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ABSTRACT

We have detected X-ray emission up to 25 keV from the supernova remnants Cas A and Tycho with the A-2 spectroscopy experiment on HEAO 1. The spectra must include continuum components with $T_{eff} \gtrsim 10^8$ K which could arise from optically thin plasmas in the collisionless shock fronts. This is the first indication of electron-ion temperature equilibrium in the expanding shell of young remnants. We have also measured the equivalent widths of the Kα and Kβ iron line blends in Cas A, and find that their ratio is not compatible with the measured X-ray temperature in the collisional ionization equilibrium model. Finally we have unsuccessfully searched for hard X-ray pulsars in both remnants.

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I. INTRODUCTION

Cassiopeia A and Tycho are young supernova remnants (SNR) with ages estimated at 300 and 400 years respectively (e.g. Kamper and van den Bergh 1976, 1978; Gorenstein, Harnden, and Tucker 1974). The shock velocities in the standard supernova model (Shklovsky 1962) can be roughly taken as the observed mean velocities of the optical filaments--between 3000-6000 km sec^{-1} (Woltjer 1972). Spectral measurements have shown that the X-ray temperatures of both remnants (Coleman et al. 1973; Charles et al. 1975) are an order of magnitude less than the kinetic temperatures of expansion. Since the equilibration time between electrons and ions via Coulomb collisions is large compared to these supernovae ages, Shklovsky (1968) has assumed that temperature equilibrium is not reached in these remnants, an assumption seemingly confirmed by the X-ray results. McKee (1974), however, has argued that electrodynamic coupling of electrons and ions in the collisionless shock can bring about equipartition. In this paper we present new evidence regarding this fundamental question of SNR theory.

We also present evidence regarding a different sort of equilibrium, that among the various stages of ionization of heavy elements as a result of the balance between ionization and recombination rates. The X-ray spectra of both SNR contain multiple continuum components (Charles et al. 1975) and iron lines which have been interpreted as emission from hot plasmas in thermal equilibrium (Davison, Culhane, and Mitchell 1976; Pravdo et al. 1976) with approximately "cosmic" elemental abundance (e.g. Allen 1973). Possible detections of line emission from silicon (Coleman et al. 1973; Hill, Burginyon, and Seward 1975) have been confirmed and lines below $\sim$ 3 keV from other abundant species such as sulphur and argon have also been detected (Mason et al. 1979; Becker et al. 1979a,b; Pravdo et al. 1979). However, it is no longer clear whether these results can be interpreted in the collisional ionization equilibrium model. We have made sensitive measurements of the Kα and Kβ iron line blends in the spectrum of Cas A. The "Kα" iron line blend includes the strong n=2 to n=1 transition in FeXXV, Lyman α of FeXXVI (an important contributor at $kT \gtrsim 7$ keV), Kα transitions from inner shell excitation in FeXVII through FeXXIV (important for $kT \lesssim 2$ keV), and dielectronic recombination satellites of all the preceding transitions. The "Kβ" line blend consists of the n=3 to n=1 analogs of the iron Kα blend plus the Kα lines of nickel (weaker than Fe Kα by the abundance ratio Ni/Fe $\approx$ 1/18). Since most of the flux in these blends arises from the same ions of iron, a comparison of the line ratio to the ratio expected in collisional equilibrium (which is a function of temperature; see e.g. Raymond and Smith 1977) is a good test of the applicability of this model.

II. HIGH ENERGY RESULTS

The A-2[+] experiment (Rothschild et al. 1979) pointed at Cas A on

[+] 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.

August 2-3, 1978 and at Tycho on August 7, 1978 for respective net times of ~ 25000 s and ~ 24000s. High energy spectra were obtained with a xenon-filled proportional counter (3-60 keV) which had a net area of 820 cm^2 and a $3^o \times 3^o$ field of view, effectively isolating either source. A similar argon-filled detector (1.8 - 18 keV) was also used in the iron line measurements. Data below 5 keV are not analyzed here to avoid the low energy effects of photoelectric absorption, low-temperature continuum emission, and lines.

