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DISCRETE X-RAY SOURCES AND THE X-RAY BACKGROUND

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ABSTRACT

Since the discovery, more than twenty years ago, of a highly uniform X-ray background (XRB) in the 2-10 keV range, its nature has not yet been fully explained. It appears clear from the results of "Einstein" medium and deep surveys that at least 50 percent of the XRB is due to individual extragalactic sources when their contribution is integrated to $Z = 3$. This includes contribution from Quasi Stellar Objects (QSO's), Active Galactic Nuclei (AGN's), galaxies, and clusters of galaxies. The average spectrum of each of the individual contributing sources is softer than that of the observed XRB (power law index $\alpha \approx -0.4$ from 3 to 10 keV). Therefore, the remaining contribution must have a rather hard spectrum of $\alpha \approx 0.0$ - 0.2. It is unlikely that this spectrum can be produced by diffuse processes. Therefore, the remainder of the XRB must be due to individual sources with the appropriate spectrum. This requires either that the spectrum of the already identified sources changes at early epochs or a new class of objects. Advanced X-ray Astrophysics Facility (AXAF) observations will extend survey sensitivity to limiting fluxes of order of 3×10^{-16} erg cm^{-2} s^{-1}, some 50 times fainter than any previous survey. They will have sufficient sensitivity and angular resolution to permit identification and study of these objects.

1. INTRODUCTION

The existence of an isotropic X-ray background with intensity of 1.7 photons $cm^{-2}\ s^{-1}\ sr^{-1}$ (in the 2 to 8A° range), was established in the same flight of June 18, 1962, which discovered the first X-ray star, Sco X-1, Giacconi et al. [1962], Figure 1.

Due to the high degree of isotropy, it became evident, even after the first few observations, that the X-ray background had to be mainly extragalactic in origin. If extragalactic and due to a uniform distribution of sources, a substantial fraction of it (> 20%) had to originate at large distances (Z > 1), and therefore would carry information of cosmological interests. The very first theoretical paper after the discovery of X-ray sources, by Hoyle [1963], pointed out that the hot steady-state cosmological model of Hoyle and Gold predicted

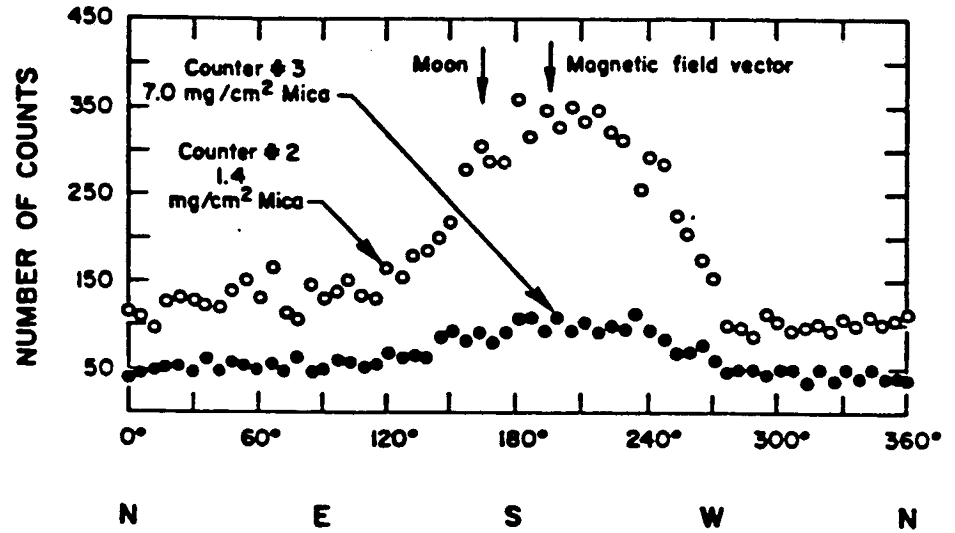

Figure 1. Azimuthal distributions of recorded counts from Geiger counters flown during June 1962. Giacconi, R. and Gursky, H., eds., X-ray Astronomy, D. Reidel Publishing Company, 1974.

a greater flux of background X-rays than was observed. This single observation marked the beginning of the demise of the steady-state theory. More important was that it demonstrated the potential of X-ray observations in studying the early universe.

In the twenty years since then we have learned a great deal about the spectrum and angular distribution of the X-ray background. It is generally accepted that about half of it is the result of the superimposed emission from many distant individual extragalactic sources: normal galaxy, low luminosity active galaxies, QSO's, and clusters of galaxies all contribute to the observed emission. As to the question whether the X-ray background can all be explained in this manner, the answer is "no". If the remainder of the background is due to individual sources they must differ in their emission spectrum and/or evolution from any of the known classes. Perhaps protogalaxies or early stages of QSO's may provide this emission. While there is no evidence for a truly diffuse component, a contribution as large as 10-20% cannot be excluded.

2. EARLY OBSERVATIONS AND THEORY

Opportunity for indepth study of the nature and origin of the background came from the "Uhuru" mission, Figure 2. It is clear from the figure that, in X-rays, the background radiation dominates the night sky, a result quite different qualitatively from what one obtains in the visible range of wavelength. From the study of Uhuru data, it could be determined that fluctuations of the background were less than about 3% on angular scales of 10 degrees. This was strong confirmation of the extragalactic origin of the background. It was shown by Schwartz and Gursky [1974] that under reasonable assumptions on the density and composition of intergalactic gas, optical depth of unity would not be reached in the X-ray regime, until $Z \approx 7$, even in the hypothesis of a closed universe. This means that X-rays generated at very early epochs can reach us unimpeded by absorption or scattering effects. If we now ask from what range of distances may the radiation actually be coming, we find that this depends on assumptions about the emissivity function. For a uniform emissivity (in co-moving coordinates) throughout the universe, one finds that some 20% of the background must come from $Z > 1$; if we assume any kind

