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HIGH-RESOLUTION X-RAY SPECTROSCOPY OF M87 WITH THE *EINSTEIN* OBSERVATORY: THE DETECTION OF AN O VIII EMISSION LINE[1]

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ABSTRACT

Observations were performed with the focal plane crystal spectrometer of a $3' \times 30'$ (19×190 kpc) region centered on M87 which includes 10% of the total emission from the Virgo cluster. We have detected Lα emission from O VIII with a flux of 0.013 ± 0.003 photons cm^{-2} s^{-1} corresponding to 1.2×10^{42} ergs s^{-1} at the source within the specified region. Upper limits of 0.0029 and 0.0025 photons cm^{-2} s^{-1} ($3\ \sigma$) are set for *L*-lines of Fe XXIII and Fe XXIV at $\sim$1.1 keV (10.7–11.0 Å) and of Fe XVII at 0.83 keV (15.0 Å), respectively. The O VIII Lα flux is more than 7 times greater than that expected for an isothermal gas at 3×10^7 K, which is the dominant temperature in the source, if the gas has a cosmic abundance ratio of oxygen to iron. It similarly exceeds the line flux predicted by adiabatic and hydrostatic models. This observation indicates that additional cooler gas must be present in the vicinity of M87, as has been suggested in models describing radiatively regulated accretion of the intracluster gas onto M87. The results restrict the dominant temperature of the cooler gas to near 10^7 K or $< 2 \times 10^6$ K. The line luminosity estimated for the detailed radiatively regulated accretion model of Mathews and Bregman is within a factor of 2 of our measured value. Measurements of line emission should provide tight constraints on allowable model parameters.

Subject headings: galaxies: clusters of — galaxies: general — galaxies: intergalactic medium — X-rays: spectra

I. INTRODUCTION

We have performed high-resolution X-ray spectroscopy of the extended source surrounding the giant elliptical galaxy M87 in the Virgo cluster. The observations were carried out with the focal plane crystal spectrometer (FPCS) on the *Einstein* Observatory (*HEAO 2*). We have detected Lα emission from hydrogenic oxygen (O VIII) and have set upper limits on lines from intermediate ionization states of iron. These observations reveal the presence of a quantity of cooler matter surrounding M87 which has important implications for cluster models and favors a radiatively controlled accretion mechanism.

The X-ray emission from clusters of galaxies is thought to arise predominantly from a hot intracluster medium enriched with heavy elements (cf. Gursky and Schwartz 1977). The source in the Virgo cluster differs from many of the other cluster sources in that it appears to have two components, one which extends through much of the cluster (with a size scale of at least 1°) and another which is concentrated around M87 (with a core radius of $\sim$12′–15′; Malina *et al.* 1976; Gorenstein *et al.* 1977; Lawrence 1978; Davison 1978; Lea *et al.* 1979). The latter is presumably due to an increased concentration of intracluster gas settling in the local gravitational potential well and possibly accreting onto the massive galaxy (cf. Bahcall and Sarazin 1977; Mathews 1978; Mathews and Bregman 1978). Iron emission from Virgo as a whole has been detected with proportional counters at 6.7 keV (Serlemitsos *et al.* 1977; Mushotzky *et al.* 1978) and at $\sim$1.1 keV (Lea *et al.* 1979). Fabricant *et al.* (1978) also detected the $\sim$1.1 keV Fe emission from the component surrounding M87 and showed that it was spread over at least $\sim$25′.

