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OBSERVATION OF THE CORE OF THE PERSEUS CLUSTER

WITH THE EINSTEIN SOLID STATE SPECTROMETER:

COOLING GAS AND ELEMENTAL ABUNDANCES

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ABSTRACT

Solid State Spectrometer observations of the core of the Perseus cluster have resulted in the detection of X-ray emission lines due to Si, S, and Fe. Analysis of the spectrum indicates that the X-ray emission has at least two characteristic temperatures. This is interpreted in the framework of radiative accretion in the core of the cluster. The derived parameters are a cooling time $t_c \lesssim 2 \times 10^9$ yrs for the low temperature gas, a mass accretion rate of ~ 300 $M_\odot$/yr and a characteristic size of 10-20 Kpc for the cool gas. The Fe abundance in the core, ~ 0.4, is similar to the Fe abundance averaged over the whole cluster indicating that Fe emission is not strongly concentrated about NGC 1275. The Si and S abundances are consistent with solar values.

Keywords: Galaxies clusters of - X-ray sources - X-ray spectra galaxies - intergalactic medium; Abundances

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I. INTRODUCTION

In the last few years theoretical work (Fabian and Nulsen 1977, Cowie and Binney 1977, Mathews and Bregman 1978) has suggested that gas in the cores of X-ray emitting clusters can accrete and cool on to slowly moving giant galaxies in the cluster center. Recent X-ray observations (Canizares et al. 1979; Mushotzky et al. 1979) have suggested that this phenomenon probably has been observed in the giant galaxy M87 in the Virgo cluster.

Previous work on the X-ray spectrum of the Perseus cluster (Mushotzky et al. 1978; Serlemitsos et al. 1977; Mitchell et al. 1977) shows it to have a "typical" cluster spectrum with $kT \approx 6.7$ keV, an emission integral $n_e^2V \approx 1.4 \times 10^{68}$ cm^{-3} and a 400 eV-equivalent-width Fe line implying a .4 solar abundance of Fe. Examination of the X-ray cluster luminosity function (McKee et al. 1980) shows that clusters as luminous as Perseus are rare, with a space density $\sim 10^{-8}$ Mpc^{-3}.

Soft X-ray images of the X-ray emission from Perseus (Gorenstein et al. 1978) suggest that there exists enhanced emission from the core of the Perseus cluster above what one would expect from isothermal models. These authors have suggested that this could be the result of cooling gas in the core of the cluster. Data at higher energies (Helmken et al. 1978) confirm the existence of a core-like structure with a 3' scale.

If clusters were well described by spherical, polytropic models in which the gas and galaxies were in equilibrium with each other, then observations of the integral X-ray spectrum, combined with measurements of the X-ray surface brightness as a function of radius, would completely describe the cluster gas and the potential. Recent spectral and spatial analyses of A576 (White and Silk 1980, Rothenflug et al. 1980) however, have suggested that this standard polytropic approximation cannot satisfy the new relatively high-precision spatial and spectral data. In such a situation one needs spatially resolved spectral information to truly understand the nature of the X-ray emitting gas.

We report in this paper, X-ray spectral data obtained with the Einstein solid state spectrometer (SSS) which suggest that the core of the Perseus cluster contains a very low emission measure, low temperature component. In addition, we report the detection of low energy X-ray lines from Si, S, and Fe and place constraints on their elemental abundances.

II. INSTRUMENT DESCRIPTION AND OBSERVATIONS

The SSS consists of a cryogenically cooled Si(Li) detector at the focus of the Einstein telecope. It has a 3' radius circular aperture with roughly uniform response across the field. The detector and telescope combination is sensitve in the 0.5 - 4.5 keV band with a 160 eV FWHM energy resolution approximately independant of energy. A more complete description of the instrumentation may be found in Holt et al. (1979).

