THE X–RAY BACKGROUND: OBSERVATIONS

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1. INTRODUCTION

It is a heavy responsibility for me, as it would be for everybody else, to give a paper on the X–ray background (XRB) in this particular meeting, held in honour of Riccardo Giacconi. Everybody knows the enormous contribution that Riccardo has given to the development and better understanding of the subject from the very beginning 30 years ago up to now. A significant fraction of the results which I will describe in this paper either are his own results or are based on experiments which he conceived and led to success.

In Section 2 I will give a brief historical overview of the XRB problem, from its discovery up to the results obtained in the eighties with the HEAO–1 and EINSTEIN missions. During these years the origin of the XRB has been discussed mainly in terms of two alternative interpretations: the truly diffuse hypothesis (e.g. hot intergalactic gas) and the discrete source hypothesis. The existence of these radically alternative hypotheses has not been “neutral” with respect to devising experiments which wanted to study the XRB. In fact, if the XRB is mainly due to discrete sources, experiments aimed at studying the single sources responsible for it obviously need high angular resolution in order to study and resolve the large number of expected faint sources. Vice versa, if the XRB is mainly diffuse, source confusion is not a problem anymore and one could safely abandon the high angular resolution option. In this case the crucial experiment would be a measurement as accurate as possible of the spectrum in order
to reveal the physical production processes. The two working hypotheses led various groups of scientists to design very different sets of experiments (Giacconi and Burg 1992). In Section 3 I will show some recent results from deep surveys with ROSAT. These surveys have already resolved into discrete sources $\sim 60\%$ of the measured XRB in the 1–2 keV band. The available optical identifications, still in progress, suggest that AGNs are the dominant population at these faint X–ray fluxes. Finally, in Section 4 I will discuss some recent results on the X–ray spectra of AGNs at higher energy and a few models which, making use of these data, are able to produce acceptable fits to the spectrum of the XRB up to about 100 keV.

2. EARLY HISTORY

The existence of a diffuse XRB was discovered more than thirty years ago (Giacconi et al. 1962). Figure 1 shows data from the discovery flight. It is interesting to note that in these data both the diffuse emission and a strong source (i.e. the two elements which became the basis for the two main hypotheses for the production of the XRB) are already present. The first important step with respect to our knowledge of the XRB has been made with the first all–sky surveys (UHURU and ARIEL V) at the beginning of the seventies. The high degree of isotropy revealed by these surveys led immediately
to realize that the origin of the XRB has to be mainly extragalactic. Moreover, under the discrete source hypothesis, the number of sources contributing to the XRB has to be very large ($N > 10^6 \, \text{sr}^{-1}$; Schwartz 1980).

In the same years a number of experiments were set up to measure the spectrum of the XRB over a large range of energy. It was found that over the energy range 3–1000 keV the XRB spectrum is reasonably well fitted with two power laws with slopes $\alpha_1 \sim 0.4$ for $E \leq 25$ keV and $\alpha_2 \sim 1.4$ for $E > 25$ keV (see Figure 1 in Tanaka 1992).

At the beginning of the eighties two different sets of measurements led additional fire to the debate between supporters of the discrete source and diffuse hypotheses. On the one hand, the excellent HEAO–1 data showed that in the energy range 3–50 keV the shape of the XRB is very well fitted by an isothermal bremsstrahlung model corresponding to an optically thin, hot plasma with $kT$ of the order of 40 keV (Marshall et al. 1980). Moreover, it was shown by Mushotzky (1984) that essentially all the Seyfert 1 galaxies with reliable 2–20 keV spectra ($\sim 30$ objects, mostly from HEAO–1 data) were well fitted by a single power law with an average spectral index of the order of 0.65, significantly different from the slope of the XRB in the same energy range. These two observational facts were taken as clear “evidences” in favour of the diffuse thermal hypothesis. On the other hand, the results of the EINSTEIN deep surveys showed that about 20% of the soft XRB (1–3 keV) are resolved into discrete sources at fluxes of the order of a few $\times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}$ (Giacconi et al. 1979, Griffiths et al. 1983, Primini et al. 1991, Hamilton et al. 1991). A large fraction of these faint X–ray sources have been identified with Active Galactic Nuclei (AGNs). Because of the difference between the spectra of the XRB and those of the few bright AGNs with good spectral data, the supporters of the diffuse, hot plasma hypothesis had to play down as much as possible the contribution of AGNs to the XRB to a limit which was close to be in conflict with an even mild extrapolation of the observed log $N$ − log $S$. Actually, a number of papers were published in which it was “demonstrated” that even in the soft X–ray band AGNs could not contribute much more than what had already been detected at the EINSTEIN limit.

