THE ASTROPHYSICAL JOURNAL, Vol. 160, April 1970

X-RAY CHARACTERISTICS OF THREE SUPERNOVA REMNANTS

P. GORENSTEIN, E. M. KELLOGG, AND H. GURSKY
American Science and Engineering, Inc., Cambridge, Massachusetts
Received 1969 September 15; revised 1969 October 16

ABSTRACT

Spectral analyses were made of the X-ray data ($1 \leq E \leq 10$ keV) obtained during a rocket flight from two sources that have been identified with Cas A and SN 1572 (Tycho's supernova). The Crab Nebula was also observed. Relative observed counting rates from the Crab, Cas A, and SN 1572 are 1, 0.1, and 0.04, respectively. The Crab is found to have the hardest spectrum of the three. Extrapolation of the radio spectrum of Cas A and SN 1572 results in agreement with the measured intensity at 1 keV, although the spectrum appears to have steepened in the X-ray region. Interstellar attenuation affects the spectrum of Cas A to an extent that is consistent with or perhaps less than presently accepted values. Comparison of X-ray and 21-cm absorption effects in the spectrum of the supernova remnants implies that the concentration of oxygen and neon relative to hydrogen along the line of sight to the sources is at most equal to presently accepted values of cosmic abundances.

I. INTRODUCTION

The anticenter region of the galactic equator, $200° < l^{II} < 100°$, was surveyed from a sounding rocket that was flown on 1968 December 5 (23:05 MST). As a result of that flight the positions of two X-ray sources in the Cassiopeia region were determined to a precision of about one-tenth of a square degree. The positions are consistent with the locations of the two supernova remnants, Cas A and SN 1572 (Tycho's supernova). More details concerning the survey, the determination of these locations, and the identification of the X-ray sources with the supernova remnants will be given in a forthcoming paper. During the same flight, the Crab Nebula was also observed.

In this paper we report the results of a spectral analysis of the counts from each of the three sources for the energy range 1–10 keV. It is found that the spectrum of the Crab Nebula is harder than either Cas A or Tycho. There are indications of a finite amount of interstellar attenuation in the spectrum of Cas A, and upper limits have been derived for the Crab and Tycho. Comparison of these results regarding X-ray attenuation with 21-cm interstellar-absorption effects in the radio spectrum of the supernova remnants implies that the concentration of interstellar oxygen and neon relative to hydrogen along the line of sight to the sources is at most equal to the presently accepted values of cosmic abundances.

II. ANALYSIS OF THE DATA

The experimental equipment was almost identical with a payload that has been described previously (Gorenstein, Giacconi, and Gursky 1967; Gorenstein, Kellogg, and Gursky 1969). Calibration procedures, techniques for reducing the non-X-ray background, and the methods used to reduce and analyze the data were substantially the same as those described in these papers. The energy, rise-time and arrival-time information of individual proportional-counter events were contained in the telemetry records. No preselection of events other than vetoing penetrating charged particles was made prior to telemetry.

The principal modification consisted of replacing several proportional counters with new 0.001-inch beryllium-window counters so that the 0.001-inch units constituted 500 cm² of the 800 cm² effective area, the remainder being 0.003-inch units. Four detectors, each of 200 cm² effective area, were arranged in two different fields of view each $2° \times 45°$

full width at half-maximum (FWHM). The long dimensions of the fields of view were inclined +60° and −60° to the direction of scan. Scans took place at rates of 0°.5–1° sec^{-1} so that during each scan a source was within the FWHM for 2–4 seconds.

About 250, 900, and 1400 net counts within the FWHM were obtained from Tycho, Cas A, and the Crab, respectively. The Crab was observed in a single scan, and Cas A and SN 1572 were scanned several times each. Background was determined during a period of about 30 seconds while a region in Cassiopeia that was apparently free of discrete sources was within the field of view. The rise-time acceptance efficiency as a function of energy was determined from a comparison of the data obtained from the Crab within the FWHM with and without rise-time selection criteria. It was applied to all the other spectra considered. As a check upon possible systematic errors associated with the difference in intensity between the three sources we also analyzed the data obtained from the Crab outside the FWHM and the background from the source-free region. As in the previous papers, the analysis was carried out by comparing the experimental data with the computed instrumental response to an assumed spectrum with variable parameters and determining the best values of the parameters on the basis of minimum χ^2 (best fit). A major objective of the analysis was a determination of the degree to which photoelectric absorption affects the source spectrum. Whether the absorbing material is in the interstellar medium or surrounds the source itself, the photoelectric cross-section at energies above 0.9 keV is rather free of edge effects. It can be described fairly well by a single parameter, *Ea*, which represents the energy at which the opacity is 1 mean free path. Below 0.9 keV, significant changes in the cosmic photoelectric cross-section occur at the edges of oxygen and neon (Bell and Kingston 1967). Hence absorption effects at lower energies cannot be represented by a single parameter unless the elemental abundances of the absorbing medium are known.