The SSS observations of the core of the Perseus cluster were obtained in a 10,000 second exposure centered on NGC1275 in February 1979. This observation resulted in 37,500 source counts. The cluster was re-observed for a shorter 3000 sec exposure in August 1978 resulting in 23,000 source counts.

III. RESULTS

We have modeled the pulse height distribution of the SSS data as an isothermal hot gas in collisional equilibrium (Raymond and Smith 1977, 1979) with the abundances of Si, S, and Fe left as free parameters. The abundances of C, N, O, Al, Mg and Ne were fixed at half-solar similar to previously known Fe abundances (Mushotzky 1979) (Ca and Ar were fixed at solar similar to our derived abundance for Si and S, but the fitting procedure is relatively insensitive to these less abundant species). The resulting fit to the two observations was unacceptable, with a χ^2 of 96 and 109 for 60 degrees of freedom for the 1st and 2nd observations respectively. The best fit values of the temperature kT = 4.2 and kT = 2.5 for the first and second observations do not agree well with the previously measured value (Mushotzky et al. 1978). In addition the one temperature model does not properly account for the observed ratio of the hydrogen and helium like lines of Si and S nor for the observed shape of the Fe L blend. The best fit abundances relative to solar (Meyer 1979a,b) for this one temperature model were Si $\approx$ 1.0, S $\approx$ 1.2 and Fe $\sim$ 0.40 for the first observation and Si and S $<$ 1.5 and Fe $\sim$ .2 for the second observation which had poorer statistics. Because the fits were unacceptable error bars are not assignable.

We then added a second thermal component, and constrained the elemental abundances to be the same for both components. This reduced χ^2 by 22 for the first observation and 30 for the second observation. We note that a decrease in χ^2 of 9.2 is significant at the 99% confidence level for the two additional degrees of freedom introduced. The best fitting temperatures were kT $>$ 4.0 keV for the high temperature component and .60 $<$ kT $<$ 1.4 for the low temperature component. The fitting procedure required the spectrum to be redshifted with a fitted redshift of z = .013$\pm$ .005 (1σ error) compared to the optical redshift z = .0183. The best fit values of emission integral $\langle n_e n_V \rangle$ were 4.8×10^{66} cm^{-3} for the low-temperature component and 3.7×10^{67} for the high component. No statistically significant changes in the low temperature component were seen with an upper limit of a $\pm$ 50% change in its emission integral or temperature on a time scale of 6 months. Neither the addition of a third temperature component nor the removal of the constraint of the same abundances for the two components reduced χ^2 significantly.

The effect of this extremely low emission measure low KT component is illustrated in Figures 1 and 2. The best fitting abundance values and their errors are indicated in Figure 3. Si and S have roughly solar abundance values (Si = 0.9 ± 0.5, S = 1.4 ± .4 where 1 = solar and we have used $\frac{Si}{H} = 3.7 \times 10^{-5}$ and $S/H = 1.58 \times 10^{-5}$) and Fe has a value which is roughly half-solar (Fe = .44 ± .2) (90% confidence errors). Our upper limit on Mg is ≤ 1.3 solar. This Fe abundance is the same as measured from the higher energy total cluster spectrum (Mushotzky et al. 1978) when allowance is made for the adoption in the present paper of a solar Fe value of 3.2×10^{-5} vs. the 3.9×10^{-5} in the previous work.

The best fitting absorption in the line of sight corresponds to $N_H = 3 \pm 1.5 \times 10^{21}$ H-atoms/cm^2, of cold material similar to the range of allowed values, $1.4 - 2.2 \times 10^{21}$ H atms/cm^2, derived from the soft X-ray data of Malina et al. (1978) when the Fe L lines are taken into consideration. This value of N_H is consistent with the galactic HI value in this direction of 1.5×10^{21} (Heiles 1975).

