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Abstract

We report X-ray observations of the galaxy M87 and of a region in the Virgo cluster displaced 7' from the center of M87. We obtained X-ray spectra at these two locations with the Solid State Spectrometer onboard the *Einstein* Observatory. Emission lines were observed in both locations, indicating the presence of heavy elements at abundances ≈ solar (to within a factor of 2). There is no strong abundance gradient, within our errors. We have detected a temperature gradient: T increases from ~ 1.4 keV at the position of M87 to T ~ 3.35 keV 7' away. There is lower temperature thermal emission at the center of M87 with T ~ 0.6 keV, consistent with models for cooling flows in this cluster. We obtain a mass infall rate of $\dot{M} \sim 20\ M_{\odot}\ yr^{-1}$. In addition to the thermal emission, we have detected a power-law component in the spectrum of M87, consistent with that observed by HEAO-1, indicating that this component probably originates in the galaxy itself.

Comparison of our results with those of other observers and with theoretical models for this source indicates the presence of intracluster gas having density ~ 10^{-3} cm^{-3} and temperature ~ 3 x 10^7 K.

Subject headings: galaxies: clusters of -- galaxies: individual (M87) -- galaxies: intergalactic medium -- X-ray: sources

I. INTRODUCTION

The giant galaxy M87 in the Virgo cluster has been known to be an X-ray source for many years. Recently it has become clear that the source is complex both spatially (Lawrence, 1978; Lea et al., 1979; Forman et al., 1979) and spectrally (Lea et al., 1981). In addition, attention has been focussed on this galaxy because of observations which may indicate the presence of a black hole in the nucleus (e.g. Young et al., 1978). In a previous paper (Lea et al., 1981) we presented spectral observations of this object using the A-2 and A-4 detectors on board the HEAO-1 satellite. These data indicated the presence of a power law (or very high temperature thermal) component in addition to a thermal component of kT ≈ 2keV. We were unable to determine the spatial location of the spectral components we observed, due to the large field of view of the detectors. However, the possibility of variability of the hard component led us to suggest that the nucleus of M87 was the location of the power-law component.

The solid state spectrometer (SSS) onboard the Einstein Observatory has a 6' diameter circular beam, and offers the opportunity to obtain better spectral resolution, combined with spatial resolution, and thus to disentangle the various components of the source. In this paper we report SSS observations at two positions, centered on M87 and 7' offset from the center of M87. Observations more distant from M87 proved impractical due to the rapidly decreasing surface brightness. The distance to M87 is taken to be 20 Mpc throughout, so that one arcminute is approximately equivalent to 6 kpc.

II. OBSERVATIONS

The observation of the central region of the galaxy M87 was obtained by the SSS in 1978 June 22-26, during which time a total of 16,500 seconds of data were accumulated. The observed spectrum is complex (see figure 1) and no one single component model fits the data. Our basic model is that of thermal emission from a hot, thin plasma (Raymond and Smith, 1977, RS), including line emission from heavy elements. The importance of the lines is shown in figure 2, which shows the ratio of lines to the "continuum".

Our analysis procedure was to attempt to fit a simple model, and to gradually increase the complexity until an acceptable fit was obtained. The amount of ice accumulated on the detector was an additional free parameter, which was allowed to vary over reasonable values, as discussed by Holt et al. (1979). The results obtained were consistent with the expected value based on an empirical model for the rate of ice accumulation.

A two component RS model with the abundances for elements with $z > 5$ all allowed to vary together relative to H, gave a χ^2 of 221 for 58 degrees of freedom and was, therefore, unacceptable. Introducing a third thermal component, we found that the third temperature was so high as to be indistinguishable from a power-law mimicking the free-free Gaunt factor, as indicated by our observations at higher energies (Lea et al., 1981). For models including a power law of form $F \propto E^{-\alpha}$ keV (cm^2 sec keV)$^{-1}$, α is constrained to lie in the range $0.4 \lesssim \alpha \lesssim 1.0$. Adding a fourth component does not improve the fit. All the residuals appear to lie in the iron L band at around 1 keV.

The best-fit model has a χ^2 of 129, $T_L = 0.6$ keV, $T_H = 1.4$ keV, abundance of heavy elements (in solar proportions) approximately solar and an associated absorbing column $5 \times 10^{20} < N_H < 2 \times 10^{21}$ cm^{-2}, plus a power law of energy index $\alpha \sim 1$ with an associated absorbing column $N_H \sim 10^{22}$ cm^{-2}. The 21 cm hydrogen column in the direction of M87 is $N_H \sim (2 - 3) \times 10^{20}$ (Heiles 1976, Heiles and Cleary, 1978). The cool component that we have observed itself contributes to the absorbing column, since about 15% of the oxygen at this temperature has an inner shell electron. We find $N_H \approx 3 \times 10^{20}\ R_{kpc}^{-1/2}\ cm^{-2}$ due to this material, where R is the size of the cool component, defined below. Therefore, we do not consider our measured column for the thermal component to be in disagreement with the 21 cm value. However the measured value for the power law component is ~ 50 times the 21 cm value and is clearly discrepant.

A formally acceptable fit ($\chi^2 = 87$ for 55 degrees of freedom) was obtained by allowing the abundances to vary independently. All were well within a factor of two of solar, except for Neon, which, with a value of about 6, more likely represents an inadequacy in the atomic physics computations for the iron L shell blend (Raymond, private communication, see also Smith, Mushotzky and Serlemitsos, 1979) than a physically significant abundance anomaly. It appears that the atomic physics calculations we are using (Raymond and Smith, 1977) do not accurately reproduce the detailed shape of the iron L shell line group at ~ 1 keV. Ne also has a transition in this region, and the shape of the emission in this region can be changed by changing the Ne abundance. For this reason, the values in table I are for the case where the heavy element abundances are fixed to solar proportions.

We have also observed a region in the cluster 7' from M87, during the same time period. We obtained 24,300 seconds of data at this location, R.A. $12^h27^m50^s$, declination 12°42'22". A simple thermal bremsstrahlung fit with no lines gave a χ^2 of 107 for 62 degrees of freedom. A better fit ($\chi^2 = 70$ for 61 degrees of freedom) was obtained by introducing heavy elements, in solar proportions, and the best fit for the ratio of heavy elements to hydrogen was 0.95 solar. The importance of line emission in this spectrum is shown in figure 2. The gas temperature for this fit was 3.35 keV, with $2.8 < T < 4.5$ keV at 90% confidence, for 3 significant parameters (the temperature, abundance and emission integral). The range of abundances determined in the same way is

$0.30 < X < 2.00$. The amount of ice on the detector was fixed at the value found for the M87 observation, although at this higher temperature our results are not as sensitive to the amount of ice. Introducing further components, or allowing the elemental abundances to change independently did not produce any significant improvement in the fit.