Functions of the following form, representing the photon number per unit energy, were considered:

a) $dN/dE = A \exp[-(Ea/E)^{8/3}]E^{-E/kT}/E$, bremsstrahlung with attenuation.

b) $dN/dE = A \exp[-(Ea/E)^{8/3}]E^{-\alpha}$, power law with attenuation.

The variable parameters were *Ea* and T (or α). For each fixed set of *Ea* and T (or α), A was determined independently by minimizing the χ^2. It should be emphasized very strongly that the attenuation parameter *Ea* and the spectral-hardness parameter T (or α) are correlated and cannot be expressed independently of each other. Fitting the same data to a larger value of T (or smaller α) will result in a smaller value of *Ea*. Consequently, an error in T (or α) implies a correlated error in *Ea*. Similarly, the value of the normalization parameter A is correlated with *Ea* and T (or α). In the case of Cas A and SN 1572, because of poor statistics it is not possible from these data alone to determine whether (*a*) or (*b*) provides a significantly better fit. For the Crab, it is known from other measurements at higher energies that (*b*) is a better description.

The best fit was found by varying *Ea* and T (or α) in a search for the absolute minimum χ^2. Separate analyses were made of the data from each of the four individual detectors in addition to the combined data. In all cases except Cas A the χ^2 was acceptably low and the errors in *Ea* and T (or α) were taken as the increment in each parameter which increases the χ^2 of the combined data by 1 while the other is held fixed at its best value. For Cas A it was felt that the minimum χ^2 was not low enough for the increment to be the basis of the error estimate, so the errors were taken as the standard deviation of the results from the four individual detectors.

III. RESULTS

Each of the sources is discussed below. Only for Cas A do we believe that we have observed a finite value of *Ea*. For the others, the probability associated with the minimum χ^2 is not improved significantly by allowing *Ea* to vary as a free parameter. The upper limit was taken as that value of *Ea* which increased the minimum χ^2 of the two-parameter fit by one unit.

The data from the Crab that appeared outside the FWHM points were consistent with the larger number of data that appeared inside. This indicates that no spectral distortions were introduced in the application of a rise-time acceptance efficiency. To an extent it is also a check upon the background subtraction.

a) Crab Nebula

This observation was consistent with a measurement made by us on 1968 February 2 (Gorenstein *et al.* 1969) for a somewhat narrower range of energy. Comparing the two results, we conclude that the intensity of the Crab Nebula remained constant to within 10 percent in 1968 between February 2 and December 5. The combined spectrum from both measurements is:

$$dN/dE = (9.0^{+0.7}_{-1.0})E^{-2.0\pm0.1} \text{ photons (cm}^2\text{ sec}^{-1}\text{ keV}^{-1}), \; 1 < E < 12 \text{ keV}\,,$$
$$Ea \leq 0.9 \text{ keV}\,.$$

The error in the normalization constant refers only to the part that is correlated with the error in the spectral index. In addition there is also an error of about ± 8 percent due to counting statistics, uncertainties in effective area, etc. Analysis of the data outside the FWHM gave essentially the same result but a less precise one. The upper limit on Ea is in agreement with the value previously reported by Rappaport, Bradt, and Mayer (1969). It is also consistent with the results of Grader *et al.* (1970), who report a finite amount of absorption at lower energies. The interstellar-attenuation characteristics of Bell and Kingston (1967) require a column density of matter along the line of sight to the Crab that is equal to from one-third to two-thirds of our upper limit in order to explain their observed effect.

