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THE X-RAY SPECTRUM OF 3C 273

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ABSTRACT

We report an X-ray spectral measurement of the quasar 3C 273 with the HEAO-A2+ experiment in June/July 1978. The best power law fit to the photon flux over the range 2-60 keV gives a slope of 1.41 ± 0.02. However, structure is observed, indicating a slope of 1.52 between 2 keV and 9 keV and a slight flattening between 9 keV and 30 keV. Observations with the same experiment in December 1977 and OSO-8 in June 1976 allow us to confirm reports of 40% intensity variability on the time scale of months, although within limits provided by the poorer statistical quality of the additional data we do not discern any spectral change. Absorption from the source is found to be low, with the 1978 data yielding a 90% confidence upper limit to the hydrogen column density of 4.5 10^{21} atoms cm^{-2}.

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\+ The HEAO-A2 experiment is a collaborative effort led by E. Boldt of GSFC and G. Garmire of CIT with collaborators at GSFC, CIT, JPL and UCB.

Subject headings: quasars - X-rays: sources - X-rays: spectra

I. INTRODUCTION

X-rays of energy between 1 keV and 10 keV were first detected from the direction of 3C 273 by Bowyer et al. (1970) with a rocket borne detector, and confirmation with satellite experiments shortly followed (Kellogg et al. (1971); Sanford and Ives (1976); and Cooke et al. (1978)). Firm identification of the X-ray source with the quasar has now been furnished by the scanning modulation collimator on HEAO-1 (Bradt et al. 1979).

Recently, Swanenburg et al. (1978) reported detection of 50-500 MeV radiation which they attributed to the quasar, although the large error box for the γ-ray source necessarily leads to some ambiguity. If the γ-ray identification is correct, observations of the quasar range over 15 orders of magnitude in energy.

In this paper, the spectrum in the energy range 2-60 keV, determined with high statistics from point maneuvers of HEAO-1 in June/July 1978, is presented and contrasted with HEAO-1 scanning data from the source taken six months earlier, and an OSO-8 observation in June 1976.

II. OBSERVATIONS

The Goddard Space Flight Center detectors on the HEAO-1 spacecraft are described in detail by Rothschild et al. (1978), and those on OSO-8 by Serlemitsos et al. (1976).

3C 273 was observed by HEAO-A2 on June 30 and July 5, 1978 in maneuvers of 6 hours and 10 hours respectively in which the source and a nearby source-free region of sky were alternately viewed for periods of about 15 minutes. This type of maneuver allows for reliable background subtraction. The net source spectrum from these combined observations, for the xenon detector which has $3^{\circ} \times 3^{\circ}$ and $3^{\circ} \times 1\frac{1}{2}^{\circ}$ collimation, is shown in Figure 1. The top portion of the figure shows the p.h.a. channel counts, together with those predicted for a single power law model with best fit parameters. The lower portion shows the implied incident spectrum after folding this featureless spectrum back through the detector response. The parameters for the functional form $dN/dE = AE^{-\Gamma}$, together with one sigma errors, are given in Table 1.

The best power law fit, that of $\Gamma = 1.41$ and zero absorption, has a reduced χ^2 of 1.4. Figure 1 shows the 70% and 99% error boundaries on the slope and hydrogen column density, following the statistical procedure of Margon et al. (1975). Although this fit is just acceptable at the 5% confidence level, it is improved by applying a spectral form with added structure. Indeed, the possibility of obtaining an improved fit is apparent from mere inspection of the data. Between 2 keV and 9 keV a good fit is obtained for a single power law with $\Gamma = 1.51 \pm 0.06$ (1 sigma error), and there is evidence for a slight flattening between 9 keV and 30 keV and a probable steepening above 30 keV. The data from the argon detector (2-20 keV) are consistent with this structure since they are fit well to a power law slightly softer than that of the 2-60 keV fit. The best parameters, along with one sigma errors, are given in Table 1, and Figure 1 shows 70% and 99% error limits to the slope and absorption.

