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X-RAY SPECTRA OF THE CASSIOPEIA A AND TYCHO SUPERNOVA REMNANTS AND THEIR ELEMENT ABUNDANCES

HIROSHI TSUNEMI, KOUJUN YAMASHITA, AND KUNIAKI MASAI[1]
Department of Physics, Faculty of Science, Osaka University
SATIO HAYAKAWA
Department of Astrophysics, Faculty of Science, Nagoya University
AND
KATSUJI KOYAMA
Institute of Space and Astronautical Science, Tokyo
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ABSTRACT

X-ray spectra of the supernova remnants Cas A and Tycho were obtained with the gas scintillation proportional counters on board *Tenma*. The observed spectra can be well fitted with single thermal bremsstrahlung continuum spectra with several emission features due to line blends of silicon, sulfur, argon, calcium, and iron. The mean energies of these line blends cannot be accounted for by invoking an equilibrium ionization model, but a simple, nonequilibrium model gives satisfactory agreement with the data. In particular, the mean energy of each of the five line blends implies a value for the ionization time scale (the product of the electron density and time) of 1.0×10^{11} cm^{-3} s and 6.0×10^{9} cm^{-3} s for Cas A and for Tycho respectively. The line intensities compared with those predicted by the nonequilibrium model give the element abundances in these objects. The results support current models of Type I and Type II supernovae.

Subject headings: nebulae: abundances — nebulae: supernova remnants — X-rays: sources

I. INTRODUCTION

Recently the nuclear synthesis in supernovae (SNs) and the ejection of heavy elements by their explosions have been calculated quantitatively, and the results have been compared with the solar abundances of elements (Woosley and Weaver 1982; Nomoto, Thielemann, and Yokoi 1984) and with the spectra of Type I SNs (Woosley, Axelrod, and Weaver 1984; Branch *et al.* 1985). Since these methods of comparison are not free from additional assumptions, such as the SN explosion rate for the element abundances and mixing with outer envelope materials for the absorption spectrum, it is desirable to obtain further information by different means. X-ray spectroscopy of supernova remnants (SNRs) may provide a means of obtaining the element abundances in SN ejecta.

For example, for young SNRs (such as Cas A and Tycho) the reverse shock waves which propagate backward into the ejecta may dominate the X-ray emission (McKee 1974), so that X-ray spectroscopy may provide direct evidence for the synthesis of heavy elements in the SN event. Even for older SNRs, where the X-ray emission is due primarily to the effects of the blast wave, there may be sufficient mixing between the circumsource material and the ejecta for X-ray spectroscopy to reveal heavy-element enhancements (Canizares and Winkler 1981).

Cas A and Tycho are well-known remnants of Type II and Type I SNs which exploded ~ 300 yr ago and in 1572 respectively. They form irregular but basically circular shells in radio and in X-rays with angular radii of 1.′8 (Dickel *et al.* 1982) and 4′ (Reid, Becker, and Long 1982), which correspond to 1.6 pc and 2.9 pc for the assumed distances of 3 kpc and 2.5 kpc (Raymond 1984) respectively. The bright X-ray shells of Cas A and Tycho are probably associated with the reverse shocks, while the expanding shocks are likely to produce faint, outer shells (Raymond 1984).

There have been a number of high-quality X-ray spectroscopic measurements of Cas A and Tycho over the past decade. The existence of a silicon line at 1.8 keV in Tycho was suggested by Coleman *et al.* (1973). Hill, Burginyon, and Seward (1975) detected the silicon line from Cas A and Tycho to be stronger by an order of magnitude than expected for the cosmic abundance of silicon. A spectroscopic observation of better quality was performed by Becker *et al.* (1979, 1980) in the energy range of 0.5–4.5 keV with a solid-state spectrometer (SSS) on board the *Einstein Observatory*. They observed emission lines of helium-like ions of magnesium, silicon, sulfur, calcium, and so forth superposed on a continuum represented by thermal bremsstrahlung spectra at two different temperatures. The focal plane crystal spectrometer on board the *Einstein Observatory* observed Doppler-shifted emission lines of silicon and sulfur in Cas A at a high spectral resolution (Markert *et al.* 1983). Serlemitsos *et al.* (1973) detected iron line emission from Cas A around 7 keV. Pravdo *et al.* (1980) observed these objects in the energy range of 0.5–20 keV with proportional counters on board *HEAO 1* and detected silicon and sulfur K line blends and iron/nickel L and K line blends superposed on continua represented by a combination of thermal bremsstrahlung spectra of two temperatures.

In most earlier works the element abundances were derived by the collisional ionization equilibrium model, although Cas A and Tycho are probably too young to have reached ionization equilibrium. The observed results should be analyzed with a nonequilibrium ionization model, as has been successfully applied by Itoh (1977), Hayakawa *et al.* (1979), Pravdo and Nugent (1983), and Shull (1983), among others.

