NASA Technical Memorandum 86175

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MARCH 1985

NASA

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National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1985

X-RAY EMISSION FROM ACTIVE GALACTIC NUCLEI

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It is often held (see Rees this symposium) that the x-ray emission from active galactic nuclei (AGN) arises from a region close to the central energy source. Thus x-ray observations may provide our best constraints on the central engine. In particular, the shape of the x-ray continuum gives information about the mechanism for photon generation, x-ray time variability data can constrain the "size" and "mass" of the continuum source, and x-ray "occultation" data give constraints on the relative sizes of the continuum source and the intervening absorbing material (often assumed to be the broad line clouds). In addition, since a fair fraction of the total energy of an AGN is emitted at x-ray wavelengths, direct measurement of the amount and spectral form of this radiation is important for modeling of the optically emitting clouds.

I. The Continuum

A. The "Normal" Objects

The "normal" x-ray continuum properties of broad line AGN (in particular Seyfert I galaxies) and BL Lac objects have been reviewed by Mushotzky (1984) and Culhane (1984). In brief, for broad line objects and narrow emission line galaxies (selected for sensitivity reasons on the basis of their 2-10 keV flux), the spectrum in the 0.7-100 keV band is well fit by a simple power law whose spectral index alpha has a very narrow distribution, alpha = 0.65 +/- .15, for almost all measured objects (Mushotzky 1982, Rothschild et al. 1983, Petre et al. 1984). With the exception of NGC 4151 (see below) and 3C 120 (see below), there is no evidence for changes in spectral form with changes in flux, or for the existence of a more complicated continuum form.

For BL Lac objects (Urry 1984) this stability in spectral form does not occur and the derived spectral indices are very broadly distributed (see fig. 1) Often the spectrum is not well fit by a single power law, being steeper at low energies and flatter at high energies. In addition, the spectrum of an individual object is not stable, with strong changes in spectral index or spectral form occuring frequently (but not always).

Even given the complications seen in the BL Lac objects, the observed continuum of AGN in the x-ray band is much simpler than the observed continuum in the IR-UV spectral range (see the talk by Ulrich in this symposium). While the more complex form of the IR-UV continuum probably carries more information about the physical processes responsible for the generation of photons in AGN, the simpler x-ray continuum lends itself more readily to model development and thus to an understanding of these processes. Unfortunately, there are several simple models (see Lightman 1982 and Mushotzky 1984) that seem to fit the available data. The critical observations needed to distinguish between models are (1) stronger constraints on spectral variability during changes in flux, (2) measurements of the spectrum at energies greater than 200 keV, and (3) correlated observations over the entire electromagnetic spectrum.

B. The "Exceptions"

There are at least three well measured exceptions to the general rules given above: NGC 4151, 3C 120 and E 1821+643. There probably exist many other such objects but various selection effects have prevented their discovery (see paper by Branduardi-Raymont in this symposium). Perhaps an understanding of why these objects differ from the norm may lead to a better understanding of the general situation.

a) NGC 4151 -- a break in the spectrum

Detailed HEAO-1 spectra of NGC 4151 (Baity et al. 1984) show that, at energies above 50 keV, the spectral slope varies. In particular, during two of the three HEAO-1 observations, when the 2-10 keV flux was "low" (but not quite as low as during the times observed by Tenma, reported by Matsuoka in this symposium), the spectrum was well fit out to 500 keV by a single power law with a slope alpha = 0.65+/-.15 . However during the third observation, when the source was twice as bright (in the 2-10 keV band), the spectrum showed a rollover at energies greater than 50 keV. This rollover was gradual in character and could be fit by a change in the power law slope of roughly 0.5. The limited sensitivity of the HEAO scintillators did not allow a good determination of the form of the high energy spectrum (the source was not detected above 200 keV). Balloon observations of this object (Perotti et al. 1979; Auriemma et al. 1978) have reported a flattening of the spectrum above 30 keV. It is not at all clear if this variable high energy spectrum is a common property of Seyfert galaxies. However, it is certain that the claimed spectral flattening does not occur frequently at energies less than 100 keV (Rothschild et. al 1983).

b) A Steep spectrum Object -- E1821+643

The ratio of the optical to x-ray fluxes in AGN has often been characterized by a mean optical-x-ray spectral index alpha(ox). The normal observed values of this parameter (Zamorani et al. 1981) are in the range 1-1.6. The local spectral indices in both the UV and x-ray range are not well fit by alpha(ox) (with the exception of BL Lac objects). However, the x-ray spectrum of E 1821+643, an AGN selected on the basis of its low energy (E<1 keV) flux by the HEAO-1 low energy all sky survey, is well fit in the 0.25-10 keV range by a power law whose slope, alpha=1.3, is very close to alpha(ox) (Pravdo and Marshall 1984); however time variability in the x-ray band may make this agreement fortuitous. This may suggest that there is a selection effect in the apparent narrow distribution of spectral indices seen in AGN. That is, since flat spectrum objects would be preferentially detected in a high energy survey, the lack of steep spectrum objects in such samples (e.g. the Uhuru, Ariel-V or HEAO-1 data sets) may be a selection effect. This suggests that objects found in a soft x-ray survey (the HEAO-1 LED survey or the Einstein Medium survey) may tend to have steeper spectral indices. Comparison of the ratio of IPC to HEAO-1 fluxes for an optically selected sample of AGN (the Markarian objects) suggests that there are some steep spectrum objects.

c) 3C 120 -- "Thermal Emission from an AGN?"

As reported by Petre et al. (1984) the Einstein Solid State Spectrometer (SSS) data showed that 3C 120 was the only high luminosity object whose spectrum was not well fit by a power law. The excess in the 0.5-2.0 keV band was modeled as the sum of a power law and a thermal bremsstrahlung (T-B) component with a temperature near 1 keV and solar abundances of metals (fig. 2). The signature of this component was the presence of weak emission lines at energies consistent with Fe L, Mg K and Si K. The T-B emission seems to be variable on time scales less than 6 months. The fact that this type of emission is seen only in 3C 120, surely one of the strangest of all AGN, makes interpretation difficult. The lack of moderate resolution spectroscopy in the 0.5-4.0 keV band on any present (or soon to fly) x-ray astronomy mission will make confirmation of this discovery unlikely in the near future.

