New hard X-ray emitters discovered by BAT

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We have analyzed the BAT hard X-ray survey data of the first 39 months of the *Swift* mission. To this end we developed a dedicated software based on a FFT algorithm that performs data reduction, background subtraction, mosaicking and source detection on the BAT survey data. This software is completely independent from the one developed by the *Swift*-BAT team. The large BAT field of view, the large geometrical area, and the *Swift* pointing strategy have allowed to obtain of an unprecedented, very sensitive and quite uniform sky coverage. We analyzed the BAT dataset in three energy bands (14–150 keV, 14–30 keV, 14–70 keV) obtaining a list of 967 detections above a significance threshold of 4.8 standard deviations. The identification of the source counterparts was pursued using three strategies: cross-correlation with published hard X-ray catalogues, analysis of field observations of soft X-ray instruments, cross-correlation with the Simbad databases. We derived a catalogue of 748 identified sources, of which $\sim 65\%$ are extragalactic, $\sim 25\%$ are Galactic objecs, $\sim 10\%$ are already known X-ray or gamma ray emitters whose nature has not been determined yet.

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1. Introduction

The Burst Alert Telescope (BAT; [3]) on board the *Swift* observatory [5], with its large field of view ($100° \times 60°$ half coded) and large detector area (a factor 2 greater than ISGRI) offers the opportunity for a large increase of the sample of objects that contribute to the luminosity of the sky in the hard X-rays allowing for a substantial improvement of our knowledge of the AGN and of the cosmic hard X-ray background. The first results of the BAT survey have been presented in [6, 1, 2, 8]. The latter presents a catalogue of sources detected in the first 9 months of the BAT survey data, identifying 154 extragalactic sources (129 at $|b| > 15°$).

In order to fully expoit the BAT survey archive, we developed the BATIMAGER [7], a software independent from the one developed by the Swift-BAT team[1]. A complete and detailed description of the software and its performance is presented in [7]. In this paper we present the results obtained from the analysis of 39 months of BAT sky survey.

2. Detection strategy

We have created all-sky maps in three energy bands: 14–150 keV, 14–70 keV, 14–30 keV. The source detection in the all-sky map is performed by searching for local excesses in the significance map above the absolute value of the local lowest negative excess. The source position and its peak significance are then calculated with a two dimensional Gaussian fit restricted within a region of a few pixels where the excess dominates over the noise distribution. Only detections with peak significance greater than 4.8 standard deviations are included in our list of detected sources. This threshold represents the optimal value that maximizes the number of detectable sources, maintaining at the same time an acceptable number of spurious detections. The resulting catalogues (one for each of the three energy bands) have been cross-corraleted (nearest match within the BAT error circle) in a single catalogue. We obtain a final number of 967 source candidates above our threshold in at least one of the three energy bands.

The identification of the counterpart of the BAT detections was performed following three different strategies.

a- The position of each of the 967 detected excess was cross-checked (nearest match within the BAT error circle) with the coordinates of the sources included in the INTEGRAL General Reference Catalogue[2] (v. 27), that contains 1652 X-ray emitters, and with the coordinates of the counterpart of the 48 new identifications of BAT sources already published [6, 8, 1, 2] and not included in the above catalogue. We accepted as counterpart sources candidates that were within $R = 8.4'$ from the BAT position (4 standard deviations error circle, [7]). With this method we obtain 484 identifications, 318 with $|b| > 5°$.

