THE X-RAY BACKGROUND

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ABSTRACT

Various models of the X-ray background are discussed. It is postulated that the only explanation consistent with all the existing data is discrete sources. Present observational material suggests that known classes of active galactic nuclei also dominate the source counts below the lowest detectable flux levels.

1. MODELS FOR THE X-RAY BACKGROUND

Discussion of what physical processes are responsible for the diffuse X-ray background (XRB) has lasted for almost 30 years following its discovery by Giacconi et al. (1962). In this review I will concentrate on the more recent data gathered by means of various X-ray devices aboard satellites launched in the late '70s and '80s.

We start with a familiar picture of a spectrum of the electromagnetic radiation filling the Universe (fig. 1). The X-ray part is marked schematically; the exact shape of the spectrum will be discussed below. See the paper of De Zotti and Burigana here for discussion of the optical and IR bands.

From fig. 1, we see that the density of radiation in the X-ray domain is close to 0.01 of the radiation density in the optical + IR. Cowie (1989) pointed out that this relatively high ratio of X-ray to optical + IR intensity effectively precludes models in which X-rays are produced during some stages of stellar evolution, viz. in X-ray binaries and supernova explosions. This is because in both cases the total energy emitted in the optical region due to thermonuclear reactions exceeds by more than a factor 100 the energy released in the X-ray region. This constraint is not valid for the X-ray emission of AGN, however: the ratio of L_X/L_{opt} is sufficiently large to compensate for the relatively small contribution of AGN to the EBL (Soltan, 1982; Cowie, 1989).

A model of the XRB in which high energy photons result from inverse Compton scattering of starlight by relativistic electrons was

J. Bergeron (ed.), Highlights of Astronomy, Vol. 9, 299–308.

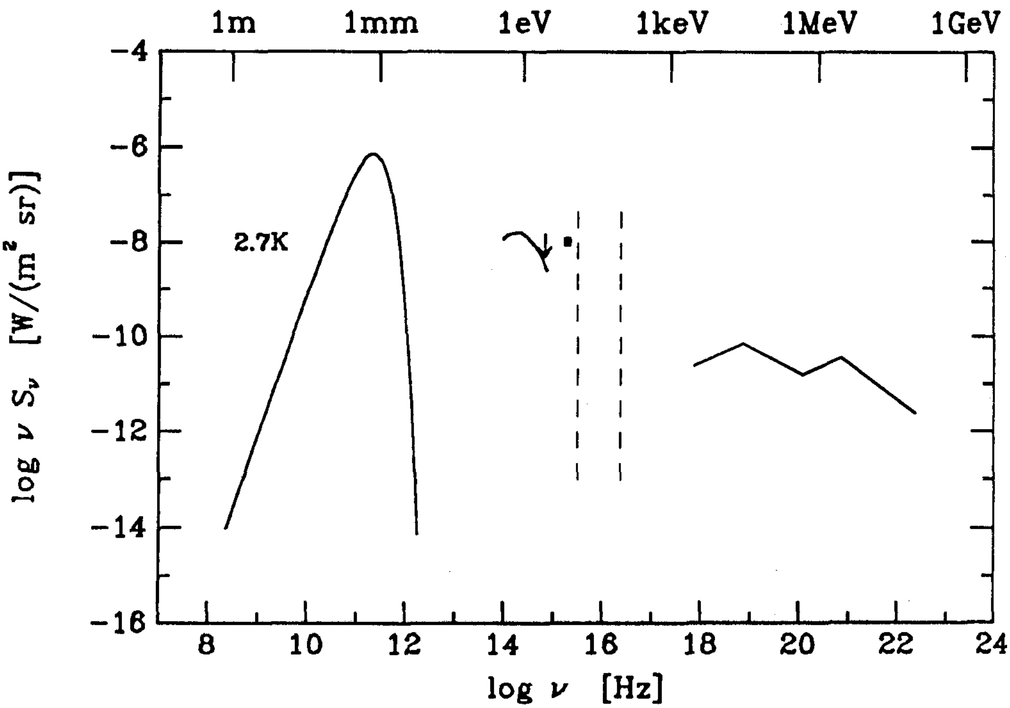

Fig. 1 Schematic view of the electromagnetic spectrum of background radiation. See fig. 2 of De Zotti and Burigana for detail. The far IR part is omitted because it is dominated by local sources in our Galaxy. Dashed lines denote the inaccessible region of the extragalactic background due to absorption by neutral gas in our Galaxy.

proposed by Felten and Morrison (1963). Similar calculations using the blackbody relict photons were performed by Fazio et al. (1966). Although it is now believed that this mechanism is not adequate to explain the spectrum of the entire XRB (Cowsik and Kobetich, 1972), it is mentioned here because its validity in the high energy γ region (above ~10 MeV) is not ruled out.