Low energy absorption is found to be negligible, yielding a 90% confidence upper limit for the hydrogen column density, N_H, of $4.5\ 10^{21}$

atoms cm^{-2}. Iron line emission is not evident; the 90% confidence upper limit to the equivalent width of a fluorescence line at the appropriate redshifted energy of 5.53 keV ($z = 0.158$ for 3C 273) is 33 eV. No significant difference in count rate or spectral shape is found between the June 30 and July 5 observations. Thermal models yield worse χ^2, giving $kT > 60$ keV for the 2-60 keV xenon detector data and $kT \approx 33$ keV for the lower energy component, 2-20 keV, as measured by the argon detector. However, an acceptable thermal fit, with $kT > 90$ keV, is obtained for the xenon detector data above $\sim$ 6 keV.

Six months prior to the point maneuvers, the A2 experiment viewed the region containing 3C 273 while HEAO-1 was in its nominal scanning mode of operation. Using the method described by Marshall et al. (1979), a fit was obtained for a source which maintained the same daily intensity over the five day period it remained in view. The 95% confidence error box has an area of 0.15 square degrees which includes the quasar position. The spectrum, statistically much poorer than for the point observations, was obtained by subtracting counts recorded while the detector viewed nearby regions from those while the source was in the field of view. The spectral parameters for a power law fit, together with the one sigma errors which are now much larger than for the point mode data, are given in Table 1.

A third observation was made in June 1976 with the A detector on OSO 8. The exposure was such as to yield spectral parameter statistics intermediate between the HEAO 1 point and scanning observations. The data, fitted to the best power law model, are shown in Figure 2 and the parameters for the fit in Table 1. The source intensity is in good agreement with that found from HEAO 1 in point mode. Within two sigma errors on the parameters, the spectrum agrees with the HEAO 1 data. There is agreement with the other observations in the requirement of a low value for the absorption hydrogen column density.

III. DISCUSSION

a. Spectra

We have measured the 2-60 keV X-ray spectrum of 3C 273 with good statistics and find that, although the best overall power law fit is somewhat flatter than the best slopes from the two other observations we report, there is no formal disagreement. Previously reported spectral indices (Giacconi 1973; Margon, Bowyer and Lampton 1972; Margon et al. 1975; and Sanford 1977) have large quoted error limits and also are not inconsistent with this more precise spectrum.

The overall best fit spectrum is comparable with that found for several of the X-ray emitting Seyfert galaxies (see Mushotzky et al. 1979 and references therein), supporting similar origins for the X-ray emission.

It has been suggested that quasars can make up the diffuse X-ray background if a large amount of evolution is assumed (see e.g. Silk 1970). It is therefore tempting to consider 3C 273 as an "average" quasar and compare its spectrum with that of the diffuse background, which itself is now known with very good statistics. The most recent measurement has shown the background between 3 and 60 keV to be well represented by a thermal bremsstrahlung form with a temperature of 45 keV (Boldt 1978), and since the "average" quasar should be at $z \gtrsim 1$ we would expect it to be fit by the same functional form with $kT \gtrsim 90$ keV. Indeed an acceptable fit for 3C 273 is obtained for such a temperature, using data above the appropriate redshifted energy of 6 keV. The flux below 6 keV would be contributing to the low energy X-ray background which is less well known at the present time.

A power law extrapolation from the intensity at X-ray energies to that at $\sim$ 100 MeV requires a photon flux index steeper than the index 1.41 found from the 2-60 keV data presented here, and hence a spectral break or gradual steepening must exist. This is pointed out by Primini et al. (1979) who suggest that their index of $\sim$ 1.7 for the energy range 13-120 keV may indicate a break near 20 keV. Support for this comes from the steepening at $\sim$ 30 keV weakly evident in our data (see Figure 1).

