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SEARCH FOR LINE STRUCTURE IN THE X-RAY SPECTRUM OF SCO X-1

by

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ABSTRACT

Recently obtained data from a rocket-borne exposure to x-rays from Sco X-1 are shown to yield a positive indication of iron line emission at 3.25 σ which is at a level approximately an order of magnitude below previously published upper limits. Such emission is consistent with a bremsstrahlung source of universal abundance, but the overall continuum shape indicates significant departures from an isothermal source.

In a recent communication (Holt, Boldt and Serlemitsos, 1968), we discussed the practical possibility of searching for iron line emission with proportional counters as a positive indication of the thermal nature of discrete x-ray sources. We report, here, the results of a rocket-borne exposure to Sco X-1 carried out on March 3, 1969. Comparison of this data with proposed collisional emission models places severe constraints on the iron abundance and the degree to which an isothermal source region may be used to approximate the emission region.

Sco X-1 was observed for 150 seconds with, essentially, the same detector system used in our exposure to the Crab Nebula (Boldt, Desai and Holt, 1969; Boldt, et al., 1969). Almost all of the source exposure is obtained in two nominally identical P-10 proportional counters with 2-mil beryllium windows. The data from the higher-resolution counter are presented here explicitly, but any conclusions which we draw from these are consistent with all of the data. We note that the data presented have not been folded back through the detector response; such an unfolding procedure is necessarily non-unique, and can be particularly misleading if there is the possibility of discontinuous structure in the input spectrum. For this reason, we have performed model-dependent analyses by folding trial spectra forward through the detector response, i.e.,

$$P(E') = \int S(E)\, G(E,E')\, dE$$

so that the pulse-height spectrum $P(E')$ arising from the input spectrum S(E) can be directly compared with the measured pulse-height spectrum. The detector response kernel G(E,E') specifically includes the effects of energy-dependent efficiency, resolution and escape radiation, as well as such second-order effects as the measured perturbations of the kernel arising from the flourescence of metallic counter components, incomplete energy conversion and window contaminants.

Because of the statistical significance of the data points are much better than has been usual for x-ray astronomy, we have chosen a more detailed method of graphical data presentation than is commonly employed. Each 1/4 keV bin is plotted (with background subtracted) as a percentage difference between the observed count and that expected on the basis of the trial input spectrum corresponding to each model. In addition, we have also lumped the data in 3/4 keV bins, since the two expected iron lines fall symmetrically in a bin of this size, and more than half of the photons in the lines will fall into this bin with our resolution on $\sim$ 1 keV FWHM. We note that the higher energy line actually falls 1/4 keV lower in energy than the 7.15 keV stated in Tucker (1967) and, subsequently, elsewhere in the literature (we are grateful to Dr. G. Steigman for pointing this out to us).

The goodness (more properly, badness) of fit to each of the assumed models is determined by a χ^2 test in the energy range 4-15 keV. Our experiment dynamic range extends from < 2 keV to > 20 keV, but we pick 4 keV as the lower energy bound to minimize possible systematic effects which would preferentially complicate the low energy end of the spectrum, such as optical thickness in the source. Above 15 keV, the data rapidly lose statistical significance.

The initial comparison was made to a simple exponential in energy, the "standard" approximate procedure for analyzing the emission from a suspected thermal source. The fit is sufficiently good to disallow outright rejection on the basis of χ^2, as discussed below, but there is a 3.25 σ feature at precisely the location where iron line emission is to be expected from a thermal source (see upper trace of Fig. 1).

