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LOW-ENERGY X-RAY LINE EMISSION FROM IC 443

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ABSTRACT

HEAO 1 observations of the spectrum of the supernova remnant IC 443 in the energy range of 0.4–3 keV reveal the presence of a complex structure suggestive of emission from Fe XVIII–XX, S XV–XVI, and Si XIII–XIV ions. The best electron temperature in our band for simple model fits is $\sim 6-11\times10^6$ K. Raymond and Smith collisional equilibrium emission models do not adequately fit the data. These results are discussed in terms of possible nonequilibrium effects in the remnant.

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

I. INTRODUCTION

The supernova remnant (SNR) IC 443 displays, in its northeast section, pronounced optical filamentary structure that is highly reminiscent of the Cygnus Loop and Vela X SNRs. Indeed, X-ray maps of IC 443 with sufficient spatial resolution (Levine *et al.* 1979; Parkes *et al.* 1977) have shown a correlation between the X-ray emission and the optical filaments that is similar to that of these older SNRs. However, observations by Lozinskaya (1979) have now demonstrated the existence of faint fast-moving Hα filaments, with velocities as high as 300 km s^{-1}, more characteristic of younger remnants. In addition, crude measurements of the X-ray spectrum (Malina, Lampton, and Bowyer 1976; Parkes *et al.* 1977) yield a temperature estimate $\sim 10^7$ K, much higher than the $2-3\times10^6$ K temperatures observed for the Cygnus Loop and Vela X. More recently, however, Woodgate, Lucke, and Socker (1979) have observed the Fe X λ6374 coronal line from IC 443 which, under equilibrium conditions, would imply the existence of *some* gas at $\sim 10^6$ K.

The distance to IC 443 is usually taken as ~ 1.5 kpc, based on the apparent interaction of the remnant with the nearby H I nebula S249 (see Charles, Culhane, and Rapley 1975, and references therein). The column density to the source, $\sim 4\times10^{21}$ cm^{-2} (Malina, Lampton, and Bowyer 1976), is roughly consistent with this distance.

Here we present the first soft-X-ray (<3 keV) spectrum of IC 443 with sufficient sensitivity and spectral resolution to investigate the presence of X-ray emission features. Substantial line emission is expected in this energy band from plasmas with near solar abundances. Measured line positions can be used to indicate average charge states for different elements and, hence, collisional equilibrium temperatures. Iron L-shell lines around 1 keV are particularly important; these have been observed in local stars (Capella: Cash *et al.* 1978; Holt *et al.* 1979) and clusters of galaxies (Virgo: Lea *et al.* 1979), as well as in other SNRs (Cas A: Becker *et al.* 1979). Other prominent lines in this range are Kα transitions in magnesium, silicon, and sulphur, the latter two having been seen in Cas A (Becker *et al.*) and Tycho (Pravdo *et al.* 1980).

II. OBSERVATIONS

The X-ray spectrum of IC 443 was obtained during a 3-hour pointed observation with the *HEAO 1* A-2[4] experiment (Rothschild *et al.* 1979) in 1978 October. Specifically, we utilized the low-energy detectors (LEDs) of this experiment to define the 0.1–3 keV spectrum. The target position was the radio centroid of the SNR at $6^h14^m +22°35'$ (1950), but given the large field of view of LED 1 ($1\overset{\circ}{.}5\times3\overset{\circ}{.}0$ FWHM), we are assured of observing X-rays from anywhere within the remnant at close to maximum response. Earlier scans of this region with the *HEAO 1* detector yielded a position for the X-ray emission that is consistent with previous observations,

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i.e., the centroid appears to be located just inside the principal filamentary region.

Background count rates for the spectrum were estimated from the earlier scans of IC 443. The pointing data, however, were obtained late in the experiment lifetime when the satellite was at a relatively low altitude. Thus, the spectrum is also affected by a variable flux of very soft X-rays due to solar radiation scattered off the upper atmosphere. To eliminate any possible contamination by this effect, only ~1 hour of data were summed, representing the darkest portion of each orbit. In addition, all events below 0.4 keV were rejected. The gain of the detector was calibrated shortly before the IC 443 pointing to an accuracy of $\lesssim 1\%$, using a radioactive source that produces Kα lines of carbon, fluorine, and aluminum.