b- We have searched for observations from *Swift*/XRT containing the remaining (484) unidentified excess in their field. We found *Swift*/XRT observations for 167 BAT source candidates. Source detection inside these X-ray images was performed using XIMAGE (v4.4). When a source was detected inside a 6.3 arcmin error circle (99.7% confidence level) we first checked for its hardness ratio in the 0.3–10 keV range (with 3 keV as a common boundary of the two ratio bands) and for

its count rate above 3 keV. We identified a source as the counterpart of the BAT detections requiring at least one of the following conditions to be satisfied: hardness ratio > 0.5, count rate above 3 keV > 5×10^{-3} c s^{-1}. In the seven cases where two candidates, satisfying at least one of the threshold conditions, were found inside the BAT error circle, we chose as counterpart the source nearest to the BAT position. We also searched for field observations with other X-ray instruments (XMM-Newton, Chandra, BeppoSAX), finding 21 identifications, out of 26 pointings. With this method we identified 173 source counterparts.
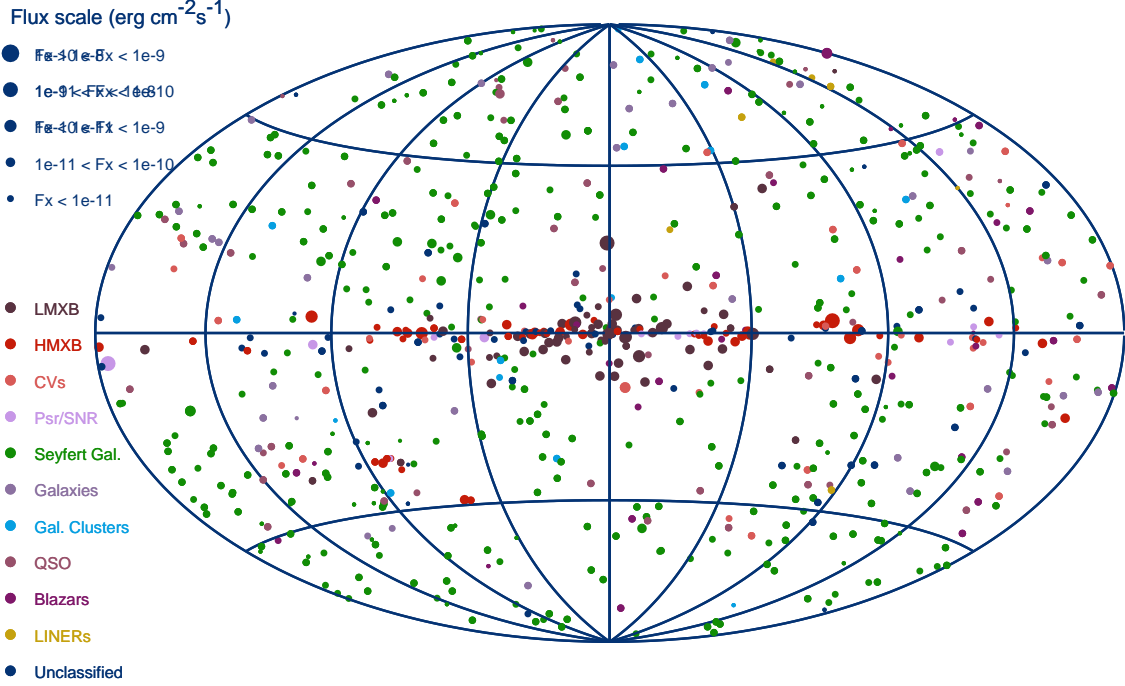

Figure 1: Map of the 748 sources detected in the BAT survey data. Different colors denote different object classes, as detailed in the legend. The size of the symbol is proportional to the source flux in the 14–150 keV band.

c- For the remaining unidentified sky map excesses (312) we searched for spatial coincidence inside an error circle of 4.2 arcmins radius (90% confidence level, [7]) with sources included in the Simbad catalogues. The size of the search radius was fixed to 4.2 arcmin in order to have a negligible number of spurious identifications (see below). We restrict our search to the following Simbad object classes: Cataclysmic variable (CV), High mass X-ray binaries (HXB), Low mass X-ray binaries (LXB), Seyfert 1 (Sy1), Seyfert 2 (Sy2), Blazar and BlLac (Bla,BLL), LINERS (LIN), for a total of 22425 objects in the Simbad database. This strategy allows us to identify 91 detections, with only one source at low Galactic latitude ($|b| > 5°$).

