X-RAY SURVEYS

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ABSTRACT A review of recent developments in the field of X-ray surveys, especially in the hard (2-10 and 5-10 keV) bands, is given. A new detailed comparison between the measurements in the hard band and extrapolations from ROSAT counts, that takes into proper account the observed distribution of spectral slopes, is presented. Direct comparisons between deep ROSAT and BeppoSAX images show that most hard X-ray sources are also detected at soft X-ray energies. This may indicate that heavily cutoff sources, that should not be detectable in the ROSAT band but are expected in large numbers from unified AGN schemes, are in fact detected because of the emerging of either non-nuclear components, or of reflected, or partially transmitted nuclear X-rays. These soft components may complicate the estimation of the soft X-ray luminosity function and cosmological evolution of AGN.

1. INTRODUCTION

Over the past 30 years many X-ray surveys have been successfully carried out with the aim of both discovering new types of X-ray emitters and to investigate the nature of the historically first, and still very popular, source of extragalactic X-rays: the cosmic X-Ray Background (XRB). It is now widely accepted that most, and probably all, the XRB can be explained as the superposition of faint discrete sources, the vast majority of which are believed to be AGN. This result, however, is strictly valid only at soft X-ray energies (1-3 keV) where imaging telescopes, necessary to carry out sensitive surveys, until very recently could operate. The energy density of the XRB peaks at about 30 keV, so that the power emitted at 10 keV is about three times that emitted at 1 keV. The extrapolation of the low energy results to energies where most of the XRB power is emitted would in principle be straightforward if the spectra of the sources detected in the soft X-rays were the same as that of the XRB (i.e. $\alpha \sim 0.4$). It is well known that this is far from being the case, with a "canonical" 2-10 keV energy spectral index of bright AGN $\alpha \sim 0.7$ and a much steeper average AGN soft X-ray spectral slope ($\alpha \sim 1.5$, Yuan et al. 1998), that probably hardens to $\alpha \sim 1.0$ at very faint fluxes (Hasinger et al. 1993, Almaini et al. 1996). This frustrating situation, where AGN are detected in sufficient number to easily explain the XRB but with a wrong (or very wrong) spectral slope, is usually referred to as the spectral paradox. Moreover, the unified schemes of AGN predict that many obscured AGN that cannot be easily (or at all!) detected in the ROSAT band could play an important role in the contribution to the XRB at higher energies (Setti & Woltjer 1989, Madau et al. 1994, Comastri et al. 1995). In a comparison between the soft X-ray logN-logS and the counts in the
2-10 keV band, it appeared that the extrapolation of the soft sources could only contribute about one third of the observed counts if the assumed spectral slope is $\alpha = 1.0$. (e.g. Georgantopoulos et al. 1997, Cagnoni et al. 1998). This has been interpreted as possible evidence for a new population of cosmic sources that could dominate the hard X-ray counts and therefore also make up most of the XRB.

2. SOFT X-RAY SURVEYS

Recent findings from the deepest soft X-ray surveys have been reported in several papers (e.g. Hasinger et al. 1998, McHardy et al. 1998, Georgantopoulos et al. 1996, Bower et al. 1996, Boyle et al. 1995, Branduardi-Raymont et al. 1994). Here we only give a brief summary of the results and refer the reader to the literature for details. The present knowledge in this field is condensed in Figure 1 which shows the total (that is including all sources regardless to their optical identification) 0.5-2.0 keV logN-logS assembled using several data sets. These include a) the ROSAT all sky survey bright source catalog (Voges et al. 1995), b) the RIXOS survey (Mason et al. 1998), c) the deep (207 ksec) PSPC pointing and d) the ultra-deep (1.1 Msec) 0.3 $\text{deg}^2$ HRI survey of the Lockman Hole region (Hasinger et al. 1998). The integral number-count distribution is a steep function of flux until $2 \times 10^{-14}$ $\text{erg cm}^{-2} \text{s}^{-1}$ where a break to a flatter than Euclidean slope is clearly present. The
counts, reaching a value of $\sim 1000 \text{ deg}^2$ at $S = 1 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ imply that 70-80% of the XRB at 1 keV is resolved into discrete sources. Several programs for the identification of these X-ray sources are well under way. Results from the deepest surveys show that a large fraction of the faint sources are classical broad-line AGN, although the possibility that a significant fraction of narrow emission line galaxies (NELG) could be present (e.g. McHardy et al. 1998) is still debated. The identification program from the HRI ultra-deep survey, the deepest survey ever made, however, shows that the number of sources identified with NELG is small (Schmidt et al. 1998).