The absorption of X-rays from 3C 273 was found to be negligible, yielding a 90% confidence upper limit to the hydrogen column density of 4.5 10^{21} atom cm^{-2}. An upper limit of 2 10^{22} atom cm^{-2} was simultaneously determined by Bradt et al. (1979) from the A3 detectors on HEAO 1. This low value is in agreement with that from the rocket data of Margon, Bowyer and Lampton (1972) and Margon et al. (1975). The inconsistency with the higher UHURU values reported by

Giacconi (1973) and Kellogg (1973) may be evidence for variable absorption, but it is contrary to those authors' argument that high absorption is a characteristic by which non-cluster compact extragalactic sources can be distinguished. Indeed, it would now appear that low X-ray column density is often a feature of compact extragalactic sources (c.f. Mushotzky et al. 1979).

The absorption limit can be interpreted as indication either for a low gas column density or an additional source of low energy X-rays. If the former, the additional constraint of optical line measurements can limit allowed source geometry. Shields and Mushotzky (1979) have considered a sphere of filaments ionized by a central source and have shown that low X-ray absorption can be consistent with the presence of strong optical lines. Equation 4 of their paper expresses the hydrogen column density in terms of a dimension less parameter, U_1, a function of ionizing photon flux and electron density, which can be determined empirically from observed line ratios. For a standard quasar model, Davidson (1977) gives a value for U_1 of 7×10^{-3}, from the observed ratio C_{III}/C_{IV}. Shields and Mushotzky would predict a value of N_H, 2×10^{21} atoms cm^{-2}, consistent with the upper limit from the X-ray measurements. This may be reduced for a non-spherical geometry in which the number of filaments between observer and X-ray source are fewer.

b. Iron Line Emission

It is not unreasonable to consider further consequences of a model in which gas filaments are distributed spherically around a central ionizing source of radiation, since consistency is achieved with optical emission line strengths and the presently reported hydrogen column density upper limit. From such a model, it is also possible to derive the expected equivalent width of the iron fluorescence line in terms of the X-ray flux density spectral index, Γ, the hydrogen column density, N_H, and the relative iron to hydrogen abundance, f. Including the appropriate redshift for 3C 273 of 0.158, and taking $\Gamma = 1.41$, the equivalent width of the iron emission line at 5.53 keV is predicted to be $\sim f\ N_H\ 1.9\ 10^{-17}$ eV. Using solar abundances, $f = 2.6\ 10^{-5}$, the upper limit of N_H of $4.5\ 10^{21}$ atoms cm^{-2} gives an equivalent width < 2.2 eV, consistent with our measured upper limit of 33 eV. Although in this instance the iron fluorescence measurement is only a weak consistency check, we have demonstrated that with present statistics we have ability to measure a line with as low an equivalent width as 33 eV, and, in a case in which the average N_H is in excess of $\sim 7\ 10^{22}$ atoms cm^{-2} for a typical quasar model, the fluorescence line could be used as a tool for investigating allowed geometries for the gas distribution in a source.

c. Time Variability

The difference of about 40% in the flux values measured by HEAO-1 in December 1977 and June/July 1978 confirms intensity variability on the time scale of months, as reported by the Ariel 5 experimenters (Pounds 1977). The intensity we find for the December 1977 observation is inconsistent with the upper limit given by the modulation collimator experiment of Bradt et al. (1979) for a null detection of the source at this time. This discrepancy, between different experiments on the same spacecraft, is somewhat of a mystery, especially since the June/July 1978 intensities from the two instruments are in good agreement. We have no sensible explanation for the inconsistency.

No intensity difference was found between our observations of June 30 and July 5, and, to a 90% confidence level, no variability was found on time scales from a few hours to a day for the December scanning data collected over the $\sim$ 5 days for which the source was in the detector field of view.