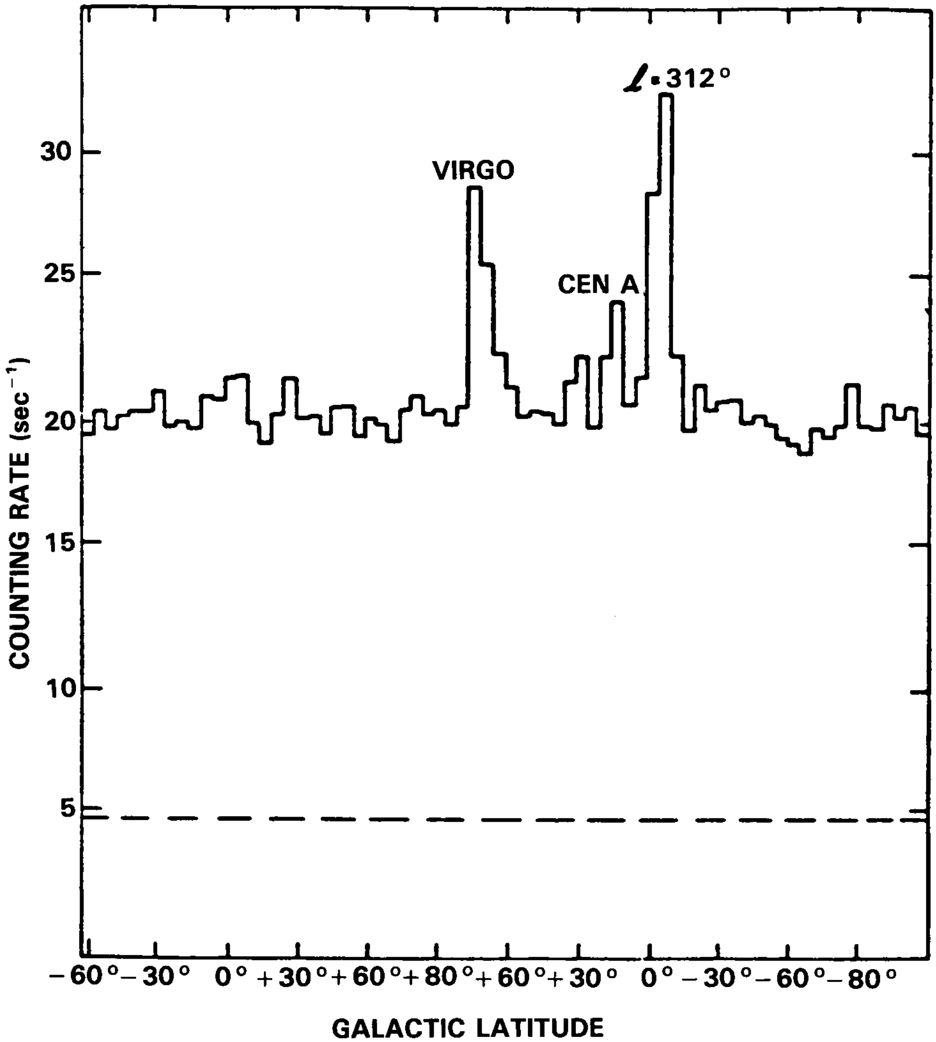

Figure 2. Uhuru counting rates along a great circle passing through high galactic latitudes. Except for discrete sources, the telescope records a general radiation background which is not related to the galaxy. The small contribution of non-X-ray background is indicated by the dashed line. Giacconi, R. and Gursky, H., eds., X-ray Astronomy, D. Reidel Publishing Company, 1974.

of evolution (the simplest being an additional factor of $(1+Z)^3$ as would be expected if the emissivity depends on ρ^2) then we find that most of the background must originate at $Z > 1$, Figure 3.

As to the spectrum of the observed radiation, an early compilation by D. Schwartz of results from a number of groups is shown in Figure 4. Schwartz concluded that the spectrum could be best fit by two power laws of the form

$$I(E) = \begin{cases} 8.5\ E^{-0.40} & 1 \leqslant E \leqslant 21\ \text{keV} \\ 167\ E^{-1.38} & E \geqslant 21\ \text{keV} \end{cases}$$

with I(E) in keV/keV cm^2 s sr or by an exponential fit of the form $I(E) = 4.1\ \exp\text{-}(E/35)$ as would be expected from thermal emission by a gas with effective temperature of 4×10^8 K. He noted that an exponential spectrum provided a poor fit both at low energies (< 1 keV) and at very high energies (> 300 keV).

A number of theories were proposed to explain the background radiation origin in the early 1960's and 1970's. The first proposal, already mentioned, was by Hoyle [1963] of X-ray production from a hot intergalactic medium, whose existence had been predicted by Gold and Hoyle [1959] as a consequence of matter formation in their steady-state cosmological model. It turned out that this model would predict a flux one hundred times greater than observed! Felten and Morrison [1966] suggested that inverse Compton scattering of cosmic ray electrons on the 3 K radiation may reproduce the power law spectral shape. If the intergalactic electrons could be assumed to have the same spectrum as cosmic electrons in our galaxy (spectral index $\alpha \approx 2.6$), then a spectrum of the type $E^{-1.5}$ could be obtained. The main difficulty with this model is the lack of detailed knowledge on cosmic electron fluxes at early epochs. Then current estimates yielded a derived X-ray flux one or more orders of magnitude less than that observed.

