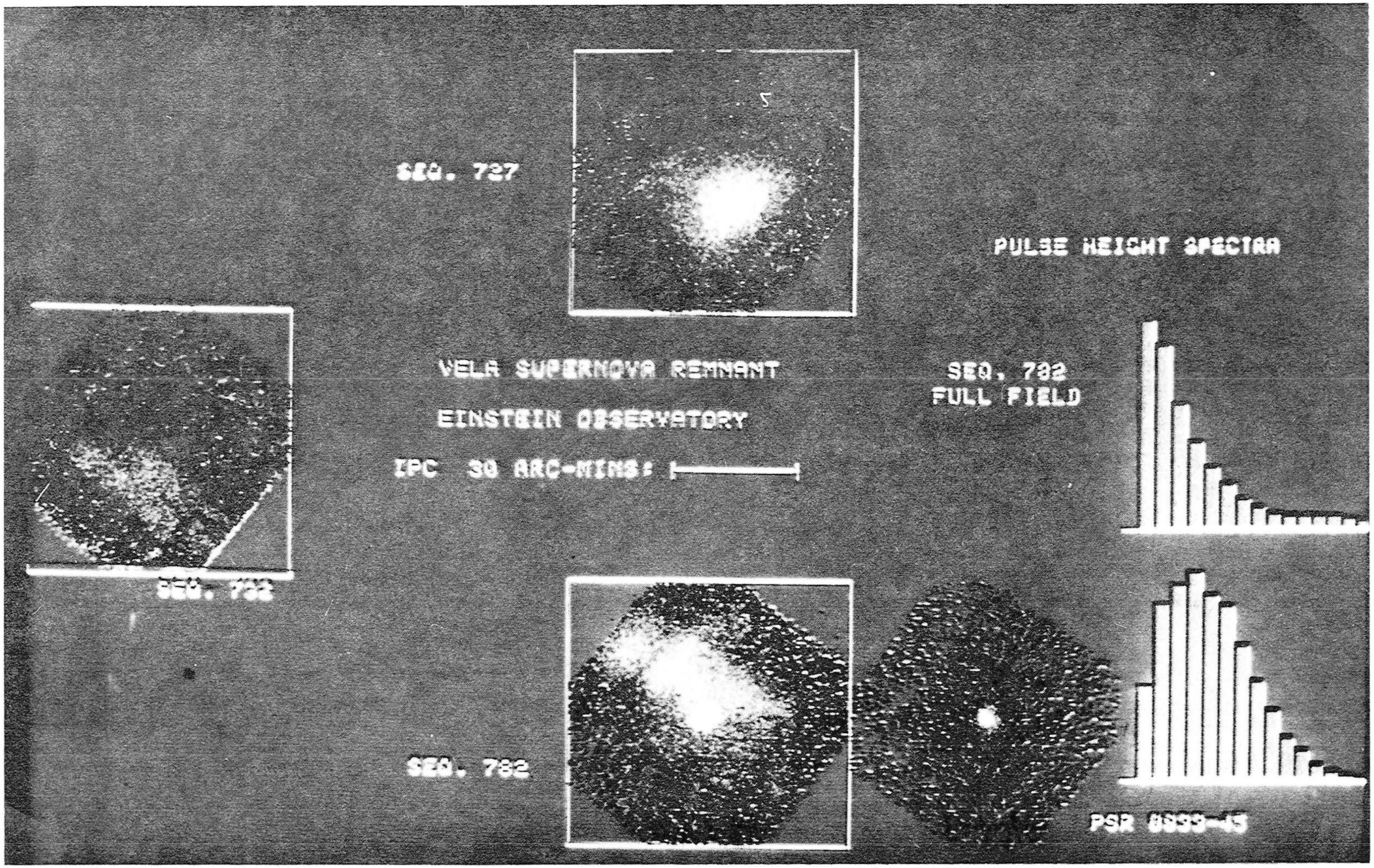

Figure 8. Three IPC fields in the Vela X SNR. The lower right field is shown twice: at left with all energies included and at right with only high energies included.

