SOFT X-RAY OBSERVATIONS OF SUPERNOVA REMNANTS

J. C. ZARNECKI, J. L. CULHANE, A. C. FABIAN*,
C. G. RAPLEY, and R. L. F. BOYD
Mullard Space Science Laboratory, University College London, England
and
J. H. PARKINSON** and R. SILK
Physics Dept., Leicester University, England

Abstract. Observations of a number of supernova remnants have been carried out with the low energy X-ray telescope on the Copernicus satellite. Data are presented on the X-ray structure of the remnants Cassiopeia A and Puppis-A. Marginal detections or new upper limits are reported for the remnants IC443, DR4, MSH15-52A, Downes 83, Downes 84 and 3C392.

1. Introduction

In the past, supernova remnants have been recognised and studied as extended sources of non-thermal radio emission. A few of these objects exhibit pronounced filamentary structures at optical wavelengths. About 100 supernova remnants have been identified in the Galaxy. Recently a number of them have been identified as X-ray sources but most of the X-ray data have been obtained with either mechanically collimated detectors or with one dimensional reflecting systems having fields of view of about 0.2° by 10°. Use of the grazing incidence paraboloidal reflectors on Copernicus has allowed us to examine, for the first time, the structure of several supernova remnants with fields of view that range from 3′ to 12′ in size.

2. Studies of Individual Supernova Remnants

Following a supernova explosion, a number of phases may be distinguished in the evolution of a remnant as the shock wave moves out from the explosion site. The propagation of a shock wave in the interstellar medium has been discussed by Taylor (1950) and by Sedov (1959). Up to several hundred years after the explosion, the mass of ejected gas is greater than the mass swept up from the interstellar medium. At this time also the radio observations suggest that much of the energy is in the form of relativistic electrons, which radiate by the synchrotron process. After several thousand years however, the swept up interstellar gas, which has been heated by the passage of the shock front, dominates the appearance of the remnant. Preliminary analysis of the data from Copernicus has provided new information on the structures of both young and old supernova remnants.

* Now at the Institute of Astronomy, Cambridge.
** Now at Mullard Space Science Laboratory.

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2.1. Cassiopeia-A

The structure of this remnant was observed with the 1.4 to 4.2 keV telescope using the 3′ field of view. The data obtained are shown in Figure 1 together with the UHURU error box for the source and the equivalent beamwidth of the Copernicus telescope. The data points have been input to a simple contour plotting programme but the contours produced represent a convolution of the telescope impulse response and the X-ray source structure. In order to unfold the impulse response, various trial source distributions were convolved with the impulse response and the resulting convolutions were χ^2 fitted to the 13 data points. The validity of this procedure was first tested on data from the point source GX2+5. The results of this work showed that the chosen impulse response adequately represented the properties of the telescope.

The symmetry of the 'contour map' as well as the shape of the radio maps of Cas A suggested trial source distributions in the form of a point source, annuli of

