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X-RAY LINE EMISSION FROM THE TYCHO SUPERNOVA REMNANT

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ABSTRACT

The A-2 experiment onboard HEAO-1 has observed the X-ray spectrum of the Tycho supernova remnant in the energy range 0.5 - 20 keV. The spectrum reveals four significant line features: the Kα lines of silicon, sulphur, and iron; and the L lines of iron. Comparisons between the silicon and sulphur equivalent widths and Kα iron line energies of Tycho and Cas A suggest that the X-ray emitting plasma in Tycho is further from collisional ionization equilibrium than that of Cas A.

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I. INTRODUCTION

Tycho's supernova of 1572 is now observed as a remnant with a pronounced, almost circular shell structure in radio (e.g. Henbest 1972) and X-ray (Long 1979) images. Faint optical filaments are superposed on this shell (van den Bergh et al. 1973, Kamper and van den Bergh 1978). The expansion rate measured by Kamper and van den Bergh is in close agreement with that expected for a remnant in the Sedov blast wave phase of evolution, a conclusion which is independent of the distance to the remnant. Hence the shock wave should have swept up a mass of interstellar gas at least several times the mass ejected by the explosion.

The X-ray spectrum of Tycho's remnant should then be dominated by the emission of the blast wave, with a contribution from a reverse shock (McKee 1974). In fact, two and perhaps three temperature components are needed to fit the spectrum as measured by gas proportional counters (Davison, Culhane, and Mitchell 1976; Pravdo and Smith 1979). Both of these papers report detection of the Kα iron line complex around 6.7 keV. If the spectrum arises in hot swept-up interstellar gas, one can also expect to see (e.g. Raymond and Smith 1977) lines of silicon at around 2 keV (reported by Hill, Burginyon, and Seward 1975), sulfur at about 2.5 keV, and iron at .8 to 1.5 keV. Here we report the HEAO-1 A2[+] observations of the 0.5 to 20 keV spectrum of Tycho which demonstrate the existence of all these line features.

[+] The A2 experiment on HEAO-1 is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT, with collaborators at GSFC, CIT, JPL and UCB.

II. OBSERVATIONS

The Low Energy Detectors (LED; 0.15-3 keV) scanned the region of Tycho's supernova remnant during early February 1978. Data were obtained with the Medium Energy Detector (MED; 1.8-19 keV) during an extended pointed observation in August 1978. These detectors are proportional counters with $1\frac{1}{2}^{\circ} \times 3^{\circ}$ and

$3^{o} \times 3^{o}$ fields of view and are fully described by Rothschild et al. (1979).

The pulse height spectrum shown in Figure 1 was derived by subtracting contemporaneous measurements of the off-source diffuse X-ray background. Models were fit to this data with the conventional technique of comparison with χ^2 but enhanced and automated by use of the Marquardt algorithm (Bevington 1979). Two optically thin thermal bremsstrahlung models were used:

1. Combinations of continua and individual emission lines in which the free parameters were the temperatures and intensities of the continuum components, and the intensities and energies of the lines.

2. Combinations of the emission spectra of plasmas in collisional ionization equilibrium (CIE; see Raymond and Smith 1977, 1979) in which the free parameters were the continua temperatures and intensities, and the elemental abundances.

Table 1 summarizes the results of the model fitting. In general, the simple model (number 1 above) described the data significantly better than the equilibrium model.

The simple model contains four statistically significant lines: the Kα lines of iron, sulphur, and silicon; and the L lines of iron. Table 1 lists the line intensities and equivalent widths. For the CIE model, we show the ratios of the abundances required to the abundances tabulated by Meyer (1978). Meyer's abundances relative to hydrogen are He (11.04), C (8.68), N (7.93), O (8.93), Ne (8.11), Mg (7.59), Al (6.49), Si (7.57), S (7.20), Ar (6.41), Ca (6.36), Fe (7.51), Ni (6.26). All these elements are included in the Raymond and Smith (1979) model, but the abundances were fixed at Meyer's values except for the elements listed in Table 1. One interesting result of the fitting analysis is that the abundances of both Si and S appear enhanced by factors of about three over standard values.