3. ASCA AND BEPPOSAX SURVEYS IN HARDER X-RAY BANDS.

The many important achievements in the soft X-ray band contrast with the situation at slightly higher energies (2-10 keV) where until very recently only a tiny percentage ($\approx 3\%$) of the XRB could be resolved into discrete sources. This situation significantly improved when the first satellites carrying on board instruments capable of producing X-ray images at energies as large as 10 keV (ASCA and BeppoSAX ) became operational. Several surveys have been carried out in the 2-10 keV band with ASCA. The most recent results are reported in Ueda et al. 1998 (Large Sky Survey, LSS) Ogasaka et al. 1998 (Deep Sky Survey, DSS), and Cagnoni et al. 1998, Della Ceca et al. 1998 (ASCA GIS Medium Survey), Georgantopoulos et al. 1997, (ASCA deep observations of ROSAT deep fields). The contributions of these surveys to the 2-10 keV logN-logS are shown in figure 2 together with the preliminary results from the BeppoSAX deep surveys (see below). About 30% of the XRB is now resolved into discrete sources at $S \sim 5 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$. Optical identification programs have just started; however, due to the relatively large ASCA position uncertainties for serendipitous sources, this process may require a long time. Initial results clearly indicate (Fiore et al., this volume) that samples selected in the 2-10 keV band include a quantitatively different mix of optical counterparts than that seen in the soft X-rays (e.g. Ueda et al. 1998).

3.1 THE BEPPOSAX DEEP AND SERENDIPITOUS SURVEYS

The BeppoSAX deep surveys are an on-going project to analyze in a homogeneous way the deepest X-ray images taken with the MECS instrument. At this moment the analysis covers 16 high galactic latitude fields for a total exposure of 1.3 million seconds. Initial results (Giommi et al 1998) are limited to the analysis of the central 8.5 arcminutes where the sensitivity is relatively constant and no complications due to the window support structure are present. The area covered is therefore about one degree, with a sensitivity limit of $\approx 4 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 2-10 keV band. The resulting LogN-LogS is shown in figure 2 together with several other results obtained with ASCA, Ginga and HEAO1. This project will be extended to the full MECS field of view and will also include serendipitous sources found in all public BeppoSAX fields. This type of approach has already started with the HELLAS survey in the hard part (5-10 keV) of the MECS sensitivity range (Fiore
et al. this volume). So far the HELLAS survey includes data from 120 high Galactic latitude MECS fields. Sources are searched in images accumulated between $\sim 4.5$ and 10 keV using an improved version of the DETECT routine of the XIMAGE package (see Ricci et al. 1998 and Giommi et al. 1998 for details). Correction for the energy dependent vignetting and PSF are applied to the counts that are then extracted in three bands 4.5-10, 2.5-4.5 and 1.3-2.5 keV. So far 120 MECS fields have been analyzed and 177 sources have been detected at a confidence level $> 3.5\sigma$. The source fluxes range from $4 \times 10^{-14}$ to a few $\times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 5-10 keV band. The resulting cumulative LogN-LogS is shown in figure 2.