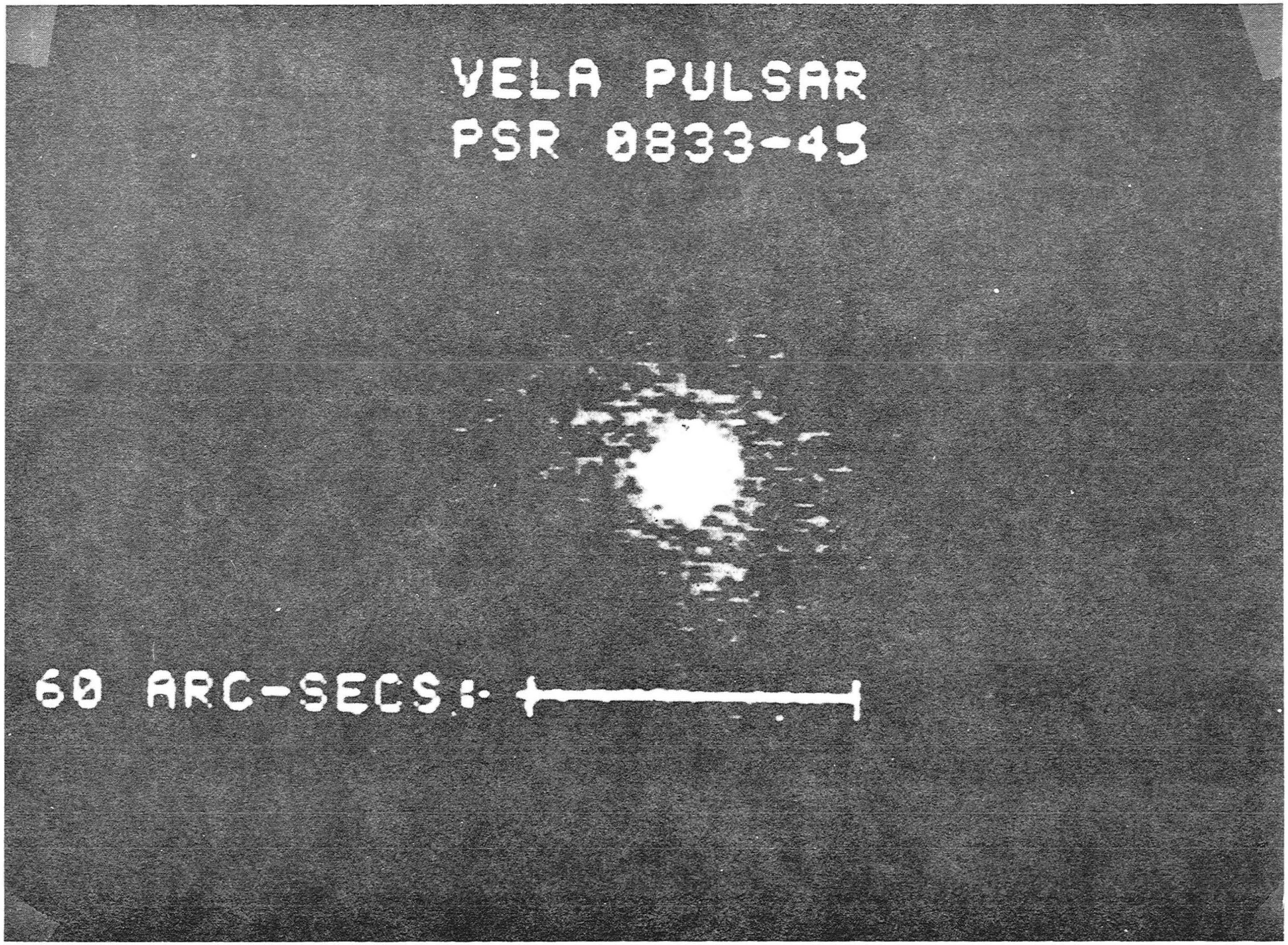

Figure 9. HRI picture of Vela pulsar and surrounding diffuse nebula. Exposure approximately 10^4 sec.