Thus we are left with three general possibilities regarding the origin of the XRB:

a. truly diffuse emission by hot plasma
b. discrete sources (dominated by AGN's)
c. some exotic processes (or models).

Into the last category (c) we include (among others) models which utilize non-standard cosmologies. In the following I shall consider only the two first points (a, b).

For many years the first possibility was tempting due to the apparent conformity of the spectrum emitted by hot optically thin plasma and the observed XRB (e.g., Subrahmanyan and Cowsik, 1989). Fig. 2 (based on the compilation by Boldt, 1987 and Fabian et al, 1989) shows both the X- and γ-ray intensities. Here we are interested in the lower energy part. It appears that for $3 \leq E \leq 100$ keV the spectrum is fitted by thermal bremsstrahlung with $kT \approx 40$ keV ($T \approx 5\times10^{8}$ K). Below 3 keV only upper limits are available and smooth extrapolation of the XRB data from $E \geq 3$ keV to the *EINSTEIN* domain (~0.15 to ~3.5 keV) has no observational ground. Upper limits for the XRB at ~2 keV are above the usually assumed extrapolated level by a factor 1.5-2. Systematic slope changes with energy are shown using power law fits ($I \sim E^{-\alpha}$) to the observed XRB:

Energy range (keV)	α
3-10	0.4
10-30	0.7-0.8
30-100	~1.5

A question of the contribution of discrete sources to the XRB is discussed below. It is now widely accepted that at least 50 percent of the nominal background at 2 keV is produced by discrete sources (e.g., Hamilton and Helfand, 1987; Soltan, 1991). Giacconi and Zamorani (1987) pointed out that the remaining "residual" background has extremely flat spectrum ($\alpha \leq 0.2$ at $3 \leq E \leq 10$ keV), incompatible with the thermal bremsstrahlung. Similar conclusions were reached by Boldt (1989) who found that if more than ~30 percent of the XRB at 3 keV is produced by sources with the energy index $\alpha = 0.7$ the residual diffuse component cannot be produced by a hot thin plasma at redshift $z \leq 8$. A flat slope of the residual spectrum results from the assumption that discrete sources in fact have steep spectra ($\alpha \geq 0.7$) in the range 3-10 keV. However, if the foreground sources--on the average--have spectral slope similar to the XRB, no restrictive constraints are imposed on the diffuse part of the XRB. Giacconi and Zamorani noticed that in the latter case, the most straightforward conclusion is to assume that the whole XRB is produced by discrete sources and the contribution of thermal bremsstrahlung is negligible. The last statement--attractive mainly from methodological point ("*Entities are not to be multiplied beyond necessity*"; William of Ockham, ~1285 to 1349)--has been confirmed recently by the *FIRAS* experiment on *COBE* satellite (Mather et al. 1990).

