9. X-RADIATION FROM SUPERNOVA REMNANTS

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Abstract. Available X-ray observations of supernova remnants are reviewed. The number of SNR seen above 2 keV remains small after inclusion of the UHURU results and for only the Crab Nebula is the data adequate to clearly indicate the radiation mechanism. The increasing importance of low energy X-ray studies (below 1 keV) of older and relatively nearby remnants is noted. Brief discussion is given of the relation of the X-ray data to current ideas of the evolution of SNR.

This meeting marks the 10th anniversary of the discovery of the first cosmic X-ray source, Scorpius X-1. In the following few years it was considered that most of the newly discovered and obviously powerful sources were associated with supernovae and, indeed, the first identification of a cosmic X-ray source was with the Crab Nebula in 1964 (Bowyer *et al.*, 1964). This expectation has not been realised and of the 40 or so Galactic sources known by the end of 1970 only four others had been reliably linked with supernova remnants, these being Cas A, SN 1572 (Tycho's nova), Vel X and Pup A. A comparison of a further forty sources listed in the second UHURU catalogue (Giacconi *et al.*, 1972) with the positions of 120 non-thermal Galactic radio sources (Milne, 1970 and Downes, 1971) (generally thought to be SNR) has revealed only three additional associations, none of which are considered convincing. Conversely, a number of X-ray sources previously associated with nearby SNR such as Nor X-1, Nor X-2 and a source near Doradus in the LMC, have been ruled out by improved UHURU locations.

The available X-ray results on all the above (certain and possible) SNR/X-ray source associations are briefly reviewed below, including recent soft X-ray observations which indicate that SNR sources may play an increasingly important role in the newly emerging regime of X-ray astronomy below 1 keV photon energy.

1. Confirmed Identifications

A. CRAB NEBULA

This is by far the most observed and best understood SNR X-ray source. Figure 7 of Peterson (this volume, p. 51), shows a representative selection of spectral data with good statistical precision, which cover the wide energy range from 1.0 keV, below which interstellar absorption is important, to 500 keV. As the figure shows, the data are fit quite well over this entire energy range by the power law photon spectrum*:

$$dN/dE = 10.5\,(E/1\ \text{keV})^{-2.25}\ \text{photons/cm}^2\ \text{s keV} \quad (1\text{–}500\ \text{keV}).$$

* Individual experiments in limited energy ranges have yielded slopes which are slightly flatter, i.e., 2.0 to 2.15 (see Gorenstein *et al.*, 1970a; Ducros *et al.*, 1970; Jacobson, 1968).

Bradt and Giacconi (eds.), X- and Gamma-Ray Astronomy, 105–117.

Integrating from 1–500 keV, this yields the flux

$$5.4 \times 10^{-8}\ \text{erg/cm}^2\ \text{s} \quad (1\text{–}500\ \text{keV})$$

and a luminosity, assuming a distance of 1500 pc:

$$L_x = 1.4 \times 10^{37}\ \text{erg sV}^{-1} \quad (1\text{–}500\ \text{keV}).$$

A recent detection of an overall X-ray polarisation of $15 \pm 5\%$ by the Columbia University Group (Novick *et al.*, 1972) has provided strong evidence for the common (synchrotron) nature of the X-ray, visible continuum and radio fluxes, as suggested by extrapolation of the Crab Nebula electro-magnetic spectrum (Figure 1). Discovery

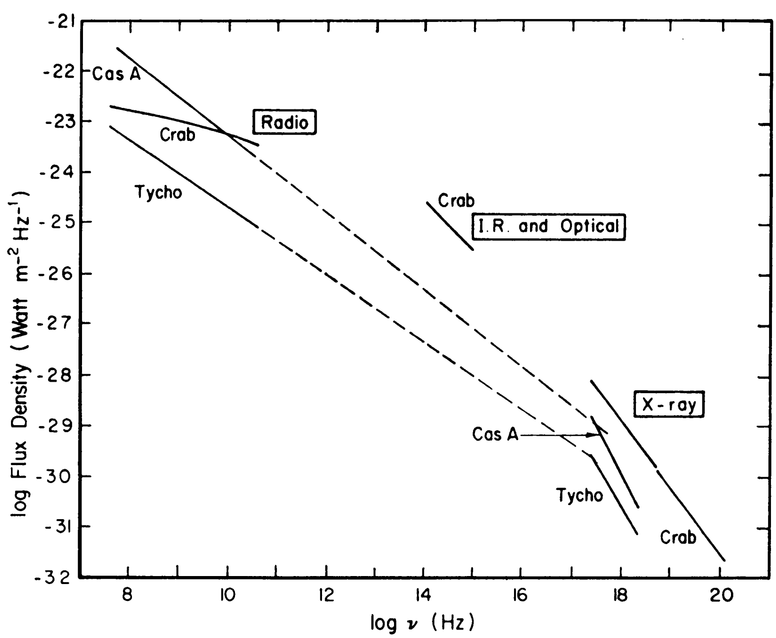

Fig. 1. Electromagnetic spectra of the Crab Nebula, Cas A and Tycho's Nova over a broad frequency range (from Gorenstein *et al.*, 1970a).