Intensity variability at optical and radio wavelengths has been reported, but a search for correlated changes between these and X-ray fluxes, by Bradt et al. (1979), has proved somewhat inconclusive due to many gaps in coverage at all the wavelengths. An observed correlation between X-ray and either optical or radio flux would aid the choice of a preferred emission model.

d. Emission models

Several theories have been proposed to explain the emission from 3C 273, but, as yet, no single model explains all the flux between radio and γ-ray energies. Colgate, Colvin and Petschek (1975) have proposed that the radio and optical radiation are produced by upscattering of photons by oscillations in a turbulent plasma, with the X-ray radiation provided by Compton scattering. Swanenburg (1978) suggests that radiation beamed from the nucleus in the form of $\gtrsim 10^{14}$ eV γ-rays may pair produce, providing synchrotron radiation extending to the X-ray and γ-ray regimes.

A strong candidate is the synchrotron-self-Compton model (SSC), about which there has been much discussion (see references given in

Katz (1976)). Jones (1979) shows such theory to be a strong candidate because, based on prior X-ray measurements, second order scattering can give γ-rays of roughly the observed intensity. A fit to the shape and intensity of the radio flux, along with the X-ray spectral shape, will predict intensities for the X-rays and γ-rays, and the calculations show predicted fluxes to approximately agree with observations. Assuming that the radio and X-ray spectral shapes do not vary with time, the spectrum reported here provides the input for a more detailed calculation. The SSC model predicts that temporal variations between X-ray intensity, radio flux above $\sim$ 20 GHz, and the 100 MeV γ-ray intensity should be correlated, but insufficient data are at present available with which this can be tested in detail. However, temporal variations at radio and X-ray energies each imply a source size and these may be checked for consistency. Jones, O'Dell and Stein (1974) define a convenient temporal parameter, $t_\nu \equiv |d \ln F_\nu/dt|^{-1}$, for changes in flux f_ν, where for a spherical source expanding at non-relativistic velocity, βc, the radius is given by $r = 3\,\beta c t_\nu$. The 40% change in X-ray intensity over a 6 month period reported here implies $t_x \sim 1.2$ years, and this is in reasonable agreement with values for t_r similarly determined from 90 G Hz radio measurements of Hobbs and Dent (1977). The angular radius of the high frequency radio component (3C 273D) has been found from VLBI measurements to be $\lesssim 0.0002$ arc sec (Kellermann et al. (1971)), implying a radius of $\lesssim$ 2.2 light years. Applying the SSC model we find consistency with non-relativistic spherical expansion for this component with $\beta < 0.6$. The optical emission is not addressed in this model and must be accounted for by a separate process.

Katz (1976) has proposed a model in which non-relativistic electrons Comptonize soft photons, accounting for the optical radiation and X-rays. In this case, therefore, temporal variations between the optical and X-ray fluxes should be correlated. The γ-ray flux cannot be produced since the Comptonized photons must have an energy less than the temperature of the non-relativistic electron gas. However, there remains the possibility that the γ-ray emission is not associated with the quasar, or that it is from the quasar but that another mechanism is responsible for the flux. To account for photons up to $\sim$ 120 keV (3C 273 has been observed up to this energy by Primini et al. (1979)) with the observed spectrum, requires an electron gas of temperature $\sim$100 keV. The size of the optical emitting region is severely limited if the $\sim$ 10 day variations reported by Smith and Hoffleit (1963) are to be accommodated. An electron density of $> 10^9$ cm^{-3} is required, together with a radius for a spherical optical and X-ray emitting region $<10^{16}$ cm, which is smaller than that predicted for the radio and X-ray emitting region by the SSC model. For the Katz model the X-ray spectral shape and intensity would be expected to vary if the thermal energy of the Compton scattering electrons changes with time, or intensity alone will vary with changes in the soft photon source intensity. Present data do not allow us to distinguish between these.