Cowsik and Kobetich [1972] proposed that the spectrum could be interpreted as a thermal bremsstrahlung from a gas at a temperature of several hundred

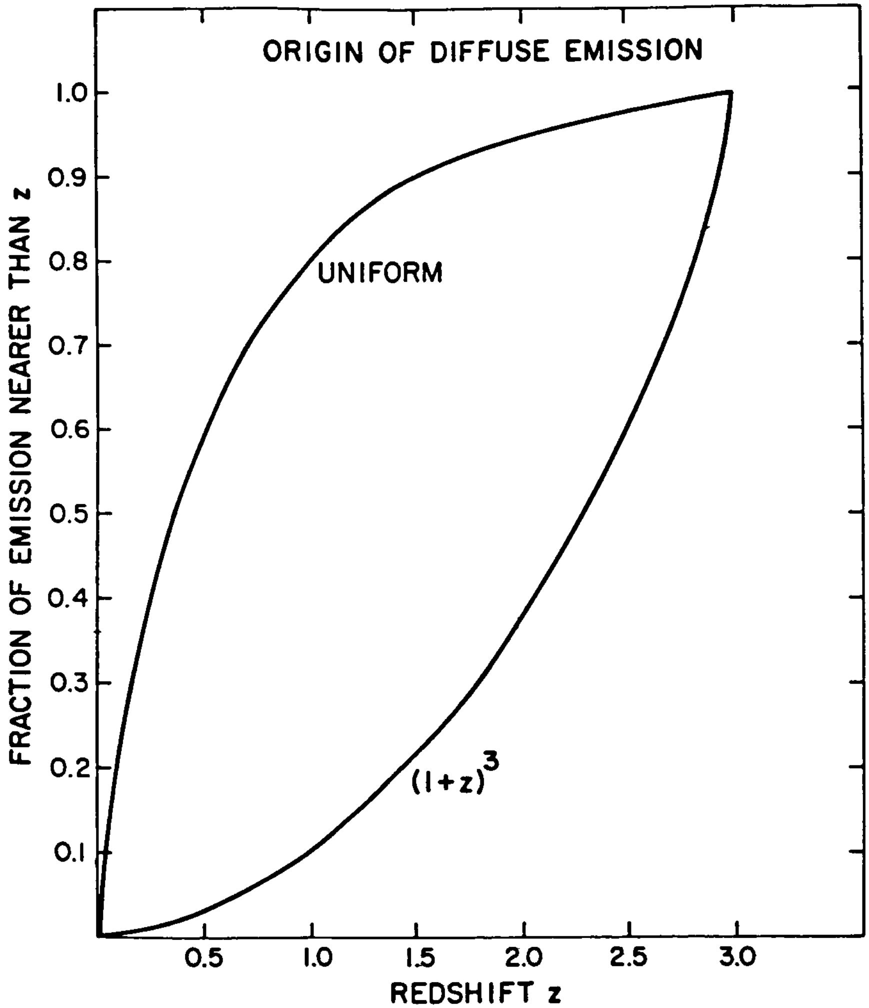

Figure 3. Fraction of the X-ray background which is produced nearer than the indicated redshift. Two models are shown: uniform emissivity (in comoving coordinates; upper left curve) and emissivity which evolves by an additional factor $(1 + z)^3$ (lower right curve). In both cases we assume $q_0 = 0.5$, the X-ray energy spectral index is -0.5, and the emission is cut off at $z = 3$. Schwartz, D. A., 1978, Proc. IAU/COSPAR Symposium on X-ray Astronomy, Innsbruck, Austria.

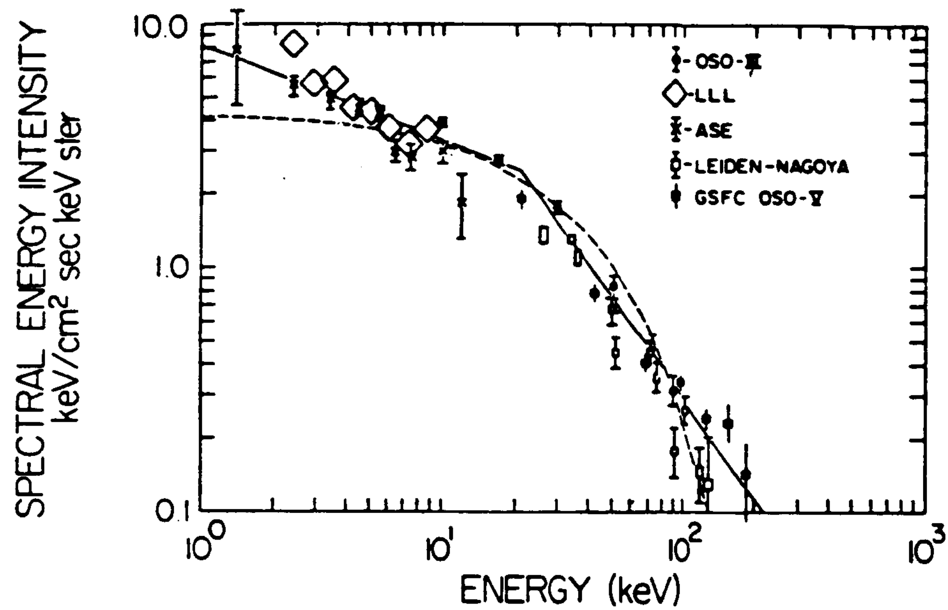

Figure 4. Measurements of the diffuse X-ray energy spectrum in (keV keV^{-1} cm^{-2}sr^{-1}s^{-1}). Data were selected from published results according to the following criteria: (1) The experiment either spanned a wide range of geomagnetic conditions, or (2) included means of directly detecting and reducing effects of charged particles in the detector. Results reported only in the form of parameters for an assumed spectral shape are excluded. The data presented here have sufficient precision to reject the hypothesis that a single power law shape fits all the data between a few keV and a hundred keV. OSO 3: SD 70b, SD 73a. LLL:PT 71. ASE:GP 69. Leiden-Nagoya: BJ 70. OSO5: DB 73. Schwartz, D. A., 1978, Proc. IAU/COSPAR Symposium on X-ray Astronomy, Innsbruck, Austria.

million degrees. They computed a detailed fit of the model to the existing spectral data, Figure 5. They obtained a temperature of 3.3×10^8 K, $\int N_e N_p dl \sim 10^{17}$ cm^{-5}, $\rho \approx 3 \times 10^{-6}$ H atoms cm^{-3} and $\rho \approx \rho_{crit}$ if $H_o = 55$ Km s^{-1} Mpc^{-1}.