Our flux values for the 2 components in different energy bands are shown in Table 1. These values refer to the flux emitted from the source with the best fitting galactic column density removed. In the 3' radius observed by the SSS the low temperature component has ~ 12% of the bolometric luminosity of the high temperature component. However, this low temperature component has only 0.8% of the 2-10 keV flux of the entire cluster (Mushotzky et al. 1978). This explains why this component has not been seen by previous proportional counter X-ray spectrometers.

The bolometric luminosity measured by the SSS is ~ 25% of the total flux measured by OSO-8. If the Perseus cluster could be described by a isothermal spherically symmetric (King) model then the flux measured by 2 detectors of different angular responses should fix the core radius. Comparing the SSS and OSO-8 fluxes gives a core radius of 8' for the cluster, identical to the optical core radius of Bahcall (1979). If we assign a fraction of the total flux in a 3' radius beam to a point source, similar to the best fit value of 25% of Gorenstein et al. (1978) and the recent results of Branduardi-Raymont et al. (1980), we derive a core radius of $\sim 10'$. Gorenstein et al. (1979) have considered several models of the Perseus cluster X-ray emission. In their models in which the core radius was a free parameter the best fit core radius ranged between 17 and 28 arc min depending on the value of β, the ratio of the velocity dispersion to gas temperature. We also note that Gorenstein's et al. data is consistent with an 8' core radius if $\beta = .62$, a value favored by recent larger angular scale data (Nulsen and Fabian 1980).

IV. DISCUSSION

A. The Low Temperature Component

We shall interpret the lower temperature component as cooling gas in the core of the Perseus cluster. However there do exist other possibilities, such as emission due to gas whose origin lies inside the potential well of NGC1275 or the direct effect of the active galactic nucleus on gas associated with NGC 1275.

Observation of the emission measure and temperature of the gas allows the estimation of a rough cooling time. If the gas is cooling at constant pressure $t_{cool} \sim 5\ KT/n_e\Lambda$ where Λ is the cooling function of Raymond, Cox and Smith (1976). In order to calculate the density in the core one needs to estimate its physical size.

For the purposes of this discussion we shall parameterize the size of the cooling region in terms of the 3' radius beam size of the SSS ($3' \approx 100$ Kpc at $z = .0183$, $H_o = 50$ km sec^{-1} Mpc^{-1}). If the volume of the cooling region is smaller then the SSS beam size, as the theoretical calculations of Fabian and Nulsen (1977) indicate it should be, then the density of the gas would be $n_e \sim 6 \times 10^{-3}\ r_{100}^{-3/2}\ cm^{-3}$, where r_{100} is the radius of the cooling region in units of 100 Kpc. The value of the cooling function at $T \sim 10^{7o}$ K for a gas with half-solar Fe abundance is $\Lambda \sim 2 \times 10^{-23}$ erg cm^3/sec. Therefore $t_{cool} \sim 2 \times 10^9\ r_{100}^{3/2}$ yrs, much less then the Hubble time. In 10^{10} yrs there would accumulate, in a steady state situation, $\sim 2.9 \times 10^{12}\ M_o$ of cooled material, an amount similar to the estimated mass of NGC 1275. This flow of 290 M_o/yr is similar to that required to account for the optical filaments seen near NGC 1275 (Cowie, Fabian and Nulsen 1980). This result seems to confirm the suggestion of Cowie and Binney (1977) and Silk (1977) that cooling flows can result in the accumulation of large amounts of material in the core of a cluster and the formation of a massive central galaxy.

