SQT

(NASA-TM-85103) TEMPERATURE AND ELEMENTAL ABUNDANCES IN THE ABELL CLUSTER A 576 DERIVED FROM X-RAY OBSERVATIONS (NASA) 33 p HC A03/MF A01 CSCL 03B

N84-35238

Unclas G3/90 23130

NASA

Technical Memorandum 85103

TEMPERATURE AND ELEMENTAL ABUNDANCES IN THE ABELL CLUSTER A 576 DERIVED FROM X-RAY OBSERVATIONS

R. Rothenflug
L. Vigroux
R. F. Mushotzky
S. S. Holt

SEPTEMBER 1983

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

Submitted to The Astrophysical Journal

TEMPERATURE AND ELEMENTAL ABUNDANCES IN THE ABELL CLUSTER A 576 DERIVED FROM X-RAY OBSERVATIONS

R.Rothenflug, L.Vigroux

Service d'Astrophysique

C.E.N. Saclay

91191 Gif-sur-Yvette Cedex France

and

R.F.Mushotzky, S.S.Holt

Laboratory for High Energy Astrophysics

NASA/Goddard Space Flight Center

Greenbelt, Maryland 20771 USA

Received 1982, February 23

Running title: X-Ray Spectrum of A 576

ABSTRACT

We report results of Einstein Solid State Spectrometer observations of the central region of Abell 576 combined with HEAO-1 spectra of the total cluster. We detected line emission due to Fe, Si and S from a hot ($< 2.4\ 10^7$ °K) plasma in the central region. The temperature of the total cluster spectrum ($4^{+3.3}_{-1.4}\ 10^7$K) may be in conflict with the central temperature. This difference can be explained either if cooling takes place in the center, or if part of the measured emission is due to individual galaxies. If the X-ray emission comes from the intergalactic gas only, there is some difficulty in producing all the silicon observed in the galaxies of A 576.

Subject headings: Abundances - Galaxies: clusters of - X-rays: sources
X-rays: spectra

I. INTRODUCTION

Recent theoretical work (Sarazin and Bahcall 1978; Smith, Mushotzky and Serlemitsos - S.M.S.-,1979) has stressed the importance of X-ray spectra in interpreting the physical conditions in X-ray clusters of galaxies. In addition recent imaging results from the Einstein Observatory (White and Silk 1980 (hereafter refered to as W.S.); Branduardi-Raymont et al.1981) have pointed out the need for high quality X-ray spectra in order to unfold the X-ray spatial results. Furthermore it is only through high quality X-ray spectral measurements that the chemical abundances of the heavy elements can be determined for the intergalactic gas in clusters. The abundance of heavy elements in the intergalactic gas can place strong constraint on galactic and cluster evolutionnary models. In the classical picture, the heavy elements have been expelled from the galaxy either by a hot wind driven by supernovae explosion (Larson 1974) or by stripping of the interstellar gas by the ram pressure due to the motion of the galaxies in the cluster (Gunn, Gott, 1972). At later stages evaporation could be important in removing gas. However, most of the observations have been done so far on untypical high X-ray luminosity clusters, which generally are dynamically evolved.On the contrary we wanted to observe a typical X-ray cluster populated with normal galaxies. The cluster A 576 was selected on the basis of its galaxy content and X-ray flux which look like a "typical" Abell cluster.

In this paper we report results of Einstein Solid State Spectrometer (SSS) observations of the central region of Abell 576 combined with HEAO-1 spectra of the total cluster. These results indicate, as do the imaging data of W.S. that the X-ray gas in A 576 cannot obey a $\gamma = 5/3$ polytropic equation of state. We shall, tentatively, interpret this either as evidence for a cooling flow in the core of A 576 similar to that in the Perseus cluster (Fabian, Nulsen, 1977; Mushotzky et al. 1981) or due to the presence of soft X-rays associated with individual galaxies in the center of the cluster. We also present data on the elemental abundances in A 576 and find that Fe, S and Si have roughly half solar abundance, consistent with the Fe results for many other clusters (Mushotzky 1979). Consequences of this measurement for galactic evolution are presented in the last section.

II. DATA ANALYSIS AND INSTRUMENT DESCRIPTION

The SSS consists of a cryogenically cooled Si(Li) detector at the focus of the Einstein Observatory X-ray telescope. It has a 3' radius circular beam with roughly uniform response across the field. The detector and telescope combination is sensitive in the 0.5 - 4.5 keV band with $\sim$ 160 eV FWHM energy resolution approximately independent of energy. A more complete description of the instrumentation may be found in Holt et al. (1979). The SSS observations of the central region of A 576 were obtained in a $\sim$ 15,000 second exposure in September 1979 resulting in $\sim$ 4000 source counts. Of this total number, the contribution of the 8th mag K star in the field of view is estimated to be far less than 10% (Vaiana et al. 1981).

The SSS spectra have been fit to the model of an isothermal gas in collisional equilibrium. Two models of such a gas have been used, one, that is due to Raymond and Smith, R-S, (1977) has been described in detail before (Holt, 1979). The other model referred to as K-R (Rothenflug, Arnaud, 1983) was developed at Saclay, mainly based on the compilation of atomic data listed in Kato (1976). The main difference between these two models lies in the ionization balance. The R-S model is based primarily on ionization cross sections of Summers (1974) while the K-R model is based on the cross sections of Lotz (1967) (see appendix and also Schnopper et al., 1982). The net result is that the maximum of equilibrium abundance is shifted to higher temperatures for the R-S model in comparison with the K-R model. This shift is most noticeable for the least ionized species (e.g. Fe XVII or Fe XVIII). For helium like and hydrogen like ions the differences are small.

The HEAO-1 experiment A-2[a] instrumentation has been described in detail by Rothschild et al. (1978). Previous HEAO-1 observations of A 576 have been reported by Pravdo et al. (1980) who used a summed rate combination, R15, in their analysis. In this paper we have used the results of a long pointing at A 576 which occurred on day 297 of 1978.

This exposure of 8600 seconds resulted in $\sim$ 6500 source counts in the 2 - 20 keV band. The major origin of uncertainty in the data is not due to photon counting statistics or uncertainty in the internal background, but is due to intrinsic fluctuations in the diffuse X-ray background.

a. The A-2 experiment on HEAO-1 was a collaborative effort led by E.Boldt of GSFC and G.Garmire of CIT, with collaborators at GSFC, CIT, JPL, and UCB.