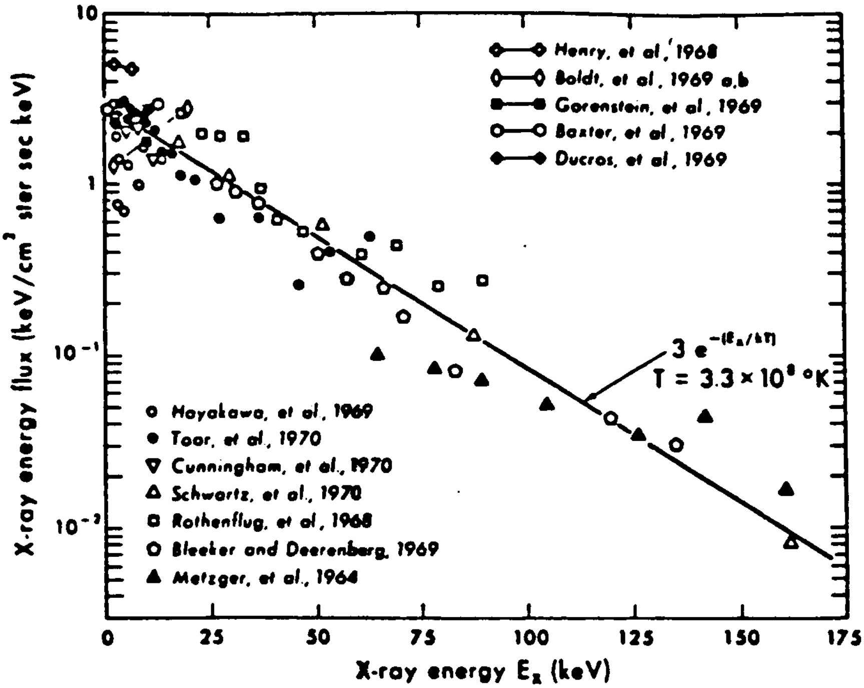

Figure 5. The difference between the observed energy flux and the calculated flux in the energy interval 2 keV E_x 200 keV is plotted as a function of X-ray energy. The line represents the thermal-bremsstrahlung emission for a hydrogen plasma at 3.3×10^8 K. The line-of-sight integral $\int N_e N_p\, dl$ for this emission is 1.3×10^{17} cm^{-3}. If one assumes no clumping and $\int dl \approx 2c/3H_o \approx 10^{28}$ cm, one gets $N_e \approx N_p \approx 3 \times 10^{-6}$ cm^{-3}. Such a density is adequate to close the Universe if $H_o \approx 55$ km s^{-1} Mpc^{-1}. Cowsik and Kobetich, 1972, Astrophys. J., 177, 585.

Field and Perrenod [1977] gave the most complete and critical treatment of this model. They start from the fit of Cowsik and Kobetich. They compute the energy content of the gas which turns out to be larger than any other form of energy in the universe except that in the 3 K or in the rest mass. They pose the question of how the heating of the gas could occur. They suggest that an early population of QSO's with numbers evolving as $(1+Z)^6$ might be the source. They assume that heating occurred at $Z=3$ and that adiabatic cooling has taken place since, Figure 6. Then they can provide a description of → and under the assumption that $\rho \approx \rho_o (1+Z)^3$, they find that the integrals from $Z=0$ to $Z=3$ would yield a fit with $T = 4.4 \times 10^8$ K and $\Omega = 0.46\ C^{-1/2}$ (where C is the clumping factor $C = \langle n^2 \rangle / \langle n \rangle^2$). They remain skeptical of this explanation because of the very large energy requirements, the large value of Ω (in baryonic matter) and the existence of diffuse HI clouds in intergalactic space which would evaporate in the presence of the postulated hot intergalactic medium, [Mattewson, Cleary, and Murray, 1975; Cowie and McKee, 1977].

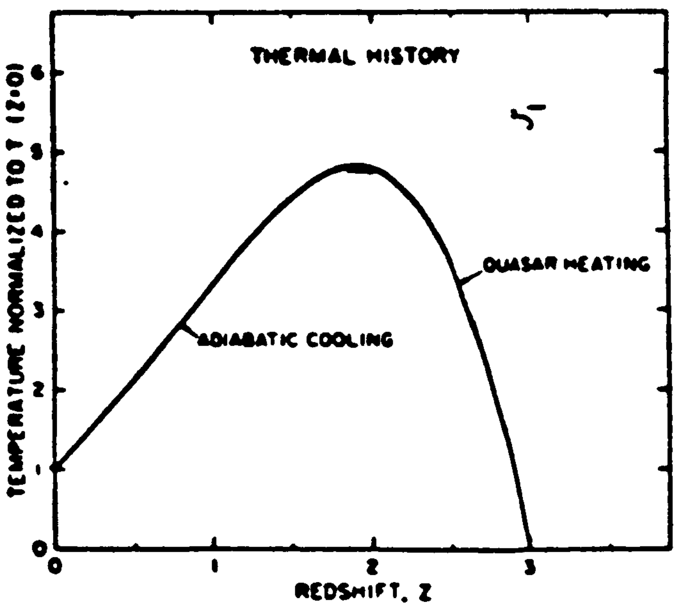

Figure 6. The variation of the temperature of intergalactic gas with redshift. The temperature scale is in units of its present value, T_0, which is determined to be 4.4×10^6 K from the observations. Field and Perrenod, 1977, Astrophys. J., 215, 717.