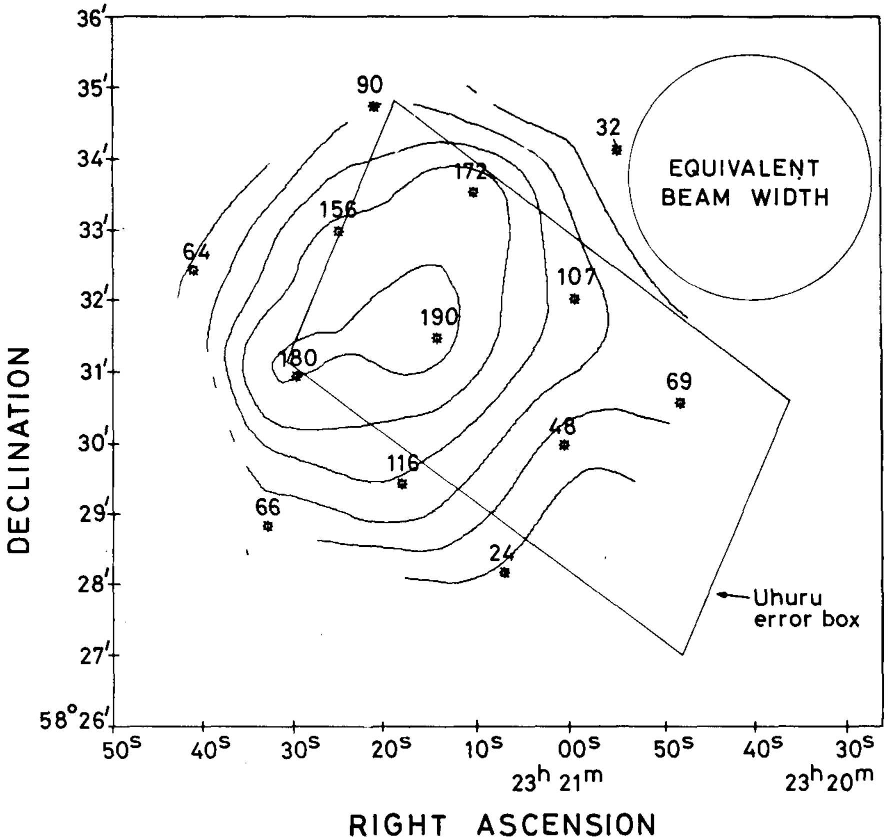

Fig. 1. The numbers of counts registered in the 1.2 to 4.6 keV band during the various samples of data from Cassiopeia A. The UHURU error box, the Copernicus equivalent beam width and a simple contour map are also shown.

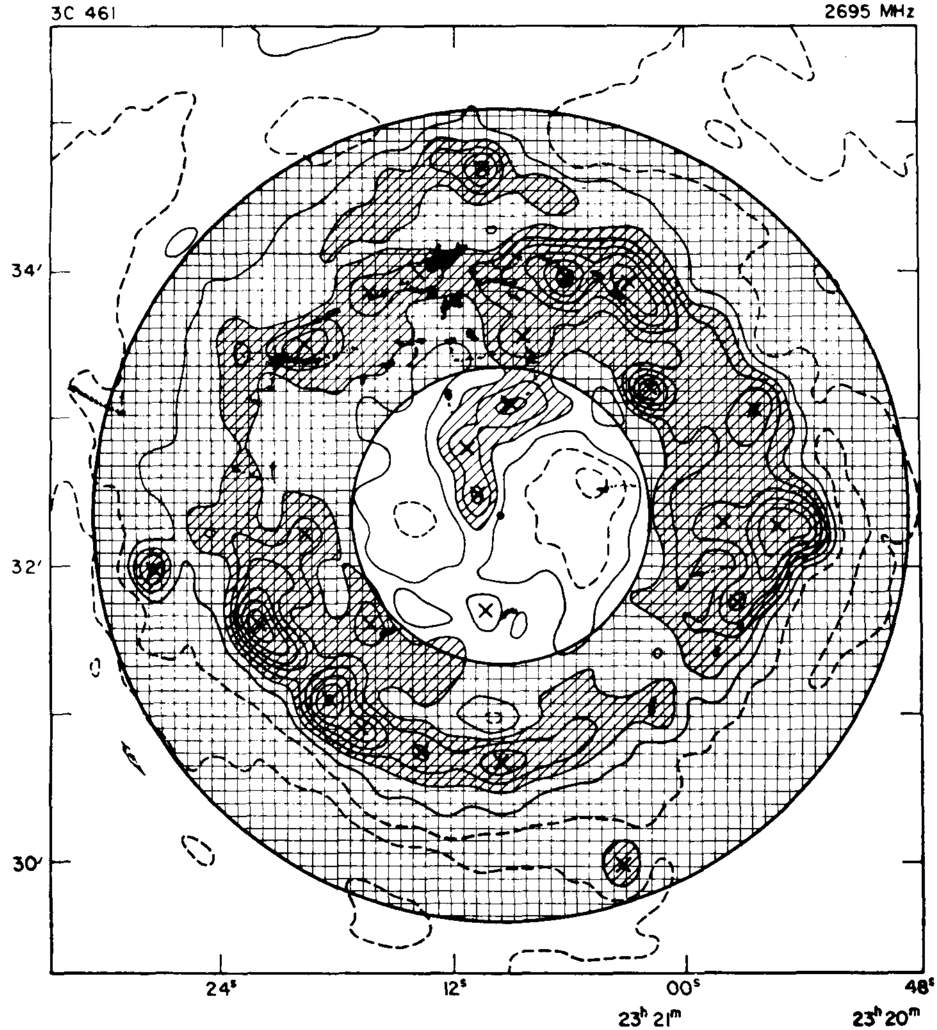

Fig. 2. The best fitting X-ray emission model – a uniformly emitting annulus is shown superimposed on the Cambridge radio map.

various inner and outer radii (approximating to a shell), and discs of varying diameter. The convolution was performed by a Fourier transform method and the χ^2 fitting was done by moving an array of values representing the source, where elements of the array were separated by 0.5′ intervals. Source position, intensity and size were altered and χ^2 values computed for each case. The number of degrees of freedom is equal to 13 minus the number of free parameters.