A compilation of selected recent measurements of the X-ray spectrum of the Crab Nebula is shown in Figure 1. All of the data shown plus those of Boldt, Desai, and Holt (1969) are consistent with an almost constant spectral index of about 2 above 1 keV. Points at lower energy reported by Grader *et al.* (1970) are consistent with an extrapolation of this spectrum to lower energies and presently accepted values of interstellar attenuation along the line of sight to the Crab.

b) Cas A

Neither the simplified thermal nor the power-law expressions provided a fit to the data from Cas A with a value of χ^2 that was acceptably low. This could be either a result of systematic errors or an indication that the spectrum of Cas A is more complex. However, in both cases the fits were improved considerably by a finite value of Ea. Due to the correlation between Ea and T (or α), the normalized expression for our result on Cas A is necessarily somewhat cumbersome. Below we present equations that represent the most probable expression for the number of photons (cm^2 sec^{-1} keV^{-1}) and two bounds. The true spectral function lies in the region defined by the two bounds. The units of E in the expressions below for Cas A and Tycho are keV, and the energy range is $1 < E < 10$ keV.

Power Law:

Most probable: $dN/dE = 3.7 \exp[-(1.35/E)^{8/3}]E^{-3.3}$,

First bound: $dN/dE = 8.3 \exp[-(1.67/E)^{8/3}]E^{-3.9}$,

Second bound: $dN/dE = 1.7 \exp[-(0.9/E)^{8/3}]E^{-2.7}$;

Thermal:

Most probable: $dN/dE = 3.5 \exp[-(1.13/E)^{8/3}] \exp[-E/1.25]/E$,

First bound: $dN/dE = 6.5 \exp[-(1.37/E)^{8/3}] \exp[-E/1.00]/E$,

Second bound: $dN/dE = 1.7 \exp[-(0.64/E)^{8/3}] \exp[-E/1.67]/E$.

Figure 2 shows the data on the observed counting rate from Cas A plus the computed instrumental response to both of the "most probable" fits. In addition to the uncertainty in the normalization that is correlated to the other parameters, there is an error of about ± 10 percent in the normalization constant due to uncertainties in counting statistics, effective area, detector-window thickness, etc.

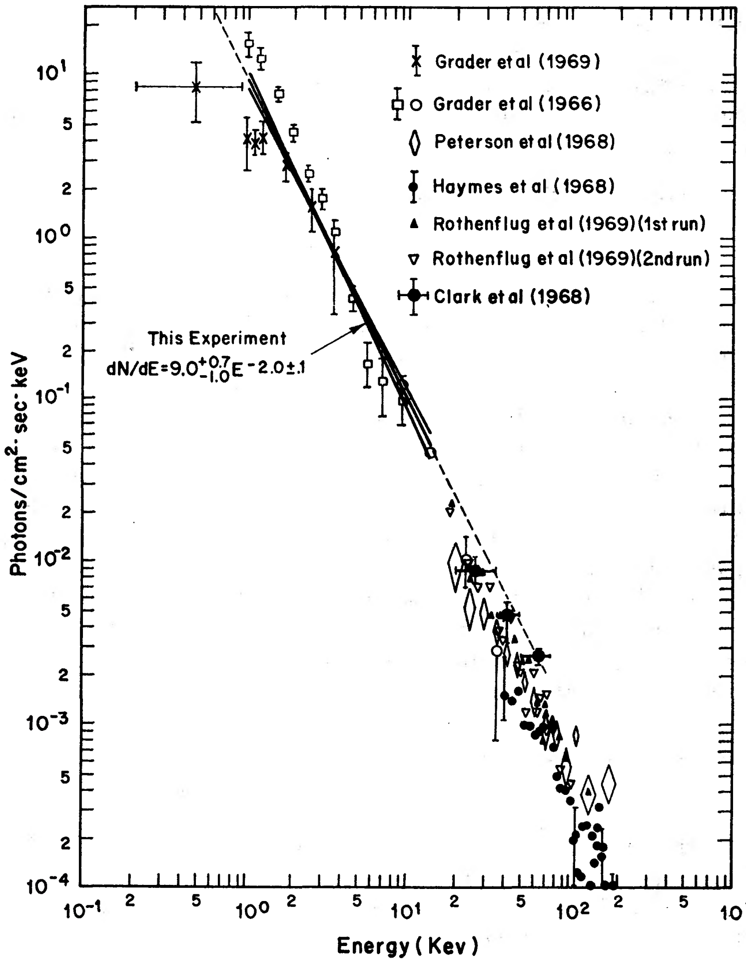

FIG. 1.—Selected measurements of the spectrum of the Crab Nebula. The dashed line is the extrapolation of the best fit to the data of this experiment. The lowest energy point of Grader *et al.* (1970; shown on figure as 1969) is significantly affected by interstellar attenuation.