More accurate values for the size and cooling time for the cooling material can be estimated if it is assumed that pressure equilibrium exists between the cool material and the rest of the intergalactic medium in Perseus. We can use the imaging results from the Einstein Observatory to estimate how much of the flux seen in the 0.5 - 4.5 keV band originates from the cluster foreground gas and the local emission around NGC 1275. Intergration of the high resolution imager data in a 3' radius beam centered on NGC 1275 (Fabricant 1980, private communication) shows that only ~ 1/3 of the flux seen by the SSS is probably due to the extended cluster emission (foreground and background gas). This enables one to calculate the pressure of the "high" and "low" kT gas on the assumption that the high kT gas fills the beam while the cooler material lies inside it. Requiring the two components to be in pressure equilibrium results in a size of ~ 10-20 kpc for the cool gas, a pressure $nT \simeq 1.4 \times 10^6$ K cm^{-3}, and a cooling time of $\sim 2 \times 10^8$ yrs. The mass flow rate and the infered mass of accumulated material are unchanged because they do not depend on the inferred size. This compares to a pressure in the optical filaments of $1.2 \times 10^7 \, T_4^{3/2}$ K cm^{-3} (Cowie, Fabian and Nulsen (1980) and the theoretical calculation of Cowie and Binney (1977) which predicted a pressure of $\sim 2 \times 10^6$ K cm^{-3} at the stagnation radius. The inferred "size" of the cool gas compares to a "half-flux" size of ~ 10 Kpc predicted by Cowie and Binney (1978). It, therefore, seems that the theoretical modeling has been verified by our observational results.

It is interesting to see why the particular temperature measured by the SSS stands out in the observation of a cooling flow with a range of temperatures by examining the cooling curve of Raymond, Cox and Smith (RCS) (1976). The gas would spend most of its time in the region of the minimum of the cooling curve. However, we see this cool component by its line emission in the .800 - 4.0 keV band and one sees from Figure 5 of RCS that the maximum emission in this band occurs at roughly a temperature of 10^7 K°. Therefore we would expect most cooling clusters observed by instruments on the Einstein Observatory to exhibit a temperature component in the .5 - 1.5 keV range.

B. Chemical Abundances & Line Emission

The observation that the abundance of Fe in the core is similar to that averaged over the whole cluster indicates that Fe line emission is a property of the cluster as a whole and that the Fe lines seen in many clusters (Mushotzky 1979) are not due to dominance by a single galaxy. This result also indicates that the gas is reasonably well mixed out to a few core radii.

The 90% confidence abundance contours for Si, S and Fe do not completely overlap in the simple two temperature model. Since this model does not completely describe the true distribution of temperatures in a cooling flow we feel that we cannot, at this time, make strong statements as to the possibility of relative abundance differences between S, Si and Fe. However, the lack of a requirement in our data for a third temperature component indicates that the approximate solar abundances for Si and S will not be changed greatly by additional modeling. Similarly, the approximate half-solar abundance for Fe is in agreement with independent measures of the abundance inferred from observations of the Fe K-line emission at higher energies.

V. CONCLUSION

The solid state spectrometer on the Einstein Observatory has observed a low temperature component in the core of the Perseus cluster. The existence of this component is consistent with the theoretically predicted existence of a cooling core in the cluster. This gas which has an emission measure of $\sim 3\%$ of that of the total cluster X-ray emission, has a cooling time $\lesssim$ of 2×10^9 yrs, and this cooling would result in more than 2×10^{12} $M_\odot$ of material accreting onto NGC 1275 over a Hubble time.

The abundance of Fe in the core of $\sim .5$ solar is similar to the abundance inferred from previous proportional counter observations indicating that the Fe emission is not strongly peaked about NGC 1275. The Si and S abundances are also roughly solar.

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FIGURE CAPTIONS

Figure 1 - The pulse height distribution of counts from the core of the Perseus cluster centered on NGC 1275. The solid line represents the best fitting low temperature model folded through the detector response function normalized relative to the total counting rate.

Figure 2 - The 3 panels show the significance of the residuals (σ) of the data minus the model in a channel by channel scale. For the top panel the model is isothermal bremsstrahlung with only H and He. For the middle panel the model is isothermal bremsstrahlung (1 kT R-S) with variable abundances of Si, S and Fe and fixed abundances of other elements. For the bottom panel the model is two temperature bremsstrahlung with variable Si, S and Fe and fixed abundances of other elements. The subscript "L" refers to lines and line complexes which originate from Fe, Si and S primarily at low ($kT < 1.5$ keV) temperatures while the "H" refers to lines of these same elements due to high ($kT > 2$ keV) temperature gas.

