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X-RAY SPECTRAL CONSTRAINTS ON THE BROAD-LINE CLOUD GEOMETRY OF NGC 4151

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ABSTRACT

X-ray spectral data from NGC 4151 taken with the Einstein Solid-State Spectrometer (SSS) and the HEAO-1 A-2 experiment cannot be simply reconciled with absorption from a uniform column of cold gas. The SSS data can, however. be explained in terms of a clumped absorber with approximately 10% uncovered fraction and factor-of-two overabundances in $Z \geq 14$ elements relative to solar oxygen. We show that these and previously reported spectral and variability data can be quantitatively reconciled with absorption arising in the cold clouds responsible for the broad optical line emission if the cloud dimensions are small compared to the central source size. We suggest that the lack of significant X-ray absorption observed from much higher luminosity Seyferts and quasars is a natural consequence of our picture for NGC 4151.

Subject headings: X-rays: sources -- X-rays: spectra -- Galaxies: Seyferts

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I. INTRODUCTION

The nearby Seyfert 1 galaxy NGC 4151 has been extensively studied in X-rays. All the reported data are consistent with a relatively hard power law energy spectrum ($0.4 < \alpha < 0.7$) which extends from 2 keV (e.g. Mushotzky, Holt and Serlemitsos 1978) through 100 keV (e.g. Paciesas, Mushotzky and Pelling 1977), and which may extend out beyond 1 MeV (Perotti, Della Ventura and Sechi 1979). All the soft X-ray measurements require absorption from a relatively large amount (10^{22} - 10^{23} H-atoms cm^{-2}) of cold material in the line of sight (e.g. Ives, Sanford and Penston 1976). Such large column density is atypical of the measured X-ray spectra of higher luminosity Seyfert 1 galaxies, which require no column density in excess of the approximately 10^{21} H-atoms cm^{-2} expected from their observation through the Milky Way (Mushotzky et al. 1980).

Some observations indicate variation in the column density to NGC 4151 on time-scales of months (Barr et al. 1977), quite apart from variations in the continuum source underneath this absorber (Mushotzky, Holt and Serlemitsos 1978). This has led to a widely-accepted picture of the absorption arising from the cold condensed matter which is also responsible for the broadened optical emission lines. The absorption variations have been interpreted in terms of the creation/destruction and orbital motion of these cold filaments or clouds in the broad-line region (BLR) of the Seyfert galaxy, assuming that the breadth of the optical lines can be directly ascribed to a combination of orbital and turbulent Doppler velocities of order 10^4 km s^{-1}.

We present evidence here from both the Solid State Spectrometer (SSS) onboard the Einstein Observatory and the HEAO-1 A-2 experiment[1] that the absorption observed in the X-ray spectrum of NGC 4151 supports the general picture of cold clouds along the line of sight, but with two important qualifications. We find that the clouds cannot cover the X-ray source uniformly, and that the heavy element abundances ($Z \geq 14$) relative to oxygen are likely to be at least twice the "cosmic" values

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

associated with the solar system. We suggest that the high apparent column density in NGC 4151 relative to that in other X-ray-emitting Seyfert 1 galaxies may be a natural consequence of its lower luminosity.

II. RESULTS

NGC 4151 was observed by the SSS (see Holt et al. 1979 for experiment description) for a total of 10^4 s on 1979 May 27. The raw (background-subtracted) pulse-height data are displayed in Figure 1, fitted with a variety of trial models, as described below. No combination of single spectral index and uniform column density is capable of reproducing the SSS data. For all trial models with uniform column densities commensurate with previously reported values, there is a pronounced excess measured at energies below 2 keV.

Some fraction of the low energy excess may arise from several causes. The Einstein high-resolution imaging experiment has observed an X-ray-emitting point source located approximately 5 min from NGC 4151 (J.P. Henry, private communication), but the 3 min-radius field-of-view of the SSS should completely exclude any contribution from this source to our NGC 4151 exposure. Another possibility is that the low energy excess is produced within NGC 4151, but farther out from the central source than is the bulk of the X-ray emission, so that it is less (or not at all) obscured by the absorbing column (e.g. Davidson and Netzer 1979). It is always possible to invoke such a secondary component because there is no *a priori* restriction on its spectral form. The lack of such soft secondary components in SSS observations of other Seyferts (Holt 1980) argues against a reconciliation which is so completely *ad hoc*.