II. Time Variability

As discussed in Mushotzky (1984) most broadline AGN do not show strong variability on any time scale. As shown by Zamorani et al. (1984), while most objects may vary by up to a factor of two on time scales of less than a year, variability by larger factors is quite rare. As discussed by Tennant and Mushotzky (1983) variability by more than 20% on time scales less than 12 hours (5 sec-12 hours) is an extremely rare occurence. Apparently the recent EXOSAT observations confirm this general behavior.

However we do not know the characteristic time scale for variability in these objects. At present we only have a poor sample of the time variability behavior because of the poor time coverage and sensitivity limits of previous x-ray astronomy satellites. For example, as discussed by Terrell and Snyder (this symposium) the very few AGN which have been monitored continuously for longer than 60 days seem to show, despite a large range in intrinsic luminosity, characteristic times of 10-30 days. For NGC 4151, perhaps the most intensively studied of all AGN (Lawrence 1980), the combined HEAO-1 and OSO-8 data, which covered 29 days, saw only two "one day flares". What is clearly needed is some type of all sky monitoring device with a time resolution of better than 6 hours and a flux threshold such that changes as small as 20 % in sources as weak as 1 UHURU count can be measured. There are roughly 50 AGN in the whole sky that can be detected at this flux threshold.

III. Absorption

a) General Characteristics

Any material along the line of sight which has a low enough ionization state that the metals (that is elements with Z greater than or equal to 8) still possess K shell electrons will photoelectrically absorb x-rays from the central source. For gas in coronal equilibirum, iron atoms still possess K shell electrons at temperatures less than log T=7.9 K and thus can produce a Fe K edge feature; the gas must be colder than log T=6.4K to produce an oxygen feature (Petre et al. 1984). In AGN we expect the gas to be in photoionization rather than collisional equilibrium so that the "temperature" will depend on the input photon spectrum. For spectra similar to AGN (Kallman and and McCray 1984) the equivalent electron temperatures such that Fe and O are totally ionized are $2*10^6$ and $2*10^5$ respectively. Thus x-rays can sample a much wider range of ionization states in absorption than can optical or UV resonance absorption or emission lines. X-ray absorption measurements can therefore provide constraints on the matter distribution relatively near the central object and give integral column densities over the whole, postulated, accretion flows. Of course, given the poor resolution and sensitivity of the present generation of x-ray instrumentation we can only accurately measure, in a model free manner, equivalent hydrogen column densities of $>3*10^{20}$ at/cm^2 (due to continuum absorption), and require equivalent hydrogen column densities 20 times larger to detect the edges of Si, S and Fe.

It is well known (Mushotzky 1982, Lawrence and Elvis 1982) that low luminosity (log L(x) <43.5 ergs/sec) AGN tend to exhibit photoelectric absorption in the x-ray spectral data while higher luminosity objects do not (Petre et al. 1984). The higher quality SSS data (fig. 3) show that this is not a selection effect due to the inability of older instrumentation to measure low column densities. Based on the SSS data (Reichert et al. 1984) sources of luminosity log L(x) <43.5 have approximately 70% probability of being absorbed by column densities greater than $7*10^{21}$ at/cm^2 while higher luminosity objects have less than a 25% chance. While this is a general trend, it does not mean that there do not exist high luminosity objects, such as MR2251-179 with log L(x)=44.7, which are absorbed (Halpern 1984) and low luminosity objects, such as MCG-6-30-15, which are not.

b) Partial Covering Models

While many of these objects can be well fit by a model of a point source absorbed by a uniform distribution of a cold gas, the SSS data for four objects show a soft excess above the uniform absorption model (fig. 4). This result was explained by Holt et al. (1980) for NGC 4151 as a partial covering of the source. That is, the absorbing clouds do not fully cover the continuum region. These four objects, NGC 2992, 3227, 3783 and 4151, have measured covering fractions on the order of 60-95% (at 90% confidence). However the lower bound is a selection effect since, given the bandpass and sensitivity of the SSS, covering fractions less than 70% are difficult to determine accurately. There do exist objects with substantial absorption, such as NGC 5506, which appear to have covering fractions consistent with unity. The column densities measured in all of these objects are in the range from 10^{22} to 10^{23} at/cm^2, consistent with the column densities inferred for the broad line optical clouds from the theoretical Balmer line ratios (Kwan and Krolik 1981). In addition the rough calculations of the line strengths of the CIV and hydrogen lines in these objects are consistent with large covering fractions. Thus all the data are consistent with the x-ray absorbing objects being the broad line clouds (Ives, Sanford and Penston 1976).

While most of the low luminosity objects are absorbed, the distribution of covered fraction versus luminosity (fig. 5) is not smooth. There appears to be a rather sharp transition region around log L(x) = 43.5. If this sharp transition is real, and not an artifact of the small sample (31 objects), then at least one simple explanation can lie in a matching of the cloud size and continuum source size at this transition luminosity (fig. 6). That is, If the clouds are much larger than the continuum source, then one would tend to observe the object either being totally absorbed or unabsorbed. If the cloud and continuum are roughly the same size then one may expect to see partial covering (as is observed), and if the clouds are much smaller than the continuum source (and there are not a very large number of them per unit solid angle) then the source would look to the observer as if it were uncovered. One must distinguish the covering fraction as seen by an external observer in x-ray absorption from the mean covering fraction as measured by the flux in the broad lines. While an object could look to be a 100% covered if a "large" cloud lay along the line of sight, the solid angle average as seen by the ensemble of broad line clouds could be much smaller.