Figure 3 - The probability contours for the relative abundance of Si, S and Fe relative to solar. The dotted lines correspond to 68, 90 and 99% confidence limits.

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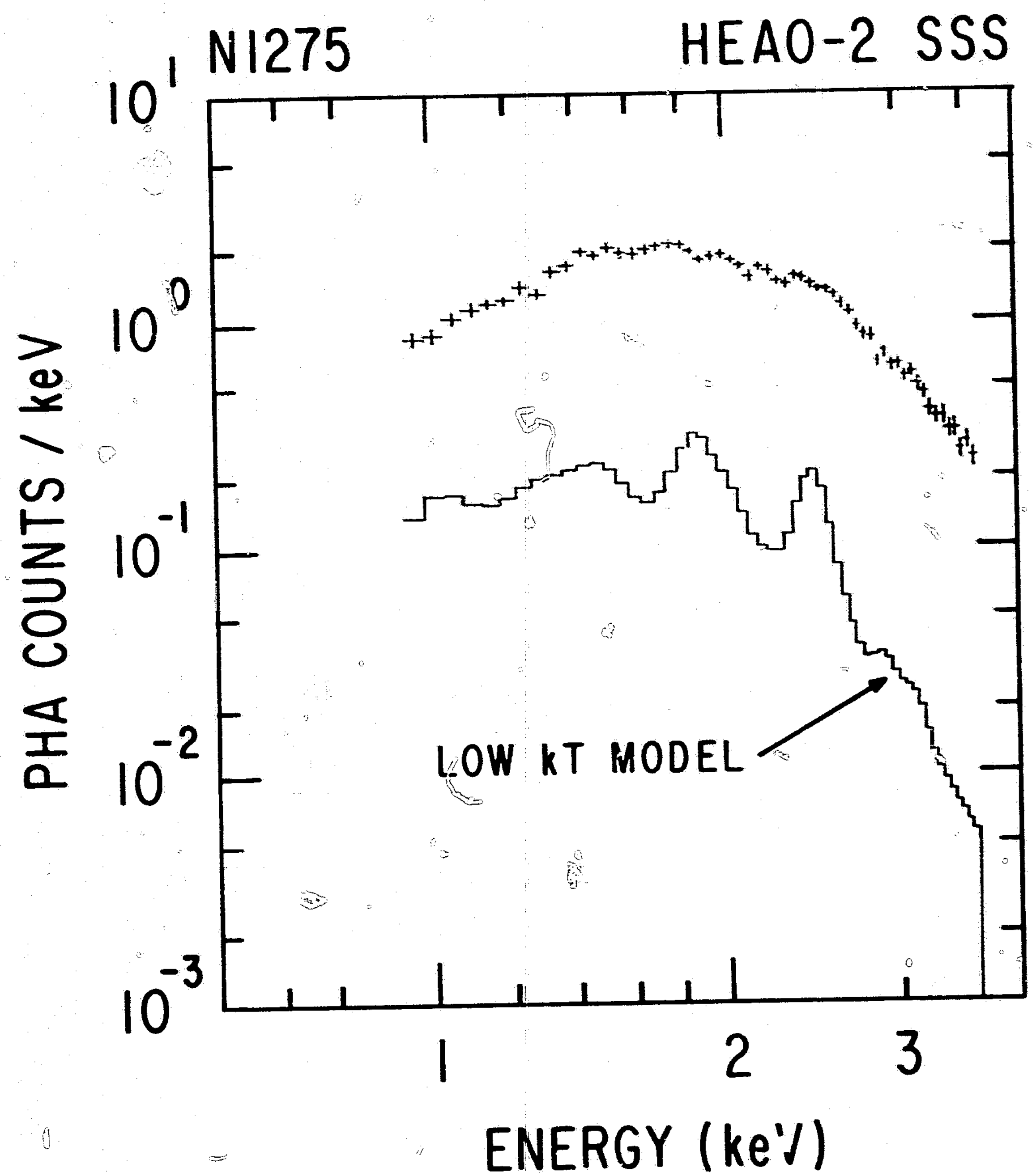