III. SPECTRAL ANALYSIS

The 22-channel background-subtracted count spectrum is depicted in Figure 1*a*. Simple thermal continuum models, such as those invoked by Malina *et al.*, do not provide acceptable fits to the data. In order to ascertain the general shape of the incident spectrum, we used the spectral deconvolution procedure discussed by Kahn and Blissett (1980). This method provides a smoothed estimate of the incident spectrum characterized by an effective resolution determined by the statistical quality of the data. We have used it previously in the analysis of the spectra of the Crab Nebula (Charles *et al.* 1979), the SNR G65.2+5.7 (Mason *et al.* 1979), and the Cygnus Loop (Kahn *et al.* 1980).

In Figure 1*b*, we show a 1σ envelope of allowable spectra obtained using the Kahn and Blissett prescription. As can be seen, the spectrum is not smooth, but instead exhibits structure suggestive of discrete emission features. The reality of this structure has been verified through use of an iterative "selective weighting" procedure (see Kahn and Blissett [1980] for details) and through simulations with smooth artificial incident spectra. Because of the complexity of the spectrum, however, the interpretation of the deconvolution is not obvious. In particular, it is unclear which sections of the spectrum are actually representative of the underlying continuum and which sections may be representative of emission or absorption features.

Some further insight can be gained through model fitting. In Table 1, we summarize the results of fitting models allowing for a thermal continuum (exponential with a Gaunt factor) plus spectral lines at adjustable positions and intensities. As can be seen, the χ^2 drops precipitously with the addition of each line until an acceptable fit is obtained with three lines. The required line positions of 0.89, 1.87, and 2.34 keV are consistent with emission from Fe L-shell, Si Kα, and S Kα transitions, respectively. Such transitions are expected to be excited collisionally in equilibrium plasmas with temperatures near 10^7 K. For comparison, this best-fit model is plotted over the raw data and the deconvolved spectral estimate in Figures 1*a*, *b*, respectively.

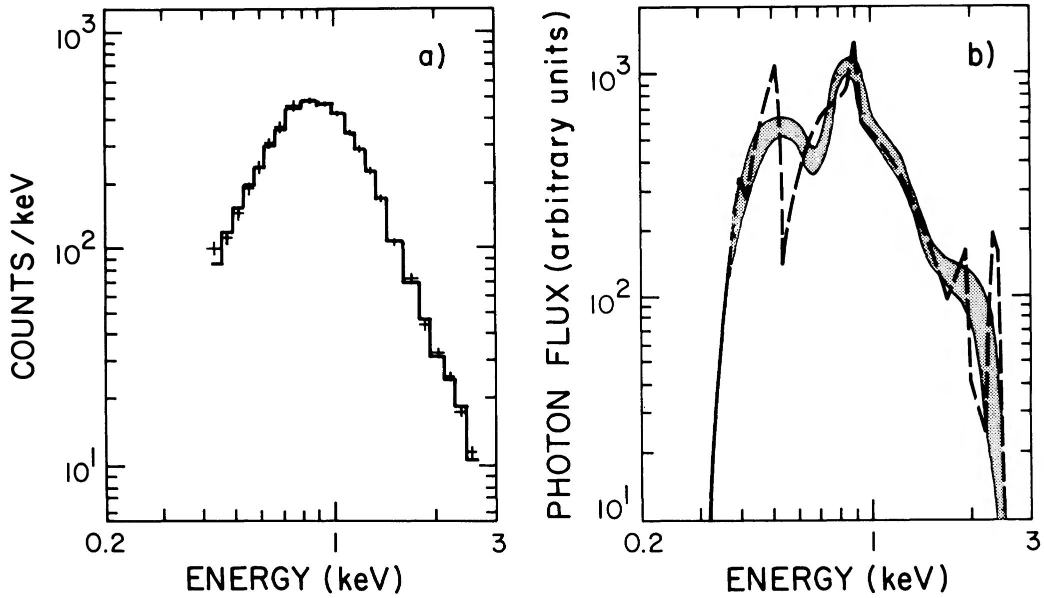

FIG. 1.—(*a*) The raw count spectrum (*crosses*) of IC 443 as detected by the *HEAO 1* A-2 low energy detectors. The best-fit model, consisting of a simple bremsstrahlung continuum plus three emission lines, is plotted as a solid-line histogram for comparison. (*b*) The deconvolved photon spectrum of IC 443 obtained using the Kahn and Blissett prescription. The shaded region is the 1σ envelope of allowable curves. The best-fit model is plotted as a dashed line.