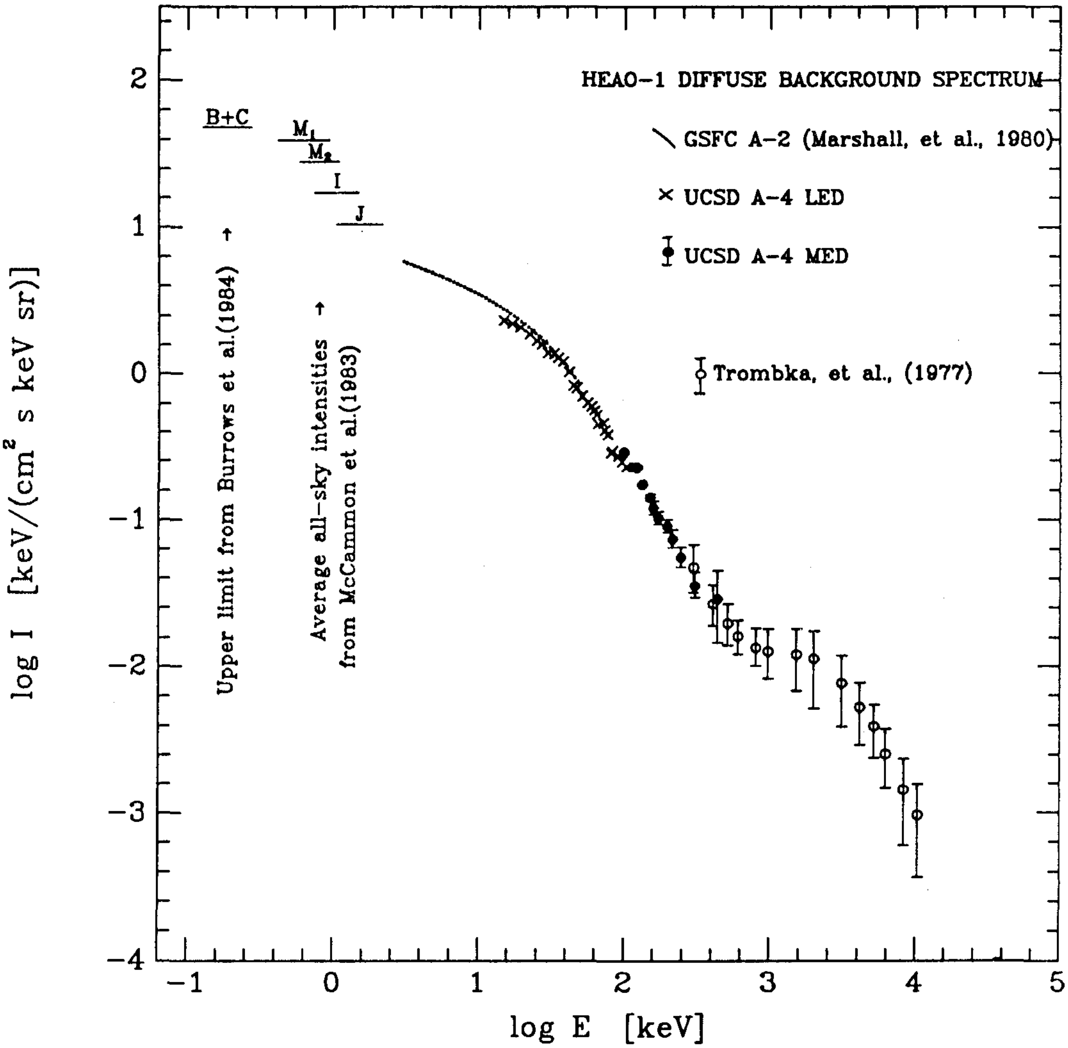

Fig. 2 X- and γ-ray background spectrum (see text for references).

2. AGN AS THE SOURCE OF THE XRB

Various subclasses of AGN have frequently been proposed as the main contributors to the XRB. Before I discuss this model in detail,

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some information on clusters of galaxies seems appropriate. At high fluxes (say, above the *UHURU* sensitivity limit $\approx 3\times10^{-11}$ erg s^{-1} cm^{-2} at 2–6 keV), clusters constitute $\geq$ 50 percent of all the extragalactic sources. However, at low flux levels their contribution diminishes. A log N – log S relationship for clusters is not well determined, but a recent estimate of the cosmological evolution of X-ray properties of clusters (Gioia et al. 1991) shows that the present volume density of high luminosity clusters is greater than it was in the past. This result is based on *EINSTEIN* observations of 67 X-ray selected clusters with redshifts $0.14 \leq z \leq 0.60$. Various estimates (assuming no evolution) of the cluster contribution at 2 keV based on the *HEAO* 1 A-2 sample (Piccinotti et al., 1982) are at or below 10 percent (Schmidt and Green, 1986); adding evolutionary effects, the actual contribution is smaller. Because of the thermal spectral shape with kT ~6 keV, cluster emissivity at higher energies becomes negligible compared to AGNs. Prior to the launch of the *EINSTEIN* satellite other classes of extragalactic objects were recognized as potential sources of the XRB (Seyferts, QSOs). Observations made with the *EINSTEIN* X-ray telescope revealed that practically all types of AGNs are strong X-ray emitters. Many authors analyzed relationships between X-ray luminosity and luminosities in the optical, IR and radio bands (e.g., Tananbaum et al., 1979; Ku et al., 1980; Kamorani et al., 1981; Kriss and Canizares, 1985). Definite correlations between L_X and L_{opt}; L_X and optical spectral features; and L_X and radio activity have been found. These correlations were used to calculate the total X-ray volume emissivity of various types of AGNs selected by their optical and/or radio properties (e.g., Elvis et al, 1984; Avni and Tananbaum, 1986; Schmidt and Green, 1986). Estimates of the fractional AGN contribution to the XRB range from ~0.3 to 1. Large discrepancies between various estimates are caused by different assumptions made when extrapolating the X-ray properties of a small sample of observed objects to the whole population of AGNs. For instance, the conclusion of Avni and Tananbaum (1986) that the calculated X-ray number counts are sensitive to the shape of the L_X/L_{opt} distribution and to the functional form of the evolution and optical luminosity function reflects present uncertainty of estimates of AGN contribution to the XRB.