Two continuum components can adequately describe the data over this energy range. The higher of the two temperatures is greater than previously measured values (e.g. Davison et al. 1976). This appears to be caused by a proportionality between the measured temperature and the high energy sensitivity of the experiment. Such an effect and the implications of the highest temperature emission are discussed by Pravdo and Smith (1979; hereafter Paper 1). In the two-temperature model the ratio of low to high temperature bolometric intensities (without lines) is $\sim$ 2.4. If the effect of low energy photoelectric absorption (Fireman 1974) is removed, this ratio becomes $\sim$ 12. The observed continuum plus line intensities from Tycho in units of 10^{-11} erg cm^{-2} sec^{-1} are 10 $\pm$ 5, 2.5, 2.9, and 3.1 in the 0.5-2, 2-6, 2-10, and 2-20 keV energy bands respectively. The uncertainty in the > 2 keV intensities is < 0.1 in these units. In the 0.5-2 keV band the uncertainty is large because of the limited statistics. This is also true of the intensities measured for the iron L lines and the silicon line (see Table 1).

These detectors performed a similar observation of Cas A only four days earlier. Several comparisons between the two remnants are discussed below. In this section, however, we note that onboard calibration has indicated that the detector gains are stable with a characteristic timescale of $\sim$ year for changes of $\sim$ 1%. Therefore while the absolute energy calibration is now known to $\sim$ 1%, we are confident of the <u>relative</u> calibration to <<1% between the Cas A and Tycho observations.

The Kα iron lines have been studied in some detail (see also Paper 1). The Tycho line energy is 6.62 (+0.09,-0.07) keV while in Cas A it is 6.81 (+0.05,-0.07) keV (2σ errors). Figure 2 illustrates the line residuals. In the CIE model the centroid energy of the Kα iron line blend is a sensitive measure of temperature. Table 2, which is derived from Raymond and Smith (1977) plus improvements listed in Paper 1, shows this effect. In addition, the average ionic charge states also shown for the CIE model. A similar dependence of line energy on charge state is expected for many nonequilibrium situations.

III. DISCUSSION

Recently both broad-band (Mason et al. 1979, Paper 1, this work) and high resolution (Becker et al. 1979a,b) X-ray spectra of the Tycho and Cas A remnants have become available. There is consistency between these results in that many of the same line features are identified. In particular, the relative results of Tycho to Cas A appear to be in good agreement. Specifically both experiments find that the equivalent widths of the silicon and sulphur lines are a factor of 3-5 larger in Tycho. This enhancement could be due to higher abundances of these elements in Tycho (CIE model). Alternatively, as discussed by Itoh (1977), it may be a signature of nonequilibrium line emission with normal abundances. The second of these explanations is supported by other line evidence in Cas A (Mason et al. 1979, Paper 1) as well as the analysis of the Tycho spectrum presented above.

In the nonequilibrium model, the ionization of shock-heated plasmas lags behind the electron heating. The resulting underionization of silicon and sulphur compared to their CIE charge states enhances their line emission. Since the magnitude of this enhancement depends on the degree of underionization, we can conclude that Tycho is further from CIE than Cas A if this model is correct. The roughly 0.1 keV difference between the Kα iron energies is a further indication of lower ionic charge states in Tycho, and is qualitatively consistent with this model.

The young supernova remnants Tycho and Cas A exhibit different X-ray line properties despite the general similarity of their broad-band continuum emission (Mason et al. 1979, Paper 1, this work). These differences can be ascribed to a number of contrasts between the remnants ranging from the supernova type to the initial circumstellar conditions. There is evidence for example that the Tycho circumstellar density was about 5 times less than that in Cas A (e.g. Paper 1). X-ray spectroscopy, the results of which now support a non-equilibrium model for the X-ray emitting plasmas, is a powerful diagnostic tool in the continuing study of these remnants.

REFERENCES

Becker, R.H., Holt, S.S., Smith, B.W., White, N.E., Boldt, E.A., Mushotzky, R.F., and Serlemitsos, P.J. 1979, Ap. J. (Letters), in press.

Becker, R.H., Holt, S.S., Smith, B.W., White, N.E., Boldt, E.A., and Serlemitsos, P.J. 1979, submitted to Ap. J. (Letters).

Bevington, P.R. 1969, Data Reduction and Error Analysis in the Physical Sciences (New York: McGraw-Hill).

Charles, P.A., Culhane, J.L., Zarnecki, J.C., and Fabian, A.C. 1975, Ap. J. (Letters) 197, L61.