of the shortest period pulsar, NP 0532 – observed also at X-ray energies (see Figure 1 of Fazio, this volume, p. 303) – near the centre of the Nebula has suggested a probable means by which the short-lived high energy electrons ($\sim 10^{13}$ eV to produce keV synchrotron X-rays in a milligauss field) may be continually regenerated. Thus, the $\sim 2'$ extent of the diffuse X-ray component at 1–10 keV (Bowyer *et al.*, 1964 and Oda *et al.*, 1967) may be simply a measure of the life span of these electrons and the source may be considerably smaller at the high photon energies. New observations, with higher spatial resolution (such as may be obtained with planned grazing telescope experiments, or during the series of lunar occultations in 1974–5) should check this and could, for example, yield an 'image' of the magnetic field distribution in the Nebula.

The attenuation of the Crab Nebula spectrum below 1 keV (Fritz *et al.*, 1971) is particularly interesting since it is unlikely to be intrinsic absorption in so extended a source. Thus, detailed observations should provide a measure of the column densities of those elements – particularly helium, oxygen and neon – which contribute most to the photoelectric opacity of the interstellar gas at 0.5–1 keV for a source at the Crab's distance (1.5–2.5 kpc).

B. CAS A AND SN 1572 (TYCHO'S NOVA)

The identification of comparatively weak X-ray sources with these two SNR's was confirmed on an AS&E rocket experiment in 1969 (Gorenstein *et al.*, 1970b). More recent UHURU observations show them to have 2–6 keV fluxes of 5% and 1% of Crab, respectively. The published spectra, from the earlier rocket data, are reproduced

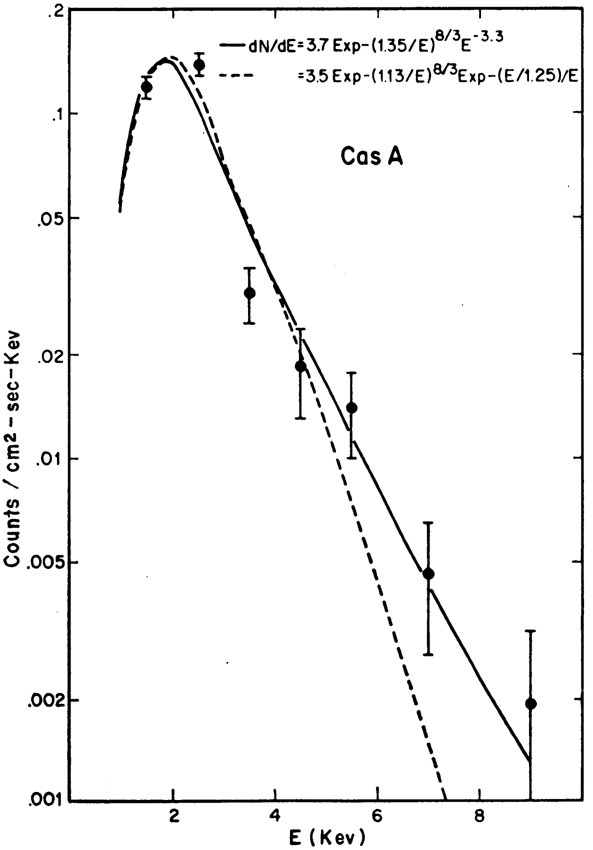

Fig. 2. The measured count rate spectrum of Cas A (circles, with $\pm 1\sigma$ error bars) compared with the best-fit power law (solid line) and exponential (dashed line) input spectra (from Gorenstein *et al.*, 1970a).

in Figures 2 and 3 and are seen to be inadequate to favour power-law or exponential spectral fits. The UHURU results should be of considerably better statistical quality but are probably of insufficient bandwidth to clearly indicate spectral type. Furthermore, as early discussions (Sartori and Morrison, 1967) of the Crab Nebula X-ray source illustrated, even a well-defined power-law can be imitated by exponential (or thermal) spectra from a multi-temperature plasma. Though such an interpretation