A more restrictive class of possible explanations for the apparent excess has its origin in some characteristic of the absorber which allows the lower energy X-rays to emerge with significantly less attenuation than expected. If statistical consistency can be achieved with such a "leaky" absorber approximation having a single underlying power-law input spectrum, we would appear to have a more natural reconciliation of the data than we could obtain with the postulation of a second emission component. The remainder of this section will be devoted to the extraction of quantitative limits on the parameters of such a model.

Deviations from the expectation from a uniform, cold absorber can arise from exceptions to either the uniformity or the neutrality assumptions, or from abundance anomalies. Pursuing the neutrality exception, for example, it is conceivable that the absorption may arise primarily from the relatively hot medium which supports the cold clouds in pressure equilibrium, rather than from the cold clouds themselves, if the total column density it presents to the X-rays is much higher. This interpretation is suggested by the apparent absorption feature just below 2 keV, which can be reconciled with cold silicon if its abundance (relative to oxygen) is more than an order of magnitude larger than its solar value, or if a large fraction of the $Z < 10$ material in the absorber is completely ionized. Collisional equilibrium and photoionization models with underlying X-ray spectra similar to that observed from NGC 4151 can completely photoionize oxygen, but the colocated $Z \geq 14$ elements will be in highly ionized states (Hatchett, Buff and McCray 1976). Since we cannot simultaneously satisfy the conditions that the oxygen is photoionized and the $Z \geq 14$ material is relatively cold without the postulation of an additional soft-spectrum ionizing component below 1 keV, such a scenario is no more constrained than is the attribution of the low energy excess to a secondary component directly. A self-consistent picture would require the $Z \geq 14$ elements to exhibit hydrogen- and helium-like edges rather than those characteristic of neutral material, so that HEAO-1 A-2 measurements of iron K-absorption provide an unambiguous test because there are no potentially abundant contaminants to confuse neutral absorption at 7.1 keV or the highly ionized edges (8.8 - 9.2 keV). HEAO-1 A-2 data taken on 1978 June 16 and June 18 locate the iron absorption edge at $7.1^{+.3}_{-.5}$ keV, so that the absorber must be relatively cold, and the "excess" low energy photons cannot be reconciled with a highly photoionized column if the iron is colocated with the lower-Z constituents.

The remaining possibility which does not invoke a secondary emission component is that the absorber has spatial non-uniformity which allows some fraction of a single underlying X-ray continuum to emerge with significantly less attenuation than does the large fraction of the emission. Before attempting to fit the SSS data in accordance with such a model, we note that HEAO-1 A-2 (and other data at higher energies) may provide useful a priori constraints to the SSS analysis if we demand consistency in all the data. Barr et al. (1977) have reported that the underlying spectral shape of the NGC 4151 emission does not appear to change with observation epoch, but that the effective columnar absorption may vary by as much as a factor of 5 (quite apart from any possible changes in the underlying luminosity). Our OSO-8 (Mushotzky, Holt and Serlemitsos 1978) and HEAO-1 A-2 data are consistent with this supposition, but with column density variations up to a factor of 2, so that we have constrained the spectral shape to our best-determined value from HEAO-1 A-2 of $\alpha = 0.55^{+.05}_{-.08}$ (90% confidence errors, as are all errors quoted here unless otherwise indicated). This new determination was made by simultaneously fitting for the spectral index, the solar-abundance column density, any additional iron K-absorption edge optical depth and the iron K-fluorescence intensity; the latter three parameters were found to be $N_H = 5.8^{+.3}_{-1.7} \times 10^{22}$ H-atoms cm^{-2}, $\Delta\tau = .29 \pm .08$ and $W = 223 \pm 107$ eV equivalent continuum width (see Figure 2). The optical depth in the edge corresponds to a factor 3.6 ± 1.0 in the abundance of iron relative to solar (Fireman 1976); Barr et al. (1977) previously reported a similar overabundance from Ariel 5 at lower statistical significance (2.1 ± 1.4) without fitting simultaneously for reemission via fluorescence, using a best-fit spectral index $\alpha = 0.53$ and a column density of 1.6×10^{23} H-atoms cm^{-2}. The total column of iron inferred from the edge is independent of any assumed abundance distribution, and is found to be approximately 10^{19} atoms cm^{-2} from both Ariel 5 and HEAO-1 A-2.