We may conclude that the available data on many samples of AGNs are not sufficient to determine either the contribution to the XRB of various classes of these objects (QSOs, Seyferts, low luminosity AGNs) or the total AGN contribution. In the rest of my talk I would like to address a less ambitious question: are the available data consistent with the conjecture that the entire XRB is produced by a population of faint discrete sources which are similar to sources detected with the present-day devices at higher flux levels and smaller distances?

The most direct data to solve this question are X-ray source counts at low flux levels (Giacconi et al., 1979; Griffiths et al, 1983, 1988; Primini et al., 1991). The *EINSTEIN* Deep Survey (EDS) revealed population of faint sources with fluxes $3\times10^{-14} \leq S$ (0.8–3.5

keV) $\leq 7\times10^{-13}$ erg s^{-1} cm^{-2}. Subsequent optical identification and spectroscopic work showed that the majority of sources (apart from galactic stars) are QSOs of low and moderate redshifts. In the soft X-rays at the EDS limit, discrete sources produce ~20 percent of the XRB with 1σ limits of 16 and 25 percent (Primini et al. 1991). The distribution of sources on the redshift-X-ray luminosity plane is shown in fig. 3. The elongated cluster of points extending from $z \sim 0.001$ and $L_X \sim 0.001$ to $z \sim 0.2$ and $L_X \sim 100$ shows a complete sample detected in the *HEAO* 1 A-2 experiment at 2-10 keV (Piccinotti et al., 1982). Points distributed between ~0.1 and 1 in z and 0.1 and 10 in L_X are identified sources with spectroscopic redshifts from the EDS (Primini et al. 1991). Number counts in the EDS are consistent with the Extended Medium Sensitivity Survey (EMSS, Gioia et al., 1990).

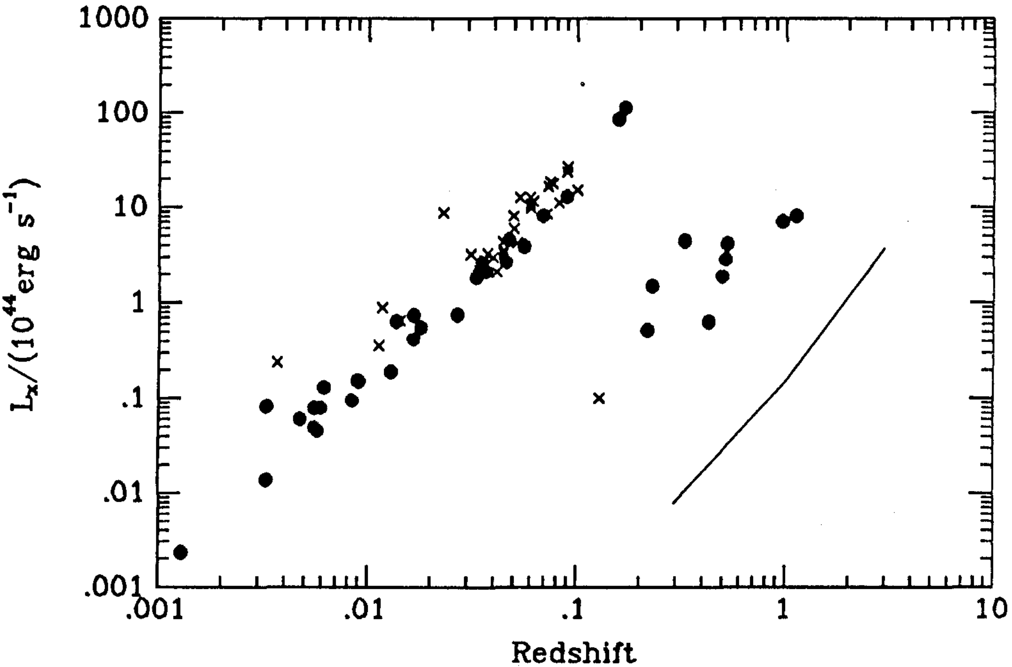

Fig. 3 Distribution of sources on the redshift-X-ray luminosity plane in the *HEAO* 1 A-2 and EDS samples: crosses--clusters of galaxies; filled circles--active galactic nuclei. Solid curve shows the predicted position of sources producing the XRB (see text).