II. INSTRUMENTATION AND OBSERVATIONS

The FPCS is described in some detail elsewhere (Canizares *et al.* 1977; Donaghy and Canizares 1978; Giacconi *et al.* 1979). Briefly, it is a curved-crystal Bragg spectrometer which operates at the focus of the *Einstein* Observatory X-ray telescope. Figure 1 shows a schematic of the instrument and illustrates its operation. X-rays from a celestial source are brought to a focus by the telescope, pass through one of several selectable apertures, and strike one of six curved crystal diffractors. X-rays with wavelengths very near to that specified by the Bragg condition for the selected angle setting of the diffractor are reflected and astigmatically refocused onto one of two redundant, position-sensitive proportional counters. In a given observation, the crystal is rocked through a small angular range, thereby tuning the bandpass of the instrument back and forth across a limited spectral region. The instrument can be reconfigured to study an entirely different region by changing the diffractor, its angle with respect to the incident X-rays, and the relative positions and orientations of the diffractor and detector. The instrument covers the range 0.2–3 keV, with a

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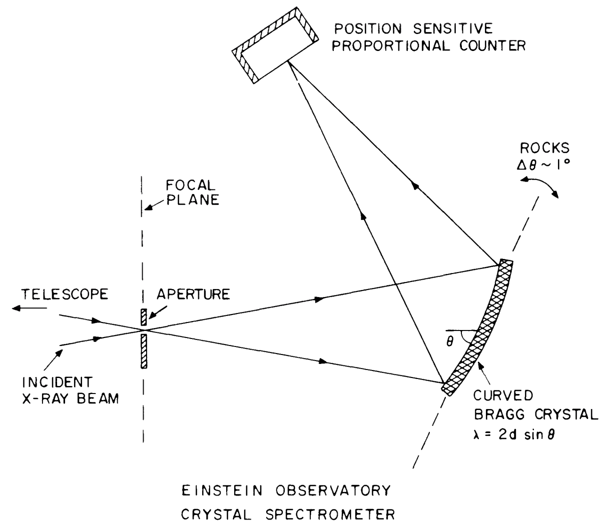

FIG. 1.—Schematic diagram of the focal plane crystal spectrometer on the *Einstein* Observatory.

resolving power $E/\Delta E$, of 50–500. A typical observation involves a scan width of three to five spectral resolution elements centered on some specific spectral feature, and lasts 5000–40,000 s. The end result of the data reduction process is a list of photons tagged with arrival time, proportional counter pulse height, position in the proportional counter, and effective Bragg angle. The position and Bragg angle are corrected for the instantaneous source-image location in the focal plane using the satellite aspect solution from on-board star trackers.

The observations of M87 were carried out in 1978 December and 1979 January. In every case the source was viewed through a $3' \times 30'$ aperture (19×190 kpc at 21.9 Mpc, the distance given by Sandage and Tammann 1976) centered on M87 to within $\sim 20''$. The aperture contains $\sim 25\%$ of the region of enhanced emission centered on M87. We deduce this value by outlining our aperture on the X-ray image of M87 obtained with the imaging proportional counter on the *Einstein* Observatory (and kindly made available to us by Paul Gorenstein) and comparing the number of photons inside the aperture to the total number in the image. The ratio varies by $\lesssim 10\%$ of its value with energy 0.5–3 keV. A similar procedure performed with the earlier image of Gorenstein *et al.* (1977) gives a similar value. Lea *et al.* (1979) estimated that this earlier image contained $\sim 40\%$ of the total emission from the Virgo cluster. Thus our aperture includes $\sim 10\%$ of the total.

We carried out spectral scans centered on the wavelengths corresponding to (i) Lα radiation from hydrogenic oxygen (O VIII), (ii) L-lines from Fe XVII, and (iii) several L-lines from Fe XXIII and Fe XXIV (as well as Fe XVIII and Fe XIX). Details of the observations are given in Table 1.

III. RESULTS

The analysis procedure is as follows. First the data are selected to exclude times of Earth blockage, high particle background, and poor satellite aspect determination. Then further selections are made to exclude all photons which fall outside the appropriate pulse-height interval and the appropriate region of the detector which contains the astigmatic image of the source. The final spectrum consists of a histogram of counting rate versus wavelength (computed from the aspected-corrected Bragg angle for each photon), corrected for the exposure time in each wavelength interval.