c) Tycho

The best fits for the number of photons (cm^2 sec^{-1} keV^{-1}) are:

Power Law: $dN/dE = (0.44 \pm 0.11)E^{-2.3\pm0.3}$ $(Ea \leq 1.6 \text{ keV})$;

Thermal:

Most probable: $dN/dE = 0.49 \exp[-E/2.20]/E$,

First bound: $dN/dE = 0.71 \exp[-E/1.61]/E$,

Second bound: $dN/dE = 0.28 \exp[-E/3.6]/E$ $(Ea \leq 1.4 \text{ keV})$.

In addition, the statistical error in the normalization is ± 12 percent; including the systematic errors brings the total uncorrelated uncertainty in the normalization constant of Tycho's spectrum to about ± 17 percent. Figure 3 shows the data on the observed counting rate from Tycho plus the computed instrumental response to the most probable fits.

d) Background

Events from Cas A and Tycho were accompanied by a considerable contribution from background. In fact, the ratios of signal to background counts were about one for Cas A and one-half for Tycho. Under these conditions, if the background spectrum that is sub-

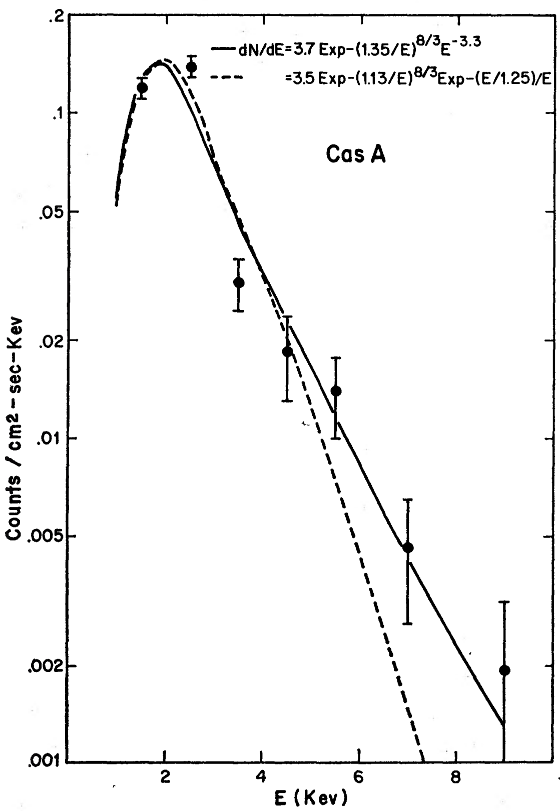

FIG. 2

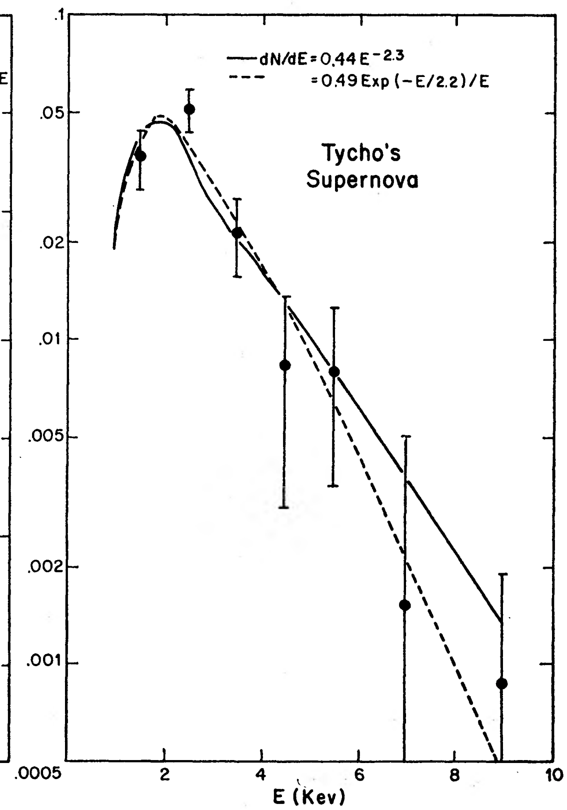

FIG. 3

FIG. 2.—Counting-rate spectrum of Cas A as observed in this flight with 0.001-inch beryllium-window proportional counters. Solid and dashed curves are smoothly drawn connections between computed points that represent the response of the detectors to the power-law and thermal spectra that fit the data most closely. Observed data points consist of intervals whose width is 1 keV centered at 1.5, 2.5, . . . , 5.5 keV, plus 2-keV intervals centered at 7.0 and 9.0 keV.

FIG. 3.—Counting-rate spectrum of SN 1572 (Tycho's supernova). See Fig. 2 caption for further details.

tracted from the sources is not constant, then a considerable error is introduced, particularly as the background appears to have a much harder spectrum than either of the two sources. Principally to assay the quantity and quality of the background, a spectral analysis was made of the diffuse X-ray component which accounted for about 85 percent of the total background. The non-X-ray component was removed by subtracting the rate of events observed early in the flight 20 seconds prior to opening a 0.040-inch aluminum door in front of the detectors. The region in Cassiopeia that provided the 30 seconds of background data was bounded by the galactic coordinates $150° \leq l^{II} \leq 100°$, $30 > b^{II} > -18°$. Time intervals in which Cas A and Tycho were within the field of view were excluded. Possible unresolved discrete sources could not have made a significant contribution.