We then fit the SSS data in stages, as follows. Using the data above 2 keV only, we fit simultaneously for the best spectral slope and universal-abundance column density. As the 1σ errors in the best-fit slope included the $\alpha = 0.55$ determined from HEAO-1 A-2, we then fixed the spectral index at this value in further analysis. Although visual inspection of the data are suggestive of overabundances in sulphur and argon (absorption edges at 2.5 keV and 3.2 keV), the simple model of a power law of index $\alpha = 0.55$ with a solar-abundance absorber at a best-fit column density of 4.9×10^{22} H-atoms cm^{-2} yielded a χ^2 value of 16.5 for 21 degrees of freedom (DOF), so that the sulphur and argon abundances are not determinable with any statistical significance. This fit is displayed in Figure 1a.

The silicon abundance can be measured with considerable significance, but in a model-dependent manner. Fitting the data above 1.5 keV with the same simple model, we obtain $\chi^2 = 40.9$ for 31 DOF. Inserting another parameter for the optical depth at the silicon absorption edge, we obtain $\chi^2 = 23.0$ for 30 DOF (i.e. a decrease of 3.7 would be significant at the 90% confidence level, compared with the 17.9 observed). This parameterization forces an overabundance of silicon by a factor of four, as the column density responsible for absorption below the silicon edge must be reduced to 3.9×10^{22} (displayed in Figure 1b). Alternatively, we can achieve a fit which is formally as good without significant silicon overabundance by allowing some fraction of the incident spectrum to emerge completely unabsorbed. The best-fit values for this scenario are an absorbing column of 6×10^{22} H-atoms cm^{-2} with an uncovered fraction of 6%.

Virtually the same parameters are obtained if we fit the data all the way down to 500 eV with the latter approximation: the deduced parameters are $(6.1 \pm .6) \times 10^{22}$ H-atoms cm^{-2} and an uncovered fraction of $.057 \pm .007$. Although formally acceptable, the fit (displayed in Fig. 1c) still exhibits excess structure near the K-edges of silicon, sulphur and argon, and more significant deviations near 1 keV. The latter may reflect the idealization of the modelling (i.e. the "holes" in the model absorber have sharp boundaries, rather than the partially ionized fuzzy boundaries we might expect in a more realistic picture of the situation), but the statistics do not allow (nor do they unambiguously require) further refinement. Although the same is true for the absorption edges, their coincidence in energy with those expected from silicon, sulphur and argon suggest that we should attempt to place limits on their possible overabundance. Utilizing the data above 1.5 keV only (which should be more sensitive to these values than should the total spectrum), we varied the three together, preserving solar proportions to each other, while allowing the column density, uncovered fraction and overall normalization to be free parameters. This procedure resulted in a 90% confidence upper limit of 5 times overabundance of the three relative to oxygen, with an uncovered fraction of 21% at this extreme; this may not be unreasonable in view of the fact that the sharp idealization of the "hole" boundaries should underestimate the uncovered fraction when the spectrum is fit below energies at which the optical depth of the covered portion exceeds unity.