A point source gave the worst fit to the data. We suggest therefore that Cas A is not a compact X-ray emitting object. While none of the uniform extended source models gave a really good fit, it is clear that χ^2 is minimum for an object of about

5.5′ diameter. For extensions of less than 5.5′, the χ^2 value is further reduced by employing a uniform annular source. For extensions greater than 5.5′, the need for annular structure becomes less and disc models can give acceptable fits. Of the models tried, the data are best fitted by a uniform annular or disc source of outer diameter 5.5′. Such an annular source has been superimposed on the Cambridge 2695 MHz radio data (Rosenberg, 1970) in Figure 2.

Since all of the extended trial sources were of uniform surface brightness and since this is unlikely to be true in practice, we believe that the discrepancies in the χ^2 fits, even for the best source models, arise due to the existence of structure in the X-ray emission. This is supported by the fact that further studies of the remnant, carried out with smaller fields of view, suggest some non-uniformity in surface brightness in addition to confirming the overall extension discussed in the previous paragraph.

In summary, the results of our preliminary analysis (1) Identify the UHURU source 2U 2321+58 with the radio source Cas A, (2) Suggest that the X-ray emission arises in an annular source of outer diameter $5.5' \pm 1.5'$ and inner diameter $2.0' \pm 2.0'$, (3) Indicate that the surface brightness of the annulus is non-uniform and (4) Indicate that the bulk of the X-ray emission does not come from a compact object.

The data are suggestive of a shell source. The X-ray emission may originate in thermal Bremsstrahlung from a blast wave, or the synchrotron mechanism. Further studies of this object with better spatial and spectral resolution may allow us to discuss the radiation production mechanism in greater detail.

2.2. The X-ray structure of Puppis-A

The Puppis-A supernova remnant is much older than Cas A (3×10^4 as against 3×10^2 yr). Because of its age, its emission is probably from the shock heated plasma of the interstellar medium. This conclusion is supported by earlier observations which suggest that the plasma temperature is about 4×10^6 K (Burginyon *et al.*, 1973b). While a number of other workers have observed the remnant with collimated proportional counters and one dimensional X-ray optical systems, the data presented here are the first to be obtained with high spatial resolution in two dimensions.

The remnant has been mapped with the 0.5–1.5 keV telescope system by sampling the intensity at 27 discrete points both inside and outside the radio shell using the nominal 10′ field of view. The duration of each sample was approximately thirty of the instrument's 62.5 S integration periods. The mean background rate during these observations was approximately 90 counts per sample. In Figure 3 are shown the corrected number of X-ray counts in each sample. These data have been processed using a standard computer contour routine to produce the map of Figure 4. For comparison we show selected contours of the radio map of Milne (1971) chosen because of its similar spatial resolution. The X-ray map represents a convolution of the telescope impulse response with the real X-ray source distribution. It is clear that the bulk of the X-ray emission originates from within the radio shell and it is likely that any apparent emission from outside the shell is entirely due to the effect of the