Of the three thermal models proposed by Tucker (1967), models II and III (low and high mass supernova remnants, respectively) demand considerably more iron line emission than the data allow. Model I (universal abundance) would appear to be consistent with the data on the basis of the observed "iron" excess alone, but closer examination of this hypothesis yields, in fact, a less satisfactory fit to all of the data than does the simple exponential if such a source is restricted to being isothermal. The reason for this apparent contradiction is that while the contribution to the spectrum in line emission is consistent with universal abundance, the overall shape of the continuum is not; Chodil, et al. (1968) have pointed out that the assumption of a constant free-free Gaunt factor is not applicable in this energy range and, while the approximation is better for the contribution of heavy elements to the continuum, the fact that the greatest contribution is made by light elements distorts the exponential sufficiently to result in a less satisfactory fit. We have followed the method of

Tucker (1967) to calculate the emission from an isothermal, optically thin gas a function of temperature and elemental abundance, using the results of Karzas and Latter (1961) for the energy-, temperature-, and Z-dependence of the free-free Gaunt factor. As shown in Fig. 2, the minimum value of χ^2 attainable with universal abundance is $\sim$ 100 at kT $\approx$ 7.5 keV for 45 degrees of freedom. Tucker's models II and III give minimum values of χ^2 which are considerably worse.

Since, for as many as 45 degrees of freedom (n) the expectation value of χ^2 is n (with standard deviation $\sqrt{n}$), thermal emission from an isothermal, optically thin gas would appear to be an extremely poor fit. On the other hand, a simple exponential gives a value of χ^2 which is within 3σ of n. For this reason, and because of the statistically significant excess where iron line emission would appear, we have also considered the highly artificial model of iron bremsstrahlung, line emission and recombination radiation superimposed on a pure exponential. In order to compare this result with those obtained by other experimenters, we define

$$R = \frac{\text{power in iron lines}}{\text{power in 2-8 Å continuum}}$$

to characterize the iron abundance chosen. We find that $10^{-3} < R < 5\times10^{-3}$ results in a minimum value of χ^2 within 2σ of n and, as seen from Fig. 1, the disappearance of the "iron" excess. Previous experiments (Rappaport, et al., 1969; Fritz, et al., 1969) have set an upper limit of 0.05 for R. On the basis of the above analysis, our 3.25σ positive indication is at a level about one order of magnitude less than this upper limit. By the same token, we can set an upper limit of 0.01 at better than 3σ.

We are still faced with the difficulty that a simple exponential is a better fit to the data than is the emission from an isothermal source region. We note that the effects of optical thickness and scattering cannot completely resolve the disparity in the overall shape of the observed spectrum with that expected from an isothermal source region. Of course, it is always possible to (non-uniquely) assume a distribution of source regions as a function of temperature which can masquerade as an exponential over a limited energy range (as Sartori and Morrison (1967) have suggested to masquerade as a power law in the case of the Crab Nebula); such a procedure would not be unreasonable since it is now well established that the electromagnetic radiation observed in other energy bands cannot be reconciled with the isothermal source first associated with X-ray emission from Sco X-1. We must conclude, therefore, that either the source has observable (but non-unique) temperature dispersion in the few-keV region, that the X-ray emission is only partially thermal in character, or that the feature which we have tentatively identified with iron line emission is a statistical fluke on an apparently non-thermal continuum (such as that first suggested by Manley (1966)). Truly conclusive evidence for the presence of line emission, therefore, remains lacking, but its eventual unambiguous detection provides the only decisive test for the hypothesis of a thermal bremsstrahlung source.

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FIGURE CAPTIONS

1. Percentage deviation of the actually measured pulse height spectral points from those computed from trial input spectra. The upper trace represents a fit to a pure exponential in energy with kT = 5.5 keV, and the lower trace a fit to an exponential with kT = 5.3 keV and with iron added such that R = .005. The errors indicated on both the 1/4 keV points and the 3/4 keV bins are 1 σ.
2. χ^2 for 45 data points as a function of temperature. The trace labelled universal abundance is a true isothermal source, while the others are exponentials with varing amounts of iron added.