The number of expected spurious identifications for all three strategy has been evaluated negligible: $\sim$6 out of 748 identifications.

A set of 220 detections could not be associated with a counterpart. These source candidates have detection significance between 4.8 and 14 standard deviations and flux in the 14–150 keV band between 6.7×10^{-12} and 2.7×10^{-11} erg s^{-1} cm^{-2}. Out of 220 sources 34 are detected in

all enegy bands, 72 only in two energy bands, 201 are located above the Galactic plane ($|b| > 5°$) and are likely extragalactic objects.These candidate sources will be object of a follow-up campaign with *Swift*-XRT in the future.
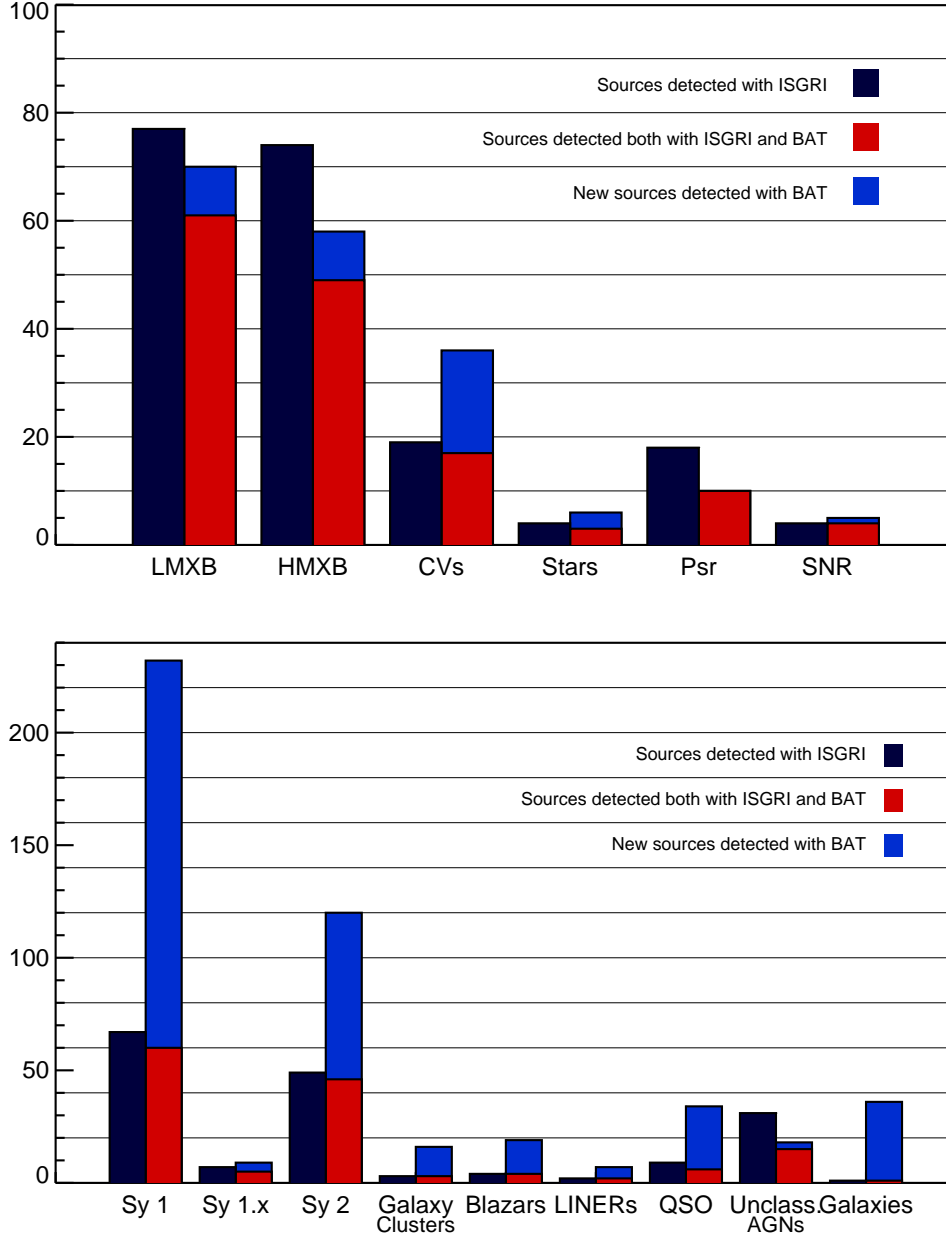
Figure 2: Comparison between the sources in our catalogue and those reported in the third ISGRI catalogue [4]. Top: Galactic sources. Bottom: Extragalactic sources.