III. DISCUSSION

a) Abundance and Temperature Gradients

The spectrum taken 7' from M87 shows that X-ray lines due to heavy elements are present at this location. The abundances at 7' from the center of M87 are consistent with those found at the center, implying that no strong abundance gradients (i.e. greater than a factor of 2) are present. In contrast, we find that the gas temperature is not consistent in the two observations; the temperature is definitely lower in the observation centered on M87. This result is consistent with models for the X-ray halo which involve cooling in the inner regions of M87. The temperature which best fit the HEAO-1 data ($T \sim 2$ keV) is bracketed by the temperatures in the inner region ($T = 1.4$ keV) and farther out ($T = 3.35$ keV). The lowest temperature ($T = 0.6$ keV) is representative of a very small amount of gas. The emission measure for this component is 4.6×10^{64} cm^{-3}. For a spherical volume of radius R_{kpc}, this implies a density of $\langle n^2 \rangle^{1/2} \sim 0.6\ R_{kpc}^{-3/2}$ cm^{-3}, a mass of $\sim 6 \times 10^7\ R_{kpc}^{3/2}\ M_\odot$, and pressure $\sim 10^{-9}\ R_{kpc}^{-3/2}$ dynes cm^{-2} sufficient to confine the radio jet if $R_{kpc} < 0.4$ (Owen et al., 1980). The temperature gradient in the Virgo cluster has also been estimated from the IPC image of M87 by Fabricant et al. (1980). Our measured temperatures in the inner 6' and 7' from the center of M87 are consistent with theirs.

We have calculated the mass infall rate implied by our data as follows. Using the cooling rates in Raymond, Cox and Smith (1976), corrected to an iron abundance of 3.2×10^{-5}, the cooling time at the 5×10^6 K temperature we measure is $\sim 2 \times 10^6\ n^{-1}$ yr, where n is the gas density. Using our value of n given above, we find $t_{cool} \sim 3.3 \times 10^6\ R_{kpc}{}^{3/2}$ yrs, for a total mass of gas $6 \times 10^7\ R_{kpc}{}^{3/2}\ M_\odot$, which implies $\dot{M} = 18\ M_\odot$/yr, independent of the size of the cool region. This result is also independent of the degree of clumping of the gas. We can also calculate the infall rate from our observations of the hotter component in the central region of M87, $T \approx 1.4$ keV $\approx 1.5 \times 10^7$ K. For this component the emission measure is $2 \times 10^{65} = \langle n^2 \rangle V$. Assuming that the source fills the SSS beam, we obtain $\langle n_e{}^2 \rangle^{1/2} = 1.8 \times 10^{-2}$ cm^{-3}, $t_{cool} \sim 4 \times 10^8$ yrs, $M \sim 9 \times 10^9\ M_\odot$ and $\dot{M} \sim 23\ M_\odot\ yr^{-1}$, in good agreement with our estimate from the low temperature component. The computed value of $\dot{M}$ depends on the size of the 1.5×10^7 K region if it is larger than the beam size, with $\dot{M}$ scaling approximately as $(\ell/23\ \mathrm{kpc})^{-1}$ where ℓ is the length along the line of sight of the emitting region. This estimate is sensitive to the iron abundance, and to the detailed physics of the cooling process. In particular, if the cooling is isobaric the computed $\dot{M}$ is a factor of 2 lower.

We have compared our results with the radiative accretion flow model of Mathews and Bregman (1978). Our measured temperatures of 1.4 keV and 3.3 keV over the central 6' and at 7' radius are reasonably consistent with their preferred $30\ M_\odot\ yr^{-1}$ accretion model, although our temperature gradient is somewhat steeper (see figure 3). We have calculated emission measures for the model by approximating their density distribution by the formula $n = 0.56\ r^{-1.4}$ where r is the radial distance in kpc. This formula is a good approximation to the numerical results for 1 kpc $\lesssim r \lesssim$ 100 kpc. Our observed emission measure for the 1.4 keV gas is in reasonable agreement with that predicted by the model (corrected for our aperture). The emission measure of 0.6 keV gas agrees very well with the model. On the other hand the emission measure predicted for our beam at the 7' radius location is deficient by a factor of 2. We conclude that there must be more material at T ~ 3 keV at larger radius than is predicted by the model (see also §b below). We note that this model implies that the temperature should continue to increase outward. The emission measure of ~ 8 keV gas in the model is ~ 10^{65} cm^{-3}, barely consistent with our previous limits from HEAO-1 (Lea et al., 1981), although it is not clear how valid the model is at this large radius.

The radiative accretion model of Binney and Cowie (1981) provides a slightly worse fit, since the lowest observed temperature of 5 x 10^6 K is never achieved in this model. The model of Takahara and Takahara (1981) is too hot everywhere, and does not fit our data. The temperature profiles for the three models, together with our observed temperatures, are shown in figure 3. We caution, however, that these models were designed to match to a hot intracluster gas (T = 10^8 K for MB and BC, T = 5 x 10^7 K for TT). We have been unable to find any evidence for gas at 10^8 K in our data, (see also Lea et al. 1981 and §b below).

We can also compare our results with those of Canizares et al. (1979, 1982) using the Focal Plane Crystal Spectrometer onboard the Einstein observatory. Their aperture is larger than ours, but may intercept about the same fraction of the emission measure of the 1.4 keV component (based on the Mathews and Bregman model), because of its different shape (3' x 30' rectangular versus 6' diameter circular). They calculate an emission measure of about (3-4.5) x 10^{64} at ~ 1.5 x 10^7 K and about 1.5 x 10^{64} at 5 x 10^6 K. Their model assumes that there is a continuum of temperatures, and the curve of emission measure versus T is fairly flat at ~ 10^7 K. To obtain a better comparison with our simple, two component model we have integrated over the bandwidth 7.1 < log T < 7.3 to find the total emission measure in the peak of their distribution, and we find a value of 1.5 x

10^{65} cm^{-3}, which should be compared with our value at a comparable temperature (1.35 keV), 2 x 10^{65} cm^{-3}. A somewhat smaller correction factor should be applied at 5 x 10^{6} K, which also brings the numbers from the two experiments closer together.