If we accept this simple idea, we can infer the sizes of the central continuum source if we have some idea of the sizes of the broad line clouds. Most models of the clouds require them to have densities between 10^9 to 10^{10} cm^{-3} Given our column density limits, this gives a physical thickness on the order of 10^{12} and 10^{14} cm. If both the broad line region and the clouds are spherical this implies that the continuum source is on the order of 1/3 to 3 times this size at luminosities of 10^{43} ergs/sec (at the 90% confidence value, derived from matching the observed probabilities of various amounts of covering, Reichert et al. 1984). An Eddington limited black hole with this bolometric luminosity would have a size of $7*10^{10}$ cm for the region (10 Schwarzschild radii) producing the x-rays. Therefore the "occultation" data indicates that the region producing the x-rays is more than 5 times larger than simple Eddington arguments would indicate. If the clouds are more like "pancakes" (Matthews 1982) than spheres, then an even larger size for the x-ray emission region is indicated. This size agrees with the limits derived from time variability arguments (Tennant and Mushotzky 1983) and may indicate that many of the Seyfert galaxies are well below the Eddington limit (cf. Bassani and Dean 1983).

c) X-ray Spectral Features

With the exception of 3C 120 the only spectral features seen in the x-ray spectra of broad line AGNs have been due to the K absorption edges of Fe, Si and S, and the Fe fluorescent line at 6.4 keV. The strength of the fluorescent Fe feature relative to the depth of the 7.1 keV absorption line is a measure of the geometry of the absorbing region (fig. 7). As shown in this figure if the material is distributed in a flattened configuration parallel to our line of sight, then we can see a strong Fe fluoresence feature without a strong K edge. If the structure is perpendicular, one can have a strong Fe edge and a weak line. The absolute strength of the Fe emission feature is simply related to the total amount of Fe (if the medium is thin to Compton scattering). If the x-ray source is emitting isotropically then the equivalent width is roughly 8 A*N*M eV (where N is the hydrogen column density in units of 10^{23} at/cm^2, A is the Fe abundance in units of $4*10^{-5}$, and M is the solid angle subtended by the fluorescing material in sterradians). Thus, for full solid angle coverage, spherical symmetry and a column density of of 5×10^{22} (as indicated by the observed low energy roll over), the very high equivalent widths of 200-400 eV in the Fe line seen in NGC 4151 require Fe to be 4-8 times overabundant. However such large enhancements would be inconsistent with the observed strength of the Fe K edge absorption feature. In a face-on disklike geometry the column density in the disk is likely to be considerably larger than the column density along the line of sight. If the abundance of the metals is 2-3 times solar, as indicated by the strength of the edges (Holt et al. 1980), this would require the column density in the plane of the disk to be greater than 6 times the column density perpendicular to the disk (if the solid angle subtended by the disk is less than 1/2) and we view the disk face-on. It thus seems that observation of very strong Fe 6.4 keV fluorescence may imply the existence of a disk viewed face-on in these objects. The ratio of the strength of the line to the depth of the edge in NGC 4151 (Holt et al.) indicates that the system is not very flattened.

d) Constraints on models of the Broad Line Region

Detailed photoionization models (e.g. Kwan and Krolik 1981, Ferland and Mushotzky 1982) developed to explain the broad emission lines in AGN can be well constrained by six external parameters: the ionization parameter,the covering factor, the cloud thickness, the global geometry (spherical, disk shaped etc.), the metallicity and the form of the continuum. X-ray observations permit the determination of all but one of these parameters, (the ionization parameter), in a relatively model independent way.

As we have seen above, the column density measured by x-ray observations (due to photoelectric absorption) determines the column density of the clouds. Because these clouds are optically thick to almost all optical and UV line radiation it is impossible to determine their hydrogen column density in any other way (except by fitting the observed line ratios to a photoionization model, with column density being the fitted parameter). Of course high resolution optical absorption line spectrosocopy might be able to measure the column density in individual ions if the lines are not saturated. The covering factor is measured by the form of the low energy absorption rollover, i.e., the partial covering model. While the mean covering factor may be determined by the absolute strength of the emission lines the result is quite model dependent and can really be used only to check the x-ray derived value. The global geometry of the absorption region is determined by the absolute strength of the Fe fluorescent line and the ratio of the line to the absorption edge. I do not know of any simple way that optical data can be used to determine this shape. The mean metallicity of the absorbing medium can be measured by the absolute strengths of the x-ray absorption edges. Given sufficient energy resolution and signal to noise, this is a quite straightforward result. Determination of the relative (and not the absolute) metallicity from optical emission line data is virtually impossible because of the bolometric nature of the strongest lines (Ferland and Mushotzky 1984).

Finally it is possible (Kallman and Mushotzky 1984) that x-ray spectroscopic measurements with a resolution of better than 50 eV can determine the column density and temperature of the heretofore invisible intercloud region in the broad line region. Already, using imaging x-ray data from the Einstein observatory Elvis, Briel and Henry (1983) have determined constraints on the intercloud medium in the narrow line region.

Acknowledgments: I thank Gail Reichert for considerable textual and scientific help. I would like to thank Martin Elvis for interesting and invigorating discussions and Drs. E. Boldt, P. Serlemitsos and S. Holt for making this work possible.

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Figure Captions

1) Distribution of spectral indices for two classes of active galaxies, BL

Lac's and Seyfert galaxies. The Seyfert galaxy distribution is from Mushotzky (1984) and each point is a different object. For the the BL Lac's each point represents a separate observation of each of the 5 objects.

2) The Einstein SSS spectrum of 3C 120. The solid lines represent the best fitting power law and thermal-bremmstrahlung models respectively. The emission complexes due to Mg, S and Si lines are especially noticeable.

3) The distribution of column densities in AGN from SSS observation (Petre et al. 1984,Reichert et al. 1984) (notice the break in the scale at $N(H)\sim10^{22}$). Almost all of the low column density sources are high luminosity, and all of the high column density objects in this sample are low luminosity.

4) Various x-ray spectra in the 0.1-100 keV band labeled by covering fraction. The spectra are all absorbed by a galactic column density of 3×10^{20} at/cm^2. Notice the relative flatness in the 0.5-4 keV band of sources with 0.6-0.8 covering fraction.

5a) X-ray column density vs. 2-10 keV luminosity. Notice the strong anti-correlation of absorption with luminosity and the existence of low luminosity unabsorbed sources. The data are from Reichert et al. 1984.