In order to obtain more definitive information on the element abundances in these young SNRs, we observed Cas A

[1] Yukawa Research Fellow from Nagoya University; now at Institute of Plasma Physics, Nagoya University.

and Tycho with the X-ray astronomy satellite *Tenma*, taking advantage of the good energy resolution of gas scintillation proportional counters (GSPC). We thus obtained rather accurate line energies and line intensities. The present paper reports on the results of these observations and the application of a nonequilibrium ionization model to derive model parameters and the element abundances.

II. OBSERVATION AND DATA ANALYSIS

We observed Cas A and Tycho with eight GSPCs on board *Tenma* on 1983 October 7–10 and November 2–4 respectively, the effective observation time for each being $\sim$15,000 s. The GSPCs possess an effective area of 640 cm^2 and an energy resolution of 9% at 6 keV (Koyama *et al.* 1984). Using only the data not heavily contaminated by particle background, we obtained on-source data after subtracting the background in the vicinity of the sources and making aspect corrections.

The pulse height spectra thus obtained for Cas A and Tycho are shown in Figure 1 (error bars are $\pm 1\,\sigma$ statistical). Above 5 keV, each of them can be well represented by a thermal bremsstrahlung spectrum and a prominent emission line identified with the Kα emission of iron. A weak enhancement at $\sim$8 keV is indicated for Cas A and corresponds to the Kβ line of iron. If the thermal bremsstrahlung spectra are extrapolated to low energies, there are large residuals left, which in some earlier works were interpreted as due to thermal bremsstrahlung components of low temperatures. However, we notice two prominent peaks at about 1.9 keV and 2.5 keV, which can be identified with silicon and sulfur Kα line blends respectively. Moreover, there are two shoulders at about 3.1 keV and 3.9 keV, which can be identified with argon and calcium Kα line blends respectively (Koyama and Tsunemi 1984). Fitting the observed spectra with the model spectra including these lines, we still find small residuals left in gaps between these lines. The gaps can be filled by the addition of lines corresponding to silicon and sulfur Kβ.

After such trial fittings, we attempted to fit each observed spectrum with that expected for a thin thermal bremstrahlung plasma of a single temperature, taking into account the interstellar absorption and eight emission lines, which roughly correspond to the Kα lines of silicon, sulfur, argon, calcium, and iron and the Kβ lines of silicon, sulfur, and iron. The electron temperature T of the thermal bremsstrahlung, the continuum intensity, the line energies, the line intensities, and the line width of iron Kα were left as free parameters for fitting each spectrum. The iron Kα line width was allowed to be a free parameter because it was the only line blend which could potentially have a width greater than the resolution of the GSPC (in fact, the iron blend was found to be consistent with a single, unbroadened line). The hydrogen column density N_H for absorption was fixed at 1×10^{22} H cm^{-2} (Murray *et al.* 1979). In fact, the counter window of 100 μm thick beryllium is so thick that the result is rather insensitive to the value of N_H. Thus, we found the χ^2 minima of 81.3 and 64.3 for 74 and 69 data points of Cas A and Tycho spectra respectively, a formally adequate fit. The best-fit spectra obtained in this way as well as the contributions of individual line components are shown by solid lines in Figure 1. The best-fit values of 19 parameters are given in Table 1.

A remark may be necessary to clarify the line designation. The Kα line designates a blend of the $n = 2$ to $n = 1$ transitions of ions; for iron, for example, this covers the energy range 6.4 keV (neutral iron) to 6.97 keV (Fe XXVI). "Line energy" refers to the intensity-averaged energy of these lines blended. The Kβ lines are relatively weak and may be partly confused with nearby Kα lines; for example, silicon Kβ lies midway between silicon Kα and sulfur Kα. Because of the poorer statistical significance of the Kβ line blends and possible confusion with their strong Kα neighbors, we have not used the Kβ results in any of the following discussion.

Since the line energies are of great importance in the following discussions, we here describe the method of energy cali-

TABLE 1

OBSERVATIONAL RESULTS[a] FOR SUPERNOVA REMNANTS

A.

Component	Cassiopeia A: Temperature (keV)	Cassiopeia A: Intensity (2–10 keV) ($\times 10^{-10}$ ergs cm^{-2} s^{-1})	Tycho: Temperature (keV)	Tycho: Intensity (2–10 keV) ($\times 10^{-10}$ ergs cm^{-2} s^{-1})
Continuum	3.76 ± 0.10	11.3 ± 0.9	2.9 ± 0.3	1.7 ± 0.4

B.