Figures 1 and 2 show the count and photon spectra for Cas A and Tycho (see Pravdo et al. 1976 for a description of how the photon spectra are inferred). Significant detections were achieved in both sources up to 25 keV. Acceptable values of χ^2 were obtained for the spectra although for Cas A it was necessary to introduce systematic errors of $\sim$ 4%, which dominate the statistical errors of < 0.5% in many channels. In all of the following fits a very low temperature component ($T \sim 10^7$ K) has been included and fixed at the intensities measured by Mason et al. (1979) for Cas A and Pravdo et al. (1979) for Tycho with data starting from 0.5 keV. If the data above 5 keV are modeled as single additional continua, the best fit temperatures are 10. (+0.6,-0.5) x 10^7 K in Cas A and 8.4 (+2.1,-1.1) x 10^7 K in Tycho (3σ errors). These lower limits are larger than previously measured values. However, we note that with an increase in observational sensitivity, the measured temperatures have also increased (Charles et al. 1975; Davison et al. 1976; Mason et al. 1979). A possible explanation for this phenomena is that a higher energy component is beginning to contribute a significant flux which increases the apparent temperature. This hypothesis was tested by introducing an additional thin thermal bremsstrahlung component into the model. This improved the fits at the 90% confidence level for both spectra, although we could not accurately determine the temperature of this component. As an example, the model histograms in Figures 1 and 2 include a component with temperature 2.6 x 10^8 K. Figure 3 shows the best-fit and upper limits to the intensity of the high temperature components as a function of temperature. Note that in this model an intermediate temperature thin bremsstrahlung component must be present in addition to the lowest and highest temperature components which are specifically discussed.

We now assume that the high temperature components exist with an effective temperature of 30 keV, and that they are associated with shocked interstellar material behind the blast waves (McKee 1974). The r.m.s. particle density in these components with $T = 2.6 \times 10^8$ K can be written as

$$n_{B.W.} = 12.5 \left[\left(\frac{I}{10^{-10} \text{ erg cm}^{-2}\text{sec}^{-1}} \right) \left(\frac{\text{arc min}}{\theta} \right)^3 \left(\frac{\text{Kpc}}{d} \right) \frac{1}{f} \right]^{1/2} \text{ cm}^{-3}$$

where I is the bolometric intensity, θ is the X-ray angular radius, d is the source distance, and f is the fraction of the spherical volume within which the uniformly distributed (for simplicity) component is contained. For Cas A we use d=2.8 Kpc and θ=2.35' (Charles, Culhane, and Fabian 1977, Murray et al. 1979); and for Tycho d=3 Kpc and θ=4.25' (Long 1979). Distance estimates are taken from Gorenstein et al. (1974). The blast wave density is 2.9 $f^{-1/2}cm^{-3}$ in Cas A and 0.58 $f^{-1/2}cm^{-3}$ in Tycho. With the standard shock theory relation $n_{BW} = 4\, n_o$ ($n_o \equiv$ initial interstellar density), it follows that $f \sim 1/4$ and $n_o = 1.4\ cm^{-3}$ in Cas A and 0.29 cm^{-3} in Tycho. Finally, the total mass swept up by the blast wave is $1.0\mu\ M_\odot$ in Cas A and $1.4\mu\ M_\odot$ in Tycho where μ is the mean molecular weight.

If the highest temperature component alone is associated with the blast wave, then both the densities and the swept up masses for these SNR, particularly Tycho, are lower than earlier estimates (e.g. Gorenstein et al. 1974). Much of the X-ray emission below 10 keV would then be associated with ejecta heated by a reverse shock (McKee 1974; Itoh 1977) and cannot be used directly in a determination of the initial interstellar density.

These data require that there be more electrons with energies > 10 keV than would be predicted from previous temperature measurements of these remnants. This is evidence for the existence of an electron-ion interaction (McKee 1974) which is much stronger than the long-range Coulomb interaction alone (Spitzer 1962). The highest energy data are characterized in our analysis as a thin bremsstrahlung component due to a Maxwellian distribution of electrons. Departures from a Maxwellian distribution in the form of a high energy tail are expected during the electron-ion equilibration process. However, if the electron-electron equilibration time is much shorter than the electron-ion time as in the Coulomb case (where the ratio of times is roughly the mass ratio), then the electron distribution can be adequately treated as a Maxwellian for our purposes. Calculations of the skewness of the distribution for comparison with observation are not yet justified by the data

III. Kα AND Kβ IRON LINES IN CAS A

The Kα iron lines are readily observed in the count spectra of both Cas A and Tycho (Figures 1,2). While the Kβ lines are not visually apparent, they are statistically required in the Cas A spectrum. As mentioned above, systematic errors were introduced in the Cas A data in order to obtain acceptable fits. With acceptable fits parameter confidence limits can be rigorously determined using the method described by Avni (1976). The Kβ lines are present in Cas A at the 4.5σ confidence level, after the systematic errors are added. In Tycho, the Kα intensity is $(4.8 \pm 0.4) \times 10^{-4}$ photons cm^{-2} sec^{-1} and Kβ could be present at the same relative intensity but is not statistically required. Line emission from Tycho is discussed by Pravdo et al. (1979). There is good agreement between the Kα intensities measured here and previous measurements for both SNR (Davison et al. 1976, Pravdo et al. 1976).