III. RESULTS

The SSS spectrum was well fit by either the R-S or K-R model with a reduction in χ^2 of 18 compared to a simple thermal bremsstrahlung fit (Figure 1). For the addition of 4 additional parameters, the reduction in χ^2 is significant at greater than the 90% confidence level. The best fit temperature is 1.6 keV ($^{+.4}_{-.3}$) (90% confidence errors) with roughly half solar abundances of Fe, Si and S (see Table 1 and Figure 2). As seen in Table 1, there is no significant difference found for the temperature or the abundance determinations between the R-S and K-R models. The best fit absorption of 1.1×10^{21} at/cm^2 is consistent with the 6×10^{20} at/cm^2 derived from 21 cm data (Heiles, 1975). The best fit emission integral, n_e^2V, is $\sim 6.6 \times 10^{66}\ h_{50}^{-2}$ cm^3.

The HEAO-1 experiment A-2 data with a larger angular resolution of 3° x 1.5° were fit to a simple thermal model (Figure 3). The best fit temperature was $kT = 3.5^{+3.0}_{-1.2}$ keV (90% confidence). The statistical significance of the difference between this temperature (appropriate for the cluster as a whole) and the SSS temperature (corresponding to the cluster center) can be determined by the F test. The value of F indicates that they differ at the 99.7% confidence level or roughly 3σ. The emission integral for the whole cluster is $n_e^2V \sim 3.7 \times 10^{67}\ h^{-2}$. The integral 2-6 keV flux is 1.7×10^{-11} erg/cm^2 sec. and the 2-10 keV flux is 2.6×10^{-11} ergs/cm^2 sec. Because of the weakness of the source, the upper limit on the Fe K line equivalent width is large, $<$ 1900 eV, and does not place an interesting bound on the Fe abundance.

IV. DISCUSSION

A. Flux and angular size

The flux measured by the HEAO-1 pointed observation is in good agreement with the upper limit of Pravdo et al. (1979) when the present measured temperature is used to convert R15 counts to flux. This result is in conflict with the 4U catalog (Forman et al., 1978a) 2-6 keV flux of $3.7 \pm .53 \times 10^{-11}$ ergs/cm^{2}sec. Because the pointed data refers to the total flux in a 3 x 3° beam while the result of Pravdo et al.refers to the flux from a point-like source the agreement strengthens the argument against the existence of a "extended halo" of X-ray emission around A 576 (Forman et al., 1978b) (see W.S.)

The spatial distribution of the X-ray flux from A 576 can be well modeled by a modified Hubble law (W.S.). In this situation one can use the ratio of emission measures seen by the SSS and HEAO-1 to get an estimate of the core radius of .85 - 1.2' which corresponds to 60-100 h_{50}^{-1} kpc at the distance of A 576(234 h_{50}^{-1} Mpc). This compares to a best fit value of 160 h^{-1} kpc from IPC data (but note that W.S.state that this value is small enough that it may be affected by instrumental resolution problems in the IPC). However our data do confirm that the X-ray core radius is on the order of or less than 1/2 the optical core radius of$\sim$ 4.5' (Birkinshaw, 1979; the data of Bruzal and Spinrad, 1978, give an effective core radius of$\sim$ 4.7' when fit to an isothermal sphere model).

As S.M.S.(also see Cavaliere and Fusco-Femiano, 1976) note, the parameter $\mathcal{E} = \frac{\mu m \sigma_v^2}{KT}$ where σ_v is the line of sight velocity dispersion, is roughly the ratio of the scale heights of the galaxies to the gas in the center of the cluster. For A 576, using a velocity dispersion of 1211 Km/s (Danese et al., 1980) $\mathcal{E} = 2.6^{+3.5}_{-1.9}$ for kT = 3.5 keV appropriate to the cluster as a whole. This value of $\mathcal{E}$ is thus consistent with the observed allowed range in the ratio of scale heights of the galaxies and the gas of 5.3 - 2.2 (from W.S.).

B. Emission

i) If we interprete the cluster center emission in terms of emission by the gas, the inferred central density is $2.5\ (^{+0.4}_{-0.3}).\ 10^{-3}\ h_{50}^{1/2}\ cm^{-3}$, calculated from the emission integral measured by the SSS.

As the HEAO-1 and HEAO-2 temperatures do not agree at the 99.7% confidence level, this possibly indicates that cooling is occuring in the center of A 576 as was claimed by W.S. from Einstein IPC and MPC data. At constant pressure the cooling time is:

$$t_c = \frac{5KT}{\Lambda n_e}$$ where Λ is the radiative cooling rate

For T = 1.9 10^7K corresponding to the value of kT = 1.6 keV obtained for the central region, $\Lambda \simeq 2.10^{-23}$ ergs cm^3/s (Raymond, Cox, Smith, 1976).

With the above value of the central density inferred from our measurement, we can calculate the value of the actual cooling time in the center:

$$t_c \simeq 8(\pm 2.5)\ 10^9\ h_{50}^{-1/2}\ \text{years},$$

somewhat less than the Hubble time (1.5 10^{10} years).

Therefore the central regions of A 576 are slightly unstable to cooling on a Hubble time and one might expect a cooling flow (Cowie and Binney, 1977, Fabian and Nulsen, 1977) in this region. This cooling flow would change the nature of the distribution of the gas away from a polytrope. The fact that W.S. find an effective polytropic index of .4 in the central regions of A 576 is also an argument for cooling.

However, no significant H_α emission was detected for this cluster, as opposed to its detection in A 426 and some other clusters which have X-ray evidence for cooling flows (Cowie, Hu, Jenkins, York, 1982). This fact backs up the opposite idea that cooling does not take place in the core and that another explanation must be found for the low temperature component.

ii) Alternatively the low temperature, small size, high surface brightness and low emission integral of the central region of A 576 suggest that the central flux may be produced by X-ray emission from gas associated with an individual galaxy rather than with the potential well of the cluster as a whole (Forman et al., 1979).

The center of A 576 contains several galaxies of unusual morphology, the nature of which may be important in understanding the X-ray properties of the cluster. The brightest cluster galaxy is a db (Yerkes classification) that is, two approximately equal nuclei in a common envelope. The visible size is slightly larger than one arc minute. There is a second db, of very similar brightness, about 3 arc minutes to the North-West of the first. This analysis is due to Richard White (1982, private communication) who suggests that these galaxies may be approaching the final stage of merging into a cD with multiple nuclei.

Scaling to the X-ray emission of a giant galaxy like M 87 in the Virgo cluster, (Fabricant, Lecar, Gorenstein, 1980), one would predict $KT \sim 2$ keV, a size of about 1' and an emission integral of about 2×10^{66} cm^3 (Lea, Mushotzky, Holt, 1982). These figures are not very far from those actually observed for the core of A 576.