3.2 THE BEPPOSAX GRATIS SURVEY

The GRATIS Survey (GRand Area Target acquisition Intermediate pointings Survey, Perri et al. 1998) consists of all MECS short observations that are performed as part of the (single gyro and gyro-less) procedure to point the spacecraft from one target to the following. Typical exposures are 4,000 seconds corresponding to a sensitivity of $\sim 3-4 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The logN-logS estimated from the 8 sources detected in an initial set of 32 distinct pointings covering a total of about 14 degrees of sky are shown in figures 2. At the end of the mission the GRATIS survey will cover about 50 square degrees of high galactic latitude sky. Although its sensitivity limit is only moderate the GRATIS survey has the advantage of not suffering from incompleteness at fluxes comparable (or higher) than those of the targets; a bias that is hardly avoidable in serendipitous surveys. This survey is therefore a nice complement to the deep and serendipitous surveys and provides a fair estimation of the bright end of the logN-logS.
4. A COMPARISON BETWEEN SOFT AND HARD X-RAY SURVEYS

Extrapolations of the soft X-ray source counts to the harder 2-10 keV band have been done under the assumption that all sources are characterized by a single spectral slope, generally assumed to be $\alpha = 1$. (e.g. Georgantopoulos et al. 1997, Cagnoni et al. 1998, Ueda et al. 1998). While this a fair approximation at faint fluxes (Hasinger et al. 1993) it is certainly not a good one above $2 - 3 \times 10^{-14}$ $\text{erg cm}^{-2} \text{s}^{-1}$ where the average source spectral slope is much steeper and the dispersion around the mean is large (Yuan et al. 1998). This large dispersion is most probably present at all flux levels and may be the cause of large uncertainties.

To minimize difficulties arising from these problems we have used the WGA catalog of ROSAT PSPC sources (White Giommi & Angelini, 1994) to derive the LogN-LogS taking into account the spectral slope of each detected source as estimated from its hardness ratio. The sample includes about 9,000 sources extracted from the WGA catalog according to the following criteria:

- Distance from target $> 2.5$ arcminutes
- Off-Axis angle $< 11$ or 25 $< \text{off-axis} < 45$ arcminutes (to avoid the target area and problems with reduced sensitivity due to window support structure + wobble)
- $N_H < 3 \times 10^{20} \text{cm}^{-2}$
- exposure between 4,000 and 100,000 seconds
- exclude fields centered on clusters of galaxies ($800000 < \text{ROR} < 899999$)
- $-60 < \text{Dec} < +90$ (to avoid the Magellanic Clouds region)

The detailed sky coverage for different assumptions of the power law energy index ($\alpha$) is shown in figure 3. Note the very large dependence on $\alpha$, especially for steep spectra. To compare the resulting 0.5-2 keV logN-logS with previous results we have first assumed a single spectral slope $\alpha = 1$. as in Hasinger et al. 1998. Our logN-logS is in very good agreement with the counts shown in figure 1 up to $\sim 1 \times 10^{-14}$ $\text{erg cm}^{-2} \text{s}^{-1}$; this proves that the WGA catalog, which was not originally designed for this purpose, can be successfully used for statistical studies. At very faint fluxes problems connected with source confusion and incompleteness of the WGA catalog cause an underestimation of about a factor 2 at $S(0.5 - 2\text{keV}) = 5 \times 10^{-15}$. We conclude that our logN-logS is a good representation of reality at fluxes larger than $1 \times 10^{-14}$ $\text{erg cm}^{-2} \text{s}^{-1}$. Next we have estimated the 0.5-2 keV logN-logS calculating the X-ray flux taking into account the measured spectral slope of each source (when available) and assuming an absorption equal to the amount of Galactic $N_H$ along the line of sight. For sources near the detection limit, where no reliable estimation of the hardness ratio is available, we have taken Monte Carlo simulated spectral slopes drawn from a distribution equal to that observed in good signal-to-noise ratio detections. At fluxes below $2 \times 10^{-14}$ $\text{erg cm}^{-2} \text{s}^{-1}$ we have assumed a gaussian distribution of spectral indices with a mean value of 1.0 and a dispersion of 0.4. The resulting 0.5-2 keV logN-logS is similar in shape to that of figure 1, but with a normalization that is about 25% lower. We have then extrapolated our WGA logN-logS to the 2-10 keV and 5-10 keV bands again using the measured spectral
slopes of each source as described above. We have compared the resulting counts with data from various satellites, including ASCA and BeppoSAX. In the 2-10 keV band the counts at bright fluxes (HEAO1-A2, Ginga points) are reasonably well predicted, in all other cases a deficit of a factor 2-3 is apparent, especially in the 5-10 keV band (figure 2). As a last exercise we have extrapolated the 0.5-2 keV logN-logS assuming that the spectrum of each source hardens above 2 keV by a fixed value $\Delta \alpha$. We find that for $\Delta \alpha = 0.5$ both the 2-10 and the 5-10 keV counts are reasonably well matched.