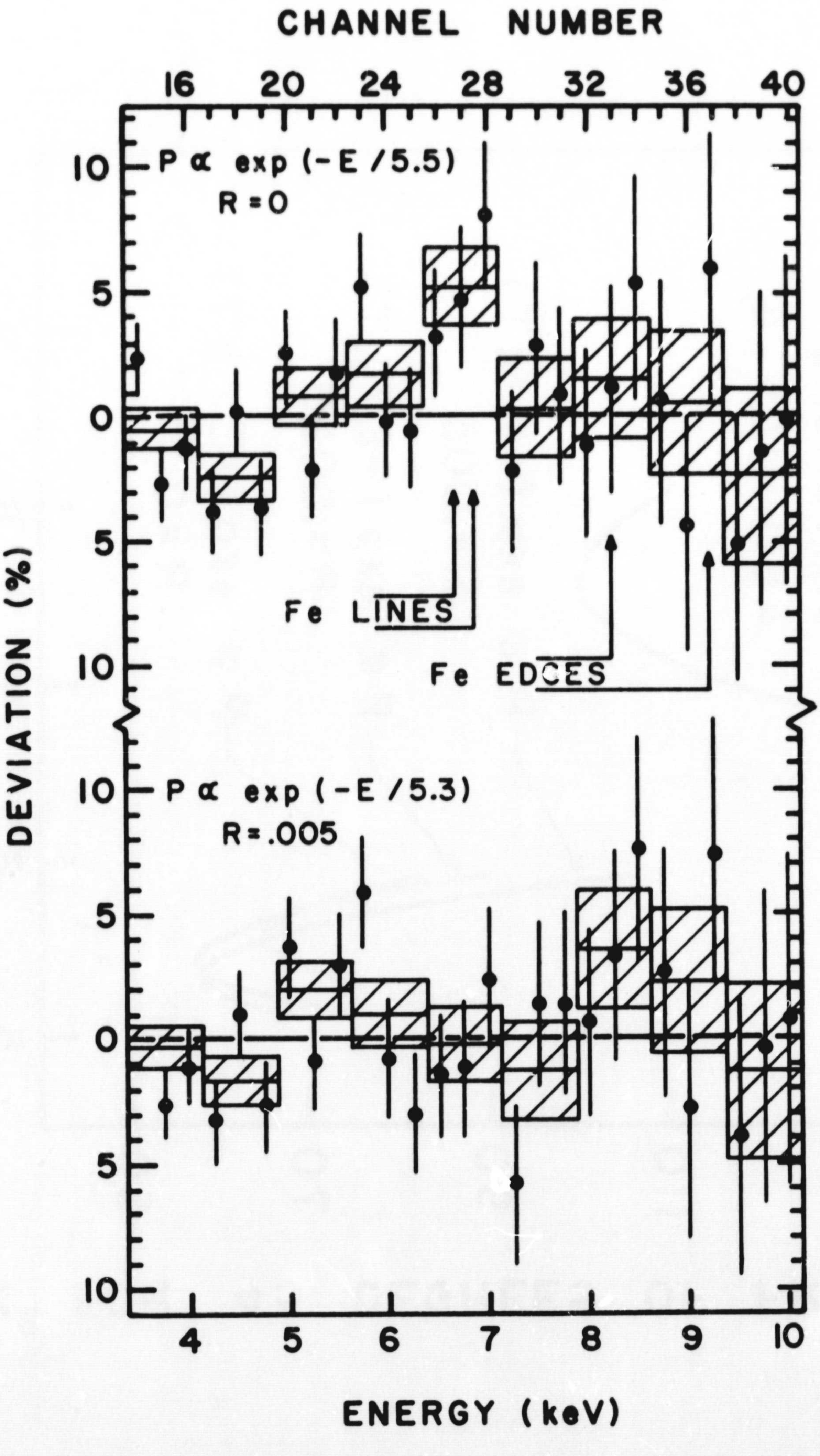
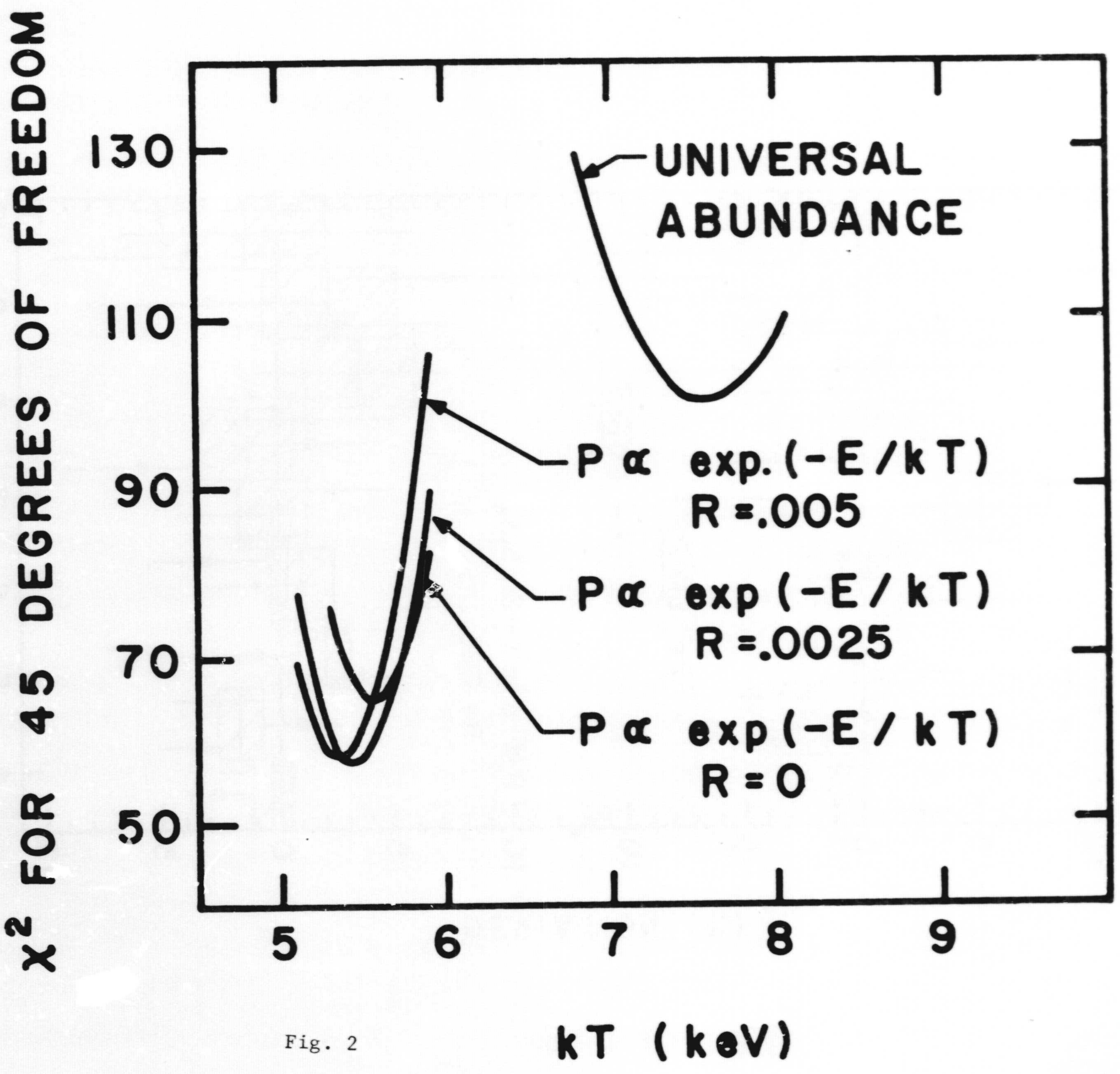

CHANNEL NUMBER
16
20
24
28
32
36
40
P ∝ exp (-E /5.5)
R = 0
Fe LINES
Fe EDGES
P ∝ exp (-E /5.3)
R = .005
DEVIATION (%)
10
5
0
5
10
4
5
6
7
8
9
10
ENERGY (keV)

Fig. 1



χ^2 FOR 45 DEGREES OF FREEDOM
130
110
90
70
50
UNIVERSAL
ABUNDANCE
P α exp.(-E/kT)
R =.005
P α exp(-E/kT)
R =.0025
P α exp(-E/kT)
R = 0
5
6
7
8
9
kT (keV)

Fig. 2