The diffuse X-ray component was found to be consistent to within 10 percent with the spectrum that we had previously reported (Gorenstein *et al.* 1969) for an adjacent region of the sky, $190° \leq l^{II} \leq 150°$, $-70° < b^{II} < 80°$. From this we conclude the background that was subtracted from Cas A and Tycho was relatively free of systematic errors and hence was likely to have remained constant while on the sources. Combining the two diffuse X-ray measurements, we find that a more precise value for the spectral index for $1 < E < 12$ keV is 1.6 ± 0.1 as compared with 1.7 ± 0.2 given in the previous paper. This implies a reduction of about 12 percent in the best value of the normalization constant. No other conclusions of the previous paper are affected by this small change in the index. There is no indication of low-energy attenuation in the diffuse X-ray spectrum. The lower limit of Ea is 0.9 keV at an average b^{II} of about 13°.

IV. PULSAR EFFECTS

Arrival times of individual counts were recorded to a precision of about 1 msec. The distribution of arrival times from each source was examined for indications of preferred frequencies. As there were not many counts (and large background levels in the case of Cas A and Tycho) compared with observations that have already reported a positive

TABLE 1

UPPER LIMITS FOR EXISTENCE OF PULSAR EFFECT* FOR $0.008 \leq T \leq 0.035$ sec

Source	Upper Limit† (percent)
Crab Nebula	10
Cas A	15
Tycho	19

* For single pulse occupying one-tenth of period.
† 99 percent confidence level.

result for the Crab (Fritz *et al.* 1969); Bradt *et al.* 1969), the search was relatively insensitive. It was carried out by trying a period, dividing it into ten intervals of uniformly increasing phase, and folding all the counts acquired while on a source about this period. The number of counts in each of the ten intervals was tested for significant positive deviation from the average per interval. About 10^5 trial periods from 8 to 35 msec were examined in steps that were sufficiently finely spaced to cover this range of periods and the 120-sec time spread of the events from Cas A and Tycho. In all cases the distribution of positive deviations was consistent with what would be expected with data that are randomly distributed in time, even though instances in which the departure from the mean exceeds 4 standard deviations occur occasionally in 10^5 trial periods. The data from the Crab were also consistent with the results of Fritz *et al.* (1969) and Bradt *et al.* (1969). Upper limits (99 percent confidence level) for the three sources are given in Table 1. They apply only to periods between 8 and 35 msec and for the situation in which a pulse occupies no more than one-tenth of the total period. For situations in which the pulse occupies a larger fraction of the period, the upper limits are larger.