Line[b]	Cassiopeia A: Line Energy (keV)	Cassiopeia A: Line Intensity ($\times 10^{-3}$ photons cm^{-2} s^{-1})	Tycho: Line Energy (keV)	Tycho: Line Intensity ($\times 10^{-3}$ photons cm^{-2} s^{-1})
Si Kα	1.94 ± 0.02	65.6 ± 2.8	1.84 ± 0.02	62.0 ± 1.9
Si Kβ	2.23 ± 0.08	15.0 ± 4.2	2.08 ± 0.04	10.9 ± 1.2
S Kα	2.53 ± 0.03	32.6 ± 4.2	2.38 ± 0.02	17.4 ± 0.66
S Kβ	2.88 ± 0.15	4.2 ± 1.5	2.65 ± 0.06	2.9 ± 1.10
A Kα	3.18 ± 0.03	7.8 ± 1.4	3.06 ± 0.02	2.0 ± 0.23
Ca Kα	3.89 ± 0.02	2.8 ± 0.33	3.76 ± 0.04	0.47 ± 0.11
Fe Kα[c]	6.59 ± 0.02	3.6 ± 0.37	6.40 ± 0.03	0.61 ± 0.09
Fe Kβ	7.67 ± 0.15	0.27 ± 0.13	...	< 0.25

NOTE.—Errors shown here are statistical at the 90% confidence level.

[a] Derived from the model of one continuum and eight emission lines with $N_H = 1 \times 10^{22}$ H atoms cm^{-2}.

[b] Candidate mainly contributing to this line.

[c] Line width of Fe Kα is <0.3 keV for Cas A and <0.4 keV for Tycho.