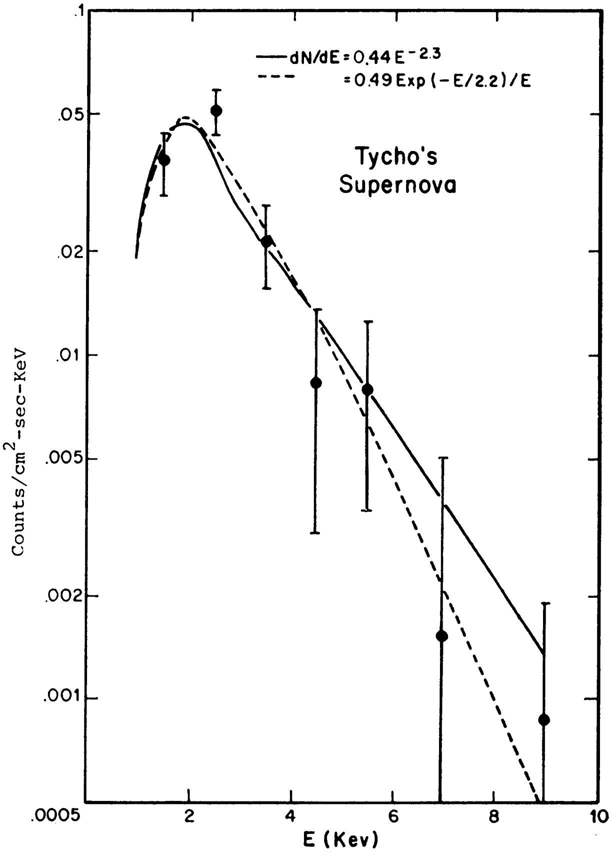

Fig. 3. The measured count rate spectrum of Tycho's Nova (circles, with $\pm 1\sigma$ error bars) compared with the best-fit power law (solid line) and exponential (dashed line) input spectra (from Gorenstein *et al.*, 1970a).

is now unlikely for the Crab source, both bremsstrahlung from a 10^7–10^8 K plasma and electron synchrotron radiation are permitted by the X-ray spectral data for Cas A and Tycho. Extrapolation of the synchrotron radio spectra of these objects to X-ray frequencies (Figure 1) may be interpreted as evidence for a common synchrotron mechanism (Gorenstein *et al.*, 1970b); however, polarized optical radiation has not been reported and this interpretation of the X-ray emission remains unconfirmed. No pulsed component has been observed in the X-ray emission from either source, while useful polarization studies must await the increased sensitivity of satellite observations. The first satellite-borne polarimeters are likely to be those of the Leicester and Columbia Groups, to be flow on UK-5 and OSO-I respectively in late 1973 or early 1974. The alternate possibility of thermal X-ray production could be