V. DISCUSSION

a) Spectral Characteristics

Characteristics of the three supernova remnants are summarized in Table 2. Figure 4 shows the electromagnetic spectra of the three supernova remnants over a broad range of frequency. The X-ray data of Cas A and Tycho are represented by their respective power-law fits. For both Cas A and Tycho it is remarkable that the radio spectrum extrapolates, possibly fortuitously, through seven decades of frequency to meet the

X-ray results at 1 keV. However, in both cases the spectrum has steepened considerably in the X-ray region.

To within a factor of 3 or so, depending on the true distances to the objects, the X-ray emission of Cas A and Tycho are qualitatively similar (within the resolution of this experiment), although the former has been described as a Type II supernova explosion and the latter as a Type I. If there are substantial differences between Type I and Type II supernova remnants, the differences are not apparent from these X-ray observations.

The apparent agreement between the extrapolation of the radio spectrum and the X-ray data could be interpreted as favoring the hypothesis that the X-ray emission of Cas A and Tycho, like that of the Crab, is nonthermal in origin. However, the data on X-ray emission by themselves are also consistent with thermal processes that have been suggested for supernovae. Shklovsky (1968) has considered the X-ray emission due to the interaction of the interstellar medium with an expanding shell that has been ejected by a Type II supernova explosion. A ring-shaped thermal plasma will be produced whose temperature is sufficient for X-ray emission. Such a model is presumably applicable to Cas A. In fact, the intensity at the Earth from Cas A is about as large as

TABLE 2

X-RAY CHARACTERISTICS OF THREE SUPERNOVA REMNANTS

Source	Relative Counts* 1–12 keV	Spectral Index	Temperature (10^6 ° K)
Crab Nebula..........	1	2.0±0.1	...
Cas A................	0.1	3.3±0.6	15±6
SN 1572..............	0.04	2.3±0.3	25 (+17, −6)

* As observed in proportional counter with 0.001-inch beryllium window, 1 atm P-10 filling 5 cm deep.

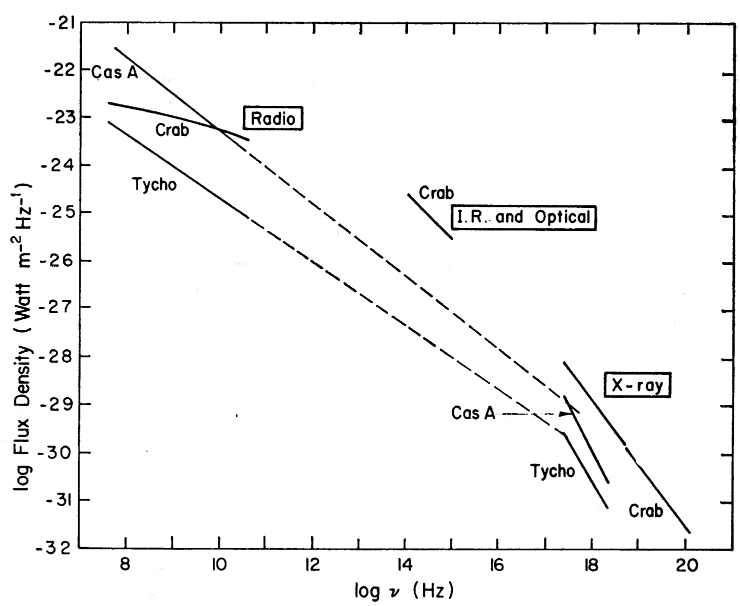

FIG. 4.—Electromagnetic spectra of three supernova remnants over a broad frequency range. Radio data have been taken from table of Poveda and Woltjer (1968). X-ray data are represented by power-law fits.