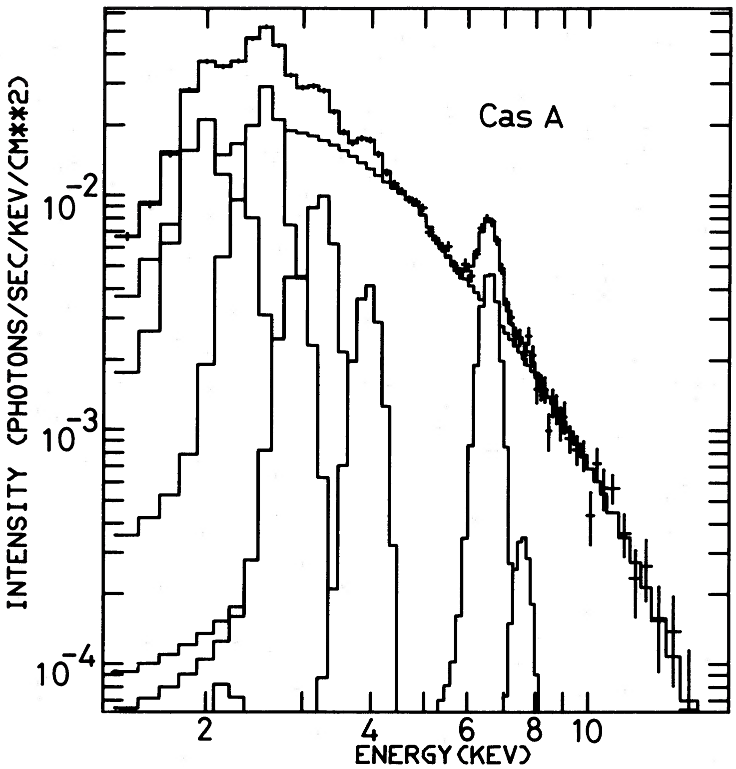

FIG. 1*a*

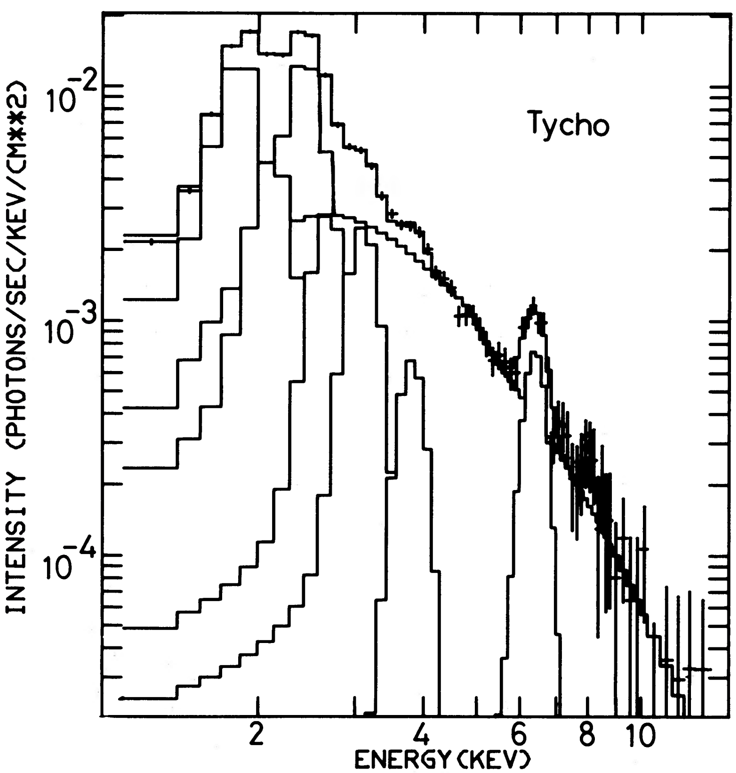

FIG. 1*b*

FIG. 1.—The X-ray spectra for (*a*) Cas A and (*b*) Tycho. The crosses show the pulse height spectra with $\pm 1\,\sigma$ statistical error bars obtained with GSPCs on board *Tenma*. Superposed on the data points is the best-fit model spectra folded by the detector response. Each of the best-fit model spectra contains one continuum spectrum and eight emission lines, as also shown by solid histograms for individual components.

bration. Each counter is continuously calibrated in flight by a radioactive source ^{109}Cd which emits the silver Kα line of 22.10 keV. In addition, the thorium Lα line of 12.97 keV arises from contamination in the beryllium window. Furthermore, the copper Kα of 8.04 keV is mainly produced by particles in ambient space and high-energy X-rays hitting bronze collimator materials. These lines provide a precise energy scale within an accuracy of 30 eV. The pulse height spectra obtained for individual counters are adjusted to a common energy scale by reference to these calibration lines. The line energies below 4.5 keV thus obtained are in good agreement with those obtained with the SSS on board the *Einstein Observatory* (Becker *et al.* 1979, 1980).

The previous observation with conventional proportional counters on board *HEAO 1* obtained the line energies of iron Kα line blend for Cas A and Tycho as $6.81^{+0.05}_{-0.07}$ keV and $6.62^{+0.09}_{-0.07}$ keV respectively (Pravdo *et al.* 1980). Manzo *et al.* (1983), using GSPCs on board a sounding rocket, obtained a still higher line energy of 6.95 ± 0.10 keV for Cas A. Comparing the results of Pravdo *et al.* (1980) with the iron Kα line energies of 6.59 ± 0.02 keV for Cas A and 6.40 ± 0.03 keV for Tycho obtained with *Tenma*, the difference of line energies between these sources is equal for the two satellites to within the statistical uncertainty, whereas the absolute values given by Pravdo *et al.* (1980) are ~ 0.2 keV higher than ours, a difference with a statistical significance of more than $3\,\sigma$. A similar discrepancy exists between the *Tenma* and Manzo *et al.* (1983) results. If we adopt our values of the iron Kα line energies and line widths, the iron Kα line blend observed in Cas A does not indicate an anomalously high state of ionization (Itoh and Fabian 1984), while that in Tycho indicates an anomalously low state of ionization.

III. MODEL OF YOUNG SUPERNOVA REMNANTS

The observational results in the preceding section indicate that the X-ray spectra of Cas A and Tycho can be fitted with models of thermal emission from thin hot plasmas of single temperatures. In this section we derive model parameters from our observational results.

If the temperatures of $\sim$2–4 keV derived from the continuum spectra are taken for granted, a question arises why the line energies are as low as given in Table 1; at these temperatures silicon and sulfur would have to be mostly hydrogen-like or fully ionized, and their energies of Kα lines would be 2.01 keV and 2.62 keV respectively, if ionization equilibria were attained. A systematic deviation of the line energies from those expected for ionization equilibria indicates that the X-ray emitting plasmas in these SNRs have not yet reached ionization equilibria but are in transient ionizing phases. This is understandable because both Cas A and Tycho are young, their ages being $\sim$300 yr and 410 yr respectively.

In order to interpret our data, we have developed a model (Masai 1984) in which an initially cool ($kT \approx 1$ eV) plasma is shock-heated instantaneously to an electron temperature T. In the resulting ionizing plasma, atoms are successively ionized by electron impacts, the degree of ionization increases as a function of nt, where n is the electron density and t is the time after the plasma is shock-heated. We calculate the average energies of the Kα lines and the emissivities of lines contributing to the observed Kα lines as a function of nt with the electron temperature $T = 3.76$ keV for Cas A and 2.9 keV for Tycho. We have included line emission arising from inner shell ionization, inner shell excitation, and dielectronic recombination using atomic data compiled by Mewe, Schrijver, and Sylwester (1980*a*, *b*); Mewe and Gronenschild (1981); Mewe, Gronenschild, and Van den Oord (1985); and Masai (1984), and references therein, as well as those revised by reference to more recent information.

The initial temperature is assumed to be 1 eV, so that the electron density can be kept essentially constant in the course of ionization, since hydrogen is almost fully ionized at this temperature. The results are not sensitive to the initial temperature, as long as it lies between 1 eV and 10 eV. In this calculation, we assume that the electron temperature is instantaneously increased to T at $t \ll t_a$, where t_a is the supernova age.