Smooth extrapolation of the log N - log S relation down to fluxes 20-25 times fainter than the EDS limit reaches the point where the entire XRB is produced by discrete sources. The solid curve on fig. 3 shows the predicted position of those sources. Fig. 4 gives the

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distribution of the EMSS sources on the z-L_X plane. Although *HEAO* 1 and *EINSTEIN* data refer to different energy bands (2-10 keV vs. 0.8-3.5 keV) some general trends in both figures are significant. First, there is a systematic shift towards higher X-ray luminosities of the *EINSTEIN* sources as compared to the *HEAO* 1 sample. The apparent deficiency of *EINSTEIN* sources with $L_X \leq 10^{43}$ erg s^{-1} is consistent with the recent finding in EXOSAT observations (Turner and Pounds, 1989) that low luminosity AGN generally have the highest absorption. Warwick and Stewart (1989), using spatial fluctuations measured by *HEAO* 1 and *GINGA* detectors, obtained estimates of the log *N* - log *S* relationship for source densities corresponding to the EMSS. They found that normalization of counts in the 2-10 keV energy band is a factor of ~3 above that for the soft *EINSTEIN* band. To reconcile source counts in both energy bands they have to assume that either the spectral slope of X-ray sources is ~0.4 rather than canonical value of ~0.7 or substantial number of sources have cut-off spectra at low energies. Thus, the effects of absorption detected by Turner and Pounds for objects with $L_X \leq 10^{43.5}$ erg s^{-1} seem to be present in the entire population of X-ray sources. Another important implication is that integrated flux of discrete sources with steep power law spectra (α ~ 0.7) and low energy absorption mimics the flat background spectrum (α ~ 0.4) (see also Grindlay, 1988).

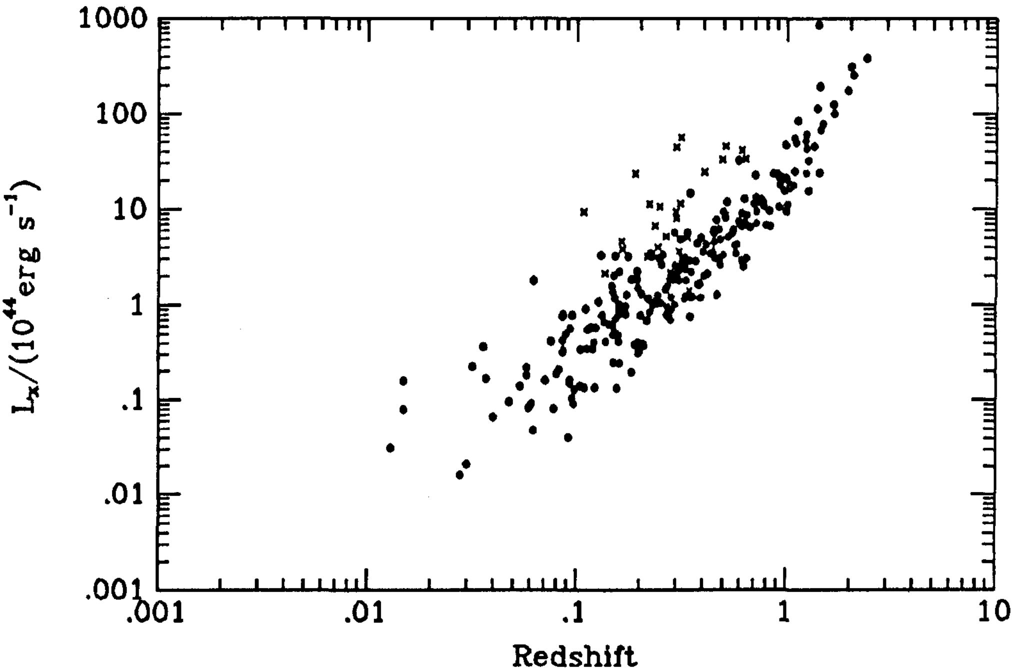

Fig. 4 Same as fig. 4 for the AGNs found in the EMSS. Filled circles denote active galactic nuclei; crosses--BL Lac objects.