5b) X-ray covering fraction vs. luminosity. Notice the change in the character of the plot at log L = 43.5 ergs/sec. The upper limits at high L are from Petre et al. 1984, while the other data points are from Reichert et al. 1984

6) A schematic model of what our line of sight would look like for a model of broad line clouds absorbing the central source. The continuum source is indicated by the stippled circle, while the clouds are the open circles. At low luminosities (low L in the figure) the clouds are larger than the continuum source. At high L, the continuum source has gotten larger while the clouds remain the same size, so that the clouds intercept a smaller solid angle and the line of sight covering fraction is small. In the middle panel we see a situation of 50 % partial covering fraction.

7) A schematic model of a flattened x-ray absorption line region. In the left panel,(1), we see the observed spectrum in the Fe K region for a flattened absorber whose axis is perpendicular to the line of sight. In panel (2) we see the result if the axis is parallel to the line of sight. In panel (1) one sees a strong Fe absorbtion edge and a weak Fe fluorsecent line while in (2) one sees a strong Fe emission line with no edge.

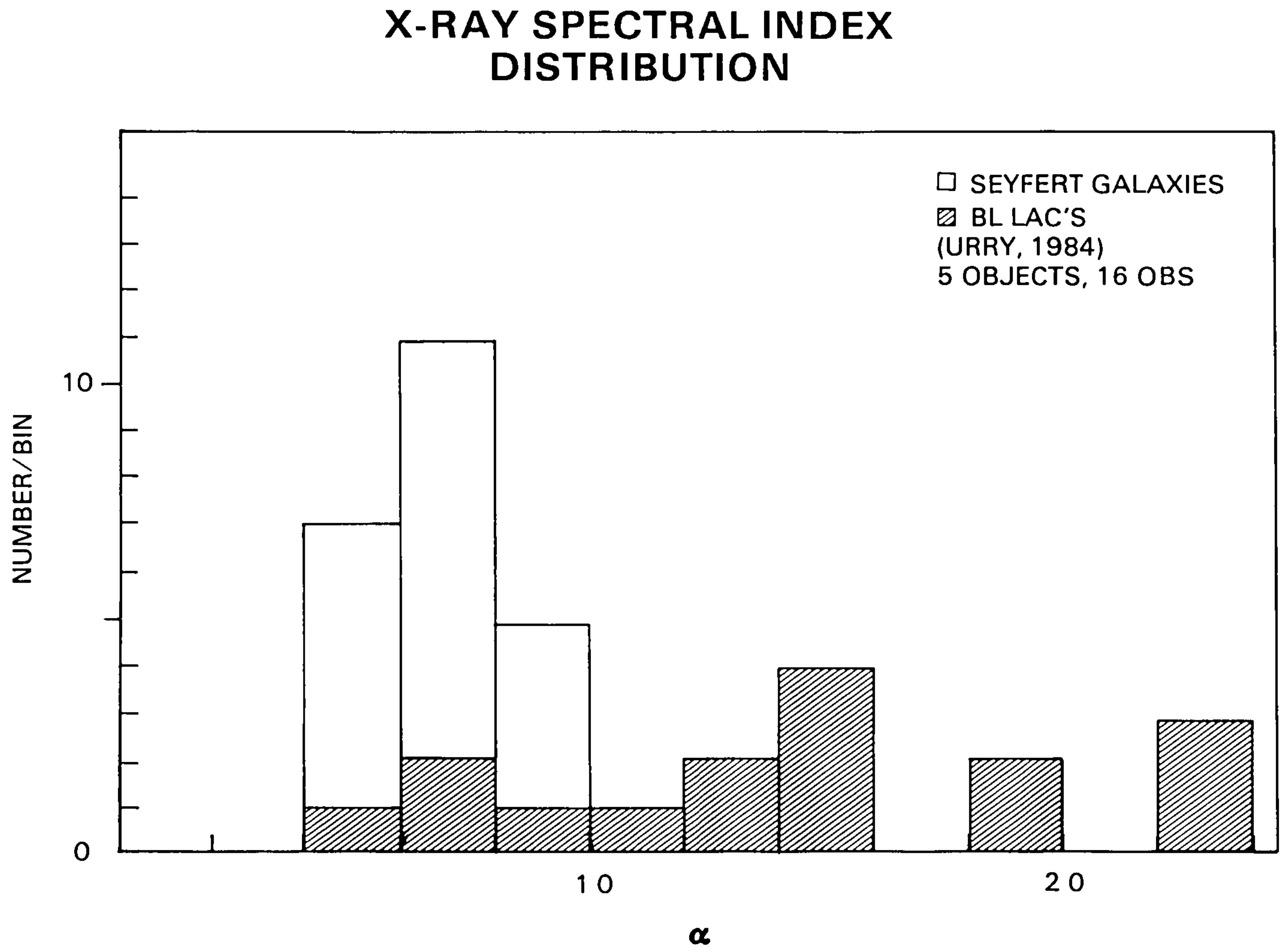


Figure 1: Distribution of spectral indices for two classes of active galaxies, BL Lac's and Seyfert galaxies The Seyfert galaxy distribution is from Mushotzky (1984) and each point is a different object. For the BL Lac's each point represents a separate observation of each of the 5 objects