IV. CONCLUSIONS

The main conclusions can be summarised as follows. Firstly, the photon flux spectral shape between 2 keV and 60 keV, as seen in June/ July 1978, shows some structure which deviates from the best overall simple form, that of a power law of slope 1.41. Other observations, both of other authors and those presented here, have statistics which are unfortunately too poor for spectral variability to be discerned. Structure in the present spectrum implies slight flattening between 9 keV and 30 keV. Secondly, variability of intensity on the time scale of months and to the order of about 40% has been confirmed. Thirdly, the source has been shown to exhibit, at least during the June/July 1978 observations, low absorption; the 90% confidence upper limit to the hydrogen column density being 4.5 10^{21} atoms cm^{-2}.

We wish to thank Drs. Hale Bradt, Bruce Margon, Frank Marshall and Jean Swank for helpful comments.

TABLE 1

SPECTRAL PARAMETERS FOR THE FORM $dN/dE = AE^{-\Gamma}\ cm^{-2}s^{-1}\ keV^{-1}$

DATE	OBSERVATION	A	Γ	N_H atoms cm^{-2}	ENERGY FLUX (2-10 keV) erg $cm^{-2}s^{-1}$ x 10^{11}
July 30 and	HEAO-A2				
July 5, 1978	xenon detector (2-60 keV)	0.016	$1.41 \pm 0.02^{*}$ 1.51 ± 0.06 (2-9 keV)	$< 2.5 \times 10^{21}$	10.6 ± 0.6
	argon detector (2-20 keV)	0.022	$1.55^{+0.05}_{-0.03}$	$< 2.2 \times 10^{21}$	11.1 ± 0.8
Dec 25-30	HEAO-A2				
1977	xenon detector	0.018	$1.73^{+1.8}_{-0.53}$	$< 1.4 \times 10^{23}$	7.4 ± 1.2
June 20-26	OSO-8				
1976	A detector	0.027	1.65 ± 0.17	$4^{+7}_{-4} \times 10^{21}$	$11.6^{+0.6}_{-1.1}$

[*] Errors, where given, are one sigma.

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FIGURE CAPTIONS

Figure 1 - The HEAO-A2 xenon detector spectrum from the June 30 and July 5, 1978 observations. The top portion shows observed counts along with the model fit (solid line), and the lower portion shows the implied incident spectrum after folding through the detector response. A power law over the whole energy range has been used and gives an acceptable fit, although additional structure can be discerned and is supported by the fact that the argon detector, sensitive 2-20 keV, is fit by a steeper power law. 70% and 99% error contours for spectral slope and hydrogen column density for both detectors are also given.

Figure 2 - The OSO 8 A detector spectrum from June 1976. The top portion shows observed counts along with the best power law model fit (solid line), and the lower portion shows the implied incident spectrum after folding through the detector response. 70% and 99% statistical error contours for spectral slope and hydrogen column density are also given.