III. DISCUSSION

The simplest reconciliation of the SSS data is with a single underlying power-law X-ray spectrum viewed through an absorber with column density corresponding to approximately 6 x 10^{22} H-atoms cm^{-2}. The data favor two specific perturbations of this simple picture: overabundance by a factor of two in the $Z \geq 14$ elements relative to solar abundances referenced to oxygen, and differential non-uniformity in the absorber such that the source is unobscured at about the 10% level (the maximum uncertainties in both the $Z \geq 14$ overabundance and the uncovered fraction are approximately a factor of two). We remark that while both of these anomalies are qualitatively suggestive of the absorption arising in dust (rather than gas), we could not expect positive detection below $\sim$ 800 eV even if all the $Z > 2$ material were locked in dust grains. Furthermore, NGC 4151 does not exhibit measurable silicate optical depth at 10 μm (Lebofsky and Rieke 1979), so that dust is an unlikely explanation for what we measure.

The HEAO-1 A-2 iron absorption and fluorescence measurements provide an independent means of probing the geometry of the X-ray absorber, which is independent of the iron abundance. The fluorescence yield of iron is 0.34 (Bambynek et al. 1972), so that approximately one-third of the photons absorbed above the iron K-edge at 7.1 keV will be accompanied by subsequent K-fluorescence at 6.4 keV. If the absorber is not spherically symmetric we expect to measure a fluorescence/edge ratio which differs from the fluorescence yield (in particular, if the column density along our line of sight is higher than average we expect a smaller ratio); note, however, that agreement with the fluorescence yield is not equatable with 4π covering factor, as a spherically symmetric lace-like absorber with small covering factor will also yield agreement with the fluorescence yield. The relevant ratio to compare with the fluorescence yield, i.e. the observed 6.4 keV line flux to the "missing" photon flux at energies above the 7.1 keV absorption edge, is .37 ± .13 (one sigma), so that the data are consistent with a spherically symmetric covering factor; they cannot rule out, however, a cylindrical BLR with height-to-diameter in the approximate ratio 2:5 (viewed close to face-on for NGC 4151), which Osterbrock (1979) has suggested for a generalized active-galactic-nucleus geometry. Since the average X-ray-absorbing column in NGC 4151 is more than sufficient to guarantee large optical depth in the Lyman continuum, Balmer recombination can be used (e.g. Bergeron 1979) to estimate a UV covering factor close to unity (Boksenberg et al. 1978). The attribution of the Balmer emission to straightforward recombination greatly oversimplifies the physical situation (e.g. Kwan and Krolik 1979), but model-dependent analysis should not substantially alter this conclusion. All the observational constraints of which we are aware, therefore, suggest that the X-ray absorption arises in the same clouds or filaments responsible for the broad lines, which may be approximately spherically symmetric about the X-ray source with a covering factor of about 0.9.

The geometry of the material in the BLR is not well-understood (see Davidson and Netzer 1979 for an excellent review of current models for active galactic nuclei). A variety of arguments lead to relatively stationary order-of-magnitude estimates for the density (10^9 cm^{-3}) and temperature (10^4 K) of the condensed BLR material, but the geometrical configuration is much less certain. Blumenthal and Mathews (1979) have recently investigated some aspects of this problem in some detail. For simplicity, we shall assume that the material exists in clouds with a typical dimension of a few times 10^{13} cm, which may be small compared with the central X-ray source size; estimates of the latter based upon the shortest timescales for variability suggest $\leq 10^{15}$ cm (Mushotzky, Holt and Serlemitsos 1978). It is conceivable, therefore, that we typically observe NGC 4151 through an average thickness of about 2 clouds, with about 100 clouds over the entire central source along our line of sight (i.e. $> 10^5$ such clouds in the BLR). Interestingly, Poisson-randomizing these clouds yields two rather satisfying numerical coincidences. If the mean number of clouds expected over a few-percent "pixel" of the source projection corresponding to the typical cloud size is 2, the probability for having no clouds over the pixel is $\underline{e^{-2}}$ (i.e. consistent with the approximate 0.1 uncovered fraction implied by the X-ray data). This "clumping" also magnifies apparent column density variations with observation epoch above that expected from just the statistical variations in the total number of clouds in the line-of-sight, so that it is not necessary to decrease the expectation value for this number to achieve apparent column density variations with observation epoch which are in excess of a factor of two.