At that time I personally think that there were already evidences (for those who wanted to see them...) that the diffuse thermal emission as main contributor to the background was not tenable (see, for example, Setti 1985). Very simple arguments in this direction were given by Giacconi and Zamorani (1987). On the basis of reasonable extrapolations of the X–ray properties and the optical counts of known extragalactic X–ray sources (mainly AGNs and galaxies), they concluded that it is unlikely that their contribution to the soft X–ray background is smaller than 50%. Given this constraint, they then discussed two possibilities:
i) either faint AGNs have the so-called (at that time) “canonical” spectrum observed for brighter AGNs. In this case the residual XRB (i.e. the spectrum resulting after subtraction of the contribution from known sources) would not be fitted anymore by optically thin bremsstrahlung;

ii) or spectral evolution for AGNs is allowed. In this case, in order not to destroy the excellent thermal fit in the 3–50 keV data, diffuse emission could still be accommodated only if discrete sources have essentially the same spectrum as the XRB. On this basis, they concluded that “since in this scenario we would already require that the average spectrum of faint sources yielding 50% of the soft XRB is essentially the same as the observed XRB, there is nothing that prevents us from concluding that the entire background may well be due to the same class of discrete sources, at even fainter fluxes”.

In other words, reversing the usual line of thought, the excellent thermal fit of the 3–50 keV XRB spectrum was shown by these arguments to be a point in favour of the discrete source hypothesis, rather than of the hot gas hypothesis! These conclusions, however, were not well received in a large fraction of the X-ray community; probably, they had the defect of being too simple and direct...

Thus, the debate between the supporters of the two hypotheses continued, until the final resolution of the controversy came from the incredibly neat results obtained with the FIRAS instrument on board COBE: the absence of any detectable deviation from a pure black body of the cosmic microwave background set an upper limit to the comptonization parameter $y < 10^{-3}$ (Mather et al. 1990), more than ten times smaller than the value required by the hot intergalactic gas model. The most recent upper limit for the comptonization parameter is now $y < 2.5 \times 10^{-5}$ (Mather et al. 1993). Discussing these data, Wright et al. (1993) conclude that a uniform, hot intergalactic gas produces at most $10^{-4}$ of the observed XRB!

3. ROSAT DEEP SURVEYS DATA

3.1 The log N – log S relation

Having the COBE data definitely eliminated the possibility of an important contribution of diffuse gas emission to the XRB, the important question to be addressed is now: what are the sources that are responsible for the observed XRB? In this Section I will discuss some recent results, relevant to this question, obtained with ROSAT.

The good angular resolution and sensitivity of the Position Sensitive Proportional
Counter aboard ROSAT have allowed to extend to significantly lower fluxes the deep imaging studies first performed with EINSTEIN. The deepest ROSAT image has been obtained by Hasinger et al. (1993) in the direction of the Lockman Hole, characterized by an extremely low neutral hydrogen column density. A total of 152 ksec of PSPC observations have been accumulated in this pointing. Seventy–five sources have been detected in the hard (0.4–2.4 keV) ROSAT band in the inner 15.5 arcminutes, corresponding to a surface density of about 360 sources/sq.deg. These data have been used by Hasinger et al., together with additional data from 26 other shallower ROSAT exposures, to obtain the log N – Log S relation shown in Figure 2. The total number of sources used in the construction and analysis of the log N – log S relation is 661 and they cover a range of more than two decades in flux.