3. EARLY LOG N-LOG S DETERMINATIONS AND THE CONTRIBUTION OF INDIVIDUAL SOURCES

Most of the theories discussed up to now attempted to explain the background as a truly diffuse emission from the Intergalactic Medium (IGM). However, starting in the early 1970's, a body of experimental evidence became available regarding the X-ray emission from extragalactic sources and also regarding the number count of extragalactic sources as a function of detected flux. These findings shifted the question of the nature of the X-ray background to a more fundamental issue, namely, whether the background was truly due to diffuse processes or to the unresolved contributions of individual sources. The salient facts were the findings that the Number-Intensity distribution for high galactic latitude, presumably extragalactic, sources ($b \geqslant 20°$) in the Uhuru catalog followed a power law distribution -1.5, while for galactic sources ($b \leqslant 20°$), it followed a -0.4 distribution, Figure 7, [Matilsky, 1973]. This was interpreted as the result of a luminosity function independent of distance, in which case the extragalactic sources much nearer than $Z = 0.1$ will dominate the counts and follow the classical $N(>S) = KS^{-3/2}$ law.

It therefore became possible to speculate that the additional contribution of fainter sources (below the Uhuru limit of 1.7×10 ergs cm^{-2} s^{-1}) might give rise to the remainder of the background. Setti and Woltjer [1970] had, in fact, pointed out as early as 1970, when only 3C273 had been observed as an X-ray source, that the integrated contribution of all QSO's could easily explain the entire X-ray background.

In a pre-"Einstein" review, Schwartz [1978] analyzed the contribution to the background from known extragalactic sources. He took into account the known X-ray luminosity function for Seyferts, clusters of galaxies, normal galaxies, and QSO's. He concluded that each class contributed several percent to the background without luminosity or density evolution. No class of discrete X-ray source could constitute the entire background without evolutionary effects, but less pronounced evolution for QSO's could account for all of the X-ray background. New data on individual sources at fainter limits would be required to settle the question.

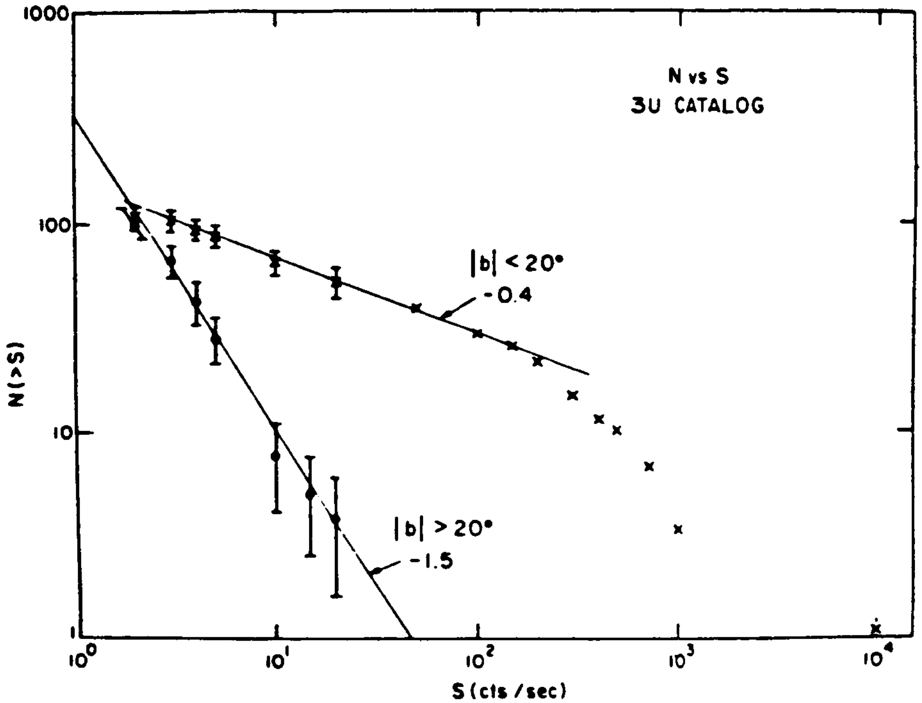

Figure 7. Number-Intensity distribution for sources in the UHURU catalog from Matilsky et al. 1973. Giacconi and Gursky, 1974, X-ray Astronomy.

4. THE HEAO-1 FINDINGS ON SPECTRAL SHAPE

Diffused emission theories of the X-ray background and thermal bremsstrahlung models in particular received new impetus after the findings of the HEAO-1 (A-2 experiment), which obtained X-ray background spectra in the 2 to 40 keV region with high statistical accuracy, Figure 8.

Marshall et al. [1980] showed an excellent fit to the Field and Perrenod model with parameters of $Z_{cutoff} = 3$, $T_o = 26$ keV and $\Omega = .36C^{1/2}$. They repeated the Schwartz arguments against the explanation of the background as due