b) Intracluster gas

Fabricant et al. (1980) derived a density distribution from their surface brightness profile. The diffuse cluster background was subtracted from their data, so that this profile represents gas associated with M87. We have calculated the emission measure expected in our 6' diameter beam from this density distribution.[1] In the beam centered on M87 we find a predicted emission measure of ~ 3.3 x 10^{65} cm^{-3}, as compared with our observed value (for both temperature components) of 2.5 x 10^{65} cm^{-3}. Since the Fabricant et al. profile was derived assuming constant temperature, it overestimates the density in the cool, inner regions. Therefore, these values are in reasonable agreement. At our second observed position 7' from M87 we infer from the IPC profile an emission measure ~ 6 x 10^{64} cm^{-3}, compared with the observed value of 7 x 10^{64} cm^{-3}. The total emission measure in the Fabricant et al. (1980) profile out to r = 300' (the OSO-8 field of view) is 2.3 x 10^{66} cm^{-3}, as compared with 6 x 10^{66} cm^{-3} observed by OSO-8 (Mushotzky et al. 1978). These results imply that there is additional gas with an emission measure of about 4 x 10^{66} cm^{-3}. This is presumably the true intracluster (as opposed to M87-associated) gas. If this gas gives rise to the large source observed by Lawrence (1978) and Lea et

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[1] We have corrected the published profile for a typographical error, the correct value of c' is 3.8 x 10^{-4}. We thank Dan Fabricant for bringing this to our attention. We have also renormalized the density to account for the different distance to M87 assumed by Fabricant et al.

al. (1979), it has a core radius of about 1°.

We may derive a model for this intracluster gas by picking a density distribution $n = n_0(1 + r^2/a^2)^{-3/2}$ where a is the core radius, and choosing a and n_0 so that the total emission measure within 5° is 4×10^{66} cm^{-3} (to achieve consistency with the OSO-8 result) and the emission measure in the SSS beam at r = 7' is 1×10^{64} cm^{-3} (the maximum allowed for consistency between the IPC and SSS results). The result is a = 67.5', $n_0 = 9.6 \times 10^{-4}$ cm^{-3}, with the relationship $n_0 = 9.6 \times 10^{-4}$ $(a/1.1°)^{-3/2}$. This size is consistent with the HEAO-1 measurements. A larger size (and hence lower n_0) is excluded since both fields of view of the HEAO-1 A-2 experiment measured the same flux as was measured with the larger field of OSO-8 (Lea et al. 1981). A smaller size would lead to too much cluster emission in the inner regions. The model implies a higher surface brightness for the cluster component than that reported by Fabricant et al., although this surface brightness is essentially uniform over the IPC field. Since the galactic background in this region is very non-uniform (Lea et al. 1979), making it difficult for the IPC to obtain an accurate background measurement for a source which fills its beam, we do not consider this a critical constraint. The cluster density of ~ 3×10^{-4} cm^{-3}, predicted using this model, at the position of M86 (1.25° away from M87) is slightly less than the value ~ 6 x 10^{-4} cm^{-3} estimated by Forman et al. (1979) at the position of M86. These results could be brought into better agreement if the cluster center were slightly displaced towards M86, as may be indicated by the optical data.

We note that for this model, most of the HEAO-1 and OSO-8 flux is contributed by the "cluster" gas rather than "M87" gas. Thus the approximately solar abundance and 2 keV temperature measured by these instruments (op. cit) must apply to the cluster component. The temperature certainly cannot exceed the T ~ 3 keV value we measured at r = 7'. The density distribution resulting from this analysis is shown in figure 4. While this model is certainly not unique, it does illustrate the importance of the cluster component in interpreting the X-ray observations of this region. The 3 keV temperature is consistent with the T-ΔV and T-emission measure correlations derived from OSO-8 data (Mushotzky et al. 1978). The total amount of intracluster gas (in this model) is 2.3×10^{12} $(a/1.1°)^{3/2}$ $M_{\odot}$ within 60', as compared with 1.9×10^{12} $M_{\odot}$ in the Fabricant et al. profile, or 2×10^{13} $M_{\odot}$ (compared with 7.4×10^{12} $M_{\odot}$) within 300'. The cooling time for this gas, if T = 3 keV, is ~ 4×10^{10} years, and hence this gas cannot participate in a cooling flow.

c) The non-thermal component

The large absorbing column associated with the power law component in our best-fit spectrum indicates that the most probable location for this component is the galactic nucleus. This conjecture can be checked for consistency by comparing the intensity of the power law component observed in the two SSS fields with that observed by HEAO-1. In order to facilitate comparison of data sets, we fixed the power law index at α = 0.75, a value typical of active galaxies (Mushotzky et al. 1980) and close to the predicted inverse Compton spectrum, α = 0.79. For this model the normalization, N, of the power law was 0.013 ph $(cm^2 \text{ sec keV})^{-1}$ for the HEAO-1 data set taken in 1978 June, and 0.017 in 1978 December. The SSS data from the central region were best fit with N = 0.012 (see Table I) but could be fit by a value as low as 0.005, or as high as N = 0.018 in extreme models. Thus we conclude that it is likely that the power law component originates within 3' of the center of M87. This result would be in accord with our inference from the possible variability of this component and with the large observed value of N_H. If the temporal variation is real, then $c\Delta t \ll 1'$. Further, our observations in the cluster itself 7' from the center of M87 do not require any power law component. This spectrum implies a 1-60 keV luminosity of 9 x 10^{42} erg s^{-1}. Using the luminosity function of Piccinotti et al. (1982) we would have expected ~ 1 source of luminosity > 9 x 10^{42} erg s^{-1} in the Virgo cluster.

In our previous paper (Lea et al., 1981) we also discussed this component in the context of a model for the hard X-ray emission of inverse Compton scattering off the 3K background. We showed in that paper that the expected size of the inverse Compton source would be about 16' x 12', the measured size of the Virgo A radio source at ν > 80MHz. If this estimate is correct, then the SSS should have detected only 15% of the inverse Compton source. We conclude that at most thirty five percent of the hard X-ray emission observed by A-4 can be due to the inverse Compton process, the rest being due to the nuclear source. This result has the effect of strengthening our previous limits to the field strength. If the source intensity at the time of our observation were as observed in June 1978 by the A-4 experiment, we find a stronger limit B > 2 x 10^{-6} Gauss. This result is consistent with the value B ~ 2.5 x 10^{-6} Gauss estimated by Dennison (1980) from radio Faraday rotation data. However, if the source were in a high state, for example N = 0.0174 as we observed in December 1978, then our limits to the B field are weaker, B > 7 x 10^{-7} Gauss.