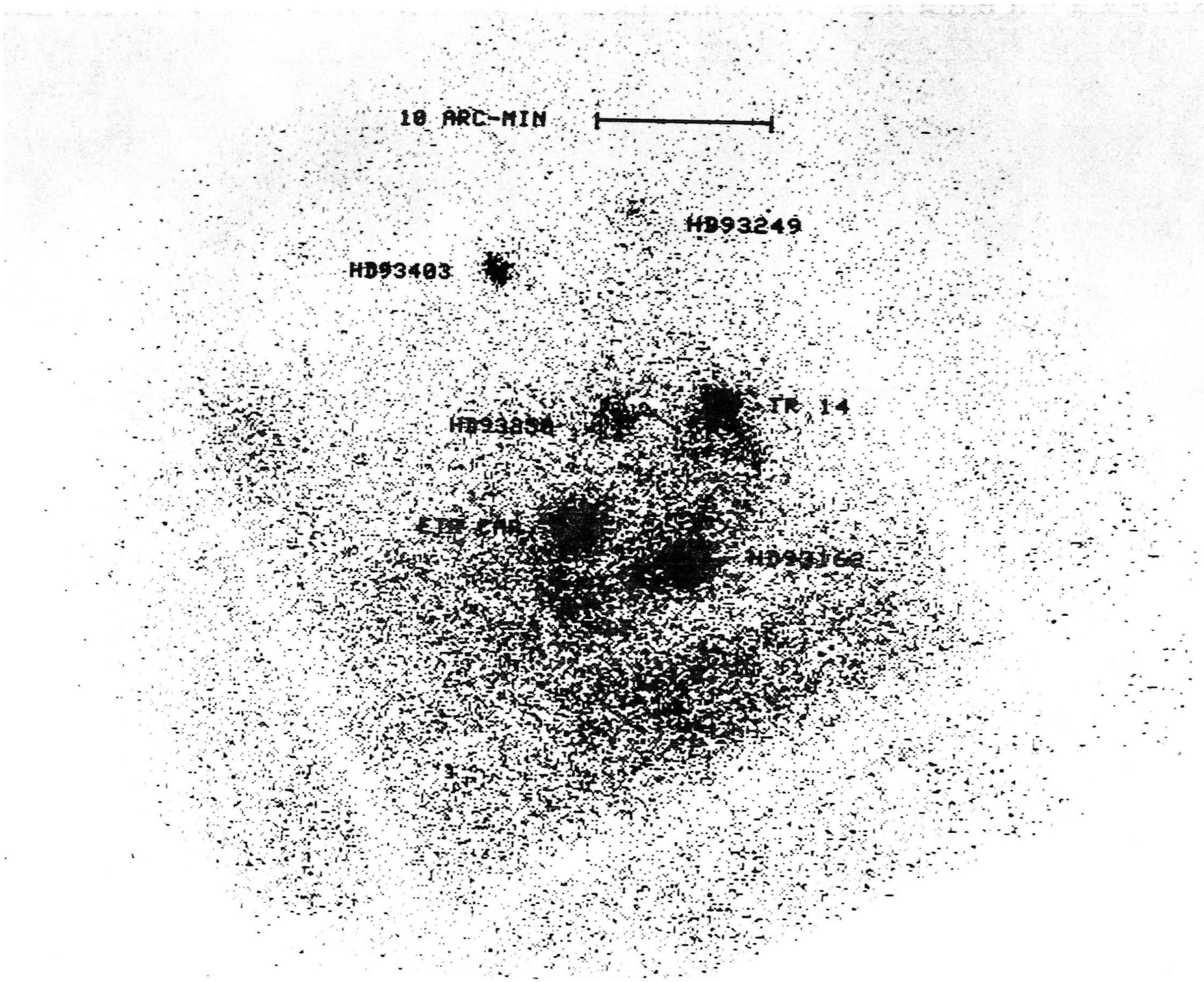

Figure 10. IPC picture of Eta Carinae Nebula. Exposure 8000 sec.