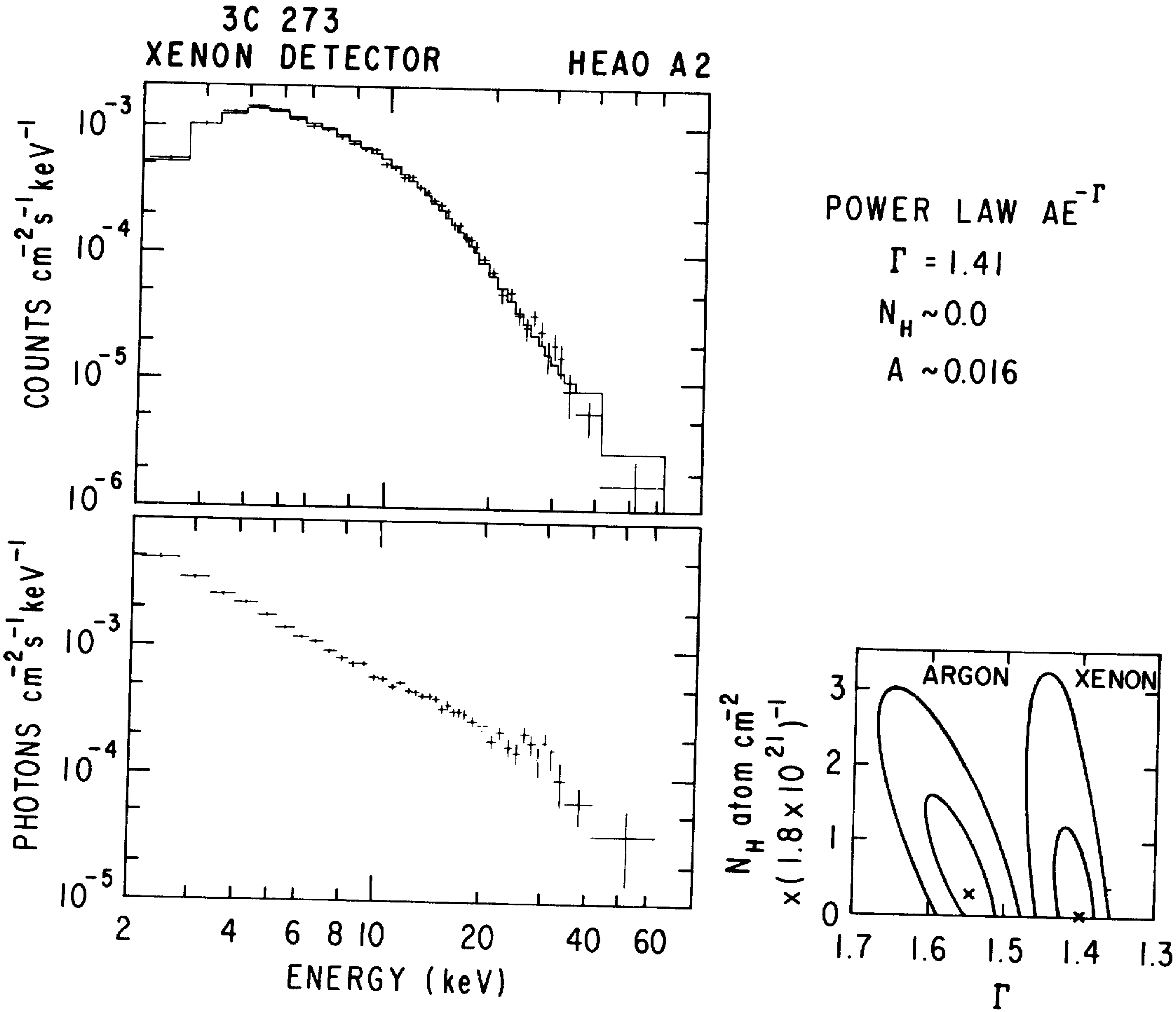
3C 273
XENON DETECTOR
HEAO A2
COUNTS $cm^{-2}s^{-1}keV^{-1}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
PHOTONS $cm^{-2}s^{-1}keV^{-1}$
10^{-3}
10^{-4}
10^{-5}
2
4
6
8
10
20
40
60
ENERGY (keV)
POWER LAW $AE^{-\Gamma}$
$\Gamma = 1.41$
$N_H \sim 0.0$
$A \sim 0.016$
ARGON
XENON
N_H atom cm^{-2}
$\times(1.8\times10^{21})^{-1}$
0
1
2
3
1.7
1.6
1.5
1.4
1.3
Γ