Furthermore, such a geometry may naturally explain why more luminous Seyferts do not exhibit the severe X-ray attenuation of NGC 4151. It is generally thought that the ionization parameter, proportional to L_x/nr^2 (where r is the mean distance to the clouds), is roughly the same for the BLR of most Seyferts and quasars. If the total number of BLR clouds does not scale as fast as linearly with luminosity L_x, the covering factor will decrease with L_x. Most of the X-ray emitting Seyferts which have been spectrally studied are at least an order of magnitude more luminous at 3 keV than is NGC 4151. For these sources, therefore, we might expect to see a very slight flattening of the spectrum at the lowest X-ray energies, but no clear indication of absorption in the continuum shape. Naively, we would also expect the equivalent widths of the broad lines to decrease with luminosity, in accordance with a decreasing covering factor, but the situation is complicated here by the fuzziness of the cloud edges since the large fraction of at least the recombination portion of the broad line emission originates in a thickness which is small compared with the typical cloud dimension we have chosen. Baldwin (1977) has reported such a tentative anticorrelation between equivalent width and luminosity for quasars, and Carswell and Ferland (1980) have recently noted that the absorption properties of quasar BLRs may be reconciled with clouds which have small covering factor and dimensions small compared to the central continuum sources, but the generality of our simplified picutre cannot be adequately tested without modelling in much more detail.

We suggest, therefore, that the anomalously high (and variable) X-ray absorption of NGC 4151 may, to lowest order, be simply attributable to its anomalously low luminosity. This conjecture may be testable with the spectra of a sample of other X-ray-emitting Seyfert galaxies, particularly those which have relatively low luminosity. The suggested absorption variation is independent of variation in the central source dimension with luminosity, as the X-ray-absorbing covering factor, resulting from the superposition of absorbers having sizes smaller than that of the source, does not change if the source size alone changes. The consistency we obtain from both the SSS and HEAO-1 A-2 data with a cold, spherically symmetric absorber of covering factor approximately 0.9, which we identify with the BLR clouds, is not sufficient to insure the uniqueness of our explanation for the X-ray spectrum of NGC 4151, or its extension to brighter Seyferts. It is important to appreciate, however, that the identification of non-uniformity in the candidate BLR clouds could not have been accomplished with the present instrumentation if the average column density were either much larger or smaller than in NGC 4151.

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FIGURE CAPTIONS

Figure 1 - Raw (background-subtracted) pulse height spectrum from SSS exposure to NGC 4151 fitted with trail spectra, each of which have the same power-law index $\alpha = 0.55$ with a best-fit normalization of $.024 \pm .002$ $cm^{-2}s^{-1}keV^{-1}$. a) Data above 2 keV fit with a solar abundance column density of $N_H = 4.9 \times 10^{22}$ H-atoms cm^{-2}. b) Data above 1.5 keV fit with a uniform column density of $N_H = 3.9 \times 10^{22}$ H-atoms cm^{-2} with an overabundance of silicon (relative to solar oxygen) of a factor of 4. c) Data above 500 eV fit with a solar abundance column density of $N_H = 6.1 \times 10^{22}$ H-atoms cm^{-2} over .94 of the source.

Figure 2 - Ratio of raw (background-subtracted) HEAO-1 A-2 pulse-height data to those expected from a power law with index $\alpha = 0.55$ (horizontal dashed trace). Also indicated is the profile expected from absorption by a column density of $N_H = 5.8 \times 10^{22}$ H-atoms cm^{-2} with iron abundance of 3.6 times solar (solid trace). The power law normalization for this exposure is $.054 \pm .004$ $cm^{-2}s^{-1}keV^{-1}$, approximately twice that for the SSS exposure a year later.