Davison, P.J.N., Culhane, J.L., and Mitchell, R.J. 1976, Ap. J. (Letters) 206, L37.

Fireman, E.L. 1974, Ap. J. 187, 57.

Gorenstein, P., Kellogg, E., and Gursky, H. 1970, Ap. J. 160, 199.

Henbest, S.N. 1977, Supernovae and Supernova Remnants, C.B. Cosmovici ed. (Dordrecht-Holland:D. Reidel), p. 303.

Itoh, H. 1977, Publ. Astron. Soc. Japan 29, 813.

Kamper, K.W. and van den Bergh, S. 1978, Ap. J. 224, 851.

Long, K.S. 1979, private communication.

Mason, K.O., Pravdo, S.H., Charles, P.A., Smith, B.W., and Raymond, J.C. 1979, in preparation.

McKee, C. 1974, Ap. J. 188, 335.

Meyer, J.-P. 1978, private communication.

Pravdo, S.H., Becker, R.H., Boldt, E.A., Holt, S.S., Rothschild, R.E., Serlemitsos, P.J., and Swank, J.H. 1976, Ap. J. (Letters) 206, L41.

Pravdo, S.H. and Smith, B.W. 1979, submitted to Ap. J. (Letters).

Raymond, J.C. and Smith, B.W. 1977, Ap. J. Supple. 35, 419.

Raymond, J.C. and Smith, B.W. 1979, in preparation.

Rothschild, R., Boldt, E., Holt, S., Serlemitsos, P., Garmire, G., Agrawal, P., Riegler, G., Bowyer, S., and Lampton, M. 1979, Sp. Sci. Instrumentation, in press.

van den Bergh, S., Marscher, A.P., and Terzian, Y. 1973, Ap. J. Supple. 26, 19.

TABLE 1

TYCHO: PARAMETERS FOR SPECTRAL MODELS

Model	T_{LOW}[a]	T_{HIGH}[a]	N_H 10^{21} H atoms cm^{-2}	Si	S	Ar-Ca	Fe-Ni	χ^2/d.o.f.
1. Simple continua with lines	0.7±0.1	6.4±0.4	7.9±0.8	--	--	--	--	68/57
a. Equivalent width[a]	---	---	---	1.6±0.7	0.7±0.1	--	L) 4.1±2.2 K) 1 2±0.1	---
b. Line Intensity 10^{-2} photons cm^{-2} sec^{-1}	---	---	---	8.8±3.8[c]	3.0±0.4	--	L) 5.3±2.8[c] K) 0.048±0.004	---
c. Line energy[a,b]	---	---	---	1.73±0.04	2.42±0.01	--	L) 0.83±0.04 K) 6.62±0.06	---
2. Collisional Ionization Equilibrium	0.6±0.1	4.4±0.2	3.8±3.8	--	--	--	---	---
a. Element Abundance[d] both T_{LOW} and T_{HIGH}	---	---	---	2.5-3.5	3.5-4.5	0-2	1.1-1.3	98/6[illegible]
b. Abundance[d] T_{LOW}	---	---	---	1.5-2	2.5-4	0.5-4.5	.15-.2	86/55
Abundance[d] T_{HIGH}	---	---	---	2.5-9	0-1.5	4.5-11.	1.5-2.5	---

[a] keV

[b] Errors are statistical only

[c] Not including uncertainty of 50% in overall intensity (see text).

[d] Relative to values of Meyer (1978); only ranges of possible values are shown since fits are not acceptable.