Einstein Observatory HRI measurements of M87 (Schreier 1981) indicate that both the nucleus and the jet are sources of X-ray emission. If the possible variability we have previously noted (Lea et al., 1981) is real, then the nucleus itself must be the source of all or most of the power law emission. The observed column density in front of our power-law component (N_H = 2.4 x 10^{22}) implies that the HRI source should be strongly absorbed. This column contributes an optical depth of almost 5 at 1 keV, sufficient to reduce the observed intensity by a factor of about 100. Our spectrum, with the best fit F_x = 0.012 $E^{-1.75}$ keV cm^{-2} sec^{-1} keV^{-1} and N_H = 2.4 x 10^{22} contributes an average flux of ~ 7 x 10^{-7} Jansky over the HRI bandpass, as compared with the observed flux of 6 x 10^{-7} Jansky (Schreier 1981). These numbers are in reasonable agreement given the uncertainties in the calculation, but our source may also include emission from the jet, which is also within our beam.

Possible models for such a nuclear source include a Synchrotron Self Compton model (Marscher et al., 1979; Lea et al., 1981). In the context of this model, variations in the X-ray should be reflected in variations in the radio. There has been only one report of radio variability in the nuclear source (Graham, 1971) which has appeared to be constant throughout all subsequent observations. This behavior is puzzling. Further searches for variability in both the X-ray and radio would be highly desirable.

A variable X-ray source could also be produced in an accretion disc around a black hole. Evidence has been produced for the existence of a black hole of mass ~ 5 x $10^{9} M_\odot$ in the M87 nucleus (Young et al., 1978). This interpretation of the data has been questioned, however, by Duncan and Wheeler (1980) and Dressler (1980) among others. The Eddington luminosity for such a black hole is ≈ 6.5 x 10^{47} ergs s^{-1}, requiring an accretion rate of $\dot{M}_{edd} \sim 100 M_\odot$/yr. We have seen that our observations of the thermal source are consistent with an accretion rate of 20 $M_\odot$/yr, which would give rise to an accretion luminosity of ~ 10^{47} ergs s^{-1}, far in excess of what we see. Thus less than 10^{-4} of the inflowing material can end up in such a black hole, or else the accretion luminosity does not emerge as X-rays. The luminosity in other energy bands is also well constrained, e.g. L < 4 x 10^{41} ergs/sec in the visible (Dressler 1980), except in the EUV, where no limits exist. Much of the luminosity is expected to be in this region if the disc temperature is ≈ 10^{5} - 10^{6} (e.g. Shakura and Sunyaev 1973, Pringle and Rees 1972, Novikov and Thorne 1973), but models with either a hot inner disc or disc corona predict $L_x \sim L_{euv}$, and then the predicted

L_x exceeds our measured value. Note also that at 20 $M_\odot$ yr^{-1} the 5 x 10^9 $M_\odot$ black hole would be formed in only 2.5 x 10^8 yr.

There is an important caveat to the above discussion. The models we have discussed all assume disc accretion onto the black hole. If the accretion is essentially spherical (i.e. if the accreted material has very low angular momentum) then the efficiency for producing energy from the accretion flow may be much reduced. For models which include heating effects due to turbulence and/or magnetic field effects (Ipser and Price, 1977, Maraschi et al. 1979) high efficiencies are regained. In particular, Maraschi et al. calculate the luminosity from a 10^9 $M_\odot$ black hole accreting at ~ few x 10 $M_\odot$/yr and find total luminosities ~ few x 10^{45} ergs s^{-1}, with a large fraction of this in the X-ray band. These models exhibit a wide range of values for the fraction of total luminosity emitted in the X-ray range, but all violate either our measurements or Dressler's (1980) optical measurements.

We conclude that if a massive (5 x 10^9 $M_\odot$) black hole exists at the center of M87, the infalling gas must be prevented from reaching it, unless the accretion flow is essentially spherical and non-dissipative.

d) The fate of the accreted material.

If the accreted matter does not reach the black hole, where does it go? Our observed absorbing column of $N_H \sim 10^{22}$ cm^{-2} for the power law component implies the existence of 320 $R^2{}_{pc}$ $M_\odot$ of cold material in the nuclear regions of M87. This amount is negligible for any reasonable values of the radius R of the nuclear region. Dressler (1980) has concluded that the central luminosity spike in M87 is a cluster of stars. However, he estimates the age of the cluster to be $\gtrsim 10^9$ years. If we take a conservative value of $\dot{M} = 10$ $M_\odot$ yr^{-1} then, 10^{10} $M_\odot$ of gas would have accumulated in the core since those stars formed, and this gas is not observed in either neutral or ionized form. Even if we speculate that the gas forms into low mass stars only, so as to be consistent with Dressler's observed spectrum in the central spike, then apart from the unusual initial mass function (IMF) this implies, we also require a mass to light ratio ~ 1000 for these stars in order to have a star cluster of total luminosity ~ 10^8 $L_\odot$. This seems unlikely.

IUE observations of M87 (Bartola et al. 1980, Perola and Tarenghi 1980) do indicate the presence of some blue stars in M87. These may be either horizontal branch stars or young blue stars. Even if they are young blue stars, our comparison of the M87 flux with that from local stars (Brune, Mount and Feldman 1979) indicates that at most 10^6 $M_\odot$ could be present in stars of mass 10-30 $M_\odot$. Assuming a Salpeter IMF, this implies ~ 10^7 $M_\odot$ of stars in the mass range 0.1-30 $M_\odot$. These stars must have formed over the ~ 10^7 yr lifetime of a 10 $M_\odot$ star, implying a gas consumption of about 1 $M_\odot$ yr^{-1}, or less than one tenth of the total mass inflow. A steeper IMF of the form $N(M) \propto M^{-3}$ could accomodate the total inflow rate at 10 $M_\odot$ yr^{-1} in star formation. Note, however, that this implies that all of the observed UV light is due to young stars of 10-30 $M_\odot$ and none is due to blue horizontal branch stars, which is perhaps unlikely. For a 20 $M_\odot$ yr^{-1} infall rate, a steeper IMF would be required. In this context, we should mention that there have been suggestions that only low mass stars form in elliptical galaxies (Jura, 1977) or in a cooling flow (Sarazin, private communication). If this is the case, the UV observations are much less constraining and all of the infalling gas may form into stars.