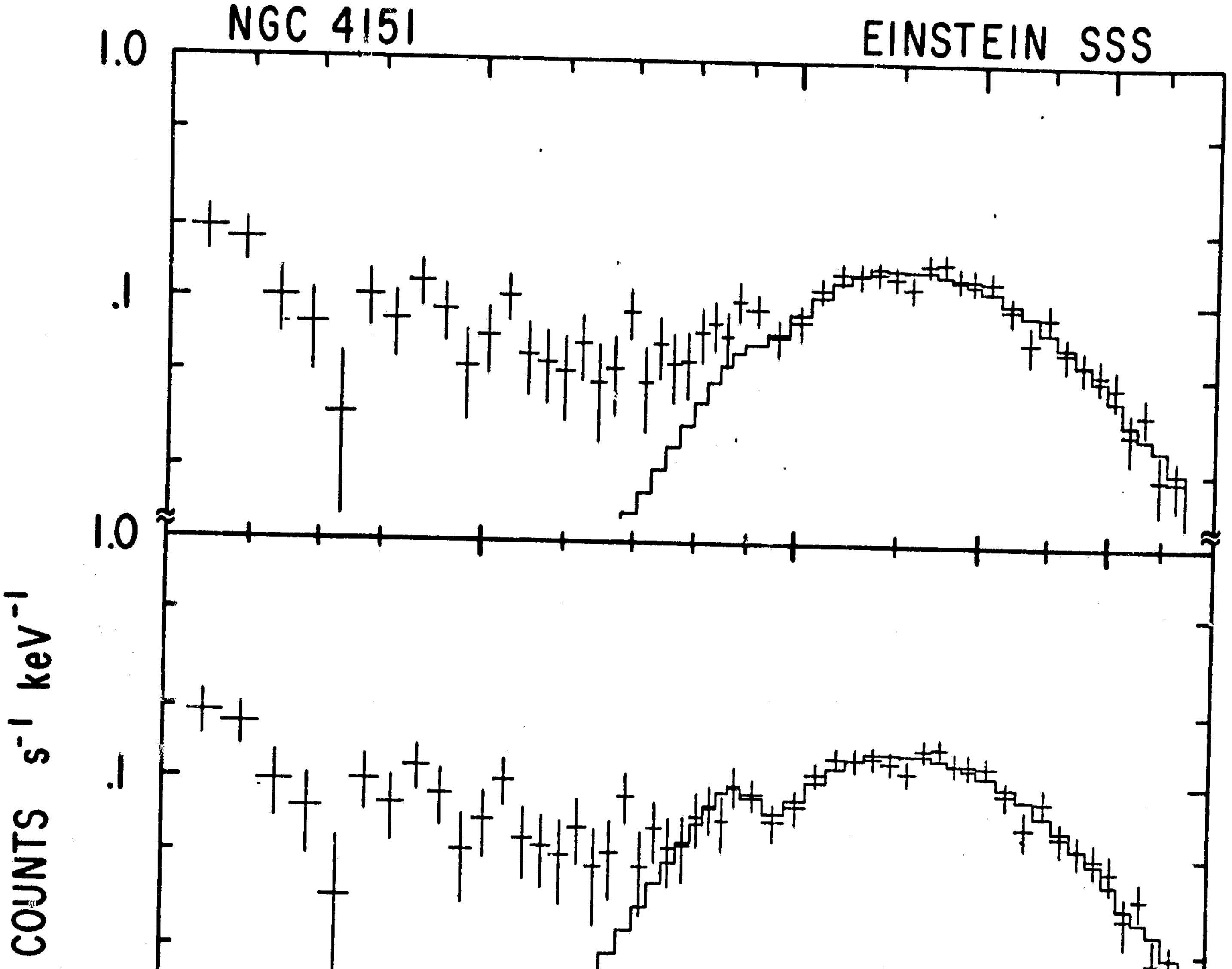
NGC 4151
EINSTEIN SSS
COUNTS s^{-1} keV^{-1}
1.0
.1
1.0
.1
1.0
.1
.01
.6
.8
1
1.2
1.6
2
2.5
3
4
ENERGY (keV)