5. BEPPOSAX LONG OBSERVATIONS OF ROSAT DEEP FIELDS

To perform a direct comparison of the sources detected in the soft X-ray band and at harder energies, some long (> 100,000 seconds) BeppoSAX observations have been done on fields that were previously studied in detail with ROSAT. These include a 130,000 seconds MECS exposure of the Lockman Hole (Trümper et al. 1999), and a 91,000 seconds image of the Marano field (La Franca et al. 1999). In addition the BeppoSAX archive includes over 100 long MECS exposures (> 50,000s) of PSPC fields. The full analysis of these data will be published elsewhere, here we only report some initial results. Figure 4 shows the BeppoSAX MECS background-subtracted image of the Marano field compared to a PSPC exposure of the same region of the sky taken from the public archive. From the MECS contours overlaid on the PSPC exposure we see that nearly all the sources detected in the 2-10 keV band are also detected in the PSPC image. A similar result has been obtained with the Lockman hole data. The systematic work on the comparison between BeppoSAX and ROSAT archival data is just started; however, we can preliminarily conclude that only a very small percentage of MECS sources is not detected in ROSAT deep fields. Part, or even all, of this small percentage of non-detections can
be due to variability. These results imply that no large completely new population of sources is present above 2-3 keV. The predicted population of new or heavily cutoff sources, that was invoked by the early comparison between the soft and hard logN-logS and by XRB synthesis models, does not seem to show up in a straight-forward manner. One possible explanation for this is that the expected hard sources not only emit through the heavily cutoff nuclear component (hardly or not at all detectable by ROSAT) but also emit a small fraction of soft X-rays from non-nuclear components such a possible starburst region, or through reflection or partial transmission of nuclear X-rays.

6. CONCLUSIONS

X-ray surveys are at a point where very important results have been obtained in the technologically simple, but astrophysically complex, soft X-ray band. Only recently significant achievements could be made at higher energies where most of the XRB power is emitted and where our view into the central parts of AGN becomes clearer. Early comparisons based on simple extrapolations of the soft X-ray counts predicted the existence of a large population of previously unknown sources. We have shown that the present data indicate that the situation is more complex. Taking into proper account the observed distribution of spectral slopes we see that the hard X-ray counts are not under-predicted if a moderate spectral hardening or a non-power law spectral shape is present. Direct comparisons between X-ray images show that most of the hard sources, many of which are expected to be heavily cutoff objects that should not be visible below 2-3 keV, are instead detected at moderately
low soft X-ray fluxes. A possible explanation for these soft X-ray detections is that a second component arising from a region external to the circumnuclear absorbing material (e.g. starburst, reflection component etc.) could make these sources detectable at soft energies. Another possible cause for the detection at soft energies could be that a fraction of the nuclear radiation could escape from the AGN nucleus unabsorbed because of partial covering of the circumnuclear material. These unforeseen sources of soft X-rays could affect the estimation of the luminosity function and the cosmological evolution of AGN. More data is however clearly necessary, and this will be abundantly available with the advent of the next generation of X-ray astronomy satellites.

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