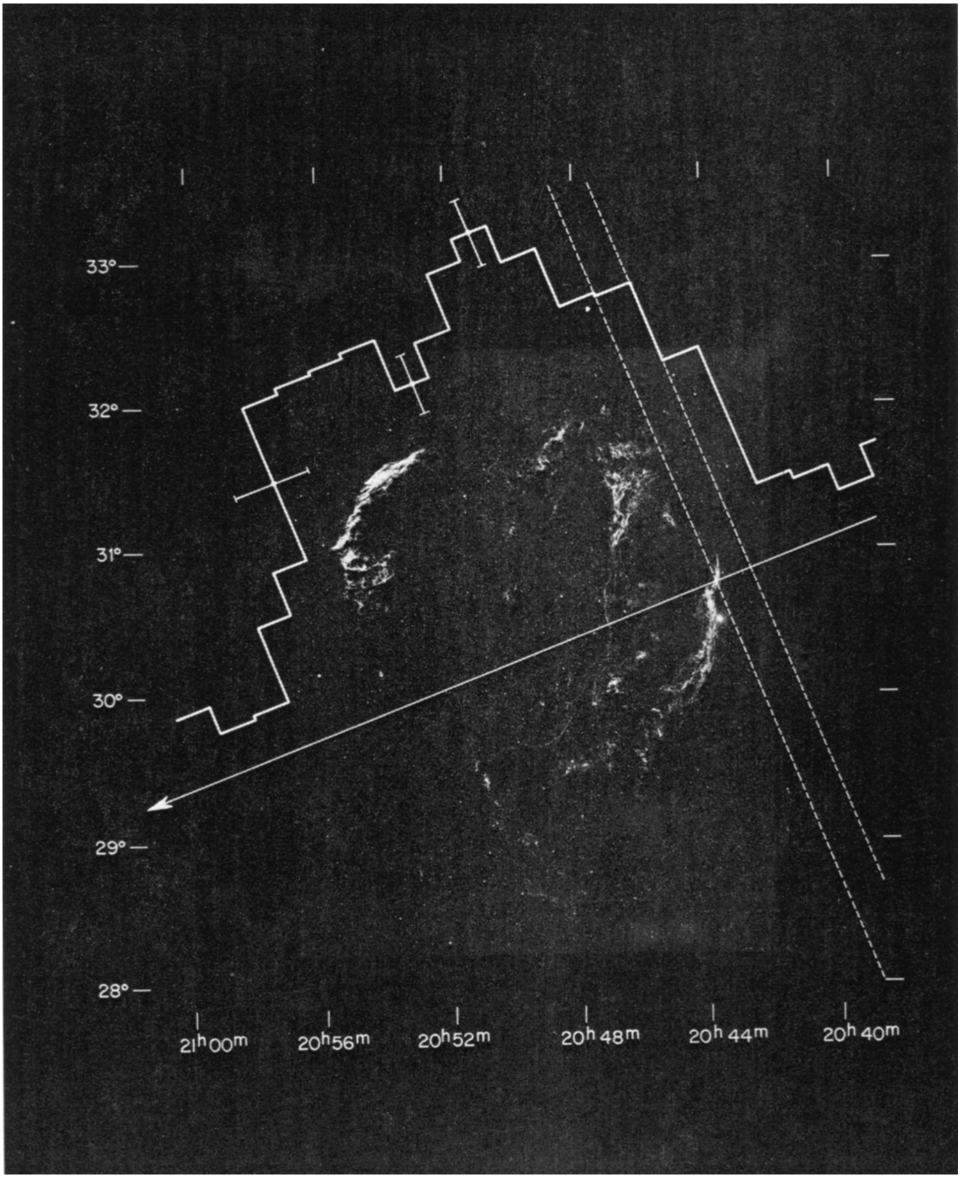

Fig. 4. The one-dimensional X-ray profile of Cygnus loop superimposed on a 48-in. Schmidt red-light photograph of the nebula. The field-of-view of the ASE-Columbia instrument used to obtain these X-ray data is represented by the dashed lines (from Gorenstein *et al.*, 1971).

checked by the same instrument operating as a Bragg crystal spectrometer, to search for emission lines of highly ionised Mg, Si, S, Ca and Fe.

C. CYGNUS LOOP

First identified (Grader *et al.*, 1970) by the LRL Group in 1968 as an intense and extended source at 0.2–1.0 keV, recent surveys by the ASE-Columbia (Gorenstein *et al.*, 1971) and Leiden-Nagoya Groups (Bleeker *et al.*, 1972) have provided further detail on the spatial extent and spectrum of this relatively old SNR X-ray source. Figure 4 reproduces data from the ASE-Columbia survey with a one-dimensional reflecting telescope, having 0.5° spatial resolution. A general extent of $\sim 3°$ and consistency with a shell-structure emission is indicated, though much better resolution

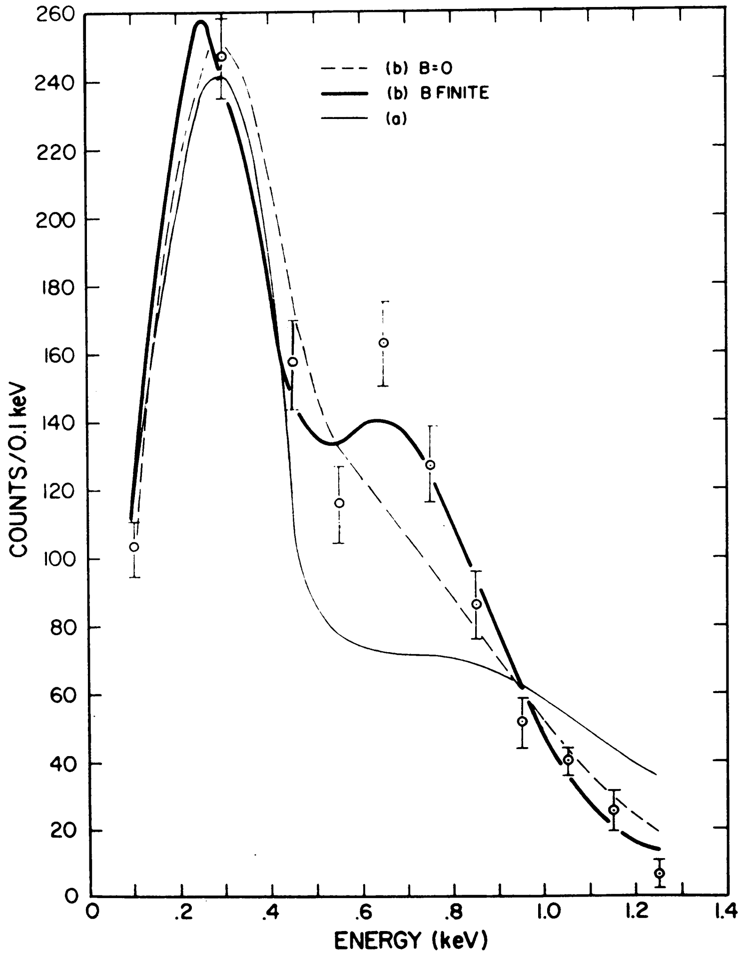

Fig. 5. The measured count rate spectrum of Cygnus loop (circles, with 1σ error bars) compared with the best-fit power law (curve a and exponential (curves b) input spectra. For the solid curve b,a monoenergetic (line) feature is included at 0.65 keV in the input spectrum (from Gorenstein *et al.*, 1971).