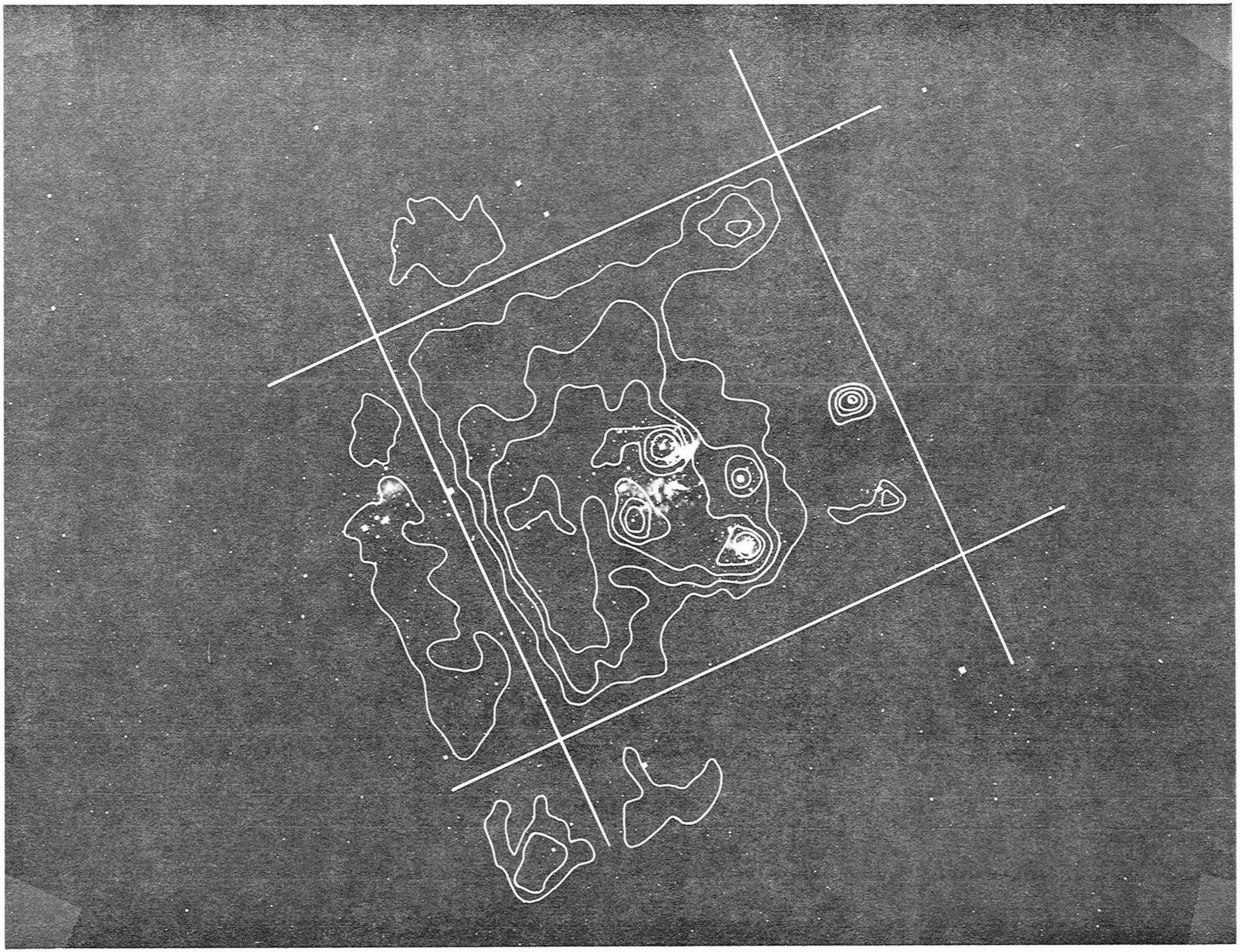

Figure 11. Contours of constant X-ray emission overlaid on optical photograph of Eta Carinae Nebula.