TABLE 2

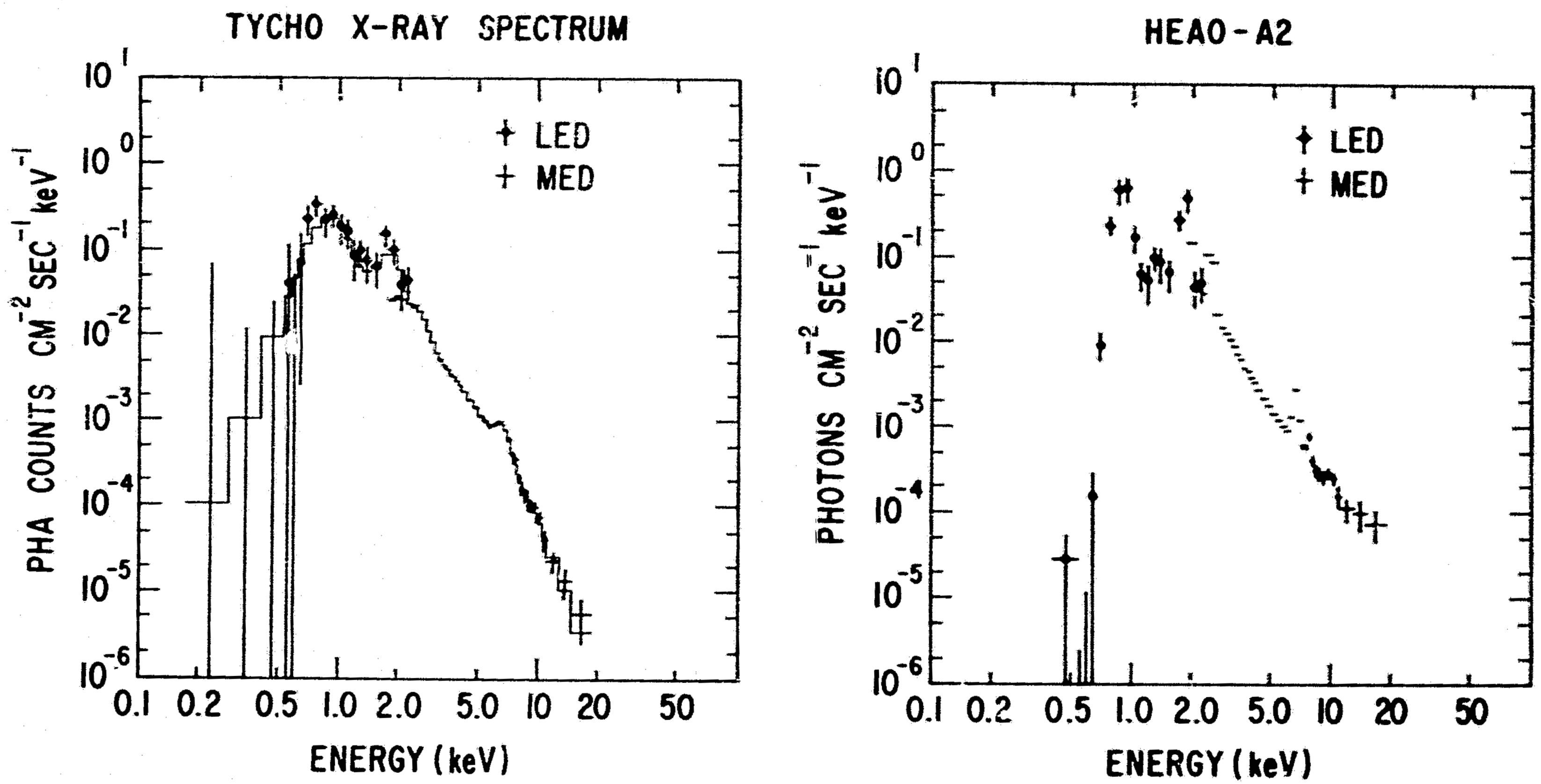
ENERGY OF Kα IRON LINE BLEND VS. TEMPERATURE