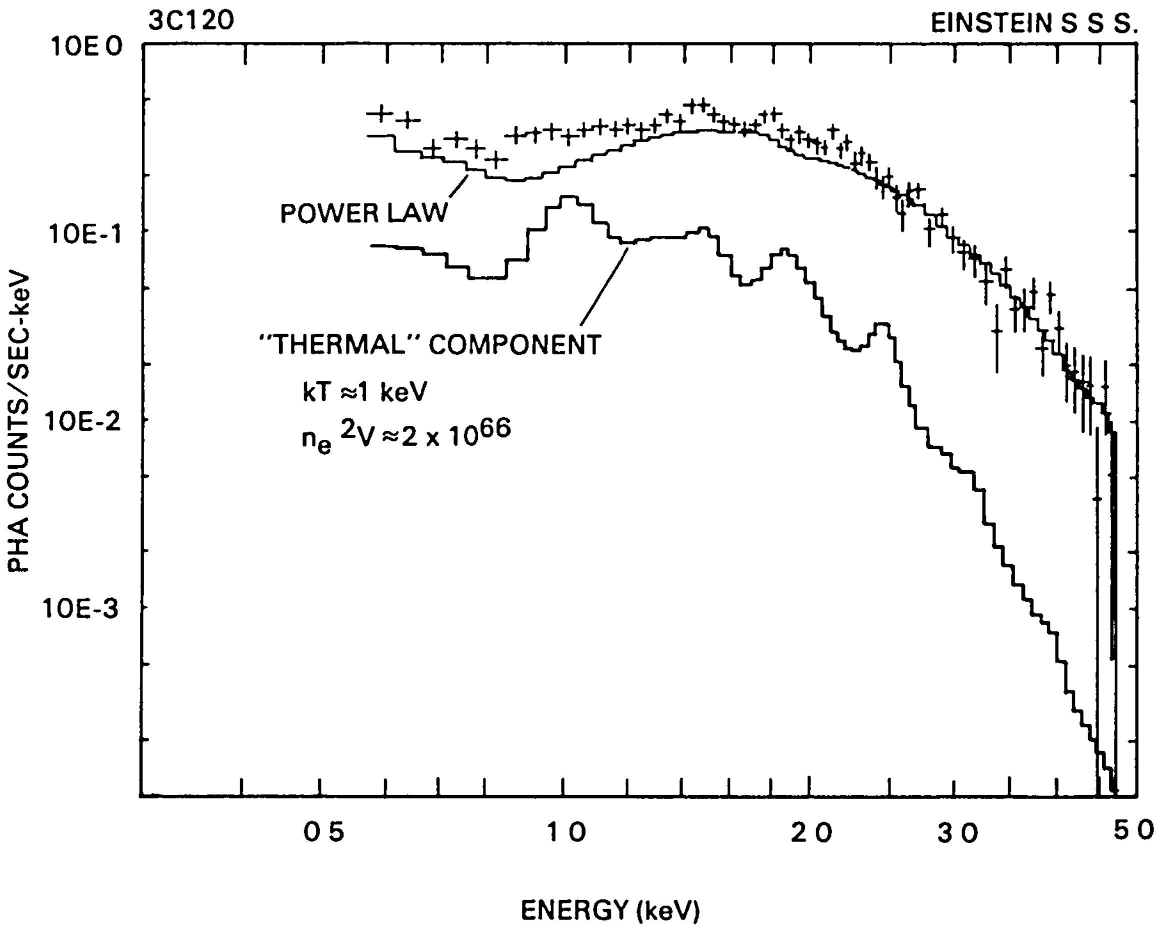
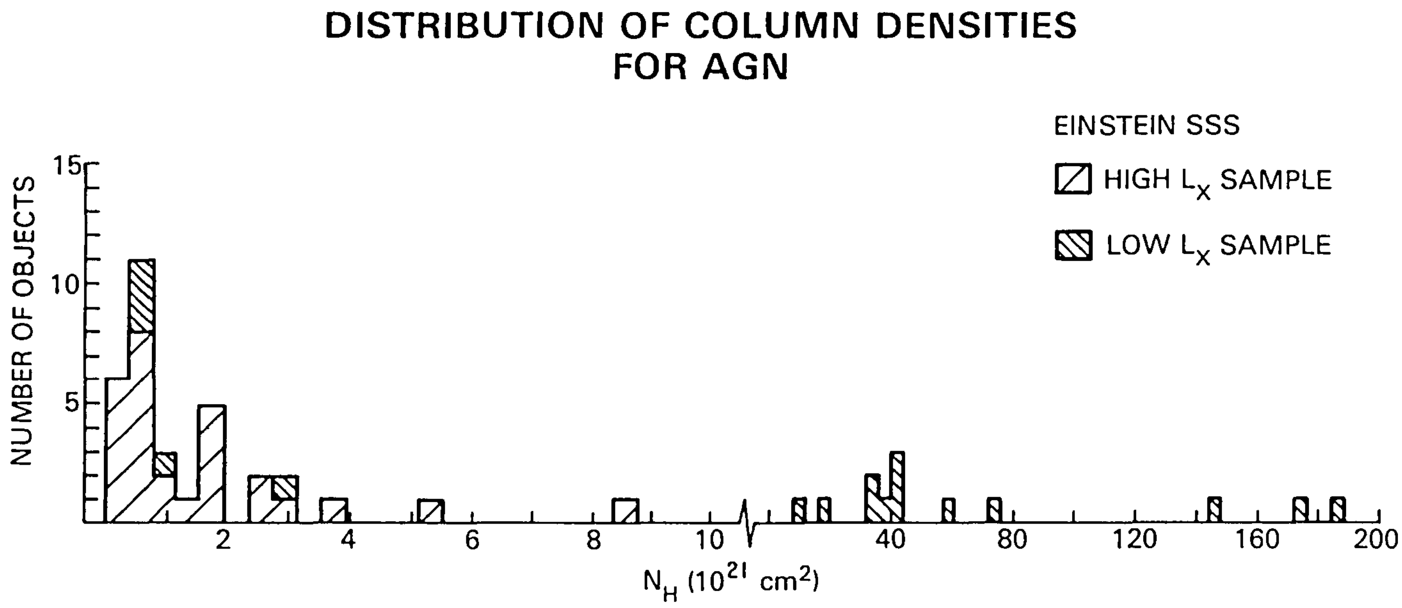


Figure 2 The Einstein SSS spectrum of 3C 120 The solid lines represent the best fitting power law and thermal-bremmstrahlung models respectively The emission complexes due to Mg, S and Si lines are especially noticeable