The temperature of the true intracluster gas can be calculated using the formalism derived by SMS. One can compute an effective polytropic index for the gas in A 576 such that the central temperature T_c is:

$$T_c = \frac{3GM_c}{a_g} \frac{m}{K} \frac{\gamma_e - 1}{\gamma_e}$$

(where a_g is the core radius of the galaxies and M_c the viral core mass). Using Figure 3 and Table 2 of SMS, we infer $\gamma_e \sim 1.1$ for $T_c = 3.5$ keV for a velocity dispersion of 1211 Km/s (where we have assumed $\frac{GM_c}{a_g} = 3\,\sigma_v^{-2}$). This is consistent with an "isothermal" cluster, which in turn implies that conduction is important.

Moreover, assuming that the brightness due to the gas is only 20% of that due to the galaxy, the central density becomes on the order of $10^{-3} cm^{-3}$ for all the range of temperatures given by the HEAO-1 data. In this case, the cooling time is always equal or greater than the Hubble time.

We therefore conclude that the available data, with the possible exception of the IPC hardness ratio variation, are consistent with A 576 either having a cooling core or with the "excess" cool flux in the center being due to X-ray emission associated with a single galaxy. This question will be only settled by the measurement of the emission of the central galaxies in the cluster by an X-ray detector with a high spatial resolution.

V. COMPARISON WITH OTHER CLUSTERS

A. Luminosity

A 576's 2-10 keV luminosity of 1.7×10^{44} erg/sec places it very near the characteristic luminosity, 1.9×10^{44}, of the cluster luminosity function (McKee et al., 1980). Thus in this respect, A 576 is a "typical" cluster. McKee et al. find that the median luminosity for Bautz-Morgan Type III cluster is 3.1×10^{44} erg/sec also making A 576 typical.

B. Temperature, emission integral

The data obtained so far on clusters (Mushotzky et al., 1978, SMS 1979, Hintzen, Scott, 1979) showed that X-ray temperature and optical velocity dispersion are related. The line of sight velocity dispersion of A 576 has been reestimated by Danese et al.(1980) from the measurement of Melnick and Sargent (1977). They found $\sigma_V = 1211$ (+ 254, - 158, 1σ) Km/s. So we can predict from the OSO-8 best fit kT vs σ_V relation an X-ray temperature of $kT \sim 7.1^{+2.5}_{-2.0}$ keV which is somewhat higher than the measured HEAO-1 temperature. However, at the 3σ level of Danese et al. (1980), the velocity dispersion can be as low as 740 Km/s, which corresponds to a temperature of 2 keV. Besides, the histogram of the number of galaxies versus the velocity is far from a Gaussian one and we think it is not very easy to derive from that curve the true value of the velocity dispersion for this cluster.

A 576's emission integral (EI)of 3.7 x 10^{69} places it on the best fit kT vs. EI regression line of Mushotzky et al.(1978) in a position very close to A2199, a cDp cluster with a very similar kT. A more recent $L_X \sim$ kT analysis (Mushotzky, 1982b) would produce kT$\sim$ 3.4 keV, very close to the value measured.

C. Optical correlation

Bahcall (1977) showed that the central galaxy density N_o correlated well with the X-ray luminosities of clusters. Mushotzky et al.(1978) and SMS found that this central galaxy density N_o, correlated also extremely well with the spectral X-ray properties of clusters. Although there is a relatively large error in the HEAO-1 measured temperature, the measured N_o of [illegible] for A 576 (Bahcall, 1981) places it along the kT vs. N_o and the emission integral vs. N_o best fit regression lines. We also note that this value of N_o is relatively high for a BM III cluster and agrees with the estimate of White (1978) that A 576 is intermediate in its compactness, similar to A2199 in that study. The spiral fraction in A 576 is relatively high 35% (Melnick and Sargent, 1977). This places it along the correlation line of Mushotzky et al.(1978) for the f(SP) vs. $Q = (n_e{}^2V)^{1/2}$ kT relation.

In summary, the optical X-ray properties of A 576 are in no way unusual and it appears in all respects to be a "typical" cluster.

VI. METALLICITY

The Fe abundance of A 576 in its core is very similar to the average Fe abundance of other clusters observed by HEAO-1 (Mushotzky, 1982a). This indicates that the gas in A 576 has undergone processing in stars in a manner similar to other clusters. The Si and S abundances, while less well determined, are quite similar to the abundances of these elements in the core of the Perseus cluster (Mushotzky et al., 1980). In the following discussion, we assume that the measured abundances in the core are typical of the total cluster abundances, i.e. there is no abundance gradient in the gas, contrary to the assumption of Fabian and Pringle (1977). Rephaeli (1978) showed that the intracluster iron could not have sedimented in the cluster core in a Hubble time and concluded that heavy elements and gas are similarly distributed.

The relative constancy of elemental abundances in clusters of various type and richness indicate that the mechanism of enrichment of the intergalactic gas is linked to normal galactic evolution rather than cluster evolution. This further implies that stripping of gas from spirals, which may depend on the dynamical evolution of clusters has not added appreciably to the Fe abundance in clusters.

The low upper limit on magnesium abundance is intriguing. It may be due to an incorrect cross section (Pradhan et al. 1981). However, if real, this deficiency may give the clue of the origin of this gas. In all young supernovae remnants observed by the Einstein spectrograph, the Mg/Si ratio is much less than 1/3 of the solar value (Becker et al.1980).

This is contrary to the theory of stellar evolution (e.g. Arnett 1978, Weaver et al., 1979) which predicts a comparable yield for magnesium and silicon in massive stars. These observations of supernovae remnants suggest that magnesium is not produced by massive stars, but as a secondary element in low mass stars. In this case, the low Mg/Si ratio in the intracluster gas implies that ejection of interstellar gas takes place in a time scale short in comparison with life time of stars which produce Mg. In current chemical evolution models the transition between primary enrichment and secondary enrichment occurs at an age of 10^9 years. This may be an upper limit for the ejection of the gas from galaxies.

Moreover, one must notice that a very high supernova rate is necessary in the galaxies in order to sustain a hot wind, such that the gas will be pushed outside the galaxies into the cluster. Larson (1974) has shown, in the framework of his model, that such a wind is possible only at the beginning of galactic evolution. A typical time for the appearance of this wind is $\sim 10^8$ years, which is comparable to the time scale indicated by the Mg/Si ratio.

There exist in the literature discussions (Vigroux, 1978, DeYoung, 1978, etc) of the importance of the Fe abundance on models of cluster evolution. However since Fe comes primarily from type II supernovae associated with low mass stars while Si, Mg and S come from type I supernovae associated with massive stars, one can think that the constraints put on cluster evolution from Si are different than those based on Fe. In principle, the fact that both elements have ½ solar abundance in all measured clusters indicates that the ratio of type I to type II supernovae that produced the cluster gas metals was similar to that which produced the solar system metals. That means that, if differences in the IMF existed in the past, they must have been concentrated at the low mass end. Thus the constraints derived from a discussion on the Si abundance will be equivalent to those derived with the Fe abundance.