Recent work by Gunn, Stryker and Tinsley (1981) also indicates that star formation is occurring in giant elliptical galaxies. For M87, they find that the observed blue light may be due to "young stars", implying a star formation rate of 1-2 $M_\odot$ yr^{-1}, or the blue light may come from evolved "blue straggler" stars, implying that 10-30% of the stars in the galaxy are of this type. In the latter case, we estimate a rather uncertain star formation rate of about 20 $M_\odot$ yr^{-1}. These authors favored a flatter (rather than steeper) IMF, $N(M) \propto M^{-\alpha}$ with $\alpha < 1$, and an upper mass limit of 2 $M_\odot$ in the stars formed.

The radio source Virgo A and the observed X-ray/optical/radio jet imply that $\sim 5 \times 10^{50}$ ergs yr^{-1} of energy are being ejected from the nucleus of M87. Mathews and Bregman (1978) have noted that this power is comparable to the power in the accretion flow, and they speculate that the infalling material is re-ejected into the radio source, perhaps in the jet. Recent work by DeYoung (1981) indicates that matter may be entrained in the jet and carried outward to the radio lobes. The mass is entrained in the nuclear regions where the interstellar density may be relatively high. The rate at which matter may be removed from the nucleus by this process is

$$\dot{M} = 60R_j^2\ \delta\ \times n_o \times c_8\ M_\odot/yr.$$

where R_j is the jet radius in kpc, n_o is the gas density in the entrainment region, δ is a parameter, $\delta < 1$, and c_8 is the sound speed in the entrainment region in units of 1000 km/sec. If entrainment occurs in the region of our lowest temperature component, we may calculate values for n_o and c_8. DeYoung argues, however, that because of interaction with the jet the material in the entrainment region next to the jet may have $c_8 \sim 1$. The calculated value of n_o depends on the radius of the central region. For a radius of $\sim$ 0.1 kpc, $n_o \sim$ 20 cm^{-3}. The jet radius is obtainable from the VLA map (Owen et al. 1980); we take $R_j \lesssim 50$ pc to find

$$\dot{M} \lesssim 3\delta c_8\ M_\odot/yr$$

Thus this mechanism is not sufficiently efficient to remove the accreted material unless the entrainment region lies interior to our observed 0.5 keV gas and has $n_o >> 20$. Recent VLA observations of the jet (Owen et al 1980) indicate a density of perhaps 0.1 cm^{-3} in knot A. Even if material of this density were present throughout the jet, the maximum mass outflow rate would be ~ 6(v/c) $M_\odot$/yr where v is the speed of the material in the jet, much less than the required 10-20 $M_\odot$/yr for any reasonable values of v/c. Thus, if the DeYoung mechanism is operative, the entrained material must remain unmixed with the jet magnetic field.

Another possibility is of the existence of some sort of invisible ejection, either a continuous wind taking place concurrently with the infall and interleaved with it, like segments of an orange, perhaps, or sporadic violent ejection. In this latter scenario, the most recent outburst must have occurred fairly recently (within about a million years) so that the amount of material accumulated since the outburst remain invisible, but long enough ago that no obvious vestiges of its occurrence remain. In this picture the large radio source Virgo A and the jet may be the long-term residuals of these explosive outbursts. The ultimate cause of the outbursts is a mystery.

One further possibility is that our inflow calculations are in error. The inflow need not occur if there exists a heating mechanism to balance the cooling of the gas and prevent inflow. Such an equilibrium state is not only improbable but may be unstable.

e) The origin of the infalling material

Previous models of this object have assumed that the material we see emitting X-rays has come from the member galaxies of the Virgo cluster. However, it is worth noting that the 10-20 $M_\odot$ yr^{-1} which we see accreting onto the M87 nucleus could be provided by M87 itself, if the galaxy is massive. If the mass loss rate from stars is 10^{-12} - 10^{-11} $M_\odot$ $(M_\odot\ yr)^{-1}$ (e.g. Faulkner and Freeman, 1977), then we need a total stellar mass of 10^{12} - 10^{13} $M_\odot$ to provide the necessary material. There have been several estimates of the mass of M87 in this range (e.g. Mathews, 1978, Fabricant et al., 1980, but see also Binney and Cowie, 1981). Of course most of this mass is invisible and we have no evidence to suggest that this mass is shedding gas. Certainly if low mass stars, neutron stars or black holes are responsible for the large galaxy mass estimates, no mass loss from these objects is expected. Faber and Gallagher (1976) have estimated the mass loss rate in terms of the galaxy luminosity. Using their value and the luminosity of M87 from Oemler (1976) we find a total mass loss rate of 3 $M_{\odot}$ yr^{-1} plus or minus a factor of 3. Given the uncertainties in our knowledge of all these numbers, it is certainly possible that M87 is simply eating itself. Sparke (1981) has recently discussed models of this type. If this is the correct explanation for M87, then similar objects may be found which are not members of rich clusters. Kriss et al. (1980) have reported that three D or cD galaxies in small groups are x-ray sources. Perhaps these are also self-cannibals.

IV. CONCLUSIONS

We have observed the X-ray spectrum of M87 and a nearby region in the Virgo cluster. From our spectra we conclude that the power law component previously observed in this source most likely originates in the galaxy M87 itself. This result allows us to improve our previous limit to the magnetic field strength in Virgo A to $B > 2 \times 10^{-6}$ Gauss. The non-thermal X-ray source that we have observed is not unusual for an active galaxy, and probably does not result from some peculiarity in M87 itself, but is an example of a more general phenomenon.

For the thermal source we conclude:

(i) We see no evidence for strong abundance gradients in our data.

(ii) We see a strong temperature gradient, T increasing from ~ 1.4 keV in the inner 6' to T ~ 3.35 keV at r ~ 7'. In addition, there is a small emission measure component at T ~ 0.6 keV in our M87 data. We stress that this is the simplest model that fits our data. Such a model is probably indicative of a continuum of temperatures ranging from ~ 3.35 keV down to at least 0.6 keV, with emission measure decreasing as a function of temperature. Such models are discussed by Canizares _et al_. (1982).