At first inspection, this simple model, characterized by a single nt and T, would not seem to be appropriate to a young SNR in which a large range of the nonequilibrium parameters must coexist due to the evolution of the remnant. However, as Hamilton and Sarazin (1984*b*) have shown, the X-ray spectra of SNRs can be well represented with averaged values of nt and T, although both nt and T are distributed over wide ranges. The electron temperature is assumed to be constant, since it increases only slowly with time due to collision with shock-heated ions, in the nt range concerned. The value of nt may also vary from one region to the other on account of the density inhomogeneity and shock evolution, but its average value can be estimated with an uncertainty of a factor of 2. In our space-unresolved observation, therefore, we assume a simplified model with single values of nt and T.

The observed line energies are compared with the average Kα line energies against nt shown in Figure 2 to obtain the value of nt. The boxes in Figure 2 show the ranges of nt determined by the observed line energies. As can be seen from the figure, the values of nt obtained from five Kα line blends are in reasonable agreement with each other. The mean values of nt are 1.0×10^{11} cm^{-3} s for Cas A and 6.0×10^9 cm^{-3} s for Tycho, as given in Table 2. According to a simple reverse shock model (see, for example, Hamilton and Sarazin 1984*a*), we can calculate the mean elapsed time $\langle t \rangle$ weighted by the processed mass after shock heating and find $\langle t \rangle \approx 0.5 t_a$ and estimate the value of $\langle n \rangle$ from the line energies.

Information on the electron density can also be obtained from the continuum intensity. The intensity I_c integrated over the whole energy range is given by

$$I_c = \mathrm{EM}\, (4\pi D^2)^{-1} \epsilon T^{1/2} \text{ ergs cm}^{-2}\text{ s}^{-1}\,, \tag{1}$$

where D is the distance to the source, $\epsilon T^{1/2}$ is the specific emissivity of the continuum, and EM is the emission measure.

TABLE 2

PLASMA PARAMETERS IN SUPERNOVA REMNANTS

Parameter	Cassiopeia A	Tycho
Age t_a (yr)	300	410
D[a] (kpc)	3.0	2.5
θ	1'.8	4'.0
nt (cm^{-3} s)	1.0×10^{11}	6.0×10^9
$\langle n \rangle$ (cm^{-3})	21	0.9
I_c (ergs cm^{-2} s^{-1})	1.5×10^{-9}	2.8×10^{-10}
EM (cm^{-6} pc^3)	5.6×10^3	8.8×10^2
$\langle n^2 \rangle^{1/2}$ (cm^{-3})	33	5.1
Energy (10^{49} ergs)	5.2	1.1
Mass ($M_\odot$)	2.4	0.6

[a] Raymond 1984.