The observed flux distribution of these sources has been fitted with a model in which the differential counts \( N(S) \) are represented by two power laws:

\[
\begin{align*}
N(S) &= N_1 \times S^{-\beta_1} \quad \text{for} \quad S > S_b \\
N(S) &= N_2 \times S^{-\beta_2} \quad \text{for} \quad S < S_b.
\end{align*}
\]

After detailed Monte Carlo simulations aimed at understanding and correcting all possible systematic effects present in the source detection procedure, the best fit parameters obtained for the above parameterization are: \( \beta_1 = 2.72 \pm 0.27, \beta_2 = 1.94 \pm 0.19, S_b = (2.66 \pm 0.66) \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1} \).

In order to obtain constraints on the shape of the log N – log S relation below the discrete source detection threshold, a fluctuation analysis of the intensity distribution in the inner region of the Lockman field has been performed. On the basis of extensive simulations, which took into account all known systematic instrumental effects, it has been obtained the 90% confidence region shown by the dotted area at faint fluxes in Figure 2.

In summary, the main results of this analysis of the ROSAT log N – log S relation are:

a) There is a reasonably good agreement between the ROSAT log N – log S and the EINSTEIN EMSS (Extended Medium Sensitivity Survey) source counts in the flux range where both surveys have good statistics.

b) There is a highly significant flattening of the log N – log S relation at a flux of \( \sim 2.5 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1} \). The need for such a flattening had already been inferred by fluctuation analyses of the EINSTEIN deep survey fields (Hamilton and Helfand 1987; Barcons and Fabian 1990).

c) The integral surface density of X–ray sources above a flux of \( 2.5 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \),
resulting from the integration of the log N – log S shown in Figure 2, is $\sim 410 \text{ deg}^{-2}$ and the corresponding integrated flux amounts to $\sim 60\%$ of the measured XRB in the 1–2 keV band.

d) The flattest power law extrapolation allowed by the fluctuation analysis resolves 85\% of the background, while the steepest allowed slope resolves all of the background already at a flux of $\sim 10^{-16} \text{erg cm}^{-2}\text{s}^{-1}$, i.e. only a factor $\sim 20$ below the flux limit of the resolved sample.

**Figure 2.** Integral source counts for ROSAT data. The dash–dotted line represents the best fit to the EINSTEIN Medium Sensitivity Survey total sample (i.e. galactic and extragalactic). The open circle represents the EINSTEIN Extended Deep Survey point. The dotted area at faint fluxes shows the 90\% confidence regions from the fluctuation analysis of the deepest ROSAT field in the Lockman Hole (Hasinger et al. 1993).
3.2 The optical identifications

The X–ray log N – log S shown in Figure 2 includes all the X–ray sources, without any selection on the basis of the optical counterparts. The obvious questions now are: which fraction of these sources are extragalactic? what are the optical identifications of these sources? Systematic work aimed at identifying the optical counterparts of faint ROSAT sources is in progress. Such a work requires a large amount of telescope time because of the faintness of some of these counterparts. Typical magnitudes for various classes of sources with a ROSAT flux $\sim 10^{-14} erg cm^{-2} s^{-1}$ are shown in Table 1; these magnitudes have been estimated on the basis of the typical X–ray to optical ratios of the about 800 X–ray selected sources of the EMSS (Maccacaro et al. 1988).