(iii) Our results are consistent with previous observations using the IPC and with the radiative accretion model of Mathews and Bregman (1978), and imply $\dot{M} \approx 10\text{-}20\ M_\odot\ yr^{-1}$. Infall at this rate is difficult to reconcile with the presence of a black hole of mass $5 \times 10^9\ M_\odot$ in the nucleus of M87, and poses severe problems as to the ultimate disposition of this material unless the accretion is essentially spherical and with a very low ($\varepsilon < 10^{-5}$) efficiency of photon production. However, by pushing all the numbers to the limit we can dispose of the material by a combination of star formation and jet entrainment. In particular, we require that the stars formed be low mass, ($\lesssim 2M_\odot$).

(iv) Comparison of the SSS data, the IPC data (Fabricant _et al._ 1980), the HEAO-1 data (Lea _et al._ 1981) and the OSO-8 data (Mushotzky _et al._ 1978) implies the existence of true intracluster gas having a core radius of about 1°, a central density of ~ 10^{-3} cm^{-3} and temperature $\lesssim$ 3 keV.

(v) The abundance ratios in this cluster are consistent with solar values.

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TABLE 1

SPECTRAL PARAMETERS FOR M87 AND THE VIRGO CLUSTER

PARAMETER	M87[5]	7' FROM M87[5]
T_1	$0.58^{+.07}_{-.18}$ keV	-
$EM(T_1)$[1]	$3^{+1.8}_{-1.1} \times 10^{64}$ cm^{-3} (3)	$< 7 \times 10^{63}$ cm^{-3}
	$4.3^{+2}_{-1} \times 10^{64}$ cm^{-3} (4)	
T_2	$1.36^{+.14}_{-.16}$ keV	$3.35 \pm ^{1.5}_{0.8}$ keV
$EM(T_2)$[1]	$1.77^{+.48}_{-.33} \times 10^{65}$ cm^{-3} (3)	$7.2^{+0.95}_{-1.2} \times 10^{64}$ cm^{-3}
	$2.0^{+.5}_{-.3} \times 10^{65}$ cm^{-3} (4)	
N_H(thermal component)	$1.3^{+0.7}_{-0.8} \times 10^{21}$ cm^{-2}	$1.7^{+1.0}_{-0.6} \times 10^{21}$ cm^{-2}
Abundances:[2]	$1.1^{+1.0}_{-0.4}$	$0.95^{+1.0}_{-0.6}$
Power law normalization(1,4)	0.012 ± 0.002	None required
N_H (power law component)(4)	$2.4 \pm 1 \times 10^{22}$ cm^{-2}	

[1] At solar abundance.

[2] Abundances are relative to solar values as given in Allen (1973), exept Fe, for which we take a solar value of 3.2×10^{-5} relative to H.

[3] Power law index free to vary.

[4] Power law index fixed at 0.75.

[5] All errors are 90% confidence for two significant parameters ($\chi^2 + 4.6$).

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Figure Captions

Figure 1a: The pulse height data for M87 from the SSS for the central pointing position. The solid histogram is the best fitting model to t. data.

Figure 1b: The photon spectrum of the central position. Sharp spectral features show the instrumental resolution of the SSS (160eV FWHM).

Figure 2: The ratio of the SSS pulse height to "continuum" as a function of energy for the central postion (solid line) and the position 7' off center (the dotted line). The expected energies of the most prominent lines are indicated. The "continuum" has been determined separately for the central and offset positions, and is a smooth exponential which passes through the lowest points in the data.

Figure 3: Observed temperatures for the M87 source are shown along with models by Mathews and Bregman (1978) (MB), Binney and Cowie (1981) (BC) and Takahara and Takahara (1981) (TT).

Figure 4: One model of the gas density distribution in the Virgo cluster, as deduced from the x-ray data. The dashed line indicates the total density, while the two solid lines indicate the (somewhat artificial) division into "M87" and "cluster" components. The bar and arrow at the top of the figure indicate the extent of the IPC observations of this source. The cluster component dominates outside of the IPC field.

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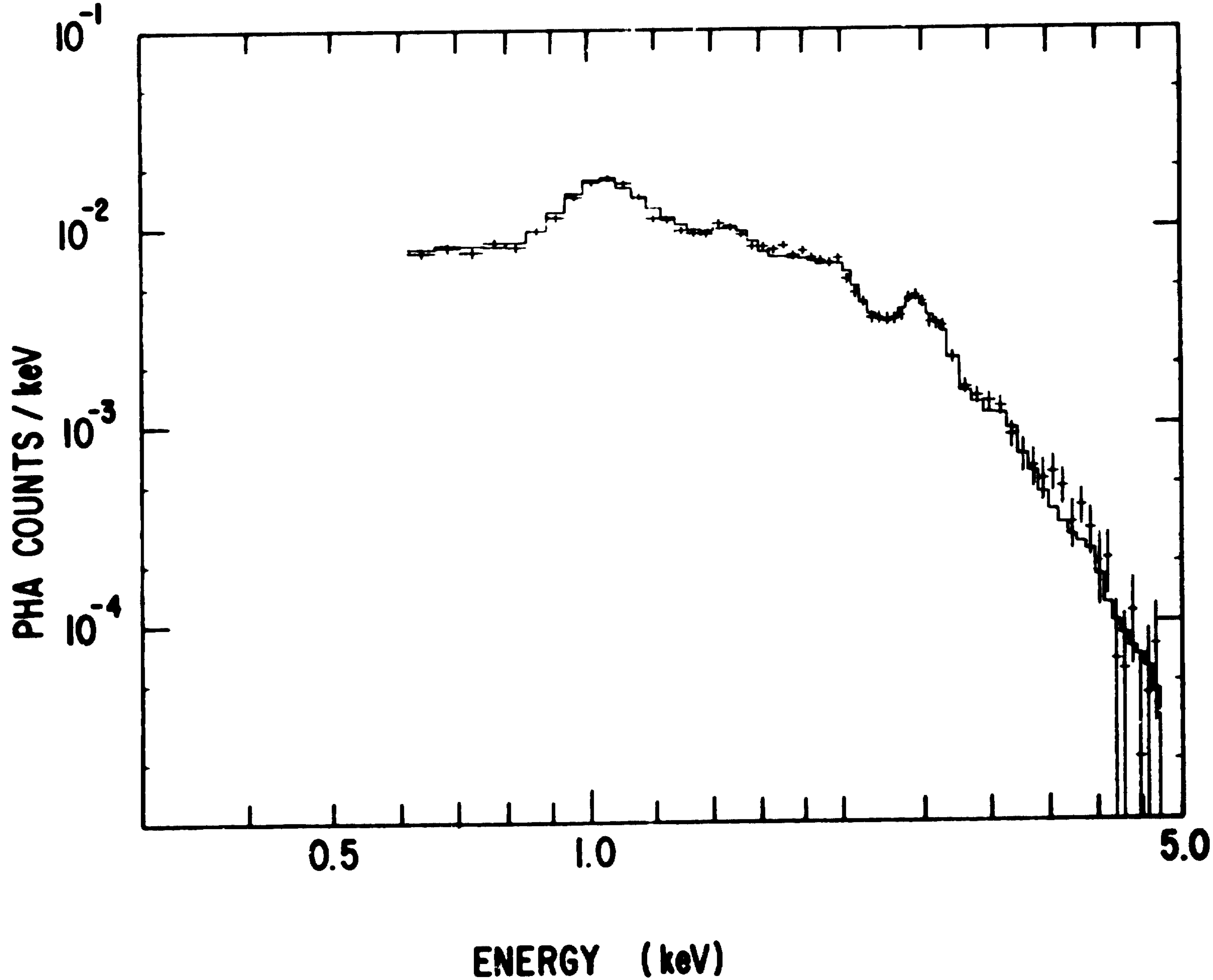