A. Galaxy mass constraint from Si production

In fact, a problem seems to exist for the net production of Si. If all the X-ray emission comes from the intergalactic gas, the gas mass is $1.7\ 10^{14} M_{\odot}$ (W.S.). It contains $8.5\ 10^{10} M_{\odot}$ of Si assuming $\frac{Si}{Si_{\odot}} \sim 0.5$.

A typical supernova remnant has a mass of 10 $M_\odot$ and an abundance $Si/Si_\odot \sim 3$ (Becker et al.1979-1980)[b]; it contains $3\ 10^{-2} M_\odot$ of Si.

The number of supernova explosions needed to account for all the intracluster silicon is then $\sim 3\ 10^{12}$; since there are about 100 galaxies in A 576, this corresponds to $3\ 10^{10}$ supernovae per galaxy.

---

b. These abundances derived from X-ray observations of SNR are not dramatically modified in the case of magnesium and silicon by more sophisticated models including probable ionization non-equilibrium effects (Shull, 1982). We must also point out that theoretical calculations of metallicity yields produced by stars giving these SNR lead to a factor of 10 times more silicon (Arnett, 1978; Weaver et al., 1979; Wheeler et al., 1980). But even the detailed calculations of Weaver et al. (1979) do not predict good abundance ratios for heavy element production. Because of the uncertainty inherent to this kind of estimates, we prefer to rely on observational data.

For a normal initial mass function, there is one supernova for each 100 $M_\odot$ of stars formed. If this proportion holds, the mass of an individual galaxy may be estimated to be $3\ 10^{12} M_\odot$ which is quite large for the spiral and SO galaxies which populate A 576. Moreover, this estimate is strictly a lower limit on the number of supernovae needed to enrich the intracluster gas since it assumes that all the supernovae remnants are blown out into the intracluster gas. However, a part of them must serve to enrich the successive generations of stars in the galaxy. In all realistic chemical evolution models, the available mass of heavy elements mass in the interstellar gas rises up at the beginning, reaches maximum, and then, decreases slowly (e.g. Tinsley, 1980).

B. Effect of a more realistic chemical evolution model

To estimate this effect we used a numerical model of chemical evolution of galaxies (e.g. Alloin et al., 1979) to calculate the available mass of Si in the interstellar medium. We adopted the theoretical yields of Arnett (1978) for the Si production and we verified that for a classical evolutionary model of the solar neighborhood with infall, we can reproduce the Si solar abundance. Then we calculated the Si in the interstellar medium for various assumptions concerning the star formation rate. The results show that whatever the star formation rate is the maximum Si mass lies near 10^{-4} times the galactic mass. The maximum Si mass is available when the gas mass fraction in the galaxy is about 0.35.

Two conclusions can be drawn from this model. First, with a Si mass fraction of 10^{-4}, the total mass in galaxies needed to account for all the intracluster Si is $8\ 10^{14} M_\odot$, that is with a 100 cluster galaxies each galaxy must have a mass of $8\ 10^{12}\ M_\odot$. This increases the difficulties indicated by the previous order of magnitude calculation (see sec.B). Secondly, if we assume that the ejection of gas from the galaxy took place when the Si mass fraction is at its maximum (a reasonable asumption if we consider the difficulties in producing the observed silicon), then this ejection occurred very early in the galaxy history. For an exponentially decreasing star formation rate with a characteristic time τ a gas mass fraction of 0.35 is obtained at a time $t = 1.5\tau$. A canonical value for τ for elliptical galaxies is about 10^8 years (e.g.Larson, 1974). Then the ejection of gas from galaxies into the IGM must have been done on a comparable time scale.

All these figures are derived with a typical value of $Si/Si_{\odot}$ of ~ 0.5. Our measurements allow an abundance as low as 0.2 (at the 99% confidence level). In this case, the estimate of the mass of each galaxy becomes $3.10^{12} M_{\odot}$ which is still quite a large value.

C. Concluding remarks

The very high mass implied for the galaxies in A 576 and other clusters indicates that they might have massive haloes. However, our mass estimate assumes a normal IMF all along the evolution history of all the galaxies. If the IMF was very enriched in massive stars (compared to very low mass stars) at the beginning of the evolution, the galaxy mass derived from the number of supernovae or from the numerical model is overestimated and it is easier to build up all the observed silicon. This enrichment in massive stars relative to the normal IMF from a low metallicity gas is predicted by the theory of stellar formation (Silk, 1977). Whatever is the IMF, if we assume that the gas ejected from the galaxies comes only from the very hot phase of the interstellar medium, i.e. approximately the supernova remnants, the total mass of gas ejected is about $3\ 10^{13} M_{\odot}$ which is small compared to the total gas mass of $17\ 10^{13} M_{\odot}$ in the IGM of A 576. The other $14\ 10^{13} M_{\odot}$ of gas may be primordial gas left over after the galaxy formation and still present in the cluster. There is no contradiction between the dilution of the rich gas ejected from the galaxies by an already existing intracluster gas and the assumed chemical homogeneity of the present intracluster gas since for a gas at $2\ 10^{7}$K the size of the cluster divided by the sound speed is $2\ 10^{9}$ years. Hence, since in our picture all the gas would have been blown off in the first 10^{9} years, it would have all the time needed to mix with the primordial gas.

All this discussion is somewhat speculative, for example, part of the central emission may be due to the X-ray emission of a galaxy. In this case, the central density of the intergalactic gas is only 1/6 of the one in the White and Silk model. The intergalactic mass of silicon scales with the same factor. Therefore, the problem still exists, but is less dramatic.

VII. CONCLUSION

We have detected line emission due to Fe, Si and S from a hot, $kT \simeq 1.9\ 10^7$K, plasma in the central region of Abell 576. Abundances, roughly 1/2 of the solar value, are derived for these elements. Only an upper limit of Mg abundance can be determined. The total cluster spectrum is well fit by a thermal bremsstrahlung model with $T = 4^{+3.5}_{-1.4}\ 10^7$K. This temperature is in conflict with the SSS temperature determination for the center of the cluster. This difference can be explained if cooling takes place in the central part of the cluster as proposed by White and Silk (1980)[c]. Alternatively, the X-ray emission in the center may be dominated by the emission of a single galaxy. If the X-ray emission comes from the intergalactic gas only, the intergalactic gas contains $8\ 10^{10} M_\odot$ of Si. There is a difficulty in producing all this silicon by the galaxies of A 576 in a "normal" evolutionary scenario.