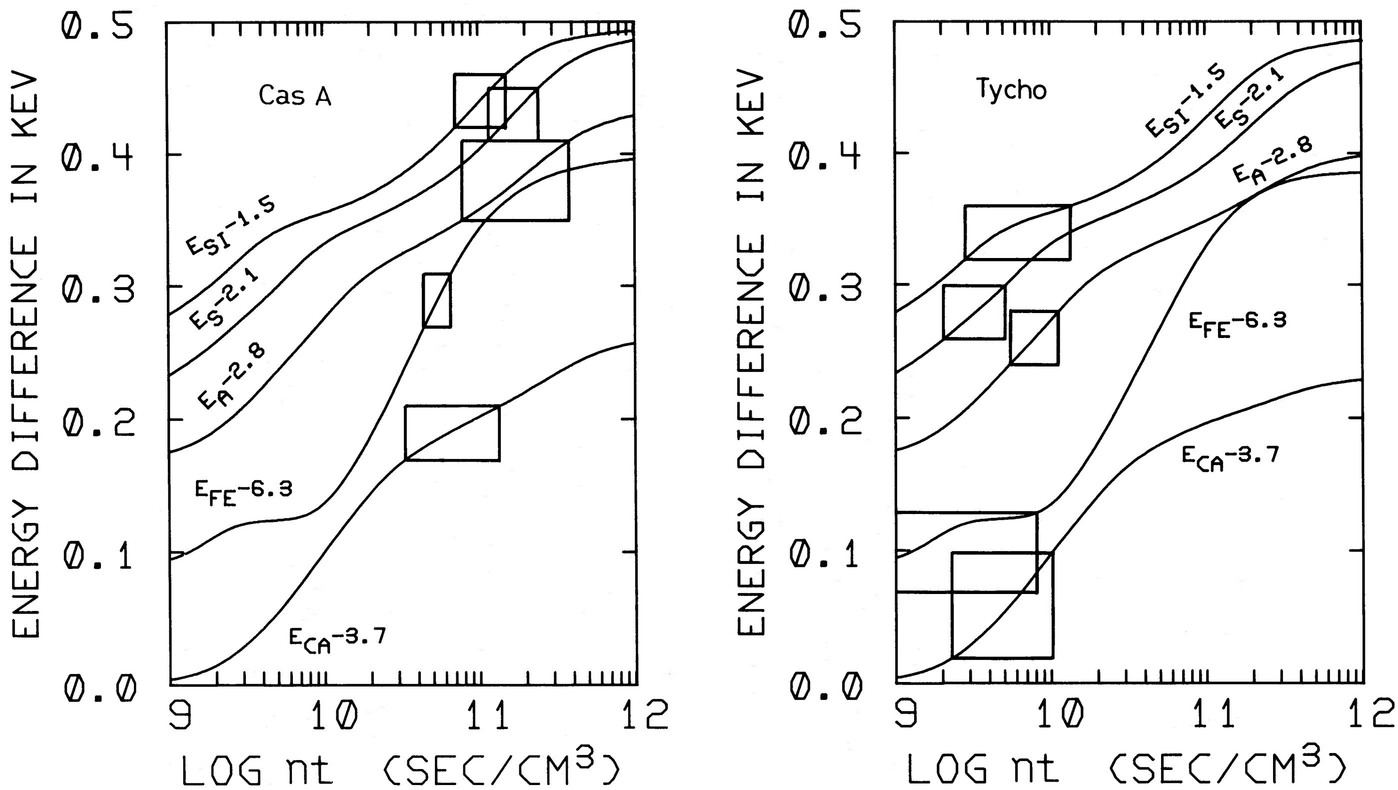

FIG. 2*a* FIG. 2*b*

FIG. 2.—The variations of the mean energies in keV of the Kα lines for silicon, sulfur, argon, calcium, and iron. The boxes correspond to the observed line energies with a confidence level of 90%. The ordinate represents the line energy minus an energy value indicated for each element in the figure. (*a*) Cas A is for T = 3760 eV, and (*b*) Tycho is for T = 2900 eV.

Because the X-ray emitting region occupies a fraction f within the sphere of angular radius θ, the emission measure is expressed as EM = $(4\pi/3)(D\theta)^3 f \langle n^2 \rangle$. The specific emissivity is given by

$$\epsilon T^{1/2} = 5.6 \times 10^{-24} T^{1/2} \sum_i n_i z_i^2/n \text{ ergs cm}^3 \text{ s}^{-1} , \quad (2)$$

where T is the electron temperature in keV, n_i is the ion density, and z_i is the ionic charge. Using the values of I_c, D, and θ in Table 2, and assuming $f = 0.25$ and the cosmic abundances, we obtain EM and $\langle n^2 \rangle^{1/2}$ as given in Table 2. The values of $\langle n^2 \rangle^{1/2}$ thus obtained from the continuum intensity are in reasonable agreement with the values of $\langle n \rangle$ derived from the line energies. We attribute the differences mainly to the clumpiness of matter in the SNR, and partly to the uncertainties in nt, D, f, and the abundances of elements.

The values of $\langle n \rangle$, T, and the plasma volume $(4\pi/3)(D\theta)^3 f$ allow us to obtain the masses and the thermal energies contained in the X-ray emitting regions. The values thus derived for Cas A and Tycho are also given in Table 2. These values are somewhat smaller than those estimated from the X-ray data at energies below 4 keV (Fabian *et al.* 1980; Reid, Becker, and Long 1982). The differences are not great when one considers the uncertainties in the various input parameters. For example, if we use D = 3.0 kpc (as adopted by Reid, Becker, and Long 1982) and $n = \langle n^2 \rangle^{1/2}$ derived from the continuum intensity with this distance for Tycho, we find $M = 5.3\ M_\odot$ rather than $0.6\ M_\odot$ (as shown in Table 2). This higher value is in much better agreement with the range ($7 < M < 15\ M_\odot$) found by Reid, Becker, and Long (1982).

It should be noted that the masses and energies given in Table 2 are the lower limits of the total masses in the SNRs and explosion energies, since a considerable fraction of matter is not heated yet. Hence these masses and energies are not inconsistent with the generally adopted values for Type II and Type I SNs.

The present model explains why the line energies for Cas A and Tycho are different. This is simply because the value of nt for Cas A is much larger than that for Tycho.

IV. ELEMENT ABUNDANCES

The intensity of each line of element i is given by

$$I_i = \text{EM } (4\pi D^2)^{-1}(n_H/n)\alpha_i \epsilon_i(T, nt) \text{ photons cm}^{-2} \text{ s}^{-1} , \quad (3)$$

where α_i is the abundance of the element i relative to hydrogen. The specific line emissivity $\epsilon_i(T, nt)$ in units of photons cm^3 s^{-1} is calculated for a given electron temperature in the same manner as in the calculation of the average line energies. The nt-dependences for ϵ_i at the two given electron temperatures are shown in Figure 3. The values of ϵ_i for T and nt in Table 2 are shown in Table 3. Comparison between equations (1) and (3) gives the element abundances α_i as $\alpha_i = (\epsilon T^{1/2}/\epsilon_i)(n/n_H)(I_i/I_c)$ independently of the values of EM and D. The values of α_i relative to the cosmic abundances α_{i0} from Allen (1973) are shown in Table 3.