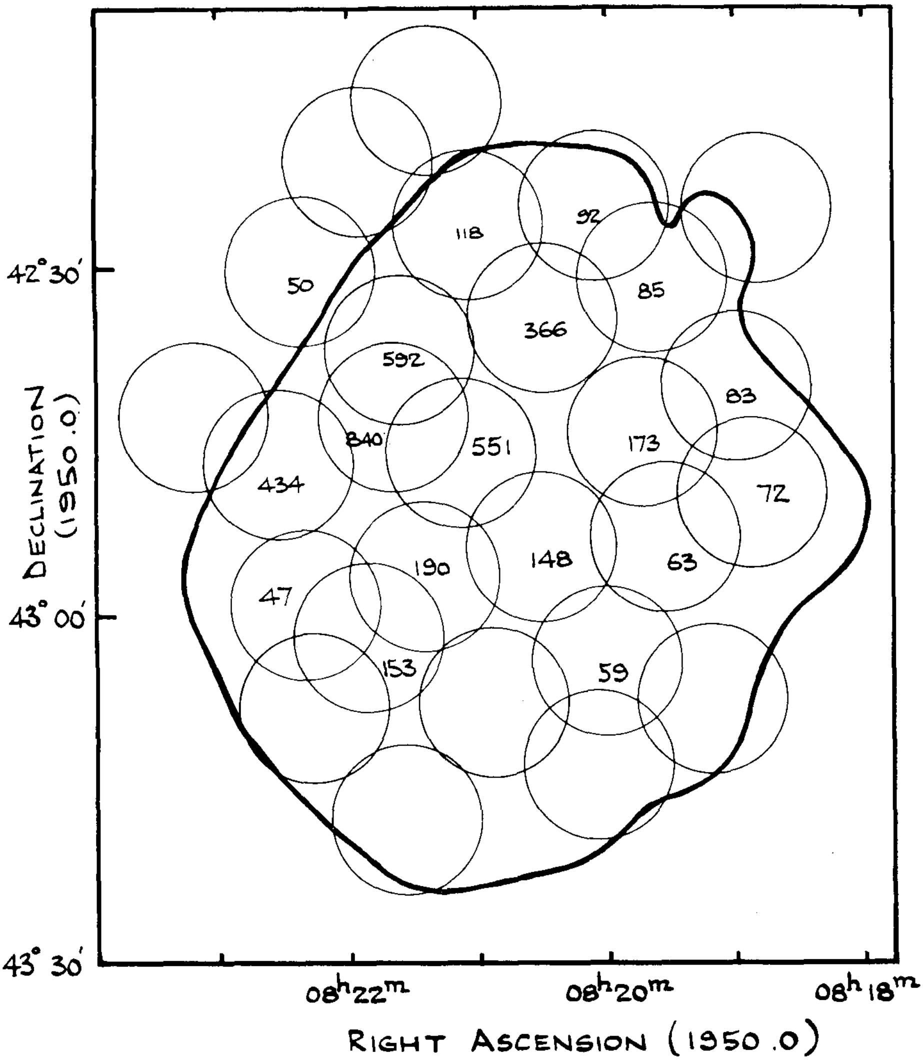

Fig. 3. The numbers of counts registered in the 0.5 to 1.5 keV band during the various samples of data from Puppis A. The outermost radio contour is shown as a solid line. Empty circle denote samples where the significance of the data was less than 3σ.

convolution. The X-ray emission is strongly peaked and does not coincide with any of the obvious radio or optical features. Furthermore the strong radio regions do not appear to emit significantly in soft X-rays although we note that the X-ray emission is concentrated in the more intense half of the radio shell. We find that over 50% of the observed counts originate from the central 20% of our contoured region which has a total extent of ~0.5 sq deg. We note that the peak of the distribution lies within the UHURU error box. However, the source is extended with some evidence of elongation towards the north-west and south-east. An attempt to unfold our data using a minimum χ^2 technique has shown that no simple combination of point and disc sources will adequately describe the X-ray distribution.

If it is assumed that the site of the original Puppis-A explosion lies within the present X-ray emitting region, current supernova theory can be invoked to at least qualitatively explain the features of the X-ray and radio emission. The asymmetry of the radio distribution with respect to the X-ray region can be accounted for by assuming the existence of density gradients in the surrounding interstellar medium, the density being greater on the north-east side of the remnant which is nearest the galactic plane. The application of the models of Stevens (1973) which attribute the X-radiation to thermal emission can then lead to an explanation of the separation between the edges of the X-ray and radio emission in the southern and western sections of the remnant. In discussing recent observations of the Cygnus Loop, Stevens has shown that the passage of a low velocity ($\sim 150 \text{ km s}^{-1}$) shock wave through a uniform interstellar medium can lead to a separation of X-ray and radio emission similar to that now observed in Puppis-A. Recent calculations by Lada and