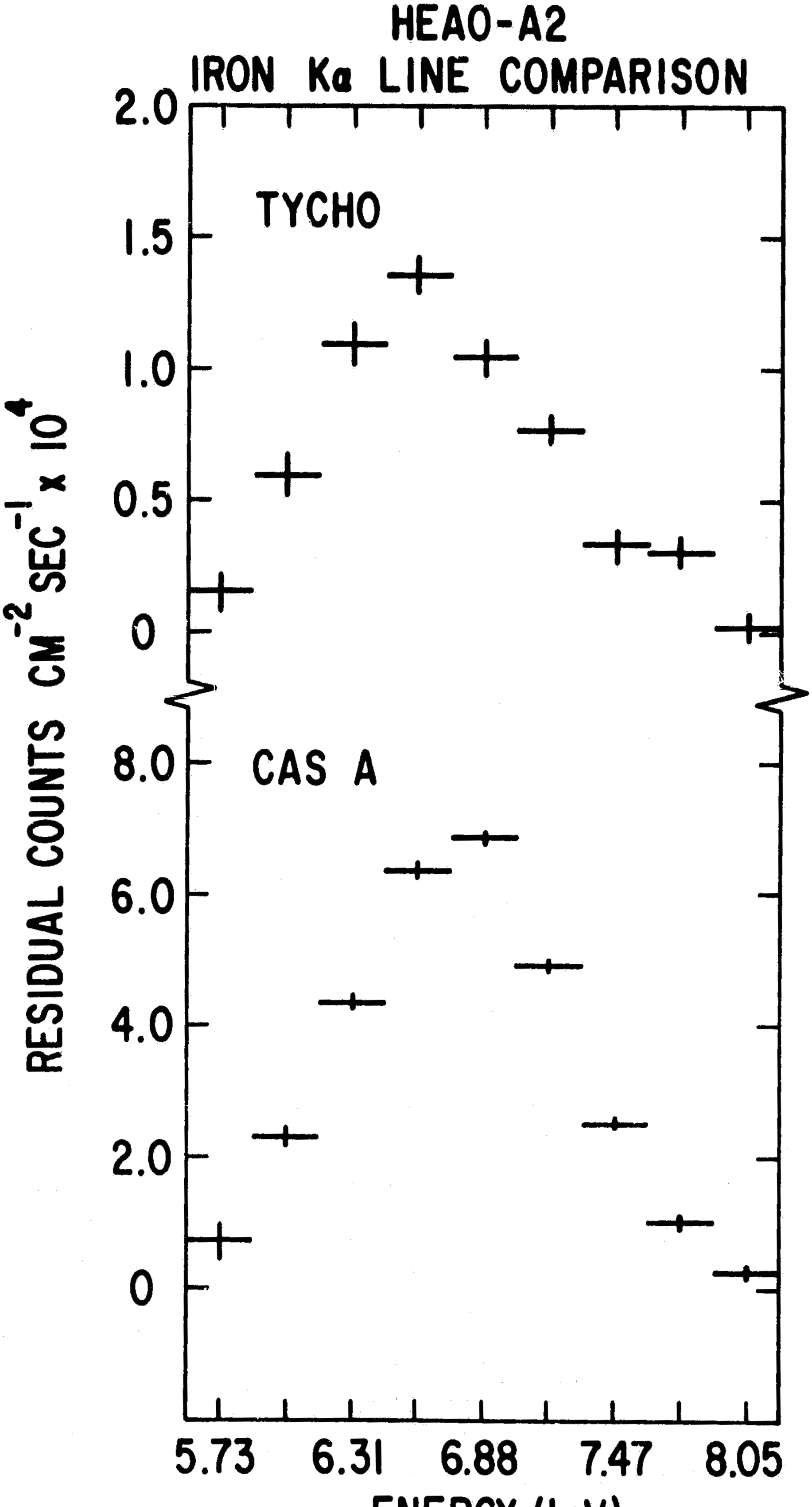
TEMPERATURE (keV)	CENTROID (keV) ENERGY	AVERAGE CHARGE
0.8	6.55	+ 19.6
1.0	6.59	+ 21.0
1.2	6.64	+ 22.0
1.5	6.65	+ 22.8
1.7	6.66	+ 23.1
2.0	6.67	+ 23.4
2.5	6.68	+ 23.6
3.0	6.69	+ 23.8
4	6.71	+ 24.0
5	6.73	+ 24.2
7	6.77	+ 24.8
10	6.81	+ 25.0
15	6.86	+ 25.5
20	6.89	+ 25.7
25	6.89	+ 25.8

FIGURE CAPTIONS

Figure 1 - The pulse-height-analyzed count spectrum and optically thin model histogram (model 1 in text) for Tycho is shown on the left. The inferred incident spectrum is on the right.

Figure 2 - The residuals near 6.7 keV for Tycho and Cas A after subtracting the best-fit continua.


TYCHO X-RAY SPECTRUM
LED
MED
PHA COUNTS CM^-2 SEC^-1 keV^-1
ENERGY (keV)
HEAO-A2
LED
MED
PHOTONS CM^-2 SEC^-1 keV^-1
ENERGY (keV)


HEAO-A2
IRON Kα LINE COMPARISON
TYCHO
CAS A
RESIDUAL COUNTS CM^{-2} SEC^{-1} x 10^{4}
2.0
1.5
1.0
0.5
0
8.0
6.0
4.0
2.0
0
5.73
6.31
6.88
7.47
8.05
ENERGY (keV)

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