The spectrum near O VIII Lα is shown in Figure 2. There is a clear enhancement near the expected wavelength of the line (18.97 Å redshifted to 19.05 Å; the estimated uncertainty in our absolute wavelength calibration is ~ 0.05 Å). We fitted the spectrum to a flat continuum alone and to a continuum plus a Gaussian line of the expected wavelength and width (~ 0.2 Å for an extended source). The continuum was constrained to have zero slope since it is dominated by non–X-ray background (cosmic rays); furthermore, the expected slope in the source continuum over our narrow spectral range due to the combined (and compensating) effects of interstellar absorption (Brinkman *et al.* 1978) and variations in the efficiency of the instrument is $\lesssim 7\%$.

The fit with no line gives a reduced χ^2 of 1.53 for 13 degrees of freedom, which is unacceptable at a 90%

TABLE 1

SUMMARY OF OBSERVATIONS AND RESULTS

RANGE OF SCAN Å (keV)	TIME (10^3 s)	DOMINANT LINES: Ion[a]	Wavelength[b]	Energy[b]	DETECTED FLUX[c] (10^{-3} photons cm^{-2} s^{-1})	EQUIVALENT WIDTH[d] (eV)	STRENGTH AT M87[e] (10^{41} ergs s^{-1})
18.8–19.5 (0.636–0.660)......	36	O VIII	18.97	0.654	13 ± 3	330	12
10.2–11.4 (1.09–1.22)........	32	Fe XXIV	10.65	1.164	<2.9	<165	<3.3
		Fe XXIII+XXIV	11.01	1.127			
14.8–15.5 (0.800–0.838)......	33	Fe XVII	15.01	0.826	<2.5	<140	<2.2

[a] See Raymond and Smith 1977 for specific transitions.
[b] Line wavelengths and energies in the rest system.
[c] The uncertainty is statistical only. The upper limits are for a *single* line at 99.7% confidence (3σ).
[d] Using 10% of the continuum value from Lea *et al.* 1979.
[e] For the region within our aperture, a distance to M87 of 21.9 Mpc (Sandage and Tammann 1976), and corrected for absorption by a column density of 7×10^{20} cm^{-2} (Brinkman *et al.* 1978), and the abundances of Brown and Gould 1969.

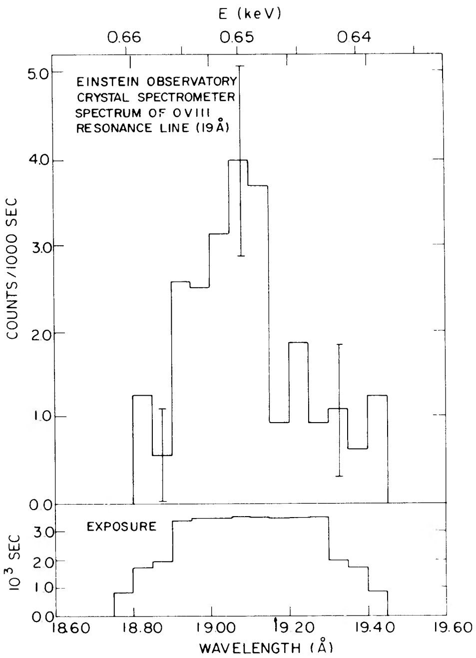

FIG. 2.—Spectrum of M87 in the vicinity of the Lα line of O VIII. The upper curve shows the count rate versus wavelength corrected for exposure. The exposure is shown in the lower curve. The redshifted wavelength of the line is 19.05 Å.