Figure 1

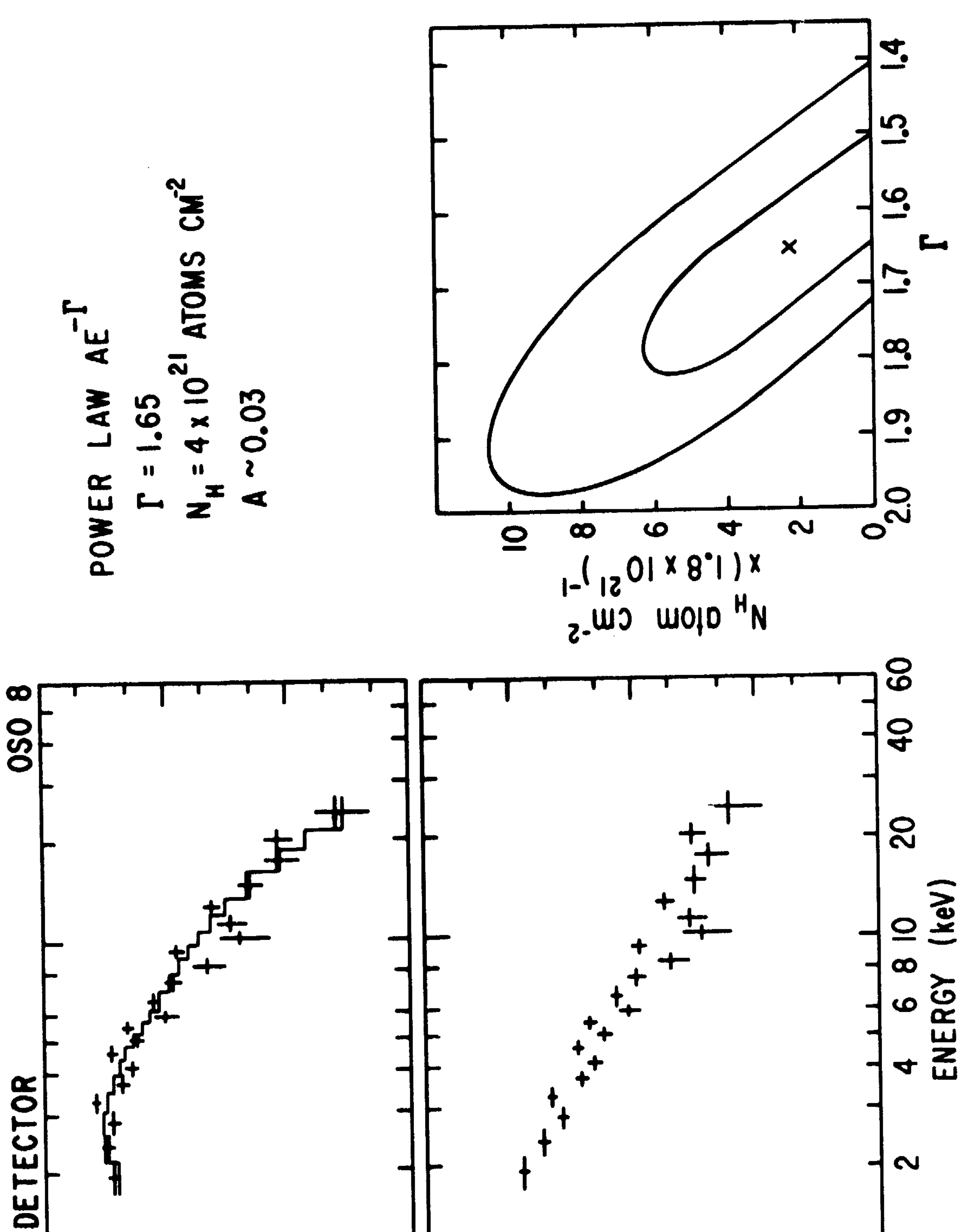
3C 273
'A' DETECTOR
OSO 8
COUNTS cm^{-2} s^{-1} keV^{-1}
PHOTONS cm^{-2} s^{-1} keV^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2
4
6
8
10
20
40
60
ENERGY (keV)
POWER LAW AE$^{-\Gamma}$
Γ = 1.65
$N_H = 4 \times 10^{21}$ ATOMS CM^{-2}
A ~0.03
N_H atom cm^{-2} x(1.8 x 10^{21})$^{-1}$
0
2
4
6
8
10
2.0
1.9
1.8
1.7
1.6
1.5
1.4
Γ

Figure 2