Figure 1

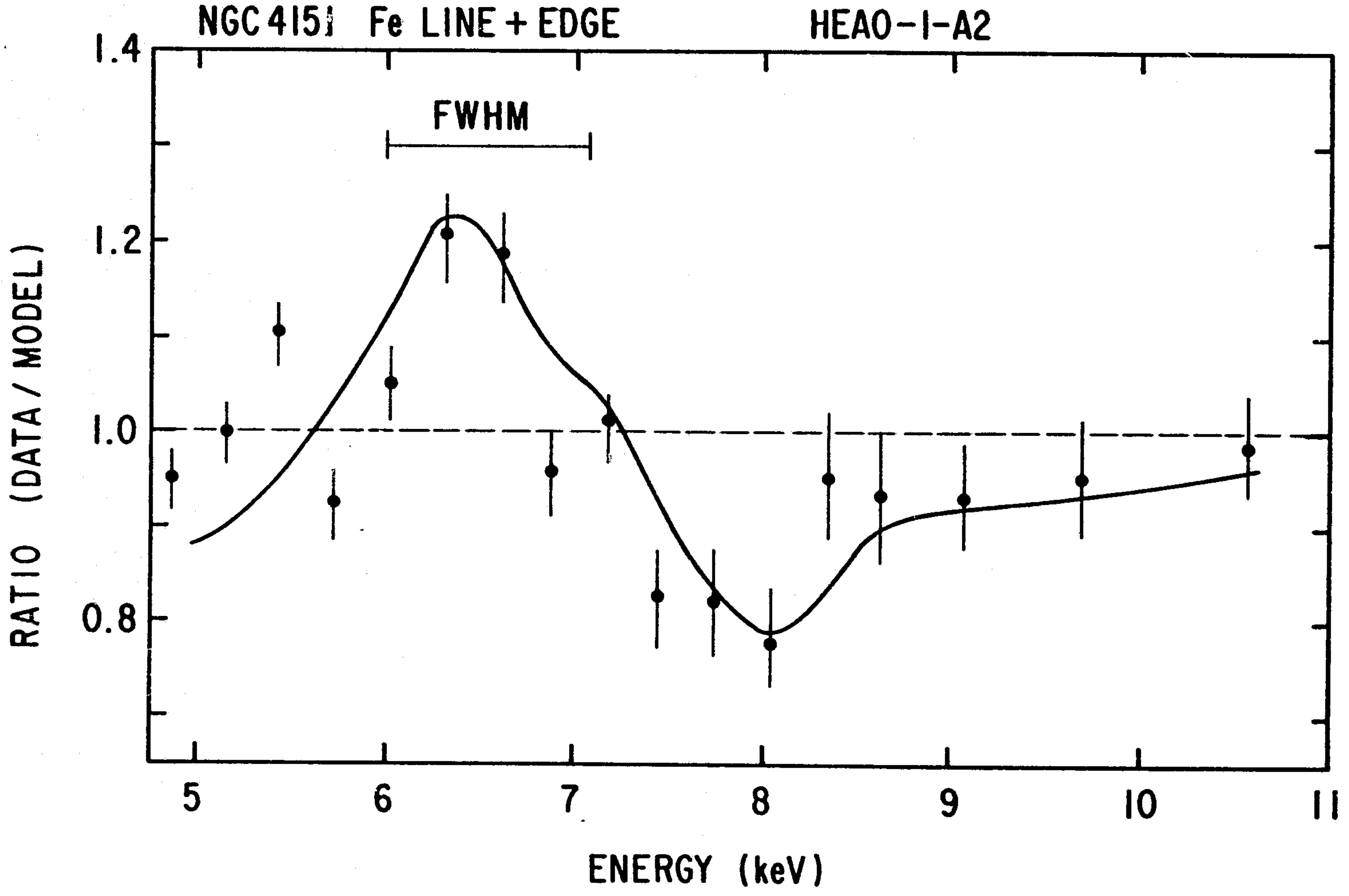
NGC 4151 Fe LINE + EDGE
HEAO-1-A2
FWHM
RATIO (DATA / MODEL)
1.4
1.2
1.0
0.8
ENERGY (keV)
5
6
7
8
9
10
11

Figure 2

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16. Abstract

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