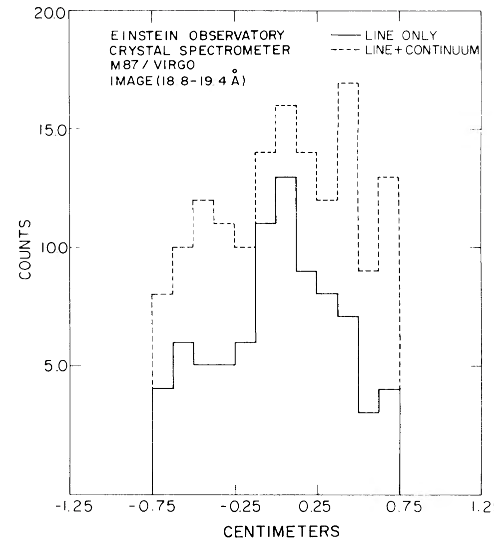

FIG. 3.—Histogram of counts versus position in the detector corrected for image motion showing the projection of the astigmatic image of the source formed by X-rays in the O VIII Lα line and in the line plus continuum (mainly background). The scale is $\sim$1 mm per arcmin on the sky, and the expected width of the M87 image is $\sim$4 mm.

confidence level. However, the significance of the line is even greater than this might suggest for two reasons. First, it appears at the expected wavelength with the correct width. A second and more important reason is that the X-rays contained in the line form an astigmatic image of the source in the detector, whereas no such image is evident when all of the X-rays in the spectrum are used. Figure 3 shows the two cases, which indicate that the spectral enhancement is indeed an emission line of O VIII Lα from M87 superposed on a background composed almost entirely of non–X-ray events.

The fitted line strength for O VIII Lα is listed in Table 1 together with the equivalent width as normalized to the continuum of Lea *et al.* (1979) corrected for our aperture size as indicated above, and with the implied luminosity at a distance of 21.9 Mpc corrected for interstellar absorption (Brinkman *et al.* 1978). The uncertainty is statistical only. We estimate the systematic uncertainty in our sensitivity to be $\sim$30% based on preflight calibrations and an observation of the Crab nebula.

The spectra of the Fe *L*-lines show no features and are consistent with a smooth continuum. Table 1 lists the 3 σ upper limits to the flux in a *single* line. However, the fact that the data for the Fe XXIII/Fe XXIV region do form an image in the detector indicates that we are detecting photons from M87 in this narrow spectral range. The continuum of Lea *et al.* (1979) can account for only $\sim$20% of this, and it is most likely that the excess is due to the presence of several lines, none of which is strong enough to stand above the others. The required flux in these lines is $\sim$0.007 $\pm$ 0.002 photons cm^{-2} s^{-1}, which is consistent with 10% (the aperture correction) of the value 0.020 (+0.038, −0.016) photons cm^{-2} s^{-1} which Lea *et al.* (1979) determined for the blend of Fe *L*-lines in this spectral region (which is, of course, unresolved in their data).

IV. DISCUSSION

The results listed in Table 1 can be used to deduce some properties of the intracluster material surrounding M87. We use the calculated line emissivities from the models of Raymond and Smith (1977, 1979) to deduce the volume emission measure required by our measured line luminosity and upper limits. This is done as a function of the temperature of the emitting material. Because cosmic abundances are assumed, the deduced emission measures must be corrected upward if the abundances are lower. Figure 4 shows a plot of the emission measures versus temperature together with a single point deduced in a similar fashion from the 6.7 keV Fe XXV line flux of Serlemitsos *et al.* (1977) corrected for our aperture size (on the assumption that the line and continuum have the same distribution) and plotted at the continuum temperature of 3×10^7 K. The dashed lines are the upper limits from our iron line measurements. The Fe XVII emissivity is sensitive to several outstanding uncertainties in the atomic cross-sections which are used in the emissivity calculations. The curve labelled Fe XVII*a* is probably closer to the true curve, which should lie between it and curve Fe XVII*b* (B. Smith, private communication; some of the caveats discussed by Smith, Mushotzky, and Serlemitsos 1979 are relevant, although we are insensitive to continuum calculations or to any effects which apply to both the O and Fe lines).