In the standard models, elements formed in the pre-SN stage are stratified in such a way that heavier elements are formed in inner layers. This "onionskin" structure is approximately maintained in the ejecta. X-rays are emitted mainly from an

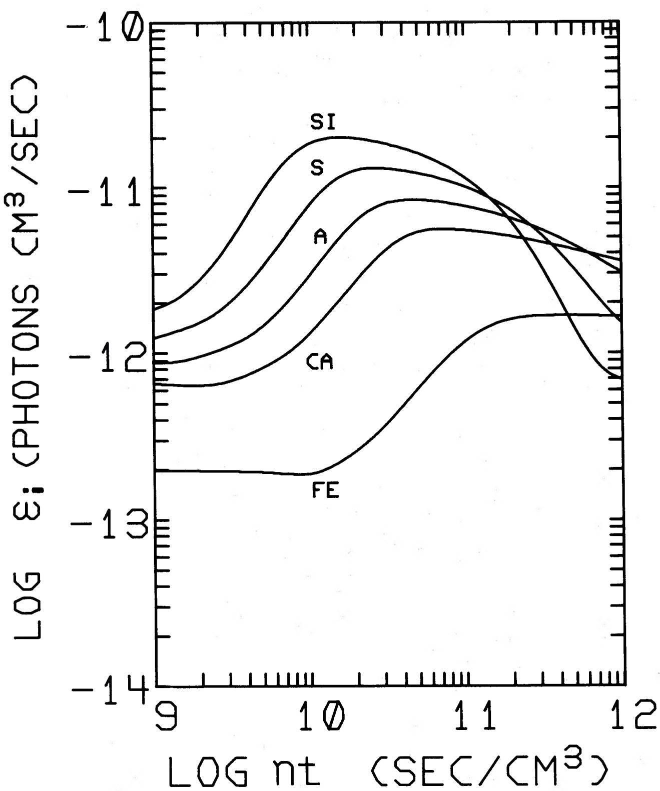

FIG. 3a

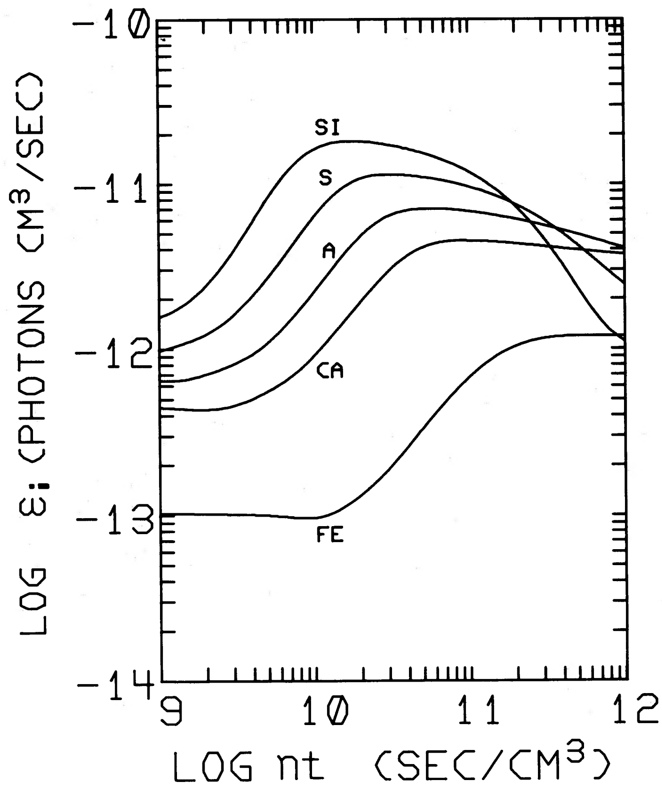

FIG. 3b

FIG. 3.—The variations of the specific photon emissivities (excluding the abundances of elements) for the Kα lines of silicon, sulfur, argon, calcium, and iron. (*a*) Cas A is for $T = 3760$ eV, and (*b*) Tycho is for $T = 2900$ eV.

intermediate region which is recently shock-heated by the reverse shock. Hence the observed line intensities do not necessarily represent the element abundances for the whole ejecta but only those in the shock-heated region.

For Type II SNs, a model of 25 $M_\odot$ calculated by Woosley and Weaver (1982) gives the abundance enhancements of heavy elements relative to solar values. The abundances of heavy elements for Cas A in our work are not much different from those of cosmic abundances, though somewhat enhanced (Table 2). This suggests that the reverse shock has just reached the silicon-calcium–rich layer but not the iron core.