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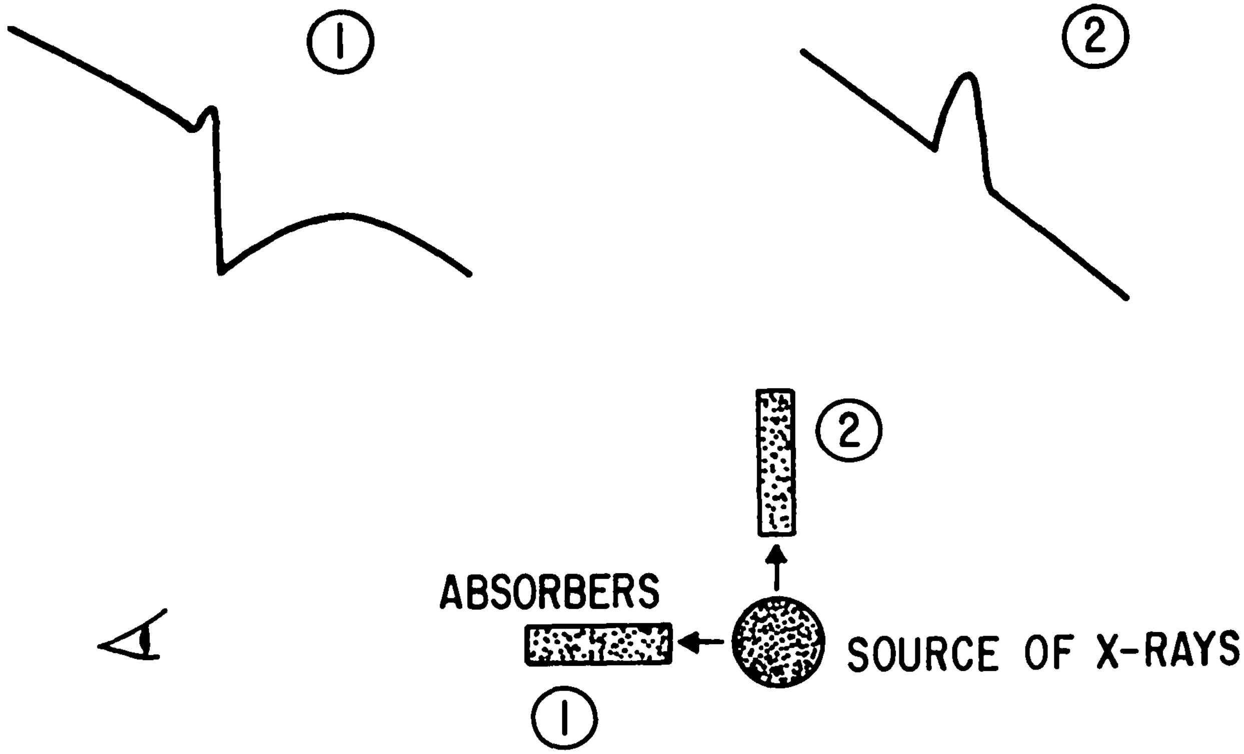

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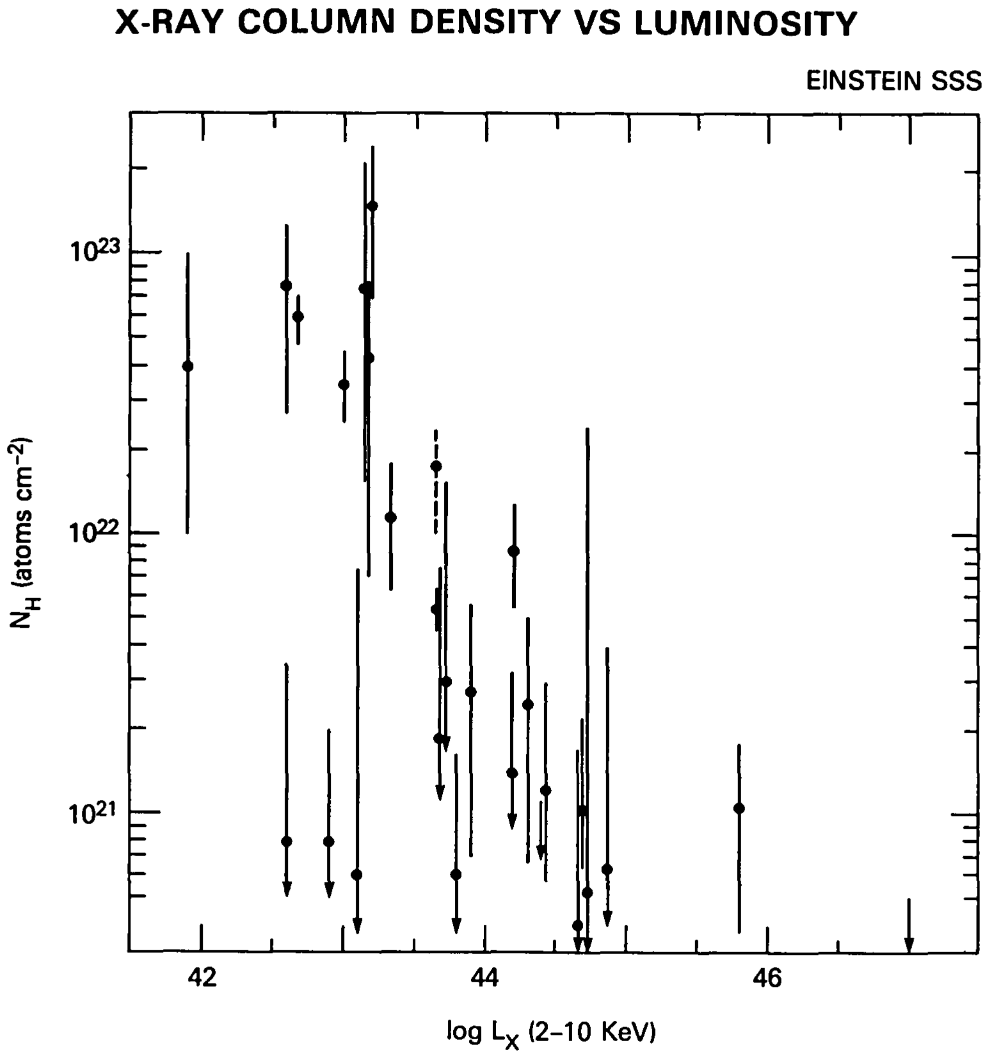


Figure 5a. X-ray column density vs. 2-10 KeV luminosity Notice the strong anticorrelation of absorption with luminosity and the existence of low luminosity unabsorbed sources The data are from Reichert et al 1984