Table 1 details the distribution of the sources in our catalogue among different object classes: $\sim 65\%$ of the catalogue is composed of extragalactic objects, $\sim 25\%$ are galactic objects, $\sim 10\%$ are already known X-ray or gamma ray emitters whose nature is still to be determined. Figure 1 shows the distribution of all the sources in our catalogue, colour-coded according to the type classification,

Class	# of sources	% in the Catalog
LXB	70	9.4
HXB	58	7.8
Pulsars	10	1.3
SN/SNR	5	0.7
Cataclysmic variables	36	4.8
Stars	6	0.8
Galactic (total)	185	24.8
Seyfert 1 galaxies	232	31.0
Seyfert 1.X galaxies	9	1.2
Seyfert 2 galaxies	120	16.0
LINERs	7	0.9
QSO	34	4.5
Blazars	19	2.5
Galaxy clusters	16	2.1
Normal galaxies	36	4.8
Unclassified AGN	18	2.4
Extragalactic (total)	491	65.4
Other types	72	9.8

Table 1: Classification of the known sources detected in the BAT survey. *Other types* includes all sources that have a catalogued counterpart but have not been classified yet.

with the size of the symbol proportional to the 14–150 keV flux (for those sources not detected in the 14–150 keV band the flux in the widest band of detection has been extrapolated into the 14–150 keV range using a Crab-like spectrum). Most of detected sources have a flux below 1×10^{-10} erg s^{-1} cm^{-2} and are located outside the Galactic plane.

We have compared this distribution with the third ISGRI catalogue [4]. The results are plotted in Figure 2. We find a significant increase in the number of detected cataclysmic variables, and a dramatic improvement in the detection of extragalactic objects, both in the nearby Universe (normal galaxies, LINERs) and at higher distances (Seyfert galaxies, QSO, clusters of galaxies). This can be explained in part with the different pointing strategy of the two instruments.

3. Summary

The large BAT field of view, the large geometrical area, and the *Swift* pointing strategy have allowed to obtain an unprecedented, very sensitive and quite uniform sky coverage that has provided a significant increase of sources detected in the hard X-ray energy band (> 10 keV).

We have derived a catalogue of 748 identified sources detected above a significance threshold of 4.8 standard deviations.

The extragalactic sources represents $\sim 65\%$ of our catalogue (491 objects), $\sim 25\%$ (181 sources) are Galactic objecs, $\sim 10\%$ (73 sources) are already known X-ray or gamma ray emitters whose nature is still to be determined. Compared with the 3rd ISGRI catalogue [4], we identify

172 more Seyfert galaxies, 35 more normal galaxies, 13 more galaxy clusters, 28 more QSOs, 15 more Blazars and 5 more LINERs.

Among the Galactic sources we significantly increase the number of cataclysmic variables detected in the hard X-ray band (19 new objects). We also detect 18 X-ray binaries that are not included in the ISGRI catalogue, even though the total number X-ray binaries we detect is lower than the sample included in the ISGRI catalogue.

The list of all identified hard X-ray emitters is going to be published in electronic form at http://www.pa.iasf.cnr.it/~cusumano/PalermoBatSurveyCatalogue.

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