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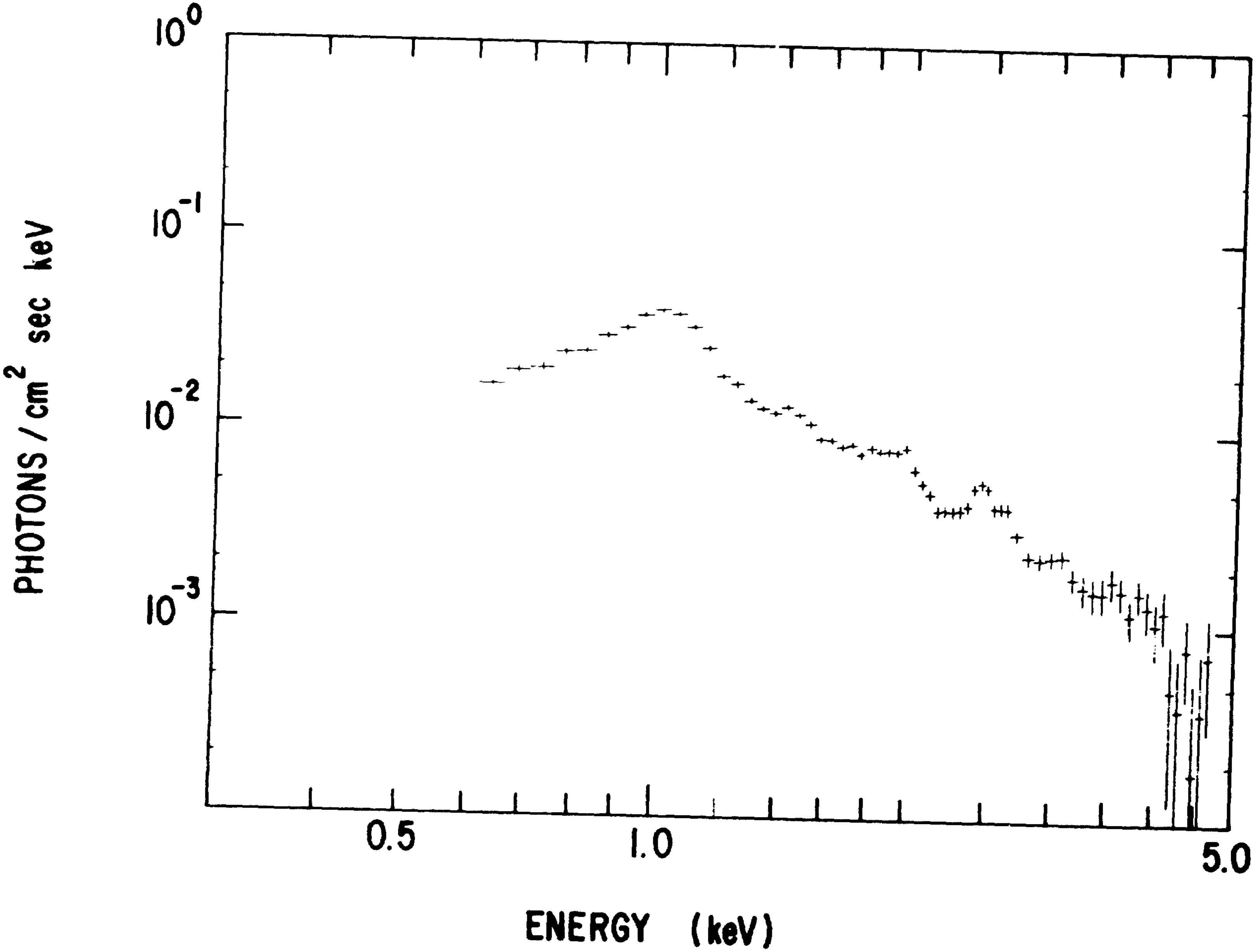