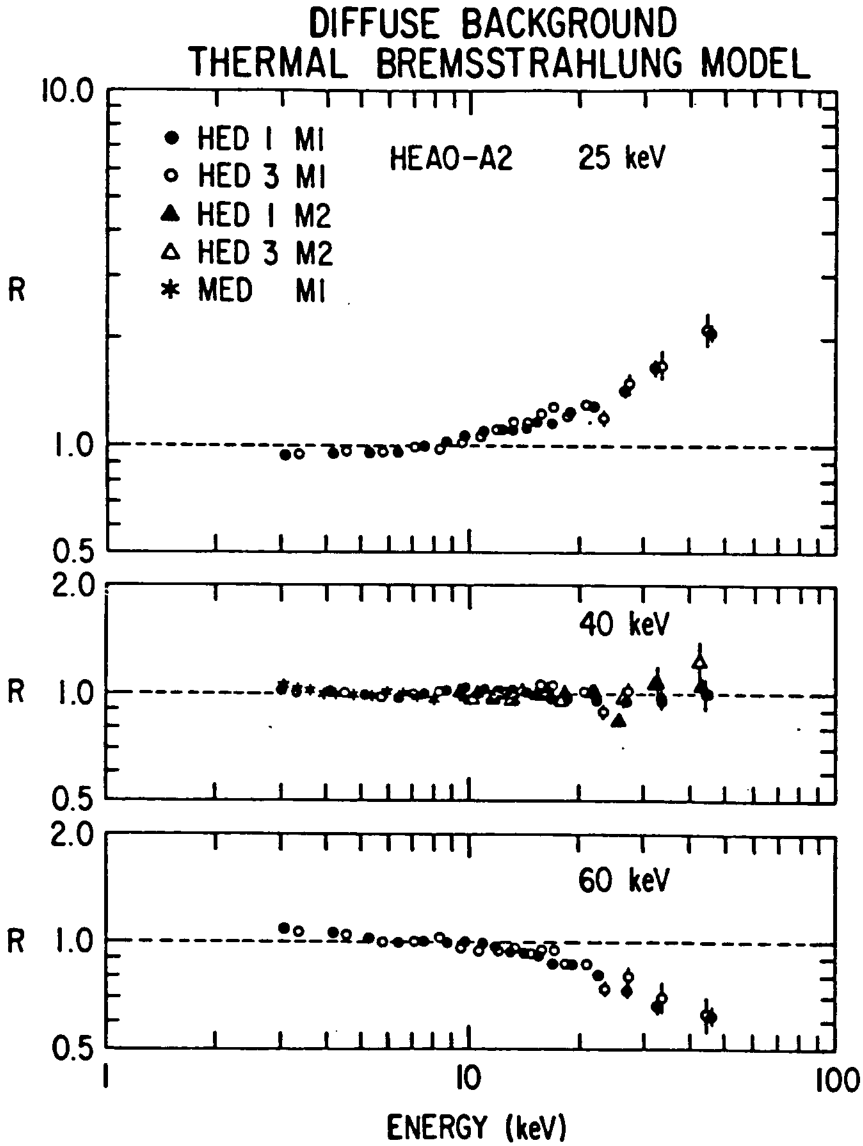

Figure 8. Marshall, F. et al., 1980, Astrophys. J., 235, 4, and Boldt, E., 1981, Comments on Astrophysics, 9, 97.

to discrete sources without evolution. They further questioned whether an evolving population (QSO's) would have the right spectrum to mimic thermal bremsstrahlung emission. They concluded that the measured spectrum strongly suggested that a substantial fraction of the background is due to a hot intergalactic gas with near closure density.

Several arguments have been raised against this interpretation. These are: (1) the argument of Field and Perrenod based on energetics; (2) the high density of the IGM in baryonic matter which is in contradiction with the value of $\Omega \approx .1\ \Omega_{crit}$ derived from deuterium abundances; (3) the existence of HI intergalactic clouds, which would evaporate in the presence of this postulated hot intergalactic medium; (4) the argument first proposed by Cavaliere and Fusco-Femiano [1976] and more recently discussed by Forman, Jones, and Tucker [1984] based on the existence of clusters; and (5) the realization that such good fits only hold over the restricted energy range 2 to 40 keV. At energies > 100 keV, the spectrum steepens significantly requiring, in the thermal bremsstrahlung interpretation, a higher temperature component of $\leqslant$ 95 keV, Schwartz [1978].

5. DIRECT MEASUREMENTS OF DISCRETE SOURCE CONTRIBUTIONS FROM "EINSTEIN" (HEAO-2)

The Einstein Observatory was used to study the contribution of discrete extragalactic sources to the background in a number of ways.

There are basically three methods to determine the contribution of a class of discrete sources to the background from the "Einstein" data:

(1) Direct measurement of Log N-Log S and identification of the extragalactic nature of the sources in the 0.5 to 3 keV energy range.

(2) Measurement of the X-ray luminosity function for a specific class of objects and knowledge of its evolution.

(3) Measurement of optical properties (luminosity function and evolution) of a specific class of objects and knowledge of their Lx/Lopt ratio.

All these methods have been employed by analysis of the Einstein data and have resulted in mutually consistent estimates of the contribution of sources to the background.

Method 1 was implemented through the deep surveys [Giacconi et al., 1979] which resulted in extending the Log N-Log S measurements by about three orders of magnitude from the Uhuru limit of 10^{11} erg cm^{-2} s^{-1}, 1-3 keV range, to 1.3×10^{-14} erg cm^{-2} s^{-1}. The medium Einstein survey [Maccacaro et al., 1982] filled the gap between these extremes. From integration of the Log N-Log S relation a background contribution of $\geqslant 35\%$ could be directly computed [Murray, 1981], Figure 9.

Method 2 was implemented by use of the medium survey data to obtain a local luminosity function for AGN's and the evolution parameter c in the assumption of a pure luminosity evolution [Maccacaro et al., 1983]. (The assumption of a density evolution could be shown to be inconsistent with the data.) Maccacaro estimated a contribution to the background of the evolving AGN's of $78\ ^{+35}_{-17}\ \%$. A lower limit to this contribution consistent with the range of parameters if 42%; the upper bounds exceed 100%.

Method 3 was implemented by using Einstein data on QSO's X-ray luminosity, determination of the ratio L_x/L_o and its dependence on L_o [Zamorani, 1982; Avni and Tananbaum, 1982; Maccacaro et al., 1983], and use of the optical evolutionary models to compute the contribution of QSO's to the background (BKG). Marshall reports a value of $75\ ^{+66}_{-32}\ \%$ [Marshall, 1983].

It is worth noting that Methods 2 and 3 are quite uncertain because they are to a degree dependent on a number of parameters describing the luminosity function, the limits of integration L_x min and L_x max, the evolutionary laws of the specific class of objects (for instance QSO's), as well as on the parameters of the assumed world models. It should also be noted that a substantial fraction of the sources that would give rise to the background have not been directly observed.