TABLE 1

IC 443 SPECTRAL FITS—THERMAL BREMSSTRAHLUNG + LINE EMISSION

MODEL	Log T (K)	Log N_x (cm^{-2})	LINE ENERGIES (E) AND EQ. WIDTH (W) (keV) E_1	W_1	E_2	W_2	E_3	W_3	χ^2	d.o.f.
Exp. + Gaunt ...	6.76	21.52	...	...	...	...	...	...	758	19
+1 line..........	7.06	21.28	0.92	0.20	...	...	...	...	148	17
+2 lines	6.82	21.49	0.90	0.11	2.27	0.86	...	...	27.6	15
+3 lines	6.70	21.59	0.89	0.07	1.87	0.25	2.34	2.0	15.4	13
Errors (1σ)	0.05	0.04	0.01	0.02	0.07	0.08	0.04	0.6	...	...

More self-consistent models are provided by the collisional equilibrium emission calculations of Raymond and Smith (1977; 1981, hereafter RS). In Table 2A, we summarize the results of fitting single temperature RS spectra to the data. As can be seen, we *do not* obtain acceptable fits with these model spectra, even if the abundances of the important elements are allowed to vary. In Table 2B, we list the results of fitting multitemperature RS spectra (assuming cosmic abundances). The inclusion of additional thermal components does substantially improve the fit. However, the reduced χ^2 obtained, even with three components, is still unacceptable at the 99% level. Allowance for additional degrees of freedom in such models is not warranted in relation to the number of independent data points available.

IV. DISCUSSION

The observation of line emission in IC 443 opens up a new avenue for investigating the physics of the remnant and its interaction with the surrounding interstellar medium. The intensities of the observed emission features can provide information about the elemental and ionic species present in the emitting matter.

Of particular interest concerning the present observations is the poor quality of the Raymond and Smith model fits to the data, as compared to the model involving simple bremsstrahlung with three emission lines. As has been pointed out by Smith, Mushotzky, and Serlemitsos (1979), there is some uncertainty inherent in the RS model itself; excitation cross sections used in the

TABLE 2

RS MODEL FITS TO IC 443

A. SINGLE TEMPERATURE MODELS

Log T	Log N_x	LOG ABUNDANCES COSMIC Fe	Si	S	Mg	χ^2	d.o.f.
6.85	21.98	...	...	...	...	1315	19
6.78	21.58	−1.21	...	0.93	...	52.5	17
6.74	21.64	−1.20	0.17	1.11	...	43.1	16
6.74	21.64	−1.18	[0.17]	1.12	0.02	41.2	16
Errors[a]:							
0.01	0.01	0.05	0.05	0.05	0.02	...	...

B. MULTITEMPERATURE MODELS

COMPONENT 1 Log T (K)	f[b]	COMPONENT 2 Log T (K)	f[b]	COMPONENT 3 Log T (K)	f[b]	Log N_x (cm^{-2})	χ^2	d.o.f.
7.02	0.001	6.00	0.999	...	...	21.98	103	16
7.14	0.0003	5.98	0.999	6.47	0.001	22.03	36	14
Errors[a]:								
0.05	0.0002	0.02	0.001	0.10	0.001	0.02	...	...

[a] Based on the second partial derivatives of the χ^2 function at minimum.

[b] Fractional emission measure.

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calculations may be incorrect by as much as 30% for some transitions. However, it is more likely that the poorness of fit is related to the RS assumption of complete ionization equilibrium. As an SNR evolves, the individual element populations may not have time to reach the equilibrium ionization structure characteristic of the time-dependent, average electron temperature. Recent numerical calculations (Itoh 1979; Gronenschild 1979) have shown that nonequilibrium effects may well be important, even for remnants as old as IC 443. Itoh (1979) finds that the low-energy X-ray lines should be enhanced with respect to their equilibrium values, thus giving the appearance of a multicomponent spectrum.

A qualitative estimate of the departure from equilibrium conditions in the emitting gas may be obtained from a study of the actual line positions we derive from the data. The iron lines, in particular, provide a sensitive discriminator of the ionization structure, since the L-shell transitions for Fe XVII–XXI are spread throughout the range of 0.85–1.1 keV. The centroid of the iron emission, therefore, gives a measure of an effective ionization temperature for the remnant, which can then be compared with the continuum temperature or the temperature estimated from other lines. In order to calibrate this effect, keeping in mind the low intrinsic resolution of our detector, we performed the following analysis. At a variety of temperatures, we used the equilibrium RS model to produce artificial pulse-height analyzer data sets at a statistical level comparable to that of our IC 443 data. We then fit these artificial data sets with the model involving the simple bremsstrahlung continuum plus emission lines at arbitrary positions and intensities. The energies of the required lines can then be plotted as a function of the temperatures parameterizing the collisional equilibrium model.