C. After this manuscript was submitted it was brought to our attention by the referee that similar conclusions about the core radius, central density and cool center of A 576 have been reached by C. Jones and W. Forman, Ap.J., submitted.

We are grateful for the constant help of R. Becker and A.E. Szymkowiak during the analysis of the SSS data. R. Rothenflug wishes to thank Dr. E. Boldt and his team for their kind hospitality during his stay at GSFC, and L. Koch who gave him the opportunity to participate in this work.

APPENDIX

The model developped in Saclay is mainly based on the compilation of atomic data listed in Kato (1976). It includes the following improvements:

i) For the ionization balance, it takes into account the recent calculations of Jacobs et al. (1977-1979) for elements Ne, Mg, Si, S and Fe. Otherwise, results of Jordan (1969) or those of Jain and Narain (1978) were used.

ii) The contribution of satellite lines of hydrogenic and helium-like ions, following dielectronic recombination, were included as a contribution of resonance lines, with the data of Vainshtein and Safronava (1978).

iii) This model uses also the recent compilation of collision strengthes for He-like ions of Mewe and Schrijver (1978) together with those of Davies et al.(1976) for some ions of iron.

TABLE 1

Temperature and abundance determinations

from the A 576 SSS spectrum

		R.S. model best fit	K.R. model best fit	90% confidence range for K.R. model
	Temperature keV	1.67	1.55	1.3 - 2
	N_H (10^{21} at/cm^2)	1.1	1.1	
ABUNDANCES*	Mg	0.0	0.0	$\lesssim$ 0.4 (99%)
ABUNDANCES*	Si	0.72	0.45	0.3 - 1
ABUNDANCES*	S	0.41	0.40	0.1 - 1.2
ABUNDANCES*	Fe	0.18	0.18	0.1 - 0.5
	χ^2	39	36	
	Degrees of freedom	46	46	

* All abundances are ratio to solar values from Meyer (1979).

FIGURE CAPTIONS

Figure 1 — The pulse height distribution of counts from the core of the A 576 cluster obtained with the Solid State Spectrometer. The solid line represents the best-fitting curve for a pure bremsstrahlung model (without lines) with a temperature of 2.3 10^7K.

Figure 2 — Same as in figure 1, except that the solid line now represents the best-fitting curve for a model of plasma emission including lines (here the K-R model). The positions of the main line blends are indicated with arrows. The plasma temperature is 1.9 10^7K.

Figure 3 — The probability contours for the relative abundance of Si, S, and Fe relative to solar and for the temperature derived from the SSS spectrum. The dotted lines indicate the confidence limits.

Figure 4 — The pulse height distribution and inferred photon spectrum for the total cluster obtained with the HEAO-1-A2 detector.

REFERENCES

Alloin, D., Collin-Souffrin, S., Joly, M. and Vigroux, L., 1979
Astron.Astrophys., 78, 200

Arnett, W.D., 1978, Ap.J., 219, 1008

Bahcall, N.A., 1977, Ann.Rev.Astrophys., 15, 505

1981, Ap.J., 247, 787

Becker, R.H., Holt, S.S., Smith, B.W., White, N.E., Boldt, E.A.,Mushotsky,R.F
Serlemitsos, P.J., 1979, Ap.J., 234,L73

1980, Ap.J., 235, L5

Becker, R.H., Boldt, E.A., Holt, S.S., Serlemitsos, P.J., White, N.E., 1980,
Ap.J., 237, L77

Birkinshaw, M., 1979, MNRAS, 187, 847

Branduardi-Raymond, G., Fabricant, E., Feigelson, E., Goreinstein, P.,
Grindlay, J., Soltan, A., and Zamorani, G., 1981, Ap.J.,248, 55

Bruzal, G., Spinrad, H., 1978, Ap.J., 220, 1

Cavaliere, A., Fusco-Femiano, R., 1976, Astron.Astrop., 49, 137

Cowie, L.L., Binney, J., 1977, Ap.J., 215, 723

Cowie, L.L., Hu, ,Jenkins, E.R., York, D.G.,, 1982, Preprint

Danese, L., De Zotti, C., di Tullio, G., 1980, Astron.Astrop., 82, 322

Davies, J., Kepple, P.C., Blaha, M., 1976, J.Quart.Spec.Rad.Tr., 16, 1043

De Young, D.S., 1978, Ap.J., 223, 47

Fabian, A.C., Nulsen, P.E.J., 1977, MNRAS, 180, 479

Fabian, A.C., Pringle, J.E., 1977, MNRAS, 181, 5p

Fabricant, D., Lecar, M., Gorenstein, P., 1980, Ap.J.,241, 552

Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, C.,
Tananbaum, H., and Giocconi, R., 1978a, Ap.J.Suppl., 38, 357

Forman, W., Jones, C., Murray, S., Giaconni, R., 1978b, Ap.J., 225, L1

Forman, W., Schwarz, J., Jones, C., Liller, W., and Fabian, A.C.
1979, Ap.J., 234, L27

Gunn, J.E., Gott, J.R., III, 1972, Ap.J., 176, 1

Heiles, C., 1975, Astron.Astrophys.Suppl., 20, 37

Hintzen, P., Scott, J.S., 1979, Ap.J., 232, L145

Holt, S.S., 1979, Proceedings of the NATO X-Ray Astronomy Institute, Erice, ed.by R.Giacconi and G.Setti,p.35

Jacobs, V.L., Davis, J., Kepple, P.C., Blaha, M., 1977, Ap.J., 211, 605

Jacobs, V.L., Davis, J., Kepple, P.C., Blaha, M., 1977, Ap.J., 215, 690

Jacobs, V.L., Davis, J., Rogerson, J.E., Blaha, M., 1979, Ap.J., 230, 627

Jain, N.K., Narrain, U., 1978, Astron.Astrop.Suppl., 31, 1

Jordan, C., 1969, M.N.R.A.S., 142, 501

Kato, T., 1976, Ap.J.Suppl., 30, 397

Larson, R.B., 1974, M.N.R.A.S., 166, 585

Lea, S.M., De Young, D., 1976, Ap.J., 210, 647

Lea, S.M., Mushotzky, R., Holt, S.S., 1982, Ap.J.,262, 24

Lotz, W., 1967, Ap.J.Suppl., 14, 207

Mc Kee, J.D., Mushotzky, R.F., Boldt, E.A., Holt, S.S., Marshall, F.E. Pravdo, S.H., and Serlemitsos, P.J., 1980, Ap.J.,242, 843