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data – in two dimensions – is clearly required, and should be forthcoming quite soon for such an intense source. The relatively crude, proportional counter spectrum obtained in the above experiment has been fitted (Figure 5) with a simple exponential of effective temperature 4×10^6K, with a mono-chromatic feature at 0.65 keV. The latter is suggested to be due to O VIII Ly α, which certainly may be expected to be strong in a thermal spectrum of such a characteristic temperature. Though this particular spectral data may be criticised on grounds of inadequate resolution, experiment calibration difficulties and an over-simplified interpretation (several other strong lines would complicate the spectrum and be unresolved, for example), recent observations from a Cal. Tech. rocket experiment, using discrete oxygen and teflon filters to give more certain wavelength discrimination, are consistent with the presence of strong oxygen lines. Direct confirmation of this may come next year with the rocket flight of a Bragg crystal spectrometer by the UCL Group.

D. VELA X AND PUPPIS A

Two rocket flights in May 1970 by the LRL Group, surveyed the Vela region with thin window, large area proportional counters. These had conventional 'egg-crate' collimators, with a 1.3° × 20° field (FWHM) and electrostatic shields for low energy

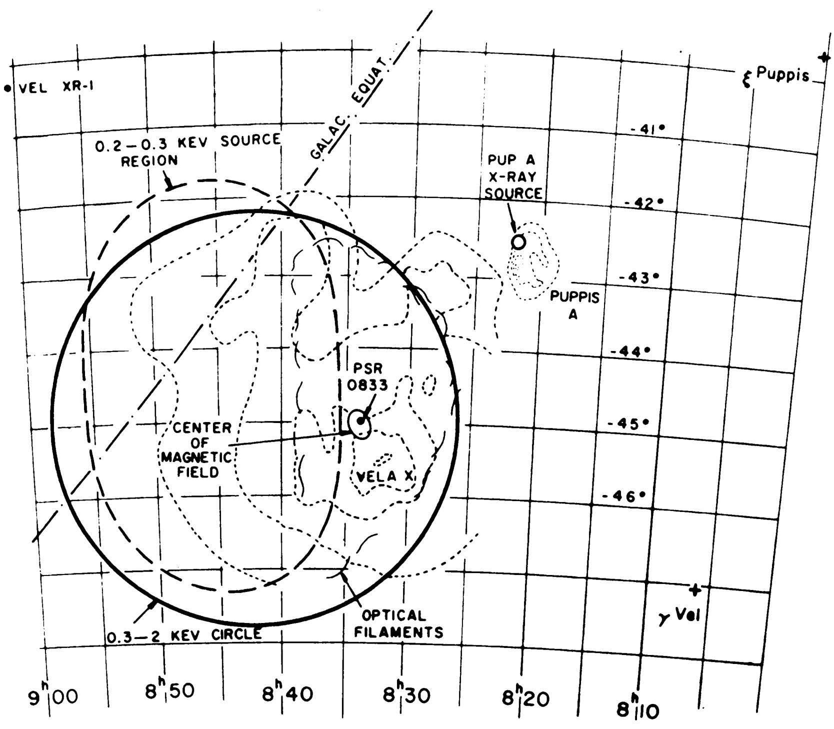

Fig. 6. A map of the Vela-Puppis region showing the radio brightness contours (dashed lines), the pulsar 0833-45 and the optical filaments (wispy lines), together with the extended X-ray source found by the LRL observations in 1970 (Seward *et al.*, 1971). (Figure from Bunner, 1972).

particle rejection. An intense and extended source was found at 0.3–2 keV (Palmieri *et al.*, 1971; Seward *et al.*, 1971), coinciding with the Vela X supernova remnant (Figure 6), believed to be the only SNR younger than 5×10^4 yr as close as 500 pc and possibly the outstanding object in the southern sky. Again, the count rate profile across this source is a flat-topped trapezoid, consistent with the observation of a shell source or alternatively, as the experimenters point out, with 3 or more unresolved point sources. New observations in the near future, employing a mirror system such as that used on Cyg Loop by the ASE-Columbia Groups, or with the UCL-Leicester X-ray package on OAO-C, may be expected to clarify this, providing X-ray maps with 10–20′ resolution. The relation of the (probably) extended source to the Vel X radio object and to the pulsar PSR 0833-45 will be of particular interest in these future observations. From the available LRL data, it is clear that the Vel X spectrum is very soft, but a clear choice between a thermal spectrum ($T \sim 3 \times 10^6$ K) and a steep power law spectrum is not yet possible. As with the Cyg Loop source, the steep spectrum is compatible with the age of the remnant (2×10^4 yr) in terms of either the slowing down of the supernova blast-wave as it pushes against the interstellar gas, thereby yielding a lower temperature for the heated gas, or by the electron spectrum steepening with age and giving a correspondingly steep synchrotron X-ray spectrum.