At a flux limit of $S_x \sim 10^{-14} erg cm^{-2} s^{-1}$ there are at least four ROSAT fields with a high percentage of optical identifications already available. These fields are the Lockman and the Marano fields, studied by Hasinger and collaborators, and the QSF1 and QSF3 fields studied by Boyle, Shanks and collaborators. While the spectroscopic observations for the optical identifications of the Lockman field have been obtained after acquiring the ROSAT data (Schmidt et al., in preparation), the other three fields had already been studied spectroscopically before the ROSAT data in order to obtain complete optically selected samples of AGNs with $m_B \leq 22.0$ (Marano, Zamorani and Zitelli 1988; Zitelli et al. 1992; Boyle et al. 1990). X–ray data and a discussion of the optical identifications of the QSF1 and QSF3 fields have been presented by Shanks et al. (1991) and Boyle et al. (1993). The total number of X–ray sources with $S_x \geq 10^{-14} erg cm^{-2} s^{-1}$ in the inner regions of these four ROSAT fields is 119; 90 of these sources ($\sim 76\%$) have already been classified spectroscopically. The results of this identification process are shown in Table 2, along with a comparison with the almost

### Table 1

| Objects          | $m_v$     |
|------------------|-----------|
| B - F stars      | 10.0 – 14.5 |
| M stars          | 13.5 – 19.5 |
| Normal Galaxies  | 16.0 – 19.0 |
| AGNs             | 18.5 – 23.5 |
| BL Lacs          | 21.5 – 25.0 |

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complete identifications of the EMSS survey (Stocke et al. 1991).

Most of the objects still without optical identifications are optically faint and therefore are likely to be extragalactic (see Table 1). In addition to AGNs, BL Lacs and galaxies, some of these sources will turn out to be clusters. Although a few possible cluster candidates have already been identified, no percentage for clusters in the Rosat deep surveys has been given in Table 2, because more spectroscopic data on faint galaxies are needed in order to establish the reliability of the proposed identifications. Since almost all the stars in the sample have probably already been identified, we can conclude that the final percentage of stars in the ROSAT deep surveys should be $\leq 10\%$, significantly smaller than the percentage of stars found in the brighter EMSS survey. Vice versa, already at this preliminary stage the fraction of AGNs in the ROSAT deep surveys (61%) is higher than in the EMSS survey, and could be as high as 86% in the extreme hypothesis that all the sources still to be identified are AGNs. This shows without any doubt that AGNs are the dominant population among the X-ray sources at this flux.

What are expected to be the X-ray sources at fluxes even fainter than the current ROSAT flux limit? The most “economic” hypothesis is that they are still AGNs, fainter than those detected so far. If so, which region of the redshift–luminosity plane are they expected to fill? Figure 3, which shows redshift versus X-ray luminosity for the EMSS (small dots) and ROSAT deep surveys (large dots) AGNs, can help us in defining the region of interest. The figure clearly shows the increase in the median redshift from $\sim 0.3$ for the EMSS AGNs to $\sim 1.4$ for the ROSAT AGNs. Shanks et al. (1991) have shown that the redshift distribution of the ROSAT deep survey AGNs is similar to that of faint optically selected AGNs. Because of the presence of the redshift cutoff at $z \sim 2.5$, however, we expect that AGNs at even fainter X-ray fluxes will mainly populate the region corresponding to the faint part of the X-ray luminosity function in the redshift interval 0.4–2.5 (see area “A” in Figure 3), rather than the higher redshift region. The best fit of the differential slope of the log N – log S in the fluctuation analysis is $\sim 1.8$ (Hasinger et al. 1993); on the other hand, the slope of

| Sample               | AGNs | BL Lacs | Galaxies | Clusters | Stars | No Id. |
|----------------------|------|---------|----------|----------|-------|--------|
| ROSAT Deep Surveys   | 61%  | 1%      | 5%       | --       | 8%    | 24%    |
| EMSS                 | 51%  | 4%      | 2%       | 12%      | 26%   | 4%     |
the faint part of the X–ray luminosity function, as derived by Boyle et al. (1993), is $1.7 \pm 0.2$. The agreement between these two slopes suggests that it is quite possible, or at least consistent with the presently available data, that AGNs would provide the bulk of the X–ray sources at least down to fluxes $2 \times 10^{-16} \text{erg cm}^{-2} \text{s}^{-1}$. It is also clear from the figure that in this case most of the AGN contribution to the XRB would come from objects with X–ray luminosities smaller than $10^{44} \text{erg s}^{-1}$, similar to the X–ray luminosity of Seyfert galaxies.