Melnick, J., Sargent, W.L.W., 1977, Ap.J., 215, 401

Mewe, R., Schrijver, J., 1978, Astron.Astrop., 65, 99

Meyer, J.P., in "Les éléments et leurs isotopes dans l'Univers",1979, Inter.Astrophysical Symposium,Univ.of Liège Press,pp.153,465,477,489

Mushotzky, R.F., 1979, Proceedings of the NATO X-Ray Astronomy Institute - Erice, ed.by R.Giacconi and G.Setti,p.171

Mushotzky, R.F., 1982a, Proceedings of the Conf.on Hot Astrophysical Plasmas, Nice

1982b (in preparation)

Mushotzky, R.F., Serlemitsos, P.J., Smith, B.W., Boldt, E.A., Holt, S.S., 1978, Ap.J., 225, 21

Mushotzky, R.F., Holt, S.S., Smith, B.W., Boldt, E.A., Serlemitsos, P.J. 1981, Ap.J., 244, L47

Pradhan, A.K., Norcross, O.W., Hummer, D.G., 1981, Phys.Rev.A, 23, 619

Pravdo, S.H., Boldt, E.A., Marshall, F.E., McKee, J., Mushotzky, R.F., Smith, B.W., Reichert, G., 1979, Ap.J., 234, 1

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

Raymond, J.C., Cox, D.P., Smith, B W., 1976, Ap.J., 204,290

Rephaeli, Y., 1977, Ap.J., 225, 335

Rothenflug, R., Arnaud, M., 1983 (in preparation)

Rothschild, R., Boldt, E., Holt, S., Serlemitsos, P., Garmire, G., Bowyer, S., and Lampton, M., 1979, Space Sci.Instr., 4, 269

Sarazin, C.L., Bahcall, J.N., 1978, Ap.J., 219, 781

Silk, J., 1977, Ap.J., 211, 638

Schnopper, H.W., Delvaille, J.P., Rocchia, R., Blondel, C., Cheron, C., Christy, J.C., Ducros, R., Koch, L., Rothenflug, R., 1982, Ap.J.,253,131

Smith, B.W., Mushotzky, R.F., Serlemitsos, P.J., 1979, Ap.J., 227, 37

Summers, H.P., 1974, Internal Memo 367, Appleton Laboratory, Ditton Park, Slough, England

Tinsley, B.M., 1980, Fundamentals of Cosmic Physics, 5, 287

Vaiana, G.S., Cassinelli, J.P., Fabbiano, G., Giacconi, R., Golub, L., Gorenstein, P., Haisch, B.M., Harnden,Jr., F.R., Johnson, H.M., Linsky, J.L., Maxson, C.W., Mewe, R., Rosner, R., Seward, F., Topka, K., and Zwaan, C. 1981, Ap.J., 244, 163

Vainshtein, L.A., Safronova, U.T., 1978, Atomic Data and Nuclear Data Tables, 21, 49