Shklovsky predicts: an order of magnitude smaller than the Crab. However, the characteristic temperature of the X-ray emission falls short by a factor of 5 from the value estimated. Sartori and Morrison (1967) have described how thermal X-ray emission could occur in nonthermal radio sources. They selected the Crab as the prototype object for this effect. Clearly, as Figure 1 illustrates, the Crab was a poor choice. However, Cas A and Tycho are still possible candidates for being this kind of object. In particular, the temperature and intensity of Tycho are in reasonable agreement with the values they predict.

b) Interstellar Attenuation

Attenuation effects in the X-ray spectra of supernova remnants can be used to measure the opacity of the interstellar medium. Furthermore, the combination of effects of X-ray and radio absorption determines the abundance of heavier elements relative to hydrogen along the line of sight to the object, provided there is knowledge of the kinetic spin temperature. Interpretations of this nature require that the absorption not be intimate to the source. If the volume of X-ray emission is comparable to that of the radio emission, the mass content of the nebula can never be large enough to impose appreciable absorption. Measurements of the angular size of the Crab have indeed shown that most of the X-ray emission originates from an extended volume (Bowyer *et al.* 1964; Oda *et al.* 1967). Pulsar effects in the Crab imply that at least 9 percent is from a small volume. Nothing is known as yet concerning the X-ray angular size of Cas A or Tycho. The lack of a conspicuous central object in either nebula (van den Bergh and Dodd 1969 [Cas A]), plus the negative result on the existence of a strong pulsar effect, is at least consistent with the notion that the X-ray sizes of Cas A and Tycho are extended. Muller (1957), Clark (1965), and others have observed absorption effects of interstellar hydrogen in the continuum radio emission of the Crab and Cas A. Two groups of absorption maxima corresponding to discrete gas complexes in the Orion and Perseus arms are seen for Cas A, and a single group corresponding to the Orion arm is seen for the Crab. No such measurements have been reported for SN 1572. Presumably it will show effects from both arms similar to Cas A. For an assumed kinetic temperature that has generally been taken as 100°–125° K, the amount of hydrogen along the line of sight can be calculated from the 21-cm absorption profiles.

Absorption effects in the X-ray continuum of the supernova remnants results from heavier elements in the interstellar gas. For wavelengths longer than 23.3 Å, most of the attenuation is due to helium. For wavelengths shorter than 14.2 Å, the region of the present measurements, oxygen and neon account for most of the attenuation. Hence, in principle, measurements of absorption features in the X-ray region in conjunction with the radio region determine the abundance of several heavier elements along the line of sight to the supernova remnants relative to hydrogen. Alternately, if there is prior knowledge of the relative abundances, such as the generally accepted cosmic values, then the X-ray absorption determines the amount of hydrogen. A comparison of it with the hydrogen absorption in the radio region provides an estimate of the kinetic temperature of the interstellar medium.

Table 3 compares the observed X-ray attenuation with predictions based on the observed 21-cm absorption features and the cosmic X-ray absorption coefficients of Bell and Kingston (1967). The X-ray attenuation parameters are those based on the power-law fits to the spectra. To our knowledge, no 21-cm measurements of interstellar absorption have as yet been reported for Tycho. In the absence of data we assume that the quantity of hydrogen along the line of sight is the same for Tycho as for Cas A.

The principal conclusion that can be drawn from a comparison of the radio and X-ray attenuation measurements is that the interstellar medium is not more opaque to X-rays than the model of Bell and Kingston suggests and could be less opaque. This implies in turn that the abundance of oxygen and neon relative to hydrogen in the interstellar gas is not more than the presently accepted values.

Two recent observations of the diffuse X-ray background at low energy (0.28 keV) have indicated considerably less interstellar attenuation than expected on the basis of the known distribution of galactic hydrogen (Bowyer, Field, and Mack 1968; Bunner *et al.* 1969). Bowyer and Field (1969) explain the disparity by a quantitative model in which the interstellar matter is largely contained in clouds. In this model the clouds are opaque at low energies so that their absorption properties are not fully utilized. Above 1 keV where the clouds are no longer opaque the behavior of the "cloudy" interstellar medium does not appreciably differ from that of a uniform one. Our most probable result for the attenuation along the line of sight to Cas A indicates that interstellar absorption above 1 keV is indeed much closer to the value expected from a uniform

TABLE 3

COMPARISON OF OBSERVED X-RAY ATTENUATION WITH PREDICTIONS

Source	N_H (atoms cm^{-2})*	Ea_{calc} (keV)†	Ea_{obs} (keV)
Crab Nebula	1.6×10^{21}	0.73	≤ 0.9
Cas A	1.0×10^{22}	1.55	1.35 (+0.32, −0.45)
SN 1572 (Tycho's supernova)	(1.0×10^{22})‡	(1.55)‡	≤ 1.6

* Muller (1957) and Clark (1965).