As seen in Table 2, the percentage of galaxies in the ROSAT deep surveys ($\sim 5\%$) is higher than the corresponding percentage in the EMSS ($\sim 2\%$). At the limit of $S_x \sim 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}$ the number of galaxies is only $10\%$ of the number of AGNs. However, while the differential slope of the X–ray log N − log S at these fluxes is
slightly flatter than two, the corresponding slope for the optical counts of galaxies in
the B band is $\sim 2.1$ (Tyson 1988) in the range of magnitudes 18–27. The steeper
slope in the optical counts of faint galaxies implies that, even without evolution in
the ratio of X–ray to optical blue fluxes, the ratio between galaxies and AGNs might
increase toward fainter X–ray fluxes. Actually, Griffiths and Padovani (1990) have
suggested that star–forming galaxies, with some evolution, may be a major component
of the XRB. The expected X–ray log N – log S for these galaxies is strongly model
dependent. From Figure 5 in Griffiths and Padovani (1990) it is seen that, under some
assumptions, these objects might become a very substantial fraction of the faint X–ray
sources at fluxes $S_x \leq 10^{-15} \text{erg cm}^{-2} \text{s}^{-1}$. Griffiths et al. (1993) are presenting some
evidence from their preliminary optical identifications that the galaxy population is
already becoming important and of the same order as the AGN population in the flux
range $S_x = (5 - 10) \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1}$. Obviously, this result has to be confirmed
with more extensive identifications of X–ray sources at faint ROSAT fluxes.

4. AGN SPECTRA AND FITS TO THE XRB SPECTRUM

In the last few years detailed spectral data of AGNs have been obtained by GINGA
in the energy range 2–30 keV. These high quality data have changed substantially our
views on the spectral characteristics of AGNs. As shown convincingly by Pounds et al.
(1990) and Nandra (1991), the typical spectrum of Seyfert 1 galaxies shows a flattening
at $\sim 10$ keV, with respect to the observed power law slope in the range 2–10 keV. Such
a flattening has been interpreted either as a partial coverage of an underlying X–ray
power law continuum or as reprocessed emission (reflection) from thick relatively cold
matter, possibly in an accretion disk. These observations showed that the average
spectrum for these objects is very similar to the shape of the spectrum hypothesized
by Schwartz and Tucker (1988). In their illuminating paper they had shown that such a
spectrum, integrated through redshift with reasonable assumptions on the cosmological
evolution, could provide an adequate fit to the shape of the observed XRB above 3
keV.

The Ginga data have immediately led a number of groups to construct models
for fitting the XRB spectrum with various combinations of AGN spectra (see, for
example, Morisawa et al. (1990), Fabian et al. (1990), Terasawa (1991), Rogers and
Field (1991)). Although qualitatively in agreement with the overall shape of the XRB
in the energy range 3–100 keV, these first models have been shown not to be able to fit
satisfactorily the position and the width of the peak of the XRB spectrum (Zdziarski
et al. 1993a). In the same paper Zdziarski et al. discuss two models which produce improved fits to the XRB. In the first model the major contribution to the XRB is due to an as yet unobserved AGN population at high redshift, while in the second model most of the XRB emission comes from foreground AGNs. Neither model is, however, fully compatible with the observed XRB spectrum and/or with the available AGN spectral data; in particular, the average spectra of the required foreground AGNs are different from the observed ones.

Figure 4 shows the results of a fit to the XRB spectrum obtained by Comastri et al. (1993). This model takes into account the observed spectral properties of different classes of AGNs over a broad energy range and is based on the X–ray properties of AGN unified schemes (Setti and Woltjer 1989). The main ingredients of the model are the following:

a) The X–ray spectrum of Seyfert 1 galaxies is described by the reflection model, with about half of the flux of the primary spectrum reprocessed (Pounds et al. 1990).

b) As required by the adopted unified scheme, the Seyfert 2 galaxies are assumed to have the same intrinsic spectrum as the Seyfert 1 galaxies, but modified by absorption
effects (Awaki et al. 1991). A break to a steeper power law ($\alpha_E \sim 2.0$) has been introduced in the spectrum of Seyfert galaxies, as indicated by recent OSSE observations (Cameron et al. 1993).

c) For the high luminosity AGNs (i.e. quasars with $L_x > 5 \times 10^{44} \text{ erg s}^{-1}$) a single power law spectrum ($\alpha_E = 0.9$) has been assumed (Williams et al. 1992).