Vigroux, L., 1977, Astron.Astrophys., 56, 473

Weaver, T.A., Zimmerman, B., Woosley, S.E., 1978, Ap.J., 225, 1021

Wheeler, J.C., Miller, G.E., Scalo, J.M., 1980, Ast.Ap.,82,152

White, R.A.,1978, Ap.J., 226, 591

White, S.D.M., Silk, J., 1980, Ap.J., 241, 864

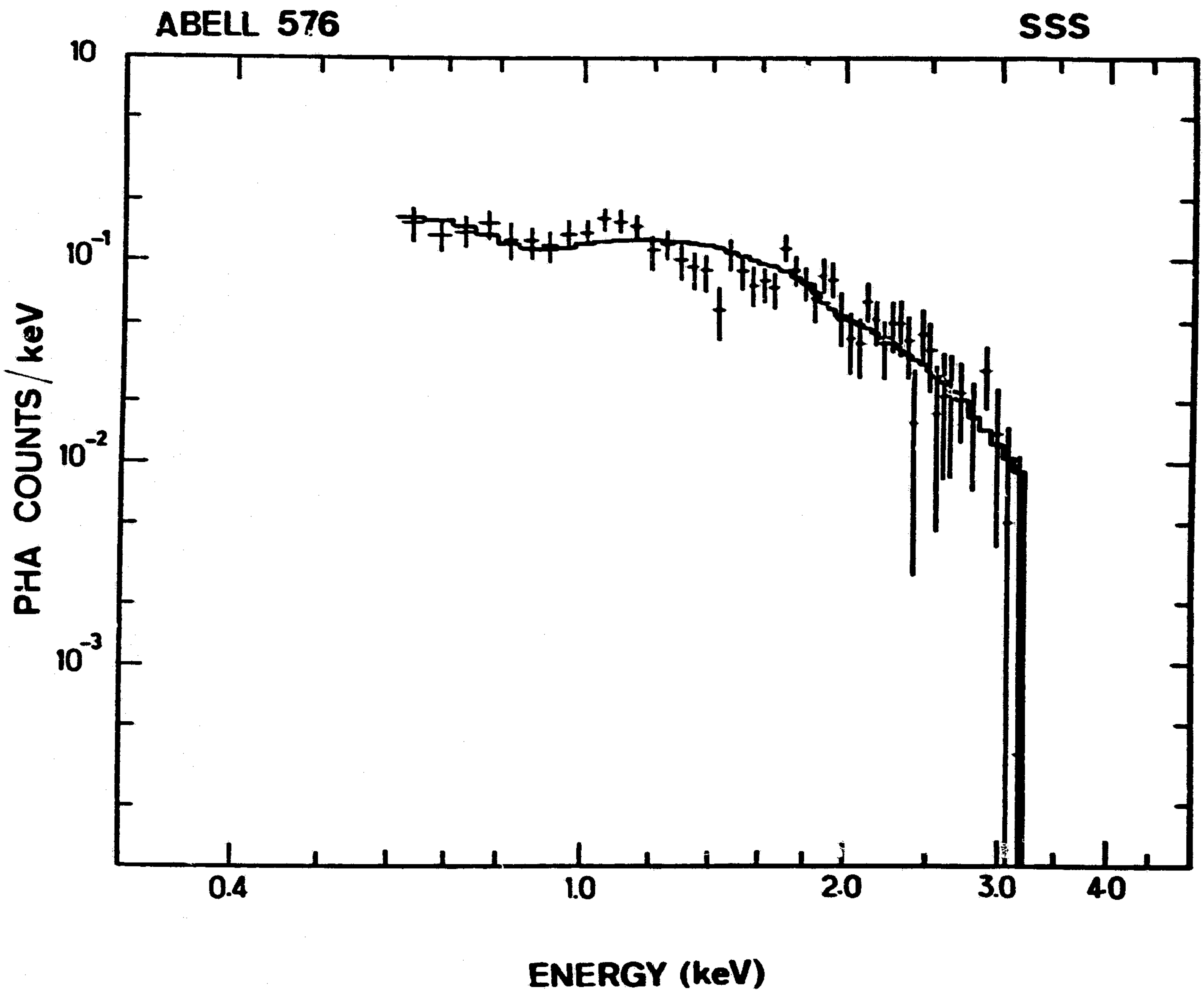
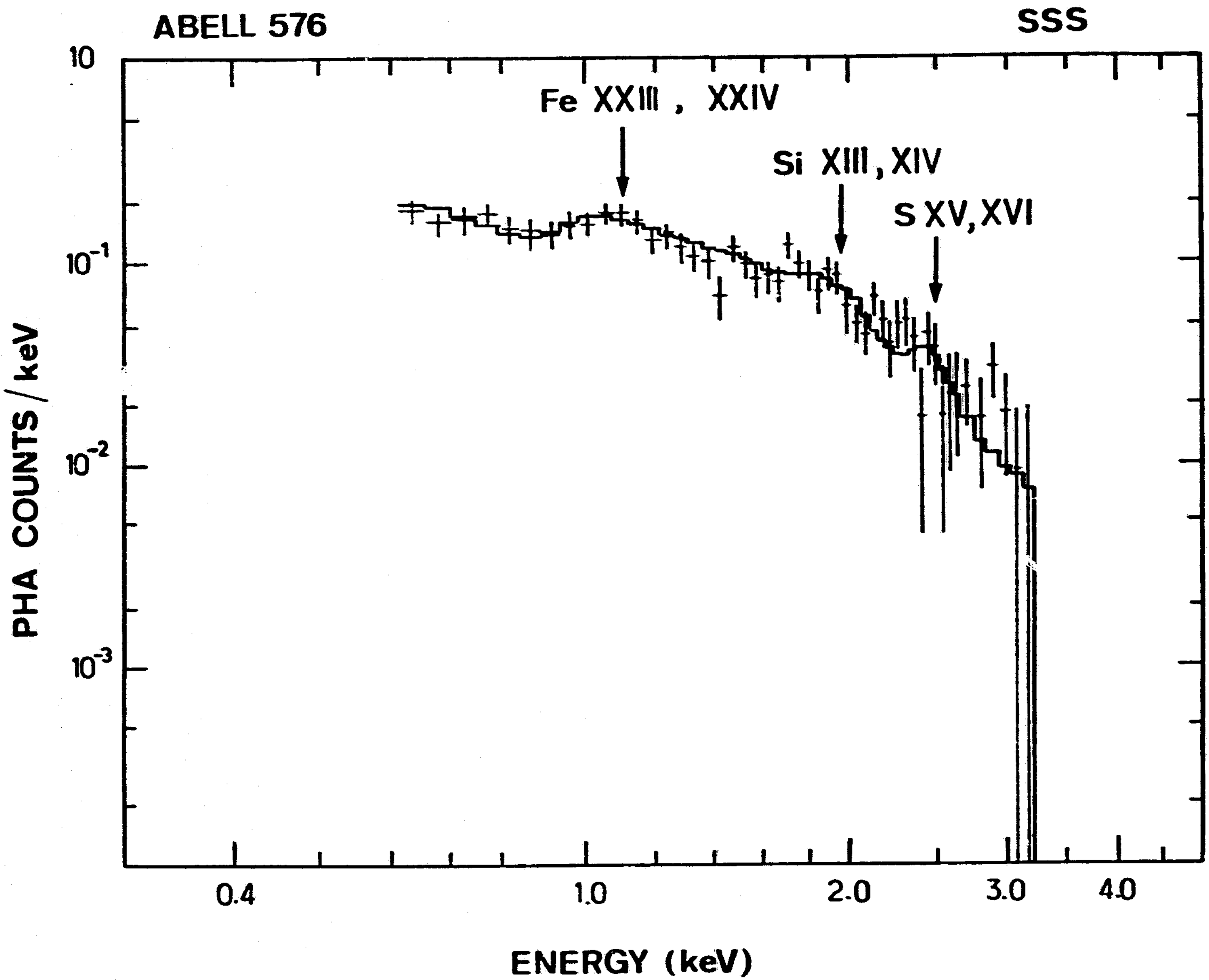

ABELL 576
SSS
10
10^-1
10^-2
10^-3
PHA COUNTS/keV
0.4
1.0
2.0
3.0
4.0
ENERGY (keV)

fig.1



ABELL 576
SSS
Fe XXIII , XXIV
Si XIII, XIV
S XV, XVI
10
10^{-1}
10^{-2}
10^{-3}
PHA COUNTS / keV
0.4
1.0
2.0
3.0
4.0
ENERGY (keV)