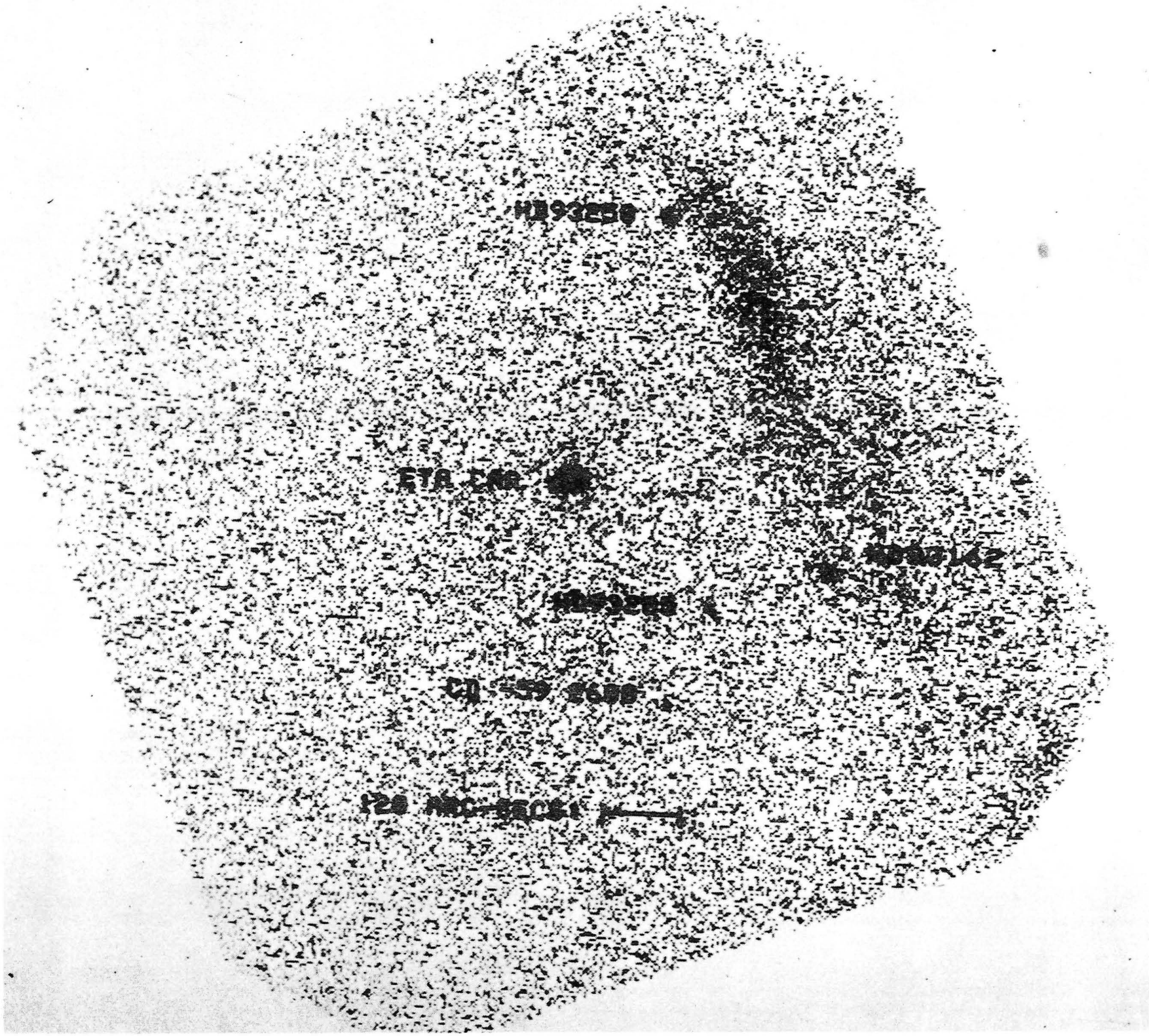

Figure 12. HRI picture of Eta Carinae Nebula. Exposure 13 000 sec.