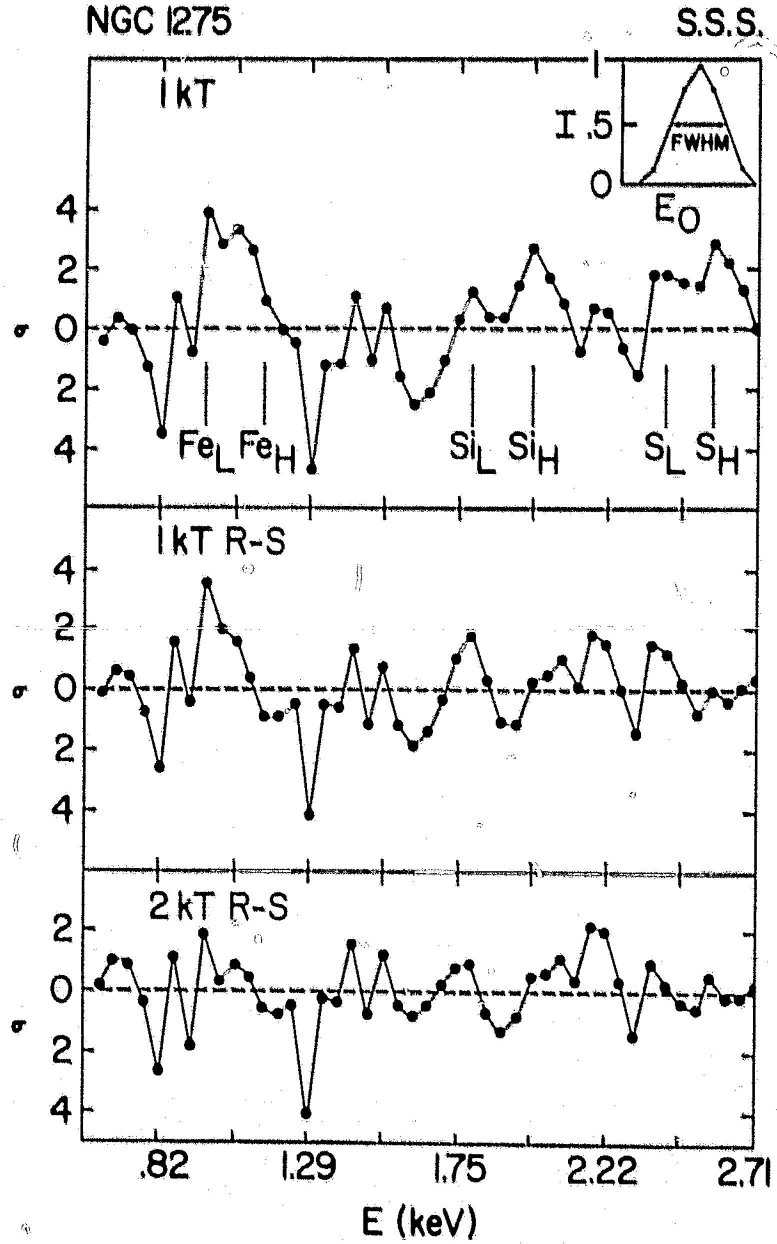
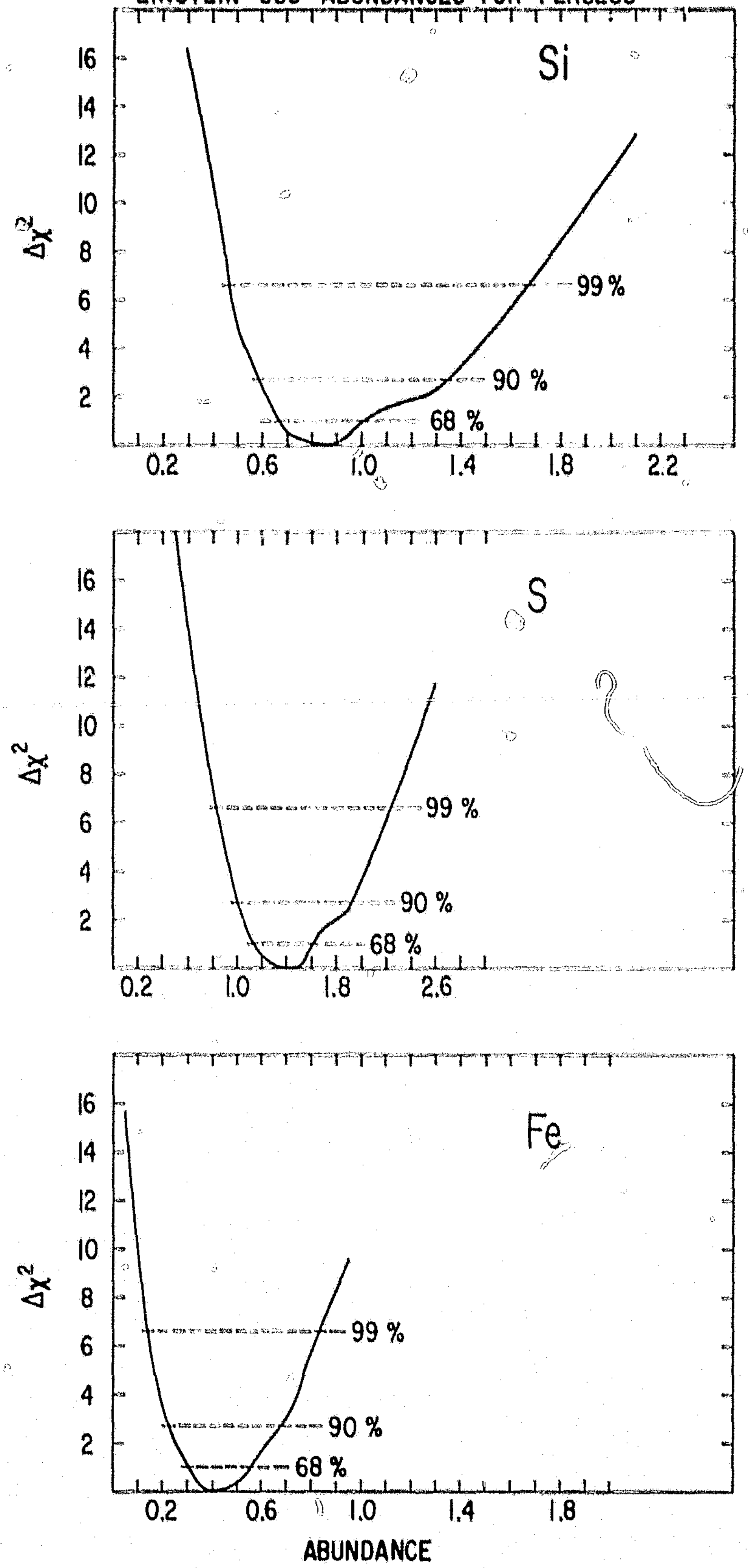

N1275
HEAO-2 SSS
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
PHA COUNTS / keV
LOW kT MODEL
1
2
3
ENERGY (keV)



NGC 1275
S.S.S.
1 kT
I
.5
0
1
FWHM
E_O
Fe_L
Fe_H
Si_L
Si_H
S_L
S_H
1 kT R-S
2 kT R-S
σ
4
2
0
.82
1.29
1.75
2.22
2.71
E (keV)

EINSTEIN SSS ABUNDANCES FOR PERSEUS



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