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A second inference from fig. 4 could be that evolution of high luminosity AGNs is stronger than that of low luminosity ones. Rapid cosmological evolution makes sources with fixed L_X pack tightly near the maximum redshift defined by survey sensitivity limit. This effect is expected because of the $L_X \sim L_{opt}$ correlation and the fact that in the optical band bright sources are subject to stronger evolution (e.g., Petrosian, 1973; Schmidt and Green, 1983), the so-called luminosity dependent density evolution. Although the number of BL Lac objects is too small to draw firm statistical conclusions on their evolution, it seems that the rate of evolution of those objects is not as rapid as other AGN of comparable X-ray luminosity.

Finally, one can estimate from fig. 3 that for luminosities typical for the EDS, the redshifts of objects producing the XRB are in the range of ~1 to 3-4, which matches the general QSO population.

Soft X-ray observations (Wilkes and Elvis, 1987; Canizares and White, 1989) show that AGNs (including QSOs) have strong excess soft emission. Power law fits in the *EINSTEIN* IPC band are significantly steeper than the standard value of 0.7 from higher energies (2-10 keV). Radio quiet quasars, which are supposed to be a major contributor to the XRB have α typically in the range ~1 to ~1.3. At present almost all measurements are limited to nearby Seyferts and QSOs ($z \leq 0.6$) and the average slope at the IPC energies of high redshift QSOs is very uncertain (Canizares and White, 1989). It is quite probable that the soft energy excess (common in nearby quasars) is shifted below ~0.6 keV in more distant objects ($z \geq 2$). Nevertheless, if such steep slope ($\alpha \geq 1.0$) is confirmed in the high redshift quasars in general, then either the data become incompatible with the upper limit for the XRB at ~0.2 keV measured by Burrows et al. (1984), or QSOs contribute less than 46 percent to the XRB at 2-10 keV (Fabian et al. 1989).

I have mentioned earlier a possible explanation of the apparent discrepancy between flat XRB spectrum between ~3 and ~10 keV and a steep spectral slope of nearby Seyfert galaxies by using a low energy absorption frequently observed in the low-luminosity AGNs. Another explanation is proposed by Pounds (1989). Accurate *GINGA* observations of 3 nearby Seyfert galaxies allowed for detailed spectral fitting. Apart from the iron line and edge below 10 keV, a hard X-ray tail above ~12 keV has been detected. It is interesting to note that the spectral slope between 10 and 35 keV of ~0.45 was obtained. This value closely corresponds to the XRB below ~10 keV. Thus, the required "effective" redshift of AGNs forming the XRB is about 3. The observational indication that the AGN spectra on the average harden above ~10 keV conveniently fits to the ad hoc suggestion by Schwartz and Tucker (1988) that the AGN spectra are not exact power laws between 3 and 100 keV. They showed that if the AGN spectra become flatter at higher energies, both the spectrum and intensity of the XRB can be explained.

The fundamental assumption made at the beginning of this (incomplete) review of the X-ray background was that the number counts defined by the EMSS and EDS can be extrapolated with constant slope to the flux level of $1\text{-}2\times10^{-15}$ erg s^{-1} cm^{-2} (0.8-3.5 keV). Investigation of count fluctuations in the IPC field of view by Hamilton and Helfand (1987) and Barcons and Fabian (1990) shows that the log *N* - log *S* relation flattens at a flux level 3-4 times below the EDS limit. It implies that a larger number of sources per square degree (>5000) is required to explain the XRB as compared to the smooth extrapolation (<2000). Recently I have made a similar analysis (Soltan, 1991) and found that the EINSTEIN data are insufficient (in terms of statistics) to put restrictive constraints on the log *N* - log *S* relationship, though the observed amount of fluctuations favors relatively small source densities. *ROSAT* results show that in the soft X-ray band the source counts show significant flattening below the EDS limit (Hasinger et al., 1991). However, at the lowest flux levels there seems to be a turn-on in this relationship and only ~200 sources per sq. deg. produce almost half of the background (Hasinger, 1991). Obviously, if the assumption of the smooth number counts extrapolation is relaxed, one is not able to specify region on the $z\text{-}L_X$ plane (fig. 3) occupied by sources contributing substantially to the XRB. I am not sure that speculations on this subject would be conclusive and I look forward to the *AXAF* era.

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