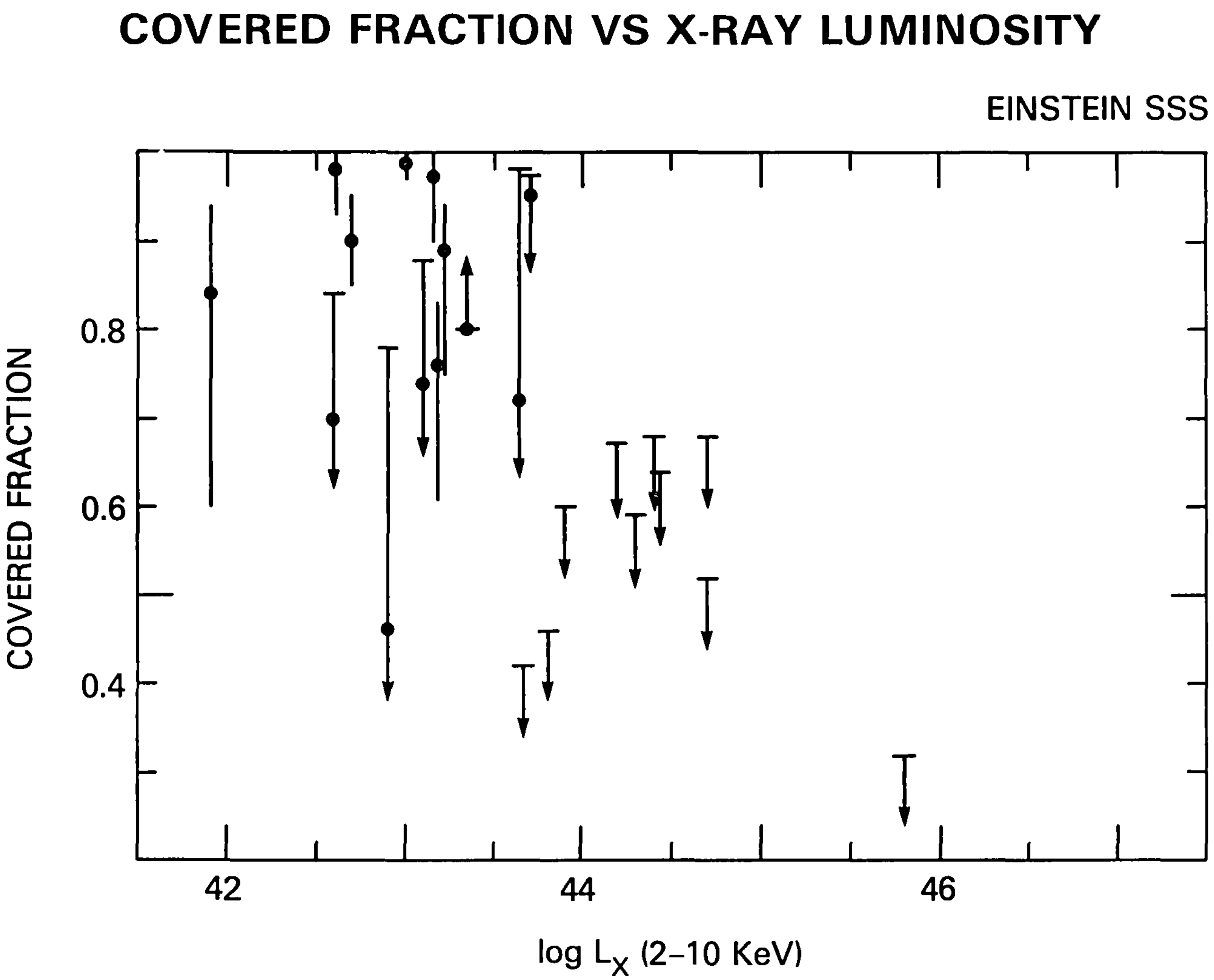
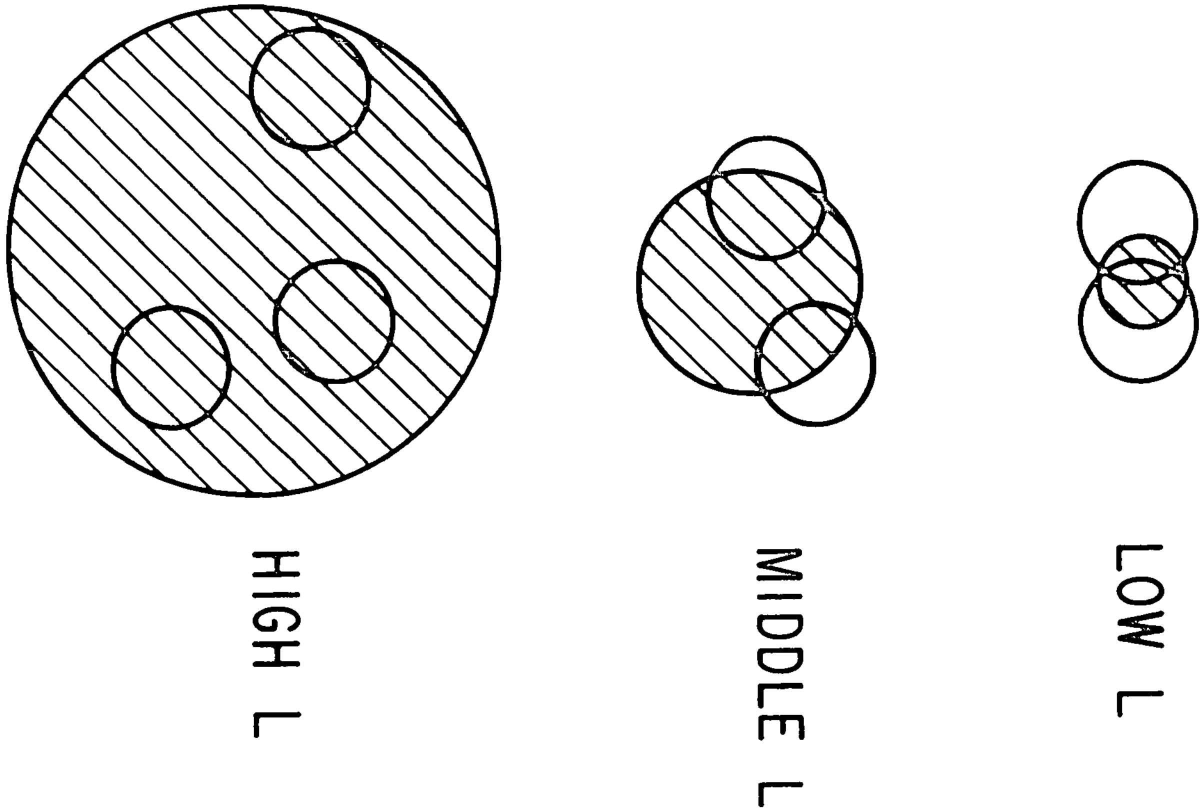