The iron line equivalent widths in Table 1 were calculated theoretically, within the framework of Raymond and Smith (1977), with two exceptions: (1) Dielectronic recombination rates were modified from the Burgess (1965) formula to bring them into approximate agreement with those of Jacobs et al. (1977), and corrections to the effective excitation rates of the n = 2 levels of the helium-like lines were estimated from the effect of autoionization to excited states (see Raymond 1978); (2) Inner shell excitation of Kα transitions in Fe XVIII to Fe XXIV were included using the oscillator strengths of Merts, Cowan and Magee (1976). Moreover, weak lines are included that were omitted from Table 3 of Raymond and Smith for reasons of space. The assumed abundances were $Fe/H = 3.25 \times 10^{-5}$, $Ni/H = 1.8 \times 10^{-6}$, and $He/H = 0.11$ by number.

Table 2 summarizes the line results with 1σ errors. The temperature indicated by the measured Kβ/Kα ratio, 0.017 ± 0.C6, is less than 2×10^7 K, with a best fit value of 1.7×10^7 K. Mason et al. (1979) show that a continuum component in Cas A can be at or near this temperature. However, iron would have to be overabundant by a factor of ≳ 20 in this component to reproduce the observed K line intensities. Furthermore, this possibility would imply a strong iron L line near 0.8 keV which is not observed (Mason et al. 1979). Similarly, a combination of equilibrium components would require that one be iron-enriched. The high temperature component discussed in Section II will tend to lower the observed Kβ/Kα ratio since it makes a larger relative continuum contribution at the Kβ energy versus the Kα energy, compared to the possible equilibrium continuum. However, this would also lower the intensity of the equilibrium component and force the iron abundance to enhanced values in order to reproduce the observed equivalent width. Once again this would contradict the iron L line observations (Becker et al. 1979a). The alternative model which is supported by other spectral line evidence (Mason et al. 1979; Pravdo et al. 1979) is that the emitting plasma is not in collisional ionization equilibrium (e.g. Cowie 1977; Itoh 1977). In this case, iron is underionized and produces a lower Kβ/Kα ratio than at the same temperature in equilibrium.

IV. HIGH ENERGY PULSAR SEARCH

X-ray counts data with an accumulation time of 80 msec were obtained during the observations of Cas A and Tycho. There was no evidence for X-ray pulsations with periods between 160 msec and 120 sec in the 2-20 keV range with an upper limit for sinusoidal pulsations of 0.03. In addition Cas A was observed in the 16-30 keV range with an upper limit to sinusoidal pulsations of 0.08 in the same period interval.

V. CONCLUSIONS

The results are summarized as follows:

1. We have detected X-ray emission up to 25 keV from two young SNR which could originate from electrons in temperature equilibrium with the expanding shell.

2. The measured ratio of iron $K\beta/K\alpha$ line emission indicates that in Cas A line emission does not arise from a plasma or plasmas in collisional ionization equilibrium.

3. There was no detectable pulsar in either remnant.

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TABLE 1

EQUIVALENT WIDTHS (keV) IN COLLISIONAL EQUILIBRIUM

LOG T (K)	Kα+	Kβ++	Kβ/Kα RATIO
7.1	343	24	.07
7.2	642	93	.14
7.3	860	207	.24
7.4	1109	301	.27
7.5	1169	353	.30
7.6	1193	409	.34
7.7	1148	398	.35
7.8	1030	363	.35
7.9	854	301	.35
8.0	664	233	.35
8.1	496	162	.33
8.2	357	120	.34
8.3	257	81	.32
8.4	186	60	.32
8.5	135	39	.29

+Iron Kα

++Iron Kβ and Nickel Kα

TABLE 2

CAS A IRON K LINES

	Line Intensity Photons cm^{-2} sec^{-1}	Line Equivalent Width (keV)
Kα	$5.29 \pm 0.30 \times 10^{-3}$	1.37 ± 0.08
Kβ	$4.99 \pm 1.40 \times 10^{-4}$	0.23 ± 0.07