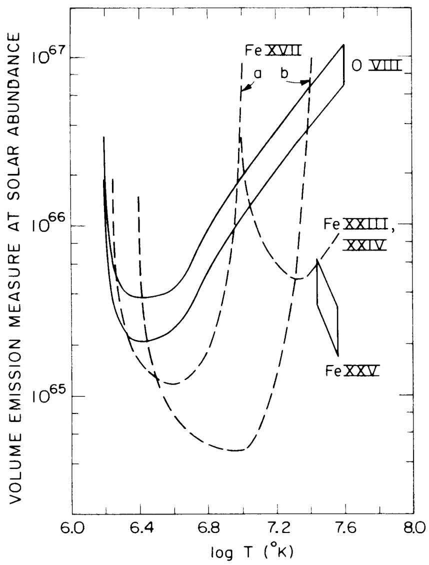

FIG. 4.—Volume emission measure (in cm^{-3}) versus temperature deduced as described in the text assuming solar abundances. The dashed lines are upper limits. The true curve for Fe XVII lies between those marked *a* and *b* but probably closer to *a*.

Figure 4 shows that the O VIII Lα emission *cannot* be due to an isothermal plasma at a temperature of 3×10^7 K if the ratio of O to Fe atomic abundance is at its cosmic value of 17 (Allen 1973; this conclusion is independent of the *absolute* abundance). If the O to Fe abundance ratio were 7 times its cosmic value, then an isothermal plasma could account for all our observations. Current models of nucleosynthesis and heavy element enrichment fall far short of accounting for such an extreme enhancement (Arnett 1978; DeYoung 1978).

Similarly, adiabatic and hydrostatic models of intracluster gas, such as those reviewed by Bahcall and Sarazin (1978), cannot explain the strong O VIII line unless the O to Fe ratio is several times its cosmic value. These models predict some enhanced O VIII emission due to cooler gas in the outer portions of the source, but even the total amount of this emission is insufficient to explain our observed line flux and it would be significantly reduced by our aperture since it arises at distances >3 core radii ($\sim 35'$) from the center (see Sarazin and Bahcall 1977).

It is much more likely that the intracluster medium is not isothermal and that it cools radiatively in the higher density regions around M87. A cooler region at the center of the source is indicated by observations of M87 performed with the solid state spectrometer on the *Einstein* Observatory (Mushotzky *et al.* 1979) and also appears to be present around NGC 1275 in the Perseus cluster (Ulmer and Jernigan 1978). Models in which this cooling regulates the accretion of gas onto the central galaxy have been presented by Silk (1976), Cowie and Binney (1977), Fabian and Nulsen (1977), and Mathews and Bregman (1978).

The data of Table 1 can be used to constrain the properties of the intracluster gas surrounding M87. For example, the curves of Figure 4 set general constraints on the possible properties of a cool component. If the O to Fe abundance ratio is cosmic then the allowed values of emission measure/temperature are those indicated by the portions of the O VIII curve lying below the curves indicating the upper limits for Fe XXIII, Fe XXIV, and Fe XVII (between curve *a* and *b* but closer to *a*). Thus the dominant temperature must be around 10^7 K or below $\sim 2 \times 10^6$ K.

Specific models can be tested in more detail. The most specific calculation of radiatively regulated accretion is that of Mathews and Bregman (1978). They show temperature and density distributions for a model with an accretion rate of $30\, M_\odot\, \mathrm{yr}^{-1}$. The dominant central temperature is in fact 10^7 K. We have estimated the O VIII Lα luminosity for this model to be $\sim 2 \times 10^{42}$ ergs s^{-1} using the data from their Figure 1 with the emissivities of Raymond and Smith (1977). This estimate, which assumes solar abundances, is within a factor of 2 of our measured luminosity 1.2×10^{42} ergs s^{-1}, which we take to be a remarkably close agreement. Undoubtedly, equality could be achieved with slight adjustments of abundance and model parameters.

It is clearly important that future model calculations include estimate of line emission, since the advent of moderate- and high-resolution X-ray spectroscopy with the *Einstein* Observatory makes possible very detailed tests of the validity of the models and imposes tight constraints on their parameters.

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