The Vela observations also detected a soft X-ray source coincident with Pup A, a supernova remnant believed to be at a distance of 1400 pc and somewhat younger than either Cyg Loop or Vel X. The X-ray observations give only an upper limit of 0.5° to the size of this source, again in line with the radio source diameter of 30′. The LRL spectral data on Pup A are best fitted with an exponential distribution, the effective temperature being $\sim 4.5 \times 10^6$ K.

2. Possible New SNR X-Ray Sources from the UHURU Catalogue

A. IC443

A weak X-ray source (2U 0601 + 21) has been detected at 0.4% Crab and provisionally identified with this non-thermal radio source in the second UHURU catalogue (Giacconi *et al.*, 1972). Reference to Table I shows the similarity of IC 443 to Pup A at radio wavelengths and the existence of an X-ray source of comparable intensity to that associated with Pup A appears reasonable. However, the best X-ray position of 2U 0601 + 21 is some 3° from IC 443, and while this is consistent with the present large uncertainty of location of the X-ray source (being $\sim 2\sigma$), this association must be tentative until a refined location is obtained. It does not appear that a low energy X-ray survey has yet been made of the anti-centre region (IC 443 is at $l^{\mathrm{II}} = 188°$) and, if similar to Pup A, this source may be expected to be much brighter below 1 keV than in the UHURU (2–6 keV) energy band.

B. MSH 15–52

The UHURU catalogue includes a weak source (2U 1509–58, 0.7% Crab) within 0.1°

TABLE I
Radio and optical properties of SNR discussed in the paper

	l^{II}	b^{II}	F_{GHz} (f.u.)	D arcmin	d (kpc)	D (pc)	F_{2-6keV} (relative)
Crab Nebula	184.6	− 5.8	1000	4	1.5–2.5	2–3	950
Tycho	120.1	+ 1.4	58	6	2–5	4–9	11
Cas A	111.7	− 2.1	3000	4	3	4	53
Cygnus Loop	74.0	− 8.6	180	180	0.8	43	–
Vela X	263.4	− 3.0	1800	200	0.5	30	10
Puppis A	260.4	− 3.4	145	55	~ 1.4	24	7.5
IC 443	189.1	+ 2.9	160	40	1.5–2.0	18–24	4
MSH 15−52A	320.4	− 1.0	40	8	~ 8	19	7
SNR 1811−17	13.4	+ 0.1	~ 13	7	~ 9	19	294
Lupus Loop	330.0	+ 15.0	340	270	0.8	65	–
HB 21	89.1	+ 4.7	175	120	1.2	42	–
MSH 14−63	315.4	− 2.3	33	40	~ 2.5	30	–
References	(1)	(1)	(1)	(1)	(1,2,3)		(4)

References (1) Milne (1970)
(2) Downes (1971)
(3) Woltjer (1972)
(4) Giacconi *et al.* (1972).

of the double non-thermal radio source MSH 15–52. The radio source is again similar to Pup A, though it may be 2 or 3 times more distant (Table I). The X-ray flux at 2–6 keV is similar to Pup A, but examination of the LRL low energy survey of this region (Hill *et al.*, 1972) reveals no signal greater than ~5% of Pup A at 0.35–2.8 keV. This is generally consistent with the greater interstellar absorption for a source at 3 or 4 kpc and in the Galactic Plane.

C. SNR 1811–17

This is the third SNR which is provisionally listed as a new X-ray identification in the 2U catalogue. The corresponding X-ray source (2U 1811–17, previously Sgr X-2 and GX 13 + 1) is strong, about 0.3 Crab, apparently non-variable, and is located only 0.1° from the non-thermal radio source. If confirmed, this must be an extremely powerful supernova X-ray emitter, as compared with Kepler's supernova, believed to be at a similar distance (8–10 kpc) and having twice the radio flux at 1400 MHz, but remaining undetected at X-ray energies, shows.

3. Possible Soft X-ray Emission from Extended, Nearby Supernova Remnants

A. LUPUS LOOP

The Galactic Plane survey by the LRL Group in May 1970 (Hill *et al.*, 1972) observed a broad increase in counting rate in the direction of the Lupus Loop, a non-thermal radio source having much in common with the Cygnus Loop and also believed to be a relatively old and nearby SNR. Because of a high background nearby, this detection requires confirmation.