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FIGURE CAPTIONS

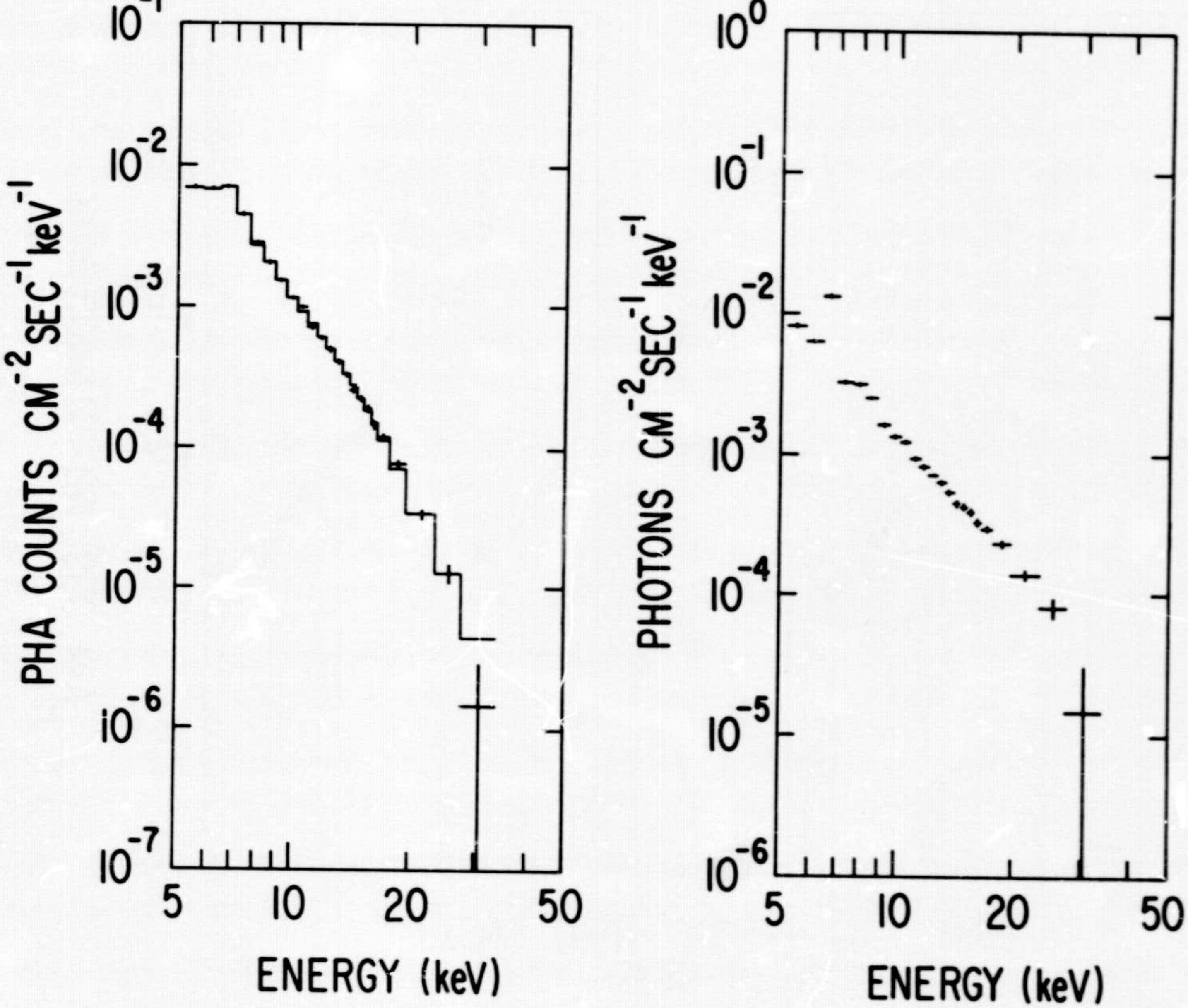
Figure 1 - Count rate and inferred photon spectrum of Cas A. The histogram model includes a continuum component with T = 2.6×10^8 K and line complexes at $\sim$ 6.7 and $\sim$ 8.1 keV, in addition to a lower temperature continuum.