The results are illustrated in Figure 2. At temperatures below $\sim 2.5\times10^6$ K, only one emission line is necessary; the addition of other lines does not significantly improve the fit. The line appears at ~ 0.6 keV and may be identified as primarily O VII–VIII emission. At temperatures above 2.5×10^6 K, it is necessary to include a higher energy line at ~ 0.85 keV in order to obtain a satisfactory fit. This higher energy line is associated with the iron L emission. As can be seen from the figure, the energy of this line is a smoothly increasing function of temperature up to $\sim 2\times10^7$ K.

The iron feature detected in the IC 443 spectrum peaks at 0.89 keV. Comparison with Figure 2 shows that under equilibrium conditions this emission would be characteristic of temperatures $\lesssim 4\times10^6$ K. The overall "spectral hardness" found by us and by previous higher energy experiments is characteristic of temperatures ~ 6–11×10^6 K. Finally, the strong silicon and sulphur lines imply temperatures $\sim \text{few}\times10^7$ K. Thus, the complete spectrum of IC 443 suggests severe departures from ionization equilibrium in the remnant.

Similar conclusions can be drawn from the results of our trial fits with the multitemperature RS models. Improvements in the fit can only be obtained by introducing very soft extra components at temperatures $\lesssim 10^6$ K. Because IC 443 is so highly cut off ($N_x \sim 4$–10×10^{21} cm^{-2}), most of the flux from these soft components is

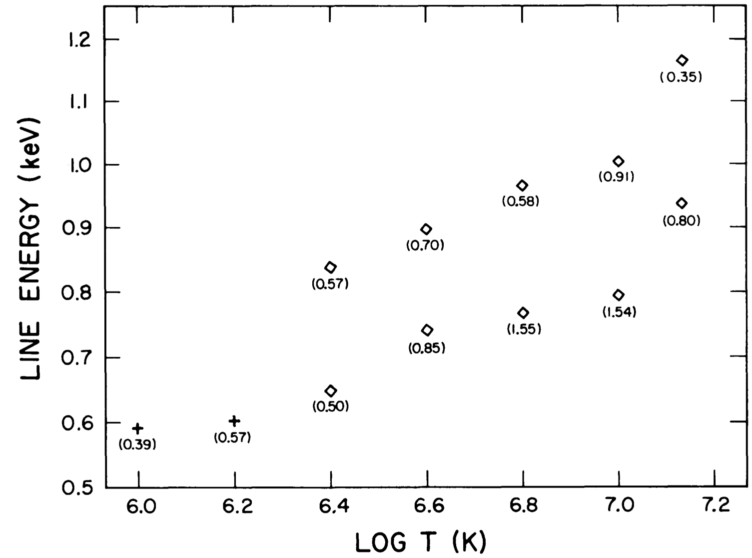

FIG. 2.—The results of fitting simple continuum plus emission-line models to the count spectra produced by folding Raymond-Smith model spectra through the detector response. For log $T<6.4$, only one emission line is necessary to obtain a satisfactory fit. The energy of this line is plotted as a cross. For log $T\gtrsim 6.4$, two emission lines are necessary. The energies of these lines are plotted as diamonds. In all cases, the numbers in parentheses represent the required equivalent widths (in keV) for the respective emission lines.

absorbed in the interstellar medium. Their inclusion merely provides a better fit to the profile of the iron line complex which, as demonstrated above, is indicative of lower equilibrium temperatures. The higher temperature component, required by the fits, is constrained by the intensities of the silicon and sulphur features. The ionization structure of these elements should be closer to equilibrium since they have fewer electrons to get rid of and thus take less time to equilibriate. The true electron temperature in the remnant is likely to be higher than that inferred for any of the components using the collisional equilibrium models.

For the case of IC 443, as well as for other SNRs, further high-resolution observations would be very valuable. Future observations of the individual line series from several different ionic species may allow the separate determinations of the temperature and ionization structure in the remnant, and may thus yield quantitative constraints on the physical conditions in the shocked emitting gas.

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