Figure 5b X-ray covering fraction vs luminosity Notice the change in the character of the plot at log L = 43 5 ergs/sec The upper limits at high L are from Petre et al 1984, while the other data points are from Reichert et al 1984.



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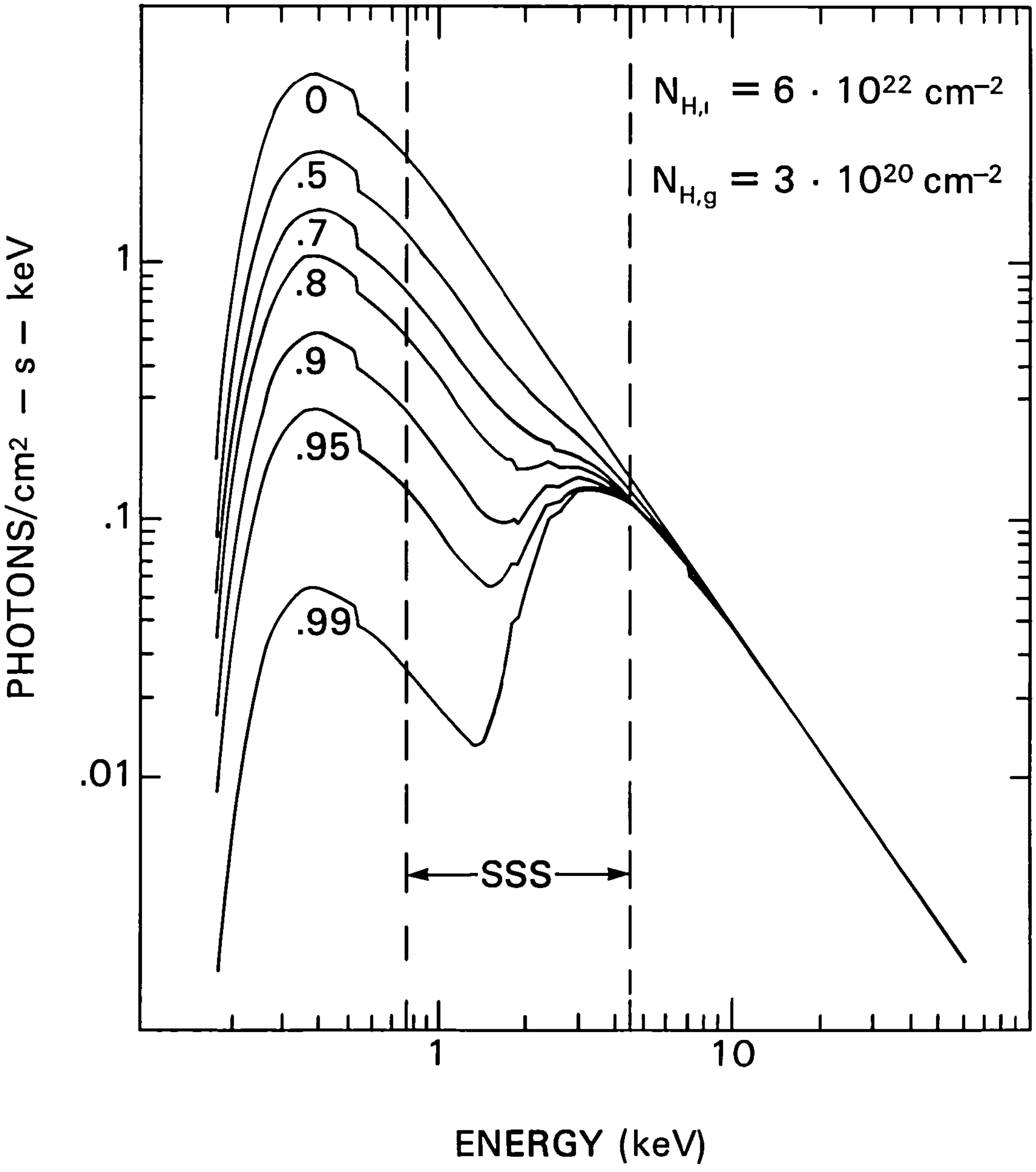
EFFECTS OF PARTIAL COVERING ON X-RAY SPECTRA



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1 Report No NASA TM-86175	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle X-RAY EMISSION FROM ACTIVE GALACTIC NUCLEI		5 Report Date March 1985 6 Performing Organization Code 661
7 Author(s) Richard Mushotzky		8 Performing Organization Report No 85B0239
9 Performing Organization Name and Address NASA/Goddard Space Flight Center Laboratory for High Energy Astrophysics Greenbelt, MD 20771		10 Work Unit No 11 Contract or Grant No
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13 Type of Report and Period Covered Technical Memorandum 14 Sponsoring Agency Code
15 Supplementary Notes Invited talk presented at X-Ray Astronomy '84, Bologna, Italy and X-Ray and UV Emission from Active Galactic Nuclei Meeting, Munich, West Germany, July 1984.		

16 Abstract

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17 Key Words (Selected by Author(s))		18 Distribution Statement	
X-Ray Emission Galactic Nuclei		Unclassified - Unlimited Subject Category 90	
19 Security Classif (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No of Pages 24	22 Price* A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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