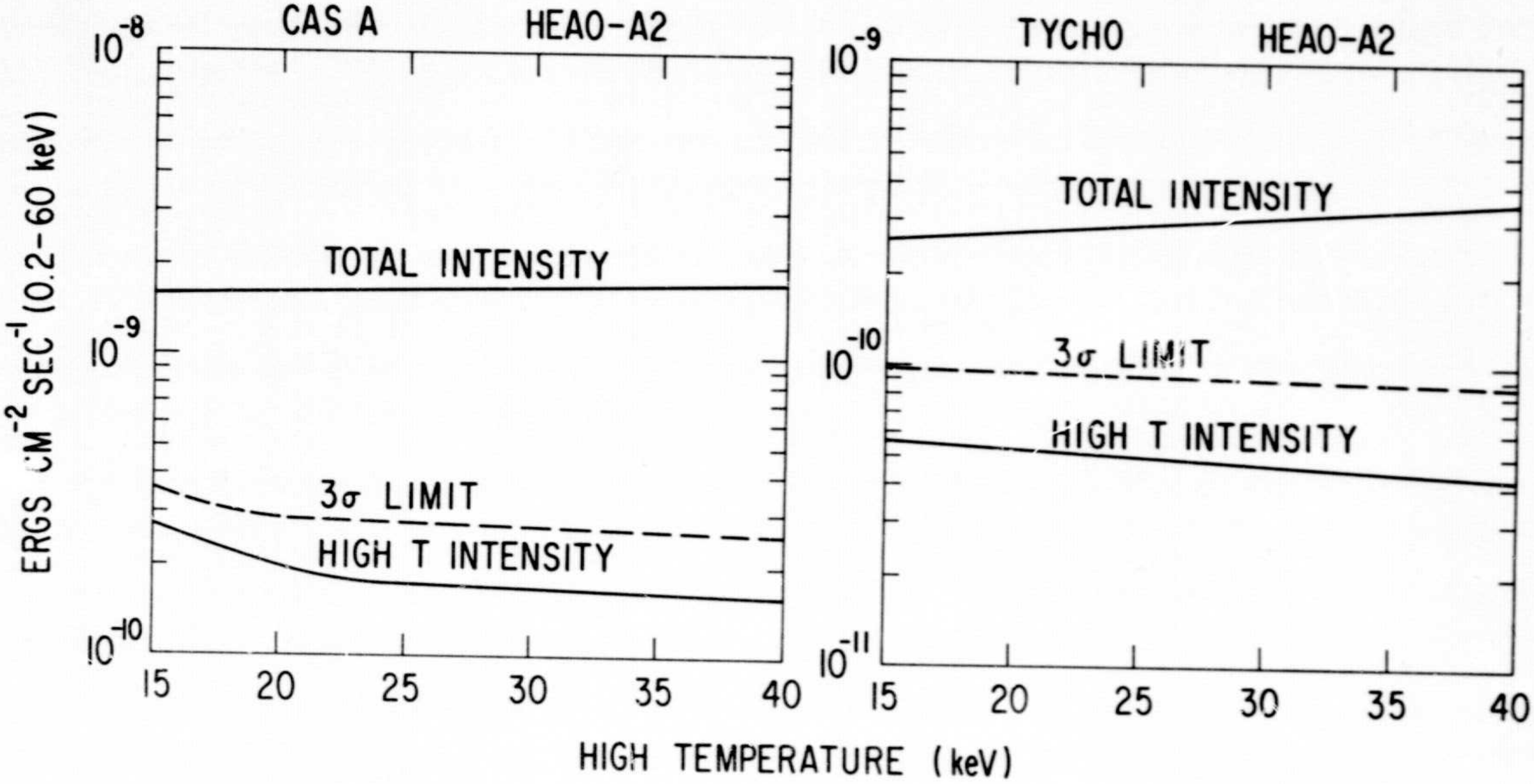
Figure 2 - Same as Figure 1 but for Tycho. Only the $\sim$ 6.7 keV line complex is statistically required in these data.

Figure 3 - The total continua intensities with the best-fit and upper limit intensities for the high temperature components of Cas A and Tycho.

HEAO-A2

CAS A HIGH ENERGY SPECTRUM




CAS A
HEAO-A2
TOTAL INTENSITY
3σ LIMIT
HIGH T INTENSITY
TYCHO
HEAO-A2
TOTAL INTENSITY
3σ LIMIT
HIGH T INTENSITY
ERGS CM-2 SEC-1 (0.2-60 keV)
HIGH TEMPERATURE (keV)