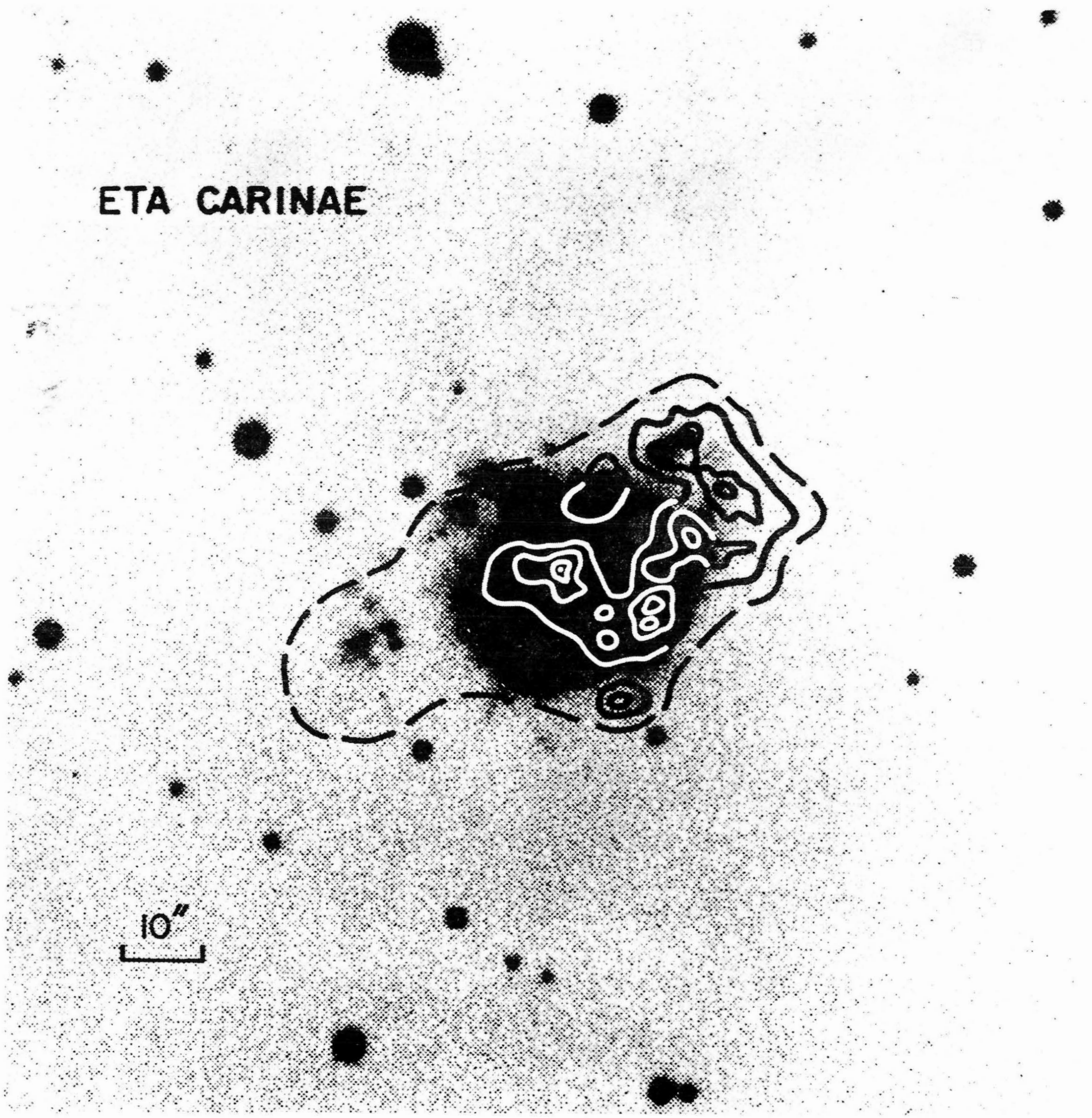

Figure 13. Contours of constant X-ray emission overlaid on an optical photograph of Eta Carinae taken from Walborn (1976).