Furthermore, as pointed out by De Zotti et al. [1982] and Boldt and Leiter [1984], the sources which dominate the X-ray background cannot have spectra similar to the power laws measured locally for AGN's. It follows that the

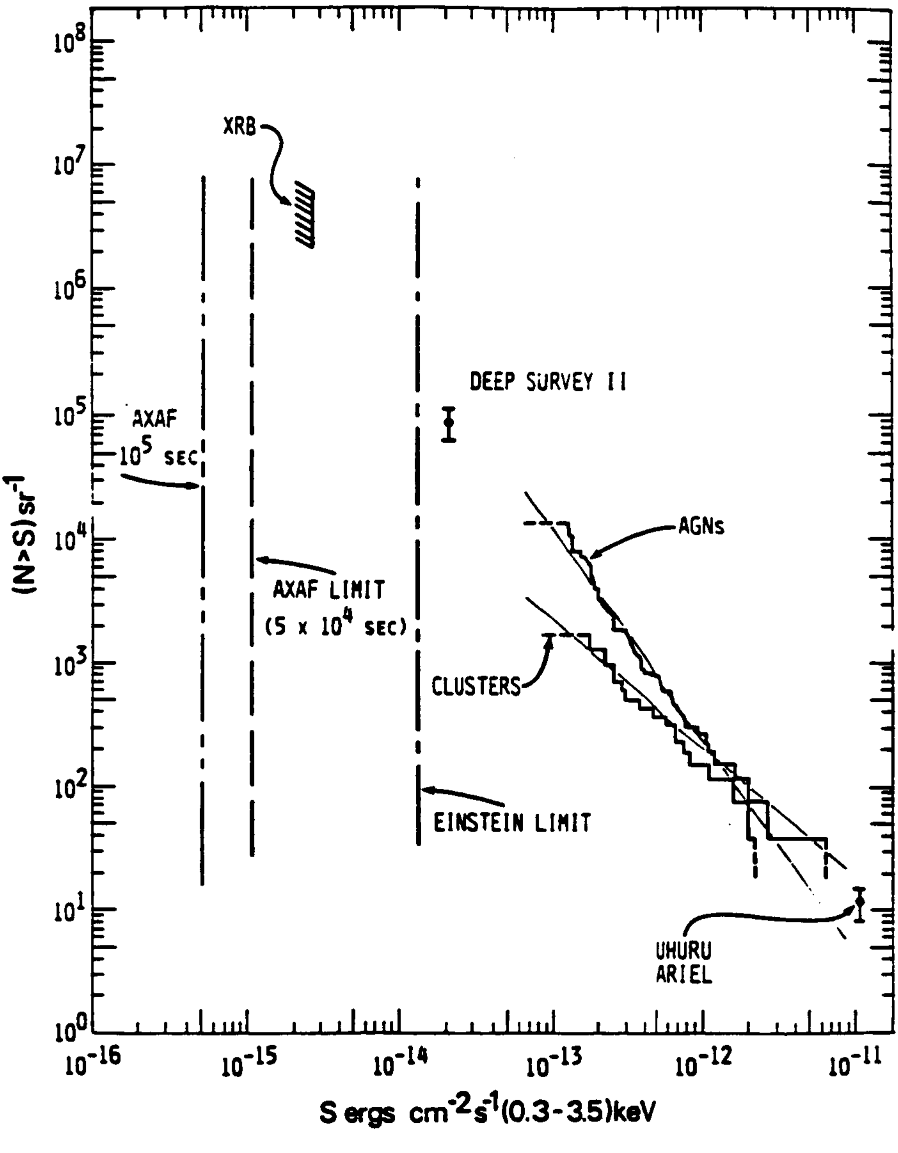

Figure 9. Shows Log N versus Log S as a function of S. The results from previous surveys are shown as well as the estimated limits of the AXAF survey here proposed.

objects must be either QSO's with characteristics different from that of the nearer QSO's or a different class of objects altogether (protogalaxies?). The fact that the spectrum must change renders the extrapolations necessary in Methods 2 and 3 even more uncertain.

The only certain assessment of the contribution of discrete sources to the X-ray background comes, therefore, from the extension of Log N-Log S to the Einstein limit. As to the nature of the objects, the current program of Deep Survey source identification yields mainly QSO's with $0.5 \leqslant Z \leqslant 2$ as optical counterparts of the extragalactic component.

6. CURRENT PROBLEMS AND POTENTIAL FOR FUTURE CLARIFICATION

The current situation can be summarized as follows:

(a) It is certain that a very substantial fraction of the X-ray background is due to the contribution of individual sources. The most complete current evaluation of the contribution from the different classes of objects is that of Schmidt and Green [1986]. The contributions to be expected as a function of increasing sensitivity of the surveys are shown in Figure 10.

(b) There is no direct evidence for the existence of a true diffuse component. Current estimates set an upper limit of 10-20%. These limits come from the current estimates of baryonic matter content from the existence of diffuse HI clouds in intergalactic space and from the survival of clusters; and may be somewhat relaxed by the recent arguments of Fabian on the effect of considering mildly relativistic effects on the gas emissivity [Fabian, 1984]. In order to invoke such effects, Fabian must postulate emission of gas with temperature ~200 keV at Z~5. (See comment below.) It should be noted that the fact that some 50% of the background is due to known individual sources makes it very unlikely that the remainder of the BKG can be explained as thermal bremsstrahlung emission from a hot thin gas. As noted by many authors [Boldt