B. HB 21

A University of Wisconsin rocket experiment flown in December 1969 detected a further low energy source in Cygnus (Coleman *et al.*, 1971), designated Cyg X-6. The rather large error box ($1.7° \times 6°$ at 1σ) includes a part of the SNR HB 21, a remnant similar in its radio appearance to Cyg Loop. No obvious extension of the X-ray source is seen, which probably sets an upper limit of 1° or so to the main emission region. Because of the large positional uncertainty and the crowded area of sky involved this SNR association must be considered very uncertain at present.

4. Possible X-Ray Emission from Possible SNR

A. NORTH POLAR SPUR

A recent University of Wisconsin rocket experiment has revealed (Bunner *et al.*, 1972) a broad ridge of excess radiation in the <0.28 keV and 0.5–1.0 keV energy bands in general direction of the North Polar Spur (Figure 7), an extended region of non-thermal radio emission which has been suggested (Hanbury Brown *et al.*, 1960 and Elliot, 1970) to be an old and relatively nearby SNR (but see Mathewson, 1968). If confirmed, X-radiation from Galactic radio loops, such as this and the Cetus Arc, could contribute significantly to the soft X-ray background radiation.

B. ETA CARINAE

An intense low energy X-ray source was detected by the 1970 LRL Galactic survey rocket flight at $l^{\text{II}} \sim 288°$, $b^{\text{II}} \sim 4.0°$, within 0.5° of the bright infra-red star η Car which, one school of thought suggests, is a 'slow supernova'. The crude X-ray spectrum is steep and may be interpreted as thermal, with a characteristic temperature of $\sim 3 \times 10^6$ K, or non-thermal with a spectral index similar to that in the infra-red region, suggesting the X-rays could arise by inverse Compton scattering of these low energy photons. (For a distance of 1.6 kpc, $L_{\text{IR}} \sim 8 \times 10^{39}$ erg s^{-1} (Westphal and Neugebauer, 1969) and $L_x \sim 2 \times 10^{36}$ erg s^{-1})

C. MSH 14–63

A weak non-thermal radio source, located at $l^{\text{II}} = 315.4°$ and $b^{\text{II}} = -2.3°$ in the Milne list of probable SNR, lies close to the X-ray source Cen X-1. First seen in 1965 NRL survey (Byram *et al.*, 1966) this faint X-ray source has been observed latterly by the Leicester (Cooke and Pounds, 1971) and LRL (Seward *et al.*, 1971) Groups, though not by UHURU. Since each positive sighting was with plastic window detectors, these apparently conflicting results might be reconciled if the X-ray spectrum is steep, as indeed the 40′ extension of the radio source would suggest.

5. Discussion

The currently available X-ray data on Galactic SNR show a gradual 'softening' of

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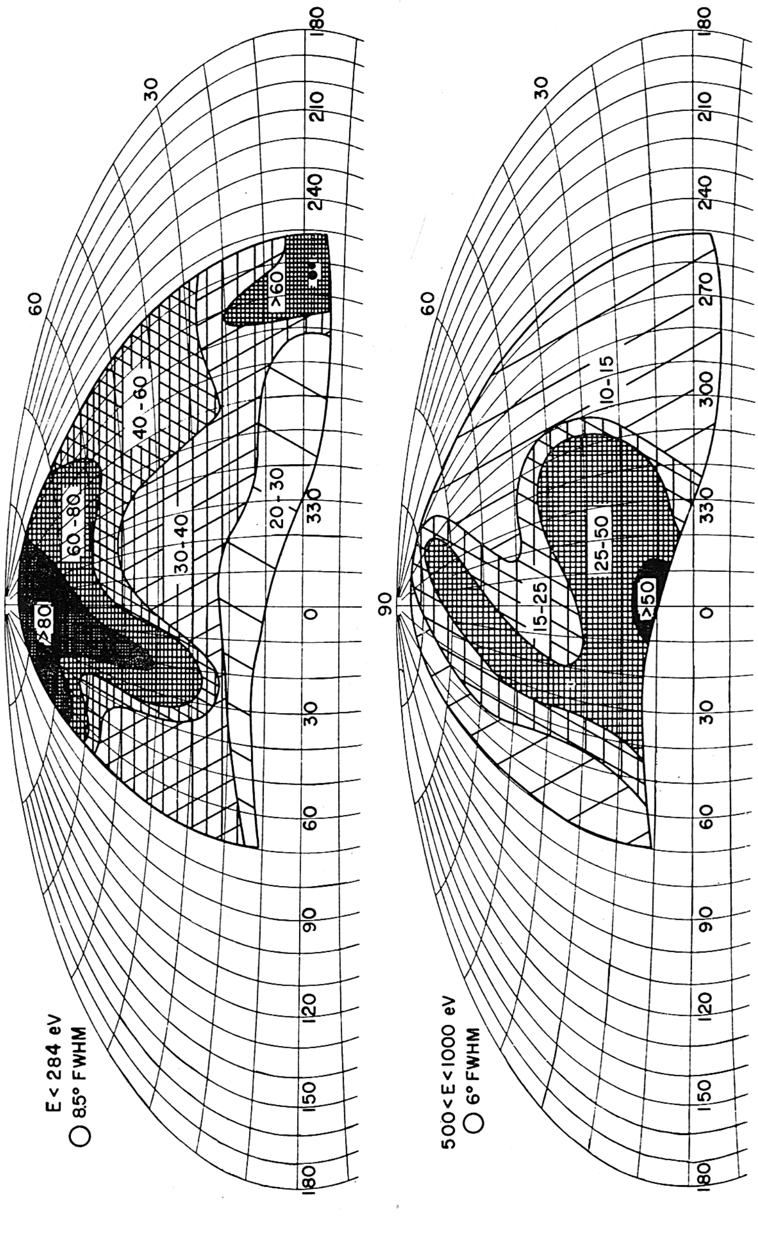