† Calculated according to cross-sections of Bell and Kingston (1967).

‡ We assume that the column density along the line of sight is the same for Tycho as for Cas A.

interstellar medium (although the uncertainty cannot exclude a discrepancy like that observed at low energy). If the Cas A direction is assumed to be typical of the Galaxy, then our result, in conjunction with those of Bowyer *et al.* (1968) and Bunner *et al.* (1969), appears to support the model of a "cloudy" interstellar medium.

We appreciate the efforts of Dr. R. Talbot of Rice University, who carried out the search for pulsar effects, and H. Zmijewski, who helped in the analysis of the data. Informative discussions with Professor B. Burke of MIT and Professor G. Garmire of Caltech are gratefully acknowledged. We would like to thank R. Giacconi of AS&E for his comments on this paper. The support of the sounding rocket branch of the Goddard Space Flight Center and the Navy personnel at the launch facility of the White Sands Missile Range is very much appreciated. This work was supported by the Office of Space Science Applications of the National Aeronautics and Space Administration under contracts NASW-1796 and NASW-1888.

REFERENCES

Bell, K. L., and Kingston, A. E. 1967, *M.N.R.A.S.*, **136**, 241.
Bergh, S. van den, and Dodd, W. W. 1969, *Nature*, **223**, 814.
Boldt, E., Desai, U., and Holt, S. 1969, *Ap. J.*, **156**, 427.
Bowyer, C. S., Byram, E. T., Chubb, T. A., and Friedman, H. 1964, *Science*, **146**, 912.
Bowyer, C. S. , and Field, G. B. 1969, *Nature*, **223**, 573.
Bowyer, C. S., Field, G. B., and Mack, J. E. 1968, *Nature*, **217**, 32.
Bradt, H., Rappaport, S., Mayer, W., Nather, R. E., Warner, B., MacFarlane, M., and Kristian, J. 1969, *Nature*, **222**, 728.
Bunner, A. N., Coleman, P. C., Kraushaar, W. L., McCammon, D., Palmieri, A., Shilepsky, A., and Ulmer, M. 1969, *Nature*, **223**, 1222.
Clark, B. G. 1965, *Ap. J.*, **142**, 1398.
Clark, G. W., Lewin, W. H. G., and Smith, W. B. 1968, *Ap. J.*, **151**, 21.
Fritz, G., Henry, R. C., Meekins, J. F., Chubb, T. A., and Friedman, H. 1969, *Science*, **164**, 709.
Gorenstein, P., Giacconi, R., and Gursky, H. 1967, *Ap. J.* (*Letters*), **150**, L85.
Gorenstein, P., Kellogg, E. M., and Gursky, H. 1969, *Ap. J.*, **156**, 315.
Grader, R. J., Hill, R. W., Seward, F. D., and Toor, A. 1966, *Science*, **152**, 1499.
Grader, R. J., Hill, R. W., Seward, F. D., and Hiltner, W. A. 1970, *Ap. J.* **159**, 201.

Haymes, R. C., Ellis, D. V., Fishman, G. J., Kurfess, J. D., and Tucker, W. H. 1968, *Ap. J.* (*Letters*), **151**, L9.
Muller, C. A. 1957, *Ap. J.*, **125**, 830.
Oda, M., Bradt, H., Garmire, G., Spada, G., Sreekantan, B. V., Gursky, H., Giacconi, R., Gorenstein, P., and Waters, J. R. 1967, *Ap. J.* (*Letters*), **148**, L5.
Peterson, L. E., Jacobson, A. S., Pelling, R. M., and Schwartz, D. A. 1968, *Canadian J. Phys.*, **46**, 437.
Poveda, A., and Woltjer, L. 1968, *A.J.*, **73**, 65.
Rappaport, S., Bradt, H. V., and Mayer, W. 1969, *Ap. J.* (*Letters*), **157**, L21.
Rothenflug, R., Boclet, D., Claisse, J. Durouchoux, P., and Rocchia, R. 1969 (submitted to *Astr. and Ap.*).
Sartori, L., and Morrison, P. 1967, *Ap. J.*, **150**, 385.
Shklovsky, I. S. 1968, *Supernovae* (New York: Interscience Publishers), p. 163.