For Tycho, all the abundances we have determined are enhanced relative to the cosmic values by factors of ~ 6–~ 15. However, we must keep in mind that the enhancement factors of silicon, sulfur, argon, and calcium depend sharply on *nt* in a similar way in the range concerned, while that of iron does not. In other words, the relative abundances among the elements silicon to calcium depend little on the accuracy of *nt*, while their values relative to the hydrogen abundance are ambiguous by a factor of a few (see Table 3). We obtained the abundances of sulfur, argon, and calcium relative to silicon to be approximateley solar, a result consistent with that of the Type I SN model of Nomoto, Thielemann, and Yokoi (1984). They calculated the absolute amount of these elements to be a few tenths of a solar mass for the SN explosion of a ~ 1 $M_\odot$ star. The X-ray emitting matter in the Tycho SNR is estimated to be about 0.6 $M_\odot$, as already mentioned. Therefore, the abundances of these elements relative to hydrogen could be one or

TABLE 3

EMISSIVITIES OF Kα LINES AND RELATIVE ABUNDANCES OF ELEMENTS

Z	α_{i0}[a] ($\times 10^{-6}$)	ϵ_i ($\times 10^{-12}$ photons cm^3 s^{-1}) Cassiopeia A	Tycho	α_i/α_{i0}[b] Cassiopeia A	Tycho
Si	33	11	11	1.5 ± 0.5	$6.7^{+11.6}_{-1.8}$
S	16	10	3.3	$1.4^{+0.4}_{-0.2}$	$11^{+12.2}_{-4.0}$
A	6.3	8	1.2	$0.83^{+0.11}_{-0.10}$	$6.5^{+3.3}_{-2.6}$
Ca	2.0	5.4	0.6	$2.1^{+0.2}_{-0.1}$	15^{+10}_{-6}
Fe	40	1.1	0.1	$0.7^{+0.6}_{-0.2}$	6.0 ± 0.2

NOTE.—For Cas A: $T = 3.76$ keV, $nt = 1.0 \pm 0.5 \times 10^{11}$ cm^{-3} s; for Tycho: $T = 2.9$ keV, $nt = 6.0 \pm 3.0 \times 10^9$ cm^{-3} s.

[a] Cosmic abundances (Allen 1973).

[b] Abundance relative to cosmic value and its error (90% confidence).

two orders of magnitude greater than the cosmic values, and the iron abundance is still larger. In this context, we presume that a small fraction of the iron core is shocked.

It is therefore likely that the shock wave in Tycho has very recently reached the core region, so that the value of nt is rather small (6×10^9 cm^{-3} s), as assumed in the preceding section. For Cas A, on the other hand, the contribution of the outer region, rich in hydrogen and helium, may be so large as to reduce the relative intensities of heavy elements such as argon and iron.

V. CONCLUSION

We observed the Cas A and Tycho SNRs with gas scintillation proportional counters and found several emission lines superposed on thermal bremsstrahlung spectra with temperatures of 3.76 keV and 2.9 keV respectively. The X-ray spectra below 4.5 keV were consistent with those obtained previously by the SSS on board *Einstein*, whereas the energies of the iron Kα line were found to be lower than those obtained by an *HEAO 1* experiment. The line energies we obtained are lower than those expected from the ionization equilibrium model and can be accounted for in terms of nonequilibrium ionization.

The iron line energy as well as its line width for Cas A indicates that the line is a blend of $n = 2$ to $n = 1$ transition lines of Fe XXII–XXIII which are formed in the transient ionizing phase. The abundances of heavy elements relative to hydrogen derived from the observed line intensities by reference to the ionizing plasma models are somewhat larger than those for the cosmic matter, and the relative abundances among the heavy elements are roughly consistent with those predicted by the Type II SN model of Woosley and Weaver (1982).

The line energies for Tycho are apparently lower than those for Cas A. In particular, the iron line feature in Tycho is identified with that of ionic states lower than XIX. This fact is attributed to a small value of nt, so that the ionization stage in Tycho is appreciably less advanced than in Cas A. The line intensities indicate that the heavy elements in Tycho are more abundant than in Cas A, thus being qualitatively consistent with the nuclear synthesis model of Type I by Nomoto, Thielemann, and Yokoi (1984). In particular, the overabundance of iron is clearly indicated.

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S. HAYAKAWA: Department of Astrophysics, Faculty of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464 Japan

K. KOYAMA: Institute of Space and Astronautical Science, 6-1, Komaba 4-chome, Meguro-ku, Tokyo 153 Japan

K. MASAI: Institute of Plasma Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464 Japan

H. TSUNEMI and K. YAMASHITA: Department of Physics, Faculty of Science, Osaka University, 1-1, Machikaneyama-cho, Toyonaka, Osaka 560 Japan