fig. 2

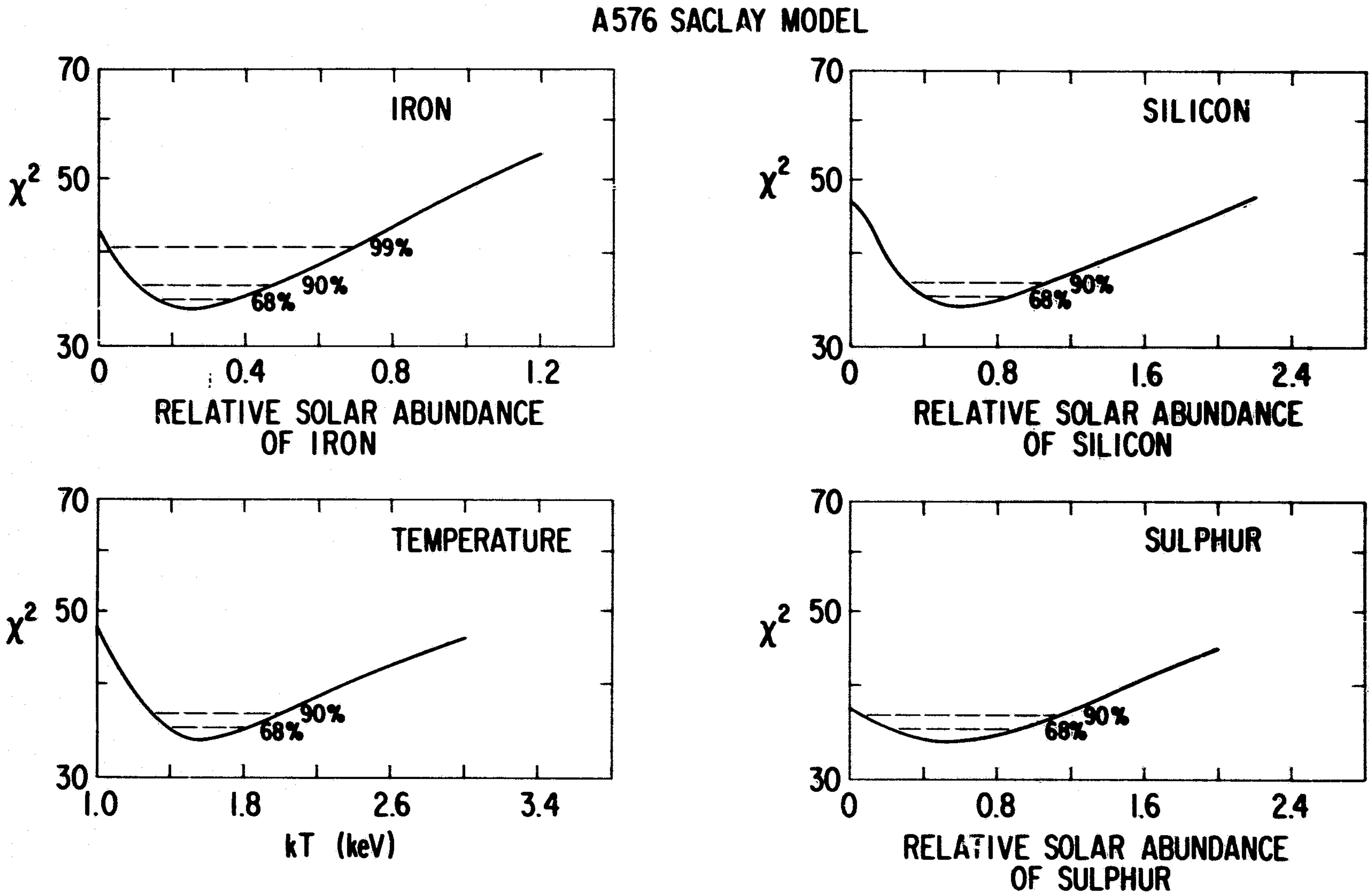
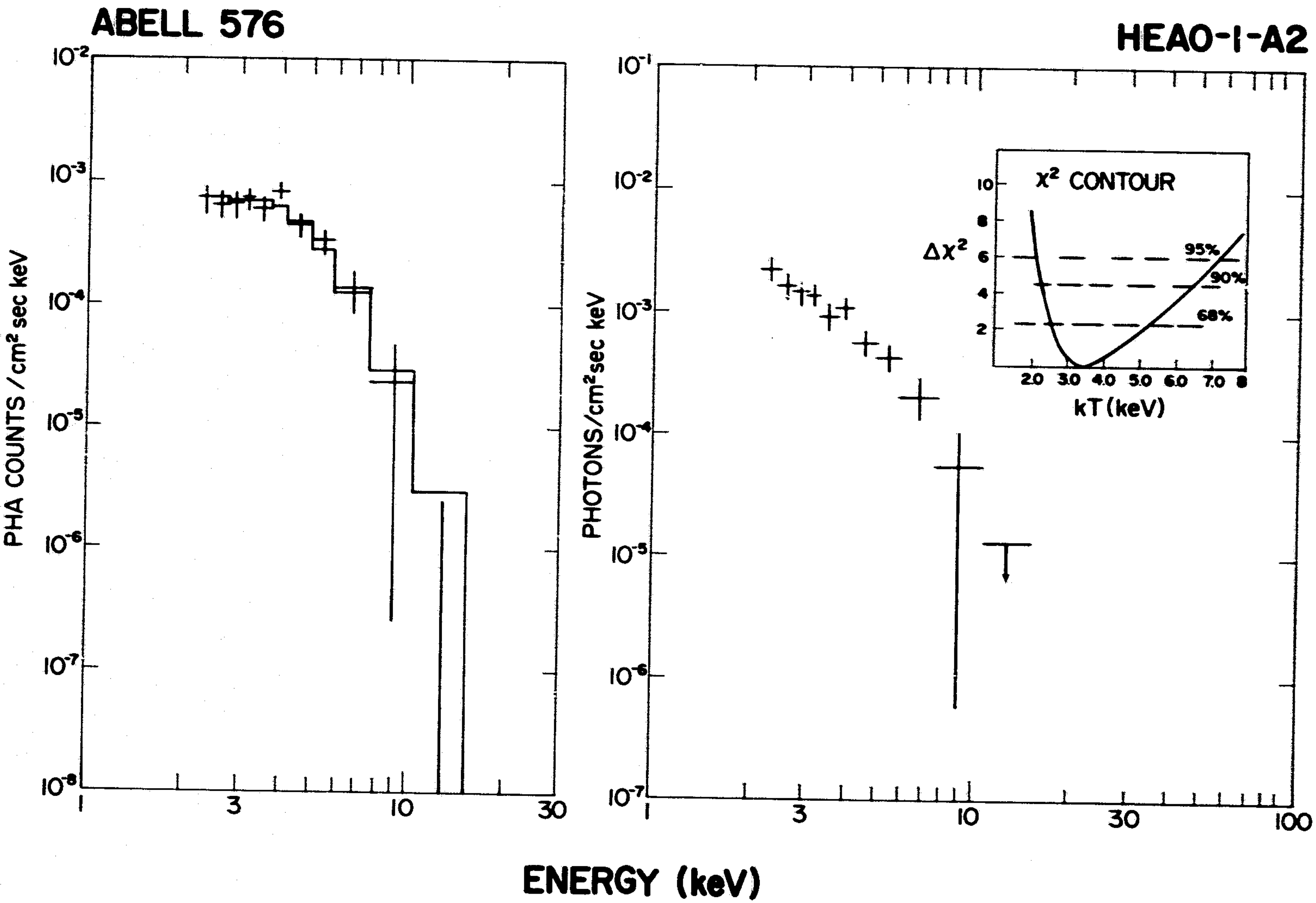

A576 SACLAY MODEL
IRON
SILICON
TEMPERATURE
SULPHUR
χ^2
70
50
30
99%
90%
68%
0
0.4
0.8
1.2
1.6
2.4
1.0
1.8
2.6
3.4
RELATIVE SOLAR ABUNDANCE OF IRON
RELATIVE SOLAR ABUNDANCE OF SILICON
kT (keV)
RELATIVE SOLAR ABUNDANCE OF SULPHUR

FIGURE 3



ABELL 576
HEAO-1-A2
PHA COUNTS / cm² sec keV
PHOTONS/cm²sec keV
χ² CONTOUR
Δχ²
95%
90%
68%
kT (keV)
ENERGY (keV)

FIGURE 4