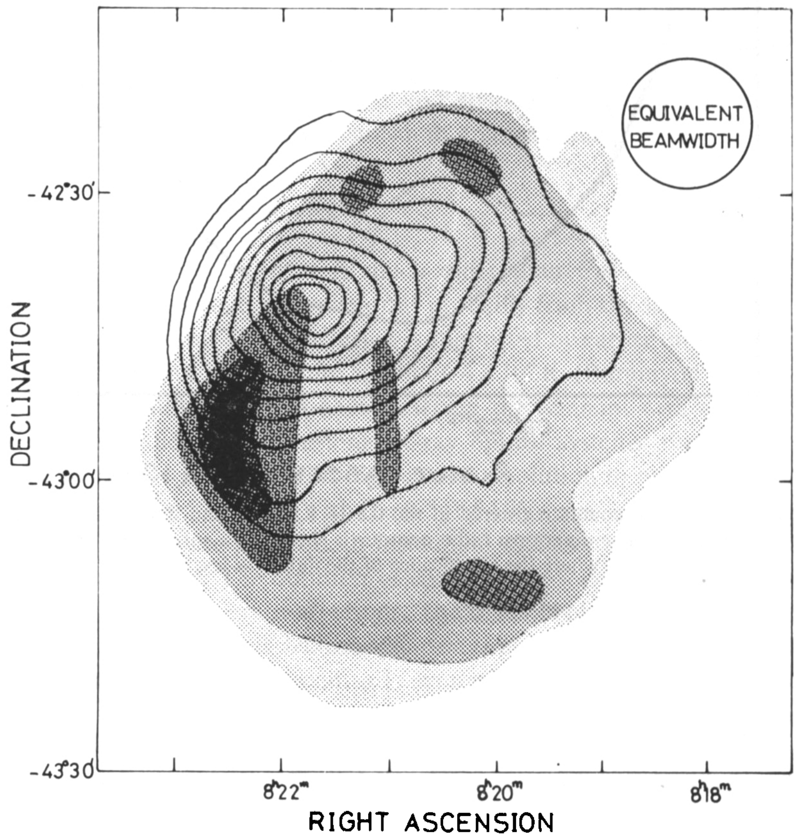

Fig. 4. The solid lines are contours of soft X-ray emission from Puppis A. They are superimposed on the radio map of Milne.

Straka (1973) lead to a similar conclusion. The low radial velocities of the optical filaments led support to such theories.

The existence of a bright compact X-ray emitting region leads to speculation on the possible presence of a compact object. If such an object does exist it is noteworthy that it still lies within the radio shell and the extended X-ray region and hence must have a low runaway velocity. It is worth emphasizing that our data are not consistent with a simple point source and disc model.

We may summarise the significant features of the observations as follows:

(1) All the 0.5–1.5 keV X-ray emission is contained within the radio shell.

(2) The distribution of X-ray emission is very different from that of the radio emission and does not correlate well with radio or optical features.

(3) The X-ray emission is extended but strongly peaked.

(4) The possibility of existence of a compact object is of great interest but the present evidence is not conclusive.

(5) In several parts of the remnant, particularly in the south and west, there exists a marked separation between the edges of the X-ray and radio emission.

(6) The observed radio and X-ray features can be accounted for by current supernova models in which the interstellar gas is heated to a temperature of several million degrees by the passage of a shock wave.

2.3. Observations of other supernova remnants

X-ray observations of a number of remnants have been carried out in order to confirm results obtained by other workers. These sources are weak ones and so either marginal detections of X-ray flux or upper limits have been achieved.

2.3.1. *IC443*

The radio structure and size of this remnant are very similar to those of Puppis-A. Unlike Puppis-A however, this object has pronounced and well developed optical filaments but only weak X-ray emission. The diameter of the remnant is 45′. Seven observations were carried out with the 10′ telescope field of view. By combining data from all of these samples, the source was detected a significance level of 5.3σ thereby confirming the identification of this remnant with the source 3U 0620+23 as suggested in the UHURU catalogue (Giacconi *et al.*, 1972). There is some suggestion in the data that the X-ray emission is associated with the brightest filament but further observations of greater significance are required to confirm this. A 3σ upper limit of *0.02 photons* $cm^{-2}\ s^{-1}$ *(2–6 keV)* can be assigned to the emission from the nearby pulsar.

2.3.2. *DR4*

This remnant has been suggested by Burginyon *et al.* (1973a) as a candidate for a source of low energy X-ray emission which they detected in Cygnus. The flux registered in their observation was 0.06 photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (0.5–1.5 keV). From our observations of DR4 with the low energy telescope, we find a 3σ upper limit to the flux in the same band of *0.01 photons* $cm^{-2}\ s^{-1}$. A power law spectrum of photon number index -3 was assumed in deriving this limit. There are a number of other supernova remnants in the region observed by Burginyon *et al.* that could be sources of the emission which these workers detect.

2.3.3. *MSH15–52A*

This source was observed for 100 minutes by the Copernicus telescopes. For an assumed power law spectrum with a photon number index of -3, a 3σ upper limit of 4.5×10^{-11} *erg* $cm^{-2}\ s^{-1}$ was obtained for the 2–6 keV band. The UHURU source 3U 1510–59 has been suggested as a possible candidate for association with this remnant. However, the UHURU catalogue flux is 1.1×10^{-10} *erg* $cm^{-2}\ s^{-1}$ *in the same band.*

2.3.4. *Downes No. 83 and 84*

A possible detection of these sources has been claimed by Schwartz *et al.* (1972). Copernicus observations have established a 3σ upper limit of *0.01 photons* $cm^{-2}\ s^{-1}$ for the 2–6 keV band.

2.3.5. *3C392*

We have obtained a signal of 5σ significance in the 3–9 keV band. This result confirms a marginal identification by Schwartz *et al.* of this source as an X-ray emitter. However, our result was obtained with the 3° field of view proportional counter. So while the nearest UHURU source is more than 3° array, a further observation is probably required for final confirmation. No low energy signals were detected from this source.

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