Given these assumptions, all of them consistent with the available observational data, the fit shown in Figure 4 has been obtained assuming an evolving volume emissivity $(nL)_{z} = (nL)_0 \times (1 + z)^{\beta}$, with $\beta = 2.75$ (Boyle et al. 1993) for $z \leq z_{\text{max}} = 3.0$. The number ratio between absorbed and unabsorbed Seyfert galaxies which is more consistent with the data is $\sim 2.5$, in good agreement with results from optical surveys (Huchra and Burg 1992). As shown in the Figure, the fit is really good over the energy range 3–100 keV; above 100 keV the computed model starts to depart significantly from the XRB data. It may be interesting to note, however, that while the data points in the energy range 20–100 keV derive essentially from the low energy experiment on HEAO–1 A4, most of the data between 100 and a few hundred keV are from the medium and high energy experiments on HEAO–1 A4: a difference in relative calibration of about (20–25)% between the low and high energy data would be enough to allow an acceptable fit at least up to $\sim 300$ keV. At even higher energies additional ingredients to the model are required in order to reproduce the observed data.

Given the good fit to the XRB spectrum shown in Figure 4, can we conclude that the problem of the production of the XRB is definitely solved? Unfortunately, the answer is still “no”. In fact, equally good fits to the XRB spectrum in the energy range 3–100 keV have recently been obtained with significantly different assumptions on the dominating AGN population by Zdziarski et al. (1993b) and Madau et al. (1993). While one of Zdziarski et al. models does not include any contribution from self–absorbed AGNs and identifies the primary sources of the XRB with AGNs detectable by soft X–ray imaging, Madau et al. model is instead dominated by type 2 objects at all energies > 3 keV.

The somewhat paradoxical conclusion from these results is that using the most recent AGN spectral data it has become too easy to obtain good fits to the XRB spectrum: very different models give equally good fits! As a consequence, a model that produces an acceptable fit to the XRB spectrum may not be the correct model. Before accepting it, one has to compare its predictions with other observational constraints, such as the soft (ROSAT) and hard (GINGA) $\log N – \log S$, the redshift distributions and the average spectra of soft and hard X–ray selected AGNs as a function of flux (see, for example, Franceschini et al. 1993). Finally, also the optical classification of X–ray selected AGNs (i.e. type 1 versus type 2) as a function of the X–ray band and flux
would provide additional constraints and would help in reducing the wide parameter space still acceptable.

5. CONCLUSIONS

The past history of the XRB has been characterized by the “hot” controversy between supporters of two alternative models: diffuse emission versus discrete sources. The recent COBE data, which have conclusively set strong upper limits to a substantial contribution of diffuse gas emission to the XRB, have finally solved this long-standing controversy.

The present controversy has now shifted focus. ROSAT deep surveys on the one hand, and high energy spectra on the other hand suggest that, indeed, AGNs can produce a very substantial fraction of the observed X-ray background over a large range of energy. However, substantially different models for the AGN population seem to provide very similar and almost equally acceptable fits to the XRB spectrum. The questions which have to be answered in the next years are therefore more related to the X-ray properties of these AGN populations rather than to the XRB itself. What are the X-ray luminosity functions and evolution of the different classes of AGNs? Are different classes of AGNs dominating different energy ranges? Are unified schemes required by or at least consistent with the X-ray data? Optical identifications of very faint ROSAT sources, coupled with the study of sources selected at higher energy, should provide some of the answers to these questions.

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