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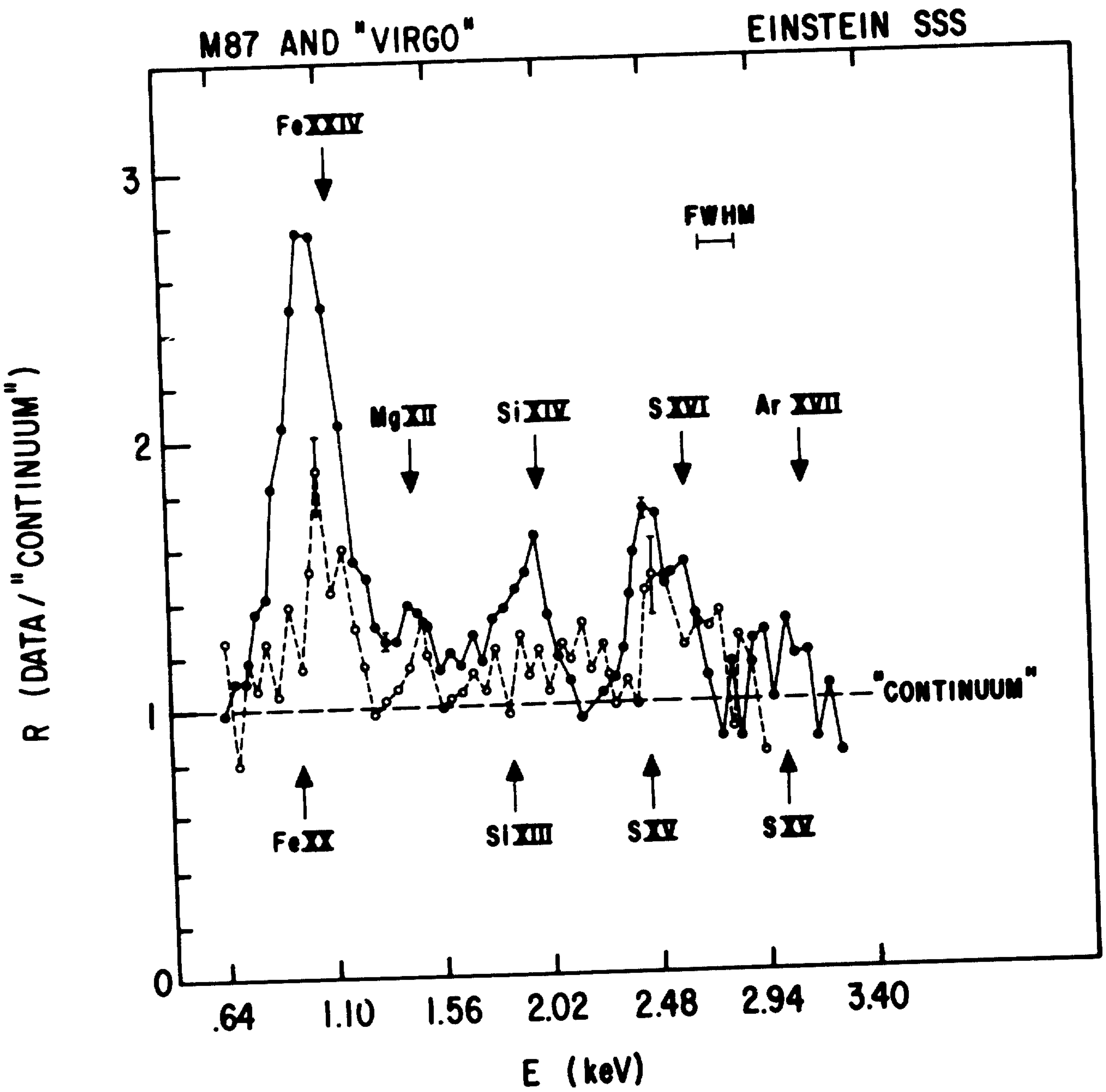
M87 AND "VIRGO"
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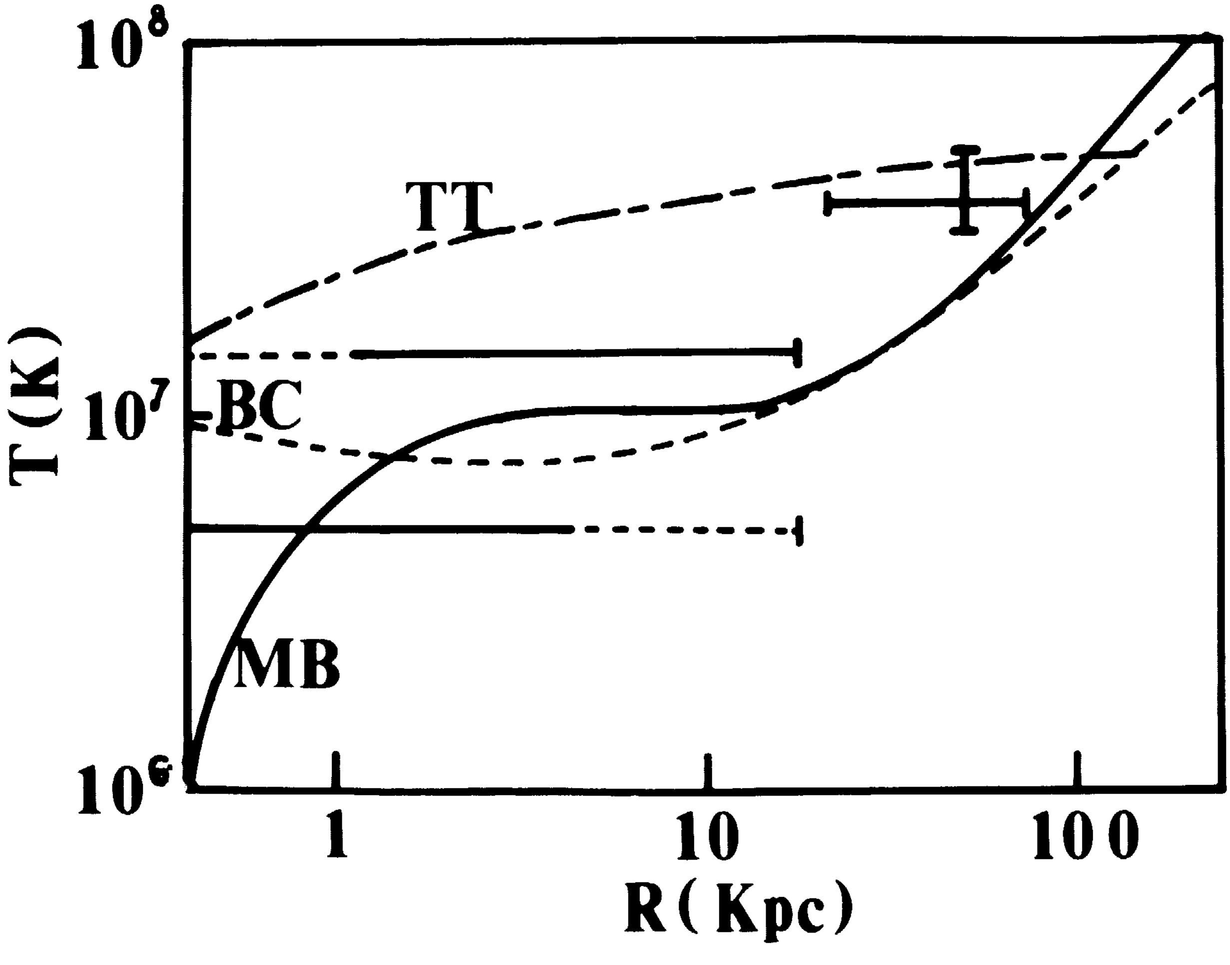
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