Fig. 7. X-ray isophotes at $E < 284$ eV and $500 < E < 1000$ eV showing a ridge of high intensity near the North Polar Spur (Bunner *et al.*, 1972).

the X-ray emission with increasing size (and age) of the remnant. Thus, the three youngest SNR's listed (Crab, Cas A and Tycho) are bright well into the kilovolt range. Of these, the Crab source is outstandingly bright and hard and this unique property is almost certainly attributable to the existence of the fast pulsar NP 0532, continually injecting 10^{12}–10^{13} eV electrons into the Nebula to maintain the X-ray synchrotron emission. The considerably lower X-ray to radio luminosities of Cas A and Tycho may be due to the absence of a similar central pulsar. Alternatively, it may take several centuries for a pulsar to build up the electron store to its maximum energy (Setti and Woltjer, 1972). In this way the absence of still more luminous objects (there should be ~ 10 younger SNR than Cas A if supernovae occur at a mean rate of 1 per 40 yr) may be understood also.

For only two sources does it appear that the available spectrum is adequate to firmly indicate the dominant X-ray production mechanism. These are the Crab, for which synchrotron radiation appears to be clearly established, and Cygnus Loop, almost certainly a thermal X-ray source. For the others, the X-ray emission process remains uncertain, and will remain so until better spectral (and polarization) measurements become available.

At the same time, it is interesting to consider the known and suspected SNR X-ray sources in terms of current ideas on the evolution of such remnants. Cox (1970), for example, distinguishes three phases in the expansion of a SNR shell:

I The free expansion phase, proceeding up to a time when deceleration effects of the interstellar gas become important. The diameter at this time is $D = 4 (M/M_{\odot})^{1/3} n_H^{-1/3}$ pc, where M is the ejected mass and n_H the local interstellar density.

II An adiabatic deceleration phase, during which the shell diameter increases as $D = 26 (E_0/n_H)^{1/5} (t/10^4)^{2/5}$ pc, where E_0 is the energy released in the SN explosion in units of 7.5×10^{50} erg and t is the age in years. This phase will continue until radiation losses (mainly by X-radiation) become significant compared with E_0.

III A momentum-conserving phase, in which the diameter increases as $D \sim (M_0 v_0)^{1/4} n_H^{-1/4} t^{1/4}$ pc. Here $M_0 v_0$ is the shell momentum at the beginning of phase III.

Reference to Table I indicates that the Crab, Cas A and Tycho remnants are still in phase I or early phase II. Most of the other SNR X-ray sources listed in Table I should be within phase II and are very probably thermal emitters. During this phase the expanding shell will shock-heat the ambient interstellar gas to a temperature depending on the squared shock-wave velocity. For typical values of E_0 and n_H, the resulting temperature is given approximately by $T = 3 \times 10^6 \ t^{-6/5}$ K, for t in units of 10^4 yr (Ilovaisky and Bowyer, 1972), yielding soft X-ray spectra strong in the 0.2–2 keV energy band. During this phase the temperature of the emitting plasma will decrease, but the total 'emission measure' ($N_e^2 V$) will increase considerably as the shell grows larger. Thus, the X-ray luminosity at a given photon energy will at first rise, due to the increasing emission measure and then rapidly fall as the gas continues to cool. Further spectral and spatial observations of these older, extended X-ray sources are needed to establish the validity of this interpretation in each case. As pointed out by Woltjer (1972), correct interpretation of the X-ray production and the stage of evolution reached by a particular remnant will be vital to evaluating its energetics and unravelling its history.

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