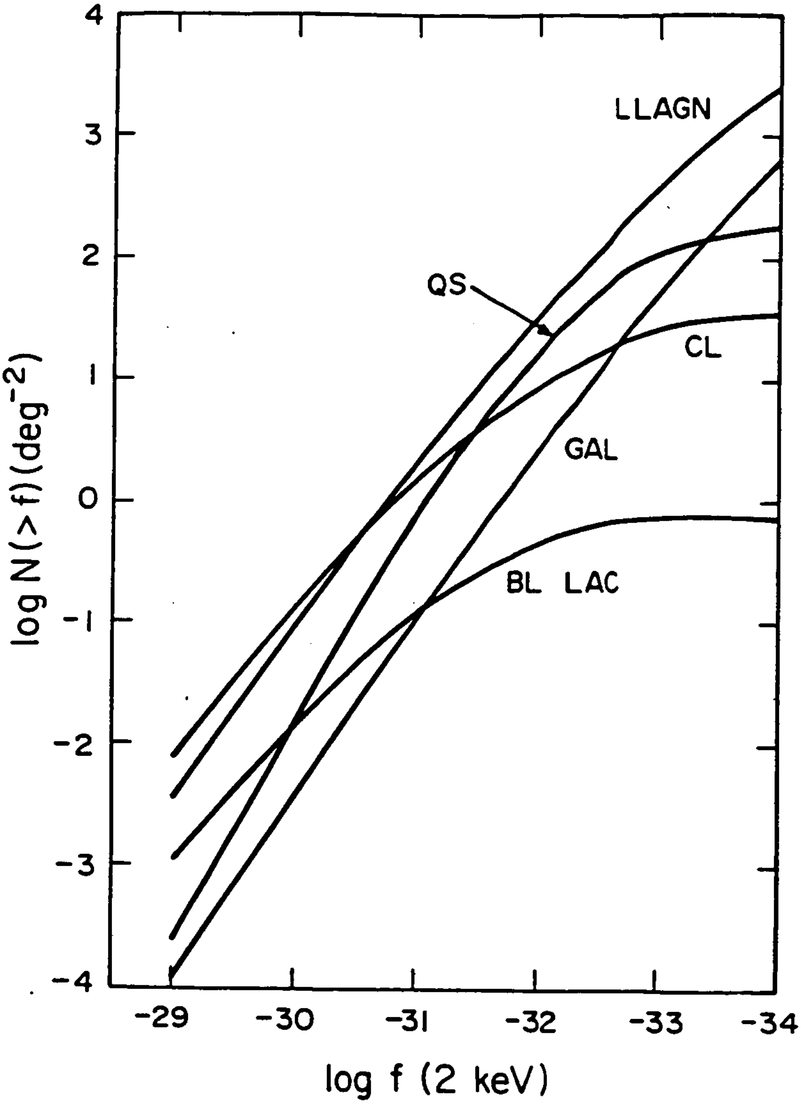

Figure 10. Schmidt, M., and Green, R. F., 1985, "Counts, Evolution and Background Contribution of X-ray Quasars and Other Extragalactic X-ray Sources," preprint.

and Leiter, 1984; Schmidt and Green, 1986], the spectrum of the remainder of the BKG, after subtraction of the known individual source contribution which is softer than the background, becomes very hard. Power laws of index $\pi < 0.2$ are required. In the thermal bremsstrahlung model, this would require $\geqslant 200$ keV at the source and, in order to obtain an effective K $\rightarrow$ at the current epoch of ~ 40 keV, one would require that the emission occur at Z $\gtrsim 6$ [Boldt and Leiter, 1984]. The existence of a heating mechanism for such a high temperature gas at such an early epoch is unknown and, perhaps, not entirely plausible.

(c) Therefore, it appears most likely that the remainder of the X-ray BKG originates in compact extragalactic sources of some kind capable of giving rise to the required hard spectral component. This requires a different emission spectrum from members of a known population (QSO's?) at an early epoch and/or evolutionary effects or a new class of objects (protogalaxies?). The study of this subject, therefore, offers a potential for exciting new discoveries. The most promising approach appears to be a refinement of the direct measurement of individual source contribution at ever smaller limiting fluxes, with high resolution instruments capable of directly imaging the background.

AXAF offers a very substantial opportunity to resolve this problem once and for all. By repeating the deep surveys with increased sensitivity it can extend Log N-Log S to fluxes more than one order of magnitude weaker than detected in Einstein, from 2×10^{14} to 10^{-15} erg cm^{-2} s^{-1} in the 1-10 keV range in 5×10^{4} sec. It can reach 5×10^{-16} erg cm^{-2} s^{-1} in the 1-10 keV range in 10^{5} sec. It can do so over fields of view of the same order as those used in the Einstein HRI deep survey provided that the HRI which ultimately is adopted has the sensitivities recently reported [Fraser and Pearson, 1983] or that a large format charge coupled device (CCD) is selected. Extension of the survey limit to $5 \times 10^{-16} - 10^{-15}$ erg cm^{-2} s^{-1} (1-10 keV) brings us to a range of fluxes such that we must observe a turnover in the Log N-Log S relationship in order not to exceed the X-ray background. In addition, the AXAF angular resolution of a 0.5 arc-sec will provide the necessary precision to carry out a program of source identifications. It should be noted that this precision is essential. It was only after the positions for Einstein HRI sources were refined to a few arc-seconds that one and only one optical counterpart would be identified for all X-ray sources. [Some counterparts were found in J plates at magnitudes 20 to 23, Griffith et al., 1983.]

If Lx/Lopt ratios observed in Einstein are maintained for the sources found in these surveys, it follows that when we increase the X-ray sensitivity by factors of 20-40, we will need to observe optical counterparts fainter by three or four magnitudes. We can expect, therefore, that the optical counterparts at the AXAF survey limit will be in the range of m = 24-27. Detection and identification of these objects will require in all probability use of the space telescope (ST) imaging and spectroscopy instruments.

The expected returns from this survey are:

(a) A new determination of Log N-Log S for extragalactic X-ray sources to Smin $\approx 5\times10^{-16}$ erg cm^{-2} s^{-1} (1-10 keV).

(b) A complete X-ray selected sample of 500 to 2500 X-ray sources with fluxes between 5×10^{-16} and 2×10^{-14} erg cm^{-2} s^{-1} (1-10 keV), per square degree surveyed [see for instance estimates derivable from Schmidt and Green, 1986]. This sample will probably consist of QSO's at high redshifts, or clusters or protoclusters and possibly protogalaxies.

Additional work on this survey might include:

(1) Measurement of source position and extent [clusters should have core radius of ~ 20 arc-sec, Bahcall, 1979].

(2) X-ray spectral measurements of individual sources to determine spectral shape for point sources.

(3) X-ray spectral measurements of individual extended sources to determine the presence of emission lines, in particular redshifted Fe Ka emission.

(4) Optical identification and broadband spectroscopy of the candidate objects.

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